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Architecture, heterogeneity, and origin of late Miocene fluvial deposits hosting the most important aquifer in the Great Plains, USA

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Abstract

The Ash Hollow Formation (AHF) of the Ogallala Group is an important sedimentary archive of the emergence of the Great Plains and it contains major groundwater resources. Stratal patterns of constituent alluvial lithofacies demonstrate that the AHF is much more heterogeneous than is commonly assumed. Very fine- to fine-grained sandstone dominate overall, chiefly lithofacies Sm (massive to locally stratified sandstone). Stacked, thin sheets of Sm with accretionary macroform surfaces are common, indicating that many sandstone architectural elements originated as compound-bar deposits in dominantly sand-bed streams. Channel forms are difficult to identify and steep cutbanks are absent. Multiple units of lithofacies Sm show dense, and sometimes deep, burrowing by insects well above water tables under ancient floodplains. Massive, pedogenically modified siltstones (Fm), which compose floodplain fine architectural elements, are subsidiary in volumetric abundance to sandstones. Paleosols in these siltstones lack evidence for well-developed B horizons and advanced stages of maturity. Thin lenses of impure carbonate and laminated mud (lithofacies association Fl + C), which appear in most exposures, are deposits of ponded water in abandoned channels. Paleosols, ponded-water elements, and large vertebrate burrows in both Sm and Fm indicate that episodes of floodplain deposition, bar accretion, and channel filling were regularly followed by intervals of nondeposition on floodplains and by channel migration and abandonment. This study documents a major down-dip change in the Ogallala Group overall, from source-proximal gravelly successions in the Wyoming Gangplank and deep, narrow paleovalley fills extending eastward into the Nebraska Panhandle. The lithofacies composition, stratigraphic architecture, and stratal dimensions of the AHF in the present study area are compatible with the planform geometries and floodplain soils of modestly-sized, sandy, low-sinuosity braided streams in Nebraska today, namely the modern North, South, and Middle Loup Rivers, rather than being the signatures of “big rivers.”

Keywords: High Plains aquifer, Ash Hollow Formation, Alluvial carbonates, Macroform deposits, Nebraska

1. Introduction

The dominantly alluvial strata of the upper Miocene Ogallala Group (Figure 1) underlie ~ 45,000 km² in eight U.S. states. There is a widespread and tacit assumption that these strata are effectively homogeneous, even though fluvial deposits are generally regarded as architecturally complex. This general failure to appreciate the lithologic heterogeneity and architecture of the Ogallala Group is paralleled by an inadequate conceptualization of the enclosing High Plains aquifer (e.g., Macfarlane et al., 2005), the source of water for ~ 30% of the USA's irrigated farmland (Dennedy, 2000). Such large gaps in understanding will likely prove problematic as water-use pressures increase in the interior of North America. Globally-calibrated paleoclimatic, paleogeographic, and

paleoecologic records within the Ogallala Group (e.g., Fox and Koch, 2004; Tedford et al., 2004), furthermore, are somewhat diminished by the comparatively rudimentary sedimentologic and stratigraphic framework. Several excellent, broad studies of the Ogallala Group have been carried out (e.g., Frye et al., 1956; Frye and Leonard, 1959; Diffendal, 1984; Diffendal et al., 1985; Swinehart et al., 1985; Diffendal, 1991) and other studies have focused on particular aspects of the unit in specific areas (Seni, 1980; Shepherd and Owens, 1981; Diffendal, 1982; Diffendal, 1983; Diffendal, 1991; Gustavson and Finley, 1985; Gustavson and Winkler, 1988; Helland and Diffendal, 1991; Helland and Diffendal, 1993; Gardner et al., 1992; Diffendal et al., 1996; McMillan et al., 2002; Macfarlane et al., 2005). Exceedingly few contemporary studies (e.g., Goodwin and Diffendal, 1987; Fielding et al., 2007), however, have

Figure 1. Stratigraphic and geochronologic context for this study. A) Composite section of Ogallala Group in Nebraska (Diffendal and Voorhies, 1994; Tedford et al., 2004); identification and stratigraphic position of Ft. Randall Formation in Nebraska is tentative. Survival of large land tortoises (4) indicates warmer-than-present climates (e.g., Holman, 1971; Voorhies, 1977), even after subregional extinction of crocodilians (cf. Mook, 1946; Tedford et al., 2004; Liggett, 1997); see text for discussion of other events. B) Location of study area within Nebraska, USA, and distribution of High Plains aquifer (shaded). C) Simplified lithostratigraphy in immediate study area; maximum thicknesses of Neogene units in parentheses.

discussed outcrop-scale lithofacies composition and architecture in the Ogallala Group in the key High Plains subdivision of Great Plains. This paper is the first to comprehensively characterize such aspects in a highly representative section of the Ash Hollow Formation, the upper part of the Ogallala Group, in the vicinity of the type sections for both units. Our results document lithologic

and stratigraphic heterogeneity of a major part of the Ogallala Group. We also begin to address questions about how physical environments and depositional systems on the Great Plains may have changed during the transition from partially wooded environments to open grasslands and from wetter to drier climates during the Late Cenozoic.

Figure 2. Late Miocene paleogeography of interior USA. Streams emerged from Rocky Mountains (1), depositing particularly coarse sediments in the Wyoming Gangplank (2). Fills of narrow, well-defined, incised paleovalleys were deposited in southern panhandle of Nebraska (3), but much broader late Miocene paleovalleys existed in the present study area (4). In east-central Nebraska (5), extensive fluvial aprons ("megafans") were deposited. Trunk streams likely flowed to ancestral Mississippi River (6). Speculative drainage pattern from Great Plains follows Galloway et al. (2011). Abbreviations of USA states are: Colorado (CO), Iowa (IA), Kansas (KS), Nebraska (NE), New Mexico (NM), Oklahoma (OK), South Dakota (SD), Texas (TX), Wyoming (WY).

2. Geological setting

Streams flowing across the present Great Plains have had strong eastward components of flow since the early Paleocene (Peppe et al., 2009; Boyd and Lillegraven, 2011; Galloway et al., 2011). The record of Cenozoic fluvial systems in Nebraska dates back to ~50–55 Ma (Voorhies, 1987a), but the vast bulk of it was deposited after 35 Ma (Swinehart et al., 1985; Diffendal and Voorhies, 1994; Larson and Evanoff, 1998; Tedford et al., 2004). Mantle buoyancy, isostasy, exhumation, and drainage evolution in the Rocky Mountain headwaters (Aslan et al., 2010; Hyndman and Currie, 2011; Karlstrom et al., 2011) was a primary driver of the deposition of the Ogallala Group by Miocene streams on the Great Plains (Figure 2). During the Miocene, the region experienced shifts toward drier climates, monsoonal rainfall, open grasslands, and a dominance of grazing ungulates as global cooling set in after the middle Miocene climatic optimum (Webb, 1977; Thomasson, 1979; Thomasson, 1991; Gabel et al., 1998; Strömberg, 2002; Strömberg, 2005; Fox and Koch, 2004; Keeley and Rundel, 2005; Darnell and Thomasson, 2007; Chapin, 2008; Kohn and Fremd, 2008; Kürschner et al., 2008; Tripathi et al., 2009; Edwards et al., 2010; Foster et al., 2012) (Figure 1, Events 1–4). Specific information about stream systems and landscapes on the Great Plains during the late Miocene is sparse. Multiple indirect lines of evidence about preglacial drainage on the Central Lowlands (Heim and Howe, 1963; Dreeszen and Burchett, 1971;

Stanley and Wayne, 1972; Witzke and Ludvigson, 1990) suggest that late Miocene drainages with paleo-headwaters in the Rockies continued from present-day Nebraska across Iowa and into the ancestral Mississippi River (Figure 2).

The Ash Hollow Formation (AHF) and age-equivalent strata are more widespread than are the older subunits of the Ogallala Group (Darton, 1899a; Darton, 1899b; Lugn, 1938; Elias, 1942; Condra and Reed, 1959; Breyer, 1981; Diffendal, 1984; Swinehart et al., 1985; Diffendal and Voorhies, 1994; Tedford et al., 2004), making it a particularly relevant focus for detailed studies. We studied a ~50 m composite section of the AHF exposed at man-made Lake C. W. McConaughy, Nebraska (Figure 3). This stratigraphic interval contains the transition between the Clarendonian and Hemphillian North American Land Mammal Ages (Leite, 1986) at ~9 Ma within the Tortonian Stage (Tedford et al., 2004). Outcrops in the study area are better and more informative than those in the nearby type areas of both the Ogallala Group and of the AHF (Darton, 1899a; Darton, 1899b; Lugn, 1938; Elias, 1942; Diffendal, 1984).

The AHF disconformably overlies a paleotopographic high on the Oligocene Brule Formation at Lake McConaughy (Figure 4) and it is chiefly exposed parallel to depositional dip and generalized regional paleoflow (Swinehart et al., 1985, their Figure 15; Diffendal, 1991; Diffendal et al., 1996; Joeckel et al., 2011). The lower contact of the AHF exhibits only ~11 m of relief across 8 km in the immediate study area, but the same contact exhibits

Figure 3. Composite section of Ash Hollow Formation (Noah) of Ogallala Group from disconformable contact with Oligocene Brule Formation (PgB) to stratigraphically highest exposures in vicinity of emergency spillway of Lake C. W. McConaughy, Nebraska. Architectural elements are channel fill (CH), floodplain fines (FF), accretionary macroform (MA), ponded water (PW). See Figure 5 for location of boxed area of index map (upper left).

Figure 5. Map of exposures on south shore of Lake McConaughy, Nebraska, showing locations of figures in this paper, as well as Kingsley Dam (KD) and Lake Ogallala (LO) downstream. See Figure 1 for location of study area in Nebraska and USA; see Figure 2 for enlarged area (white box) around emergency spillway. Roads and highways are Ogallala Beach Road (OBR), K-1 Road (K-1) and Nebraska Highway 61.

relief of 70 m or more in the subsurface nearby (Figure 4). Resistivity, spontaneous potential, and lithologic logs from six fully-penetrating boreholes along a nearby ~ 30 km transect reveal parts of at least two very broad, filled paleovalleys in the AHF on either side of the paleotopographic high at Lake McConaughy (Figure 4). Data from these boreholes also suggest the presence of large sandstone bodies within these putative filled paleovalleys (Figure 4). The stratigraphic interval overlying these sandstone

bodies, in comparison, contains a fining-upward succession of very fine- to fine-grained sandstone and subordinate siltstone.

3. Materials and methods

Exposures were photographed using a high-resolution digital camera at ground level in the emergency spillway of Lake McConaughy, and in the case of exposures along the southern shoreline,

Figure 4. Regional cross section from Lake McConaughy southward with six boreholes (32-B-75, 34-B-75, 10-A-49, 9-A-49, 7-A-49, and 3-B-75). Large sandstone bodies (1-4) are interpreted on basis of spontaneous potential, resistivity, and lithologic logs. See text for further discussion.

at high lake level from a powerboat (Figure 3 and Figure 5). These photographs were referenced by GPS coordinates and assembled into photomosaics for architectural analysis. Outcrop descriptions and measured stratigraphic sections are the basis for the classification of lithofacies and the assessment of stratigraphic architecture. The majority of the outcrops in the study area are fully accessible, but some of them have high vertical faces that can only be mapped from ground level. Significant challenges to the characterization and interpretation of the Ash Hollow Formation in the study area include: the limited size and quality of outcrops (although still very good by regional standards), generally uniform sediment textures, and widespread bioturbation. We separate architectural elements (e.g., Miall, 1985; Miall, 2006) within these outcrops on the basis of sediment composition, sediment-body geometry and relationships, and sedimentary structures.

4. Lithofacies analysis

The classification of lithofacies in this study generally follows the scheme of Miall (2006). Nine lithofacies identified in the Ash Hollow Formation (AHF) in the outcrop study area range from rare biogenic and chemical deposits of diatomite and impure carbonate (lithofacies D and C, respectively; Figure 6A, B), to laminated claystone to siltstone (Fl; Figure 6A, B) and massive coarse siltstone (Fm; Figure 7A, C), to sandstones (Sm, Sr, Sh, St; Figure 7A–C) and gravel or conglomerate (Gt; Figure 7D). The detailed characteristics of these lithofacies and their common associations are provided in Table 1.

