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Exhumed fluvial landforms reveal evolution of late Eocene–Pliocene rivers on the Central and Northern Great Plains, USA

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ABSTRACT

Cenozoic strata on the Great Plains are the products of a long-lived, continental sediment routing system, and yet strikingly little is known about these ancient rivers. This article details the discovery of ~3100 fluvial ridges—erosionally inverted alluvial-fan, channel-fill, channel-belt, and valley-fill deposits—extending from the Rocky Mountain front to the eastern margin of the Great Plains. The direct detection of these channel bodies reveals new insights into late Eocene–Pliocene drainage evolution. Late Eocene–Oligocene streams were morphologically diverse. Alluvial fans adjacent to the Rocky Mountain front changed eastward to parallel or downstream-divergent, fixed, single-thread, straight to slightly sinuous (S = 1.0–1.5) streams <50 m in width. At ~100 km from the Rocky Mountain front, streams became sinuous and laterally mobile, forming amalgamated channel bodies as much as 3 km in width. Streamflow in all these systems was highly dispersed (southeast to northeast) and temporally variable. These characteristics reveal a nascent Great Plains alluvial apron hosting small, poorly integrated drainages undergoing abrupt changes. By the Miocene, more uniform streamflow generally trended east-northeast. Channel deposits are identifiable 500 km from the Rocky Mountain front. Middle Miocene valley fills gave way to fixed, multithread channels a few kilometers in width by the late Miocene. These patterns evince a mature alluvial apron hosting bigger rivers in well-integrated drainages. We interpret the systematic changes between fixed and mobile channel styles to record spatially and temporally variable aggradation rates. The widening of channels in the late Miocene likely reflects increased discharge relating to wetter climates upstream or the integration of once-isolated Rocky Mountain drainage basins into a continental-scale drainage system.

INTRODUCTION

Fluvial channels link genetically related landscapes at continental scales because they convey sediment from its source through the catchment to its eventual sink (Sømme et al., 2009). Channel geometry and depositional style adjust to the prevailing regimes of discharge and sediment supply in a drainage basin. These parameters respond to extrinsic and intrinsic forcing mechanisms over various spatial and temporal scales (Blum and Törnqvist, 2000; Bridge, 2003; Knighton, 2014). Thus, fluvial erosion, transport, and deposition are the messengers of perturbations in upstream environmental signals such as climate, uplift, subsidence, and drainage basin evolution (Sømme et al., 2009; Romans et al., 2016). As long as a fluvial link between landscapes persists, such signals are propagated through the source-to-sink system, producing a stratigraphic record of long-term landscape evolution in the sediment sink. However, the storage of sediment within a segment of the system effectively decouples these signals from downstream sinks (Sinclair et al., 2019). Therefore, the disconnectivity of a landscape is as important as its connectivity in understanding the propagation of environmental signals (Brierley et al., 2006).

Fluvial systems on the Great Plains have been a major part of the Mississippi River source-to-sink system since the Paleocene Epoch because they have linked sediment sources in the Rocky Mountains to the sediment sink of the Gulf of Mexico for at least 60 m.y. (Galloway et al., 2011; Blum et al., 2017). Slow subsidence and increased sediment supply during the late Eocene to the Pliocene caused widespread aggradation on the Great Plains, sequestering vast volumes of sediment within the catchment area of this system (McMillan et al., 2006; Bentley et al., 2016). These sediments have long been appreciated as archives of biotic, paleoclimatic, paleoenvironmental, paleogeographic, and tectonic changes (Skinner et al., 1977; Swinehart et al., 1985; McMillan et al., 2002; Tedford et al., 2004; Hunt, 2005; Chapin, 2008; Duller et al., 2012). The interpretation of the fluvial deposits themselves, however, has been limited, and possibly even distorted, by the general paucity of subsurface data and the small size and localized nature of outcrops (e.g., Diffendal et al., 1985; Swinehart et al., 1985; Evans and Terry, 1994; Joeckel et al., 2014; Korus et al., 2020). Moreover, previous studies of Great Plains fluvial deposits concentrated on incised channels and channel fills at unit-bounding unconformities, rather than on the strata lying between major unconformities (Diffendal, 1982a, 1982b, 1983; Diffendal et al., 1985; Swinehart et al., 1985; Goodwin and Diffendal, 1987; Swinehart and Diffendal, 1987). The latter, however neglected until now, are crucial in developing a holistic understanding of the sediment delivery system because they represent periods of long-term sediment storage. Accordingly, several important questions have gone unanswered: (1) What were the channel geometries and sizes, and how did they

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Jesse Korus https://orcid.org/0000-0001-7153-3152 change over time? (2) Were fluvial systems confined or unconfined, aggrading or degrading, and laterally mobile or immobile? (3) How did depositional systems and sediment dispersal patterns vary over time and space? In this study, we sought answers to these questions to begin deciphering environmental signals on the Great Plains and to better understand the continental source-to-sink system.

Herein, we report the discovery of ~3100 fluvial ridges—exhumed late Eocene to Pliocene fluvial channels and channel deposits (sensu Hayden et al., 2019; Hayden and Lamb, 2020; Zaki et al., 2021b)—over an area of ~250,000 km^2 on the Great Plains. Observations on fluvial ridges have largely eluded detection in the study area until now. These new data can substantially compensate for the sparsity of outcrop and subsurface data. Using high-resolution aerial or satellite imagery and light detection and ranging (LiDAR) in combination with field studies, we identified fluvial ridges on the present landscape and documented diverse ancient fluvial depositional styles and systems that evolved in response to geologic events on the Great Plains and the Rocky Mountain hinterland over ~35 m.y. Our new data set adds substantially to the global inventory of fluvial ridges (Zaki et al., 2021b). Moreover, it supplies new knowledge about the Mississippi River source-to-sink system, and it contributes to the interpretation of signal transfers through continental-scale sediment routing systems.

SIGNIFICANCE OF FLUVIAL RIDGES

Fluvial ridges are elongate, inverted-relief landforms capped by channel-fill, channel-belt, and alluvial-valley-fill deposits (Maizels, 1987; Pain and Oilier, 1995; Pain et al., 2007; Williams et al., 2007; Cuevas Martínez et al., 2010; Foix et al., 2012; Hayden et al., 2019; Cardenas et al., 2020; Phillips et al., 2021; Zaki et al., 2021a; Zhao et al., 2021). They are formed by differential erosion of coarse, single-channel or composite-channel deposits and intervening fine deposits. Examples of fluvial ridges ranging in age from Late Ordovician to late Holocene have been identified on every continent except Antarctica (Zaki et al., 2021b). The identification of fluvial ridges on Mars (Malin and Edgett, 2003; Pain et al., 2007; Davis et al., 2016) and Titan (Burr et al., 2013) has only intensified interest in terrestrial examples (Malin and Edgett, 2003; Pain et al., 2007; Burr et al., 2009, 2010; Davis et al., 2016).

Fluvial ridges record the planimetric patterns of paleochannel networks, and they reveal aspects of ancient sediment dispersal systems. Ridge-forming channel deposits can be understood by examining the relationship between ridge geometry and the formative channels. Capping strata of fluvial ridges are either: (1) the fills of single ancient channels (single-channel ridges) or (2) compound deposits that developed from multiple generations of channel migration or vertical accretion (Hayden and Lamb, 2020). The geometries of single-channel ridges are strictly constrained during the process of inversion by the dimensions of the precursor channel (Hayden and Lamb, 2020). Scrutiny of such ridges can reveal the orientations, planform geometries, cross-sectional profiles, paleohydrology, and fluvial style of precursor streams at a snapshot in time (Bridge, 1977; Miall, 1985, 2010; Bridge, 1993, 2003; Schumm, 1993; Church, 2006; Fielding, 2007; Hooke and Yorke, 2011; Ashmore, 2013; Carling et al., 2014; Ielpi, 2018; Sambrook Smith et al., 2019). The geometries of compound-deposit ridges, in comparison, are constrained by the dimensions of multistory channel bodies (Gibling, 2006). Ridge-capping strata in these cases disclose alluvial architecture across a broader range of space and time and implicate changes in fluvial aggradation, degradation, and channel migration (Miall, 1991; Blum and Törnqvist, 2000; Gibling, 2006; Hajek and Heller, 2012; Blum et al., 2013; Colombera et al., 2015).

GEOLOGIC SETTING

History of Uplift and Erosion

Postorogenic erosion of Laramide uplifts supplied coarse-grained sediments to late Eocene–Pliocene fluvial systems on the Great Plains (Fig. 1; Stanley, 1971; Stanley and Wayne, 1972; Bart, 1975; Clark, 1975; Stanley, 1976; Seeland, 1985; Dickinson et al., 1988; Yonkee and Weil, 2015; Copeland et al., 2017; Li and Fan, 2018). Laramide subsidence in the Great Plains was minimal, and some of the Laramide arches (including the Black Hills uplift) and basins were gently reactivated (Bunker et al., 1988; Tikoff and Maxson, 2001; Burberry et al., 2015). Volcanism to the west and southwest also produced abundant, finer pyroclastic sediment during the late Eocene to early Miocene (Sato and Denson, 1967; Best et al., 2013). This sediment was carried onto the central and northern Great Plains by dry westerly winds and reworked by streams, leaving extensive tuffaceous deposits (Rowley and Fan, 2016). Aggradation on the Great Plains was dominated by pyroclastic sediment until ca. 18 Ma (Best et al., 2013), making coarser-grained fluvial deposits minor components of the White River and Arikaree Groups (Swinehart et al., 1985). The Ogallala Group, in contrast, records waning volcanism and the deposition of a nearly continuous, sandy alluvial plain eastward of the Rocky Mountains (McMillan et al., 2006).

The late Cenozoic evolution of the Rocky Mountains and western Great Plains involved dynamic topography (Aslan et al., 2010; Hyndman and Currie, 2011; Karlstrom et al., 2012; Nereson et al., 2013; Heller and Liu, 2016), the exhumation of ranges (Miocene onward), differential uplift of the adjacent Great Plains (McMillan et al., 2002), and the eventual beheading of Miocene rivers draining eastward from the mountain front. Widespread erosion left a broad plateau from the Cheyenne Table to the Gangplank as the only large remnant of the Ogallala alluvial plain (Fig. 1). In the Pliocene, increased stream power associated with a warm, wet climatic optimum dispersed gravels of the Broadwater Formation east-northeastward across Nebraska (Duller et al., 2012). From the beginning of the Pleistocene, major streams such as the North and South Platte rivers deeply incised their valleys (Duller et al., 2012).

Major Stratigraphic Units

Each of the major late Eocene through Miocene stratigraphic units in the study area has distinctive characteristics (Fig. 1). The lower part of the White River Group consists chiefly of bentonitic claystones (Chamberlain Pass and Chadron Formations), and

