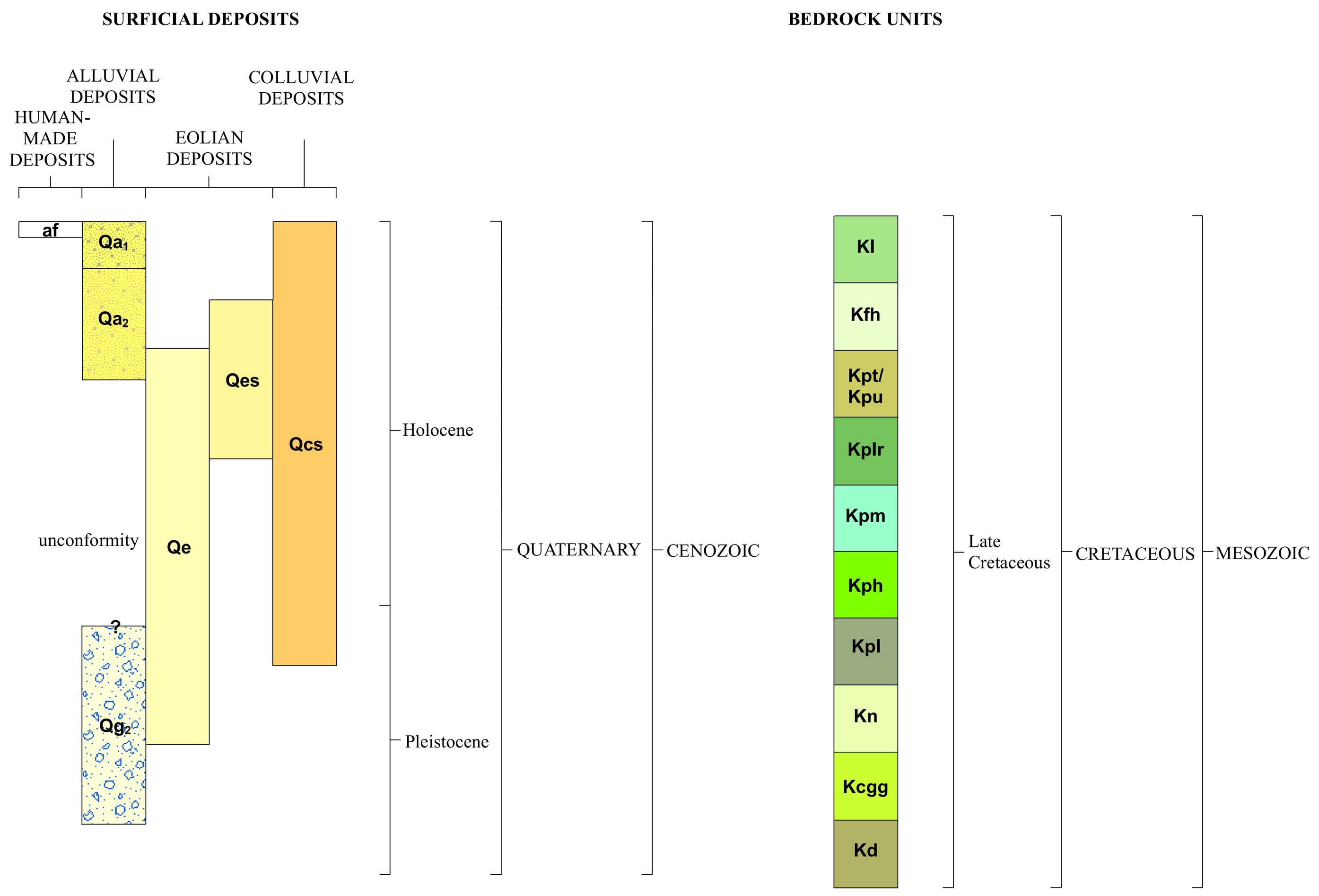
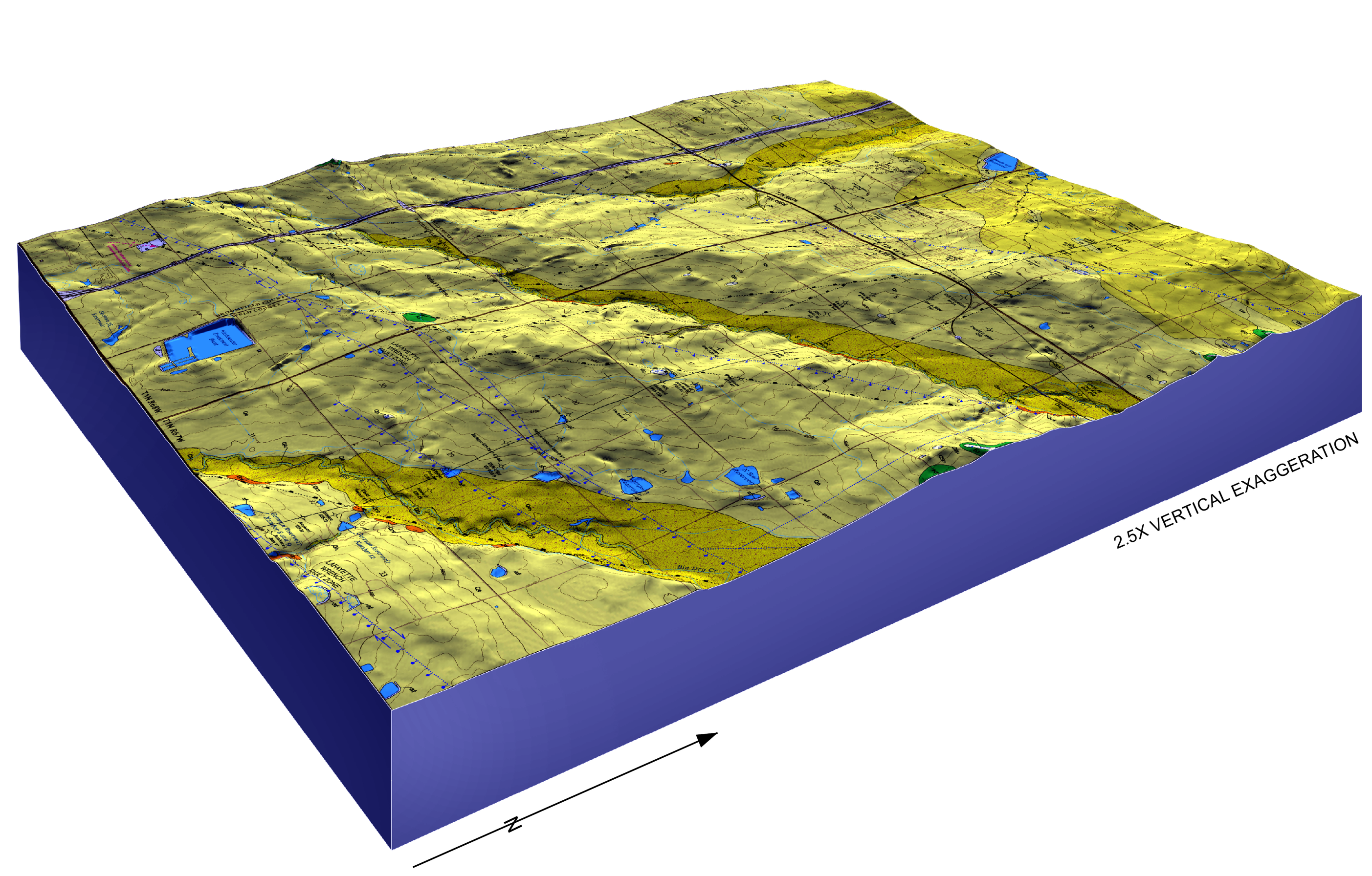
