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Epeirogenic and Climatic Controls of Early Pleistocene Fluvial Sediment Dispersal in Nebraska

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Abstract

The change from Pliocene to Pleistocene fluvial sedimentation in Nebraska is denoted by gravel with relative enrichment of mechanically weak rock species and a two-fold increase in largest clast size. These changes in fluvial sediments suggest modification in degradational energy affecting detritus apparently related to deterioration of climate in the early Pleistocene. Cooler Pleistocene climates with increased moisture resulted in greater discharge and carrying capacity for streams headed in the Rocky Mountains and flowing across Nebraska. These streams carried granitic detritus eastward toward the continental glacier margin in easternmost Nebraska. There, streams flowing off ice sheets carrying sedimentary and metamorphic detritus derived from the ice joined the east-flowing streams from the mountains. Detritus derived from continental glaciers in easternmost Nebraska, therefore, was not transported westward, but instead, was mixed with Rocky Mountain-derived detritus and transported southward along the ice-front margin.

Even though the drainage basin of the Platte River system came into existence in the Tertiary, the present course of the Platte River dates only from mid-Pleistocene time. Widespread occurrence of lower Pleistocene braided channel deposits east of the Chadron-Cambridge Arch that contain Laramie Range-derived anorthosite indicates repeated channel switching and meandering during times of aggradation over surfaces of minimal relief. Relations of these gravels to the Chadron-Cambridge and Siouxana Arches suggest that uplift on these structures was sufficient to deflect and control the course of streams headed in the Laramie Range and flowing

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across the plains. Activity on the Chadron-Cambridge Arch also is suggested by the distribution of earthquake epicenters, modern drainage patterns, and the relation of the pre-Pleistocene bedrock surface to the arch and the profile of the Platte River. The presence of knickpoints on rivers crossing the arch suggests that these rivers are maintaining a course antecedent to a spasmodically rising arch. Rivers are entrenched now, but during the early Pleistocene when streams carried a heavy load of sand and gravel, similar activity along the Chadron-Cambridge Arch would have been adequate to spill the aggrading stream over its fan and divert it southward where it could follow a new course. Eastward-flowing streams heading in the Rocky Mountains were controlled by changes in discharge of streams and movement on epeirogenic structures during the early Pleistocene.

Introduction

Fluvial sands and gravels dispersed onto the northern Great Plains from the Rocky Mountains have long been regarded as being contemporaneous, in part, with Nebraskan and Kansan continental glacial deposits in easternmost Nebraska. Their stratigraphic relations to glacially derived sediments in eastern Nebraska were described in part by Lugn (1935), Condra and Reed (1947), and Reed and Dreeszen (1965). These published studies have alluded to gentle eastward tilting of the plains and (or) advance and retreat of continental glaciers as possible factors that controlled drainage and sedimentation. The suggestion that early Pleistocene fluvial sedimentation was controlled only by eastward tilting of the plains and advance and retreat of continental glaciers is probably oversimplified. Another hypothesis, that of climatically controlled stream regime changes and spasmodic activity of epeirogenic structures during the Pliocene-Pleistocene better explains early Pleistocene sedimentation patterns west of the Kansan till border.

Presently held concepts about the depositional history of lower Pleistocene fluvial sediments in Nebraska are based on paleontologic and stratigraphic observations made over the past four decades by Lugn (1935), Condra and Reed (1947), Dreeszen (1970), Schultz and Stout (1945), and Schultz and Martin (1970). Their concepts do not explain areal distributions of lower Pleistocene gravels, nor do they relate well to recently recognized suites of compositionally distinct Pearlette-like ash beds reported by Izett and others (1971). This paper attempts to examine the areal and temporal changes in early Pleistocene streams flowing into Nebraska from the Rocky Mountains, factors controlling their dispersion and deposition of sediment, and their relations to streams fed by continental ice sheets then in easternmost Nebraska.

Stratigraphy

One of the problems that must be resolved before attempting to unravel the history of early Pleistocene fluvial sedimentation in Nebraska is the stratigraphic relation of tills in easternmost Nebraska to fluvial deposits west of the till border. Because of recently acquired information about Pearlette-like ash beds, it is now possible to speculate on these relations by comparing vertebrate faunas and Pearlette-like ashes between sections at critical localities. Of particular interest is the type-S Pearlette-like ash of Izett and others (1971) that occurs above sand that has yielded late Blancan fossils at the type section of the Sappa Formation (Schultz, 1971, oral commun.), and below Nickerson till (Kansan) in fine-grained sediments assigned to the Fullerton Formation (Dreeszen, 1970; Izett and others, 1971) (Fig. 1). Fission

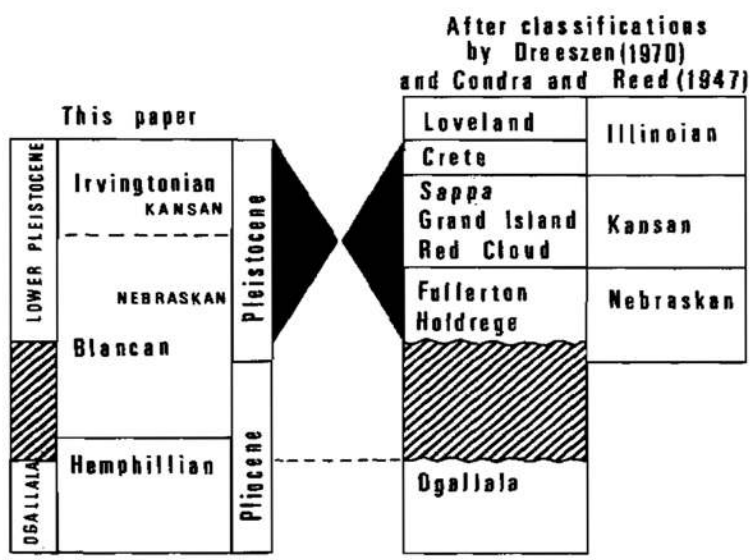

Figure 1. Correlation chart of lower Pleistocene rocks in Nebraska showing the relation between nomenclature used in this paper and the Pleistocene stratigraphic classification adopted by most previous workers. The Holdrege through Crete Formations recognized in previous classifications, as a whole, are considered Nebraskan-Kansan in age and equivalent to our lower Pleistocene. Stratigraphic hiatus indicated by diagonal ruling.

track dates on both ash units are approximately 1.5 m.y. (Boellstorff, 1972), which is a radiometric date consistent with the approximate upper limit for the Blancan land-mammal age as suggested by Savage and Curtis (1970, p. 223). Nearby Blancan-age continental glaciers are indicated by the presence of till-derived detritus in fluvial gravels below the Nickerson till (Kansan) in Cuming County where Frankforter (1950) has reported Blancan fossils. Tills assigned to the Kansan Stage by Dreeszen (1970) appear to be latest Blancan and Irvingtonian in age. This age assignment is in agreement with that suggested by Flint (1971, Fig. 21-22) with the aid of Hibbard, who also assigns the Nebraskan to the Blancan land-mammal age. How much of the Blancan land-mammal age is represented by fluvial deposits in Nebraska is not known. The maximum possible time range for the Blancan appears to be from about 4.0 to about 1.7 m.y. ago (Savage and Curtis, 1970). However, fluvial sands and gravels that locally have yielded Blancan fossils occupy channels cut more than 100 ft into pre-Pleistocene Ogallala rocks. Erosion before deposition of Blancan-age gravels and following deposition of Hemphillian-age (Pliocene) Ogallala rocks may represent considerable time, perhaps a large part of the Blancan land-mammal age.