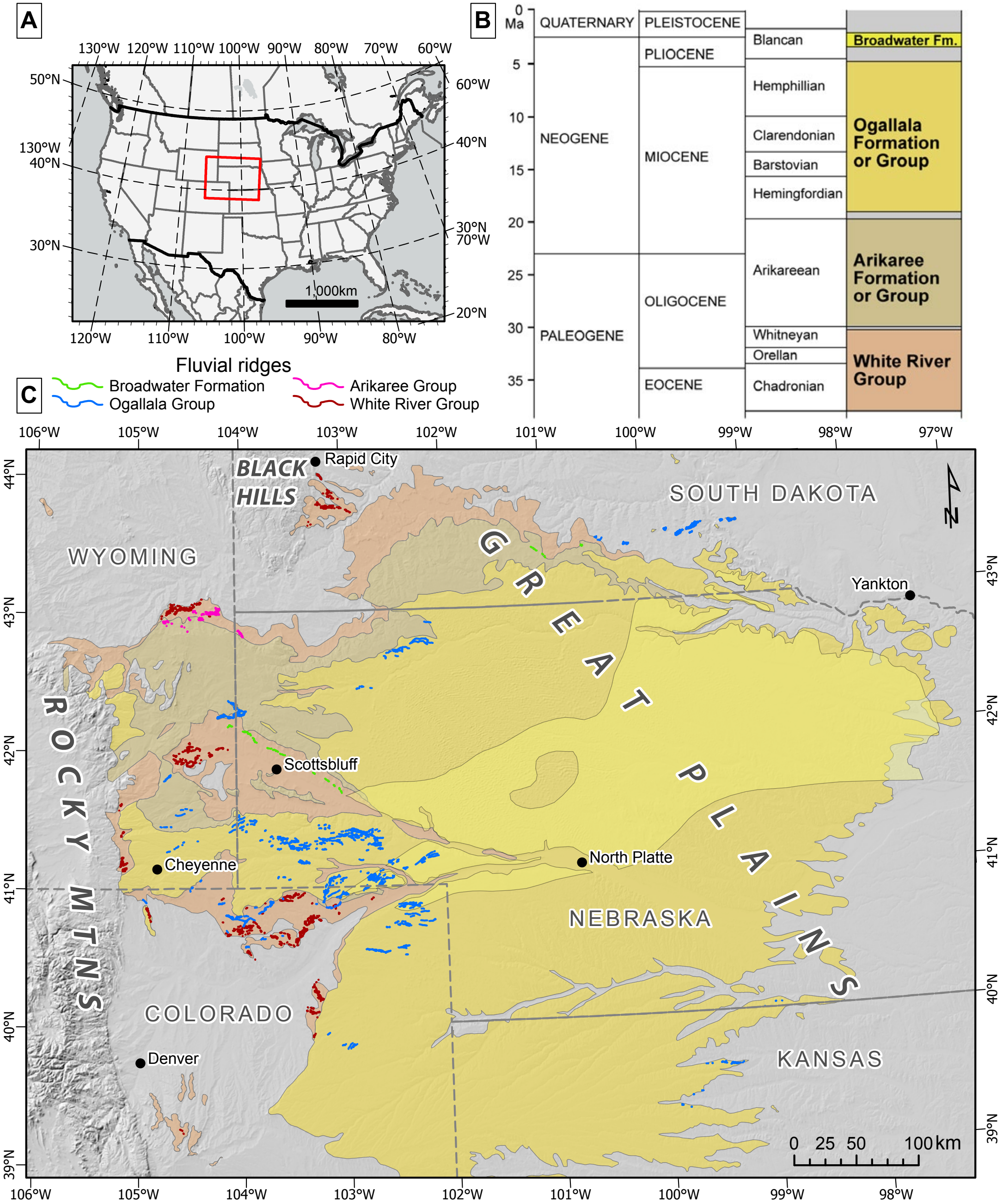

Figure 1. Geologic setting of study area. (A) Location of study area in the central United States. (B) Stratigraphic column showing, from left to right, period, epoch, North American Land Mammal Ages (NALMAs), and lithostratigraphic units. Ranks of some units differ from state to state. (C) Study area showing fluvial ridges and extent of lithostratigraphic units in B.

the upper part is dominated by tuffaceous siltstones containing regionally extensive ash beds (Brule Formation). Narrow ribbons to broad sheets of coarse-grained sandstones and conglomerates fill isolated channels throughout the White River Group (Swinehart et al., 1985; Terry et al., 1995; Sibray, 2011; Divine and Sibray, 2017; Korus and Joeckel, 2022). The Arikaree Group comprises very fine-grained to fine-grained, friable, volcaniclastic sandstones and minor siltstones, claystones, and volcanic ash beds. Sheets of coarse-grained sandstones and granule to pebble conglomerates fill local paleovalleys at the base of the unit (Schultz et al., 1967; Vondra et al., 1969; Scott, 1982; Korus and Joeckel, 2022). Bouldery conglomerates are present in at least one narrow (1–2 km) paleovalley in the upper part of the Arikaree Group (Korus et al., 2020). The Ogallala Group is a heterogeneous succession of unconsolidated sediments and friable sedimentary rocks. It contains multiple channel bodies and paleovalley fills composed of sands, sandstones, gravels, and conglomerates (Korus and Joeckel, 2022). Floodplain fines constitute as much as 50% of the Ogallala Group in part of southwestern Kansas (Macfarlane et al., 2005), but comparable assessments have not been made elsewhere. In western Nebraska, floodplain sediments in the Ogallala Group comprise silts, siltstones, and sandy siltstones with minor clays, claystones, carbonates, and diatomites. These sediments appear as lenses or sheets a few tens to a few hundred meters in width and a few centimeters to a few meters in thickness (Joeckel et al., 2004, 2014). The Pliocene Broadwater Formation comprises pebble to cobble gravels, sands, and minor silts, clays, and diatomite units (Swinehart and Diffendal, 1997). It includes the informal Remsburg Ranch beds (Swinehart and Diffendal, 1987), which fill discontinuous, narrow channels incised into older strata along the north side of the North Platte River valley in the Nebraska Panhandle and eastern Wyoming.

METHODS

Fluvial ridges were identified based on their geomorphologic expressions in plan view. Most of the fluvial ridges, whether isolated or existing atop larger landforms, are narrow, elongate, and curvilinear in planform (Fig. 2). Smaller numbers of ridges are effectively straight. Ridge-capping strata in our study area include gravels, friable sandstones, or hard to very hard sandstones (sensu Stowe, 2005) and, rarely, freshwater limestones. Ridges capped with unconsolidated gravels and friable sandstones tend to have flat, undulating, hilly, or hummocky tops, whereas sandstone- and limestone-capped ridges tend to be flat-topped. We did not observe morphologic gradations between these two types of ridges. In some cases, however, isolated ridges capped by hard sandstones extend continuously into ridge-bearing buttes, mesas, plateaus, or cuestas (Fig. 2D).

We defined six classes of fluvial ridges and ridge-bearing landforms (Table 1):

(1) Low-relief, sandstone-capped ridges appearing either as isolated landforms (Fig. 2A) or in groups atop larger landforms (Fig. 2D): Ridges in this class are discontinuous outcrops or trains of fitted, in situ cobbles and boulders. They are generally less than 5 m in height, and many are less than 1 m. They transition laterally into high-relief ridges in some cases.

(2) High-relief, sandstone-capped ridges with flat tops and steep sides, with many bearing talus slopes consisting of eroded blocks of ridge-capping sandstones (Figs. 2B–2D): Ridges in this class are generally 5–30 m in height and may be continuous for several kilometers. Most of these ridges are gradational into larger, ridge-bearing landforms.

(3) Sandstone-capped, ridge-bearing plateaus, mesas, buttes, and cuestas with flat to gently sloping tops, steep sides, and talus slopes consisting of eroded blocks of capping sandstones (Fig. 2D): These ridges are as much as 3 km in width and 60 m in height. Thin soils cover the tops of most of these landforms, but capping sandstones crop out locally, particularly in the scattered, low-relief ridges atop them.

(4) Low-relief, gravel-capped ridges representing discrete landforms that have broad, flat tops and gentle side slopes (Fig. 2F): These ridges rise generally less than 10 m above the surrounding plains and extend for as many as 20 km. Because of their low relief and gentle, rounded edges, most of these features are detectable only in high-resolution LiDAR.

(5) High-relief, gravel-capped ridges representing discrete, narrow chains of rounded hills and hummocks (Fig. 2E): These ridges are as much as 30–40 m in height and typically extend for several to several tens of kilometers. The edges of gravel-capped ridges are commonly gullied and eroded.

(6) High-relief, limestone-capped ridges that have flat to undulating tops and gullied and eroded sides (Fig. 2G): These ridges are ~10–30 m in height and extend as far as 15 km. Their widths are variable, but may attain 500 m.

We digitized the centerlines of fluvial ridges in a geographic information system (GIS) project using two different procedures according to the above classification. The first method was applied to ridge classes 1, 2, 3, 5, and 6: those with sharp edges and steep sides, exposed cap-rock surfaces, or at least several meters of relief. These ridges were identifiable in 2016–2022 high-resolution (<3 m/pixel) imagery in Google Earth (https://www.google.com/earth/) by systematically scanning the imagery using nadir view and three-dimensional (3-D) terrain perspectives. The second method was applied to ridge class 4. These ridges could not be identified in Google Earth because they are vegetated, and they exhibit rounded edges, gentle sides, and low relief. These ridges were mapped using hillshaded, bare-earth, digital elevation models (DEMs) obtained from the U.S. Geological Survey 3D Elevation Program (3DEP, https://www.usgs.gov/core-science-systems/ngp/3dep). Most of these low-relief landforms were mapped from 1–2-m-resolution LiDAR DEMs, but a few were mapped from 1/3 arc-second (~10 m) DEMs where LiDAR data were unavailable.

We conducted field surveys to inspect numerous isolated ridges and groups of ridges on the surfaces of buttes, mesas, and cuestas. We verified their fluvial origins in the field by characterizing the lithology, sedimentary structures, diagenetic features, and architecture of capping strata and by measuring any paleocurrent indicators—chiefly plan-view exposures of dune-scale cross-beds (i.e., "rib-and-furrow" structures), but also plan-view

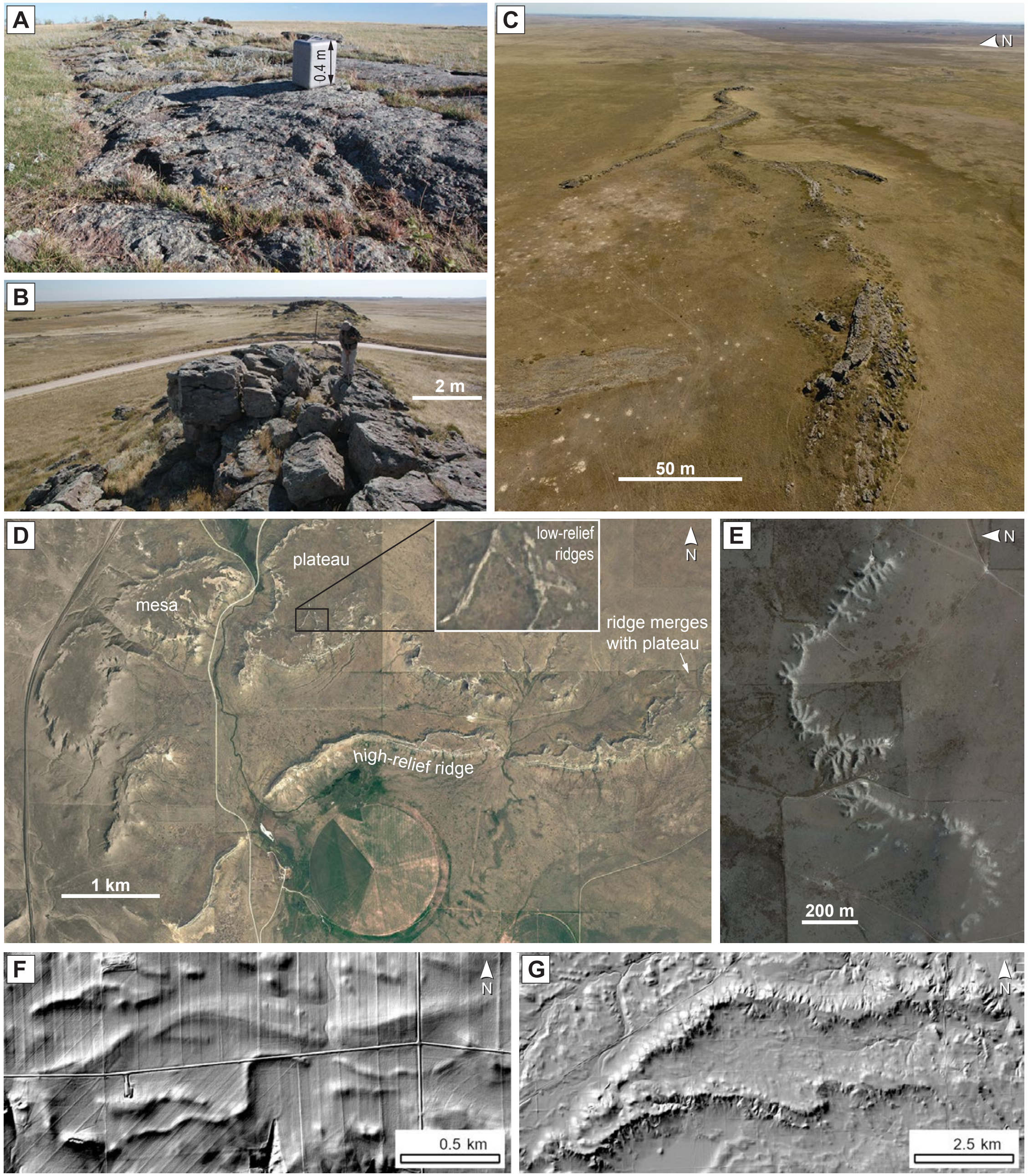

Figure 2. Examples of fluvial ridges from the six classes defined in this study. (A) Low-relief, sandstone-capped ridge in White River Group near the Black Hills. Box is 0.4 m tall. (B) High-relief, sandstone-capped ridge in White River Group in Goshen Hole. Human is ~2 m tall. (C) Oblique aerial view of same high-relief, sandstone-capped ridge in B. (D) Google Earth image of sandstone-capped mesas and plateau in basal Ogallala Group near Carpenter Butte. Low-relief ridges exist atop these landforms. High-relief ridge merges with plateau on right side of image. (E) Google Earth image of high-relief, gravel-capped ridge in Ogallala Group near Pawnee Buttes consisting of rounded hills and hummocks. (F) Hillshaded digital elevation model (DEM) showing low-relief, gravel-capped ridges in Ogallala Group atop Cheyenne Table. Light detection and ranging (LiDAR) data are from U.S. Geological Survey 3D Elevation Program (USGS 3DEP). (G) Hillshaded DEM showing high-relief, limestone-capped ridges in Ogallala Group in the Niobrara River Valley. LiDAR data are from USGS 3DEP.

