SITE CHARACTERIZATION
240 CFR 146.82(a)(2), (3), (5), (6) and 40 CFR 146.83

FRONT RANGE STORAGE COMPLEX

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List of Acronyms and Abbreviations

3D = three-dimensional
ANSS = Advanced National Seismic System
AoR = Area of Review
bbl = barrels
bbl/yr per km^2 = barrel per year per squared kilometer
bpd = barrels per day
CO_2 = carbon dioxide
ComCat = Comprehensive Earthquake Catalog
EOR = enhanced oil recovery
FMI = Formation Micro-Imager (QuantaGeo)
ft = feet
ft bgs = feet below ground surface
ft MSL = feet, referenced to mean sea level
g/cc = grams per cubic centimeter
gpm = gallons per minute
GS = geologic sequestration
GSDT = Geologic Sequestration Data Tool
km = kilometers
mb_lg = mg_lg scale, short-period surface wave magnitude scale
MD = measured depth
mD = millidarcy
mg/L = milligrams per liter
M_L = local magnitude
MMA = maximum monitoring area
MMI = Modified Mercalli Intensity
mmol/L = millimoles per liter
mmol $m^{-2}s^{-1}$ = micromoles per square meter per second
mS/cm = microsiemens per centimeter
ppm = parts per million
psi/ft = pound-force per square inch per foot
Sv = vertical stress
SHmax = maximum horizontal stress
Shmin = minimum horizontal stress
TDS = total dissolved solids
TVD = true vertical depth
UIC = Underground Injection Control
US = United States
USDW = Underground Source of Drinking Water
US EPA = United States Environmental Protection Agency
USGS = United States Geological Survey

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A.I.2. Regional Geologic Structure, Stratigraphy and Hydrogeology [40 CFR 146.82(a)(3)]

A thorough evaluation of regional geology, hydrogeology, and local geology is presented using geologic maps, topographic maps, and cross sections. The full stratigraphic sequence is provided, along with hydrogeologic units and their associated structures. In the vicinity of the geologic sequestration (GS) site, the shallow geologic units include recent undifferentiated alluvial deposits underlain by a series of interbedded shales, limestone, and sandstone formations. Corresponding aquifer systems generally include shallow regional aquifers and deeper aquifers throughout the stratigraphic column.

A.I.2.1. Data Used for Geologic Characterization

Data used to evaluate and characterize the Front Range 1-1 project area for carbon capture and sequestration potential include publicly available drilled well records, academic literature, well log data, directional drilling surveys, and seismic data, as well as site specific data captured from the drilling and testing of the Front Range 1-1 itself. Well locations were captured from the Colorado Oil and Gas state dashboard database and loaded into Kingdom Suite geological interpretation software. Well log data penetrating the Lyons Sandstone were then also identified, captured from the Colorado online database, and imported into the Kingdom project. Well log data from the Front Range 1-1 were also imported into the project. Available well log data consisted of a mix of digital .las file curves, as well as raster log images. Log curves included a mix of Gamma, SP, Density, Neutron, Sonic, and Resistivity curves. Well top horizons were then picked across the study area to build a stratigraphic framework to characterize the Lyons injection interval and regionally present confining units. The Lyons was defined in 36 wells across the regional study area to identify regional injection-interval structure and formation thickness. 2D seismic lines in the area were also reviewed to assess structural features in the area proximal to the AoR.

Data Used for Geologic Characterization:

- Drilled well Records
- Petrophysical Logs
- Academic Literature and Other Published Data
- Federal and State Geotechnical Databases
- Directional Drilling Surveys
- Seismic Data
- Core Data from Front Range 1-1

A.I.2.1.1. List of Regional Maps and Cross Sections

The following maps and cross sections were referenced and/or generated to study and characterize the geology in and around the Front Range 1-1 GS area.

- Figure A.I.2-1. Regional Map Showing Location of the Study Area
- Figure A.I.2-2. Cross Section Showing General Structure
- Figure A.I.2-3. Map Showing Front Range 1-1 Site Relative to Wrench Fault Zones in the Region
- Figure A.I.2-4. Regional Cross Section Showing General Stratigraphy from West to East Across the Northern Portion of the Basin
- Figure A.I.2-5. Regional Cross Section North to South Showing General Stratigraphy Across the Basin
- Figure A.I.2-6. General Stratigraphic Column Across Study Area
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- Figure A.I.2-9. Regional Hydro-Stratigraphic Column
- Figure A.I.2-10. Paleo-Groundwater Flow Direction
- Figure A.I.2-11. Modern Groundwater Flow Direction
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- Figure A.I.2-13. Oil and Gas Wells in the Area
- Figure A.I.3-1. Stratigraphic Column from FR 1-1
- Figure A.I.3-2. Well Control Map
- Figure A.I.3-3. Cross-Section Location Map
- Figure A.I.3-4. Stratigraphic Cross-Section N-S
- Figure A.I.3-5. Stratigraphic Cross-Section W-E

A.I.2.2. Regional Structure

The Front Range 1-1 CCS site is situated in the Denver-Julesburg (DJ) Basin, approximately 15 miles east of the Front Range mountains, in Weld County, Colorado. The DJ Basin is an asymmetrical, north-south trending foreland-style structural basin spanning the subsurface across portions of southeastern Wyoming, western Nebraska, southwestern-most South Dakota, the Nebraska Panhandle, and northeastern Colorado.

The DJ Basin is bound to the northwest by the Hartville Uplift, the Chadron Arch to the northeast, the Apishapa Uplift to the southwest, and the Las Animas Arch to the southeast. The basin axis, where sedimentary strata are deepest and approach 13,000 ft in thickness from surface to basement (Higley and Cox, 2005), trends north to south near Denver and Greeley in Colorado, and northward into Wyoming. The axis is flanked by steeply dipping western strata rising to the Front Range Uplift to the west, and a gently rising eastern flank (Higley et al., 2006). The Front Range 1-1 CCS Site, near Greeley, Colorado, is close to the basin axis, where sedimentary strata are deep (Figure A.I.2-1, Figure A.I.2-2).

The structural configuration and resulting deposition and stratigraphy of the DJ Basin has been impacted by processes first starting in the Precambrian. Even prior to the acceptance of plate tectonics in the role of basin evolution, the importance of topography and the impact of the changes of depositional environments for the region was understood. McCoy, 1953 summarizes the evolution of the basin: "*Early Paleozoic troughs became Late Paleozoic mountain ranges and Early Paleozoic positives gradually subsided to retain marine sediments. Late Paleozoic troughs became post-Cretaceous mountain ranges and Late Paleozoic mountain ranges became Tertiary and Recent plateaus and shallow basins*."

Stresses from basin formation and multiple, regional orogenies through time created a series of vertical, right lateral wrench faults that can produce geologic structures such as folds from Precambrian basement up through the Muddy J in some areas of the DJ Basin (Weimer, 1996). These faults are along Precambrian suture zones and trend northeast to southwest. Two of these wrench faults, the Windsor and Johnstown, are north and south of the Front Range 1-1 site, respectively (Figure A.I.2-3). The Windsor wrench fault was interpreted by Stone, 1985 to have formed from compressional forces which the basin was subjected to during the Laramide orogeny. Some north to northwest trending faults associated with the Black Hollow and Pierce anticlines north of the Windsor fault have also been thought to originate from Laramide orogenic processes.