Very fine- to fine-grained sandstone dominates outcrops of the AHF. Sm—massive to locally stratified very fine- to fine-grained sandstone (Table 1; Fig. 7A–C)—is probably the most common lithofacies. Determining the abundance of lithofacies Sm is problematic, however, because: (1) most sandstone units in the study area are very well-sorted and only weakly cemented, rendering

difficult the identification of stratification in all but the best exposures; (2) some sandstone units appear to be structureless overall but locally exhibit stratification on very close inspection; and (3) inaccessible sandstone units high in vertical exposure faces appear to be massive through field glasses at ground level, but may have some stratification that is not visible at that scale of observation (Fig. 3, Fig. 8, Fig. 9, Fig. 10, Fig. 11 and Fig. 12). Thick mudstone, shale, or claystone units are notably absent in the AHF in the study area.

Outcrops in and around the emergency spillway of Lake McConaughy are critical in our study, given their large and nearly continuous nature. These outcrops are also dominated by sheets of sandstone and they exhibit multiple distinctive features (Figure 3 and Figure 7A, Figure 8, Figure 9 and Figure 10). Outcrops to the west of the spillway along the southern shoreline of the lake are dominated by stacks of multiple sheets of sandstone (mostly lithofacies Sm, but also St and, more rarely, Sh) or stacks of thin sandstones and massive siltstones (lithofacies Fm). In all cases, individual sheets are typically a few meters or less in thickness (Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12). Much thinner—typically 50 cm or less—lenses or sheets of lithofacies C and Fl appear as minor components within these lakeshore exposures (Figure 10, Figure 11 and Figure 12). A few lakeshore exposures also contain thin gravels or conglomerates of lithofacies Gt (Table 1) or pebbly sands or sandstones of lithofacies association St + Gt (Figs. 7D, Figure 10 and Figure 12). Sharp sedimentary contacts dominate in these stacked successions. Faint redox boundaries delineating differences in sediment color—very slightly light greenish-gray vs. very slightly reddish brown—cross through entire stacks of strata along the shoreline. These boundaries must post-date deposition because they cut completely across bedding.

Intermittent, erosion-resistant carbonate-cemented ledges are generally characteristic of outcrops of the Ogallala Group, and particularly those of the AHF (e.g., Frye et al., 1956), and there

Figure 6. Lithofacies C (impure to pure carbonate) and Fl (laminated siltstone); in outcrop. A) Underside of thin bed of lithofacies C showing desiccation cracks. B) Irregular, nodular beds of C with intervening, thin strata of Fl within lithofacies association Fl + C, representative of our ponded water (PW) architectural elements. C) Lithofacies Fl, represented here by crudely laminated siltstone (1) and also lens of laminated clay (2), which is probably altered volcanic ash. D) Thin unit of Fl within a sandstone unit of lithofacies Sm (Table 1); carbonate beds (c) lie above and below.

Figure 7. Lithofacies commonly encountered in Ash Hollow Formation in study area. A) Massive siltstones with soil features (lithofacies Fm) and lithofacies association FI + C of our PW architectural element, overlain by thin gravel and sandstones of lithofacies Gt, St, and Sm (see Figure 3F). B) Fill of small channel or CH element (Figure 8A: CH2) in emergency spillway (Figure 3), showing succession of lithofacies St (with thin drape of FI) and Lithofacies Sm. Lithofacies Sm here shows platy soil structure or relict horizontal lamination (ps/rhl) and intense bioturbation (see Figure 16A, B). C) Typical appearance of sheets of Fm and Sm, interpreted as floodplain fines (FF) and channel (CH) or combined channel and accretionary macroform (CH + MA) architectural elements. D) lithofacies Gt, including very large intraformational sandstone clast (sc), filling scour cut into remnant bank of sandy channel deposits (sb). 15 cm scale at right.

has been a tendency to attribute these features to Miocene pedogenesis. Hollow-stem auger coring carried out in the study area, however, demonstrated that such ledges cannot be traced backward even a few tens of meters into hillslopes. Irregular, subspherical to vertical-cylindroidal nodules of opaline silica are also common in certain horizons within the AHF, especially in the study area and adjacent parts of western Nebraska. Vertical-cylindroidal silica nodules attain lengths of several tens of centimeters and may be loosely associated in horizons or cemented into crude beds, in many cases at stratal boundaries. These features, unlike the aforementioned carbonate-cemented ledges, must have formed coevally with late Miocene sedimentation because they are commonly engulfed by small rhizoliths and because fragments of similar siliceous material, as well as fragments of authigenic carbonate, are found as intraformational clasts. Some authors (e.g., Stout, 1971) have interpreted these vertical-cylindroidal nodules as large rhizoliths in themselves, perhaps of ancient *Yucca* spp., but a comprehensive study of them has not yet been carried out.

5. Large-scale soft-sediment deformation

Several large soft-sediment deformations, and many small-scale ones, are visible within a stratigraphic interval of ~ 10 m along the southern shore of Lake McConaughy. We focus on notable large-scale examples. In the first examples, a 10 cm-thick bed of lithofacies C that is folded upward at an acute angle through at least 1.7 m of a sediment body consisting of lithofacies Sr, FI, and C (Figure 11C, E, F). This fold lies very near the lateral truncation of its host body of sediment and it is directly adjacent to a body of sediment with contrasting characteristics (Figure 11C, E). Thin beds alongside the contact between these bodies also exhibit slight flexure (Figure 11C, E). A second antiformal structure appears in a correlative unit of lithofacies C nearby to the east (Figure 11D), but only the axial region is visible on the shoreline of the lake. This fold and the latter one may have been a single continuous fold many tens of meters in length prior to the erosion of the local outcrop.

Another outcrop exhibits a complete transition from a single, coherent 20–40 cm-thick bed of sandstone to a disrupted bed and large, detached, masses of sandstone (pseudonodules of Selley, 1969; Owen, 1995; Owen, 2003) reaching 3.8 m in length and 1.25 m in thickness (Figure 13). This outcrop also exhibits gently undulating, contorted bedding in sandstones; small siltstone flame structures extending upward into sandstone; a ruptured sandstone bed; and an unusually large, rounded, synformal structure 3.8 m in width and 1.4 m in depth (Figure 13A, B). The interior of the latter structure is a large pillow (*sensu* Stowe, 2005) of massive sandstone (lithofacies Sm) partially detached from a disrupted bed at the top of the synformal structure. Several, thin, isolated masses of sandstone and concentric relict bedding planes exist below the pillow. Large cusps (*sensu* Owen, 1995) appear on both sides of the synformal structure, and the feature is in close lateral and vertical association with multiple expressions of soft-sediment deformation in multiple units of different lithofacies.

6. Trace fossils

Fine (< 1 to 5 mm in diameter) rhizoliths are common, and in many cases pervasive, in units of sandstone (chiefly lithofacies Sm). These rhizoliths also appear in many massive siltstone (Fm), although less densely. Notably, rhizoliths a centimeter or more in diameter, potentially attributable to large, woody plants, are very rare. In many units of Sm, fine rhizoliths are particularly abundant and form thick, weakly to strongly carbonate-cemented sodlike zones below erosional contacts and exposure surfaces. We have found neither fossil tree stumps nor logs in the study area. In comparison to the Ash Hollow Formation in the present study area, silicified limbs, large logs, and stumps are common in the older Valentine Formation of the Ogallala Group, where it is widely exposed in northern Nebraska (e.g., Voorhies, 1987b). On the other hand, fossil seeds of hackberries, *Celtis* spp.—trees that are by no means limited to humid, dense forests today—are locally common in the Ash Hollow Formation (e.g., Thomasson, 1977; Thomasson, 1987), and they do appear in strata in the present study area.

Burrows, which are much less common than rhizoliths, are prominent and can readily be differentiated as: (1) small invertebrate burrows (Figure 14), and (2) very large vertebrate burrows (Figure 15). Both burrows and rhizoliths are associated with varying degrees of sediment bioturbation (see Table 1). Small (invertebrate) burrows are most prominently displayed in units of lithofacies Sm; they appear more rarely in units of lithofacies Fm, even more rarely in other lithofacies. Two morphologic subtypes are: (1) short, subvertical to horizontal burrows with prominent meniscate fills (Figure 14A, B), and (2) very short or long, vertical, tubular burrows that lack meniscate backfills (Figure 14C–E). Subtype 1 burrows are generally oriented within 0 to 5° from the vertical (Figure 14A, B) and range from 5 to 20 mm in diameter (typically 10 mm or less). In some cases they penetrate a few to several tens of centimeters below exposure surfaces, rarely as deeply as 180 cm. Very short examples of subtype 1 burrows appear below well-preserved bedding planes in lithofacies Sh, St, Fl, and C, and they typically extend no more than 20 mm in depth. Subtype 2 burrows appear in large concentrations and are usually 10 to 20 mm in diameter. A particularly prominent concentration of these kinds of burrows is in the faint channel fill in the spillway exposures (Figure 7B), in which the upper 60 cm of the fill is 70–90% bioturbated (Figure 14C–E).

Very large (vertebrate) burrows are a completely distinct group found mostly within lithofacies Sm and Fm (Figure 15), but in some cases they extend deeper from units of one of these facies into underlying units, typically of lithofacies association Fl + C. With one exception (Figure 15A), these very large burrows range in diameter from 20 to 45 cm and they extend for several tens of centimeters to a few meters. Many of the very large burrows have

orientations of 0 to 20° from the horizontal, but some have orientations within ~ 10° from the vertical. A few of the very large burrows have a slightly funnel-shaped opening with a greater diameter up dip or terminate into a slightly bulbous chamber downdip. The fills of very large burrows may be either: (1) laminated clayey silt, silt, fine-grained sand, and carbonate; or (2) massive coarse silt or fine-grained sand. In the examples containing a laminated fill, laminations range in orientation from 0° to 2° from the horizontal.

7. Discussion

7.1. Interpretations of lithofacies

Outcrops in the study area exhibit exceedingly few mud drapes, interbar mud deposits, or channel-lining muds (*sensu* Lynds and Hajek, 2006), and there is only a very minor to minor component of horizontally stratified sands (cf., Tooth, 2000; Miall, 2006). Moreover, desiccation cracks are common only in lithofacies C, Fm, and Sm, in which they are associated with the episodic evaporation of standing water in the former case and longer-term subaerial exposure and pedogenesis in the latter two cases. We surmise from these observations that flow in Ash Hollow Formation (AHF) streams was permanent, albeit variable, rather than being ephemeral.

The absence of thick mudstone, shale, or claystone units in the AHF contrasts markedly with many fluvial successions interpreted as the deposits of meandering streams (e.g., Allen, 1970; Puigdefàbregas, 1973; Puigdefàbregas and Van Vliet, 1978; Nami and Leeder, 1978; Stewart, 1983; Willis, 1993; Davies and Gibling, 2010) and even with some interpreted as the deposits of braided streams (e.g., Bentham et al., 1993). Immature paleosols, nonetheless, are common in lithofacies Fm and Sm. They consist of horizons distinguished by weak to moderate soil structure, rhizoliths, and slight reddening in some cases. The abundant fine rhizoliths, within pedogenically-modified units of Sm in particular, were most likely formed by grasses and forbs, considering the coeval emergence of grassland biomes on the Great Plains (Strömberg, 2002; Strömberg, 2005; Edwards et al., 2010). Empirical studies on modern soils have demonstrated that the abundant below-ground biomass of grass roots in a sod layer increases soil shear strength and topsoil resistance to erosion by runoff and concentrated flows (e.g., Tengbeh, 1993; De Baets et al., 2006; Zhou and Shangguan, 2007; Shit and Maiti, 2012). There is no evidence in AHF paleosols in the study area for intense chemical weathering, the extensive translocation of clay (Bt horizons: Schoeneberger et al., 2012), pervasive and intense soil redoximorphic features (Schoeneberger et al., 2012), or for the long-term vadose accumulation of secondary carbonates (Bkk or Bkm horizons: Schoeneberger et al., 2012). With respect to the latter point, a pedogenic origin for calcareous ledges in the study area is excluded by three lines of evidence: (1) most of the ledges can be traced laterally for no more than 20 m; (2) they lack the fabrics, such as authigenic nodules, laminar carbonate coatings, brecciation and recementation, that should be employed as a discerning criterion for petrocalcic horizons (e.g., Schoeneberger et al., 2012); and (3) coring indicates that they are a surficial case-hardening effect. This study does not speculate on the origins of large siliceous nodules in the Ash Hollow Formation, but observations indicate that they are synsedimentary features and that they warrant closer study.

