Geologic Studies of the Platte River, South-Central Nebraska and Adjacent Areas—Geologic Maps, Subsurface Study, and Geologic History

Professional Paper 1706

U.S. Department of the Interior
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Cover—View from the bridge over the Platte River just south of Overton, Nebraska,
looking downstream (to the east). (USGS photo taken in 2002 by Steven M. Condon.)

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Geologic Studies of the Platte River, South-Central Nebraska and Adjacent Areas—Geologic Maps, Subsurface Study, and Geologic History

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Abstract

The Platte River of south-central Nebraska was studied at three scales to place the river in its geological context and to trace its evolution through geologic time. At the largest scale the Elm Creek West and the Newark 7.5 minute quadrangles were mapped. These quadrangles are located just west and just east of Kearney and serve to illustrate the main geomorphic elements of the present Platte River Valley. The central elements of the quadrangles are the Platte River channels, islands, and bottomlands, which are flanked by terraces that step up away from the river to the north and south. Significant other elements of the landscape are eolian sand and loess deposits. The geologic maps are supplemented by topographic profiles of the mapped terraces and graphical representations of subsurface units in test wells that occur within the quadrangles.

An intermediate-scale study consisted of examining descriptions of well cuttings in a 17 county area in south-central Nebraska, which includes the Platte River Valley, and building a database of information about sediment lithology and thickness. The wells penetrated a sequence of gravel, sand, silt, and clay beds from the ground surface to the top of the subsurface Tertiary Ogallala Group or Cretaceous formations. The sequence consists of Pliocene-, Pleistocene-, and Holocene-age strata that document the deposition of a veneer of alluvium by late Tertiary and Quaternary streams intermixed with and overlain by wind-blown loess. Various isopleth and structure maps illustrate the distribution and alluvial architecture of the sedimentary sequence, and support the interpretation of former positions of the Platte River.

A regional-scale study consisted of documenting the geologic history of the Front Range and adjacent mountains and depositional areas east of the mountains in Colorado, Wyoming, Kansas, and Nebraska from the end of the Cretaceous Period, about 65 million years ago, to the present. The structural and sedimentary history of the region is outlined, and a series of paleogeographic maps shows the development of the drainage system in the east-central Rocky Mountains and adjacent Plains. Ancestral South Platte, North Platte, and Laramie Rivers are recognized as early as the late Eocene, although the South Platte probably flowed to the southeast from the mountain front at that time. Deposits of the North Platte River are recognized on the west side of the Medicine Bow Mountains of Wyoming in the Miocene, and the presence of distinctive rock clasts indicates that the Laramie River flowed from the North Park area of Colorado northeast across a filled Laramie Basin and the Laramie Range of southeastern Wyoming in the Miocene. The present drainage system developed in the late Miocene to the Pliocene and included the capture and diversion of the South Platte River into its present channel. The combined North and South Platte Rivers deposited gravel and sand across Nebraska and flowed southeast from Kearney, Nebraska through the middle to late Pleistocene. Within the past 25,000 years the Platte River below Kearney was captured and diverted into its present course and confined there by bounding valley walls of loess.

Introduction

The Platte, South Platte, and North Platte Rivers and their valleys in Nebraska, Colorado, and Wyoming (fig. 1) have been important to the human history of the region from the time of the early Native Americans to the present. In prehistoric time, the area was a site of abundant buffalo and antelope herds that were a main source of food for hunting and gathering Native Americans. In late prehistoric time, the Platte River Valley was the site of many large Native American villages. Beginning in the early 19th century, the valleys became main thoroughfares for military exploration expeditions, for fur trappers and traders, for homesteaders bound for Oregon, and for adventurers headed to the gold fields of California and Colorado. In the 1860s, the Platte River Valley in Nebraska included part of the route of the Pony Express, the coast-to-coast telegraph line, and the first transcontinental railroad. In the 20th century, the valley maintained its importance to transcontinental travel by hosting parts of the Lincoln Highway (U.S. Highway 30) and then Interstate 80. Thousands of people a year have traveled east and west along the Platte and its two branches from the mid-1800s to the present. Along with its use as a mainstream transportation route, the Platte River Valley also became the site of farms and ranches early in its development (Mattes, 1969).

Although the first inhabitants had little effect on the Platte River Valley, later development has had a major impact. Probably the first noticable change would have been the removal of trees for fuel by the masses of people migrating westward, estimated at some 350,000 individuals between 1841 and 1866 (Mattes, 1969). As settlers populated the valley they started farming, and the semiarid climate west of the 98th meridian requires irrigation for bountiful crops. Dams were built in several places, most notably on the North Platte (the north fork of the Platte River), which changed the flow conditions and sedimentation patterns. Diversion canals altered the flow of the river and changed surface run-off and groundwater movement. Deep irrigation wells have changed the configuration of the water table. Farming practices, such as vegetation clearing activities, have tended to change the river bank stability in many places. Vegetation patterns have changed, from prehistoric conditions when trees were mainly limited to the islands, to current conditions of dense trees and brush along the banks in addition to those on the islands. Road construction has added fill to many areas on the floodplain, altering channel patterns and affecting the lateral migration of channels. Bridges cross the river, and associated roads are built above the grade of the floodplains and act as de facto dams, impeding the flow of high water in the spring, and causing extensive flooding in some lowland areas. The result of these changes is a river system that is perennial rather than intermittent, has a reduced annual discharge, is narrower and more deeply channeled, and is more confined by the stabilizing effects of bankside vegetation (Williams, 1978; Nadler and Schumm, 1981; Eschner and others, 1983; Karlinger and others, 1983; Schumm, 1999; Collier and others, 2000). In addition, the water is clearer and has a higher erosive capacity

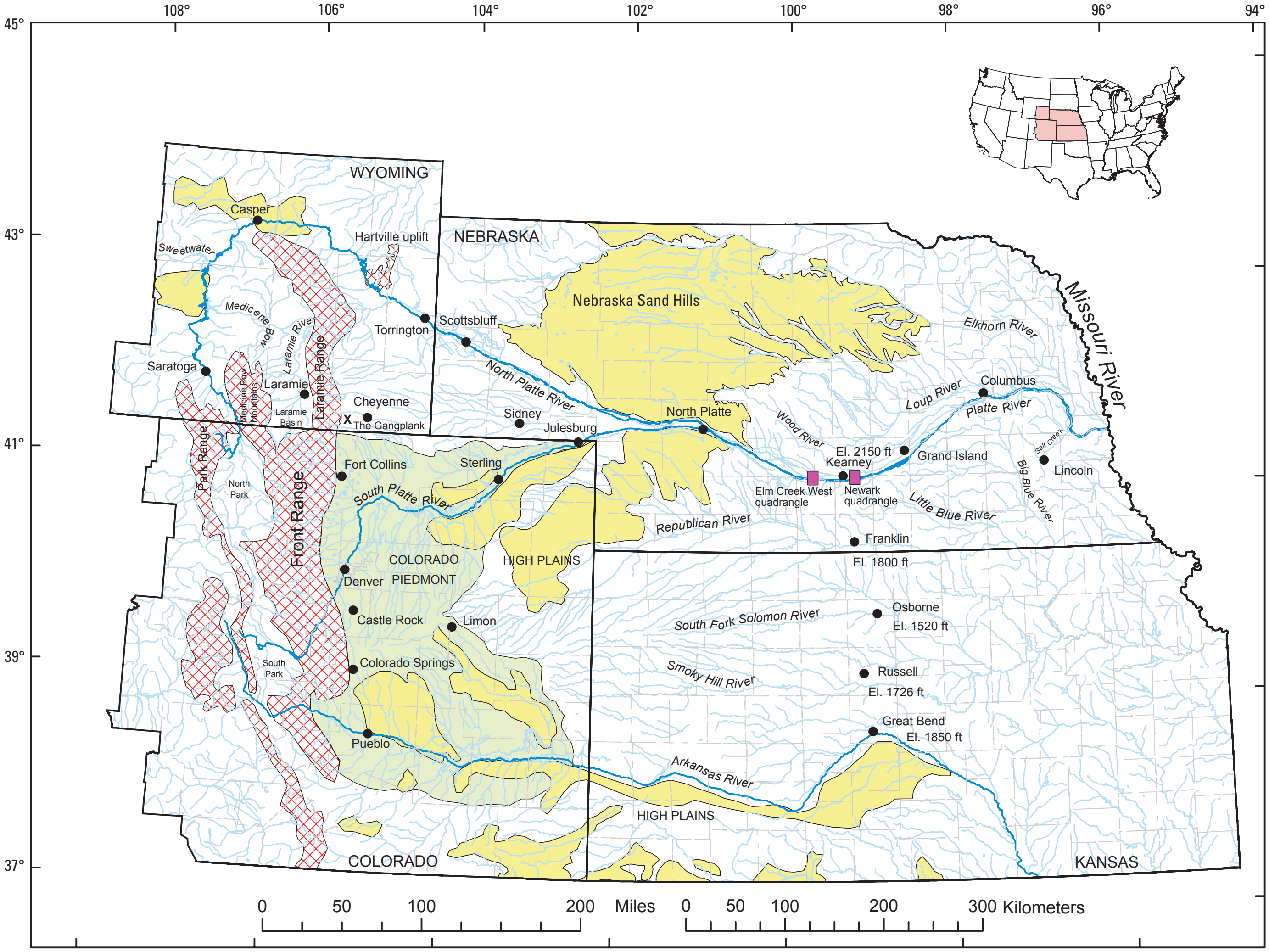

Figure 1 Regional map of the study area in Wyoming, Colorado, Nebraska, and Kansas. Red cross-hatching indicates Precambrian granitic or metamorphic rocks, generalized from Green (1992) and Green and Drouillard (1994); the Colorado Piedmont is in green (modified from Trimble, 1980b); eolian sand areas are yellow (modified from Muhs and others, 1999a). The location of the study area within the United States is shown in the inset map.

than in pioneer days, because of the sediment-trapping effect of dams.

A river system is complex and responds to natural phenomena as well as manmade changes. This report reviews structural and depositional events that shaped the fluvial systems that have drained eastward from the Front Range of Colorado and the Laramie Range of southern Wyoming since the Cretaceous Period (about 65 million years ago), combined with new data gathered for the current project. New data include the surface geology of two 7.5 minute topographic maps, Elm Creek West and Newark (just west and just east of Kearney, Nebraska, respectively) that were mapped to show the relations and hierarchy of landforms in key areas where other research is being done. These maps show river terraces, sand dunes and sand sheets, alluvial fans, and loess hills. Additionally, pre-Tertiary topography and thickness maps of Tertiary, Pleistocene, and Holocene sedimentary units were constructed for a 17-county area in south-central Nebraska. These maps show the alluvial architecture of the Pliocene to Holocene sediments that underlie the region between the Platte and Republican Rivers.

This report is not a commentary on the changes that have occurred in the Platte River system since man's influence has been in effect—its purpose is to provide a summary of (1) the geomorphic elements of the floodplain and bounding valley walls, (2) the physical arrangement and characteristics of the alluvial fill underlying and forming the Platte River Valley and adjacent areas, and (3) the chronological development of the modern drainage system. In essence, this report provides a geological foundation for biological and hydrological studies of the Platte River. The report is divided into three sections that cover the topics listed above.

Acknowledgments

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I. Geologic Maps of the Elm Creek West and Newark Quadrangles

Introduction

Geologic mapping was undertaken in two quadrangles where biological and hydrological studies on the Platte River Project were also being conducted (plates 1 and 2). One map is the Elm Creek West quadrangle, which includes the Cottonwood Ranch property, and the other is the Newark quadrangle, which includes the Audubon Society's Rowe Sanctuary headquarters. The Elm Creek West quadrangle is west of Kearney, Nebraska, and includes the west edge of the town of Elm Creek. The Newark quadrangle is east of Kearney and west of Shelton. Although there are similarities between the quadrangles, there are also significant differences, so the descriptions and discussions of each map are presented separately below.

Methods

The quadrangles were mapped on a combination of digital orthophoto quads, aerial photographs, and topographic maps of the areas. After careful review and study of the orthophoto quads, the primary technique used to discern terraces was to systematically traverse the quadrangles north to south along county roads, noting any variations in topography, slope breaks, vegetation changes, or other indicators of terrace edges. A combination of the topographic base map, orthophoto quads, and field observations were used to draw contacts between geologic or geomorphic units.

The digital orthophoto quads were downloaded from the Nebraska Department of Natural Resources web site (http://www.dnr.state.ne.us/databank/doqall.html). The digital topographic base maps were downloaded from the University of Nebraska at Lincoln, Institute of Agriculture and Natural Resources, Conservation and Survey Division web site (http://csd.unl.edu/general/drgdownloads.asp). Topographic profiles for each of the maps were constructed using digital elevation model (DEM) files for the quadrangles. These files were also obtained from the Nebraska Department of Natural Resources at http://www.dnr.state.ne.us/databank/dem.html.

Graphic representations of test wells in the quadrangles were also constructed, using the descriptions of well cuttings from the wells, and are included on the geologic map plates. The test wells were drilled by the Conservation and Survey Division (CSD) and the U.S. Geological Survey (USGS) starting in 1930, and descriptions of cuttings from most of the wells were published by county. I examined some unpublished descriptions from files at the CSD offices in Lincoln, Nebraska. The descriptions used are reproduced in this report with the discussions of each quadrangle.

The descriptions of terraces that follow include estimates of the average height of the units above the current floodplain. These elevations were calculated by averaging the elevations of the edges of the terraces closest to the river on the west and east extents of their occurrence in the quadrangles. The calculated averages do not take into account variations in the elevations of the terraces laterally north and south away from the river, which can be seen on the profiles of each quadrangle.

Elm Creek West Quadrangle

Description of Map Units

All of the mapped units in the Elm Creek West quadrangle are unconsolidated deposits. No lithified bedrock was observed, and few exposures of parent material are visible. Scattered exposures of loess in the hills in the northeast corner of the map, and loess in drainages cutting terraces in the southern part of the map, were the only parent material seen. Because no coring was done for this study, the mapped unit descriptions are of the main soil types present on their surfaces, which were originally mapped by Bowman and others (1973), Brown and others (1978), and Buller and others (1974). Some soils occur in more than one map unit, but most map units are defined on the basis of their geomorphic setting and are therefore lithologically and pedologically distinct.

Qfp Floodplain deposits (Holocene)—Lowest flood plain and island areas of the Platte River. Deposits of this unit are mostly poorly sorted and clast supported. They consist of unconsolidated gravel in a sandy or silty matrix, interbedded with or overlain by sandy silt and silty sand. Clasts are round to subangular and are composed of plutonic, metamorphic, and sedimentary rock types. Outside the active channels, many soil types are at the surface of this unit, including Gothenburg soils or comparable Loamy alluvial beds, Platte loam or comparable Platte soils, Gibbon loam, Lex loam, Alda loam, Leshara and Gibbon silt loam, Platte-Alda complex, and Platte-Wann complex. The Gothenburg soil and corresponding Loamy alluvial beds are the most abundant soil types recognized where Qfp is mapped

Qaf Alluvial fan deposits (Holocene)—An apron of alluvium derived from and deposited at the base of the loess hills in the northeastern part of the map. The unit extends southward over the Qt1b terrace. Soil types consist of Uly-Holdrege-Coly silt loams, Hobbs silt loam, Cozad silt loam, and Hord silt loam

Qal Alluvium (Holocene)—Thin veneer of alluvium derived mainly from stream that enters the map from the south in section 34, T. 8 N., R. 19 W. Soil types consist primarily of Wann loam, and lesser amounts of Leshara silt loam and Hord silt loam. Overlies terrace Qt1a and northern edge of dune field Qd in the southeastern part of the quadrangle

Qd Dune deposits (Holocene and Pleistocene)—Main dune area in southeast part of the map consists of wind-deposited dune sand and sheet sand intermixed with alluvial material in drainages. Soil types are heterogeneous, and include Valentine loamy sand, the Anselmo series, Kenesaw silt loam, and Kenesaw-Coly silt loam. Small areas of Qd mapped in and south of the Platte River channel are composed of small dunes and sandy zones intermixed with other soil types. Dunes in the main area of deposition have relief of as much as 40 ft. Dunes in other areas have relief of 10 ft or less. Eolian deposits in the southeast part of the map overlie and obscure older terrace deposits

Ql Loess (Pleistocene and Holocene)—Loess that forms hills at the northeast corner of the map. Soil types are mainly Uly silt loam, Coly silt loam, Holdrege silt loam, and Uly and Holdrege silt loams, combined. Loess probably consists of the Pleistocene Peoria Loess and the Holocene Bignell Loess

Qt1a Terrace 1a deposits (Holocene)—Deposits of the first terrace above the Platte River floodplain on the south side of the river. Two areas of this terrace were mapped, (1) immediately adjacent to the Platte River floodplain (Qfp), in the western and central parts of the map, and (2) immediately south of the Qal unit, about 0.75 mile south of the river floodplain in the eastern part of the map. In the first area, the surface is cut by numerous small abandoned stream channels; low areas are boggy and hold standing water in the spring. The second area is slightly drier and has sandier soils. In the first area, soil types are mainly saline Leshara silt loam, Leshara silt loam, Grigston silt loam, and Wann loam. Soils in the second area are Anselmo fine sandy loam, Meadin loamy sand, Meadin silt loam, and O'Neill fine sandy loam. This terrace stands at an average of 5 ft above the floodplain

Qt1b Terrace 1b deposits (Holocene)—Deposits of the first terrace above the Platte River floodplain on the north side of the river. This terrace is somewhat higher and better drained and may be slightly older than the Qt1a terrace on the south side of the river. This was the only terrace identified between the river and the loess hills on the north side of the river and thus covers a significant portion of the map (about 24 square miles). A large number of soil types occur on this terrace, including the Cozad series, Gosper series, Hord series, Rusco silt loam, and Wood River series. This terrace stands at an average of 7.5 ft above the floodplain

Qt2 **Terrace 2 deposits (Holocene? and Pleistocene)**—Deposits of the second terrace above the Platte River floodplain on the south side of the river. In plan view, this terrace is triangular, wedging out because of erosion by the Platte River just to the west of the map boundary. The terrace widens eastward to about the middle of the quadrangle; in the southeast part of the map the terrace is mantled by dune deposits of Qd. The northern edge of the terrace is defined by a topographic break and by a change to the soil types Kenesaw silt loam and Kenesaw and Coly silt loams. Soil types over most of this terrace are Hord silt loam. Kenesaw silt loam occurs mainly along the eastern edge of exposure. This terrace stands at an average of 45 ft above the floodplain

Qt3 **Terrace 3 deposits (Pleistocene)**—Deposits of the third terrace above the Platte River floodplain on the south side of the river. In plan view, this terrace narrows to the west and was removed by Platte River erosion in about the middle of the adjacent Overton quadrangle. The terrace widens to the southeast and is partially mantled by dune deposits in the south-central part of the map. The southern edge of the terrace trends generally east-west just south of the map boundary. Soils on this terrace are the same as those on the Qt2 terrace. A change to Kenesaw silt loam and Kenesaw and Coly silt loams mark the northern edge of the terrace. The majority of the terrace surface is composed of Hord silt loam, with some Kenesaw silt loam along the eastern-most exposures. This terrace stands at an average of 50 ft above the floodplain

Qt4 **Terrace 4 deposits (Pleistocene)**—Deposits of the fourth terrace above the Platte River floodplain. Only a small part of this terrace occurs in the Elm Creek West quadrangle, in the southwest corner of the map. Soil type is Holdrege silt loam. This terrace stands at an average of 97.5 ft above the floodplain

Discussion

The Elm Creek West quadrangle is located about 15 miles west of Kearney, Nebraska, and straddles the valley of the Platte River (fig. 1; plate 1). The quadrangle has representatives of all the main geomorphic and genetic elements of the Platte River Valley. The northeastern corner of the quadrangle includes the edge of the valley where it abuts an extensive, dissected loess upland. The upland consists of the Peoria Loess, which was deposited in western Nebraska between about 25,000 years before the present (B.P.) and about 10,500 years B.P. (Muhs and others, 1999a; Roberts and others, 2003), and the Bignell Loess, deposited between about 9,000 and 3,000 years B.P. (Pye and others (1995). An apron of alluvium, in the form of coalesced alluvial fans, bounds the loess hills and extends southward toward the Platte River. No test holes have been drilled in these units in this quadrangle.

The main geomorphic features of the Elm Creek West quadrangle are the channels and islands of the Platte River, bottom lands that bound the river, and terraces that flank the river on the north and south. A numbering sequence for the terraces was adopted for this map that partially follows that established by Schultz and Stout (1945) and Stout (1983). In this quadrangle the floodplain, in which the river flows, is designated as Qfp, and successively older terraces are numbered Qt1, Qt2, Qt3, and Qt4.

In this quadrangle, the channel system of the Platte is highly braided, having small to large islands separated by active channels and other channels in various stages of abandonment. One large island in this quadrangle extends almost the entire width of the map, near the north side of the Qfp unit. Its width varies along its length, and is about 0.25 mi wide at its widest. The Cottonwood Ranch property is on part of this island. There is also another large island area that is partially attached to the south bank of the river. On the eastern side of the map, this island is bounded by the South Channel of the Platte River on the south and by the main channel at the Elm Creek bridge on the north.

The Qfp floodplain surface ranges in elevation from about 2,290 ft on the west side of the map to about 2,245 ft on the east, giving an average drop of 6.9 ft per mile. The river has become increasingly entrenched since dams and water diversion structures have been built upstream (Eschner and others, 1983), which has resulted in a major reduction in channel area and an increase in island area. The decreased channel width also has led to increased accretion of the islands, both vertically and horizontally. Although much of the nonisland areas are flooded during high water in the spring, some islands are now high enough to escape being flooded. One major cause of flooding in this quadrangle is the constriction of the channel at the Elm Creek Bridge. The bridge approaches act as dams during times of high water, backing up the river and flooding the upstream lowlands.

The Qt1 terrace was originally defined as the low, broad surface just above the floodplain in localities west of the study area (Stout, 1983). In the Elm Creek West quadrangle, there are differences between the Qt1 terrace on the south and north sides of the Platte, and this terrace is divided here into the Qt1a and Qt1b terraces, respectively. The Qt1a terrace is thought to be the youngest terrace above the river. It stands at an average of 5 ft above the floodplain (Qfp), and is characterized by low, boggy land that commonly contains standing water in fields and ditches. This terrace is just high enough above the floodplain to avoid extensive flooding in the spring. The surface of this terrace is cut by numerous, small abandoned channels that are readily visible on aerial photographs. The immaturity of the landscape suggests that this area was recently occupied by the Platte River, and that lateral migration of the river has been northward, cutting into the Qt1b terrace. The western areas of the Qt1a terrace stand at an elevation of about 2,290 ft, dropping to about 2,255 ft at the eastern map edge, for an average drop of 5.4 ft per mile.

Test well number 29-B-47 was drilled in the Qt1a terrace a short distance south of the floodplain (plate 1). The upper units tested consist of silty and sandy soil and silt, and gravel within 3.5 ft of the surface. Most of the subsurface alluvium consists of sand and gravel, and bedrock of the Ogallala Group was reached at 34.5 ft (plate 1).

The Qt1b terrace is characterized by a higher elevation, a better-developed drainage system, and a different soil association than that of the Qt1a terrace. This terrace stands at an average of 7.5 ft above the average elevation of the floodplain (Qfp). Eight north-south traverses, from the river to the north valley wall, were made over this terrace, to try to distinguish any other terraces north of the river. Although the land surface rises gradually to the north and northwest, no topographic or geomorphic breaks were found that would indicate a higher terrace surface in that area. Thus, only the Qt1b terrace is recognized from the northern floodplain of the Platte River to the alluvial fan deposits in the northeastern corner of the map and to the northwestern corner of the map in this quadrangle. This is probably due to older terraces having been removed by erosion by lateral migration of the river in this area. Measured just north of the river and parallel to it, the highest elevation of the Qt1b terrace is about 2,295 ft. The lowest elevation is along the eastern border of the map, at about 2,255 ft, for an average drop of 6.2 ft per mile.

Test well number 28-B-47 was drilled in the Qt1b terrace a short distance north of the floodplain. Soil, clay, and silt were found to a depth of 8 ft. Mixed sand, gravel, and clay were encountered deeper in this well, underlain by the Ogallala Group at a depth of 56 ft (plate 1).

On the south side of the Platte, a marked topographic break separates the Qt1a terrace from the Qt2 terrace. The Qt2 terrace stands at an average of 45 ft above the average elevation of the floodplain. This terrace is mantled by a layer of loess of undetermined depth, indicated by the Hord association of soils on its surface. The Bignell Loess is the youngest loess unit in central Nebraska (Pye and others, 1995), and may partially mantle the Qt2 and older terraces in this area. The Bignell is discontinuous though, and is only identified if the underlying Brady soil is present. The older Peoria Loess is also present on these terraces. The Qt2 terrace is at an elevation of about 2,325 ft on the west edge of the map and drops to about 2,300 ft before it is covered by younger eolian material, for an average drop of 6.7 ft per mile.

Another topographic break distinguishes the Qt2 terrace from the Qt3 terrace. The Qt3 is also covered by a layer of loess, and it stands at an average of 50 ft above the average elevation of the floodplain. This terrace has the same soil association as the Qt2 terrace, and is probably also mantled by Bignell and Peoria Loesses. The Qt3 terrace ranges in elevation from 2,330 to 2,305 ft along a line just south of, and parallel to, its northern edge, for an average drop of 7.1 ft per mile. The Jensen Mammoth site is in Qt3 terrace deposits on the north side of the river northwest of the Elm Creek West quadrangle (May and Holen, 1994; Holen, 1995; S.R. Holen, written commun., 1999). Radiocarbon dating indicates the age of the terrace alluvium from that site is about 14,000 years B.P.

Test well 31-B-47, which was drilled in about the middle of this terrace, indicates 20 ft of soil and silt (loess) at the surface of the terrace, underlain by a mixture of sand, silt, gravel, and minor clay. The Ogallala Group was reached at a depth of 114 ft.

The highest and oldest terrace in the Elm Creek West quadrangle is the Qt4, which is only present in a small area in the southwestern corner of the map. The terrace stands at an average of 97.5 ft above the average elevation of the floodplain. This surface might be considered part of the southern uplands of the river, however, it is surmounted by a yet higher surface in an area approximately 12 miles southwest of the Elm Creek West quadrangle. The Qt4 terrace is considered to be the highest (and oldest) terrace of the ancestral Platte River in this quadrangle. This unit has a slightly different soil association than the Qt3 and Qt2 terraces, but is still mantled with loess.

An important feature of the southeastern part of the map is the area mapped as Qd, which consists of wind-deposited sand. Some areas are flat, and are composed of sand sheets, while other areas consist of sand dunes. Both units overlie, and partially obscure, the Qt1a, Qt2, and Qt3 terraces described above. The sand is very fine grained, and is interpreted to have been blown out of Platte River channels by northwest-to-southeast winds. The physical relations of the dune area with the terraces and the minimal degree of soil development in dune sand indicate that the dunes are relatively young.

There are other small areas of dunes also mapped, and which are even younger than the large area of Qd. Some of these other areas lie on the Qfp floodplain, most noteworthy of which is a long, linear dune area in section 2, T., 8 N., R. 19 W. This dune area has several feet of relief and is immediately south of a former channel of the river. Other small areas mapped as Qd were noted as “sand spots” on the county soil survey maps. These youngest eolian deposits are also interpreted to have been blown out of Platte River channels.

Another depositional unit is alluvium (Qal) that was deposited on the Qt1a terrace, and sourced from the south by an unnamed creek that passes by the Williamsburg church (plate 1). Test hole number 30-B-47 was drilled in this unit, near the point at which the Qal unit was first deposited on the Qt1a terrace. Strata in this well consist of a series of stacked soils, 4.5 ft thick, underlain by clay and silt to a depth of 14 ft. Thirty-seven feet of sand and gravel were then drilled until the Ogallala Group was reached at a depth of 51 ft.

No material from the Elm Creek West quadrangle was dated for this study, so inferences about the age of terraces can only be made by comparison with other areas and from other studies. On a geologic map that includes this quadrangle (Swinehart and others, 1994), the Qt2, Qt3, and Qt4 terraces are mapped as part of a unit interpreted to be Illinoian and pre-Illinoian in age. In numerical age, this would be older than about 120,000 years B.P. but younger than about 710,000 years B.P. (Haq and Van Eysinga, 1987). Souders and Dreeszen (1991) described a site about 10 miles southeast of the Elm Creek West quadrangle on the Qt4 terrace. At that site the stratigraphy consists of Peoria Loess at the surface, underlain by a paleosol, which is in turn underlain by a sandy sequence. The paleosol was radiocarbon dated at 24,260±260 years B.P., indicating that the sands that comprise the Qt4 terrace alluvium may be equivalent to the Gilman Canyon Formation of mid-Wisconsin age.

Terrace Qt1b was mapped by Swinehart and others (1994) partially as a late Wisconsin unit (older than ±10,500 years B.P.) and partially as a late Wisconsin and Holocene unit (younger than ±10,500 years B.P.). Terrace Qt1a and the floodplain were mapped as a part of the late Wisconsin and Holocene unit, younger than ±10,500 years B.P. The Bignell Loess, dated between about 9,000 and 3,000 B.P. (Pye and others, 1995) partially mantles the Qt2, Qt3, and Qt4 terraces, but is not found on the Qt1a or Qt1b terraces or on the floodplain. This absence of the Bignell Loess on the younger terraces helps establish a maximum age of about 3,000 years B.P. for those units, and a minimum age of 3,000 to 9,000 years B.P. for the older terraces.

Swinehart and others (1994) indicated that stream capture changed the course of the Platte River in the Wisconsin glacial stage to approximately the configuration it is in today (also, see the discussion in section III, later in this report). Since establishing its new course, the river has migrated back and forth across its valley, alternately aggrading and then downcutting, forming the younger terraces. As noted above, the Qt1a terrace appears to be the youngest terrace outside the floodplain, based on its elevation, and the relative immaturity of the landscape on its surface. The river thus appears to be migrating northward in this area, eroding into the Qt1b terrace at the present time.

