COLORADO GEOLOGICAL SURVEY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

GEOLOGIC MAP OF THE WINDSOR QUADRANGLE, LARIMER AND WELD COUNTIES, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE, GEOLOGIC HISTORY,
GROUNDWATER, AND MINERAL RESOURCES AND CROSS SECTIONS
OPEN-FILE REPORT 22-08
PLATE 2 OF 2
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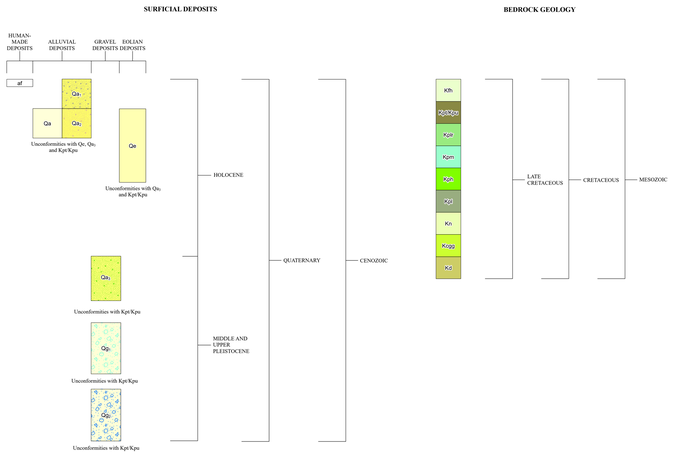
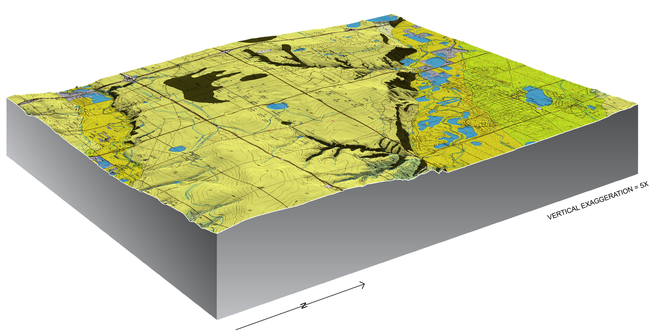
CORRELATION OF MAP UNITS



3-D OBLIQUE



CROSS SECTION A-A'

