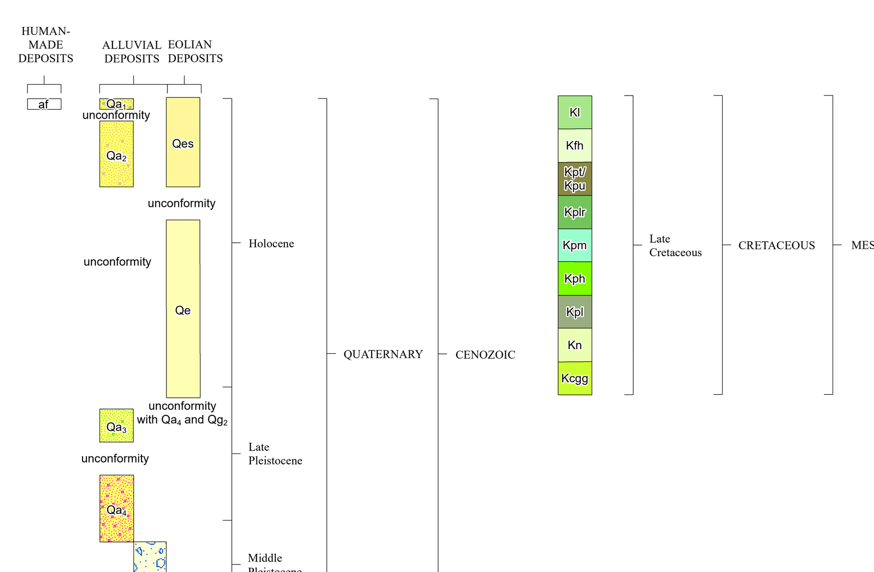
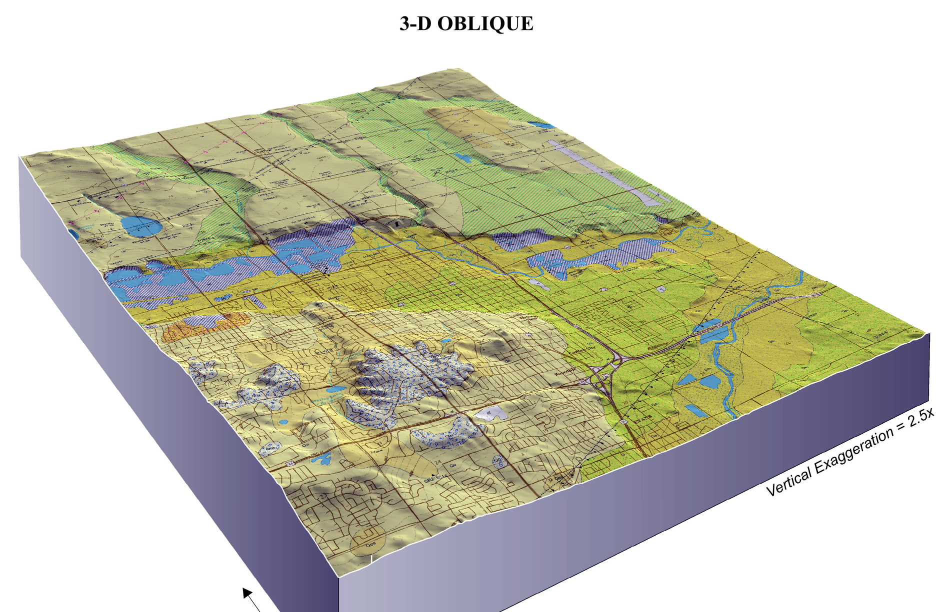
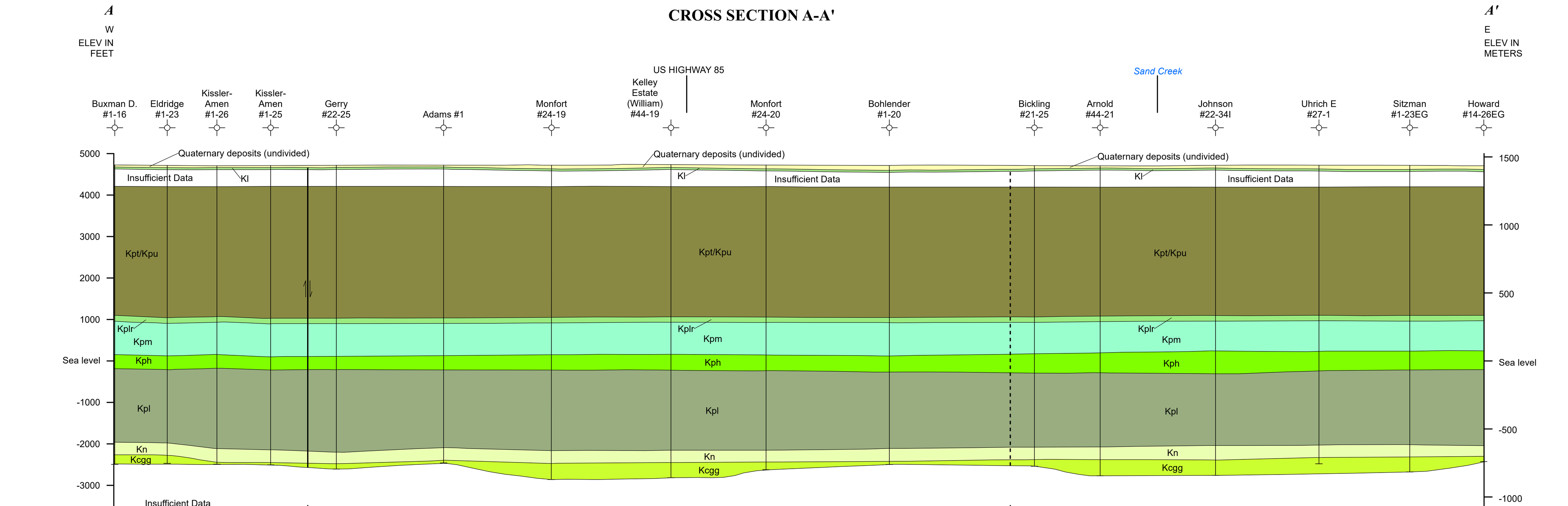
CORRELATION OF MAP UNITS



