Evaluation of CO_2 Sequestration Potential for the State of Colorado: Ranking Criteria, Resource Assessment, and Storage Capacity

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CO_2 Sequestration Evaluation for Colorado State Lands

Executive Summary

The Colorado State Land Board (SLB) commissioned the Colorado School of Mines (CSM) to create an evaluation of SLB's acreage across the entire state as the final deliverable of a two-stage collaborative project. The SLB commissioned this work to further their endeavor to maintain safe, economic, and environmentally friendly stewardship of the state lands entrusted to them. Carbon Capture and Sequestration (CCS) is a critical component of state plans to meet future net-zero carbon emission standards as specified in the Colorado Greenhouse Gas Pollution Reduction Roadmap (Polis, 2021). CCS and storage operations reduce emissions of CO_2 into the atmosphere by capturing carbon dioxide (CO_2) at point sources, such as power plants or industrial facilities, and sequestering the captured CO_2 into underground geological formations permanently. Funding for this work was augmented through the DOE-IWEST project.

This study serves as a site-specific guideline for CO_2 sequestration evaluation at properties owned by the SLB and as an extension of the current literature on Colorado sequestration potential. In this report, we first present ranking criteria and other considerations that were evaluated when evaluating potential CO_2 sequestration projects on SLB lands. Using the criteria defined in this evaluation, key geologic formations, structures, and settings have been identified and a ranking methodology for characterizing the carbon storage potential of geologic formations and reservoirs was applied in Pueblo and El Paso counties (Phase 1) and the entire state (Phase 2, this report). We generated geologic models from the criteria and identified candidate formations for future development in carbon sequestration and storage operations. In this report, we first present a brief overview of the state geology, and of the ranking used for the evaluation of geosequestration potential for the SLB surface estate, then follow with a summary of the results of the statewide assessment, identifying target areas and formations.

1 Introduction

Carbon Capture, and Sequestration (CCS) is a critical component to meeting future net-zero carbon emission standards specified in the Colorado Greenhouse Gas Pollution Reduction Roadmap (Polis, 2021). CCS and storage operations reduce emissions of CO_2 into the atmosphere by capturing carbon dioxide (CO_2) at point sources, such as power plants or industrial facilities, and sequestering the captured CO_2 into underground geological formations permanently. Identification of potential geologic targets where CCS operations would have ample storage volume and permanence is critical to the success of such CO_2 sequestration projects in reducing the total atmospheric CO_2 concentration to meet future carbon emission standards. To meet climate goals, governments are increasingly incentivizing geologic carbon storage projects through tax credits. For example, the compilation by PricewaterhouseCoopers (https://www.pwc.com/gx/en/services/tax/green-tax-and-incentives-tracker.html) provides the various incentives offered by governments to promote Carbon Capture, Utilization, and Storage (CCUS) initiatives. Such tax incentives, for example the 45Q tax credit (https://www.federalregister.gov/documents/2021/01/15/2021-00302/credit-for-carbon-oxide-sequestration), encourage and provide the financial support for industry and state technologists to collaborate to sequester CO_2. State-owned lands offer the potential to serve as sites where such collaborations can be carried out.

The primary mission of the SLB has been the utilization and stewardship of working trust lands in the SLB estate for the funding and modernization of Colorado public schools. Utilization includes grazing, agriculture, mining, oil and gas leasing, recreation, and additional revenue generating activities. The state of Colorado is the 8th largest by area in the United States and consists of approximately 66.7 million acres. Of this acreage, the SLB owns 2.8 million surface acres and an additional 4 million sub-surface mineral acres, making the SLB the second largest landowner in the state. Across all the programs that the SLB is currently engaged in, it is charged with protecting the long-term economic value of the trust's physical assets in the estate acreage that they manage.

The state of Colorado has recognized CCS as an important element in achieving the state's economy-wide greenhouse gas (GHG) reduction goals (Colorado Energy Office, 2022). In 2003, as part of the Southwest Regional Partnership (SWP) on Carbon Sequestration project, the Colorado Geological Survey (CGS) evaluated the CCS potential by assembling CO_2 source and sink data, and estimated carbon storage capacity in Colorado (Young et al., 2007). Building on the Young et al. (2007) assessment, the current study evaluates of CO_2 storage potential and capacity for the state of Colorado.

Here, we outline and evaluate the CO_2 sequestration storage potential in the state of Colorado with a focus on the Colorado State Land Board (SLB) properties. This work serves as a site-specific guideline and as an extension of the current literature on the sequestration potential in Colorado statewide. We have identified ranking criteria and other considerations to evaluate when defining potential CO_2 sequestration projects for Colorado. The evaluating criteria (outlined in Phase I) include: key geologic formations, structures, physical properties, and structural settings. Using the criteria listed, a geologic model was generated identifying favorable candidate formations for future development in carbon sequestration and storage operations. The digital maps were provided separately for uploading to the SLB website. This report is intended to serve only as a guideline. It is not intended to be used for specific CO_2 storage sites. Note that in addition to storage operations, a sequestration project must meet, among other criteria, EPA requirements for Class VI well permitting before and long-term monitoring after storage operations. Data obtained were used to estimate the total CO_2 storage capacity of potential reservoirs across Colorado. The digital maps were provided separately for uploading to the SLB website.

The Phase 2 study proceeded along two different paths, evaluating many of the same formations, but did not completely overlap with respect to the formations evaluated. The first effort described here (Sections 4, 5, and 6) prepared isopach maps (thickness in feet) of formations considered to be the best targets for sequestration statewide. These included five primarily sandstone formations: the Cretaceous Codell Formation and Dakota Group, the Jurassic Entrada Formation, the Permian Lyons Formation, and the Permian-Pennsylvanian Weber Formation.

The second effort (Section 7) prepared estimates of CO_2 storage capacity in three large fields anticipated to have substantial storage capacity in Colorado: the Wattenberg Field near Denver, the Ignacio Blanco Field in the San Juan Basin, and the Wilson Creek Field in the Sand Wash Basin. The estimates were made using average properties for the field derived from studies of both oil and gas potential and carbon sequestration potential. Multiple formations were evaluated in each field, and seven different formations were evaluated. These included the

Cretaceous Sussex and Shannon units of the Pierre Shale, Niobrara and Codell Formations combined, and Dakota Group in the Wattenberg Field, the Cretaceous Mesaverde and Dakota Groups and Jurassic Morrison Formation in the Ignacio Blanco Field, and the Jurassic Morrison Formation and Entrada Formation in the Wilson Creek Field. This effort also evaluated the potential of storage in saline aquifers in eight formations across Colorado, using the same major studies to derive average properties for the formations. These included the Cretaceous Dakota Group and Mesaverde Formation, Jurassic Morrison Formation and Entrada Formation, Permian Lyons Formation, Permian-Pennsylvanian Weber Formation, Pennsylvanian Hermosa Group, and Mississippian Leadville Limestone.

2 Geologic History

The continental crust of current-day Colorado was assembled from a variety of island arcs accreted along the coast of the Archean Wyoming Craton approximately 1.7 billion years ago (Mueller and Frost, 2006). During the Colorado, Berthoud, and subsequent orogenies, granitic intrusions, uplifts, and rifts altered and disrupted coastal sedimentary rocks of this craton (Sims and Stein, 2003; Sims 2009). Approximately 300 million years ago, the Ancestral Rocky Mountains rose, and erosion of these mountains resulted in burial of older sedimentary rock by thick sheets of sediment across Colorado until the region became relatively flat (Kluth and Coney, 1981). Transgressional and regressional sea levels resulted in the deposition and erosion of additional sediment until the Laramide Orogeny approximately 70 million years ago. During the Laramide Orogeny, large-scale uplift and subsequent crustal deformation resulted in formation of uplifted mountain blocks and adjacent intermontane structural basins (such as the Uinta, Raton, and Denver-Julesburg [DJ] Basins. Erosion of uplifted Cretaceous and Cenozoic sedimentary rocks filled the orogenic basins, resulting in interlayered sandstone and shale sediments (Bird, 1998).

Colorado can be divided into three major topographic/geologic regions: the Colorado Plateau; the Southern Rocky Mountains; and the Great Plains (Figure 1). Phase 1 of this study (Pueblo and El Paso counties) lies on the border between the Southern Rocky Mountains, and the Great Plain (Figure 1). This phase (Phase 2) of the study covered the entire state. Figure 2 shows major faults that in part delineate these regions.

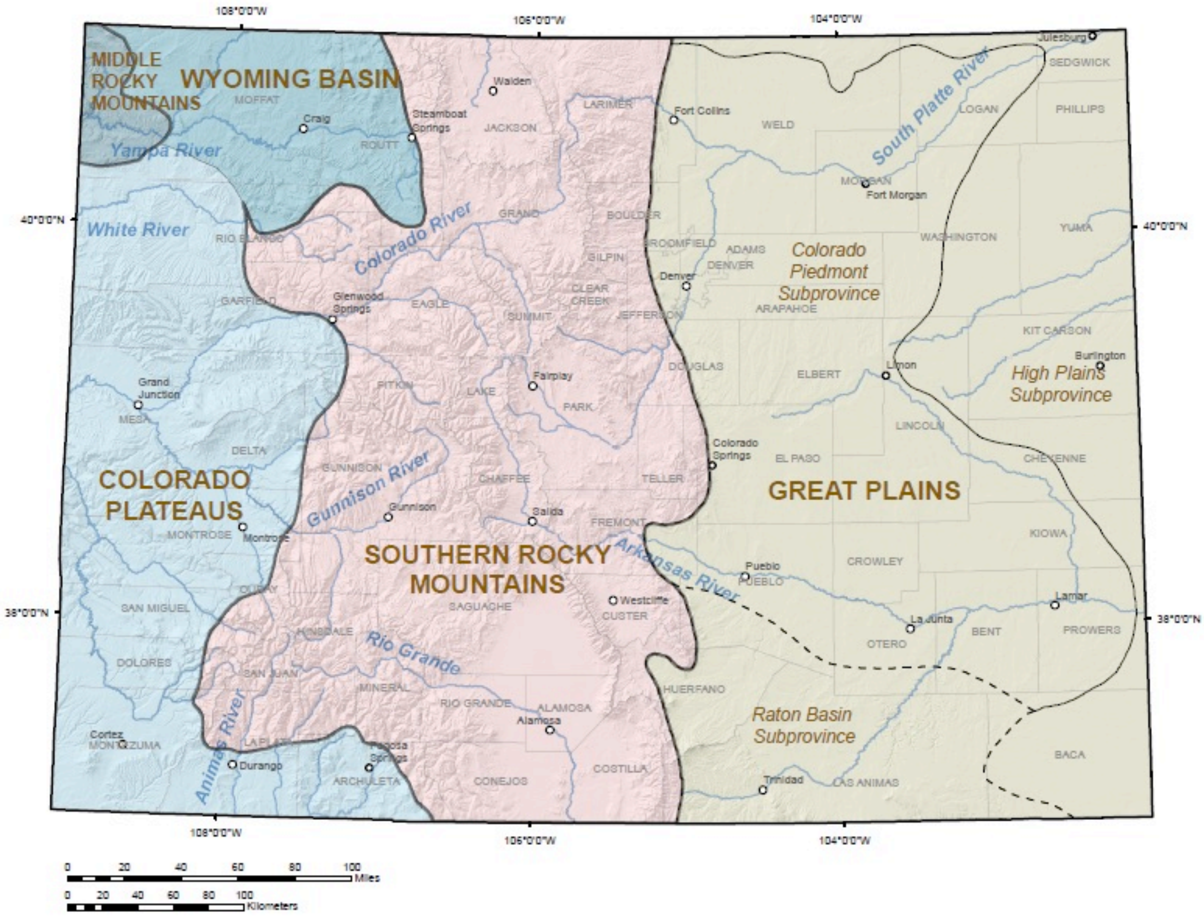

Figure 1: Major geographic and topographic zones for Colorado (Barkmann et al., 2020).

3 Previous CO_2 Sequestration Evaluations

Colorado has significant large-scale geologic CO_2 storage potential due to the laterally extensive, interbedded clastic sedimentary rocks described above. Interbedded shale and sand-stone intervals allow for a variety of reservoir and seal formations that are potentially conducive to CO_2 storage and eventual permanence in the formations. CO_2 storage can occur in a variety of formations and locations, including oil and gas reservoirs, underground gas storage facilities, natural CO_2 fields, coalbed reservoirs, and deep saline aquifers. Permanence can be achieved

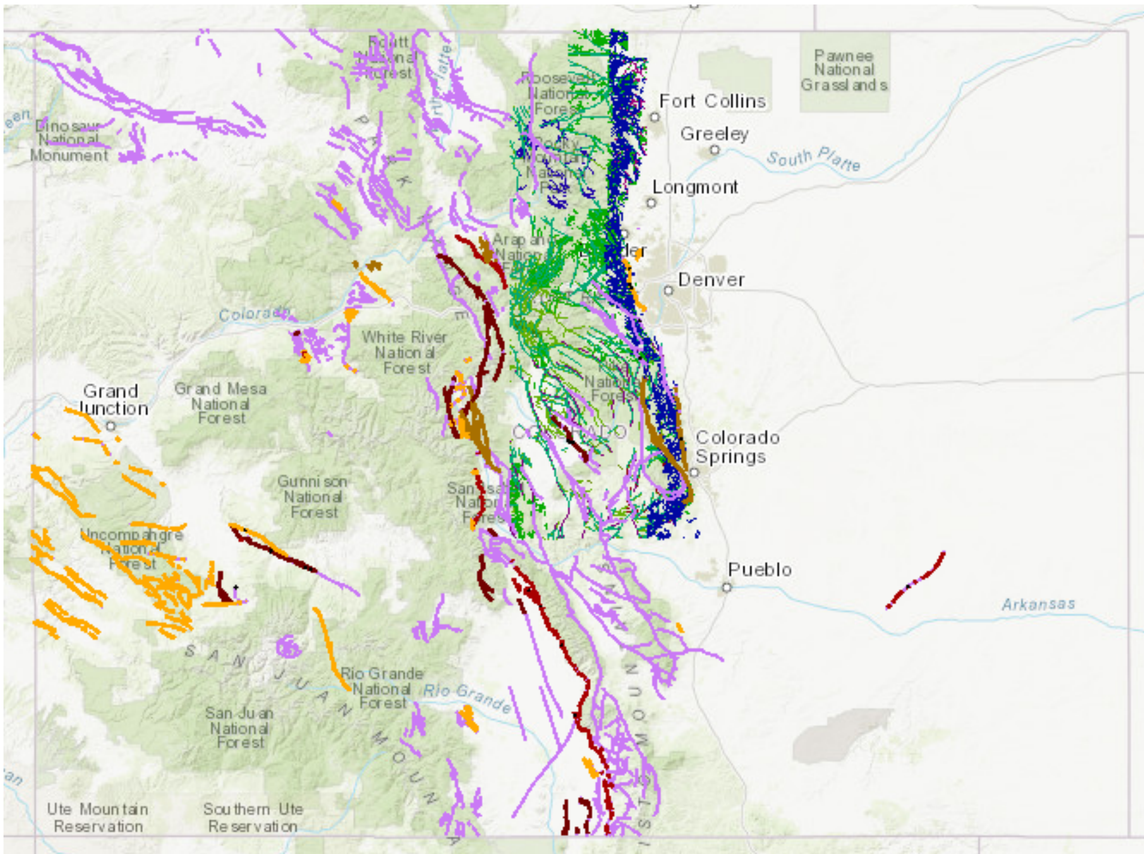

Figure 2: Map of Colorado showing major faults of Quaternary age (in shades of brown), Cenozoic age (pink), and Front Range faults (blue and green). GIS source: Colorado Earthquake and Fault Map Server (https://cgsarcimage.mines.edu/ON-001/).

through advanced mineralization processes in these reservoir types. SLB State Trust Lands in these reservoir areas are shown in Figure 3.

