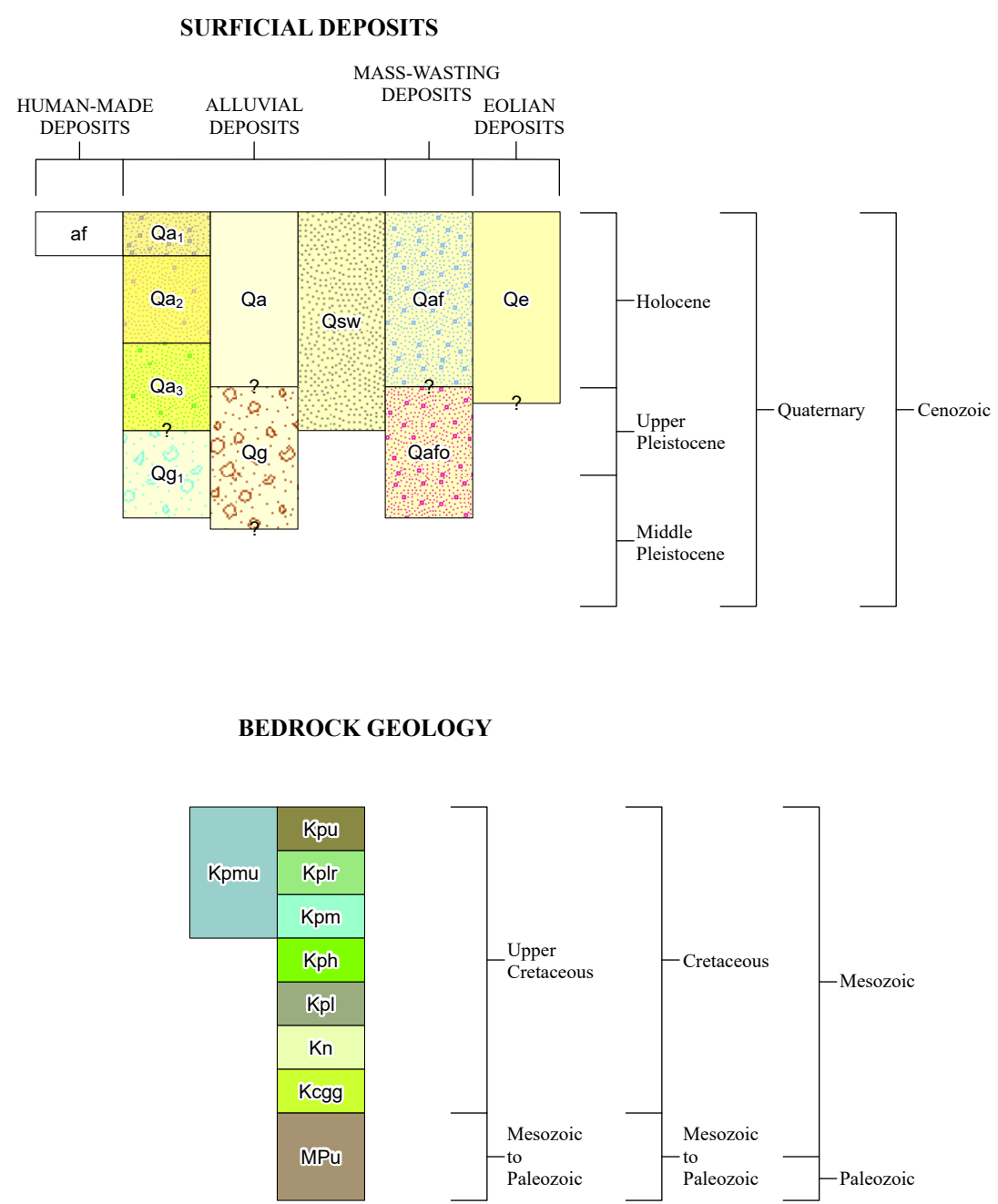


CORRELATION OF MAP UNITS



SUMMARY OF THE GEOLOGIC HISTORY, GEOLOGIC HAZARDS, GROUNDWATER RESOURCES, AND MINERAL RESOURCES

The Loveland quadrangle is situated in the northern part of the Colorado Piedmont section of the Great Plains. The western edge of the Denver Basin underlies the area and is bounded by the Southern Rocky Mountains on the west side. The mapped area is directly south of the Fort Collins 1:24,000-scale quadrangle and contains part of the City of Fort Collins and most of the City of Loveland. The Western Interior Seaway (WIS) occupied most of Colorado during the Late Cretaceous, depositing transgressive and regressive sedimentary rock sequences that underlie the mapped area. The early phase of the Laramide orogeny (~70 Ma) is correlative with the final stages of the WIS in the region (Weimer, 1996). The Carlile Shale, Greenhorn Limestone, and Codell Sandstone (collectively known as the Colorado Group, map unit Kegg), Niobrara Formation (Kn), and the Pierre Shale (units Kpu, Kpr, Kpm, Kph, and Kpl) record some of the final WIS transgressive and regressive marine sequences. The Pierre Shale members and the upper part of the Niobrara Formation are the only Cretaceous rocks exposed in the mapped area; however, just west of the quadrangle, older Mesozoic and Paleozoic rocks are exposed in the fold belt of the eastern margin of the Southern Rocky Mountains (Braddock and others, 1970). The Pierre Shale and its derived soils contain expansive clay minerals that have a high-swell potential, making areas underlain by the unit prone to swelling and collapsible soil hazards.

Major thrust faulting and associated structures are located west of the mapped area, on the Masonville quadrangle (Braddock and others, 1970). A Colorado Energy and Carbon Management Commission (ECMC) oil and gas well located south of the quadrangle boundary

start at about 25-degrees and decrease to about 20-degrees where Kph and Kpmu are exposed on the surface. With these assumptions, a thrust fault or high-angle fault can account for the higher Niobrara top at the location of well 60024 (cross-section C-C'). Alternatively, unit Kpl could have undergone structural thinning, owing to its relatively soft, ductile