TABLE 1. DESCRIPTION AND INTERPRETATION OF FLUVIAL RIDGES ON THE CENTRAL AND NORTHERN GREAT PLAINS

Description and interpretation	Relative position along depositional gradient		
	Proximal	Medial	Distal
Broadwater Formation			
Number of ridges	ND	37	5
Landform classes	ND	5	5
Interpretation	ND	Fixed channels	Fixed channels
Upper Ogallala Group			
Number of ridges	74	732	ND
Landform classes	4	4, 6	ND
Interpretation	Fixed channels	Fixed channels	ND
Lower Ogallala Group			
Number of ridges	3	322	132
Landform classes	5	2, 3, 5	2, 3
Interpretation	Fixed channels	Fixed channels and valley fills	Valley fills
Arikaree Group			
Number of ridges	40	22	59
Landform classes	1, 3	1, 2	2, 3
Interpretation	Alluvial fans	Fixed channels	Mobile channel belts
White River Group			
Number of ridges	248	645	775
Landform classes	1, 3	1, 2	2, 3
Interpretation	Alluvial fans	Fixed channels	Mobile channel belts

Notes: ND—no data.

exposures of planar cross-beds and vertical exposures of channel axes. We also measured the orientations of bar-accretion surfaces.

EVIDENCE OF FLUVIAL AND ALLUVIAL-FAN ORIGINS

Strata from which the ridges were exhumed are indisputably continental (e.g., Wanless, 1922; Skinner et al., 1977; Hunt, 1978; Swinehart et al., 1985; Bunker et al., 1988; Galloway et al., 2011). Previous work has demonstrated that fluvial-channel and floodplain deposits dominate the pre-Pleistocene Cenozoic succession in the study area (Diffendal, 1982b; Goodwin and Diffendal, 1987; Hunt, 1990; Evans and Terry, 1994; Joeckel et al., 2014; Korus et al., 2020).

Numerous ridge characteristics evince fluvial origins (Fig. 3). First, the curvilinear geometry of most ridges is reminiscent of stream planforms. Ridge widths fall well within the range of widths of modern stream channels and channel belts (Gibling, 2006; Fielding, 2007). Also, many of the ridges bifurcate in a manner that is geometrically identical to extant streams (Fig. 3A). In the context of paleoflow, these bifurcations represent both confluences and diffluences, which are inherent features of extant multichannel rivers (Best, 1986; Bridge, 2003; Nichols and Fisher, 2007; Ashmore, 2013; Carling et al., 2014; Sambrook Smith et al., 2019). Additionally, some sinuous ridges preserve sedimentary evidence for the migration of point- and counter-point bars (Fig. 3B; Hooke and Yorke, 2011; Ghinassi et al., 2016; Strick et al., 2018; Sylvester et al., 2021). Unidirectional trough cross-stratification, oriented parallel to ridge axes, is notably common (Fig. 3C). Other features typically associated with modern and ancient fluvial deposits—such as nonmarine trace fossils, rhizoliths, fossil bones from terrestrial mammals, cut-and-fill deposits (Fig. 3D), and midchannel and bank-attached bar deposits (Bridge, 2006; Miall, 2010)—are also present in ridge-capping strata.

There are multiple examples of closely grouped, low-relief sandstone ridges with arrays comparable to the distributary patterns of channels on extant alluvial fans (Blair and McPherson, 1994; Nichols and Fisher, 2007). Dense arrays of these ridges exist in late Eocene–Oligocene strata. They lie on cuestas that slope gently (~4°) eastward toward the Great Plains (Fig. 4). They radiate downslope from the mouths of a few valleys exiting the Rocky Mountain front in eastern Wyoming, forming semiconical fans with radial lengths of a few kilometers, i.e., well within the size range of modern mountain-front alluvial fans. Extensive, flat-bedded sandstones lacking channel deposits exist between the radiating ridges, suggesting ancient unconfined flows, a critically distinctive process on mountain-front alluvial fans (Blair and McPherson, 1994; Fisher et al., 2007; Cain and Mountney, 2009).

DEPOSITIONAL SYSTEMS

White River Group

We mapped ~1600 fluvial ridges and ridge-bearing landforms in the White River Group west of 103°W and between ~40°N and 44°N (Fig. 5; Table 1). All these landforms are capped by sandstones, and they are mostly isolated, low-relief ridges, but high-relief ridges and ridge-bearing plateaus, mesas, buttes, and cuestas are present locally. Many of these landforms appear to have been exhumed from the Chadron or Chamberlain Pass Formations in the lower White River Group. The ridge-forming sandstones in the White River Group occupy several stratigraphic horizons within the lowermost ~60 m of the unit. However, it is difficult to ascertain their exact stratigraphic positions because outcrops of enclosing and underlying strata are very limited. The characteristics of White River Group fluvial ridges change substantially with increasing distance from the Rocky Mountain front, attesting to major differences in depositional settings.

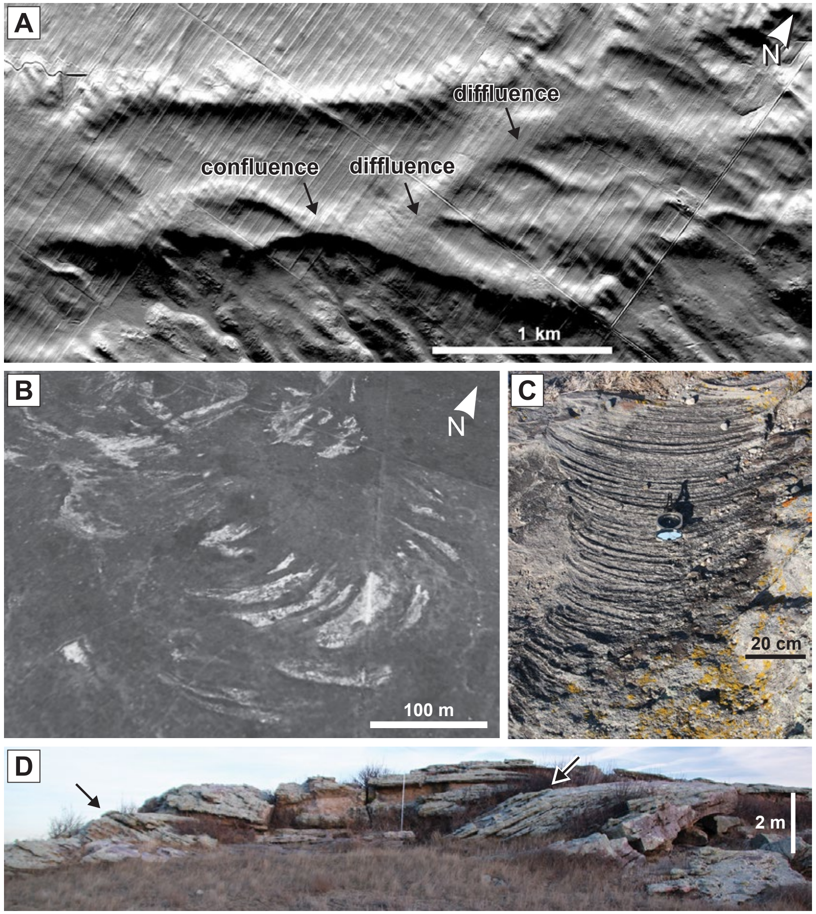

Figure 3. Ridge geometries and sedimentary structures revealing fluvial processes. (A) Hillshaded digital elevation model (DEM) showing low-relief, gravel-capped ridge in Ogallala Group near Goshen Hole. Bifurcations represent confluences and diffluences of inverted, multithread channel. (B) Oblique aerial view of plateau surface in White River Group near Pawnee Buttes. Arcuate, light-gray regions are low-relief sandstone ridges representing meander scrolls. Imagery is modified from Google Earth. (C) Rib-and-furrow structures in sandstones of White River Group formed by the exposure of trough cross-strata in bedding plane. (D) Concentric channel fill in White River Group near Pawnee Buttes. Arrows show inward-dipping beds on either side of channel.

Alluvial Fans

The remnants of alluvial fans are preserved in the White River Group as radial arrays of fluvial ridges atop cuestas and mesas at a few locations immediately east of the Rocky Mountain front near the Gangplank (Fig. 4). The locations of fan apices were inferred from the projected upgradient convergence of each radial pattern. The minimum radial lengths of these ancient fans—the distance from each inferred apex to the downgradient terminus of mapped channels on each fan—are 4–7 km. The relationships between these alluvial fans and more distal depositional environments cannot be examined because there are no exposures of equivalent strata immediately downgradient.

Fixed Channels

Numerous fluvial ridges exist in the White River Group ~40–100 km east of the Rocky Mountain front (103.8°W to 104.7°W), well downgradient from the few examples of alluvial fans (Fig. 5). These ridges are generally <50 m in width and <1 km in length. There are, however, examples of discontinuous, highly erosion-segmented ridges exceeding 5 km in length.

In a few locations, ridges intersect the land surface at surface-subsurface contacts (Fig. 6A). These contacts show the lateral pinch-outs of ridge-forming channel fills. The width of a ridge along such a contact is the original width of the fluvial channel fill (Phillips et al., 2021). The widths of sandstone bodies at these contacts are comparable to widths measured along the entire length of the same ridge. We concluded from these observations that the widths of the fluvial ridges measured at the present land surface are reliable indicators of the widths of the coarse-grained portions of precursor fluvial channels.

Most ridges are straight (S = 1.0) to slightly sinuous (S = 1.2), where S is the ratio of stream length to valley length, and they exhibit unidirectional paleoflow parallel to the channel axis (Fig. 7B). The widest fluvial ridges (100–150 m) are rare, and they typically exist at ancient meander bends where there is evidence for point-bar accretion. Meandering morphologies (S >1.5) are rare, but where they do occur, they preserve point- and counter-point-bar deposits. These bars are also present on the insides of channel bends connecting two straight reaches.

Most of these fluvial ridges exist as parallel or downstream-divergent threads with few intersections with other ridges (Fig. 2C). Where one fluvial ridge crosses another, the tops of the ridges are

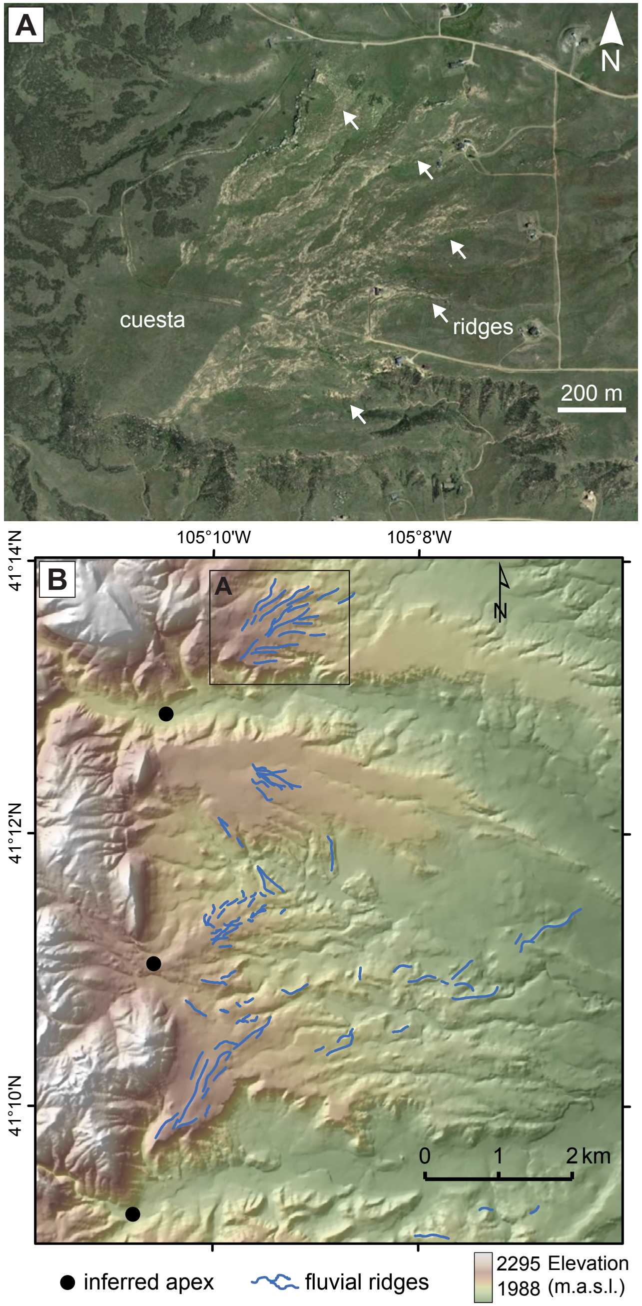

Figure 4. Eastward-sloping ridges and ridge-bearing cuestas, interpreted as exhumed alluvial fans, adjacent the Rocky Mountain front near the Gangplank. (A) East-sloping (~4°) cuesta and closely grouped, radiating arrays of ridges. Imagery is modified from Google Earth. (B) Map showing radial arrays of fluvial ridges interpreted as alluvial fans. Apices of fans were inferred from the projected upgradient convergence of radial patterns, which coincide with gaps in the mountain front. Abbreviation: m.a.s.l.—m above sea level.

commonly offset vertically by 5–7 m, meaning that the precursor channel fills occupied different stratigraphic positions and had different relative ages. There are a few Y-shaped intersections of ridges resembling inverted river diffluences and confluences. We were unable to determine whether these features represent contemporaneous branches of the same river or whether they are merely different generations of channels within the same stratigraphic interval.