Gravels that fill channels in pre-Pleistocene rocks also extend across divides between channels and form a nearly continuous sheet of sand and gravel over large parts of Nebraska (Lugn, 1935; Condra and Reed, 1947). Throughout the state, these gravels are overlain by fine-grained sediments assigned to the Sappa or Loveland Formations (Fig. 1) or by younger sediments; in some exposures they are capped by a caliche paleosol. Correlations, age assignments, and classifications of these coarse-grained deposits and associated fine-grained sediments have been complicated, and perhaps confused, by a complex stratigraphic nomenclature (Fig. 1) in which some formations were defined in drill holes (Holdrege and Grand Island Formations) and others at surface exposures (Red Cloud and Sappa Formations). In addition, age assignments and correlations of these formations have been based on the presumption that all units are nearly everywhere present with fine-grained units assigned to interstadial or interglacial ages and coarse-grained units to glacial ages (Lugn, 1935; Schultz and Martin, 1970). The validity of these stratigraphic practices is doubtful in light of recent geochemical and radiometric correlations of Pearlette-like ash by Izett and others (1971) and Boellstorff (1972), who have recognized the type-S Pearlette-like ash in sediments assigned to Fullerton and Sappa Formations (Fig. 1); and in light of mapping of surficial deposits by Miller and others (1964) and Stevenson (1971), who mapped gravel assigned to the Red Cloud, Grand Island, and Crete Formations, one into another.

Because there is some doubt about presently accepted stratigraphic correlations and classifications of pre-Loveland Formation Nebraskan and Kansan sediments, all such sediments are herein considered lower Pleistocene (Fig. 1). That the Crete Formation is Kansan and not Illinoian in age as suggested by Condra and Reed (1947) and Dreeszen (1970) is indicated by the presence of till-derived boulders in the formation and the presence of late Kansan snails in silt overlying the gravel.

Source Areas for Fluvial Gravels

Gravel-size detritus from lower Pleistocene deposits in Nebraska (**Fig. 2**; Appendix 1) analyzed by the methods outlined in Appendix 2 fall

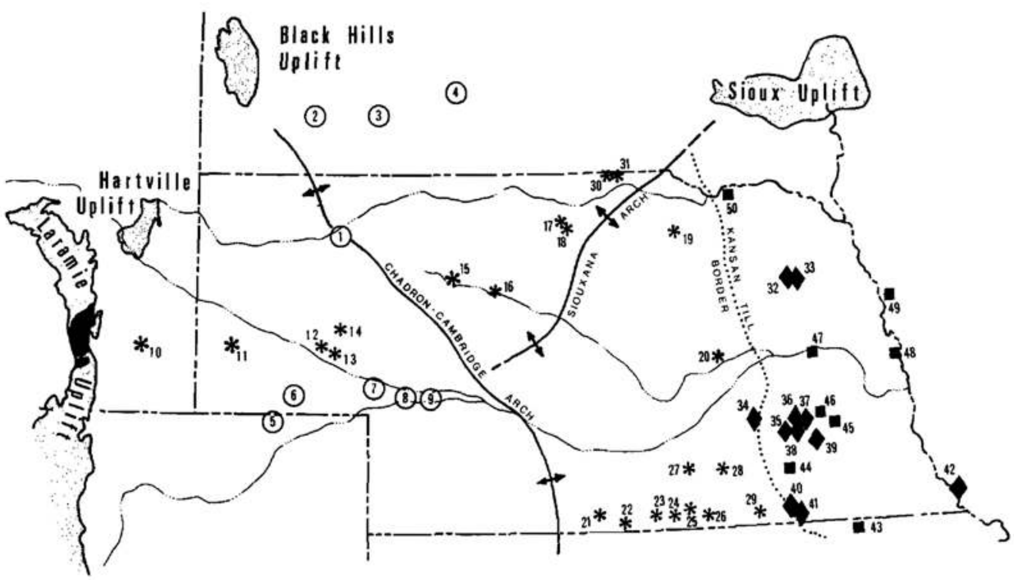

Figure 2. Index map of Nebraska and parts of adjoining states showing the areal distribution of lower Pleistocene gravel suites: asterisk = anorthosite-bearing granitic gravel; circle = anorthosite-free granitic diamond = red metaquartzite- and anorthosite-bearing gravel. Areas of exposed Precambrian rocks are stippled; anorthosite bodies in the Laramie Uplift are shown in black. Numbers correspond to sample localities in Appendix 1.

into four compositionally distinct gravel suites based on the presence or absence of unique constituents: (1) anorthosite-bearing granitic gravel; (2) anorthosite-free granitic gravel; (3) red metaquartzite-bearing gravel; and (4) gravels containing an admixture of clast types present in gravels 1 and 3 (**Fig. 3**). The two lower Pleistocene granitic gravel suites occur throughout Nebraska west of the Kansan till border, but are uncommon farther east (Fig. 2). Red metaquartzite-bearing gravel and admixed gravels with clasts common to both granitic and red metaquartzite-bearing gravels are present only within the glaciated part of Nebraska (Fig. 2). These four gravel suites represent detritus derived from two lithologically distinct source terranes, as well as the admixture of detritus from these terranes in easternmost Nebraska. Granitic gravels both with or without anorthosite clasts are composed principally of Sherman Granite detritus derived from the front ranges of the Rocky Mountains in Wyoming and Colorado. Red metaquartzite-bearing gravel, however, is characterized by the presence of locally derived clasts of upper Paleozoic and Upper Cretaceous

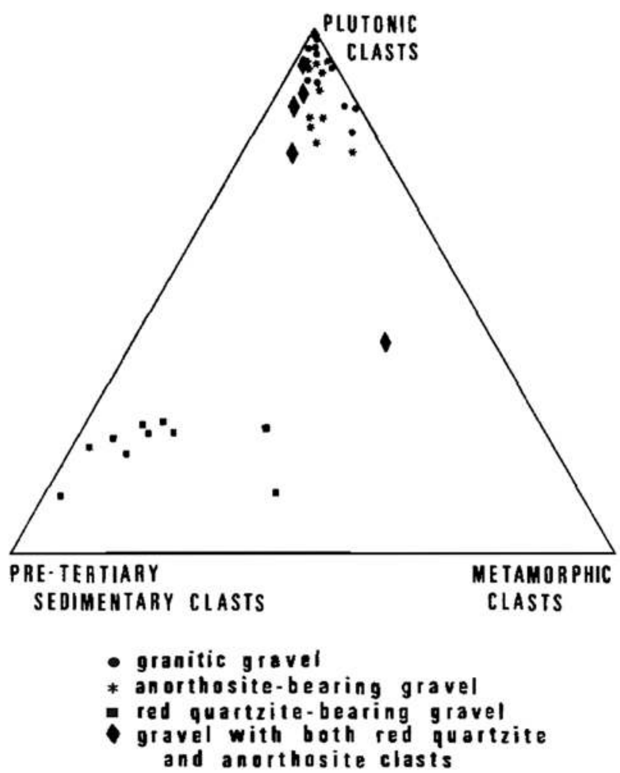

Figure 3. Triangular diagram showing compositional differences between the four lower Pleistocene gravel suites.

carbonate and sandstone rocks, and less abundant red metaquartzite (Sioux Quartzite), dark green metavolcanic, granitic, and metagraywacke clasts derived from afar (Fig. 3). These clast types in similar proportions also occur in Nebraskan-Kansan tills in easternmost Nebraska. They are interpreted as detritus transported southwestward from the Sioux Uplift (Fig. 2), and Precambrian terrain of Minnesota into easternmost Nebraska by early Pleistocene continental ice sheets. Red metaquartzite-bearing gravel is interpreted to be Nebraskan-Kansan outwash. These outwash gravels also are distinguished from gravels derived from the Rocky Mountains by the relative abundance of igneous, metamorphic, and sedimentary clasts (Fig. 3).