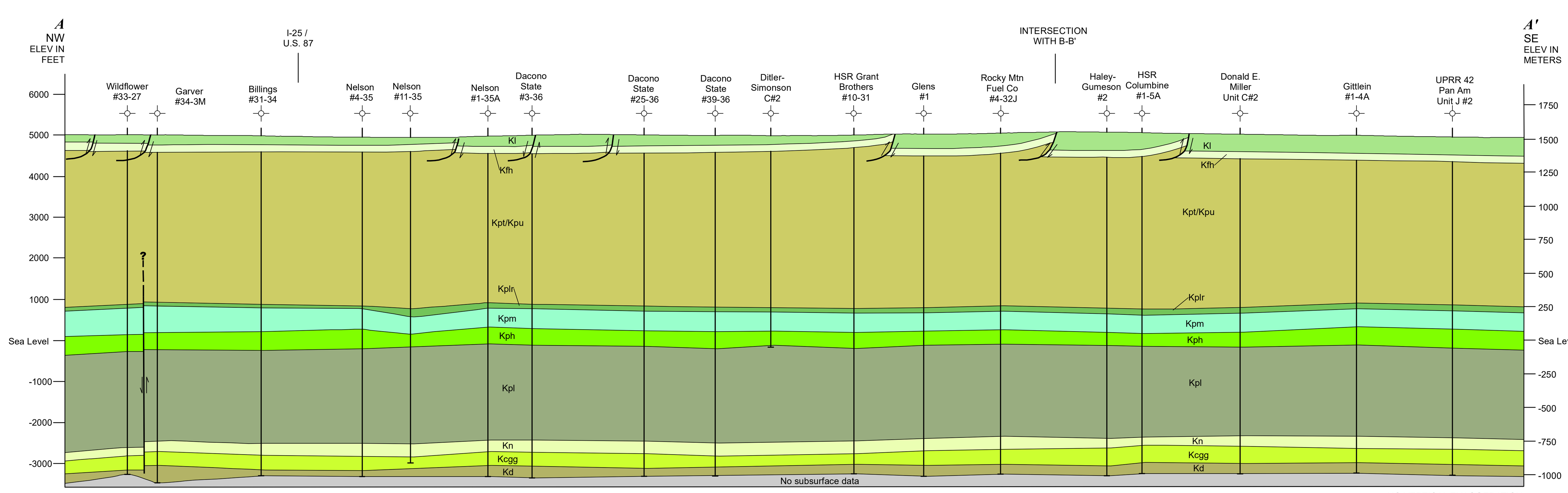
CORRELATION OF MAP UNITS