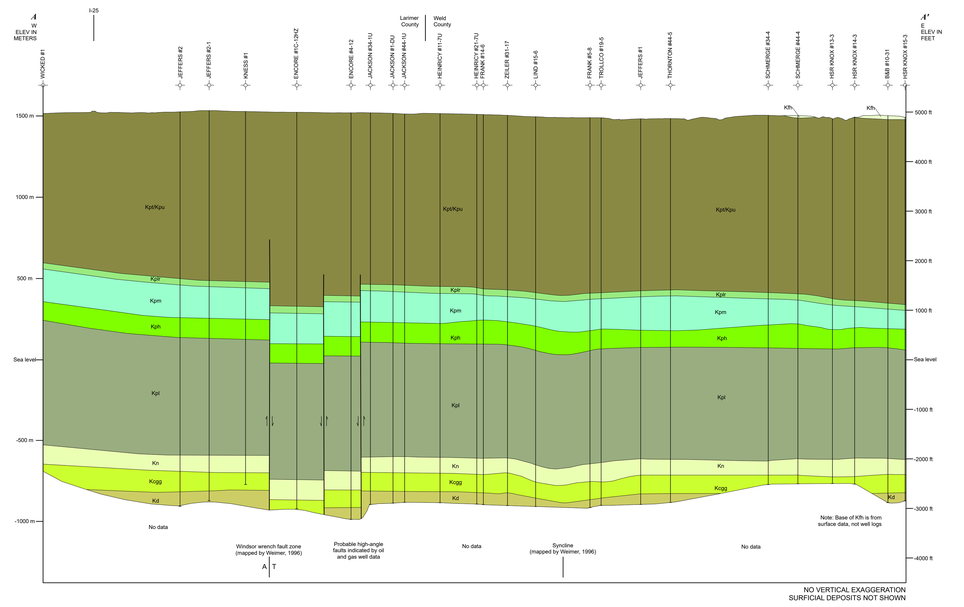


TABLE 1. DETAILED CHARACTERISTICS OF QUATERNARY UNITS IN THE WINDSOR QUADRANGLE

Map Unit	Grain Size Distribution	Bedding	Sorting	Roundness	Color	Sand Composition	Gravel Composition	Cohesion	Secondary Carbonate	Soils
Qa_1	Sand is medium (mL) to coarse (cU) or very coarse (vcU) sand; gravel is granules to cobbles (up to 9 cm)	(Could not be observed)	Poor to moderate	Sand is subangular to subrounded; gravel is subrounded to rounded	Grey and light gray of hue 10YR	Quartz 75-85%, feldspar and others 10-15%, opaques 5-10%	Granitics, gneiss, fine-grained dark metamorphics, vein quartz, red sandstone, minor volcanics	Loose or weak	None	Riverwash
Qg_2	Sandy gravel or gravelly sand, poorly sorted mixture of 50% sand and 50% gravel; sand is very fine (vfL) to fine (fU) with ~25% medium (mL); gravel is from granules to cobbles (up to 20 cm)	Indistinct bedding indicated by alignment of clasts	Very poorly sorted	Sand is subangular to subrounded; gravel is rounded to well rounded	Pale brown of hue 10YR	Quartz 75%, feldspar and others 20%, <5% opaques	Granitics, gneiss, dark-colored fine-grained metamorphics, vein quartz, quartzite	Weak to moderate	Carbonate rinds on many pebbles and cobbles; sand matrix has pervasive stage III or stage IV secondary carbonate	Cascajo gravelly silt loam
Qg_1	Matrix of clay- and silt-sized secondary carbonate, with <50% gravel of pebbles and cobbles (up to 30 cm)	Exposure too poor to see bedding	Poorly sorted	Gravel subrounded to rounded	Pinkish white of hue 7.5YR	Not applicable	Granitics, gneiss, vein quartz, quartzite	Very cohesive	Stage IV secondary carbonate, carbonate rinds 3 mm thick on cobbles	Larim gravelly sandy loam
Qe	Most locations are silty clay or clayey silt, with minor sand ranging from very fine (vfL) to medium (mL); locally, very fine (vfL) to medium (mU) sand with minor fines, and very fine (vfL) to medium (mU) or very coarse (vcU) sand, with minor fines	Massive	Moderately to well sorted	Mostly silt and clay, did not record sand roundness	Very pale brown, pale brown, light yellowish brown, brown, grayish brown, dark grayish brown of hue 10YR	Mostly silt and clay, did not record sand composition	Not applicable	Moderately to strongly cohesive	Most locations have moderate to violent effervescence but no visible carbonate; some locations have scattered carbonate filaments and nodules 1-3 mm; rare locations have nodules up to 9 cm, or nearly continuous carbonate zones (stage III)	Colby loam, Kim loam, Nunn clay loam, Vona sandy loam, Wiley silt loam

Note: Unit Qa is not included because exposures of this unit were not observed in the quadrangle.

TABLE 2: C14 AND OSL GEOCHRON DATA

Table 2a: Optically stimulated luminescence (OSL) ages (Baylor University, Waco, Texas, April 28, 2022)

Field Sample Number and Map Location	Laboratory Number	Map Unit	Latitude	Longitude	Depth Below Ground Surface (bgs) (m)	Date Collected	Material Dated	Aliquots	Grain Size (microns)	Equivalent Dose (De) (Gy)[a]	Overdispersion (%)[b]	U (ppm)[d]	Th (ppm)[d]	K_2O (%)[d]	H_2O (%)	Cosmic Dose Rate (mGray/yr)[e]	Dose Rate (mGray/yr)	SAR-OSL Age
WA019AOSL	5215	Qa_3	40.378331	-104.93603	2.1	8/4/2021	Bedded sandy gravel	37/41	250-355	3.35 +/- 0.13	20 +/- 2	2.71 +/- 0.1	12.25 +/- 0.01	2.61 +/- 0.02	15 +/- 3	0.218 +/- 0.022	3.36 +/- 0.16	1035 +/- 50
WA091COSL	5221	Qa_3	40.383888	-104.95521	3.7	9/29/2021	Laminated medium to v coarse sand	22/36	250-500	60.04 +/- 3.06	22 +/- 3	2.92 +/- 0.01	16.35 +/- 0.01	3.06 +/- 0.01	15 +/- 3	0.208 +/- 0.021	5.87 +/- 0.18	16,285 +/- 9.8