Logs of Test Holes Drilled by the Conservation and Survey Division-UNL in the Elm Creek West Quadrangle

(Position of the Ogallala Group and Pierre Shale in brackets [ ] were determined by the author and may not represent the interpretations of the Conservation and Survey Division)

Phelps County–(Anonymous, 1953h)

Location	Well number	Ground elevation
Section 12, T. 8 N., R. 19 W.	29-B-47	2,264 ft

	Depth, in feet	
	From	To
Soil: silt, sandy, dark brownish gray; contains very fine sand	0	1
Silt, sandy, slightly to moderately calcareous, grayish-brown; contains very fine to fine sand and a few calcareous nodules	1	2.5
Soil: silt, sandy, moderately to very calcareous, dark brownish gray; contains fine sand to medium gravel	2.5	3.5
Sand, clayey, buff-gray; fine texture; contains some limonitic stain	3.5	4.5
Sand and gravel, grayish tan; texture grades from very fine sand to very coarse gravel	4.5	32
Silt, clayey, slightly to very calcareous, very light-green to gray	32	34.5
[Ogallala Group] Silt, clayey to sandy, pinkish tan; contains some interbedded pinkish to greenish gray sandstone	34.5	40
Sandstone, in part calcareous, pinkish to greenish gray; contains a few rootlets and seeds; reddish brown below 58 ft; grades into a siltstone below 75 ft	40	80
Siltstone to claystone, brownish to greenish gray; blocky	80	90
Sandstone, slightly to very calcareous, grayish green; contains a few rootlets; quartzitic layer from 96 to 98.5 ft; few yellowish gray marl beds below 110 ft	90	120

Phelps County–(Anonymous, 1953h)—Continued

Location	Well number	Ground elevation
Section 12, T. 8 N., R. 19 W.	29-B-47	2,264 ft

	Depth, in feet	
	From	To
Marl, grayish yellow	120	121
Sandstone, very calcareous, greenish gray with a slight brownish tint; contains many rootlets	121	133
Sand, silty, to silt, sandy, slightly calcareous, grayish green	133	142.5
Sandstone, slightly to moderately calcareous, brownish gray-green; fine textured; few rootlets; texture grades from fine to medium sand below 170 ft	142.5	202.5
Sandstone, very calcareous, very light grayish green; fine texture	202.5	215
Silt, clayey, very calcareous, light-gray to very light greenish gray	215	217.5
Clay, green; contains some limonitic stain and reworked clay fragments	217.5	223
[Pierre Shale] Clay, light-gray; contains much limonitic material	223	259
Clay shale, dark-gray to black	259	270

Location	Well number	Ground elevation
Section 14, T. 8 N., R. 19 W.	30-B-47	2,280 ft

	Depth, in feet	
	From	To
Soil and road fill: silt, slightly sandy, brownish black	0	1
Soil: silt, clayey to slightly sandy, brownish black	1	3
Soil: silt, clayey, dark brownish gray	3	4.5
Silt, clayey to sandy, buff-gray; contains fine sand	4.5	5.5
Clay, soil-like, sandy to silty, dark buff-gray; contains very fine sand	5.5	7.5
Silt, sandy to slightly clayey, grayish buff; contains very fine sand; a few calcareous nodules; light brownish gray below 9 ft	7.5	10
Clay, silty to silt, sandy, grayish brown; contains very fine sand; limonitic stain in lower foot	10	14
Sand and gravel, pinkish gray; texture grades from fine sand to medium gravel with some coarse gravel; texture grades from coarse sand to coarse gravel below 40 ft	14	51
[Ogallala Group] Sandstone, brownish gray-green; fine texture	51	53.5
Sandstone, very calcareous, light-gray; contains a few seeds	53.5	56.5
Sandstone, brownish gray-green; fine texture; in part calcareous; contains rootlets and seeds below 60 ft	56.5	64
Sandstone, light-gray to brownish gray-green; very calcareous from 64 to 67 ft; reddish brown below 70 ft	64	76
Sand and some sandstone, grayish tan; texture grades from fine to coarse sand with some fine gravel	76	79.5
Sandstone, very calcareous, light greenish gray; grading to a slightly sandy silt from 85 to 91 ft; pinkish tan below 91 ft	79.5	97

Phelps County–(Anonymous, 1953h)—Continued

Location	Well number	Ground elevation
Section 14, T. 8 N., R. 19 W.	30-B-47	2,280 ft

	Depth, in feet	
	From	To
Silt, clayey, very calcareous, light greenish gray; contains a few marl layers below 100 ft	97	105.5
Sandstone, slightly calcareous, greenish to brownish gray; fine texture; few rootlets and seeds; light-gray and very calcareous from 119 to 130 ft and 145.5 to 148 ft	105.5	151
Sand and gravel, light grayish brown with pinkish tint; texture grades from fine sand to fine gravel	151	155
Sandstone, moderately calcareous, brownish gray to grayish green; fine texture; very calcareous from 174 to 175 ft; some interbedded silt from 180 to 185 ft	155	195
Silt, sandy, to sandstone, in part slightly calcareous, light grayish green	195	201
Clay, silty to silt, clayey, light-gray to light grayish green; few marl layers	201	207
Siltstone, sandy, grayish green; contains very fine sand	207	224.5
Gravel, consists mainly of green silt pebbles and limonitic fragments; contains some volcanic ash	224.5	233
[Pierre Shale] Clay, light to medium-gray; contains some weathered material at top	233	239
Clay shale, dark ray to black; contains some weathered material; trace of light-gray bentonitic clay from 240 to 245 ft	239	250

Location	Well number	Ground elevation
Section 28, T. 8 N., R. 19 W.	31-B-47	2,316 ft

	Depth, in feet	
	From	To
Soil: silt, sandy to slightly clayey, brownish black; contains very fine sand	0	1
Soil: clay, sandy to silty, slightly to moderately calcareous, brownish gray; contains very fine sand	1	3
Silt, clayey, slightly to moderately calcareous, buff-gray; few small calcareous nodules	3	4
Silt, in part sandy, slightly to moderately calcareous, tan-gray; contains very fine sand; limonitic flecks and calcareous rootlets; slightly coarser texture below 17 ft	4	20
Sand, tan to buff-gray; texture grades from fine to coarse sand; contains some limonitic stain and small gastropod shells, some fine to medium gravel below 45 ft	20	66
Silt, clayey to slightly sandy, grayish green	66	69.5

Phelps County–(Anonymous, 1953h)—Continued

Location	Well number	Ground elevation
Section 28, T. 8 N., R. 19 W.	31-B-47	2,316 ft

	Depth, in feet	
	From	To
Sand and gravel, pinkish gray; texture grades from fine sand to coarse gravel	69.5	80
Clay, silty, light-gray with a slight greenish tint	80	84
Clay, silty, to silt, clayey, pinkish tan; calcareous nodules in lower part	84	93.5
Silt, reddish brown; contains a few rootlets	93.5	96
Silt, clayey, moderately to very calcareous, light-gray to brownish tan; slightly calcareous with some sandy silt below 110 ft	96	114
[Ogallala Group] Sandstone, slightly to very calcareous, brownish tan; fine texture; contains a few rootlets and seeds; grayish green 126 to 140 ft; brownish gray to grayish brown below 140 ft	114	142
Clay, reddish brown, and marl, grayish white, interbedded	142	147
Clay, slightly calcareous, reddish brown; blocky	147	155
Sandstone, brownish tan to grayish green; contains a few rootlets and seeds; moderately to very calcareous below 160 ft; some fine to coarse sand below 190 ft	155	195
Sand, greenish gray; texture grades from fine to coarse sand; slightly finer texture and some interbedded silty sand below 205 ft	195	210
Sand, slightly silty, grayish green; texture grades from fine to medium sand	210	220
Sandstone, slightly to moderately calcareous, light grayish green to brownish gray-green; contains a few rootlets	220	238
Silt, clayey, grayish green	238	243
Quartzite, in part calcareous, grayish green	243	244.3

Buffalo County–(Anonymous, 1953b)

Location	Well number	Ground elevation
Section 5, T. 8 N., R. 18 W.	28-B-47	2,262 ft

	Depth, in feet	
	From	To
Soil and road fill: clay, silty, dark brownish gray; brownish black and granular below 1 ft	0	2.5
Clay, silty, light brownish gray	2.5	3.5
Soil: silt, medium brownish gray; granular; contains a few limy nodules	3.5	4
Clay, silty, to silt, clayey, contains a few limy nodules	4	5
Silt, calcareous, buff-gray; contains a limy nodular zone	5	7.5
Silt, clayey to sandy, soil-like, dark grayish brown	7.5	8
Sand and gravel, buff-gray; texture grades from fine sand to coarse gravel	8	10

Buffalo County–(Anonymous, 1953b)—Continued

Location	Well number	Ground elevation
Section 5, T. 8 N., R. 18 W.	28-B-47	2,262 ft

	Depth, in feet From	To
Gravel with some sand, buff-gray with many yellow and pink grains; texture grades from coarse sand to coarse gravel with some large pebbles	10	27.5
Clay, silty, in part sandy, slightly calcareous, gray with slight pink tint; contains very fine sand; moderately to very calcareous below 32.5 ft; less silty below 37 ft	27.5	40
Clay, in part silty, moderately calcareous, tan-gray; contains many limy nodules	40	47
Clay, silty, to silt, clayey, in part sandy, buff-tan with slight gray tint	47	51
Gravel with some sand, pink; texture grades from coarse sand to medium gravel with some large pebbles	51	56
[Ogallala Group] Sandstone, tan; grayish tint below 62.5 ft	56	68
Sandstone, very calcareous, light grayish green	68	69.5
Sandstone, slightly to moderately calcareous, grayish green with slight brown tint; contains some rootlets	69.5	72.5
Sandstone, reddish brown	72.5	76
Sand, gray; texture grades from medium to coarse	76	80.5
Sand, silty, light-gray to light greenish-gray	80.5	86
Sandstone, grayish green to grayish brown	86	96
Sand and gravel, tan-gray; texture grades from fine sand to medium gravel	96	97.5
Sandstone, grayish brown; contains some white siliceous material below 100 ft	97.5	105
Sandstone, brownish gray to green; contains many calcareous rootlets	105	110
Sandstone, very calcareous, light buff-gray; contains many calcareous and siliceous rootlets and a few fossil seeds	110	112
Sandstone, very calcareous, light-gray; contains fossil seeds	112	115
Sand and sandstone, slightly calcareous, grayish tan; texture grades from fine to medium with some coarse	115	123
Sandstone, light greenish gray with buff tint; contains some rootlets	123	130.5
Silt, sandy, light greenish gray	130.5	140
Sandstone, moderately calcareous, buff-gray; contains interbedded calcareous silty sand below 143 ft	140	145
Sandstone, very calcareous, buff-gray; contains some interbedded reddish brown clay and thin, limy layers	145	150
Sandstone, moderately calcareous, grayish brown; contains some rootlets	150	151.5
Sand and some gravel, light brownish gray with green and pink grains; texture grades from fine sand to fine gravel; slightly coarser in lower part	151.5	162

Buffalo County–(Anonymous, 1953b)—Continued

Location	Well number	Ground elevation
Section 5, T. 8 N., R. 18 W.	28-B-47	2,262 ft

	Depth, in feet	
	From	To
Sandstone, very calcareous, grayish green with a yellowish tint; light-gray with greenish tint below 164 ft	162	167
Sandstone, grayish green with slight yellowish tint	167	168.5
Silt, sandy, in part slightly calcareous, light grayish-green	168.5	171.5
Sandstone, moderately to very calcareous, grayish green with slight yellowish tint	171.5	180
Sand, clayey to silty, light grayish green	180	185
Sand, brownish gray; texture grades from fine to medium with some coarse	185	192
Sandstone to sand, brownish gray with greenish tint; contains a few rounded silty clay granules	192	214
Sand, in part slightly silty and consolidated, brownish gray with greenish tint; texture grades from very fine to medium sand	214	220
Sand and gravel, greenish gray with pink grains; texture grades from fine sand to fine gravel; contains many green clay pebbles	220	230
Sand and gravel, greenish brown with some pink grains; texture grades from coarse sand to medium gravel	230	242.5
Sand, silty, to sandstone, very calcareous, light greenish gray	242.5	247.5
Sandstone, very calcareous, light greenish gray	247.5	250
Sandstone, very calcareous, ligh-gray with buff and greenish tints	250	255
Sandstone, moderately calcareous, light buff-gray	255	260
Sandstone, very calcareous, light-buff to yellowish gray	260	265.5
Sandstone, moderately calcareous, buff to brownish gray	265.5	273
Sand and slightly consolidated sandstone, slightly calcareous, brownish gray; texture grades from fine to medium sand	273	283
Siltstone, grayish green	283	285
[Pierre Shale] Clay, light-gray; contains many limonitic fragments	285	291
Clay shale, medium-gray to black	291	310

Newark Quadrangle

Description of Map Units

All of the mapped units in the Newark quadrangle are unconsolidated deposits. No bedrock was seen, and few exposures of soil parent material are visible. Because no coring was done for this study, the mapped units are described to include the main soil types that formed on their surfaces, which were previously mapped by Buller and others (1974) and Wahl and others (1984). Some soils occur in more than one map unit, but most map units are defined on the basis of their geomorphic setting, and are therefore lithologically and pedologically distinct.

Qfp **Floodplain (Holocene)**— Lowest floodplain and island areas of the Platte River. Deposits of this unit are mostly poorly sorted and clast supported. They consist of unconsolidated gravel in a sandy or silty matrix interbedded with or overlain by sandy silt and silty sand. Clasts are round to subangular and are composed of plutonic, metamorphic, and sedimentary rock types. Outside the active channels, many soil types mantle this unit, including Loamy alluvial land, Platte soils, Platte-Alda complex, Alda loam, Alda fine sandy loam, Leshara and Gibbon silt loam, Inavale, and minor Wann fine sandy loam. The Platte soils, Platte-Alda complex, and Leshara and Gibbon silt loam are the most abundant soil types recognized where Qfp is mapped. The Elm Island area, between the Middle and South channels of the Platte River, is the topographically lowest land area within this unit. Other island areas between the Middle and North channels (Killgore Island, Fort Farm Island) are slightly higher topographically

Qs **Sand sheet (Holocene)**—The sand sheet in the south part of the quadrangle that borders the area of sand dunes consists mainly of Simeon sandy loam, and lesser amounts of Valentine loamy fine sand

Qd **Dunes (Holocene)**—Main area in southeast part of the map consists of wind-deposited dunes and sand sheets intermixed with alluvial material in drainages. Soil types are mainly Valentine loamy fine sand. Small areas of Qd mapped on the Platte River floodplain are composed of small eolian dunes and sandy zones intermixed with other soil types. The dune area on the west margin of the map consists mainly of Inavale fine sandy loam. Small areas of dunes in the northeast corner of the map are mantled with Cozad silt loam and Wood River silt loam. Dunes in the main area of deposition in the southeast corner of the map have relief of as much as 20 ft; dunes in other areas have relief of 10 ft or less. Eolian deposits along the south edge of the map overlie older terrace deposits

Qt1a **Terrace 1a deposits (Holocene)**—Deposits of the first terrace above the Platte River floodplain on the north side of the river. The surface is cut by numerous small abandoned stream channels; low areas are boggy and hold standing water in the spring. Soil types are mainly Alda loam, Lex silt loam, Platte soils, and Gibbon silt loam. Cass fine sandy loam, Wann loam, and Wann fine sandy loam are also present in minor amounts. There is an elevation gradient from south to north, from low-elevation Platte and Lex soils on the south to Gibbon silt loam farther north, mainly in the area within T. 9 N., R. 14 W. (Gibbon township). This terrace stands at an average of 1 ft above the floodplain

Qt1b **Terrace 1b deposits (Holocene)**—Deposits of the first terrace above the Platte River floodplain on the south side of the river. This terrace is slightly higher, somewhat better drained, and is thought to be older than the Qt1a terrace on the north side of the river. Soil types that occur on this terrace include Alda loam, Boel fine sandy loam, Wann fine sandy loam, Gibbon loam, and Lex loam. This terrace stands at an average of 5 ft above the floodplain

Qt2 **Terrace 2 deposits (Pleistocene)**—Deposits of the second terrace above the Platte River floodplain on the north side of the river. The southern edge of the terrace is defined by a marked topographic break, and by the soil types Wood River silt loam, Hall silt loam, and Hord silt loam, all on 1 to 3 percent slopes. Soil types over most of this terrace are Hord silt loam and a significant area of Hall silt loam. This terrace stands at an average of 5 ft above the floodplain

Ql **Loess (Pleistocene?)**—Area of loess of unknown age in the northeast part of the quadrangle. A similar feature east of the quadrangle was drilled by the Conservation and Survey Division, UNL, and was found to be underlain by clayey silt (J.D. Swinehart, written commun., 2001)

Qt3 **Terrace 3 deposits (Pleistocene)**—Deposits of the third terrace above the Platte River floodplain on the north side of the river. This terrace forms the drainage divide between the Platte River and the Wood River in this area. A subtle elevation break separates this terrace from the Qt2 terrace to the south, and the railroad tracks are built along the boundary between the terraces. This surface is distinguished from the Qt2 terrace by extensive soil mottling that is visible on aerial photographs. Main soil types are Wood River silt loam and Hall silt loam. This terrace stands at an average of 12.5 ft above the floodplain

Discussion

The Newark quadrangle is located about 5 miles east of Kearney, Nebraska, and straddles the valley of the Platte River (fig. 1; plate 2). The quadrangle is representative of most of the main geomorphic and genetic elements of the Platte River Valley, lacking only the bounding loess uplands that are north and south of the quadrangle.

The main geomorphic features of the Newark quadrangle are the channels and islands of the Platte River, bottom lands that bound the river, and terraces that flank the river to the north and south. A numbering sequence for the terraces was adopted for this map that partially follows that established by Schultz and Stout (1945) and Stout (1983). In this quadrangle the floodplain, in which the river flows, is designated as Qfp, and successively older terraces are numbered Qt1, Qt2, and Qt3.

In the Newark quadrangle, the channel system of the Platte River is only moderately braided, compared to other areas, such as the Elm Creek West quadrangle west of Kearney. Three main channels of the Platte are recognized in this quadrangle, the North, Middle, and South channels. The Middle Channel is the largest, and is about 0.3 mile across at its widest. It has relatively few islands that interrupt the channel, or, in other words, the amount of open channel to island area is relatively large. The North Channel is the next largest, but is substantially smaller than the Middle Channel. The North Channel has more islands and is more highly braided than the Middle Channel. Single channels within it are only about 0.1 mile or less across, but the channel complex is about as wide as the Middle Channel (up to about 0.3 mile across). It appears that the North Channel is being abandoned. The South Channel is narrow and is nearly abandoned.

Within the Qfp map unit that is defined by the river channels, there are a number of large islands. The largest of these is the combined Killgore and Fort Farm islands, which are only separated by minor drainages representing former Platte channels. This island complex lies between the North and Middle channels of the Platte. The North Channel merges with the Middle Channel a short distance to the east of the Newark quadrangle, and Killgore and Fort Farm islands are not recognized beyond that point. Elm Island occurs between the Middle and South channels, and is the lowest and wettest of the island areas in the quadrangle. The Audubon Society's Rowe Sanctuary headquarters is located on this island. The South Channel eventually dies out to the west, just southeast of the city of Kearney, and Elm Island is no longer recognized in that area. Elm Island does extend eastward quite some distance east of this quadrangle.

The Qfp floodplain surface ranges in elevation from about 2,110 ft on the west side of the map to about 2,065 ft on the east, giving an average drop of 6.7 ft per mile. The river has become increasingly entrenched since dams and water diversion structures have been built upstream (Eschner and others, 1983), which has resulted in a major reduction in channel area and an increase in island area. The decreased channel width also has led to increased accretion of the islands, both vertically and horizontally. Although much of the bottom land is flooded during high water in the spring, some islands are now high enough to escape being flooded.

Test well number 73-B-47 was drilled along the South channel in the Qfp map unit (plate 2). In this well, a thin soil layer is underlain by about 68 ft of sand and gravel and then by a mixed interval of sand, gravel, and silt, 135 ft thick. The Ogallala Group does not seem to be present in this location, and the Pliocene sequence of sediments is underlain by the Pierre Shale at a depth of 204 ft.

The Qt1 terrace is defined as the low, broad surface just above the floodplain. In the Newark quadrangle, there are differences between the Qt1 terrace on the north and south sides of the Platte, so the Qt1 terrace has been divided into the Qt1a and Qt1b terraces, respectively. The Qt1a terrace is thought to be the youngest terrace above the river. It is characterized by low, boggy land that commonly contains standing water in fields and ditches. The average elevation of this terrace is slightly (1ft) above the average elevation of the floodplain, just high enough to avoid extensive flooding in the spring. In this area Interstate 80 also forms a de facto levee between the floodplain and the Qt1a terrace. The surface of this terrace is cut by numerous small, abandoned channels that are readily visible on aerial photographs. The immaturity of the landscape suggests that this area was recently occupied by the Platte River, and that lateral migration of the river has been cutting southward into the Qt1b terrace, opposite to the migration direction in the Elm Creek West quadrangle. The western exposures of the Qt1a terrace stand at an elevation of about 2,112 ft, dropping to about 2,065 ft at the eastern map edge, for an average drop of 7.1 ft per mile. No test wells were drilled in the Qt1a unit in this quadrangle.

The Qt1b terrace is characterized by having a higher elevation, a better-defined drainage system, and development of a different soil association than that of the Qt1a terrace. This terrace stands at an average of 5 ft above the average elevation of the floodplain. The highest elevation of the Qt1b terrace is about 2,115 ft, and the lowest elevation is along the eastern border of the map is about 2,070 ft, for an average drop of 6.8 ft per mile.

Test well 72-B-47 was drilled in about the middle of the exposed area of the Qt1b terrace south of the river. Pleistocene and Pliocene sediments in this well consist mainly of sand and gravel from the surface to a depth of 217 ft where the Pierre Shale was reached (plate 2). The Ogallala Group is not present in this well.

A marked topographic break separates the Qt1a terrace from the Qt2 terrace. The Qt2 terrace is covered with a layer of loess of undetermined depth, indicated by the Hord association of soils on its surface. This terrace also stands at an average of 5 ft above the average elevation of the floodplain. The Qt2 terrace is at an elevation of about 2,116 ft on the west edge of the map and falls to about 2,069 ft on the east edge, for an average drop of 7.1 ft per mile. Many of the older farmhouses and out-buildings in this area are built on the southern edge of the Qt2 terrace, suggesting that the farmers who first settled the area were aware of the flooding potential of the lower Qt1a surface. Even though the average elevations above the floodplain are the same for the Qt1b and Qt2 terraces, features such as soil associations and degree of maturity of the terrace surfaces distinguishes them.

Test wells 42-31 and 43-A-54 were drilled on the Qt2 terrace (plate 2). Well 42-31 consists of a surface layer of soil, 3 ft thick, underlain by 55 ft of gravel and 22 ft of silty sand. Well 43-A-54 consists of a surface layer of soil underlain by sand and gravel, about 51 ft thick. Below the sand and gravel is an interval, 186 ft thick, which consists mainly of silt that lies on the Pierre Shale (plate 2).

A very slight topographic break separates the Qt2 terrace from the Qt3 terrace. The Qt3 terrace is also mantled by a layer of loess, and stands at an average of 12.5 ft above the average elevation of the floodplain. The Qt3 terrace ranges in elevation from 2,125 to 2,075 ft along a line parallel to the railroad tracks, for an average drop of 7.4 ft per mile.

Well 42-A-54 was drilled in the Qt3 terrace on the north side of the map. In this well a 2 ft thick surface soil layer is underlain by 14 ft of silt, probably loess. Below this is a mixture of sand, gravel, and silt, 141 ft thick, underlain by 54 ft of the Ogallala Group. The well penetrated the upper 39 ft of Pierre Shale (plate 2).

Important features of the southern part of the map are the areas mapped as Qd and Qs, which consist of wind-deposited sand. Some areas are flat, and are composed of sand sheets, while other areas consist of sand dunes. Both units overlie, and partially obscure, the Qt1b terrace. The sand of both units is very fine grained, and is interpreted to have been transported out of the Platte River channels by northwest-to-southeast winds. The physical relations of the dune area with the terrace and the minimal degree of soil development in dune sand indicate that the dunes are relatively young.

Other small areas of dunes are also mapped which are even younger than the mapped area of eolian sand. Some of these other areas lie on the Qfp floodplain, mainly on Killgore and Fort Farm islands. A small dune also was mapped just northeast of the Rowe Sanctuary in Sec. 10, T. 8 N., R. 14 W. This dune has several feet of relief and is immediately south of the river. Other small areas mapped as Qd occur in the northeast corner of the quadrangle.

A large hill in the northeastern corner of the quadrangle was first thought to be a large sand dune. The hill has about 25 ft of relief and is elongated southwest-northeast. It is slightly steeper on the southeast side, resulting in a morphology of a transverse dune formed by northwest-to-southeast-blowing wind. The soils mapped in this northeast area are not characteristic of eolian dunes (Buller and others, 1974), however, field checking of road cuts and animal burrows along the north-south road that crosses the hill indicated the presence of very fine grained sand in surface deposits. According to J.B. Swinehart (written commun., 2001) a similar feature was drilled by the Conservation and Survey Division in an area east of the Newark quadrangle. The drilling indicated that the feature consisted of clayey silt, signifying loess, not dune sand. This feature in the Newark quadrangle is thus shown as loess, of questioned Pleistocene age.

No material from the Newark quadrangle was dated for this study, so inferences about the age of terraces can only be made by comparison with other areas and from other studies. On a geologic map that includes this quadrangle (Swinehart and others, 1994), the Qt3 terrace was mapped as part of a unit interpreted to be of late Wisconsin age, slightly older than about 10,500 years B.P. All the younger terraces were included in a unit interpreted as late Wisconsin to Holocene in age (Swinehart and others, 1994).

Although a similar numbering system was used for terraces in the Newark and Elm Creek West quadrangles, terraces in one area may not be entirely comparable with those in the other area, especially regarding the older terraces. The Platte River flowed southeasterly from about Kearney toward the Republican River drainage as late as the late Wisconsin glacial stage (Souders and Dreeszen, 1991; Swinehart and others, 1994). In the Elm Creek West quadrangle the terraces mapped as Qt2, Qt3, and Qt4 appear to have been formed as part of that southeast-flowing stream system. The river was diverted into its present northeasterly course by stream capture later, some time in the late Wisconsin (Lugn, 1935; Souders and Dreeszen, 1991; Swinehart and others, 1994).

The Newark quadrangle is at the transition point where capture and diversion of the Platte occurred. Without age-dating the terraces of the Elm Creek West and Newark quadrangles it is difficult to know if the Qt2 and Qt3 terraces represent the same depositional and erosional events in both quadrangles. The height of the terraces above the Platte River floodplain suggests that the terraces in the Newark quadrangle are not comparable to those in the Elm Creek quadrangle. In the Elm Creek West quadrangle the Qt2 terrace is an average of 45 ft above the floodplain; in the Newark quadrangle the Qt2 terrace is only an average of 5 ft above the floodplain. In the Elm Creek quadrangle the Qt3 terrace is an average of 50 ft above the floodplain; in the Newark quadrangle it is only 12.5 ft above the floodplain. The significantly different relative elevations of the terraces may indicate that those in the Newark quadrangle were formed after the river was diverted and established a new channel.

Since the Platte River began to flow northeastward toward Grand Island, Nebraska and beyond, it has migrated back and forth across a wide valley. The valley is considerably wider at Grand Island than at Kearney. The young landscape of the Qt1a terrace in the Newark quadrangle suggests that the river is now migrating southward and is eroding the Qt1b terrace at this locality.

There have been many attempts to divide the unconsolidated sediments into formations, first by Lugn (1935) and Lugn and Wenzel (1938), and later by Condra and others (1947), Condra and Reed (1950), Schultz and others (1951), Reed and Dreeszen (1965), and Reed and others (1965). In later years, many of the older names have been abandoned, and some provisional names have been used (Wayne and others, 1991; May and others, 1995). For this report, an attempt was initially made to apply some of the older names, but the variable quality of the test hole logs and heterogeneity of the sedimentary sequence made this impossible on a regional basis. This report thus divides the unconsolidated sediments into a dominantly fluvial sequence and a dominantly eolian sequence. The fluvial sequence typically underlies the eolian sequence, but one or the other sequence may predominate or may be absent in any given well. After the initial divisions were made, the data were entered into a database. Various maps were constructed and certain picks were re-examined and modified based on the preliminary maps. The test hole locations were downloaded from the University of Nebraska web site http://csd.unl.edu/general/gis-datasets.asp.

A separate data set was used to create a structure contour map on top of Precambrian rocks (fig 3). For this map, data for the top of Precambrian rocks from approximately 4,000 wells were retrieved from a publicly available database (IHS Energy Group, 2003). This, and the other contour maps in this report, were constructed using Discovery R2002.1, version 7.2 (Landmark Graphics Corporation, Houston, Texas). The location map (fig. 1), paleogeography maps (discussed in section III), and the geologic map plates were compiled in ESRI ArcMap, version 8.3 (Environmental Systems Research Institute, Inc., Redlands, Calif.), and were exported to Adobe Illustrator for final editing.