Rocky Mountain detritus was transported eastward into the glaciated part of Nebraska and mixed with glacial-derived detritus (Figs. 2, 3). Such gravels could have formed marginal to continental ice sheets where eastward-flowing streams headed in the Laramie Range and proglacial streams coalesced; or in the glaciated area where tills left by retreating continental ice sheets were eroded by eastward-flowing streams, the till clasts derived from the northeast would have been combined with detritus derived from the Rocky Mountains to the west. Recognition of dispersal paths in granitic gravels derived from the Rocky Mountains is based on the presence or absence of clasts of anorthosite, a diagnostic rock that occurs in a restricted source area in the Laramie Range (Fig. 2). Anorthosite detritus eroded from the Laramie Range during the Tertiary was deposited adjacent to the mountain front (Stanley, 1971). The dearth of anorthosite in Ogallala gravels (Pliocene) exposed in Nebraska excludes these gravels as a major source of anorthosite in lower Pleistocene gravel (**Fig. 4**). Gravel-size detritus in lower Pleistocene deposits contains clasts larger than those in Tertiary gravel and higher proportions of mechanically weak clast types (**Figs. 4, 5**; **Table 1**). These compositional and textural differences cannot be accounted for by reworking Tertiary gravel. Instead, the larger portion of lower Pleistocene gravel-size detritus was derived directly from the mountains. Thus, anorthosite exposures in the Laramie Range constitute a point source from which detritus was dispersed. Similar anorthosite exposures do not occur elsewhere in the front ranges of the Rocky Mountains. The only alternative source would be the Lake Superior region (Phinney, 1966). The absence of anorthosite in Nebraskan-Kansan till and outwash, as well as the

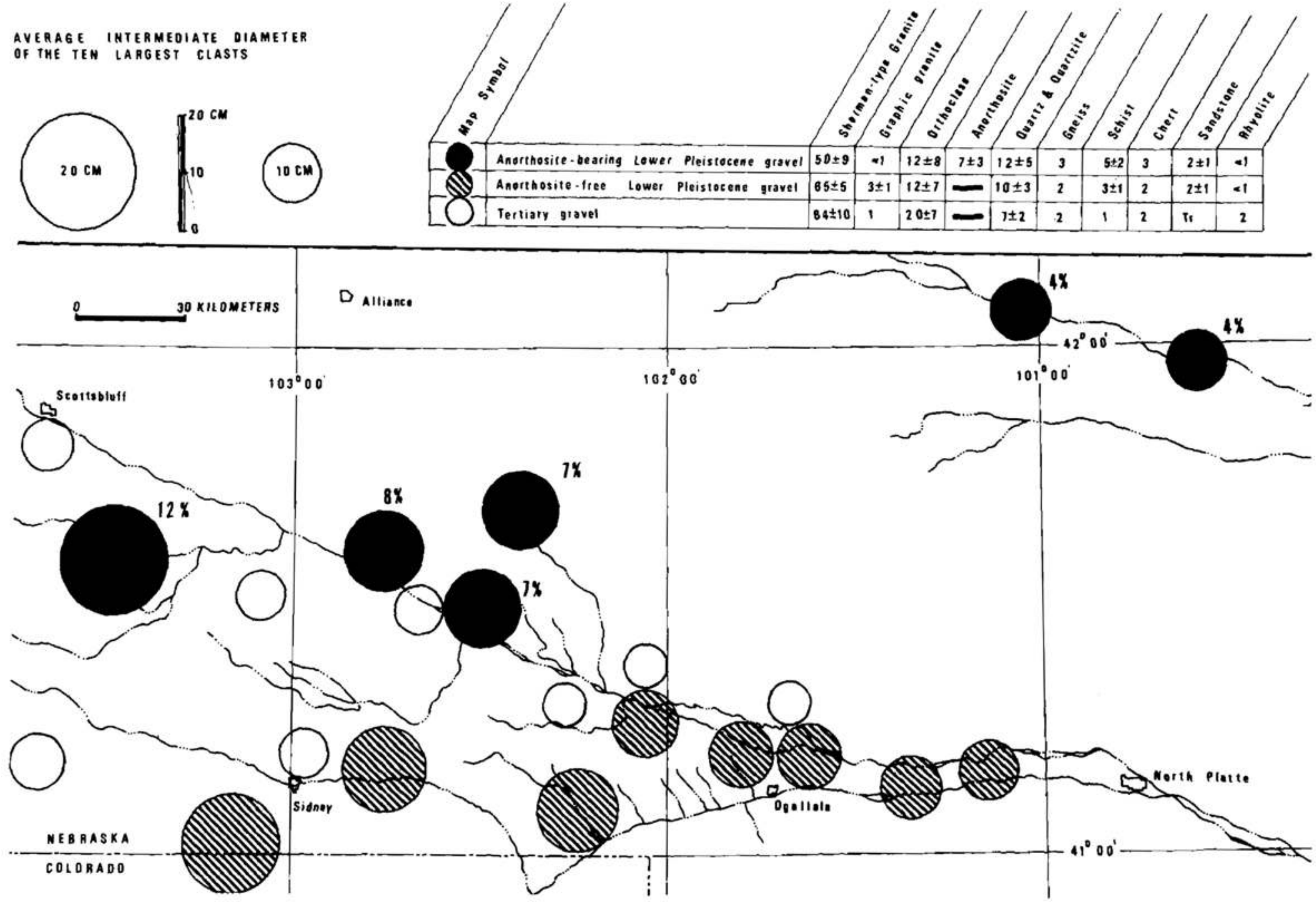

Figure 4. Compositional and textural comparison between lower Pleistocene and Tertiary gravel suites in the panhandle of Nebraska. Anorthosite clast percentages greater than 1 percent are shown adjacent to anorthosite-bearing gravel symbols.

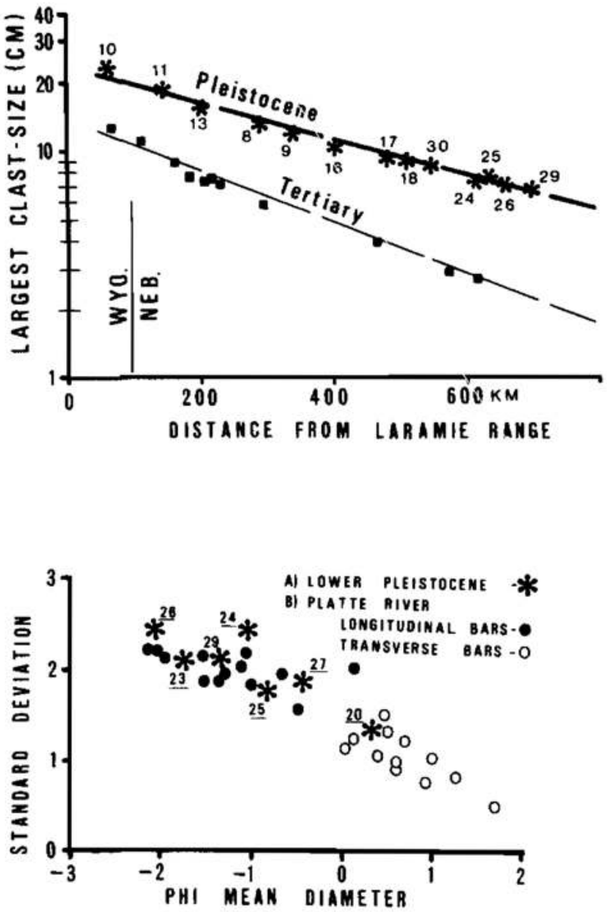

Figure 5. Top: Decrease in maximum clast size in Tertiary and Pleistocene granitic gravels with increased transport distance from the front ranges of the Rocky Mountains. The mean intermediate diameter of the ten largest clasts is plotted at each locality. Numbers correspond to those localities shown on Figure 2. **Bottom:** Textural similarity of lower Pleistocene gravelly deposits in south-central Nebraska to sediments described by Smith (1970) in active channels of the South Platte and Plane Rivers in Colorado and Nebraska. Both longitudinal and transverse bars occur in the South Platte; transverse bars characterize the Platte. Numbers correspond to localities of lower Pleistocene gravelly deposits on Figure 2. Two-kilogram samples were sieved to determine mean and standard deviation of lower Pleistocene sediments.

decrease in anorthosite abundance and clast size toward the east, together indicate that no anorthosite was contributed from the north or east (Fig. 2). Dispersal paths defined by anorthosite detritus, therefore, include major streams flowing from the anorthosite areas in the Laramie Range and downstream rivers joined by these streams to form a drainage system carrying sediment across the plains of Nebraska.

Table 1. Comparison of Pliocene (Ogallala) and Lower Pleistocene Gravel Compositions in South-Central Nebraska

	Pliocene	*Lower Pleistocene*
Shennan Granite	36 ± 7	59 ± 4
Graphic Granite	* *	1
Pegmatite	* *	1
Anorthosite	* *	2 ± 1
Orthoclase	10 ± 3	10 ± 3
Quartz and quartzite	30 ± 8	15 ± 2
Gneiss	tr	3
Schist	* *	2
Chert	23 ± 11	4 ± 2
Sandstone	* *	1
Volcanic rocks	tr	1

Mean and first standard deviation are shown for each category counted. Calculations are based on 35 samples from 10 localities.

