

Reconstructing the Quaternary Depositional History Using Geologic Mapping and Three-Dimensional Modeling of the Subsurface Near Fort Morgan, Northeastern Colorado

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Cover. Quaternary geologic map of the study area.

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By Emily M. Taylor, Margaret E. Berry, Shannon A. Mahan, and Jeremy C. Havens

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Conversion Factors

International System of Units to U.S. customary units		
Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Abbreviations

3D	three dimensional
ka	thousand years
lidar	light detection and ranging
NRCS	Natural Resources Conservation Service
OSL	optically stimulated luminescence
USGS	U.S. Geological Survey

Abstract

Centered on Fort Morgan, Colorado, this study is intended to build from previous work by adding a three-dimensional (3D) view of the subsurface to better understand the depositional history of Quaternary deposits. A 1:100,000 scale geologic map was made by combining previous geologic maps, regional soil maps, and recent field investigations. In addition to the geologic mapping, drill hole lithologic data from water wells and oil and gas exploration were compiled and lithologic units simplified to best represent the stratigraphy of the Quaternary deposits. From these subsurface data, a 3D subsurface model was constructed, trimmed at the surface by a digital elevation model, and a bedrock surface gridded from drill hole data was added. The surface of the 3D model was then compared visually to the surficial geologic map. Cross sections were constructed from the 3D model and compared to site-specific drilling that was done as part of this project. Finally, the model was examined in detail to reconstruct the depositional history of the subsurface alluvial and eolian units. Alluvial and fluvial drainage basins exposed in the subsurface have a greater areal extent than the present-day narrow drainages. Older eolian sand in the subsurface tends to be interbedded with loess indicating coeval deposition. Holocene sand, both eroded from bedrock exposed at the surface north of the study area and reworked from the South Platte River, buries most of the interbedded older sand and loess.

Introduction

Surficial geologic mapping has been done extensively in the United States, but such efforts have traditionally not included three-dimensional (3D) modeling. Here, we explore the use of 3D modeling paired with conventional surficial geologic mapping. The study area is centered on Fort Morgan, Colorado (fig. 1A), and was selected to reconstruct the depositional history of the regional Quaternary geology. Fort Morgan is about 130 kilometers northeast of Denver on the eastern plains of Colorado, within the Colorado Piedmont (Madole, 1995). The study area is an agricultural area focused on the cattle industry including both dairy and meat production. The area has a long, complex history of settlement and water use (Condon, 2005). The study area is within the drainage basin of the east-flowing South Platte River, a once intermittent drainage that is now engineered to a perennial drainage (Eschner and others, 1981; Condon, 2005). Oil and gas wells in open range land are common north of the South Platte River.

This area is ideal for the purposes of this investigation, because the geologic units tend to be lithologically distinct and can be identified with the geomorphic processes that produced them. In the simplest terms, gravelly sand units are dominantly from fluvial systems, sandy units are typically of eolian origin and reworked from local fluvial deposits, and silt-rich units are loess deposits derived from more regional sources. All of these deposits can serve as proxies to determine dominant paleoclimatic conditions.

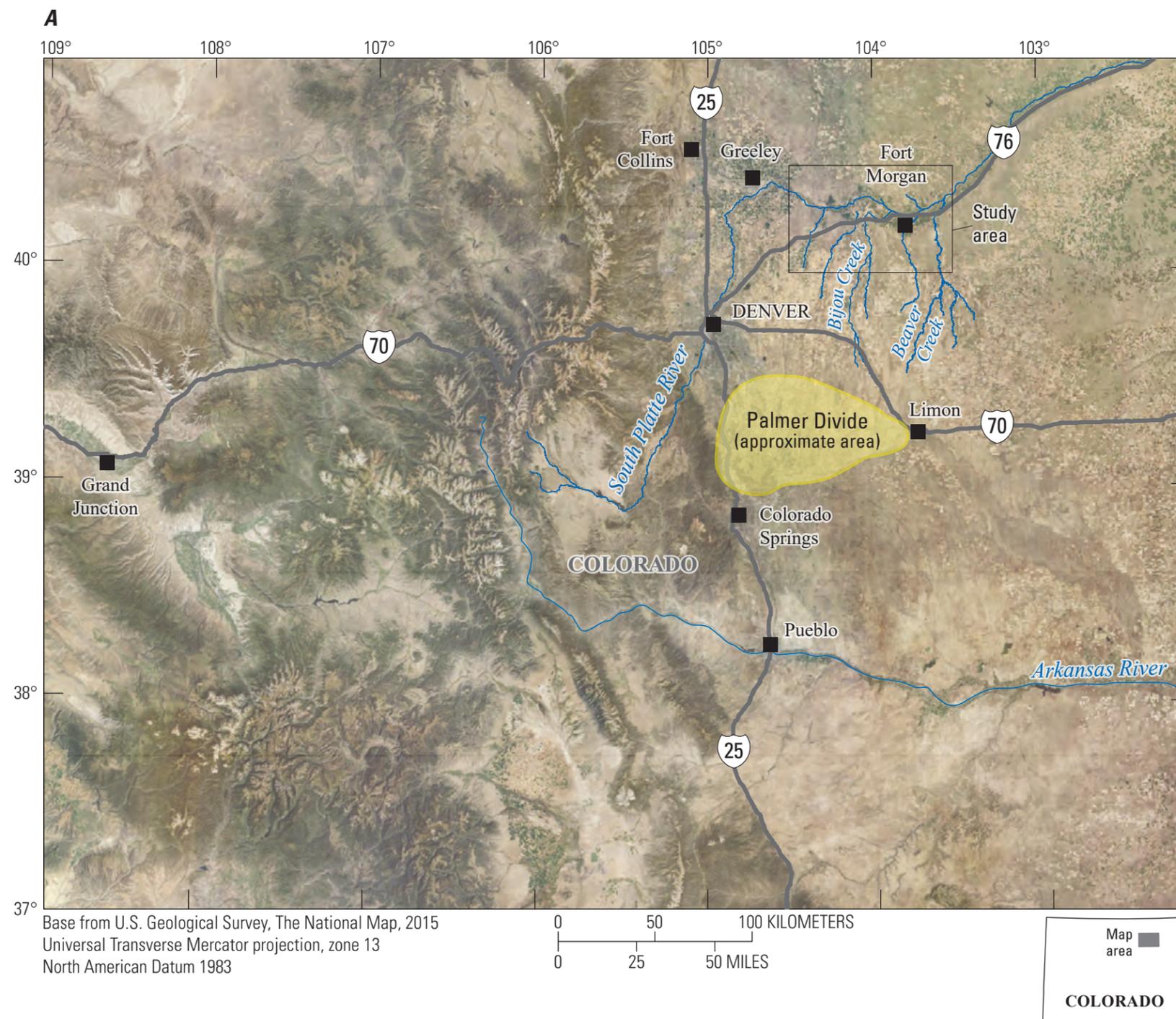
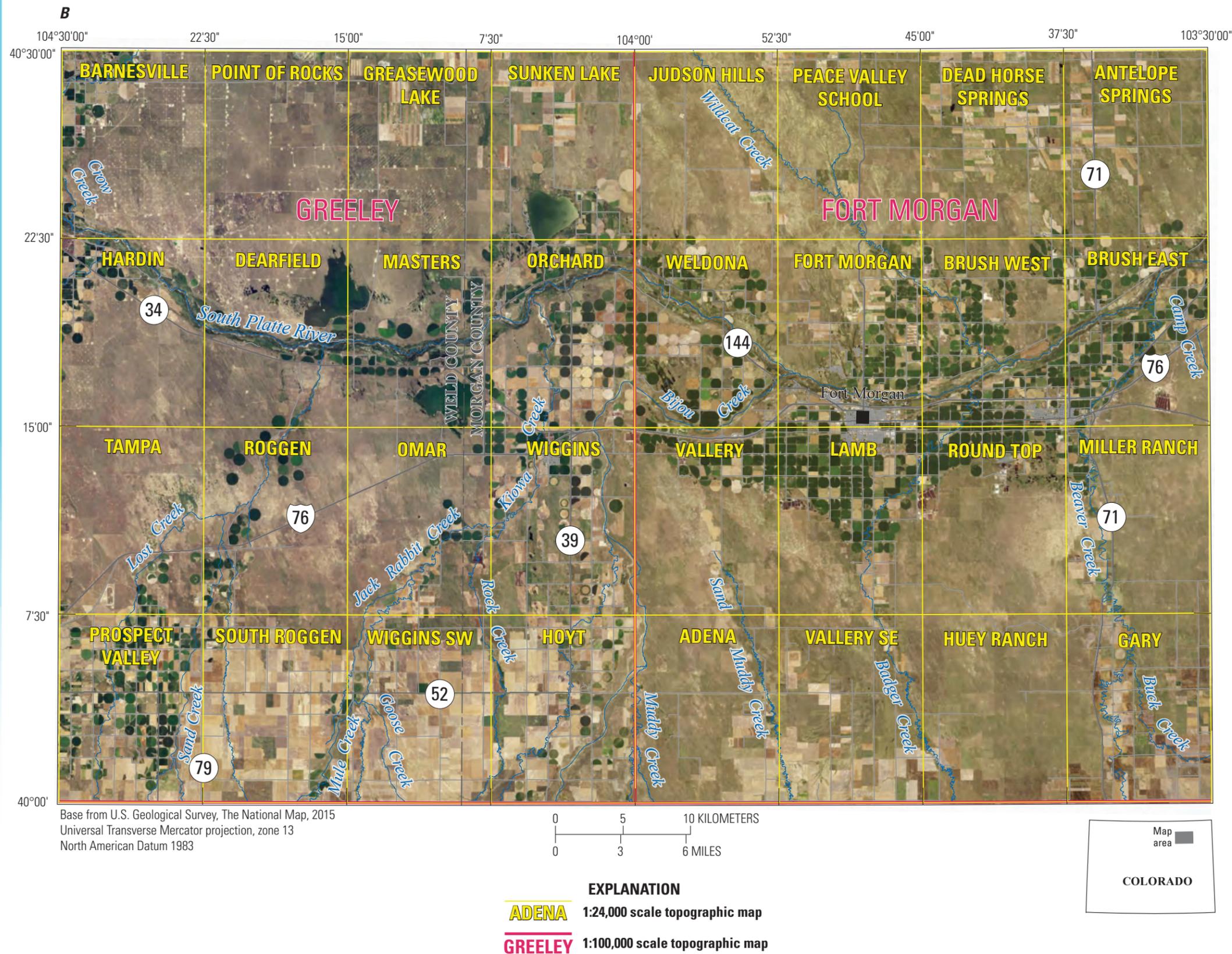


Figure 1. Map showing A, Location of the study area in northeastern Colorado; and B, Boundary of the study area centered on Fort Morgan, Colorado.



A surficial-geologic map was created, using soil morphology as a guide, to distinguish lithology and deposit age. The geologic units provided the generalized geology that was extended to the subsurface. A 3D model was constructed using data from water wells and oil and gas drill holes. Subtleties in lithologic characteristics are often difficult to interpret in drillers' nomenclature. However, the differences between fluvial gravel, eolian sand, and fine-grained silts (loess) can usually be recognized in drillers' records. After a satisfactory 3D model was produced (one where the intersection of the topographic surface reasonably matched the surficial geologic map), the model was examined in detail to interpret the depositional history. Cross sections were created from the 3D model and shallow drill holes were drilled to generate field-based cross sections to compare to the 3D model. Surficial geologic mapping and the 3D modeling were used to reconstruct the depositional history of the Quaternary sediments in the study area.

The mapped area covers the eastern half of the Greeley and the western half of the Fort Morgan U.S. Geological Survey (USGS) 1:100,000 scale topographic maps (USGS, 1982 and 1980, respectively). This area includes 32, 1:24,000 scale USGS topographic quadrangles. The study area (fig. 1B) includes the southeastern corner of Weld County and all of Morgan County. In this area, relatively thin Quaternary deposits unconformably overlie Paleocene and Upper Cretaceous bedrock. The thickness of the Quaternary deposits range from less than 1 meter (m) to a maximum of about 50 m.

The South Platte River originates in the mountains west of Colorado Springs, flows northward through Denver, turns east near Greeley, and ultimately joins the North Platte River in western Nebraska. The modern drainage system was developed in the middle Miocene (Izett, 1975) and the present landscape of the southern Rocky Mountains and the western Great Plains has evolved since the beginning of the Pliocene, about 5 million years ago (Condon, 2005). Tributary drainages flow northward into the South Platte River; the largest tributary is Bijou Creek that originates at the Palmer Divide, a caprock escarpment east of Colorado Springs that separates the Arkansas River Basin from the South Platte River Basin (fig. 1A). At the mouth of Bijou Creek, a large fan has deflected the South Platte River northward in the vicinity of Fort Morgan (fig. 1B, centered on the Orchard and Weldona 1:24,000 scale topographic maps).

Figure 1.—Continued

Previous Work—Soil and Geologic Mapping

Published geologic maps (fig. 2) in the study area include 1:250,000 scale map of the Greeley (Braddock and Cole, 1978) and, 1:24,000 scale maps of the Masters, Orchard, Weldona, and Fort Morgan quadrangles (Gardner, 1967; Berry and others, 2015a, b, 2018a, b). Northeast of the study area, geologic mapping includes 1:250,000 scale map of the Sterling area (Scott, 1978, 1982). Regional mapping also includes a geologic map derived from soil mapping and centered on Fort Morgan (Muhs and others, 1999b). The geologic map of the Denver West 30'x60' quadrangle (Kellogg and others, 2008) provided useful perspective on the regional stratigraphic units. Lindsey and others (2005) provided detailed descriptions of the evolution of alluvial deposits along the South Platte River west of the study area. These maps vary in detail, but all share similar geologic map units that were used for a basic understanding about the study area. Berry and others (2018a, 2019) provides a summary of the dating history of Quaternary deposits in the region. Detailed digital soil maps of Weld and Morgan Counties were also an important resource (Natural Resources Conservation Service, 2015). The detailed soil units were used in conjunction with the previous geologic mapping at a 1:24,000 scale. Soil mapping units were correlated to geologic mapping units where both were available and then extrapolated over the entire study area.

The following brief summary describes the previously published map units pertinent to this study and table 1 presents a comparison of stratigraphic nomenclature used for Quaternary deposits in the Fort Morgan, Colorado, area. For a more comprehensive discussion on the physical characteristics of these deposits, including their ages, readers are referred to Berry and others (2015a, b, 2018a, b, 2019). Detailed unit descriptions for this study are provided in the “Methods” section of this report.

Young alluvium is found along the South Platte River and its tributaries (Braddock and Cole, 1978; Scott, 1978; Lindsey and others, 2005; Berry and others, 2015a, b, 2018a, b). In the detailed mapping of Berry and others, young alluvium is subdivided. The young alluvium is early to late Holocene with minimal degrees of soil development (A/C to A/Bw/Bk/C profiles). These Holocene units are commonly referred to as “post-Piney Creek Alluvium” and “Piney Creek Alluvium.”

Intermediate-aged alluvium occurs as an extensive, broad, flat terrace surface 20–30 m above the active drainages. This alluvium, mapped as Broadway Alluvium, also interfingers with distal alluvial fan deposits of Bijou Creek (Scott, 1978; Berry and others, 2015a, b, 2018b). Broadway Alluvium is considered coeval with the Pinedale glaciation (Berry and others, 2015a, b, 2018b, 2019). Soils typically have an A/Bt/Bk/Cox profile with a stage II secondary carbonate accumulation. Carbonate terminology is from Gile (1966).

Older alluvial deposits that are early to middle Pleistocene are mostly buried but are locally exposed in gravel quarries, along canals, and in gully and arroyo walls. These older deposits have been mapped as, or correlated with, Louviers Alluvium, Slocum Alluvium, Verdos Alluvium, and Rocky Flats Alluvium (Gardner, 1967; Scott, 1982; Lindsey and others, 2005; Kellogg and others, 2008; Berry and others, 2015b, 2018a, b). Soils developed on these deposits typically have an A/Bt/Bk(K) profile with a stage II–IV secondary carbonate accumulation in the Bk(K) horizon.

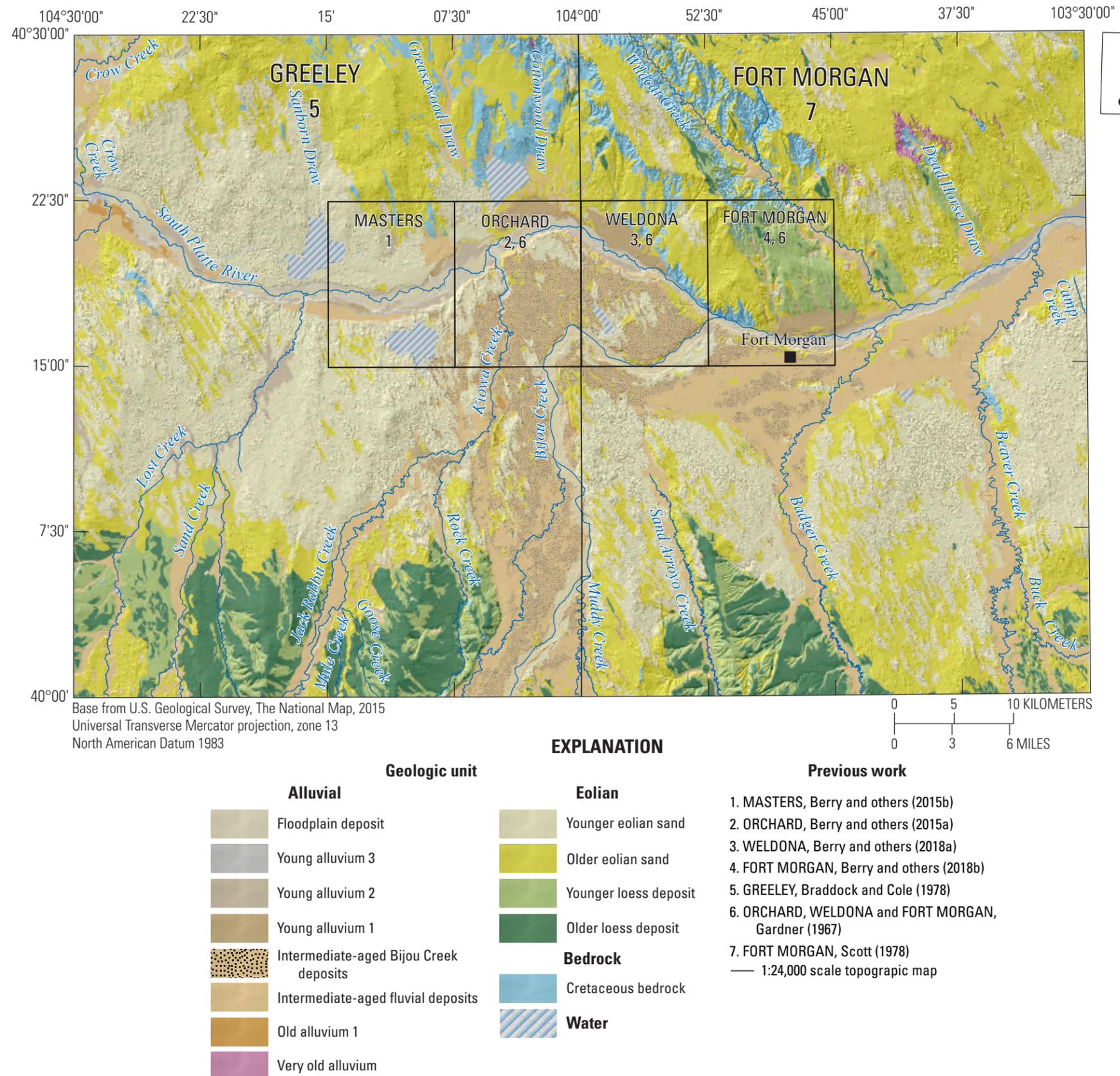


Figure 2. Map of the study area showing locations of previous geologic mapping studies.

Table 1. Comparison of Quaternary stratigraphic nomenclature in the Fort Morgan area.

[Soil characteristics including typical profile, approximate height above active floodplain, and estimated thickness modified from Berry and others (2018b) and Soil Survey Staff (2010). Ma, million years; ka, thousand years; ~, approximately; —, no data; >, greater than; ≤, less than or equal to; ±, plus or minus]

Marine isotope Stage	Geologic series age estimate or correlation to mountain glaciations (Ma, ka) ¹	Age estimate (Ma, million years; ka, thousand years)				Map units						Typical soil profile (carbonate morphology)	Approximate height above active floodplain	Estimated thickness	
		Berry and others (2018b, and references therein)	This study	Kellogg and others (2008, and references therein)	Kellogg and others (2008, and references therein)	Braddock and Cole (1978)	Scott (1978)	Gardner (1967)	Berry and others (2018b)	Simplified from Braddock and Cole (1978), Scott (1960 and 1982), Gardener (1967), Kellogg and others (2008), and Berry and others (2015a, 2015b, 2019, 2018a, and 2018b)	This study				Modified from Berry and others (2018b) and Soil Survey Staff (2010)
Fluvial deposits, Holocene 0–11.7 ka															
—	late Holocene (0–4.2 ka)	late Holocene	—	1,500–0 yrs ago	Qa	Qa	Qal	Qpp	Qaa	post-Piney Creek alluvium (active floodplain)	Qfp	A/C, A/AC/C	floodplain	3–5 m	
—	late Holocene (0–4.2 ka)	late Holocene	—	1,500–0 yrs ago	Qa	Qa	Qal	Qpp	Qa1	post-Piney Creek alluvium (occasionally flooded)	Qay3	A/C, A/AC/C	1.5 m	3–6 m	
—	late Holocene (0–4.2 ka)	late Holocene	—	1,500–0 yrs ago	Qa	Qa	Qal	Qpp1	Qa2	post-Piney Creek alluvium (occasionally to rarely flooded)	Qay2	A/C, A/Bw/C	3 m	3–6 m	
—	middle Holocene (4.2–8.2 ka) to early Holocene (8.2–11.7 ka)	>5–6 ka (top), 9–12 ka (base)	—	1.1–2.2 ka, 1.9–3.9 ka	Qa	Qa	Qal	Qp	Qa3	Piney Creek Alluvium	Qay1	A/Bt/Bk (stage I–II)	3–6 m	2–6 m	
2	coeval with Pinedale glaciation (13–15 to >31 ka) ²	15–11.5 ka (upper section)	—	30–12 ka	Qb	Qg	Qb (lower member)	Qb	Qba (main-stream)	Broadway Alluvium (mainstream or lower member)	Qao2	A/Bt/Bk/C (stage II)	15–18 m	12–30 m	
Fluvial deposits, late Pleistocene 11.7–126 ka															
2	coeval with Pinedale glaciation (13–15 to >31 ka) ²	17–12 ka (upper section)	—	—	—	—	Qb (upper member)	Qbf (Bijou Flats)	Qbs (side-stream)	Broadway Alluvium (sidestream or upper member)	Qa-o2s	A/Bt/Bk/C (stage II)	21–27 m	6 to >18 m	
Fluvial deposits, middle Pleistocene 126–781 ka															
6	coeval with Bull Lake glaciation (≤130–190 ka) ²	190 to ≤130 ka	—	170–120 ka	Qlv	—	Ql	Ql	Qlv	Louviers Alluvium (not exposed at surface)	Qao1	A/Bt/Bk (stage II–III)	—	35–45 m	
8–10	pre-Bull Lake glaciation (>190 ka)	382 ±16 ka, 334 ±9 ka	—	390–320 ka	Qs	Qgo	Qs	Qs	Qai	Slocum Alluvium	Qao1	A/Bt/Bk/K (stage III), some weathered granite clasts	21–25 m, 32–40 m	4–12 m	
12	—	~640 ka	—	475–410 ka, 675–610 ka	Qv	—	Qv	Qv	Qv	Verdos Alluvium (usually buried, exposed in gravel pits and canals)	Qao1	A/Bt/Bk/K (stage III–IV)	49–55 m	6–8 m	
Fluvial deposits, early Pleistocene 781 ka–2.58 Ma															
—	—	2–1.5 Ma	—	2–1.4 Ma	QNr	—	Qrf	Qrf	Qao	Rocky Flats Alluvium (not exposed at surface)	Qao1	A/Bt/K (stage III–IV)	65–70 m	15–20 m	
Fluvial deposits, Quaternary–Tertiary 781 ka–greater than 2.58 Ma															
—	—	late Pliocene and early Pleistocene (?)	—	~3 Ma	QNpr	—	Qn	Qn	QNn	Nussbaum Alluvium (often cemented sandstone that overlies Pierre Shale)	Qta	Bt/K (stage III+)	122–137 m	7–21 m	
Eolian deposits, Holocene 0–11.7 ka															
1 (?)	late Holocene (0–4.2 ka) and middle Holocene (4.2–8.2 ka)	~1.4 ka, 8–4 ka	—	<1.5 ka	Qes	Qe	Qes	Qsh	Qes	Eolian sand (young, common buried soils)	Qe2	A/C, A/AC/C	—	≤10 m	
Eolian deposits, late Pleistocene 11.7–126 ka															
3(?)	late Pleistocene	<31–26 ka (possibly as young as 13–12 ka)	—	11–4.5(?) ka, 27–11 ka	Qes	Qe	Qes	Qsh	Qes	Eolian sand (old, common buried soils)	Qe1	A/Bt/Cox to Bt/Bk (stage I–II)	—	—	
2	late Pleistocene and/post Pinedale glaciation	late Pleistocene	16.00 ±0.24 ka, 15.42 ±0.77 ka, 14.90 ±0.55 ka, 12.69 ±1.53 ka	13–10 ka, 20–14 ka	Qes	Qe	Qp	Qpb	Qel	Peoria Loess and Bignell Loess	Ql2	A/C, A/Bk/C to A/Bt/Bk/C (stage I–II)	—	6–9 m	
Eolian deposits, middle Pleistocene 126–781 ka															
6–5e	Late (?) Bull Lake glaciation	middle Pleistocene	>82.96 ±47.69 ka, >80.72 ±17.85 ka	170–120 ka	Qes	—	Qll	Qll	Qlg	Loveland Loess (?)	Ql1	—	—	—	
Bedrock															
—	Upper Cretaceous	—	—	—	Kl	Kl	Kl	—	—	Laramie Formation	Ku	—	—	—	
—	Upper Cretaceous	—	—	—	Kf	Kf	Kf	—	—	Fox Hills Sandstone	Ku	—	—	—	
—	Upper Cretaceous	—	—	—	Klf	Klf	—	—	—	Laramie Formation and Fox Hills Sandstone	Ku	—	—	—	
—	Upper Cretaceous	—	—	—	Kp	Kp, Kpu, Kpm, Kpl	Kpt	Kp	Kp	Pierre Shale	Ku	—	—	—	

¹Ages for time divisions are from Walker, J.D. and others (2012), Walker, M.J.C., and others (2012), and Cohen and others (2013). Subdivisions of the Holocene are informal divisions advocated by Walker, M.J.C., and others (2012).²Refer to Berry and others (2018b) and references cited therein for a summary of Pinedale and Bull Lake glaciations.

A late Pliocene and early Pleistocene (?) unit, the Nussbaum Alluvium, is exposed at the surface north of the South Platte River and in gravel quarries north of Fort Morgan. Most exposures are too small to map at the scale of this publication. This deposit is characterized by carbonate- and silica-cemented gravel and pebbles, although not all secondary carbonate and silica cement in this deposit is necessarily pedogenic. A large component of the cement is likely derived from groundwater precipitation. The Nussbaum Alluvium often overlies bedrock. Soils developed on this alluvium lack a preserved A horizon. Characteristic soil horizons are Bt/K with stage III+ secondary carbonate accumulation.

Scott (1982) used the elevations of the Nussbaum Alluvium through the Slocum Alluvium gravel deposits to reconstruct elevations of paleovalleys of the South Platte River. The gravel deposits were laid down on the ancient valley floors between the times when the South Platte River periodically incised. These deposits are not superposed but form distinct terraces as morpho-stratigraphic units. The oldest unit in this study, the Nussbaum Alluvium, is topographically the highest terrace and the farthest from the active drainage. Below the Nussbaum Alluvium, the Rocky Flats Alluvium, Verdos Alluvium, and Slocum Alluvium descend in elevation toward the South Platte River.

In previous quadrangle-based mapping, eolian deposits are subdivided into eolian sand and loess. Eolian sand is informally subdivided into possible Holocene and Pleistocene deposits only on the more recent 1:24,000 scale maps (Berry and others, 2015b, 2018a, b). Holocene eolian sand deposits have little or no soil development (A/C or A/AC/C profiles) and occur as dunes that often bury older late Pleistocene eolian sand dune deposits. The degree of soil development on older eolian sand is significantly greater with an A/Bt/Bk/Cox soil profile with stage I–II secondary carbonate accumulation in the Bk horizon.

The fine-grained loess at the surface is mapped as late Pleistocene Peoria Loess (Scott, 1978; Berry and others, 2018a) and is thought to be correlative to the later stages of Pinedale glaciation, based on radiocarbon dating (Muhs and others, 1999a). Gardner (1967), Scott (1978), Muhs and others (2008), and Berry and others (2018a) also recognized middle Pleistocene loess deposits that could correlate to Loveland Loess, considered coeval with the Bull Lake glaciation. Soils developed on Peoria Loess are weakly to moderately developed with a typical A/C to A/Bt/Bk/C profile with stage I–II secondary carbonate accumulation.

Methods

The study area is large and has a very subdued topography. In conjunction with field work, a combination of analysis, interpretation and simplification of regional soil maps were used to construct a Quaternary geologic map. Existing drill hole data were simplified to create a 3D lithologic model of the subsurface. These subsurface lithologic units are correlated to the surficial geologic map units. Cross sections were constructed from the 3D model and are used to locate drill holes to compare field evidence with the subsurface model. The model also served to reproduce the distribution and timing of individual depositional units at depth in the study area.

Mapping Quaternary Deposits Based on Natural Resources Conservation Service Maps, Field Investigations, and Previous Mapping

Digital soil maps from the Natural Resources Conservation Service (NRCS) served as the basis for the geologic map compilation. The NRCS data were imported into ArcGIS 10.4 software. The study area includes data from all of Morgan County and the southeast corner of Weld County (NRCS, 2015). A certain amount of variability in mapping style is expected because NRCS soil scientists responsible for mapping differ from county to county. Therefore, some effort is required to create consistency between the Weld County and Morgan County maps for the purpose of making an internally consistent geologic map. Initially, soil nomenclature inconsistencies were resolved between the two counties and a map was created of the distribution of individual soil series by soil name (fig. 3). Because geomorphic processes have an important effect on soil development through deposit composition, age, and slope position, simplified soil maps provide a general overview of the distribution of landforms including drainages, associated terraces, and alluvial fans. Three criteria are used to determine whether individual soil series are developed in alluvium, eolian sand, or silty-clay loess: (1) position in the landscape, (2) shape and orientation of individual deposits on soils maps, and (3) associated soil series (Madole and others, 2005). Relative age of individual soils can be determined from the associated NRCS laboratory data by first grouping soils by parent material, then comparing soil horizonation or typical soil profiles, thickness of the B horizon, and abundance of secondary carbonate. These are all soil properties that have been shown to vary with soil age (Birkeland and others, 1991; Birkeland, 1999).

Numerous other approaches were used to identify and link soil properties and Quaternary geologic mapping units. This report provides two examples of the approaches used: “soil great groups” and “slope and dominant soil texture” (Soil Survey Staff, 1999).

The distribution of soil great groups makes a few important geologic distinctions. For this discussion, the soil great groups have been simplified to soil orders. The only major soil orders in the study area are Entisol and aquic soils in blue and purple, Mollisols in green, and Aridisols in pale yellow (fig. 4). Alfisols, in pink, are a minor component in the study area.

South of the South Platte River, Entisols generally correspond to young eolian sand units. Aridisols in Weld County and Mollisols in Morgan County (fig. 1B) correspond to finer-grained, older (Pleistocene), eolian sheet sands found in interdune areas. North of the South Platte River, both Entisols and Mollisols are mapped on older eolian sand units. This discrepancy in the soil types associated with eolian sand is likely an artifact of a difference in county mapping styles. Aridisols and Mollisols are also developed on alluvium, including both terrace alluvium and distal alluvial-fan deposits on the Bijou Creek fan.

Soil texture visually differentiates clayey (blue map units on fig. 5), loamy (dark green map units on fig. 5), sandy loam (pale green map units on fig. 5) and sandy (yellow map units on fig. 5) textured soils, where texture is based on the particle size distribution of the best developed B horizon, if one is present, or the uppermost C horizon if no B horizon is present. With a few exceptions, loamy soils define the boundaries of the loess highlands. Sandy textures are confined to sand

dunes, whereas older interdune areas often have soils with loamy sand textures. Sandy loam and clayey loam textures are associated with soils developed on fine-grained alluvium. Boundaries between the clayey alluvial soils and the sandy dunes are clear along the South Platte River, in and east of Fort Morgan.

Because the topography is relatively flat in the study area, slope angles greater than 5 degrees were measured from a digital elevation model (U.S. Geological Survey, 2015) and displayed on large-scale maps to use in the field to help find natural or artificial exposures, including quarries and road cuts to investigate. The efforts revealed that areas with slope angles greater than 5 degrees are typically very young parabolic sand dunes (figs. 5 and 6A). The largest fields of such dunes are south of the South Platte River, but dunes also occur north of the river. These young parabolic dunes have arms that point to the northwest and noses that slope to the southeast, indicating a predominant sand-transporting paleowind direction from the northwest (fig. 6A). Assuming that historical wind data from Fort Morgan (fig. 6B) are a good proxy for direction of parabolic dune formation, dune formation appears to be affected primarily by infrequent strong winds from the northwest rather than the predominant (that is, most frequent) wind direction from the west-southwest. Most of these very windy days occur during the winter and early spring (fig. 6C) when vegetation is dormant, and deposits are vulnerable to wind erosion.