These fluvial ridges represent single-channel threads or multithread channels around which intervening fine-grained deposits were eroded. The sparsity of lateral accretion deposits and the isolated nature of the channels suggest that most of them were laterally immobile or "fixed" (Friend, 1983; Nanson and Knighton, 1996; Gibling, 2006). Sandstones atop these ridges very likely preserve the true widths of the coarse-grained portions of the channel fills, but a few observations suggest that fine sediments originally filled parts of some of the fills. Therefore, the original channel geometries of precursor channels remain unconstrained. Nevertheless, where evidence exists for confluent and divergent branches, these multithread channel networks appear to be as much as 200–500 m in total width. The wavelengths of rare meandering channels are less than 600 m, and their amplitudes are less than 200 m.

Mobile Channel Belts

Eastward from the area dominated by fixed channels, there is an area dominated by wide (1–3 km) plateaus and mesas (Fig. 5), which are capped by strata composed of multiple, horizontally amalgamated channel fills (Figs. 6 and 7). These discontinuous plateaus and mesas are as much as 22 km in length. The true widths of these paleochannel belts, however, can only be estimated from two surface-subsurface contacts along the same train of landforms (Fig. 6A). Near Pawnee Buttes in Colorado, the upgradient width of a sandstone cap rock is 3 km where it emerges from a side slope, forming an eastward-narrowing plateau. This same plateau can be traced to a train of mesas

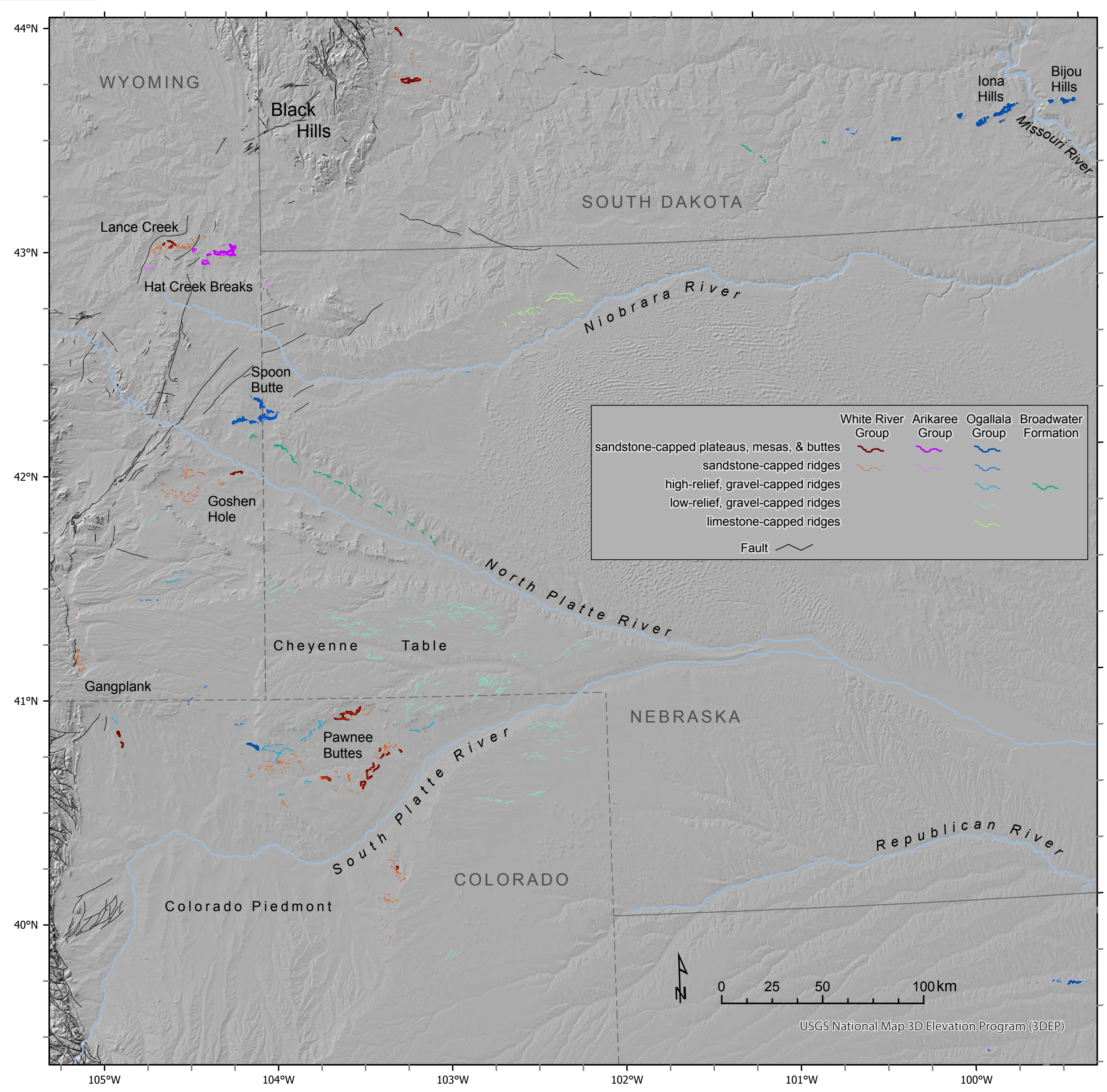

Figure 5. Detailed reference map for fluvial ridges and locations mentioned in the text and figures. Colored lines denote classification of ridges and ridge-bearing landforms as defined in this article. Sandstone-capped ridges are not subdivided into low- and high-relief classes in this map because they are gradational and extremely variable over small distances.

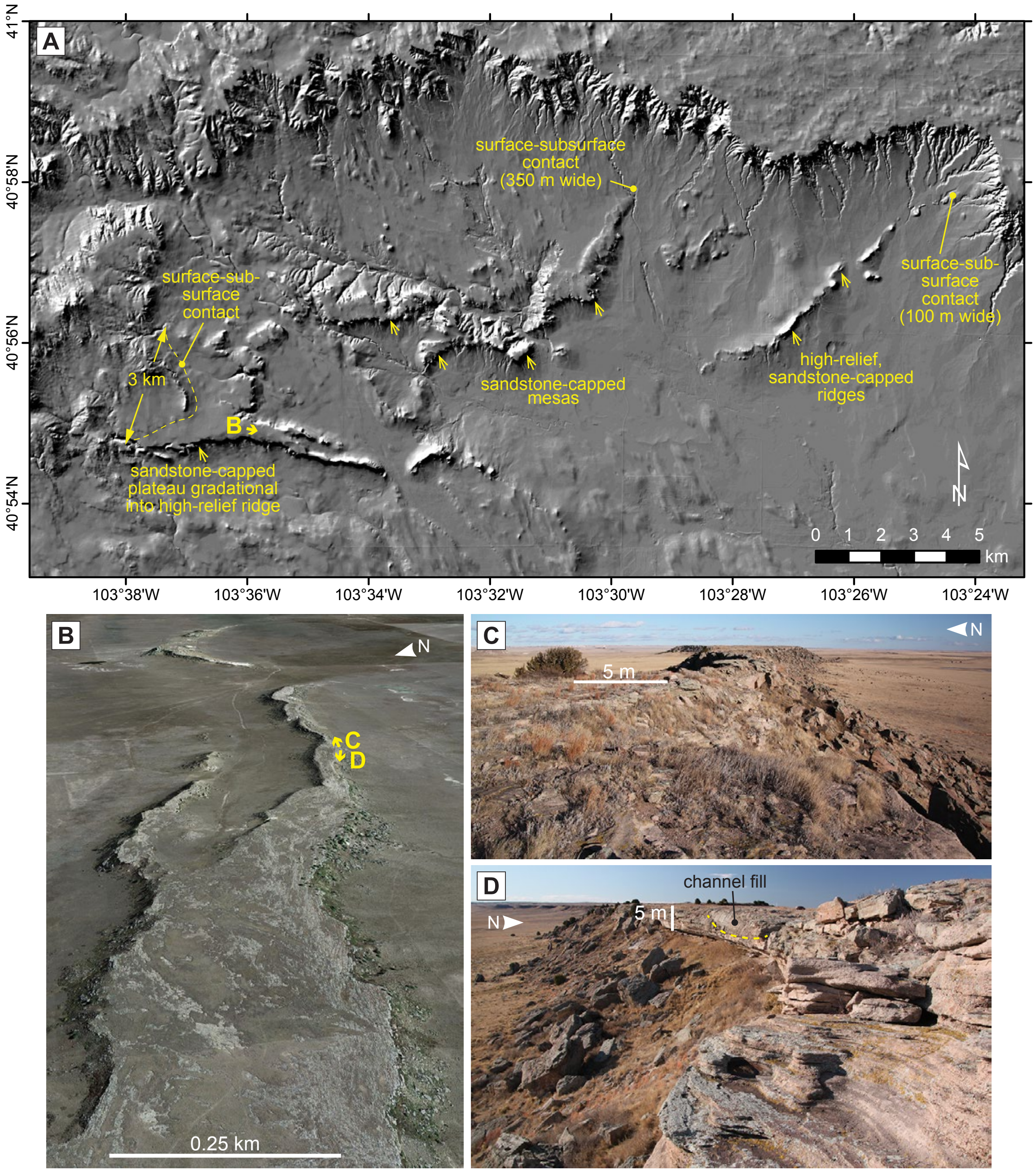

Figure 6. Sandstone-capped fluvial ridges and ridge-bearing landforms in the White River Group near Pawnee Buttes. (A) Hillshaded digital elevation model (DEM) showing surface-subsurface contacts. Widths of the sandstones along these contacts reflect the widths of the precursor channels. Light detection and ranging (LiDAR) data are from U.S. Geological Survey 3D Elevation Program (3DEP). (B) Oblique aerial view of eastward-narrowing ridge. Location of view is shown in A. (C) Photograph looking east along same ridge as in B. Location of photography is shown in B. (D) Photograph looking west along same ridge as in B. Location of photograph is shown in B.