The Southwest Partnership for Carbon Sequestration (SWP), established in 2003 by the U.S. DOE, has studied the economic and technical feasibility of capturing and permanently storing CO_2 in Colorado. The partnership was charged with determining the best geologic formations and conditions for CO_2 sequestration in the American Southwest and contributing these findings to NETL's National carbon sequestration database and geographic information maps for CCS potential. The SWP in conjunction with the Colorado State Geological Survey identified the Cretaceous Dakota Sandstone, the Jurassic Entrada sandstone, and the Pennsylvanian Weber Sandstone as three of the most promising formations for geologic sequestration (McPherson, 2006; Young and others, 2007). The Cañon City region comprising western El Paso and Pueblo

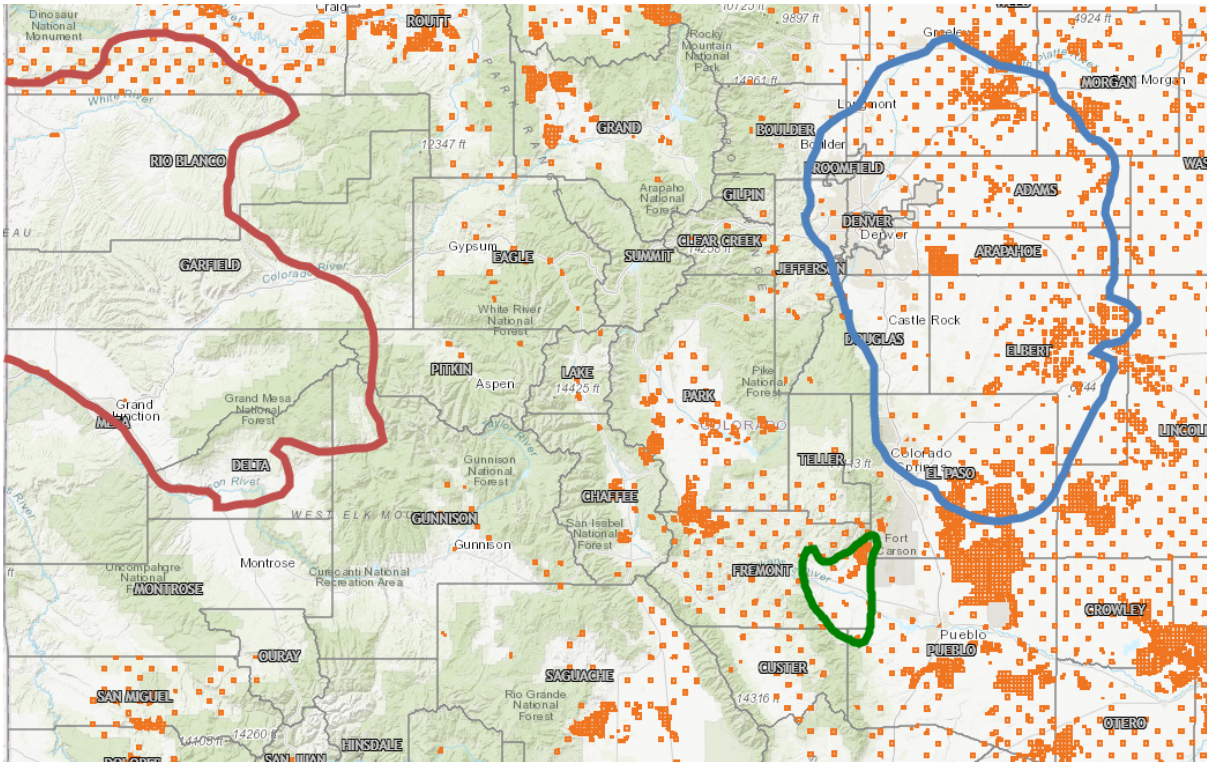

Figure 3: SLB State Trust Lands by county shown in orange located in the Piceance Basin (red outline), the Denver Basin (blue outline), and the Cañon City Embayment (dark green outline). Significant CO_2 storage opportunities exist in these basins as identified by Young and others (2007); SLB acreage within these locations should be assessed for future CO_2 injection operations

counties was estimated to have a total theoretical CO_2 sequestration potential of over 15 billion tons at 100% sequestration efficiency, with expected efficiencies as low as 15 percent (>2.25 billion tons) (Young et al., 2007). Efficiency is defined as the portion of the fluid and pore space that is physically capable of sequestering CO_2 within the volumetric limit dictated by pressure and temperature conditions. Actual efficiencies are limited due to permeable injection pathways into the formation, capillary trapping of interstitial fluids, and buoyancy effects from injection into the formation limiting accessibility of injected CO_2 into the formation.

In addition to the work performed by the SWP, the Great Plains Institute has found a combined storage potential of 773 billion metric tons of CO_2 in secure geologic saline formations in Colorado and Wyoming with further capacity in oil and gas fields (Abramson et al., 2022; Great Plains Institute, 2022). Whereas the existence of saline formations associated with SLB State Trust Lands was not verified in this study, existence of these formations has the potential for significant storage. Figure 4 outlines identified formations of interest in Colorado and their storage capacity in oil and gas fields as well as in saline aquifers, from Young and others (2007).

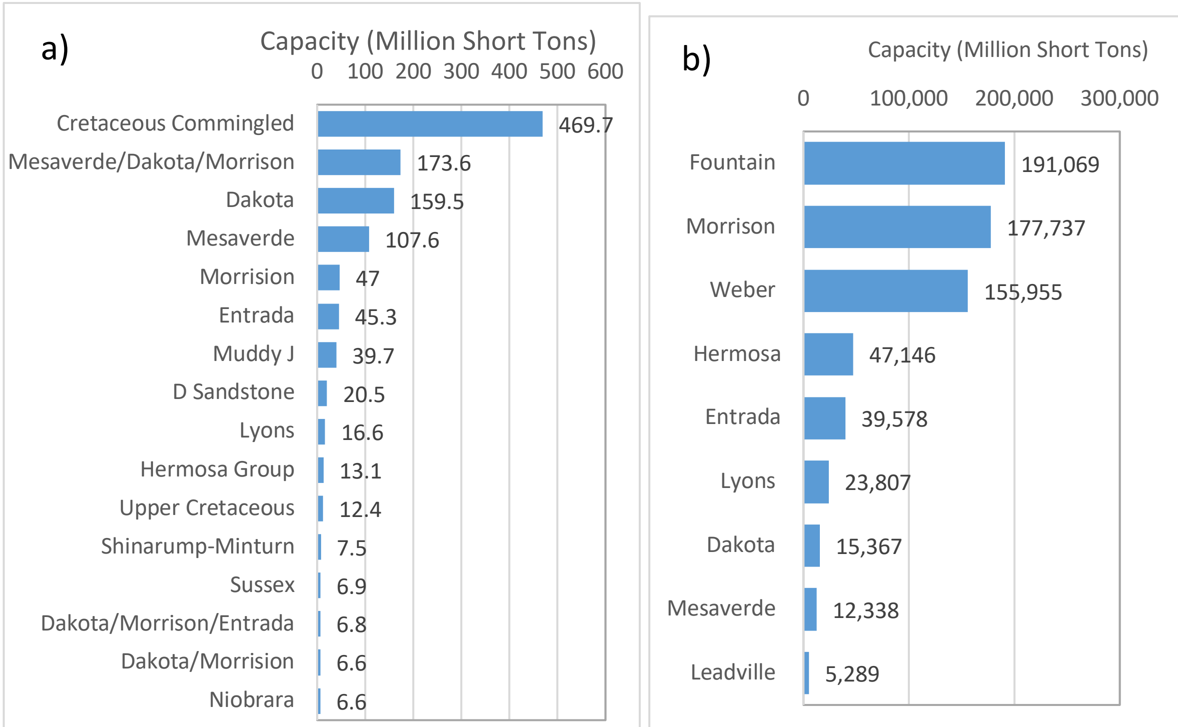

Figure 4: Estimated CO_2 sequestration storage capacity in Colorado a) in oil and gas-producing formations and b) in saline aquifer formations, for which values for 4% storage capacity are shown (data summarized from Young and others, 2007).

4 Key Geologic Features and Formation Ranking Criteria

Potential target formations for CO_2 sequestration should be evaluated by a variety of criteria including reported pore volume capacity (thickness and porosity), matrix permeability, formation fracture characteristics related to both injectivity and to escape and migration, regional stress state, potential for induced seismicity, and existing infrastructure, especially oil and gas wells penetrating the reservoir interval. In addition to these reservoir parameters, overlying seal formation integrity needs consideration for ensuring storage containment, and geochemical formation compatibility with injected CO_2 for ensuring storage permanence. Here, we outline key features of the geologic structures that are appropriate for carbon storage.

4.1 Reservoir Formations:

Formation evaluation of reservoir intervals in CO_2 sequestration operations centers on characterizing formation storage capacity and the ability to inject into the formation. Formation thickness, lateral extent, and porosity determine ultimate storage volumes of the reservoir. Ideal geologic conditions for reservoir formations include: a thick, laterally extensive and continuous interval with high porosity. High matrix permeability with the presence of fractures allows for high injectivity into the formation. Geomechanical properties such as formation stiffness and fracture potential also control how much CO_2 can ultimately be injected into tight reservoir sections. Slight structural dips and formation fractures may allow buoyancy of injected CO_2 to reach further into formation intervals with fewer injectors. Geochemistry of the reservoir should be compatible with CO_2 sequestration mechanisms and allow greater volumes of CO_2 to be ultimately stored. An additional factor can contribute to permanence, namely reactivity potential. When CO_2 is introduced into formations with reactive minerals such as mafic and ultramafic formations or certain carbonate formations, secondary mineralization processes can occur with varying timescales. These processes lock CO_2 into stable secondary minerals, permanently sequestering the CO_2 (Kelemen et al., 2019).

4.2 Seal Formations

A desirable CO_2 injection reservoir must have an accompanying seal formation to keep CO_2 in place. Ideal geologic conditions for seal formations include low permeability with low porosity, and the absence of fractures that would allow CO_2 to pass through the formation interval and migrate away from the storage target. In addition to having little storage capacity and injectivity, seal formations should be continuous and thick with mineralogy that doesn't react with CO_2. Fracturing of the seal formation with increased reservoir pressures from CO_2 injection is highly undesirable. An important factor to consider is the potential for CO_2 to migrate into seal formations through diffusion. Although diffusion is a geologically slow process, recent studies (Kumar et al., 2015) indicate the possibility of CO_2 migrating in the dissolved state into organic-rich components of seal formations. Detailed assessments of storage potential and storage capacity should assess the leakage and storage potential in seal formations.

4.3 Pressure-Temperature Conditions

In conjunction with the outlined properties of optimal reservoir and seal formations, depth is an additional criterion: the target formations must be deep enough in the basin so that injected CO_2 stays in the liquid, or ideally, supercritical state. This requirement on the CO_2 phase is generally met for injection depths greater than 3000 ft. For especially deep reservoir intervals, injection pressures of CO_2 can be prohibitively expensive and may approach the fracture gradients, thus potentially compromising formation integrity. Reservoir intervals should be chosen to be below the critical injection depth, but not so deep as to make injection pressures prohibitive and uneconomic. In addition, a lack of critically stressed faults and low horizontal stresses can aid in reducing formation fracturing and induced seismicity from CO_2 injection mechanisms. A low induced seismicity risk is important for gaining public support and trust, and to ensure safety associated with CO_2 storage operations. These safety considerations also ensure the infrastructure integrity of CO_2 projects. Desirable attributes of these formation properties are summarized in Table 1.

4.4 Identification of Potential CO_2 Sequestration Targets in all Colorado SLB Properties

To identify potential CO_2 storage targets, we used formation criteria outlined in this section to identify formations that meet the requirements for geologically relevant reservoir intervals with overlying seal integrity. Note that the identification of reservoir intervals and their thicknesses in the geologic model presented here should serve as guidance for further refinement using site-specific data from the selected location. Given the geologic and topographic diversity in the state, this report differentiates between SLB estate lands in Eastern and in Western Colorado. By analyzing stratigraphic sequences from wells in our geologic model and evaluating formation properties of the varying formations of interest, varying geologic formations of interest were identified as targets for future CO_2 storage in Eastern and Western Colorado.

Formation candidates identified for CO_2 sequestration in Eastern Colorado ranked from the most to the least promising are:

1) Permian Lyons Sandstone

2) Jurassic Entrada Sandstone

3) Cretaceous Dakota Group

4) Cretaceous Codell Sandstone

For CO_2 sequestration in Western Colorado, formation ranking from the best to the least promising are:

1) Jurassic Entrada Sandstone

Table 1: Summarized desirability of formation attributes for carbon sequestration projects. Note: the cell color indicates whether the formation attribute is desirable when considering potential reservoir rocks and seal formations, or the injectability of CO_2.

			Formation Type		Fluid
		Major/Minor Attribute to Consider	Reservoir Rock	Seal	Injectibility of CO_2
Formation Attributes	High Porosity	Major	[green]	[red]	[green]
	High Permeability	Major	[green]	[red]	[green]
	Low Porosity	Major	[red]	[green]	[red]
	Low Permeability	Major	[red]	[green]	[red]
	Thickness	Major	[green]	[green]	[green]
	Reservoir Dip Angle	Major	[yellow]	[yellow]	[green]
	Lateral Continuity	Major	[green]	[green]	[green]
	Presence of Fractures	Major	[green]	[red]	[green]
	Critically Stressed Faults	Major	[red]	[red]	[red]
	Formation Stiffness	Minor	[green]	[green]	[green]
	Depths > 3000 ft	Major	[green]	[yellow]	[green]
	Reactivity with CO_2	Major	[green]	[red]	[yellow]
	CO2 Storage in Caprock	Minor	[green]	[green]	[green]
	Characterized Local Stress Regime	Minor	[green]	[green]	[yellow]
	Quantification of Anisotropic Horizontal Stresses	Minor	[green]	[green]	[yellow]

[green]	Desireable Formation Attribute
[red]	Undesireable Formation Attribute
[yellow]	Partially Desireable Formation Attribute

2) Cretaceous Dakota Sandstone group

3) Permian-Pennsylvanian Weber Sandstone

Some other formations were screened out in the beginning of this task, such as the Morrison Formation, but were found in the other task to have very substantial potential for storage. Unfortunately, time and resources did not permit adding this formation to the mapping exercise.

5 Generation of Geologic Model for Estimating Carbon Storage Capacity

To build a geologic model of formations of interest in this study, publicly available well log data for subsurface wells in the investigation area were input into IHS Petra™ (an integrated geologic/engineering mapping software package from IHS Markit), using the IHS locations shown in Figure 5. The publicly provided formation tops as identified in the well log data were used to generate formation extent and formation thickness (isopach) maps for each formation of interest. Users of this study are advised to verify and augment the information and maps provided by this report with detailed site-specific studies.

Formation tops were picked from available well logs using gamma ray, induction, sonic, and density logs for identifying formation type and formation horizons as outlined below. Well log information was extracted from the COGCC database in tiff file format and imported into Petra as IHS Raster logs. These raster logs were then depth corrected for each well and used for subsequent geologic picks in Petra. Geologic picks submitted to IHS from well operators as well as internal IHS picks were used to identify geologic intervals in Petra and were then evaluated for quality. Adjustments to picking locations were performed as needed to ensure proper formation picking from the imported log suite. Locations of wells with imported raster logs (Figure 5) were selected by availability of induction and sonic logs and distributed across the counties and SLB locations to ensure accurate calculations of isopach thickness across this study location.