[a] Aliquots measured, used and that define lowest most De.
[b] Equivalent dose calculated on a pure quartz fraction with ultra-small aliquots with 20-80 grains/aliquot and analyzed under blue-light excitation (470 ± 20 nm) by Single Aliquot Regeneration (SAR) protocols.; Murray and Wintle, 2003. Wintle and Murray, 2006. Equivalent dose (De) was calculated by the Finite Mixture Model (Galbraith and Green, 1990) and the four parameter Minimum Age Model (Galbraith and Roberts, 2012).
[c] Overdispersion values reflects precision beyond instrumental errors; values of ≤ 20% (at 1 sigma limit) indicate low dispersion in equivalent dose values and defines a unimodal distribution. Values > 20% are associated with mixed equivalent dose signatures reflecting multiple grain populations or partial solar resetting.
[d] U, Th, Rb and K content analyzed by inductively-coupled plasma-mass spectrometry by ALS Laboratories, Reno, NV, and includes dose contribution from Rb and an assumed moisture content of 10 ± 5% for the burial period.
[e] Includes also a cosmic dose rate calculated from parameters in Prescott and Hutton (1994) and includes soft components.
[f] Systematic and random errors calculated in a quadrature at one standard deviation by the Luminescence Dating and Age Calculator (LDAC) (Peng and others, 2019) at https://www.baylor.edu/geosciences/index.php?id=962356. Datum year is AD 2010.

Table 2b: Accelerated mass spectrometry (AMS) radiocarbon ages (Beta Analytic, Inc., Miami, Florida, March and May, 2022)

Field Sample Number and Map Location	Laboratory Number	Map Unit	Latitude	Longitude	Depth Below Ground Surface (m)	Date Collected	Material Dated	delta ^{13}C (‰)[a]	Measured Radiocarbon Age (radiocarbon B.P.)[b]	Calibrated Age (cal B.P.)[c]
WS028C14A (S part of Timnath quadrangle)	Beta - 618596	Qe	40.514965	-104.94861	0.8 (2.6 ft)	7/27/2021	silt to very fine sand, with 3% very coarse sand and granules	-17.4	2,190 +/- 30	2,320 +/- 30
WS028C14B (S part of Timnath quadrangle)	Beta - 618597	Qe	40.514965	-104.94861	2.2 (7.2 ft)	7/27/2021	very fine to fine sand with 3% granules to small pebbles	-20.7	6,510 +/- 30	6,580 +/- 30
WS019BC14A	Beta - 625829	Qg_2	40.382622	-104.95494	0.3 (1.0 ft)	9/29/2021	very fine to medium sand with minor fines, 7% gravel	-19.6	3,500 +/- 30	3,590 +/- 30
WS019BC14B	Beta - 618958	Qg_2	40.382622	-104.95494	2.4 (7.9 ft)	9/29/2021	very fine to medium sand with minor fines, 7% gravel	-21.4	4,300 +/- 30	4,360 +/- 30

[a] Relative difference between 13C/12C ratio of carbon extracted from sample and that of Vienna Pee Dee Belemnite (VPDB) international standard.
[b] Conventional radiocarbon age, based on 5,568-year half-life; 0 yr B.P. = 1950 A.D.
[c] Calibrated range at 95.3% probability, using method of Bronk (2009) and IntCAL13 data set (Reimer and others, 2013).

TABLE 3. GRAIN-SIZE DISTRIBUTION IN WINDSOR QUADRANGLE QUATERNARY UNITS

Quaternary Unit	Number of Samples (total of all sites)	Number of Sites[1]	Gravel Average (%)	Gravel Range (%)	Sand Average (%)	Sand Range (%)	Fines (silt and clay)[2] Average (%)	Fines (silt and clay)[2] Range (%)
Eolian sediment (Qe)	73	7	NA[3]	NA[3]	19	15-49	81	47-96
Alluvium two (Qa_2)	22	6	2	0-10	57	24-92	41	2-72
Alluvium three (Qa_3)	28	8	40	12-64	51	32-82	9	3-28

[1] Construction project sites identified in geotechnical reports obtained from Colorado State Archives and Town of Windsor
[2] Analysis for fines (combined silt and clay content) was the norm in the geotechnical reports used here; with a few exceptions,
  silt and clay were not measured separately
[3] Not applicable

GEOLOGIC HISTORY AND STRUCTURE

The Windsor quadrangle lies in the northern part of the Colorado Piedmont, where topographic relief is relatively low; the quadrangle has 94 m difference between its lowest and highest elevations. The quadrangle contains some continuous, elongate outcrop areas of weathered bedrock, notably along the dissected southwest side of the Cache la Poudre River valley (geologic map, Plate 1). There are upland locations where weathered bedrock lies just below a thin residual soil cover, as in the area northeast of the intersection of Interstate Highway 25 and Colorado Highway 34. Fresh bedrock was observed only in the lower faces of gravel pits in the Big Thompson River valley. Unconsolidated Quaternary deposits cover most of the quadrangle, and the few natural exposures of these surficial units are along river cut banks. Topographically, most of the Windsor quadrangle consists of a broad, northwest-to-southeast-trending swath of upland bounded on the southwest and northeast by the valleys of the Big Thompson River and Cache la Poudre River, respectively. The quadrangle is drained by these two southeast-flowing rivers and their tributary streams, and their valleys are ~1 km and ~5 km wide, respectively. The present-day landscape of the Colorado Piedmont results from the downcutting and geomorphic evolution of the South Platte River and Arkansas River drainage basins mainly during late Neogene and Quaternary time. This began with removal of Paleogene and Neogene rocks and sediments that once covered Upper Cretaceous strata in the basins (Madole, 1991). The predominant Quaternary deposits in the piedmont, including those in the Windsor quadrangle and surrounding area, are fluvial sediments of the South Platte River and its major tributaries, and eolian sediments deflated from alluvium in the stream valleys and from upwind bedrock exposures (Madole, 1991; 2016).