Field work and interpretation of orthoimagery, including quality-level 2 light detection and ranging (lidar) data (1-foot resolution) from the 2013 South Platte River Flood Area 1 lidar dataset (U.S. Geological Survey, 2015) and National Agriculture Imagery Program orthoimagery (U.S. Department of Agriculture Farm Service Agency Aerial Photography Field Office, 2009, 2011, 2013, 2015), were combined with previous mapping efforts (Gardner, 1967; Braddock and Cole, 1978; Scott, 1982; Natural Resources Conservation Service, 2015; Berry and others, 2015a, b, 2018a, b) to associate soil characteristics with Quaternary map units (fig. 7, table 2). These map units are based primarily on the previous mapping efforts. The process of correlating individual soils to unique map units involved an understanding of soil processes and how they can be used to identify parent material, relative soil age, and environment of deposition. These techniques have been used by previous geologic mappers (refer to examples in Birkeland, 1999). Our emphasis in this study is to generalize the surficial geologic mapping units over a large area so that we can extend our understanding of the depositional history to the subsurface. In the coarsest sense, the simplified soils separate the fluvial, alluvial, eolian sand, loess, and bedrock units.

Fluvial and Alluvial Deposits

Fluvial deposits are defined here as “sediment deposited by a stream that, in the study area, tend to be the confined to the main channel.” Surficial fluvial deposits are confined to the South Platte River, Wildcat Creek, and the north-flowing drainages (fig. 7). Texturally, fluvial deposits are gravelly with a fine-grained sand and sandy loam matrix. Alluvial deposits are a more general term for a heterogeneous mixture of sediments transported by water.

Soils that developed in fluvial deposits (Aquolls and Aquent; fig. 3, tables 1 and 2) adjacent to the South Platte River, are clearly distinguished from the young sandy soils that flank the drainage to the north and south (Valent soil; fig. 3). Floodplain deposits, Qfp, are immediately adjacent to the active drainages and are less than 1.5 m above the active drainage. Floodplain deposits are best expressed along the South Platte River, and have no soil development or only an A/C soil profile (Bankard and Riverbank soils; fig. 3, tables 1 and 2). These soils are typically unconsolidated Entisols or Inceptisols and are seasonally flooded. Unit Qfp is also mapped along Bijou Creek. Although this unit may be present adjacent to the lesser north-flowing tributaries, it is not mappable at a similar scale. Unit Qfp is late Holocene (table 1).

Adjacent to the South Platte River, three young alluvial units, Qay3, Qay2, and Qay1, occur as inset terraces 1.5 to 6 m above Qfp (table 1). About 1.5 m above the South Platte River, the youngest terrace (Qay3) typically has an Entisol or Inceptisol with an A/C or A/Bw/C profile developed in the alluvium (Aquent and Aquent; table 2). Unit Qay3 occurs as narrow bands adjacent to Qfp and is occasionally flooded. Unit Qay3 is late Holocene (table 1).

Unit Qay2 is about 3 m above the South Platte River and is occasionally to rarely flooded. Unit Qay2 is characterized by an Entisol (Las), or more commonly a Mollisol (Aquolls, Loup, and Wann soils), developed on the surface. These soils have an A/C (Entisol) to A/Bw/Bt (Mollisol) profile. The presence of the weakly consolidated Bt horizon indicates surface stability and the secondary accumulation of pedogenic clays. Unit Qay2 is late Holocene (table 1).

Unit Qay1 is from 3 to 6 m above the South Platte River. The largest exposure occurs in the distal faces of the Bijou Creek fan (Qao2s) that has been eroded by a previous higher stand of the South Platte River. Unit Qay1 is mappable because of its unique elevation in relation to the active drainage. With the exception of its relative position, soils developed on Qay1 are indistinguishable from soils developed on Qao2s, suggesting that the deposition of terrace sediment of Qay1 was close in time to the deposition of the sediment of Qao2s. Soils developed in alluvium coeval with Qay1 have variable morphologies (Fort Morgan, Gilcrest, and Heldt soils; table 2), but they typically have an A/Bt/Bk/C soil profile with stage I–II secondary carbonate accumulation. Accumulations of secondary clay and carbonate indicate a longer period of pedogenesis and therefore a longer period of terrace stability. Thus, unit Qay1 is interpreted to be middle to early Holocene (table 1).

Intermediate-aged fluvial deposits, units Qao2s and Qao2, form fans and terraces and have a similar degree of soil development as unit Qay1 along the South Platte River. Unit Qao2s is fluvial and associated with the Bijou Creek alluvial fan discussed above. The Bijou Creek alluvial fan forms a distinctive deposit in the center of the study area (fig. 7). Unit Qao2 is a fluvial terrace comprised of alluvium associated with the South Platte River and tributary drainages. Both Qao2s and Qao2 have similar soils developed on them. The parent material of soils developed on the fan deposits of unit Qao2s is much finer grained than that of unit Qao2 deposits of the South Platte River and its tributaries. Loamy soils (Bijou and Bresser series) are

developed on the alluvial fan surface (Qao2s) which is at a topographically similar position to the broad Qao2 alluvial terrace surface east of the alluvial fan and south of the South Platte River. The Qao2s and Qao2 deposits are thought to be interfingered (Berry and others, 2015a, b, 2018b).

Deposits of unit Qao2s host soils developed on sheetflood deposits of fine sand and silty sand (figs. 3 and 7). The Bresser series is a Mollisol and is coarser than the Bijou series, which is an Aridisol. Both soils are characterized by an A/Bt/Bk/C profile with stage II secondary carbonate. The coarser Bresser series tends to be more proximal to the active drainages and has a better developed Bt horizon than the Bijou soil. Scott (1982) proposed that, during these flooding events, the South Platte River was deflected northward and sheetflood deposits may have episodically dammed the South Platte River for short periods of time. The upper section of unit Qao2s is dated to 17–12 thousand years (ka; table 1).

Where unit Qao2 flanks the South Platte River, it is mostly buried by younger eolian deposits. Unit Qao2 is also extensive along the north-flowing tributaries in the southern half of the map area where it is covered in part by eolian sand. The predominant soils developed on the terrace surfaces are the Nunn and Heldt series. The soils are very sandy and probably derived from fluvially reworked eolian sand. The Nunn series is a Mollisol and the Heldt series is an Aridisol. These soils have an A/Bt/Bk/C profile with stage II secondary carbonate. They differ from each other primarily in the abundance of secondary carbonate. Unit Qao2 also includes some areas of Bresser series and Qao2s includes some areas of Heldt series, supporting the similarity of ages of units Qao2s and Qao2 (fig. 3). The upper section of unit Qao2 is dated to 15–11.5 ka (table 1), which overlaps the age range of Qao2s. Similarity of ages and elevations at the contact of Qao2 and Qao2s supports the interpretation of Berry and others (2015a, b, 2018b) that the deposits are interfingered.

Both the Bijou Creek fan and the coeval fluvial terrace are in abrupt contact with sandy deposits to the south (fig. 7). The deposition of units Qao2s and Qao2 are correlated in time to the Pinedale glaciation in the Rocky Mountains (Benson and others, 2005) when fluvial sediment load may have been greatest during and shortly after the deglaciation (Berry and others, 2018a, 2019, and references cited therein).

Older alluvial deposits, Qao1 and QTa, are poorly expressed at the surface. Like modern alluvial deposits, they are gravelly, but soils are better developed with more secondary clay, more carbonate, and silica accumulation more abundant than in the younger alluvial deposits. Although generalized to one unit on our geologic map (fig. 7), previous investigators subdivided Qao1 into the Louviers Alluvium, Slocum Alluvium, Verdos Alluvium, and Rocky Flats Alluvium (table 1; summarized in Madole 1991). For our purposes, we have generalized this poorly exposed, older fluvial gravel into a single unit, Qao1. Unit Qao1 is exposed in gravel quarries, canal exposures, and cutbanks, and is a pebble-to-cobble gravel with a sandy or finer-grained matrix. The deposits are also exposed in drainages eroded into bedrock north of Fort Morgan. Unit Qao1 has been previously mapped (Gardner, 1967; Berry and others, 2018a) in the bedrock highlands north of Fort Morgan, where it has been eroded by Wildcat Creek and is buried by younger alluvium or eolian deposits. Soil profiles are typically A/Bt/Bk to K with a carbonate morphology varying from stage III to IV. The unit is typically 20–70 m above the active drainage (table 1).

Unit QTa has been mapped previously as Nussbaum Alluvium (table 1; Gardner, 1967; Scott, 1978; Berry and others, 2018a). Unit QTa is mapped in the northeast corner of the study area, where it has been exposed by erosion in Dead Horse Draw (fig. 2), and also at the northern edge of the study area (figs. 1B and 7) where it is

exposed at the surface. Buried primarily by eolian deposits, QTa is well cemented by secondary carbonate and silica. Some of the cement appears to be from groundwater precipitation rather than pedogenic processes. The base of QTa is commonly a resistant conglomerate bed composed of lithologic clasts that are cemented by calcium carbonate derived from the underlying calcareous bedrock (Scott, 1982). The exposed soil profiles are stripped but typically retain Bt/K profiles with stage III+ secondary carbonate. Unit QTa is estimated to be late Pliocene to early Pleistocene (table 1).

Eolian Deposits

Eolian deposits are subdivided into older (Qe1) and younger (Qe2) eolian sands and older (Ql1) and younger (Ql2) silty-sandy loess deposits. Unit Qe1 is ubiquitous across the map area in the form of sand sheets (fig. 7; Madole, 1995). Soils developed on Qe1 are most commonly Mollisols and Alfisols, 1.5–2 m deep with well-developed Bt horizons. This older sand also forms a thin mantle over the bedrock north of the South Platte River where Vona series in the west, and Ascalon series in the east, are predominant (fig. 3). South of the South Platte River, unit Qe1 is often expressed as long, narrow interdunes dominated by soils of the Osgood and Truckton series (fig. 3). The variation in soils (fig. 3) north and south of the South Platte River may be due in part to differences in sand sources or soil parent material. On the west side of the study area, both north and south of the South Platte River, Qe1 is largely buried by Qe2. The geochemistry of Holocene sands north of the river indicates that the sands are sourced from the local bedrock upwind of the dunes and the sands south of the river tend to be derived predominantly from the Rocky Mountain-sourced alluvium derived from the South Platte River (Muhs, 2017). Unit Qe1 is 31–26 ka and possibly as young as 13–12 ka (Berry and others, 2015b, 2018a, and references cited therein).

Sand transportation is common in arid and semi-arid regions with either warm or cold temperatures. The most significant causes of increased eolian activity are likely decreased vegetation cover and increased wind strength and duration; neither is an exclusively glacial or interglacial phenomenon (Muhs and others, 1996). An important condition for sand dune activity, as described by Muhs and Holliday (1995), is droughts accompanied by high temperatures. Under this condition, the precipitation-to-evaporation ratio lowers, and stabilizing vegetation cover is diminished.

In unit Qe2, parabolic dunes are often formed in a northwest-southeast orientation (fig. 6A). This dune orientation is observable in the distribution of mapped soils. The older sandy soils formed in Qe1 are buried by the younger dunes, and the Qe1 soils are preserved as narrow parallel features oriented in a northwest–southeast direction. Characteristically immature Entisols are developed on unit Qe2, including the soils of the Valent and Valentine series. These soils have A/AC/C profiles and are easily redistributed by the wind. Ages on unit Qe2 cluster from younger than 4.2 ka (late Holocene) and from 4.2 to 8.2 ka (middle Holocene), suggesting at least two cycles of dune formation during the Holocene.

The predominantly silty-sandy deposits are primarily loess with soils of the Colby, Colby-Adena, and Weld series developed in the uppermost part of the loess (fig. 3). These soils occur mostly along the southern margin of the mapped area and to a lesser extent just north of Fort Morgan. The Weld series typically caps the stable upland surfaces and the Colby or Colby-Adena series form in slope deposits reworked from loess. The Weld series is better developed than the others with a thin Bt horizon, and the Colby-Adena series typically have an A/C profile. These seemingly younger slope deposits (the Colby-Adena) could be derived primarily from reworked Weld series soils.

Dated loess deposits that are exposed at the surface in the study area (Q12), fall within the age range of Peoria Loess (table 1). Peoria Loess, deposited between about 20–14 ka (Muhs and others, 1999a) is correlated with the Pinedale glaciation and Marine Isotope Stage 2 (Roberts and others, 2007). During cold climate conditions, Peoria Loess in Colorado and Nebraska was derived from eroded volcanoclastic material from the Tertiary White River Group, exposed in the northern Great Plains. During warm climate cycles, the loess was eroded from glaciofluvial deposits derived from the Rocky Mountains (Aleinikoff and others, 1999). During the time when the Peoria Loess was deposited, there was a shift from a primarily Tertiary bedrock source while glaciers were advancing to their maximum position, to a primarily glaciofluvial source as glaciers retreated. Loess deposition in eastern Colorado occurred mostly toward the end of the last glacial maximum, under cooler and drier conditions, as the age range for the Peoria Loess suggests (Muhs and others, 1999a).

Peoria Loess is often interfingering with eolian sand. This interfingering is most common closest to the sand sources north and south of the South Platte River, and appears to be a rapidly alternating deposition based on the absence of buried soils.

The older loess, Q11, is not mapped at the surface. However, where it was dated at depth in this study, both samples were older than 80 ka and can be tentatively correlated to the Loveland Loess deposited during Marine Isotope Stage 6 (Roberts and others, 2007), which is dated at 163±34 ka (Maat and Johnson, 1996). Regionally, this older, buried loess is correlated to the Bull Lake glaciation.

Bedrock Units

For this study, only Quaternary units above the much-older bedrock were investigated. Simplified from Tweto (1979), bedrock at the surface and buried at depth includes (1) Tertiary sedimentary rocks (Ogallala and White River Formations), (2) lower Tertiary to Upper Cretaceous sedimentary and igneous rocks (Denver Formation), and (3) Cretaceous sedimentary rocks (Ku; Laramie Formation, Fox Hills Sandstone, and Pierre Shale). Only Ku is exposed at the surface (fig. 7).

Table 2. Map units and associated soil names, landforms, parent materials, and taxonomic classifications based on Natural Resources Conservation Service (NRCS) information (Natural Resources Conservation Service, 2015).

NRCS soil survey ¹	Map unit	NRCS soil name	NRCS landform	NRCS parent material	NRCS taxonomic classification
Fluvial deposits					
Both	Qfp	Bankard	Floodplain	Sandy alluvium	Sandy, mixed, mesic Ustic Torrifluvents
Morgan	Qfp	Riverbank	Floodplain	Sandy alluvium	Riverwash
Weld	Cutbanks	Ustic Torriorthents	Cutbanks	Alluvium	Ustic Torriorthents
Weld	Qay3	Aquents	Floodplain	Alluvium	Aquents
Weld	Qay3	Aquepts	Floodplain	Alluvium	Aquepts
Weld	Qay2	Aquolls	Floodplain	Alluvium	Aquolls
Morgan	Qay2	Las	Drainageways	Alluvium	Fine-loamy, mixed, superactive, calcareous, mesic Aquic Ustifluvents
Weld	Qay2	Loup	Streams, swales	Sandy alluvium	Sandy, mixed, mesic Typic Haplaquolls
Morgan	Qay2 and Qay3	Wann	Floodplain, terrace	Sand	Coarse-loamy, mixed, superactive, mesic Fluvaquentic Haplustolls
Morgan	Qay2	Wet alluvial land	Floodplain	Wet alluvial land	Fluvaquentic Haplaquolls
Weld	Qao2	Altvan	Terrace	Old alluvium	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Argiustolls
Morgan	Qao2	Apishapa	Floodplain, terrace	Alluvium	Fine, smectitic, calcareous, mesic Vertic Fluvaquents
Weld	Qao2	Colombo	Floodplain, terrace	Alluvium	Fine-loamy, mixed, superactive, mesic Torrifluventic Haplustolls
Both	Qao2 and Qay1	Fort Collins	Terrace	Alluvium	Fine-loamy, mixed, superactive, mesic Aridic Haplustalfs
Morgan	Qao2 and Qay1	Gilcrest	Terrace	Gravelly alluvium	Coarse-loamy, mixed, superactive, mesic Ustic Haplargids
Both	Qao2, Kp drainages	Haverson	Floodplain, terrace	Alluvium	Fine-loamy, mixed, superactive, calcareous, mesic Aridic Ustifluvents
Both	Qao2 and Qay1	Heldt	Terrace	Clayey alluvium	Fine, smectitic, mesic Ustertic Haplocambids
Both	Qao2	Nunn	Terrace	Alluvium	Fine, smectitic, mesic Aridic Argiustolls
Weld	Qao2	Paoli	Terrace	Alluvium	Coarse-loamy, mixed, superactive, mesic Pachic Haplustolls
Morgan	Qao2s	Bijou	Terrace	Alluvium	Coarse-loamy, mixed, superactive, mesic Ustic Haplargids
Both	Qao2s	Bresser	Terrace	Coarse alluvium	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls
Morgan	Qao1	Bonnacord	Paleoterrace	Clayey alluvium	Fine, smectitic, calcareous, mesic Ustertic Torriorthents
Weld	Qao1	Dacono	Terrace	Alluvium	Clayey over sandy or sandy-skeletal, smectitic, mesic Aridic Argiustolls
Weld	Qe on Qao1	Kim	Floodplain, fans	Eolian	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents
Weld	Qe2 on Qao1 (Greeley)	Otero	Plains	Eolian over outwash	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents
Both	QTa and Qao1	Cascajo	Terrace, upland	Gravelly outwash	Sandy-skeletal, mixed, mesic Ustic Haplocalcids

Table 2. Map units and associated soil names, landforms, parent materials, and taxonomic classifications based on Natural Resources Conservation Service (NRCS) information (Natural Resources Conservation Service, 2015).—Continued

NRCS soil survey ¹	Map unit	NRCS soil name	NRCS landform	NRCS parent material	NRCS taxonomic classification
Eolian deposits					
Morgan	Qe2	Dune land	Dunes	Eolian sands	Mixed, mesic Ustic Torripsamments
Weld	Qe2 on Qao2 (Greeley)	Otero	Plains	Eolian over outwash	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents
Weld	Qe2 (major unit)	Valent	Dunes	Eolian sands	Mixed, mesic Ustic Torripsamments
Morgan	Qe2	Valentine	Dunes	Eolian sands	Mixed, mesic Ustic Torripsamments
Both	Qe1	Ascalon	Upland	Sandy loam	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls
Morgan	Qe1	Dwyer	Terrace	Sand	Mixed, mesic Ustic Torripsamments
Morgan	Qe1	Haxtun	Terrace	Eolian over outwash	Fine-loamy, mixed, superactive, mesic Pachic Argiustolls
Both	Qe1	Olney	Terrace	Alluvium or eolian	Fine-loamy, mixed, superactive, mesic Ustic Haplargids
Weld	Qe1 (interdune)	Osgood	Plains	Eolian sand	Loamy, mixed, superactive, mesic Arenic Ustollic Haplargids
Both	Qe1	Platner	Uplands	Loam	Fine, smectitic, mesic Aridic Paleustolls
Morgan	Qe1 (Kp + Qe)	Stoneham	Uplands	Eolian over outwash	Fine-loamy, mixed, superactive, mesic Aridic Haplustalfs
Morgan	Qe1 (interdune)	Truckton	Uplands	Loamy sand	Coarse-loamy, mixed, superactive, mesic Aridic Argiustolls
Both	Qe1 (major unit)	Vona	Plains, eolian	Loamy sand	Coarse-loamy, mixed, superactive, mesic Aridic Haplustalfs
Both	Ql2	Colby	Uplands	Loess	Fine-silty, mixed, superactive, calcareous, mesic Aridic Ustorthents
Both	Ql2	Colby-Adena	Hills, plains ridges	Loess	Fine-silty, mixed, superactive, calcareous, mesic Aridic Ustorthents
Morgan	Ql2	Rago	Streams, swales	Loamy alluvium, colluvium	Fine, smectitic, mesic Pachic Argiustolls
Both	Ql2	Weld	Upland	Sand, loess	Fine, smectitic, mesic Aridic Argiustolls
Bedrock units					
Morgan	Ku	Briggsdale	Uplands	Loam on bedrock	Fine, smectitic, mesic Ustic Paleargids
Both	Ku	Renohill	Uplands	Weathered shale	Fine, smectitic, mesic Ustic Haplargids
Morgan	Ku	Samsil	Breaks, hills	Weathered shale	Clayey, smectitic, calcareous, mesic, shallow Aridic Ustorthents
Both	Ku	Shingle	Uplands	Weathered shale	Loamy, mixed, superactive, calcareous, mesic, shallow Ustic Torriorthents
Both	Ku	Tassel	Uplands	Weathered sandstone and shale	Loamy, mixed, superactive, calcareous, mesic, shallow Ustic Torriorthents
Both	Ku	Terry	Uplands	Weathered sandstone and shale	Coarse-loamy, mixed, superactive, mesic Ustic Haplargids
Morgan	Ku	Travessilla	Hills, ridges	Weathered sandstone	Loamy, mixed, superactive, calcareous, mesic Lithic Ustic Torriorthents

¹Morgan information from NRCS (Natural Resources Conservation Service, 2015). Weld information from NRCS (Soil Survey Staff, 2010). Both indicates that the information is from both Morgan and Weld. NRCS, Natural Resources Conservation Service.

Creating a Three-Dimensional Lithologic Model of the Subsurface and Correlating to the Surficial Geologic Map

A 3D lithologic model was constructed using Rockware Rockworks17 3D modeling software to represent the subsurface geometry and the thickness and distribution of lithologic units. The initial step in constructing a 3D lithologic model is the compilation and simplification of drill hole data (Taylor and others, 2025). Lithologic data from 3,612 water-well records were compiled from a variety of sources, including USGS water resources reports (Bjorklund and others, 1957), Colorado Division of Water Resources (2013), and site-specific drilling completed by the USGS during this study.

The 3D model is constructed through 3D extrapolation of the lithologic data from the drill holes. The 3D solid volume is filled using a nearest-neighbor approach, by extrapolating data at 200-m horizontal and 1-m vertical discretization away from data points to fill solid model voxel nodes out to the midpoint between adjacent data. This extrapolation method does not directly account for spatial structure of the data, but can work well where data density is sufficiently high (Taylor and Sweetkind, 2014). There are no known faults in the study area that need to be considered in the model.

For the 3D model, drill hole data were simplified to better represent the geologic map units (table 3). Fortunately, each of the geologic formations are generally lithologically distinct. Driller's descriptions of grain size, presence or absence of gravel, degree of consolidation, and abrupt color changes were standardized to a limited number of lithologic units by interpreting the descriptions with reference to observations of the major geologic units. Because our goal was to translate the surficial deposits to the subsurface and reconstruct the depositional history, the subsurface interpretations would be more reliable the more closely the model represented the geologic map.

Success in model building was measured by visually comparing the map view or top of the model (fig. 8A) to the surficial geologic map (fig. 8B). The top of the model was determined by slicing the 3D model with the 10-m digital elevation model of the study area created from the National Elevation Dataset (USGS, The National Map, <https://nationalmap.gov/>). The model was also constrained at depth by the top of the bedrock, derived from the drill hole data. The final 3D lithologic model, used to generate cross sections, was built with a more complex lithology than what is used in this model (table 3).

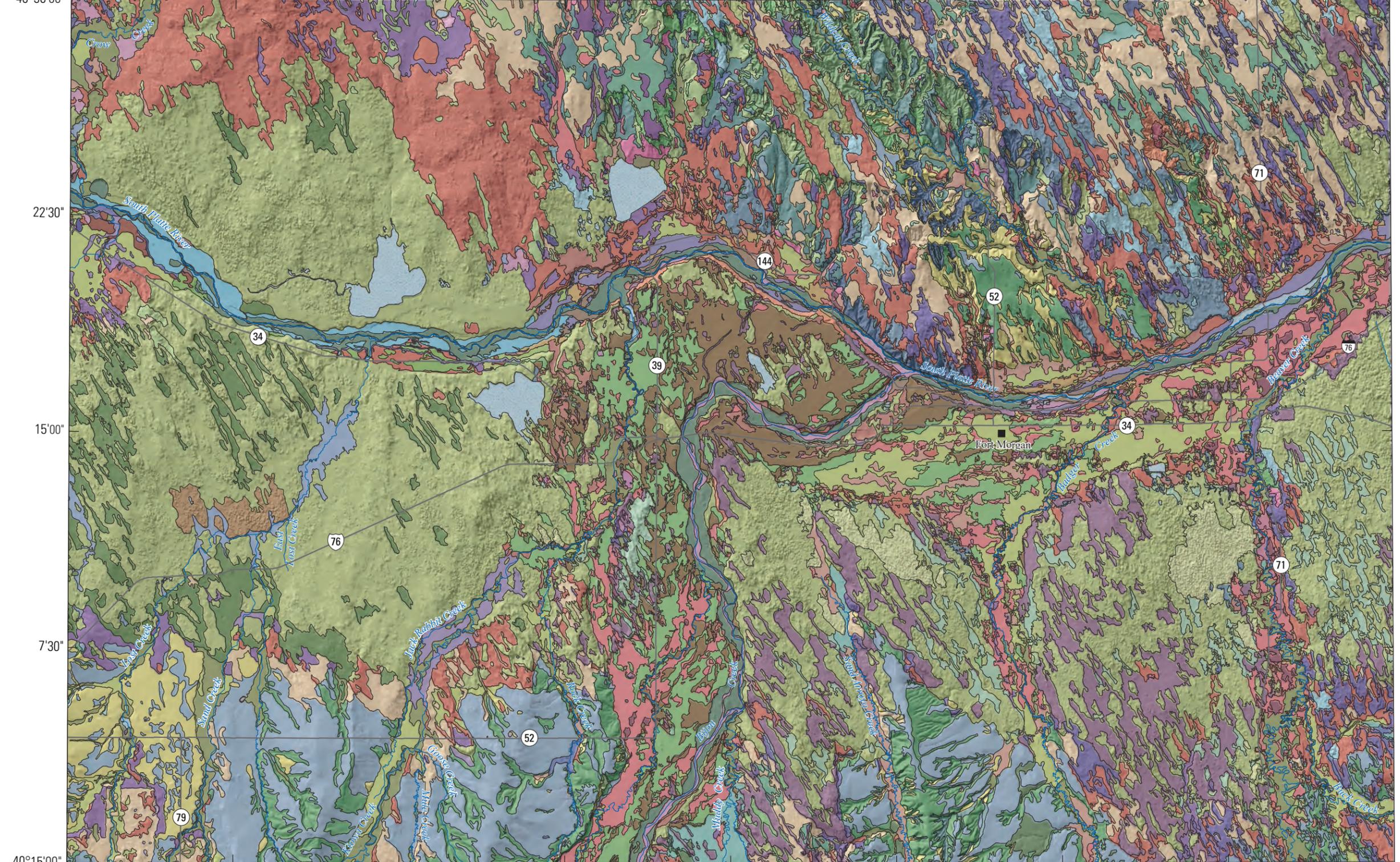
The top of the model reasonably matches the surficial geologic map (fig. 8A–B). Gravelly deposits are brown and orange, sandy deposits are yellow, silty and clayey sands are dark yellows, and clayey deposits are green. Gravelly alluvium, in brown and orange colors, is associated with the South Platte River (Qfp and Qay). The older alluvium (Qao2), which dominates the topography south of the South Platte River, is correlated to the distribution of clayey sand and silty sand (dark yellow). These fine-grained sandy units extend the length of the Bijou Creek fan and include the terrace surface east of Bijou Creek. The loess deposits characterized by sandy and silty clay (fig. 8A–B, shown in green), occur in the southern margins of the model top. Young eolian sand (Qe2) shown in pale yellow is not as extensive on the model top as it has been mapped in the study area. Older eolian sand (Qe1) has the same textural characteristics as Qao2 and is not easily differentiated. The topographic high, to the north of the

South Platte River, is mapped as a thin deposit of typically Qe1 sediments that mantle gullies that expose bedrock. In the lithology model, the combination of poor data distribution and thinness of the Quaternary deposit are apparent at the top of the bedrock, and areas of no reliable data occur over a broader area than what was mapped in the field.

Table 3. Simplified driller's nomenclature used for interpreting drilling logs in this study (Taylor and others, 2025).

Driller's nomenclature	Lithologic unit for cross section	Lithologic unit simplified for three-dimensional model
Alluvial gravel		
Gravel; gravel and boulders; gravel and pebbles; gravel sand and rock; includes gravel, gravel and rocks, pebble, cobble, boulder	Gravel	Gravel
Gravel and sand; gravel, sand; gravel and sandstone (cemented sandy gravel)	Sandy gravel	Sandy gravel
Gravel sand coal; gravel and coal; gravel, sand and lignite	Sandy gravel and coal	Sandy gravel
Alluvium; caliche or hard pan; (fine-coarse) sand and (fine-coarse) gravel; sand gravel; some gravel, sand	Gravelly sand	Sandy gravel
Fine sand, coal, gravel; coal and gravel	Gravelly sand and coal	Sandy gravel
Sand and clay and some gravel	Clayey sand and gravel	Clayey sand and gravel
Clay and (some) sand and gravel; clay, sand and (fine) gravel; sand, gravel and shale(?); soil and gravel	Sandy clay and gravel	Clayey sand and gravel
Dirty gravel; gravel and clay; gravel and silt; gravel and shale	Clayey gravel	Clayey sand and gravel
Sand and gravel and clay; sand gravel silt	Gravelly sand and clay	Gravelly sand and clay
Gravel sand clay; gravel and sand, dirty; gravel clay sand; gravel, sand and silt	Sandy gravel and clay	Gravelly sand and clay
Clay and (thin) gravel; clay and pebbles; clay and rock; clay gravel	Gravelly clay	Gravelly sand and clay
Eolian sand		
Sand (fine-coarse; blue, brown, clean, gray, red, tan, white, yellow)	Sand	Sand
Clay sand coal; sand and coal; coal and sand	Sand and coal	Sand
Loam; sandy loam; silt; soil, top and topsoil	Silty sand	Silty sand
Clay and quicksand; dirty or clayey sand; sand and (some, traces) clay; quicksand	Clayey sand	Clayey sand
Sandy and silty clay loess		
Clay and (fine, some, strips) sand; clay and silt; clay sand (sandy); clay silt sand; sand clay; silty sand	Sandy clay	Sandy and silty clay
Clay and silt; clayey silt; (fine) silt	Silty clay	Sandy and silty clay
Clay (black, blue, brown, calico, gray, green, hard, reddish, soft, tan, thin, white, yellow); gumbo	Clay	Clay
Bedrock		
Cap rock, cement rock, clay and shale, clay and sandstone, clay rock, claystone, coal, gravelly shale, lignite, mudstone, rock (when interbedded with shale, at the bottom of a hole, above shale), rock and shale, rocks and shells, sand and shale, sand rock, sandstone clay, sandstone, sandy shale, shale and coal, shale and rock, shale rock sand, shale sand coal, siltstone, slab rock	Bedrock	Bedrock
No data		
Asphalt black, cannot read, cow manure, fill, no data, spoil, unknown, water, well pit	No data	No data

104°30'00" 22'30" 15'30" 7'30" 104°00" 52'30" 45'00" 37'30" 103°30'00"



Soil Survey for Morgan and Weld Counties, Colorado, U.S. Department of Agriculture, Natural Resources Conservation Service
Base from U.S. Geological Survey, The National Map, 2015
Universal Transverse Mercator projection, zone 13
North American Datum 1983

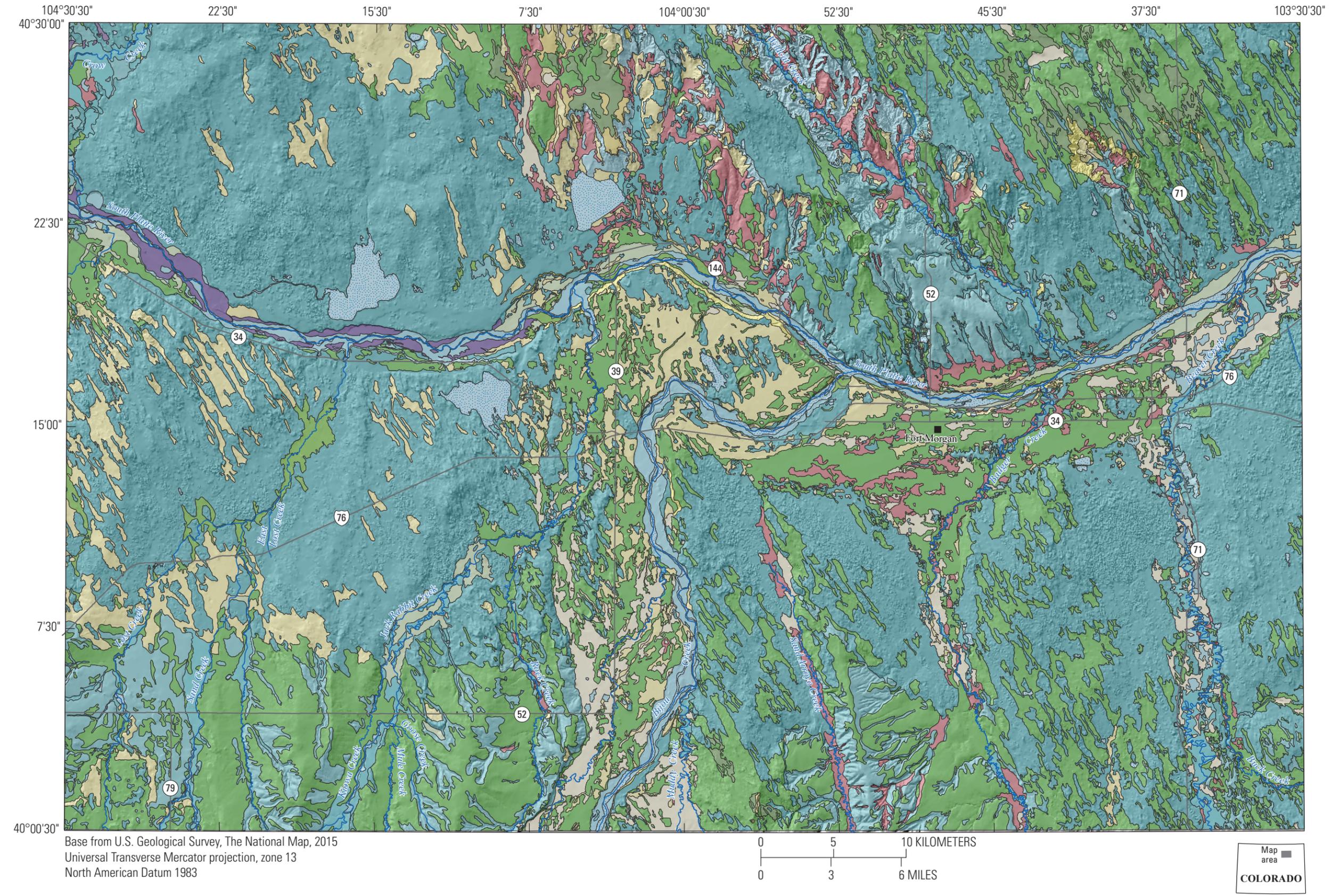
0 5 10 KILOMETERS
0 3 6 MILES

Map area
COLORADO

Figure 3. Map showing the distribution of soils in the study area simplified to series name (Natural Resources Conservation Service, 2015, and Soil Survey Staff, 1999).