Logs of Test Holes Drilled by the Conservation and Survey Division-UNL in the Newark Quadrangle

(Position of the Ogallala Group and Pierre Shale in brackets [ ] were determined by the author and may not represent the interpretations of the Conservation and Survey Division)

Buffalo County–(Anonymous, 1953b; Anonymous, unpublished [1954])

Location	Well number	Ground elevation
Section 13, T. 9 N., R. 15 W.	42-A-54	2,105 ft

	Depth, in feet	
	From	To
Soil: silt, slightly clayey, dark-gray; coarse texture	0	2
Silt, moderately clayey, medium yellow-gray; in part slightly calcareous, medium brown-gray from 3 to 4 ft	2	4
Silt, slightly to moderately clayey, slightly calcareous, light yellow-gray; contains a few limy nodules; less clayey from 4.5 to 5 ft; coarse textured with a trace of mottled yellow-brown from 5 to 7.5 ft; slightly to moderately clayey, light yellow-gray and contains some shell fragments below 7.5 ft	4	10
Silt, slightly clayey, slightly calcareous, light yellow-gray; contains much mottled yellow-brown; noncalcareous, light-gray below 12.5 ft	10	16
Sand texture grades from fine to very coarse; contains a trace of fine gravel; principally quartz with pink silicates	16	20
Sand and gravel texture grades from medium sand to fine gravel ; contains 10 to 20 percent fine gravel	20	30
Sand and gravel texture grades from medium sand to fine gravel , with a trace of medium gravel	30	40
Sand and gravel texture grades from fine to very coarse sand w ith some medium to coarse gravel; contains 50 to 60 percent gravel.	40	59.5
Silt, very clayey, medium-brown; coarse texture silt, moderately clayey, slightly sandy, medium yellow-gray; contains very fine sand from 60 to 61 ft; very clayey and medium-gray from 61 to 63.5 ft; slightly clayey, slightly sandy; contains very fine to fine sand below 63.5 ft	59.5	64.5
Sand texture grades from very fine to fine	64.5	71
Silt, slightly clayey, slightly calcareous, light olive-gray, coarse texture; contains limy nodular layer at 72.5 ft; contains very fine sand below 80 ft; noncalcareous from 84 to 86.2 ft; moderately clayey from 86.2 to 88 ft; contains very fine to fine sand below 90 ft	71	94
Sand texture grades from very fine to coarse with a trace of f ine gravel	94	100
Sand and gravel texture grades from fine to very coarse sand; contains 15 percent fine gravel; contains 30 percent fine gravel with a trace of medium gravel below 105 ft	100	107
Silt, slightly clayey, slightly calcareous, medium-gray; coarse texture; contains limy nodules; medium olive-gray from 110 to 118.5 ft; noncalcareous from 115 to 120 ft; medium yellow-gray from 118.5 to 123 ft; contains more clay below 120 ft; medium-brown and noncalcareous below 123 ft	107	123.5
Silt, slightly clayey, medium-brown; coarse texture; contains more clay from 125 to 128.5 ft, slightly calcareous from 125 to 130 ft	123.5	130
Silt, slightly clayey, moderately to very sandy, coarse texture silt to very fine sand below 132 ft	130	140

Buffalo County–(Anonymous, 1953b; Anonymous, unpublished [1954])—Continued

Location	Well number	Ground elevation
Section 13, T. 9 N., R. 15 W.	42-A-54	2,105 ft

	Depth, in feet	
	From	To
Silt, slightly to moderately clayey, slightly calcareous, medium-brown; coarse texture silt; contains limy nodules; noncalcareous and slightly sandy below 145 ft, moderately calcareous from 150 to 151.5 ft; contains very fine to medium sand from 151.5 to 153.5 ft; slightly calcareous below 153.5 ft; contains very fine to coarse sand from 153.5 to 154 ft; contains very fine to very coarse sand from 154 to 154.5 ft; contains very fine to coarse sand from 154.5 to 155 ft……….	140	155
Sand and gravel, slightly clayey, very silty; texture grades from very fine to very coarse sand; contains 10 percent gravel………….………….	155	157
[Ogallala Group] Sandstone, very silty, medium-gray; poorly cemented; texture grades from very fine to fine sand…………………………..….	157	160
Silt, moderately sandy, medium olive-gray; slightly cemented; contains very fine to medium sand…………………………………………...….	160	161.5
Silt, slightly clayey, slightly sandy, light olive-gray; contains embedded very fine to coarse sand; moderately sandy below 165.5 ft……………	161.5	166.5
Sand, texture grades from very fine to very coarse; contains some fine gravel….…………………………………………………………..	166.5	168
Silt, slightly clayey, slightly sandy, light olive-gray; contains coarse texture silt to very fine sand; contains a few rootlets below 170 ft….....	168	174
Sand and some gravel texture grades from very fine to very coarse gravel; contains 5 to 10 percent fine gravel with some medium gravel………………………………………………………………...	174	180
Sand and gravel texture grades from fine to very coarse sand; contains 30 percent fine gravel with some medium gravel…………………...…	180	185
Sand texture grades from very fine to coarse with some very coarse…….	185	191.5
Siltstone, marly, to sandstone, very calcareous, white; contains very fine to fine sand…………………………………………………………..	191.5	195
Sandstone, slightly to moderately silty, very calcareous, light olive-gray; texture of sand grades from very fine to fine; slightly silty, slightly calcareous and contains a trace of medium sand below 197 ft…...……	195	210
Sand, slightly calcareous; texture grades from very fine to very coarse; contains some reworked green siltstone……………………………..…	210	211
[Pierre Shale] Shale, clayey, moderately calcareous, light-gray; contains some mottled yellow-brown; contains 10 percent mottled yellow-brown from 212 to 215 ft, 25 percent mottled yellow-brown from 215 to 219.5 ft; 10 percent mottled yellow-brown from 220 to 229 ft; contains bentonitic layer at 227.5 ft; medium-gray from 229 to 230.5 ft and below 236 ft; slightly friable texture below 239 ft………………	211	250

Buffalo County–(Anonymous, 1953b; Anonymous, unpublished [1954])—Continued

Location	Well number	Ground elevation
Section 36, T. 9 N., R. 15 W.	43-A-54	2,094 ft

	Depth, in feet	
	From	To
Road fill	0	1
Soil: silt, moderately clayey, slightly sandy, slightly calcareous, dark brown-gray; contains very fine with a trace of coarse sand; noncalcareous and contains more clay from 2.8 to 3.2 ft	1	3.4
Sand and gravel, quartz with pink feldspar; texture grades from medium to fine sand with a trace of medium gravel; contains 20 to 35 percent gravel; contains a thin sandy silt layer at 33.3 ft; contains some iron stain at 30 to 40 ft; 40 to 50 percent gravel below 40 ft	3.4	54
Silt, moderately to very clayey, yellow-brown; light-brown, slightly calcareous from 57 to 60 ft; slightly clayey and noncalcareous, medium brown-gray, coarse texture silt from 60 to 61.5 ft; light brown-gray below 61.5 ft	54	63
Sand texture grades from very fine to medium with a little coarse to very coarse; contains a trace of fine gravel, quartz with pink silicates below 70 ft	63	78
Silt, moderately clayey, slightly calcareous, light-gray; contains more clay below 80 ft; mottled light-gray and light-brown below 81.5 ft; contains coarse texture silt grading to slightly sandy below 85 ft	78	86.5
Silt, very sandy, slightly calcareous, light-brown; granular structure; contains very fine sand	86.5	87.5
Silt, slightly clayey, slightly sandy, moderately calcareous, light-gray; contains coarse texture silt to very fine sand; slightly calcareous below 90 ft; light-brown to olive-gray below 93 ft; moderately sandy and contains very fine to fine sand below 101 ft; noncalcareous below 110 ft	87.5	112
Sand texture grades from very fine to medium with a trace of coarse to very coarse sand	112	114.5
Silt, slightly clayey, slightly calcareous, medium yellow-gray; medium gray and contains more clay below 117 ft	114.5	121
Clay, very silty, slightly calcareous, medium-gray	121	121.5
Silt, very clayey, moderately calcareous, light-gray; contains coarse texture silt from 124 to 125 ft	121.5	125
Silt to sandy silt, slightly calcareous, medium-gray, interbedded; contains many gastropods	125	129.5
Silt, slightly to moderately clayey, slightly sandy, slightly calcareous; contains coarse texture silt to very fine sand; moderately clayey to in part very sandy from 131.5 to 135 ft; slightly clayey, very sandy, contains many gastropods below 135 ft; less sandy below 139 ft	129.5	143.5
Sand and some gravel texture grades from very fine to very coarse sand with some fine gravel; contains mostly quartz and silicates; contains black staining	143.5	144.5
Silt, moderately clayey to in part slightly sandy, slightly calcareous, dark-gray	144.5	145
Silt, slightly to moderately sandy, slightly calcareous, light-gray; contains very fine to fine sand, interbedded	145	150
Silt, slightly clayey, moderately sandy, slightly calcareous, medium-gray; contains very fine to fine sand; contains a trace of medium sand below 152 ft	150	155

Buffalo County–(Anonymous, 1953b; Anonymous, unpublished [1954])—Continued

Location	Well number	Ground elevation
Section 36, T. 9 N., R. 15 W.	43-A-54	2,094 ft

	Depth, in feet	
	From	To
Silt, sandy, to sand, silty, moderately calcareous; contains very fine to fine with a trace of medium sand	155	156
Silt, moderately clayey, slightly sandy, slightly calcareous, medium-gray; contains coarse texture silt to very fine to fine sand; contains less clay and more sand with a trace of fine gravel from 160 to 64 ft; noncalcareous from 164 to 165 ft	156	170
Silt, slightly clayey, slightly calcareous, light olive-gray; contains coarse texture silt; in part slightly sandy, contains very fine sand from 180 to 185 ft; moderately clayey from 185 to 186 ft, slightly clayey to in part slightly sandy, medium-gray below 186 ft	170	195
Silt, moderately sandy, slightly calcareous, medium-gray; contains very fine to fine sand	195	200
Silt, slightly clayey, slightly calcareous, medium-gray, coarse texture silt; moderately calcareous from 201.5 to 203 ft; in part slightly to moderately sandy below 203 ft	200	205
Silt, slightly clayey, slightly sandy, slightly calcareous, light-gray; contains coarse texture silt to very fine sand; moderately clayey from 208 to 209 ft; contains a trace of embedded sand from 210 to 215 ft; contains limy nodules below 215 ft; moderately clayey from 216 to 220 ft; contains a trace of embedded fine sand and noncalcareous below 225 ft	205	229
Sand texture grades from very fine to very coarse with a trace of fine gravel	229	239.5
[Pierre Shale] Shale, clayey, moderately calcareous, medium-gray; contains a white, light-gray, and yellow-brown bentonite layer at 253.5 ft	239.5	290

Location	Well number	Ground elevation
Section 2, T. 8 N., R. 15 W.	42-31*	2,110 ft

	Depth, in feet	
	From	To
Soil: silt, buff	0	3
Gravel, coarse texture	3	58
Sand, silty, calcareous, light-gray	58	80

*The published log of this test hole indicates a well number of 42-31 (Anonymous, 1953b, p. iv), however, J.B.Swinehart (written commun., 2001) corrected the well number to 42-32.

Buffalo County–(Anonymous, 1953b; Anonymous, unpublished [1954])—Continued

Location	Well number	Ground elevation
Section 24, T. 8 N., R. 15 W.	73-B-47	2,094 ft

	Depth, in feet	
	From	To
Soil: sand, silty, brownish-gray; texture grades from fine to coarse sand with some gravel	0	0.7
Sand, light buff-gray; texture grades from fine to medium with a trace of coarse	0.7	0.9
Sand and gravel, brownish gray with some pink grains; texture grades from sand to medium gravel with some coarse gravel and pebbles; limonitic-stained; contains a thin yellowish brown silty clay layer at 15 ft.	0.9	29
Sand and gravel, brownish gray with some pink and black grains; texture grades from sand to coarse gravel; limonitic-stained	29	69
Silt, slightly clayey, brownish gray; limonitic-stained in upper part	69	70
Silt, slightly clayey to sandy, brownish tan with slight grayish tint; contains very fine sand	70	77.5
Sand and gravel, brownish gray with pink grains; texture grades from sand to medium gravel	77.5	81
Silt, clayey, brownish tan with grayish tint	81	91
Sand and gravel, brownish gray with pink grains; texture grades from sand to fine gravel with some medium gravel; contains a thin silt layer at 98.5 ft	91	109.5
Silt, in part slightly clayey to sandy, light to medium brownish gray	109.5	124
Sand and some gravel, brownish gray with some pink grains; texture grades from sand to medium gravel	124	165
Silt, clayey to clay, silty, light to medium-gray; contains yellowish to grayish brown layer from 165 to 165.7 ft	165	179.5
Sand, slightly silty, light brownish gray; texture grades from very fine to medium sand; contains light-gray clay pebbles, aragonite and thin shell fragments from 195 to 200 ft	179.5	204
[Pierre Shale] Clay, light-gray to light yellowish gray	204	210

Kearney County—(Anonymous, 1953f)

Location	Well number	Ground elevation
Section 19, T. 8 N., R. 14 W.	72-B-47	2,096 ft

	Depth, in feet	
	From	To
Soil: sand, moderately silty, dark brown-gray; texture grades from very fine to fine sand with a trace of coarser grains	0	0.8
Sand, slightly silty, light brown-gray; texture grades from very fine to coarse with a trace of very coarse sand and fine gravel; yellow-brown and very silty to slightly clayey below 2 ft	0.8	2.5
Sand and gravel, light brownish gray with many pink grains; texture grades from medium sand to fine gravel with some medium gravel; iron stained	2.5	10
Gravel texture grades from fine to medium with some coarse gra vel and a trace of sand, 85 to 90 percent gravel; principally quartz and pink feldspar; iron-stained from 10 to 20 ft	10	24.5

Kearney County–(Anonymous, 1953f)—Continued

Location	Well number	Ground elevation
Section 19, T. 8 N., R. 14 W.	72-B-47	2,096 ft

	Depth, in feet	
	From	To
Silt, moderately clayey to sandy, soil-like, medium grayish brown to light-gray	24.5	25.2
Gravel, light-gray; texture grades from fine to coarse gravel with some sand; principally quartz with some pink feldspar; 75 percent gravel; finer below 30 ft	25.2	48
Silt, sandy, light-gray; very fine texture sand; iron-stained in upper part	48	51
Sand and gravel, iron-stained; texture grades from coarse sand to medium gravel; contains some yellow-brown clay	51	58
Clay, silty, in part sandy, yellowish-brown; contains very fine to medium sand	58	61
Sand and gravel, light brownish gray with some pink feldspar; texture grades from medium sand to medium gravel, 50 to 60 percent gravel; iron-stained	61	70
Sand and gravel, light brownish gray; texture grades from fine sand to fine gravel with some medium to coarse gravel, 45 to 50 percent gravel; contains 80 percent gravel below 90 ft	70	107
Sand and gravel, light brownish gray; texture grades from fine to very coarse sand with some fine to medium gravel; contains yellowish brown silty clay layers below 111.5 ft	107	115.5
Sand and gravel, light brownish gray with iron stain; texture grades from medium sand to medium gravel, 50 percent gravel	115.5	123
Silt, sandy, light-gray; contains very fine sand	123	127.5
Sand and gravel, light brownish gray; texture grades from fine sand to fine gravel with a trace of medium to coarse gravel	127.5	140
Sand, grayish white; texture grades from fine to very coarse with a trace of gravel; principally quartz	140	143
Silt, clayey, moderately to very calcareous, light-brown; contains a trace of very fine to fine sand	143	153
Silt, moderately calcareous, light brownish gray; contains limy nodules at 167 ft; clayey below 170 ft	153	180
Silt to siltstone, very calcareous, light-brown	180	186
Sand, light brow-gray; texture grades from very fine to coarse	186	187
Silt to siltstone, very calcareous, light-brown	187	199
Sand texture grades from fine to very coarse sand with some fine gravel; principally quartz with some light green-yellow feldspar; contains limonite and bone fragments	199	209.5
Clay, very calcareous, grayish white with yellow tint; mottled brownish yellow below 210 ft	209.5	217
[Pierre Shale] Clay shale, very calcareous, medium-gray	217	220

II. Subsurface Cenozoic Geology of South-Central Nebraska

Introduction

The Conservation and Survey Division (CSD), University of Nebraska at Lincoln, and U.S. Geological Survey (USGS) began a program of systematically drilling test wells for groundwater studies in Nebraska in 1930. The well cuttings that were recovered were described by CSD geologists, and descriptions of the sedimentary sequence in each hole were published in a series of reports. Examination of the test-hole reports in a block of counties in south-central Nebraska was used in the current study to gain an understanding of the lithology, thickness, and distribution of Pliocene, Pleistocene, and Holocene sediments in the region. Examples of the test hole descriptions are shown in section I. Similar previous studies were published by Lugn (1935) and Lugn and Wenzel (1938).

Methods

The test hole records were examined from CSD publications and unpublished material on file at the CSD offices in Lincoln, Nebraska. Data from 380 wells were used for this study (fig. 2). The quality of the recorded descriptions

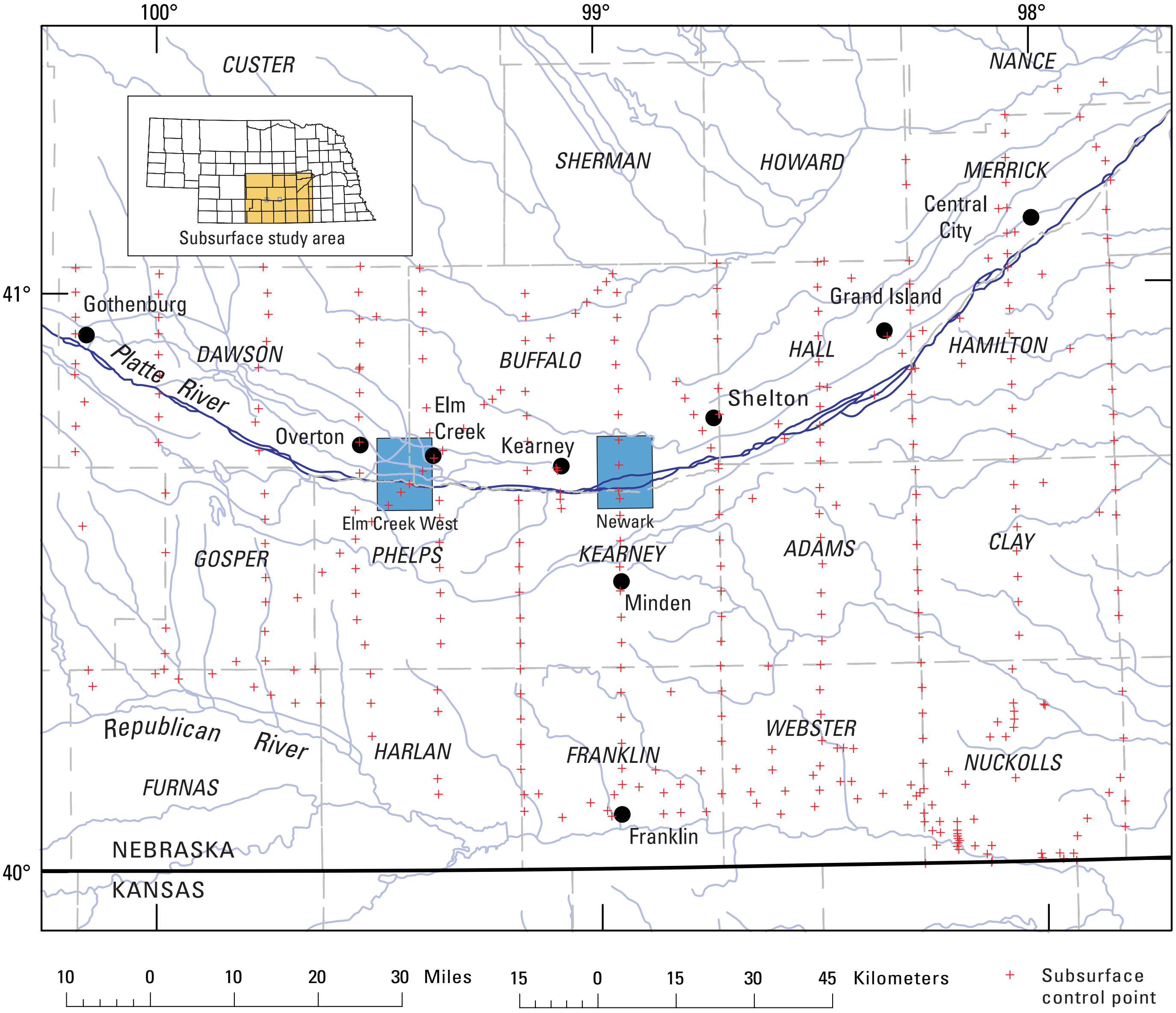

Figure 2. Location map of the subsurface study area in south-central Nebraska. The course of the Platte River is shown in dark blue. The locations of the Elm Creek West (left) and Newark (right) quadrangles are in blue. Source of the test wells is the Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

ranges widely—early records are very general and lump many lithologies together, but later descriptions are more complete, and some of the reports identify the top of the Ogallala Group or the top of Cretaceous rocks in the well cuttings. In the descriptions examined, there are only a few identifications of named Pliocene or Pleistocene formations within the sedimentary sequence above bedrock.

Subsurface geology

The subsurface study area extends from about Gothenburg, on the west, to about Central City on the east, and south to the Republican River (fig. 2). On this map the test hole locations, county lines, towns, and drainage system are shown. The course of the Platte River is shown in dark blue, and is also shown on the other maps in this section as a reference. The counties from which test-hole data were studied include Custer (Anonymous, 1953c), Dawson (Anonymous, 1953c), Buffalo (Anonymous, 1953b; Anonymous, unpub., 1954), Howard (Smith, 1965), Hall (Smith, 1965), Nance (Anonymous, 1953g), Merrick (Anonymous, 1953g), Hamilton (Keech, 1960), Clay (Burchett and Smith, 1994), Adams (Anonymous, 1953a), Kearney (Anonymous, 1953f), Phelps (Anonymous, 1953h), Gosper (Anonymous, 1953d), Furnas (Waite and others, undated), Harlan (Anonymous, 1953e; Waite and others, undated), Franklin (Burchett and Summerside, 1997a; Waite and others, undated), Webster (Burchett and Summerside, 1997b; Waite and others, undated), and Nuckolls (Burchett and Smith, 1989; Waite and others, undated).

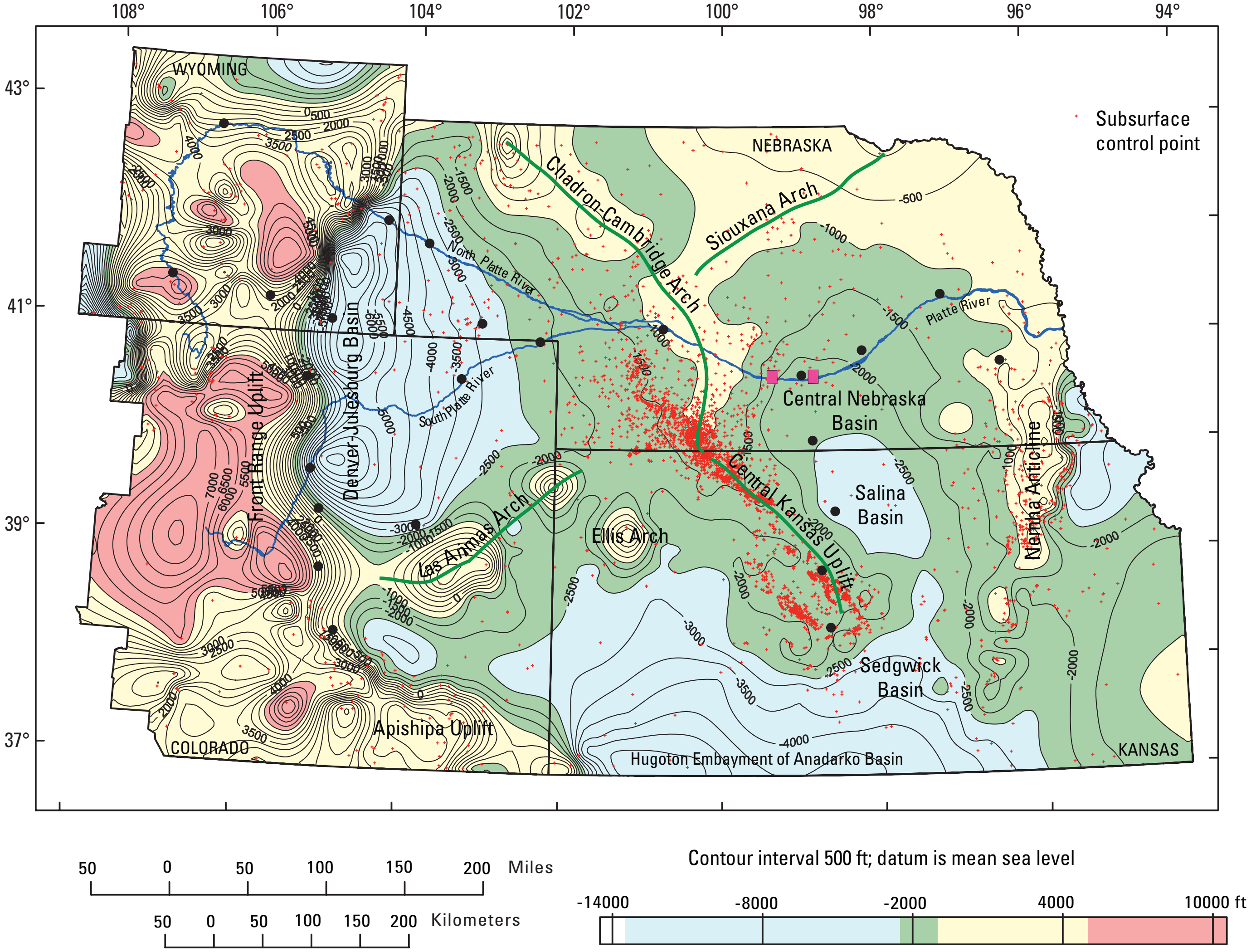

Figure 3. Structure contour map drawn on top of Precambrian rocks. Heavy green lines indicate crest lines of structural highs in the Great Plains part of the study area. The locations of the Elm Creek West and Newark quadrangles are in magenta. Cities are indicated by black dots and are the same as those shown on figure 1. The configuration of mountainous areas is highly generalized because of a lack of oil and gas exploration wells in outcropping Precambrian rocks. Well data from IHS Energy (2003).

Era	Period	Epoch	Glacial stage	Stratigraphic unit			
				Western and South-central Nebraska	Northeastern Colorado	Southeastern Wyoming	Age (Ma)
Cenozoic	Quaternary	Holocene		Sand Hills dune sands Bignell Loess	post-Piney Creek alluvium Piney Creek Alluvium pre-Piney Creek alluvium dune sand and loess	Present flood plain alluvium	.01
		Pleistocene	Wisconsin	Brady soil Peoria Loess Gilman Canyon Formation	Broadway Alluvium Peoria Loess Louviers Alluvium	Stock Farm terrace alluvium Pahlow strath alluvium	.115
			pre-Wisconsin	Loveland Formation Beaver Creek Loess Grafton Loess Walnut Creek Formation	Slocum Alluvium Verdos Alluvium Rocky Flats Alluvium	Harmony bench alluvium Airport bench alluvium Eagle Rocks bench alluvium Table Mountain alluvium	1.65-2.3
	Tertiary	Pliocene		Broadwater Formation Fullerton Formation	Nussbaum Alluvium	Broadwater(?) equivalent	5.3
		Miocene		Ogallala Group Arikaree Group Upper Harrison beds Harrison Formation	Ogallala Formation Arikaree Formation (part)	Ogallala Formation Arikaree Formation (part)	23.8
		Oligocene		Monroe Creek Formation Gering Formation White River Group Brule Formation	Arikaree Formation (part)	Arikaree Formation (part) White River Formation (part)	33.7
		Eocene		Chadron Formation	Chadron Formation and Castle Rock Conglomerate Wall Mountain Tuff Dawson Formation (part)	White River Formation (part) Wasatch and Wind River Formations	~55.0
		Paleocene			Dawson Formation (part) Green Mountain Conglomerate Denver Formation (part)	Hanna and Fort Union Formations	65.5
Mesozoic	Cretaceous			Pierre Shale Niobrara Formation Carlile Shale	Denver Formation (part) Arapahoe Formation Laramie Formation Fox Hills Sandstone Pierre Shale	Medicine Bow Formation Fox Hills Sandstone Lewis Shale	

Figure 4. Chart showing late Mesozoic and Cenozoic stratigraphic units in south-central Nebraska, northeastern Colorado, and southeastern Wyoming. Compiled from Swinehart and Diffendal (1989), Swinehart and others (1985, 1994), May and others (1995), Robinson (1972), Scott (1960, 1963, 1978), Knight (1953), Mears (1991), Montagne (1991), and Flanagan and Montagne (1993). Time scale is from Berggren and others (1995), Haq and Van Eysinga (1987), and Dawson (1992).

As noted by Lugn in 1935, the unconsolidated Pliocene, Pleistocene, and Holocene sediments that overlie bedrock are not confined to the current Platte Valley. Instead, the whole of south-central Nebraska and areas north and south is underlain by a variable sequence of sand and gravel, silt, and clay. This is because the present course of the Platte River is a relatively recent phenomenon, and Pliocene and Pleistocene versions of the Platte followed different courses than the present river. As the river migrated across Nebraska, it left deposits of gravel, sand, silt, and clay behind.

A structure contour map was constructed to show the regional structural setting of the Platte River system (fig. 3). This map was drawn on the top of Precambrian basement rocks deep in the subsurface of the plains and with a few control points in mountain areas. The map shows that the elevation of this horizon gradually rises eastward out of the Denver-Julesburg Basin in eastern Colorado and western Nebraska to a broad ridge extending northwest-southeast through Nebraska that has been named the Chadron-Cambridge Arch. This ridge branches southwestward into the Las Animas Arch, and extends southeastward as the Central Kansas Uplift. The arch borders the west side of the study area; however, there is a slight structural high that extends eastward along the south county line of Dawson and Buffalo

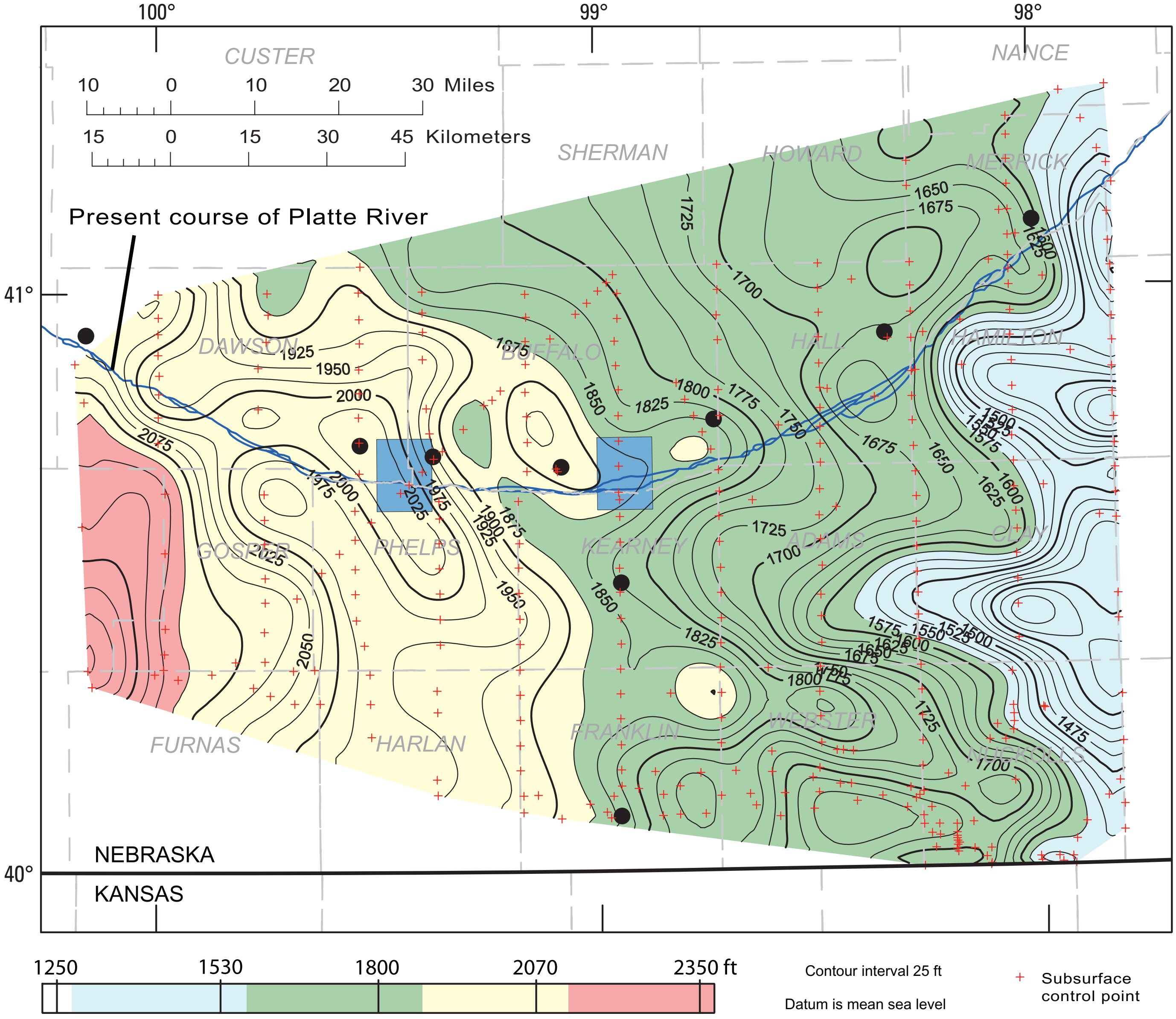

Figure 5. Map showing the configuration of the erosional unconformity on top of Cretaceous rocks in south-central Nebraska. Town and quadrangle locations are as shown in figure 2.

counties. The main part of the subsurface study area is on the northwestern flank of the Central Nebraska Basin.