The Windsor quadrangle is in the central part of the Greeley Arch, a structural saddle separating the Denver Basin to the south from the Cheyenne Basin to the north (Decheese and others, 2011). Cross section A-A' (Plate 2) indicates that bedrock strata in the quadrangle are essentially flat-lying, except between wells Wicked #1 and Jeffers #2 where the local dip is ~5° east. This eastward dip may be due to Laramide deformation along the west side of the Denver Basin during Late Cretaceous and Paleogene time, as indicated in the Figure 5 cross section of Decheese and others (2011). The Windsor quadrangle is ~110 km north of this cross section, but is on the west margin of the basin, as is the west side of the cross section where strata are shown as eastward-dipping. In Windsor quadrangle outcrops of Pierre Shale, located at the intersection of Colorado Highway 392 and Larimer County Road 3 (geologic map, Plate 1), two of four attitude measurements (strike 10°, dip 8° east; strike 175°, dip 9° east) are in accord with a north-south regional strike along the western side of the Denver Basin and a gentle eastward dip due to Laramide deformation. Two measurements (strike 40°, dip 9° southeast; strike 47°, dip 5° southeast) are not in accord with this setting. Their locations lie ~0.4 km east of the surface trace of the Windsor wrench fault zone (geologic map, Plate 1) and it is possible that the two discordant attitudes resulted from deformation associated with fault movement along the zone.

The Windsor wrench fault zone trends south-southwest to north-northeast across the western side of the quadrangle, as presented in a structure map of central Denver Basin fault zones in Weimer (1996) and included in the geologic map of the present report (Plate 1). As shown in cross section A-A' (Plate 2), the surface trace of the zone on the geologic map is confirmed by a fault inferred to lie between oil and gas wells Kness #1 and Encore #1C 12HZ. This fault is downthrown 140 m to the east, in accord with the Windsor wrench fault zone being downthrown to the east (Weimer, 1996). Right-lateral movement along this oblique-slip fault zone occurred during Cretaceous time and was intermittent from 110 to 65 Ma (Weimer, 1996), an interval that includes the beginning of the Laramide orogeny. Cross section A-A' also intersects two high-angle faults not presented in Weimer (1996) but inferred from the displacements observed between oil and gas wells. Data are insufficient to indicate if the faults are normal or reverse, both are downthrown to the west, and their displacements are 44 m (west fault) and 68 m (east fault). The trend of the syncline of Weimer (1996) (geologic map, Plate 1) parallels the trend of the Windsor wrench fault zone and runs through the City of Windsor. In cross section A-A' the syncline is confirmed by oil and gas well data.

All the bedrock units shown in cross section A-A' are Cretaceous formations deposited in the Western Interior Seaway, which at its maximum extent reached from the Arctic Ocean to the Gulf of Mexico and divided the North American continent in two. From Middle Jurassic into Late Cretaceous time the seaway occupied the Western Interior Foreland Basin adjacent to the east of the Cordilleran Orogenic Belt. This basin and orogenic belt were formed as North America drifted westward away from Europe, and the Pacific (Panthalassan) oceanic crust was subducted beneath the North America Plate. The Late Laramide orogeny during Late Cretaceous and Paleogene time, along with a drop in eustatic sea level, caused the Western Interior Seaway to retreat from the interior of North America (Slattery and others, 2013). The Late Cretaceous Fox Hills Sandstone is the youngest of the marine deposits present in the Windsor quadrangle and represents near-shore and beach environments on the west side of the retreating seaway. The Late Cretaceous Laramie Formation, youngest of the Cretaceous units in the Colorado Piedmont, overlies the Fox Hills Sandstone in nearby quadrangles (notably Frederick and Erie, ~43 km to the south), but in the Windsor quadrangle this unit has presumably been lost to erosion. The Laramie Formation consists of terrestrial sediments deposited inland from the seaway.