3-D OBLIQUE

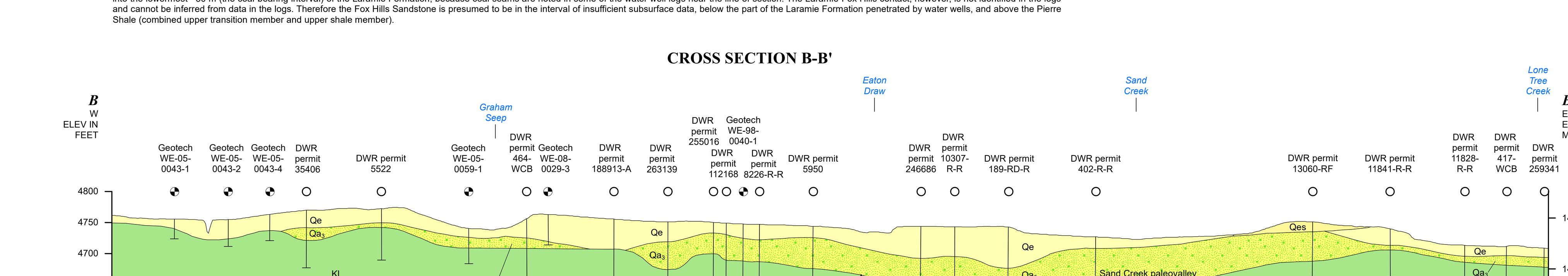


CROSS SECTION A-A'



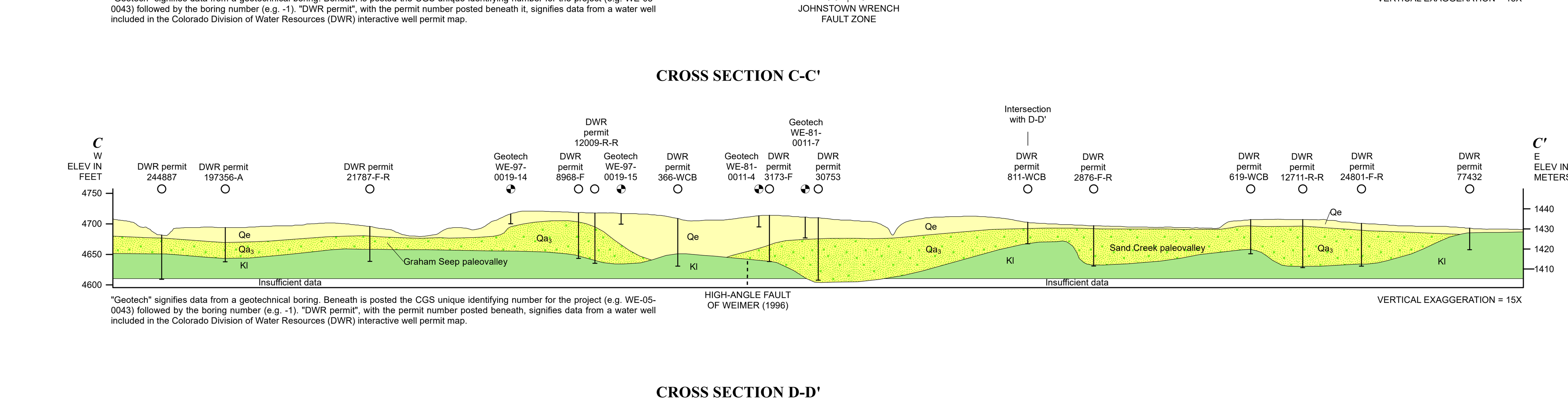
The Fox Hills Sandstone is not depicted on the cross section because the oil and gas wells, water wells, and geotechnical soil borings in the Greeley quadrangle present insufficient data to identify this unit. Water wells do penetrate into the lowermost ~30 m (the coal-bearing interval) of the Laramie Formation, because coal seams are noted in some of the water well logs near the line of section. The Laramie-Fox Hills contact, however, is not identified in the logs and cannot be inferred from data in the logs. Therefore the Fox Hills Sandstone is presumed to be in the interval of insufficient subsurface data, below the part of the Laramie Formation penetrated by water wells, and above the Pierre Shale (combined upper transition member and upper shale member).

CROSS SECTION B-B'



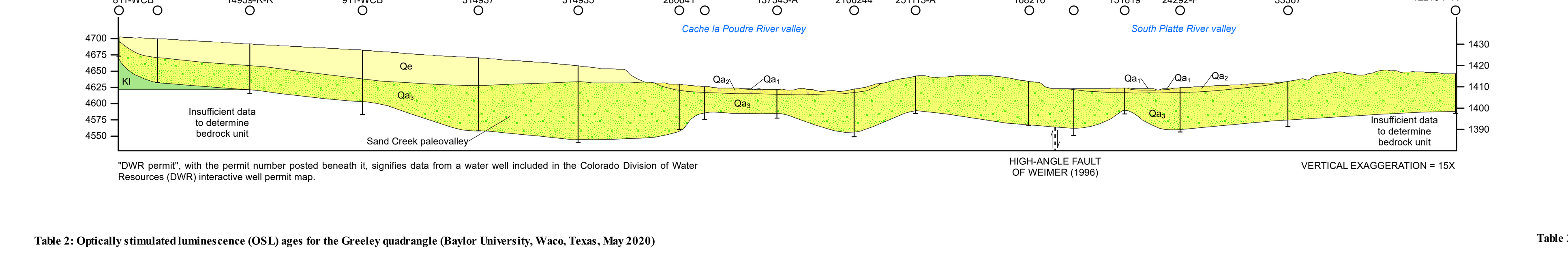
"Geotech" signifies data from a geotechnical boring. Beneath is posted the CGS unique identifying number for the project (e.g. WE-05-0043) followed by the boring number (e.g. -1). "DWR permit", with the permit number posted beneath it, signifies data from a water well included in the Colorado Division of Water Resources (DWR) interactive well permit map.

CROSS SECTION C-C'



"Geotech" signifies data from a geotechnical boring. Beneath is posted the CGS unique identifying number for the project (e.g. WE-05-0043) followed by the boring number (e.g. -1). "DWR permit", with the permit number posted beneath it, signifies data from a water well included in the Colorado Division of Water Resources (DWR) interactive well permit map.

CROSS SECTION D-D'



"DWR permit", with the permit number posted beneath it, signifies data from a water well included in the Colorado Division of Water Resources (DWR) interactive well permit map.