characteristics, allowing unit Kn to more steeply dip on the western side of the mapped area. However, with this hypothesis, unit Kn appears to project to the surface on the Masonville quadrangle where Braddock and others (1970) did not map it. Without more subsurface data, it is difficult to fully identify the structural relationships of these units in this area. All oil and gas data obtained from the ECMC (URL link in references).

The Windsor Wrench Fault Zone is located east of the mapped area (Weimer, 1996). An associated thrust fault and dome are mapped on the Berthoud-Loveland quadrangle border by Keller and others (2017). On the Berthoud quadrangle, there is an approximately 9 m upward inflection of the base of unit Kn. The dome projects to roughly between ECMC wells 06175 and 05073 on the Loveland quadrangle; between wells 06175 and 06110, well logs record a 14 m upward inflection of the tops of units Kn and Kegg. The thrust fault is more difficult to identify in well logs. There is a noticeable increase in dip beginning on the eastern flank of the dome around wells 05073 and 05074 that becomes relatively consistent through the eastern edge of the quadrangle. The thrust fault projects between wells 06165 and 06181, and there is a difference of approximately 113 m of both the tops of the Niobrara Formation (unit Kn) and Codell Sandstone (unit Kegg) between the two wells. Owing to the relatively consistent easterly dip of the units in the area of the projected thrust fault, it is possible that it begins to attenuate further north along the fault strike and that the fault only extends into and effects unit Kegg, or older, units. All oil and gas data obtained from the ECMC (URL link in references).

Structural deformation in the area formed traps that contribute to hydrocarbon accumulation in Cretaceous units. The Loveland quadrangle is located in a localized, isolated portion of the Wattenberg Field on the field's western edge. The Wattenberg Field is a world-class oil and gas production area (Weimer, 1996). In contrast to its hydrocarbon potential, the area within the quadrangle does not contain major groundwater resources because the Fox Hills Sandstone and Laramie Formation and associated aquifers are not present here.