Dispersal Paths of Lower Pleistocene Fluvial Sediments

Early Pleistocene channel switching and meandering of the stream carrying anorthosite detritus across the panhandle of Nebraska was restricted to a broad, shallow valley a few tens of miles wide (Figs. 2, 4, 6). Multiple gravel bodies separated by fine-grained deposits that characterize measured stratigraphic sections (Schultz and Stout, 1948) and drill-hole records (Swinehart, 1972, oral commun.) suggest a complex history of gravel deposition. To the north, lower Pleistocene gravels are absent or thin (Figs. 2, 6). Where they do occur anorthosite clasts are absent in the gravel-size fraction. These “anorthosite-free” gravels (Fig. 2, areas 1 through 4) must represent sedimentation in rivers originating beyond the anorthosite source area in the front ranges of the Rocky Mountains and (or) the Black Hills. South of the anorthosite-bearing gravels and west of the Chadron-Cambridge Arch, lower Pleistocene granitic gravels are common but contain no anorthosite clasts (Fig. 4). These gravels define the position of streams headed in the Laramie Range and Front Range south of the anorthosite bodies.

Lower Pleistocene gravel is absent or thin over the Chadron-Cambridge Arch, but to the east of the arch, gravels containing anorthosite detritus are common along the western portion of the Middle

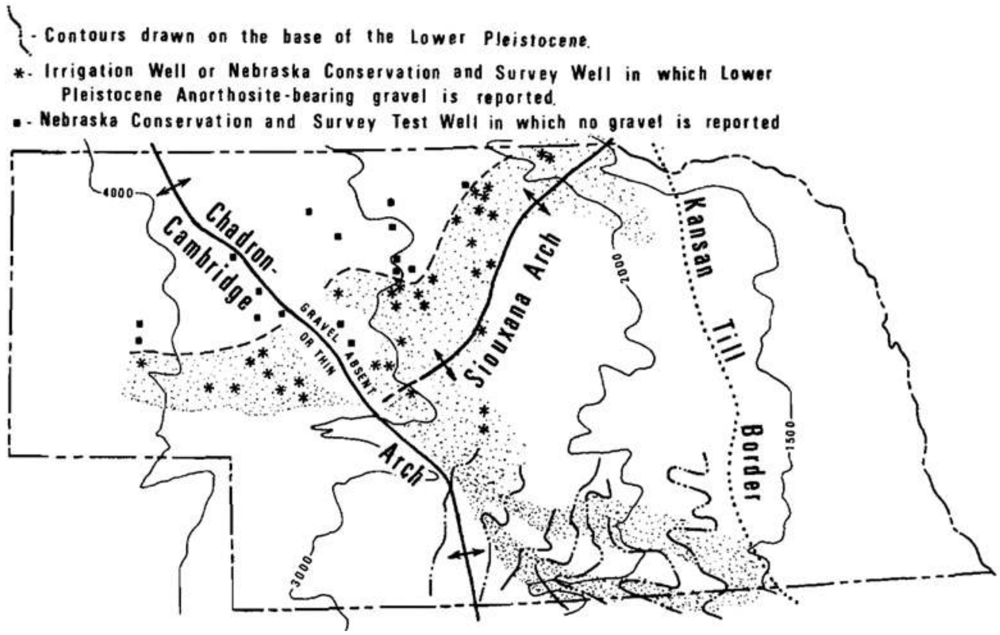

Figure 6. Distribution map of anorthosite-bearing lower Pleistocene gravel (stippled areas) in the vicinity of the Siouxana and Chadron-Cambridge Arches showing the relation of the gravels to the arches, modern physiography north of the Siouxana Arch (1,500-, 2,000-, and 3,000-ft contour lines), and pre-lower Pleistocene bedrock topography in south-central Nebraska. Also shown are the northern and southern limits of anorthosite-bearing gravel in Nebraska, which are based on samples from outcrops (Fig. 3) and well samples examined by J. S. Swinehart of the Nebraska Conservation and Survey Division. Pre-Pleistocene bedrock topography is based on contour maps of Miller and others (1964) and Ryan (1959).

Loup River and northeastward beneath the Sand Hills into the Niobrara River drainage basin (Figs. 2, 6). They define a northeastward dispersal path from the Chadron-Cambridge Arch toward the South Dakota border near the present-day Missouri River (Fig. 7). From there anorthosite-bearing gravel appears to be present only toward the south and east (Fig. 2). This dispersal path crosses the Chadron-Cambridge Arch at a low structural position (Carlson, 1967). The northern limit of anorthosite-bearing gravel roughly parallels the Siouxana Arch (Figs. 2, 6). Topographic maps of Nebraska show that contour lines trend northward south of the Siouxana Arch, but curve northwestward near the crest of the arch and continue this trend on the northwest flank of the structure (**Fig. 6**). The direction of dispersal of lower Pleistocene anorthosite-bearing gravel is normal to these contour lines, hence down the present-day slope which may be a remnant

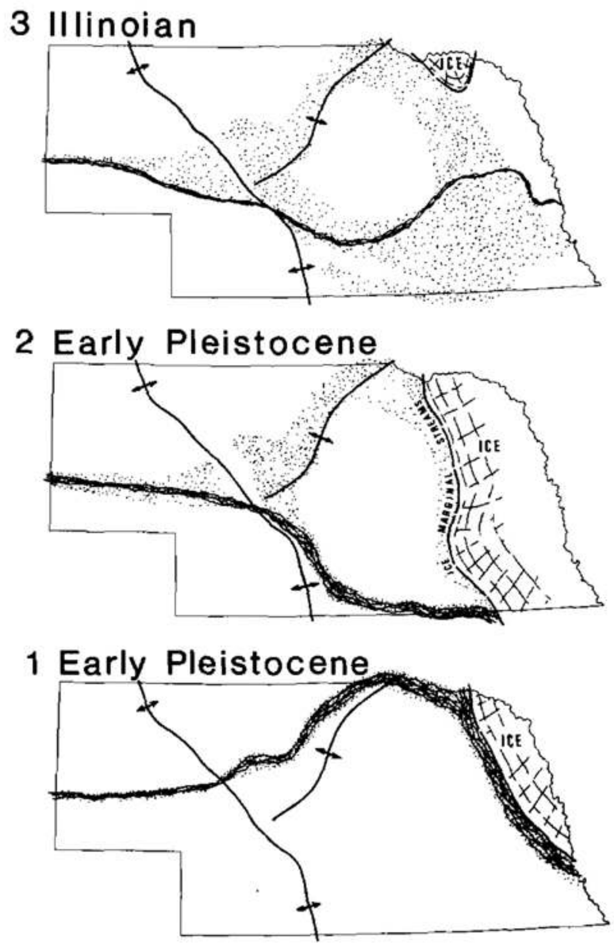

Figure 7. Sketch maps of Nebraska showing the shifting pattern of early Pleistocene streams that transported anorthosite detritus across Nebraska.

of an early Pleistocene paleoslope. If the early Pleistocene river flowed across the Chadron Arch north of the Siouxana Arch, the northeastward path would be favored (Figs. 6, 7).

The nearly continuous sheet of anorthosite-bearing lower Pleistocene gravel also occurs east of the Chadron-Cambridge Arch to the south of the Siouxana Arch (Figs. 2,6). These gravels lie beneath Loveland loess and fill channels discordant to present-day rivers (Fig. 6). Two such channels have been mapped from the Chadron-Cambridge Arch near the present-day Platte River southeastward into the Republican River drainage system, one subparallel to the arch (Fig. 6). Gravel sheets both north and south of the Siouxana Arch can be traced westward where they join the single narrow sheet of gravel west of the arch (Fig. 6). The absence of granitic gravel with no anorthosite clasts east of the Chadron-Cambridge Arch in Nebraska requires that streams carrying anorthosite- free granitic gravel joined those carrying anorthosite detritus near the arch, just as the North and South Platte Rivers do today.