Lithofacies, C and Fl are evidence for repeated conditions of ponded water in environments outside of throughgoing, active fluvial channels. Thin units of C and Fl lie atop or within packages of floodplain fines (lithofacies Fm), whereas others appear in stratigraphic association with sandstones that show evidence for fluvial flow. Ponded-water sediments of the AHF are inferred to have been deposited in shallow, inactive channels as parts of abandonment fills or in sloughs alongside active channels, and possibly in floodbasins as well, although it is impossible to test the

Table 1. Characteristics of Ash Hollow Formation lithofacies summarized from outcrop observations in study area.

Lithofacies	Lithology	Color	Sedimentary structures, soil structure, and other features	Trace and body fossils, with estimated bioturbation index (BI) of Pearson and Gingras (2006)	Sedimentary geometries	Contacts	Occurrence, estimated volumetric abundance (VA; 1 = minimal, 5 = major), and lithofacies associations
D	Massive diatomite	White (10YR 8/1)	—	Few to common, small, white, siliceous rhizoliths; BI = 1–4	Shallow lenses 0.1–0.6 m in thickness and extending laterally for meters to several tens of meters	Sharp upper and lower contacts	Appears in few outcrops; VA = 1
C	Impure carbonate ranging in composition from carbonate-cemented siltstone to domains of pure micrite and microspar	White (7.5YR 8/1, 10YR 8/1) to pinkish white (7.5YR 8/2)	Common fenestral fabrics in carbonate-dominated domains; common polygonal desiccation cracks on bedding planes; a few units exhibit prominent, large-scale soft-sediment deformation	Rare, millimeter-scale invertebrate burrows; rare, small pulmonate gastropods in more carbonate-rich variants; very rare mammalian and testuninid (land tortoise) bones, and, in one unit, an intact carapace; BI = 0–2	Sheets or lenses; individual units are ~1–30 cm in thickness and extend for a few to several tens of meters	Typically sharp upper and lower contacts, rarely gradational; ranges from horizons of large, irregular nodules to irregular, discontinuous to continuous beds, which form prominent ledges	Appears as thin units in lower half of composite section; VA = 2; almost always appears in FI + C in extensive, shallow, lenticular fills as much as 1.1 m in thickness, rarely appears in Sr + FI + C and Sr + C
FI	Laminated fine- to medium-grained siltstone or, very rarely, claystone (probably altered volcanic ash)	Pinkish white (7.5YR 8/2) to very pale-pale brown (10YR 7/3 and 10YR 6/3)	Polygonal desiccation cracks appear commonly upon upper bounding surfaces; thin, weak to moderate laminae, very rare current ripple forms	Vertical to subvertical, millimeter-scale invertebrate burrows range from rare to common and extend 2–10 cm below bedding planes; BI = 0–1	Almost always very thin lenses or sheets extending laterally for tens of meters	Typically sharp upper and lower contacts, rarely gradational; bed contacts range in geometry from horizontal and planar to wavy	Common in lower half of composite section; VA = 2 appears in FI + C, Sr + FI, Sr + FI + C; rarely appears as very thin, typically asymmetrical, lenses within Sm
Fm	Massive, coarse-grained siltstone to fine-sandy coarse-grained siltstone containing a few “floating” granules; rare massive silty claystone	Commonly light brown (7.5YR 6/3), pink (7.5YR 7/3, 7/4, 8/3), white (7.5YR 8/1), and pinkish white (7.5YR 8/2); rarely pale yellow (2.5YR 8/4) or reddish yellow (7.5YR 7/6); single silty claystone bed is light brown (7.5YR 6/4); distinct pedogenic reddening in upper parts of some units	Localized, very weak horizontal stratification; upper parts of individual units have common horizontal cracks a few to several millimeters in width and also exhibit medium to coarse platy soil structure; few to common vertical cracks extending downward a few to several centimeters from upper bounding surfaces; cracks are frequently filled with white authigenic carbonate or mats of white siliceous rhizoliths (Fig. 5B–D); some units also exhibit moderate fine to coarse subangular blocky soil structure	Common to abundant, millimeter-scale white siliceous rhizoliths; several examples of large invertebrate burrows as much as 50 cm in diameter; BI = 4–6	Sheets generally 0.25–2.2 m in thickness and extending for tens to hundreds of meters between outcrops	Sharp or gradational contacts; frequently overlain by lithofacies FI and C or by lithofacies Sm and St	Appears in most outcrops; VA = 4; appears as thin sheets or broad lenses in stacks of sheetlike bodies of Sm
Sr	Ripple cross-laminated very fine- to fine-grained sand or friable sandstone	Pinkish white (7.5YR 8/2) to pink (7.5YR 8/4)	Ripple cross-laminated, sets 1–5 cm in thickness	BI = 0–2	Sheets to lenses 0.2–1.9 m in thickness, extending laterally for meters to tens of meters	Sharp upper contacts, sharp to gradational lower contacts; upper contacts draped by thin, lenticular FI in some cases	Appears in several outcrops; VA = 3; dominates in Sr + FI, Sr + FI + C, and Sr + St

Sh	Horizontally stratified to very low-angle cross-stratified sand or friable sandstone, very fine- to very coarse-grained with few sub-angular to rounded granules and pebbles	White (10YR 8/1)	Thin horizontal laminae or very low-angle cross strata	BI = 0–1	Sheets 0.5–1.7 m in thickness, extending for a few meters to several tens of meters	Sharp contacts; usually underlain by Sm and overlain by Fm	Appears in several outcrops; VA = 2–3; minor component in St + Gt + Sh
Sm	Massive to weakly stratified, friable, well-sorted, very fine- to fine-grained sandstone with few granules and pebbles;	Pinkish white (7.5YR 8/2), pinkish gray (5YR 7/2), pink (7.5YR 7/4), yellowish red (5YR 5/6, 5YR 5/8), and very pale brown (10YR 8/2 and 10YR 8/3)	Common horizontal and vertical cracks filled with silt, sand, white authigenic carbonate, or mats of white siliceous rhizoliths, vertical cracks 5–20 cm in depth, associated with prominent columnar jointing; upper parts of most units exhibit weak to strong, coarse platy soil structure and many units exhibit weak to moderate, fine to coarse, granular to subangular blocky soil structure; basal parts of some units exhibit localized, faint trough cross-strata and upper parts of some units exhibit localized, faint horizontal strata and ripple cross strata; some units exhibit lateral accretion surfaces	Most units contain abundant to pervasive, fine to medium rhizoliths (see terminology for roots in Schoeneberger et al., 2012); rare, low-angle or diagonal vertebrate burrows 20–45 cm in diameter; small, 1–2 cm, vertical to horizontal invertebrate burrows; BI = 4–6	Sheets 0.15–5 m in thickness, but generally 1–2.5 m in thickness, and extending laterally for tens of meters to hundreds of meters and probably traceable as much as ~1 km between outcrops	Sharp to gradational contacts, but typically having sharp lower contacts; rounded subconical projections extending 10–30 cm below sharp lower contacts of some beds are interpreted as load structures	Appears in almost all outcrops; VA = 5—possibly most abundant lithofacies of all; stacks of thin, sheetlike units of Sm are common and sometimes include thin sheets or lenses of Fl and other lithofacies as well
St	Trough cross-stratified, well sorted to poorly sorted, fine- to very coarse-grained and pebbly friable sandstone	White (5Y 8/1) or pinkish white (7.5YR 8/2)	Sets of trough cross-strata are typically 10–40 cm thick, and very rarely as thick as 1.5 m or more; few units contain low-angle silt drapes (lithofacies Fl)	BI = 0–1; rare, abraded mammalian and testudinid bones	Sheets 0.1–1.5 m thick and extending laterally for tens of meters	Lower contacts are scoured as deeply as 40 cm; intra-formational clasts of carbonate and siltstone as much as 20 cm in diameter appear along scours; usually overlain by Sm and rarely by Sr	Appears in many outcrops; VA = 3, but is difficult to assess, although it is likely greater than those of D, C, Fl, Sr, Sh, and Gt; commonly appears as dominant member in St + Gt, but also in St + Gt + Sh
Gt	Trough cross-stratified, matrix-to clast-supported friable pebble conglomerate or gravel; matrix is poorly sorted coarse to very coarse sand	White (5Y 8/1) or pinkish white (7.5YR 8/2)	Sets of cross strata are ≤ 40 cm in thickness; clasts include common quartz, anorthosite, feldspar, granite, and other crystalline rock fragments, rare to common reworked siliceous rhizoliths, and rare to common intraformational clasts of massive siltstone, friable massive sandstone, and authigenic carbonate and rare, abraded vertebrate bones; rare horizontal to low-angle silt drapes	BI = 0–1	Elongate thin lenses to sheets 1–3 m in thickness and extending for meters to several tens of meters	Sharp, erosional lower contacts, some upper contacts are gradational into St	Appears in a few outcrops; VA = 2–3; commonly St + Gt

Figure 8. Exposure at western end of emergency spillway of Lake McConaughy immediately east of Nebraska Highway 61, represented in two consecutive panels (A, B) joining at “x” and located by panoramic photograph of north wall of spillway (C), relating location of present figure relative to Figure 9. Particular measured units, traceable across most or all of spillway are identified as u 5, u 6, u 7, and u 8 (see Figure 3B–D).

Figure 9. Northern wall of emergency spillway of Lake McConaughy, east-northeast of area represented in Figure 8. Extensive stacked sheets of mostly massive sandstone (Sm) are distinguished by accretionary macroform surfaces. Note continuation of measured units u 7 and u 8 from Figure 8 (see also Figure 3B–D). Measured unit 7 (u 7) appears to exhibit an upward gradation from St to Sm, as illustrated in Figure 7B, throughout its length; measured unit 6 (u 6 in Figs. 3B and 8A, B) is not depicted here, but is traceable under u 7 across this outcrop face.

Figure 10. Line drawings of closely spaced continuous exposures of the Ash Hollow Formation in the area of Ogallala Beach on south shore of Lake McConaughy (LMcC), produced from digital photo panoramas. (A) 83 m-long outcrop of sheetlike sandstones (mostly lithofacies Sm and minor component of St) with only a single, definite but poorly defined CH architectural element. Sheetlike sandstones in which sedimentary structures are difficult to discern are likely to consist of both MA and Ch architectural elements. Unit of trough cross-stratified sandstone and gravel or conglomerate (St + Gt) near top of section here is rare example of occurrence of that gravelly lithofacies and may be an example of architectural element GB or CH, or both. (B) Closeup view of part of A (above) showing several potholes (white arrows) at base of trough cross-stratified gravel. (C) 77 m-long outcrop showing laterally-extensive sheets of floodplain fines (architectural element FF) consisting of massive siltstones of lithofacies Fm and multiple ponded-water elements (PW) consisting of lithofacies association FI + C. (D) 44 m-long exposure face oriented at right angle to C (panels C and D join at line “x”); (E) Isolated, 31 m-long exposure face showing further continuity of sheetlike bodies of sedimentary rock. Interval “I” can be correlated with certainty across A, C, D, and E. See Figure 5 for locations and see text and Table 1 for details of lithofacies and discussion of architectural elements.

latter hypothesis with existing data. The floodplains of modern streams show patterns of sediment deposition and lateral fining into silt and clay deposits that are generally analogous to the appearance of our lithofacies FI. In modern rivers, even floods with 100-year to 500-year or greater recurrence intervals may deposit only a few millimeters or centimeters of overbank clastic sediment per event at distances of hundreds of meters to a few kilometers from trunk channels (e.g., Kesel et al., 1974; Gomez et al., 1995; Middelkoop and Asselman, 1998; Benedetti, 2003; Lecce et al., 2004; Wood and Ziegler, 2008). Likewise, although oxbow lakes on modern floodplains can experience average sedimentation rates of a few centimeters per annum, individual flood layers within their sedimentary fills may be only one to a few centimeters in thickness (e.g., Wolfe et al., 2006). Oxbow lakes on certain temperate floodplains are known to persist for a few to several thousand years (e.g., Gaigalas and Dvareckas, 2002; Gąsiorowski and Hercman, 2005; Wren et al., 2008), but the comparative thickness of ponded-water deposits in our study area suggests shallower and shorter-lived bodies of water. Accurate data about modern alluvial carbonate analogs are sparse, but the genesis of authigenic carbonate sediment in alluvial settings is generally a product of sediment provenance, the supply of calcium in dissolved and suspended load

in floodwaters, and, most importantly, of the long-term isolation of depositional sites from the input of siliciclastic sediment, rather than strictly being a result of geochemical forcing under dry climates (Truchan, 2009; Gierlowski-Kordesch et al., 2011). Carbonate-producing environments in AHF times must have been shallow, highly fluctuating, and not conducive to the development of diverse aquatic ecosystems, because they contain evidence for episodic subaerial exposure and their fossil content is nil or extremely limited, and lacking in remains from fish and other aquatic vertebrates. Moreover, there is a basis for comparison in nearly coeval Miocene strata in the region. Diatomaceous lacustrine deposits in the upper Ogallala Group of east-Central Nebraska record deeper, more persistent, and more biologically diverse lacustrine systems, but these deposits are much thicker (> 2 m), finely stratified, have a large biogenic component, and contain abundant gastropods and charophytes, as well as a few vascular plant fossils and fish remains (e.g., Joeckel et al., 2004). There are similar and approximately coeval diatomaceous lake deposits in central Kansas (Darnell and Thomasson, 2007). It is likely that the bodies of interstratified authigenic carbonate sediments (lithofacies C) and laminated siltstones (lithofacies FI) in the present study area required timeframes on the order of 10^2 years for accumulation.