3-D OBLIQUE VIEW

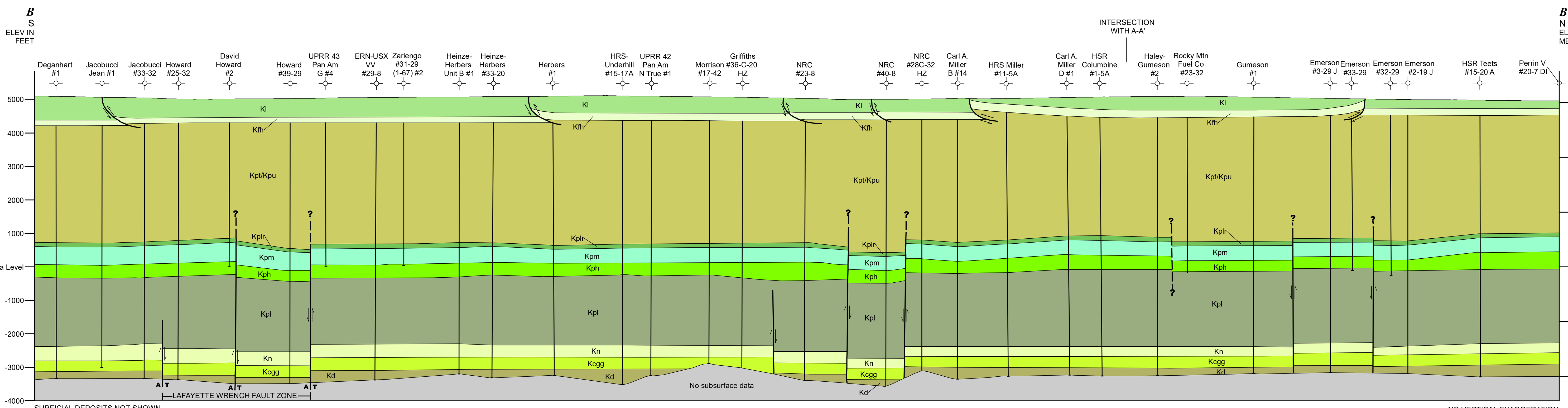


CROSS SECTION A-A'