Figure 3.—Continued



EXPLANATION

Entisol and aquic soils

- Aquolls and Aquepts
- Aquolls and Aquepts
- Fluvaquepts
- Torrifluvents
- Torripsamments
- Torriorthents
- Ustifluvents
- Ustorthents

Soil great groups

Mollisols

- Argiustolls
- Haplustolls
- Haplaquolls
- Paleustolls

Aridisols

- Haplargids
- Haplocalcids
- Haplocambids
- Paleargids

Alfisols

- Haplustalfs

Water

-

Figure 4. Map showing the distribution of soil great groups in the study area (Soil Survey Staff, 1999).

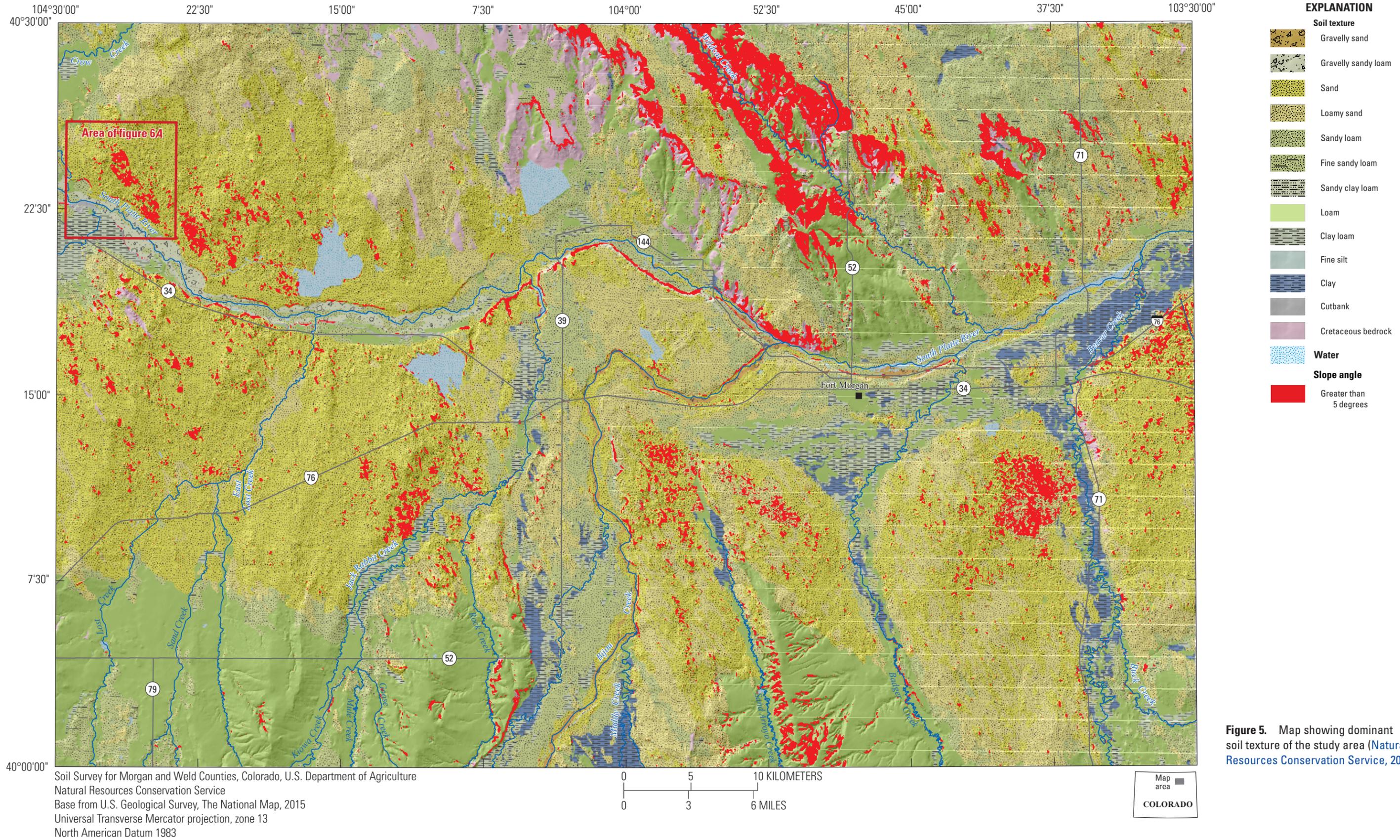
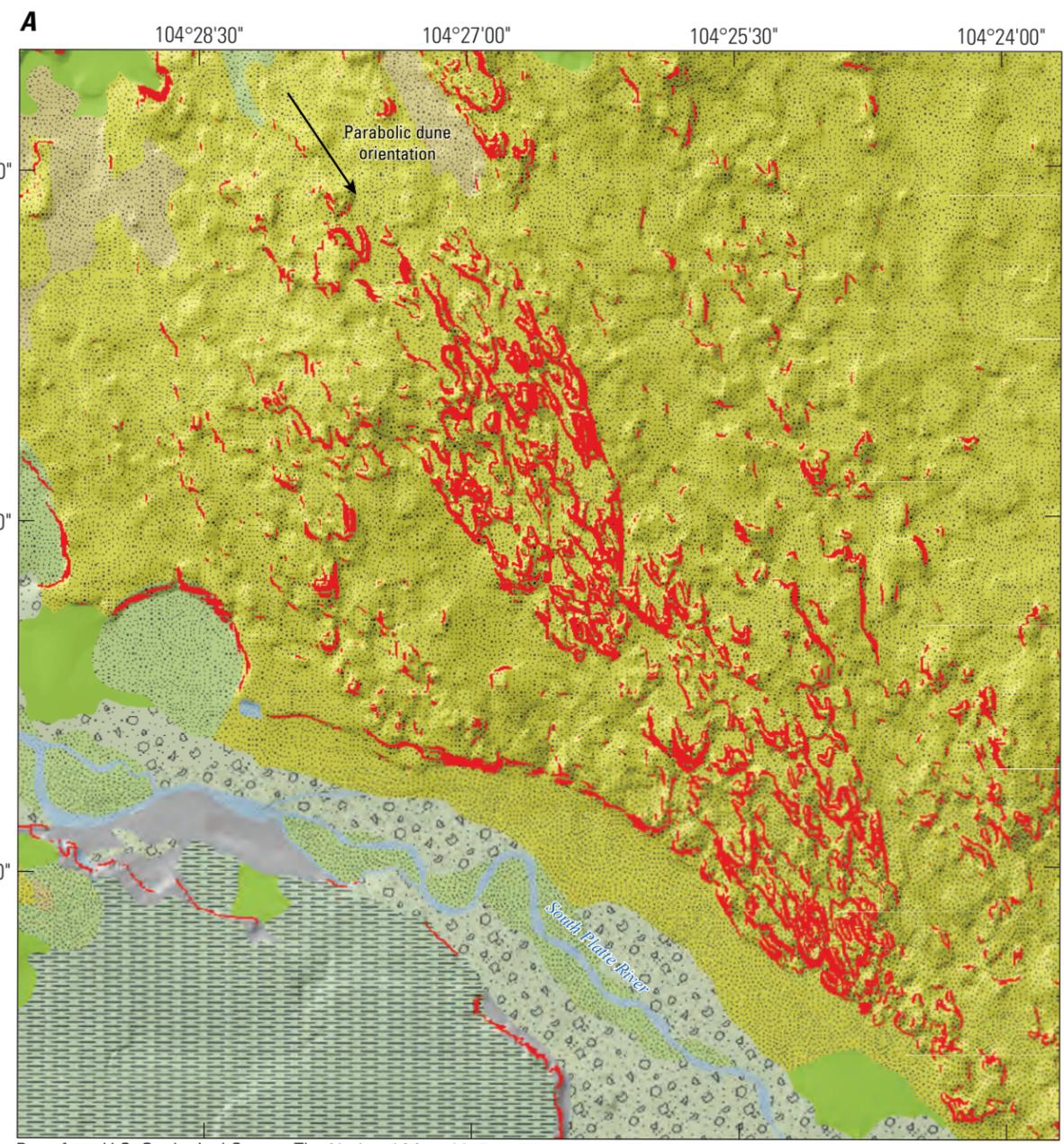


Figure 5. Map showing dominant soil texture of the study area (Natural Resources Conservation Service, 2015).



Base from U.S. Geological Survey, The National Map, 2015
 Universal Transverse Mercator projection, zone 13
 North American Datum 1983

0 0.5 1 KILOMETER
 0 0.25 0.5 MILE

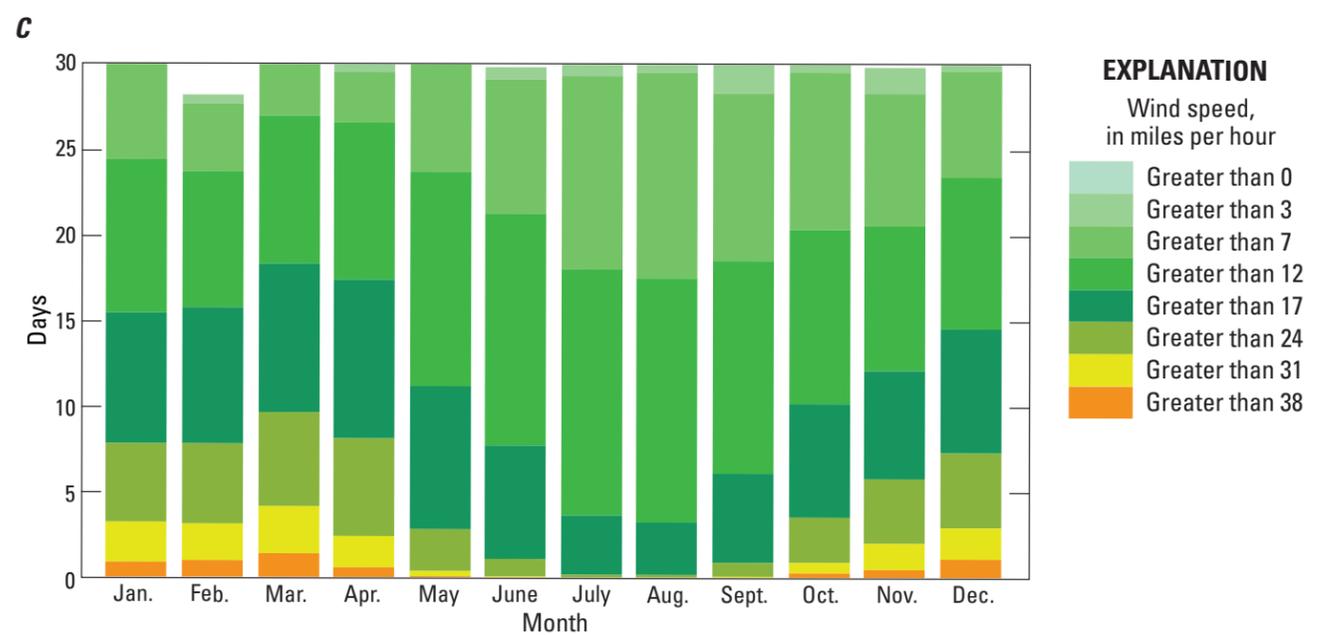
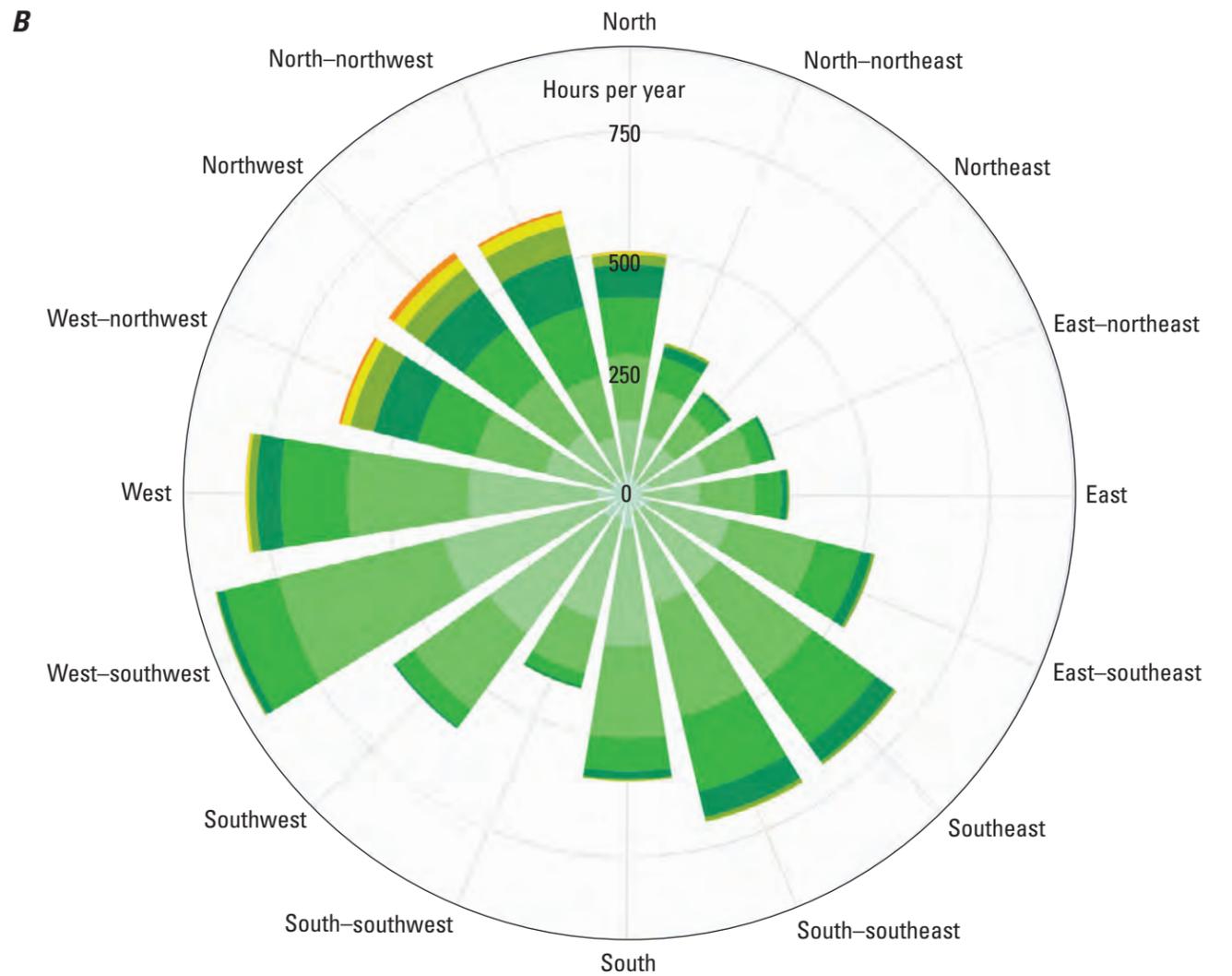
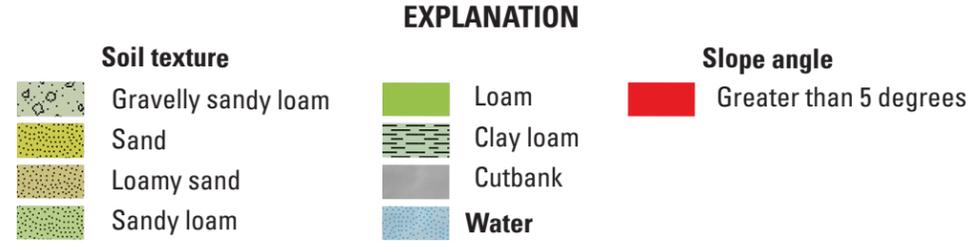


Figure 6. Dune orientation in the northwest study area (fig. 5) determined from surface slope-angles in sandy geologic unit. *A*, Geologic map (this study) and surface slope angle; *B*, Historical wind direction data at Fort Morgan, Colorado, 1985–2019 (Meteoblue, 2019); *C*, Average daily wind speed by month at Fort Morgan, Colo., 1985–2019 (Meteoblue, 2019).

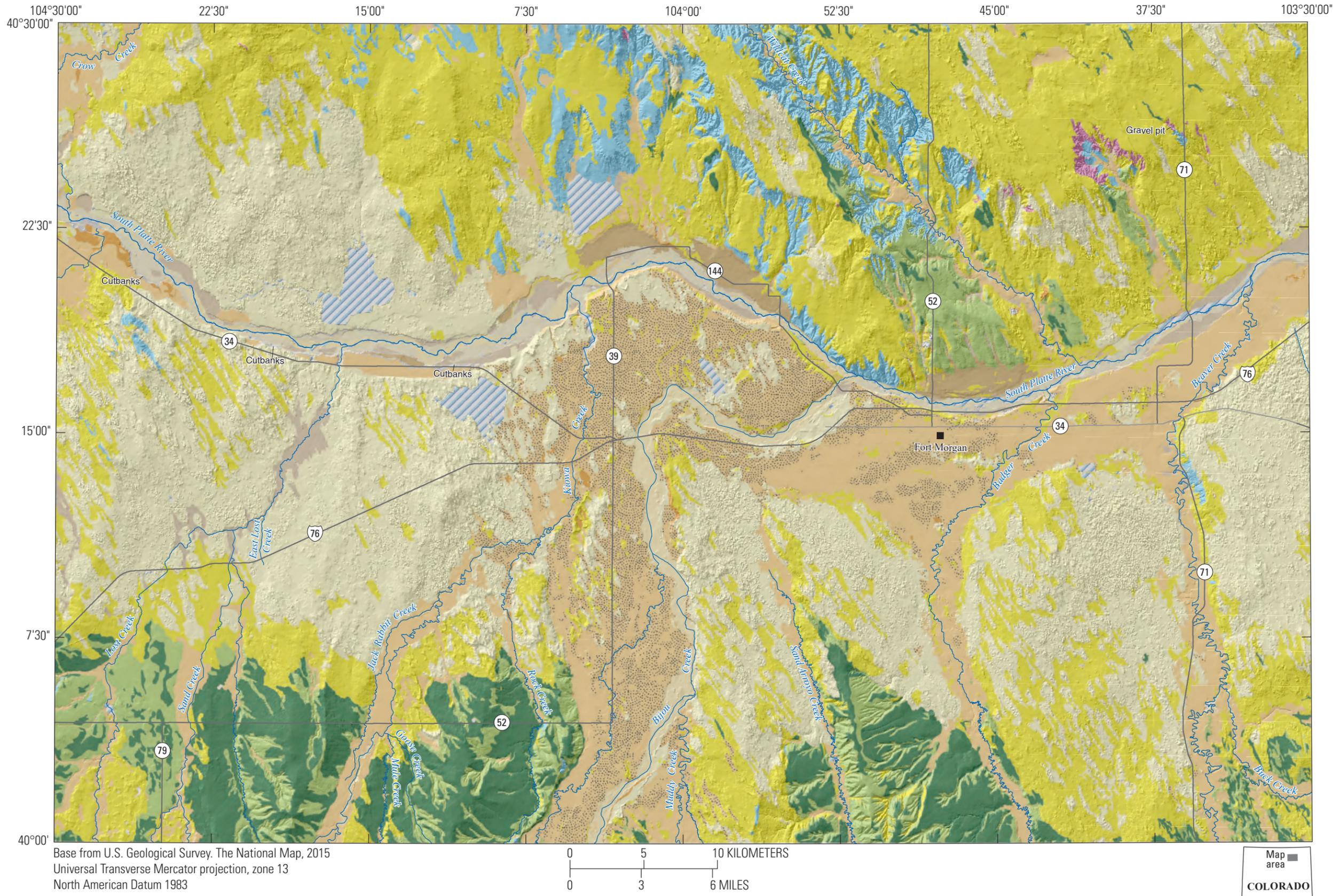
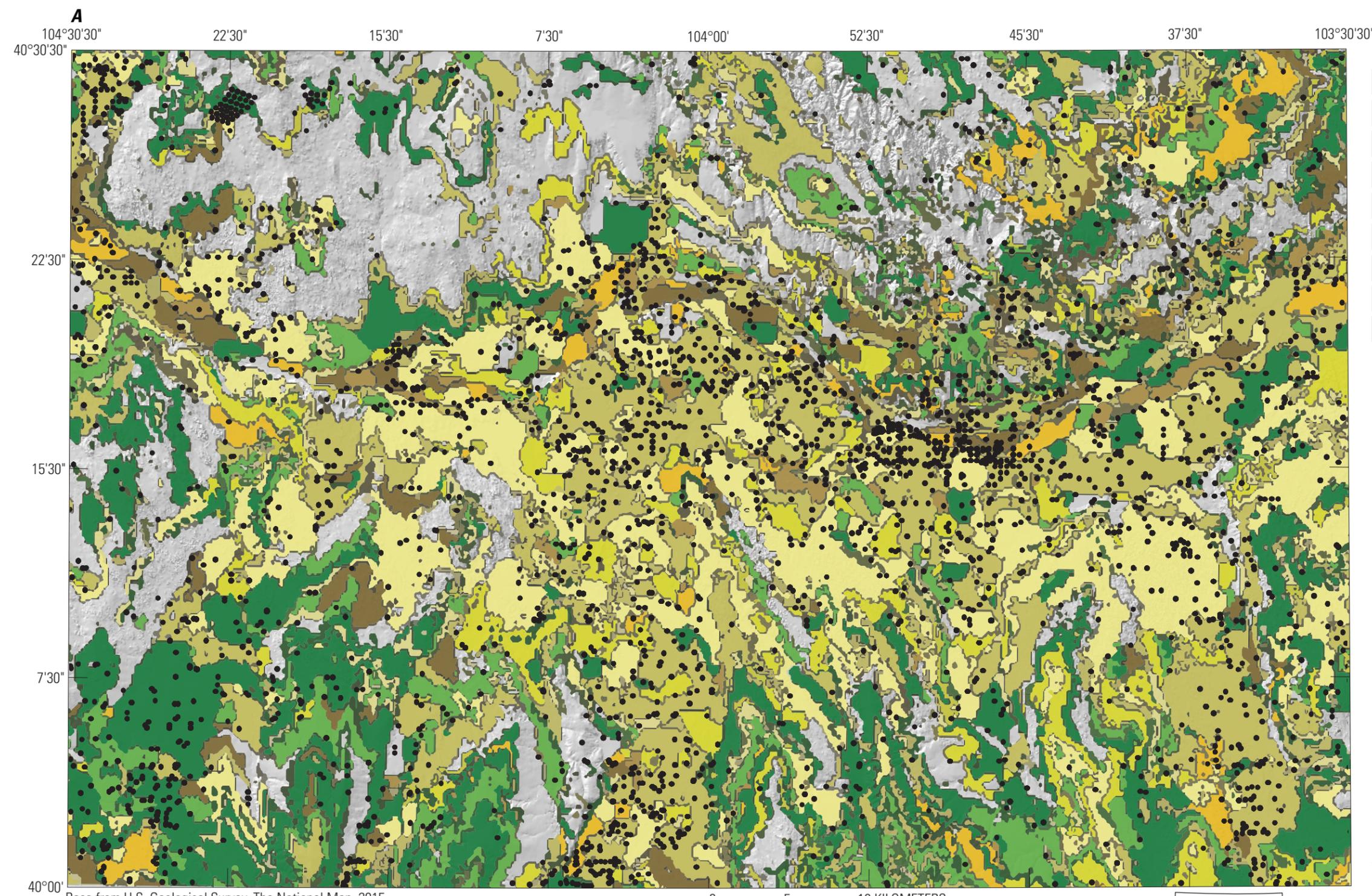


Figure 7. Quaternary geologic map of the study area from this study.

Base from U.S. Geological Survey. The National Map, 2015
Universal Transverse Mercator projection, zone 13
North American Datum 1983

0 5 10 KILOMETERS
0 3 6 MILES

Map area
COLORADO



- EXPLANATION**
- Gravel
 - Sandy gravel
 - Clayey sand and gravel
 - Gravelly sand and clay
 - Sand
 - Silty sand
 - Clayey sand
 - Sandy and silty clay
 - Clay
 - Drill hole locations

Base from U.S. Geological Survey, The National Map, 2015
 Universal Transverse Mercator projection, zone 13
 North American Datum 1983

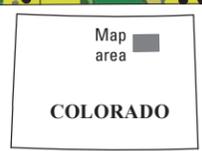
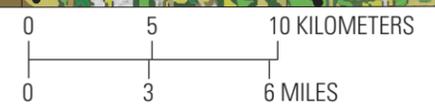


Figure 8. A, Map view of the surface of the simplified three-dimensional lithologic model. B, Surficial geologic map of the study area.

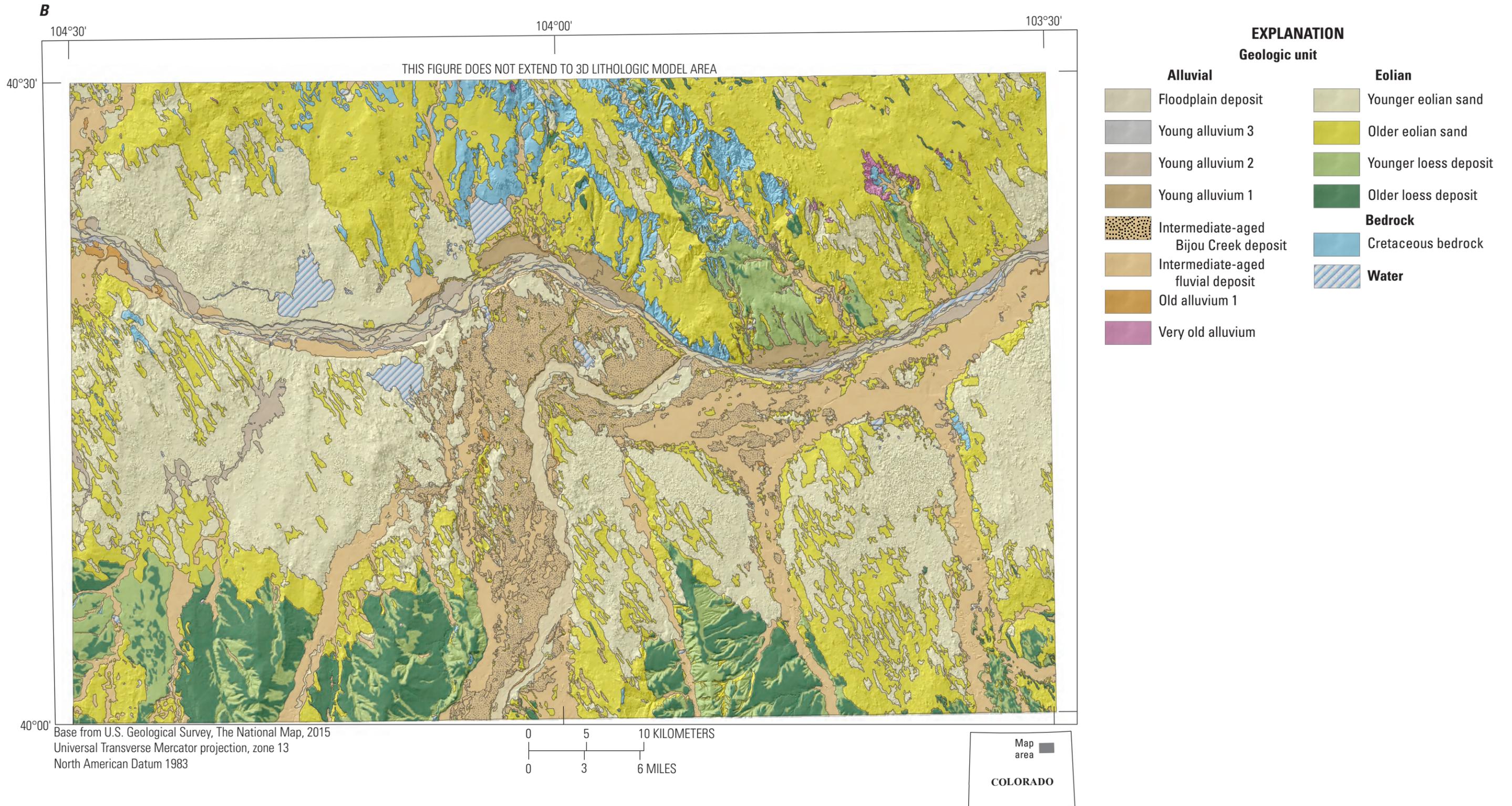
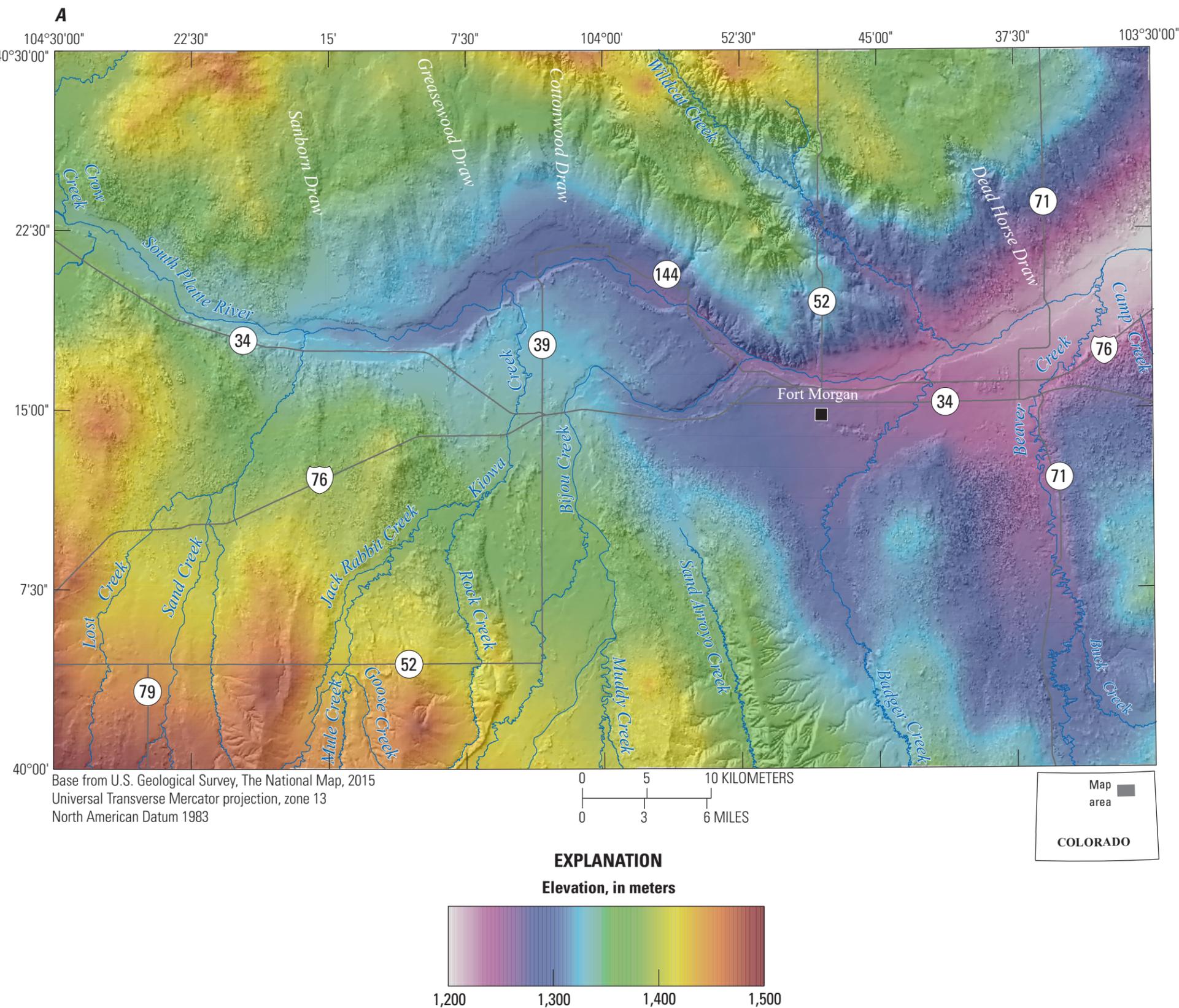


Figure 8.—Continued.



