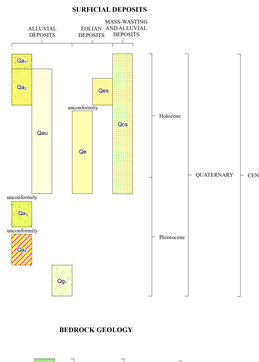
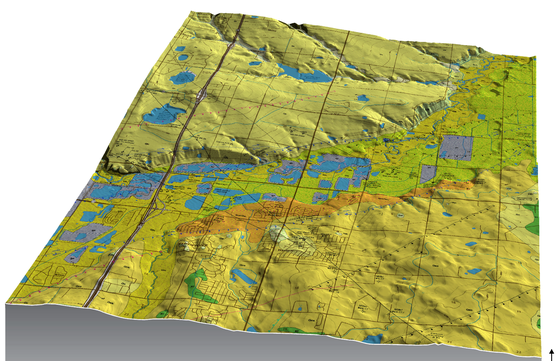
COLORADO GEOLOGICAL SURVEY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

CORRELATION OF MAP UNITS



3-D OBLIQUE VIEW



GEOLOGIC HISTORY AND STRUCTURE

The Gowanda quadrangle lies in the northern part of the Colorado Piedmont. Like much of the piedmont the topography in the quadrangle has low relief (76 m elevation 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 in only a few places. The present-day topography of the Colorado Piedmont results from the downcutting and geomorphic evolution of the South Platte River and Arkansas River drainage basins mainly during Pliocene 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 of the piedmont, including the Gowanda quadrangle and surroundings, are fluvial sediments of the South Platte River and its tributaries, and eolian sediments derived from alluvium in these stream valleys and from upwind bedrock exposures in the piedmont (Madole, 1991, 2016). The Gowanda quadrangle is drained by St. Vrain Creek and its tributaries. St. Vrain Creek is a tributary of the South Platte River and flows northeast out of the mapped area to join the river at ~2.5 km north of the quadrangle's northeastern corner. The St. Vrain Creek valley is ~2 km wide and divides the quadrangle approximately in half. Near the southwestern corner of the quadrangle a small portion of the alluvial plain is within the Boulder Creek valley. The confluence of Boulder Creek and St. Vrain Creek lies south of Colorado Hwy. 119, ~0.8 km west of the western quadrangle boundary.

The Gowanda quadrangle is on the northwest flank of the Denver Basin, approximately halfway between the basin axis and the basin's western edge (Dechesne and others, 2011). The Laramie Formation (Kl) is the youngest bedrock unit in the quadrangle and underlies the Quaternary cover in most of the area southeast of the St. Vrain Creek valley. The Laramie Formation is a coal-bearing unit that was deposited in a low coastal-plain environment, on the western margin of the Western Interior Seaway during the Late Cretaceous (100 to 66 Mya). The Fox Hills Sandstone (Kfh) lies beneath the Laramie Formation and underlies the Quaternary cover along the northwest side of St. Vrain Creek, in the northeast part of the quadrangle. This unit was deposited in near-shore and beach environments as the seaway retreated to the east (Dechesne and others, 2011). The upper transition member of the Pierre Shale (Kpt) underlies the Fox Hills Sandstone and the Quaternary cover in the northwest and north-central parts of the quadrangle. This unit was deposited in deeper marine environments of the seaway. Oil and gas wells and drill holes in the Gowanda quadrangle have penetrated underlying Cretaceous formations down to the Dakota Group (cross section A-A'), but none of these formations are exposed in the quadrangle. The few bedrock outcrops in the quadrangle are insufficiently exposed to yield attitude measurements. The geologic maps of Colton (1976) and Dechesne and others (2011) indicate that the local strike is approximately N45E. On the basis of cross section A-A' (line of section is perpendicular to strike), the bedrock units dip very gently to the southeast (~5.3 m/km).