There are five alluvial units mapped in the quadrangle. Unit Qg is comprised of unit Qg₁ and older gravel documented in well logs and geotechnical boring logs, but eolian sediment (unit Qe) conceals most of the older gravel in the mapped area; therefore, unit Qg is only shown on the cross-section. Unit Qg₁, correlative with deposits previously mapped as Silexum Alluvium, crops out along the Big Thompson River and underlies surfaces approximately 14 and 17 m above the stream channel. Unit Qg₁ and Qg₂ may be a source of sand and gravel. Perched, localized groundwater may be present within these gravel units. As these Middle Pleistocene to late Middle Pleistocene aged fluvial gravels were deposited, coval or possibly slightly earlier, river systems were periodically depositing sediments that now comprise unit Qa₁₀. These fan deposits have since been incised, exposing members of the Pierre Shale along the gully margins. Unit Qa₁₀ underlies fan-shaped surfaces that are preserved at several (at least three) distinct levels, which may indicate an episodic adjustment in base-level coupled with multiple episodes of deposition during the Pleistocene. Two samples collected from unit Qa₁₀, LV-LCL-01 and LV-LCL-02, were analyzed by infrared stimulated luminescence techniques, and yielded age estimates of 17.8 ± 1.86 ka and 166.2 ± 21.8 ka, respectively.

Though the samples were taken at different sites below the same fan surface, the elevations

of the samples are within approximately 1 m of each other. This age gap could indicate the great spans of time between depositional periods and indicate that episodic deposition occurred during both the Pinedale glaciation (Late Pleistocene) and Bull Lake glaciation (late Middle Pleistocene). It is more likely that LV-LCL-01 may have been contaminated by younger sediment from pedogenic, biotic, and (or) other geologic processes such as younger eolian sediment deposition and infiltration to the subsurface. The older of the two samples could be correlative with either the early part of the Bull Lake glaciation, which began sometime around 170 ka (Kellogg and others, 2008), potentially as early as 200 ka (Maddole, 1991), or with deposits mapped as the Silexum Alluvium along the Front Range. The Silexum Alluvium was dated to around 160,000 ± 60,000 years in Canon City, CO (Szabo, 1980); however, more recent optically stimulated luminescence (OSL) analysis of samples collected by CGS geologist from the same deposit indicates that parts of it may be as young as ~34 ka (Lindsey and Morgan, 2025). Unit Qa₁₀ is not a likely source of sand and gravel. Perched groundwater may be present locally, especially in areas underlain by shales and claystones of the Pierre Shale. The clayey minerals form a natural barrier to groundwater flow, leading to locally perched groundwater.

Along the Big Thompson River, a series of younger deposits underlie inset terraces topographically below unit Qg₁. The upper part of unit Qa₁ records the end of the Pinedale glaciation in the mapped area. Two samples (LV-LRM-01 and LV-LRM-03) were collected from the unit and analyzed by OSL techniques. Sample LV-LRM-01 was collected 4.9 m below ground surface (bgs) and yielded an age estimate of 15,625 ± 900 yrs BP. Sample LV-LRM-03 was collected 2.7 m bgs and yielded an age estimate of 12,780 ± 1,025 yrs BP. Unit Qa₁ directly overlies unit Qa₂ along the Big Thompson River, suggesting that unit Qa₁ forms part of the modern river valley's subsurface. Deposits mapped as unit Qa₁ are a

source of sand and gravel. Perched groundwater may be present in the unit, especially if it is underlain by the Pierre Shale. Since unit Qa₁ was deposited, the river has incised further and deposited Upper Holocene alluvium (unit Qa₁₀) which underlies the modern river channel and recent floodplains. A sample was collected from a cutbank, LV-WOS-01, in a terrace approximately 2 m high. It yielded an OSL age estimate of 340 ± 15 yrs BP. The sample was taken at the base of a sandy alluvial deposit, approximately 0.6 m below ground surface, above the units contact with a clast-supported cobble-gravel assumed to be unit Qa₁₀. The possibility of contamination by younger sediments is uncertain. Units Qa₁ and Qa₂ are sometimes mapped together as unit Qa in parts of the mapped area where either: (1) the units are not differentiable at this map scale such as along Fossil Creek, or (2) ephemeral drainages have deposited alluvium periodically during the Holocene such as those adjacent to unit Qa₁₀ in the western part of the mapped area. Two samples collected from unit Qa, LV-FCW-01 and LV-RENA-01, were analyzed by OSL techniques and yielded age estimates of 2,940 ± 270 yrs BP and 1,500 ± 70 yrs BP, respectively. Areas underlain by Qa₂, Qa₃, and Qa₄ may be prone to flooding. Other Holocene and Upper Pleistocene deposits include younger debris-flow deposits (unit Qa₁) and sheetwash alluvium (unit Qw), which were deposited during periods of above-average precipitation. Areas underlain by units Qa₁ and Qw may be prone to debris flows, overland flow, and (or) stream or sheet flooding. Perched groundwater may be present in these same areas. Eolian sediment (unit Qe), also primarily deposited during the Holocene and potentially during the Upper Pleistocene, in the quadrangle, is mapped primarily in the eastern and southern portions of the mapped area and mantles most of the older Quaternary and bedrock units. Areas underlain by unit Qe may be prone to settlement related to collapsible soils. All water-well logs are obtained from the Colorado Department of Water Resources (URL in references).