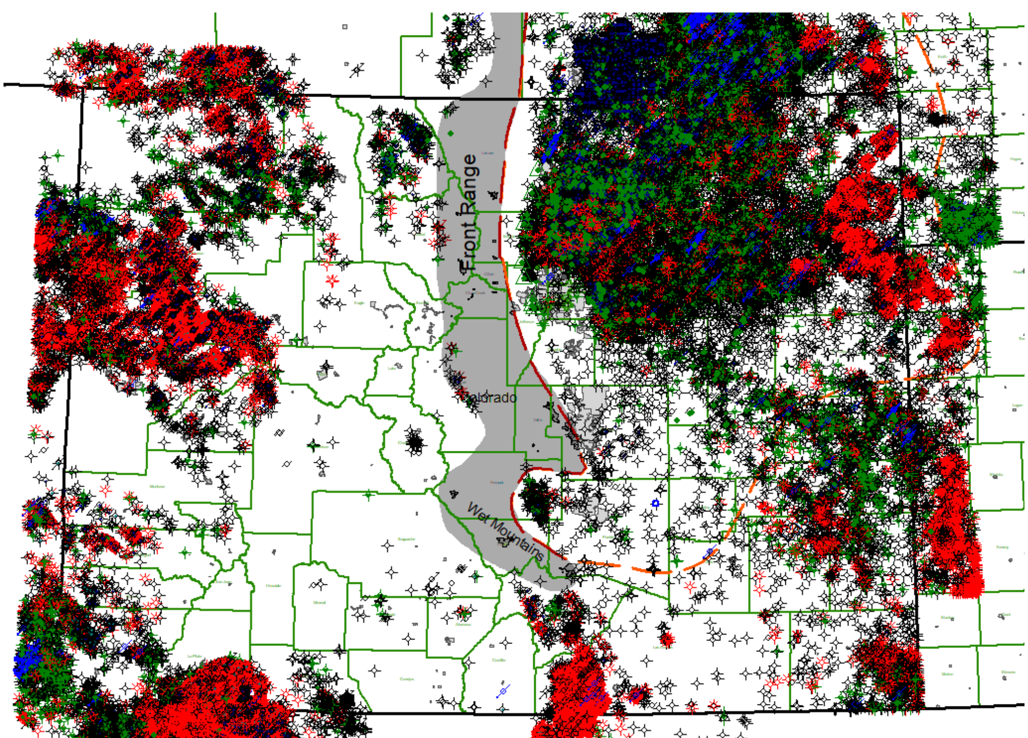

Figure 5: Imported well locations (shown in black, red, blue, and green) from IHS used to generate the geologic model for the state of Colorado. Note the high density of wells in petroliferous basins on the eastern and western slopes of Colorado.

In this study, interval definitions of each of the respective formations of interest were different due to the presence of different underlying or overlying stratigraphic units between Eastern and Western Colorado. In Eastern Colorado, the Permian age Lyons Formation was defined as the top of the Lyons down to the top of the Si Tanka (Santanka) Formation; the Jurassic age Entrada Formation was defined as the top of the Entrada down to the top of the Lykins Formation; the Cretaceous age Dakota Group was defined as the top of the Dakota-D down to the top of the Morrison Formation; and the Cretaceous age Codell Formation was defined as the top of the Codell down to the top of the Carlisle Formation (Figure 6). Some formations highlighted in Figure 6 and following figures are discussed only in section 6, and were not mapped as part of this section.

In Northwestern Colorado, the Jurassic age Entrada Formation was defined as the top of the Entrada/Sundance down to the top of the Lykins/Chinle Formation; the Cretaceous age Dakota Group was defined as the top of the Dakota-D down to the top of the Morrison Formation, and the Permian-Pennsylvanian age Weber Formation was defined as the top of the Weber down to the top of the Maroon Formation (Figure 7). In identifying the formation upper and lower bounds, and their thicknesses, the Dakota thickness in this study was calculated as a gross thickness of the entire Dakota Group, and not as a net thickness of the sandstone intervals. In Southwestern Colorado (Figure 8), formation boundaries for isopach thickness maps of the Dakota Group and Entrada Formation are the same as for Northwestern Colorado. Additional highlighted formations are discussed on section 8, which discusses CO_2 capacity of various formations, some of which were not included in the mapping study of this section.

Table 2 compares and summarizes the different formation picks for Eastern and Western Colorado. Geologic picks submitted to IHS from well operators as well as internal IHS picks were used to identify geologic intervals in Petra and were then used to create the geologic model. Generation of the geologic model was performed using a minimum curvature model or highly connected features model implementing a least squares algorithm selected for generation of the isopach thicknesses. Using these two methods, the best geologic model output was selected for the isopach thickness maps. Although IHS data provided statewide formation top depths used for creation of the geologic models, further evaluation of these logs to ensure consistency of formation picks independently would ensure accuracy of resulting models.

AGE	*STRATIGRAPHIC UNIT*
Upper Cretaceous	*Arapahoe Formation*
	Laramie Formation
	Fox Hills Sandstone
	Pierre Shale
	Parkman (Richards) Sandstone Member
	Terry (Sussex) Sandstone Member
	Upper Hygiene (Shannon) Sandstone Member
	Niobrara Family
	Smoky Hill Chalk Member
	Fort Hays (Timpas) Member
	Benton (Colorado) Group
	Carlile Shale
	Codell Sandstone Member
	Greenhorn Limestone
	Graneros Shale
	D Sandstone
	Mowry (Huntsman) Shale
Lower Cretaceous	*Dakota Group*
	Lower Muddy (J) Sandstone
	Skull Creek Shale
	Plainview (Dakota) Formation
	Lytle Formation (Lakota)
Jurassic	*Morrison Formation*
	Ralston Creek Formation
	Entrada (Sundance) Sandstone
Upper Triassic	*Jelm (Chugwater Group)*
Lower Triassic	*Lykins Formation*
Upper Permian	*Forelle Limestone Member*
Lower Permian	*Upper Santanka Shale*
	Lyons Sandstone
	Lower Santanka Shale
	Ingleside Formation
Permian/Pennsylvanian	*Fountain Formation*

Figure 6: Generalized stratigraphic column of the Denver Basin for Eastern Colorado formations of interest in this study (modified from Young et al., 2007). Formations mapped in this section are highlighted in yellow; formations discussed in section 7 are highlighted in light orange.

AGE	*STRATIGRAPHIC UNIT*
Eocene	*Green River Formation*
Eocene	*Wasatch Formation*
Paleocene	*Fort Union Formation*
Upper Cretaceous	*Lance Formation*
	Fox Hills Formation
	Mesaverde Group
	Williams Fork Formation (Almond, Ericson)
	Iles (Rock Springs) Formation
	Mancos Shale
	Morapos Sandstone Member
	Niobrara Member
	Carlile (Benton) Member
	Frontier Sandstone
Lower Cretaceous	*Mowry Shale*
Lower Cretaceous	*Dakota Group*
Jurassic	*Morrison Formation*
	Curtis Formation
	Entrada Sandstone
	Carmel Sandstone
	Nugget Sandstone
Triassic	*Chinle Formation*
	Shinarump Sandstone Member
	Moenkopi Formation
Upper Permian	*Phosphoria (Park City) Formation*
Lower Permian	*Weber Sandstone*
Pennsylvanian	*Morgan (Belden) Formation/Maroon Formation*
Mississippian	*Madison or Leadville Limestone*

Figure 7: Generalized stratigraphic column of the Sand Wash Basin for Northwestern Colorado formations of interest in this study (modified from Young et al., 2007). Formations mapped in this section are highlighted in yellow; formations discussed in section 7 are highlighted in light orange.

AGE	STRATIGRAPHIC UNIT
Upper Cretaceous	*Mesaverde Group*
	Mancos Shale
Lower Cretaceous	*Mancos Shale*
	Dakota Sandstone
	Burro Canyon Formation
Jurassic	*Morrison Formation*
	San Rafael Group
	Summerville (Wanakah) Formation
Jurassic	*Entrada Sandstone*
Jurassic	*Carmel Formation*
Jurassic	*Glen Canyon Group*
Jurassic	*Navajo Sandstone*
	Kayenta Formation
Upper Triassic	*Wingate Sandstone*
	Chinle Formation
	Shinarump Conglomerate Member
Lower Permian	*Cutler Group*
Pennsylvanian	*Hermosa Group*
	Honaker Trail Formation
	Paradox Formation
	Ismay Member
	Desert Creek Member
	Akah Member
	Barker Creek Member
	Pinkerton Trail Formation
	Molas Formation
Mississippian	*Leadville Limestone*
Devonian	*Ouray Formation*
	Elbert Formation
	Upper Elbert Member
	McCracken Sandstone Member
	Aneth Formation
Cambrian	*Ignacio Quartz*
Precambrian	*Precambrian Rocks*

Figure 8: Generalized stratigraphic column of the Paradox Basin for Southwestern Colorado formations of interest in this study (modified from Young et al., 2007). Formations mapped in this section are highlighted in yellow; formations discussed in section 7 are highlighted in light orange.

Table 2. Comparison of the formation names, ages, and upper and lower limits between Western and Eastern Colorado are summarized to allow easier comparison.

Location	**Eastern CO: Formation**	**Western CO: Formation**
	Cretaceous	
Formation	**Codell**	
Upper limit	Top of Codell formation	
Lower limit	top of Carlisle formation	
	Dakota	**Dakota**
Upper limit	Top of Dakota-D formation	Top of Dakota-D formation
Lower limit	Top of Morrison formation	Top of Morrison formation
	Jurassic	
Formation	**Entrada**	**Entrada**
Upper limit	Top of Entrada formation	Top of Entrada / Sundance formation
Lower limit	Top of Lykins formation	Top of Lykins / Chinle formation
	Permian	**Permian-Pennsylvanian**
Formation	**Lyons**	**Weber**
Upper limit	Top of Lyons formation	Top of Weber formation
Lower limit	Top of Si Tanka formation	Top of Maroon formation

6 Isopach Maps of Target Formations

Thicknesses for the isopach maps were calculated by subtraction of formation tops and bottoms. A contour map was then generated from the calculated thicknesses in the wells across the areas for the five identified targets by stratigraphic depth. Blank values for thicknesses in the isopach model occur where (1) there are insufficient well log data to choose individual well formation tops, (2) the model was unable to interpolate due to the sparseness of data or (3) the defined formation top or bottom is not present due to regional unconformities.

Due to the large area of study in this report, mapping results for the SLB estate in Colorado are presented as quadrants of the state (as shown in Figure 9). The Northwest quadrant of Colorado is defined as extending from the eastern boundary of Grand County to the border of Utah, and from the center of Mesa County to the Wyoming border. The Southwest quadrant of Colorado is defined as extending from the eastern boundary of Saguache County to the border of Utah, and from the center of Mesa County to the New Mexico border. The Northeast quadrant of

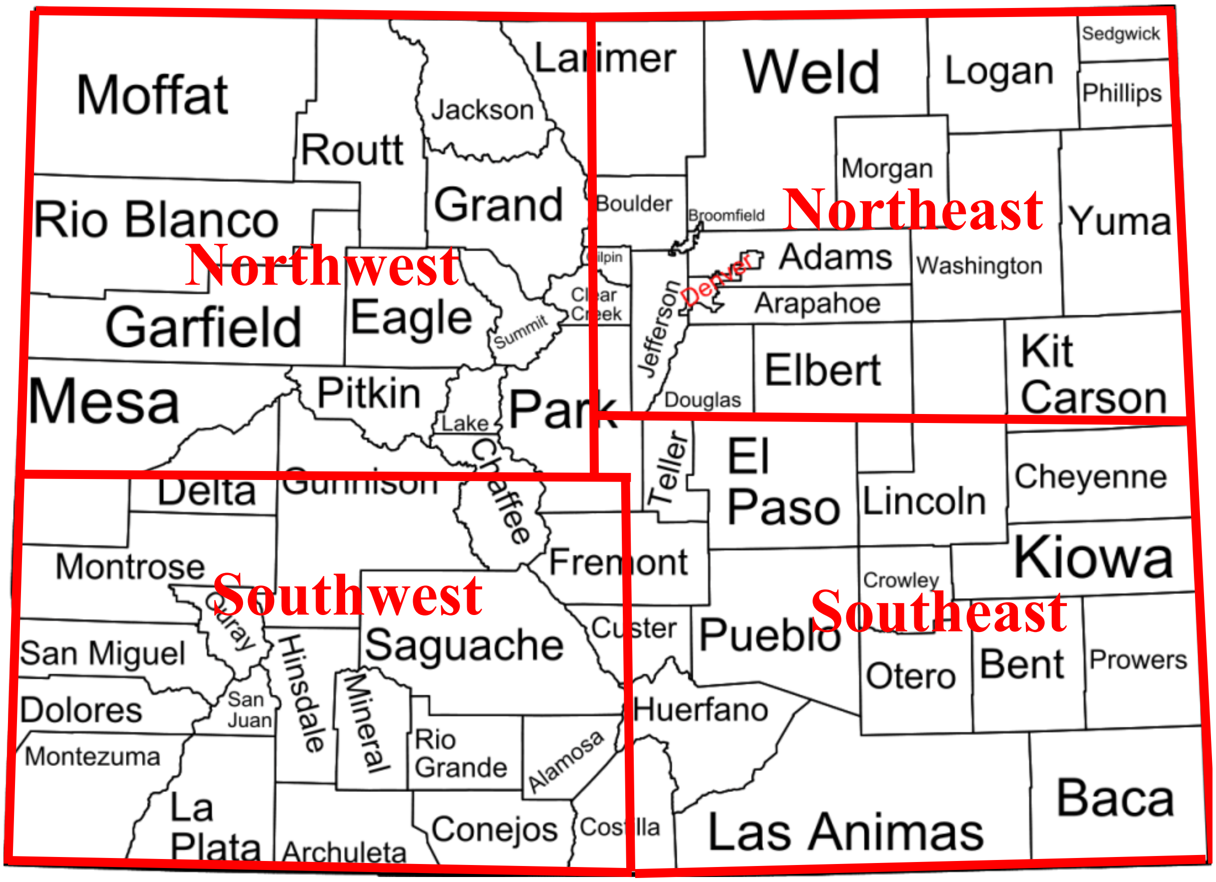

Figure 9: Quadrants of the state of Colorado (labelled in red) used to present the mapping results generated in this study.

Colorado is defined as extending from the eastern boundary of Grand County to the border of Kansas, and from the northern boundary of El Paso County to the Wyoming border. The Southeast quadrant of Colorado is defined as extending from the eastern boundary of Saguache County to the border of Kansas, and from the northern border of El Paso County to the New Mexico border. In the following subsections, the major formations of interests are presented for each quadrant.

6.1 Statewide Evaluation of the Permian Lyons Sandstone

The isopach maps of target formations modeled here provide a first level assessment of the storage potential for the state of Colorado . The primary target, the Lyons formation is only present in the eastern half of Colorado as shown by Figures 10 and 11. For ease of comparison, all quadrants are presented together in Figure 12. The Lyons sandstone has isopach thicknesses of greater than 50 ft for much of the Eastern Plains region of the state with increasing storage potential toward the Foothills in the western part of the eastern portion of the state. Isopach thicknesses of greater than 200 ft exists in Morgan, Weld, Adams, Arapahoe, Jefferson, Denver, Teller, and Douglas counties in the northeast quadrant of the state (Figure 10) and in Pueblo, Crowley, Otero, Bent, and northern Las Animas in the southeastern quadrant of the state (Figure 11). Particularly large thicknesses of the Lyons sandstone (>800 ft) exist in Crowley, Otero, and Bent counties in the Southeastern portion of the state make SLB acreage in these counties' potential targets for development of the Lyons sandstone layer.