Figure 11. (A&B) Diagram produced from photomosaic of exposures along south shore of Lake McCaughy showing stacks of sheetlike sandstones and some intervening floodplain fines elements (FF); see Figure 5 for locations and see text and Table 1 for details of lithofacies and discussion of architectural elements. (C) Diagram showing another exposure consisting of two likely channel fill elements: (1) a fill dominated by lithofacies association $Sr + Fl + C$ (1) and (2) another dominated by lithofacies Sm and St , with an exposure surface with filled desiccation cracks (line with downward-pointing triangles) atop. Overlying these sediments is a stack of thin, massive sandstones (3) with at least one exposure surface with filled desiccation cracks (line with downward-pointing triangles). (D) Probable continuation of folded bed of lithofacies C as plunging fold to east of outcrop depicted in "C." Position of prominently up-folded bed of lithofacies C is shown by box labeled "E," and also in photographs (E, F). (G) North-facing outcrop continuing from outcrop depicted in "C" and showing extensions of sediment bodies 1 and 2.

7.2. Interpretations of stratigraphic architecture

Exposures of the Ash Hollow Formation in the study area are dominated by stacked, laterally-extensive units, many of which are very fine- to fine-grained sandstones, in which horizontal to very low-angle contacts are the norm. We recognize in the study area, in broadly increasing order of volumetric abundance: (1) possible CS or channel-splay wing elements (*sensu* González Bonorino et al., 2010) (Figure 8), (2) GB or gravel bars, (3) PW or ponded water elements, (4) CH or channel fill elements (Figure 8, Figure 10 and Figure 12), (5) FF or floodplain fine elements (Figure 10 and Figure 11), and (6) MA or accretionary macroform elements (Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12). We group sandstone units containing any large-scale cross-stratification as accretionary macroform (MA) elements—rather than attempting to subdivide downstream (DA), lateral (LA) and downstream lateral (DLA) accretion elements as many other authors have—because: (1) the recognition of accretion surfaces is difficult in itself; (2) exposures in the study area are of moderate quality relative to the high standards of many other studies of fluvial architecture; and (2) there are no large, three-dimensional outcrops.

7.2.1. Channel fill (CH), channel splay (CS), and gravel bar (GB) elements
Channel fill, channel splay and gravel bar elements are not prominent in the study area. Channel fill (CH) elements are difficult to

identify because of the generally paleoflow-oblique to paleoflow-parallel orientation of long outcrops. The few CH elements that can be identified with confidence range in thickness from a few tens of centimeters to approximately 3.8 m. Some incompletely exposed examples may be slightly thicker, but the distribution of thickness is definitely bimodal. The widths of all of these CH elements range from several meters to a maximum of ~ 30 m, but the latter measurement was made at an unknown angle oblique to paleoflow. Other, very rare and very thin CH fills consist of lithofacies Fl alone (Figure 12). These very rare bodies of laminated siltstone are similar in shape and scale to the interbar mud deposits and channel-lining muds described in modern and ancient sandy braided systems by Lynds and Hajek (2006).

Thick CH elements representing throughgoing streamflow usually consist of lithofacies Sm or lithofacies associations $St + Gt$. Fewer thick CH elements are filled with lithofacies associations dominated by rippled sandstone (lithofacies Sr), namely $Sr + St$, $Sr + Fl$, or $Sr + Fl + C$. CH elements consisting of $Fl + C$, $Sr + Fl$, or $Sr + Fl + C$ can be considered abandonment fills because their lithofacies compositions indicate intermittent ponded-water conditions affected by episodes of weak traction flows in shallow waters, and hence overall waning flow and sediment supply. Thin (< 0.5 m) CH elements consist of lithofacies Fl or lithofacies association $Fl + C$. These thin elements can also be considered representatives of our ponded-water (PW) elements.

Figure 12. Comparative morphologies of CH and MA architectural elements; MA elements (A–C) appear to be dominated by lateral accretion and could be specifically subdivided as such. Ponded water (PW) and floodplain fines (FF) elements are also present; see Figure 5 for locations and see text and Table 1 for details of lithofacies and discussion of architectural elements.

A few, faint channel forms are exposed obliquely to paleoflow in the emergency spillway of Lake McConaughy (Figure 8 and Figure 9). The largest of these CH elements has indistinct margins and it is interpreted chiefly because it is laterally juxtaposed against GB and MA elements (Figure 8A, B, CH1). A second small CH appears to be nested within this larger channel form (Figure 8A: CH2). The fills of these channels consist of a thin lower unit of trough cross-stratified fine-grained sandstone that grades upward into massive to locally faintly stratified fine-grained sandstone (Sm) that is pervasively bioturbated near its upper contact (Figure 7B). These CH elements are laterally equivalent to a gravel bar (GB) element and an accretionary macroform (MA) element that is continuous along the north side of the emergency spillway (Figs. 8A, B, 9: u 6 and u 7). Other CH elements containing lithofacies St are visible in direct association with MA units (Figure 12A–C).

Only one potential channel splay (CS) element can be identified as a “wing” extending laterally from a CH element in the spillway (Figure 8A), although splay and levee deposits can be difficult to distinguish in vertical exposures (Ielpi and Ghinassi, in press). Gravel bar (GB) elements in the study area are limited to comparatively thin beds of lithofacies Gt and, inasmuch as we are able to ascertain, to narrow geographic tracts as well. These deposits must represent the paleochannels of perhaps one or a very few higher-order streams in the local area.

7.2.2. Accretionary macroform (MA) elements

Accretion surfaces in MA elements describe dip at 2° to 15° and commonly extend from the upper contact of a unit to its lower contact, although a few MA elements clearly contain more than one large-scale bedset (Figure 9). In a few cases, accretion surfaces can be seen to dip generally toward the axis of an associated paleochannel or CH element, as would be expected in side bars of various kinds. MA elements are most prominent in exposures within the emergency spillway (Figure 8 and Figure 9), but good examples appear elsewhere as well (e.g., Figure 12 and Figure 13). MA elements exhibit no significant lateral variability in grain size and are overwhelmingly dominated by very fine- to fine-grained sandstones of lithofacies Sm and St. MA elements also have sheet geometries and can extend for as much as ~ 300 m oblique to paleoflow, if not more in some cases. The vertical succession of trough cross-stratified sandstone (St) through weakly stratified and massive sandstone (Sm) with bioturbation, as noted in one of the CH elements (Figure 7B), was also noted in two other accessible places along the steep north wall of the emergency spillway in one of our MA elements within the same measured unit (Figure 3, Figure 8 and Figure 9, u 7), but only through excavation and close observation of faint sedimentary structures. This kind of vertical succession may be characteristic of MA units in general, although it was impossible to excavate them in most places along the shoreline of Lake McConaughy. Indeed, the upper parts of many MA elements—and in some cases the entire

Figure 13. Extensive soft-sediment deformation affecting multiple lithofacies, represented as three consecutive panels joining at “x” and “y.” See Figure 5 for location and see text for additional discussion.

element—exhibit abundant rhizoliths, cracking, and weak to moderate soil structure. Such MA elements were most probably subjected to subaerial exposure and pedogenesis after active streamflow migrated away from their locations.

7.2.3. Ponded water (PW) elements

PW elements consist of lithofacies association F1 + C (Figs. 6A–B, 7A), although we consider the single occurrence of lithofacies D to be a PW element as well. Individual beds of impure to pure carbonate are usually continuous in these thin (0.2–1 m), flat-topped or concave-upward, lenticular to apparently sheetlike bodies, which extend laterally as far as many tens of meters, and possibly in some cases for ~ 100 m. It is likely that PW elements that we have characterized as apparently sheetlike in the field are actually very broad lenses, the lateral termini of which cannot be discerned in smaller outcrops. The upper and lower contacts of PW elements are typically sharp. PW elements display little if any lateral variability and either fine upward slightly or show no salient vertical trend in grain size. PW elements are enclosed within FF elements, or they sit at the top of an apparent upward-fining trend. PW elements also exist within stacked sheets of sandstone and within indistinct CH elements consisting of sandstones (Figs. 7A, 8A–B, Figure 10, Figure 11 and Figure 12). PW elements represent deposition in shallow abandoned channels or sloughs separated at a distance from active fluvial channels. The rare association of rippled sands (lithofacies Sr) with ponded water lithofacies C and F1 indicates deposition by episodic overbank floods, distal crevasse splays, or the temporary rejuvenation of throughgoing weak traction flows in secondary or abandoned fluvial channels.

7.2.4. Floodplain fines (FF) elements

Floodplain fines (FF) elements are single units or two to three stacked units of massive, pedogenically modified siltstone of lithofacies Fm. They attain thicknesses of a few meters and extend laterally for tens to hundreds of meters. Units of Fm display widespread evidence for ancient soil development in the form of subangular blocky to prismatic soil structure, cracking, slight reddening, rhizoliths, and burrowing by invertebrates and vertebrates. Paleosols in FF elements lack horizons diagnostic of truly long-term pedogenic processes. Although prominent soil redoximorphic features are lacking, faint, bed-crossing color boundaries in stacks of sediments (including FF elements) likely relate to postburial water-table positions.

7.2.5. Stacked thin sheets of sandstone

Stacked, thin sheets of sandstone along the shores of Lake McConaughy are more difficult to interpret because they are revealed only in low (≤ 10 m) exposures oriented subparallel to overall paleoflow. Few clear-cut sedimentary structures can be found in the sandstone sheets themselves, but the very few gravel sheets associated with them clearly exhibit trough cross stratification. Furthermore, many of the sandstones contain rhizoliths in variable concentrations and some of them have upper contacts distinguished by filled desiccation cracks, columnar jointing, and weak soil structure, all of which indicate episodes of subaerial exposure and pedogenesis. These shoreline exposures of stacked sandstones are likely to be analogous to the thicker and more laterally-extensive succession of accretionary macroform (MA) elements and the indistinct, shallow channel fill (CH elements) exposed in

Figure 14. Invertebrate burrows in Ash Hollow Formation. (A) Thoroughly bioturbated sandstone in upper part of channel fill (see Figure 7B) with abundant *Naktodemasis* burrows (arrows). (B) Individual *Naktodemasis* burrow with meniscate fills from same unit. (C) Short burrow extending from pebbly sandstone (1) downward into rippled fine-grained sandstone (2). (D) Long, vertical burrows (arrows) extending deeply into massive sandstone of lithofacies Sm, which also exhibits moderate soil structure. (E) Closeup of two (1, 2) long, vertical burrows from D, showing blocky soil structure (bs) and coatings of siliceous rhizoliths and carbonate (sc) along ped faces.

the emergency spillway. Similarly, stacked thin sandstones (St and Sm), massive siltstones (Fm), and tabular bodies of lithofacies association Fl + C, which are also exposed along the lakeshore, are interpreted as fining-upward sediment packages consisting, respectively, of: (1) thin MA elements and probably a few laterally-equivalent shallow CH elements, (2) PW elements that are abandonment fills of very shallow channels, and (3) overlying FF elements. We speculate that the thinnest sandstones within these stacked successions may be CS elements, rather than MA or CH elements (cf., Rust et al., 1984; O'Brien and Wells, 1986; Mjøs et al., 1993; Smith and Pérez-Arlucea, 1994; Willis and Behrensmeier, 1994; Donseelaar and Overeem, 2008), although we have identified no clear-cut sedimentary evidence in that regard.