TABLE 1. OSL analysis for Quaternary deposits in the Loveland quadrangle. Analysis by Steve Forman, Baylor University.

SAMPLE ID	LAB NUMBER	LATITUDE	LONGITUDE	UNIT	DEPTH (m)	SAMPLE DESCRIPTION	ALIQUOTS ^a	EQUIVALENT DOSE (D ₀ (Gy)) ^b	OVER DISPERSION (%) ^c	U (ppm) ^d	Th (ppm) ^d	K ₂ O (%) ^d	H ₂ O (%)	COSMIC DOSE RATE (mGray/yr) ^e	DOSE RATE (mGray/yr)	SAR-OSL AGE (yr) ^f
LV-RENA-01	5434	40.382462	-105.095322	Qa	1.07	fine to medium sand	43/44	3.83 ± 0.13	68 ± 10	2.68 ± 0.01	8.23 ± 0.01	1.99 ± 0.01	20 ± 3	0.247 ± 0.025	2.53 ± 0.07	1,500 ± 70
LV-LRM-01	5401	40.394001	-105.117996	Qa ₁	4.89	medium sand	27/35	63.33 ± 1.77	31 ± 5	2.20 ± 0.01	12.25 ± 0.01	3.92 ± 0.01	15 ± 3	0.166 ± 0.017	4.05 ± 0.21	15,625 ± 900
LV-LRM-03	5402	40.394001	-105.117996	Qa ₁	2.74	medium sand	44/45	63.20 ± 4.76	40 ± 4	5.31 ± 0.01	27.60 ± 0.01	2.91 ± 0.01	15 ± 3	0.223 ± 0.022	4.94 ± 0.15	12,780 ± 1025
LV-WOS-01	5397	40.387001	-105.014	Qa ₁₀	0.63	fine sand to silt	33/35	1.62 ± 0.06	20 ± 2	5.17 ± 0.01	20.30 ± 0.01	2.62 ± 0.01	10 ± 3	0.244 ± 0.024	4.63 ± 0.14	340 ± 15

^a Aliquots measured, used to define De population by Central or Minimum age models (Galbraith and Roberts, 2012)

^b Equivalent dose calculated on a pure quartz fraction with ultra-small aliquots with 20-80 grains/aliquot and analyzed under blue-light excitation (470 ± 20 nm) by Single Aliquot Regeneration protocols (SAR; Murray and Wintle, 2003; Wintle and Murray, 2006). Equivalent dose (De) was calculated by Central or Minimum age models (Galbraith and Roberts, 2012)

^c Overdispersion values reflects precision beyond instrumental errors; values of ≤ 20% (at 1 sigma limit) indicate low dispersion in equivalent dose values and defines a unimodal distribution. Values > 20% are associated with mixed equivalent dose signature reflecting multiple grain populations or partial solar resetting.

^d U, Th, Rb and K content analyzed by inductively-coupled plasma-mass spectrometry by ALS Laboratories, Reno, NV; and includes dose contribution from Rb.

^e Includes also a cosmic dose rate calculated from parameters in Prescott and Hutton (1994) and includes soft components.

^f Systematic and random errors calculated in a quadrature at one standard deviation by the Luminescence Dating and Age Calculator (LDAC) at <https://www.baylor.edu/geosciences/index.php?id=962356>. Datum year is AD 2010.