The Longmont wrench fault zone (WFZ) trends east-northeast (as two main oblique-slip faults) across the center of the Gowanda quadrangle, as mapped by Weimer (1996). The northern, main oblique-slip fault is near well HSR Weld #3–A2 and is supported by offset as shown on cross section A-A'; the southern, main oblique-slip fault is between wells Borgmann #L01-16J1 and Wandell #21–7 and is not supported by offset in the cross section. A subsidiary fault, near well Carma #21–35 and splaying from the northern main fault, also is not supported by offset in the cross section. Right-lateral oblique movement along these zones occurred during Cretaceous time and was intermittent from 110 to 65 Ma (Weimer, 1996), an interval that includes the beginning of the Laramide orogeny. Within the Gowanda quadrangle, Weimer's map (Weimer, 1996, Fig. 34) and his north-south cross section (Weimer, 1996, Fig. 35) show several vertical, east to northeast-trending normal faults associated with movement on the Longmont WFZ. Two of these faults, the ones near the ends of the line of section, are supported by the offsets shown in cross section A-A'. Two other faults are indicated on cross section A-A' but were not mapped in Weimer (1996) and are not shown on the Plate 1 geologic map. These occur between wells Weld #27-2 and Victoria U#1-12J1, and between wells Miller #24-17 and Miller #44-17J. Weimer's cross section shows displacements on normal faults of up to ~30 m, from the Niobrara Formation (Kn) upward through the Hygiene Sandstone Member of the Pierre Shale (Kph), with displacements decreasing upward to as little as 9 m in the Middle Shale Member of the Pierre Shale (Kpm). The interval above this unit is not presented). Cross section A-A' (west of Weimer's cross section) indicates displacements in the Niobrara Formation of 122 m and 61 m in the two faults that correspond to Weimer's faults; these are near the ends of the line of section. Weimer's cross section shows smaller normal faults extending upward at low angles from the vertical or nearly vertical faults, but these faults are not shown on cross section A-A'. Colton (1976) shows a fault passing through the location of well HSR Foster Ridge #1-27A, which may be the same fault shown in cross section A-A', ~335 m southeast of that location.

In the Frederick quadrangle (adjacent to the south), there are many high-angle, northeast-trending faults of the Boulder-Weld fault zone displacing the Laramie Formation, Fox Hills Sandstone, and Pierre Shale upper transition member (Spencer, 1986). These are interpreted by Spencer (1986) as a northeast-trending zone of en echelon normal and reverse faults, but reinterpreted by Kittleson (1992, 2009) as a zone of footwall ramps at the southeast end of a large, gravity-driven decollement zone extending from ~10 km east of Longmont southwest to Rocky Flats, about 3 km southwest of Superior, Colorado. The reinterpretation of this faulting is explained in more detail in Keller and Morgan (2018). Spencer (1986) shows only one fault that extends as far northeast as the Gowanda quadrangle. The fault extends only a short distance into the quadrangle and is a ramp fault upthrown to the northwest by ~15 m. It is possible that other faults of the Boulder-Weld fault zone are present in the southeast portion of the quadrangle, but stratigraphic tops for the shallower bedrock units are not included in the available oil and gas well data for the area (Colorado Oil and Gas Conservation Commission [COGCC], 2018). Colton (1976) shows three northeast-trending faults in the Gowanda quadrangle. One of these faults crosses the line of section of cross section A-A'; the fault is included in the section but is not supported by observed offset.

Sonnenberg and Underwood (2013) studied 3D seismic data within an area ~67 km east-northeast of the Gowanda quadrangle, in Morgan County. The seismic sections indicate layer-bounded systems of minor normal, (apparently) randomly oriented faults in the Niobrara Formation (Kn) and lower Pierre Shale (Kp). The faults dip at less than 45°, have vertical displacements of 6 to 27 m and horizontal lengths of generally less than 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 during compaction. In the seismic sections of Sonnenberg and Underwood (2013) these polygonal fault systems resemble the minor, positive flower structures in the Niobrara Formation, as shown in Weimer's (1996, Fig. 35) cross section.