Figure A.I.2-1. Regional Map Showing Location of the Study Area

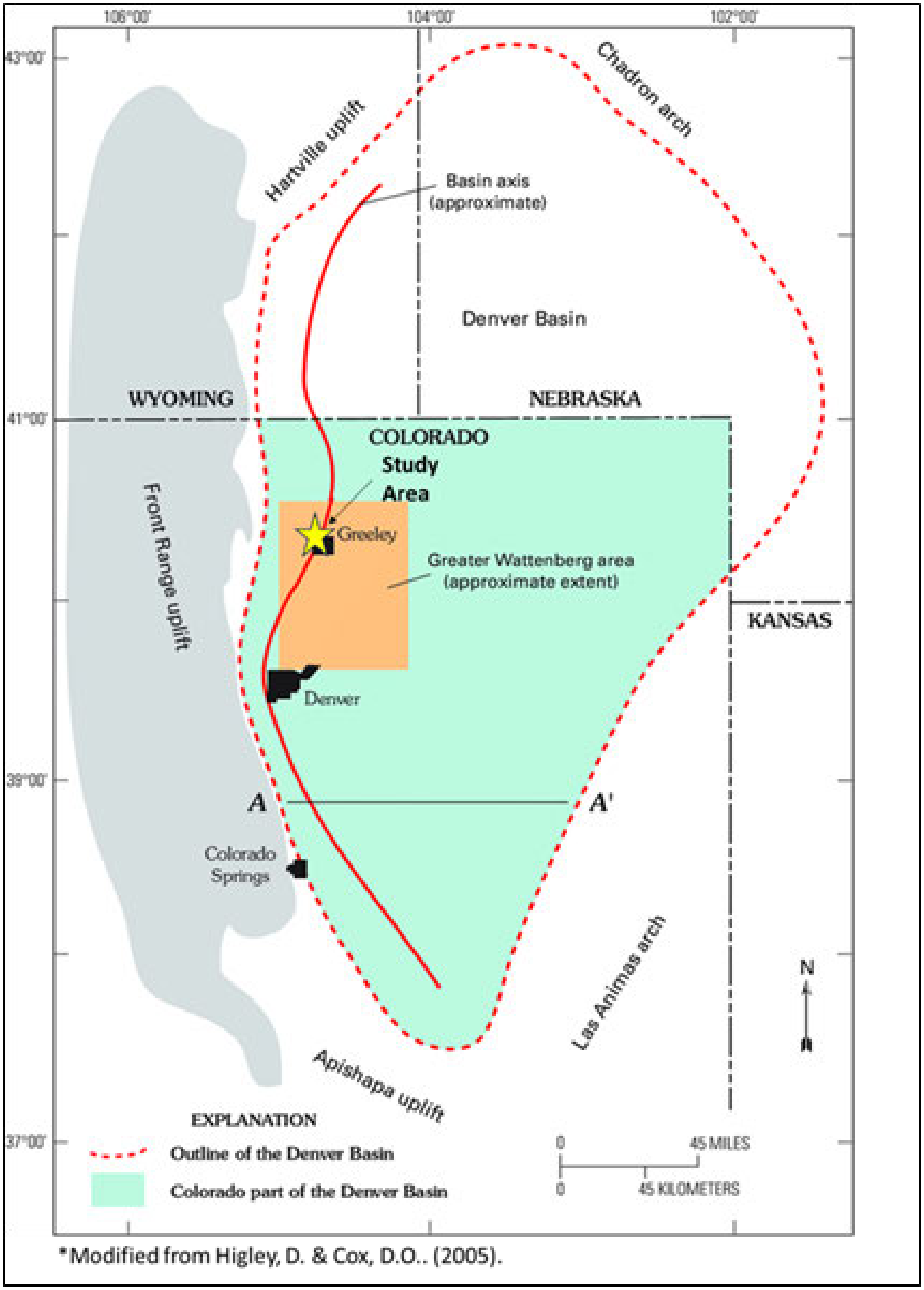
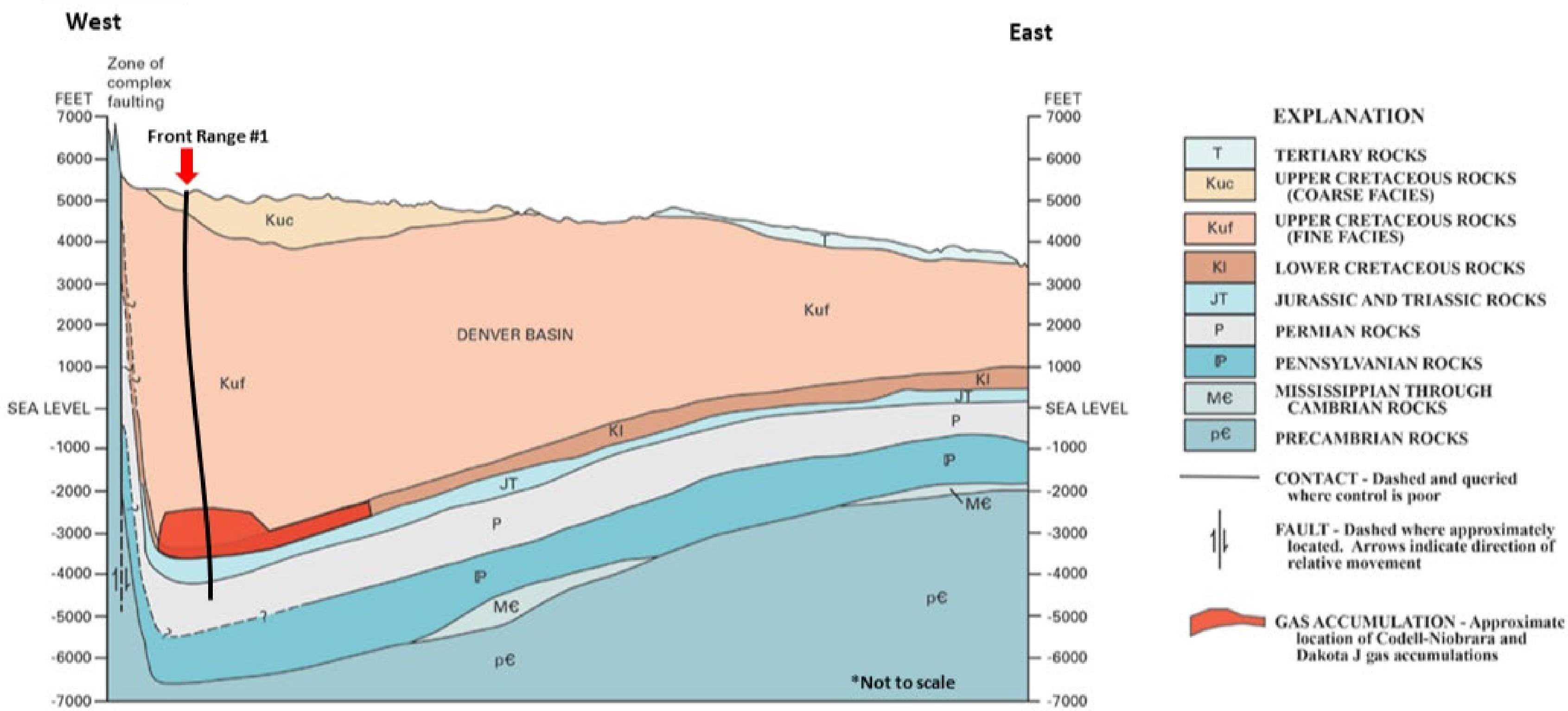
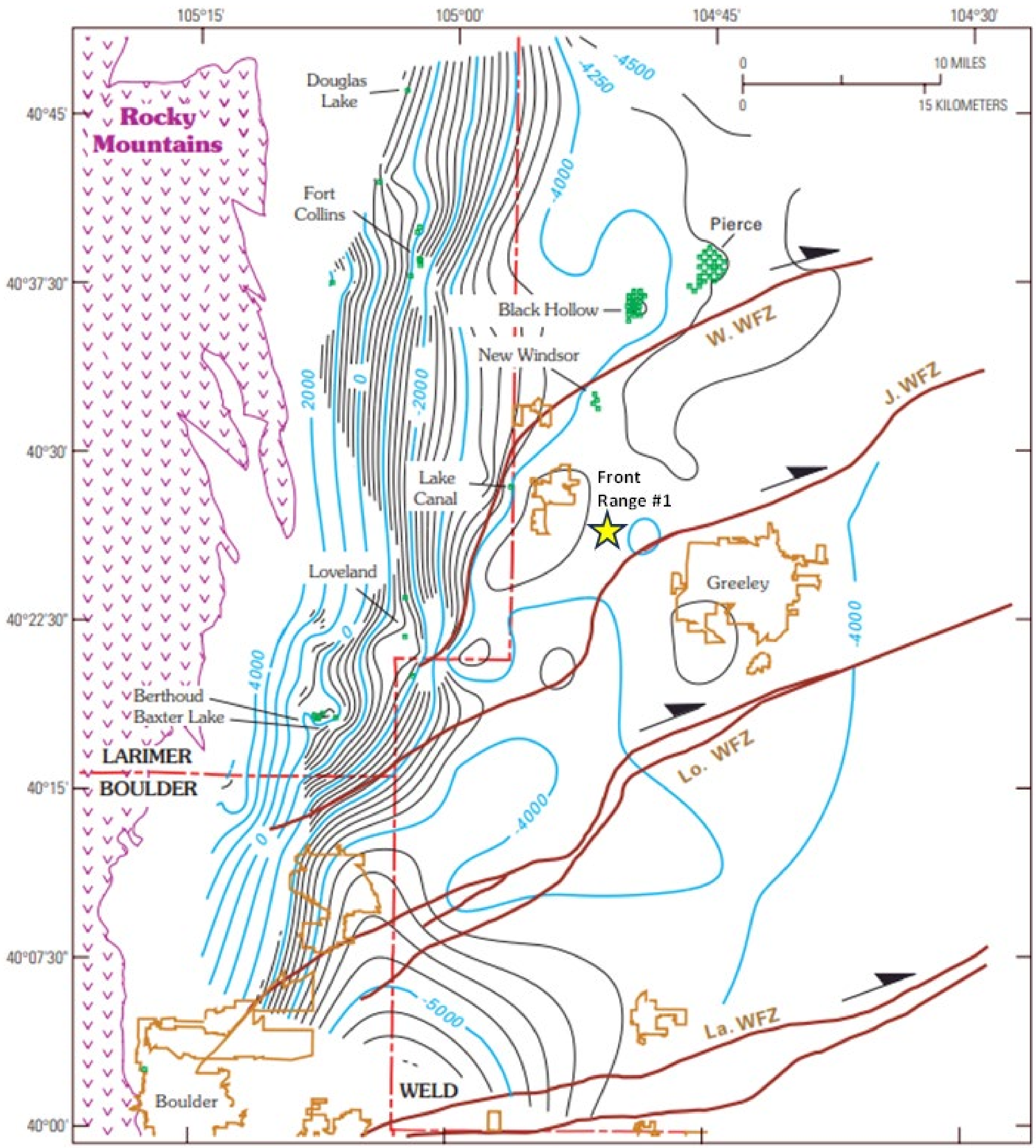


Figure A.I.2-2. Cross Section Showing General Structure
Across the DJ Basin and Relative Location of Front Range 1-1 Site Near the Basin Axis



*Modified from Nelson and Santus, (2011).

Figure A.I.2-3. Map Showing Front Range 1-1 Site Relative to Wrench Fault Zones in the Region



Modified from: Higley, D.K., & Cox, D.O. (2005)

Elevation in feet relative to sea level on the top of the Permian Lyons Sandstone in the Front Range Urban Corridor. Contour interval is 250 feet (76 meters). Producing oil wells (green) are shown for the labeled fields. Labeled wrench faults are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), and Lafayette (La. WFZ); arrows indicate direction of lateral movement.

The first major Phanerozoic tectonic event that influenced the basin began about 325 Ma and created the Ancestral Rockies. The subsequent erosion of Ancestral Rocky Mountain sediments is recognized as the source material for some formations in the basin (Oldham, 1996). Continued development and deepening of the basin took place during the Laramide Orogeny, about 71-50 Ma, with the most down-warping happening between 64 and 50 Ma (Weimer, 1996). This created additional accommodation space and sedimentary infill, which paved the way for the deposition of younger sediments and led to current basinal conditions during "*the major tectonic event that folded these originally flat-lying rocks...and uplifted the Rocky Mountains to the west*" by some estimates over 25,000 feet (Higley and Cox, 2005). In addition to impacting sedimentary deposition and character, these two orogenic events also produced minor intra-basinal deformation, such as selective reactivation of Precambrian suture zones.

A.I.2.3. Regional Stratigraphy

The DJ Basin is filled with geologic formations ranging from Cambrian to Tertiary in age. Relative to total volume, most of the strata (over 70%) are Cretaceous age sandstones, shales, and limestones (Hemborg, 1993a-d). In the area proximal to the Front Range 1-1 site, Pennsylvanian age strata deposited from erosional processes acting on the Ancestral Rockies unconformably overly Precambrian basement. Permian through Upper Cretaceous age formations were later deposited in a series of marine basins, and from the subsequent erosion of the Front Range mountains and overly Pennsylvanian formations. Two regional stratigraphic cross sections (Moredock and others, 1977) illustrate the general stratigraphy from north-south, and east-west across the portion of the basin in which the Front Range 1-1 sequestration project area is located (Figure A.I.2-4 and Figure A.I.2-5).