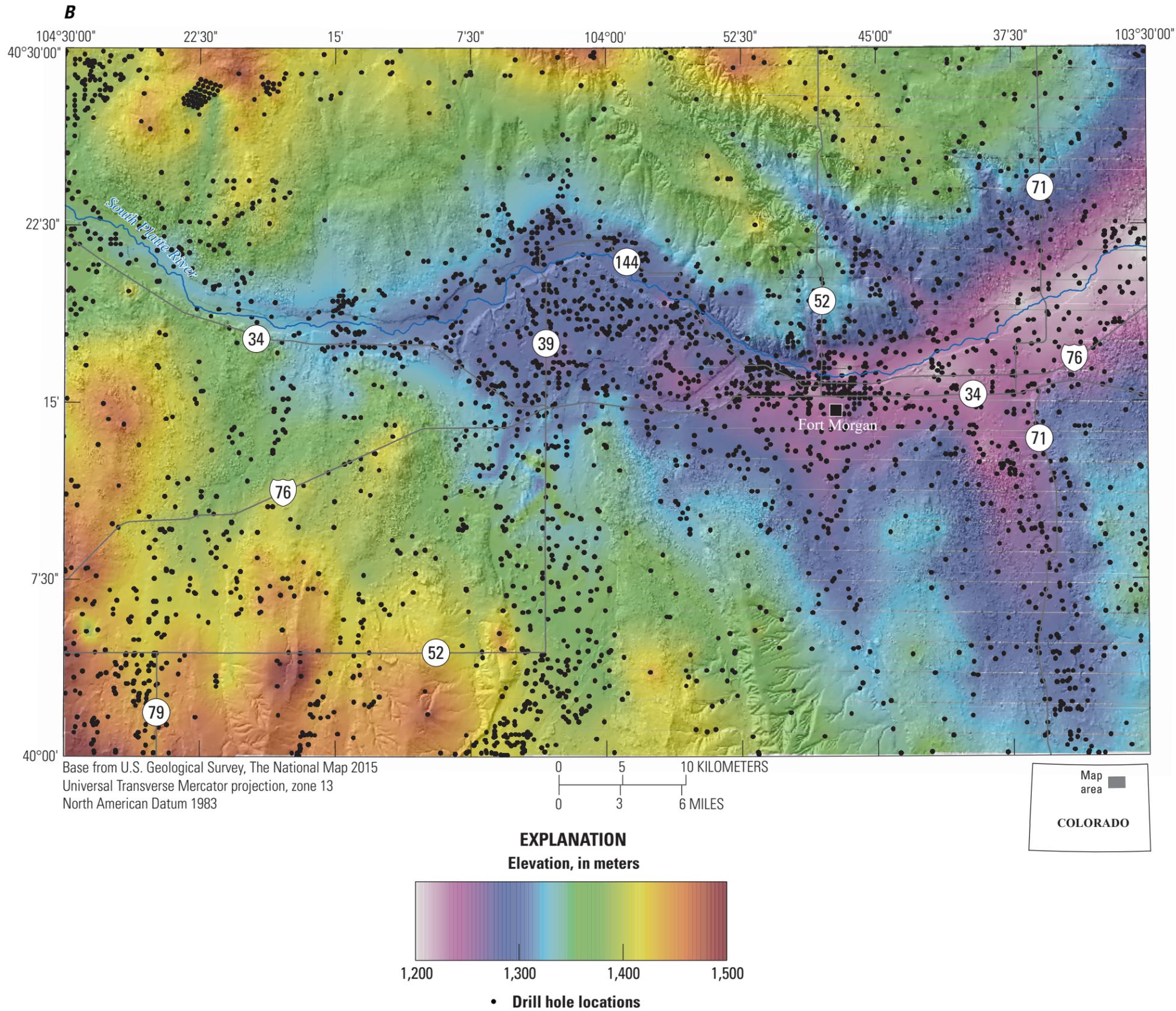
Contoured Surface Elevation, Top of Bedrock, and Thickness of Sediments

Most of the drill holes (3,550 of the total 3,612) intersect bedrock. The top of the bedrock at depth or the depth at which bedrock was intersected was gridded and used to trim the 3D model. The contoured surface elevation (fig. 9A) was visually compared to the contoured top of the bedrock (fig. 9B). With a few exceptions, the topographic surface and the top of the bedrock look very similar. The South Platte River appears to have previously occupied a much broader valley than it does at present. The older, broader valley is defined by an extensive surface both north and south of the drainage that has a similar elevation across the map area (primarily light blue shades in the range of about 1,340 m elevation; figs. 9A and 9B). This older valley floor was subsequently incised by the South Platte River and the north-flowing Badger and Beaver Creeks. Younger erosional features are inset into the older valley and range from an elevation of about 1,300 m in the west to about 1,225 m in the eastern part of the study area.

The distribution of sediments above the bedrock, at 10-m thickness intervals across the study area, provides insight into the depositional history of the Quaternary deposits by visually comparing the distribution of the geologic units (fig. 7) to the generalized thicknesses of the sediments (fig. 10A–D). Most sediment is less than 50 m thick, with the exception of the distal part of the Bijou Creek fan and associated alluvial terraces that are as much as about 80 m thick (fig. 10D). Sediment is less than 10 m thick north of the South Platte River and a few places south of the river (fig. 10A). Eolian sands, at least Holocene sands (fig. 7, Qe2), are derived primarily from eroded bedrock to the north (Muhs, 2017) and, as a result, are thinner (fig. 10B) than the dunes south of the South Platte River where source sands are alluvial (fig. 10C). When compared to the geology (fig. 7), sediments 10 to 20 m thick, in general, are the older eolian sand sheets (Qe1) and loess deposits (Ql1 and Ql2), whereas deposits 20 to 30 m thick are the young dunes (Qe2).

The Bijou Creek fan appears to have been deposited into a deep eroded trough in the distal part of the fan where the South Platte River has been deflected northward (fig. 9B). During the deposition of the Louviers Alluvium, the South Platte River was south of its current position. Some of the thickness of the Bijou Creek fan is due to the cutting and filling of Louviers paleochannels which are now buried by Qao2 and Qao2s (Scott, 1982).

Figure 9. A, Map showing the contoured surface elevation within the study area. B, Map showing the contoured top of bedrock and drill hole locations in the study area (Taylor and others, 2025). Topographic bedrock highs (yellow and red hues on the map), on the northwest and southwest sides of the study area, constrain the South Platte River drainage. The drainage becomes less constrained and forms a broad valley where it exits the bedrock high in the western half of the map area. There is very little expression of the regional north-flowing tributaries that incise the bedrock surface, with the exception of Badger and Beaver Creeks in the southeastern part of the study area.



Using the Three-Dimensional Lithologic Model to Construct Regional Cross Sections

After the 3D model was determined to adequately match the geologic map (fig. 8), areas with a high density of drill hole data were selected to create cross sections in the 3D model (figs. 11 and 12A–J). Cross sections allowed us to translate the surficial deposits to the subsurface. Cross sections provide an estimated thickness, distribution of a unit, as well as its relation to other units.

Figure 9.—Continued.

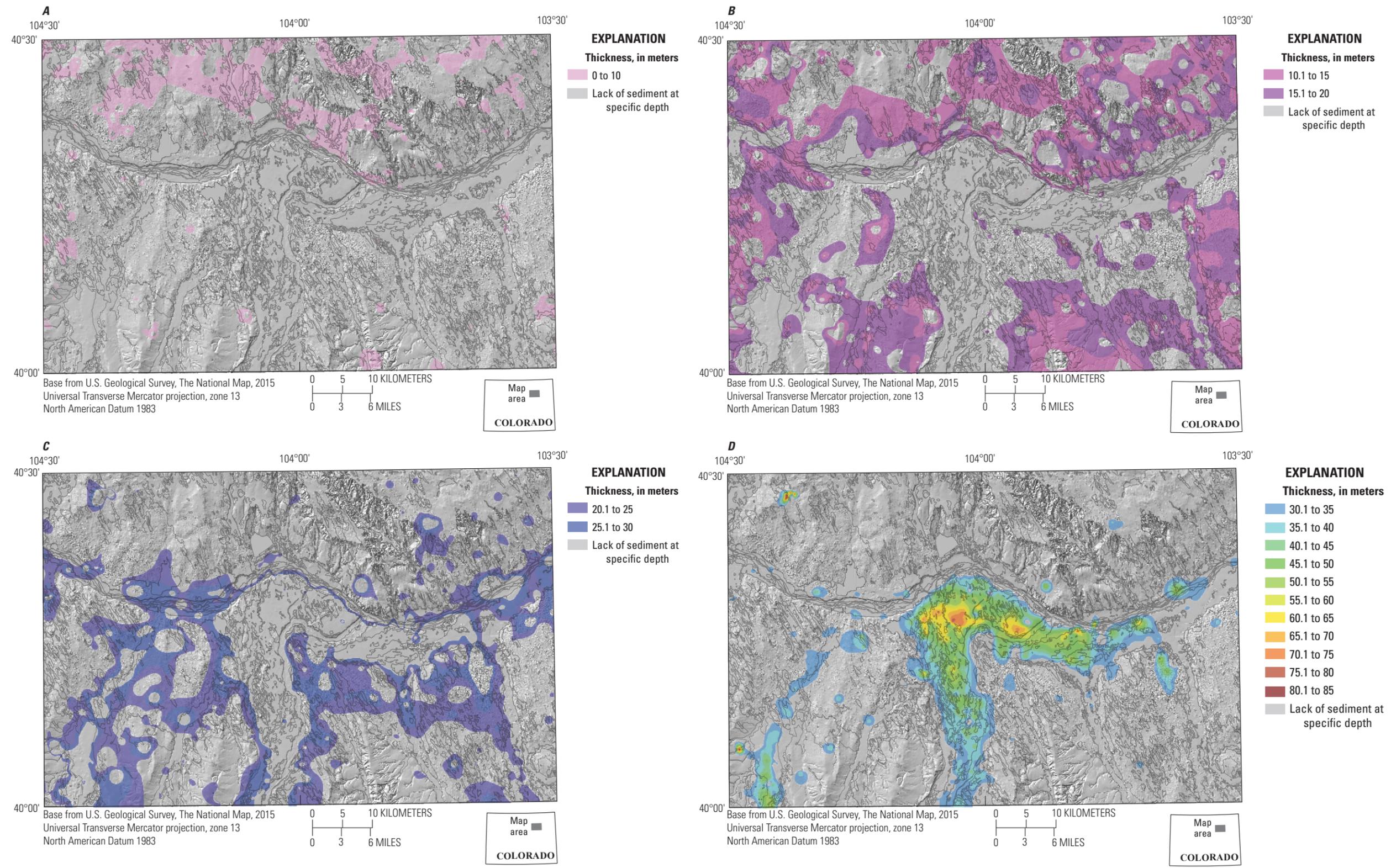


Figure 10. Maps showing the thickness of Quaternary sediments above the bedrock. *A*, Sediments that are 0 to 10 meters above the bedrock *B*, Sediments that are 10 to 20 meters above the bedrock *C*, Sediments that are 20 to 30 meters above the bedrock *D*, Sediments that are more than 30 m above the bedrock.

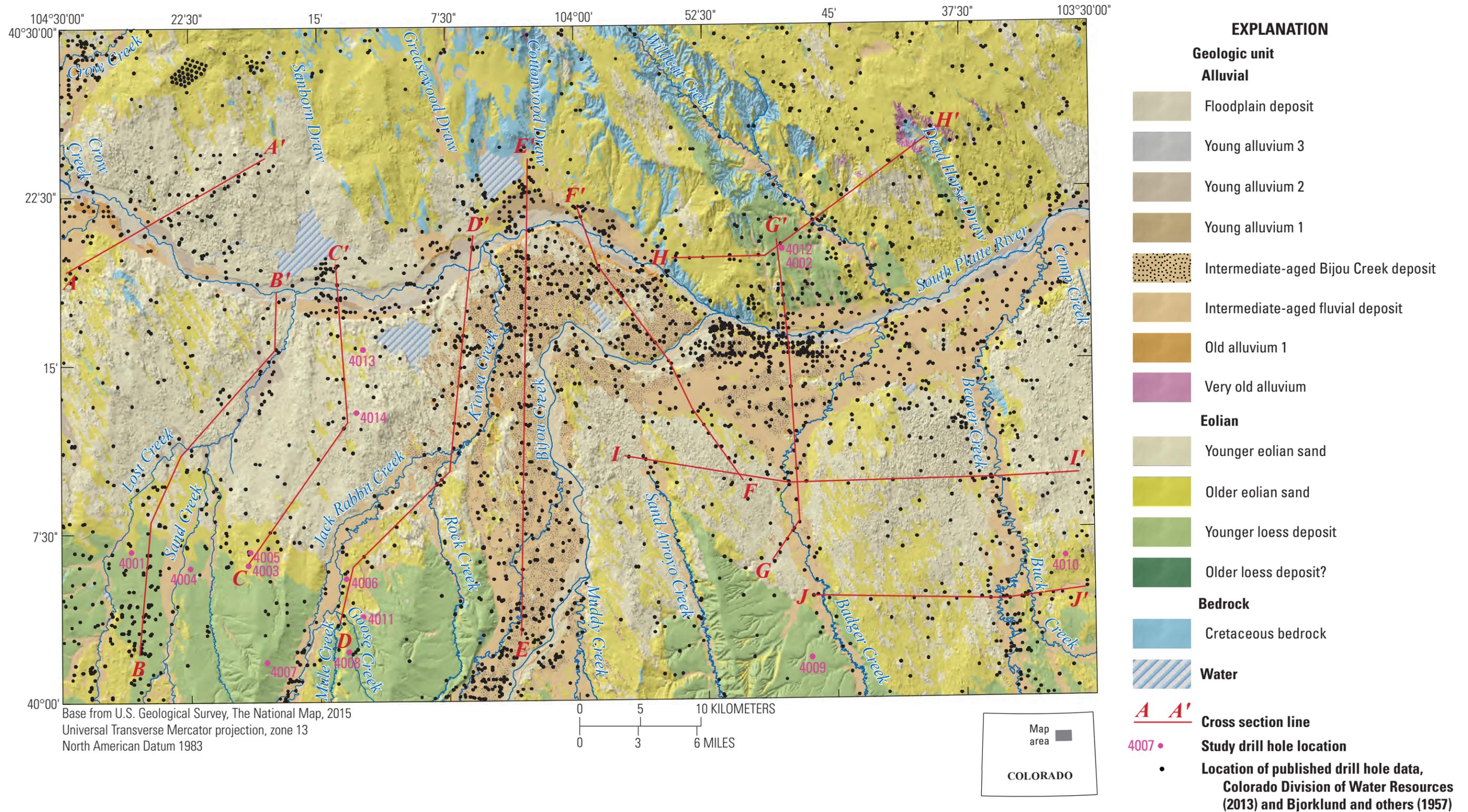


Figure 11. Geologic map of the study area showing locations of cross sections used for this study and drill holes. Drill hole information is from Taylor and others (2025).

Cross Section A–A'

Cross section A–A' crosses the South Platte River in the western edge of the map area (fig. 11). In the southwestern part of the cross section, young sand (Qe2) buries clayey loess (Ql) and old eolian sand (Qe1). Gravelly alluvial extends from below the eolian deposits northeast to the South Platte River. At its highest point in the section, this alluvium (gravelly sand) is about 15–20 m above the active drainage. This elevation corresponds to the elevation range of Qao2 (table 1). The gravelly alluvium was deposited on a planed surface of bedrock, which is interpreted as an eroded strath terrace of the South Platte River. We interpret this gravelly sand to represent a paleochannel, extending northeastward across the drainage where it is buried by young active dunes (Qe2). In the highland to the northeast, a thin mantle of old eolian sand (silty sandy clay, Qe1) and younger eolian sand (Qe2) bury an eroded bedrock terrace surface 20–30 m above the floodplain. If this interpretation is correct, it could be correlative with the time of Qao1 erosion and deposition. Modeled sediment data were not reliable immediately above the sediment-bedrock contact in the northeast part of the cross section.

Cross Section B–B'

Cross section B–B' was located to understand better the relation between the loess and eolian sand units and the distribution of these sediments to the north-flowing drainages. The southern margin of the study area is dominated by surficial loess deposits (Ql1 and Ql2) composed of sandy and silty clays that are about 20 m thick. The loess deposits are interfingered at depth with eolian and fluvial sand, suggesting that their deposition was close in time. Interdune areas are typically Qe1 and are expressed in the cross sections as silty clay and sandy clay, although Ql1 may have a similar texture. Below the eolian units, gravelly alluvium is in contact with the bedrock. Based on the location of the buried alluvium, the alluvium is derived from contributions from Lost Creek as well as the broader South Platte River floodplain. The buried alluvium closest to the South Platte River is about 15 m above the active drainage and correlates to Qao2 (table 1). A second gravelly unit southwest of the buried Qao2 unit is approximately 35 m above the active drainage and possibly correlative to Qao1.

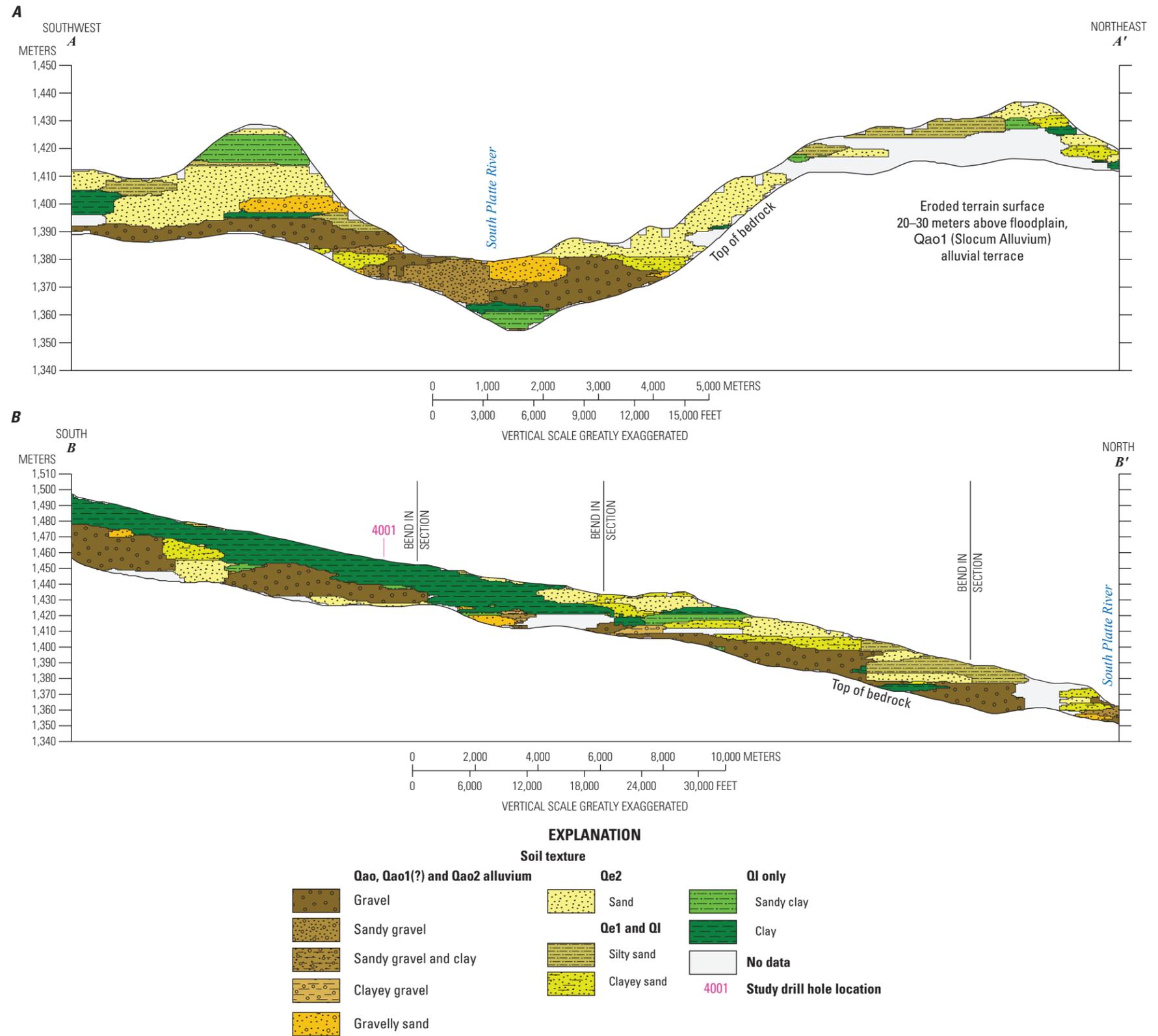


Figure 12. Cross sections of the sediments above the bedrock in the study area. A, Western edge of map area across South Platte River cross section. B, Sand Creek from Lost Creek to South Platte River cross section. C, South of Riverside Reservoir cross section. D, Kiowa Creek to South Platte River cross section. E, Bijou Creek to across South Platte River cross section. F, Dunes, Bijou Creek fan to across South Platte River cross section. G, Badger Creek to across South Platte River cross section. H, North of South Platte River to northeast map area cross section. I, Bijou Creek to Beaver Creek cross section. J, Badger Creek to east of Beaver Creek cross section. Locations of cross sections are shown in figure 11. (Taylor and others, 2025)

Cross Section C-C'

Cross section C-C', runs parallel to cross sections B-B', and D-D', but avoids active drainages flowing from the south. Paleoerosional surfaces that resemble four distinct strath terrace levels are observed in the cross section on top of the bedrock. Remnants of gravelly alluvium also are preserved near the tops of terraces 3, 4, and possibly 2. Terrace 3 is capped by remnants of gravel about 50 m above the active floodplain, suggesting it is one of the older gravelly deposits in unit Qao1, which is currently not exposed at the surface (table 1). The proposed paleovalley, expressed by the top of the bedrock (fig. 9B), does not extend south beyond the bend in this cross section and is represented most likely here as terrace 4. Sandy and silty clay, typically associated with loess, is modeled at about 20 m thick at the south end of the cross section, and Qe1 is mapped at the surface. This further suggests the interbedding of weathered, older eolian sand (Qe1) and loess (Ql). Sand dunes (Qe) extend from where they are interfingering with buried loess to the south, northward of the South Platte River.

Cross Section D-D'

Cross section D-D', extends from the loess deposits in the southern edge of the map area, along Kiowa Creek to the western edge of the Bijou Creek fan, and across the South Platte River. Older eolian sand (Qe1) mantles the loess (Ql) progressing northward. Buried patchy, clayey deposits, interpreted to be loess, extend toward the South Platte River. Particle size of surface sediments generally decreases from sand to silty sand to clayey sand toward the distal end of the Bijou Creek fan, where the fan intersects the South Platte River valley. Gravelly alluvium occurs at depth on top of the bedrock, north of Kiowa Creek, where the gravel is about 50–60 m above the floodplain. This older deposit may be correlative to Qao1 (Rocky Flats Alluvium).

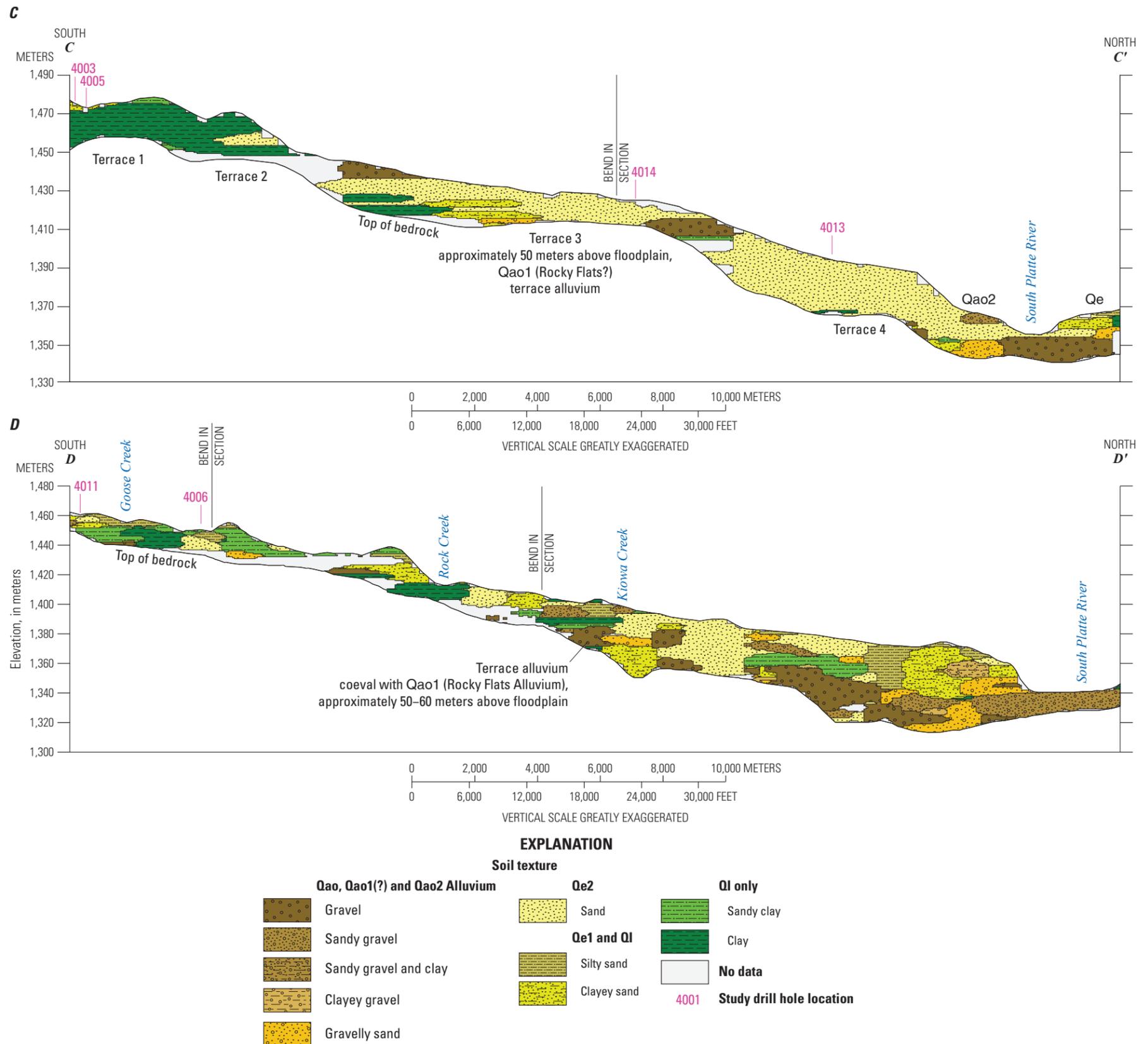


Figure 12.—Continued.

Cross Section E-E'

Cross section E-E', extends along the mapped length of the Bijou Creek fan (Qao2s), northward across the South Platte River. Gravelly alluvium, about 20–25 m thick, occurs on the eroded top of the bedrock along the full length of the cross section. Gravelly sand, sand, silty sand, clayey sand, and clay are interbedded above the buried gravel and are consistent with alluvial fan sediments. The maximum thickness of this heterogeneous mix of sediment is about 65 m (fig. 10D). The high density of water wells on the fan surface indicates that reliable water is available at depth (fig. 11). The surface of the fan is very flat with a few young sand dunes on the surface. The Bijou Creek fan is composed of alluvium (Qao2s) and is finer grained than the axial alluvium associated with the South Platte River (Qao2). In the past, both Bijou Creek and the South Platte River extended across a larger floodplain than the present-day floodplains extend. Evidence for the extensive floodplains will be discussed in the Summary.

Cross Section F-F'

Cross section F-F', begins southwest of the Fort Morgan in Qe2 and Qe1 and proceeds northwest across a section of Qao2 and Qao2s to the north side of the South Platte River. The southeast end of the cross section intersects young dunes (Qe2) that bury old eolian sand (Qe1) and loess (Ql). Northwestward, a buried paleochannel composed of alluvial gravel, occurs near the contact of the Qe2 dunes and the Qao2s/Qao2 terrace surface. At depths, alluvial gravel occurs at the bedrock contact near Bijou Creek and continues to the northwest. This extensive buried alluvial gravel records the top of a once-continuous channel of Louviers Alluvium (Scott, 1982) that likely represents a South Platte River paleochannel that formed before deposition of the Bijou Creek fan deflected the river northward. The deepest scour of the paleochannel occurs at about an elevation of 1,310 m along the cross section. Sediments above the gravel tend to fine from sand to clayey sand to clay toward the distal facies of the fan where it intersects the South Platte River. The large component of sand in the alluvial fan suggests that fluviually reworked eolian sediments have been incorporated into the deposits. Observed at the northwest end of the cross section is a dramatic bluff, nearly 25 m high, that has been created by the South Platte River undercutting the south side of the drainage.

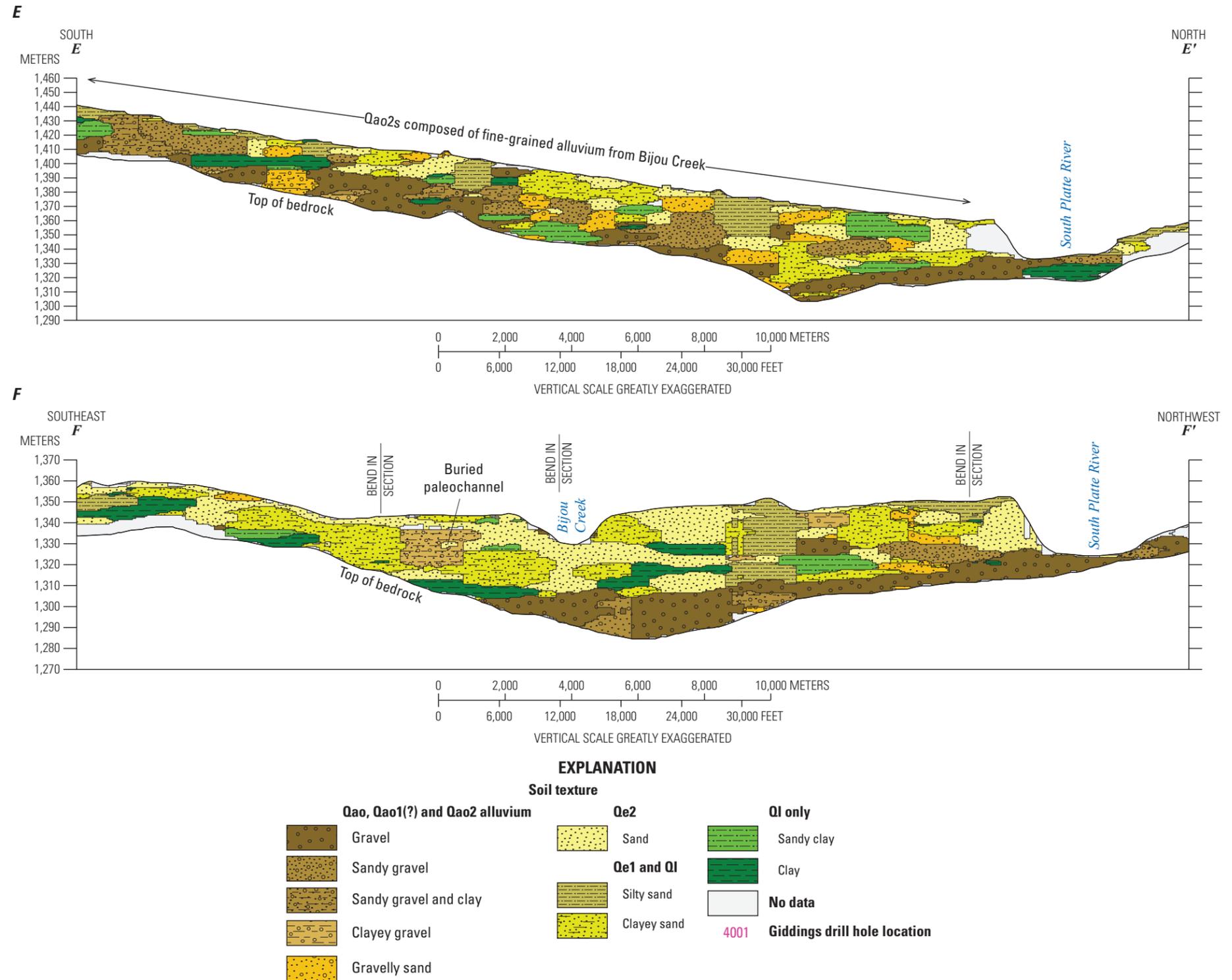


Figure 12.—Continued.

Cross Section G-G'

Cross section G-G', trends in a general south-north orientation extending across upland eolian sands, down the Badger Creek, across the South Platte River valley to the northernmost upland loess deposits in the study area. South of the South Platte River, gravelly alluvium at depth overlies bedrock along the entire cross section. Above the gravelly deposits, loess deposits (Ql) are buried by eolian sand (Qe2 and Qe1). Badger Creek has little or no surface expression where the cross section intersects the drainage. The area has been cultivated and surface flow is infrequent. Clay and clayey sand (Ql) are buried by sandy deposits on the Qao2 terrace surface, although in places, these units are interbedded. North of the South Platte River, clay and interbedded silty sand (Ql2, Ql1, and Qe1) extend from the top of the bedrock to the ground surface with a thickness of about 20–25 m.

Cross Section H-H'

Cross section H-H', extends in a west-northeast direction across thinly mantled bedrock in the northeast section of the map area. In the western end of the cross section, clayey sand (Qe1) buries sandy clay (Ql). Thin wedges of gravelly alluvium are exposed 30 m and 15 m above Wildcat Creek in outcrops along the valley sides. Field investigations (Berry and others, 2018a) indicate these alluvial deposits are correlative to Qao1. The broad surface between Wildcat Creek and Dead Horse Draw is capped by 15 m of Ql. At the east end of the cross section, QTa mapped at the surface is expressed as gravelly alluvium.

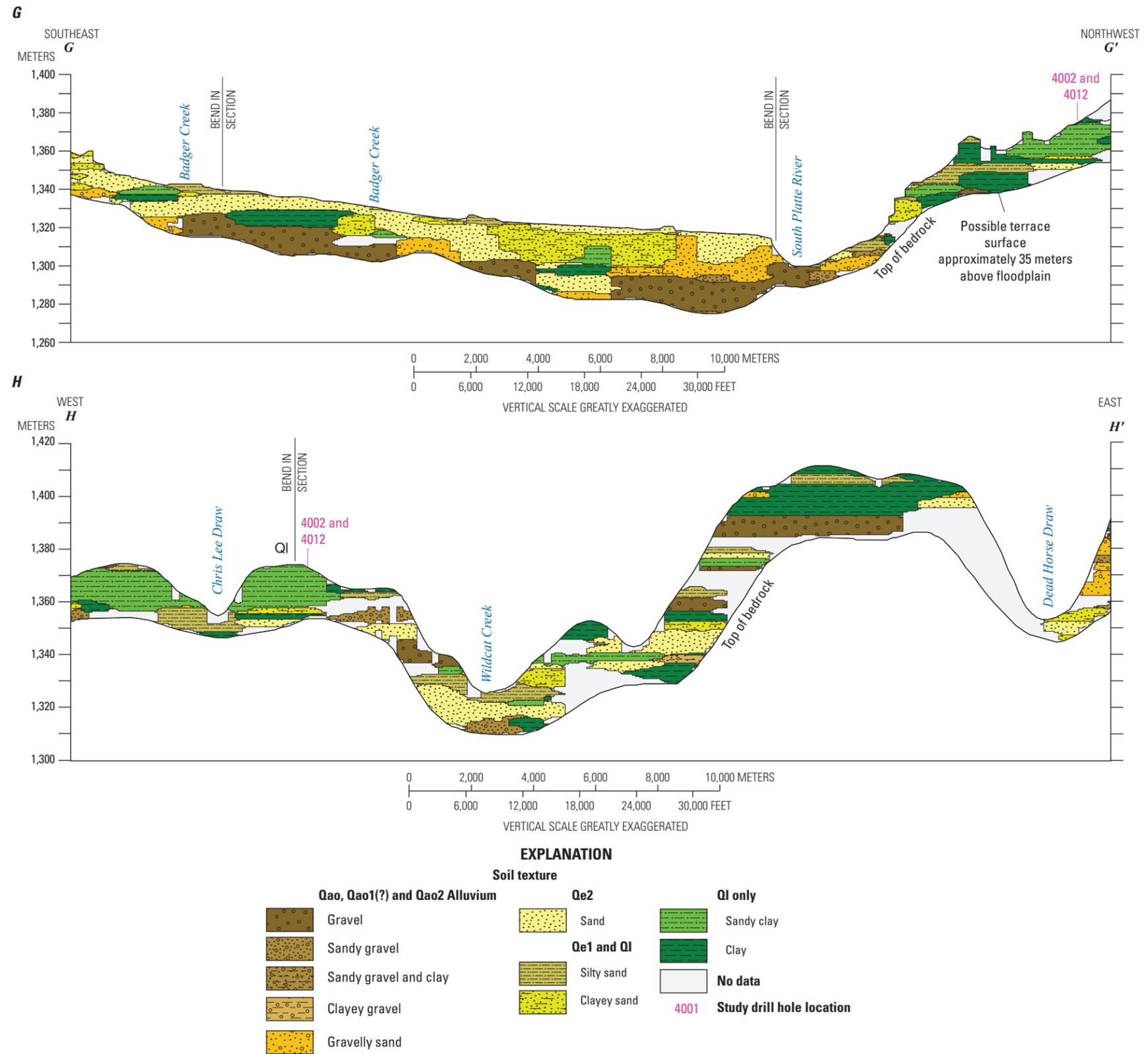


Figure 12.—Continued.