Table 1. Particle size and Munsell color data for Greeley quadrangle map units

Map Unit	Grain Size Distribution and Other Characteristics	Colors (per Munsell Color, 1991)
Qa_1	Coarse-grained sediment - Point bar sand ranges from fU to vcU in size, angular to subangular, ~80% quartz and ~20% feldspar and other minerals, the latter portion including ~3% opaque minerals and no mica. Point bar gravel ranges from granules to pebbles with a few cobbles; subrounded to rounded, mainly granitic rocks with subordinate gneiss, white and bluish-gray quartzite, and red and brownish-yellow sandstone. Fine-grained sediment - Mixture of clay, silt, and very fine to fine sand; locally, very fine to fine sand, very micaceous.	Pinkish-gray of hue 5YR. Dark grayish-brown of hue 2.5Y; bluish-black locally.
Qa_2	Fine-grained beds - 1) silty clay to silt and very fine sand, moderately to strongly cohesive, local blocky structure, no visible carbonate but local slight effervescence, locally micaceous; and 2) moderately to well-sorted very fine to medium sand, some fines, subangular to subrounded, rare granitic granules and small pebbles, moderately to strongly cohesive, ~80% quartz and 20% feldspar and other minerals, including ~3% opaque minerals, locally micaceous. Coarse-grained beds - Moderately to poorly sorted sand (with no gravel) and gravelly sand; sand is subangular to angular, 80% quartz and 20% lithics, with no mica. Gravel content of gravelly sand is 5 to 30%, granules plus pebbles from <1 cm up to 4 cm, subrounded to rounded, mainly white and pink granitic rocks with subordinate vein quartz and quartzite; weakly to moderately cohesive and mostly not effervescent.	Dark grayish-brown of hues 10YR and 2.5Y, light yellowish-brown of hue 2.5Y, and yellowish-brown of hue 10YR. Dark-brown, grayish-brown, and very dark grayish-brown of hue 10YR; light olive-brown of hue 2.5Y; and pale-red of hue 2.5YR.
Qa_3	Gravelly sand and sandy gravel - Proportions of sand and granule matrix and larger gravel content vary widely: from 30% matrix and 70% clasts, to 65% matrix and 35% clasts. Both matrix and clasts are poorly sorted; matrix size ranges are fine (fU) to coarse (cU) sand, fine (fU) to medium (mU) sand, fine (fU) to very coarse (cvU) sand, and medium (mL) sand to granules. Sand is angular to subangular, or subangular to subrounded; sand composition is 70 to 80% quartz and 20 to 30% feldspar and other minerals, the latter including 2 to 3% opaque minerals. Gravel clasts range in size from small pebbles to 8-cm cobbles, and are subrounded to rounded, or rounded to well rounded. Pink and white granitic clasts are dominant, with subordinate vein quartz, quartzite, and gneiss, and rare sandstone and andesite. Effervescence is rare in matrix. Cohesion is weak to moderate and the material can retain steep faces in gravel pits. Very fine to very coarse sand with little or no gravel - Very fine to very coarse sand, ranges from poorly to well sorted. Size ranges are very fine to medium sand, fine sand, fine (fU) sand to granules, medium to coarse sand, and medium sand to granules; fines are absent. Sand composition is 75 to 80% quartz and 20 to 25% feldspar and other minerals, the latter including up to 3% opaque minerals. The sand is angular to subangular, or subangular to subrounded. No effervescence, cohesion is weak. Clayey silt or silty clay with minor gravel - Contains small (usually up to 5%) coarse fraction ranging from coarse (cL) sand to granitic pebbles, the latter up to 3 cm and subrounded to rounded. Cohesion is strong, effervescence is absent to strong.	Pinkish-white and pinkish-gray of hue 5YR, and subordinate very pale-brown and brownish-yellow of hue 10YR; orange-brown iron-oxide staining is locally prominent. Pale-yellow of hue 2.5; yellow, brownish-yellow, and brown of hue 10YR; and pinkish-white and pinkish-gray of hue 5YR. Dark-gray and very dark-brown of hue 10YR, dark-brown of hue 7.5YR, and black of hue 2.5Y.
Qa_4	Sand to granule matrix - Poorly sorted, subangular to subrounded, weakly cohesive to loose; 75% quartz and 25% feldspar, and < 1 % other minerals, and lithics. Gravel clasts - Up to 10 cm, subrounded; granitic rocks, dark-colored gneiss, vein quartz, and quartzite. Some have carbonate coatings on 20 to 50% of the surfaces of clasts.	Dark grayish-brown of hue 10YR.
Qg_2	Matrix sand has high carbonate content with Stage III to IV carbonate morphology (Machette, 1985), and violent effervescence. Gravel clasts are subrounded to rounded granitic rocks, vein quartz, and quartzite, with thick carbonate coatings covering many of the clasts.	Pinkish-white of hue 7.5YR.
Qes	Very fine to medium sand with few fines, locally with a very small content up to very coarse (vcU) size, and with trace granules and pebbles; and fine (fL) to very fine to medium sand with few fines, locally with a very small content up to very coarse (vcU) size. Moderately to well sorted; subangular to subrounded, or subrounded to rounded; moderately cohesive to nearly loose, and massive. Strongly effervescent but without visible carbonate. Composition is 75 to 85% quartz and 15 to 25% feldspar and other minerals, including 3% opaque minerals.	Light to dark yellowish-brown and dark grayish-brown of hue 10YR, and olive-brown of hue 2.5Y.
Qe	Very fine (vfL) sand to fine sand with some larger sand and some fines; very fine (vfU) to fine (fU) sand with some fines; and (in a few places) fine (fL) to medium (mU) sand with some fines. Well sorted with rare coarse sand and granules; mainly subangular to subrounded, moderately cohesive. Clayey silt to very fine sand, and clayey silty very fine (vfL) to fine (fU) sand with trace larger sand up to very coarse (vcU); moderately to strongly cohesive, with blocky structure.	Light to dark yellowish-brown, brownish-yellow, and very pale-brown to dark-brown of hue 10YR. Light to dark yellowish-brown, brown, dark to very dark grayish-brown, and very dark-gray of hue 10YR.