The nomenclature of Tertiary units in Colorado, Wyoming, and Nebraska is complex, and there are significant differences between regions. The nomenclature of Cretaceous through Holocene units is shown on figure 4. Cretaceous rocks are present beneath nearly all of Nebraska, including the study area (Carlson, 1993). On a state-wide scale these rocks dip to the west (interrupted by the Chadron-Cambridge Arch) and are truncated by an unconformity, resulting in progressively older Cretaceous rocks being present eastward in the study area (Burchett and Pabian, 1991; Carlson, 1993, p. 60). Most of the eastern part of the study area is underlain by either the Pierre Shale or formations of the Colorado Group (Niobrara Formation or Carlile Shale). A long period of erosion in central Nebraska followed the Cretaceous Period. The end of the Cretaceous is considered to be about 65.5 million years ago (Ma) (Berggren and others, 1995), but deposition of the Miocene Ogallala Group is not thought to have begun in this area until about 14 Ma (J.B. Swinehart, written commun., 2001). The Eocene to Miocene-age White River and Arikaree Groups (fig. 4) are only present west or north of the subsurface study area. Another period of erosion occurred after deposition and lithification of the Ogallala between about 5.4 and 3.5 Ma (May and others, 1995). Renewed deposition of Pliocene, Pleistocene, and Holocene sediments began after about 3.5 Ma and continues to the present (fig. 4).

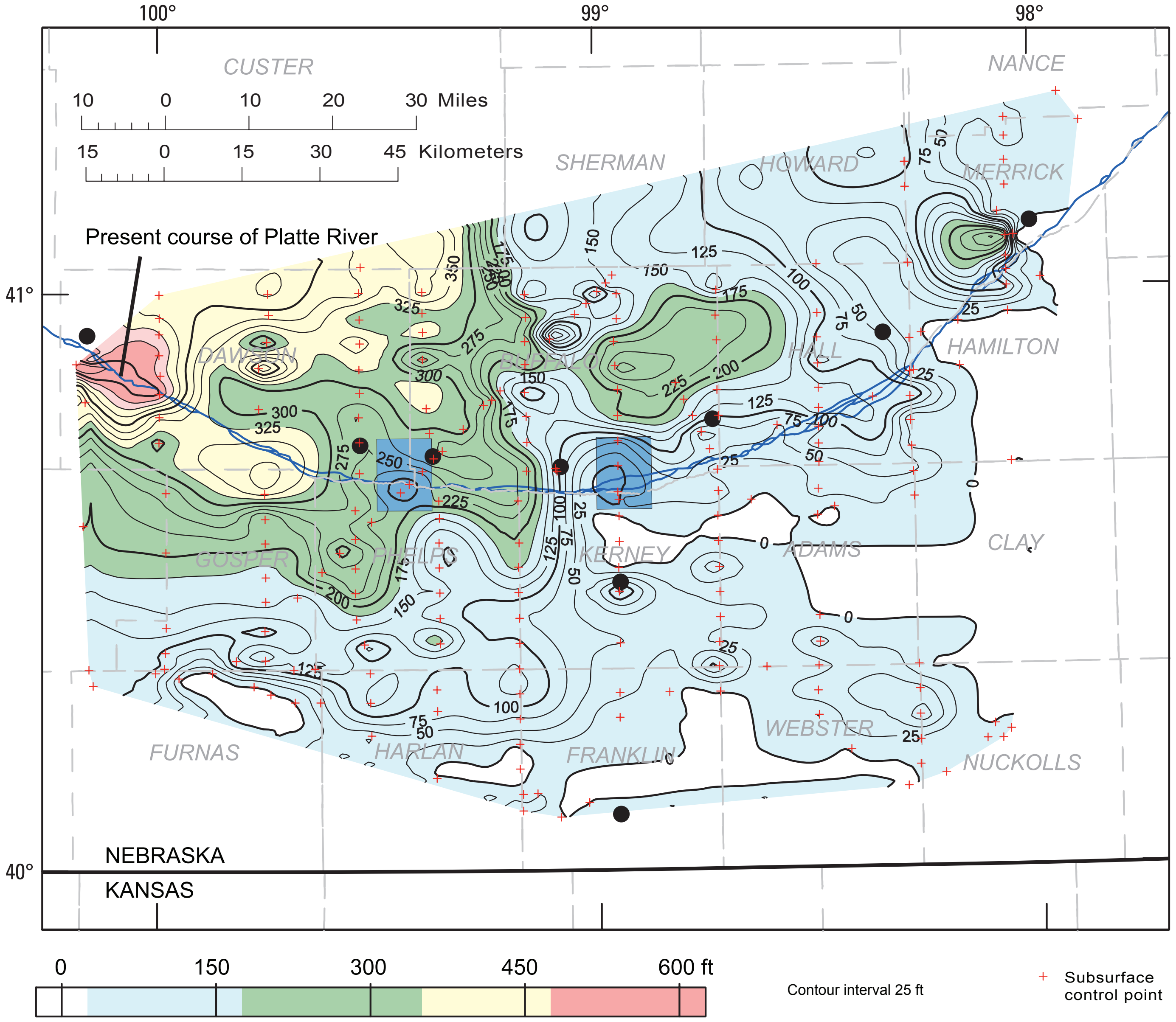

Figure 6. Map showing thickness of the Ogallala Group. Town and quadrangle locations are as shown in figure 2.

A contour map drawn on top of Cretaceous rocks in south-central Nebraska shows the configuration of this surface (fig. 5). The map shows a pattern of ridges and valleys that were incised into the top of Cretaceous rocks both prior to and after deposition of the Tertiary Ogallala Group. The Ogallala was deposited over most of the map area and then later partially eroded, so the top of the Cretaceous, portrayed on figure 5, mostly represents the erosion surface that developed in the approximately 50 million years between the end of the Cretaceous and the beginning of deposition of the Ogallala. However, the far eastern side of the map was additionally modified in the erosion cycle that removed some of the Ogallala. The most prominent features of the map are the series of valleys and ridges on the eastern side of the map where the surface was deeply eroded. The relatively low area in northeastern Gosper and western Phelps counties is also noteworthy because it acted as a site of deposition and preservation of the overlying Ogallala Group. A similar map of this surface in the Sand Hills area was presented by Swinehart and Diffendal (1989).

The Ogallala Group, of Miocene age, about 14 - 5.4 Ma (Swinehart and Diffendal, 1989; J.B. Swinehart, written commun., 2001), unconformably overlies Cretaceous rocks in most of the study area. Rocks of Paleocene, Eocene, Oligocene, and early Miocene age are not present in the study area, so the unconformity at the base of the Ogallala represents

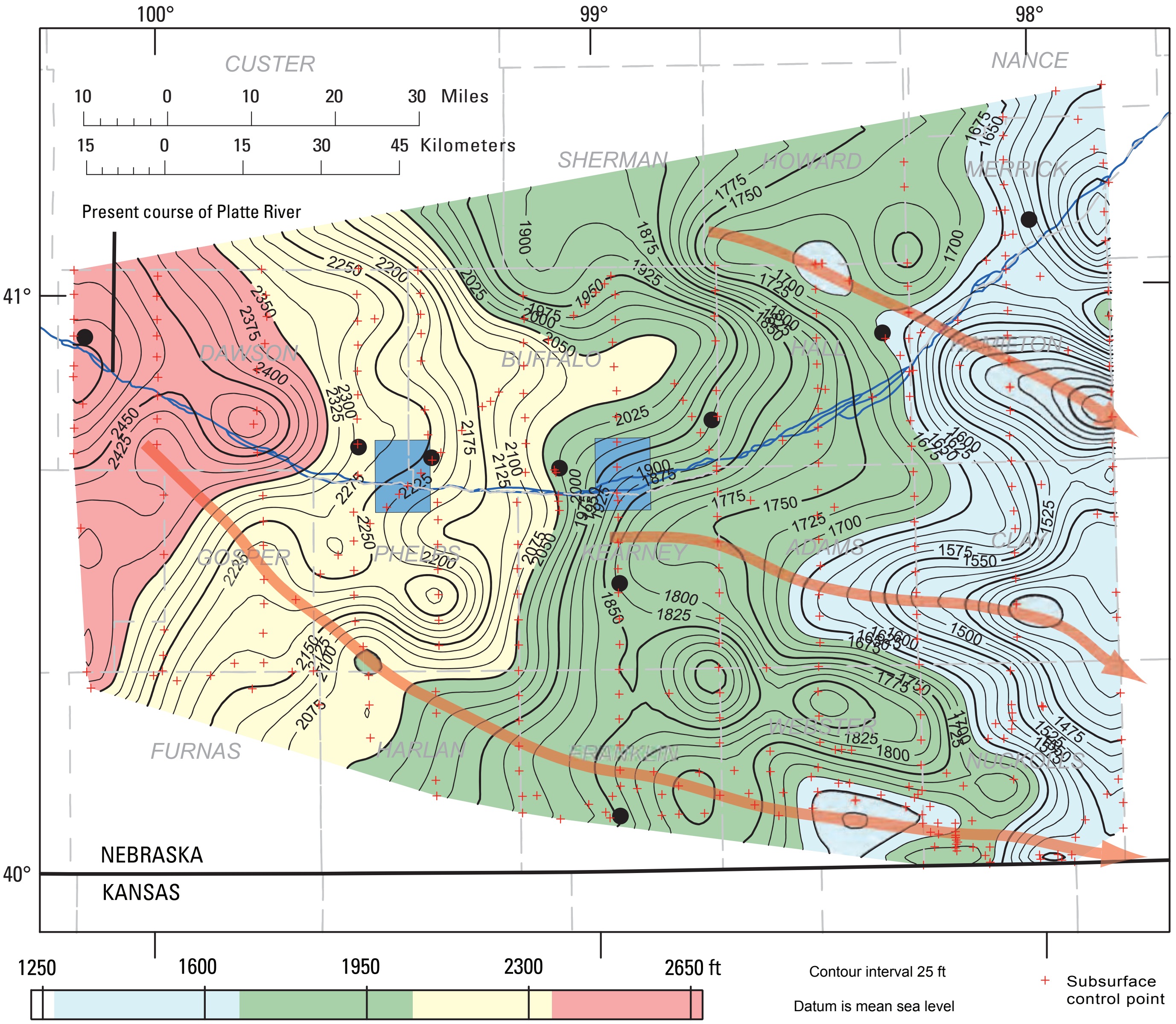

Figure 7. Map showing the configuration of the erosional unconformity on top of either the Ogallala Group or Cretaceous rocks in south-central Nebraska. Axes of paleovalleys are shown by red lines. Town and quadrangle locations are as shown in figure 2.

a gap of about 50 million years of time. The Ogallala was in turn truncated by an erosional surface, and was entirely removed in the eastern part of the study area. Figure 6 shows that the Ogallala reaches a thickness of over 400 ft in one well, and is over 300 ft thick in much of the northwestern part of the area. It is erosionally truncated along an irregular line trending northeast across the eastern part of the study area. In several places on the western side of the study area, the Ogallala is thick or thin over corresponding low or high areas, respectively, on the post-Cretaceous unconformity (fig. 5). This trend may show some topographical control of deposition and preservation of the Ogallala, a process that was repeated later in the Pliocene and Pleistocene.

Another interpretation of Ogallala distribution was presented by Condra and others (1947) and Condra and Reed (1950). They introduced the name 'Seward Formation' which was believed to be a fine-grained distal facies of the Ogallala that extended into eastern Nebraska. Subsequent studies found that the Seward strata were younger than the Ogallala (Reed and Dreeszen, 1965), and the eroded edge shown in the current study (fig. 6) was accepted as the eastern extent of the Ogallala.

The unconformity surface that overlies the Ogallala illustrates the drainage pattern that developed in post-Ogallala time prior to deposition of Pliocene sediments in the area. Figure 7 is a map that is drawn on the top of the Ogallala Group, or

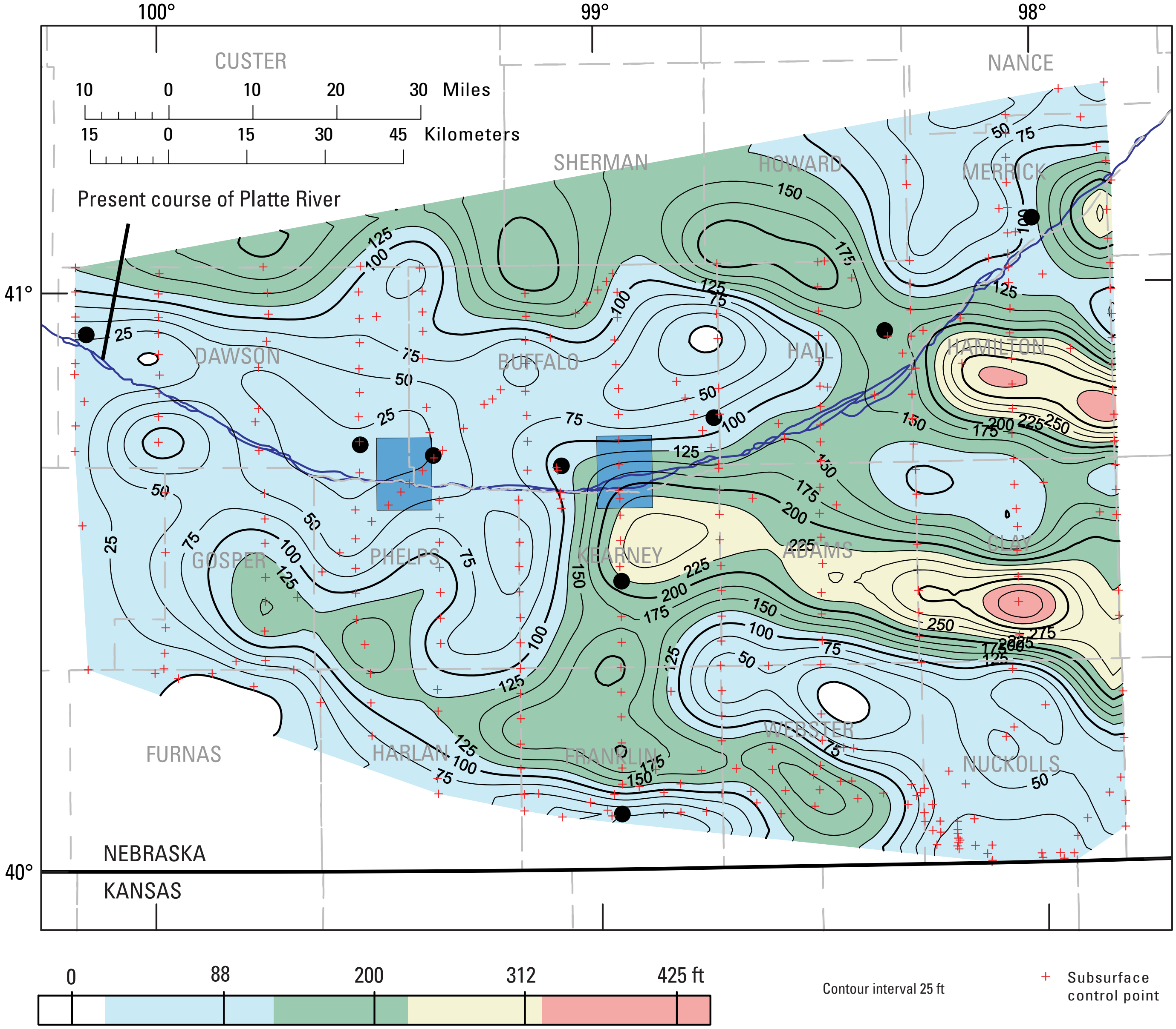

Figure 8. Map showing the thickness of predominantly fluvial Pliocene and Pleistocene sediments in south-central Nebraska. Town and quadrangle locations are as shown in figure 2.

on top of Cretaceous rocks where the Ogallala is not present, that represents the top of the bedrock surface below Pliocene and younger sediments. The map shows a series of valleys and intervening drainage divides that extend east-southeastward from a high area on the west side of the study area. Three of the valleys or "basins" were discovered early in the process of drilling test holes and were named by Lugn (1934). The valley in central Hamilton county was named the Aurora Basin, the valley in central Adams and Clay counties was named the Hastings Basin, and the valley in southeastern Gosper and southwestern Phelps counties was called the Holdrege Basin. After those areas were named, additional drilling has defined other areas of low elevation on the erosion surface, notably an area in east-central Franklin and southern Webster counties, and extension of the Hastings Basin northwestward, to southeast of Kearney. A small-scale map of this surface over most of the southern and eastern parts of Nebraska was presented by Reed and Dreeszen (1965) and Reed and others (1965).

The study area again became the site of deposition in the early Pliocene, and deposition continued into the Pleistocene and Holocene. A sequence of gravels, sands, and interbedded silt and clay beds, largely of fluvial origin, was named the "Platte Series" by Lugn (1935). This series consisted of the Holdrege Formation (sand and gravel), Fullerton Formation (silt), Grand Island Formation (sand and gravel), and Upland Formation (silt). The nomenclature of this series was modi-

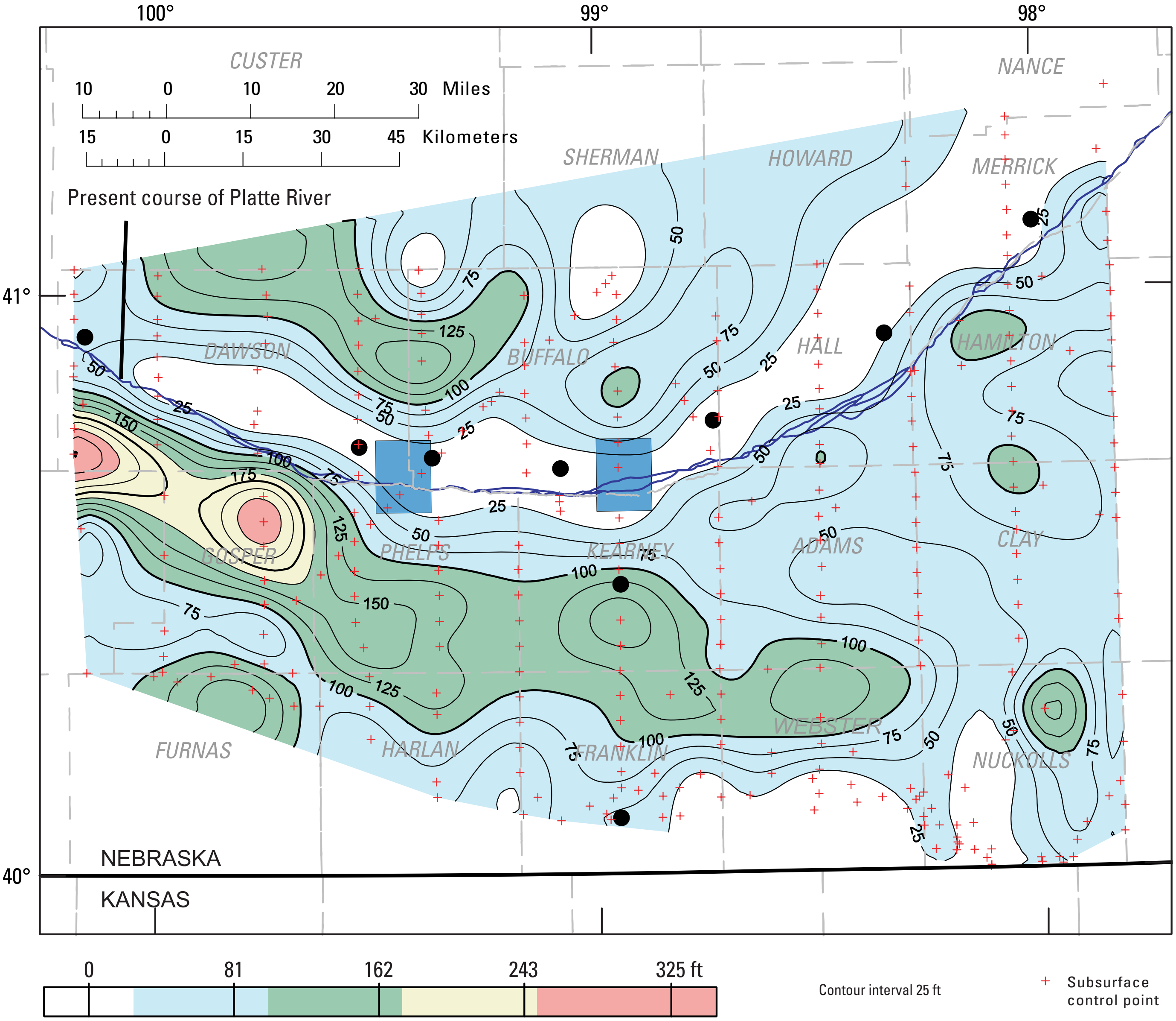

Figure 9. Map showing the thickness of loess in Pleistocene and Holocene strata in south-central Nebraska. Town and quadrangle locations are as shown in figure 2.

fied by Reed and Dreeszen (1965), and later most of the names fell into disuse as researchers became aware of uncertainties in correlation of the units. Above the alluvial part of the section is a largely loess sequence that was originally named the "Plains Series" by Lugn (1935). This sequence consists of Pleistocene and Holocene units that have been named the Grafton Loess, Beaver Creek Loess, Loveland Formation, Gilman Canyon Formation, Peoria Loess, and Bignell Loess, from oldest to youngest (Reed and Dreeszen, 1965; Reed and others, 1965; Swinehart and others, 1994).

For this study I have divided Pliocene and younger sediments into two parts, a lower, largely fluvial part and an upper, largely eolian part. The lower part consists of irregularly distributed sand and gravel beds and associated silt or clay beds that previously have been included in the Holdrege, Fullerton, and Grand Island units. The base of the interval is picked at the top of the underlying Ogallala Group or Cretaceous rocks. The lithology of Cretaceous rocks is distinctive dark shale or even more distinctive yellow or white limestone or chalk, and it is not difficult to distinguish these rocks from the overlying Pliocene and younger unconsolidated sediments. The division between the Ogallala Group and younger sediments is more problematic because of lithologic similarities between those units.

The lithology of the top of the Ogallala changes from place to place, due to the unconformity at the top exposing successively older beds eastward. One of the main features that was used to distinguish the Ogallala was the presence

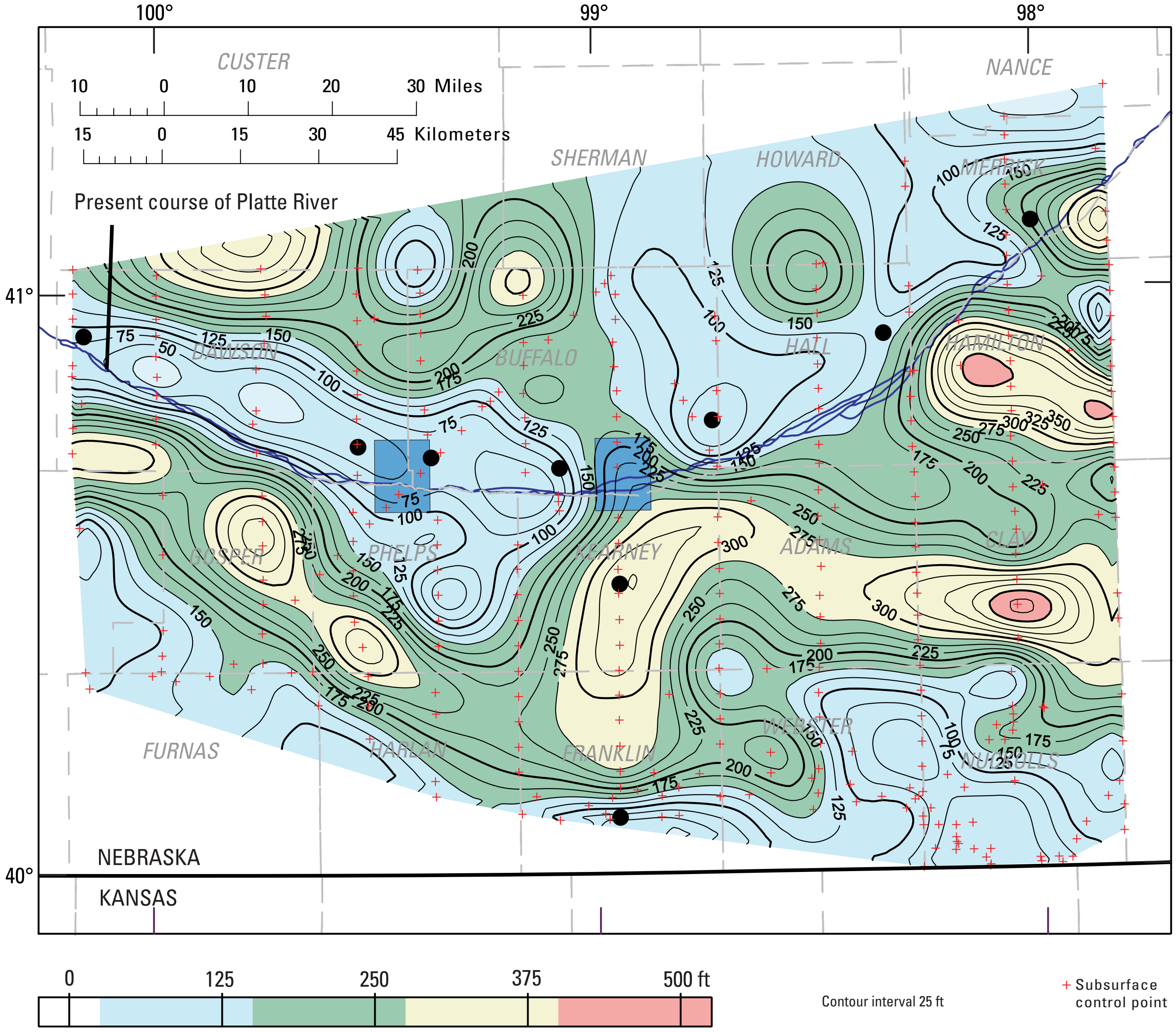

Figure 10. Map showing the thickness of all Pliocene, Pleistocene, and Holocene alluvium in south-central Nebraska. Town and quadrangle locations are as shown in figure 2.

of lithified sandstone, conglomerate, or siltstone versus the unconsolidated sediments of Pliocene and younger strata, although the well logs also describe the Ogallala as unconsolidated sand and gravel in places. The color of Ogallala strata is a common distinguishing feature as well. The Ogallala is typically a darker brown, greenish, or reddish color that contrasts with the lighter tan colors of younger strata. Other distinguishing features of the Ogallala include extensive zones having carbonate cement, rare limestone or marl beds, and siliceous rootlets in the upper part of the unit. In many areas the sands and gravels overlying the Ogallala contain pink grains of feldspar that do not occur in underlying rocks. Any one of the above-mentioned features may not be sufficient to separate the Ogallala from overlying beds. However, when examining many well records in a limited area a combination of features can be used to distinguish the units in most cases.

The alluvial sequence above the Ogallala consists of a mixture of gravel, sand, silt, and clay. Colors are various shades of brown, tan, greenish-gray, white, and yellow. White ash beds were described in logs of some wells, although they were not recorded in enough wells to be used as marker beds. Logs of some wells noted the presence of abundant bone fragments. Figure 8 shows the thickness of the predominantly alluvial Pliocene and Pleistocene sediments in the study area. Of particular note is the relative thickness of this interval in the valleys or basins that previously had been incised into underlying bedrock in central Hamilton County, southeastward from central Kearney County, in central to southern Franklin and Webster counties, and in southeastern Gosper and southern Phelps counties. Relatively thin areas are in northern Buffalo County, southern Gosper County, and northern Webster and southwestern Nuckolls counties. These areas correspond well with low and high areas on the map of the top of bedrock (fig. 7).

Loess was distinguished from the underlying alluvial sequence by the presence of thick silt intervals, associated soils, snail shells, and rootlets. Some sand intervals are also included in this sequence, whose lithology of well-sorted, rounded, very fine to medium grained quartz clasts indicates a probable eolian origin. Rare marl beds, less than 2 ft thick, were noted in Buffalo County. Colors of this sequence are mostly shades of tan or gray; soil intervals are dark-gray to black, and the Loveland Formation is noted for its reddish color. An isopach map of this sequence is shown as figure 9. This map shows a generally thin area along the present course of the Platte River where much of the unit was removed as it was deposited, and a thick area that trends southeastward across the southern part of the map from Gosper to Nuckolls counties. The thickest area is on the western map border.

An isopach map that shows the entire sequence of Pliocene- to Holocene-age sand, gravel, silt, and clay that is present above the Ogallala or Cretaceous rocks is shown as figure 10. A similar map that included much of the study area was by Dreeszen and others (1973), and another detailed map of the same stratigraphic interval, just north of the study area, is by Souders (2000). Noteworthy features of this map (fig. 10) include a thin area extending southeastward from the western map boundary to about the position of Kearney. This area has thin deposits due to both limited deposition of fluvial strata over an underlying topographic high, shown on fig. 5, and to erosion or non-preservation of the Peoria Loess in the Platte River Valley. A relatively thick area extends southeastward, parallel to the Platte River from southern Dawson and northern Frontier counties to central Franklin County, then abruptly trends north-northeastward into Kearney County and again trends abruptly southeastward in western Adams County.

A combination of the paleo-topographic map (fig. 7) and the isopach map of alluvial sediments (fig. 8) suggests two or three possible courses of a paleo-Platte River through the study area. These paleo-stream courses correspond well with postulated drainages in the early to late Pleistocene sketched by Swinehart and others (1994): (1) A northern stream course extends southeastward from southeastern Sherman County through south-central Hamilton County; (2) an intermediate stream course extends southeastward from northern Dawson County through southern Clay County; and (3) a southern stream course trends from southwestern Dawson County, through central Franklin County, and to southeastern Webster County. The southeastward-trending thick, sandy area in central Hamilton County may represent a drainage outlet for the Loup River system, which may have also flowed southeastward until stream capture diverted it. The chronology suggested by Swinehart and others (1994) was that the paleo-Platte River shifted northward during the Pleistocene, but it was not until the Wisconsin glacial stage that stream capture diverted the Loup River system and the Platte River into their present courses (Bentall, 1982).