Cross Section I-I'

Cross section I-I', begins in the middle of the study area at Sand Creek and extends eastward across Badger and Beaver Creeks. At the west end of the cross section, thin gravel deposits less than 5 m thick occur intermittently at the bedrock contact. In Badger and Beaver Creeks, gravelly deposits up to 10 m thick are either at the ground surface or buried. Fine-grained eolian units (Qe and Ql) are interbedded in the near surface. Sandy units usually occur above the buried clayey units. Clayey units (Ql) are often buried by thin mantles of sand and clayey sand. Eolian units conform to the bedrock and vary in thickness from 20–40 m.

Cross Section J-J'

Cross section J-J', is in the southeast corner of the study area, extends from west to east, and crosses the Badger and Beaver Creeks. Units intersected in the cross section are finer grained than units to the north crossed by cross section I-I'. In general, Qe1 is less than 10 m thick and buries Ql, which can be up to 20 m thick. Gravelly deposits are confined to drainages. Eroded strath terraces on the bedrock surface, associated with Beaver Creek, occur both east and west of the drainage.

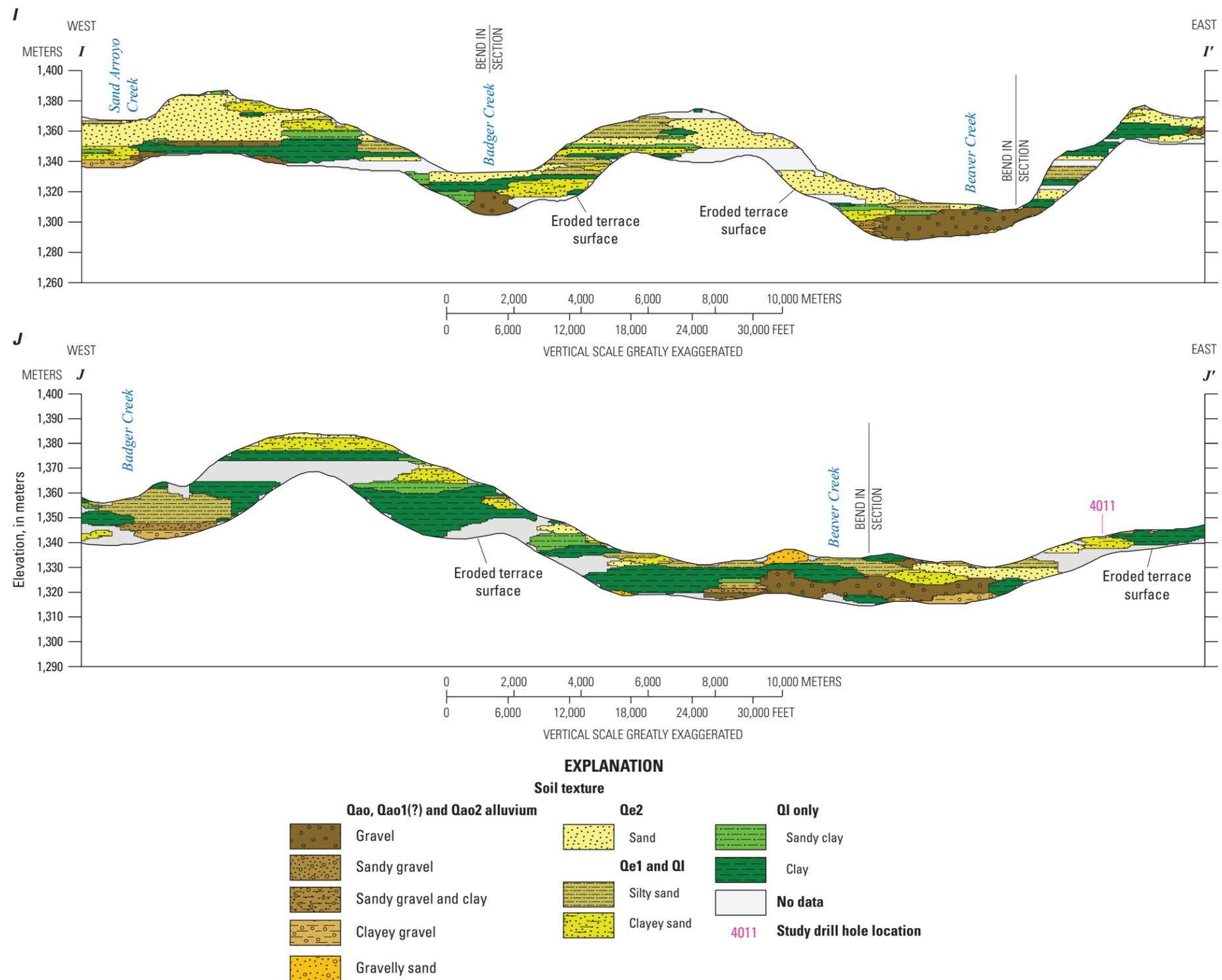


Figure 12.—Continued.

Site Specific Drill Hole Data

Sediment retrieved from 14 cores (table 4) were logged and described to understand thickness and distribution of the study units (figs. 13 and 14) and to compare these data to the modeled results displayed in the cross sections (figs. 11 and 12). The holes were drilled using a Giddings drill rig, a small rig about the size of a tent trailer that is towed and can be easily maneuvered in agricultural fields and along roadsides. The drill rig can acquire up to 25–30 m of intact core in fine-grained sediment. The drill rig cannot penetrate gravelly alluvial deposits; therefore, drill holes ended if they intersected Qa.

We are not entirely conventional in our use of soil nomenclature. Our emphasis is on the stratigraphic relation of units at depth. Each stratigraphic map unit, below the surface soil, is marked by a buried soil. We have not appended each buried soil master horizon with “b” to indicate a buried soil. Numeric prefixes (2, 3, and so on) are used to denote lithologic discontinuities and mark the tops of individual stratigraphic units.

Table 4. Study drill hole locations. Map view of drill hole locations is provided in figure 13. Northing and easting coordinates are in North American Datum of 1983 (NAD 83) Universal Transverse Mercator Zone 13.

Drill hole number	Northing, in meters	Easting, in meters	Elevation, in meters
4001	4,440,327	548,334	1,460.6
4002	4,465,501	601,952	1,373.9
4003	4,439,245	557,970	1,478.5
4004	4,438,989	553,194	1,458.3
4005	4,440,356	558,134	1,471.0
4006	4,438,191	566,086	1,449.5
4007	4,431,285	559,534	1,525.8
4008	4,432,179	566,274	1,479.6
4009	4,431,853	604,516	1,388.6
4010	4,440,303	625,399	1,362.9
4011	4,435,037	567,455	1,473.2
4012	4,465,501	601,952	1,373.9
4013	4,457,072	567,428	1,391.6
4014	4,451,848	566,860	1,432.3

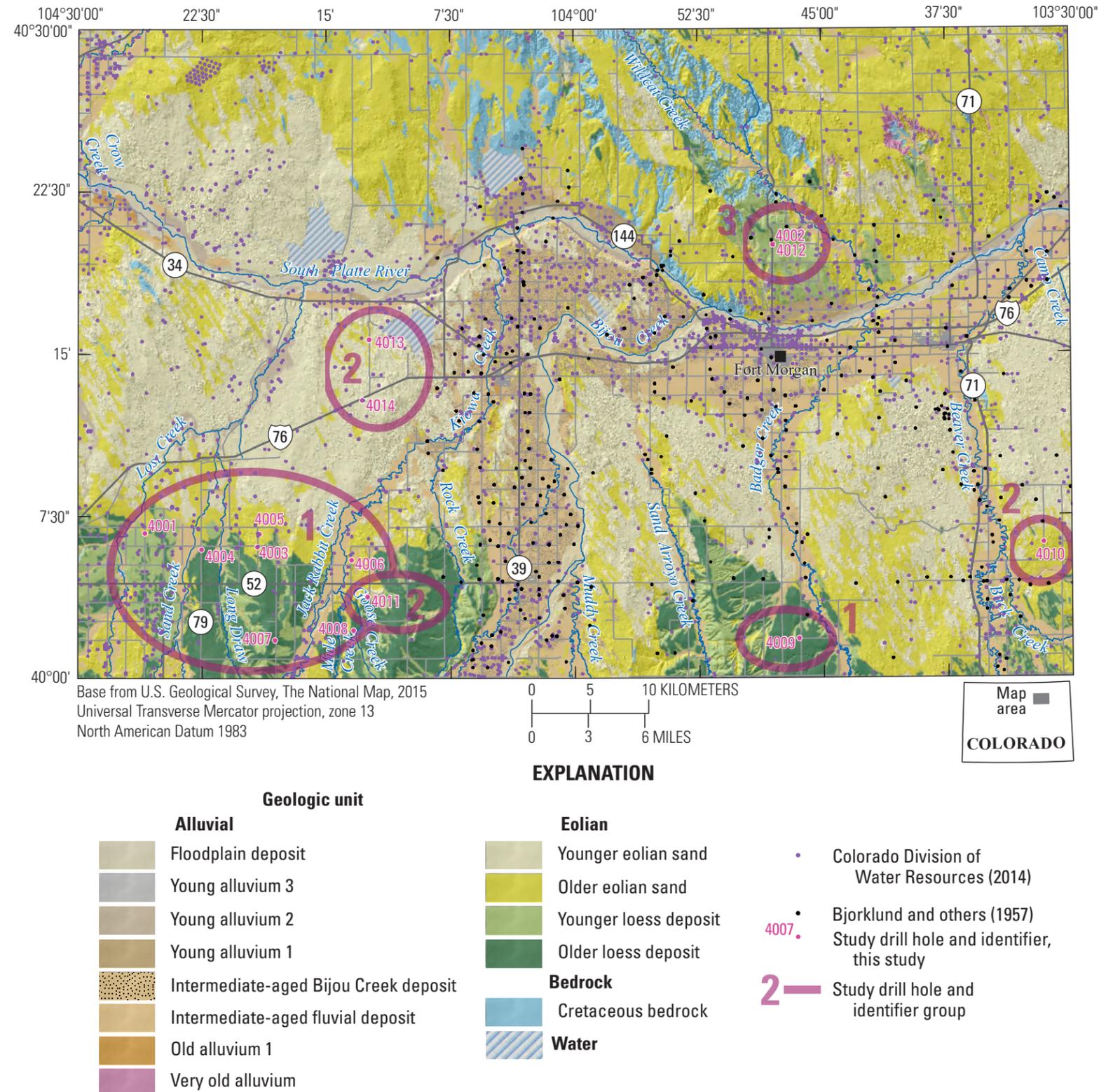


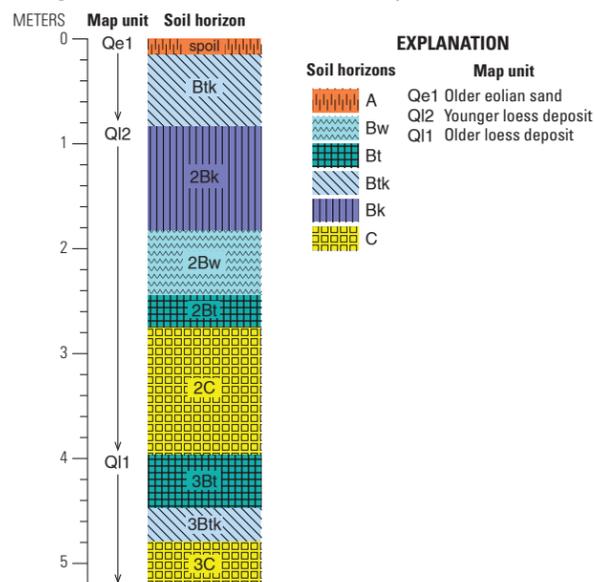
Figure 13. Study drill hole locations. The drill holes were grouped for easier description and interpretation. Group 1 drill holes were located south of the South Platte River where Q12 was mapped at the surface or mantled by a thin deposit of Qe at the surface, Group 2 drill holes were located where Qe1 or Qe2 are mapped at the surface, and Group 3 drill holes were located in the loess body north of the South Platte River.

Group 1 Core 4001

Core 4001 is 5 m deep and intersects Qe1 above Q12 and Q11 (fig. 14A). The Olney series (table 2) is mapped at the surface and exposed in the top meter. Upper horizons may have been stripped or reworked. A typical Olney series is sandy, and well drained with an A/Bt/Btk/Bk profile. At this location, the Olney series is less than 1 meter thick and welded to the finer grained loess (Q12) at about 1 m depth. This suggests that very little time separated the deposition of the predominantly sandy unit (Qe1) and the deposition of the underlying finer grained silty-clay loess (Q12). At 4 m depth there is an abrupt contact between the base of Q12 and the top of Q11 marked by the presence of a well-developed, clay-rich, reddish Bt horizon, typical of

A. Group 1 Study drill hole 4001

Wagner—Southeast corner of County Road 67 and County Road 8, Weld County



Loveland Loess (Madole and others, 2005). The basal soil 2Btk horizon is carbonate-rich with both filaments and nodules. The southern end of cross section B–B', (fig. 12B) approaches core 4001 and displays about 20 m of loess. Very thin irregular patches of Qe1 are at the surface of the cross section in the area of core 4001.

Group 1 Core 4003

Core 4003 is nearly 9 m deep and intersects a complex interfingering of eolian sand, loess, and alluvium—from top to bottom: Qe1, Q12, Q1+Qe, Q11, Qe, and Qa (fig. 14B). The Ascalon series (table 2) is mapped at the surface. This series has a morphology very similar to the Olney series with an A/AB/Bt/Bk profile, but the Ascalon series has less secondary carbonate accumulation than the Olney series. Below the modern soil, major breaks in the stratigraphy are based mostly on texture, alternating between sandier and more clayey deposits. Some soil welding has occurred between paleosols in the upper deposits at the Qe1 and Q12 contact. The soil developed in Qe1 is sandy, weak, and less than 1 m thick. The thin mantle

of Qe1 at the surface is also displayed at the southern end of cross section C–C', (fig. 12C) where core 4003 is intersected. The buried surface of Q12 is marked by a thin 2Bk horizon with stage I+ carbonate filaments. As in core 4001, Q12 was probably buried soon after deposition by Qe1, indicated by the welding of soils developed in Qe1 and Q12. Below Q12, there is a series of alternating sandy and silty layers, with individual layers about 5 centimeter (cm) thick (Q1+Qe). These layers are in abrupt contact with the top of Q11, marked by a well-developed, red (rated 7.5 yellow-red [YR] hue on the Munsell Soil Color Chart Munsell Color Company, Inc., 1990), clayey 4Bt horizon. This horizon caps a 4Bk horizon with stage II+ secondary carbonate accumulation. Both the well-developed 4Bt and 4Bk horizons indicate an older soil than that developed in Q12, which lacks a substantial Bt horizon. Below Q12, at 7 m, is a 2-m section of oxidized, carbonate-cemented undifferentiated sand (Qe). The presence of mottles and carbonate nodules imply the deposit is or was periodically saturated by groundwater. The base of Qe is in abrupt contact with oxidized gravelly sand and clay, an alluvial unit (Qa).

B. Group 1 Study drill hole 4003

Conservation Reserve Program—Southwest corner of County Road 79, south of County Road 16, Weld County

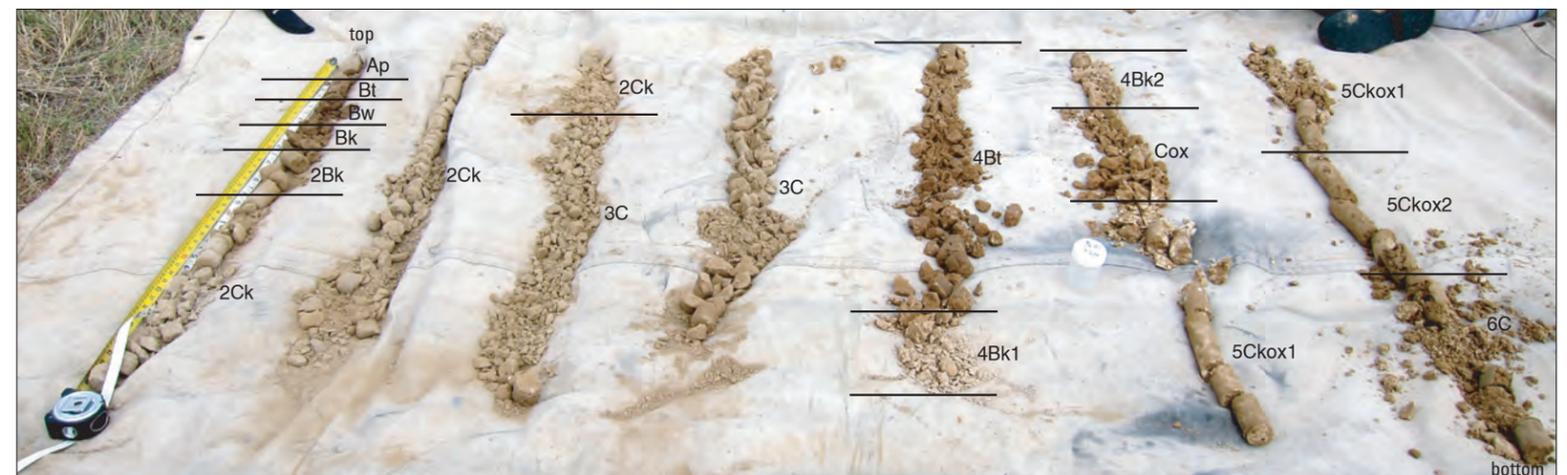
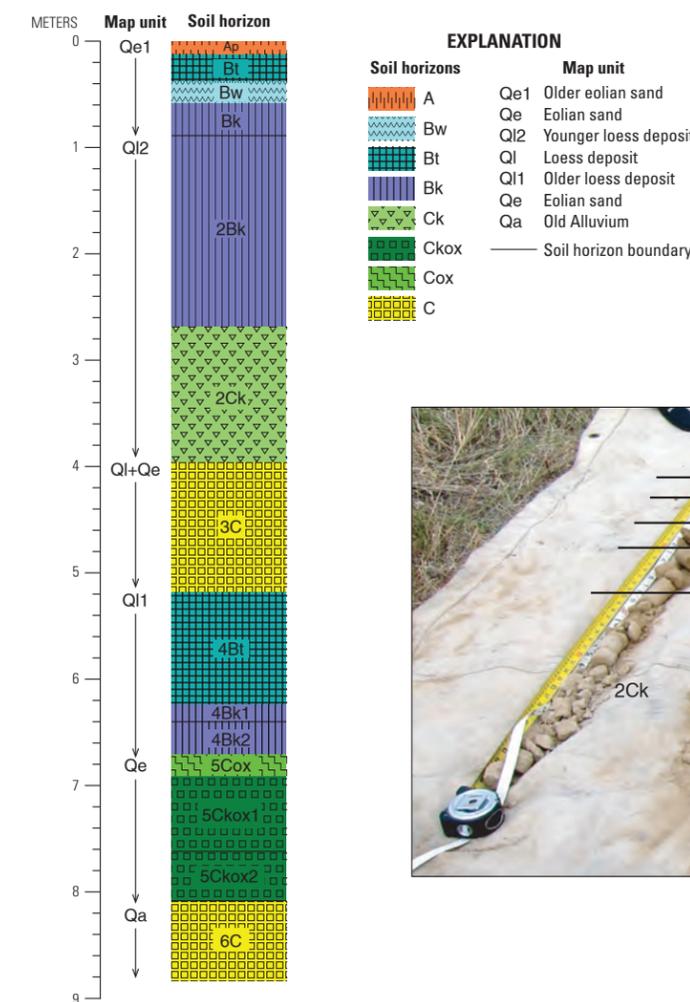


Figure 14. Core descriptions of the drill holes and photographs of the study area (all photographs by Emily Taylor and Margaret Berry, USGS, 2016). *A*, Core description of Group 1 Core 4001. *B*, Core description of Group 1 Core 4003 and photograph of core. *C*, Core description of Group 1 Core 4004 and photographs of surface expression of Q12 and core samples. *D*, Core description of Group 1 Core 4005 and photographs of surface expression of Q12 and core samples. *E*, Core description of Group 1 Core 4006 and photographs of surface expression of Qa and core samples. *F*, Core description of Group 1 Core 4007 and photographs of surface expression of Q12 and core samples. *G*, Core description of Group 1 Core 4008 and photographs of dated animal remains and core samples. *H*, Core description of Group 1 Core 4009 and photographs of surface expression of Q12 and core samples. *I*, Core description of Group 2 Core 4011 and photographs of surface expression of Qe1 and core samples. *J*, Core description of Group 2 Core 4010 and photographs of core samples and surface expression of Qe1. *K*, Core description of Group 2 Core 4013 and photograph of core samples. *L*, Core description of Group 2 Core 4014 and photographs of surface expression of Qe2 and core samples. *M*, Core description of Group 3 Core 4002 and photograph of core samples. *N*, Core description of Group 3 Core 4012 and photographs of core samples and surface expression of Q12. The 14 drill holes were grouped into three groupings for easier description and interpretation (fig. 13). Group 1 drill holes were located south of the South Platte River where Q12 was mapped at the surface or mantled by a thin deposit of Qe at the surface. The only exception was drill hole 4006, which intersected only alluvium. Group 1 drill holes were selected to help understand better the relation between the surface loess and the older buried loess (Q11). We were also interested in determining the near surface relation between the eolian sands (Qe) and Q1. Group 2 drill holes were located where Qe1 or Qe2 were mapped at the surface. Group 3 drill holes were located in the loess body north of the South Platte River.

Group 1 Core 4004

Core 4004 exposes a mantle of less than 2 m of Ql2 over undifferentiated gravelly alluvium (Qa; fig. 14C). The NRCS soil survey map shows the Weld series (table 2) at the surface, which typically is a well-drained soil formed in calcareous loess with an A/Bt/Btk/Bk profile. Here, the profile is a less well developed Ap/Bk1/B2k/C profile. Between the loess and alluvial deposits is a poorly sorted transitional unit composed of reworked loess and alluvium (Ql2+Qa). The drill hole is located between Sand Creek and Long Draw, and either of these is a potential source for the alluvium (Qa) at the base of the core. The alluvium is poorly sorted silty sand with granules and fine pebbles and layers of coarse sand.

Group 1 Core 4005

Core 4005 intersects a complex interfingering of loess, eolian deposits, and alluvium. From top to bottom the sequence is Ql2, Qe+Ql, Qe, Ql, and Qa (fig. 14D). Although, in the soil survey, the Ascalon series is mapped at the surface, sediments from core 4005 represent the Weld series at the surface. The Weld series is also exposed at the surface of core 4004. The soils that developed in Ql2 and Qe1 are very similar. The soil here has a Bt horizon with weak prismatic structure but abundant clay films. The Bk horizons have stage I carbonate filaments. Below Ql2 is a transitional depositional zone, about 1 m thick, where Qe+Ql are weakly interstratified. Unit Qe+Ql is in abrupt contact with Qe that hosts a weakly expressed 3A+Bk horizon. A second package of loess (Ql), about 1 m thick, is below Qe. The loess lacks soil horization, suggesting it was buried by Qe shortly after deposition. Below the buried loess, the core intersects a well-developed soil developed in gravelly alluvium (Qa). Soil properties in the 4Bt horizon developed in the alluvium include common clay films on ped faces and a 7.5YR hue soil color. The water table was intersected at 8 m in the 4COx horizon and is marked by oxidized sand, stringers of magnesium oxide, and weakly developed carbonate concretions. Cross section C-C', (fig. 12C) intersects core 4005, but the complex interbedding observed in the core is not apparent in the cross section. Interbedded eolian deposits are observed in the section farther north.

C. Group 1 Study drill hole 4004
Stolle—Southeast corner of County Road 73 and County Road 16, Weld County

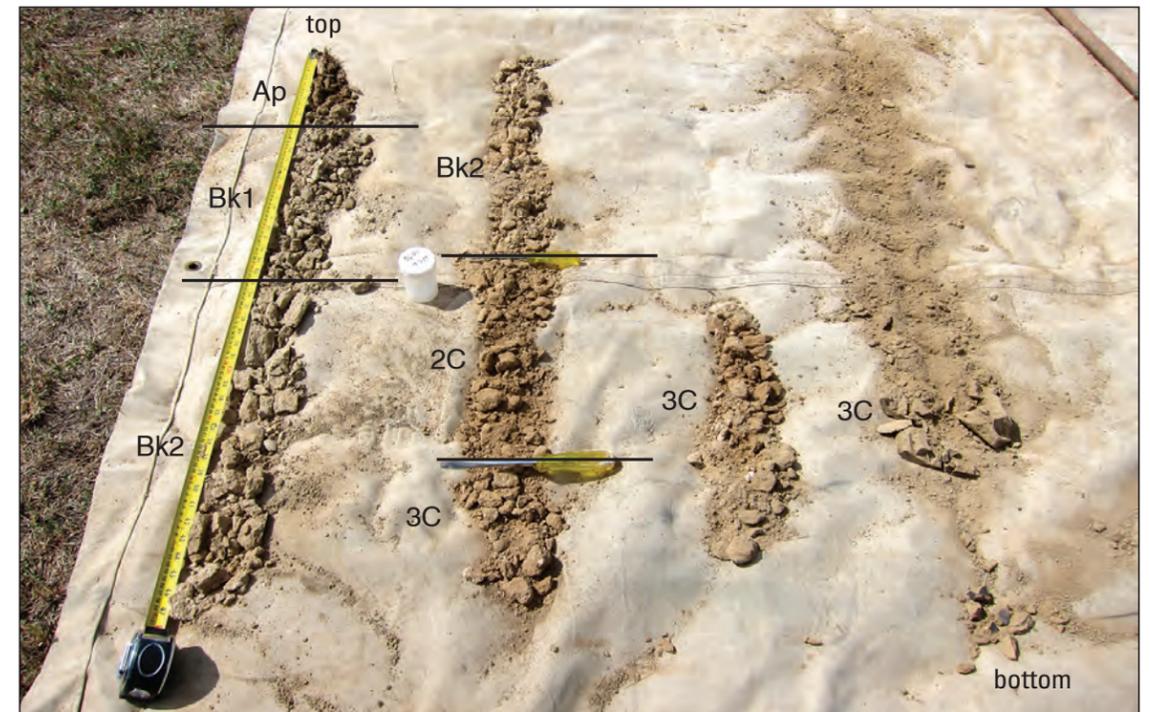
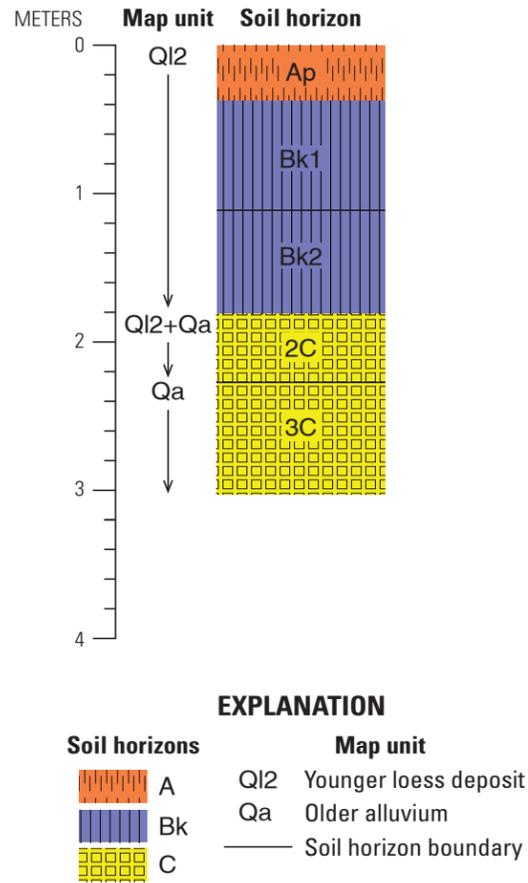


Figure 14.—Continued.

D. Group 1 Study drill hole 4005

Klausner North—Southeast corner County Road 79 and County Road 18, Weld County

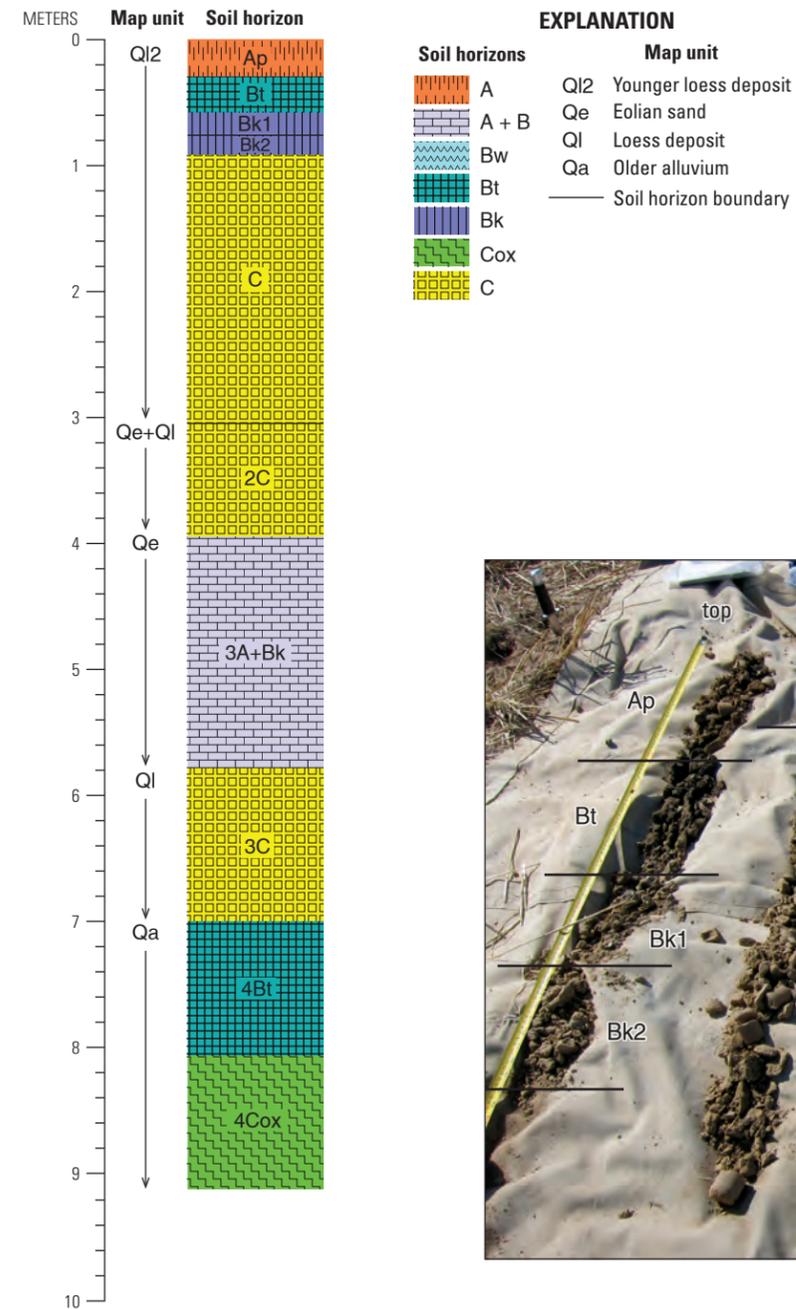
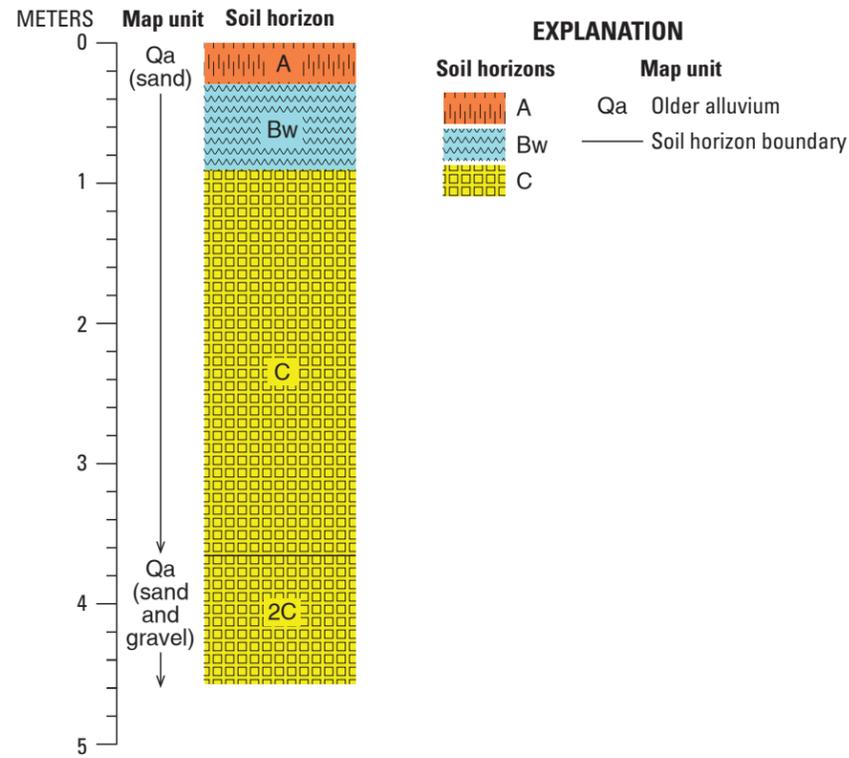


Figure 14.—Continued.