Table 2: Optically stimulated luminescence (OSL) ages for the Greeley quadrangle (Baylor University, Waco, Texas, May 2020)

Field Sample Number and Map Location	Laboratory Number	Map Unit	UTM Easting[1]	UTM Northing[1]	Depth Below Ground Surface (bgs) (m)	Date Collected	Material Dated	Aliquots[2]	Grain Size(µm)	Central Minimum Age Model (D_e) (Gy)[3]	Over-dispersion (%)[4]	U (ppm)[5]	Th (ppm)[5]	K_2O (%)[5]	Cosmic Dose Rate (mGray/yr)[6]	Dose Rate (mGray/yr)	Central/ Minimum Model SAR age (yr)[7]
GR163BOSL and GR163Bcalib Bucklen Equipment Co. pit, Cache la Poudre River valley	BG4870	Qa_3	524534	4476421	2.1 m bgs, 0.3 m below Qa_2-Qa_3 contact	25-Oct-19	Sandy gravel or gravelly sand	0.75	250-355	14.72 +/- 0.45	11 +/- 2	2.24 +/- 0.01	5.82 +/- 0.01	2.47 +/- 0.01	0.218 +/- 0.022	2.99 +/- 0.12	4,920 +/- 280[8]
GR163COSL and GR163Ccalib Bucklen Equipment Co. pit, Cache la Poudre River valley	BG4869	Qa_3	524652	4476578	4.3 m bgs, 1.7 m above Qa_3/Kl contact	25-Oct-19	Gravelly sand	0.63	355-500	190.93 +/- 10.57	23 +/- 4	2.09 +/- 0.01	6.35 +/- 0.01	3.62 +/- 0.01	0.173 +/- 0.018	3.92 +/- 0.13	48,730 +/- 3,135
GR166AOSL and GR166Acalib Tri-State Commodities bluff, Eaton Draw	BG4868	Qa_3	526374	4477295	4.0 m bgs, at base of exposure bedded sand	25-Oct-19	Bedded vfL to fL	0.97	63-100	259.38 +/- 10.75	20 +/- 3	5.54 +/- 0.01	10.55 +/- 0.01	1.98 +/- 0.01	0.179 +/- 0.018	3.68 +/- 0.13	70,430 +/- 4,460

[1] UTM zone 13, 1983 North American Datum (NAD 83).
[2] Aliquots measured, used and that define lowest most D_e.
[3] 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 (D_e) was calculated by the Finite Mixture Model (Galbraith and Green, 1990) and the four parameter Minimum Age Model (Galbraith and Roberts, 2012).
[4] 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 signature reflecting multiple grain populations or partial solar resetting.
[5] 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 ± 3% for the burial period.
[6] Includes also a cosmic dose rate calculated from parameters in Prescott and Hutton (1994) and includes soft components.
[7] Systematic and random errors calculated in a quadrature at one standard deviation by the Luminescence Dating and Age Calculator (LDAC) at
[8] This age probably spurious because too young for Qa_3.
https://www.baylor.edu/geosciences/index.php?id=962356. Datum year is AD 2010.

Table 2 (continued): Radiocarbon ages for the Greeley quadrangle

Accelerated mass spectrometry (AMS) radiocarbon ages (Beta Analytic, Inc., Miami, Florida, December 2019)

Field Sample Number and Map Location	Laboratory Number	Map Unit	UTM Easting[1]	UTM Northing[1]	Depth Below Ground Surface (m)	Date Collected	Material Dated	delta^{13}C (0/00)[2]	Radiocarbon Age (radiocarbon ka B.P.)[3]	Calibrated Age (cal ka B.P.)[4]
GR067C14 Fresh irrigation ditch exposure	Beta-545256	Qe	527316	4479472	1.5	25-Oct-19	Disseminated fine organic matter in well-sorted very fine sand (vfL) to fine sand (fL) with some fines	-20.6	9,260+/- 30	10,554-10,296
GR163BC14 Bucklen Equipment Co. pit face	Beta-545257	Qa_2	524534	4476421	1.2	8-Oct-19	Disseminated fine organic matter in clayey silt to very fine sand	-18.7	3,200+/-130	3,475-3,366
GR218C14 Large fresh exposure at housing development	Beta-545258	Qes	523094	4470414	0.5	8-Nov-19	Disseminated fine organic matter in moderately sorted very fine sand (vfU) to medium sand (mL) with minor larger sand up to vcU	-18.2	850+/- 30	798-690

[1] UTM zone 13, 1983 North American Datum (NAD 83).
[2] Relative difference between $^{13}C/^{12}C$ ratio of carbon extracted from sample and that of Vienna Pee Dee Belemnite (VPDB) international standard.
[3] Conventional radiocarbon age, based on 5,568-year half-life; 0 yr B.P. = 1950 A.D.
[4] Calibrated range at 95.5% probability, using method of Bonk (2009) and IntCAL13 data set (Reimer and others, 2013).

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GEOLOGIC HISTORY AND STRUCTURE

The Greeley quadrangle lies in the northern part of the Colorado Piedmont. Like much of the piedmont, the quadrangle's topography has relatively low relief (76 m difference between lowest and highest points), and natural exposures of bedrock and surficial units are rare except along stream banks. Quaternary deposits cover almost all the quadrangle and bedrock is exposed only at a few places, most being in the sumps of gravel pits. The present-day landscape of the Colorado Piedmont results from the down-cutting and geomorphic evolution of the South Platte River and Arkansas River drainage basins mainly during late Neogene and Quaternary time, beginning with removal of Paleogene and Neogene rocks and sediments that once covered the Upper Cretaceous strata in the basins (Madole, 1991). The predominant Quaternary deposits in the piedmont, including those in the Greeley quadrangle and surrounding area, are fluvial sediments of the South Platte River and its tributaries, and eolian sediments deflated from alluvium in these stream valleys and from upwind bedrock exposures in the piedmont (Madole, 1991; 2016). Most of the Greeley quadrangle is drained by the Cache la Poudre River and its south-flowing tributaries (Graham Seep, Eaton Draw, and Sand Creek); a smaller portion is drained by the South Platte River and its tributary Lone Creek. The Cache la Poudre River is a tributary of the South Platte River. The alluvial valleys of both of the major streams coalesce in the eastern part of the City of Greeley. The Cache la Poudre River valley is ~2.5 km wide at Greeley and trends northwest to southeast across the quadrangle. The South Platte River valley is ~3 km wide at Greeley and trends southwest to northeast near the southeast corner of the quadrangle.