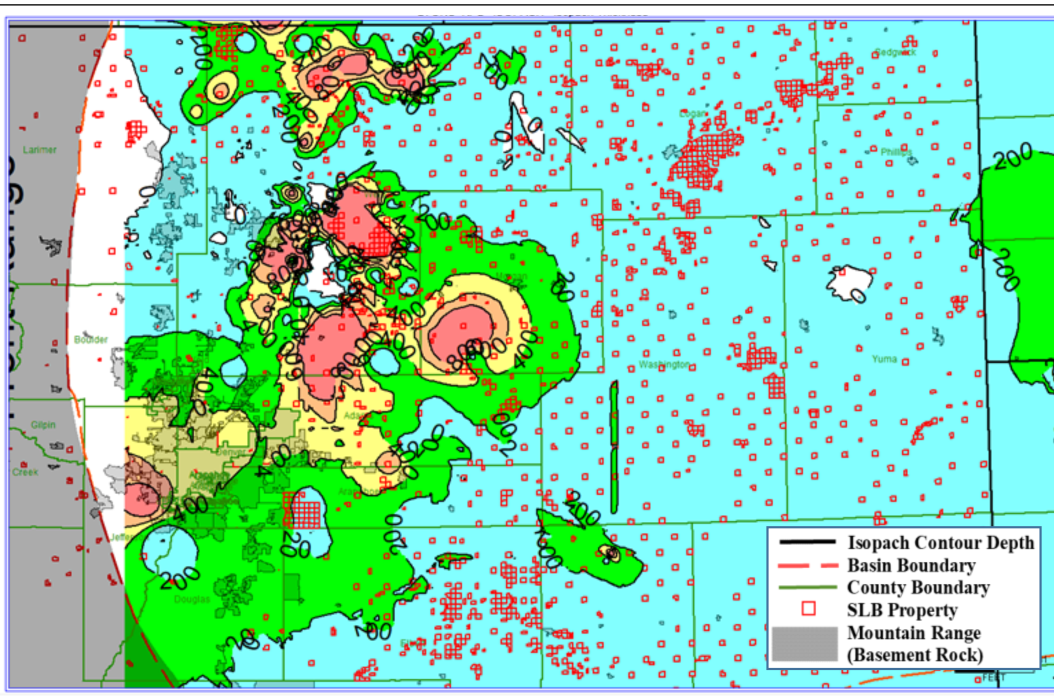

Figure 10: Isopach contour map (thickness in feet) of the Lyons Sandstone in the Northeast quadrant of Colorado.

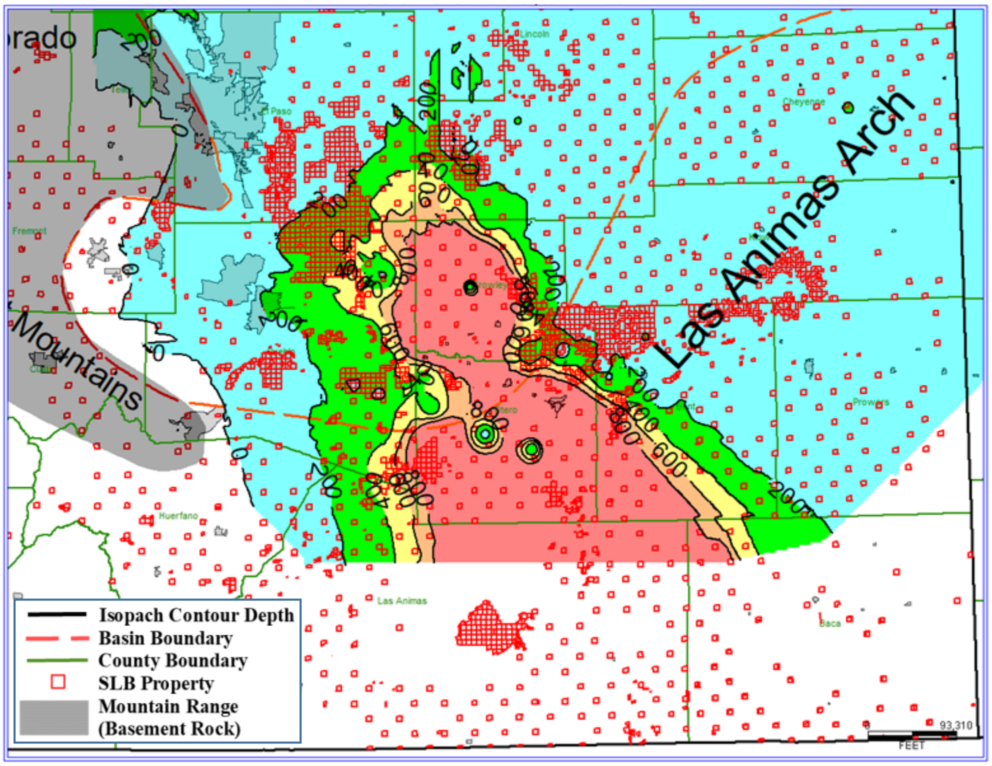

Figure 11: Isopach contour map (thickness in feet) of the Lyons Sandstone in the Southeast quadrant of Colorado.

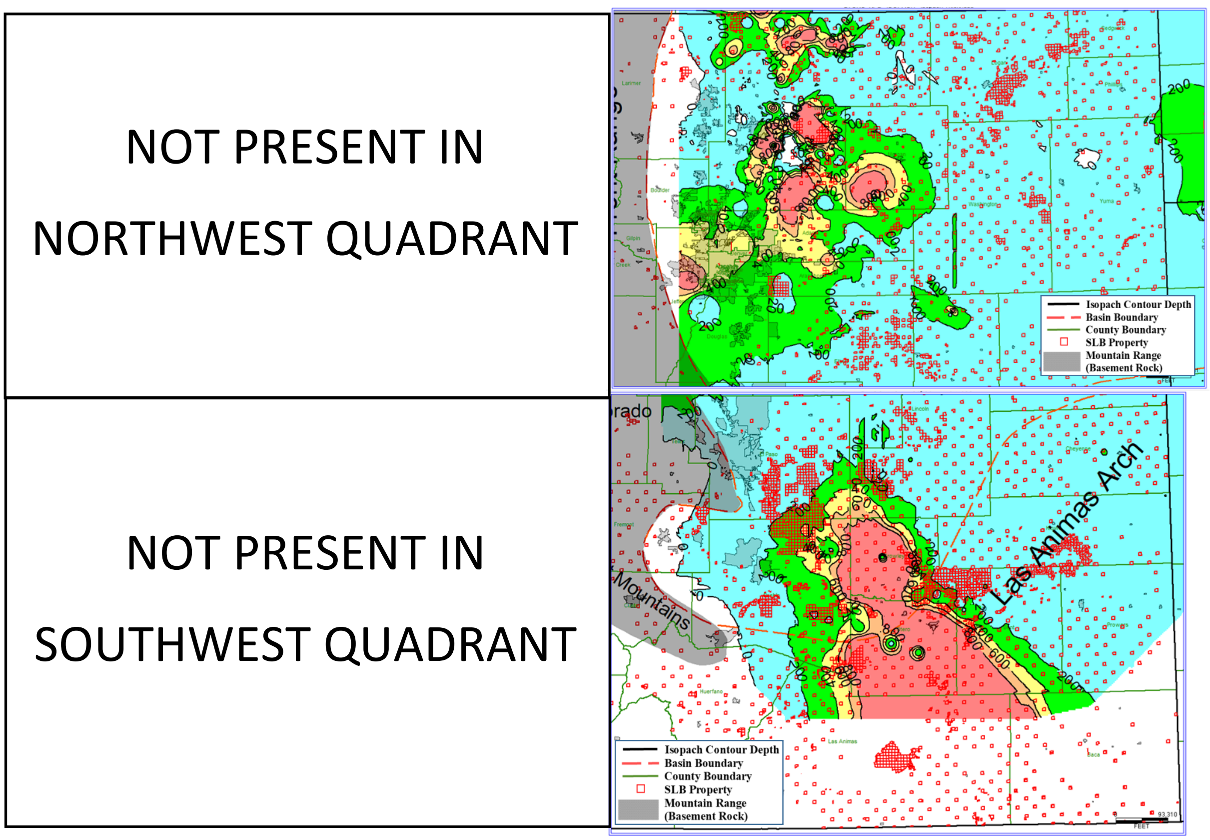

Figure 12: Combined isopach contour map (thickness in feet) of the Lyons Sandstone in the Northeast (upper) and Southeast (lower) quadrants of Colorado.

6.2 Statewide Evaluation of the Jurassic Entrada Sandstone

Sequestration potential in the second most favorable target, the Entrada Formation, exists across Colorado. As shown in Figures 13 to 16, the Entrada target is up to 800 ft thick in the western half of the state and up to 500 ft thick in the eastern half of the state. The Entrada sandstone shows thicknesses that increase to greater than 800ft in a westward direction in both the northwest and southwest quadrant of Colorado. Increasing thicknesses are observed in the Uintah and Sand Wash basins (Figure 13) and in the Paradox and San Juan basins (Figure 14). In the eastern half of the state, lower thicknesses are observed for the Entrada sandstone with greatest thickness in the deep portion of the Denver-Julesburg basin (Figures 15 and 16). The thickest portion of the Entrada in the eastern half of the state is east of Denver, in the southwest corner of Morgan County and in Larimer and Weld counties. Good potential locations for CCS operations in SLB acreage exist in these counties and along the Colorado –Utah border in the west. For ease of comparison, all quadrants are presented together in Figure 17.

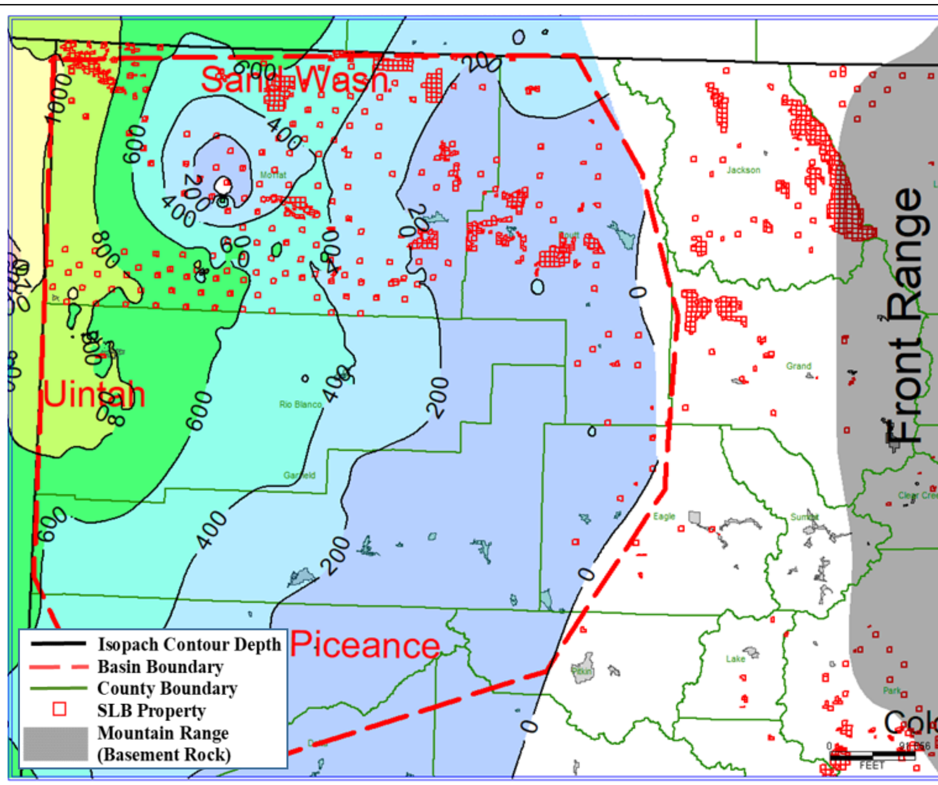

Figure 13: Isopach contour map (thickness in feet) of the Entrada Sandstone in the Northwest quadrant of Colorado.

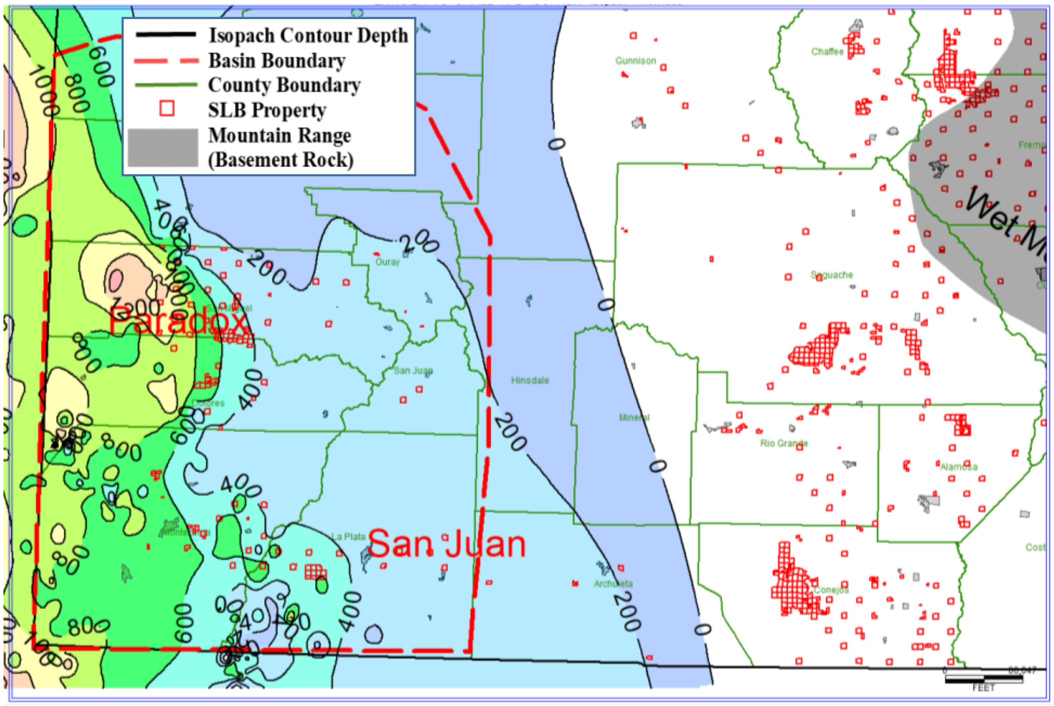

Figure 14: Isopach contour map (thickness in feet) of the Entrada Sandstone in the Southwest quadrant of Colorado.

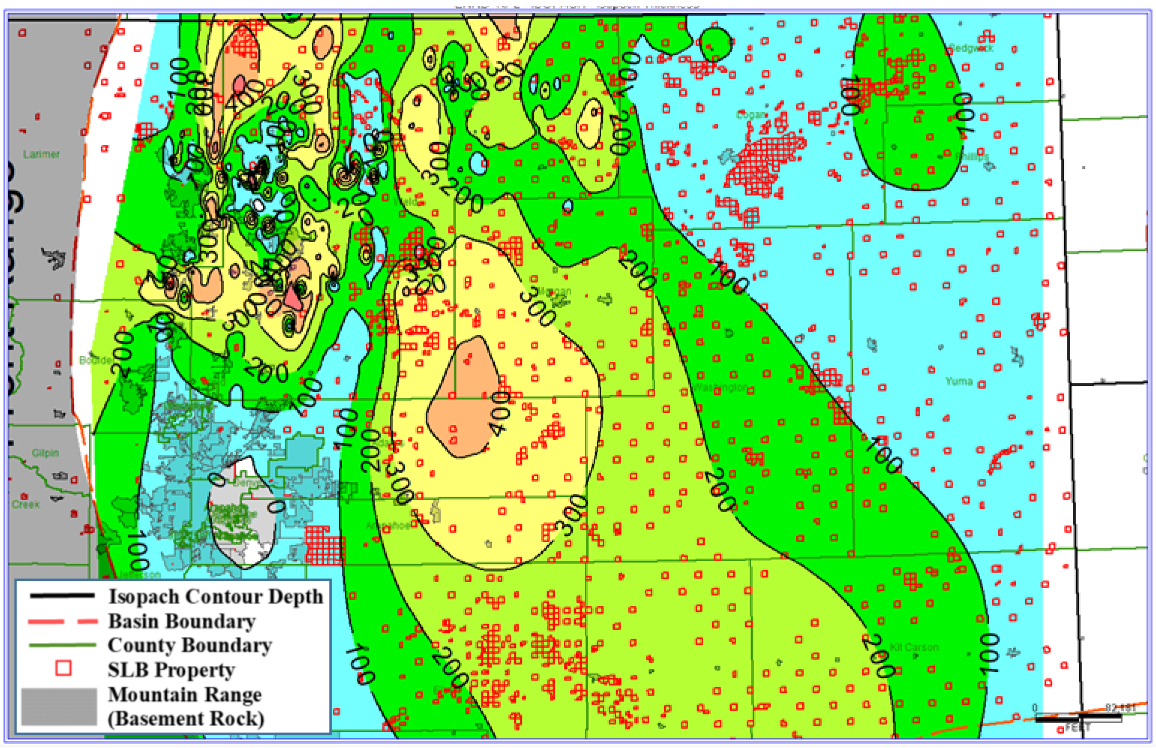

Figure 15: Isopach contour map (thickness in feet) of the Entrada Sandstone in the Northeast quadrant of Colorado.