TABLE 2. OSL analysis for Quaternary deposits in the Loveland quadrangle. Analysis by Utah State University Luminescence Lab.

SAMPLE ID	LAB NUMBER	LATITUDE	LONGITUDE	UNIT	BURIAL DEPTH (m)	SAMPLE DESCRIPTION	ALIQUOTS ¹	IN SITU H ₂ O (wt%) ²	K (%) ³	Rb (ppm) ³	Th (ppm) ³	U (ppm) ³	DOSE RATE (Gy/kyr) ⁴	FADING RATE (FELD, IRSL) R _{fast} (%) ⁵	EQUIVALENT DOSE ± 2σ (Gy) ⁶	AGE ± 1σ (ka) ⁷	ANALYSIS
LV-LCL-01	USU-4305	40.498291	-105.117401	Qa ₁₀	0.69	poorly sorted sand	14/15	5	1.05	56	7.37	4	3.42 ± 0.17	1.26 ± 0.05 (3)	60.90 ± 3.77	17.08 ± 1.86	IRSL
LV-LCL-02	USU-4306	40.489761	-105.117516	Qa ₁₀	1.10	poorly sorted sand	13/19	5	1.12	59.7	8.62	4.9	3.80 ± 0.20	2.83 ± 1.26 (n=3)	632.34 ± 107.23	166.2 ± 21.8	IRSL
LV-FCW-01	USU-4307	40.438999	-105.051102	Qa	2	poorly sorted sand	14/22	5	1.99	92.4	9.96	3.1	3.42 ± 0.14	NA	10.04 ± 0.94	2.94 ± 0.27	OSL

¹ Age analysis using the single-aliquot regenerative-dose procedure of Wallinga and others (2000) on 1mm small-aliquots of 75-150 μm feldspar sand for IRSL Analysis at 50°C and 150-250 μm quartz sand for OSL analysis. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

² No moisture content measured, 5% weight percent moisture content used for dose-rate calculation.

³ Radio-elemental concentrations determined using ICP-MS (Rb, U, Th) and ICP-AES (K) techniques; dose rate is derived from concentrations by conversion factors from Guérin and others (2011). IRSL dating: Grain-size based internal beta dose rate determined assuming 12.5% K and 400ppm Rb following Megdahl (1979). Alpha contribution determined using an efficiency factor, or 'e-value', of 0.15±0.05 after Balesar and Lamothe (1994) (Duncan and others, 2015).