In cross section A-A' the attitudes and thicknesses of the Kl and Kfh are taken from cross section D-D' in Plate 1 of U.S. Geological Survey Bulletin 1619 (Spencer, 1986). A-A' and D-D' are along the same line of section. Per Kittleson (1992, 2009), Spencer's high-angle reverse faults are instead portrayed as footwall ramps of a decollement zone and his high-angle normal faults are not shown. Geology below the Kfh is based upon oil and gas well data from the Colorado Oil and Gas Commission Interactive Map.

CROSS SECTION B-B'



In cross section B-B' the attitudes and thicknesses of the Kl and Kfh are taken from the intersections of B-B' with cross sections D-D', E-E', and F-F' in Plate 1 of U.S. Geological Survey Bulletin 1619 (Spencer, 1986). The surface positions of Spencer's high-angle reverse faults are taken from the geologic map in his Plate 1. Per Kittleson (1992, 2009), Spencer's high-angle reverse faults are instead portrayed as footwall ramps of a decollement zone and his high-angle normal faults are not shown. On both sides of the footwall ramp faults, elevations for the top of the Kfh are derived from Spencer's structure contour map of coal bed No. 3 (geologic map in Spencer's Plate 1). Geology below the Kfh is based upon oil and gas well data from the Colorado Oil and Gas Conservation Commission Interactive Map.

GEOLOGIC MAP OF THE FREDERICK QUADRANGLE, WELD AND BROOMFIELD COUNTIES, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE VIEW, GEOLOGIC HISTORY, AND CROSS SECTIONS

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GEOLOGIC HISTORY AND STRUCTURE

The Frederick quadrangle lies in the northern part of the Colorado Piedmont, near the axis of the Denver Basin and approximately midway along its length. Like much of the piedmont, the quadrangle has low relief (330 ft, 101 m). Quaternary deposits cover almost all its area and bedrock is exposed in only a few places. The Laramie Formation is the uppermost and youngest bedrock unit and underlies much of the Quaternary cover. It is a coal-bearing unit that was deposited in a low coastal-plain environment, on the west margin of the Cretaceous Interior Seaway during the Late Cretaceous (100-66 Mya). Oil and gas wells in the Berthoud quadrangle have penetrated underlying Cretaceous formations down to the Dakota Group (cross sections A-A' and B-B'), but none of these formations are exposed in the quadrangle.

The present-day topography of the piedmont region results from evolution of the South Platte River and Arkansas River drainage basins during Quaternary time, beginning with removal of Paleogene and Neogene rocks that once covered the Upper Cretaceous strata (Madole, 1991). The dominant Quaternary deposits of the Colorado Piedmont in the Frederick quadrangle and surroundings are fluvial sediments of the South Platte River and its tributaries, and eolian sediments derived from these stream valleys and from bedrock exposures along the Piedmont (Madole, 1991, 2016). Northeast-flowing Little Dry Creek and Big Dry Creek drain most of the quadrangle and are tributaries to the South Platte River. In the northwest corner of the quadrangle there is an unnamed north-flowing tributary to St. Vrain Creek.

The Quaternary history of the Frederick quadrangle began with erosion of the Paleogene-Neogene landscape, likely during the early Pleistocene (2.58 to 0.781 Mya). This was followed by deposition of stream and alluvial fan gravels of unit Qg_2 during the middle (?) Pleistocene. Deposition probably occurred as alluvial fan distributary channels that were ancestral to the mainstem drainages. Later incision and lateral cutting of surrounding, finer-grained, less resistant alluvial deposits resulted in inversion of the topography, leaving isolated remnants of unit Qg_2. In support of the above sequence of events, the small Qg_2 occurrences along the east quadrangle boundary are mapped as Rocky Flats Alluvium by Soister (1965) where they extend eastward into the Fort Lupton quadrangle; they lie 100 to 120 ft (30 to 36 m) above stream level. Along the west side of the Fort Lupton quadrangle the Verdos Alluvium is mapped near to and ~20 ft (6 m) lower than occurrences of Rocky Flats Alluvium (Soister, 1965). The small Qg_2 occurrence along the west Frederick quadrangle boundary extends into the Erie quadrangle, where it is mapped as Verdos Alluvium by Colton and Anderson (1977). This and two nearby Verdos occurrences in the Erie quadrangle are 70 to 90 ft (21 to 27 m) above stream level. Lindsey and others (2005) recognize occurrences of dissected alluvial fans and terraces of middle and early Pleistocene age that extend as far east as 3 mi (5 km) east of Fort Lupton. These can include the Rocky Flats and Verdos Alluviums. These names and age assignments were based solely on soil profile development and height above stream level and are subject to change with new radiometric ages.