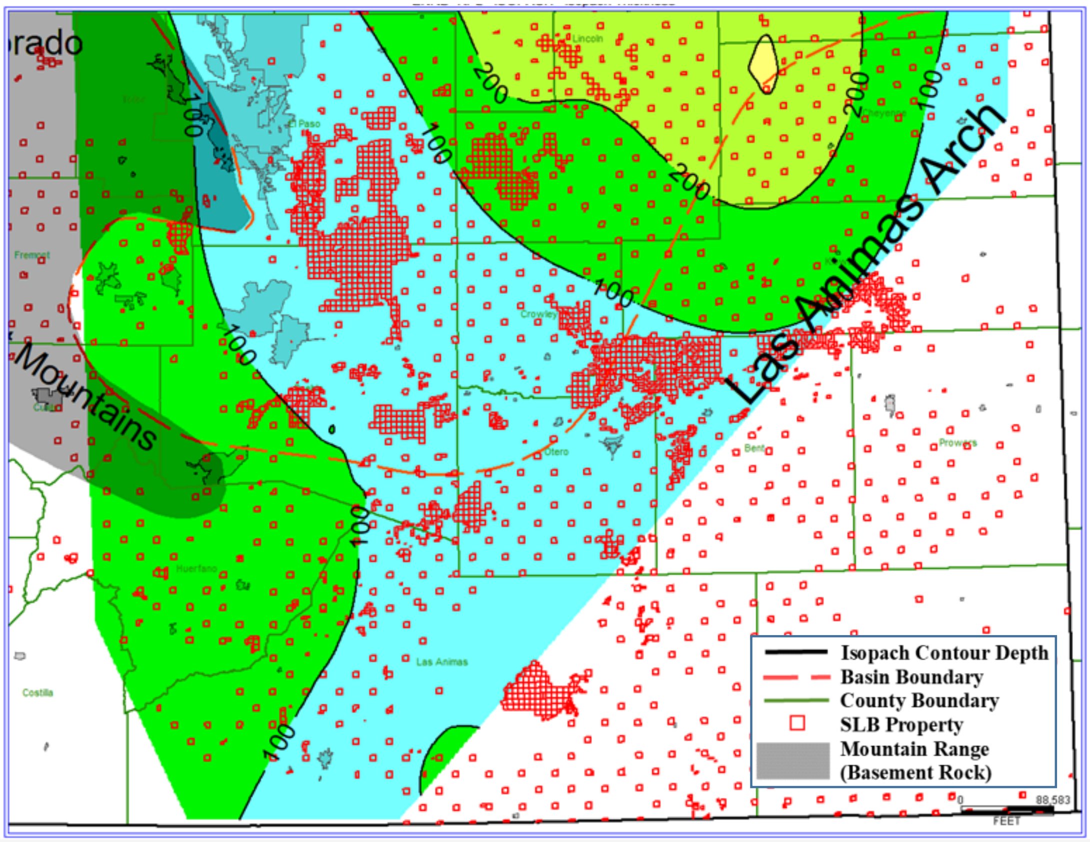

Figure 16: Isopach contour map (thickness in feet) of the Entrada Sandstone in the Southeast quadrant of Colorado.

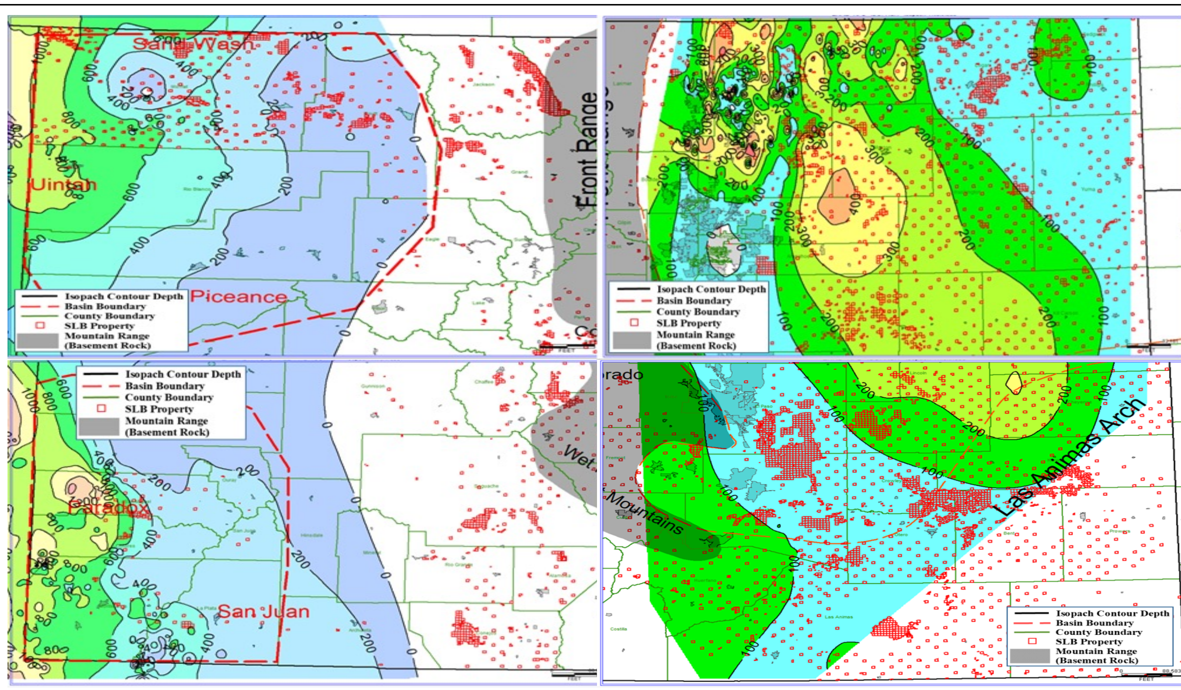

Figure 17: Combined Isopach contour map (thickness in feet) of the Entrada Sandstone in all quadrants of Colorado.

6.3 Statewide Evaluation of the Cretaceous Dakota Sandstone Group (Gross Thickness)

Isopach thicknesses derived from the geologic model for third most favorable target, the Dakota sandstone group, exists in both Western (Figures 18 and 19) and Eastern (Figures 20 and 21) Colorado. Formation thicknesses vary and reach a maximum thickness of approximately 400 ft in the western half to over 600 ft in the eastern half of the state.

The Dakota group has gross isopach thicknesses that increase toward the south in the western half of Colorado and increase toward the east in the eastern half of the state. Increasing thicknesses are observed in the Uinta (Fig. 18) and in the Paradox and San Juan basins (Fig. 19). Increased isopach thicknesses are observed on contiguous SLB lands in Logan County and in Bent and Kiowa counties making development of this acreage potentially very good for CCS. For ease of comparison, all quadrants are presented together in Figure 22.

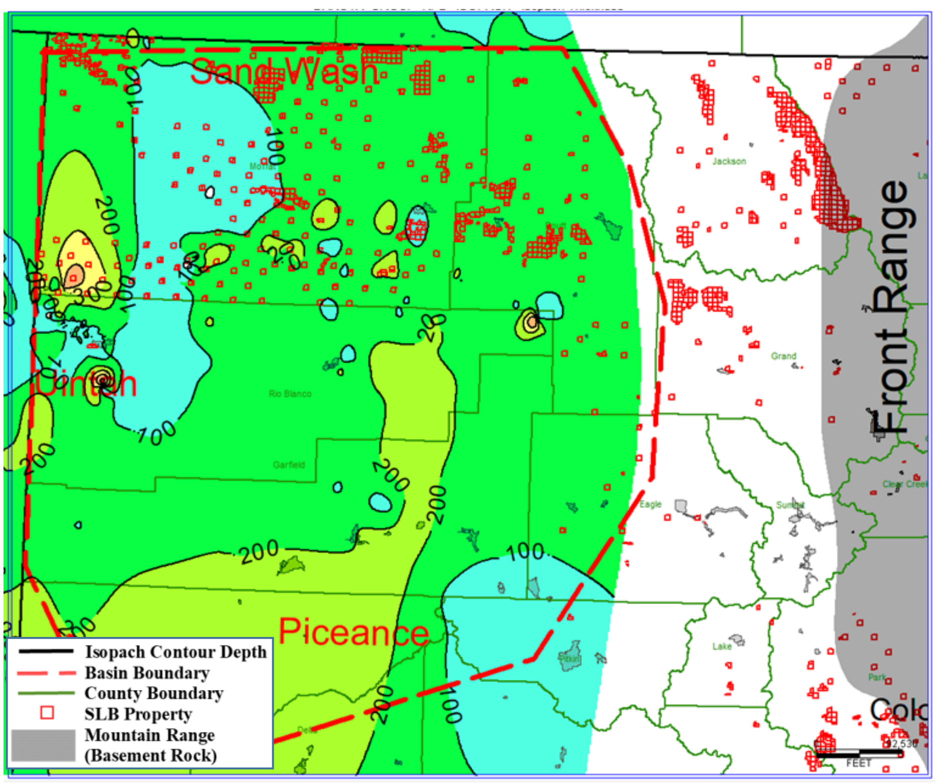

Figure 18: Isopach contour map of the Dakota Sandstone group in the Northwest quadrant of Colorado with units shown in feet.

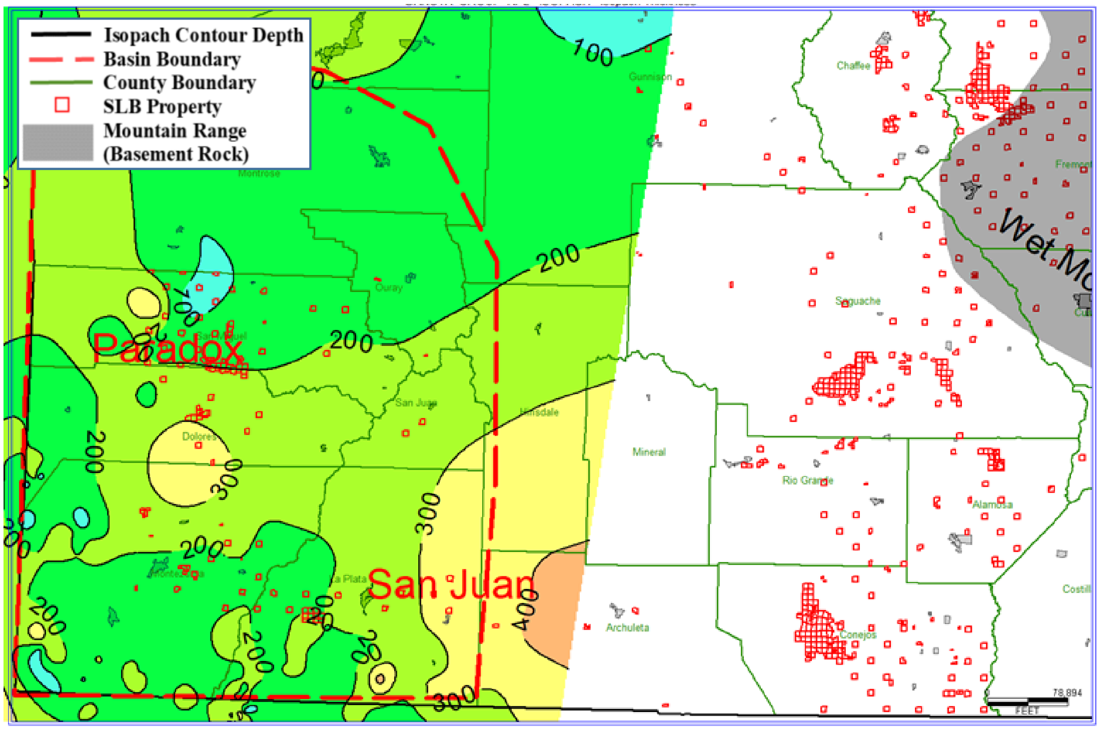

Figure 19: Isopach contour map (thickness in feet) of the Dakota Sandstone group in the Southwest quadrant of Colorado.

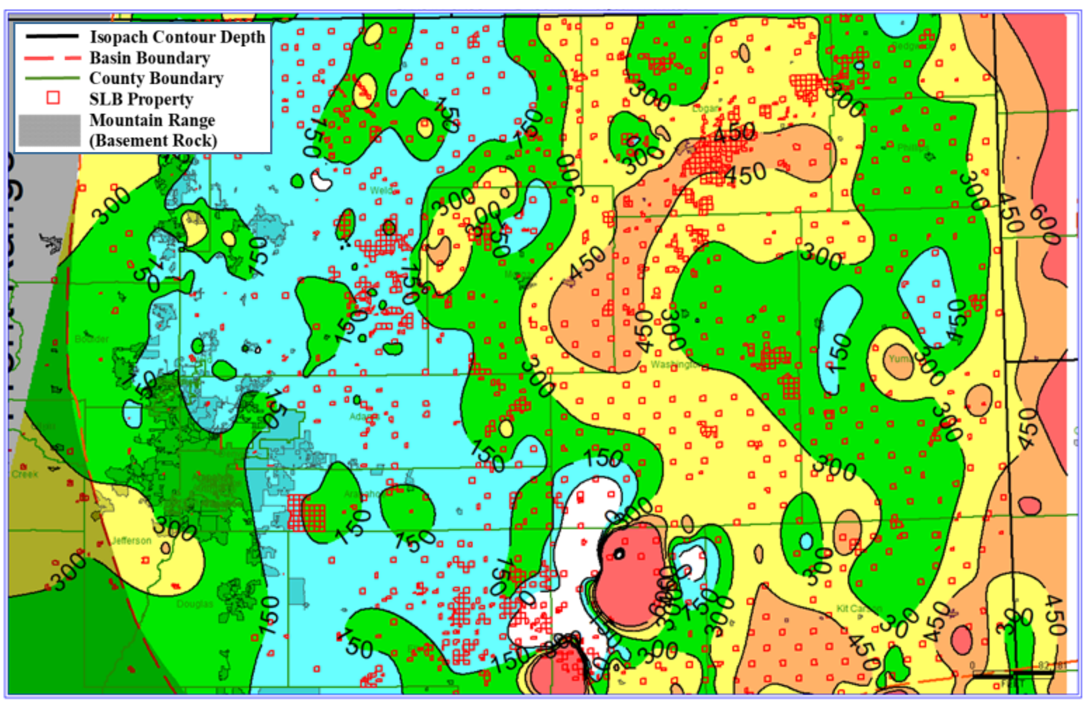

Figure 20: Isopach contour map (thickness in feet) of the Dakota Sandstone group in the Northeast quadrant of Colorado.