The Greeley 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 (Dechesne and others, 2011). Cross section A-A' indicates that bedrock strata in the quadrangle are essentially flat lying. The Laramie Formation is the uppermost and youngest bedrock unit in the quadrangle. It is a coal-bearing formation composed of sediments deposited in a low coastal-plain environment along the western margin of the Western Interior Seaway during the Late Cretaceous (100-66 Ma). The formation immediately underlies Quaternary surficial deposits, as indicated by coal seams recorded in the bedrock portions of water-well logs (Colorado Division of Water Resources, 2020). The coal seams are in the lowest 60 to 90 m of the formation. In the north part of the Denver Basin, the Fox Hills Sandstone lies beneath the Laramie Formation and overlies the Pierre Shale. It is presumed to do so in the Greeley quadrangle, but the Laramie Formation-Fox Hills Sandstone contact and the Fox Hills Sandstone-Pierre Shale contact are not recorded in the water-well driller's logs or oil and gas well geologic logs examined for the present study. Thus, the depth and thickness of the Fox Hills Sandstone are not shown in cross section A-A'. Sediments of the Fox Hills Formation were deposited in near-shore and beach environments as the Western Interior Seaway retreated to the east (Dechesne and others, 2011). The Upper Transition Member of the Pierre Shale underlies the Fox Hills Sandstone. Sediments of this member were deposited in deeper marine environments of the seaway. Oil and gas wells in the Greeley quadrangle have penetrated underlying Cretaceous formations down into those of the Colorado Group (cross section A-A').

The Johnstown wrench fault zone trends southwest to northeast across the northern part of the Greeley quadrangle, as shown in a structure map of central Denver Basin faults zones in Weimer (1996). Right-lateral movement along this oblique-slip fault zone, with the downthrown side on the southeast, occurred during Cretaceous time and was intermittent from 110 to 65 Ma (Weimer, 1996), an interval that includes the beginning of the Laramide orogeny. This fault zone may be the cause of slight changes in the dip of deeper Cretaceous units on the west side of cross section A-A', but this is uncertain. Weimer's structure map also shows an anticline and a high-angle fault in the north part of the Greeley quadrangle. The fault is included on the Greeley quadrangle map, even though it is not supported by any apparent displacement on cross section A-A' where the mapped fault crosses the line of section (west of well Bickling #E 21-25). The 1:100,000-scale geologic map of the Boulder-Fort Collins-Greeley area (Colton, 1976) shows no structural features in the Greeley quadrangle.

During Pliocene time, major streams incised rocks and sediments of Neogene and Paleogene age as well as Upper Cretaceous sedimentary rocks in the Colorado Piedmont; no rocks or sediments of Paleogene or Neogene age remain in the Greeley quadrangle. This incision presumably resulted in the development of the South Platte River and its tributaries; the stream network in and near the Greeley quadrangle also includes the Cache la Poudre River and its three south-flowing tributaries in the north part of the quadrangle. The Quaternary depositional history of the piedmont near Greeley begins with deposition of Early and Middle Pleistocene stream and alluvial fan gravels, termed "old alluvium" by Lindsey and others (2005). These deposits include the Nussbaum Alluvium (spanning the Pliocene and Early Pleistocene(?), and the Rocky Flats, Verdos, and Slocum alluviums. Verdos Alluvium mapped in the Greeley quadrangle by Colton (1976) is termed unit Qg_2 in the present study. It is the only "old alluvium" exposed in the quadrangle, and its estimated age ranges from between 410 and 475 ky to ~631 ky in this area (see unit Qg_2 section in Description of Map Units). Lindsey and others (2005) recognize occurrences of dissected alluvial fans and terrace gravel of Middle Pleistocene age extending as much as 5 km east of Fort Lupton (~25 km south of the Greeley quadrangle). These deposits include the Rocky Flats and Verdos alluviums. The former is not mapped in the Greeley quadrangle, but ranges in estimated age from ~400 ka to 2 Ma (Middle to Early Pleistocene; Riihimaki and others, 2006). 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 resulted in inversion of the topography. The inversion left isolated remnants of the older, more resistant alluviums at higher elevations, such as the unit Qg_2 deposits preserved in the upland areas within the City of Greeley. The ages of alluvial deposits in the Colorado Piedmont that are considered to be of Early and Middle Pleistocene age are based chiefly upon: 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 ~631 ka Lava Creek B tephra. The above ages of the Verdos Alluvium are based chiefly on its stratigraphic relationship with Lava Creek B tephra and also on soil-carbonate morphology in the greater Denver area (Kellogg and others, 2008). There are also younger age estimates for the Verdos Alluvium. Near Fountain, Colorado, alluvial gravel mapped as Verdos Alluvium by Scott and Wobus (1973) and Trimble and Machette (1979) yielded optically stimulated luminescence (OSL) ages of ~35 ky and ~142 ky (White and others, 2017), and pediment gravel mapped as Verdos Alluvium by Scott and Wobus (1973) and Trimble and Machette (1979) yielded OSL ages of >210 ky and >250 ky (White and others, 2017).

Four Quaternary alluvial map units were deposited by the Cache la Poudre River, South Platte River, or their tributaries, or were deposited as alluvial fan sediments. From oldest to youngest (highest to lowest elevation) they are units Qg_2 (gravel two, also mapped by Colton (1976) as Verdos Alluvium), Qa_4 (alluvium four, previously identified in the Greeley quadrangle and adjacent area as Louviers Alluvium in cross section F-F' of Lindsay and others, 2005), Qa_3 (alluvium three, also known as Broadway Alluvium), and Qa_2 (alluvium two, also known as Piney Creek Alluvium). The positions of units Qa_3 and Qa_2 in the landscape are shown in cross sections B-B', C-C', and D-D'. Units Qa_4, Qa_3, and Qa_2 are aggradational fill deposits underlying terrace surfaces that are recognizable in the field, on lidar imagery, and on the 7.5-minute topographic map. The three terrace-fill deposits resulted from periods of increased stream discharge and deposition of bed load deposits. Each aggradational terrace surface subsequently was incised by stream erosion, and the younger stream-cut valley was filled later by younger alluvium. Stream incision followed by alluvial aggradation formed cut-in-fill terraces of units Qa_4 (highest and oldest), Qa_3 (middle) and Qa_2 (lowest and youngest). The terraces are recognizable by a flat to gently sloping upper surface (tread) and a steeply sloping bank (riser).