Muhs and others (1999) describe two periods of loess deposition in eastern Colorado: a late Pleistocene period spanning ca. 20,000 to 12,000 [14]C yr B.P., during the time of culmination and retreat of Pinedale glaciation in the Front Range; and an early Holocene episode spanning ca. 11,000 to 9,000 [14]C yr B.P. The latter period includes the loess at Beecher Island near Wray, Colorado. Eolian loess (unit Qe) covered most of the entire Frederick quadrangle and was deposited mainly on Laramie Formation bedrock. At some locations Qe became intermingled with eroded Qg_2. Three potential sources for Qe are: silt from retreating alpine glaciers in the Front Range to the west, volcaniclastic silt from the Oligocene White River Group to the north, and clay from the Pierre Shale exposed west of the quadrangle (Muhs and others, 1999). Paleowind directions probably were from the northwest, west, and southwest (Muhs and others, 1999). Frederick quadrangle Qe radiocarbon ages are 4,420 and 4,950 [14]C yr B.P. (Table 1), younger than the loess at Beecher Island (9,250 to 11,090 [14]C yr B.P.) (Muhs and others, 1999), but are within the age range for the Bignell Loess at Bignell Hill, Nebraska (1,400 to 10,070 [14]C yr B.P.). Colorado and Nebraska loess deposits are similar in composition, and to some extent the two may share sediment sources (Muhs and others, 1999). Both ages for Frederick Qe are younger than the age of the loess at Beecher Island. The 4,950-yr age in the Frederick quadrangle is from Qe at the bedrock contact, whereas the bracketing ages at Beecher Island are from soils above and below the loess. If the Frederick quadrangle Qe ages are valid, then the second depositional episode of Muhs and others (1999) would extend into the middle Holocene. Given that only two Qe radiocarbon samples (both yielding middle Holocene dates) were analyzed in the Frederick quadrangle, it is probable that late Pleistocene loess also is present.

From late Pleistocene to late Holocene time, eolian sand (Qes of the present report) was deposited over much of the eastern plains of Colorado, although late Pleistocene deposits are more extensive (Madole, 2005). Qes covers much of the north quarter of the Frederick quadrangle and consists of fine to medium sand. (Note that the geologic map in the present report uses a dense array of data points and shows Qes as somewhat less extensive than in Madole's smaller-scale map.) Eolian sand originated mainly from stream channels and flood plains, and in northeastern and east-central Colorado the sediment was transported by northwest prevailing winds (Madole, 2005). Frederick quadrangle Qes may have originated from the St. Vrain Creek flood plain to the northwest. A large body of eolian sand is mapped by Madole (2005) southeast of St. Vrain Creek and north of Colorado Hwy. 52, with no corresponding sand body in the area northwest of the creek. Aleinikoff and Muhs (2010), however, demonstrated that the Laramie Formation was the major source for eolian sand in the Greeley dune field to the east. It is therefore possible that the Laramie Formation also could have contributed to Qes sediment in the Frederick quadrangle. Most Qes in the quadrangle was deposited upon Qe, and a Qes sample yielded an age of ~2,700 [14]C yr B.P., corresponding to Madole's late Holocene age group for eolian sand (4-0 ka). In a small area 1 mi (1.6 km) east of Firestone, Qes of age ~7,500 [14]C yr B.P., corresponding to Madole's middle Holocene age group for eolian sand (8-4 ka), was deposited directly upon Laramie Formation bedrock.