The presence of extensive bodies of lower Pleistocene "anorthosite-bearing" granitic gravels east of the Chadron-Cambridge Arch can be explained only by extensive shifts in course of one major river system that carried anorthosite detritus (**Fig. 7**). Stream shifting at the Chadron-Cambridge Arch implies that the arch was active and controlling drainage during times of aggradation. The northern and southernmost paths followed by the stream carrying anorthosite detritus are shown on Figure 7. Vertebrate faunal evidence suggests that the northern stream path is the oldest (McGrew, 1944; Schultz and others, 1951). Once the river system crossed the Chadron Arch south of the Siouxana Arch, as it does today, the stream would flow southeastward into south-central Nebraska (Fig. 7). Presently available data indicate that the stream crossed the Siouxana Arch at several positions, spreading gravel nearly continuously across Nebraska. The stream probably did not shift abruptly from the northern course into those recognized in the south (Fig. 7).

Characteristics of Streams That Deposited Lower Pleistocene Sediments

Water-laid lower Pleistocene sediments exhibit grain-size distributions, sedimentary structures, and sedimentary facies that can be used to deduce the nature of streams that transported sediments to their site of deposition. Based on grain-size parameters and sedimentary structures, three distinct sediment types are recognized: (1) moderately well-sorted, ripple-drift cross-laminated, coarse silt and very fine sand; (2) poorly sorted, parallel-laminated or massive, sandy silt to silty clay; and (3) poorly sorted, cross-stratified planar-bedded, sandy gravel and gravelly sand. The two former fine-grained sediment types are associated with gravel-rich deposits and therefore must be considered the product of sedimentation in environments related to active fluvial channels. Poorly sorted, sandy silt to silty clay deposits occur throughout Nebraska. Moderately well-sorted silts and fine sands, however, are found only in the glaciated part of Nebraska where they are associated with till-derived outwash gravel.

Poorly sorted sandy silt to silty clay deposits exhibit textures and sedimentary structures, which, together with faunal assemblages (Martin and Schultz, 1971), indicate deposition in standing or slow-moving water. Laminated and massive silt-rich deposits contain carbonaceous material, diatomaceous silty clays, and volcanic ash beds that are either graded or laminated. Most of the poorly sorted silt-rich deposits rest conformably on cross-stratified gravel deposits and are incised by younger sand and gravel bodies; locally they are intercalated with gravels. These stratigraphic relations, in addition to textures and depositional structures of fine- and coarse-grained sediments, are similar to stratigraphic relations and sediment types described by Schumm (1968) and Schumm and Lichty (1963) for bed-load channels.

Channels occupied by fluvial sands and gravels are cut more than 100 ft into pre- Pleistocene rocks and, in the glaciated part of Nebraska, into lower Pleistocene tills. It is unlikely that fluvial deposits of these dimensions represent a single-channel deposit. Instead, lower Pleistocene alluvial valley fills are composed of multiple channel fills formed as an aggrading stream meandered and switched course over an alluvial plain. Sandy gravels and gravelly sands that fill channels are cross-stratified and horizontally bedded. Horizontal and inclined bedding are defined by vertical and lateral changes from gravelly sand to sandy gravel. The abundance of large-scale planar and trough cross beds and horizontal stratified beds in lower Pleistocene gravel deposits is similar to that reported for longitudinal bars that floor the South Platte River (Smith, 1970). Horizontal stratified beds usually are coarser and more poorly sorted than cross-stratified gravel and coarse sand. Where coarse sand-size material is abundant planar cross beds predominate. Planar cross-stratified sands associated with gravel-rich deposits may reflect downstream margins of longitudinal bars like those described in the South Platte River and (or) transverse bars described from the Platte River (Smith, 1970). Longitudinal bars in the modern Platte River System are accumulations of gravel with varying admixtures of sand, whereas transverse bars are better sorted coarse sand (Fig. 5). The relative abundance of cross beds to horizontal stratified beds and textural similarities between lower Pleistocene alluvial valley fills and longitudinal bar deposits flooring present-day rivers in Nebraska suggest that both originated by the same fluvial processes (Fig. 5). Lower Pleistocene channel sediments are interpreted as the product of aggradation in braided rivers (bed-load streams) floored by longitudinal bars and perhaps transverse bars. Sedimentary structures in lower Pleistocene deposits suggest that early Pleistocene braided-channel sedimentation took place during both lower and upper regime flow (Simons and others, 1965). Planar and trough cross beds with steeply dipping avalanche faces (20° to 25°) suggest deposition by downstream migration of bars and dunes under lower regime flow (Simons and others, 1965). Horizontally stratified sand beds with scattered pebbles and cobbles are evidence of upper regime flow (Fahnestock and Haushild, 1962), which also is suggested by associated cross beds with gently dipping avalanche faces (<10°).

The largest material in lower Pleistocene braided-channel deposits exhibits area patterns that can be used to deduce relative competence of streams. Outwash gravels deposited by streams flowing off continental glaciers in easternmost Nebraska and "admixed gravels" deposited by streams flowing marginal to the ice front contain boulders 100 cm in diameter. West of the till border, boulders in lower Pleistocene gravel vary in size according to their distance from source areas in the Laramie Range (Fig. 5). The presence of mechanically weak rock species in lower Pleistocene gravels throughout Nebraska, particularly in the largest clast sizes, suggests that the progressive downstream decline in maximum clast size, which corresponds with decreased slope, reflects progressive deposition of coarser clast sizes during reduction in stream competency rather than attrition of larger material by abrasion and breakage (Figs. 4, 5; Table 1). Once the stream flowed marginal to the ice front, the addition of water and sediment from glacier-fed streams was sufficient to increase competency so that boulders 100 cm in diameter could be carried.

Climatic Influence on Fluvial Sedimentation

Early Pleistocene streams flowing across Nebraska drained both the Great Plains and the front ranges of the Rocky Mountains. Climatic changes in these two areas could have significantly modified runoff and sediment yield from the mountains and the character of streams flowing across the plains. The nature of Pliocene- Pleistocene climates on the Great Plains was summarized by Frye and Leonard (1957), who considered the transition from late Pliocene arid conditions to colder and wetter conditions during the early Pleistocene the sharpest climatic change during the late Cenozoic. More important, however, were climatic changes in the headwater areas. Though no evidence has been reported for early Pleistocene glaciers in the front ranges of the Rocky Mountains, there can be little doubt that they supported glaciers. Early Pleistocene tills and outwash gravels have been reported from several other ranges in the central Rocky Mountains (Richmond, 1965). Even if ice fields did not develop in the Laramie Range, periglacial conditions must have existed there when glaciers were nearby.

Late Pleistocene glaciations in the Rocky Mountains are believed to have required a 16° to 17°F decline in mean annual summer temperature during glacial maxima (Richmond, 1965). Lowered temperatures in headwater areas during early Pleistocene glacial ages would have increased frost action and mass wasting over that during either late Pliocene time or the Pleistocene interglacial ages. In western Colorado today minor frost action plays an important role in determining the geomorphology and hydrology of drainage basins (Schumm and Lusby, 1963). In the Laramie Range, these processes probably supplied inordinately large amounts of fresh rock to the rivers, for as noted by Corbel (1959), sediment yield from cold, snowy, and periglacial mountain areas is about 1.5 times that of high mountains of Mediterranean climate. Where glaciers were present in headwater areas, the sediment yield from glacial erosion was even greater. Glacial meltwater and (or) runoff from periglacial areas, with the likelihood of greater precipitation during glaciation, surely would have produced stream discharge consistently greater than that of Pliocene time or the present (Schumm, 1965). The rivers draining glaciated or periglacial regions would be expected to have an influx of coarse sediment with onset of glaciation. On the Great Plains the decrease in temperature and wetter conditions would reduce effective evaporation and add runoff to the already large discharge from the mountains. With the disappearance of glacial ice in the headwater areas during interglacial ages, climates became warmer and stream discharge and sediment load returned to a level similar to the present. Streams today are not aggrading; however, during glacial ages when they were loaded with sediment they built alluvial slopes. Fluvial deposition in areas away from the headwater regions undoubtedly corresponds with glaciation. Reduced load and discharge during interglacial ages would have resulted in downcutting of channels in Nebraska.