Unit Qa_4 (Louviers Alluvium of Lindsay and others, 2005) is believed to be outwash from glaciers during the Bull Lake glaciation (Marine Isotope Stage 6) in the Front Range. The unit was deposited by very large and sustained stream discharges (Madole, 1991). Unit Qa_4 in the Greeley quadrangle could not be sampled for dating by optically stimulated luminescence (OSL), but in a summary table of ages for alluviums in the portion of the piedmont from Boulder south to Chatfield Lake, Kellogg and others (2008, and references therein) give a range of 120 to 170 ka for Louviers Alluvium. Riihimaki and others (2006) provide Be10 exposure ages for a "Slocum" surface, which may or may not overlie Louviers Alluvium near Ralston Creek. The age for the Slocum surface ranged between 200 and 300 ka, which may or may not constrain the maximum age of unit Qa_4. Subsequent stream incision, probably during the Late Pleistocene, removed most of the valley-fill alluvium of unit Qa_4, and in the Greeley quadrangle there is only one remnant terrace (near the western quadrangle boundary) underlain by this unit. Subsequent aggradation, later in the Late Pleistocene, partly filled the incised valleys of the rivers and tributaries with alluvium of unit Qa_3.

In the present study, the OSL age estimate of unit Qa_3 (likely equivalent to previously mapped Broadway Alluvium) in the Cache la Poudre valley is ~48.7 ka, and the OSL age estimate for unit Qa_3 in the Eaton Draw paleovalley is ~70.4 ka. Both of these ages are older than published ages for Broadway Alluvium (12 to 30 ky) and younger than published ages for Louviers Alluvium (120 to 170 ky; Kellogg and others, 2008). Considering 1 sigma values, both samples are Early Wisconsin in age, a period of time for which there are no known alluvial deposits mapped in the Colorado Piedmont at and near Denver (Kellogg and others, 2008) or farther north on the western margin of the piedmont (Cole and Braddock, 2009; Workman and others, 2018). There are no corresponding glacial deposits of Early Wisconsin age identified in the Front Range with which alluvium of this age can be correlated. However, deposition by glacial meltwater is not the only possible explanation for alluvium of this age. In Table 2 these two age values are assigned to unit Qa_3 but might be from a putative underlying deposit that predates unit Qa_3. OSL age estimates for unit Qa_3 in the Gowanda quadrangle (~22 km southwest of Greeley) are ~42.3 ky, ~54.5 ky, and >56 ky (Keller and Morgan, 2020). The age estimate for unit Qg_1 in the Milliken quadrangle (~24 km southwest of Greeley) is ~56 ky determined by OSL. Uranium-series dating yields an age range for Milliken quadrangle unit Qg_1 of ~44 to ~76 ky, with a much older than expected outlier at 256 ky (Palkovic and others, 2018). The above ages of deposits mapped as unit Qa_3 (Greeley and Gowanda quadrangles) and the unit mapped as Qg_1 (Milliken quadrangle) are comparable. All of these ages (except for the Milliken quadrangle unit Qg_1 uranium-series outlier) are Late Pleistocene and fall between ages for Louviers Alluvium (120 to 170 ka, associated with Bull Lake glaciation in the Front Range) and Broadway Alluvium (12 to 30 ka, associated with Pinedale glaciation; Kellogg and others, 2008). The age of ~54.5 ky is Early Wisconsin, a period of time for which there are no known alluvial deposits identified and (or) mapped in the Colorado Piedmont from Boulder south to Chatfield Lake, and also north to the Wyoming state line (Kellogg and others, 2008; Cole and Braddock, 2009; and Workman and others, 2018). In Kellogg and others (2008) table 1 of ages for alluviums younger than Rocky Flats Alluvium, there are no known Early Wisconsin deposits. In the summary of U.S. Geological Survey Quaternary mapping of four contiguous quadrangles along the South Platte River, from Fort Morgan westward (Berry and others, 2019), there is no mention of alluvial deposits of this age (i.e., between Louviers Alluvium and Broadway Alluvium ages). Considered together, however, the above alluvial deposit ages suggest the following possibilities: 1) unit Qa_3 is older than Broadway Alluvium; 2) unit Qa_4 is younger than Louviers Alluvium; 3) there were one or more episodes of Late Pleistocene stream aggradation that occurred during the interval between the Bull Lake and Pinedale glaciations; and 4) these ages could be spuriously old, possibly due to inheritance or issues related to assumptions concerning water content over time in the dated sediments. Until more age data become available for alluviums in the region, however, unit Qa_3 in the Greeley quadrangle should be considered equivalent to Broadway Alluvium, and unit Qa_4 in the Greeley quadrangle should be considered equivalent to Louviers Alluvium of Lindsay and others (2005) and Colton (1976).

As depicted in cross section D-D', unit Qa_3 underlies terrace surfaces in the South Platte River and Cache la Poudre River valleys and is overlain by unit Qa_2 deposited by both rivers. Thus, unit Qa_2 (equivalent to the Piney Creek Alluvium of Scott) is depicted as inset into unit Qa_3 (likely equivalent to the Broadway Alluvium). Madole (1991, Fig. 14 caption) states that in valleys headed in the glaciated part of the Front Range (such as is the Cache la Poudre River valley), Broadway Alluvium (unit Qa_3) underlies the valley floor and Louviers Alluvium (unit Qa_4) underlies terraces above the valley floor. This is in accord with the relative positions of these alluviums as presented in cross sections F-F' (spanning the Cache la Poudre River valley on the west side of Greeley) and G-G' (spanning the Cache la Poudre River valley on the east side of Greeley) of Lindsey and others (2005). As depicted in cross section D-D' of the present study, unit Qa_3 deposits in the Sand Creek paleovalley appear to be continuous with those in the Cache la Poudre River valley. The Cache la Poudre valley Qa_3 deposits appear to be continuous with those of the South Platte River valley.

The Sand Creek paleovalley formerly was a major tributary to the Cache la Poudre River, as indicated by the paleovalley width and the thickness of valley-fill deposits; the paleovalleys of Graham Seep and Eaton Wash were smaller tributary valleys. Tracing the Sand Creek paleovalley from the Cache la Poudre valley north to Stage, Colorado (15 km north of the Greeley quadrangle northern boundary), the valley width increases from 1.3 km to 4 km and bedrock depth (and corresponding thickness of unit Qa_3) decreases from ~30 m to ~9 m. Cross sections B-B' and C-C' indicate that unit Qa_3 extends east and west (beneath a cover of unit Qe) for considerable distances outside the present topographic valleys of Graham Seep and Sand Creek. Water-well logs indicate that most of unit Qa_3 sediments in the north half of the quadrangle are sandy gravels and gravelly sands (channel deposits), but that there is a significant component of clay and sandy clay layers (overbank deposits). It is possible that the courses of Graham Seep and Sand Creek migrated laterally during Late Pleistocene time, depositing interbedded channel and overbank deposits over a wide area in the north part of the quadrangle.