III—The development of the Cenozoic Platte River drainage system

Introduction

This section traces the structural and depositional history of the east-central Rocky Mountains and adjacent plains from Late Cretaceous time—about 65.5 million years ago—to the present (fig. 4). The purpose of this summary is to examine the geological processes that affected the development of the Platte River drainage system through this time period.

The Platte River in Nebraska is formed by the combination of the North and South Platte Rivers, whose headwaters are in the mountains of Colorado (fig. 1). The North Platte has a drainage area of approximately 35,000 mi^2, and the South Platte drains approximately 24,000 mi^2 (Sidle and Faanes, 1997). The North Platte flows northward from the North Park area of northern Colorado, skirts the west side of the Medicine Bow Mountains in southern Wyoming, and follows a semicircular course around the north end of the Laramie Range. It then flows southeastward in a nearly straight valley to North Platte, Nebraska, where it joins the South Platte. Major tributaries of the North Platte in Wyoming are the Sweetwater, Medicine Bow, and Laramie Rivers. Many dams have been built on the North Platte—from the headwaters downstream they form the Seminoe, Pathfinder, Alcova, Glendo, and McConaughy reservoirs.

The South Platte rises in the mountains west of South Park in Colorado, turns and flows northeast through Denver, and then flows east-northeast through northeastern Colorado to the junction with the North Platte in Nebraska. Several perennial streams flow out of the Front Range and join the South Platte, the main ones being Bear Creek, Clear Creek, Boulder Creek, St. Vrain Creek, the Big Thompson River, and the Cache la Poudre River. Relatively smaller dams on the South Platte have created the Spinney, Eleven Mile Canyon, Cheeseman, Strontia Springs, Chatfield, and Prewitt reservoirs. Flow in the South Platte is augmented by several diversion tunnels that carry water from west of the Continental Divide to the east side of the mountains.

Between North Platte and Columbus, Nebraska, the Platte River has few tributaries—the major one being the Wood River on the north side of the Platte. South of the Platte, in this reach, most drainage is internal or flows south to the Republican River or southeast into the Blue River system. North of the Platte, several streams in central Nebraska combine to form the Loup River, which joins the Platte at Columbus. The smaller Elkhorn and Salt Creek drainages join the Platte farther downstream, just above its confluence with the Missouri River. There are no dams on the Platte in Nebraska from the confluence of the North and South Platte Rivers downstream to the Missouri River.

The role of the Platte River Valley as a main transcontinental transportation route resulted in early descriptions of the river and descriptions of the geology of surrounding areas. The earliest accounts were by military exploration surveys by Lt. Zebulon Pike, Major Stephen Long, Captain John Fremont, and others in the first half of the 19th century (Muhs and Holliday, 1995). Many people passed through the Platte River Valley in the middle 19th century with the establishment of the Oregon and Mormon Trails and later with the building of the Union Pacific Railroad along the Platte River across Nebraska. Systematic geologic studies of Nebraska Territory were first undertaken by F.V. Hayden and F.B. Meek in the mid-1850s and continued through the 1870s, when Hayden's survey was combined with those of King, Powell, and Wheeler into the U.S. Geological Survey. Hayden and Meek's studies were the first to describe the geology and paleontology of the region in detail.

The latter half of the 19th century saw the development of the geological staff at the University of Nebraska, the Nebraska State Museum, and, eventually, the Nebraska Geological Survey, now operating as the Conservation and Survey Division of the Institute of Agriculture and Natural Resources, the University of Nebraska at Lincoln. At first, the emphasis was on studies of the natural resources of the State in support of economic development, but the appointment of the vertebrate paleontologist E.H. Barbour in 1891 heralded the broadening of studies to include the richly fossiliferous Cenozoic strata of the State. The beginning of the 20th century saw a diverse range of geological studies conducted by State and Federal researchers in Nebraska, Kansas, Colorado, and Wyoming on topics such as mineral and energy resources, water resources, and paleontology. Popular books that describe some aspects of the geologic history of the Platte River Basin include Webb (1931), Mattes (1969), and McPhee (1998).

Structural setting

Precursor events

As the Atlantic Ocean opened in Jurassic time, about 150 million years ago, the western margin of the North American Craton was displaced westward and collided with several oceanic plates in the Pacific. This collision led to an actively subducting plate margin and the development of a series of shallow crustal thrust sheets that were transported eastward (Lawton, 1985). This tectonic event was termed the "Sevier Orogeny", and lasted from approximately 119 Ma to 50 Ma. The thrust sheets were stacked into mountainous terrain, but the area east of the mountains subsided and is known as the Rocky Mountain Foreland Basin (Gries and others, 1992; Bird, 1998; Willis, 1999).

In Early Cretaceous time the Rocky Mountain Foreland Basin deepened, and, because of a worldwide rise in sea level, a shallow ocean that connected boreal and tropical seas across the interior of the North American continent was formed. At its maximum, this Western Interior epicontinental sea extended north-south from the pole to the Caribbean, including an arm that extended northeast through Canada to Greenland, and east-west from the mountain front to eastern Minnesota and Iowa, central Missouri, and western Arkansas (Gries and others, 1992; Roberts and Kirschbaum, 1995). In cross section, the seaway was asymmetric, deeper on the west and shallower on the east (McGookey and others, 1972). Clastic sediments were shed from the western mountains into the sea, while fine-grained muds and chalks were deposited in the shallower central and eastern parts of the sea.

These conditions persisted throughout much of Cretaceous time, varying in the degree of uplift or erosion of the mountains and by low-stand or high-stand extremes of sea level. At irregular intervals, the amount of debris shed from the mountains exceeded the space available in the basin, and shoreline and continental deposits prograded eastward across parts of the sea. At times of lower erosion rates in the mountains or accelerated subsidence rates in the foreland basin, the seas transgressed far to the west and marine shale and calcareous mud were deposited across the depositional basin.

Laramide orogeny

Renewed opening of the North Atlantic Ocean began at about 75 Ma and initiated another episode of subduction and deformation on the western margin of the North American Craton (Gries and others, 1992). This event, termed the “Laramide Orogeny”, overlapped in time with the Sevier Orogeny, but was of a greater magnitude, had a different compressional direction, and involved deep basement rocks in contrast to shallow Sevier thrusting (Tweto, 1975; Gries and others, 1992; Bird, 1998). The dominant displacement of basement rocks and overlying cover rocks was vertical, producing fault-bounded uplifted areas without a great deal of horizontal dislocation of strata. This deformational style lasted from Late Cretaceous time (about 75 Ma) until about 35 Ma in the Tertiary Eocene Epoch.

Laramide tectonics caused buckling of the earth’s crust into a series of mountain ranges and intervening basins and had effects far east of the Rocky Mountains. Much of the structure east of the present-day mountain front is a result of Laramide deformation or of Laramide enhancement of older structures (Moore and Nelson, 1974). Figure 3 is a structure contour map drawn on the top of Precambrian rocks. Major basins shown on the map include the Denver-Julesburg Basin, just east of the mountain front; the Central Nebraska and Salina Basins, in south-central Nebraska and northern Kansas; and the combined Hugoton Embayment of the Anadarko Basin and Sedgwick Basin of southwestern and south-central Kansas. Intervening uplifted areas are the Chadron-Cambridge Arch through western Nebraska and its extension into Kansas as the Central Kansas Uplift. Branching westward into Colorado from the Chadron-Cambridge Arch is the Las Animas Arch, and branching northeastward from Nebraska to South Dakota and Minnesota is the Siouxana Arch (fig. 3).

At the end of the Cretaceous Period at 65.5 Ma, the Rocky Mountains had been uplifted by Laramide tectonics into a series of isolated mountain ranges separated by

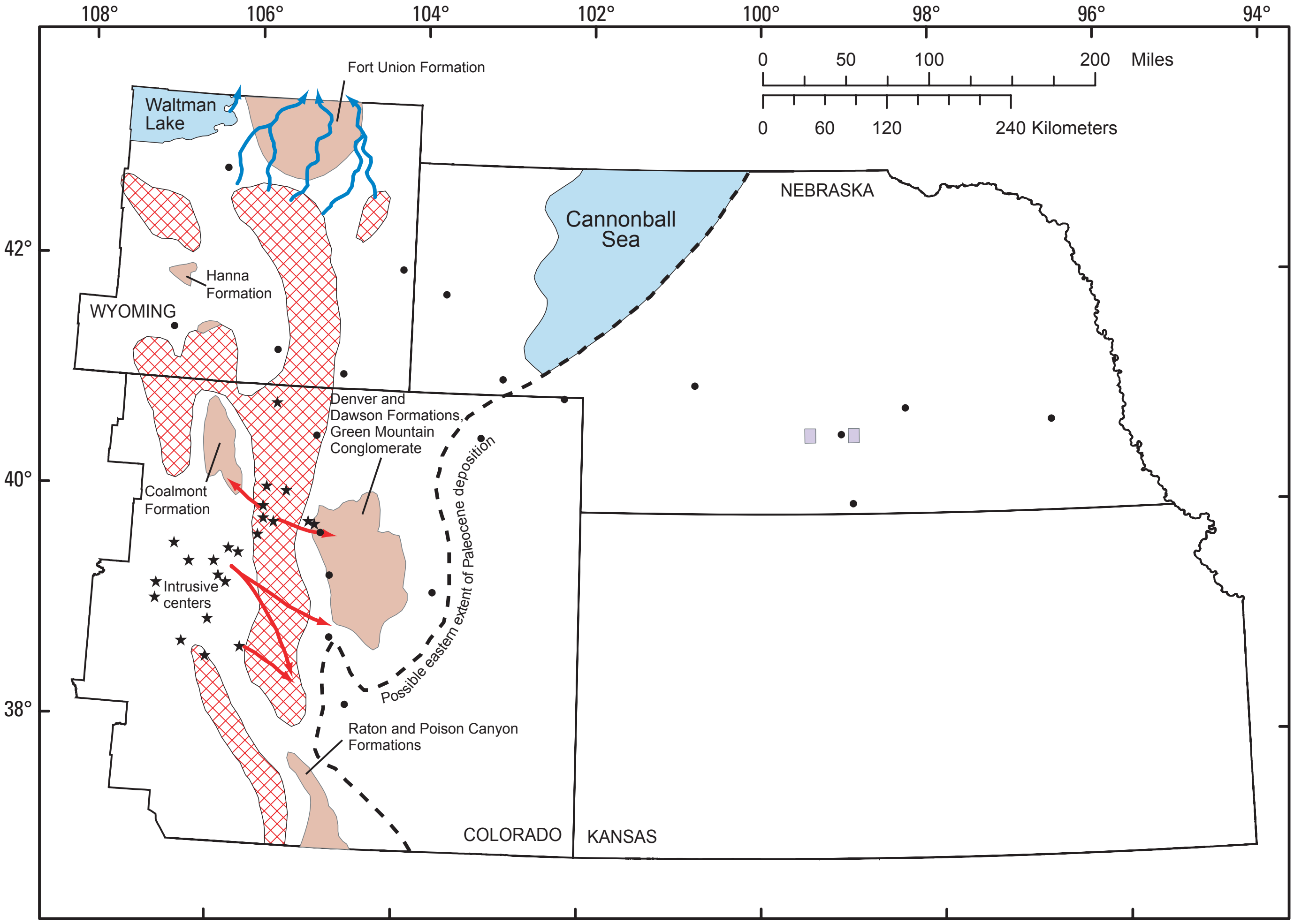

Figure 11. Paleogeography in Paleocene time. Uplifts in red cross-hatched pattern and basins in brown modified from Robinson (1972), Waltman Lake and Cannonball sea modified from Blackstone (1975), streams in Wyoming modified from Seeland (1988), and streams and intrusive centers in Colorado modified from Scott (1975). Cities and mapped quadrangles are as shown on figure 1.

basins. Kluth and Nelson (1988) suggested that uplift of much of the Front Range of Colorado occurred in a relatively short time. The climate was warm and temperate (Parrish, 1998), and erosion of the mountains was progressing vigorously. Debris from the mountains was deposited in the adjacent basins, some of which were subsiding fast enough to capture all the sediment that they received. The rock record of the east-central Rocky Mountains and adjacent plains, from the beginning of the Tertiary to the present, records the interplay between erosion and deposition, between sediment capture in basins adjacent to the mountains or widespread dispersal of the sediments far to the east by streams, and the addition of significant amounts of volcanic ash from sources west of the mountains. Subtle variations in uplift, climate, and subsidence had large effects on the preserved rock record.

Geologic history of the Tertiary and Quaternary

The following subsections summarize the geologic history of the Tertiary and Quaternary Periods in the east-central Rocky Mountains and adjacent plains in Colorado, Wyoming, Nebraska, and Kansas. Each part summarizes (1) the occurrence and distribution of formations recognized in the study area, (2) the lithology and depositional environments of the units, (3) the paleogeography of the region, (4) major fossil fauna and flora, and (5) inferences about the climate that existed at the time.

When reviewing the published material for this section, two problems became evident. First, the boundaries between epochs, in numerical age, have been modified by various researchers, and this is an ongoing process. For example, the boundaries between the Miocene and Pliocene, and between the Pliocene and Pleistocene have been redefined. Second, improved dating techniques have shifted the assignment of some formations from one epoch to another—for example, the Chadron Formation was previously considered to be Oligocene, but is now considered Eocene, based on placement of the Eocene-Oligocene boundary with respect to dated parts of the Chadron. The result of these changes is that previously published geologic histories of the region do not conform to the modern accepted grouping of formations into certain epochs. An important purpose of this section, then, is to note these changes in a somewhat revised chronology of the Tertiary and Quaternary, using the currently accepted time divisions and age assignments of formations.

The ages of formations for this report were checked against the geologic names lexicon in the USGS National Geologic Map Database. This is the official USGS repository for information on the correct accepted usage and age designation (by the USGS) for lithologic and geochronologic unit names. The web site for this database is http://ngmdb.usgs.gov/Geolex/geolex_home.html. The database is a work in progress, however, so some given unit ages lag behind current research results. Disagreement between epoch boundaries exists among current workers too, so the boundaries used in this report may vary from those used in other reports. The time scale used for this report is that of Berggren and others (1995), supplemented by Haq and Van Eysinga (1987) and Dawson (1992).

Paleocene

The Paleocene is the oldest epoch of the Tertiary Period (fig. 4), and in the Denver-Julesburg Basin Paleocene units are the upper part of the Denver Formation, the Green Mountain Conglomerate, and the lowermost part of the Dawson Formation. This package of rocks is in the upper part of the synorogenic D1 sequence of Raynolds (1997). The Paleocene and Eocene Coalmont Formation was deposited in North Park, and the Upper Cretaceous and Paleocene Raton and Poison Canyon Formations were deposited in southern Colorado (fig. 11). In Wyoming, the Fort Union Formation was deposited in the Powder River Basin, the Hanna Formation was deposited in the Hanna Basin, and the Waltman Shale Member of the Fort Union Formation was deposited in the Wind River Basin. The Cannonball Member of the Fort Union Formation was deposited farther north, in North and South Dakota, and may have been present in parts of Nebraska, Kansas, and Colorado (Blackstone, 1975). All traces of any previously existing Paleocene rocks have been removed from Nebraska and Kansas.

The lithology of many of these units is conglomeratic arkose or volcaniclastic conglomerate, sandstone, siltstone, and claystone. The Coalmont, Fort Union, Hanna, and Raton Formations contain coal beds (Beekley, 1915; Flores and Bader, 1999; Pillmore, 1976), and the Denver Formation contains thick lignite beds on the eastern side of the Denver-Julesburg Basin (Kirkham and Ladwig, 1979, Raynolds, 1997; Nichols, 1999). The Waltman Shale and Cannonball Members of the Fort Union Formation are shale units deposited in lacustrine and marine environments, respectively.

The paleogeography of the study area in Paleocene time is shown on figure 11. This map shows the major uplifted areas and sites of deposition in Colorado and southeastern Wyoming, inferred intrusive centers and stream locations in Colorado, inferred locations of a lake in Wyoming, and a sea, mainly in western Nebraska. Deposition was largely from streams that carried eroded material from the mountains to adjacent basins. Much, if not all, of the material was probably trapped near the mountain sources and not dispersed very far eastward onto the Great Plains (Raynolds, 1997). The mountains have been estimated to have risen approximately 12,000 ft in the Paleocene (Scott, 1975), and uplift was accompanied by intrusive igneous and volcanic activity (Morse, 1981). Note that the reconstructed stream flow directions are oriented northwest to southeast, except for one stream shown flowing northwest to North Park. The Cannonball sea was a Tertiary remnant of the once-extensive Cretaceous Western Interior sea that soon disappeared because of infilling by sediment (Pye, 1958) or because of slight uplift that drained it.

The mammalian fauna of the Denver Formation is diverse, including multituberculates, proteutheres, "condylarths," and a marsupial (Dewar, 1996, 1997). Dewar's (1996) paleoenvironmental study of the Denver Formation indicated a subhumid to humid environment with only moderately low minimum temperatures. The presence of lignite and coal in this sequence, not only in the Denver-Julesburg Basin but also in the Powder River Basin of eastern Wyoming, in North Park, and in southern Colorado, indicates a warm, wet climate that promoted the lush growth of vegetation (Robinson, 1972; Montagne, 1991). Current and ongoing research in the Denver-Julesburg Basin is adding substantially to our understanding of the Paleocene climate in this region (Barclay, 2001; Dunn, 2001; Eberle, 2001; Ellis, 2001; Fleming, 2001; Johnson, 2001; Nichols, 2001). Fossils collected in southern Colorado in the Poison Canyon Formation include turtle and Coryphodon (Hills, 1888), both aquatic animals. Fossils from the Fort Union include invertebrate shells, crocodiles, and turtles (Brown, 1907), further supporting the interpretation of a warm, wet climate.

Eocene

A mid- to late-Eocene unconformity has been recognized in much of the Front Range area and in some areas on the plains (Scott, 1975; Trimble, 1980a; Seeland, 1985; Swinehart and others, 1985). Many geologists have inferred that the product of the erosion was an extensive, relatively flat surface that left only the highest peaks of the Front Range standing as high mountains (Knight, 1953; Epis and Chapin, 1975; Scott, 1975, 1982; Scott and Taylor, 1986; Morse, 1985; Raynolds, 1997). This interpretation has not been without critics, however, most notably Steven and others (1997).

At one time there were no Eocene-age rocks recognized in eastern Colorado or in Nebraska (Robinson, 1972; Swinehart and Diffendal, 1989). However, Soister and Tschudy (1978) recognized an early to early middle Eocene pollen assemblage above a paleosol marker bed at or near the base of the Dawson Formation in the Denver-Julesburg Basin. Additionally, the age of the Wall Mountain Tuff is now thought to be late Eocene, based on 40Ar/39Ar dating (McIntosh and others, 1992) and revision of the Eocene-Oligocene boundary (Swisher and Prothro, 1990; Berggren and others, 1995). In northeastern Colorado, southeastern Wyoming, and western Nebraska, the Chadron Formation of the White River Group was long considered Oligocene (Swinehart and others, 1985; Swinehart and Diffendal, 1989). The change in the Eocene-Oligocene boundary now places the Chadron in the late Eocene (Swinehart and Diffendal, 1997). Important revisions in White River Group nomenclature were proposed by Terry (1998) and LaGarry (1998). Their proposed changes mainly concern internal divisions of the White River Group and the Chamberlain Pass Formation in northwestern Nebraska. The Chamberlain Pass is the basal unit of the White River Group and was named by Evans and Terry (1994). The unit was previously included with the Chadron Formation and is included with the Chadron in the present report. The lower Eocene Wind River Formation is recognized in the Laramie Basin area of southeastern Wyoming (Blackstone, 1975) along with the Wasatch Formation in the Powder River Basin.

The Castle Rock Conglomerate, in the southern Denver-Julesburg Basin, has been considered as early Oligocene by most previous researchers but was considered late Eocene by Steven and others (1997). Although the unit has not been radiometrically dated, Steven and others (1997) suggest that this age assignment has merit because of the similarity in paleoslope indicated by the Castle Rock Formation compared to lower Eocene White River (Chadron) streams in northeastern Colorado. The Castle Rock contains a Chadron fauna (Morse, 1985), and because the Chadron Formation is now considered late Eocene, a similar age assignment seems appropriate for the Castle Rock. Although still considered as early Oligocene in age by the USGS as of this writing, it is discussed here as a late Eocene correlative of the Chadron Formation.

The Eocene part of the Dawson Formation consists of arkosic conglomerate, feldspathic to andesitic sandstone, and sandy claystone (Soister and Tschudy, 1978; Morse, 1981). The Dawson was deposited by high-energy streams that had their source in the nearby Front Range Uplift. The lower and upper parts of the Dawson are separated by a widespread interval of paleosols (Farnham, 2001). Dated strata above and below the paleosol zone indicate a time gap of 6 to 8 million years between the lower and upper parts of the Dawson (Raynolds, 2001). The Wall Mountain Tuff unconformably overlies the Dawson Formation in the southern part of the Denver-Julesburg Basin. It originated as an ash-flow that was ejected west of the Front Range and flowed eastward in paleovalleys into the Denver-Julesburg Basin (Epis and Chapin, 1974; Morse, 1985). The Wind River and Wasatch Formations are composed of arkosic sandstone and variegated mudstone beds that have a fluvial origin (Blackstone, 1975). They were deposited in environments similar to that of the Dawson.

The Chadron Formation consists mainly of tuffaceous claystone, siltstone, and mudstone, and relatively minor amounts of fossiliferous, coarse-grained sandstone and conglomerate (Scott, 1978; Swinehart and others, 1985; Swinehart and Diffendal, 1997). Basal coarse-grained material (now assigned to the Chamberlain Pass Formation) was deposited in shallow channels that were incised into underlying rocks, but much of the upper part of the Chadron is reworked volcanic ash that was ejected in the western United States (Stanley, 1976; Swinehart and Diffendal, 1989). The reconstructed paleodrainage of the Chadron indicates a paleoslope mainly to the east-southeast (fig. 12). In South Dakota, the upper part of the Chadron contains extensive lacustrine beds (Evans, 1995), indicating a depositional surface of low relief that allowed for ponding of groundwater. The Castle Rock Conglomerate overlies either the Dawson Formation or the Wall Mountain Tuff, and is composed of coarse conglomerate with large clasts of Wall Mountain Tuff, granite, quartzite, and metamorphic rocks (Morse, 1985). Paleocurrent analysis indicates that a high-energy stream deposited the Castle Rock and flowed to the southeast (Morse, 1985). Morse (1985) also noted that the projected line of Castle Rock Conglomerate outcrops intersect the mountain front at the point where the South Platte River now leaves the mountains. He believed that the Castle Rock represents deposits of an ancestral South Platte River that flowed to the southeast. The southeastward-oriented channels of the Chadron in northeastern Colorado (Scott, 1982; fig. 12) contain a pebble suite different than that of the Castle Rock, and are believed to have been part of a different (but parallel) stream system. The two channels that join east of the mountain uplift in southeastern Wyoming were thought to be the ancestral Laramie River (south channel segment) and the ancestral North Platte River (north channel segment) by Clark (1975). Although these channels were discussed by Clark (1975) in the context of the Oligocene, they are from basal strata of the White River Group (Chadron), which is now considered to be Eocene.

Soister and Tschudy (1978) reported a palynomorph assemblage consisting of deciduous trees and shrubs and grass in the Dawson Formation, and Scott (1978) mentioned bones and teeth of fossil vertebrates (unspecified) in basal beds of the Chadron Formation in northeastern Colorado. Bjorklund and Brown (1957) reported fragmentary remains of a titanothere, a large herbivorous mammal, from the Chadron near Sterling, Colorado, and Morse (1985) reported finding tortoise bone, ungulate, and titanothere fragments in the Castle Rock Conglomerate, as well as rhinoceros and other mammals found by others. Lovering (1929) listed upland and aquatic rhinoceros, horses, peccaries, deer, and camels as fauna of the Chadron. Just to the north of the study area, in southwestern South Dakota, Retallack (1983) reported fossil root traces that he attributed to a woodland ecosystem. Retallack (1983)

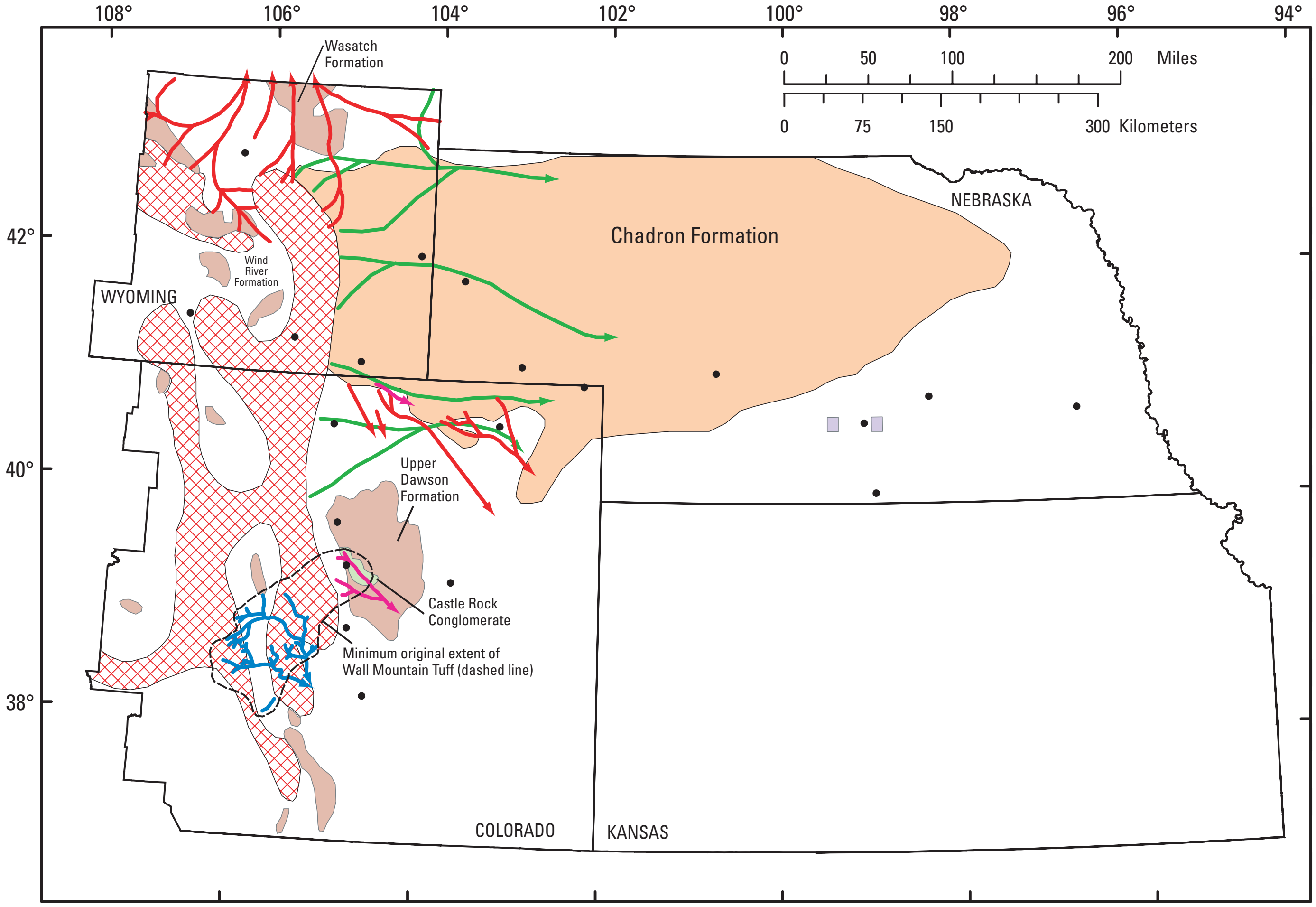

Figure 12. Paleogeography in Eocene time. Uplifts in red cross-hatched pattern and basins in brown modified from Robinson (1972), streams in green in Wyoming, Nebraska, and Colorado modified from Clark (1975), streams in red in Wyoming and Colorado modified from Seeland (1985), area of Chadron Formation modified from Swinehart and others (1985), streams in blue and outline of Wall Mountain Tuff modified from Chapin and Kelley (1997), and streams in magenta in Colorado modified from Steven and others (1997). Cities and mapped quadrangles are as shown on figure 1.

interpreted the climate during deposition of the Chadron as humid to subtropical. Evanoff (1991) used fossil land snails to interpret a subhumid climate for Chadron-age rocks in east-central Wyoming, and Evans (1995) noted fish, turtle, and abundant invertebrates in upper Chadron beds in southwestern South Dakota. In southwestern Wyoming and northwestern Colorado fossils, such as flamingos, crocodiles, palms, and magnolias, in the Eocene Green River Formation indicate a subtropical environment at this time (Mears, 1993). Chapin and Kelley (1997) noted that the early Eocene was one of the Earth's warmest time intervals, and began with a substantial warming of the oceans and a major extinction of deep benthic organisms.

Discussions of Eocene climate have been part of the debate about the development of one or more erosion surfaces in the southern Rocky Mountains and adjacent Great Plains. As few as one and as many as eleven surfaces have been recognized in the Front Range and Laramie Range since geologists began examining those areas (summarized by Bradley, 1987). Many of the interpretations have concluded that a major erosion surface developed in late Eocene time (Epis and Chapin, 1975; Scott, 1975). A typical view of this surface, west of Denver, is shown in figure 13. The assignment of a late Eocene age for this surface was in part based on the presumed Oligocene age of the immediately overlying Wall Mountain Tuff (now dated at 36.7 m.y., late Eocene) (Chapin and Kelley, 1997), and on the age of the Florissant Lake Beds (34 m.y.) and the Antero Formation (33 m.y.) (Epis and Chapin, 1975). Given that the age of the Eocene-Oligocene boundary is now thought to be approximately 33.7 m.y. (Berggren and others, 1995), the earlier chronology must be revised slightly.

Many authors (Epis and Chapin, 1975; Trimble, 1980a; Morse, 1985; Leonard and Langford, 1994) have noted that the Wall Mountain Tuff spread eastward from a source west of the Front Range (fig. 12), indicating that Front Range topography must have been subdued during this event, at least in areas where the tuff was deposited. In the northern part of the Front Range, Bolyard (1997) described an eastward-dipping surface as a pediment at grade with streams that flowed onto the Great Plains. In the southern Denver-Julesburg Basin, the Wall Mountain Tuff overlies the Dawson Formation, which has been dated as early to lower middle Eocene by Soister and Tschudy (1978). The age of the Wall Mountain Tuff is now thought to be late Eocene, on the basis of its isotopic age (McIntosh and others, 1992). These dated deposits indicate a probable middle Eocene age for the erosion surface in the southern Denver-Julesburg Basin, an age also accepted by Chapin and Kelley (1997). This surface was traced over much of the Front Range, and was thought to be roughly contemporaneous over all of that area and into Wyoming (Scott, 1975). It should be noted that the paleosol zone within the Dawson did not form at the same time as the Eocene erosion surface. The paleosols lie between the D1 and D2 synorogenic sequences of Raynolds (1997), whereas the Eocene erosion surface is at the top of the Dawson Formation (top of D2 sequence), beneath either the Wall Mountain Tuff or the Castle Rock Conglomerate.