7.3. Vertical trends and fluvial stories

In our measured stratigraphic sections, upward-fining trends involving more than one lithofacies range in thickness from 1.0 to 4.5 m (Figure 3). As a rule, these multi-lithofacies upward-fining trends begin at basal erosional surfaces and consist of one of the following upward transitions: (1) Gt, St, or Sh to Sm; (2) Sm to

Fl + C; (3) Sm to Fm; or (4) Sm to multiple units of Fm and Fl + C. The contacts between the successive lithofacies in these packages are generally sharp, although not necessarily erosional. Very weak fining-upward trends from fine- to very fine-grained sandstone into very fine-grained or silty sandstone can also be identified within some individual units of lithofacies Sm (Figure 3). The most instructive association of sediment bodies visible in outcrop is the one including elements CH and GB, as well as an extensive, sheetlike, and laterally-equivalent MA element in the emergency spillway (Figure 8 and Figure 9: u 7) that may chiefly record lateral accretion. The maximum thickness attained by this fluvial story is 3.8 m.

Overall, we distinguish fluvial stories on the basis of the thicknesses of: (1) erosionally-bounded fining upward trends in interpreted channel and bar sediments of lithofacies Gt, Sh, and Sm; (2) MA elements bounded by major horizontal or very low-angle erosion surfaces; and (3) single units of Sm that show upward increases in rhizoliths and weak soil structure, and in multiple cases subtle fining-upward trends into silty or finer-grained sandstone, to an overlying erosion surface. In the emergency spillway, the maximum thicknesses of well-exposed multi-lithofacies fining-upward

Figure 15. Vertebrate burrows (arrows) in Ash Hollow Formation. (A) Possible carnivoran burrow extending from massive sandstones of basal Ash Hollow Formation (Noah) into siltstones of Brule Formation (Pgb). (B–D) Examples of large vertebrate burrows, interpreted as rodent burrows, from lithofacies Fm and Sm.

units or of erosionally-bounded MA units surfaces range from 1.5 to 5.5 m in thickness, although the majority of these trends are 2.5 to 5 m in thickness. Erosionally-defined fining-upward trends in channel and bar deposits elsewhere in the study area range from approximately 2.5 to 4.0 m in thickness. Single and apparently erosionally bounded units of Sm with very slight upward-fining trends or with upward increases in rhizolith density attain thicknesses of as much as 5 m. From all of these measurements, we interpret the thickness of fluvial stories in the Ash Hollow Formation as being 1.5 to 5.5 m.

7.4. Significance of large-scale soft-sediment deformation

Large-scale soft-sediment deformation is common in some modern and ancient alluvial sequences (e.g., Bernard and Major, 1956; Stanley et al., 1966a; Stanley et al., 1966b; Leeder, 1987; Flint, 1983; Flint, 1986; Owen, 1995; Taşgin et al., 2011). The morphology of many of the soft-sediment deformation structures described herein is compatible with a scenario in which layers of sediment are fluidized under the load of overlying sediments (e.g., Owen, 1987; Owen, 1995; Bezerra et al., 2005; Moura-Lima et al., 2011). Soft-sediment deformations in fluvial sediments are either: (1)

the results of fluctuations in stage, bank slumps, changing flow regimes on streambeds, frictional drag, and other in-system processes (autogenic or autokinetic); or (2) triggered by seismicity, climate, and other out-of-system drivers (allogenic or allokinetic). A prominent synsedimentary fold and nearby features (Figure 11C–F) in our study area suggest that significant syndepositional slumping occurred along the contact between the hosting sediment body and the adjacent body. The contact is likely to be either a curvilinear plane of failure near the margin of a channel or the channel margin itself (Figure 11E). Owen and Moretti (2011) concluded that seismic triggering of soft-sediment deformation has commonly been applied too casually and that the “zonation of complexity with distance from a fault” is the only truly reliable criterion for it. We were unable to identify any geologic structures in direct association with the sediments we describe and almost nothing is known about Miocene tectonism in the study area. Therefore, the soft sediment deformation features that we describe could be interpreted as purely autogenic (autokinetic) in origin. The existence of multiple structures that affect more than one lithofacies (Figure 13) and the existence of essentially continuous deformation in one exposure, however, compel us not to dismiss the possibility of a seismic trigger for large-scale soft sediment deformation

in the Ash Hollow Formation, particularly considering that all of the features that we describe exist in a comparatively narrow stratigraphic interval (cf. Santos et al., 2012).

7.5. Significance of trace fossils

Invertebrate bioturbation is densest in multiple units of lithofacies Sm (Figs. 7B, 14A–E). Concentrated burrows with meniscate backfills (Figure 14A, B) represent the ichnogenus *Naktodemasis*, which probably represents the activity of burrower bugs, cicada nymphs, or soil-dwelling beetle larvae in moderately to well-drained soils (Counts and Hasiotis, 2008; Smith and Hasiotis, 2008; Smith et al., 2008). The other invertebrate burrows described herein (Figure 14C–E) are less clear in their affinities, but they too must have been excavated above an ancient water table by insects.

Fossil rodent burrows described by multiple authors (e.g., Barbour, 1892; Wood and Wood, 1933; Martin and Bennett, 1977; Joeckel et al., 2004; Gobetz, 2006; Gobetz and Martin, 2006; Joeckel and Tucker, 2013) from other Cenozoic strata on the Great Plains. These traces bear easily recognizable similarities in size, architecture, and ornamentation to those produced by modern rodent burrows excavated in vadose environments. Almost all of the very large burrows that we encountered in the Ash Hollow Formation are likewise attributable to rodents, but one burrow (Figure 15A) is distinctly different from the others. Its larger diameter and great length (cf., Criddle, 1947; Fuller, 1989; Mech and Packard, 1990),

coupled with its simple architecture and low-angle orientation (cf., Egoscue, 1956; Cutter, 1958; Anderson and Richardson, 2005), make it similar to the burrows of multiple living carivorans described in the literature.

7.6. Comparison with modern rivers in the enclosing region

Flood-stage depths for the largest sandy rivers in Nebraska, the North Platte (1.2–2.3 m) and South Platte rivers (2.7–3 m); the North Loup, South Loup, Middle Loup (Figure 16), and Loup rivers (1.5–3.2 m); the Niobrara River (1.8 m), and the Republican River (2.1–4.3 m), are all less than 5 m (National Weather Service, undated). The active channel belts of the two Platte rivers were 500–1500 m in width in early historic times and they exhibited high braid indices (Joeckel and Henebry, 2; Horn et al., 2012). Archival aerial photographs indicate show fully active compound bars 40 to 150 m in length in the North Platte River at the end of the 1930s, prior to the narrowing of the channel. The Loup rivers exhibit lower braid indices than the pre-engineering Platte rivers, and they also assume higher-sinuosity planforms with some point bars in short stretches. Most in-channel and alternate bars are 50 to 400 m in length, and most unit bars are 100 m or less in length (Figure 16). The active channels of the Loup rivers are 100–350 m in width in most places today, although they have narrowed slightly since the 1930s. The sizes of AHF sandstone bodies attributable to channels and macroforms (Table 1) are comparable

Figure 16. Valley of Middle Loup River near Boelus, Nebraska, showing Holocene channel belt (HCB) and floodplain (FP). Channel has a low braid index, alternate bars (ab), migrating unit bars (ub), and carries fine- to coarse-grained sand. Most sloughs (s) are seasonal, but pond (p) and larger slough (sp) are semi-permanent. Soils in HCB are Mollisols in sand and silty sand with A–C and A–AC–C profiles; soils on floodplain (FP) are Mollisols on sandy silt (United States Department of Agriculture Natural Resources Conservation Service, undated).

to these measurements from modern-analog streams. The comparative rarity of well-defined channel forms in the AHF and the extensiveness of sandstone sheets with accretionary macroform surfaces, likewise, are compatible with the motif of broad, sandy channel belts of other low-sinuosity, braided streams in Nebraska (cf., Bridge et al., 1998; Skelly et al., 2003). Sandy, braided rivers in modern Nebraska collectively exhibit considerable variability in planform in time and space, and it is wise to bear this plasticity in mind when interpreting ancient Great Plains rivers.

Common PW architectural elements in the AHF are evidence for sedimentation from suspension or solution in shallow abandoned channels and sloughs, but there is only a limited basis for comparison in modern alluvial environments in Nebraska. Large lakes were absent on the Platte rivers in historic times (cf., Joeckel and Ang Clement, 2005; Joeckel and Henebry, 2008; Horn et al., 2012). The Holocene channel belt of the Middle Loup River, however, exhibits small (≤ 25 m in width and ≤ 1200 m in length) abandoned channels filled with standing or very slow-moving water (Figure 16), and these features are at least partially analogous to the ancient depositional environments of PW architectural elements described herein. The consistent simplicity (A–C horizonation) of sandy to silty Entisols and Mollisols that dominate the Holocene channel belts and valley floors of the Loup rivers and other streams Nebraska today (Figure 16) is also analogous to observations of paleosols in the AHF. Indeed, Holocene alluvial fills and paleosols in the central USA overall exhibit only weakly to moderately developed soils formed over timescales of a few thousands of years (cf., Arbogast and Johnson, 1994; Baker et al., 2000).

7.7. Comparison with Ogallala Group strata up- and downdip

The deposits described herein differ significantly from the Ogallala Group updip to the west. Some 100–150 km westward of the present study area, approximately coeval paleovalley fills are comparatively narrower, steep-walled, and exceed 50 m in depth; they contain gravels derived from crystalline sources upstream, locally-derived boulders, and even paleovalley-side megaclasts (e.g., Stout, 1971; Diffendal, 1982; Diffendal, 1983; Diffendal, 1984; Diffendal et al., 1985; Swinehart et al., 1985, Figure 16). Even farther updip, Shepherd and Owens (1981) interpreted source-proximal, gravel- and boulder-bearing successions within the Ogallala Group under the Gangplank of eastern Wyoming as alluvial fan and “playa” deposits. In contrast, the Ash Hollow Formation (AHF) fluvial

systems in the present study area deposited extensive sheets of finer sediment without the constriction of deeply incised valley walls. There may be additional contrasts in fluvial architecture in the Ogallala Group even farther eastward (Swinehart et al., 1985; Diffendal, 1991; Souders, 2000; Joeckel et al., 2007; Galloway et al., 2011, Figure 17; Korus and Joeckel, 2011).

8. Conclusions

This study documents a pattern of heterogeneity in strata of the Ogallala Group in terms of sediment texture, lithofacies, vertical succession, and architecture. In its broader sense, it also identifies a major downdip change in the Ogallala Group across the western Great Plains. The AHF paleostreams represented by the deposits at Lake McConaughy were certainly not “big rivers” (sensu Potter, 1978; Fielding, 2008). Rather, stratal measurements indicate that these late Miocene streams were comparable in their depths to the major streams crossing the northern Great Plains today. Considering the constraints of Miocene paleogeography and paleoclimate (e.g., Chapin, 2008) and their likely effects on runoff and sediment transport, we propose that a large part of the Miocene fluvial record on the Great Plains could have been laid down by streams of similarly modest sizes.