In Late Pleistocene time, following the deposition of unit Qa_4 (equivalent to Louviers Alluvium) during the period approximately 170 to 120 ka, an episode of stream incision removed most of unit Qa_4 from the river valleys of the Cache la Poudre and South Platte Rivers. The incision was followed by an aggradational period during which unit Qa_3 accumulated. In both valleys there was a later, second inferred episode of Late Pleistocene stream incision, possibly extending into Early Holocene time. This episode removed some of the uppermost part of the unit Qa_3 valley fill but left some deposits of unit Qa_3 beneath the surfaces of cut-in-fill terraces. The second episode of incision apparently did not occur in the three tributary paleovalleys of the Cache la Poudre River. During this episode the south ends of the paleovalleys were truncated by the Cache la Poudre River. This relationship was observed in the field and on lidar imagery. In the upstream portions of the tributary valleys, unit Qa_3 deposits were not eroded by the second episode of incision and thus no unit Qa_3 terrace surfaces were formed in these valleys.

Eolian sediment of unit Qe was deposited over most of the quadrangle during Early to Middle Holocene time, the age being based upon the radiocarbon age of ~9,260 yr for unit Qe in the Greeley quadrangle (Table 2), and radiocarbon ages for unit Qel in the Frederick quadrangle (~4,420 yr and ~4,950 yr) (Keller and others, 2018) and Gowanda quadrangle (~4,770 yr; Keller and others, 2020). This sediment overlies unit Qa_3 in the tributary valleys north of the Cache la Poudre River, but does not overlie unit Qa_3 terraces in the valleys of either the Cache la Poudre River or South Platte River. Ages in Table 2 also indicate that unit Qe postdates unit Qa_3. The aggradational deposits of unit Qa_3 in both river valleys could have been one of the sources for unit Qe. The age of ~9,260 yr for unit Qe in the Greeley quadrangle is close to the date of ~9,100 ka for unit Qe in the Johnstown quadrangle ~20 km to the southwest (Palkovic and Morgan, 2017). Both dates fall within an early Holocene episode of loess deposition that spans ca. 11 to 9 ka (Muhs and others 1999). Unit Qe in the Greeley quadrangle lacks sufficient silt content to be termed loess, but its fines content (silt and clay) ranges between 21 and 50 percent, significantly greater than the 4 to 9% fines content reported for the eolian sand of unit Qes (Madole and others, 2005). Unit Qe may have been deposited during an early episode of Holocene loess deposition, with proximity to alluvial valley sources lending it a greater sand content than that of coeval loess deposits in the region.

From Late Pleistocene to Late Holocene time, eolian sand of unit Qes was deposited over much of the northeastern plains of Colorado and nearly as far west as Boulder. The Late Pleistocene eolian sand deposits were more extensive than those of the Middle Holocene and Late Holocene (Madole and others, 2005). It is not known how much of the Greeley quadrangle was covered by eolian sand, but coverage was probably more extensive than the present upland areas of unit Qes in the City of Greeley and in the area between Sand Creek and Lone Creek. Unit Qes in these areas presumably overlies older eolian sediments of unit Qe. Eolian sand of unit Qes originated mainly from sediment in stream channels and flood plains. In northeastern and east-central Colorado the sediment was transported by northwest prevailing winds (Madole and others, 2005). In the Greeley quadrangle, the Cache la Poudre River valley and the valleys of its tributaries may have contributed some sediment to eolian sand deposits. Aleinikoff and Muhs (2010) demonstrated that the Laramie Formation north of the City of Greeley was the major source for eolian sand in the Greeley dune field to the east of the city. It is possible that the Laramie Formation also contributed sediment to unit Qes sediment in the Greeley quadrangle. The radiocarbon age of unit Qes in the City of Greeley is 850 yr ky (Table 2) and is in accord with Madole's Late Holocene age for eolian sand (0 to 4 ky). Other recently reported dates for unit Qes in the nearby Colorado Piedmont quadrangles are ~2.7 ky and ~7.5 ky in the Frederick quadrangle (Keller and others, 2017) and ~2.8 ky in the Gowanda quadrangle (Keller and Morgan, 2020). The locations for these dated samples are ~30 km southwest of Greeley.

The second inferred Late Pleistocene and Early Holocene (?) incision of the Cache la Poudre River and South Platte River valleys, during which unit Qa_3 was incised, probably occurred before Late Holocene time. This is indicated by the radiocarbon age of the base of unit Qa_2 (~3.2 ky) in the Greeley quadrangle (Table 2). After this episode of incision, unit Qa_2 was deposited during the Late Holocene as aggradational terrace-fill deposits in both the main river valleys. The tributary paleovalleys to the Cache la Poudre River were not affected by the second period of incision and apparently do not contain deposits of unit Qa_2. The latest (third) inferred episode of incision in the river valleys, during latest Holocene time, eroded unit Qa_2 sediments in both river valleys and created cut-in-fill terrace deposits of unit Qa_2 in the South Platte River valley. This latest episode of incision by the rivers was followed by the deposition of unit Qa_1.

MINERAL RESOURCES, GROUNDWATER RESOURCES, AND GEOLOGIC HAZARDS

In the Greeley quadrangle there are many aggregate (sand and gravel) pits in the Cache la Poudre River valley. These pits, both active and inactive, are located from the quadrangle's western boundary eastward to where the Cache la Poudre River valley converges with that of the South Platte River. Within the quadrangle, the South Platte River valley contains several water-filled inactive pits, but no active aggregate operations were observed. Records of the Colorado Division of Reclamation, Mining, and Safety (DRMS) indicated 13 active mining permits in the Cache la Poudre River valley and none in the South Platte River valley. As of early 2020 there were no active mining permits elsewhere in the quadrangle. All of the aggregate pits are in alluvium three (unit Qa_3), which underlies alluvium two (unit Qa_2) in the floor of the Cache la Poudre River valley. Aggregate operations were observed at five locations and the authors were allowed access to three active pits (see geologic map for locations and names). All three pits were excavated to the base of unit Qa_3 at its contact with the underlying Laramie Formation. Schwochow mapped terrace gravel (unit Qa_3 of this report) along the Cache la Poudre River at Greeley, and reported 6 to 10 m of clean pebbly to cobbly gravel and high-quality coarse sand as well as a significant amount of fines in the terrace deposits (Schwochow and others, 1974). For the years 2016, 2017, and 2018 the annual aggregate production in Weld County was ~14.4 million, ~15.0 million, and ~12.7 million metric tons, respectively (Weld County Assessor's Office, oral commun., 2018, 2020).