During Pliocene time in the Colorado Piedmont, major streams incised rocks and sediments of Neogene and Paleogene age as well as Upper Cretaceous sedimentary rocks; no rocks or sediments of Paleogene or Neogene age remain in the Windsor quadrangle. In the Timnath quadrangle, on the north side of the Cache la Poudre valley and ~1 km north of the Windsor quadrangle north boundary, there is a small outcrop of coarse sandstone that may be Ogallala Formation. The incision resulted in the development of the South Platte River and its major and minor tributaries. Some of these tributaries, however, especially minor ones, may have formed later during the Quaternary. The stream network within and near the Windsor quadrangle includes the Big Thompson River and the Cache la Poudre River, both of which are southeast-flowing tributaries to the east-flowing South Platte River. In the northern Colorado Piedmont there are many buried paleovalleys in minor tributaries to the major South Platte River tributaries, and the paleovalleys are infilled with alluvium (Qls) and covered with eolian sand sediment (Qe) (see, for example, the paleovalleys in the Greeley quadrangle; Keller and Morgan, 2020). The paleovalleys are associated with present-day minor drainages but locally have very little surface expression. They are more easily discernable in lidar imagery than in topographic maps or even by field observation, but some of the paleovalleys can be traced by concentrations of water wells completed in the valley-filling alluvium. The portion of the Fossil Creek valley downstream from Fossil Creek Reservoir, in the northwest corner of the Windsor quadrangle, appears in lidar imagery to be such a paleovalley, but there are no supporting water well data at this location.

Within the Windsor quadrangle the Quaternary alluvial map units were deposited by the Cache la Poudre River and Big Thompson River and their tributaries, or (at a few places) possibly by rivers ancestral to these two streams. From oldest to youngest the alluvial deposits are unit Qg_2 (gravel two, also called Verdos Alluvium), unit Qg_1 (gravel one, also called Slocum Alluvium), unit Qa_3 (alluvium three, also called Broadway Alluvium), unit Qa_2 (alluvium three, also called post-Piney Creek alluvium), and unit Qa (alluvium, undivided). Unit Qa connects laterally with unit Qa_3 and the two probably are equal in age. The positions of the above units in the landscape and relative to each other are shown in cross sections B-B', C-C', and D-D'. The Quaternary history of the Windsor quadrangle and surroundings with deposition of Early and Middle Pleistocene stream and alluvial-fan gravels, termed "old alluvium" by Lindsey and others (2005). These deposits include the Late Pliocene Nussbaum Alluvium and (from older to younger) the Rocky Flats, Verdos, and Slocum alluviums. The Slocum Alluvium and Verdos Alluvium, gravel one (Qg_1) and gravel two (Qg_2) respectively in Colorado Geological Survey nomenclature, are present in the Windsor quadrangle. From Early to Middle Pleistocene time there were periods of incision as well as periods of alluvial deposition, and, probably, eolian deposition.

The incision and lateral cutting of surrounding, fine-grained, less-resistant alluvial deposits and bedrock left isolated remnants of the older, more resistant "old alluvium" at higher elevations. Lindsey and others (2005) recognize occurrences of dissected alluvial fans and terrace gravels of Middle Pleistocene age extending as far as 5 km east of Fort Lupton (~43 km south of the Windsor quadrangle). These deposits include the Rocky Flats and Verdos alluviums. The Rocky Flats Alluvium is not mapped in the Windsor quadrangle but has been mapped elsewhere in the northern Colorado Piedmont; it ranges in estimated age from ~400 ka to 2 Ma (Middle to Early Pleistocene; Rihimaki and others, 2006). Verdos Alluvium (unit Qg_2) is mapped in the southeast corner of the Windsor quadrangle by Colton (1976) and during the field work for the present study, in the Johnstown quadrangle (adjacent to the south) by Palkovic and Morgan (2017), and in the Greeley quadrangle (~20 km to the east) (Keller and Morgan, 2020). Its estimated age ranges from between 410 and 475 ky and up to ~631 ky (see unit Qg_2 section in Description of Map Units section, Greeley quadrangle, in Keller and Morgan, 2020). As summarized in Berry and others (2019), the maximum age for the Verdos Alluvium is constrained by the underlying Lava Creek B ash, erupted from the Yellowstone Plateau volcanic field at ~631 ka (Matthews and others, 2015, cited in Berry and others, 2019). The ash is present in Verdos Alluvium at sites along the South Platte River northeast of Fort Morgan; although at many sites the ash is likely to be reworked. The ash is present within and at the top of Verdos Alluvium as well as at the base. The age assignments of these Early and Middle Pleistocene Colorado Piedmont alluvial deposits are based chiefly upon the following: height above present stream level near the east side of the Front Range hogback belt; tentative correlation with marine oxygen isotope stages; and assumption of a nonlinear rate of stream incision since the deposition of the Lava Creek B tephra at ~631 ka. The above age estimate of the Verdos Alluvium is based chiefly on its stratigraphic relationship with Lava Creek B tephra but also on soil carbonate morphology in the greater Denver area (Kellogg and others, 2008); there are also younger age estimates for this alluvium. In the Windsor quadrangle unit Qg_2 is located near the Big Thompson River, and in the Johnstown quadrangle (adjacent to the south) areas of unit Qg_2 lie in a swath roughly parallel with the trend of the river. This unit may have been deposited by an ancestral Big Thompson River. The Slocum alluvium (unit Qg_1) is mapped in the northeast corner of the Windsor quadrangle by Colton (1976) and during the field work for the present study. In the Windsor quadrangle and Timnath quadrangle (adjacent to the north), areas of unit Qg_1 (mapped as Q_s, or Slocum alluvium, by Colton, 1976) lie in a swath along the northeast side of the Cache la Poudre River Valley. This unit may have been deposited by an ancestral Cache la Poudre River. The age of the Slocum Alluvium is 220 to 390 ky (Kellogg and others, 2008).