Figure A.I.2-4. Regional Cross Section Showing General Stratigraphy from West to East Across the Northern Portion of the Basin

(From Moredock and others, 1977)

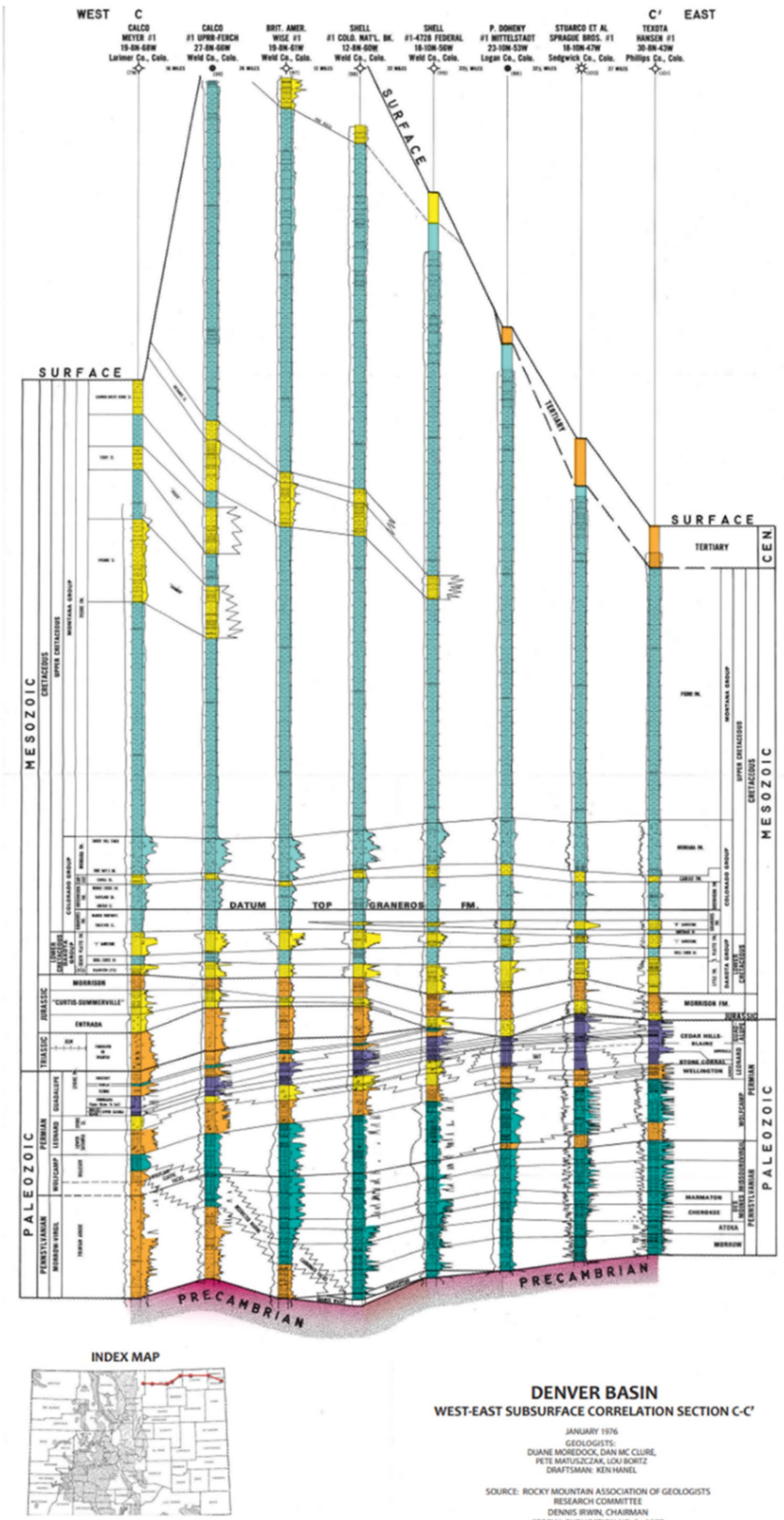
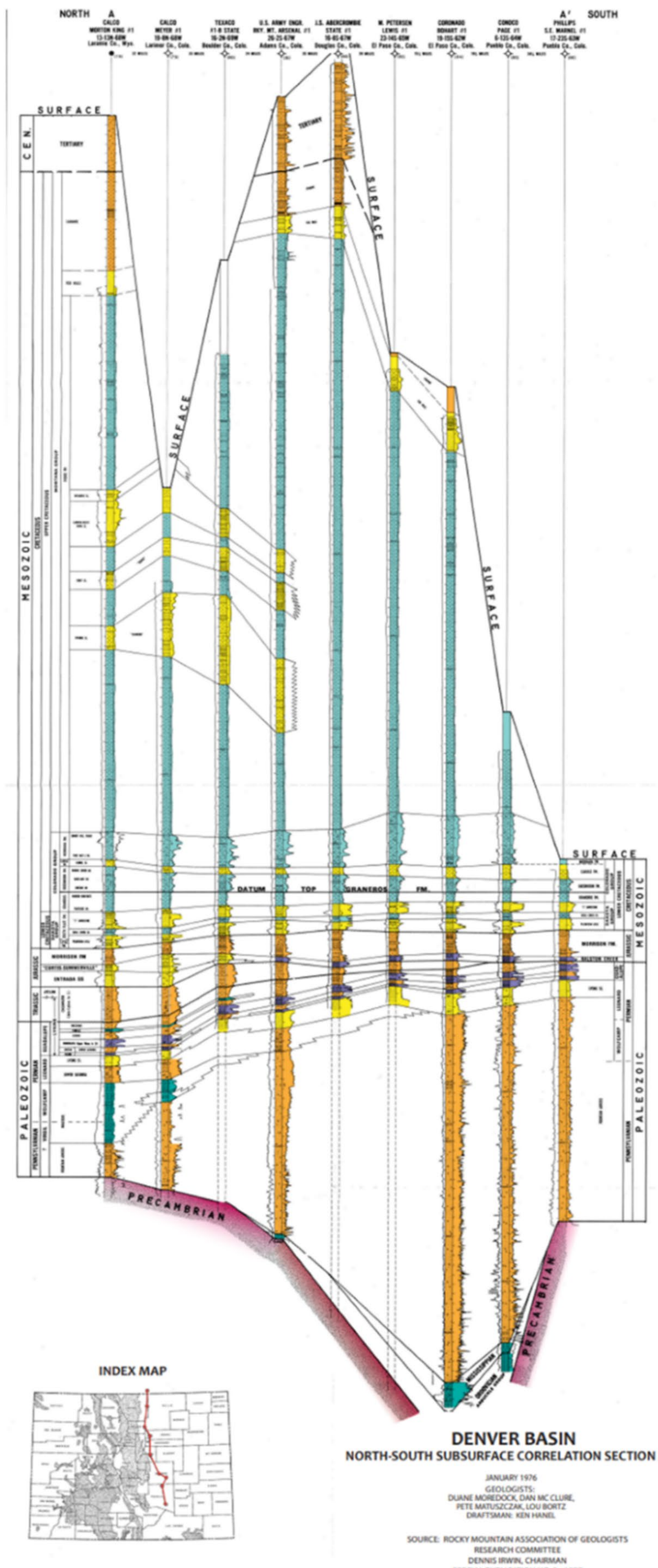


Figure A.I.2-5. Regional Cross Section North to South Showing General Stratigraphy Across the Basin

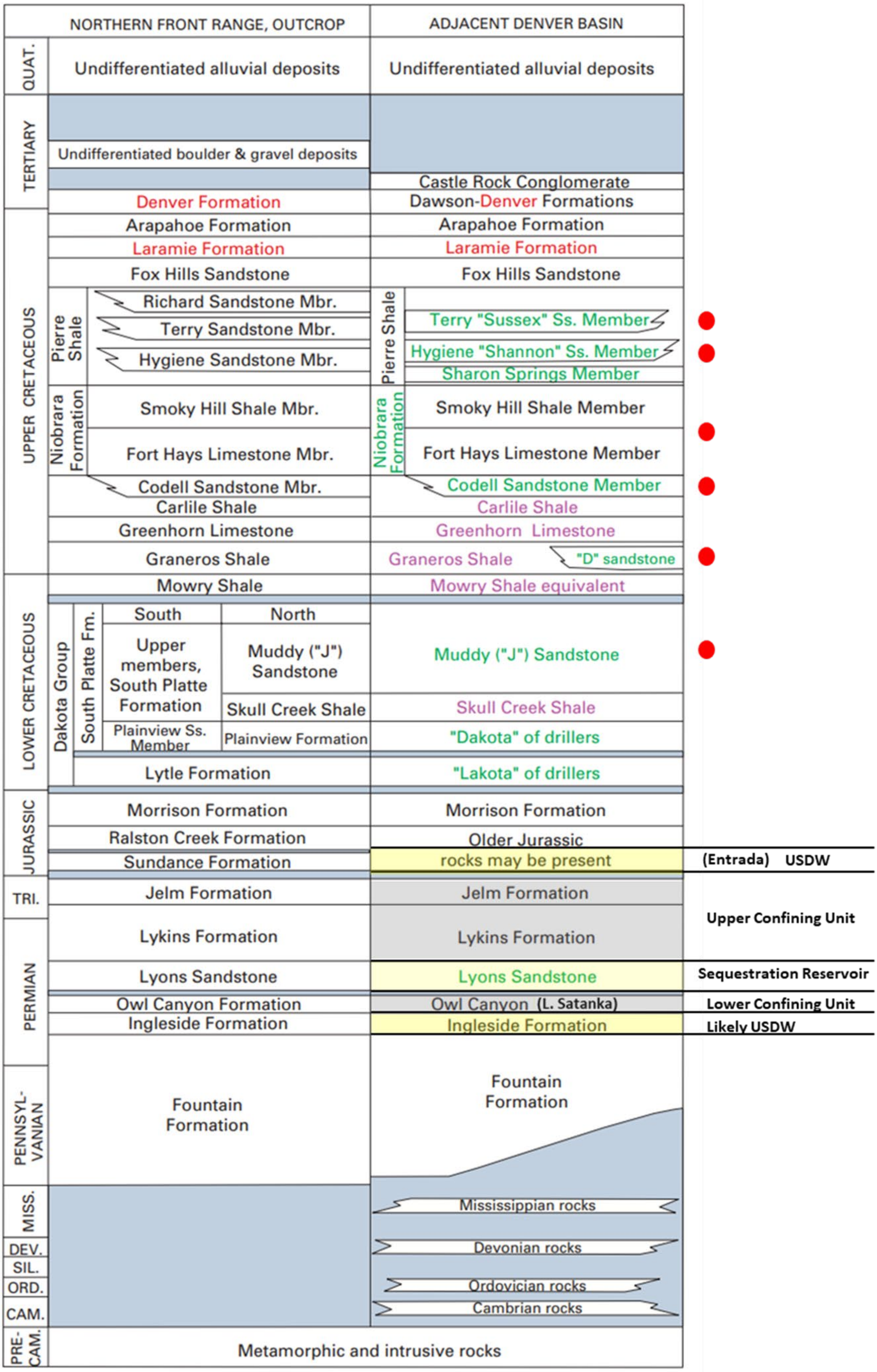
(From Moredock and others, 1977)



The general stratigraphic sequence is described below and is illustrated in Figure A.I.2-6. A stratigraphic framework constructed from available well log control captured across a grid of 25 townships (Figure A.I.2-7) demonstrates that formations that are present exhibit consistent thickness and lateral continuity across the project area.

Figure A.I.2-6. General Stratigraphic Column Across Study Area

Modified from Higley and Cox, 2005. Red dots denote formations known to be hydrocarbon reservoirs in the region



*Modified from Higley and Cox, 2005.