Evidence from Pliocene-Pleistocene fluvial sediments in Nebraska for the climate changes suggested for the Great Plains and Laramie and

Front Ranges include (1) widespread and thick lower Pleistocene gravel deposits, (2) notably larger debris in lower Pleistocene sediments, and (3) larger quantities of mechanically weak rock species in lower Pleistocene gravels (Figs. 4, 5; Table 1). The abundance of lower Pleistocene gravels, as well as their notably larger clast sizes than underlying Pliocene sediments or modern river deposits the same distance from mountain sources (Fig. 5), requires greater competency and sediment load for streams that carried lower Pleistocene sediments.

Further indicators of lowered temperature, increased discharge, and sediment yield in streams draining the Laramie and Front Ranges are mechanically weak rock species transported considerably farther during the early Pleistocene than during either the Pliocene or present (Table 1; Fig. 4). Limestone fragments occur in lower Pleistocene gravel as much as 100 km east of the Laramie Range, and unweathered anorthosite cobbles are present in easternmost Nebraska, along with cobbles of sandstone, hornblende schist, and mica schist (Fig. 4; Table 1). These clast types have been destroyed much closer to their source in Pliocene Ogallala rocks and in the present-day rivers. Presence of these rock types in gravels implies a supply of large quantities of fresh rock from the source areas, a climate in which chemical weathering rates are at a minimum, and rapid transport. That these changes in sediment characteristics are the result of climatic changes and not steepening of the river gradient by uplift is indicated by virtually the same gradient for Pliocene and younger deposits in the panhandle of Nebraska. Gradients on present-day Lodgepole Creek are 2.5 to 3.1 m per km, which also are the gradients for the Great Plains surface, base of the Ogallala, and the base of the lower Pleistocene. Farther east the effect of uplift on the Chadron-Cambridge Arch has modified gradients, and lower Pleistocene gravels are thin or absent (Fig. 6).

Epeirogenic Influence on Pleistocene Drainage

Streams that build alluvial slopes characteristically are heavily loaded with coarse clastic sediment. Such streams commonly tend to exhibit a braided pattern and flow in broad flat shallow channels. The positions of the channels across an undissected but graded slope are likely to shift frequently. Sediment accumulates in the bed of the channel so that it no longer is capable of carrying the occasional flood discharge, and the current may break out of its old channel and form a new one. The Kosi River in India, fed by Himalayan glacial runoff, is reported to have shifted laterally across its alluvial slope 70 mi in about 200 yrs and as far as 12 mi in a single year (Leopold and others, 1964, p. 291). Through many such shifts, the streams large and small that flow across an alluvial slope eventually build up an extensive low-gradient fan-shaped surface. The northern High Plains is a series of such fans, which represent times of aggradation during the early Pleistocene. The position of major streams must have shifted frequently across the surface of these broad fans as long as no changes took place in base level or eroding power of the streams. After dissection began, however, the streams became stabilized in their positions and trenched the High Plains alluvial slope.

Even though the drainage basin of the Platte River System came into existence in the Tertiary, its present course across Nebraska dates only from mid-Pleistocene time. Because of the distribution of anorthosite-bearing gravel and otherwise similar gravels that lack the indicator discussed earlier, we are suggesting that the early Pleistocene course of the river heading in the Laramie Range was toward the northeast across the Chadron-Cambridge Arch at a structurally low position, a course discordant to the present river system (Figs. 6, 7). Diversion of the river course southward took place along the Chadron-Cambridge Arch (Fig. 7). These changes in river course coincident with the arch imply early Pleistocene structural control of streams flowing across the structure. This conclusion also is suggested by the relatively gentle slope of the lower Pleistocene bedrock surface over the arch and the absence, or presence of thin gravels along the crest of the structure (Fig. 6). Although similar activity is not indicated for the Siouxana Arch, it does appear to be reflected in present-day topography (Fig. 6). This topographic expression of the Siouxana Arch would have been sufficient to control early Pleistocene drainage.

The Chadron-Cambridge Arch is crossed by three rivers in Nebraska—the Niobrara, the Platte, and the Republican; all other rivers in the state head along the crest of the structure and flow eastward (Fig. 8). Of particular note are the North, Middle, and South Loup Rivers, and the Dismal River. Where the Niobrara, Platte, and Republican Rivers cross the east flank of the arch, all three show distinct knickpoints that are difficult to account for on the basis of lithologic

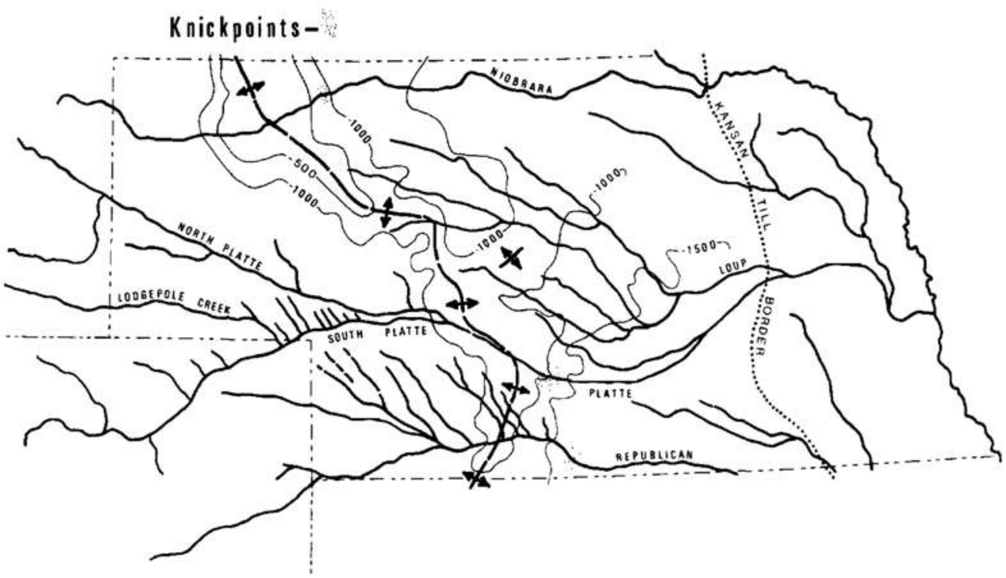

Figure 8. Drainage patterns in Nebraska and adjoining eastern Wyoming and northeastern Colorado showing the effect of movement on the Chadron- Cambridge Arch on orientations of streams along the arch. Structure contour lines are drawn on the top of the Precambrian (Carlson, 1967).

differences or added discharge from tributaries. The knickpoints on all three rivers occur where the relatively flattened crest of the arch breaks slope to form the eastern flank of the structure (Figs. 8, 9). The Niobrara River west of and on the crest of the arch has a gradient of 2.7 m per km; where it crosses the east flank of the Chadron-Cambridge Arch its gradient steepens to 3.85 m per km for a distance of about 16 km. Downstream from the arch the river slope flattens to 1.85 m per km (**Fig. 8**).

East of the Chadron-Cambridge Arch the Platte River drops more than 15.5 m in about 6 km for a gradient of 2.3 m per km. Above this stretch of the river the valley slope is almost a uniform 1.3 m per km for more than 100 km; below the knickpoint it falls an average of 1.3 m per km for more than 120 km. The steepened gradient coincides with steepening dip on the east flank of the arch (**Fig. 9**). The Republican River crosses the Cambridge Arch near its southern end where the structure has broadened and flattened. Nevertheless a steepened gradient exists in about the same place relative to the crest of the arch as has been observed on the Niobrara and Platte Rivers (Fig. 8). Over the arch the Republican River has a fairly uniform drop of 0.9 m per km for about 50 km, then in little more than 9 km, it falls at a rate of

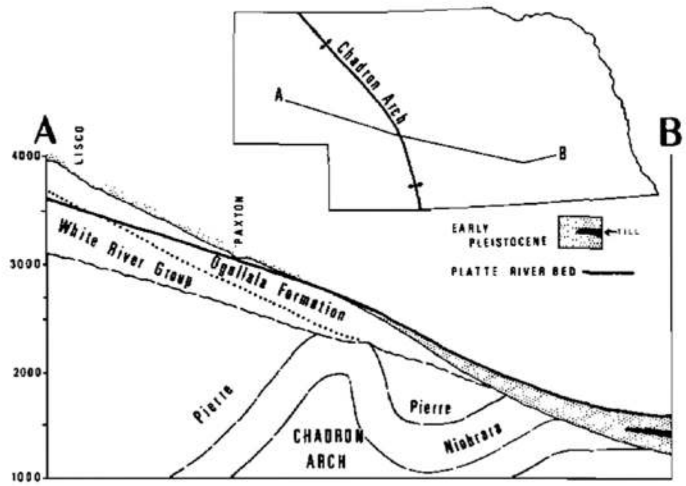

Figure 9. Cross section across Nebraska showing the relation between the profile of the North Platte-Platte River, Chadron-Cambridge Arch, and the prelower Pleistocene bedrock surface.