After the deposition of unit Qg_2 (Verdos Alluvium), at some time during the period from ~631 ka to 410 ka, an episode of incision removed most of this unit from the northern Colorado Piedmont. Unit Qg_1 (Slocum Alluvium) was deposited during a subsequent episode of aggradation, at some time during the period from 390 to 220 ka (the age range of Slocum Alluvium given in Kellogg and others, 2008). Another incision episode then removed most of unit Qg_1 from the landscape. It is possible, but not proven, that Louviers Alluvium (unit Qa4 in Colorado Geological survey nomenclature) could have been deposited in the valleys of the Cache la Poudre River and Big Thompson River during an aggradation period from 170 to 120 ka (the age range of Louviers Alluvium given in Kellogg and others, 2008) and now underlies unit Qa_3 (Broadway Alluvium). In the Gowanda quadrangle (~28 km to the south) Louviers Alluvium underlies unit Qa_3 in the valley of St. Vrain Creek and has an age of ~151 ky (Keller and others, 2019). (Note that in the Plate 2 Quaternary cross sections all alluvium below unit Qa_3 and above bedrock is shown as being unit Qa_2.) Later, unit Qa_2 filled the valleys of the Cache la Poudre River and Big Thompson River during an aggradation episode from 30 to 12 ka (the age range of Broadway Alluvium given in Kellogg and others, 2008).

During the period from ~10 to ~4 ka unit Qe (eolian sediment) was deposited in much of Windsor quadrangle and other quadrangles in the region (see eolian sediment radiocarbon ages in Table 2 of this report; Keller and Morgan, 2018; Keller and others, 2019; and Keller and Morgan, 2020). The older ages in the above period fall within an early Holocene episode of eastern Colorado loess deposition spanning approximately 11 to 9 ka (Muhs and others, 1999). Unit Qe in the Windsor quadrangle lacks sufficient silt to be termed loess or sandy loess, but it may be coeval at least in part with loess deposition and may have derived its sand content from unit Qa_3 alluvium exposed along the Cache la Poudre River. Unit Qe was deposited on the unit Qa_3 terrace on the northeast side of the Cache la Poudre River valley and on most of the Windsor quadrangle upland.

In the valleys of the Cache la Poudre River and Big Thompson River, unit Qa_3 was incised and then, during the period after ~4 ka, the incision was partially filled with unit Qa_2 (post-Piney Creek) alluvium. In the Cache la Poudre River valley both the older unit Qa_3 terrace and the younger unit Qa terrace are prominent in lidar imagery. The area of unit Qe overlying the Qa_3 terrace along the Cache la Poudre River also was incised during this time. It was probably after ~4 ka that unit Qa was deposited in drainages tributary to the two rivers, contemporary with deposition of unit Qa_2. Unit Qa_3 in the river valleys then was partially incised and the incisions subsequently partially filled by unit Qa.

From Late Pleistocene to Late Holocene time, eolian sand (unit Qes) was deposited over much of the northeastern plains of Colorado and nearly as far west as Boulder (Madole and others, 2005), but is not present in the Windsor quadrangle.