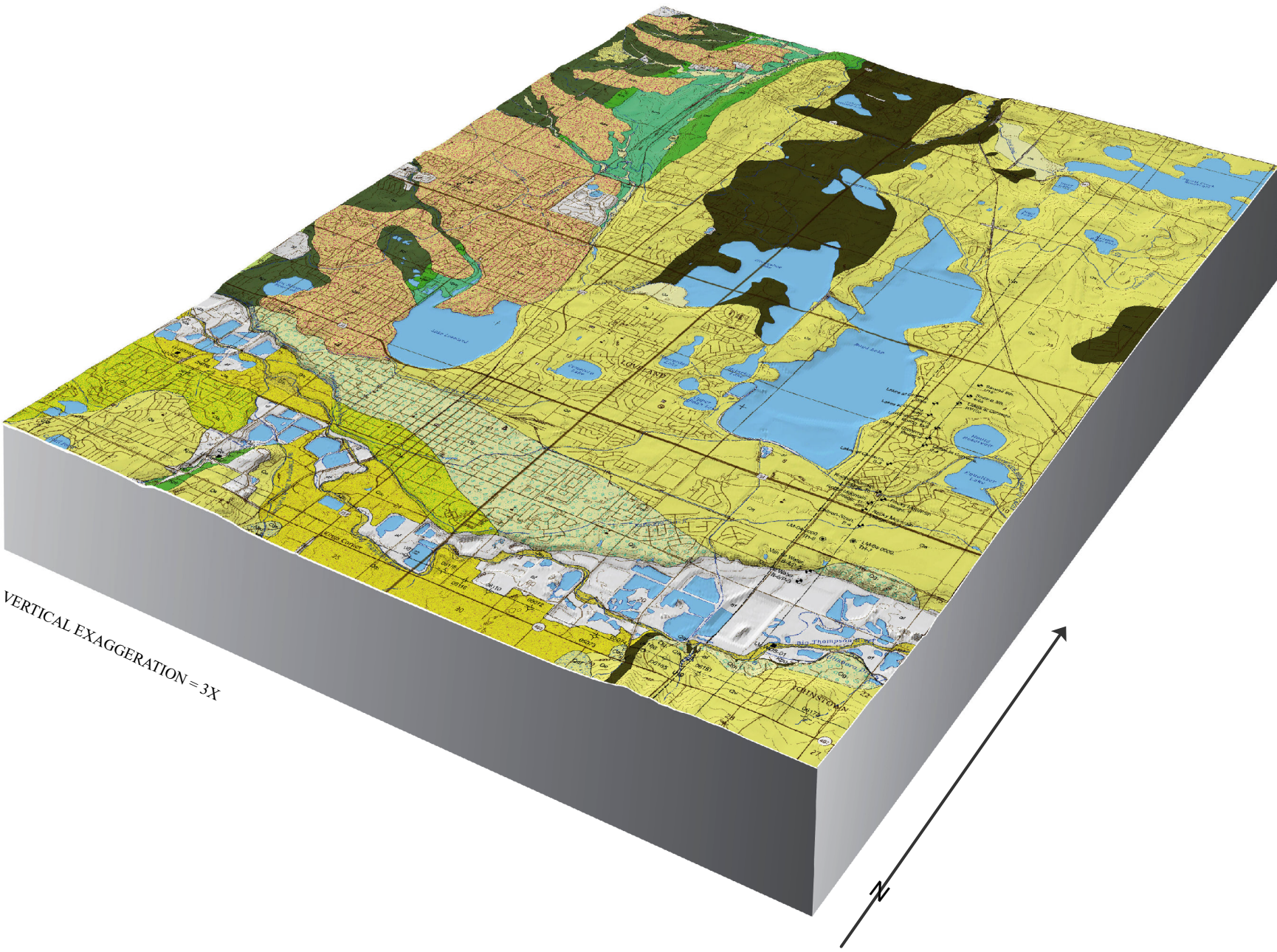
⁴ Total dose rate contribution includes internal radioactivity of the grains (for IRSL) and external contributions from the surrounding sediments and cosmic contribution (Duncan and others, 2015). See Table 3 for contributing factors for cosmic dose rate calculation. The total dose rate is corrected for grain-size and attenuation by water.

⁵ Fading rate (loss of signal) on IRSL data calculated following the methods of Huntley and Lamothe (2001). Number of measurements used for calculation included in parentheses, reported as the mean and 1 σ.

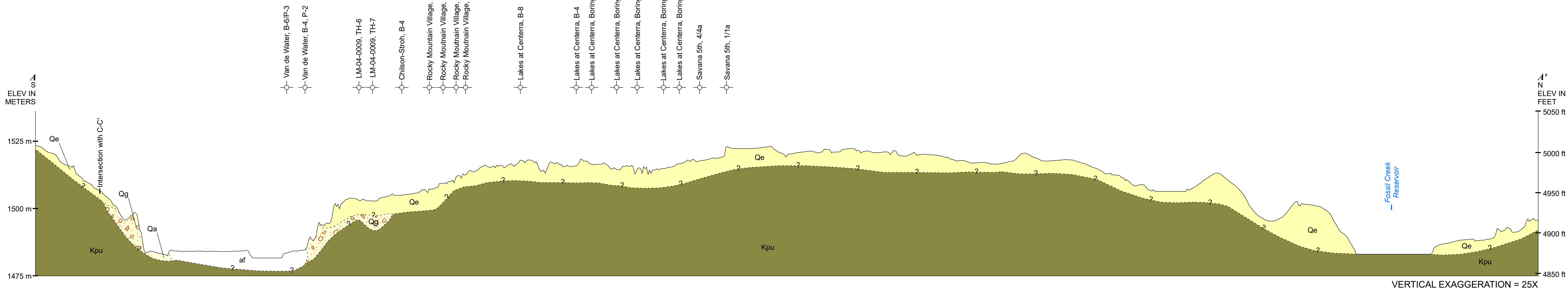
⁶ Equivalent dose (DE) corrected for fading (loss of signal) following the methods of Lamothe and others (2003) and reported as the weighted mean of aliquot values. No correction for fading required for quartz OSL samples.