Holocene alluvium covers the flood plains of many streams in the Colorado Piedmont, as it does in the Frederick quadrangle, but this sediment probably is underlain by thicker sections of Pleistocene alluvium (Madole, 1991). Accordingly, the streams underwent cycles of incision and aggradation beginning in Pleistocene time. The most recent aggradation in the flood plains of the mainstem drainages occurred during the late Holocene, depositing Qa_2 in wide valley floors. Incision and some aggradation followed, cutting into the Qa_2 valley floors and depositing Qa_1 in lower and narrower stream courses. From late (?) Pleistocene through Holocene time Qcs was deposited by mass wasting, mostly along the south slopes of Little Dry Creek and Big Dry Creek.

In most of the Frederick quadrangle the Quaternary sediments are underlain by Laramie Formation, but some areas are underlain by Fox Hills Sandstone. Strike of Laramie Formation strata in the Frederick quadrangle is approximately N35E and approximately aligns with the southwest-northeast axial trend of the Denver Basin. Dip of the Laramie Formation and Fox Hills Sandstone within the quadrangle is to the southeast at ~50 ft/mi (9 m/km) or ~0.5°, but is greater near faults and folds (Spencer, 1986). Based upon coal boreholes, coal mine records, and oil and gas wells, Spencer (1986) mapped many high-angle faults in the Laramie Formation, Fox Hills Sandstone, and upper portion of the Pierre Shale in the Frederick quadrangle. Most fault traces are approximately northeast and subparallel to the basin axis, but because of Quaternary cover, the faults are not visible at the ground surface. These faults are within the Boulder-Weld fault zone, which extends from Marshall northeast for ~20 mi (~32 km) to the Boulder-Weld coal field (Frederick quadrangle). In the southwest the fault zone width is ~2 mi (~3 km) and in the northeast the fault zone width is ~5 mi (~8 km). Cross section A-A' is on the same line of section as cross section D-D' of Spencer (1986). In the portion of A-A' between ground surface and elevation 4,000 ft (1,220 m) (the downward extent of D-D'), the overall dip and the thicknesses for the Laramie Formation and Fox Hills Sandstone are taken directly from D-D', although the interpretation of fault style is different. Spencer's (1986) four cross sections in the Frederick quadrangle indicate a few gentle flexures, but his map shows no fold structures. During the present mapping effort a northeast-trending, gently plunging anticline was found in a large excavation ~1 mi (~1.5 km) north-northeast of I-25 and Weld County Rd. 7. Weimer (1996) maps the Denver Basin axis as trending through the north part of the Frederick quadrangle, but within the quadrangle several cross sections of Spencer (1986) (including the upper portion of section A-A' in the present report) show the Laramie Formation and Fox Hills Sandstone to have a very gentle southeast dip, indicating that the quadrangle is on the west flank of the basin. The lower portion of A-A' (from Larimer and Rocky Ridge members of the Pierre Shale down through Dakota Group) does not indicate a pronounced dip either to the southeast or northwest.

The Lafayette wrench fault zone (WFZ) trends east-northeast (as two faults) across the south quarter of the Frederick quadrangle, and the subparallel Longmont WFZ passes within 1 mi (1.6 km) northwest of the quadrangle's northwest corner. Right-lateral oblique movement along these zones occurred during Cretaceous time and was intermittent from 110 to 65 Mya (Weimer, 1996), an interval that includes the beginning of the Laramide orogeny. Within the Frederick quadrangle, Weimer's map and south-north cross section show several vertical, east-to-northeast-trending, normal faults associated with Lafayette and Longmont WFZ movement. In the present report these faults appear on the geologic map, and also are approximately confirmed by normal faults shown on cross section B-B', which follows Weimer's line of section. Weimer (1996) shows displacements of up to ~100 ft (~30 m) in the Niobrara Formation up through the Hygiene Sandstone, decreasing upward to as little as 20 ft (6 m) in the Middle Shale member of the Pierre Shale (the interval above the Middle Shale member of the Pierre Shale is not presented). Weimer shows smaller normal faults flowering upward from the vertical faults, but these are not evident on the cross sections of the present report. Cross section B-B' shows displacements of the Niobrara Formation ranging from 80 to 280 ft (24 to 85 m), and the positions of these faults correspond approximately to the Lafayette WFZ and other faults on Weimer's (1996) map. Cross section A-A' shows only one, small-displacement, normal fault, which does not correspond to any of Weimer's fault locations.