MINERAL RESOURCES, GROUNDWATER RESOURCES, AND GEOLOGIC HAZARDS

Within the Windsor quadrangle there are four active construction permits (for aggregate production) in the valley of the Cache la Poudre River and three in the valley of the Big Thompson River; the quadrangle has no other active or inactive construction or mining permits (Colorado Division of Reclamation and Mine Safety [DRMS] AUGER interactive map, 2022). Of the total seven permits, five are for sand and gravel extraction and two are for gravel only; five permits are in Larimer County and two are in Weld County. The pits at all seven locations are discernable on the lidar image for the quadrangle and all are excavated in the interbedded alluvial sand and gravel of unit Qa_3. Two of the pits (Coulson Excavating Co. and Loveland Ready Mix Concrete, Inc.) in the Big Thompson River valley are locations for the unit Qa_3 optically stimulated luminescence (OSL) samples and ages presented in this report (see Description of Map Units in Plate 1 and Table 2 in Plate 2). All seven permit sites lie in portions of the river valleys mapped by Schwochow and others (1974) as flood-plain and valley-fill deposits of relatively clean and sound gravel. For the years 2020 and 2021 the annual aggregate production in Larimer County was ~1.3 million and ~1.2 million metric tons, respectively (Larimer County Assessor's Office, oral commun., 2022). For the same years the annual aggregate production in Weld County was ~14.7 million and 15.2 million metric tons, respectively (Weld County Assessor's Office, oral commun., 2021).

The Windsor quadrangle lies on the northwest margin of the Wattenberg field, a prolific oil and gas producing area located mostly in Weld County and Adams County but impinging a little into Larimer County. As of summer 2021, the Windsor quadrangle was an active area for hydrocarbon production. Oil and gas infrastructure is prominent in the south part of the quadrangle in the rural upland between the valleys of the Big Thompson River and Cache la Poudre River. As of 2021 the Wattenberg field was the fourth-largest oil field and ninth-largest natural gas field in the U.S. (U.S. Energy Information Administration, 2021). Production in the Wattenberg field is principally from the Niobrara Formation but also from the Colorado Group and Dakota Group. In 2021 the field produced ~117 million barrels of oil and ~958 billion MCF (thousand cubic ft) of natural gas (Colorado Oil and Gas Conservation Commission, 2022).

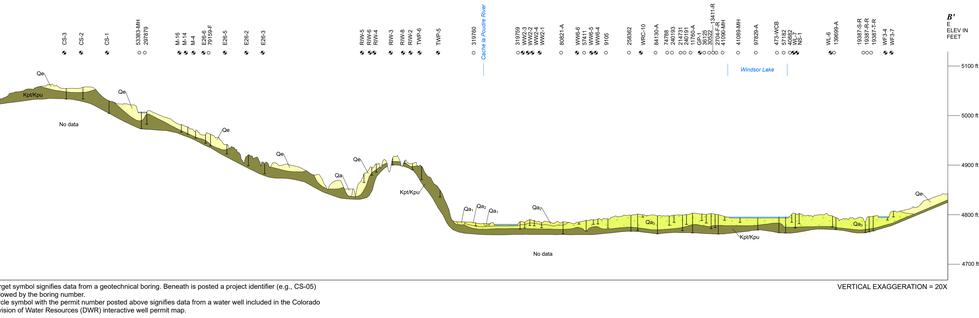
Of the 256 water wells in the Windsor quadrangle, all but 32 are completed in unit Qa_3 alluvium in the valleys of the Big Thompson River and Cache la Poudre River. The alluvium consists of interbedded layers of sand, gravel, and clay and is underlain by the Pierre Shale in the Colorado Piedmont this alluvium is found along the valleys of the South Platte River and its major tributaries, as well as in minor tributary paleovalleys (buried valleys) to these streams. In cross sections B-B', C-C', and D-D' the thickness of the unit Qa_3 aquifer ranges between 2 and 8 m. The upland wells of the Windsor quadrangle are completed in eolian sediment (unit Qe) and more rarely in the Pierre Shale; these wells are as deep as 14 m. The uppermost bedrock aquifer in the northern Colorado Piedmont is the Laramie-Fox Hills aquifer, described in Topper and others (2003). The Laramie Formation is absent in the Windsor quadrangle and there is only a small and relatively thin area of Fox Hills Sandstone present (along the east boundary). The Laramie-Fox Hills aquifer thus is not an important groundwater resource in the quadrangle.

During the catastrophic September 2013 regional flood events along the Colorado Front Range there were some fatalities, large-scale damage to property and infrastructure, and some adverse environmental effects. In the Windsor quadrangle, in the valleys of the Cache la Poudre River and Big Thompson River, flood waters covered much of the area mapped as alluvium one (unit Qa_1) and alluvium two (unit Qa_2) (Town of Windsor, 2013; Coloradoan, 2019). In the Windsor quadrangle the areas of units Qa_1 and Qa_2 in both river valleys are designated as Federal Emergency Management Agency 100-yr flood zones by Larimer County (Larimer County Land Information Locator, 2022) and Weld County (Weld County Property Portal, 2022).