The Greeley quadrangle lies in the northern part of the Wattenberg gas field, an active and prolific oil and gas producing area located mostly in Weld and Adams counties. Oil and gas infrastructure is present throughout the quadrangle. As of 2013, the Wattenberg field was the fourth most productive oil field and ninth most productive natural gas field in the U.S. (U.S. Energy Information Administration, 2015). As of summer 2019 the Greeley quadrangle was still a very active area for oil and gas production. Production is dominantly from the Niobrara Formation, but also from the Middle Member of the Pierre Shale, the Colorado Group, and the Dakota Group (Colorado Oil and Gas Conservation Commission), 2020).

The greater part of the historic Eaton coal mining area occupies several km^2 in the northwest corner of the Greeley quadrangle, and extends westward into the Bracewell quadrangle and northward into the Eaton quadrangle. The Eaton coal area was mined from 1935 to 1942, with production coming from beds between 1 and 1.5 m thick in the lower coal zone of the Laramie Formation, which is the lower 60 to 90 m of the formation (Roberts, 2005). It is one of only three historic coal mining areas in the southern part of the Cheyenne Basin, which lies north of the Greeley Arch. Because the coal seams north of the arch are thin and discontinuous, there were only 11 mines in these three coal mining areas. The Boulder-Weld coal field, adjacent to and south of the arch, had more than 160 historic mines which operated in seams that are thicker and more continuous than those north of the arch (Roberts, 2005). This latter field was active from 1859 to 1979 and does not extend into the Greeley quadrangle. Surface subsidence caused by underground coal mining in the Laramie Formation is a well-documented geologic hazard in the north part of the Denver Basin (Myers and others, 1975). The three mines of the historic Eaton coal area, however, are located within ~2 km of east and north of the community of Eaton, which is ~3 km north of the Greeley quadrangle northern boundary (Turney and Murray-Williams, 1983). Therefore, surface subsidence due to coal mining is not a potential hazard within the Greeley quadrangle.

Alluvium three (unit Qa_3) is an important aquifer in the Greeley quadrangle. This is evidenced by the water-well logs used to assemble cross sections B-B', C-C', and D-D'. These wells mostly penetrate the gravelly sands and sandy gravels of unit Qa_3 and extend only for short depths into the underlying and less permeable Laramie Formation. Along the three tributaries to the Cache la Poudre River, unit Qa_3 in paleovalleys is overlain by the less permeable eolian sediments of unit Qe. The water wells in the above cross sections produce water from depths ranging roughly between 6 and 33 m, with the Sand Creek valley having several of the deepest wells (cross section D-D'). Within the Greeley quadrangle, the Colorado Division of Water Resources (DWR) Well Permit Research Viewer (Colorado DWR, 2020, interactive web-based map) shows that the valleys of the Cache la Poudre River and South Platte River have the greatest concentration of water wells. Graham Seep and Sand Creek, with their deep bedrock valleys filled with permeable sediments of unit Qa_3, have greater concentrations of water wells than the adjacent uplands. The basal portion of the Laramie Formation contains two relatively thick sandstone units; these sandstone units and the underlying Fox Hills Sandstone constitute the Laramie-Fox Hills aquifer. This aquifer underlies much of the Denver Basin and presumably extends north on to the Greeley Arch, including the area of the Greeley quadrangle. The aquifer is as much as 107 m thick although its water-yielding thickness is seldom greater than 61 m. It is generally under artesian conditions (Topper and others, 2003) and underlies the surficial deposits in the Greeley quadrangle, but appears to be of less local importance than the shallow aquifer of unit Qa_3.

During the catastrophic September 2013 flood events along the Colorado Front Range, flood waters of the Cache la Poudre River and South Platte River covered much of the area mapped as alluvium one (unit Qa_1), alluvium two (unit Qa_2), and alluvium three (unit Qa_3) in the Greeley quadrangle. This area included parts of the City of Greeley. In the flood-affected areas of the Colorado Piedmont there was some loss of life, large-scale damage to property and infrastructure, and some adverse environmental effects. In 2016 the Federal Emergency Management Agency designated nearly all of the floodplains of the Cache la Poudre River and South Platte River lying within the Greeley quadrangle, as well as parts of the valleys of Graham Seep and Sand Creek, as various categories of high-risk flood areas. These areas are characterized by a 1% annual chance of flooding (terminology is equivalent to the 100-year flood) and a 26% chance of flooding over the life of a 30-year mortgage (Weld County, 2020). Some higher-elevation areas of unit Qa_3 terraces were classified as low-risk (500-year flood).

Eolian sediment (unit Qe) and eolian sand (unit Qes) locally may be susceptible to minor collapse when under load, owing to hydrocompaction. Soil engineers refer to these deposits as collapsible soils. The fine-grained particles (silt and especially clay) in the eolian sand and silt-rich loess give these deposits relatively high compressive strength and shear strength under dry conditions. However, when wet or saturated and under load, 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). Within the City of Greeley, the Laramie Formation bedrock (overlain by Quaternary deposits) is mapped as having high swell potential in the area from Greeley Lake Reservoir east to Garden City and from the Cache la Poudre River valley south to Evans. The area of unit Qe in the northeast corner of the quadrangle is mapped as having moderate swell potential (Hart, 1974). Ten geotechnical reports for unit Qe and three reports for either unit Qa_2 or unit Qa_3, mostly in and close to the City of Greeley, describe the subsoils as having no swell potential or very slight to low swell potential (Colorado Geological Survey, 2019; Northern Colorado Geotech, 2018; Terracon Consultants, Inc., 2018).

During June 2014 in the Greeley quadrangle, there was an apparent wastewater-injection induced earthquake of moment-magnitude intensity (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 and 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 rocks. 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, and the University of Colorado, with support from other agencies, 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. Seismicity associated with the well decreased significantly.

GEOLOGIC MAP OF THE GREELEY QUADRANGLE, WELD COUNTY, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE, GEOLOGIC HISTORY, AND CROSS SECTIONS

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COLORADO GEOLOGICAL SURVEY
COLORADO SCHOOL OF MINES