A.I.2.3.1. Precambrian Basement

The stratigraphic column of sedimentary formations filling the DJ Basin are underlain by Precambrian basement rock. These crystalline rocks are part of a wider gneiss complex consisting of Early Proterozoic rocks originating from heterogeneous sedimentary and igneous protoliths. This basement province formed and deformed during trans-continental collisions between what would become Colorado and Wyoming and extends southward through Colorado and New Mexico and north to the older Wyoming Archean province. Sedimentary and igneous bodies were subjected to metamorphism during this process (Tweto, 1987). Three wells were identified in the area that reached the basement. Thicknesses from top of Lyons to top of Precambrian basement were 1,446 ft (API 123-05513), 1,545 ft (API 123-40772) and 1,743 ft (API 123-27116). A thickness of 1,545 ft was used to estimate the depth from top of Lyons to top of Precambrian basement in the Front Range 1-1 well, which would put top of basement between approximately 10,391 ft and 10,421 ft TVD in the vicinity of the Front Range 1-1 site.

A.I.2.3.2. Pennsylvanian Age Strata

Fountain Formation

In the vicinity of the Front Range 1-1 study area, Precambrian basement is overlain unconformably by the Pennsylvanian Fountain Formation. Other names in the literature describing this interval include the Morrow, Atoka, Des Moines, Missouri, and Virgil. These are age-based intervals, not formal members or formations, that have been recognized in the DJ Basin for disposal purposes. In adjacent states, some of these do thicken and transition into entire formations or groups. The Fountain Formation consists of arkosic conglomerates and sandstones that were deposited from erosional processes of the Ancestral Rockies. It ranges from 563 ft to 751 ft thick, with an average thickness of 637 ft in 3 well logs within the study area that were deep enough to capture the entire Fountain interval.

A.I.2.3.3. Permian Age Strata

Ingleside Formation

The Fountain Formation is overlain by the Permian Ingleside Formation. Other names describing this interval in the literature include the Wolfcamp, the Admire, Council Grove, Amazon, and Wolfcamp Anhydrite (Garfield et al., 1988). The Ingleside generally consists of alternating sequences of sandstone and limestone, indicating repeated periods of sea level fluctuation. Sandstone intervals in the Ingleside, as well as any porosity present within limestone intervals, could serve as aquifers. The Ingleside has been identified as a potential USDW below the Lyons injection interval in the study area. It ranges from 577 ft to 632 ft thick, with an average thickness of 598 ft in 3 well logs within the study area that were deep enough to capture the entire Ingleside interval.

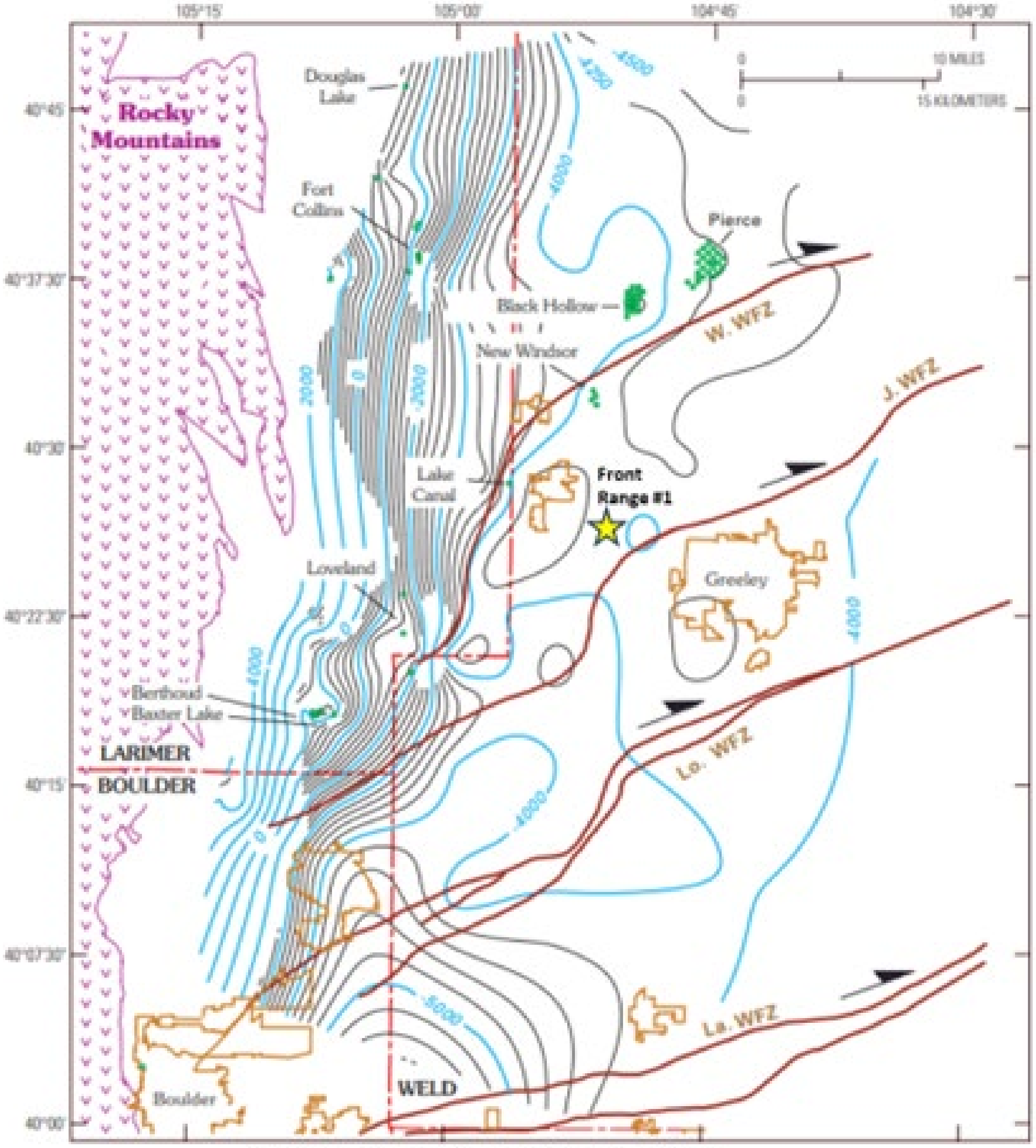
Lower Satanka (Owl Canyon) Formation

The Ingleside Formation is overlain by the Lower Satanka, (Owl Canyon) Formation. The Lower Satanka is characterized by a series of siltstones, shales, and sandstones interbedded. The Lower Satanka is identified as the lower confining unit segregating the Ingleside Formation below and the Lyons target sequestration reservoir above. Lower Satanka depositional conditions are interpreted to include fluctuations in sea level rise and fall within a marine environment. It ranges from 221 ft to 268 ft thick, with an average thickness of 240 ft in 7 well logs within the study area that were deep enough to capture the entire Lower Satanka interval.

Lyons Sandstone

The Lower Satanka is overlain by the Lyons Sandstone. The Lyons Sandstone consists of fine grained, hard quartzose sandstone. The nature of cross bedding observed in the Lyons, as well as grain size, consistency, and shape indicate that it was deposited in an erg to erg-margin environment. The Lyons is the target sequestration reservoir for this project in the Front Range 1-1. A regional structure map for the Lyons is shown as Figure A.I.2-7, and a regional isopach map is shown as Figure A.I.2-8. It ranges from 47 ft to 118 ft thick, with an average thickness of 84 ft in 27 well logs within the study area that were deep enough to capture the entire Lyons Sandstone interval. The Lyons is 82 ft thick in the Front Range 1-1 well.

Figure A.I.2-7. Map Showing Lyons Structure Top Across the Region

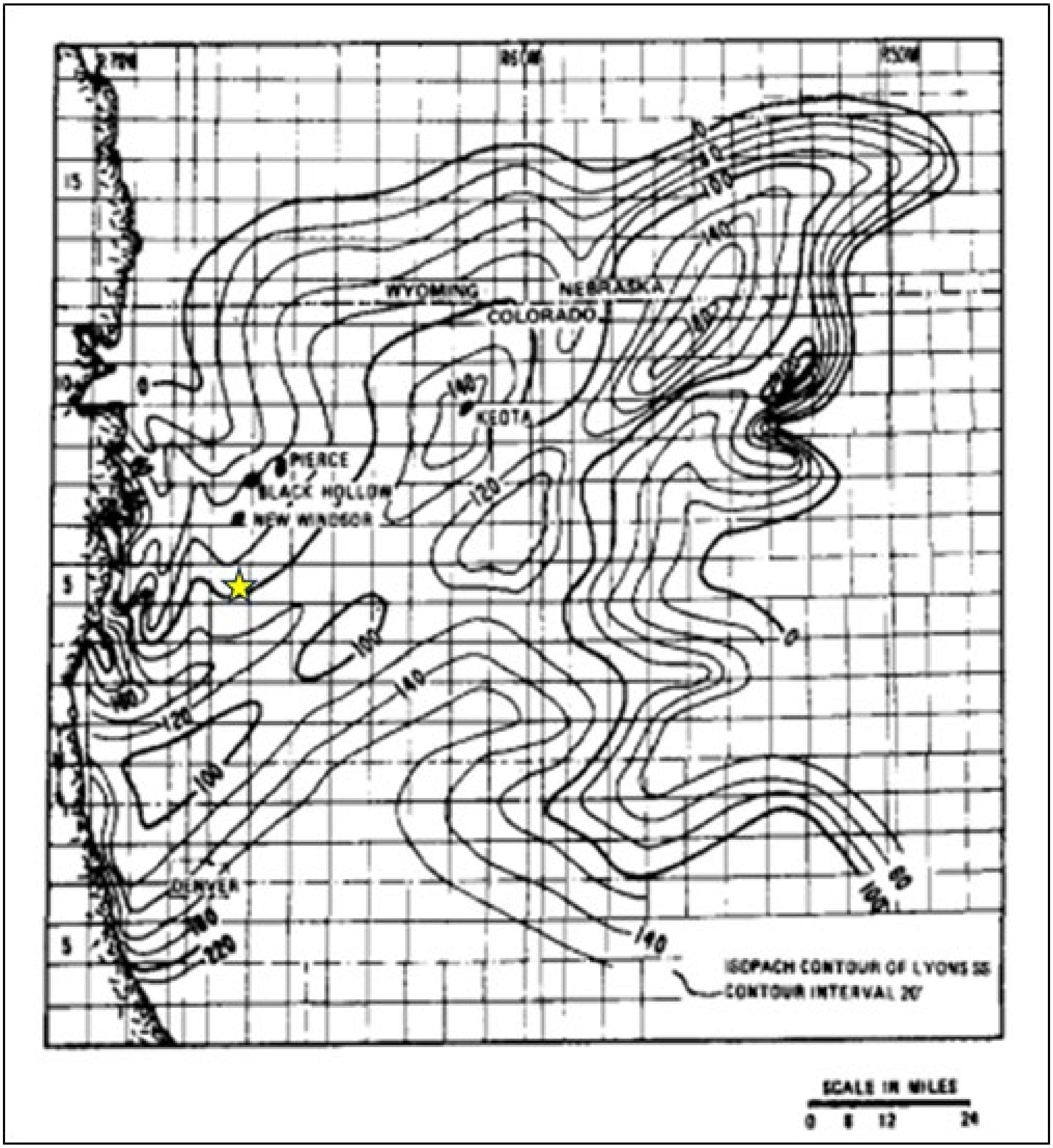


Modified from: Higley, D.K., & Cox, D.O. (2005)

Elevation in feet relative to sea level on the top of the Permian Lyons Sandstone in the Front Range Urban Corridor. Contour interval is 250 feet (76 meters). Producing oil wells (green) are shown for the labeled fields. Labeled wrench faults are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), and Lafayette (La. WFZ); arrows indicate direction of lateral movement.