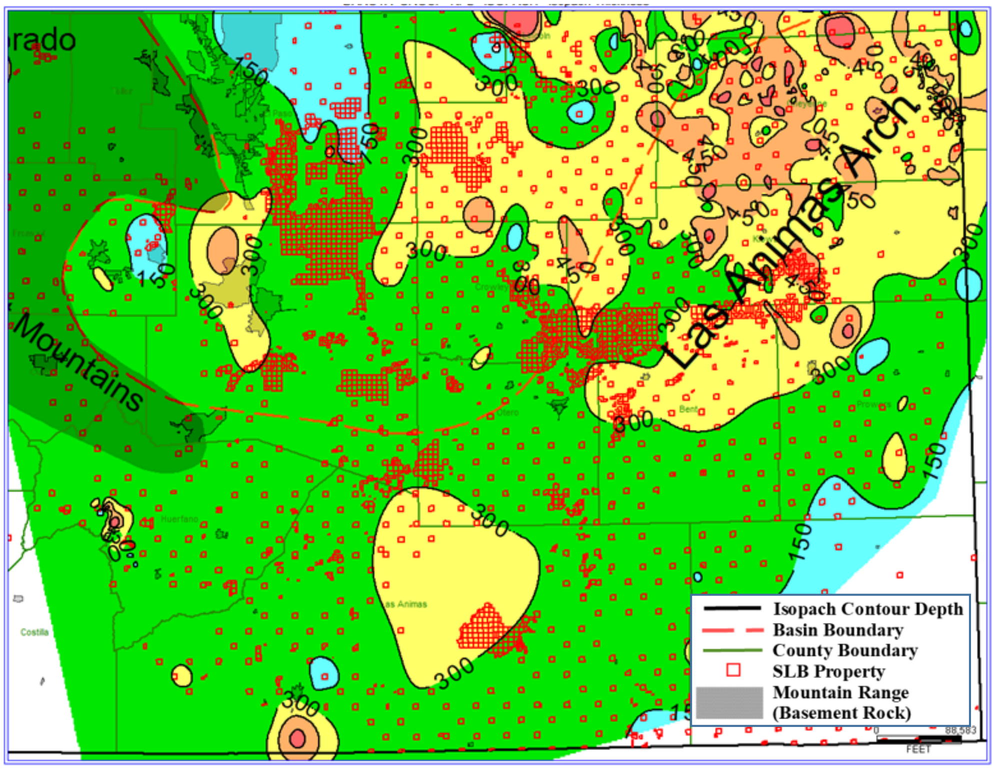

Figure 21: Isopach contour map (thickness in feet) of the Dakota Sandstone Group in the Southeast quadrant of Colorado.

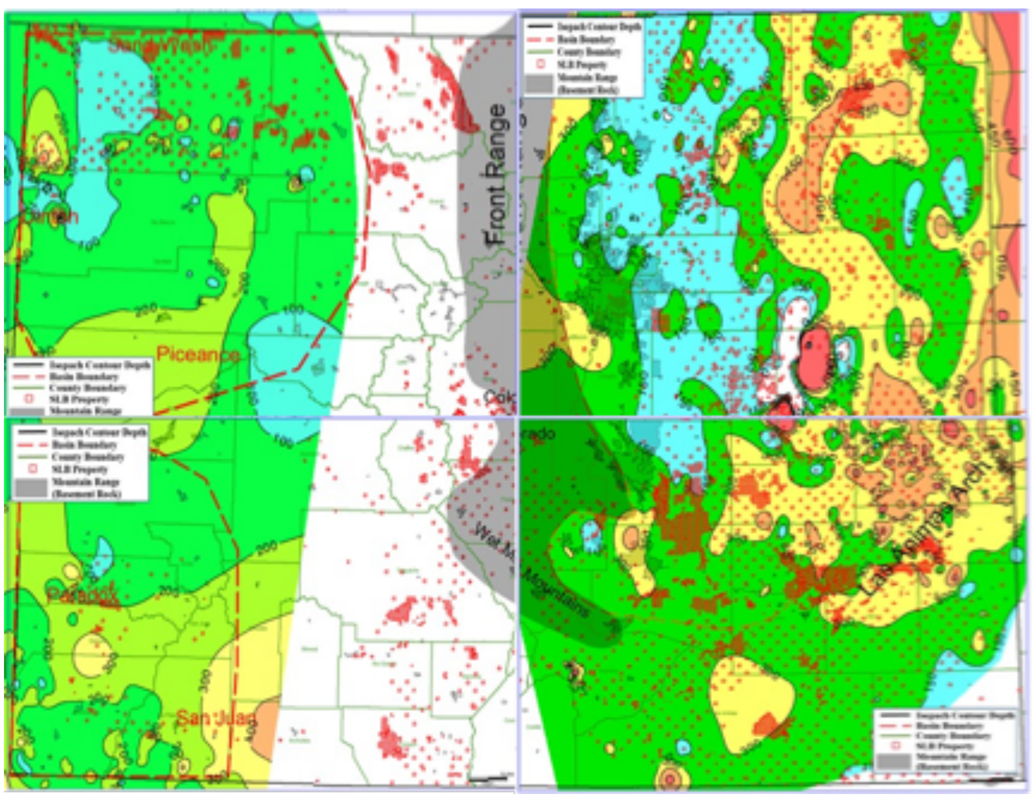

Figure 22: Combined Isopach contour map (thickness in feet) of the Dakota Sandstone in all quadrants of Colorado.

6.4 Statewide Evaluation of the Cretaceous Codell Sandstone

Sequestration potential for the Codell sandstone only exists in the eastern half of Colorado with isopach thicknesses reaching up to 80 ft in some portions of the state (Figures 23 and 24). Increased thickness of the Codell formation is observed along the Las Animas Arch and increasing toward the southeast (Fig. 24). Large thickness in SLB acreage is more common in the southeastern quadrant of the state and, particularly in contiguous SLB properties in northeast Bent and southern Kiowa counties. For ease of comparison, all quadrants are presented together in Figure 25.

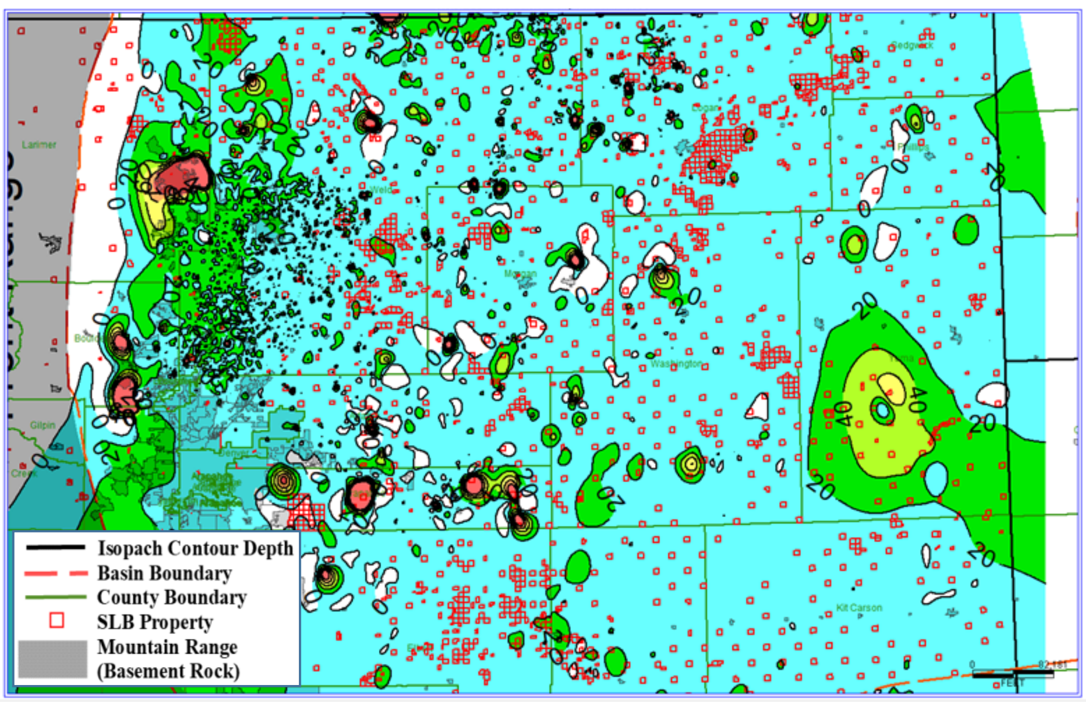

Figure 23: Isopach contour map (thickness in feet) of the Codell Sandstone in the Northeast quadrant of Colorado.

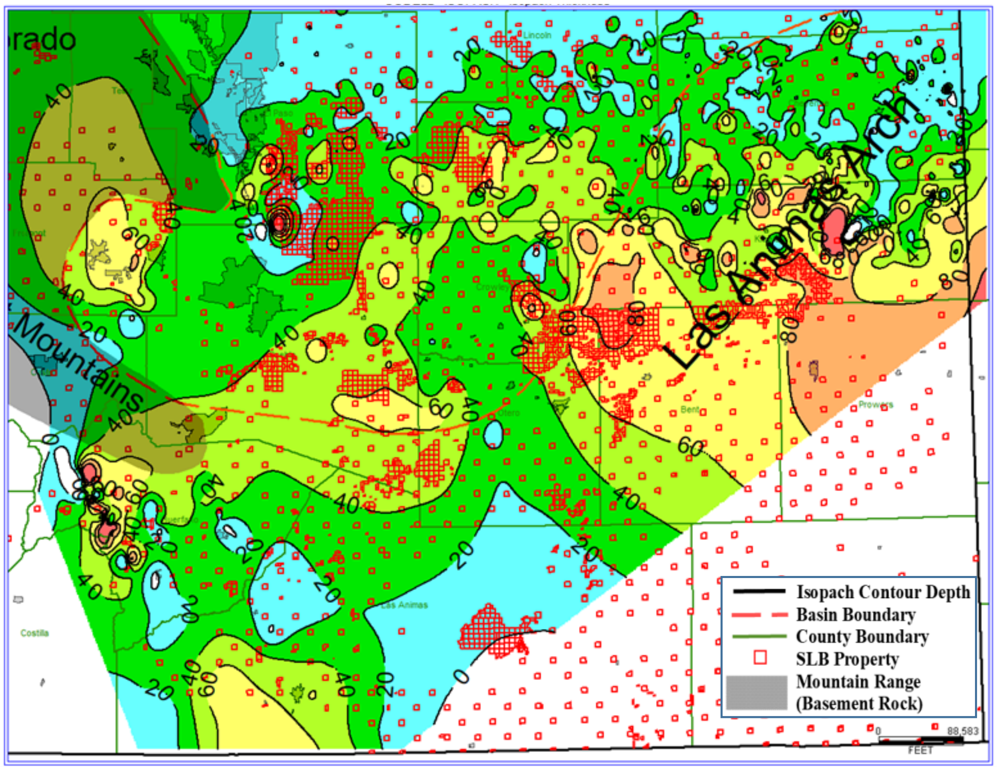

Figure 24: Isopach contour map (thickness in feet) of the Codell Sandstone in the Southeast quadrant of Colorado.

NOT PRESENT IN NORTHWEST QUADRANT

NOT PRESENT IN SOUTHWEST QUADRANT

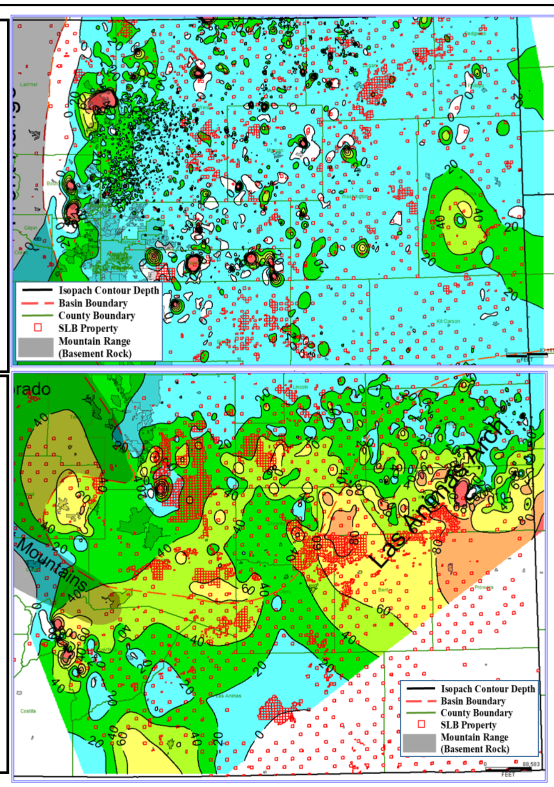

Figure 25: Combined Isopach contour map (thickness in feet) of the Codell Sandstone in the Northeast (upper) and Southeast (lower) quadrants of Colorado.

6.5 Statewide Evaluation of the Permian-Pennsylvanian Weber Sandstone

The Weber sandstone has been identified as an additional formation promising for CCS operations. As shown in Figure 26, the Weber sandstone is present only in the Northwest quadrant of Colorado in the Uintah, Piceance, and in part of the Sand Wash Basins. While thickness of the Weber isopach is promising, the SLB only has acreage in southern Moffat and southwest Routt counties that may benefit from completions of this formation. Although SLB acreage is limited in the Piceance Basin, this target is worth noting for potential further land acquisitions in this portion of the state.

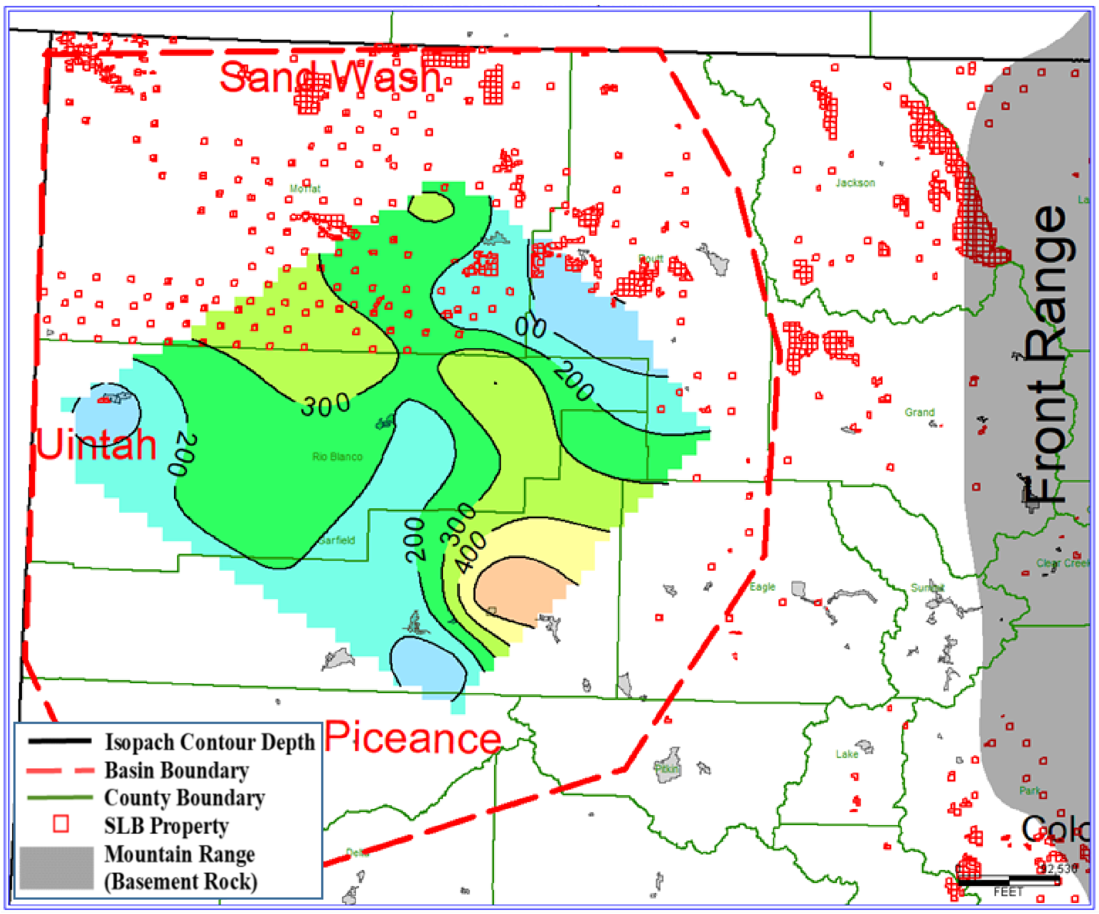

Figure 26: Isopach contour map (thickness in feet) of the Weber Sandstone in the Northwest quadrant of Colorado.