⁷ IRSL ages calculated by dividing the fading corrected DE by the environmental dose rate. OSL ages calculated by dividing the DE by the environmental dose rate

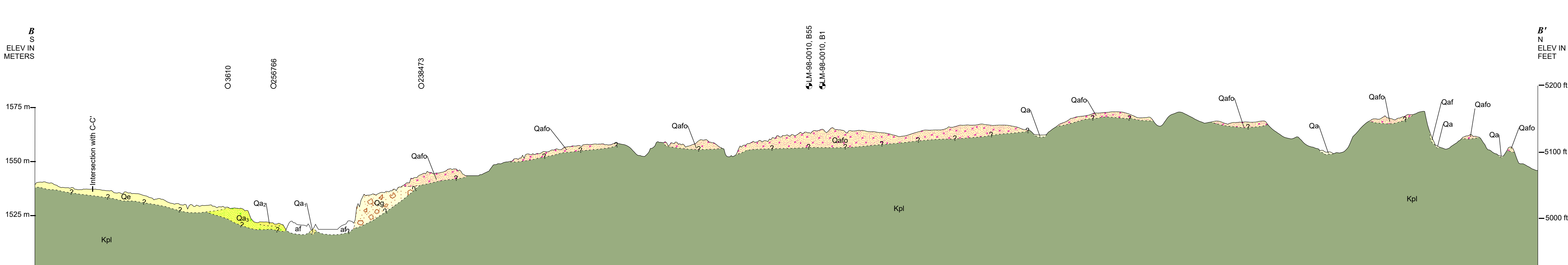
3-D OBLIQUE



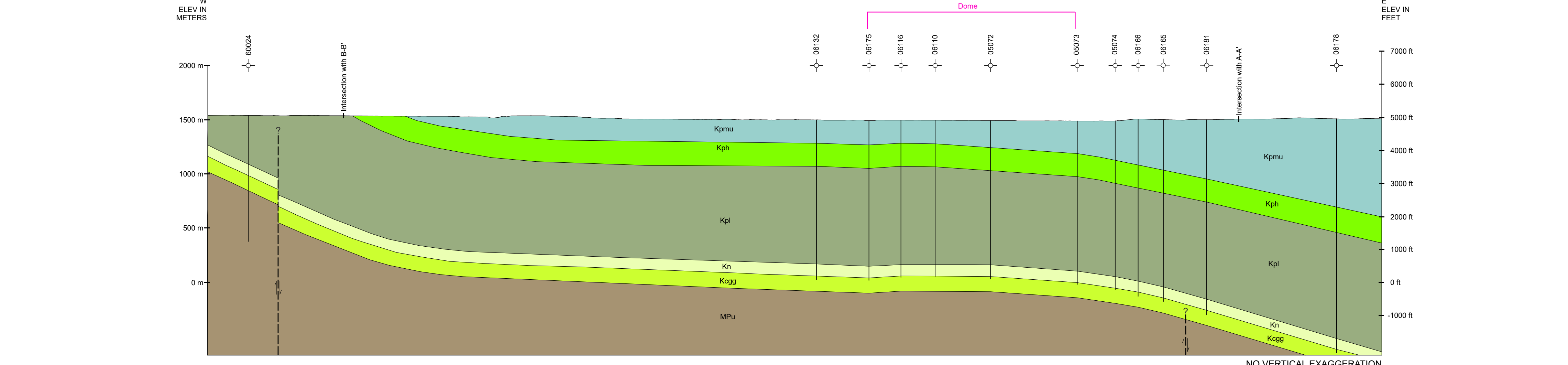
CROSS SECTION A-A'



CROSS SECTION B-B'



CROSS SECTION C-C'



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GEOLOGIC MAP OF THE LOVELAND QUADRANGLE, LARIMER COUNTY, COLORADO
CORRELATION OF MAP UNITS, 3-D OBLIQUE VIEW, GEOLOGIC SETTING, AND CROSS SECTIONS

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2024