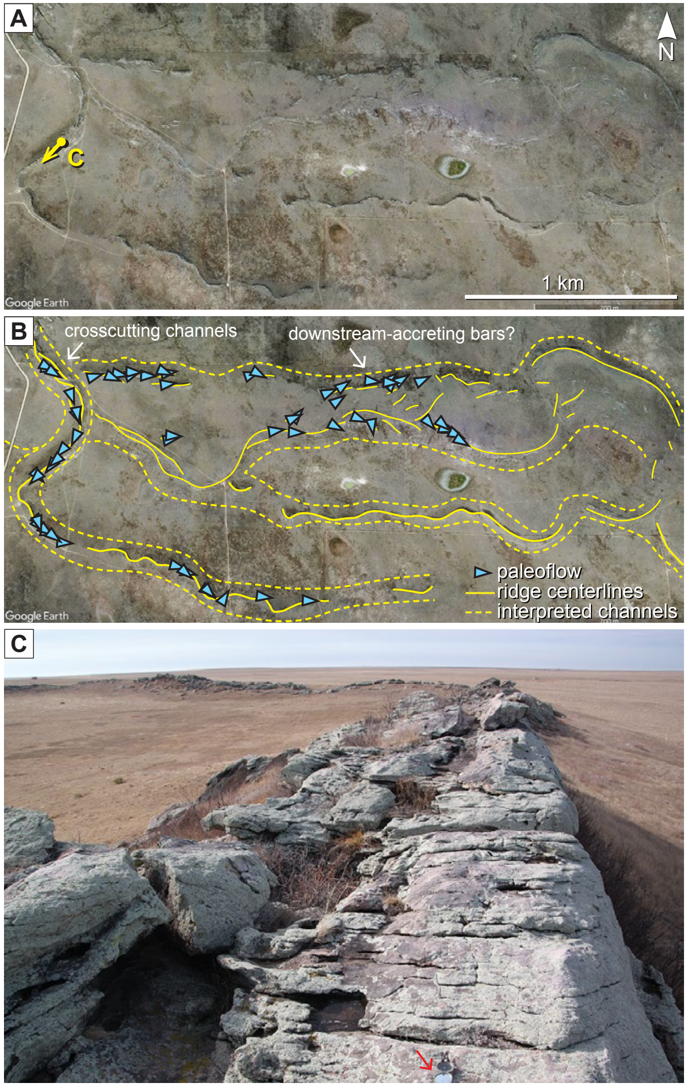

Figure 7. Sandstone-capped ridges and ridge-bearing mesa in the White River Group near Pawnee Buttes. (A) Google Earth image. (B) Interpreted image of area in A showing multiple, crosscutting channels and measured paleoflow (blue arrows). Closely grouped ridges near top center are interpreted as downstream-accreting bars. (C) Photograph of narrow ridge at location shown in A. Note cross-stratification indicating paleoflow parallel to the ridge centerline. Compass for scale (red arrow).

extending eastward for 13 km. The sandstone cap rock of the easternmost mesa is 350 m in width where it re-enters the side slope. In this example, the downgradient narrowing of the ridge appears to reflect the original geometry of the precursor channel deposit.

Fluvial ridges atop plateaus and mesas are similar in morphology to the isolated channels found farther west: They are narrow, straight to slightly sinuous, and meandering (Figs. 3B and 7). Meandering morphologies appear to be more numerous in these eastern examples, but the wavelengths and amplitudes of meanders are similar in size (less than a few hundred meters). The radius of curvature of meanders is typically ~100–200 m. Wavelengths are ~200–300 m, and amplitudes are 100–300 m. Laterally active meandering channels are indicated by a few sets of closely spaced, arcuate ridges interpreted as meander scrolls (Fig. 3B) and bar-accretion deposits (Fig. 7B). These channels also exhibit numerous intersections and crosscutting relationships (Fig. 7B). Paleoflow is parallel to the axis of the superimposed channels, but the orientation of these channels is highly variable with respect to the long axis of the plateaus and mesas.

The fluvial ridges and ridge-bearing landforms in this area are inverted deposits (sensu Hayden and Lamb, 2020). These deposits record the amalgamation of multiple, narrow (less than a few tens of meters in width) channels that migrated laterally across channel belts several kilometers in width. Many of the meandering channels were laterally active, forming point-bar deposits. Bar deposits representing downstream and oblique accretion are also observed (Fig. 7B), although detailed sedimentologic analyses have not been performed. Vertically offset channel fills are observed in some of the strata, showing that vertical accretion also played a role in amalgamation of the deposits (Fig. 6D). Abundant blocks of sandstone on talus slopes adjacent to these landforms show that backwasting likely played a role in the narrowing of these landforms (Figs. 6B–6D). Nevertheless, downgradient variability in the width of the original deposit also played some role in determining their variable widths.

Arikaree Group

We mapped comparatively few (~120) fluvial ridges in the Arikaree Group (Table 1). A group of low-relief, sandstone-capped ridges and several mesas, cuestas, and buttes is limited to the Hat Creek Breaks of eastern Wyoming and the Nebraska Panhandle (43°N and 104°W–104.75°W; Fig. 5). All these features occur near the contact between the Arikaree Group and the underlying White River Group, and therefore we are confident that they were eroded from the lower part of the unit.

Although fluvial ridges in the Arikaree Group are substantially fewer than those in the White River Group, we were still able to document a similar proximal-distal change in depositional systems.

Alluvial Fan

The single alluvial fan that we identified in the Arikaree Group lies adjacent to a reverse fault near Lance Creek, Wyoming (Fig. 5). The radial distance of the fan is ~3 km. It contains isolated channels and channel trains, but field observations confirmed that most of the fan is composed of thin-bedded sandstone sheets interpreted as sheetflood deposits. The fan deposits are upturned along the trend of the fault, showing that deposition was contemporaneous with deformation.

Fixed Channels

There are a very few fluvial ridges in the Hat Creek Breaks extending 12 km eastward from the distal end of the single Arikaree Group alluvial fan at Lance Creek (Fig. 5). These channel segments are <300 m in length and <60 m in width. We were unable to find any surface-subsurface contacts from which to measure true channel widths. Ridges are straight to slightly arcuate and parallel, but because of the limited number of observations, the assessment of channel planform is incomplete, and we were unable to examine the nature of channel intersections. Our observations suggest that these Arikaree Group ridges represent fixed channels like those in the White River Group.

Mobile Channel Belts

Broad mesas as much as 2.5 km in width are present 20–40 km east of the alluvial fan at Lance Creek (Fig. 5). The mesas form a train of landforms 20 km in length. True widths were not observed because surface-subsurface contacts are absent. Low-relief, sandstone-capped ridges are present locally atop the mesas (Fig. 8). These inverted

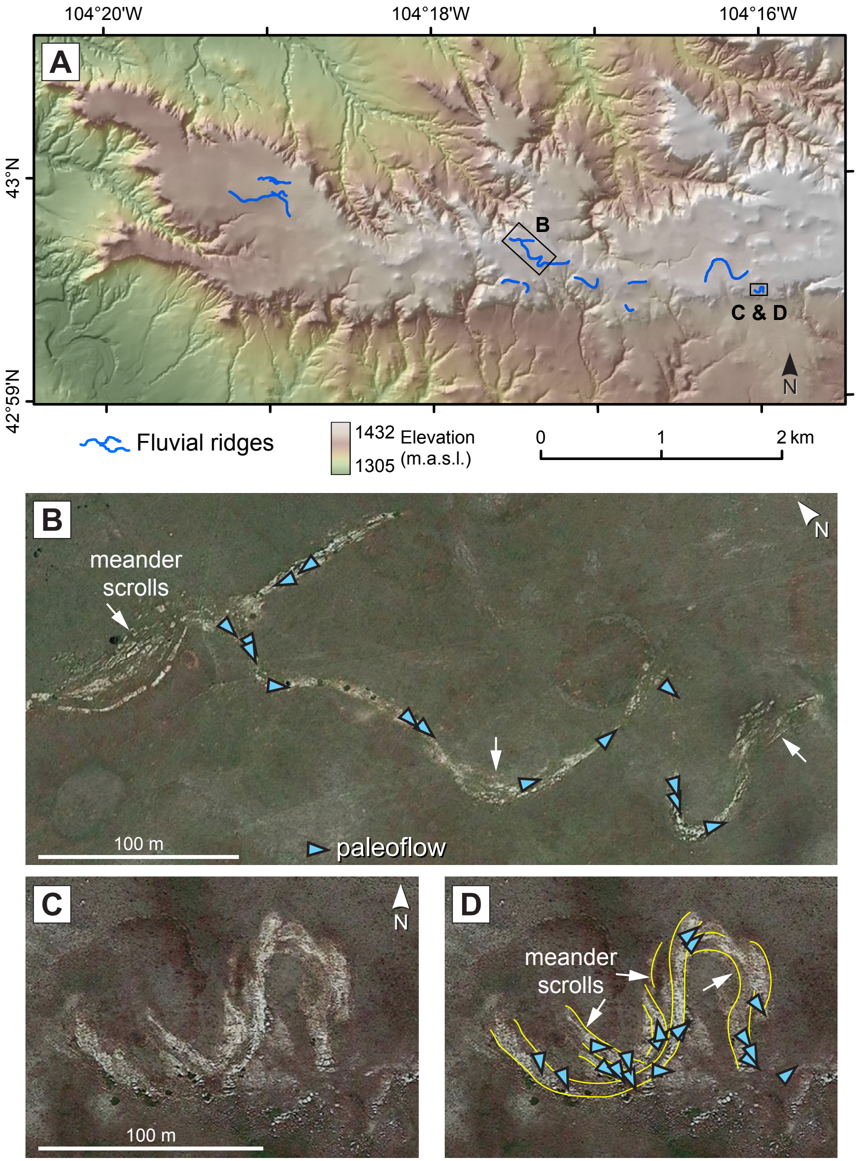

Figure 8. Sandstone-capped mesa in the Arikaree Group in Hat Creek Breaks. (A) Hillshaded elevation map showing mesa and superimposed, low-relief ridges. Light detection and ranging (LiDAR) data are from U.S. Geological Survey 3D Elevation Program (3DEP). (B) Close-up of sinuous ridge showing measured paleoflow (blue arrows) and meander scrolls. Location is shown as box in A. Image is from Google Earth. (C) Close-up of sinuous ridge in box in A. Image is from Google Earth. (D) Interpreted image of area in C showing meander scrolls and measured paleoflow (blue arrows). Abbreviation: m.a.s.l.—m above sea level.

channels are straight (*S* ~1.0) to meandering (*S* = 1.7). Radius of curvature of meandering channels varies from 25 to 100 m. The largest meandering channel observed has a wavelength of 300 m and an amplitude of 100 m. Meandering channels are clearly associated with point-bar deposits (Figs. 8B–8D). Intersecting and crosscutting channels are observed locally. Like previous examples, paleoflow is parallel to channels, but variable with respect to the long axis of mesas. The characteristics of these deposits are consistent with those observed in similar ones in the White River Group. Therefore, we interpret them as mobile channel belts.

Ogallala Group

We mapped nearly 1300 fluvial ridges in the Ogallala Group, including both sandstone- and gravel-capped landforms (Table 1). The fluvial ridges in this unit are geographically widespread, from 39.5°N to 43.5°N and from 99°W to 105°W (Fig. 5). Low-relief, gravel-capped ridges constitute nearly two thirds of these landforms, and most of these are located on the Cheyenne Table and adjacent areas of the High Plains in northeast Colorado. Low-relief and high-relief, sandstone-capped ridges as well as high-relief gravel ridges are present in highly eroded areas of the Colorado Piedmont. Notably, sandstone-capped mesas in the Ogallala Group form distinctive outliers in South Dakota and Kansas, ~300–500 km east of the main area of fluvial ridges (Fig. 5). Unlike the White River Group and Arikaree Group, the ridges in the Ogallala Group were eroded from various stratigraphic intervals, including many of them from the upper part of the unit. Channel bodies from the lower part of the Ogallala Group are comparatively few, but they include some notable examples described in the next section.

Valley Fills

Several isolated trains of sandstone-capped plateaus, mesas, buttes, and ridges were mapped in the lower part of the Ogallala Group. These landforms are as much as 3–4 km in width, and their capping sandstones are usually silica-cemented. The westernmost group of these landforms is found near Spoon Butte along the Wyoming-Nebraska border (42.3°N, 104.0°W; Fig. 2D). These rocks were first described by Hunt (2005), who showed that the capping sandstones are incised 30–43 m into the underlying Arikaree Group and White River Group. Fossils and field mapping indicate that this area contains two intersecting units of different ages: an early Hemingfordian unit trending west-southwest to east-northeast, called the Carpenter Ranch Formation by Hunt (2005), and a Barstovian unit trending northwest-southeast, which he called the Spoon Butte Beds. Superimposed upon these landforms, there are numerous low-relief, straight to meandering channels. These channels are commonly parallel, but they also exhibit crosscutting relationships and contain point-bar deposits.

Sandstone-capped ridges also exist as outliers 300–500 km east of the Rocky Mountain front. One prominent series of ridges, buttes, and mesas trending west-southwest to east-northeast exists in South Dakota at 43.5°N and between 99°W and 100.5°W (Figs. 5 and 9). The total length of this train of landforms is more than 100 km, but it also contains gaps as long as 20 km. It is located as much as 20 km from the erosional edge of the main Ogallala Group outcrop belt. Another train of widely scattered, low-relief ridges and plateaus exists in northern Kansas near 39.6°N and between 99.3°W and 99.7°W, and a few, subtle sandstone-capped fluvial ridges exist as far east as 98.9°W in southern Nebraska (Fig. 5). These outlying ridges in South Dakota, Kansas, and Nebraska are more highly eroded and covered with soil and vegetation than their western counterparts, but they nevertheless share many of the same characteristics, including superimposed, low-relief ridges and silica-cemented capping sandstones.