MacGinitie (1953) concluded that the erosion surface had formed at low altitude, on the basis of comparisons of fossils

Figure 13. Photo of middle Eocene erosion surface (tree-covered hills on left-hand side of photo) in the Front Range. View is northeast from Green Mountain, on west side of Denver. Snow-covered peaks in far background are on the present Continental Divide. Interstate 70 is in the foreground.

in the Florissant Lake Beds with modern equivalents. However, he was not aware of the major warm global temperature that is now known to have characterized the Eocene. MacGinitie's interpretation of low altitude led some workers to assume that this was evidence that the surface was essentially a peneplain at nearly sea level that was later uplifted to its present altitude (summarized by Bradley, 1987). Later, reinterpretation of the Florissant fossils led others (Meyer, 1992; Gregory, 1992; Gregory and Chase, 1992) to conclude that the erosion surface formed at elevations higher than 8,000 ft. Morphological changes in the flora of the upper Dawson also suggest an increase in elevation (Johnson, 2001). Chapin and Kelley (1997) summarized the paleobotanical arguments for development of a high-altitude erosion surface. The significance of these findings is that they indicate that the climate in the Eocene was quite warm—warm enough that plants normally found at low altitudes in today's climate were growing at much higher altitudes in the Eocene. Beginning in late Eocene time, the climate turned very much cooler, possibly reflecting the increased volcanic activity and associated ash clouds that were spread eastward from the western United States (Robinson, 1972; Chapin and Kelley, 1997).

Various aspects of the above interpretations have been disputed by some. Evanoff (1991) disputed the concept of a single, Eocene-age, low-relief erosion surface that extends from central Colorado to southern Wyoming. He found that deep paleovalleys filled with White River strata, including coarse basal conglomerates, indicated mountainous topography in pre-White River (middle Eocene) time. Because the subsumit erosion surface truncates White River strata in the paleovalleys, Evanoff (1991) concluded that the erosion surface in the Laramie Range is of Miocene or even Pliocene age. Mears (1993) also accepted the idea that topography in much of Wyoming was mountainous in the Eocene, but that the basin areas were near sea level, in sub-tropical conditions. He thought that the mountains were gradually buried by airborne pyroclastic debris in the Oligocene and through much of the Miocene, and that the widespread erosion surface on the

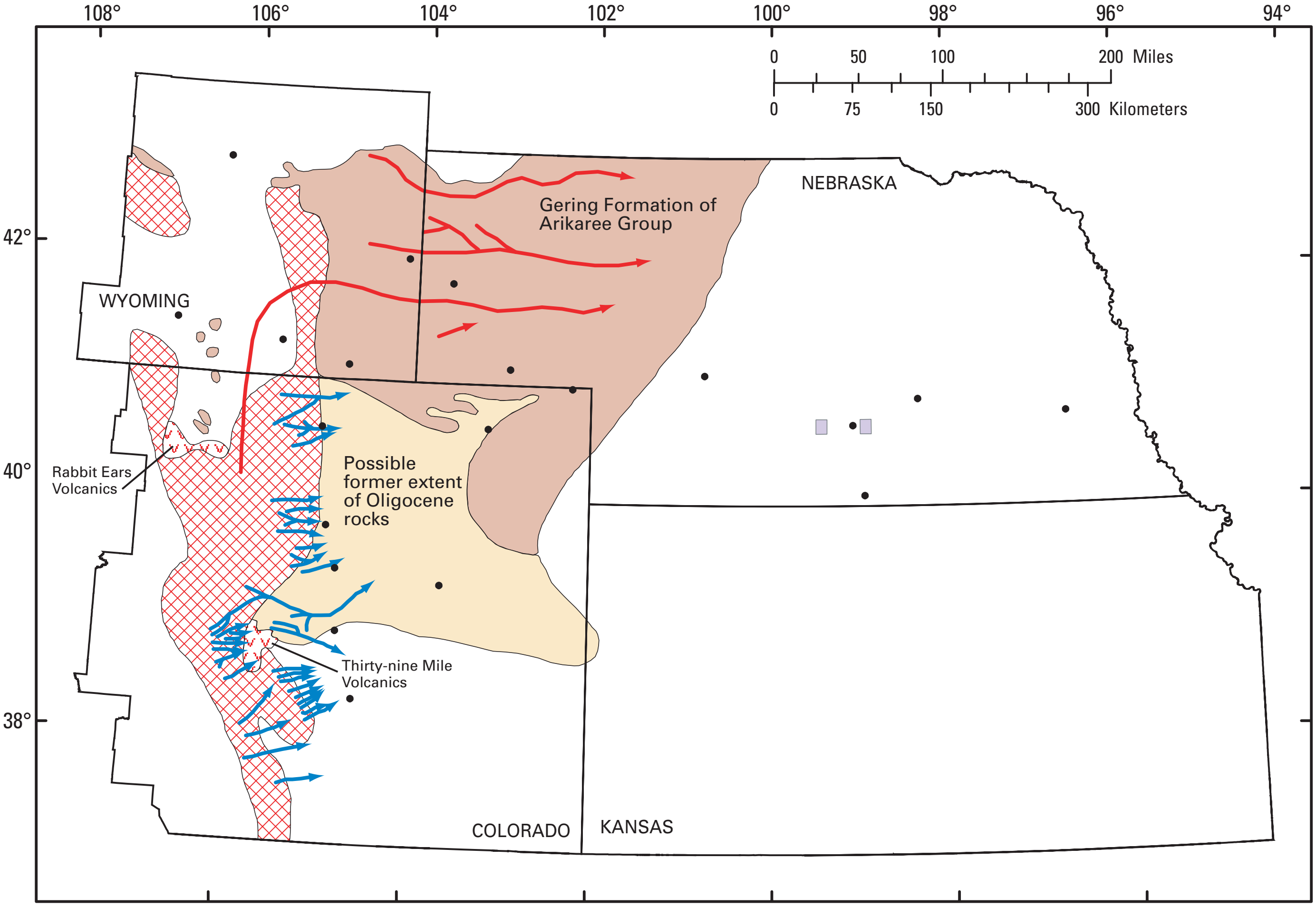

Figure 14. Paleogeography in Oligocene time. Uplifts in red cross-hatched pattern; areas of Gering Formation, Rabbit Ears Volcanics, Thirty-nine Mile Volcanics, and possible former extent of Oligocene rocks modified from Robinson (1972), streams in blue modified from Scott (1975), and streams in red modified from Swinehart and others (1985). Cities and mapped quadrangles are as shown on figure 1.

Laramie Mountains is mid-Miocene in age. Montagne (1991) noted that deep canyons were cut in the uplands adjacent to the Saratoga Valley that produced several thousand feet of local relief. Blackstone (1975) considered the erosion surface to have formed during deposition of the upper Ogallala Group, now thought to be of late Miocene age.

Steven and others (1997) did not believe that the erosion surface in Colorado was of low topographic relief, that the surface is entirely Eocene in age, or that it formed at a high elevation. Steven and others (1997) maintained that the surface had variable topography, ranging from very low to mountainous. Their interpretation was that Eocene topography was essentially a result of Laramide uplift and was similar to that in existence today—ranging from plains east of the mountain front, through a foothills area having moderate relief, to high peaks along the crest of the Front Range. Steven and others (1997) contended that the surface recognized by Epis and Chapin (1975) and Scott (1975) in the foothills was just one element of the Eocene landscape. Additionally, the Rampart surface, just northwest of Colorado Springs, considered one of the best-preserved examples of the Eocene erosion surface by Scott (1975), and used as the basis for arguing against post-Laramide uplift of the Front Range by Leonard and Langford (1994), was thought by Steven and others (1997) to be of middle to late Miocene age. Steven and others (1997) also maintained that regional base level remained stable from the late Eocene to the late Miocene, indicating to them that the region was at or near sea level for most of that time. Their conclusions require that extensive late Cenozoic mountain uplift relative to the plains, and downwarping of the Great Plains, has created much of the topographic relief between the mountains and plains that exists today.

These examples of differing views show that interpretations of Eocene paleogeography and climate cover a wide spectrum. Research on this topic is ongoing, but fundamentally different interpretations of the same data make resolution of some of the questions unlikely in the near future.

Oligocene

The close of the Eocene Epoch and the beginning of the Oligocene saw the study area inundated by volcanic ash. Volcanoes in Colorado and in a belt from central Utah to Washington State (but mainly from Utah) were the probable sources, and they ejected large volumes of ash that were carried eastward by prevailing winds and reworked by streams and rivers in the southern Rocky Mountains and western Great Plains (Stanley, 1976; Seeland, 1985; Swinehart and others, 1985).

The Chadron Formation of the White River Group was long considered to be the basal Oligocene unit on the Great Plains but is now considered to be late Eocene (Swinehart and Diffendal, 1997). The overlying Brule Formation of the White River Group is now the basal (early) Oligocene formation on the Plains. In parts of southeastern Wyoming and northeastern Colorado the White River Formation (Montagne, 1991; Izett, 1975; Scott, 1978) is a unit of presumed Eocene and Oligocene age. The Arikaree Formation or Group overlies the White River Formation in Wyoming east of the Laramie Mountains, in western Nebraska, and in northeastern Colorado. In western Nebraska, the Arikaree includes both Oligocene- and Miocene-age units. The basal Gering Formation and overlying Monroe Creek Formation of the Arikaree Group are considered upper Oligocene (Swinehart and Diffendal, 1995; 1997). Figure 14 shows that Oligocene units may have once been present over much of northeastern Colorado (Robinson, 1972), but were later removed by erosion. Although it is still considered of lower Oligocene age by the USGS, Steven and others (1997) considered the Castle Rock a time-equivalent to the late Eocene age Chadron Formation, and the Castle Rock is discussed in the Eocene section of this report.

The Brule Formation is composed of volcaniclastic silty sandstone, sandy siltstone, and mudstone. It contains several ash beds that can be correlated regionally and are useful as marker beds (Swinehart and Diffendal, 1995; 1997). Much of the Brule is composed of eolian pyroclastic strata, consisting of as much as 60 percent glass shards. Relatively minor lacustrine deposits are present locally. The rate of ash deposition increased through the duration of the White River Group, and the upper part of the group consists mostly of volcaniclastic material and only minor fluvial strata. During this time, the mountains were slowly buried by onlap of sediments, and the thickness of Oligocene strata on the Great Plains was increasing as the area slowly subsided under the influx of fluvial and air-fall sediments. Stanley (1976) noted that the mountains were not buried in their own erosional debris, but rather were buried by airfall volcanic material. Small areas of the mountain cores remained exposed and provided igneous and metamorphic clasts that were carried eastward by low-gradient streams over a flat plain of volcaniclastic-derived eolian material.

A hiatus in deposition occurred between the White River Group and the Arikaree Group, during which time the area was subjected to renewed uplift and erosion and the formation of a regional unconformity (Swinehart and others, 1985). The Gering Formation or undivided Arikaree Formation filled channels cut into the erosion surface and are composed of volcaniclastics, sandstone, silty sandstone, and sandy siltstone, and locally are composed of conglomerate, marl, and ash beds (Scott, 1978; Swinehart and Diffendal, 1995; 1997). Most of the formation consists of volcaniclastic sediments that were reworked by fluvial processes, and local lacustrine beds. The overlying Monroe Creek Formation is composed of volcaniclastic conglomerate, sandstone, and ash beds. The unit is mainly of eolian origin, but most eolian strata have been reworked by streams. Swinehart and Diffendal (1989) noted that the Arikaree Group is more areally restricted than the White River Group, and is largely confined to paleovalleys in the eastern part of its extent in the subsurface. They thought that in much of the Sand Hills area the undivided Arikaree Formation is equivalent to the Gering Formation.

Detailed Oligocene drainage maps have been reconstructed by Scott (1975) in the Front Range of Colorado (fig. 14). These were augmented by a more general drainage map by Swinehart and others (1985) in southeastern Wyoming and western Nebraska. Robinson (1972) showed that there was a slight change in highland areas of the Rocky Mountains compared to the Eocene (fig. 12), but the basic configuration of source areas remained the same. In contrast to the southeast-flowing streams of the late Eocene in Colorado, drainage in the Oligocene was more to the east. In the early Oligocene, headwaters of most streams were in the Front Range or Laramie Range, but by the late Oligocene headwaters of a few streams were in the North Park or western Front Range areas (Stanley, 1976). Drainage in the North Park area was to the south in the early to middle Oligocene (Montagne, 1991). Izett (1975) thought that much of the plains of eastern Colorado were structurally high in the late Oligocene. He reasoned that only the upper part (early Miocene) of the Arikaree Group is preserved in that area; if the whole group had been deposited and then eroded, late Oligocene rocks at the base of the group (Gering) would have been preserved. The absence of rocks of Gering age in northeastern Colorado argues for nondeposition of the lower Arikaree there.

The climate of the Oligocene remained temperate, although drier and cooler than during late Eocene Chadron time. Fossils in the Brule Formation within the study area include invertebrates, turtles, and mammals, of which oreodonts are the most numerous taxa (Swinehart and Diffendal, 1997). Scott (1982) reported two genera of oreodonts in the Arikaree Group of northeastern Colorado. Lovering (1929) noted that hackberry seeds are particularly abundant in some beds. Lovering (1929) also noted that Oligocene fauna indicated more arid conditions than in the Eocene. Stanley (1976) also interpreted the climate as semiarid during this time, based on the abundance of eolian strata. Paleoenvironmental data from Oligocene land snails and sedimentological changes from fluvial to eolian environments of deposition led Evanoff (1991; 1995) to interpret the environment as semiarid. Mears (1993) interpreted the ecosystem as a savanna in Oligocene time. Clark (1975) viewed the climate as progressively cooling from the Eocene onward, culminating in glaciation during the Pleistocene. Indeed, Prothero and Heaton (1996) described a profound climate "crash" in the transition from the Eocene to the Oligocene. They considered the change in the early Oligocene as the most fundamental in the last 65 million years, citing evidence for a dramatic drop in mean global temperatures, an increase in seasonal temperature variation, a change in vegetation from dense woodland to mixed woodland-grassland, and a shift from fluvial to eolian depositional environments interpreted from the White River Group. Surprisingly, the Oligocene Orellan mammalian fauna showed remarkably little change through this climatic change (Prothero and Heaton, 1996). Retallack (1997) presented evidence that grassland in the early Oligocene was composed of bunch grasses and shrubs in some areas. This environment is similar to that of the current intermontane west.

Miocene

The transition from the Oligocene to Miocene Epochs occurs within the Arikaree Group in Nebraska (Swinehart and Diffendal, 1995; 1997; Swinehart and others, 1985). In southwestern Nebraska, the Harrison Formation is the oldest Miocene formation recognized; younger informal units are also present. Lugn (1939a,b) and Skinner and others (1977) described a unit above the Harrison called the Hemingford Group. This unit name was not used by Swinehart and others (1985) or by Swinehart and Diffendal (1989). The Hemingford, or upper Harrison beds, is included with the Arikaree Group in this report. In northeastern Colorado the undivided Arikaree Formation was mapped (Scott, 1978), where it was considered Miocene in age. In north-central Colorado, the Browns Park and North Park Formations are recognized Miocene units (Izett, 1975) and the Browns Park is also recognized in adjacent south-central Wyoming (Montagne, 1991). In southeastern Wyoming, the undivided Arikaree Formation is recognized (Flanagan and Montagne, 1993), where it is considered transitional between the Oligocene and Miocene Epochs. Unconformably overlying the Arikaree is the Ogallala Formation or Group. In Nebraska, the Ogallala has been divided into many constituent formations, members, and informal units (Swinehart and Diffendal, 1995; 1997; Swinehart and others, 1985). In Colorado, Scott recognized upper and lower parts of the Ogallala Formation, which correspond, in part, to the Nebraska units. In southeastern Wyoming, the undivided Ogallala Formation is identified (Flanagan and Montagne, 1993), but informal subdivisions are recognized that are equivalent to Nebraska units. The Browns Park and North Park Formations are partly equivalent to both the Arikaree and the Ogallala (Izett, 1975).

The lower Miocene Harrison Formation conformably overlies and is similar in lithology to the underlying Monroe Creek Formation in southwestern Nebraska, consisting of fine grained silty sandstones (Swinehart and others, 1985). Large calcium carbonate concretions are characteristic features in many areas, and silica-cemented beds are locally present. The upper Harrison beds of Swinehart and others (1985), still considered lower Miocene, unconformably overlie the Monroe Creek-Harrison Formation interval and include some local coarse grained sandstones at the base. In Colorado, Scott (1978) described the Arikaree Formation as conglomerate, sandstone, siltstone, and claystone, but some of that unit may be equivalent to the Oligocene part of the Arikaree recognized in Nebraska. In southeastern Wyoming the Arikaree was described as consisting of fine- to medium-grained sandstone, limestone, and ash beds (Flanagan and Montagne, 1993). Calcareous concretions are also characteristic of the Wyoming exposures. The Arikaree units in all areas were deposited in mixed volcaniclastic eolian, fluvial, and lacustrine environments that represent a continuation of most conditions that existed in late Oligocene time, although with a lower percentage of fluvial environments.

The middle to upper Miocene Ogallala Group, which extends from South Dakota to Texas, is a complex unit that has been the subject of much study over the years, especially in Nebraska. Lugn (1939a) and Diffendal (1984) presented overviews of the earliest studies of the Ogallala. For this report, the lithology of the Ogallala is generalized, without separate descriptions of all the formations, members, and informal units that are recognized in Nebraska. In western Nebraska, the Ogallala is composed of conglomerate, sandstone, and siltstone at the base, which grades up into poorly consolidated gravel beds, cobble to pebble conglomerate, sandstone, and siltstone and some diatomite and ash beds (Swinehart and Diffendal, 1995; 1997). Farther east in Nebraska, the Ogallala includes a higher percentage of finer strata of silt, clay, and limestone intermixed with the coarser lithofacies (Dreeszen and others, 1973; Eversoll and others, 1988; Swinehart and Diffendal, 1989; Diffendal, 1991; Souders, 2000).

In Colorado, the lower part of the Ogallala is composed of semiconsolidated ashy sand and silt beds and volcanic ash beds that grade upward into poorly consolidated gravel beds containing clasts of granitic, sedimentary, and volcanic rocks (Scott, 1978). Coarse gravel is most abundant in the middle of the unit in northeastern Colorado (Bjorklund and Brown, 1957). The upper part of the Ogallala in northeastern Colorado consists of one or more calcite-cemented caliche layers or limestone beds that form a caprock.

In southeastern Wyoming, the Ogallala is composed of boulder to gravel conglomerate just east of the Laramie Range, and grades eastward to sandstone, siltstone, limestone, and ash beds (Flanagan and Montagne, 1993). Stanley (1976) identified several unique petrofacies in Tertiary beds of the High Plains and mapped the distribution of these petrofacies in the Ogallala. Most of the Ogallala east of the Laramie Range is composed of granitic clasts, with metamorphic and rhyolite clasts occurring in about equal abundance, and anorthosite clasts occurring in some outcrops. Over much of the area discussed in this report, and elsewhere, the upper part of the Ogallala is characterized by “mortar beds” (Haworth, 1897), sandstone beds that are firmly cemented with calcium carbonate and which stand out in bold relief capping escarpments.

The volcanic eruptions that dominated Oligocene and early Miocene sedimentation in the study area apparently ceased in the middle Miocene, and the dominant processes became erosion resulting from renewed faulting and tectonic activity in the Rockies (Izett, 1975; Scott, 1975; Epis and others, 1976; Mears, 1993; Flanagan and Montagne, 1993). The erosion caused an unconformable surface to develop on underlying rocks (Swinehart and others, 1985). As noted above, some authors believe that this period of erosion resulted in planation of some of the Front Range, Laramie Range, and Medicine Bow Mountains (Blackstone, 1975; Mears, 1993; Steven and others, 1997). Erosion was accompanied by infilling of the basins adjacent to the mountains. In the middle Miocene, sediment loading on the Great Plains caused subsidence, which created accommodation space and led to accumulation of the Ogallala Group (Lugn and Lugn, 1956). The Ogallala first backfilled the paleochannels incised in underlying rocks, and then spread laterally in a series of fining-upward cut and fill sequences. Diffendal (1982) identified at least two main episodes of erosion and deposition associated with the Ogallala in western Nebraska, one pre-Ogallala and one intra-Ogallala. Goodwin and Diffendal (1987) interpreted the Ogallala as a braided stream deposit, based on stratification types and lithofacies. In some areas the Ogallala may have been deposited on alluvial fans or on low-relief alluvial plains (Johnson, 1901; Scott, 1982; Swinehart and Diffendal, 1989; Flanagan and Montagne, 1993), and some ash beds were interpreted as having been deposited in lacustrine environments (Diffendal, 1982). A variety of other depositional environments have also been proposed for the Ogallala, summarized by Helland and Diffendal (1993). The end result of the uplift, erosion, and sedimentation at this time was an eastward-sloping wedge of coarse fluvial sediments deposited by streams that were at grade with the subsumit surface of the nearly buried mountainous highlands (Pearl, 1971; Blackstone, 1975).

The Browns Park Formation is widely distributed in north-central and northwestern Colorado and in the Saratoga Valley of southeastern Wyoming within the area considered in this report. In the Saratoga Valley the Browns Park includes, at the top, strata equivalent to the North Park Formation that is recognized in Colorado (Montagne, 1991). The Browns Park unconformably overlies various other rock units. The lower part is composed of conglomerate and sandstone, with clasts of metamorphic, sedimentary, volcanic, and plutonic rocks. Overlying the basal conglomerate is a sequence of pastel sandstone, siltstone, and ash beds that are capped by white chalcedonic and algal lacustrine limestone beds. The upper part of the Browns Park in the Saratoga Valley consists of tuffaceous sandstone and siltstone beds and ash beds (Montagne, 1991).

The North Park Formation overlies the White River Formation in North Park and is composed mainly of gray shale and sandstone. It contains several hard white calcareous sandstone and marly layers and is characterized by the presence of volcanic material. Shale beds in the North Park contain pinkish and gray ashy streaks and thin laminae of black “cinder.” Sandstone beds are usually fine grained but are locally coarse grained. Conglomerate composed of rounded basalt pebbles is irregularly distributed in the North Park (Beekly, 1915). The North Park and Browns Park Formations were also deposited primarily in fluvial environments in the middle and upper Miocene. Montagne (1991) identified a “Platte Channel facies” in the upper part of the Browns Park that consists of conglomerate and sandstone having distinctive pebble suites of volcaniclastic rocks carried northward from Colorado. This unit was thought to represent deposits of the ancestral North Platte River. Izett (1975) noted that volcanic clasts from northern Colorado were carried north and northeastward by both ancestral North Platte and Laramie rivers in the Miocene.

Data have been compiled to show the paleogeography of the study area in Miocene time (fig. 15). The distribution of the Arikaree is not shown on this map because the Harrison and equivalent units are combined with the Oligocene part of the Arikaree (see fig. 14 for the distribution of the Arikaree Group). As noted above, Swinehart and Diffendal (1989) thought that most of the Arikaree underlying the Sand Hills is equivalent to the Oligocene Gering Formation. The locations of Miocene (Ogallala) streams have been compiled from various sources, and show a general easterly trend. Drainage patterns shown by Blackstone (1975) and Swinehart and others (1985) suggest a northern Front Range source for the Ogallala in southeastern Wyoming, northeastern Colorado, northwestern Kansas, and Nebraska. The North Platte drainage was diverted northward in the earliest Miocene (Montagne, 1991). Steven and others (1997) pointed out that the east-northeast paleoslope in Colorado was at nearly right angles to the southeast paleoslope in the late Eocene. They took this change to indicate regional structural tilting to the northeast in middle Miocene time. The Ogallala in east-central and southeastern Colorado and in much of Kansas probably had a source in the central to southern Front Range, as illustrated by Pearl (1971), Scott (1975), and Morse (1985). Upland source areas are smaller than in previous times, reflecting the burial that occurred in the Oligocene and early Miocene. The areas of Miocene volcanics in North Park and the western Front Range are important, because rhyolite clasts from these outcrops have been identified in the Ogallala on the east side of the Front Range and Laramie Range (Blackstone, 1975; Stanley, 1976). The presence of these clasts in eastern Wyoming, northeastern Colorado, and western Nebraska indicates that the Laramie Basin was filled with sediment, and that the headwaters of the drainage system were in the North Park area for some of Ogallala time (Blackstone, 1975; Flanagan and Montagne, 1993). At the close of deposition of the Ogallala, the central Great Plains consisted of a vast tableland of gently eastward-dipping sediment (Pearl, 1971). Parts of this surface are preserved

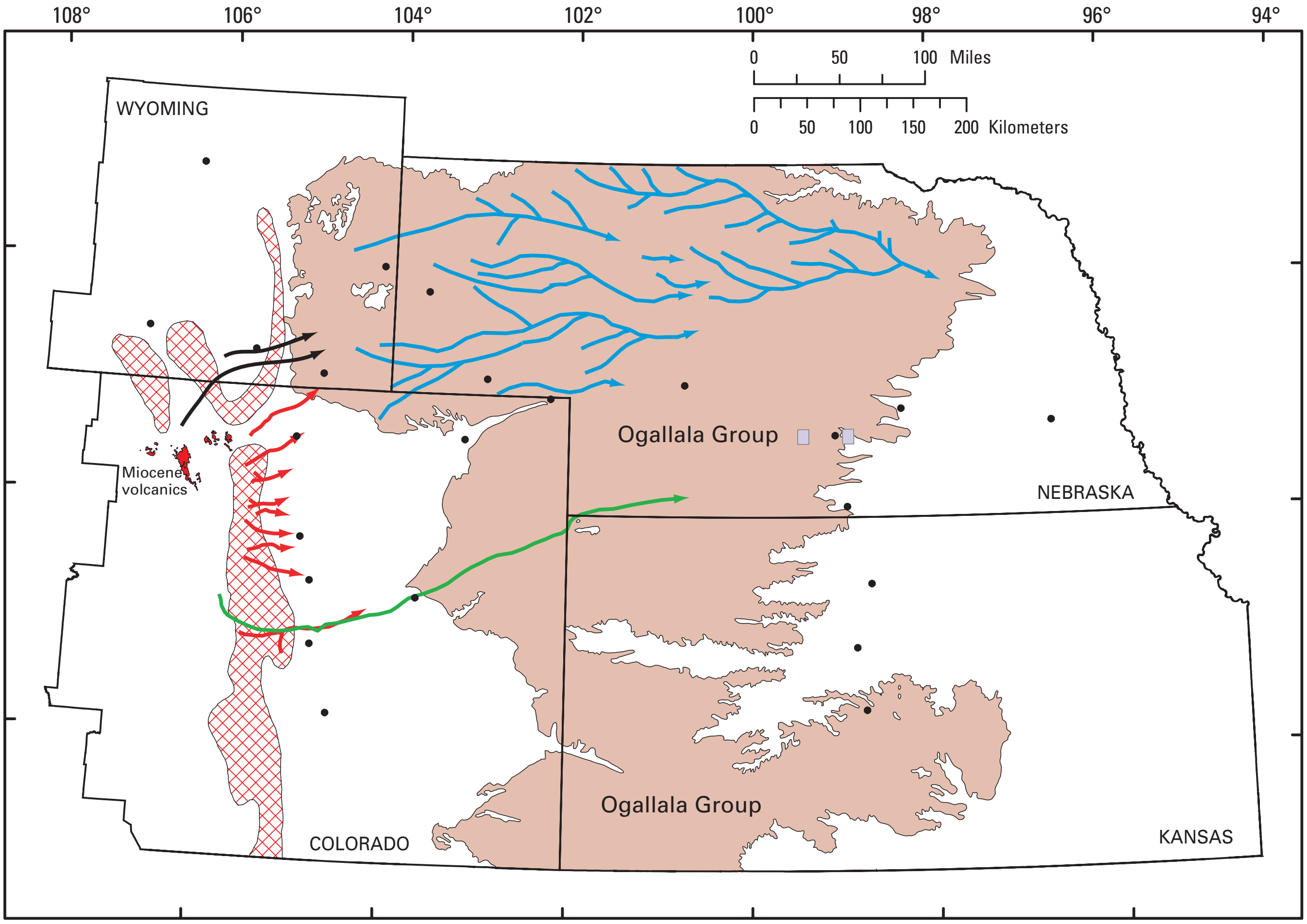

Figure 15. Paleogeography in Miocene time. Uplifts in red cross-hatched pattern modified from Robinson (1972), stream in green modified from Pearl (1971), streams in black modified from Blackstone (1975), streams in red modified from Steven and others (1997), and streams in blue modified from Swinehart and others (1985) and Swinehart and Diffendal (1989). Outline of the Ogallala Group is partially from the Groundwater Atlas of the United States (http://www.nationalatlas.gov/aquifersm.html). The eastern extent of the Ogallala Group in Nebraska was modified by the author from the outline of the High Plains Aquifer in the National Atlas, using the bedrock geologic map of Nebraska (Burchett and Pabian, 1991). Cities and mapped quadrangles are as shown on figure 1.

today in northeastern Colorado and southwestern Kansas (Johnson, 1901), and at the Gangplank, west of Cheyenne, Wyoming (fig. 1). The latter part of the Miocene (from about 10-12 m.y. ago) marks the beginning of the present-day drainage system (Izett, 1975).

Fossils are abundant in Miocene rocks in the study area. A comprehensive list of mammals from the Ogallala was published by Schultz and Stout (1948). Swinehart and Diffendal (1995; 1997) reported horses, camels, tortoises, rhinoceroses, carnivores, antelope, deer, rodents, invertebrates, and various plant fossils in southwestern Nebraska. Very fossiliferous beds from the upper part of the Ogallala in western Nebraska were described by Leite (1990) and have a diverse mammalian fauna. Leite's analysis of the fauna indicated that the environment changed in the Miocene of Nebraska from lush savanna to more arid steppe. A possible cause of the extinction of some large mammals at this time was climatic cooling and drying, which changed the vegetation available to the animals.

Fossils from the North Park Formation are similar to those in the upper Arikaree and Ogallala: horse, oreodont, beaver, camel, and mastodon (Izett, 1975). Montagne (1991) reported oreodonts, prongbucks, turtles, rabbits, gophers, merycodonts, beaver, camel, rhinoceros, horse, carnivores, mastodon, invertebrates, wood, and pollen (ponderosa pine, pinyon pine, and juniper) from the Browns Park Formation. He interpreted the climate as warm and semiarid and characterized by violent showers on the basis of the fossil assemblage and the presence of conglomeratic beds that required high-energy stream transport. Flanagan and Montagne (1993) concluded that faunal evidence indicated increasing aridity throughout the Miocene and into the Pliocene and that a change in flora from deciduous trees to alpine vegetation in some areas also indicates that the climate was cooling. Data from paleosols (Retallack, 1997) indicates a change from bunch grasslands in the Oligocene to sod-forming short-grass prairie in the Miocene. Retallack (1997) interpreted the Great Plains to have received less than 16 inches of precipitation annually in the early Miocene. In the late Miocene, increased precipitation led to the development of tall-grass prairie and an overall expansion of grasslands (Retallack, 1997).