1.7 m per km. Farther east it flattens to 0.6 m per km, then steepens to slightly more than 0.8 m per km for the next 37 km. Downstream, where it has cut a gorge through Cretaceous rocks, the gradient of the Republican steepens again.

The presence of a distinct knickpoint along the Chadron-Cambridge Arch suggests that the Niobrara, Platte, and Republican Rivers are maintaining a course antecedent to a rising arch and are keeping pace with uplift. All these rivers are entrenched now, however; none are aggrading. During the glacial phases of the Pleistocene, when the Platte was carrying a heavy load of gravel and sand, similar activity along the central Chadron-Cambridge Arch would have been adequate to spill the aggrading stream over its fan and divert it southward where it could follow a new course.

Geomorphic criteria that may further substantiate the hypothesis of a spasmodically rising Chadron-Cambridge Arch during the early Pleistocene may be oriented drainage lines of southwestern Nebraska (Fig. 8). Most of the streams west of the Chadron-Cambridge Arch that are tributary to the Republican River trend nearly S. 45° E., as do the "hanging valleys" between the North and South Platte west of Ogallala. Streams that head along the arch and flow eastward generally trend about S. 60° E. Along the crest of the arch, all the tributaries to the Republican are short and flow almost due south (Fig. 8). The distinct changes in orientation of streams on either side of the arch suggest structural control. Pleistocene uplift along the Chadron- Cambridge Arch also is suggested by the relation of the pre-lower Pleistocene bedrock surface of the arch to the profile of the Platte River (Fig. 9). Evidence of activity today includes the concentration of earthquake epicenters along the arch (Woollard, 1958).

Stratigraphic and Geomorphic Implications

The complex history of braided-channel switching and meandering, which we have suggested for early Pleistocene streams (Fig. 7), bears not only on the relation between epeirogenesis and sedimentation, but also on classifications and correlations of lower Pleistocene sediments. Dispersal of braided-channel gravels east of the Chadron-Cambridge Arch requires a depositional history of repeated stream entrenchment and aggradation. During times of entrenchment, the position of the stream was fixed, but with the onset of aggradation fluvial sediments were deposited as the stream constructed an alluvial slope. Once the channel was filled, the stream could break out of its old course and follow a new one. Repeated times of entrenchment and aggradation would result in several channels, each filled by a similar succession of fining-upward fluvial sediments. This depositional model requires that similar vertical stratigraphic sections formed in separate channels at different times, a relation not considered in published studies of lower Pleistocene sediments in Nebraska. We believe that thinking about age relations and correlations of lower Pleistocene fluvial deposits should be re-examined, as should the history of associated middle Pleistocene fluvial and eolian deposits. Our demonstration that a major river headed in the front ranges and crossed the north-central part of the Sand Hills region of Nebraska until late Kansan time makes necessary a re-evaluation of the sand source, the climatic conditions, and the time of development of the sand dunes in Nebraska.

Conclusions

1. Both early Pleistocene streams originating in the front ranges of the Rocky Mountains and those flowing off continental glaciers in easternmost Nebraska can be identified by the composition of

gravel-size detritus carried by them. Gravels derived from the Rocky Mountains are characterized by Sherman Granite detritus; whereas sediments of streams flowing from continental glaciers in eastern Nebraska contain locally derived sedimentary detritus and detritus derived from the Precambrian terranes of the Sioux Uplift and Precambrian Shield of Minnesota.

Precambrian clasts were transported southward into Nebraska by continental ice sheets and reworked by streams.

2. Lower Pleistocene gravel-size fragments were derived directly from the mountains, not reworked from underlying Tertiary deposits.
3. Carrying power of early Pleistocene streams that headed in the Rocky Mountains was greater than that of both Pliocene streams and the present-day Platte River. This increased ability to carry detritus resulted from increased stream discharge. Streams flowing from continental glaciers in easternmost Nebraska and streams marginal to the ice front were more competent than streams flowing across Nebraska from the Rocky Mountains.
4. The course of the major river system heading in the central Laramie Range and flowing across Nebraska was controlled by spasmodic uplift on the Chadron-Cambridge and Siouxana Arches. During the early Pleistocene the river flowed across the Chadron-Cambridge Arch and north of the Siouxana Arch which it roughly paralleled into northeastern Nebraska. There the east-flowing stream joined streams flowing off continental glaciers and hence flowed southward along the ice margin. Uplift on the Chadron-Cambridge Arch diverted the course of the river into south-central Nebraska.
5. Today streams flowing across the Chadron-Cambridge Arch are entrenched, but during times of aggradation in the early Pleistocene slight movement on the arch was sufficient to divert drainage into a new course. During the early Pleistocene there were repeated times of entrenchment and aggradation of streams that produced channels filled with fining-upward alluvial deposits.
6. Continued movement on the Chadron-Cambridge Arch is indicated by knickpoints on rivers flowing over the arch, drainage patterns, concentration of earthquake epicenters along the arch, and the relation of pre-lower Pleistocene topography to the arch.
7. The present-day course of the Platte River dates only from

mid-Pleistocene time. The Platte, Niobrara, and Republican Rivers are maintaining courses antecedent to a still-spasmodically rising arch.

8. Fluvial dispersal data and conclusions reported herein make necessary a re-evaluation of presently held stratigraphic practices, correlations, and classification of lower Pleistocene sediments in Nebraska.

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Appendix 1. Locations for Gravel and Sand Samples

Location numbers correspond to those in Figure 2.

1. Sheridan County, Nebraska, NW¼sec. 9, T. 29 N., R. 44 W. Rushville fossil quarry described by Schultz and Tanner (1957).

2–4. Shannon, Washabaugh, and Mellette Counties, South Dakota. Medicine Root gravel (Harksen, 1969).

5. Logan County, Colorado, SW¼sec. 2, T. 11 N., R. 52 W. Gravel pit on southern edge of the Cheyenne tableland with caliche-capped gravels resting on Ogallala rocks.

6. Cheyenne County, Nebraska, SW¼sec. 22, T. 14 N., R. 49 W. Gravel pit with caliche-capped gravel resting on Ogallala rocks.

7. Garden County, Nebraska, E½sec. 30, T. 15 N., R. 41 W. Gravels resting on Ogallala rocks and overlain by a silt which is in turn capped with a caliche paleosol. Stop 9-4 on INQUA "D" field trip (Stout and others, 1965).

8. Keith County, Nebraska, N½sec. 10, T. 14 N., R. 38 W. Gravel exposed in gravel pit south of Kingsley Dam with gravel resting on Ogallala rocks and overlain by silts capped with a caliche paleosol.

9. Keith County, Nebraska, SE¼sec. 32, T. 14 N., R. 37 W. Paxton cut where gravels resting on Ogallala rocks are overlain by silts. The gravel has yielded early Pleistocene fossils.