We interpret these ridges in the lower Ogallala Group as inverted valley-fill deposits. The ridge-capping sandstones of Spoon and Carpenter Buttes fill lows in the sub-Ogallala unconformity (Hunt, 2005), and they comprise sheets of laterally and vertically amalgamated channel fills. The silica-cemented cap rocks are reminiscent of Australian examples of inverted paleovalley systems (McNally and Wilson, 1995; Twidale and Bourne, 1998; Hill

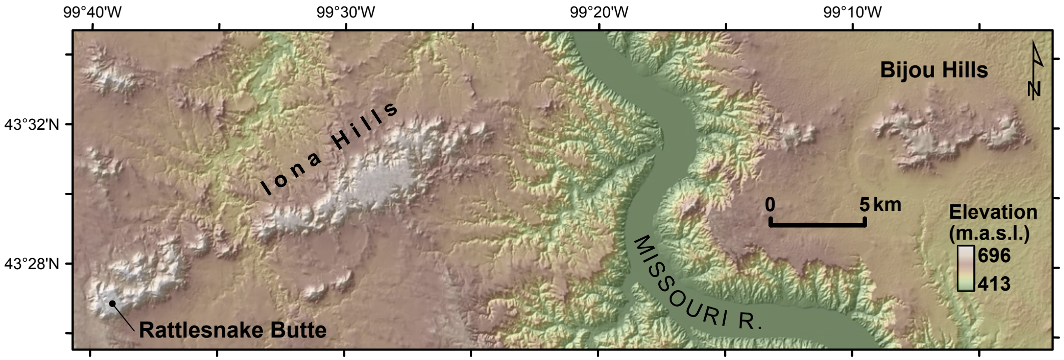

Figure 9. Hillshaded elevation map showing Iona Hills and Bijou Hills: outliers of the Ogallala Group in South Dakota. Mesas are capped by silica-cemented sandstones. Abbreviation: m.a.s.l.—m above sea level.

et al., 2003). Hunt (2005) interpreted the Carpenter Ranch paleovalley as a proximal part of the Runningwater paleovalley described by Skinner et al. (1977) based on their apparent geographic alignment and similar fossil faunas. The outlying ridges in South Dakota and Kansas are similar enough that we also interpret them as inverted valley fills.

Fixed Channels

Gravel-capped fluvial ridges are abundant and widespread in the Ogallala Group on the Cheyenne Table and adjacent areas of the Colorado Piedmont and High Plains (Fig. 5). These ridges range from ~20 m to 1 km in width and are as much as ~20 km in length. Parallel ridges separated by 1–2 km constitute networks of 10 or more channel threads (Fig. 10). These channel networks are as much as 10 km in width and 40 km in length. Channels almost always exist as such networks—isolated channels are rare. Crosscutting channels are observed locally, but most channel intersections appear to be diffluences or, less commonly, confluences (Fig. 3A and 10). Most channels are straight to slightly sinuous. A few narrower (several tens of meters) channels are sinuous ($S = 1.2$) to meandering ($S = 1.5$). The meandering channels have wavelengths of <2 km and amplitudes of <500 m (Figs. 2E–2F and 11). Lateral accretion deposits have not been identified and are presumed to be absent.

We interpret all these ridges as fixed, multithread braided channels and sinuous single-thread channels. The abundance of branching morphologies and the continuity of the ridge-top elevations across intersections suggest that these were contemporaneous branches (Fig. 10). The lack of lateral accretion deposits and the preservation of fluvial channel morphologies show that these were fixed channels in which there was little to no horizontal amalgamation (Fig. 11). Vertical amalgamation is suggested in a few locations where channels in successively higher stratigraphic positions intersect (Figs. 10A and 10C). Modern erosion is minimal on the edges of low-relief ridges, suggesting that the true widths of the channels are likely preserved. High-relief ridges, however, are heavily gullied and dissected, implying that their widths have been reduced by erosion (Fig. 2E).

Rare, freshwater limestone–capped ridges are present in northwestern Nebraska, where they parallel the Niobrara River valley for more than 40 km (Figs. 2G and 5). These ridges are straight to slightly sinuous and have several apparent diffluences. The limestones atop these ridges contain fossil gastropods and invertebrate burrows. The limestone cap rocks are lithologically similar to the ponded-water facies of Joeckel et al. (2014). We interpret them as abandoned channels that were sufficiently separated from active channels such that clastic input from overbank floods was minimal, allowing lacustrine carbonate precipitation.

Broadwater Formation

The Broadwater Formation contains only ~40 isolated threads of high-relief, gravel-capped ridges as much as 100–200 m in width (Table 1). The longest of these threads parallels the North Platte River valley in the Nebraska Panhandle (Fig. 5). This train of discontinuous ridges extends nearly 110 km and rests unconformably on top of the White River Group. These ridges lie at lower elevations than the nearby, but stratigraphically older, Ogallala Group and Arikaree Group, showing that the channel body represents the lowermost part of the Broadwater Formation. A few isolated ridges exist in South Dakota on the northern fringes of the High Plains (Fig. 5). These ridges are similar in orientation and morphology to those in the North Platte River valley. Channels in the Broadwater Formation are straight to slightly sinuous, and ridge threads are remarkably straight for distances of tens of kilometers. They exist largely as isolated channels with few branches, intersections, or parallel threads. As such, we interpret these channels as fixed, single-channel threads.

■ PALEOFLOW

The inverted channels and channel deposits reveal paleoflow trends at local to regional scales (Figs. 12 and 13). Each arrowed line in Figures 12 and 13 shows a single-thread channel, multithread channel, or channel network that was deposited along a continuous elevation profile. Paleocurrent measurements from selected localities aided in the interpretation of paleoflow direction where it was unclear or ambiguous.

Late Eocene–early Oligocene paleoflow was highly dispersed and variable (Fig. 12). Alluvial fans distributed sediment radially away from the Rocky Mountain front. Farther east, fixed, single-thread channels exhibit radial paleoflow patterns in Goshen Hole (Fig. 12C) and Pawnee Buttes (Fig. 12D). Drainage was highly variable near the Lance Creek fault zone (Fig. 12B). In this area, older channels run parallel to the fault zone, whereas younger channels are oriented perpendicular to the fault zone. Near the South Platte River in Colorado, flow patterns were largely oriented southeastward (Fig. 12D). However, a subset of northeast-oriented channel belts ran parallel to the South Platte River. Locally, these two channel belts intersect one another at right angles. Drainage was dominantly southeastward near the Black Hills in South Dakota (Fig. 12A).

Information on Oligocene drainage is sparse. Nevertheless, channels on the alluvial fan at Lance Creek, Wyoming, exhibit a radial paleoflow pattern (Fig. 12B). Farther east, channel belts trend east-southeast toward the northwest corner of Nebraska, where a major paleovalley is mapped at the base of the Gering Formation (Swinehart et al., 1985).

Miocene paleoflow is more completely resolved because channels in the Ogallala Group are widespread, and they exist at multiple stratigraphic intervals (Fig. 13). Paleoflow was less dispersed and variable than during the late Eocene and early Oligocene. There was a dominant east-northeastward component to regional drainage. This trend generally parallels the South Platte River, but it intersects the North Platte River at acute angles. This east-northeast trend continues as far east as the Missouri River—the eastern fringe of the Great Plains—some 500 km from the Rocky Mountain front. Locally, some drainages align with structural features, particularly in northwestern Nebraska.

A major change in drainage occurred in the Pliocene. Paleoflow is oriented southeastward, paralleling the North Platte River in western Nebraska and the Missouri River in South Dakota (Fig. 13).

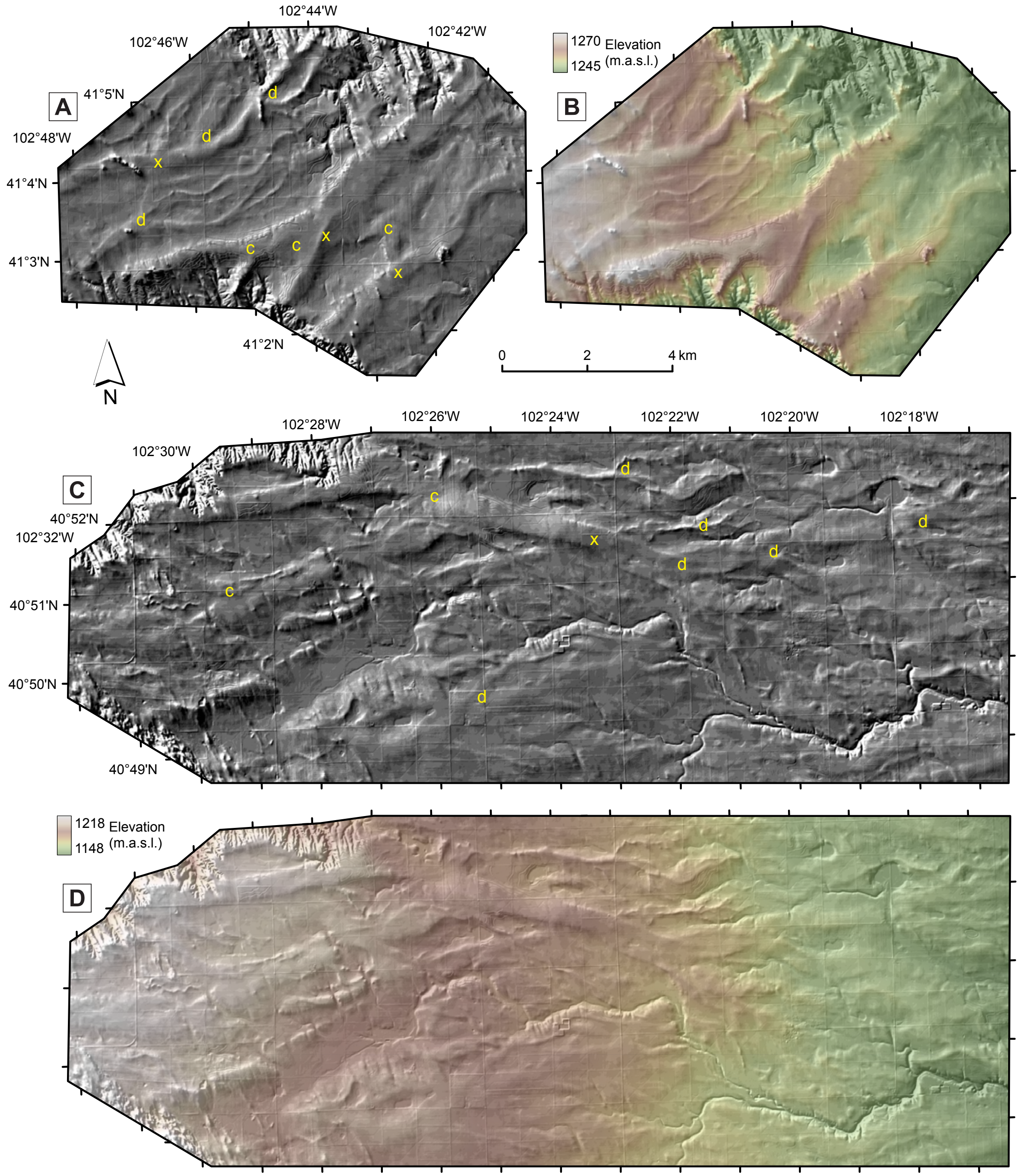

Figure 10. Hillshaded digital elevation model (DEM) and elevation maps showing low-relief, gravel-capped ridges in the Ogallala Group. Light detection and ranging (LiDAR) data are from U.S. Geological Survey 3D Elevation Program (3DEP). (A) Hillshaded DEM of a portion of Cheyenne Table showing confluences (c), diffluences (d), and crosscutting channels (x). (B) Hillshaded elevation map of same area in A. (C) Hillshaded DEM of extreme northeastern Colorado showing confluences (c), diffluences (d), and crosscutting channels (x). (D) Hillshaded elevation map of same area in C. Abbreviation: m.a.s.l.—m above sea level.