In further similarity to modern rivers on the central to northern Great Plains, and specifically in Nebraska, the AHF paleorivers carried a bedload dominated by sand and they deposited negligible mud. This absence of mud may be the result of many factors, potentially including a lack of abundant secondary clay minerals and heavily weathered regolith in the paleo-drainage basin. The unspecified occurrence of accretion surfaces in AHF strata and the apparent lack of preservation of steep ancient cut banks in the studied exposures render problematic an interpretation of single-channel meandering paleostreams with point bars. It is likelier that the AHF paleostreams were similar in planform to the modern Loup rivers, and likely some other sandy braided streams (e.g., Bridge et al., 1998), in present-day Nebraska. Ancient pedogenic features in massive siltstones and massive to locally stratified sandstones, chiefly included in our FF and MA elements, indicate that episodes of floodplain deposition, bar accretion, and channel filling during AHF times were regularly followed by intervals of nondeposition on floodplains and by channel migration and abandonment. Subsequent soil development, however, did not involve

Figure 17. Schematic stratigraphic model of Ash Hollow Formation (Ogallala Group) in study area, showing typical succession and dimensions of key surfaces and architectural elements: ponded water (PW), floodplain fines (FF), accretionary macroform (MA), channel (CH), gravel bar (GB). Overall, architectural elements are laterally extensive. Succession is dominated by sandstones of MA and CH architectural elements; gravelly sediments of architectural element GB are a very minor component. Potential pathways for the vertical movement of groundwater between stacked sandstone bodies include incised channel bodies and zones where PW and FF elements are absent or discontinuous.

long-term ($\geq 10^4$ a) and intense processes of weathering and accumulation. Similarly, PW elements in the AHF, some of which lie atop or in between FF elements, probably represent accumulation times on the order of 10^2 – 10^3 years by comparison with modern analogs. Nevertheless, the deep extensions of both vertebrate and invertebrate burrows in AHF strata indicate that late Miocene water tables in the study were generally not within 1.0 to 1.5 m of paleo-landsurfaces when these rodents were burrowing.

The heterogeneity of AHF alluvial lithofacies and the architecture of the sediment bodies they compose must exert a first-order control on groundwater flow in the AHF, but to date there has been little consideration of this complexity in assessments of the enclosing High Plains aquifer in Nebraska. Lithologic and architectural variations of the sort that we document clearly have the potential to create major lateral and vertical variations in permeability and yield, as well as marked changes in the responses of groundwater levels to drawdown across areal scales of tens to hundreds of square kilometers (cf. Macfarlane et al., 2005). These points must be considered in future assessments of the High Plains aquifer in Nebraska, the locus of nearly three-quarters of the total groundwater in that aquifer, as well as in surrounding parts of the Great Plains.

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References

- Allen, J.R.L., 1970. Studies in fluvial sedimentation: a comparison of fining-upward cyclothems, with special reference to coarse-member composition and interpretation. *Journal of Sedimentary Petrology* 40, 298–323.
- Anderson, M.D., Richardson, P.R.K., 2005. The physical and thermal characteristics of aardwolf dens. *South African Journal of Wildlife Research* 35, 147–153.
- Arbogast, A.F., Johnson, W.C., 1994. Climatic implications of the Late Quaternary alluvial record of a small drainage basin in the Central Great Plains. *Quaternary Research* 41, 298–305.
- Aslan, A., Karlstrom, K.E., Crossey, L.J., Kelly, S., Cole, R., Lazear, G., Darling, A., 2010. Late Cenozoic evolution of the Colorado Rockies: evidence for Neogene uplift and drainage integration. In: Morgan, L.A., Quane, S.L. (Eds.), *Through the Generations: Geologic and Anthropogenic Excursions to the Rocky Mountains from Modern to Ancient*. Geological Society of America Field Guide, 18, pp. 21–54.
- Baker, R.G., Fredlund, G., Mandel, R.D., Bettis III, E.A., 2000. Holocene environments of central Great Plains; multi-proxy evidence from alluvial sequences, southeastern Nebraska. *Quaternary International* 67, 75–88.
- Barbour, E.H., 1892. Notice of new gigantic fossils. *Science* 19, 99–100.
- Benedetti, M.M., 2003. Controls on overbank deposition in the Upper Mississippi River. *Geomorphology* 56, 271–290.
- Bentham, P.A., Talling, P.A., Burbank, D.W., 1993. Braided stream and flood-plain deposition in a rapidly aggrading basin: the Escanilla formation, Spanish Pyrenees. In: Best, J.L., Bristow, C.S. (Eds.), *Braided Rivers*. Geological Society, London, Special Publication, 75, pp. 177–194.
- Bernard, H.A., Major, C.F., 1956. Shell's (Bernard's) alluvial point bar model: sedimentary features diagnostic of alluvial point bar sands. EPR Memorandum Report 23. AAPG Search and Discovery Article #60003 (1999).
- Bezerra, F.H.R., da Fonseca, V.P., Vita-Finzi, C., Lima-Filho, F.P., Saadi, A., 2005. Liquefaction-induced structures in Quaternary alluvial gravels and gravelly sediments, NE Brazil. *Engineering Geology* 76, 191–208.
- Boyd, D.W., Lillegraven, J.A., 2011. Persistence of the Western Interior Seaway: historical background and significance of the ichnogenus *Rhizocorallium* in Paleocene strata, south-central Wyoming. *Rocky Mountain Geology* 46, 43–69.
- Breyer, J.A., 1981. The Kimballian land-mammal age: mene, mene, tekell, upharsin (Dan. 5:25). *Journal of Paleontology* 55, 1207–1216.
- Bridge, J., Collier, R., Alexander, J., 1998. Large-scale structure of Calamus River deposits (Nebraska, USA) revealed using ground-penetrating radar. *Sedimentology* 45, 977–986.
- Chapin, C.E., 2008. Interplay of oceanographic and paleoclimate events with tectonism during middle to late Miocene sedimentation across the southwestern USA. *Geosphere* 4, 976–991.
- Condra, G.E., Reed, E.C., 1959. The geologic section of Nebraska. University of Nebraska-Lincoln, Conservation and Survey Division, Nebraska Geological Survey, Bulletin, 14a, pp. 1–82.
- Counts, J.W., Hasiotis, S.T., 2008. Neoichnological experiments with masked chafer beetles (Coleoptera: Scarabaeidae): implications for backfilled continental trace fossils. *Palaios* 24, 74–91.
- Criddle, S., 1947. Timber wolf den and pups. *The Canadian Field-Naturalist* 61, 115.
- Cutter, W.L., 1958. Denning of the swift fox in northern Texas. *Journal of Mammalogy* 39, 70–74.
- Darnell, M.K., Thomasson, J.R., 2007. First equid remains from the late Miocene *Prolithospermum johnstonii*–*Nassella pohlii* assemblage zone stratotype locality, Ellis County, Kansas. *Transactions of the Kansas Academy of Sciences* 110, 10–15.
- Darton, N.H., 1899a. Relations of Tertiary Formations in the western Nebraska region. *American Geologist* 23, 94.
- Darton, N.H., 1899b. Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian. U.S. Geological Survey 19th Annual Report, Part 4, Hydrography, pp. 719–814.
- Davies, N.S., Gibling, M.R., 2010. Paleozoic vegetation and the Siluro-Devonian rise of fluvial lateral accretion sets. *Geology* 38, 51–54.
- De Baets, S., Poesen, J., Gyssels, G., Knappen, A., 2006. Effects of grass roots on the erodibility of topsoils during concentrated flow. *Geomorphology* 76, 54–67.
- Dennehy, K.F., 2000. High Plains regional ground-water study. U.S. Geological Survey Fact Sheet, FS-091-00pp. 1–6.
- Diffendal Jr., R.F., 1982. Regional implications of the geology of the Ogallala Group (upper Tertiary) of southwestern Morrill County, Nebraska, and adjacent areas. *Geological Society of America Bulletin* 93, 964–976.
- Diffendal Jr., R.F., 1983. Megaclasts in alluvial fills from the Ogallala Group (Miocene), Banner, Kimball, and Morrill counties, Nebraska. *Contributions to Geology* 22, 109–115.
- Diffendal Jr., R.F., 1984. Comments on the geologic history of the Ogallala Formation in the southern panhandle of Nebraska. In: Sweazy, R.M., Wyatt, A.W. (Eds.), *Proceedings of the Ogallala Aquifer Symposium II*, Lubbock, Texas, pp. 194–215.
- Diffendal, R.F., Jr., 1991. Geologic map showing configuration of the bedrock surface, North Platte 1°× 2° Quadrangle, Nebraska. U.S. Geological Survey Miscellaneous Investigations Series I-2277, Scale 1:250,000.
- Diffendal Jr., R.F., Voorhies, M.R., 1994. Geologic framework of the Niobrara river drainage basin and adjacent areas in South Dakota generally east of the 100th meridian west longitude and west of the Missouri River. Nebraska Geological Survey Report of Investigations, 9, pp. 1–17.
- Diffendal Jr., R.F., Swinehart, J.B., Gottula, J.J., 1985. Characteristics, age relationships, and regional importance of some Cenozoic paleovalleys, southern Nebraska Panhandle. *TER-QUA Symposium Series* 1, 21–32.
- Diffendal Jr., R.F., Pabian, R.K., Thomasson, J.R., 1996. Geologic history of Ash Hollow Park, Nebraska. Educational Circular 5a. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, pp. 1–36.
- Donselaar, M.E., Overeem, I., 2008. Connectivity of fluvial point-bar deposits: an example from the Miocene Huesca fluvial fan, Ebro Basin, Spain. *AAPG Bulletin* 92, 1109–1129.
- Dreeszen, V.H., Burchett, R.R., 1971. Buried valleys in the lower part of the Missouri River Basin. Pleistocene stratigraphy of the Missouri River Valley Along the Kansas–Missouri border. Kansas Geological Survey Special Distribution Publication, 53, pp. 21–25.