E. Group 1 Study drill hole 4006

Sirios North—Northeast corner County Road 89 and County Road 14, Weld County



Group 1 Core 4006

Core 4006 was acquired on a Qa02 floodplain remnant of Kiowa Creek (fig. 14E). This terrace is situated between deposits of Qe1 and Ql2. Sandy and gravelly alluvium was encountered throughout the 4.5-m core. The upper sand was well to poorly sorted with weak soil horization. The Nunn series is mapped at the surface and is characterized by an A/Bt/Btk profile. However, we did not recognize any accumulation of pedogenic clay or secondary carbonate in the surface profile, so it is possible this terrace is younger than Qa02 but cannot be separated by the scale that was mapped. Most importantly, the alluvium here is thick and is not interfingered with loess deposits. In cross section D–D', (fig. 12D), at the location of core 4006, a very thin deposit of Ql2 (clay sand and silt) overlies 15 m of sand deposited on bedrock, consistent with the observations made from the core where clayey sand (Bw) overlies sand (C).

Figure 14.—Continued.

Table 5. Quartz optically stimulated luminescence (OSL) data and ages from core 4007.

[Data from Mahan and others (2025); cm, centimeter; %, percent; K, potassium; U, uranium; ppm, parts per million; Th, thorium; Gy, gray—1 gray is the absorption of 1 joule of radiation energy by 1 kilogram of matter; ka, thousand years; N, nitrogen; DE, equivalent dose; yrs, years; ±, plus or minus; >, greater than]

Sample number	Sample depth (cm)	% water content (% field moisture) ¹	K (%) ²	U (ppm) ²	Th (ppm) ²	Total dose (Gy/ka) ³	Equivalent dose (Gy)	N, number of estimates used in DE calculation (total number of measurements) ⁴	Scatter (%) ⁵	Age (yrs) ⁶
PR-9-14-16-1 (C)	165–180	15 (41)	2.29±0.07	4.79±0.12	14.4±0.72	4.23±0.14	53.6±6.2	6 (15)	20	12,690±1,530
PR-9-14-16-1 (D)	208–223	17 (18)	2.30±0.07	4.58±0.11	16.7±0.84	4.62±0.15	71.2±2.7	11 (25)	13	15,420±770
PR-9-14-16-2 (A)	387–402	4 (37)	2.05±0.06	4.30±0.11	13.9±0.70	3.99±0.13	>331±190	3 (7)	27	82,960±47,690 ⁷
PR-9-14-16-2 (B)	402–417	13 (70)	2.11±0.06	4.75±0.12	13.7±0.69	3.73±0.12	>301±66	5 (16)	15	80,720±17,850 ⁷

¹Field moisture (figures in parentheses) indicates the complete sample saturation percent. Dose rates calculated using 25 percent of the saturated moisture (for example, 4 (48) = 48 x 0.25 = 12).

²Analyses obtained using inductively coupled plasma mass spectrometry. All errors were obtained with calibration standards and are generally about 3 percent.

³Includes cosmic doses and attenuation with depth calculated using the methods of Prescott and Hutton (1994). Cosmic doses were 0.14–0.13 Gy/ka.

⁴Number of replicated DE estimates used to calculate the total DE. Figures in parentheses indicate total number of measurements included in calculating the represented DE and age using the central age model for Peoria Loess and themaxine for Loveland Loess. Analyzed using single aliquot regeneration on quartz grains.

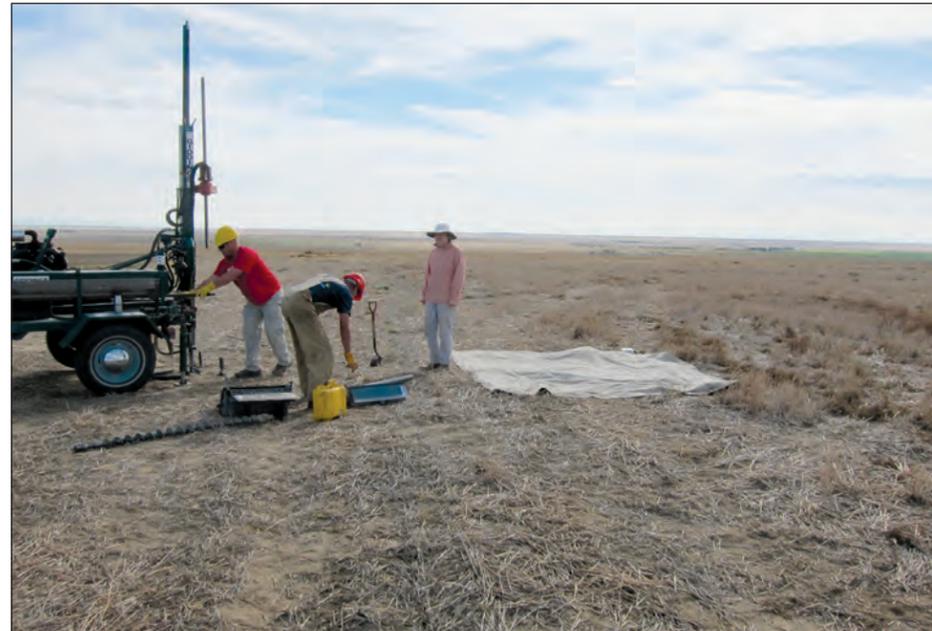
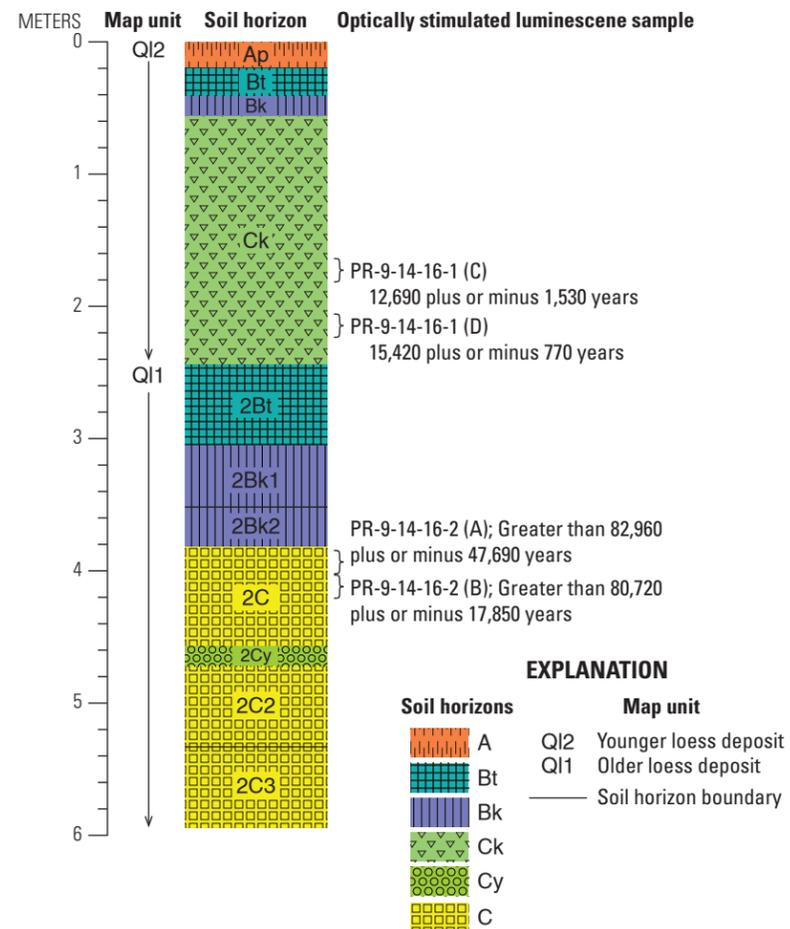
⁵Defined as “over-dispersion” of the DE values. Values >30% are considered poorly bleached or mixed sediments.

⁶DE and age for fine-grained 90–63 or 150–90 micron-sized quartz. Exponential + linear fit used on DE. Errors are 1 sigma.

⁷DE and age for fine-grained 90–63 or 150–90 micron-sized quartz using the thermal-transfer OSL peak. Exponential + linear fit used on DE, errors to 1 sigma.

F. Group 1 Study drill hole 4007

Klausner South—Southwest corner County Road 81 and County Road 6, Weld County



Group 1 Core 4007

Core 4007 penetrates two loess packages (Q12 overlying Q11) that lack any interfingering eolian sand deposits (fig. 14F). These two loess units were selected for dating analysis by optically stimulated luminescence (OSL; table 5; Mahan and others 2025). The NRCS soil survey identifies the Weld series developed in calcareous loess at the surface. The soil is characterized by an A/Bt/Btk/Bk profile. At this location, the 10-cm-thick Bt horizon has thin clay films on ped faces and a 10YR hue soil color. The Bk horizon has stage I secondary carbonate expressed as soft concretions. Samples were collected for OSL in two 15-cm intervals in the Ck horizon of Q12. Both age estimates fell within the expected range for the Peoria Loess (tables 1 and 5)—12,690 ± 1,530 years and 15,420 ± 770 years.

The buried loess, Q11, has a better developed soil than Q12. Unit Q11 has a nearly 50-cm thick 2Bt horizon with thin clay films on ped faces and a 7.5YR hue soil color. The 2Bk horizons have minor carbonate filaments and disseminated secondary carbonate. The OSL samples were collected in 15-cm intervals in the 2C horizon. Both samples provided age estimates of greater than 80,000 years, which is consistent with deposition during late- or post-Bull Lake glaciation (table 1). Below the 2C horizon is a gypsum-rich 2Cy horizon. The gypsum is probably related to water table fluctuations or vadose zone precipitation. The horizon matrix is noncalcareous. Soil horizons below the 2Cy horizon are lighter colored than horizons above and well cemented.



Figure 14.—Continued.

Group 1 Core 4008

Core 4008 is nearly 12 m long (fig. 14G). Four individual packages of loess were distinguished above the impenetrable alluvium at the base of the core. The Weld series is mapped at the surface, consistent with soils developed in map unit QI2, which we consider to be Peoria Loess (table 1). Three older loess units are preserved below QI2 and are designated QI1c, QI1b, and QI1a (youngest to oldest) indicating only that we know they are older than QI2. The 2Bt horizon developed in QI1c is very similar to the buried soil in core 4007 dated at greater than 80,000 years (table 5, fig. 14F). The 2Bt horizon is about 50 cm thick and has thin clay films on ped faces and a 7.5YR hue soil color that is much redder than the adjacent horizons. Gypsum crystals are abundant in the 2Bty horizon and the 2Bk horizon has stage I secondary carbonate filaments. Within the 2BK horizon, a krotovina was preserved that contained the bones and teeth of a small burrowing animal. The bone collagen was radiocarbon dated at 16,000 ± 240 years (table 6). This age is consistent with the Peoria Loess associated with unit QI2 described at the surface of core 4008. A possible explanation for the young age of the bone collagen relative to the probable age of the surrounding sediments is that the animal burrowed into the older QI1c deposit at the onset of deposition of QI2. The abundance of secondary carbonate accumulation in soil horizons 3K1 and 3K2, in the QI1b loess, records an extended period of pedogenesis at the surface, prior to burial by QI1c. Based on the thickness and generally weak soil development of the 4Bt horizon, unit QI1a was buried more rapidly than the overlying loess packages. The absence of interfingering eolian sand suggests that this deep section of uninterrupted loess deposition is probably related to its short distance from sandy deposits adjacent to the South Platte River. The alluvium at the bottom of the core is sand to loamy sand with scattered granules and has a 10YR hue soil color.

G. Group 1 Giddings drill hole 4008
Rosling—West end of County Road 650
off of County Road 91, Weld County

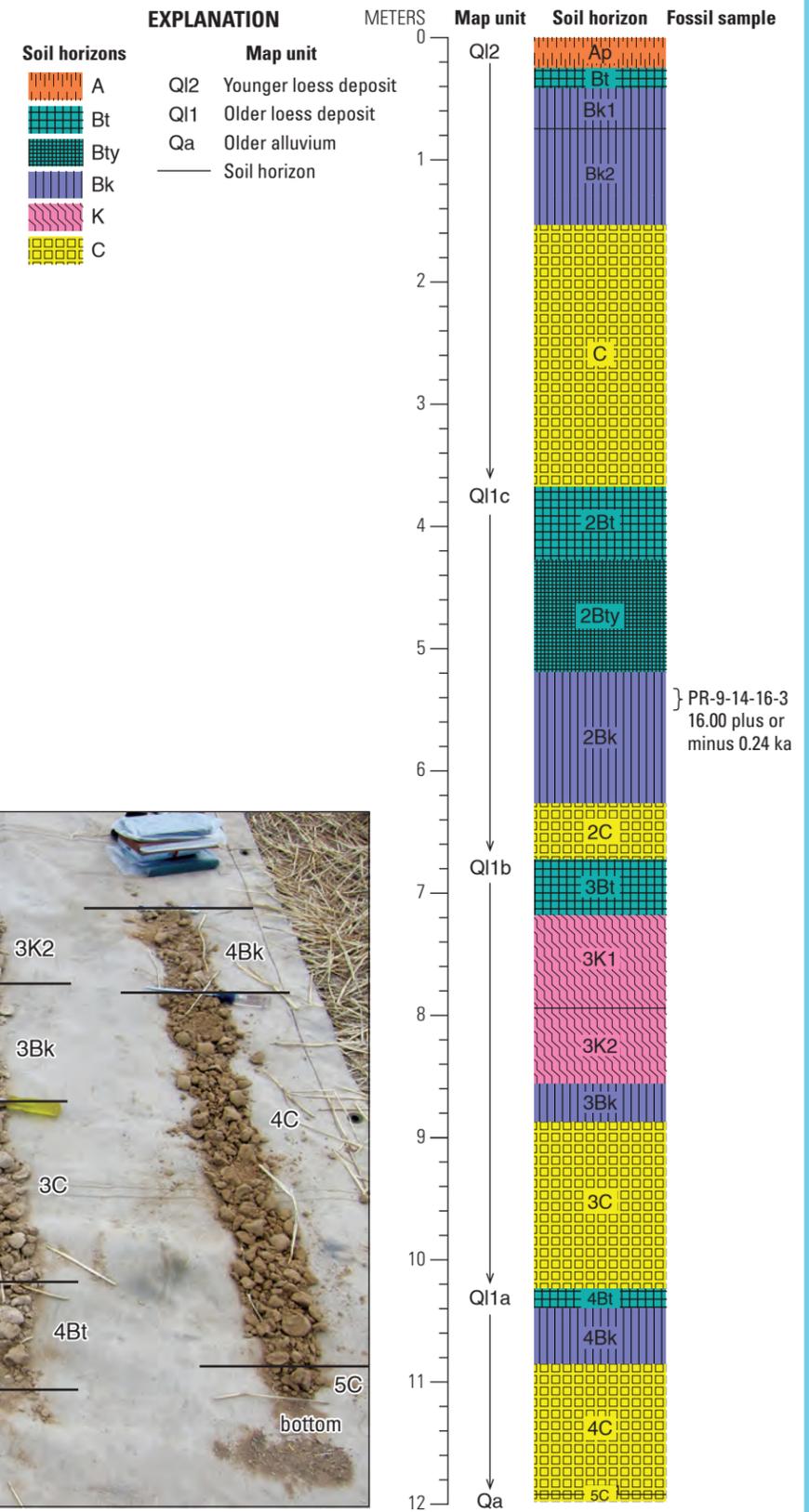
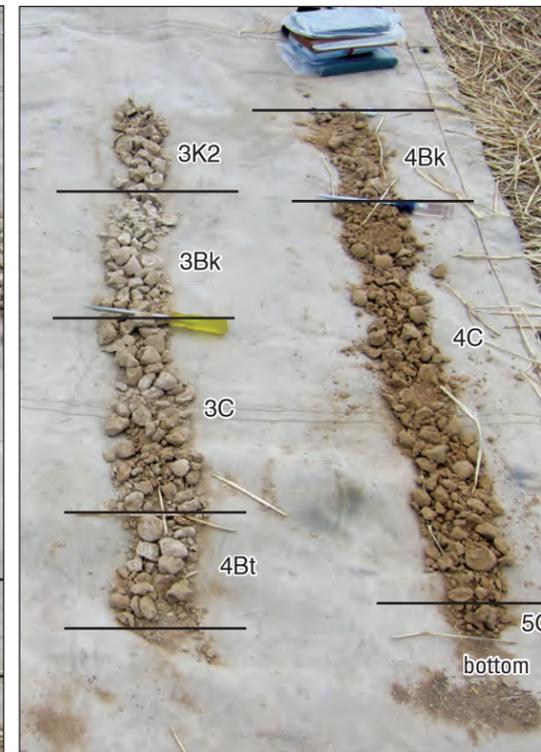
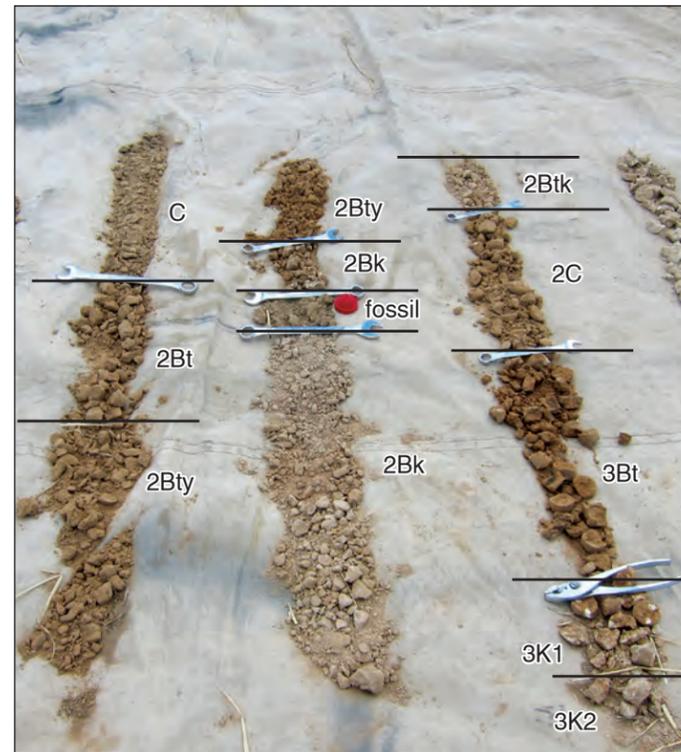
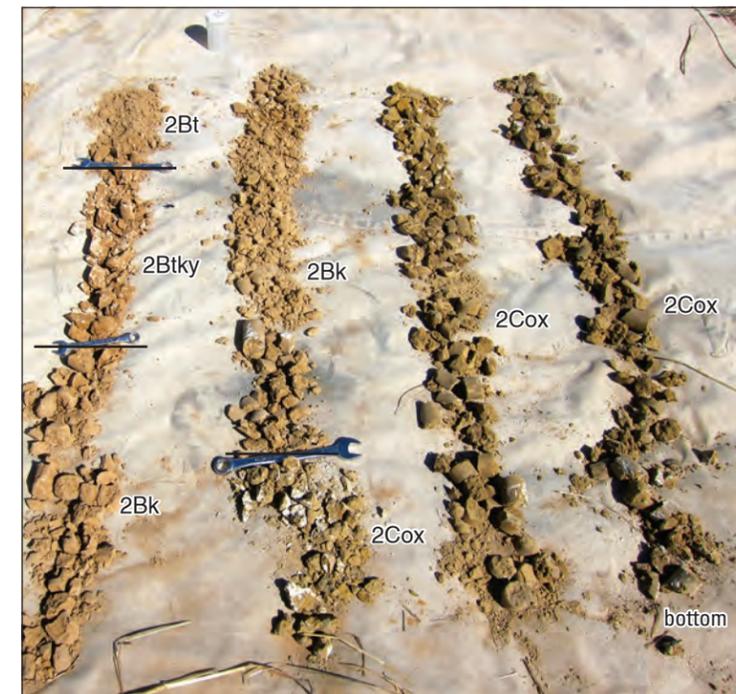


Figure 14.—Continued.

Group 1 Core 4009

The NRCS soil survey maps the Weld series, consisting of a typical A/Bt/Btk/Bk profile, at the surface of core 4009 (fig. 14H). This soil horization is consistent with the upper soil developed in Q12 loess observed in this core. The core revealed a surface soil hosting a thin Bt horizon with prismatic to subangular blocky structure, common clay films, and a 10YR hue soil color. The C horizon is very fine-grained well-sorted loess, much finer than the loess to the west in Weld County. There is little to no sand present. A buried 2Bt horizon marks the surface of an older loess (Q11) that is visually redder, although still 10YR hue soil color, and is thicker than the overlying Bt layer. Horizons below the 2Bt horizon have evidence of vadose zone gypsum and carbonate precipitation. The basal oxidized 2C horizon is gleyed with red and green mottles (2.5Y hue soil color). There are also abundant gypsum crystals and carbonate nodules in the 2C horizon.

H. Group 1 Study drill hole 4009
 Lewton—Northwest corner of County Road 20
 and County Road C, Morgan County



EXPLANATION

Soil horizons	Map unit
A	Q12 Younger loess deposit
Bt	Q11 Older loess deposit
Btky	Soil horizon boundary
Bk	
C	

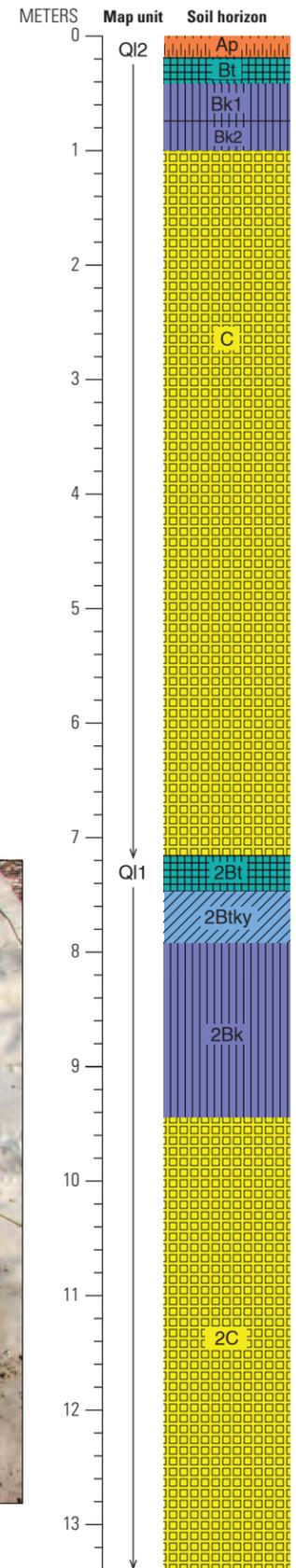
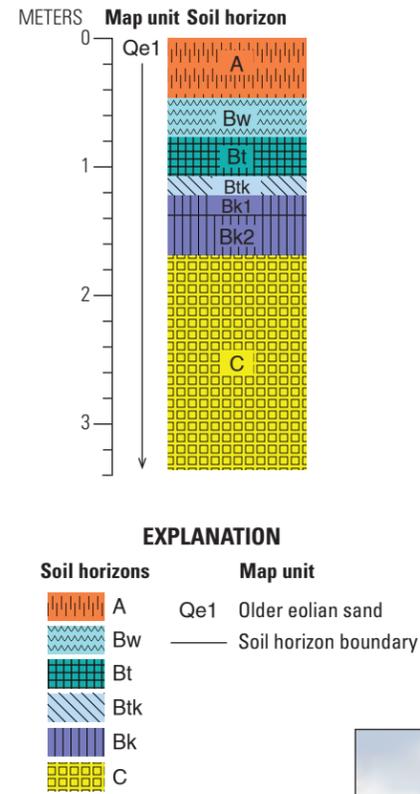


Figure 14.—Continued.

I. Group 2 Study drill hole 4011

Sirios South—County Road 91 and State Highway 52, Weld County



Group 2 Core 4011

The Ascalon series is mapped at the location of core 4011 and is characterized by an A/BA/Bt/Bk profile, typical of unit Qe1 (table 2). The soil profile observed in core 4011 has a similar morphology to the characteristic Ascalon soil (fig. 14I). The sandy loam Bw horizon has a 10YR hue soil color and is unconsolidated. The Bt horizon has accumulated clay and a 7.5YR hue soil color. The Btk horizon is also reddish with stage II secondary carbonate accumulation. The carbonate content decreases with depth and is absent in the C horizon.

Figure 14.—Continued.

J. Group 2 Study drill hole 4010

Hobbs—Northwest corner County Road 33 and approximate location of County Road H, Morgan County

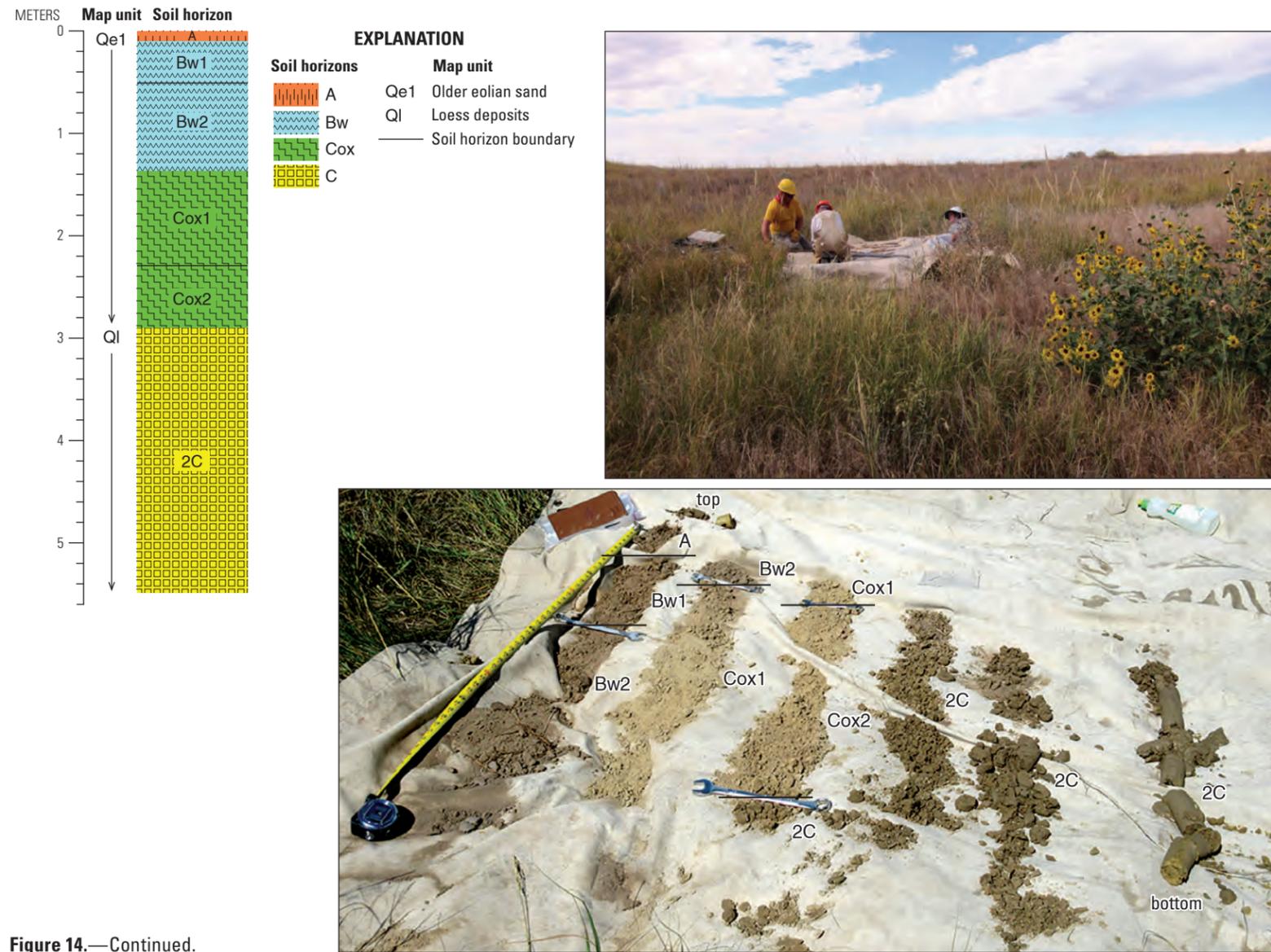


Figure 14.—Continued.

Group 2 Core 4010

The Vona series, the most common soil type developed in Qe1, is mapped at the surface of core 4010 (fig. 14J). Soils of the Vona series typically have A/AB/Bt/Bk profiles, but the soil exposed in the core lacks Bt and Bk horizons. The Bw1 horizon is slightly hard, has no clay films, and is merely a color B horizon. The Bw2 horizon is sandier and also lacks clay films. However, the presence of color B horizons precludes interpreting the host deposit as Qe2, which typically has only an A/C profile. This site could be affected by its proximity to Holocene eolian sand and is probably receiving additions of transported sand. At about 3 m depth, the sand is in abrupt contact with unweathered loess. The lack of a soil at this

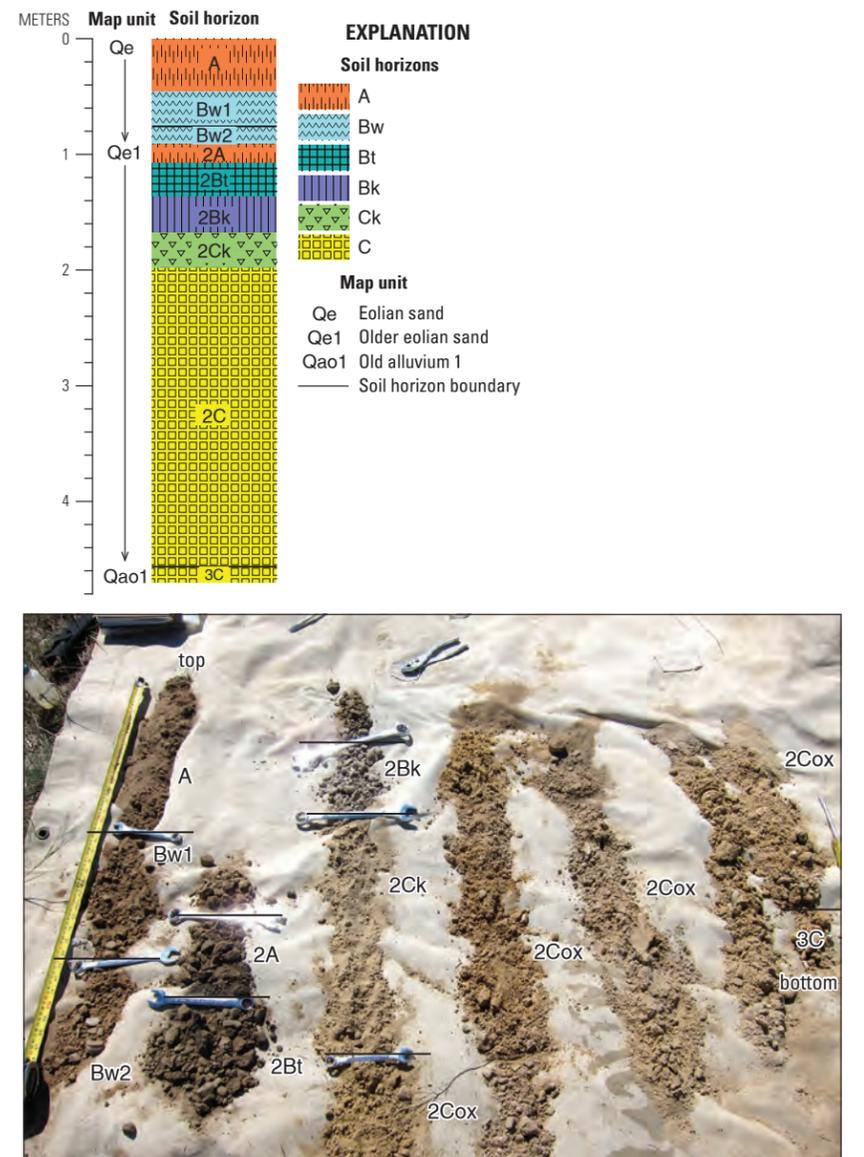
contact suggests that very little time separated the deposition of the loess and the onset of eolian sand deposition or that the unit was eroded. High water content at the base of the loess prevented further drilling at this site.