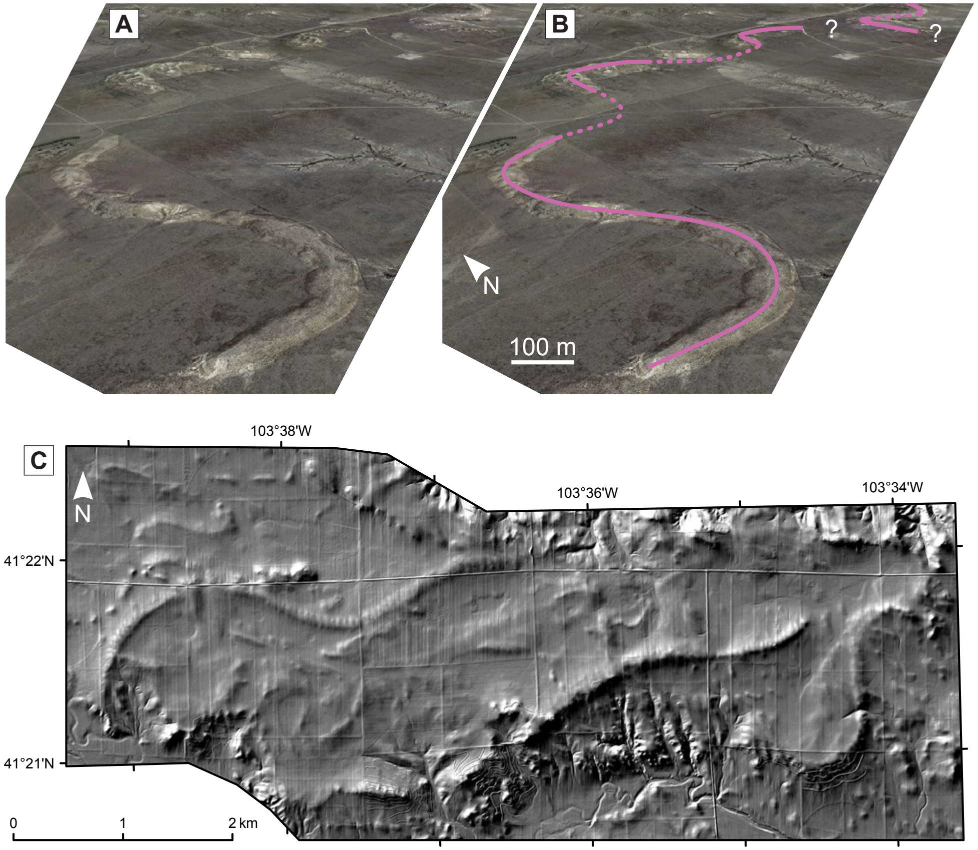

Figure 11. Gravel-capped ridges in the Ogallala Group. (A) Oblique aerial view of a chain of discontinuous, sinuous, high-relief ridges near Pawnee Buttes. Image is modified from Google Earth. (B) Interpreted channel centerlines (solid) and inferred centerlines (dashed) for same image in A. (C) Hillshaded digital elevation model (DEM) of a portion of Cheyenne Table showing sinuous, low-relief ridges. Light detection and ranging (LiDAR) data are from U.S. Geological Survey 3D Elevation Program (3DEP).

DISCUSSION

Possible Role of Regional Drainage Integration

The Eocene was a time of dramatic drainage reorganization in the western interior of the United States (Galloway et al., 2011). In the early to middle Eocene, Laramide uplifts were separated by a series of actively subsiding, closed, lacustrine basins in southern Wyoming, northwestern Colorado, and northeastern Utah. These basins sequestered coarse clastic sediments and limited the drainage divide of the paleo-Mississippi drainage system to a position near the Rocky Mountain front. These basins had filled and begun to spill into adjacent basins by the late Eocene. From the Oligocene to the early Miocene, the formerly closed basins evolved into a regionally integrated, northeastward-draining basin with headwaters as far west as eastern Idaho and Utah (Galloway et al., 2011). The continental divide was at its westernmost extent, but the volume of coarse fluvial sediments routed through the system and onward to sediment sinks along the Gulf Coast was at its minimum (Blum et al., 2017). This limited routing of fluvial sediment through the northern Great Plains was likely the result of sediment trapping in intermontane basins as well as arid climates in which river systems were too small to overcome the confining effect of the vast, eolian volcaniclastic apron of the White River Group and Arikaree Group.

Our reconstruction of Eocene–Oligocene fluvial systems and paleoflow patterns is limited to observations of channel networks (Fig. 12). Nevertheless, it sheds additional light on regional drainage and sediment routing. We infer that catchments in the Rocky Mountains had relatively high relief because alluvial fans are present immediately adjacent to the mountain front (e.g., Blair and McPherson, 1994; Ventra and Clarke, 2018). Moreover, the fans were likely fed by small, poorly integrated catchments with short-duration, high-discharge, ephemeral flows (Ventra and Clarke, 2018). Farther east, stream networks comprised parallel or downstream-divergent, fixed, single-thread channels. These channels were straight to slightly sinuous (S = 1.0–1.5), and they were generally <50 m in width. These networks formed radial patterns ~10–20 km in length, and their inferred apices were located some 40–100 km from the Rocky Mountain front. These characteristics distinguish them as fluvial fans rather than alluvial fans, implying that they were connected to feeder rivers with larger catchments (Moscariello, 2018; Ventra and Clarke, 2018). Nevertheless, these catchments would have been small in comparison to the entire Eocene–Oligocene sediment apron, so it is likely that drainage basins were poorly integrated at this time. Future studies of sediment provenance may provide an effective test of this hypothesis.

Broad (~3 km) fluvial channel belts existed ~100 km from the Rocky Mountain front, immediately downgradient from the interpreted fluvial fans. Some of these channel belts may have been

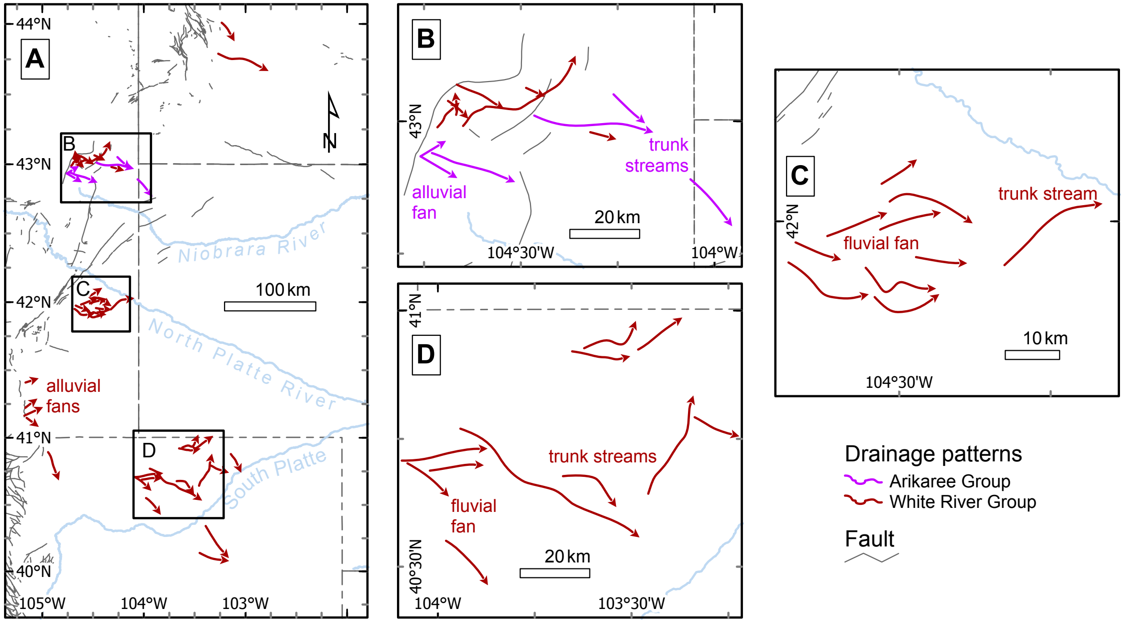

Figure 12. Reconstructed drainage patterns for the late Eocene (White River Group)–Oligocene (Arikaree Group). (A) Drainage patterns in the study area. (B) Close-up of Lance Creek–Hat Creek Breaks area. (C) Close-up of Goshen Hole area. (D) Close-up of Pawnee Buttes area.

continuous for >70 km. Flow in these streams was oblique to the mean trend of flow on the fans. These observations suggest that the mobile channel belts were trunk streams that were fed by flows coming off the fluvial fans (Fig. 12). These trunk streams may have connected to basins farther east on the Great Plains. The chain of southeast-trending channel belts on the Colorado Piedmont, for example, intersects the present South Platte River at a right angle, showing that the extant drainage line did not exist in the late Eocene. Therefore, it is possible that sediment from this river system was routed into Kansas, where Eocene–Oligocene coarse-grained fluvial sediments were recently discovered (Smith et al., 2017). Southeastward flow is also indicated by similar channel belts farther north. The Arikaree Group channel belt in the Hat Creek Breaks may have supplied sediment to the basal Gering paleovalley (Fig. 12B), which extends as far east as 102°W in west-central Nebraska (Swinehart et al., 1985). Overall, however, paleoflow was spatially dispersed (southeast to northeast) and temporally variable. Drainage rearrangement is evidenced by channel belts that intersect at right angles, and some drainages align to mapped faults (Fig. 12B). We conclude, therefore, that fluvial ridges in the White River Group and Arikaree Group reveal a nascent Great Plains alluvial apron hosting small, poorly integrated drainages undergoing abrupt changes.

In the middle to late Miocene, the drainage divide of the Mississippi drainage system was again located near the Rocky Mountain front (Galloway et al., 2011). Despite the rather limited western extent of their catchments, the water discharge and supply of coarse sediments to these rivers increased, initiating deposition of the Ogallala Group alluvial apron. The earliest of these rivers exhibited variable flow, but by the late Miocene, flow was more uniform and oriented east-northeast (Fig. 13). The extant course of the North Platte River was not yet established. Rather, fixed, multithread channels a few kilometers in width flowed east-northeast, generally parallel to the extant South Platte River. This flow direction was maintained for as much as 700 km to the Bijou Hills in South Dakota. Overall, these patterns indicate a mature alluvial apron hosting bigger rivers within well-integrated drainage basins. The observed increase in channel size could be related to an increase in the size of the catchments.

By the Pliocene, the paleo–North Platte River had begun to incise its valley in the Nebraska Panhandle (Fig. 13). This incision is manifested in the Pliocene channels that are constrained by the modern valley. These channels exist at elevations lower than late Miocene channels on the adjacent Cheyenne Table. Although only a few, small channel segments are preserved in South Dakota, the discovery of these inverted channels attests to southeastward paleoflow in that area during the Pliocene. These channels also suggest a connection between the Black Hills and the Broadwater Formation and equivalents.

Possible Role of Climate Change

We posit that the observed changes in channel size and morphology from the late Eocene to

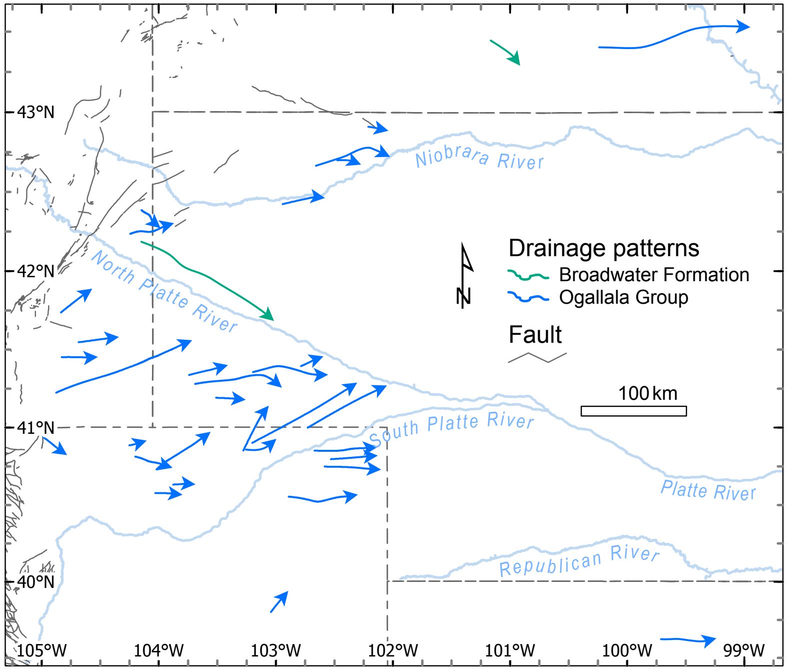

Figure 13. Reconstructed drainage patterns for the Miocene (Ogallala Group)–Pliocene (Broadwater Formation).

Pliocene may reflect evolving discharge regimes brought about by climate changes. Aridification may help to explain the ubiquity of narrow, single-thread channels in the White River Group and lower Arikaree Group, as well as the presence of short-wavelength (200–300 m), low-amplitude (<200 m), small-radius (<100 m) meanders. The Eocene-Oligocene boundary was marked by global cooling and the onset of icehouse conditions (Zachos et al., 2001). Cooling was accompanied by increasing aridity (Cather et al., 2012), which was enhanced by the rain-shadow effect of the Rocky Mountain highlands (Rowley and Fan, 2016).