- Edwards, E.J., Osborne, C.O., Strömberg, C.A.E., Smith, S.A., C4 Grasses Consortium, 2010. The origins of C4 grasslands: integrating evolutionary and ecosystem science. *Science* 328, 587–591.
- Egoscue, H.J., 1956. Preliminary studies of the kit fox in Utah. *Journal of Mammalogy* 37, 351–357.
- Elias, M.K., 1942. Tertiary prairie grasses and other herbs from the High Plains. Geological Society of America, Special Paper 41, 1–176.
- Fielding, C.R., 2008. Sedimentology and stratigraphy of large river deposits: recognition in the ancient record and distinction from 'incised valley fills'. In: Gupta, A. (Ed.), *Large Rivers: Geomorphology and Management*. John Wiley and Sons, Chichester, pp. 97–113.
- Fielding, C.R., LaGarry, H.E., LaGarry, L.A., Bailey, B.E., Swinehart, J.B., 2007. Sedimentology of the Whiteclay Gravel Beds (Ogallala Group) in northwestern Nebraska, USA: structurally controlled drainage promoted by Early Miocene uplift of the Black Hills Dome. *Sedimentary Geology* 202, 58–71.
- Foster, G.L., Lear, C.H., Rae, J.W.B., 2012. The evolution of pCO₂, ice volume and climate during the middle Miocene. *Earth and Planetary Science Letters* 341–344, 243–254.
- Fox, D.L., Koch, P.L., 2004. Carbon and oxygen isotopic variability in Neogene paleosol carbonates: constraints on the evolution of the C4-dominated grasslands of the Great Plains, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* 207, 305–329.
- Frye, J.S., Leonard, A.B., 1959. Correlation of the Ogallala Formation (Neogene) in western Texas with type localities in Nebraska. University of Texas Bureau of Economic Geology, Report of Investigations, 39 (46 pp.).
- Frye, J.C., Leonard, B., Swineford, A., 1956. Stratigraphy of the Ogallala Formation (Neogene) in northern Kansas. *Kansas Geological Survey Bulletin* 118.
- Fuller, T.K., 1989. Denning behavior of wolves in north-central Minnesota. *American Midland Naturalist* 121, 184–188.
- Gabel, M.L., Backlund, D.C., Haffner, J., 1998. The Miocene macroflora of the northern Ogallala Group, northern Nebraska and southern South Dakota. *Journal of Paleontology* 72, 388–397.
- Gaigalas, A., Dvareckas, V., 2002. The evolution of river valleys in Lithuania from deglaciation to recent changes and data from the sediment infill of oxbow lakes. *Netherlands Journal of Geology* 81, 407–416.
- Galloway, W.E., Whiteaker, T.L., Ganey-Curry, P., 2011. History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin. *Geosphere* 7, 938–973.
- Gardner, R.L., Diffendal Jr., R.F., Williams, D.F., 1992. Stable isotope composition of calcareous paleosols and ground-water cements from the Ogallala Group (Neogene), western Nebraska. *Contributions to Geology, University of Wyoming* 29, 97–109.
- Gąsiorowski, M., Hercman, H., 2005. Recent changes of sedimentation rate in three Vistula oxbow lakes determined by 210Pb dating. *Geochronometria* 24, 33–39.
- Gierlowski-Kordesch, E., Finkelstein, D., Truchan Holland, J.J., Kallini, K.D., 2011. Carbonate lakes on distal perennial river floodplains. *Geological Society of America Abstracts with Programs* 43, 62.
- Gobetz, K.E., 2006. Possible burrows of mylagaulids (Rodentia: Aplodontioidea: Mylagaulidae) from late Miocene (Barstovian) Pawnee Creek Formation of northeastern Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology* 237, 119–136.
- Gobetz, K.E., Martin, L.D., 2006. Burrows of a gopher-like rodent, possibly *Gregorymys* (Geomyoidea: Geomyidae: Entoptychinae), from the early Miocene Harrison Formation, Nebraska. *Palaeogeography, Palaeoclimatology, Palaeoecology* 237, 305–314.
- Gomez, B., Mertes, L.A.K., Phillips, J.D., Magilligan, F.J., James, L.A., 1995. Sediment characteristics of an extreme flood: 1993 upper Mississippi River valley. *Geology* 23, 963–966.
- González Bonorino, G., Colombo, F., Abascal, L., 2010. Architecture of an Oligocene fluvial ribbon sandstone in the Ebro Basin, North-eastern Spain. *Sedimentology* 57, 845–856.
- Goodwin, R.G., Diffendal, R.F., 1987. Paleohydrology of some Ogallala (Neogene) streams in the southern panhandle of Nebraska. In: Ethridge, F.G., Flores, R.M., Harvey, M.D., Wesver, J.N. (Eds.), *Recent Developments in Fluvial Sedimentology* SEPM Special Publication, 39. Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, pp. 149–157.
- Gustavson, T.C., Finley, R.J., 1985. Late Cenozoic geomorphic evolution of the Texas Panhandle and northeastern New Mexico. University of Texas, Bureau of Economic Geology Report of Investigations, 148 (42 pp.).
- Gustavson, T.C., Winkler, D.A., 1988. Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico. *Geology* 16, 203–206.
- Heim, G.E., Howe, W.B., 1963. Pleistocene drainage and depositional history of northwestern Missouri. *Transactions of the Kansas Academy of Science* 66, 378–392.
- Helland, P.E., Diffendal, R.F., 1991. Scanning electron microscopic study of quartz sand surface features, Ash Hollow Formation, Ogallala Group, Western Nebraska. *Proceedings of the Nebraska Academy of Sciences, 101st Annual Meeting, Lincoln, Nebraska*, pp. 57–58.
- Helland, P.E., Diffendal, R.F., 1993. Probable glacial climatic conditions in source areas during deposition of parts of the Ash Hollow Formation, Ogallala Group (Late Tertiary), of western Nebraska. *American Journal of Science* 293, 744–757.
- Holman, J.A., 1971. Climatic significance of giant tortoises from the Wood Mountain Formation (upper Miocene) of Saskatchewan. *Canadian Journal of Earth Science* 8, 1148–1151.
- Horn, J.D., Joeckel, R.M., Fielding, C.R., 2012. Progressive abandonment and planform changes of the central Platte River in Nebraska, central USA, over historical timeframes. *Geomorphology* 139–140, 372–383.
- Hyndman, R.D., Currie, C.A., 2011. Why is the North America Cordillera high? Hot backarcs, thermal isostasy, and mountain belts. *Geology* 39, 783–786.
- Ielpi, A., Ghinassi, M., 2014. Planform architecture, stratigraphic signature and morphodynamics of an exhumed Jurassic meander plain (Scalby Formation, Yorkshire, UK). *Sedimentology* <http://dx.doi.org/10.1111/sed.12122> (in press).
- Joeckel, R.M., Ang Clement, B.J., 2005. Soils, surficial geology, and geomicrobiology of saline-sodic wetlands, North Platte River Valley, Nebraska, USA. *Catena* 61, 63–101.
- Joeckel, R.M., Henebry, G.M., 2008. Channel and island change in the lower Platte River, Eastern Nebraska, USA: 1855–2005. *Geomorphology* 102, 407–418.
- Joeckel, R.M., Tucker, S.T., 2013. Exceptionally well-preserved latest Miocene (Hemphillian) rodent burrows from the eastern Great Plains, USA and a review of the burrows of North American rodents. *Palaio* 28, 793–824.
- Joeckel, R.M., Tucker, S.T., Ang Clement, B.J., Swigart, J.M., 2004. Lacustrine calcareous diatomite and its mining history in east-central Nebraska, USA. *Proceedings of the 39th Forum on the Geology of Industrial Minerals, Nevada Bureau of Mines and Geology Special Publication* 33, 162–176.
- Joeckel, R.M., Swinehart, J.B., Hanson, P.R., Goeke, J.W., 2007. Interpretation of alluvial architecture in the Ogallala Group of Nebraska from test-hole logs. *Geological Society of America Abstracts with Programs* 39, 66.
- Joeckel, R.M., Wooden, S.R., Korus, J.T., Howard, L.M., 2011. Surficial geology of the Ogallala Quadrangle. University of Nebraska-Lincoln School of Natural Resources Nebraska STATEMAP (http://snr.unl.edu/data/geologysoils/digitalgeologicmaps/north_platte.asp).
- Karlstrom, K.E., Coblenz, D., Dueker, K., Ouimet, W., Kirby, E., Van Wijk, J., Schmandt, B., Kelly, S., Lazear, G., Crossey, L.J., Crow, R., Aslan, A., Darling, A., Aster, R., MacCarthy, J., Hansen, S.M., Stachnik, J., Stockli, D.F., Garcia, R.V., Hoffman, M., Mckee, R., Feldman, J., Heizler, M., Donahue, M.S., The CREST Working Group, 2011. Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: toward a unified hypothesis. *Geosphere* 4, 1–22.
- Keeley, J.E., Rundel, P.W., 2005. Fire and the Miocene expansion of C4 grasslands. *Ecology Letters* 8, 683–690.
- Kesel, R.H., Dunne, K.C., MacDonald, R.C., Allison, K.R., 1974. Lateral erosion and overbank deposition on the Mississippi River in Louisiana caused by 1973 flooding. *Geology* 2, 461–464.
- Kohn, M.J., Fremd, T.J., 2008. Miocene tectonics and climate forcing of biodiversity, western United States. *Geology* 36, 783–786.
- Korus, J.T., Joeckel, R.M., 2011. New insights into the basin-scale alluvial architecture of the Ogallala Group (Neogene, central Nebraska) using statistical analyses of grain size trends. *Geological Society of America Abstracts with Programs* 43, 547.

- Kürschner, W.M., Kvacek, Z., Dilcher, D.L., 2008. The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems. *Proceedings of the National Academy of Sciences* 105, 449–453.
- Larson, E.E., Evanoff, E., 1998. Tephrostratigraphy and source of the tuffs of the White River sequence. In: Terry Jr., D.O., LaGarry, H.E., Hunt Jr., R.M. (Eds.), *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America)*, Geological Society of America Special Paper 325, Boulder, Colorado, pp. 1–14.
- Lecce, S.A., Pease, P.P., Gares, P.A., Rigsby, C.A., 2004. Floodplain sedimentation during an extreme flood: the 1999 flood on the Tar River in eastern North Carolina. *Physical Geography* 25, 334–346.
- Leeder, M., 1987. Sediment deformation structures and the palaeotectonic analysis of sedimentary basins, with case-study from the Carboniferous of northern England. In: Jones, M.E., Preston, R.M.F. (Eds.), *Deformation of Sediments and Sedimentary Rocks*. Geological Society, London, Special Publication, 29, pp. 137–146.
- Leite, M.B., 1986. Neogene stratigraphy and vertebrate paleontology of the north shore of Lake McConaughy, Keith County, Nebraska. Unpublished M.S. thesis, University of Nebraska-Lincoln, 165 pp.
- Liggett, G.A., 1997. The Beckerdite local biota (early hemphillian) and the first Tertiary occurrence of a crocodilian from Kansas. *Transactions of the Kansas Academy of Science* 100, 101–108.
- Lugn, A.L., 1938. The Nebraska State Geological Survey and the “Valentine Problem”. *American Journal of Science* 36, 220–227.
- Lynds, R., Hajek, E., 2006. Conceptual model for predicting mudstone dimensions in sandy braided-river reservoirs. *AAPG Bulletin* 90, 1273–1288.
- Macfarlane, P.A., Wilson, B.B., Bohling, G., 2005. Practical saturated thickness of the Ogallala Aquifer in two small areas of Southwest Kansas Groundwater Management District 3. Kansas Geological Survey, Open-file Report 2005-29 (33 pp. [URL http://www.kgs.ku.edu/Hydro/Publications/2005/OFR05_29/index.html]).
- Martin, L.D., Bennett, D.K., 1977. The burrows of the Miocene beaver *Palaeocastor*, western Nebraska, U.S.A. *Palaeogeography, Palaeoclimatology, Palaeoecology* 22, 173–193.
- McMillan, M.E., Angevine, C.L., Heller, P.L., 2002. Postdepositional tilt of the Miocene–Pliocene Ogallala Group on the western Great Plains: evidence of late Cenozoic uplift of the Rocky Mountains. *Geology* 30, 63–66.
- Mech, L.D., Packard, J.M., 1990. Possible use of wolf, *Canis lupus*, den over several centuries. *The Canadian Field-Naturalist* 194, 484–485.
- Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Science Reviews* 22, 261–308.
- Miall, A.D., 2006. *The Geology of Fluvial Deposits*, 4th ed. Springer, New York (582 pp.).
- Middelkoop, H., Asselman, N.E.M., 1998. Spatial variability of floodplain sedimentation at the event scale in the Rhine-Meuse Delta, The Netherlands. *Earth Surface Processes and Landforms* 23, 561–573.
- Mjøs, R., Walderhaug, O., Prestholm, E., 1993. Crevasse splay sandstone geometries in the Middle Jurassic Ravenscar Group of Yorkshire, U.K. In: Marzo, M., Puigdefàbregas, C. (Eds.), *Alluvial Sedimentation*. International Association of Sedimentologists, Special Publication, 17, pp. 167–184.
- Mook, C.C., 1946. A new Pliocene alligator from Nebraska. *American Museum Novitates* 1311, 1–12.
- Moura-Lima, E., Bezerra, F., Lima-Filho, F.P., de Castro, D.L., Sousa, M.O.L., Fonseca, V.P., Aquino, M.R., 2011. 3-D geometry and luminescence chronology of Quaternary soft-sediment deformation structures in gravels, northeastern Brazil. *Sedimentary Geology* 235, 160–171.
- Nami, M., Leeder, M.R., 1978. Changing channel morphology and magnitude in the Scalby Formation (M. Jurassic) of Yorkshire, England. In: Miall, A.D. (Ed.), *Fluvial Sedimentology*. Canadian Society of Petroleum Geologists Memoir, 5. Canadian Society of Petroleum Geologists, Calgary, Alberta, pp. 431–440.
- National Weather Service (USA), undated. Advanced Hydrologic Prediction Service (website). [URL <http://water.weather.gov/ahps2/>]. Accessed December 12, 2013.
- O'Brien, P.E., Wells, T.A., 1986. A small, alluvial crevasse splay. *Journal of Sedimentary Petrology* 56, 876–879.
- Owen, G., 1987. Deformation processes in unconsolidated sands. In: Jones, M.E., Preston, R.M.F. (Eds.), *Deformation of Sediments and Sedimentary Rocks*. Geological Society, London, Special Publication, 29, pp. 11–24.
- Owen, G., 1995. Soft-sediment deformation in Upper Proterozoic Torridonian sandstones (Applecross Formation) at Torridon, northwest Scotland. *Journal of Sedimentary Research* 65B, 495–504.
- Owen, G., 2003. Pseudonodules. In: Middleton, G.V. (Ed.), *Encyclopedia of Sediments and Sedimentary Rocks*. Kluwer Academic Publishers, Dordrecht, Boston, pp. 549–551.
- Owen, G., Moretti, M., 2011. Identifying triggers for liquefaction-induced soft-sediment deformation in sands. *Sedimentary Geology* 235, 141–147.
- Pearson, N.J., Gingras, M.K., 2006. An ichnological and sedimentological facies model for muddy point-bar deposits. *Journal of Sedimentary Research* 76, 771–782.
- Peppe, D.J., Evans, D.A.D., Smirnov, A.V., 2009. Magnetostratigraphy of the Ludlow Member of the Fort Union Formation (Lower Paleocene) in the Williston Basin, North Dakota. *Geological Society of America Bulletin* 121, 65–79.
- Plint, A.G., 1983. Sandy fluvial point-bar sediments from the Middle Eocene of Dorset, England. In: Collinson, J.D., Lewin, J. (Eds.), *Modern and Ancient Fluvial Systems*. Special Publication of the International Association of Sedimentologists, 6, pp. 355–368.
- Plint, A.G., 1986. Slump blocks, intraformational conglomerates and associated erosional structures in Pennsylvanian fluvial strata of eastern Canada. *Sedimentology* 33, 387–389.
- Potter, P.E., 1978. Significance and origin of big rivers. *Journal of Geology* 86, 13–33.
- Puigdefàbregas, C., 1973. Miocene point-bar deposits in the Ebro Basin, northern Spain. *Sedimentology* 20, 133–144.
- Puigdefàbregas, C., Van Vliet, A., 1978. Meandering stream deposits from the Tertiary of the southern Pyrenees. In: Miall, A.D. (Ed.), *Fluvial Sedimentology*. Canadian Society of Petroleum Geologists Memoir, 5, pp. 469–485.
- Rust, B.R., Gibling, M.R., Legun, A.S., 1984. Coal deposition in an anastomosing fluvial system: the Cumberland Group south of Joggins, Nova Scotia, Canada. In: Rahmani, R., Flores, R.M. (Eds.), *Sedimentology of Coal and Coal-Bearing Sequences*. Special Publication of the International Association of Sedimentologists, 7, pp. 105–120.
- Santos, M.G.M., Almeida, R.P., Mountney, N.P., Frago-Cesar, A.R.S., 2012. Seismites as a tool in the paleoenvironmental reconstruction of fluvial deposits: the Cambrian Guarda Velha Formation, southern Brazil. *Sedimentary Geology* 277–278, 52–60.
- Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderick, W.D. (Eds.), 2012. *Field Book for Describing and Sampling Soils*, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE [URL ftp://ftp-fc.sc.egov.usda.gov/NSSC/Field_Book/FieldBookVer3.pdf].
- Selley, R.C., 1969. Torridonian alluvium and quicksands. *Scottish Journal of Geology* 5, 328–346.
- Seni, S.J., 1980. Sand-body geometry and depositional systems, Ogallala Formation, Texas. University of Texas Bureau of Economic Geology Report of Investigations, 105, pp. 1–36.
- Shepherd, R.G., Owens, W.G., 1981. Hydrogeologic significance of Ogallala fluvial environments, the Gangplank. In: Ethridge, F.G., Flores, R.M. (Eds.), *Recent and Ancient Nonmarine Depositional Environments; Models for Exploration*. SEPM Special Publication, 31, pp. 89–94.
- Shit, P.K., Maiti, R., 2012. Effect of plant roots on soil anti-scourability of topsoil during concentrated flow. *Indian Journal of Engineering Research and Technology* 1, 1–7.
- Skelly, R.L., Bristow, C.S., Ethridge, F.G., 2003. Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: the lower Niobrara River, northeast Nebraska. *Sedimentary Geology* 158, 249–270.
- Smith, J.J., Hasiotis, S.T., 2008. Traces and burrowing behaviors of the cicada nymph *Cicadetta calliope*: neoichnology and paleoecological significance of extant soil-dwelling insects. *Palaos* 23, 503–513.
- Smith, N.D., Pérez-Arlucea, M., 1994. Fine-grained splay deposition in the avulsion belt of the lower Saskatchewan River, Canada. *Journal of Sedimentary Research* 64B, 159–168.
- Smith, J.J., Hasiotis, S.T., Kraus, M.J., Woody, D.T., 2008. *Naktodemas bowni*: new ichnogenus and ichnospecies for adhesive meniscate