Sonnenberg and Underwood (2013) studied 3D seismic data from an area ~50 mi (~80 km) east-northeast of the Frederick quadrangle, in Morgan County. The seismic sections indicate layer-bounded systems of minor normal, (apparently) randomly oriented faults in the Niobrara Formation and lower Pierre Shale. The faults dip at less than 45°, have vertical displacements of 20 to 90 ft (6 to 27 m) and horizontal lengths of generally less than 4,000 ft (1,210 m), and form polygonal networks in map view. They are interpreted to be the result of volume loss in the Niobrara Formation and lower Pierre Shale as formation fluid was expelled by compaction. In the seismic sections of Sonnenberg and Underwood (2013) these polygonal fault systems resemble the minor, flowering-upward Niobrara Formation faults shown in Weimer's (1996) cross section.

In the Frederick and Erie quadrangles (the latter adjacent to the west of the former), Spencer's (1986) structural interpretation for the Boulder-Weld fault zone is a system of en echelon normal and reverse faults. These are interpreted to form horst and graben structures extending from the upper Pierre Shale up through the Fox Hills Sandstone and Laramie Formation. Spencer explains that this faulting was driven by Laramide upwarping of sedimentary units along the Front Range and also by movements along a Precambrian shear zone. Because the upper part of the Cretaceous section was under less overburden pressure, it is believed to be preferentially faulted rather than folded. Spencer's interpretation is that in the lower Cretaceous section the greater overburden pressure caused stress to be taken up by folding and flowage, and faulting did not extend down into the Hygiene Sandstone.

Kittleson (1992, 2009) studied the entire Boulder-Weld fault zone from Marshall northeast to the Frederick quadrangle, and correlated ~1,450 geophysical logs from oil and gas wells. He interprets the faults to constitute a zone of footwall ramps at the southeast end of a large, gravity-driven decollement zone extending from ~6 mi (~10 km) east of Longmont southwest to Rocky Flats. Detachment of the zone was caused by movement along the Longmont WFZ of Weimer (1996). One lobe of the decollement is mapped as terminating in the center of the Frederick quadrangle. Kittleson interprets Spencer's (1986) reverse faults as footwall ramps of the decollement and as being concave-upward rather than planar. The ramps curve upward and southeastward from a detachment surface located in the upper Pierre Shale and ~200 ft (~60 m) below the base of the Fox Hills Sandstone. Kittleson (2009) does not recognize any normal faulting in the Laramie Formation and Fox Hills Sandstone, and instead proposes the upward bending of strata on the northwest sides of footwall ramps to account for what Spencer (1986) posited as the northwest sides of horst blocks. Kittleson supports his interpretation with the observation that repeated section due to reverse faulting was recognized in 39 geophysical logs, but that missing section due to normal faulting was not observed.

The authors of the present report favor the interpretation of Kittleson (1992, 2009). On the geologic map the traces of Spencer's (1986) reverse faults are included, but not those of his normal faults, and on cross section A-A' Spencer's reverse faults are depicted as footwall ramps. On the west side of cross section A-A' the fault displacements in the Laramie Formation and Fox Hills Sandstone are between 20 and 80 ft (6 and 24 m), whereas on the east side the displacements are between 300 and 350 ft (91 and 106 m).

MINERAL RESOURCES, GROUNDWATER, AND GEOLOGIC HAZARDS

The Frederick quadrangle includes a portion of the Boulder-Weld coal field. Coal mining was economically important in the quadrangle from the late 1800s to 1975, and Spencer (1986) has tabulated production from 20 mines in the quadrangle. Seventeen of these were located in a fault-bounded swath ~2 mi (~3 km) wide, trending from north-northeast to south-southwest from Firestone to the intersection of I-25 and Weld County Rd. 8. Several other mines were in the area northwest of I-25 and Colorado Hwy. 52, and one was along Hwy. 52 and ~1.5 mi west of the east quadrangle boundary. Fifteen of the mines were in coal bed No. 3, whose base is approximately 200 to 400 ft (61 to 122 m) below ground surface in the mined areas.