Pliocene

Although the modern drainage system has its origins in the middle Miocene (Izett, 1975), the beginning of the Pliocene Epoch, at about 5 Ma, can be considered the approximate point in time from which the present landscape of the southern Rocky Mountains and the western Great Plains has evolved. The close of the Miocene saw the area foundering in its own sedimentary debris, with only the highest mountain cores left standing in relief (Knight, 1953; Flanagan and Montagne, 1993). Deposition decreased or possibly ceased over the area, resulting in an unconformity at the top of the Ogallala Group and removal of the unit in east-central Nebraska.

In the middle Miocene, the entire area from the Colorado Plateau to Wyoming and east to the Great Plains slowly began to rise (Morrison 1987; Steven and others, 1997; McMillan and others, 2000). As the mountain cores gained elevation in the Pliocene, the erosional debris that had buried them began to be stripped away. Much of this material was redeposited on top of the Ogallala Group or along steams incised into the Ogallala on the Great Plains as the streams lost competency. As regional uplift continued, these deposits were partially remobilized and moved farther away from the areas of highest elevation. In the Colorado part of the study area nearly all Pliocene-age deposits have been removed and transported down the depositional slope.

In contrast, Nebraska became the site of deposition of much of the reworked gravels and other finer-grained material. Steven and others (1997) indicated that the region was tilted to the northeast, shifting the locus of deposition to western and central Nebraska. The Broadwater Formation (originally considered early Pleistocene age) was recognized and described by Schultz and Stout (1945) in western Nebraska. As a named unit the Broadwater is mainly restricted to western and northern Nebraska, but equivalent units are probably present elsewhere. In the North Platte 1° × 2° quadrangle, Diffendal (1991) recognized an older alluvium unit, of Pliocene and Pleistocene age, which was said to be partially equivalent to the Broadwater Formation. In the Broken Bow 1° × 2° quadrangle, Souders (2000) recognized Pliocene-age loess and alluvial units that were considered equivalent to the Fullerton and Broadwater Formations. The Fullerton has traditionally been considered early Pleistocene age (Reed and Dreeszen, 1965; Dreeszen, 1970), but volcanic ash dated at 2.3 Ma in the upper part of the unit (Boellstorff, 1978) indicates that the Fullerton should now be considered Pliocene (May and others, 1995). An unnamed unit and the Belleville Formation are recognized Pliocene to pre-Illinoian units along the Republican River in southern Nebraska (Swinehart and others, 1994). Swinehart and others (1994) also mapped a Pliocene to lower Pleistocene alluvial unit in much of central Nebraska (including the study area) that contains equivalents of the Broadwater Formation. It should be noted that distinguishing upper Pliocene strata from lower Pleistocene strata is difficult to impossible in many places. The lithology is similar, and the age difference between units is commonly based on fossil assemblages, which are not everywhere present. There appears to have been a gradual transition from Pliocene to Pleistocene sedimentation in the study area.

In Colorado, Scott (1963) recognized the Nussbaum Alluvium (also originally considered early Pleistocene age), which was a product of Pliocene erosion of older units. This unit is mainly found in the southern Colorado Piedmont region (fig. 1), but remnants are also in northeastern Colorado (Scott, 1975; 1982). The distribution of the Broadwater Formation in western and northern Nebraska (Swinehart and Diffendal, 1997) suggests that equivalent strata should be present along the North Platte drainage, or possibly other areas, in eastern Wyoming. Blackstone (1975) described several deposits in southeastern Wyoming that may be Pliocene in age, and

Flanagan and Montagne (1993) mentioned high-level terrace deposits (unnamed) of late Miocene to early Pleistocene age in several areas of Wyoming. In both Colorado and Wyoming, the Pliocene was a time of net erosion rather than deposition, resulting in a sparse sedimentary record.

In Nebraska, the Broadwater and equivalent formations consist of conglomerate, sandstone, siltstone, claystone, and mudstone. Schultz and Stout (1945) recognized a basal gravel member, a middle member composed of sand, peat, diatomaceous marl, and silt, and an upper gravel member. Swinehart and Diffendal (1995, 1997) mapped generally gravelly units in the panhandle of Nebraska. In south-central Nebraska, Pliocene sediments consist of gravel, sand, and less abundant amounts of silt and clay at the base, overlain by other units composed of silt, clay, and lesser amounts of sand and gravel (Souders, 2000). In northeastern Colorado, the Nussbaum Alluvium is composed of bouldery gravel, sand, and minor silt and clay (Scott, 1982). In Colorado, the Nussbaum unconformably overlies units as old as the Cretaceous Pierre Shale (Scott, 1963, 1982), and in western Nebraska the Broadwater unconformably overlies units as old as the Brule Formation (Swinehart and Diffendal, 1995). The Pliocene units are preserved there as remnants of terraces along the major present-day drainages.

Data from various sources have been compiled to show reconstructed upland areas and stream patterns in Pliocene time (fig. 16). Clasts in the Broadwater Formation indicate source areas similar to those of the Ogallala—the Medicine Bow and Laramie Ranges in Wyoming and the Front Range in Colorado. Stanley and Wayne (1972) identified a distinctive clast suite that indicates a major trunk stream flowed from the Laramie Range and swept from north to south across Nebraska, covering much of the State with a veneer of gravelly alluvium. In the Front Range, accelerated uplift resulted in significant canyon cutting and incision of the modern drainage system (Scott, 1975). Faulting in the Front Range caused disruption of some of the earlier drainage courses, and the northeastward trend of the South Platte River was established

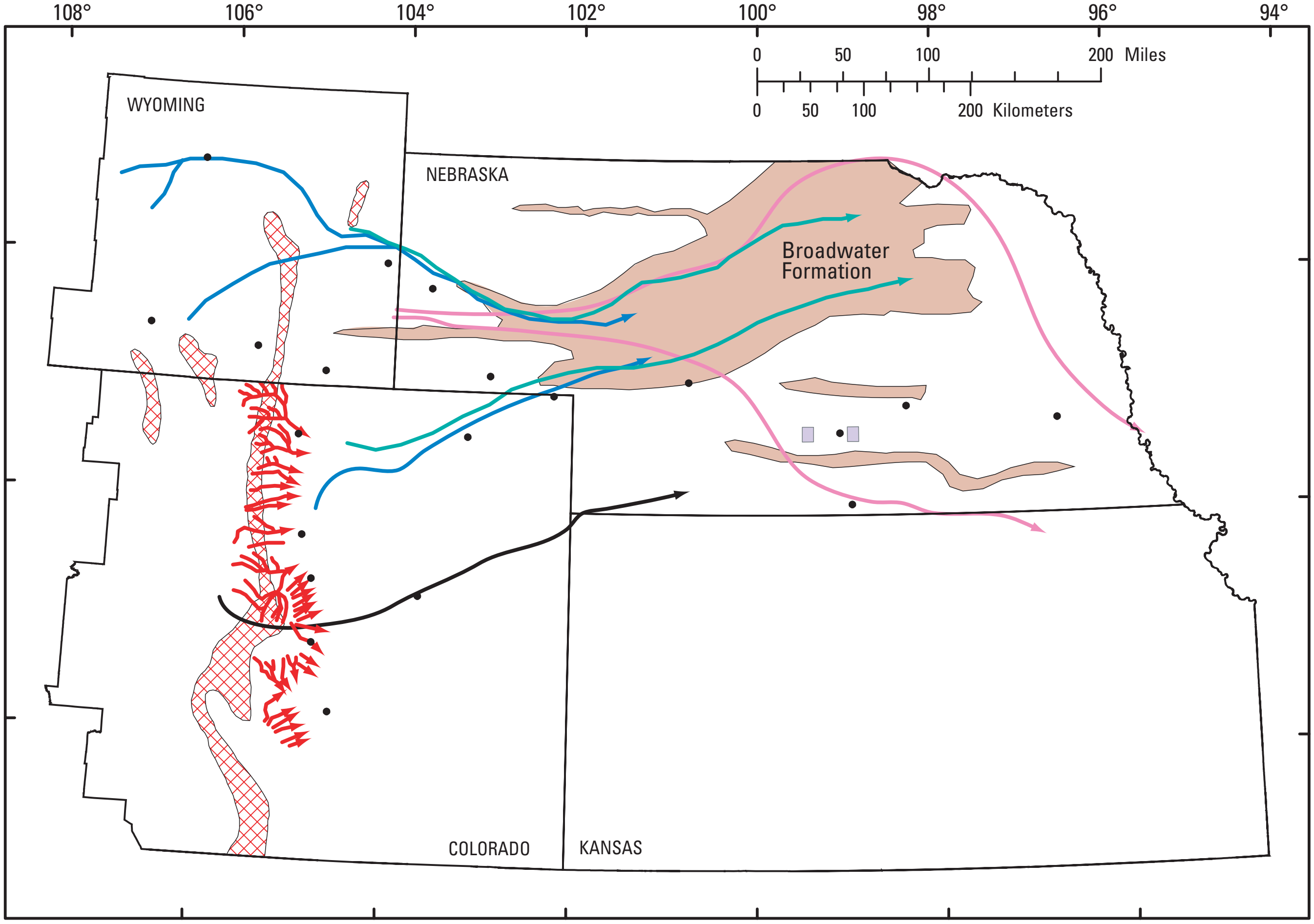

Figure 16. Paleogeography in Pliocene time. Uplifts in red cross-hatched pattern modified from Robinson (1972), stream in black modified from Pearl (1971), streams in magenta modified from Stanley and Wayne (1972), streams in red modified from Scott (1975), streams in blue modified from Swinehart and Diffendal (1989), and streams in green and area of Broadwater Formation modified from Swinehart and others (1994). Cities and mapped quadrangles are as shown on figure 1.

(Epis and others, 1976), possibly as a result of northward tectonic tilting and stream capture as described by Steven and others (1997). The sediment from northeastern Colorado has its own distinctive pebble suite, different than that of southeastern Wyoming (Swinehart and Diffendal, 1989). In south-central Nebraska, a structure contour map representing the unconformable surface at the base of Pliocene strata (fig. 7) shows an east-southeast-oriented drainage pattern. This region is just southeast of what Souders (2000) described as a major paleo-drainage divide, named the Cotesfield paleodivide, and is just east of the Cambridge Arch (Darton, 1918; Swinehart and others, 1985). These structures may have played a role in directing the flow of the ancestral Platte River southeast toward the Republican River drainage that is shown on figure 16 and that is supported by the interpretation of subsurface data in this study (section II).

Pearl (1971) showed an ancestral Arikaree River flowing eastward across the Great Plains from the Pikes Peak region of the Front Range in late Miocene to early Pliocene time. Later in the Pliocene the headwaters of this stream were diverted into the South Platte River system, possibly by stream capture (Pearl, 1971; Morse, 1985), cutting off the flow of mountain-sourced water in eastern Colorado. This event was significant, because it resulted in the erosion of the Ogallala Group and older rocks along the mountain front and led to the development of the Colorado Piedmont. The west-facing erosional scarp of the Ogallala has gradually moved eastward from Pliocene time to its present location, which defines the eastern edge of the Piedmont. Scott (1982) inferred that the scarp moved about 50 miles eastward in the 2 million years between the end of Ogallala deposition at about 5 Ma and deposition of the Nussbaum Alluvium at about 3 Ma. Since that time, the scarp has only moved an additional 10 miles eastward. Steven and others (1997) suggested that the present position of the scarp marks the eastern hingeline of late Cenozoic regional uplift of areas to the west.

The only major streams in southeastern Wyoming and eastern Colorado flowing across the Ogallala today are the North and South Platte and the Arkansas. This configuration has preserved the post-Ogallala erosion surface in parts of eastern Colorado and western Kansas with minor stream modification (Johnson, 1901). The effects of this isolation of the Plains is shown on figure 1. On the Arkansas River in central Kansas, the elevation at Great Bend is 1,850 ft. Along a north-south transect, perpendicular to the depositional slope, the elevation along the Smoky Hill River at Russell, Kansas drops to 1,726 ft, and it further drops to 1,520 ft along the South Fork of the Solomon River at Osborne, Kansas. The elevation rises to 1,800 ft at Franklin, Neb. along the Republican River and is at 2,150 ft at Kearney, Neb., along the Platte River, a rise of 350 ft in just over 40 miles. The difference between the Arkansas and the Platte and the other listed streams that causes these marked variations in elevation is that the Arkansas and Platte head in the mountains and have been net aggradational streams, or have had lower rates of incision, since the Pliocene. In contrast, the Smoky Hill, Solomon, and Republican rivers all head on the Ogallala surface east of the Colorado Piedmont, carry a smaller sediment load, and are incising at a higher rate than the Arkansas or Platte. These differences are a direct result of developments in the drainage system initiated in Pliocene time and continued to the present.

In addition to fluvial deposition of gravels, eolian deposition also occurred in the Pliocene. The Fullerton Formation of south-central Nebraska is primarily an eolian silt, or loess (May and others, 1995). The source of the loess was probably local stream channels and overbank material, in contrast to the eolian volcaniclastic deposits of older Tertiary units. Volcanism was still occurring, however, and dated volcanic ash beds (1.7 to 3.5 Ma) in the Fullerton have helped to verify its Pliocene age (Souders and Swinehart, 1996a,b).

The climate in Pliocene time is thought to have further cooled, but not necessarily dried, at least in the mountainous uplands. Ward and Carter (1999) noted that late Tertiary uplift of the mountains caused a rain shadow on the plains that increased aridity in that region and influenced rates of stream incision, but the drying of the plains may be a fairly recent phenomenon. Pliocene deposits contain a rich fauna including elephant (Stegomastodon), camel, and horse in northeastern Colorado (Scott, 1982). The Broadwater Formation is famous for its fossil content, including shrews, beavers, ground sloths, jackrabbits, elephants, horses, camels, amphibians, reptiles, dog or wolf, and saber-toothed tiger (Schultz and Stout, 1948; Swinehart and Diffendal, 1997). Lugn (1935) showed pictures of cedar and elm logs recovered from the Fullerton Formation in the eastern part of the study area, two of which were still upright in their growth positions.

Chapin and Kelley (1997) pointed out that several lines of evidence indicate increased precipitation in the Pliocene. These include (1) the establishment of the Colorado and Rio Grande River drainage systems through arid lands, (2) the opening of previously closed basins in the Rio Grande Rift and Basin and Range province by through-going streams, (3) erosion of thick sequences of Mesozoic and Cenozoic rocks from the Colorado Plateau, and (4) stable-isotope compositions of paleosol carbonates. Flanagan and Montagne (1993) also described the development of large river systems in the Pliocene that excavated Miocene and older strata from the basins of Wyoming. They attributed the presence of large perennial rivers to mountain glaciation, which Love and others (1973) interpreted as occurring at about 3 Ma in Wyoming. Morrison (1987) showed that the climate became increasingly unstable in the late Pliocene, leading to large fluctuations in erosional-depositional cycles.

Pleistocene

A list of those who have studied Pleistocene deposits in Nebraska would be a who's who of Nebraska geologists, but a few early pioneers should be acknowledged. N.H. Darton, whose keen intellect was focused on many topics in the West, did some of the first studies in Nebraska (Darton, 1903). E.H. Barbour was the first official State Geologist of Nebraska, and as such, had wide-ranging interests in the geology of the State (Souders, 1993). His primary interest was vertebrate paleontology, and he has dozens of publications on that and other topics pertaining to Nebraska geology published from the early 1890s to the 1940s. G.E. Condra succeeded Barbour as the head of geological studies in Nebraska in 1921. His first specialty was invertebrate paleontology of the Pennsylvanian, but as Director his interests were wide-ranging. With his successor, E.C. Reed, Condra published a standard reference for Pleistocene geology (Condra and others, 1947). No discussion of the Quaternary geology of Nebraska would be complete without mentioning A.L. Lugn, a staff geologist with the Nebraska Geological Survey. Lugn published in great detail on the subject, two comprehensive reports among many being Lugn (1935) and Lugn and Wenzel (1938). Finally, a contemporary of the others, C.B. Schultz, had an important impact on Nebraska Quaternary geology. Schultz was long associated with the Nebraska State Museum and published extensively on vertebrate paleontology and stratigraphy. Many of the concepts of chronostratigraphy and terrace development in Nebraska were developed by Schultz and his associates.

In Nebraska, the nomenclature of Pleistocene units west of the glaciated area has undergone several revisions. Lugn (1934, 1935) laid out the first comprehensive classification of Pleistocene units in Nebraska and assigned names to several intervals of alternating gravels and finer-grained material, some of which are still used today. Lugn's work incorporated early data from a systematic drilling program initiated in Nebraska by the Nebraska Geological Survey (now the Conservation and Survey Division), in cooperation with the U.S. Geological Survey, whose purpose was to delineate the extent of sediment types in the subsurface to better understand the State's water resources. Condra and others (1947) modified and refined some of Lugn's correlations, based on new information obtained from the drilling program. Reed and Dreeszen (1965) made further refinements based on information obtained from additional drilling. Subsequent reconsideration of some of the earlier correlations has led to more caution in assigning names to stratigraphic intervals. As Wayne and Aber (1991) noted, early names were sometimes applied to conceptual models as much as to lithostratigraphic units. Some names and provisional names have been retained, but awareness of the regional complexity of the Quaternary depositional system has led away from broad regional correlations and to more detailed local studies. Some of the more recent classifications have been published by Wayne and Aber (1991) and May and others (1995).

Without being overly concerned with names, test wells show that the sedimentary section in south-central Nebraska above the Ogallala Group consists of two gravel sequences separated and overlain by loess sequences. The thickness and relative abundance of these sequences differs from place to place, and it has been recognized that one lithology may grade laterally into another lithology (May and others, 1995), and that the lower loess sequence is not always present (Lugn, 1935). Section II of the present report on the subsurface geology of the region combines the two lower gravel sequences and interbedded loess together, and separates the upper loess unit from the lower unit.

The Fullerton Formation, and correlative coarse clastics, corresponds to the lower gravel and loess unit, and is now considered Pliocene in age, as discussed in the previous section. A post-Fullerton gravel unit is recognized, and younger, mainly loess, units are also recognized, including the Walnut Creek Formation, Sappa Formation, Grafton Loess, Beaver Creek Loess, Loveland Formation, Crete Formation, Gilman Canyon Formation, and Peoria Loess (Swinehart and others, 1994; May and others, 1995).

The gravel unit above the Fullerton consists of coarse gravel composed of clasts of granitic and metamorphic rocks interbedded with sandstone and minor silt or clay beds deposited in a fluvial system. The grain size of the unit decreases upward to fine sand in some places. Characteristic features of this gravel deposit are anorthosite clasts that were carried from the Laramie Range of southeastern Wyoming (Stanley and Wayne, 1972) by the ancestral North Platte River. Souders (2000) noted that volcanic ash beds are locally present in this unit. Ash beds in the equivalent Sappa Formation in the Republican River drainage have been dated at 1.2 to 1.27 Ma (Swinehart and others, 1994).

A rich and varied nomenclature describes the dominantly loess section that overlies the gravel-bearing horizon of Pleistocene sediments (Reed and Dreeszen, 1965; May and others, 1995). Various names have been applied in different parts of the region, but no study to date synthesizes them all. Volcanic ash beds were recognized early in the study of Pleistocene sediments in Nebraska, and were collectively referred to as the "Pearlette ash" (Condra and others, 1947). Initially this was thought to be a single bed, but later studies determined that there are at least three closely related beds, designated type O, type S, and type B (Naeser and others, 1973). Boellstorff (1976) further subdivided the ash beds and assigned different names to them. Recognition of different-aged ash beds greatly enhanced the chronostratigraphic correlations of various Pleistocene units in the study area.

The Loveland Formation is a late Illinoian loess widely recognized, not only in Nebraska, but throughout the midcontinent region. The Loveland is a fine-grained silt, but a distinguishing feature is its oxidized reddish color that makes it identifiable. The Loveland was deposited over an irregular, eroded topography, and parts of the Loveland are reworked material that includes locally derived sand concentrated in stream channels (Lugn and Wenzel, 1938). The underlying Beaver Creek and Grafton loess units also have a slightly reddish color (Reed and Dreeszen, 1965), making them difficult to distinguish from the Loveland. The Loveland (probably including the Beaver Creek and Grafton) has been dated at about 163,000 years B.P. by Maat and Johnson (1996), using thermoluminescence (TL) methods. Wayne and Aber (1991) discussed the complexity of this interval, which has been generalized in the present summary.

The Gilman Canyon Formation, mainly mid-Wisconsin in age, overlies the Loveland. The Gilman Canyon is a dark gray humic silt containing several paleosols that had been previously included with the Loveland Formation (Lugn and Wenzel, 1938). It was recognized as a separate unit by Reed and Dreeszen (1965) and has since been described in several areas of Nebraska (Souders and Dreeszen, 1991; Swinehart and others, 1994), but has not yet been noted in Colorado (Muhs and others, 1999a). Reported radiocarbon ages of the Gilman Canyon range from about 20,000 to as old as 40,000 years B.P. (most reported dates are between 20,000 and 35,000 years B.P.) (May and Souders, 1988; Feng and others, 1994; Souders and Swinehart, 1996a,b; Muhs and others, 1999a,b; Johnson and others, 1999).

The late Wisconsin Peoria Loess overlies the Gilman Canyon Formation. The Peoria is also recognized over a large area of the mid-continent region, including parts of eastern Colorado (Muhs and others, 1999a,b). The composition of the Peoria is light brownish-gray silt. Reported ages of the Peoria range from 10,000 to 25,000 years B.P. (Feng and others, 1994; Swinehart and others, 1994, Pye and others, 1995; Souders and Swinehart, 1996a,b; Muhs and others, 1999a,b; Roberts and others, 2003). It was deposited over a dissected topography on top of the Loveland Formation (Lugn, 1935).

Several terrace alluviums are present along the Platte River in western and south-central Nebraska, of both Pleistocene and Holocene age (Schultz and Stout, 1945; Reed and Dreeszen, 1965; Brice, 1964; May and Holen, 1985; and May, 1989). See the Elm Creek West and Newark quadrangles (Section II, plates 1 and 2) for examples of terraces of the Platte River in the Kearney area.

In Colorado, Bryan and Ray (1940) and Scott (1960, 1963, 1965) defined several units of Pleistocene age. These occur as gravelly veneers on pediments along the mountain

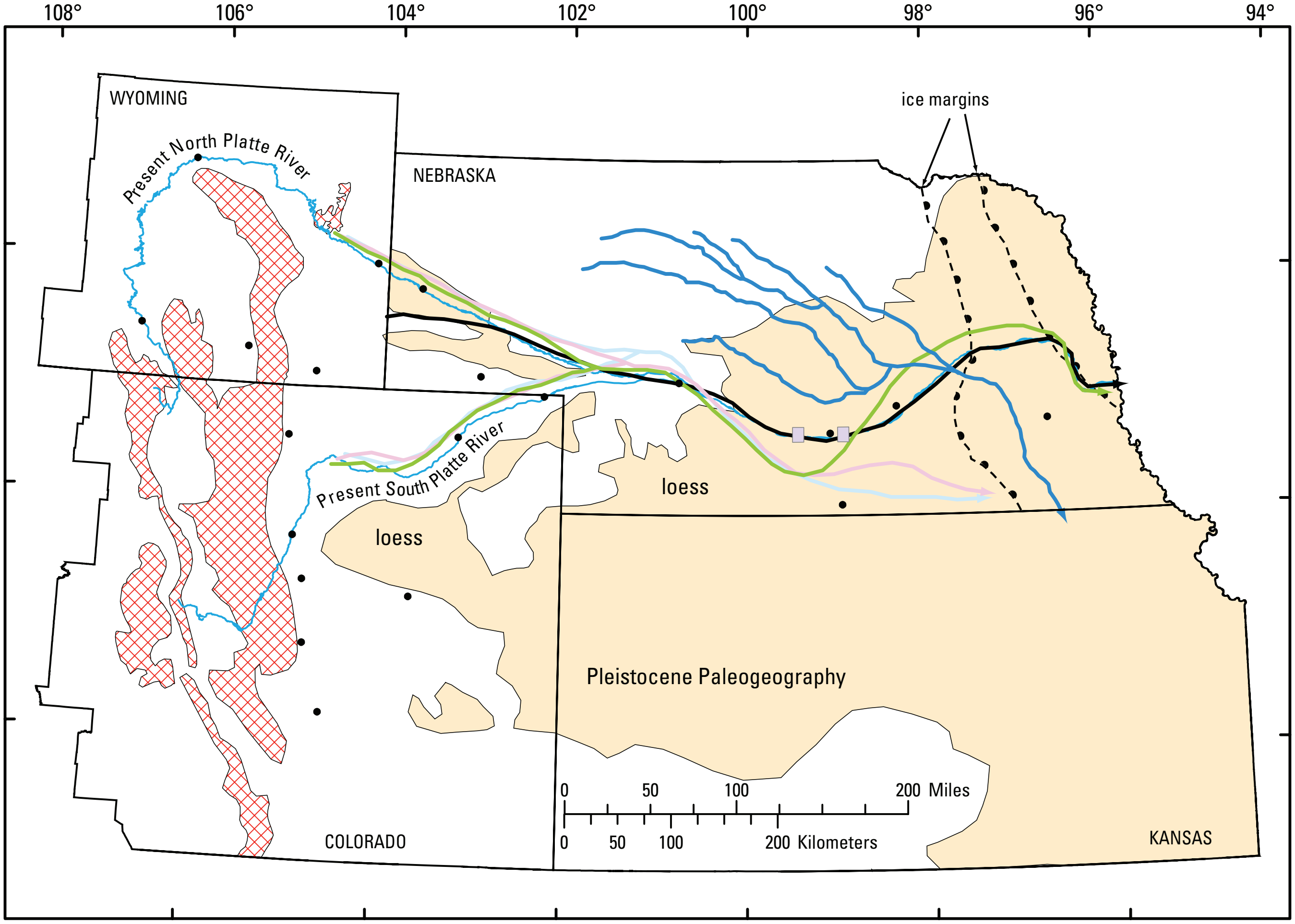

Figure 17. Paleogeography in Pleistocene time. Red cross-hatched pattern indicates Precambrian granitic or metamorphic rocks generalized from Green (1992) and Green and Drouillard (1994), stream in black and ice margins modified from Stanley and Wayne (1972), streams in green, light blue, and pink modified from Swinehart and others (1994), and loess area modified from Muhs and others (1999a). Streams in dark blue are the Loup River system, shown flowing south into the Big Blue River drainage. The modern North, South, and combined Platte Rivers (thin blue lines) are shown for reference. Cities and mapped quadrangles are as shown on figure 1.

front and as terrace remnants along streams on the plains in eastern Colorado. Names in common use are the Rocky Flats Alluvium, Verdos Alluvium, Slocum Alluvium, Louviers Alluvium, and Broadway Alluvium. A thin loess, which overlies the Louviers Alluvium, was correlated by Scott (1963) with the Peoria Loess. Pleistocene eolian sands are also present on the plains of eastern Colorado (Forman and Maat, 1990; Madole, 1991, Muhs and others, 1999b). Additional alluvial units (discussed below) are of Holocene age. As could be expected, the Pleistocene alluvial units are very coarse grained bouldery gravels and sandstones near the mountains, and grade to somewhat finer gravels and sands in eastern Colorado (Scott, 1982, Madole, 1991). The Rocky Flats, Verdos, and Slocum are considered pre-Wisconsin in age, and the Louviers and Broadway are Wisconsin (Scott, 1965).

In the Laramie Basin of southeastern Wyoming, Mears (1991) described a number of terraces and terrace alluviums. These features were dated, in part, by volcanic ash beds and fossils, and range in age from Pliocene to Holocene. One terrace alluvium, the Harmony bench, contains a bed of Bishop Tuff, dated at about 760,000 years B.P. The Bishop Tuff is also found in a unit of Illinoian age in south-central to southeastern Nebraska (Swinehart and others, 1994). An alluvial unit of comparable age in Colorado is the Rocky Flats Alluvium (Madole, 1991).

Figure 17 shows the paleogeography of the region in Pleistocene time. The uplift areas are where Precambrian rocks are shown to outcrop on the Colorado and Wyoming State geologic maps (Green, 1992; Green and Drouillard, 1994). The area shown as being covered by loess was generalized from the compilation of Muhs and others (1999a). The area of loess in Nebraska may have extended farther to the northwest in Pleistocene time, but this area is now covered by the Holocene-age Sand Hills, so the previous limit of loess deposition is not known.

Reconstructed Pleistocene stream courses are drawn from several sources and show that west of the confluence, the North and South Platte Rivers were in generally the same channels as today. Scott (1982) noted slight changes in the South Platte Valley in Colorado as indicated by channel remnants. Of interest is the series of paleochannels plotted south of the present course of the Platte River in south-central Nebraska. The positions of these channels were interpreted by Stanley and Wayne (1972) and Swinehart and others (1994). It appears that until middle to late Wisconsin time the Platte River flowed southeast from a point in western Dawson County, parallel to, but south of the present river. Lueninghoener (1947) suggested that the drainage pattern of the Loup River system may have formed the headwaters of the Big Blue River in early Pleistocene time, and that postulated configuration is also shown on figure 17.

A pertinent question is, at what point did the Platte River in south-central Nebraska begin to occupy its present channel? One way to answer this question is to look for the presence or absence of Pleistocene units outside the current channel area. Figure 8, an isopach map of mainly fluvial strata in the Plio-cene-Pleistocene section, seems to indicate the presence of the river south of its current location. Thick sand intervals, interpreted as channel deposits, occur in central Gosper, southern Phelps, and central Franklin and Webster Counties, as well as in east-central Kearney County, and central Adams and Clay Counties. The area occupied by the present Platte River has generally thinner amounts of fluvial sand and gravel. These relations are interpreted as showing that prior to loess deposition (Loveland and associated units) in this area the Platte was flowing south of its current location, but that it migrated northward to its present location before deposition of the Loveland.

If the Platte River had remained in its southern location during much or all of the time when the Walnut Creek Formation and Grafton, Beaver Creek, or Loveland Loesses were being deposited, it would be likely that these units would be absent in some areas south of the river due to syndepositional removal by the stream. Further, as the Platte migrated northward to its current position it would have removed any loess units of that age that would have been deposited just south of its current position. However, examination of the well records in this area indicates that a reddish loess (usually identified as Loveland Formation) is present in all areas south of the river except in Franklin, Webster, and Nuckolls Counties. This indicates that the river migrated to its current channel in the area west of Kearney prior to deposition of the Loveland, but that it may still have flowed southeast from Kearney in middle Pleistocene time.