- burrows (AMB), and paleoenvironmental implications, Paleogene Willwood Formation, Bighorn Basin, Wyoming. *Journal of Paleontology* 82, 267–278.
- Souders, V.L., 2000. Geologic maps and cross sections showing configurations of bedrock surfaces, Broken Bow 1° × 2° Quadrangle, east-central Nebraska. U.S. Geological Survey Geological Investigations Series, I-2725.
- Stanley, K.O., Wayne, W.J., 1972. Epeirogenic and climate controls of early Pleistocene fluvial sediment. *Geological Society of America Bulletin* 83, 3675–3690.
- Stanley, D.J., Krinitzky, E.L., Compton, J.R., 1966a. Mississippi River bank failure, Fort Jackson, Louisiana. *Bulletin of the Geological Society of America* 77, 859–866. Stanley, D.J., Krinitzky, E.L., Weaver, F.J., 1966b. Bank erosion in soils of the Lower Mississippi Valley. *Journal of the Soil Mechanics and Foundations Division* 92, 121–136.
- Stewart, D.J., 1983. Possible suspended-load channel deposits from the Wealden Group (Lower Cretaceous) of Southern England. In: Collinson, J.D., Lewin, J. (Eds.), *Modern and Ancient Fluvial Systems*. Special Publication of the International Association of Sedimentologists, 6, pp. 369–384.
- Stout, T.M., 1971. Geologic sections. In: Stout, T.M., DeGraw, H.M., Tanner, L.G., Stanley, K. O., Wayne, W.J., Swinehart, J.B. (Eds.), *Guidebook to Late Pliocene and Early Pleistocene of Nebraska*, Conservation and Survey Division of Nebraska, Nebraska Geological Survey, Lincoln, Nebraska, pp. 29–82.
- Stowe, D.V., 2005. *Sedimentary Rocks in the Field. A Color Guide*. Academic Press, Burlington, Massachusetts.
- Strömberg, C.A.E., 2002. The origin and spread of grass-dominated ecosystems in the late Tertiary of North America: preliminary results concerning the evolution of hypsodonty. *Palaeogeography, Palaeoclimatology, Palaeoecology* 177, 59–75.
- Strömberg, C.A.E., 2005. Decoupled taxonomic radiation and ecological expansion of open-habitat grasses in the Cenozoic of North America. *Proceedings of the National Academy of Sciences of the United States of America* 102, 11980–11984.
- Swinehart, J.B., Souders, V.L., DeGraw, H.M., Diffendal Jr., R.F., 1985. Cenozoic paleogeography of western Nebraska. In: Flores, R.M., Kaplan, S.S. (Eds.), *Cenozoic Paleogeography of the West-Central United States*. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section Rocky Mountain Paleogeography Symposium, 3, pp. 209–229.
- Taşgın, C.K., Orhan, H., Türkmen, I., Aksoy, E., 2011. Soft-sediment deformation structures in the late Miocene Şelmo Formation around Adıyaman area, Southeastern Turkey. *Sedimentary Geology* 235, 277–291.
- Tedford, R.H., Albright III, L.B., Barnosky, A.D., Ferrusquia-Villafranca, I., Hunt Jr., R.M., Storer, J.E., Swisher III, C.C., Voorhies, M.R., Webb, S.D., Whistler, D.P., 2004. Mammalian biochronology of the Arikarean through Hemphillian interval (Late Oligocene through Early Pliocene Epochs). In: Woodburne, M.O. (Ed.), *Late Cretaceous and Cenozoic Mammals of North America, Geochronology and Biostratigraphy*. Columbia University Press, New York, pp. 167–231.
- Tengbeh, G.T., 1993. The effect of grass roots on shear strength variations with moisture content. *Soil Technology* 6, 287–295.
- Thomasson, J.R., 1977. Late Cenozoic grasses, borages, and hackberries from southwestern Nebraska. *University of Wyoming Contributions to Geology* 17, 59–63.
- Thomasson, J.R., 1979. Late Cenozoic Grasses and Other Angiosperms From Kansas, Nebraska, and Colorado: Biostratigraphy and Relationships to Living Taxa. University of Kansas Publications, Lawrence, Kansas (68 pp.).
- Thomasson, J.R., 1987. Late Miocene plants from northeastern Nebraska. *Journal of Paleontology* 61, 1065–1079.
- Thomasson, J.R., 1991. Fossil plants from the late Miocene Ogallala Formation of central North America: possible paleoenvironmental and biostratigraphic significance. In: Gustafson, T.C. (Ed.), *Geologic Framework and Regional Hydrology: Upper Cenozoic Blackwater Draw and Ogallala Formations, Great Plains*. Texas Bureau of Economic Geology, University of Texas, pp. 99–114.
- Tooth, S., 2000. Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews* 51, 67–107.
- Tripathi, A.K., Roberts, C.D., Eagle, R.A., 2009. Coupling of CO₂ and ice sheet stability over major climate transitions of the last 20 million years. *Science* 326, 1394–1397.
- Truchan, J.J., 2009. *Genesis of Carbonate Lakes on Perennial Siliciclastic Floodplains* MS Thesis Ohio University.
- United States Department of Agriculture Natural Resources Conservation Service, undated. Web Soil Survey (website). [URL <http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>]. Accessed March 17, 2014.
- Voorhies, M.R., 1977. Giant tortoises, fossil evidence of former subtropical climate on the Great Plains. *University of Nebraska State Museum, Museum Notes* 59, 1–4.
- Voorhies, M.R., 1987a. Early Eocene (Wasatchian) vertebrates from northeastern Nebraska: the Lewis and Clark local fauna. *Geological Society of America Abstracts with Programs* 19, 340.
- Voorhies, M.R., 1987b. Late Cenozoic stratigraphy and geomorphology, Ft. Niobrara, Nebraska. In: Biggs, D.L. (Ed.), *North-Central Section of the Geological Society of America, Centennial Field Guide*, volume 3, pp. 1–6.
- Webb, D.S., 1977. A history of savanna vertebrates in the New World Part 1: North America. *Annual Review of Ecology and Systematics* 9, 323–426.
- Willis, B.J., 1993. Bedding geometry of ancient point bar deposits. In: Marzo, M., Puigdefabregas, C. (Eds.), *Alluvial Sedimentation*. International Association of Sedimentologists. Special Publication, 17, pp. 101–114.
- Willis, B.J., Behrensmeier, A.K., 1994. Architecture of Miocene overbank deposits in northern Pakistan. *Journal of Sedimentary Research* B64, 60–67.
- Witzke, B.J., Ludvigson, G.A., 1990. Petrographic and stratigraphic comparisons of sub-till and inter-till alluvial units in western Iowa; implications for development of the Missouri River drainage. *Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary History of Western Iowa*. Midwest Friends of the Pleistocene 37th Field Conference. Iowa Geological Survey Guidebook Series, 9, pp. 119–143.
- Wolfe, B.B., Hall, R.I., Last, W.M., Edwards, T.W.D., English, M.C., Karst-Riddoch, T.L., Paterson, A., Palmini, R., 2006. Reconstruction of multi-century flood histories from oxbow lake sediments, Peace-Athabasca Delta, Canada. *Hydrological Processes* 20, 4131–4153.
- Wood II, H.E., Wood, A.E., 1933. *Daemohelix in the Pleistocene of Texas*. *Journal of Geology* 41, 824–833.
- Wood, S.H., Ziegler, A.D., 2008. Floodplain sediment from a 100-year-recurrence flood in 2005 of the Ping River in northern Thailand. *Hydrology and Earth System Sciences* 12, 959–973.
- Wren, D.G., Davidson, G.R., Walker, W.G., Galicki, S.J., 2008. The evolution of an oxbow lake in the Mississippi alluvial floodplain. *Journal of Soil and Water Conservation* 63, 129–135.
- Zhou, Z.C., Shangguan, Z.P., 2007. The effects of ryegrass roots and shoots on loess erosion under simulated rainfall. *Catena* 70, 350–355.