Group 2 Core 4013

A thin (less than 1 m) mantle of young sand covers the Osgood series, the most common soil mapped in Qe1 interdune areas (fig. 14K). Soils of the Osgood series are characterized by A/Bt/Bk/C profiles and 10YR hue soil color. The weakly developed, thin soil of less than 1 m thick that overlies the Qe1 soil at core 4013 is primarily sand with little or no clay films and a 10YR hue soil color. The interdunes

K. Group 2 Study drill hole 4013

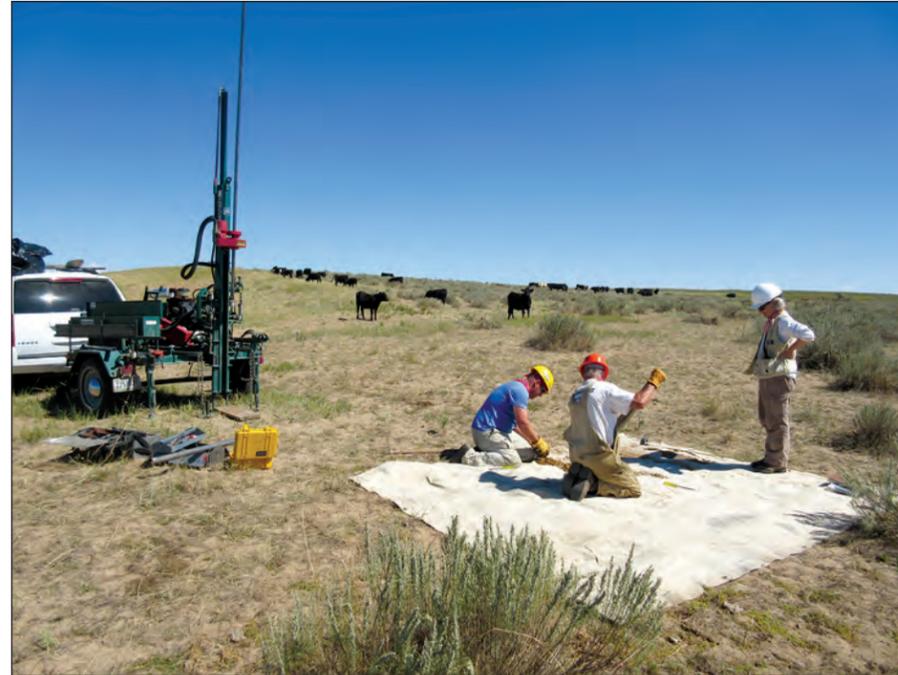
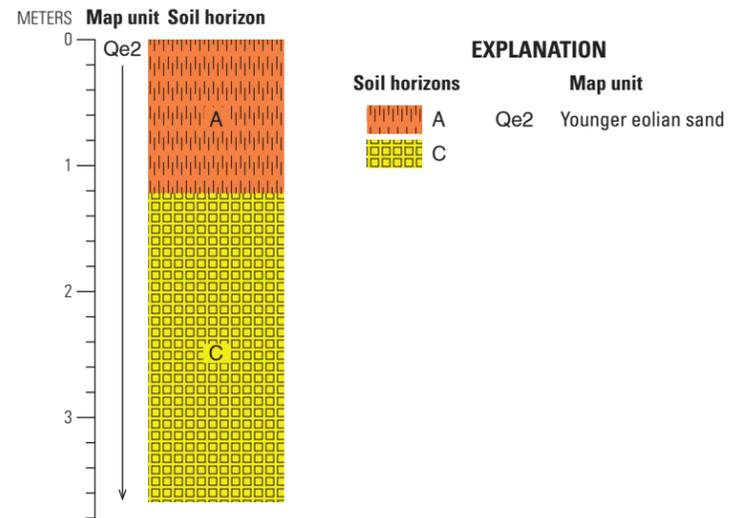
Lost Creek Ranch—West of Empire Reservoir, County Road 91 and an approximate location of County Road S, Weld County



are partly covered by young deposits of sand reworked from surrounding areas. This young, reworked sand is in abrupt contact with the underlying A horizon developed in Qe1 deposits. The 2A horizon is much browner than the soil above and has a sandy clay loam texture. The 2Bt horizon has thin clay films on ped faces and a 10YR hue soil color. Secondary carbonate accumulations in the 2Bk horizon are stage II. The basal C horizon has characteristics of water saturation including banded layers of oxidized and unoxidized sand. The 2Cox horizon is in abrupt contact with cemented sandy gravel that is correlative to Qao1 deposits exposed in gravel quarries nearby. Cross section C–C', intersects a series of buried terraces near core 4013 (fig. 12C). The shallow Qao1 gravel is patchy in the cross section, which may be due to the paucity of data in that area.

L. Group 2 Study drill hole 4014

Yocam—South end of County Road 91, south of Interstate 76,
Weld County

**Group 2 Core 4014**

Core 4014 was acquired entirely in Qe2, an unconsolidated sand resulting in unrecoverable or unreliable samples (fig. 14L). The surface soil is mapped as the Valent series with an A/C profile, which was confirmed by drilling activities that showed B horizon development was lacking. In the vicinity of core 4014, cross section C–C', displays a 15–20 m thick section of unconsolidated sand above a buried terrace gravel on a paleostrath terrace surface (fig. 12C). Unconsolidated Qe2 may bury Qe1 at this site.

Figure 14.—Continued.

M. Group 3 Study drill hole 4002

Rasmussen—Southeast corner of State Highway 52 and County Road W,
Morgan County



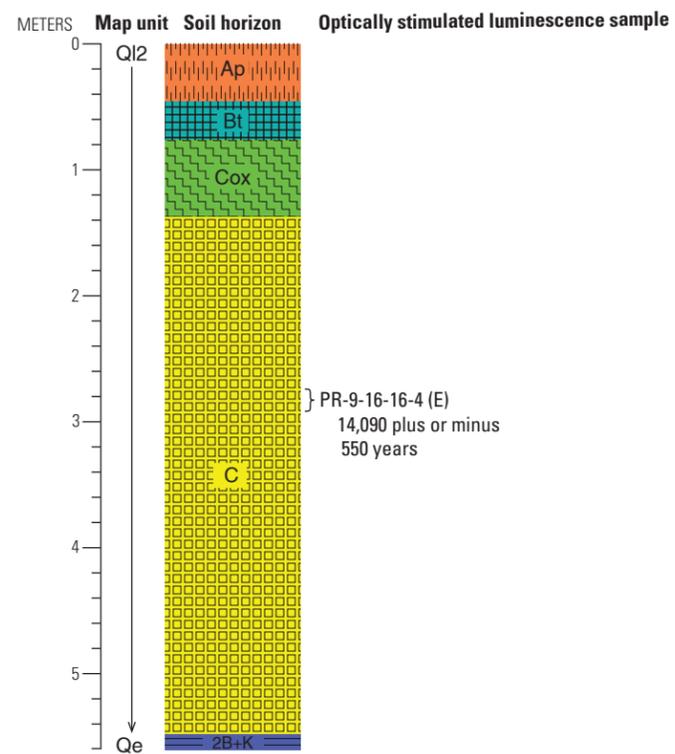
Figure 14.—Continued.

Group 3 Core 4002

Drill hole 4002 was drilled in Ql2 in an area north of Fort Morgan (fig. 14M). Most other Ql2 loess is mapped south of the South Platte River (fig. 7). The southern loess typically has soils of the Weld series developed on stable, flat surfaces and the Colby-Adena series on adjacent slopes that are prone to erosion. These soils differ from each other on the presence (Weld and Adena series) and absence (Colby series) of B horizons. The site for core 4002 was selected because the surface is flat, yet the soil mapped at the surface is the typically less well developed Colby-Adena (table 2), suggesting that the loess deposit at this site could be younger than loess deposits south of the river. Cores 4002 and 4012 (fig. 14N) were taken only 5 m apart, and yet the soils are not identical. Core 4002 penetrated an A/Bk/C profile developed in calcareous loess (Ql2). The Bk horizon has fine filaments of stage I secondary carbonate and is lighter in color than the Ap horizon above. The C horizon is in abrupt contact with a cemented sand (Qe) that is engulfed with carbonate cement that resembles vadose zone carbonate.

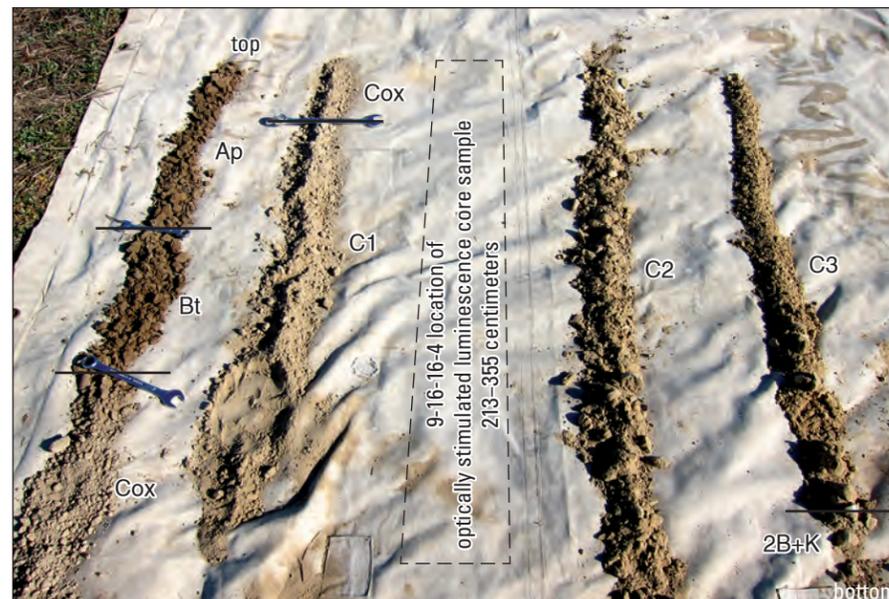
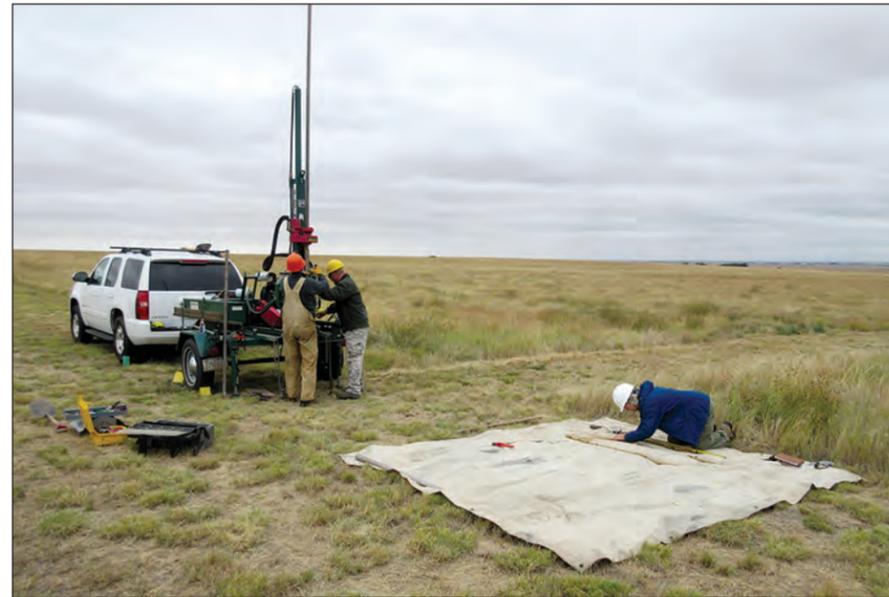
N. Group 3 Study drill hole 4012

Rasmussen—Southeast corner of State Highway 67 and County Road W, Morgan County



EXPLANATION

Soil horizons	Map unit
A	Ql2 Younger loess deposit
Bt	Qe Eolian sand
B + K	Soil horizon boundary
Cox	
C	



Group 3 Core 4012

Core 4012 was drilled 5 m west of core 4002 to sample sediment for OSL analysis (table 7, Mahan and others, 2025, fig. 14N). A thin Bt horizon was observed in core 4012 that was not present in core 4002. The Bt horizon has common clay films and a 10YR hue soil color. The OSL samples were collected from the C horizon, a well sorted silty loess (Ql2). At approximately the same depth as in core 4002, impenetrable vadose-zone carbonate-cemented sand was intersected. Even though the surface soil is less well developed at the site of core 4012, the OSL age estimate obtained (14,090±550 years) is consistent with ages obtained for Ql2 loess deposits south of the South Platte River, and likewise supports correlation to Peoria Loess. Both cross sections G–G', and H–H', (figs. 12G, H) intersect cores 4002 and 4012. The cross sections display a thick package of Ql over Qe1.

Figure 14.—Continued.

Table 6. Radiocarbon sample information, carbon-14 (¹⁴C)¹ age, and calibrated age from drill hole 4008.

[cm, centimeter; USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator; cm, centimeter; δ¹³C, delta carbon-13 (¹³C); ‰, per mil; ¹⁴C ka B.P., carbon-14 thousand years before present; cal ka B.P., calibrated thousand years before present; P, probability]

Field number	Laboratory number	USGS 7.5-minute quadrangle map	UTM Easting ²	UTM Northing ²	Material dated	Approximate depth (cm)	δ ¹³ C(‰) ³	¹⁴ C age (14C ka B.P.) ⁴	Calibrated age (cal ka B.P.) ⁵	P ⁶
PR-9-14-16-3	Aeon–2323	Wiggins SW	566274	4432179	Bone collagen	533–549	–15.9	13.31 ± 80	16.00±0.24	1.00

¹Radiocarbon (¹⁴C) activity measured by accelerator mass spectrometry.

²1983 North American Datum (NAD 83), zone 13N.

³Relative difference between ¹³C/¹⁴C ratio of carbon extracted from sub-sample and that of Vienna Pee Dee Belemnite international standard.

⁴Conventional radiocarbon age, normalized to –25‰, based on 5,568-year half-life and uncertainty of ±1 sigma.

⁵Calibrated age calculated using CALIB 7.1, IntCal13.14c dataset (Stuiver and Reimer, 1993; Reimer and others, 2013); 0 yr B.P. = 1950 A.D.; uncertainty ± 2 sigmas. Calibrated age reported as midpoint of calibrated range.

⁶Probability of calibrated age falling within reported range as calculated by CALIB.

Table 7. Quartz optically stimulated luminescence (OSL) data and ages from drill hole 4012.

[Data from Mahan and others (2025), cm, centimeter; %, percent; K, potassium; U, uranium; ppm, parts per million; Th, thorium; Gy, gray—1 gray is the absorption of 1 joule of radiation energy by 1 kilogram of matter; ka, thousand years; N, nitrogen; DE, equivalent dose; yrs, years; ±, plus or minus; >, greater than]

Sample number	Sample depth (cm)	% water content (% field moisture) ¹	K (%) ²	U (ppm) ²	Th (ppm) ²	Total dose (Gy/ka) ³	Equivalent dose (Gy)	N, number of estimates used in DE calculation (total number of measurements) ⁴	Scatter (%) ⁵	Age (yrs) ⁶
PR-9-16-16-4 (E)	272–292	7 (34)	2.40±0.07	4.02±0.10	13.1±0.66	4.13±0.13	58.2±1.4	22 (25)	0	14,090±550

¹Field moisture (figures in parentheses) indicates the complete sample saturation percent. Dose rates calculated using 25 percent of the saturated moisture (for example, 4 (48) = 48 x 0.25 = 12).

²Analyses obtained using inductively coupled plasma mass spectrometry. All errors were obtained with calibration standards and are generally about 3 percent.

³Includes cosmic doses and attenuation with depth calculated using the methods of Prescott and Hutton (1994). Cosmic doses were 0.14–0.13 Gy/ka.

⁴Number of replicated DE estimates used to calculate the total DE. Figures in parentheses indicate total number of measurements included in calculating the represented DE and age using the central age model for Peoria Loess and the maxine for Loveland Loess. Analyzed using single aliquot regeneration on quartz grains.

⁵Defined as “over-dispersion” of the DE values. Values >30% are considered poorly bleached or mixed sediments.

⁶DE and age for fine-grained 90–63 or 150–90 micron-sized quartz. Exponential + linear fit used on DE. Errors are 1 sigma.

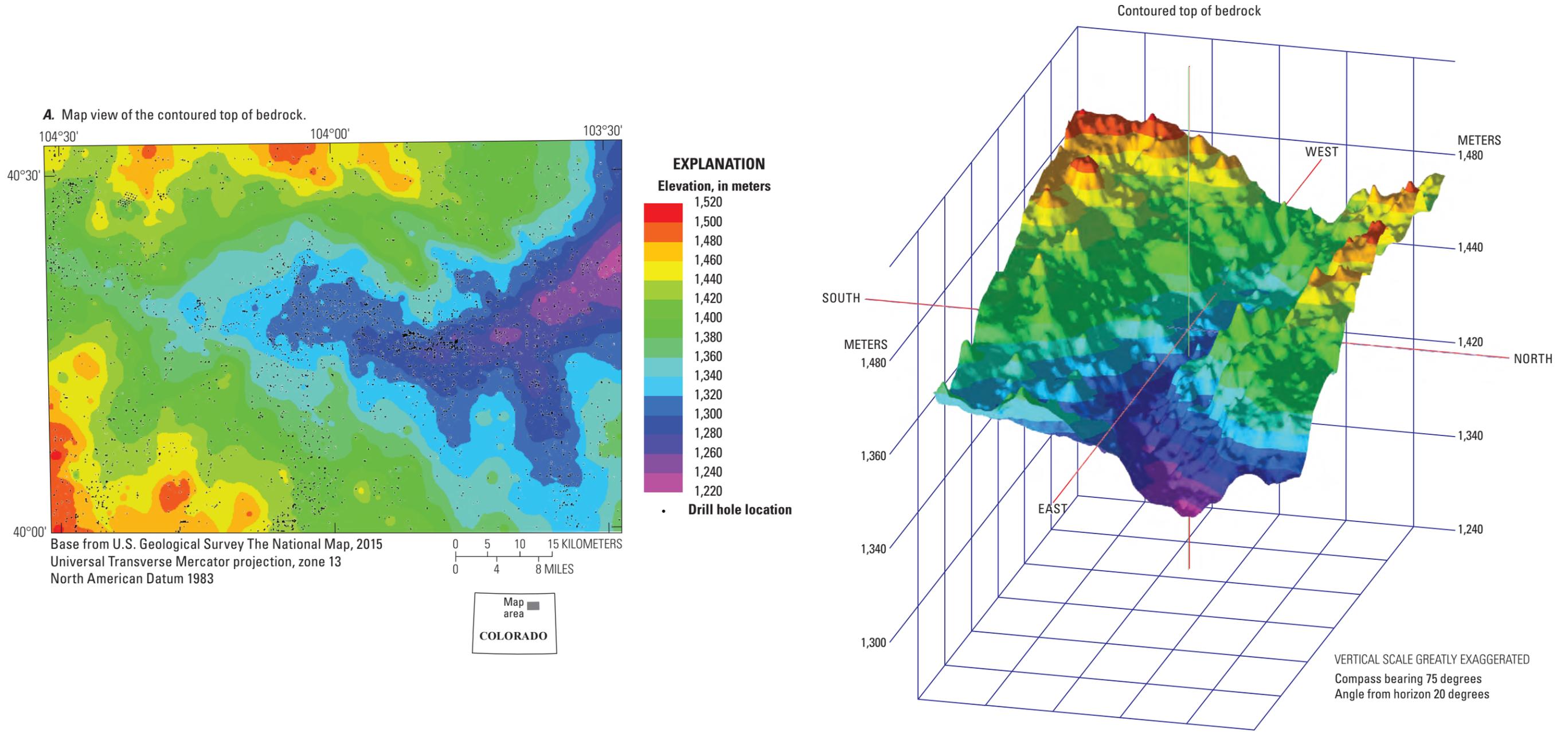


Figure 15. Map and three-dimensional (3D) views of the subsurface lithology. *A*, Map and 3D views of the subsurface geology of the study area and contoured top of bedrock. *B*, Map and 3D views showing the distribution of gravelly deposits. *C*, Map and 3D views showing the distribution of gravelly and clayey deposits. *D*, Map and 3D views showing the distribution of gravelly, clayey, and fine-grained sandy deposits. *E*, Map view of the 3D lithologic model on the left and the geologic map of the study area on the right.

B. Map view of the three-dimensional model displaying the distribution of gravelly deposits.



- EXPLANATION**
- Gravel
 - Sandy gravel
 - Clayey sand and gravel
 - Gravelly sand and clay
 - No gravelly deposit
 - Drill hole location

Three-dimensional view of the distribution of gravelly deposits

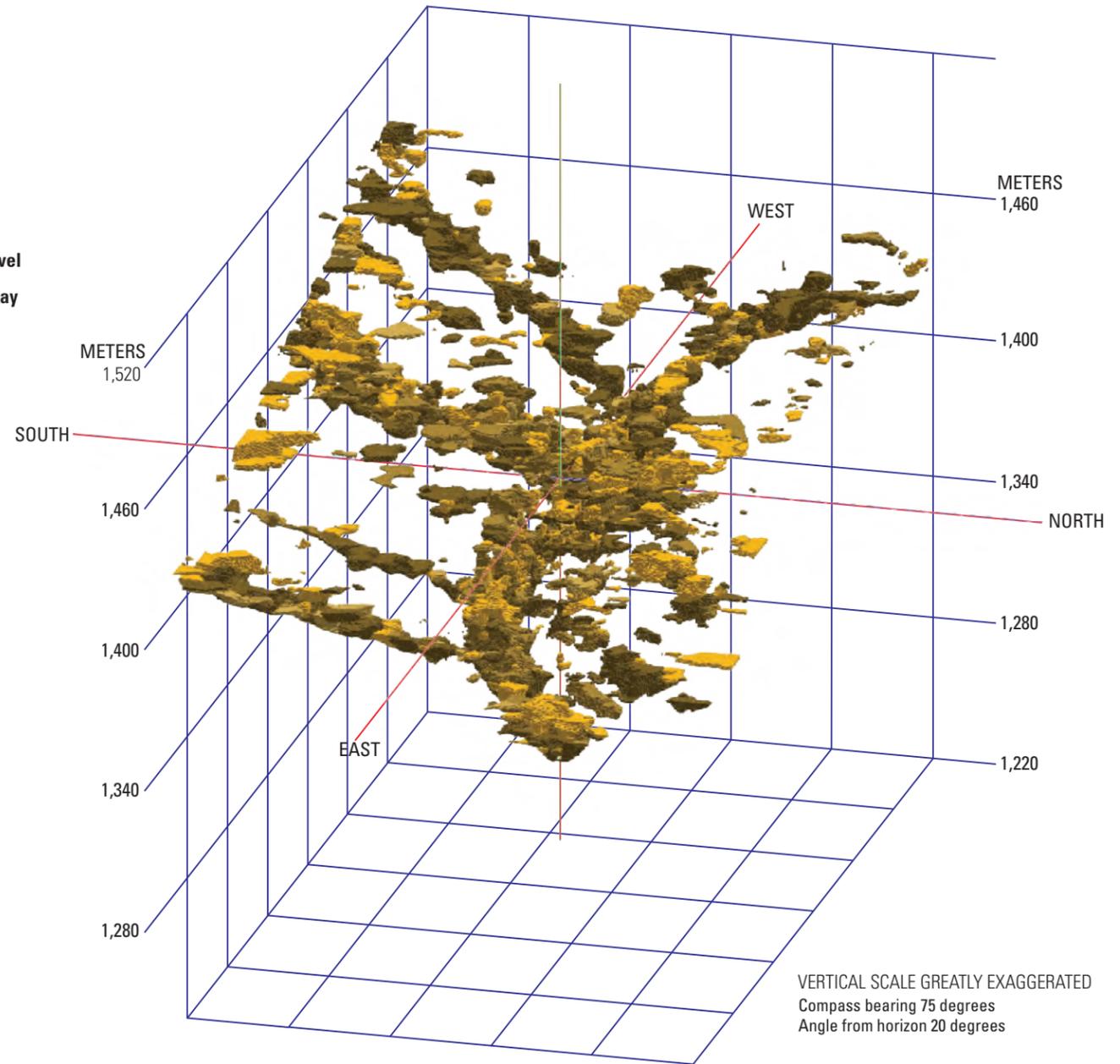


Figure 15.—Continued.

C. Map view of the three-dimensional model showing the distribution of gravelly and clayey deposits.

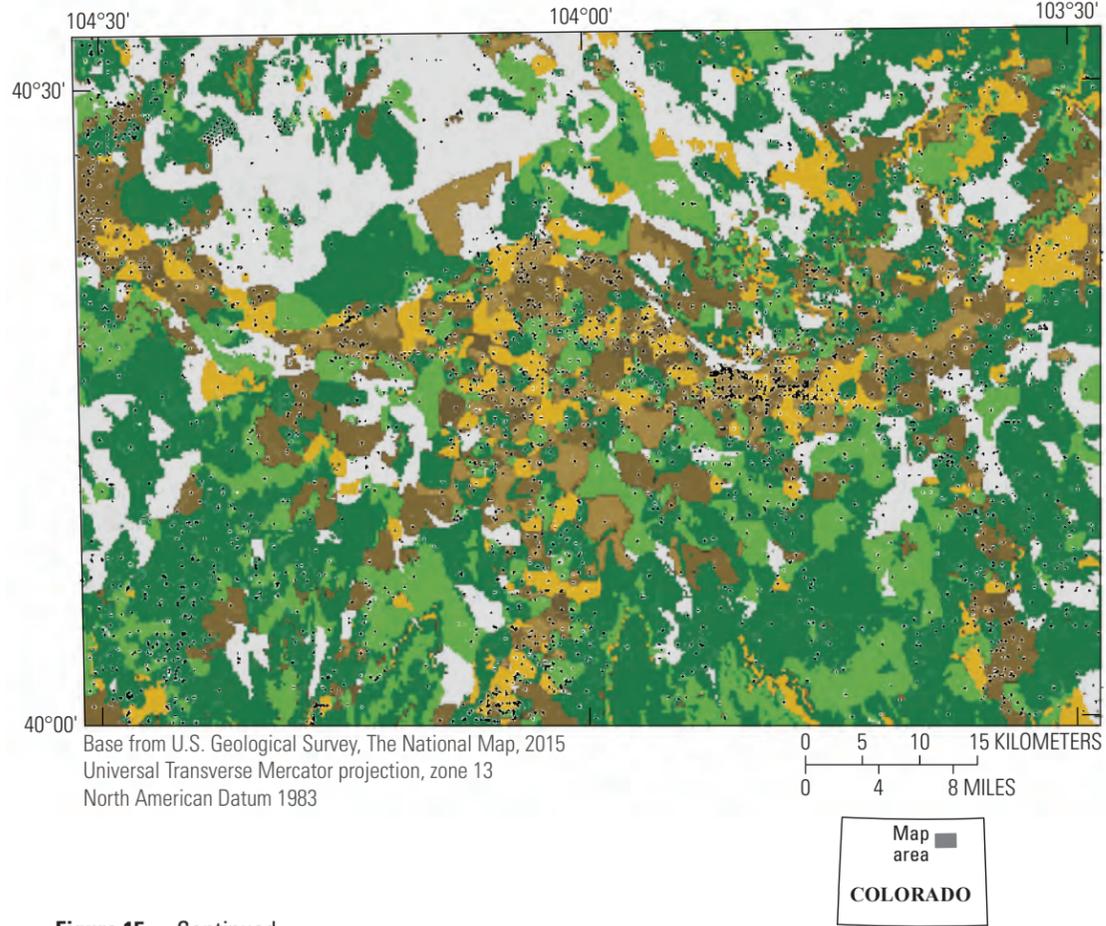
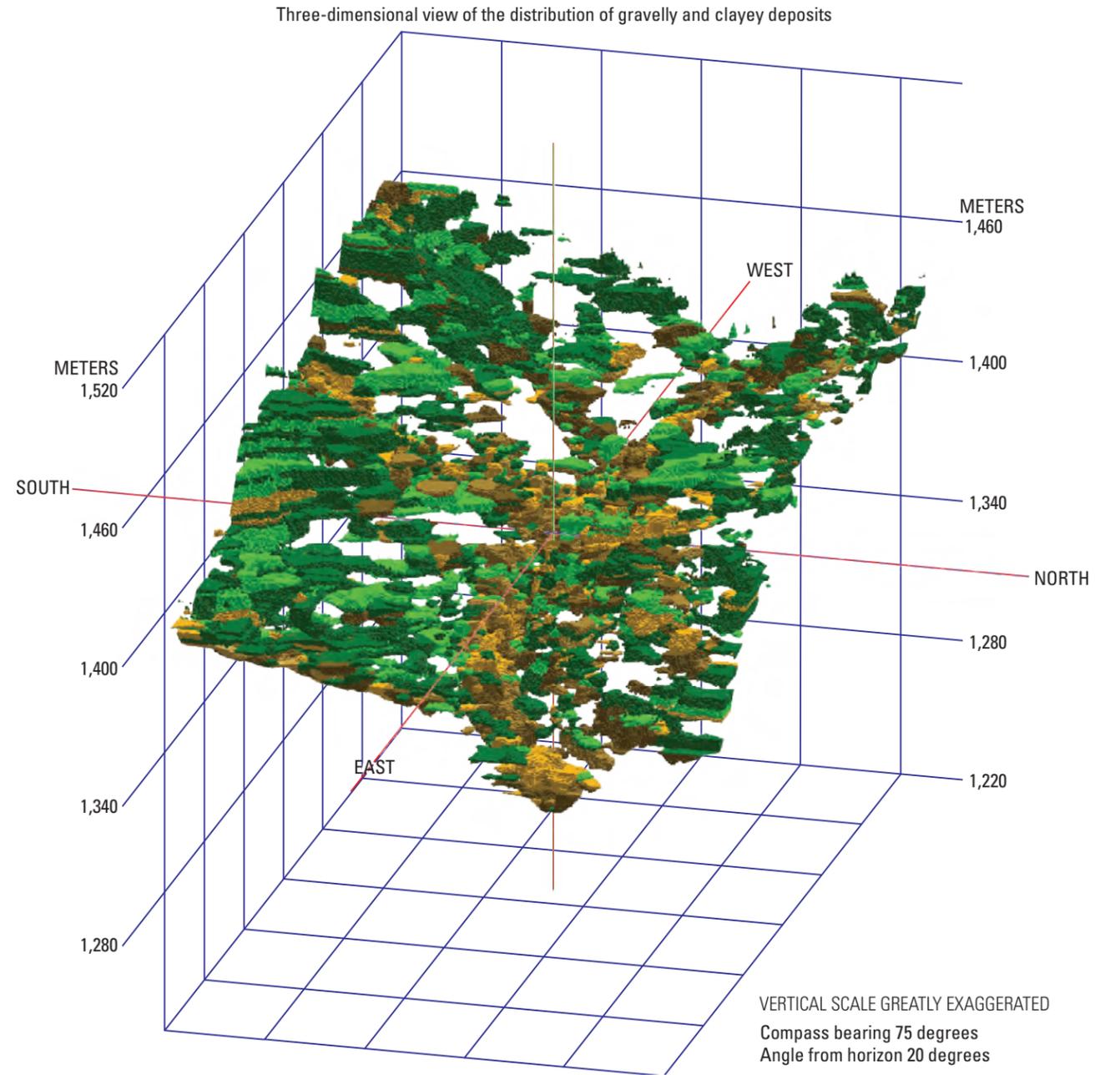


Figure 15.—Continued.



D. Map view of the three-dimensional model showing the distribution of gravelly, clayey, and fine-grained sandy deposits.

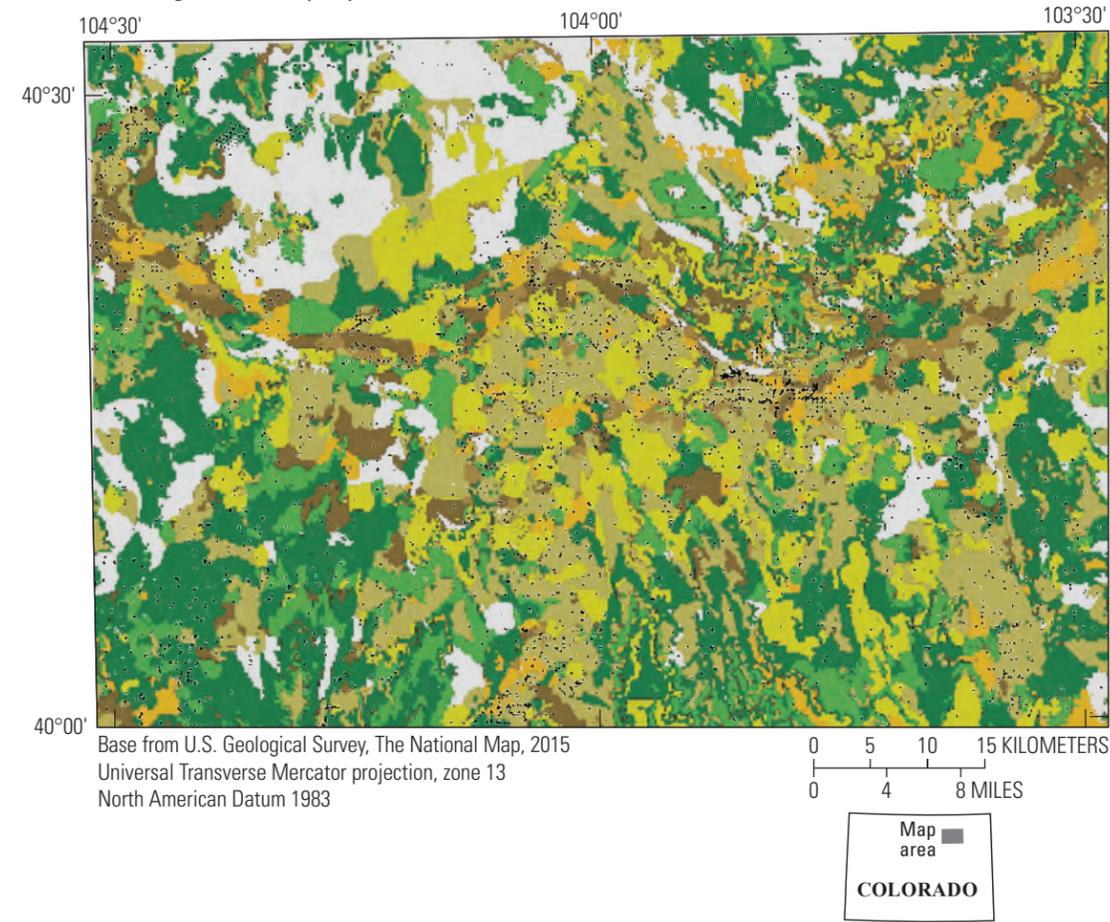
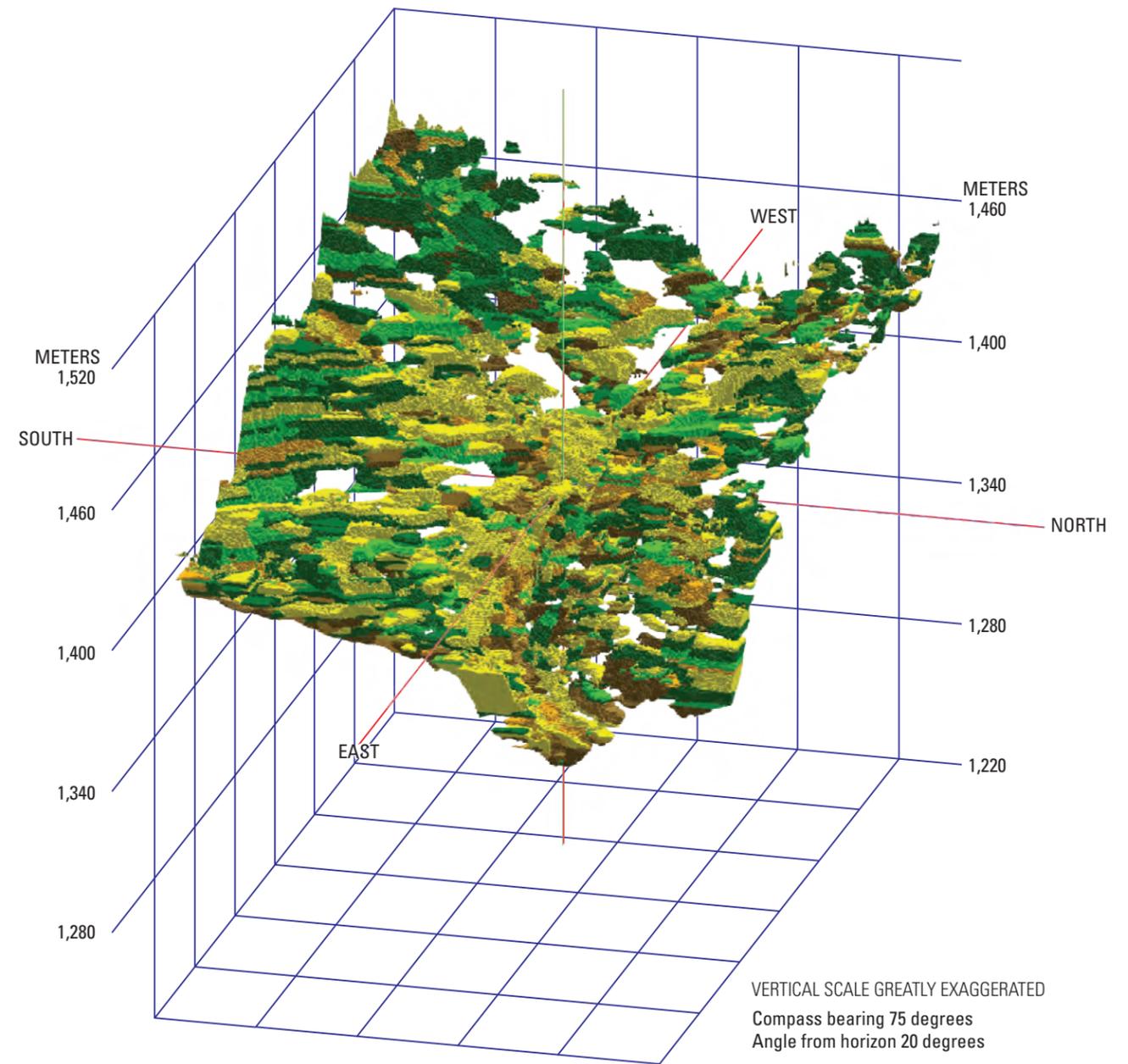


Figure 15.—Continued.