During Pliocene time, major streams incised Paleogene and(or) Neogene formations and Upper Cretaceous sedimentary rocks of the Colorado Piedmont, and no Paleogene and(or) Neogene sediments remain in the Gowanda quadrangle. The Quaternary history of the Gowanda quadrangle begins with deposition of unit Qg2 during the Early or Middle Pleistocene; the unit could be equivalent to the younger part of the Slocum Alluvium (Berry and others, 2019). Later incision and lateral cutting of surrounding, fine-grained, less resistant alluvial deposits and Upper Cretaceous bedrock resulted in inversion of the topography, leaving isolated remnants of unit Qg2 on some hills. Lindsey and others (2005) recognized the presence of dissected terraces of Pleistocene age and terraces of Middle Pleistocene age that extend as much as 5 km east of Fort Lupton, ~9 km southeast of the Gowanda quadrangle.

Five Quaternary alluvial units are associated with St. Vrain Creek in the Gowanda quadrangle. From oldest to youngest they are units Qg2 (possibly equivalent to Slocum Alluvium), unit Qg1 (possibly equivalent to Louviers Alluvium) Qa_3, (equivalent to Broadway Alluvium, Pinedale age), Qa_2 (equivalent to Piney Creek Alluvium), and Qa_1 (post-Piney Creek) (see cross sections B-B' and C-C'). The isolated erosional remnants of unit Qg2 are located in the upland along the southeast side of the St. Vrain Creek valley, ~24 m above stream level. In the Gowanda quadrangle, unit Qg1 elevation is higher than other alluvial deposits along the creek, and unit Qg2 is thus interpreted as the oldest of the St. Vrain Creek deposits in the quadrangle (see Description of Map Units).

Each of units Qa_3, Qa_2, and Qa_1 constitutes a separate aggradational (or depositional) terrace. Aggradation events "record brief reversals of long-term tectonically induced downcutting because they raise active channels" (Bull, 1990). The three St. Vrain Creek terraces have resulted from changes in climate, during which the increased stream discharge and bed load caused the deposition of new alluvium. At some time after the deposition of each terrace, it was incised and subsequently filled with younger alluvium of a lower terrace. The terraces are recognizable in the field, on lidar imagery, and on the 7.5-minute topographic map. The unit Qa_3 terrace (covered with unit Qes) is the highest and is present only on the south side of the St. Vrain Creek valley about 9 to 18 m above the creek. Unit Qa_3 deposits mostly are not exposed (except in Varra Companies' Pit 115), because they are covered by eolian sand of unit Qes, but alluvium beneath unit Qes is indicated by water well lithologic logs. Several prominent meander cuts in the unit Qa_3 terrace are floored with unit Qa_3 deposits. The unit Qa_3 terrace is prominent along the southeast side of the St. Vrain Creek valley and is present to a limited extent on the northwest side. In the northeast corner of the quadrangle the terrace consists of a widespread upper surface and a lower surface of limited areal extent, the latter occupying several meander cuts in Qa_3 deposits. Based upon its ages and its position in the landscape relative to other alluvial units, unit Qa_3 was deposited after units Qa_2 and before unit Qa_1.

The most recent aggradation in the major drainages of the Colorado Piedmont occurred during the Late Holocene, depositing unit Qa1 (equivalent to Piney Creek Alluvium) in wide valley floors. Incision of the unit Qa_3 valley floors followed, and then deposition of unit Qa_2, along lower and narrower stream courses. In one of the meander cuts in the lower level of the unit Qa1 terrace, unit Qa_2 sand is overlain by a thin layer (0.2 m) of Qa_1 sediment, possibly representing a short-lived Qa_2 aggradation event at a slightly higher elevation (0.5 m) than the main unit Qa_2 terrace. A radiocarbon age for unit Qa_2 in its main terrace is 1,344-1,270 yr B.P., and the age of the higher unit Qa_2 in the lower level of the Qa_2 terrace is 1,336-1,256 14C yr B.P. (calibrated) (Table 2); the ages are nearly the same and both are Late Holocene.