Figure A.I.2-8. Regional Lyons Isopach Map

From: Levandowski, et al., 1973). Yellow star denotes approximate Front Range 1-1 location. The Lyons interval is 82 ft thick in the Front Range 1-1 well.



The Lyons Sandstone is overlain by stacked members of the Lykins. The Lykins consists of a series of evaporite (Anhydrite at depth in the Front Range 1-1 well), shales, limestones, and siltstones. These members include, in ascending order, the Blaine Evaporite, the Opeche Shale, the Minnekahta Limestone, Glendo Shale, Forelle Limestone, Freezeout Shale, and other shale and siltstone units.

Blaine Evaporite Member

The member directly overlying the Lyons is the Blaine Evaporite. The Blaine is composed of thick beds of gypsum, with alternating beds of shale and thin dolomites. At depth in the basin in and around the Front Range 1-1 well, these thick intervals of gypsum have been dehydrated at depth to transition into hard intervals of anhydrite. The Blaine is considered to be the immediate caprock interval above the Lyons sequestration reservoir. It ranges from 42 ft to 77 ft thick, with an average thickness of 59 ft in 29 well logs across the study area.

Opeche Shale Member

The Blaine member of the Lykins is overlain by the Opeche Shale. The Opeche is characterized in the DJ Basin as predominantly shale, with some interbeds of gypsum, sandstone, and sandy shales (Benison et al, 2000). The Opeche is considered to be a secondary caprock above the Blaine confining unit, overlying the Lyons injection interval. The Opeche and Blaine section are sometimes correlated together as the ‘Upper Satanka’. It ranges from 20 ft to 46 ft thick, with an average thickness of 32 ft in 29 well logs across the study area.

Minnekahta Limestone Member

The Opeche Shale is overlain by the Minnekahta member of the Lykins. The Minnekahta consists of thick, blocky packages of Limestone, indicative of a marine depositional environment. This thick assemblage of limestone is laterally present across the study area and ranges from 77 ft to 144 ft thick, with an average thickness of 89 ft in 29 well logs across the study area.

Glendo Shale Member

The Minnekahta Limestone is overlain by the Glendo Shale. The Glendo Shale consists of shale and sandy shale and may exhibit some sandy limestone and gypsum locally.

A.I.2.3.4. Permian to Triassic Age Strata

Freezeout Member and Additional Lykins Shales and Siltstones

The Glendo Shale member of the Lykins is overlain by the Freezeout Shale. The Freezeout, along with a thick sequence of siltstones and shale intervals make up the remaining portion of the upper Lykins. The upper portion of the Lykins is correlative and has similar characteristics to the Chugwater/Jelm in the region, both being identified as ‘red beds’. They are an additional thick sequence that serves as a confining unit between the Lyons injection reservoir and sandstone in the overlying Entrada Sandstone (Sundance) that has been identified as the deepest USDW overlying the Lyons. This interval spanning from the top of Minnekahta to top of the Lykins ranges from 408 ft to 511 ft thick, with an average thickness of 458 ft in 29 well logs observed across the study area.

A.I.2.3.5. Jurassic Age Strata

Entrada Sandstone (Sundance)

The Entrada Sandstone is a thick, porous sandstone reservoir that is laterally continuous across the study area. The Entrada is interpreted to have been deposited in an erg like environment. Windblown sand dunes are thought to have influenced cross bedding characteristics that can be observed in the Entrada. The Entrada around the Front Range 1-1 well study area has been identified as the deepest potential USDW overlying the Lyons injection interval. It ranges from 33 ft to 171 ft thick, with an average thickness of 91 ft in 29 well logs across the study area.

Ralston Creek

The formation overlying the Entrada across the study area has been interpreted to be the Ralston Creek. The Ralston Creek interval variably consists of sandstone, siltstone, limestone, and gypsum (anhydrite at depth). The gypsum/anhydrite intervals indicate a shallow, low energy, evaporitic sea to salt-flat environment. The Ralston Creek ranges from 21 ft to 62 ft thick, with an average thickness of 44 ft in 19 well logs across the study area.

Morrison

The Ralston Creek is unconformably overlain by the Morrison Formation. The Morrison is composed of sandstones and siltstones that were deposited in a fluvial environment.
The Morrison is widely known to be a prolific resource for fossils in outcrop on the basin margins. It ranges from 151 ft to 257 ft thick, with an average thickness of 204 ft in 19 well logs across the study area.

A.I.2.3.6. Cretaceous Age Strata

Inyan Kara (Dakota)

The Morrison formation is unconformably overlain by units of the Inyan Kara, or Dakota. This interval is composed of thick Sandstone packages separated by packages of siltstone and shale. The lower member of this interval is referred to as Lytle formation or Lakota Sandstone. The upper interval is sometimes known as the Dakota or Plainview. An alternate name for this entire section is called the Cheyenne Sandstone. This interval is interpreted to have been formed in a lowland, flood plain like environment (Waage, 1955), as the result of sequences of sea level rise and fall, which were introduced as the midcontinent was inundated by the Cretaceous interior seaway. The Inyan Kara/Dakota interval ranges from 91 ft to 174 ft thick, with an average thickness of 124 ft in 25 well logs across the study area.

Skull Creek Shale

The Skull Creek Shale unconformably overlies the Dakota/Lytle Sandstone and was formed during a period of sea level transgression, and deposits were fed by distal deltaic conditions. The Skull Creek, along with the Mowry and Graneros shales, is considered to be a potential source-rock for hydrocarbon generation in the DJ Basin (Higley et al., 2006). It ranges from 81 ft to 139 ft thick, with an average thickness of 101 ft in 22 well logs across the study area.

Muddy J Sandstone

The Skull Creek Shale is overlain by the Muddy J Sandstone. The Muddy J, also included with Dakota intervals, is a thick, prominent sandstone interval covering much of the basin. This sandstone package was deposited in a deltaic setting (Hubbell and Wilson, 1963). The "Muddy J" Sandstone within the wider Dakota Group is a hydrocarbon producer in the Basin. It ranges from 92 ft to 157 ft thick, with an average thickness of 125 ft in 26 well logs across the study area.

Mowry Shale

The Muddy J Sandstone is overlain by the Mowry Shale. The Mowry Shale is composed primarily of shale and mudstone, with lesser quantities of fine-grained sandstone. The mudstones were deposited offshore as the result of sea-level transgression (Rojas, 1980). The Mowry is considered a source rock for hydrocarbons in the basin. The Mowry equivalent shale interval overlying the Muddy J in this project is included with the Huntsman Shale.

Huntsman Shale

The Huntsman Shale is often grouped with the underlying Mowry. The Huntsman is only recognized in areas where the overlying "D" Sandstone is developed; otherwise, it is considered to be part of the Graneros (described below).

"D" Sandstone

The "D" Sandstone overlies the Graneros and is sometimes correlated within it. The "D" Sandstone, or "D Sand", is another prominent hydrocarbon producer in the basin, largely eastward of the Front Range 1-1 study area. This sandstone interval was deposited in a fluvial point bar setting along with shallow-water tidal bars. The "D" Sandstone ranges from 13 ft to 49 ft thick, with an average thickness of 28 ft in 16 well logs across the study area.

Graneros Shale

The Graneros Shale is also called the Benton Shale. The Graneros consists primarily of dark grey shale and silty shale, laminated with thin layers of quartz sand and silt (Hattin, 1965). This interval was deposited in a shallow water, marine environment. Marine invertebrate fossils such as mollusks are commonly observed in outcrop (Bradley, 1951). The Graneros interval has been noted to contain beds of bentonite, with the "X" bentonite marking the top of the Graneros in the basin (Sippel and Cammon, 1986). It ranges from 120 ft to 158 ft thick, with an average thickness of 142 ft in well logs observed across the study area.

Greenhorn Limestone

The Greenhorn Limestone, along with the Carlile Shale, and Niobrara formation are thought to be probable hydrocarbon source-rocks for Upper Cretaceous reservoirs. The Greenhorn Limestone, Carlile Shale, Fort Hays Limestone, and Niobrara Shale make up the Colorado Group. The Greenhorn unit was deposited in a shallow, nertitic environment. It ranges from 75 ft to 123 ft thick, with an average thickness of 86 ft in well logs observed across the study area.

Carlile Shale
The Greenhorn Limestone is overlain by the Carlile shale. The Carlile Shale is a dark grey, calcareous shale, grading upwards into sandy shale. Transgressive shale deposits grading upward into sandy deposits suggest a gradually regressive sea level transition. The Codell Sandstone, the upper member of the Carlile Shale, is a hydrocarbon producer. Many horizontal wells producing from the Codell have been drilled in the vicinity of the Front Range 1-1 well site. The Carlile Shale ranges from 160 ft to 208 ft thick, with an average thickness of 196 ft in well logs observed across the study area.

Niobrara Formation
The Niobrara Formation is one of the most prolific hydrocarbon producers in the basin. The lower portion of the Niobrara consists of hard, white and light grey limestone which can be slightly argillaceous. Secondary calcite can also be present. Thin, calcareous shales are also found interbedded between more massive limestone intervals. The upper portion of the Niobrara transitions to platy shales and argillaceous limestones and is called the Smoky Hill Member. The uppermost portion of the formation consists of shales which grade into the overlying Pierre Shale (Bradley, 1951). A large number of horizontal wells have been drilled in the subsurface proximal to the Front Range 1-1 well, and throughout the wider study area. The total Niobrara Formation ranges from 223 ft to 307 ft thick, with an average thickness of 278 ft in well logs observed across the study area.

Fort Hays Limestone Member
The Carlile Shale is unconformably overlain by the Fort Hays Limestone. The Fort Hays is composed of hard, thick bedded fossiliferous limestone deposited in a shallow marine environment, with thin silty and shaly interbeds. The unit also contains beds of bentonite. The Fort Hays is classified as the lower member of the Niobrara Formation and ranges from 18 ft to 52 ft thick, with an average thickness of 33 ft in well logs observed across the study area.