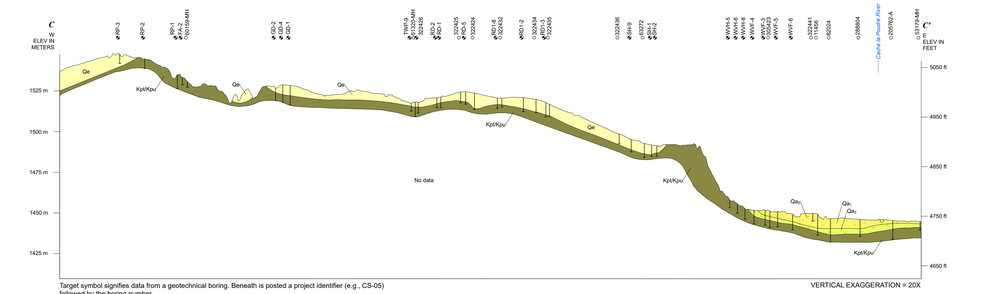
Eolian sediment (unit Qe) locally may, owing to hydrocompaction, be susceptible to collapse when under load and in a wet or saturated condition. Soil engineers refer to these deposits as collapsible soils. The fine-grained fractions (silt and especially clay) of these deposits give them relatively high compressive strength and shear strength under dry conditions. When wet or saturated and under load, however, the fine-grained particles in these deposits can be displaced into a denser configuration such that the void space between particles is reduced. Compaction and associated decrease in volume can cause settlement at and near the ground surface, potentially resulting in damage to any overlying structures and (or) infrastructure (White and Greenman, 2008).

Near Greeley in June 2014 there was an apparent wastewater injection-induced earthquake of moment-magnitude (Mw) 3.2 and Modified Mercalli intensity IV, great enough to be felt throughout the Front Range (Yeck and others, 2016). The epicenter for the earthquake was in a historically aseismic part of Colorado, ~4 km northeast of the east end of the City of Greeley/Weld County Municipal airport, and ~2.5 km northeast of a high-rate oilfield injection well. The well was being used for wastewater disposal into the Pennsylvanian-Permian Fountain Formation overlying the Precambrian crystalline basement. The monthly rate of oilfield wastewater injection in Weld County had increased significantly over the period of 2010 to 2014. Suspecting that the nearby injection well had caused the earthquake, the Colorado Oil and Gas Conservation Commission temporarily halted injection activity. The University of Colorado, with support from other agencies, then rapidly installed a local seismic monitoring network. The bottom of the well was cemented to prevent hydraulic communication between the injection zone and the basement rocks, and injection then was resumed at a lower rate. During the following 16 months (through about October 2015) there were no earthquakes greater than Mw 1.5 associated with the injection well (Yeck and others, 2016). During the period from October 2015 through February 2020 there were 21 earthquakes in the Greeley quadrangle. Half of the earthquakes ranged from local Richter magnitude (Ml) 1 to 1.9 and half ranged from 2.1 to 3 Ml (U.S. Geological Survey Online Earthquake Catalog, February 2020, cited in Keller and Morgan, 2020). (Local Richter magnitude and moment-magnitude are nearly equivalent for small earthquakes.) The local seismicity is believed to be induced by continuing injection-well operations, although the cause of these earthquakes is still a subject of debate. The Town of Windsor lies ~20 km west of the June 2014 earthquake epicenter in the Greeley quadrangle. For the period from the beginning of June 2014 through the end of April 2022 there was no recorded seismic activity in the Windsor quadrangle (U.S. Geological Survey Online Earthquake Catalog, May 2022).

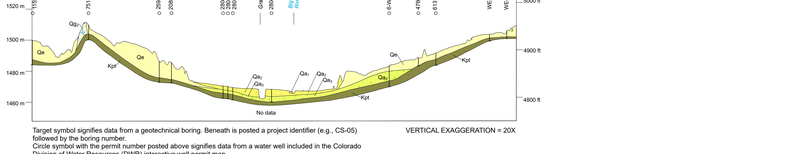
CROSS SECTION B-B'



CROSS SECTION C-C'



CROSS SECTION D-D'



Target symbol signifies data from a geotechnical boring. Beneath is posted a project identifier (e.g., CS-05) followed by the boring number.
Circle symbol with the permit number posted above signifies data from a water well included in the Colorado Division of Water Resources (DWR) interactive well permit map.

VERTICAL EXAGGERATION = 20X

GEOLOGIC MAP OF THE WINDSOR QUADRANGLE, LARIMER AND WELD COUNTIES, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE, GEOLOGIC HISTORY, GROUNDWATER, AND MINERAL RESOURCES AND CROSS SECTIONS
By Stephen M. Keller and Alexander E. Marr
2024

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