Muhs and others (1999) describe two periods of loess deposition in eastern Colorado: a Late Pleistocene period spanning ca. 20,000 to 12,000 radiocarbon 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 radiocarbon yr B.P. The latter period includes the loess at Beecher Island near Wray, Colorado. Eolian sediment (unit Qe) mantles much of the Gowanda quadrangle northwest of the St. Vrain Creek valley, where it is underlain mostly by the Pierre Shale upper transition member (Kpt) and locally by the Fox Hills Sandstone (Kfh). Unit Qe is only locally exposed southeast of the valley because it is overlain by eolian sand of unit Qes throughout much of this area. This is indicated by geologic logs of water wells (Colorado Division of Water Resources [DWR], 2018). Southeast of the valley, eolian sediment is underlain mostly by Laramie Formation (Kl). Three potential sources for the loess of Muhs and others (1999), and presumably for eolian sediment of the present report, are: silt from floodplains of retreating alpine glaciers in the Front Range to the west; volcaniclastic silt from the Oligocene White River Group to the north; and silt and clay from the Pierre Shale exposed west of the quadrangle (Muhs and others, 1999). Prevailing directions probably were from the northwest, west, and southwest (Muhs and others, 1999). The single Gowanda quadrangle radiocarbon age for unit Qe is 5,590-5,465 yr B.P. (calibrated) (Table 2). This age is younger than the loess at Beecher Island (9,250 to 11,090 radiocarbon yr B.P.) (Muhs and others, 1999), but within the age range for the Bignell Loess at Bignell Hill, Nebraska (1,400 to 10,070 radiocarbon 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). Taken together, the radiocarbon ages for eolian sediment in the Gowanda, Frederick, and Johnstown quadrangles range from ~4,000 to ~9,000 yr B.P. (Keller and Morgan, 2018; Palkovic and Morgan, 2017), suggesting, neglecting possible contamination by younger carbon from animal activity and (or) plant growth, that the second depositional episode of Muhs and others (1999) extended into the Middle Holocene. Only one Qe radiocarbon sample (yielding a Middle Holocene date) was analyzed in the Gowanda quadrangle, and this age is from the top of the unit. It is possible that older, Late Pleistocene eolian sediment is present at greater depth. On the basis of Qe, Qes, and Qa_3 radiometric ages, and because in the Gowanda quadrangle unit Qes is observed to overlie unit Qe, deposition of unit Qe occurred after deposition of unit Qa_3 and before deposition of unit Qes.

From Late Pleistocene to Late Holocene time, eolian sand of unit Qes was deposited over much of the eastern plains of Colorado, with the Late Pleistocene sand deposits being more extensive (Madole and others, 2005). Unit Qes covers most of the Gowanda quadrangle southeast of the St. Vrain Creek valley. The extent of unit Qes in the present map generally agrees with the extent mapped by Madole and others (2005). Exceptions are an area mapped as unit Qa_1 instead of Madole and others (2005) Qes in the northeast part of the quadrangle, and an area mapped as unit Qa_2 instead of unit Qes in the southwest part. Eolian sand originated mainly from stream channels and floodplains. In northeastern and east-central Colorado the sediment was transported by northwest prevailing winds (Madole and others, 2005). Unit Qes in the Gowanda quadrangle may have been deflated from the St. Vrain Creek valley; neither Madole and others (2005) nor the present map show any unit Qes deposits northwest of the valley. Aleinikoff and Muhs (2010) demonstrated that the Laramie Formation (Kl) was the major source for eolian sand in the Greeley dune field to the east. It is possible that the Laramie Formation also could have contributed to unit Qes sediment in the Gowanda quadrangle. Most unit Qes in the quadrangle was deposited upon unit Qe (eolian sediment). Unit Qes directly above the Qes/Qe contact has an age of 2,867-2,760 yr B.P. (Table 2), in accord with the Madole and others (2005) Late Holocene subdivision within the eolian sand (4 to 0 ka). Unit Qe a few centimeters below the contact has an age of 5,590-5,465 yr B.P. (Table 2). The time gap of ~2,700 yr may have been a period when the unit Qe surface was eroding or stable, prior to deposition of unit Qes. Based upon Qe, Qes, and Qa_3 ages, and also upon unit Qes observed overlying unit Qe, deposition of unit Qes occurred after deposition of unit Qe and before deposition of unit Qa_3.