Pierre Shale and Members
The Niobrara Formation is overlain by the Pierre Shale and multiple identified members. The Pierre was deposited in a marine environment within the Western Interior Seaway. Several members preside within the Pierre, due to periods of sea level fluctuation. These include the Sharon Springs Member, Shannon Member, Sussex Member, Parkman (Hygiene) Member, and Richard Member. The lower Pierre Shale interval consists of black, silty and fissile shales. The occurrence of sandstones in the middle of the Pierre suggests regressive shoaling, and lowstand periods, which resulted from activation and uplift of highlands to the west. This thick sequence of shale with minor sandstone bodies within it measured 6,565 ft thick in the Front Range 1-1 well. These sandstone intervals that include the Terry (Sussex), Hygiene, and Shannon Members can exhibit porosity, and the Sussex and Shannon members are known as hydrocarbon reservoirs in certain areas. The thick sections of shale enveloping them should serve as an additional thick caprock sequence for separating commonly utilized aquifers from sequestration activities in the deeper Lyons reservoir.

Fox Hills Sandstone
The Pierre Shale sequence is overlain by the Fox Hills Sandstone, a prominent USDW aquifer in the basin. The Fox Hills was deposited in a shallow marine to beach, or delta front environment and consists of fine grained, tan to yellow, generally massive sandstones which can be variably glauconitic and feldspathic. Thin beds of claystone and siltstone can also be present. (Kent and Porter, 1980). The Fox Hills is 61 ft thick in the Front Range 1-1 well. The Fox Hills nomenclature as defined in oil and gas wells as a driller's term in the area may actually be equivalent to sandstones in the upper Pierre in the shallow subsurface, including at the FR 1-1 site. Shale units in the shallow subsurface may be identified as Laramie rather than Pierre Shale.

A.I.2.3.7. Tertiary Deposits

Undifferentiated Alluvium
The Fox Hills aquifer is overlain by an undifferentiated alluvium aquifer. This alluvium aquifer is present along primary streams across the basin, and consists of gravel, sand, and clay (Robson, 1989).

A.I.2.4. Regional Hydrogeology

The hydrogeology of the DJ Basin has been greatly influenced by the tectonic history that shaped the basin. Tectonic uplift and flexure, which shaped the Ancestral Rockies and the Front Range, also created the accommodation space in which erosional sediments that were sourced from both orogenies were deposited (Ye et al, 1996). Multiple, often cyclical depositional environments influenced by a combination of tectonics and sea level fluctuations over geologic time are recorded in DJ Basin stratigraphy. These processes, as well as secondary post depositional processes such as compaction, cementation, and fluid migration shaped these aquifers to give them the physical properties that they exhibit today.

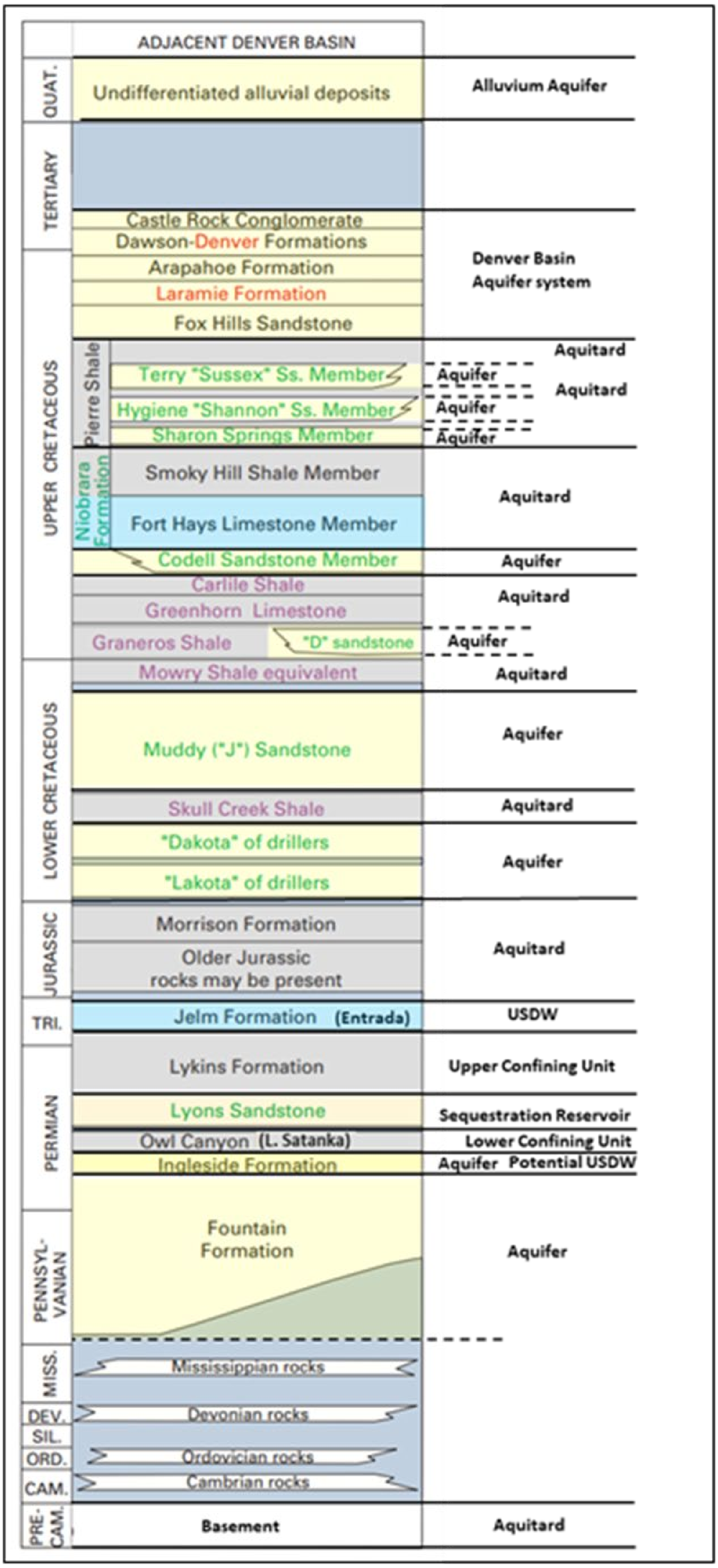
Quaternary alluvium makes up a shallow, near surface water table and possesses high permeability. This alluvium is composed primarily of unconsolidated gravel, sand, silt, and clay, and is connected to surface waters across the basin, namely the South Platte River. In areas outside the South Platte River Valley, where valley floors have eroded down into the Pierre Shale, multiple, variably isolated and dis-connected surficial aquifers reside and are connected to local streams.

Bedrock aquifers in the DJ Basin, in descending order, include the Dawson Aquifer, Denver Aquifer, Arapahoe Aquifer, and the Laramie-Fox Hills Aquifer (Flor, 2017). These individual geologic formations together make up the Denver Basin aquifer system, and overly the Pierre Shale, a thick, Cretaceous age aquitard separating the Denver Basin aquifers from sedimentary strata below the Pierre (Robson, 1989; Robson and Banta, 1995)). Only the Laramie-Fox Hills portion of this aquifer system is found at the project site.

Recharge in the alluvium and Denver Basin Aquifer system occurs from a small portion of precipitation that is not lost to evaporation or transpiration percolating into the system. Deeper aquifers below the Pierre Shale are likely recharged on the basin margin, especially to the west where steeply dipping strata outcrop before plunging to extreme depths in the central part of the basin. Additionally, mineral deposition and complex aqueous chemistry of waters as they migrate through porosity can affect and change total dissolved solids concentrations. A stratigraphic column showing aquifers and aquitards is presented in Figure A.I.2-9. Individual aquifers and aquitards present across the study area are described in more detail below.

Figure A.I.2-9. Regional Hydro-Stratigraphic Column

Stratigraphic column showing major aquifers and confining units within the regional study area. Aquifers are highlighted in yellow, while confining unit aquitards are highlighted grey. Modified from Higley and Cox, 2005.



Undifferentiated Alluvium
This water laden alluvium is fed by meteoric recharge and much of the water supply from shallow wells are sourced from this near surface aquifer. It is present along primary streams across the basin, and consists of gravel, sand, and clay (Robson, 1989).

Laramie/Fox Hills Aquifer
The Upper Cretaceous Laramie/Fox Hill Aquifer lies under the Arapahoe Aquifer and is the lowermost unit in the Denver Basin Aquifer System. This aquifer is composed of an upper Laramie portion, which ranges from 100 to 600 ft thick, and a lower portion, the Fox Hills, which ranges from 100 to 200 ft thick. The upper Laramie portion is composed of shale, silty shale, and siltstone, and is interbedded with fine sandstones and bituminous coal seams. The Fox Hills Aquifer consists of sandstone and siltstone, with shale interbeds. This aquifer is largely confined near the central portion of the basin and contains a water table only proximal to outcrops. The Fox Hills can yield as much as 300 gpm and is used more for commercial development than for domestic use.

Pierre Shale Aquitard with sandstone members (aquifers)
The Cretaceous Pierre Shale lies underneath the Laramie/Fox Hills Aquifer and can reach a thickness of 5,000-7,000 ft. The majority of the facies within the Pierre Shale function as an aquitard and consist of impermeable, dense shales, and silty shales that can be variable calcareous and fossiliferous. Aquifers within the Pierre are found in sandstone members. The upper contact of the Pierre Shale with the overlying Laramie/Fox Hills Aquifer marks the base of the Denver Basin Aquifer System. The Fox Hills/Laramie formations as identified by oil and gas drillers may actually be part of the Pierre Shale system in some locations, including at the Front Range 1-1 site.

Multiple sandstone members within the Pierre Shale are variably present across the basin. These units include the Richard Sandstone, Parkman (Hygiene), Sussex, and Shannon. The Sussex and Shannon are known hydrocarbon reservoirs in certain areas of the basin. These sandstone packages, being encapsulated by the Pierre Shale itself, are not expected to inhibit the Pierre as a thick confining unit to deeper sequestration in the Lyons.

Deeper Aquifers
Deeper aquifers below the Pierre Shale aquitard include the Niobrara, a prolific hydrocarbon reservoir, the “D” Sand, and Muddy J Sandstone, which are also hydrocarbon producers, as well as sandstones of the Dakota formation, the Morrison, and the Entrada. The Entrada has been identified as a USDW in this project area, as TDS values from water samples taken from the Entrada were below 10,000 mg/L in the Front Range 1-1 test well.

Niobrara Aquitard and Aquifer
The Niobrara contains both hydrocarbons and formation fluids in some parts; in others it functions as a confining unit. The lower portion of the Niobrara consists of hard, white and light grey limestone which can be slightly argillaceous. Secondary calcite can also be present. Thin, calcareous shales are also found interbedded between more massive limestone intervals. The upper portion of the Niobrara transitions to platy shales and argillaceous limestones. The

uppermost portion of the formation consists of shales which grade into the overlying Pierre Shale (Bradley, 1951).