A warming trend began in the late Oligocene and lasted through the middle Miocene, culminating in the mid-Miocene climatic optimum ca. 17–15 Ma (Zachos et al., 2001). Warm periods on the Great Plains were also times of higher precipitation (Retallack, 2007). Most of our observations of channel geometry in the Ogallala Group, however, are from the Cheyenne Table, and they are Hemphillian (ca. 9–5 Ma) in age (Breyer, 1981; Diffendal, 1982b). This period corresponds to global cooling and the development of the Antarctic Ice Sheet (Zachos et al., 2001; Chapin, 2008), as well as increasing aridity on the Great Plains (Chapin, 2008). Despite the return to dry-cool conditions, late Miocene rivers were multithread, wide (as much as 10 km) features that contained anabranches as much as 1 km in width (Fig. 10). Meanders were also larger, exhibiting wavelengths as much as 2 km and amplitudes of 500 m (Fig. 11). One explanation for the apparent disparity between channel size and climate is that discharge events became more extreme after 12 Ma, when the enhanced El Niño–Southern Oscillation (ENSO) was initiated (Chapin, 2008). This climate system created phases of extreme moisture and runoff in the mostly arid climate. Such periods likely formed heavy snowpacks at high elevations in the Rocky Mountains, providing large, episodic discharges to Ogallala streams and liberating large volumes of sediment (Chapin, 2008; Pelletier, 2009).

We offer the above hypotheses as avenues for further research. A thorough analysis of the role of climate change would include estimation of paleohydrologic parameters.

Spatially and Temporally Variable Aggradation Rates

Fixed channels are characteristic of distributary systems, particularly fluvial fans and distal portions of alluvial fans, and they are also common elements of eolian systems (Gibling, 2006). Fixed channels attest to high aggradation rates and low bank migration rates (Nanson and Knighton, 1996; Gibling, 2006), dominance of avulsion processes over lateral migration (Jerolmack and Mohrig, 2007), and high bank strength (Allen, 1983; Gibling and Rust, 1990). Indeed, we observed only localized lateral accretion deposits in fixed channels throughout the studied interval.

Long-term subsidence rates on the Great Plains were low (McMillan et al., 2006), and the succession exhibits evidence for multiple periods of aggradation and incision (Swinehart et al., 1985). Channel and valley incisions are marked by basal erosion surfaces, megaclasts derived from erosion of underlying deposits, colluvium, channel-side gullies, and tributary valley patterns (Diffendal, 1982a, 1982b, 1983; Diffendal et al., 1985). We found little evidence of these features in our analysis of fixed-channel deposits. Rather, the fixed channels exhibit dominantly divergent threads, radiating channel patterns, and younger channels overlapping older channels at stratigraphically higher positions (Figs. 7 and 10). These observations point toward aggradation and avulsion processes rather than incision. This presents an interesting problem. How could channel aggradation dominate in a slowly subsiding basin? We posit that these fixed channels reflect locally high aggradation rates atop spatially distributed, fluvial-fan lobes that were not confined by valleys. They could represent short periods of locally rapid aggradation tied to avulsions. An alternative explanation is that upstream incision and downstream aggradation were simultaneously active, similar to the process of alluvial-fan dissection (Harvey, 1987). Nevertheless, the presence of any given incision surface at the base of a channel does not, in itself, imply regional degradation. In fact, multiple authors (e.g., Church, 2006; Carling et al., 2014) have proposed process frameworks for localized channel incision in net-aggradational environments.

In the White River Group and Arikaree Group, fixed channels transition to compound channel deposits ~100 km from the Rocky Mountain front. These channels readily migrated, avulsed, incised, and aggraded over a comparatively broad channel belt (Figs. 6–8). These channels may have been confined to valleys, although we have no evidence of valley walls. Nevertheless, this downgradient change from fixed to mobile channels represents a fundamental difference in the variables that govern channel body geometry. We interpret this change as a transition to lower accommodation on the distal end of the alluvial apron, where the ratio between aggradation and lateral migration was much lower, promoting channel mobility and lateral amalgamation of coarse channel deposits.

In the Ogallala Group, fixed channels are the dominant elements of fluvial ridges over most of the study area, with two exceptions: the basal Ogallala Group paleovalley fills in eastern Wyoming and the extreme outliers in distal portions of the Ogallala Group outcrop area in South Dakota, Kansas, and Nebraska east of 100°W. These observations suggest that high aggradation rates in the late Miocene extended over a much larger area than in the late Eocene–Oligocene. High aggradation rates, however localized, existed as far east as 102°W, some 350 km from the Rocky Mountain front, and they may have extended as far east as 100°W, at the western edge of the outlying, mobile channel belts.

Despite a thorough review of data for the central and southern High Plains, we could not find any inverted channels in the Ogallala Group in these areas. This lack of fluvial ridges is intriguing, given that exhumed Ogallala Group strata are present as far south as 32°N. One explanation is that locally high aggradation rates and avulsions, as we infer for the northern High Plains, are prerequisites to the preservation of fluvial ridges in the Ogallala Group. Aggradation rates may have been too low in areas outside the study area to preserve fixed channels. Rather, these areas may have been dominated by mobile channel belts that were simply too wide and homogeneous to be preserved as ridges during exhumation. Ogallala Group deposits are generally devoid of thick mudstone, shale, and claystone units (Seni, 1980; Joeckel et al., 2014). Without major lithologic contrasts between intrachannel and extrachannel deposits, exceptional conditions may have been required for the preservation of inverted channels. Eolian winnowing may be one way in which finer, interchannel sands and silts are eroded, leaving behind pebbly, intrachannel sands. Such conditions may be geologically short-lived and prevalent only in areas where wind erosion prevails over water erosion. Further research is needed to explore these ideas.

Representativeness of Paleogeographic and Paleohydraulic Conditions

The Cenozoic succession of the Great Plains is the product of aggradation of a broad sedimentary apron as much as 500 m in thickness. Periods of aggradation were interrupted by major erosional events recorded in regional unconformities (Swinehart et al., 1985). The accumulation of large thicknesses of strata over a large region requires that, in terms of sediment volume, aggradation was dominant over degradation over the span of nearly 35 m.y. Despite the dominance of aggradation, previous reconstructions of Cenozoic paleodrainage (Seeland, 1985; Swinehart et al., 1985; Condon, 2005; Galloway et al., 2011) on the Great Plains have drawn chiefly from the mapping of unit-bounding unconformities in the subsurface. These reconstructions postulate tributary networks of valleys and channels atop major unconformities. Although these approaches have merits, their shortcomings are obvious considering our new findings. We mapped channel orientations directly through the observation of fluvial ridges at various stratigraphic levels, and therefore our observations are not limited to unit-bounding unconformities. We show dominantly straight to diverging channel networks that were unconfined by valley walls. Given the overall aggradational nature of the Cenozoic succession, we argue that our observations of channel geometry are more representative of the overall Cenozoic fluvial succession than are those obtained from the mapping of paleovalleys alone.

The hydraulic geometry of a fixed channel represents water and sediment discharge variables of the formative flows of the channel (Wolman and Miller, 1960). As such, many of the ridges we mapped record the "last gasp" of the formative channels immediately prior to channel abandonment (Hayden et al., 2019). It may be possible to derive paleohydraulic parameters from the geometries of these deposits, particularly if the ridges have not been considerably eroded. Our observations of surface-subsurface contacts suggest that the ridges may, in many cases, record the widths of the formative channels. However, we do not know whether a significant portion of the precursor channel was composed of fines. Additional data are required to explore the possibility of obtaining paleohydraulic parameters from these deposits and comparing such results to observations made in outcrops (i.e., Goodwin and Diffendal, 1987; Joeckel et al., 2014).

Limitations and Suggestions for Future Work

We acknowledge that the preservation of these ancient stream networks is incomplete. There are some significant gaps between areas of fluvial ridges, and much of the stratigraphic succession has been eroded between the Rocky Mountains and the western edge of the High Plains. Nevertheless, this new knowledge of ancient stream systems significantly advances our knowledge about fluvial planforms, paleodrainages, and other aspects of the geologic history of this region. Furthermore, the spatial and temporal patterns of paleoflow presented here offer new insights because they were reconstructed directly from channel orientations.

Future work should integrate analyses of sediment provenance (e.g., Bart, 1975; Seeland, 1985) with our newly reported drainage patterns to further establish connections between source areas, sediment routing systems, and sediment sinks. Ideally, such work would also establish paleohydraulic parameters from the channels we describe, but we maintain that estimating true paleoflow depths will prove challenging.

Major uncertainties remain regarding age relationships between Ogallala Group channels in different stratigraphic positions and geographic areas. These relationships are difficult to work out for many reasons, not least of which is the lack of regional marker beds. Tedford (2004) argued that gravel-capped ridges in the Pawnee Buttes area occupy elevations as much as 150 m lower than the adjacent Cheyenne Table, and that they are therefore the youngest in a succession of superposed channel bodies that exist at successively lower elevations. Such relationships are common in long-term degradational landscapes (Blum et al., 2013), but this seems at odds with our observations of fixed channels requiring high aggradation rates in the same general area. It is possible that incision of the western margin of the Great Plains was accompanied by simultaneous, downstream aggradation of recycled sediment (Sinclair et al., 2019). However, the close geographic proximity of deposits requiring long-term degradation and rapid aggradation demands additional explanation, which may be the topic of future work.

Relative ages are also important for establishing relationships between fluvial systems in different areas. The presumably Barstovian deposits at Pawnee Buttes (Tedford, 2004) apparently correlate with the deposits of Diffendal (1982b), who assigned these deposits to the Hemphillian. Farther away, a Barstovian age was assigned to the ridge-forming deposits at Spoon Butte in Wyoming (Hunt, 2005) and the Bijou Hills of eastern South Dakota (Holman, 1978)—channel bodies with markedly different characteristics than those observed on the Cheyenne Table and Colorado Piedmont. A detailed examination of fluvial ridges in these areas may help to further illuminate the stratigraphic relationships between deposits in different areas.

CONCLUSIONS

This paper reported the discovery of a vast network of >3100 fluvial ridges in late Eocene to Pliocene sedimentary strata on the Great Plains. These ridges are inverted channels and amalgamated channel deposits created by differential erosion of resistant channel deposits and erodible, intervening fines. The area of this ridge-bearing landscape (250,000 km^2) exceeds the size of most such inverted-topography landscapes on Earth, and it rivals those found on Mars. The superb preservation of these ridges permits observations across the hierarchy of scales from individual bed forms to channel planforms to regional drainage patterns. Detailed mapping revealed a great diversity of fluvial styles through geologic time, including straight, sinuous, and meandering planforms, single- and multithread channels, and fixed channels and mobile channel belts. These ridges were exhumed from multiple stratigraphic horizons spanning ~35 m.y., revealing time slices of broadly contemporaneous stream systems and providing novel insights into Cenozoic sediment routing systems in the North American interior.

Eocene and Oligocene fluvial systems of the White River and Arikaree Groups were comparatively small and morphologically diverse. Flow directions were highly dispersed and variable. Alluvial fans, limited to the Rocky Mountain front, were a few kilometers in width. Fluvial fans farther east were a few tens of kilometers in length, and their rivers were chiefly fixed, single-thread channels a few tens of meters in width. Trunk streams eastward of the fans comprised similarly small channels, but these channels migrated across a channel belt, creating comparatively broad channel bodies 1–3 km in width. These characteristics reveal poorly integrated drainages and a young alluvial apron undergoing abrupt changes. Cool, dry climates may have contributed to the relatively small sizes of the river systems. Nevertheless, fixed channels with distributary morphologies attest to locally high aggradation rates.

Miocene rivers of the lower Ogallala Group were confined to valleys and were laterally mobile, forming amalgamated channel deposits. By the late Miocene, rivers increased in size, and they were composed of multithread channels a few kilometers in width, and individual anabranches were as much as 1 km in width. These channels were fixed and laterally immobile, evincing locally high aggradation rates atop a vast alluvial apron that extended hundreds of kilometers east of the Rocky Mountain front. Paleoflow was dominantly east-northeastward, and it was less dispersed and variable. The Miocene sediment routing system of the Great Plains had developed into a well-integrated drainage with large channels capable of conveying vast volumes of sediment and water. Late Miocene climates were cool and dry, but they were highly variable and may have contributed to mountain snowpacks capable of supplying large, episodic discharges to streams on the Great Plains.

Our use of high-resolution LiDAR and imagery to identify comparatively subtle, low-relief ridges over a vast region provides a framework for identifying similar features elsewhere that might otherwise go unnoticed. Moreover, the direct detection of channel planforms allowed us to reconstruct Cenozoic paleodrainage patterns for the Great Plains in a manner that is far more representative of the aggradational succession than previous efforts. Our study of ancient Great Plains streams is the most spatially comprehensive to date. It sets the stage for further studies involving paleohydrology, provenance, and age relationships, which will doubtless reveal yet more about Cenozoic landscape evolution.

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