From Late(?) Pleistocene through Holocene time, colluvium and sheetwash of unit Qcs were deposited by mass wasting and overland flow, along the north side of the St. Vrain Creek valley in the northeast part of the quadrangle.

MINERAL RESOURCES, GROUNDWATER, AND GEOLOGIC HAZARDS

There are many aggregate (sand and gravel) pits in the St. Vrain Creek valley. They are located on flood plains and low terraces in the portion of the valley extending from the Gowanda quadrangle western boundary northeast to Colorado Hwy. 66 (see geologic map in Plate 1). Colorado Division of Reclamation, Mining, and Safety (DRMS) records (2018) show 11 active mining permits in this area, and there are also many inactive permits issued for pits that presumably were active in the past. During summer 2018, mining activity was observed at five locations. All of the aggregate pits are in alluvium three (unit Qa_3), which underlies alluvium two (unit Qa_2) in the valley floor of St. Vrain Creek. Annual aggregate production for Weld County for the years 2015, 2016, and 2017 was ~12.2 metric tons, ~14.4 metric tons, and ~15.0 metric tons, respectively (Weld County Assessor's Office, 2018a, pers. commun., 2018a).

The northern end of the Boulder-Weld coal field extends from the Frederick quadrangle (adjacent to the south) into a very small area north of the Gowanda quadrangle southern boundary (Spencer, 1986). This portion of the coal field occupies ~0.2 km2 and lies within T. 2 N., R. 67 W., sec. 19, N ½. The outline of the mined area is the same as that of the Saddleback Golf Course. Coal mining in seven coal beds in the lower part of the Laramie Formation (Kl) was economically important in the Frederick and Erie quadrangles from the late 1800s to 1975, and Spencer (1986) tabulates production from 20 mines in these quadrangles plus the small area in the Gowanda quadrangle. Fifteen of the mines were in coal bed No. 3, and one of the mines extended beneath the location of the golf course. Coal bed No. 3 is 0.9 to 3.7 m thick. In the golf course area it lies 15 to 46 m below the ground surface.

The Gowanda quadrangle lies in the western part of the Wattenberg Field, an active and prolific oil and gas producing area located in the southwest portion of the Denver Basin and mostly in Weld and Adams Counties. In area it is the largest single oil and gas field in the Denver Basin, and as of 2005 had the greatest concentration of oil and gas wells in the basin (Higley and Cox, 2005). In recent years, unconventional drilling and hydraulic fracturing have increased the concentration of wells in the Wattenberg field even more, and oil and gas infrastructure is present throughout the Gowanda 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). 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 [COGCC], 2018).