Fort Hays Member

The Fort Hays Limestone makes up the lower portion of the Niobrara. Being composed of hard, thick bedded fossiliferous limestone with thin silty and shaly interbeds, fluid bearing porosity is expected to exist within fossiliferous rich intervals, making the Fort Hays a minor aquifer. The unit also contains beds of bentonite which will be porous and are classified as minor aquifers. Tight, interbedded silty and shaly interbeds will provide confining unit capacity and are aquitards.

Codell Sandstone Aquifer/Carlile Shale Aquitard

The Codell Sandstone aquifer is a member of the Carlile Shale aquitard and is a hydrocarbon producer in the basin. The Carlile Shale aquitard below the Codell Sandstone being a variably calcareous shale unit, and grading upward into sandy deposits of the Codell, is expected to serve as a confining unit interval.

Greenhorn Limestone Aquitard

Deposition in a shallow, nertitic environment led to fine-crystalline, calcite veined limestone with calcareous shale interbeds. The Greenhorn Limestone is expected to be an aquitard in the vicinity of the Front Range 1-1 area; however, it may function as an aquifer in some parts of the basin. The Greenhorn Limestone, Carlile Shale, Fort Hays Limestone, and Niobrara Shale make up the Colorado Group.

Graneros Shale Aquitard

The Greenhorn Limestone is underlain by the Graneros Shale. The Graneros Shale is an aquitard across the Front Range 1-1 study area.

"D" Sandstone Aquifer

The "D" Sandstone, or "D Sand", is another prominent hydrocarbon producer in the basin, largely eastward of the Front Range 1-1 study area. The sand is not well developed in other areas.

Hunstman Shale / Mowry Shale

This interval functions as an aquitard and provides separation between the D and the Muddy J.

Muddy J Sandstone Aquifer

The "Muddy J" Sandstone within the wider Dakota Group is also a thick, porous, and permeable sandstone reservoir, and is another prominent hydrocarbon producer in the basin.

Skull Creek Shale Aquitard

The Muddy J aquifer is underlain by the Skull Creek Shale aquitard. The Skull Creek is expected to act as a confining unit between the overlying Muddy J, and underlying Inyan Kara/Dakota interval.

Dakota Formation Aquifer

The Dakota Formation is composed of thick sandstone packages separated by packages of siltstone and shale. Porosity within these sandstone packages serves as aquifers for sub-surface fluids. Tight siltstone and shale interbeds between these sandstone packages are expected to serve as confining units to help prevent upward migration of fluids.

Morrison Aquitard and Aquifer

The Morrison is composed of siltstones and sandstones that were deposited in a fluvial environment. Where porosity is developed within the Morrison, aquifers can occur; however, it is generally confining.

Ralston Creek Aquitard

The Morrison aquifer is underlain by the Ralston Creek aquitard which contains anhydrites.

Entrada Sandstone Aquifer

The Entrada Sandstone is a thick, porous sandstone reservoir that is laterally continuous across the study area and has been identified as the deepest potential USDW overlying the Lyons Sandstone injection interval.

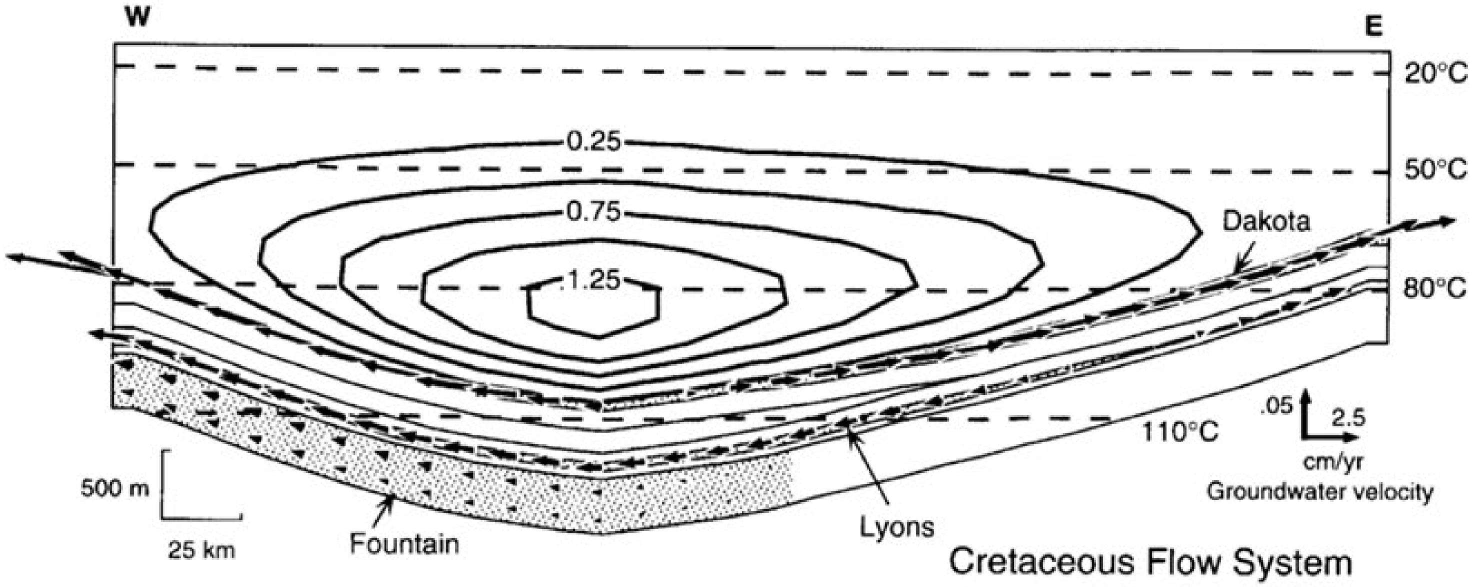
Lyons Sandstone Aquifer

The Lyons Sandstone is identified as the sequestration reservoir for this project. Both intergranular porosity as well as fractures identified within the Lyons reservoir contain sub-surface fluids. TDS values sampled during the drilling of the Front Range 1-1 test well confirmed that the TDS concentration of fluids (34,076 mg/L) within the Lyons Sandstone at the FR 1-1 site is above the 10,000 mg/L requirement.

Two general facies, red and grey, are present in the Lyons. Red facies, which are more widespread, contain iron oxide coatings over grains, along with quartz overgrowths, and also calcite cements. Grey facies occur more locally, exhibit dolomite and anhydrite cements, and may have formed within a groundwater flow regime that resulted from uplift of the Front Range during the Tertiary (Levandowski et al., 1973). Diagenetic cements in the Lyons are thought to be related to and resulted from the same fluid flow paths and processes that influenced petroleum reservoirs in the Lyons (Lee and Bethke, 1994). Groundwater is believed to have originally flowed from east to west through the Lyons and was influenced by sediment compaction during the Cretaceous (Figure A.I.2-10), while modern groundwater recharge is thought to occur along outcrops to the west along the Front Range (Lee and Bethke, 1994) (Figure A.I.2-11).

Figure A.I.2-10. Paleo-Groundwater Flow Direction

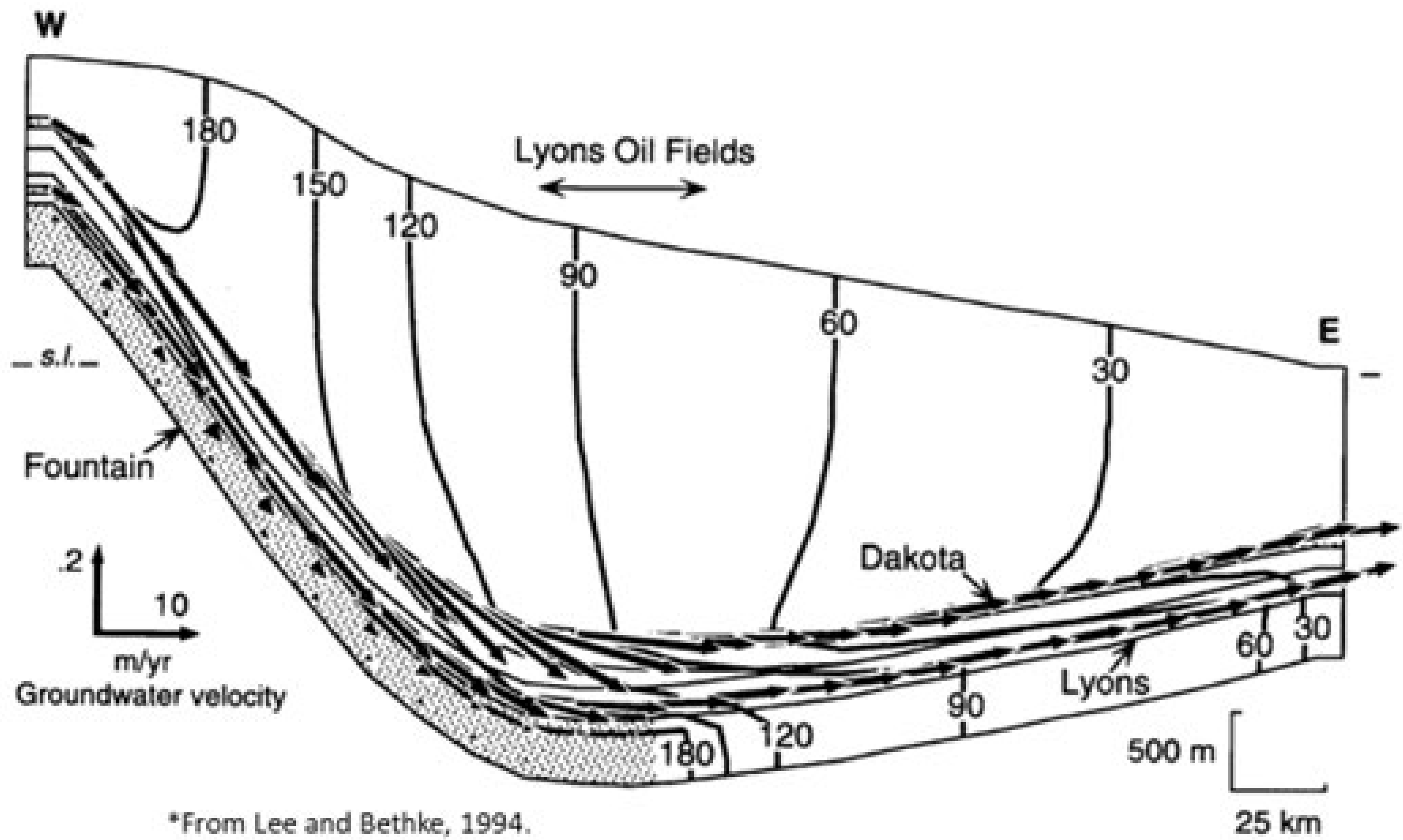
Predicted groundwater flow through the Lyons from East to West during the Cretaceous, driven by sediment compaction.