10. Goshen County, Wyoming, SW¼sec. 34, T. 20 N., R. 63 W. Gravel veneer resting on Arikaree rocks, Diamond Flats.

11. Banner County, Nebraska, N½sec. 32, T. 19 N., R. 54 W. Gravels 300 ft above the present Pumpkin Creek, but 300 ft below the Cheyenne tableland. Probably mid-Pleistocene and predating piracy on Pumpkin Creek.
12. Morrill County, Nebraska, NE¼sec. 20, T. 19 N., R. 47 W. Broadwater fossil quarries described by Schultz and Stout (1948). Early Pleistocene fossils.
13. Garden County, Nebraska, W½sec. 21, T. 18 N., R. 45 W. Lisco early Pleistocene fossil quarries described by Schultz and Stout (1948).
14. Garden County, Nebraska, SE¼sec. 3, T. 19 N., R. 44 W. Gravels resting on Ogallala rocks and overlain by sand dunes exposed in stream channel where early Pleistocene fossils have been recovered (Schultz, 1934, p. 372, no. 4).
15. Hooker County, Nebraska, N½sec. 8, T. 24 N., R. 32 W. Gravel resting on Ogallala rocks and overlain by sands that have yielded early Mid-Pleistocene fossils.
16. Thomas County, Nebraska. Gravels with early Pleistocene fossils reported by Schultz (1934, p. 372, no. 6) exposed on Middle Loup River 0.5 mi east of Seneca, Nebraska.
17. Brown County, Nebraska, NW¼sec. 25, T. 31 N., R. 22 W. Gravels at the early Pleistocene Sand Draw fossil quarry reported on by McGrew (1944) and Taylor (1960).
18. Brown County, Nebraska, NW¼sec. 30, T. 30 N., R. 20 W. Gravels exposed in roadcut on Highway 20, 0.5 mi north of Long Pine, part of the same gravel which has yielded early Pleistocene fossils in the same township, range, and section (Schultz, 1934).
19. Holt County, Nebraska, T. 30 N., R. 13 W. Gravels overlain by silts.
20. Nance County, Nebraska, "Lovers' Leap" section of Lugn (1935, p. 83–85) on south bluff of Cedar Creek about 1 mi northeast of Fullerton, Nebraska. Gravel collected from gravel lenses at elevation of 1,660 ft above sea level.
21. Harlan County, Nebraska, NE¼sec. 11, T. 2 N., R. 20 W. Type section for the Sappa Formation described in field guide for INQUA "D" (Stout and others, 1965). Gravels occur as lenses in sands both above and below Pearlette ash.
22. Harlan County, Nebraska, NE¼sec. 19, T. 2 N., R. 17 W. Gravels underlying silt with ash lens exposed in stream cut south of Highway 136 and east of Republican City, Nebraska.
23. Webster County, Nebraska, SE¼sec. 19, T. 2 N., R. 12 W. Sands and gravels overlain by Sappa silts mapped by Miller and others (1964).
24. Webster County, Nebraska, E½sec. 28, T. 2 N., R. 11 W. Type area for the Red Cloud sands and gravels (Schultz and others, 1951).
25. Webster County, Nebraska, NE¼sec. 9, T. 2 N., R. 10 W. Gravel pit 1 mi south of Cowles, Nebraska. Stop 12-3 on INQUA "D" field trip (Stout and others, 1965).
26. Nuckolls County, Nebraska, N½sec. 3, T. 1 N., R. 8 W. Gravels below Sappa silts exposed in roadcut on Highway 136 7 mi east of Guiderock, Nebraska.
27. Adams County, Nebraska, SW¼sec. 24, T. 6 N., R. 10 W. Gravel pit described by Lugn (1935, Fig. 14).

28. Clay County, Nebraska, SE¼sec. 1, T. 7 N., R. 5 W. Groundwater Survey test hole 7-5-lddd. Gravels from 1,500 to 1,585 ft above sea level.
29. Thayer County, Nebraska. Gravel pit 1 mi east of the intersection of Highways 136 and 81 where gravels are overlain by silts of the Loveland or Sappa Formations.
30. Boyd County, Nebraska, SE¼sec. 25, T. 35 N., R. 17 W. Gravels from Conservation and Survey test hole 23-B-71.
31. Boyd County, Nebraska, NE¼ec. 25, T. 35 N., R. 16 W. Gravels from Conservation and Survey test hole 20-B-71.
32. Cuming County, Nebraska, NE¼sec. 30, T. 24 N., R. 4 E. Beerbohn gravel pit with early Pleistocene fossils reported by Frankforter (1950, p. 22-23).
33. Cuming County, Nebraska, NW¼sec. 26, T. 24 N., R. 4 E. Gravel pit described by Frankforter (1950).
34. York County, Nebraska, NE¼sec. 11, T. 10 N., R. 2 W. Gravels described by Stevenson (incomplete Univ. Nebraska M.S. thesis).
35. Seward County, Nebraska, NE¼sec. 17, T. 9 N., R. 2 W. Beaver Crossing section described by Stout and others (1965, p. 110-114).
36. Seward County, Nebraska, T. 9 N., R. 2 E. along section between sec. 8 and sec. 9 in roadcut. Kansan snails present in overlying silts.
37. Seward County, Nebraska, NW¼sec. 36, T. 10 N., R. 3 E. Gravel pit 0.25 mi east of Highway 15 and 1.5 mi south of Interstate 80.
38. Seward County, Nebraska, W½sec. 26, T. 9 N., R. 2 E. Gravels above the Sappa and Pearlette ash at the Milford Ashsite. Stop 14-1 on INQUA "D" field trip (Stout and others, 1965, p. 111).
39. Saline County, Nebraska, N½sec. 32, T. 8 N., R. 4 E. Type area for the Crete Formation in roadcut on Highway 33 (Condra and Reed, 1947).
40. Jefferson County, Nebraska, SW¼sec. 17, T. 2 N., R. 2 E. Gravel pit south of Highway 136 with gravels assigned to the Holdrege-Grand Island Formations by Veatch (1963).
41. Jefferson County, Nebraska, SW¼sec. 13, T. 1 N., R. 2 E. Gravel pit at Endicott, Nebraska. Early Pleistocene fossils found in similar gravels by Schultz (1934).
42. Holt County, Missouri, W½sec. 1, T. 3 N., R. 18 E. Gravels below silts exposed in roadcut 2 mi north of Craig, Missouri, on Highway 59.
43. Marshall County, Kansas. Gravel pit east of Highway 77 about 6 mi south of Marysville, Kansas.
44. Saline County, Nebraska, NW¼sec. 35, T. 6 N., R. 2 E. Intercalated fluvial deposits and till in roadcut on Highway 15.
45. (a) Seward County, Nebraska, W½sec. 36, T. 11 N., R. 4 E. Gravels in stream bank described by Goll (1961) where Wayne has found Kansan snails in underlying silts, (b) Lancaster County, Nebraska, E½sec. 8, T. 8 N., R. 7 E. Rippledrift laminated, moderately well sorted coarse silt intercalated with gravel in south face of quarry.

46. Seward County, Nebraska, W½sec. 20, T. 12 N., R. 4 E. Till and fluvial gravels exposed in roadcut.
47. Saunders County, Nebraska, sec. 33, T. 17 N., R. 8 E. Fluvial sediments intercalated with till in bluffs south of the Platte River and west of Highway 77.
48. Douglas County, Nebraska, SE¼sec. 9, T. 16 N., R. 13 E. Sands and gravel overlying till and overlain by silts containing a volcanic ash bed mapped by Miller (1964).
49. Harrison County, Iowa. Gravels exposed below volcanic ash on east side, Little Sioux River Valley near Harrison-Monomna line, Iowa.
50. Knox County, Nebraska, N½sec. 24, T. 32 N., R. 4 E. Gravel associated with till exposed in roadcut on Highway 12.

Appendix 2. Sampling Procedure

Analysis of sediments collected from localities in Appendix 1 indicated variation in composition with change in grain size, and therefore, specific gravel sizes were selected for study. Gravel sizes were obtained by shoveling sediment into nested screens (−5 to 3 phi at one-phi intervals). Gravel-size detritus caught on the −4 and −5 phi screens was point counted in the field; enough sediment was sieved so that at least 400 pebbles were caught. An average of 445 points was counted in 120 samples collected from 48 localities (Fig. 2; Appendix 1). The maximum clast size at each locality was determined in the field by measuring the long and intermediate diameter of the ten largest clasts.

The results from analysis of 14 samples from two widely separated localities were compared to determine whether the sampling had introduced sufficient bias into data, or that such complex local variability exists as to prevent utilization of derived descriptive statistics. Application of Student's t-test to gravel composition data indicated that observed differences between sample locations had less than a five percent probability of arising by chance sampling of the same population. Consistency in point counting gravel samples also was estimated by recounting several samples from the same locality. Reproducibility of gravel-size composition percentages was within the 95 percent confidence level.

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