6.6 Statewide Evaluation of Total Isopach Thicknesses

In the outlined formations of interest for this report, isopach thicknesses can be used to estimate total carbon storage capacity in each respective formation, with thicker intervals showing larger reservoir volumes, and, as a result, being more amenable to storage of CO_2. Note that isopach maps should be refined using additional site-specific data and carefully assessing net-to-gross reservoir thickness. Here, we provide summed isopach thicknesses created from our geologic model (Figures 27-30).

CCS potential is best correlated to thicker total isopach values. Isopach thicknesses shown for the Northeast quadrant of Colorado understate the total formation thicknesses in the DJ Basin because many wells are drilled only to the Codell sandstone and hence data are lacking for the underlying geologic formations for much of the map area. Therefore, additional site-specific data and careful assessments of net-to-gross thickness are needed for the DJ Basin.

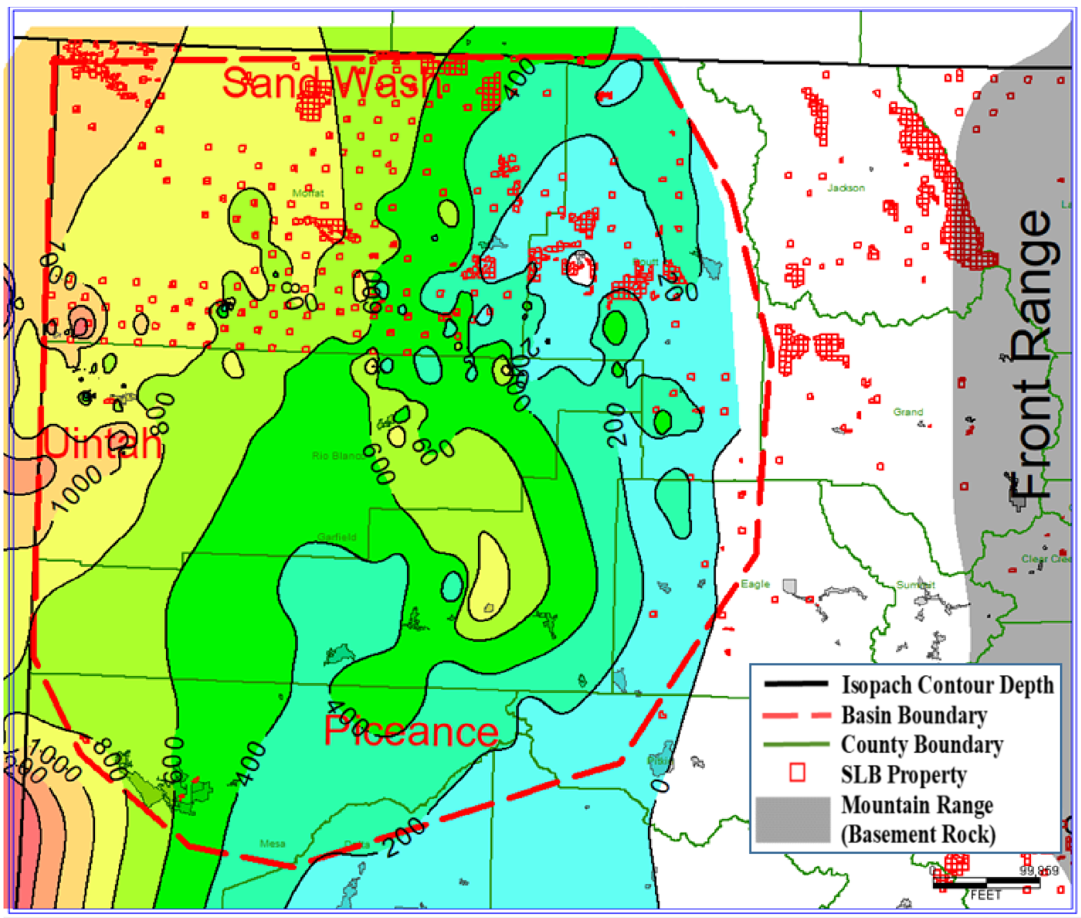

Figure 27: Isopach contour map (thickness in feet) of the formations of interest in the Northwest quadrant of Colorado.

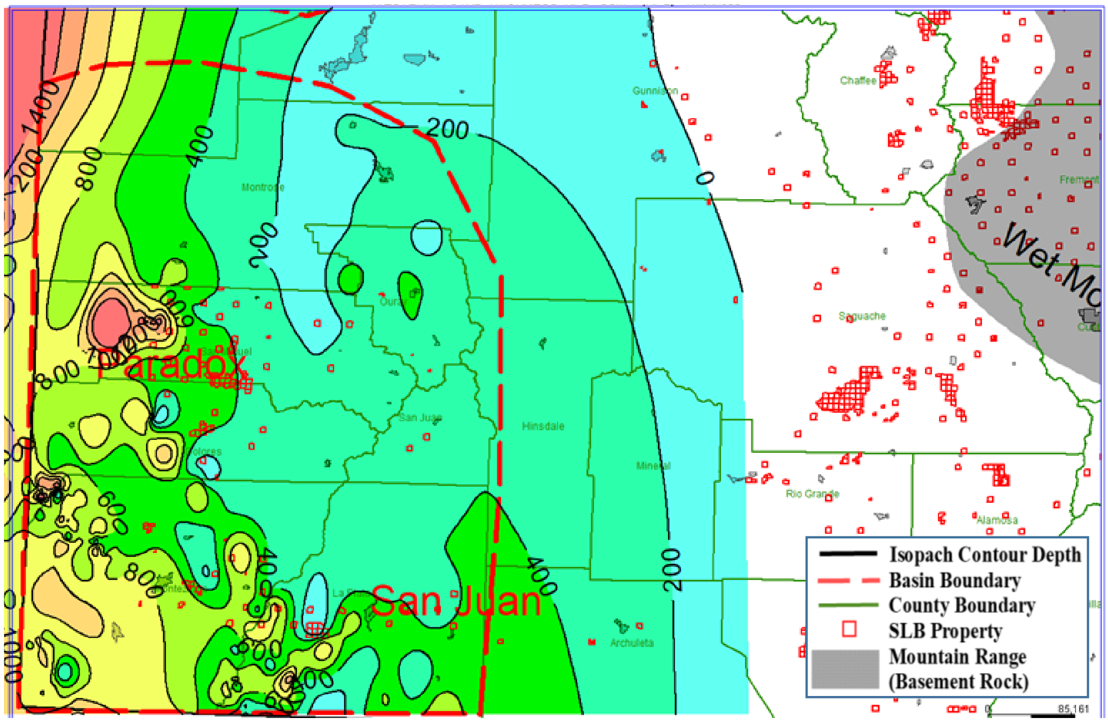

Figure 28: Isopach contour map (thickness in feet) of the formations of interest in the Southwest quadrant of Colorado.

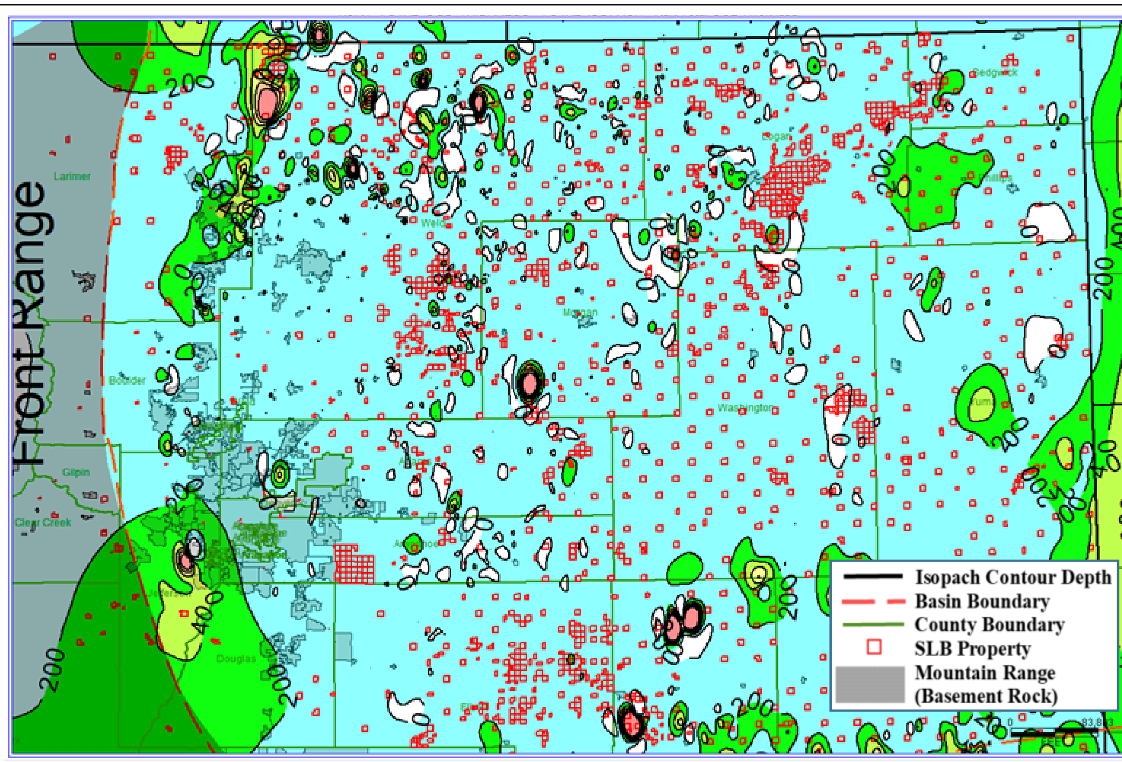

Figure 29: Isopach contour map (thickness in feet) of the formations of interest in the Northeast quadrant of Colorado.

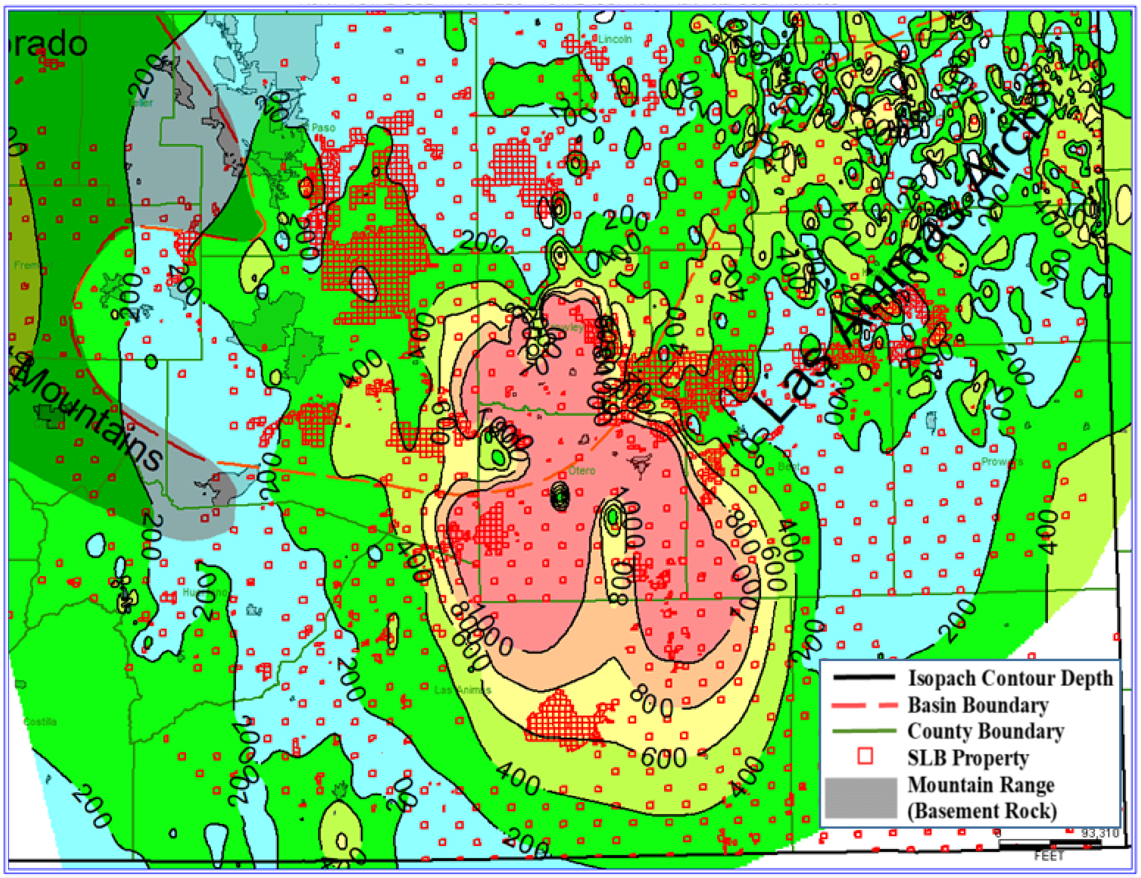

Figure 30: Isopach contour map (thickness in feet) of the formations of interest in the Southeast quadrant of Colorado.

From this mapping, in the western half of the state (Figs. 27 and 28) prospective properties for CCS are more promising near the Colorado-Utah border. In the eastern half of Colorado, good formation thicknesses exist in Otero and surrounding counties (Figure 29) making CCS operations promising in SLB acreage near these areas. More evaluation is needed for carbon storage in the Northeast quadrant of Colorado; however, the DJ basin has very good thicknesses as shown in the individual formation isopach maps (Figs. 10, 12, 15, and 23). Thus, planning completions for geosequestration in individual formation intervals in the DJ basin can be tailored using the Northeast quadrant maps presented.

7 Potential in Colorado for CO_2 Storage

Rough estimations of CO_2 storage capacity have been reported for some major saline aquifers, oil and gas fields, as well as coalbed seams across Colorado (McPherson, 2006; Young et al., 2007). The storage capacity of saline aquifers is significantly greater than that of oil and gas reservoirs and coalbed seams. This section describes the storage capacity for major formations within Colorado. Because there is little interest in carbon storage in coalbed seams, we only address oil and gas reservoirs and saline aquifers here.

7.1 Storage in Oil and Gas Reservoirs

Colorado is a major oil and gas producing state with nearly 1,400 oil and gas fields. The Energy Information Administration (EIA) ranked Colorado as the 11th in oil proved reserves and 6th in gas proved reserves for the onshore U.S. These data indicate that Colorado has a high potential of carbon storage in oil and gas reservoirs. Storage in oil and gas fields depends on displacement of oil and gas by injection CO_2 during Enhanced Oil Recovery operations or on displacement of water in fully depleted fields. Subeconomic quantities of oil and gas might remain in such fields.