Calculated groundwater flow driven by sediment compaction at the end of Cretaceous. Contours are calculated excess pressures (atm) in the basin. Dashed lines show predicted temperature distributions. Arrows indicate the flow directions in the Dakota Sandstone, Lyons Sandstone, and Fountain Formation. Vertical components of cross section are exaggerated by about 40:1, as shown by the scale bar. *From Lee and Bethke, 1994.

Figure A.I.2-11. Modern Groundwater Flow Direction

Diagram showing hydraulic potential distribution and modern groundwater flow direction from west to east through the Lyons, driven by gravity



Calculated Eocene groundwater flow and the hydraulic potential distribution (gray contours; in atm) in the Denver basin. Calculation shows relatively rapid groundwater migration in response to the uplift of the Front Range.

Lower Satanka (Owl Canyon) Formation

The Lyons Reservoir is underlain by the Lower Satanka, (Owl Canyon) Formation. The Lower Satanka is identified as a lower confining unit segregating the Ingleside Formation below and the Lyons target sequestration reservoir above. Interbedded siltstones and shales with lower porosity function as aquitards.

Ingleside Formation Aquifers and Aquitards

Sandstone intervals in the Ingleside, as well as any porosity present within limestone intervals, can function as aquifers. The Ingleside has been identified as a potential USDW below the Lyons injection interval in the study area.

Fountain Formation Aquifers and Aquitards

Precambrian basement is overlain unconformably by the Pennsylvanian Fountain Formation. The Fountain Formation consists of arkosic conglomerates and sandstones that were deposited from erosional processes of the Ancestral Rockies. These conglomerates and sandstones likely contain fluid filled porosity overtop of basement.

Precambrian Basement Aquitard

The Fountain aquifer unconformably overlies Precambrian basement across the study area. Except for potential faults and fracturing, igneous and metamorphic basement rock is expected to be tight and largely impermeable.

A.I.2.5. Potential Mineral Zones

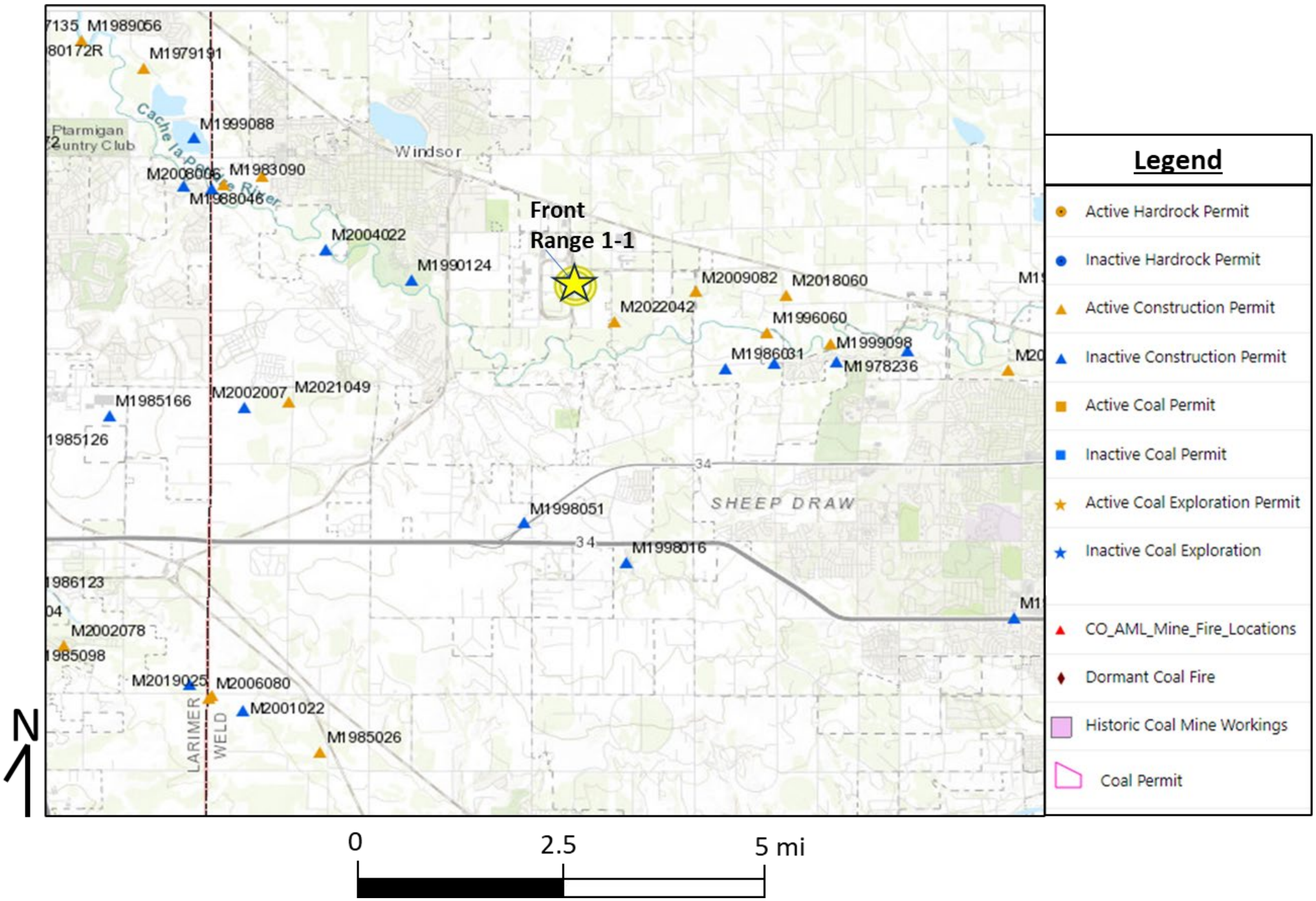
Colorado has a long history of both mining and oil and gas production. The portion of the DJ Basin in which the study area and Front Range 1-1 reside is no exception. Publicly available data were reviewed to determine whether injection activities at the Front Range 1-1 sequestration site have the potential to interfere with mineral extraction in the area.

Mining

The Colorado Division of Reclamation, Mining, and Safety map viewer (https://maps.dnrgis.state.co.us/drms/Index.html?viewer=drms) was search in 2024 for locations of surface and subsurface mining operations. Active mining operations in the vicinity of the Front Range 1-1 are surface mines for sand, gravel, and construction materials (Figure A.I.2-12). Due to the shallow depths of these mining operations relative to the depth of the Lyons injection reservoir, sequestration activities should not affect mining activities in this area, nor should mining activities impact the sequestration project.

Figure A.I.2-12. Mining Sites Near FR 1-1

Location of Front Range 1-1 well relative to mining sites in the area. Adapted from: https://maps.dnrgis.state.co.us/drms/Index.html?viewer=drms



Oil and Gas Production

To assess oil and gas drilling and production activities proximal to the Front Range 1-1 site, multiple shapefiles were captured from publicly available sources and imported into an ArcGIS project (Figure A.I.2-13). Shapefiles for oil and gas well surface locations, as well as directional well lines were captured from the Colorado Energy and Carbon Management Commission (ECMC) website. The resulting map compiled from this data shows that this area is very active with horizontal oil and gas drilling and production. Primary reservoirs targeted for Oil and Gas production in this area are Cretaceous age intervals that are located well above the primary and secondary confining zones for the Lyons injection reservoir (Figure A.I.2-6). Based on this data review, injection activities into the Front Range 1-1 Lyons reservoir are not expected to negatively impact oil and gas reservoirs in the area. Possible vectors and migration pathways for sequestered CO_2, including the Front Range 1-1 wellbore and nearby wellbores, are covered more thoroughly in Section B.5 of the Area of Review and Corrective Action Plan.

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A.I.6. Other Information (Including Surface Air and/or Soil Gas Data, if applicable)

Soil gas probes have been installed to monitor the soil (vadose zone) gas at the 5 ft bgs depth interval at the 6 monitoring stations for the preliminary site characterization. The average number of measurements from the probes was 32,267 for the November 21, 2023 to February 23, 2024 timeframe. Mean CO_2 concentrations were greater than 3,000 parts per million (ppm) at all stations. The atmospheric CO_2 concentration is currently approximately 412 ppm. These data illustrate some spatial and temporal variation of the recorded CO_2 concentrations that may potentially be associated with the soil, geology, vegetation types and surrounding land use.

Additionally, CO_2 effluxes were measured using a LiCOR gas analyzer in the field at ground surface at 16 soil collars and averaged for each of the 6 monitoring stations in December 2023. Mean CO_2 effluxes for the December 2023 sampling event ranged from 0.64 to 2.36 μmol m^{-2}-s^{-1}.

A.I.7. Site Suitability [40 CFR 146.83]

CSS believes the site is suited for the GS project. The specific requirements of 40 CFR 146.83 are addressed below:

A.I.7.1. Ability to Receive the Total Anticipated CO_2 Stream

The injection zone is of sufficient areal extent, thickness, porosity, and permeability to receive the total anticipated volume of the carbon dioxide stream. The Area of Review and Corrective Action Plan projects the areal extent of the AoR to be an asymmetrical shape with an areal extent of 6.4 mi^2 for the design basis of total injection of 1.54 million metric ton over a 12--year Injection period. This footprint for the GS project is well within the lateral limits of the-Lyons Sandstone at Front Range 1-1, and-furthermore the projection is based upon reasonable values for injection zone thickness, porosity, and permeability. See Section A.I.3 for further discussion of the lateral extent of the Lyons Sandstone injection zone across the AoR and vicinity, the thickness of the injection zone across the AoR and vicinity, and information on porosity and permeability across the AoR and vicinity.

A.I.7.2. Confining Zone Properties

The Lyons Sandstone will provide the entirety of the injection zone for the GS project. Primary upper confinement is provided by the Upper Satanka (Blaine and Opeche members of the Lykins) and secondary confinement is provided by the rest of the Lykins. The lower confining zone is provided by the Owl Canyon (Lower Satanka).

The confining zones are of sufficient areal extent and integrity to contain the injected carbon dioxide stream and displaced formation fluids and allow injection at proposed maximum pressures and volumes without initiating or propagating fractures in the confining zone. Section A.I.4.1 provides discussion on identified faults and fractures, which do not pose a concern for confinement. Integrity of the confining zones is examined in Section B.2.9 of the Area of Review and Corrective Action Plan. The computational model presented in the Area of Review and Corrective Action Plan shows pressure at the top of the injection zone should never exceed 90% of fracture pressure at the permit injection rate, thus preventing initiation or propagation of fractures during injection operations.

A.I.7.3. Properties of Additional Zones

The GS site has additional zones that will impede vertical fluid movement, allow for pressure dissipation, and provide additional opportunities for monitoring, mitigation and remediation. Secondary confining zones that will impede vertical fluid movement above the injection zone are the Lykins, Morrison, and several thick Cretaceous shales. CSS has does not believe that faults or fractures may interfere with containment within the AoR (see Section A.I.4.1 for further discussion). Additional opportunities for monitoring are discussed in monitoring well plans.

A.I.8. References

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