Three-dimensional view of the distribution of gravelly, clayey, and fine-grained sandy deposits



E. Map view of the three dimensional lithologic model on the left and the geologic map of the study area on the right.

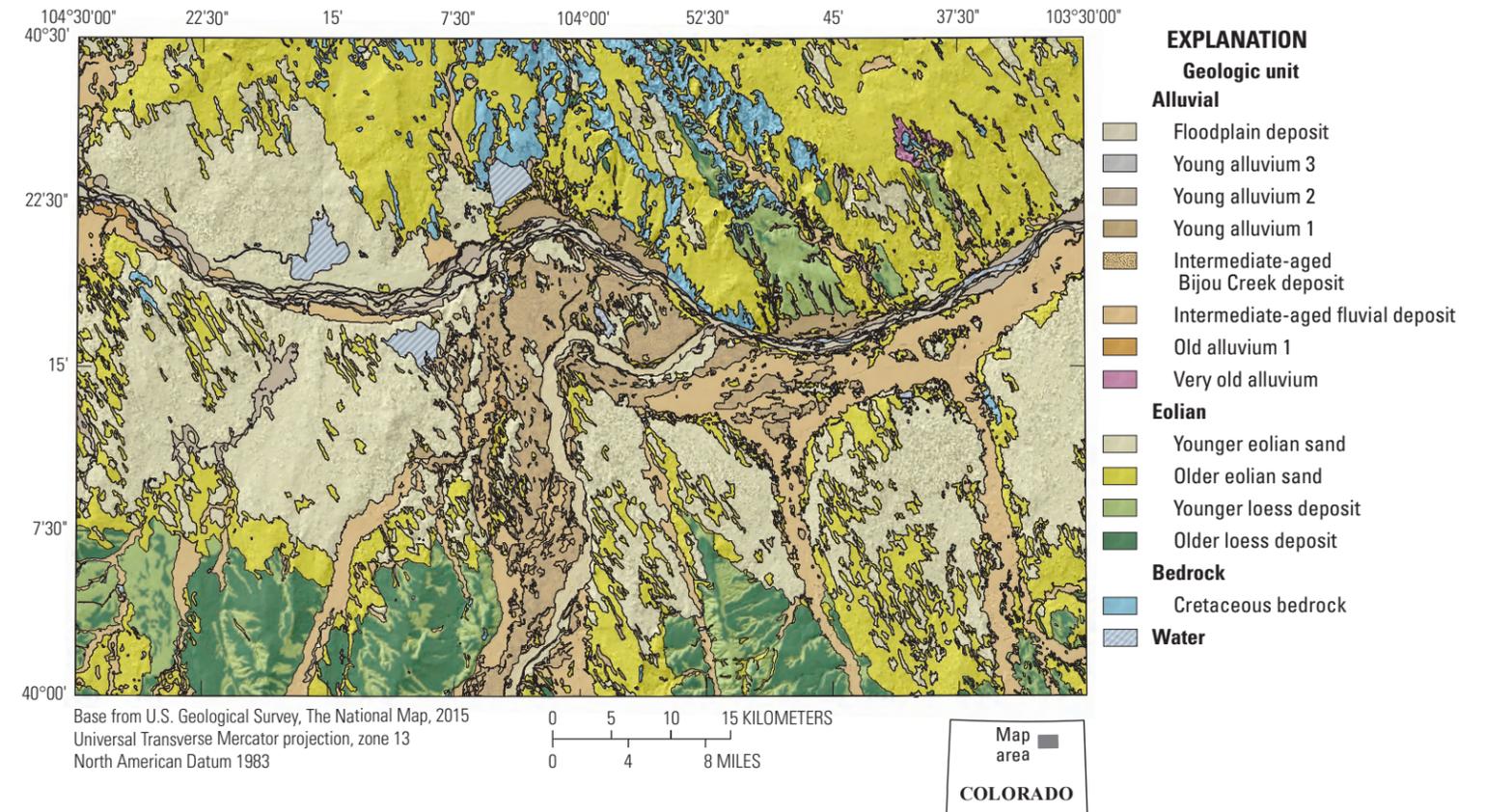
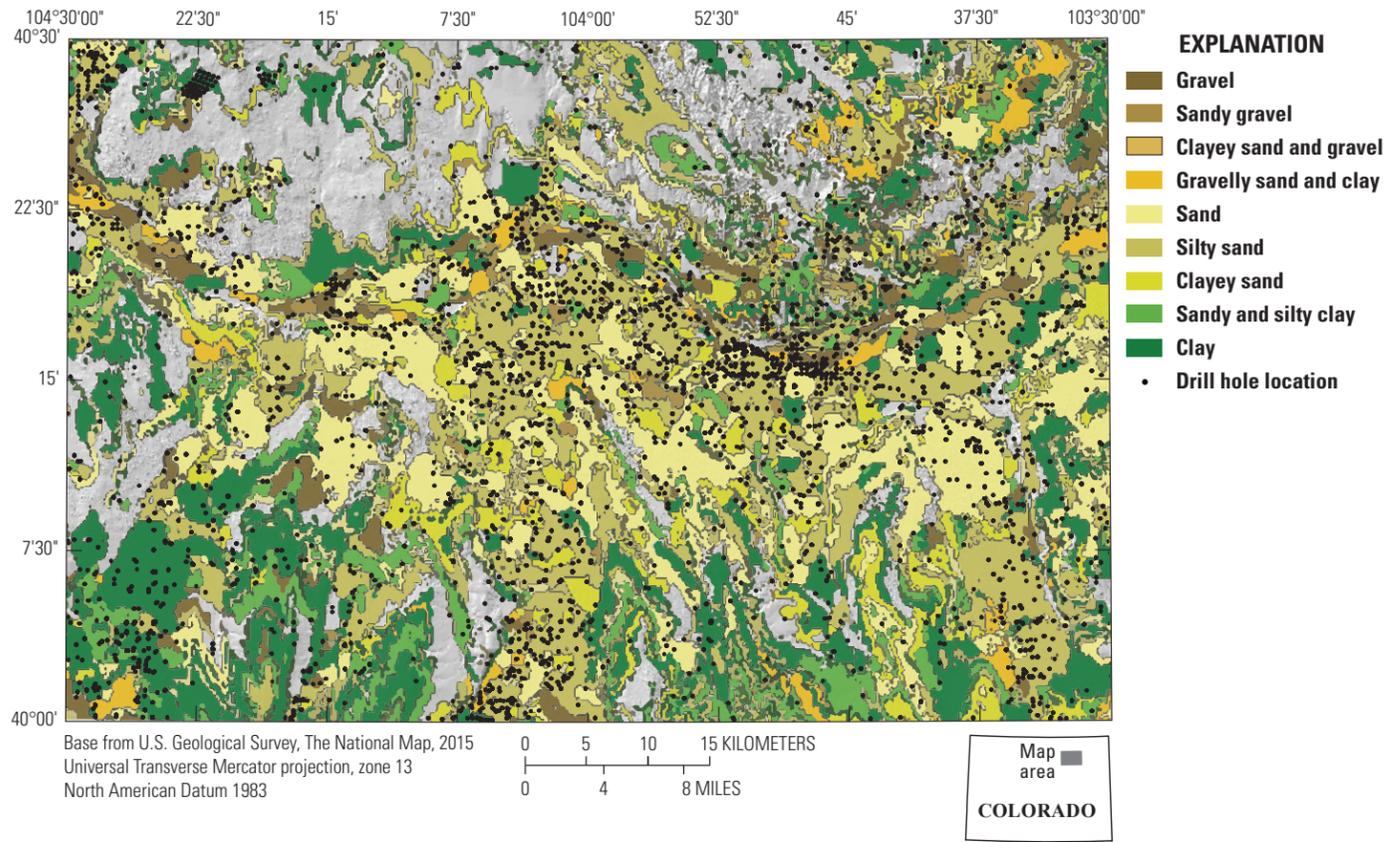


Figure 15.—Continued.

Reconstruction of the Depositional History of Sediments in the Study Area

To understand and display the reconstruction of the depositional history of the Quaternary sediments in the study, individual lithologic units were derived from the 3D model and examined in both planimetric and 3D view. The 3D lithologic model was trimmed at the top of the bedrock and is displayed in both map view and 3D view, looking northwest along the South Platte River (fig. 15A). Because most of the study area is covered by less than 50 m of sediment (fig. 10), the 3D model is vertically exaggerated (x125) to display the subsurface lithologic units better.

Different lithologies, representing different geologic units, have been combined in figure 15. All the map views are the 3D model trimmed at the elevation of the ground surface and top of the bedrock and display only the lithologies listed in the illustration. Likewise, the tilted model is also the 3D model trimmed at the ground surface and top of the bedrock but viewed in three dimensions from the east looking northwest along the South Platte River. The purpose in displaying the map view is to compare the distribution of individual lithologies at depth to the surface geologic map (fig. 7).

When only alluvium or gravelly lithologic units are present, the South Platte River and the north-flowing tributary drainages are all bound by broad paleovalleys adjacent to the location of the active drainages (fig. 15B). These gravelly paleovalleys are considerably wider than what is observed at the surface in the present day (fig. 7). The deposits in the paleovalleys extend north of the South Platte River where QTa deposits are exposed in gullies and quarries. This is consistent with previous determinations that Tertiary paleodrainages of an ancient South Platte River likely drained much of the same region in Colorado as the modern present-day South Platte River drains (Scott, 1982; Swinehart and others, 1985), but formed a braided river system that was much wider and shallower than the modern river (Madole and others, 2005).

The gravelly deposits of these paleovalleys are commonly located at the bedrock surface in cross sections and in outcrop, where they are cemented by secondary carbonate to the bedrock below (fig. 12). In places, the gravel caps a strath terrace on the bedrock surface (fig. 12A), and elsewhere it is present higher within the alluvial section. A few observations can be made with regard to age and depositional environment. Higher-velocity streams transport coarser material greater distances. The gravel could represent discharge erosional events in the Rocky Mountains that are correlative to melting glaciers and the onset of warmer climate phases. Dated alluvial events, correlated to the Qa01 and Qa02 deposits, have been interpreted to be coeval to Quaternary mountain glaciations (Scott, 1960; Lindsey and others, 2005). This may not be true for the deposits as old as the Rocky Flats Alluvium.

The relative abundance of water well drill holes (Taylor and others, 2025) in these gravelly deposits indicate that these gravels are probably a reliable source of water (fig. 15B). Although some drill holes extend beyond the boundaries of the gravelly units, most of the water wells are in the coarser subsurface units. The highest density of drill holes also corresponds to the deepest deposits in the study area (figs. 10D and 11).

Figure 15C includes both the gravelly alluvial deposits and the clayey deposits, typically composed of clay and sandy and silty clay. The fine-grained deposits include loess and clayey residuum, as well as colluvium on top of the Pierre Shale.

The clayey deposits bury most of the gravels in the tributary drainages flowing north into the South Platte River, with the exception of the Bijou Creek fan. Loess deposits also cover most of the study area except the bedrock high north of the South Platte River. For at least four cycles, the alluvium and loess are also interbedded (fig. 15C) indicating that the eolian events regionally depositing the clayey loess were extended intermittently over a long time period. Some of the clayey deposits may be alluvial. These alluvial clay deposits occur along tributaries draining to the north, which obtained much of their sediment load from the fine-grained Upper Cretaceous and Tertiary units. The surface loess is late Pleistocene and correlative to Peoria Loess deposited during the retreat of the Pinedale glaciation (table 1). The numerous older loess units may be correlative to retreating glaciations that predate the Pinedale glaciation.

Although primarily correlative to older sand units (Qe1, fig. 15D), silty and clayey sand is also a component of loess. Unit Qe1 is exposed at the surface north of the South Platte River, typically buried by younger sand (Qe2), and is exposed as interdune deposits south of the river. These silty and clayey sand deposits are also a large component of the Bijou Creek fan and associated terrace alluvium. The source of the alluvium on the fan is probably partly reworked from eolian sediment and weathering of the fine-grained bedrock. The silty and clayey sand is interfingering with, and buries, the clay-rich loess units.

Finally, in figure 15E the young sand (Qe2) from the 3D model is added to the map view of the 3D lithologic model and a geologic map of the area is provided for comparison to the 3D model. Very little of the gravelly alluvium is exposed at the surface except along the South Platte River where it is confined to a narrow band. The loess deposits (clay and sandy and silty clay) are mostly buried, except at the southern margin of the map area and the area north of Fort Morgan, generally consistent with the geologic map. The fine-grained sandy (silty sand and clayey sand) deposits occur adjacent to the loess and sand.

Summary

Numerous techniques including field investigations, soil and geologic mapping, compiling existing drill hole data, new drilling, and three-dimensional (3D) analysis provided both a visual and quantitative view of the depositional history of sediments in Fort Morgan area of eastern Colorado. This study area is an ideal location for 3D modeling of the subsurface, because the three primary sediments are unique and characteristic of unique environments of deposition. Geologic units were subdivided based on soil characteristics, and drill hole data are primarily the grain size of the sediments. Correlated soil-based geologic units and grain-size based driller's logs were used to construct the 3D model.

The three characteristic deposits are eolian sand, loess, and alluvium. Sandy eolian deposits, derived from the local bedrock and reworked from local fluvial deposits occur at the surface, and cover over most of the study area. Sand transportation is common in all climate regimes, but most significant activity occurs in environments with decreased vegetation cover and increased wind strength. Clay-rich loess deposits, derived from sediment deposited from retreating glaciers, is transported from much greater distances than sandy deposits. In the study area loess is exposed at the surface north and south of the South Platte River. Gravelly-alluvial deposits confined to the large and small drainages

record periods of active fluvial transport and erosion. Warm-climate phases in the Rocky Mountains, correlative to melting glaciers, caused large erosional and discharge events of gravel in the study area.

The geologic map and the map view of the 3D model were visually compatible, which allowed the translation of geologic map units to sediment characteristics at depth. Cross sections displayed the thickness and interbedded features of the sediments. The sediment package above the bedrock rarely exceeds 50 meters. Gravel is extensive at depth and extends far beyond the active drainages recording broad alluvial floodplains and migrating drainages now buried by sand and loess. Sandy eolian and loess deposits extensively bury the gravelly deposits. The loess tends to be discontinuous and frequently interbedded with the sandy deposits or deposited on the gravels rather than interbedded with the gravel. The sandy eolian units occur above the active drainages burying the loess, gravel, and bedrock.

References Cited

- Aleinikoff, J.N., Muhs, D.R., Sauer, R.R., and Fanning, C.M., 1999, Late Quaternary loess in northeastern Colorado, Part II—Pb isotopic evidence for the variability of loess sources: *GSA Bulletin*, December 1999, v. 111, no. 12, p. 1876–1883. [Also available at <https://pubs.geoscienceworld.org/gsa/gsabulletin/article/111/12/1876/183454/Late-Quaternary-loess-in-northeastern-Colorado>.]
- Benson, L., Madole, R., Landis, G., and Gosse, J., 2005, New data for Late Pleistocene Pinedale alpine glaciation from southwestern Colorado: *Quaternary Science Reviews*, v. 24, no. 1–2, p. 49–65. [Also available at <https://doi.org/10.1016/j.quascirev.2004.07.018>.]
- Berry, M.E., Slate, J.L., Hanson, P.R., and Brandt, T.R., 2015a, Geologic map of the Orchard 7.5', quadrangle, Morgan County, Colorado: U.S. Geological Survey Scientific Investigations Map 3331, 1 sheet, 1:24,000, accessed January 20, 2016, at <https://doi.org/10.3133/sim3331>.
- Berry, M.E., Slate, J.L., Paces, J.B., Hanson, P.R., and Brandt, T.R., 2015b, Geologic map of the Masters 7.5', quadrangle, Weld and Morgan Counties, Colorado: U.S. Geological Survey Scientific Investigations Map 3344, 10 p-pamphlet, appendix, 1 sheet, 1:24,000, accessed January 20, 2016, at <https://doi.org/10.3133/sim3344>.
- Berry, M.E., Slate, J.L., and Taylor, E.M., 2019, Pleistocene and Holocene landscape development of the South Platte River corridor, northeastern Colorado: U.S. Geological Survey Scientific Investigations Report 2019–5020, 22 p., accessed January 20, 2016, at <https://doi.org/10.3133/sir20195020>.
- Berry, M.E., Taylor, E.M., Slate, J.L., Paces, J.B., Hanson, P.R., and Brandt, T.R., 2018a, Geologic map of the Fort Morgan 7.5' quadrangle, Morgan County, Colorado: U.S. Geological Survey Scientific Investigations Map 3408, 2 sheets, scale 1:24,000, accessed June 20, 2018, at <https://doi.org/10.3133/sim3408>.
- Berry, M.E., Taylor, E.M., Slate, J.L., Paces, J.B., Hanson, P.R., and Brandt, T.R., 2018b, Geologic map of the Weldona 7.5' quadrangle, Morgan County, Colorado: U.S. Geological Survey Scientific Investigations Map 3396, 1 sheet, scale 1:24,000, accessed June 20, 2018, at <https://doi.org/10.3133/sim3396>.
- Birkeland, P.W., ed., 1999, *Soils and geomorphology* (3d ed.): New York, Oxford University Press, 430 p.

- Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Salt Lake City, Utah, Utah Geological and Mineral Survey, Miscellaneous Publication 91-3, 63 p. [Also available at digitallibrary.utah.gov/awweb/awarchive?type=download&item=40801.]
- Bjorklund, L.J., Brown, R.F., and Swenson, H.A., 1957, Geology and ground-water resources of the lower South Platte River valley between Hardin, Colorado, and Paxton, Nebraska, with a section on chemical quality of water: U.S. Geological Survey Water Supply Paper 1378, 431 p. [Also available at <https://doi.org/10.3133/wsp1378>.]
- Braddock, W.A., and Cole, J.C., 1978, Preliminary geologic map of the Greeley 1 degree x 2 degree Quadrangle, Colorado and Wyoming: U.S. Geological Survey Open-File Report 78-532, 11 p. [Also available at <https://doi.org/10.3133/ofr78532>.]
- Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart: Episodes, v. 36, no. 3, p. 199-204, accessed February 6, 2017, at <https://doi.org/10.18814/epiiugs/2013/v36i3/002>.
- Colorado Division of Water Resources, 2013, Well permit information: Colorado Division of Water Resources Laserfiche WebLink, well locations and subsurface lithologic data for Morgan and Weld Counties, accessed December 1, 2013, at <http://dwrweblink.state.co.us/dwrweblink/>.
- Condon, S.M., 2005, Geologic studies of the Platte River, south-central Nebraska and adjacent areas—Geologic maps, subsurface study, and geologic history: U.S. Geological Survey Professional Paper 1706, 63 p., 2 plates, accessed August 10, 2015, at <https://doi.org/10.3133/pp1706/>.
- Eschner, T.R., Hadley, R.F., and Crowley, K.D., 1981, Hydrologic and morphologic changes in channels of the Platte River Basin in Colorado, Wyoming, and Nebraska—A historical perspective chap. A of U.S. Geological Survey, 1983, Hydrologic and geomorphic studies of the Platte River Basin: U.S. Geological Survey Professional Paper 1277, p. A1-A39. [Also available at <https://doi.org/10.3133/pp1277>.]
- Gardner, M.E., 1967, Quaternary and engineering geology of the Orchard, Weldona, and Fort Morgan quadrangles, Morgan County, Colorado: Golden, Colo., Colorado School of Mines, Ph.D. dissertation, 224 p. [Also available at <https://hdl.handle.net/11124/174036>.]
- Gile, L.H., 1975, Holocene soils and soil-geomorphic relations in an arid region of southern New Mexico: Quaternary Research, v. 5, no. 3, p. 321-360. [Also available at [https://doi.org/10.1016/0033-5894\(75\)90037-X](https://doi.org/10.1016/0033-5894(75)90037-X).]
- Izett, G.A., 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, in Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America, GSA Memoirs, v. 144, p. 179-209. [Also available at <https://doi.org/10.1130/MEM144-p179>.]
- Kellogg, K.S., Shroba, R.R., Bryant, B., and Premo, W.R., 2008, Geologic map of the Denver West 30° x 60° quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3000, scale 1:100,000, 48-p. pamphlet, accessed August 23, 2015, at <https://doi.org/10.3133/sim3000>.
- Lindsey, D.A., Langer, W.H., and Knepper, D.H., Jr., 2005, Stratigraphy, lithology, and sedimentary features of Quaternary alluvial deposits of the South Platte River and some of its tributaries east of the Front Range, Colorado: U.S. Geological Survey Professional Paper 1705, 70 p., accessed August 14, 2015, at <https://doi.org/10.3133/pp1705>.
- Maat, P.B., and Johnson, W.C., 1996, Thermoluminescence and new 14C age estimates for late Quaternary loesses in southwestern Nebraska: Geomorphology, v. 17, no. 1-3, p. 115-128. [Also available at [https://doi.org/10.1016/0169-555X\(95\)00099-Q](https://doi.org/10.1016/0169-555X(95)00099-Q).]
- Madole, R.F., 1991, Colorado Piedmont section, in Wayne, W.J., Aber, J.S., Agard, S.S., Bergantino, R.N., Bluemle, J.P., Coates, D.A., Cooley, M.E., Madole, R.F., Martin, J.E., Mears, B., Jr., Morrison, R.B., and Sutherland, W.M., Quaternary geology of the northern Great Plains, chap. 15 of Morrison, R.B., ed., Quaternary nonglacial geology: conterminous U.S.: Boulder, Colo., Geological Society of America, The Geology of North America, v. K-2, p. 456-462.
- Madole, R.F., 1995, Spatial and temporal patterns of late Quaternary eolian deposition, eastern Colorado, U.S.A.: Quaternary Science Reviews, v. 14, no. 2, p. 155-177. [Also available at [https://doi.org/10.1016/0277-3791\(95\)00005-A](https://doi.org/10.1016/0277-3791(95)00005-A).]
- Madole, R.F., VanSistine, D.P., and Michael, J.A., 2005, Distribution of late Quaternary wind-deposited sand in eastern Colorado: U.S. Geological Survey Scientific Investigations Map 2875, scale 1:700,000, 49 p. pamphlet. [Also available at <https://doi.org/10.3133/2875>.]
- Mahan, S.A., Krolczyk, E.T., Taylor, E.M., Berry, M.E., and Havens, J.C., 2025, Luminescence data for reconstructing the Quaternary depositional history using geologic mapping and a 3D model of the subsurface in the vicinity of Fort Morgan, eastern Colorado: U.S. Geological Survey data release, <https://doi.org/10.5066/P13KTS2B>.
- Meteoblue, 2019, Simulated historical climate & weather data for Fort Morgan: Meteoblue website, accessed August 23, 2015, at https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/fort-morgan_united-states_5577158.
- Muhs, D.R., 2017, Evaluation of simple geochemical indicators of aeolian sand provenance—Late Quaternary dune fields of North America revisited: Quaternary Science Reviews, v. 171, p. 260-296. [Also available at <https://doi.org/10.1016/j.quascirev.2017.07.007>.]
- Muhs, D.R., Aleinikoff, J.N., Stafford, T.W., Jr., Kihl, R., Been, J., Mahan, S.A., and Cowherd, S., 1999a, Late Quaternary loess in northeastern Colorado—Part I—Age and paleoclimatic significance: GSA Bulletin, v. 111, no. 12, p. 1861-1875. [Also available at [https://doi.org/10.1130/0016-7606\(1999\)111<1861:LQLINC>2.3.CO;2](https://doi.org/10.1130/0016-7606(1999)111<1861:LQLINC>2.3.CO;2).]
- Muhs, D.R., Bettis, E.A., III, Aleinikoff, J.N., McGeehin, J.P., Beann, J., Skipp, G., Marshall, B.D., Roberts, H.M., Johnson, W.C., and Benton, R., 2008, Origin and paleoclimatic significance of late Quaternary loess in Nebraska—Evidence from stratigraphy, chronology, sedimentology, and geochemistry: GSA Bulletin, v. 120, no. 11-12, p. 1378-1407. [Also available at <https://pubs.geoscienceworld.org/gsa/gsabulletin/article/120/11-12/1378/2240/Origin-and-paleoclimatic-significance-of-late>.]
- Muhs, D.R., and Holliday, V.T., 1995, Evidence of active dune sand on the Great Plains in the 19th Century from accounts of early explorers: Quaternary Research, v. 43, no. 2, p. 198-208. [Also available at <https://doi.org/10.1006/qres.1995.1020>.]
- Muhs, D.R., Stafford, T.W., Cowherd, S.D., Mahan, S.A., Kihl, R., Maat, P.B., Bush, C.A., and Nehring, J., 1996, Origin of the late Quaternary dune fields of northeastern Colorado: Geomorphology, v. 17, no. 1-3, p. 129-149. [Also available at <https://www.sciencedirect.com/science/article/pii/0169555X9500100J>.]
- Muhs, D.R., Swinehart, J.B., Loope, D.B., Aleinikoff, J.N., and Been, J., 1999b, 200,000 years of climate change recorded in eolian sediments of the High Plains of eastern Colorado and western Nebraska, in Lageson, D.R., Lester, A.P., and Trudgill, B.D., eds., Colorado and adjacent areas: Geological Society of America, Field Guide I, p. 71-91. [Also available at <https://doi.org/10.1130/0-8137-0001-9.71>.]
- Munsell Color Company, Inc., 1990, Munsell soil color charts: Baltimore, Md. (NNA.920207.0001).
- Natural Resources Conservation Service, 2015, Web soil survey: U.S. Department of Agriculture, Natural Resources Conservation Service website, accessed September 25, 2015, at <https://websoilsurvey.nrcs.usda.gov>.
- Prescott, J.R. and Jutton, J.T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating—Large depths and long-term time variations: Radiation Measurements, v. 23, p. 497-500. [Also available at [https://doi.org/10.1016/1350-4487\(94\)90086-8](https://doi.org/10.1016/1350-4487(94)90086-8).]
- Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haffidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., and van der Plicht, J., 2013, IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP: Radiocarbon, v. 55, no. 4, p. 1869-1887. [Also available at https://doi.org/10.2458/azu_js_rc.55.16947.]
- Roberts, H.M., Muhs, D.R., and Bettis, E.A., III, 2007, Loess records of North America: S.A. Elias (ed.), Encyclopedia of Quaternary Science, Elsevier B.V., Oxford, v. 2, p. 1456-1466.
- Scott, G.R., 1960, Subdivision of the Quaternary alluvium east of the Front Range near Denver, Colorado: GSA Bulletin, v. 71, no. 10, p. 1541-1544. [Also available at [https://doi.org/10.1130/0016-7606\(1960\)10\[1541:SOTQAE\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1960)10[1541:SOTQAE]2.0.CO;2).]
- Scott, G.R., 1978, Map showing geology, structure, and oil and gas fields in the Sterling 1 degree x 2 degrees quadrangle, Colorado, Nebraska, and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I-1092, scale 1:250,000. [Also available at http://ngmdb.usgs.gov/Prodesc/proddesc_8950.htm.]
- Scott, G.R., 1982, Paleovalley and geologic map of northeastern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1378, scale 1:250,000. [Also available at <https://doi.org/10.3133/i1378>.]
- Soil Survey Staff, 1999, Soil taxonomy—A basic system of soil classification for making and interpreting soil surveys (2d ed.): U.S. Department of Agriculture, Natural Resources Conservation Service, Agriculture Handbook Number 436, 886 p. [Also available at https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf.]
- Stuiver, M., and Reimer, P.J., 1993, Extended 14C data base and revised CALIB 3.0 14C age calibration program: Radiocarbon, v. 35, no. 1, p. 215-230. [Also available at <https://doi.org/10.1017/S0033822200013904>.]
- Swinehart, J.B., Souders, V.F., DeGraw, H.M., and Diffendal, R.F., Jr., 1985, Cenozoic paleogeography of western Nebraska, in Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States—Proceedings of the Rocky Mountain Paleogeography Symposium 3, Denver, Colo., 1985: Denver, Colo., Society for Sedimentary Geology, Rocky Mountain Section, p. 209-229. [Also available at <https://digitalcommons.unl.edu/diffendal/28/>.]
- Taylor, E.M., Berry, M.E., Mahan, S.A., Honke, J., and Havens, J.C., 2025, Digital drillhole lithologic data and a radiocarbon age—data supporting interpretation of Quaternary depositional history in the vicinity of Fort Morgan, Eastern Colorado: U.S. Geological Survey data release, <https://doi.org/10.5066/P9AQ72FB>.
- Taylor, E.M., and Sweetkind, D.S., 2014, Three-dimensional geologic mapping of the Cenozoic basin fill, Amargosa Desert basin, Nevada and California: U.S. Geological Survey Scientific Investigations Report 2014-5003, 40 p., 2 appendixes, accessed March 3, 2015, at <https://doi.org/10.3133/sir20145003>.

Tweto, O., 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000, 2 sheets. [Also available at https://ngmdb.usgs.gov/Prodesc/proddesc_68589.htm.]

U.S. Department of Agriculture Natural Resources Conservation Service, 2009, USDA–FSA–APFO NAIP MrSID mosaic: U.S. Department of Agriculture Natural Resources Conservation Service [Geospatial Data Gateway, Morgan County, Colo., Ortho Imagery, 2009 National Agriculture Imagery Program mosaic], accessed March 4, 2011, at <https://datagateway.nrcs.usda.gov/GDGOrder.aspx>.

U.S. Department of Agriculture Natural Resources Conservation Service, 2011, USDA–FSA–APFO NAIP MrSID mosaic: U.S. Department of Agriculture Natural Resource Conservation Service [Geospatial Data Gateway, Morgan County, Colo., Ortho Imagery, 2011 National Agriculture Imagery Program mosaic], accessed January 8, 2014, at <https://datagateway.nrcs.usda.gov/GDGOrder.aspx>.

U.S. Department of Agriculture Natural Resources Conservation Service, 2013, USDA–FSA–APFO NAIP MrSID mosaic: U.S. Department of Agriculture Natural Resources Conservation Service [Geospatial Data Gateway, Morgan County, Colo., Ortho Imagery, 2013 National Agriculture Imagery Program mosaic], accessed January 3, 2014, at <https://datagateway.nrcs.usda.gov/GDGOrder.aspx>.

U.S. Department of Agriculture Natural Resources Conservation Service, 2015, USDA–FSA–APFO NAIP MrSID mosaic: U.S. Department of Agriculture Natural Resources Conservation Service [Geospatial Data Gateway, Morgan County, Colo., Ortho Imagery, 2015 National Agriculture Imagery Program mosaic], accessed January 15, 2016, at <https://datagateway.nrcs.usda.gov/GDGOrder.aspx>.

U.S. Geological Survey, 2015, 2015-06-21, USGS NED one meter CO SoPlatteRiver-Lot1 2013 IMG: U.S. Geological Survey, accessed June 1, 2015, at https://nationalmap.gov/3DEP/3dep_prodserv.html.

U.S. Geological Survey, 1980, Fort Morgan, CO, 1:100,000 topographic map 40103a1: U.S. Geological Survey.

U.S. Geological Survey, 1982, Greeley, CO, 1:100,000 topographic map: U.S. Geological Survey.

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., comps., 2012, Geologic time scale v. 4.0: Geological Society of America, accessed June 30, 2015, at <https://www.geosociety.org/documents/gsa/timescale/timescl-2012.pdf>.

Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O., and Weiss, H., 2012, Formal subdivision of the Holocene Series/Epoch—A discussion paper by a working group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommittee on Quaternary Stratigraphy (International Commission on Stratigraphy): *Journal of Quaternary Science*, v. 27, no. 7, p. 649–659. [Also available at <https://doi.org/10.1002/jqs.2565>.]

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