The lower portion of the Laramie Formation contains two relatively thick sandstone units; these sandstone units and the underlying Fox Hills Sandstone (Kfh) constitute the Laramie-Fox Hills aquifer. The aquifer underlies much of the Denver Basin and can be up to 107 m thick, although its water-yielding thickness is seldom greater than 61 m. It is generally under artesian conditions (Topper and others, 2003). The aquifer underlies the Quaternary deposits (mostly eolian sand [Qes] with underlying eolian sediment [Qe]) in most of the area southeast of the St. Vrain Creek valley. The water wells in this area are of varied depths, with the shallow wells penetrating only units Qes and Qe, and the deeper wells screened in the Laramie-Fox Hills aquifer (Colorado Division of Water Resources [DWR], 2018). The sands and gravels of contiguous units alluvium three (Qa_3) and alluvium four (Qa_4) constitute a shallow aquifer in the St. Vrain Creek valley throughout the Gowanda quadrangle, as evidenced by the large number of water wells completed in these units. The area northwest of the valley is underlain mostly by the uppermost transition member of the Pierre Shale (Kpt), which generally is a finer-grained unit than the Laramie Formation and Fox Hills Sandstone. There are relatively few water wells in this area.

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 by Myers and others (1975), the maximum possible subsidence from mining at a single level is from 1.5 to 3 m, which also is the of the range of height for the underground mine workings. Subsidence greater than 4.6 m is due to mining at multiple levels. It is estimated that 90% of subsidence that could be observed was identified in 1975, the year that the subsidence study was published and also the year when mining in the Frederick and Erie quadrangles ceased, and that no well-defined, observable subsidence had occurred as of 1975 in areas where overburden above mined coal beds is greater than 46 m. The report presents a map (Plate 6) of the coal field with areas ranked as having severe, moderate, or low subsidence hazard. The small area of historic mining in the Gowanda quadrangle beneath the Saddleback Golf Course is ranked as an area of severe subsidence hazard.

During the catastrophic September 2013 flood events along the Colorado Front Range, floodwater of St. Vrain Creek inundated the low-lying parts of the creek valley. The flood covered much of the area mapped as Qa near Longmont (Madole, 2016), ~5 km west and upstream from the Gowanda quadrangle western boundary, and the area mapped as Qa_2 in the Gowanda quadrangle. The extent of the flood was captured in 2013 photographs, including some taken from the air and showing the effects of flooding in the Gowanda quadrangle (City of Longmont, 2018). Flooding effects can be seen also on Google Earth imagery for October 6, 2013, and June 9, 2014 (Google Earth, 2018). In the Gowanda quadrangle there was some damage to property and infrastructure, but there were very few structures that were in the path of the flood (Google Earth, 2018). All of the Qa_2 area in the Gowanda quadrangle is designated by the Federal Emergency Management Agency (FEMA) as a 1% annual chance of flooding (100-yr flood plain). Also, the area of alluvium, undivided (Qau) in the stream networks that flow into New Thomas Reservoir, Bass Reservoir, and Diamond Reservoir, northwest of St. Vrain Creek, is designated as 1% annual chance flood zone (Weld County, 2018b).

Eolian sand (Qes) and eolian sediment (Qe) locally may be susceptible to collapse, owing to hydrocompaction. Geotechnical engineers refer to these deposits as collapsible soils. The fine-grained particles (silt and especially clay) in the eolian sand and sediment 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).

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Table 1. Detailed characteristics of Gowanda quadrangle map units

Map Unit	Grain Size Distribution	Colors (per Munsell, 1991)
Qa_1	Fine-grained fraction: mixture of clay, silt, and very fine to fine sand Coarse-grained fraction: mixture of medium sand to cobbles	Dark-brown of hue 10YR Pinkish-gray of hue 5YR
Qa_2	Moderately sorted, finer-grained deposits ranging from silty clay or clayey silt up to very fine or fine sand (most common type) Poorly sorted coarser-grained deposits ranging from very fine sand to granules (less common type) Moderately to poorly sorted, coarser-grained deposits, ranging from silt to granules, with rare pebbles (least common type)	Light olive-brown, olive-brown, and dark grayish-brown of hue 2.5Y; and light yellowish-brown, yellowish-brown, brown, and grayish-brown of hue 10YR
Qa_3	Ranges from clayey silt to silty clay, through sil