The Gowanda quadrangle lies in the western part of the Wattenberg Field, an active and prolific oil and gas producing area located mostly in Weld and Adams counties. Oil and gas infrastructure is found throughout the quadrangle. Some estimates of the field's potential are as high as 1 to 2 billion barrels of oil equivalent, composed of 70% oil and 30% natural gas (Rocky Mountain Energy Forum, 2018). Production is dominantly from the Niobrara Formation, but also from the Middle Shale Member and Hygiene Sandstone Member of the Pierre Shale, the Colorado Group, and the Dakota Group (COGCC, 2018).

The basal portion of the Laramie Formation contains two relatively thick sandstone units; these and the underlying Fox Hills Sandstone constitute the Laramie-Fox Hills aquifer. The aquifer underlies all of the Denver Basin and can be up to 350 ft (107 m) thick, although its water-yielding thickness is seldom greater than 200 ft (61 m). The aquifer underlies the surficial deposits throughout the quadrangle, is generally under artesian conditions, and is extensively used (Topper et al., 2003).

Surface subsidence caused by coal mining in the Laramie Formation is a well-documented geologic hazard in the Boulder-Weld coal field. According to a coal mine subsidence and land use report prepared for the Colorado Geological Survey (CGS) (Amuedo and Ivey, 1975), the maximum possible subsidence is from 5 to 10 ft (1.5 to 3 m), the height range of underground mine workings, and subsidence greater than 15 ft (4.6 m) is due to multiple-level mining. It is estimated that 90% of subsidence which could be observed (as of 1975, when mining in the Frederick quadrangle ceased) was identified, and that no well-defined, observable subsidence had occurred in areas where overburden is greater than 150 ft. The report presents a map (Plate 6) of the coal field with areas ranked as having severe, moderate, or low subsidence hazard. The 11 areas of severe hazard in the Frederick quadrangle are irregular in shape, as large as ~2 mi^2 (~5 km^2) and occur in the mined areas described above. For the present report the severe-hazard areas were compared to Google Earth imagery of 2015, which does not include the more recent spate of homebuilding (as of 2017) in the quadrangle. Many of the recent home developments in the 2015 imagery are outside the severe hazard areas, most of which remain as farmland. A subsequent map of the Boulder-Weld coal field by the U.S. Geological Survey (Roberts and others, 2001) includes the Frederick quadrangle and contains the following: extent of mining; the mine shafts, adits, and air shafts; bedrock faults; and overburden thickness for the abandoned coal mines. The map does not include a subsidence hazard ranking. Recent Lidar imagery reveals two large areas (~ 0.4 and 0.75 mi^2, ~1 to 2 km^2) where surface subsidence above coal mines has created a pattern of low-relief, alternating, parallel troughs and berms, indicating a room and pillar mine layout. The locations are northwest of I-25 and Colorado Hwy. 52 and northwest of I-25 and Weld County Rd. 10, and both correspond to mine locations mapped in Spencer (1986).

During the September 2013 flooding events, flood water of Little Dry Creek and Big Dry Creek inundated much of the area mapped as Qa_1 and Qa_2 along those drainages, causing damage to property, infrastructure, and crops (D. Johnston, pers. commun., 2018). The Federal Emergency Management Agency 100-yr flood area, updated in 2016 for Weld County, is coincident with much of the Qa_1 and Qa_2 area along Little Dry Creek, Big Dry Creek, and the unnamed tributary to St. Vrain Creek (Weld County web site Property Portal, 2018).

Units Qes and Qe locally may be, in geotechnical terms, collapsible (hydrocompactive) soils. The finer-sized particles (silt and clay content) in collapsible soils are soil-binding agents giving the soil greater compressive strength under dry conditions. Upon wetting, however, the fines can be packed into a denser configuration such that void space in the soil is reduced. This compaction can cause settlement at the ground surface with resultant damage to structures (White et al., 2008).

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