The isopach map of loess in test wells (fig. 10) also may hold a clue about the previous course of the Platte. The map shows thickest areas of loess trending southeast from southwest Dawson County through central Gosper County, southern Phelps and Kearney counties, and through northern Nuckolls County. Although Mason (2001) mapped Peoria Loess at a much smaller scale than figure 10, his map also shows an area of relatively thick loess south of the river. This overall trend indicates that the river flowed southeast from Kearney during deposition of the Loveland and that the ancestral Platte channel probably contributed to local thickening of loess downwind from the river. The relatively thin area of loess northeast of Kearney indicates that this was not a primary region for loess deposition, arguing against the presence of the river in that location in middle Pleistocene time.

The current Platte River is confined by valley walls composed of the late Wisconsin Peoria Loess and older units both upstream and downstream from Kearney, indicating that the river has occupied its current valley at least since the late Wisconsin. Lugn (1935, 1939b), Stevenson (1972), and Bentall (1982) outlined a chronology of stream capture of the lower Platte region from its mouth to about Kearney. Progressive capture of tributaries of the Elkhorn and Loup Rivers (fig. 1) eventually diverted the Platte into its present course downstream from Kearney. An area of thin loess east of Minden indicates that the capture occurred after some loess was deposited (probably after Loveland deposition), but well before the end of Peoria deposition at the end of the Wisconsin. Souders and Dreeszen (1991) estimated the time of diversion to have been after the middle Pleistocene, but before 24,000 years B.P.

The position of two early Pleistocene ice margins, from Stanley and Wayne (1972), are shown on figure 17. Wayne and Aber (1991) pointed out that the ice caused major disruptions of the drainage network in eastern Nebraska and adjacent areas. A preglacial drainage divide trending northeast through South Dakota separated streams north of the divide, flowing northeast into Hudson Bay, from streams south of the divide, flowing southeast into the Gulf of Mexico. The ice diverted all of the northern streams southward along the western ice margin and probably also disturbed the downstream reaches of the Elkhorn, Loup, and Platte River systems in eastern Nebraska. The increased flow along the ice margin was probably accompanied by ponding and flooding as the channels readjusted to the greater flow. This would have had the effect of raising local base level and causing the rivers to backfill their channels with sand and gravel and to spread sediments over a wide braidplain.

The climate during the Pleistocene was characterized by wide temperature and precipitation variations that resulted in glacial ice advances from the north and the growth of mountain glaciers in the upper Platte River drainage basin (Wayne and Aber, 1991; Madole and others, 1998). The lithology of Pleistocene alluvial units is a good indication of climatic conditions—coarse stream deposits throughout the Pleistocene section near the mountains of Colorado and Wyoming and in the lower part of the Pleistocene section in Nebraska indicate abundant water sourced from mountain glacial meltwater. Widespread loess in middle and late Pleistocene-age deposits indicates somewhat more arid conditions.

Wright (1987) summarized the general conditions that prevailed beyond the limit of the continental ice sheets. Permafrost can be expected within about 120 miles of the glacial border, so permafrost conditions may have existed as far west as Kearney at the time of maximum glaciation in eastern Nebraska in the early Pleistocene. Beyond the permafrost and tundra zone, spruce forests existed at least as far south as northeastern Kansas, but the vegetation zones shifted considerably throughout the Pleistocene, depending on whether glacial or interglacial conditions existed. The Great Plains supported a diverse fauna during the Pleistocene. Megafauna, such as bears, tigers, leopards, mammoths, and bison were listed by Schultz and Stout (1948) and Reed and others (1965), as well as numerous smaller mammals. Several early Pleistocene local faunas were mentioned by Wayne and Aber (1991), yielding fish, amphibians, reptiles, birds, and mammals. The assemblages from the early Pleistocene indicate a relatively mild and humid climate (Schultz and Stout, 1948). Grass phytoliths from the mainly middle Pleistocene-age Loveland Formation indicate a climate somewhat drier than that existing today (Fredlund and others, 1985). Fauna and carbon isotope data suggest a grassland environment in northeastern Colorado in the late Pleistocene (Muhs and others, 1999b). According to Wayne (1991) the climate during the Pleistocene was marked by wide temporal and geographic variability. In the late Pleistocene, fossils from Kansas indicate cool summers but winter temperatures about the same as today (Wayne, 1991). In Nebraska, megafauna such as caribou and muskox associated with spruce indicate cooler and wetter conditions. Data from two mammoth kill(?) sites in southwestern and central Nebraska indicate an equable, cooler, possibly drier climate (May and Holen, 1994). Prairie grassland began to replace spruce forests in the western Great Plains after about 13,000 years B.P., and mixed hardwood-grassland flora developed in the eastern part of the area in the Holocene. The wide climatic variations in the late Wisconsin caused the aggradation-erosion cycles described by Schultz and Stout (1945, 1948) and Morrison (1987) that resulted in the terrace alluvial deposits along drainages that contain much of the fossil evidence for climate. These cycles continued into the Holocene.

The end of the Pleistocene was marked by a major extinction of megafauna. Large animals reported from Pleistocene deposits in and adjacent to the Great Plains include mammoth, mastodon, camel, giant bear, horse, musk ox, saber-toothed cats, giant beaver, ground sloth, bison, cervids, and dire wolf (Mehringer and others, 1970; Schultz and Martin, 1970). Most of these animals became extinct in the late Pleistocene to Holocene, although the exact cause is not precisely known. The changes in the distribution of vegetation undoubtedly had much to do with changes in the distribution of fauna—browsing animals followed the forests and predators followed their prey. The influence of man cannot be discounted either. Haynes (1991) presented evidence for widespread drought at the end of the Pleistocene, which may have led to a concentration of animals around water holes and a greater opportunity for Clovis-age hunters. A combination of environmental stress and increased hunting pressures apparently was enough to upset the ecological balance of the late Pleistocene.

Holocene

The Pleistocene-Holocene boundary is generally considered to be at about 10,000 years B.P. (Morrison, 1991). Using this somewhat arbitrary boundary, the Bignell Loess is the oldest Holocene loess unit that is widely distributed in the study area. The Bignell overlies the Peoria Loess, and is commonly separated from the Peoria by the Brady soil, dated at about 9,240 to 9,750 years B.P. (Swinehart and others, 1994). The Bignell is a fine silt, similar to the Peoria Loess, and has a reported TL age of about 9,000 to 6,000 years B.P. (Maat and Johnson, 1996) but may be as young as 3,000 years B.P. (Pye and others, 1995). Scott (1965) correlated the Bignell with the late Wisconsin-age Broadway Alluvium of Colorado, but radiocarbon ages from the Bignell indicate that it is somewhat younger than the Broadway.

Besides the Bignell Loess, much of Nebraska and adjacent areas is covered with a veneer of Holocene wind- and stream-deposited material. The largest and most well-known example is the extensive area of eolian sand in the Sand Hills of north-central to southwestern Nebraska (fig. 1). This dune field covers about one-quarter of the State of Nebraska and is the largest dune field in North America.

An early interpretation was that the Sand Hills dune sands and the upper Pleistocene Peoria Loess were contemporaneous and were derived from Tertiary formations and from pre-Peoria Pleistocene deposits (Lugn, 1935). This was a logical interpretation because loess deposits in Nebraska are thickest just to the southeast (downwind) of the Sand Hills region (Swinehart and others, 1994; Muhs and Bettis, 2000; Mason, 2001). As radiocarbon dates became available, studies of dune and interdune strata indicated that the dune field was active several times in the Holocene (Ahlbrandt and others, 1983), the most significant occurring between 8,000 and 5,000 years B.P. (Swinehart, 1989). Other work has documented possible blockage of streams by dunes in the late Pleistocene (Swinehart and Loope, 1992), as early as 10,600 years B.P. (Loope and others, 1995) or even as early as about 12,000 years B.P. (Sweeney and others, 1998; Muhs and others, 2000). Most evidence indicates that some eolian activity occurred in the late Pleistocene but that the major part of the dune field formed or was remobilized in the middle to late Holocene (Muhs and others, 1997).

Another area of Holocene dunes in Nebraska is south of the Platte River between the longitudes of Elm Creek and Shelton. This small dune field probably originated from sand blown southeastward out of the channels of the Platte River as the river was migrating to its present position. The dunes mantle terraces as young as the Holocene Qt1a terrace and as old as the Qt3 terrace in the Elm Creek West quadrangle, and appear to lap onto the Qt4 surface south of the quadrangle (see section I of this report). Similar dune deposits are present on the northwestern floodplain of the Platte River north of Grand Island, downwind from the Loup River.

In Colorado, Holocene loess is fairly widespread, but volumetrically insignificant (Madole, 1991; 1995). Muhs and others (1999a) identified two main episodes of loess deposition, one in the late Pleistocene and one in the late Pleistocene to Holocene. Dune sands form thicker and more easily studied deposits than loess in northeastern Colorado, but whether this is due to processes of deposition or preservation is unclear. Times of estimated dunefield activity vary according to the method used and the locations studied. Muhs (1985) concluded that dunes were active from 3,000 to 1,500 years B.P. on the basis of a comparison of soils between dated sites in Nebraska and soils on dunes in northeastern Colorado. Forman and Maat (1990) suggested that the latest eolian activity started at 9,000 to 7,000 years B.P. and ended at less than 3,000 years B.P. on the basis of radiocarbon and thermoluminescence analysis of soils on and within dunes. Forman and others (1992) did further studies and identified four periods of dune activity—about 9,500 to 5,500 years B.P., 5,500 to >4,800 years B.P., 4,800 to 1,000 years B.P., and less than 1,000 years B.P. Madole (1994) concluded that more than half (in surface area) of the eolian sand in northeast Colorado was remobilized within the past 1,000 years. Dunes in Colorado were derived mainly from stream channel and floodplain alluvium, and were deposited by southeastward-blowing wind (Muhs and others, 1996).

In southeastern Wyoming, Holocene eolian features include wind-stripped terraces and benches and deflation hollows, and dunes composed of clay and silt particles that accumulate adjacent to deflation hollows. Sand dune fields occur in the Casper area along the North Platte River (fig. 1).

Features common to all streams in the study area are Holocene terraces and terrace alluviums. In Nebraska, early studies that defined the terrace hierarchy were by Schultz and Stout (1945). They numbered the terraces T0, T1, T2, etc., starting with the modern floodplain as T0. This numbering convention was partially used in preparation of the maps of the Elm Creek West and Newark quadrangles for this study (see section I). Bryan and Ray (1940) had previously mapped terraces in Colorado, and Schultz and Stout (1945) considered their T3 terrace equivalent to the Pleasant Valley terrace of Bryan and Ray in Colorado, the T2 terrace equivalent to the Kersey terrace, and the T1 terrace equivalent to the Kuner terrace. The T3 terrace was interpreted to have formed on the Brady soil, after deposition of the Peoria Loess but before the Bignell Loess (Schultz and Stout, 1948). The oldest terrace fill (T5) was correlated with the Pliocene Broadwater Formation.

This classification system was extended to other parts of Nebraska (Schultz and others, 1948; Frankforter, 1950), and a complex chronology was developed that related terraces in central and western Nebraska with glacial events in eastern Nebraska (Schultz and others, 1951). In most areas the main terrace divisions can be further subdivided (Stout, 1983). Studies by Brice (1964), May and Holen (1985), and May (1989, 1992, 1998) in the Loup River Basin, and Martin (1992a,b) in the Republican drainage, have further refined the stratigraphy of Holocene terraces and terrace fills with the aid of radiocarbon dating. There has been little dating of the terraces in the Platte River drainage anywhere in Nebraska. Of 65 sites and hundreds of radiocarbon analyses in the Central Plains, only one site was from the Platte River (Mandel, 1995).

Following Bryan and Ray (1940), further studies of terraces in Colorado identified three Holocene-age terrace alluviums—the pre-Piney Creek alluvium, the Piney Creek Alluvium, and the post-Piney Creek alluvium (Scott, 1963, 1965). Pre-Piney Creek alluvium was radiocarbon dated at about 5,500 years B.P. and contains Archaic artifacts; Piney Creek Alluvium was inferred to be 2,800 years old, based on dating of a correlative alluvium in Utah ; and post-Piney Creek alluvium forms the lowest terrace and modern floodplains and was radiocarbon dated at about 1,500 years B.P. (Scott, 1963). Woodland artifacts have been recovered from the post-Piney Creek alluvium.

Holliday (1987) studied terraces along the South Platte and used artifacts to infer ages of the terraces. The highest terrace, the Kersey, was inferred to have been available for occupation no later than about 10,000 years B.P., but it could be older. The Kersey terrace is the same surface as the late

Wisconsin Broadway terrace, mapped in the Denver area, and the Pleasant Valley terrace was considered to be the same as the Kersey terrace by Holliday (1987), on the basis of downstream convergence of the two terraces. The next lowest, and younger, is the Kuner terrace, believed to date from about 3,000 years B.P. on the basis of its artifacts. The Kuner terrace-fill alluvium may correlate with Piney Creek Alluvium, although the deposits cannot be traced from one area to the other. The youngest and lowest terrace, the Hardin, is probably less than 1,000 years old (Holliday, 1987), similar in age to the youngest terraces in Nebraska. Alluvium in this terrace is probably equivalent, or slightly younger, than post-Piney Creek alluvium.

In the Laramie Basin of southeastern Wyoming only the lowest terrace above the Laramie River is considered Holocene in age, dated on the basis of modern bison bones and Native American artifacts (Mears, 1991). All higher terraces in that area can be dated as Wisconsin or older from included fossils, ash beds, or stratigraphic position.

The Holocene climatic record has been investigated extensively in a variety of studies. Proxy data such as sedimentation patterns, pedogenesis, changes in flora (mainly determined from palynomorphs), faunal changes, oxygen, hydrogen, and strontium isotopes, major-ion and trace-element geochemistry, and other data have been combined with radiocarbon and TL dates to establish a sequence of changes through the Holocene. Lakes are ideal laboratories for combining several methods of analysis, and several sites in the northern Great Plains have been studied (Smith and others, 1997; Valero-Garces and others, 1997; Xia and others, 1997; Laird, and others, 1998). In broad terms, the climate of the study area gradually warmed and dried in post-glacial time to a maximum at about 8,000 years B.P. Relatively hot and dry conditions persisted until about 5,000 to 4,000 years B.P., during which time eolian conditions dominated. After about 4,000 years B.P. temperatures again cooled and the area gradually stabilized to the subhumid to arid conditions that exist today (Barry, 1983). The climate has been quite variable in the last 10,000 years, swinging from hot and dry to cool and moist in a nonrandom, periodic manner, the most recent cycles being the Medieval Warm Period (about A.D. 800-1,200) and the Little Ice Age (about A.D. 1,400-1,850) (Stahle and Cleaveland, 1994; Campbell and others, 1998).

Mandel (1995) outlined a chronology of Holocene alluvial sedimentation and erosion in the central Plains. He noted that early, middle, and late Holocene alluvial fills are preserved in the larger streams, but that only late Holocene material is preserved along the small streams. As indicated above, the preserved sedimentary record in terraces is variable, even along the larger streams. In southeast Wyoming only one Holocene terrace has been recognized, whereas in Colorado as many as three Holocene terraces have been described, and in Nebraska as many as four Holocene alluvial sequences have been identified. Regionally, warmer and drier climatic conditions produced net erosion and removal of material from uplands and small valleys in the early to middle Holocene, from about 8,000 to 4,000 years B.P. (Mandel, 1995). This material was redeposited on alluvial fans and floodplains in the larger valleys. Deposition of alluvial fans along the Platte River was documented by Faulkner (1997, 1998). A moderate, more humid climate led to net deposition in valleys of all sizes in the region in the late Holocene. In an area on the south side of the river, southeast of the city of North Platte, buried soils at the base of alluvial fans on the Platte flood plain were dated at 9,600 years B.P., 3,300 years B.P., and 1,500 years B.P. The long time span represented by these soils indicates that the river in this reach was not only present in the current valley but that it has been stable through the Holocene, neither aggrading or downcutting significantly (Faulkner, 1998). This contrasts with the Republican River drainage, just to the south, which saw two periods of incisement in the Holocene (Martin, 1992a,b) and with the Kearney area, as shown by the presence of Holocene-age terraces that flank the river (section I, this report).

Several periods of Holocene drought have been documented by sedimentological studies of eolian strata in Nebraska by Ahlbrandt and others (1983), Mason and others (1997), and Muhs and others (1997); in northeastern Colorado by Forman and others (1992), Madole (1994, 1995), and Muhs and others (1996); and in Kansas by Arbogast (1996), Olson and others (1997), and Arbogast and Johnson (1998). Arid to humid cycles on the plains of Colorado and Nebraska, determined from pedogenesis, were outlined by Blecker and others (1997) and Kelly and others (1998).

Changes that most impacted man in the transition from Pleistocene to Holocene on the Great Plains were those related to changes in flora and fauna. In the late Pleistocene a boreal forest, composed of spruce in the east and pine in the west, extended across parts of the central Great Plains (Wells, 1970; 1983). As the glaciers retreated northward in the late Pleistocene, deciduous forests replaced the spruce forest in the eastern part of the region, and prairie grassland replaced the forest in the central and western parts (Wright, 1970; Wayne, 1991). In the dry middle Holocene grassland spread even farther east and northeast than it does today, but in the late Holocene the prairie border shifted westward to its present location (Hoffman and Jones, 1970).

Discussion and Summary

The drainage basin of the Platte River is a complex system that has undergone many changes in the last 65 million years. The Laramide Orogeny, lasting from about 75 to 35 Ma, established the fundamental structural framework of the east-central Rocky Mountains and adjacent plains. Mountain uplifts served as a source of both water and sediment that were transported eastward into a cratonic foreland basin. The Laramide ended at about the end of the Eocene Epoch, but renewed uplift in middle Miocene and Pliocene time rejuvenated source areas. Deposition of Tertiary and Quaternary sediments on the plains has depended on a balance between sufficient upland source areas and sufficient accommodation space in the basin to store the debris from the mountains and sediment transported into the area by wind.

In the Tertiary Paleocene Epoch, coarse clastics that became the Denver Formation, Green Mountain Conglomerate, and Dawson Formation were shed from the mountains and were trapped in small basins immediately adjacent to the Front Range. No Paleocene rocks are known from Nebraska, Kansas, or far eastern Colorado, and the assumption is that this area was a lowland region, starved of sediment, undergoing minor erosion. Several Paleocene formations in Colorado and Wyoming contain coal or lignite deposits, suggesting that the region was at a low altitude. Fossils of aquatic animals and rainforest flora support the interpretation of a warm, humid climate in this area during the Paleocene. The drainage of some basins adjacent to the mountains was probably internal; drainage patterns in the eastern part of the region are unknown.

Uplift of the mountain areas continued into the Eocene Epoch, but few formations of early or middle Eocene age are known in the region, suggesting that sediment bypassed the basin areas and was transported out of the region. An unconformable surface developed on top of previously deposited units, and a widespread erosion surface has been recognized in the Front Range. Two schools of thought have developed regarding the erosion surface—(1) the surface developed at a relatively high altitude and had low topographic relief, and (2) erosion reduced much of the area to near sea level, but that significant mountainous relief still existed. In late Eocene time the plains area again began to accumulate sediments—the Chadron Formation, mainly in Nebraska, and the upper Dawson Formation, Wall Mountain Tuff, and Castle Rock Conglomerate in the central and southern Denver-Julesburg Basin. In addition to basal conglomerates, the Chadron contains significant volumes of volcaniclastic material that was brought into the area by wind from source areas to the west. Fossils from Eocene units indicate that the climate remained warm and humid during this time. The regional slope was to the southeast in the late Eocene. In Colorado, a proto-South Platte River may be represented by the Castle Rock Conglomerate, and other southeast-oriented channels have been recognized in the northeast part of the State. In Wyoming and Nebraska, reconstructed late Eocene channels are also oriented mainly to the south-southeast, one of which probably was the proto-North Platte River. An early Laramie River was also established at this time.

Volcaniclastic material continued to be brought into the area during the Oligocene Epoch, and this material dominates the lithology of Oligocene formations. The Brule Formation and Arikaree Group were deposited over much of southeastern Wyoming, northeastern Colorado, and western Nebraska. Channels were incised into the fine-grained volcaniclastic material, and gravel and sand were carried away from mountain areas in the channels. Active uplift of the mountainous areas was interrupted in the Oligocene, and the mountains were partially buried in a combination of their own debris and wind-transported material from enormous volcanic centers in the Great Basin and Colorado. The climate in the Oligocene remained temperate, but some fossils suggest a slight cooling and drying from previous times. Reconstructed Oligocene drainage patterns indicate a shift to an eastward paleoslope for the region. In the early Oligocene the headwaters of streams were in the eastern Laramie Range and Front Range, but by the late Oligocene volcanic rock clasts from the western Front Range and North Park, Colorado, were transported across a filled Laramie Basin and across the Laramie Range to the plains. Oligocene rocks are absent over much of east-central and southeastern Colorado, making paleodrainage reconstructions in that area impossible.

Uninterrupted deposition continued into the Miocene Epoch, and sediments that formed the upper part of the Arikaree Group or Formation were deposited in southeastern Wyoming, northeastern Colorado, and western Nebraska. Wind-transported volcaniclastic material from western source areas was still an important constituent of lower Miocene rocks, although this material was reworked locally by streams. Volcanic eruptions diminished in middle Miocene time and the entire area underwent erosion, resulting in the beveling of previously deposited Miocene units and an erosion surface formed on older rocks in some mountain areas. In the middle to late Miocene a coarse-grained alluvial unit, the Ogallala Group or Formation, was deposited over a wide area from South Dakota to Texas and from the mountain front to eastern Nebraska and central Kansas. The Ogallala was deposited by a series of streams draining eastward from the Front Range and the Laramie Range. The coalesced gravel and sandy strata of the Ogallala form an important aquifer on the plains. Miocene climatic indicators suggest additional cooling and drying, although the Ogallala contains an abundant and diverse fauna, indicating generally favorable conditions for life on the plains. Paleo-drainage patterns in the Ogallala are complex, consisting of multiple generations of overlapping channels. Rhyolite clasts from volcanoes of the North Park area of Colorado were transported to the plains, indicating that Miocene streams flowed northeastward across the northern Front Range. The North Platte River was also established in the Saratoga Valley in Wyoming at this time. Anorthosite clasts from the Laramie Range indicate that streams flowed across the range from the west. A period of tectonic quiescence marked the end of the Miocene and an unconformity developed at the top of the Ogallala Group.

At the beginning of the Pliocene Epoch, the area east of the mountains consisted of a vast plain of low relief underlain by sediments of the Ogallala Group, which extended westward and lapped onto the mountains. In the Pliocene most of the region experienced gradual uplift, and sediments in areas adjacent to the mountains were excavated by large river systems. The Colorado Piedmont was carved out, and the Laramie Basin of southeastern Wyoming experienced erosion. The conglomeratic Nussbaum Alluvium is preserved on pediments and in terrace deposits in the Colorado Piedmont, but Colorado and southeast Wyoming have few other Pliocene units preserved. In contrast, Nebraska became a site of deposition in the Pliocene, as exemplified by the Broadwater Formation in the west and the equivalent Fullerton Formation and other unnamed units in central and southern parts of the State. These units consist of coarse gravels and less abundant siltstones that are preserved as terrace remnants in the west but as broad tabular units in the central and southern regions of Nebraska. The Pliocene climate was cool but relatively wet with a diverse fauna. The late Pliocene climate probably became increasingly unstable with the onset of glaciation. Following capture and diversion of the South Platte River to its present position, the Pliocene drainage system was similar to that in existence today, with only minor local shifting of channels. An exception was in eastern Nebraska, where the Platte River swung from north to south across the state, depositing a veneer of gravel and sand. In the latter part of the Pliocene, the Platte flowed in a channel south of its current position from about Dawson County southeastward toward the Missouri River drainage.

The transition from the Pliocene to the Pleistocene Epoch was marked by increasing climatic oscillations leading to times of colder and wetter conditions alternating with times of warmer and drier conditions. A result of these alternating conditions was a series of erosional and depositional cycles that are documented in stream terraces. Pleistocene deposits in Colorado are preserved in the Rocky Flats Alluvium, Verdos Alluvium, Slocum Alluvium, Louviers Alluvium, and Broadway Alluvium. Partially comparable alluviums and terraces are also present in southeastern Wyoming and Nebraska along the Platte system and other rivers. Pleistocene windborne deposits are present over much of the study area. Named loess units are the Walnut Creek Formation, Grafton and Beaver Creek Loesses, Loveland Formation, and Peoria Loess in Nebraska and partially equivalent units in Colorado and Kansas. Late Pleistocene-age dune sands also have been reported in some areas of Colorado and Nebraska. Most of the study area was relatively far removed from active glaciation during the Pleistocene and was therefore not subject to the extremes of local climate that existed in areas closer to the glaciers. Major differences between then and now were that spruce forest covered a good part of Nebraska and extended partially into Kansas, and mixed grassland and pine forest probably covered parts of eastern Colorado. A megafauna consisting of mammoths, mastodons, horses, camels, and giant forms of other animals still living occupied parts of the study area. The drainage pattern of the Platte system was similar to that of today, with the exception of the area from about Kearney to the mouth. On the basis of subsurface sediment distribution patterns, it appears that the Platte River shifted into its present position from about the western side of Dawson County to Kearney by early to middle Pleistocene time and that it continued flowing southeast from Kearney until late Pleistocene time. After deposition of the Loveland Formation, but before or shortly after the beginning of deposition of the Peoria Loess the lower reach of the Platte was captured and diverted into its present position downstream from Kearney.

The Holocene Epoch has seen a continuation of the erosional and depositional cycles along stream courses. In Colorado named Holocene units are the pre-Piney Creek alluvium, the Piney Creek Alluvium, and the post-Piney Creek alluvium that are gravelly deposits preserved in terraces along valley margins. Similar terraces have been identified in Wyoming and Nebraska. Much of the study area is covered with Holocene-age wind-blown deposits. In Nebraska, the Bignell Loess is present in many areas, and comparable units are scattered in Colorado and Kansas. The major Holocene eolian deposit is the Sand Hills of Nebraska and equivalent units in Colorado and Kansas. These dune fields probably began to form in the late Pleistocene, but full development of the Sand Hills didn't occur until the middle Holocene. The climate of the Holocene warmed and dried in several cycles, culminating in late middle Holocene time, and then cooled and became slightly less arid to the present time. The streams in the Platte River system have remained in generally the same position through the Holocene, shifting back and forth in their valleys.

A fundamental question is, what is the nature of the present Platte River in the Great Bend region that centers on Kearney, Nebraska? The idea that the Platte was an example of a braided stream was established by the 1930s (Lugn, 1935). Rust (1978a) proposed a simple classification system for river channels and defined a braided stream as having multiple, low sinuosity channels. Furthermore, he defined a braided river as one that is confined between valley walls and that covers most of the valley floor during floods (Rust, 1978b). Friedman and Sanders (1978) considered a braided river to have mainly sand and gravel as bedload, to have formed on surfaces of moderate to high slope, and to have a higher percentage of longitudinal bars as compared to transverse bars as bedforms. Blatt and others (1980) distinguished proximal and distal braided streams, depending on whether the dominant bedload was gravel or sand. Braided streams in general were said to have higher slopes than meandering streams, have a variable discharge that affects the ability of the stream to carry coarse material in times of low flow, and to have bank materials that are easily eroded (Blatt and others, 1980; Walker and Cant, 1984).

Ore (1964) conducted one of the earliest studies that attempted to quantify the nature of braided streams using the South Platte and Platte Rivers as examples and observed that braiding occurs under two conditions—(1) when a stream is unable to transport the coarsest fraction of bedload in a given reach and longitudinal bars develop or (2) in waning flow conditions, when transverse bars are dissected. Smith (1970, 1971a,b) considered the South Platte and Platte Rivers as one of the best known examples of braided rivers. He found that grain size decreased, sorting increased, and that the proportion of transverse to longitudinal bars increased downstream in the Platte. Miall (1977) considered the Platte a distinctive type of braided stream. Viard and Breyer (1979) studied grain size distributions in sediments of the Platte. Blodgett and Stanley (1980) described the stratification types of the river under high and low flow regimes. A historical review of the South Platte River by Nadler and Schumm (1981) indicated that the river was a classic braided river in the mid- to late 1800s but that climatic fluctuations and man's activities have drastically changed the river. Karlinger and others (1983) noted that the channel types of the Platte River include single broad channels, multiple well-defined channels, or in an intricate mix of small channels and numerous islands. Schumm (1999) outline a sequence of changes to the Platte in two reaches—(1) from North Platte to Kearney and (2) from Kearney to Grand Island. The river originally changed from a braided channel to an anastomosing channel in the respective reaches, but both reaches are now characterized as having single-island braided channels (Schumm, 1999).

Two key observations are (1) the Platte system is large, draining a significant portion of both the mountains and plains of northeastern Colorado and southeastern Wyoming, and (2) it is only one of two rivers (the other being the Arkansas) in Colorado and Wyoming that breach the western escarpment of the Ogallala Group and flow above the Ogallala on the plains (fig. 1). It was noted previously that both the Arkansas and Platte Rivers flow at higher elevations than rivers between them that head on top of the Ogallala surface. This is a result of the greater sediment load of these rivers, the Platte more so than the Arkansas because of its larger drainage basin, and this condition has persisted through the Pliocene and Pleistocene to the present. Nebraska became the locus of deposition of much of the material eroded from the Front Range, Laramie Range, and Medicine Bow Mountains through the last 5 million years, and the Platte built up a large aggradation plain in south-central to eastern Nebraska.

Lugn (1935) emphasized that the Platte River cannot be thought of in the traditional manner of a stream occupying a valley cut into bedrock. Rather, just the opposite has occurred—paradoxically the valley was superimposed on the river. Prior to deposition of the Peoria Loess the Platte was flowing, generally unconfined by valley walls, on a relatively flat alluvial plain. This alluvial plain was, in part, the result of disruption of the stream system in eastern Nebraska by glaciers that caused a rise in local base level and foundering of the Platte in its own bedload material. The Platte was in its approximate present position when the Peoria Loess and later eolian units were superimposed on the river, and the Platte was essentially confined by loess to its valley through south-central Nebraska. During deposition of the loess the Platte merely maintained its valley by removing loess that fell in the regions of active channels while the loess piled up in adjacent areas. Since that time, the Platte River has aggraded its valley at times and has incised into its valley at other times in response to short-term climatic cycles, migrating back and forth across the valley and leaving terraces as evidence of its activity. Movement of dunes in the Sand Hills across the Platte River Valley throughout the Holocene must have added large amounts of sand to the river, contributing to the erosion/aggradation cycles. The underlying Pliocene and Pleistocene gravel beds also contribute bed load material during lateral migrations of the river, further complicating characterization of the river. This makes the Platte River, if not unique, then at least an unusual example of a braided river, and not easily comparable to other rivers.

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