We use Equation 1 to estimate the carbon storage in oil and gas reservoirs (Goodman et al., 2011).

$$G_{CO_2} = A h_n \phi_e (1 - S_{wi}) B \rho_{CO_{2std}} E_{oil/gas} \tag{1}$$

Where G_{CO_2} = the mass estimate of reservoir CO_2 storage resource,

A = reservoir area being assessed for CO_2 storage,

h_n = is net oil and gas column height in the reservoir,

ϕ_e = average effective porosity in the volume defined by h_n and A,

S_{wi} = average initial water saturation within the volume defined by h_n and A,

B = Fluid formation volume factor (ratio of surface volume to reservoir volume of oil)

$\rho_{CO_{2std}}$ = density of CO_2 at standard pressure and temperature,

$E_{oil/gas}$ = CO_2 storage efficiency factor, the volume of CO_2 stored in reservoir per unit volume of original oil or gas in place (OOIP or OGIP).

After collecting the properties for the major formations in each of the fields (Higley et al., 1995; Higley and Cox, 2007; Drake et al., 2014; Young et al., 2007; Nelson and Santus, 2011), we calculated the storage capacity and summarized estimated storage volumes in Table 3. Based on the work of Young and others (2007, the oil and gas fields with the highest carbon storage capacities in Colorado are the Wattenberg Field, Ignacio Blanco Field, and the Wilson Creek field. The storage capacities presented in Tables 3 and subsequent tables are estimates calculated from our geologic model. It should be noted that previous studies show varying properties for the same formation, due to heterogeneity of reservoirs in these fields. Also, in these three fields with the largest storage potential, the Morrison Formation shows substantial potential, although it was not chosen for isopach construction in the other portion of the Phase 2 study. These two efforts developed in parallel, and it was not possible to add the Morrison to the set of formations in the isopach mapping part of the study.

Recent studies have shown that injection of CO_2 into hydrocarbon reservoirs can potentially mobilize bypassed hydrocarbons (Prasad et al., 2021; Oduwole et al., 2021; 2022). Geosequestration pilot projects are recommended, therefore, to assess the potential for migration of hydrocarbons after injection of CO_2.

Table 3: Carbon storage capacities calculated based on Eq. (1). The CO_2 density is assumed to be 0.1161 lb/ft^3 at standard conditions, the formation volume factor is 1.1, the storage efficiency factor equals 4%.

Basin	Field	Formation	Area (sq mile)	Thickness (ft)	Porosity (%)	Sw (%)*	Storage capacity (MMt)**
Denver	Wattenberg	Pierre Shale - Sussex, Shannon	7,987	20	14	40	0.87
		Niobrara-Codell	7,987	100	10	50	2.58
		GreenHorn	9,386	13	9	40	0.43
		Dakota Group	5,445	200	11.5	40	4.85
San Juan	Ignacio Blanco	Mesaverde Group	755	560	12	40	1.97
		Dakota	1,300	190	7.5	40	0.72
		Morrison	1,400	660	13.5	40	4.83
Sand Wash	Wilson Creek	Morrison	1,300	320	15.7	40	2.53
		Entrada (Sundance)	2,900	170	20	40	3.82

*Sw = water saturation; ** MMt = million metric tons

7.2 Storage in Saline Aquifers

Equation 2 is used to calculate the carbon storage in saline aquifers (Goodman et al., 2011).

$$G_{CO_2} = A_t h_g \phi_{tot} \rho E_{saline} \quad (2)$$

Where A_t = total area,

h_g = formation gross thickness,

ϕ_{tot} = average porosity

ρ = CO_2 density,

E_{saline} = storage efficiency factor, volume of CO_2 capable of being stored per unit of saline aquifer volume

For an assumed CO_2 density ranging from 0.5-0.8 g/cc, the E_{saline} value range (10^{th} to 90^{th} percentile of probability distribution) is between 0.4% and 5.5%. Table 4 lists the calculated storage capacity for each formation of the seven major saline aquifer regions in Colorado. For these saline aquifers, values for average formation thickness, porosity, and reservoir area come

Table 4: Estimated carbon storage capacities for saline aquifers in Colorado

Study Region	Formation	Average Formation Thickness (ft)	Porosity (%)	Reservoir Area (sq mi)	Storage capacity P10 (MMt)	Storage capacity P50 (MMt)	Storage capacity P90 (MMt)
Denver	Morrison	250	15.7	5,400	769	3,700	6,630
	Entrada-Dockum	60	15.7	5,445	186	895	1,604
	Lyons	100	12	5,500	240	1,152	2,065
Fort Morgan	Morrison	250	15.7	3,300	470	2,261	4,052
	Entrada-Dockum	60	15.7	3,269	112	538	963
	Lyons	100	12	3,300	144	691	1,239
Palisade	Dakota	130	14	2,900	192	921	1,651
	Morrison	680	16	3,200	1,264	6,077	10,891
	Weber	880	12.5	2,700	1,078	5,184	9,290
Rangely	Dakota	130	14	2,600	172	826	1,480
	Morrison	680	16	2,600	1,027	4,938	8,849
	Weber	880	12.5	2,600	1,038	4,992	8,946
Ignacio	Mesaverde	560	12	755	184	886	1,587
	Dakota	190	7.5	1,300	67	323	579
	Morrison	660	13.5	1,400	453	2,177	3,902
	Entrada	150	24	1,500	196	943	1,689
	Hermosa	1,880	8	1,600	874	4,200	7,527
	Leadville	180	8	1,600	84	402	721
Craig	Entrada	170	20	2,900	358	1,721	3,084
	Weber	330	11	3,400	448	2,154	3,861
Cañon City	Morrison	320	15.7	1,300	237	1,140	2,043
	Lyons	240	4.4	1,600	61	295	529

from Appendix 13 of Young et al. (2007), which focused on specific areas of Colorado near coal-fired power plants. The full extent of the aquifers described might be substantially larger. It shows that the Morrison formation has higher carbon storage potential than other formations for CCS in saline aquifers.

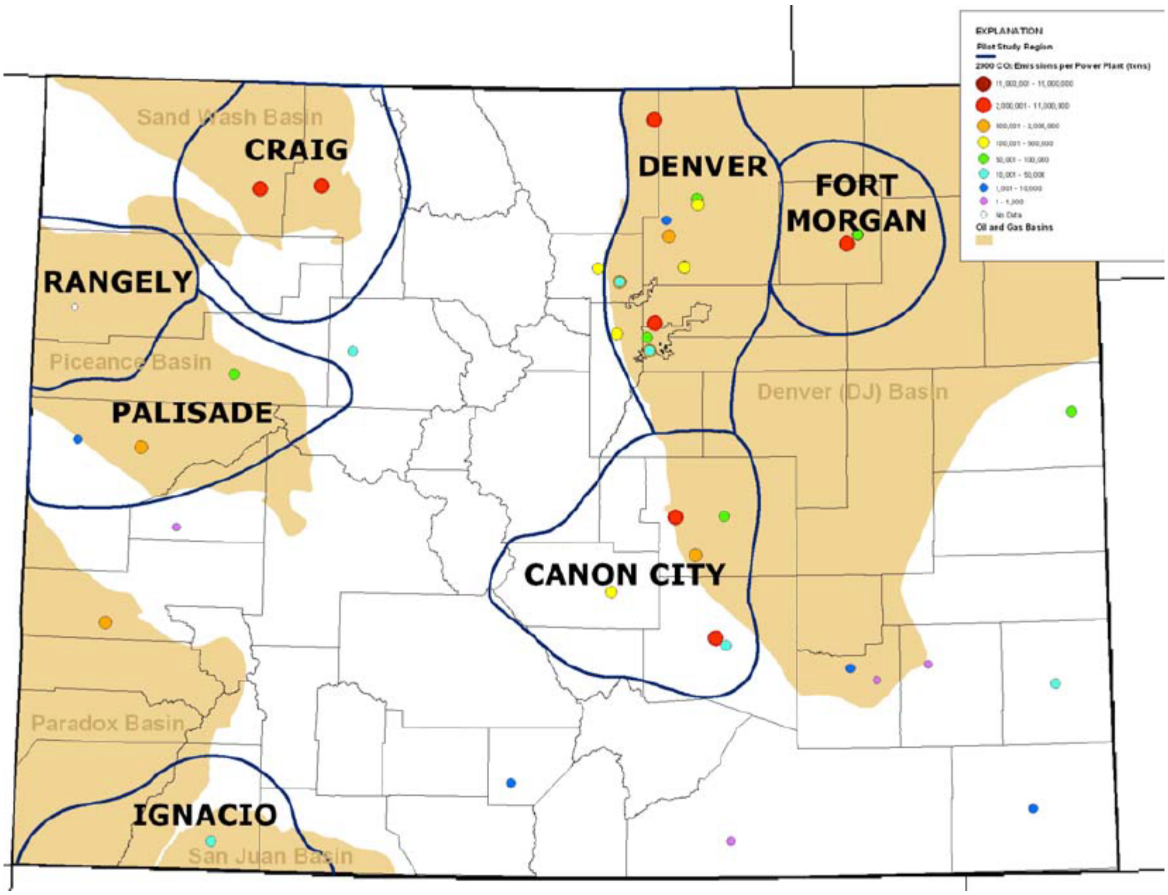

Figure 31: Areas of interest and basin margins for saline aquifer assessment.

The best estimate (P50) storage capacity values are plotted for each region in Figure 32. Denver and Cañon City have the highest carbon storage potential for saline aquifers, followed by the Palisade and Rangely areas.

8 Environmental Risks of Carbon Storage

There are operational risks associated with CCS projects that must be evaluated prior to undertaking any field-scale pilot. Risks associated with CCS projects, such the handling and in-

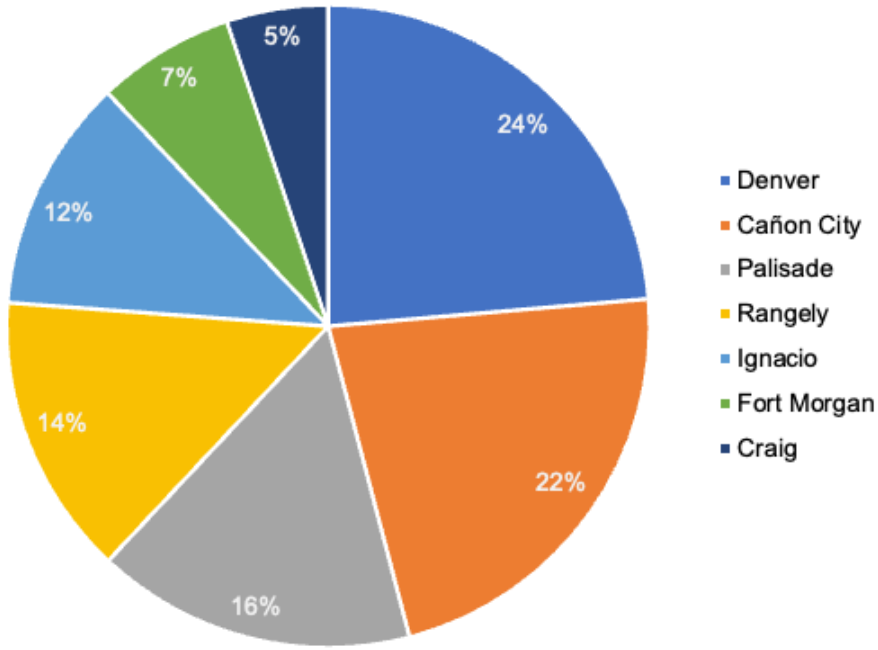

Figure 32: Integrated estimation of carbon sequestration capacities for saline aquifers in areas of interest from Young et al., 2007.

jection of CO_2, must be addressed to minimize potential harm to the public health and environment surrounding CCS operations. Here, we address potential hazards associated with CCS projects.

8.1 Leakage

Although CO_2 is part of the atmosphere that we breathe, it is an odorless gas with a density higher than air and may accumulate in low-lying surface locations in concentrations that may prove harmful to humans and wildlife. Thus, CO_2 leakage is a risk with the potential to cause environmental harm associated with CCS activities, but it poses a relatively small threat. According to the Intergovernmental Panel on Climate Change (IPCC) (Metz et al., 2005) report, risks associated with CCS are low, with well-selected geologic formations likely to retain over 99% of their storage over a period of 1000 years. Concerns regarding the long-term storage of CO_2 have centered on two types of CO_2 leakage that may occur: gradual leakage and abrupt leakage (Georgiou et al., 2007).

Gradual leakage could occur due to incorrect site selection and inadequate preparation, posing a risk to overlying groundwater resources such as aquifers. Abrupt leakage could cause catastrophic consequences to human life and the surrounding environment (Georgiou et al., 2007) and trigger seismic events. Acidification of in-situ formation waters and reactive formation minerals may lead to migration of previously stored CO_2 reserves. Evidence from projects such as the Otway Demonstration and Gorgon projects in Australia suggest that if storage sites are carefully selected, the chances of catastrophic or gradual leaks would be minimal. CSIRO and Chevron have both further contended that leakage is unlikely if sites are well selected, operators are competent, and wells are properly sealed (Georgiou et al., 2007). In these instances, risks associated with CCS projects are less than those associated with oil and gas production. To minimize risks with CCS projects, proper vetting of locations devoid of low-lying surface traps and with trained operations staff can lead to significant mitigation of potential environmental harm from these operations. In addition to these operational efforts, strict adherence to regulatory protocols in operations and infrastructure constraints will minimize the potential for project failure and regulatory liability. Other selection criteria to ensure minimal migration of acidified formation waters and seal intervals that would be non-reactive to these fluids would ensure permanence of storage.

8.2 Induced Seismicity

Induced seismicity by injecting CO_2 is of particular concern due to the potential for damage to infrastructure and downhole formation integrity. Microseismic clustering in wastewater injection sites has been observed with event Richter magnitudes of up to 5.3 recorded in Colorado [REF]. Induced seismic events in more than 180,000 Environmental Protection Agency Class II Enhanced Oil Recovery (EOR) and wastewater disposal wells in the Mid-continental U.S. occurred at a frequency of about 10% (Weingarten et al., 2015). At 75 CO_2 injection sites, Nicol et al. (2011) found that in specific cases, earthquakes at depths less than 3 km are typically detected at magnitudes greater than 2. Note that damage to infrastructure and seal formations may result from earthquake magnitudes greater or equal to 3 or 4. Thus, induced seismicity studies should be given careful consideration during planning and risk evaluation of CO_2 injection projects as their effects may impact infrastructure, formation integrity, safety, and the public perception of the safety surrounding these operations. Currently, there has been evaluation of seismic risks in Colorado in the Rangely Field and in the DJ Basin. Evaluation of induced seismicity risks for Pueblo and El Paso counties have not been performed in this project but should be considered before proceeding with sequestration projects in these counties.

9 Conclusions and Recommendations

This work addressed the feasibility of storage from CCS operations in the Colorado SLB properties from the generation of a geologic model. We have created isopach maps of major formation candidates for CO_2 sequestration in the state of Colorado and have presented a brief evaluation of potential reservoir storage volumes using values reported in the literature. These quantitative estimates were limited to some extent by the limits of the earlier literature that provided data for portions of the state near certain high intensity targets for carbon capture. In addition, this report calculated values that were distinctly lower than previous estimates. The differences have not been fully resolved, and future work will be required to resolve the differences. Nevertheless, the study identifies significant reservoirs with adequate storage volumes for valuable sequestration of CO_2. Through this work, we have highlighted major regions which are good potential candidates for CCS operations to be undertaken on SLB lands.

Due to the large scope of this study, individual rankings of each property owned by the SLB is limited; however, this guide serves as a good interpretive tool to identify geologic targets where CCS may be undertaken statewide. The provided isopach thicknesses and outlined methodology for estimating formation storage capacity serves as a reference for evaluating individual SLB properties and should be tailored with site specific evaluations to provide the best interpretation for individual SLB properties.

For proper coverage and better evaluation of the potential storage sites, adequate information such as well log data should be made available especially where the sparse or no data. Also, for generation of better geologic models and isopach thickness maps, formation picks from IHS should be subjected to rigorous quality assurance checks and should be verified for future workflows stemming from this project.

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Appendix A: Isopach maps for selected sequestration formations in Phase 1 study area

Isopach calculations were performed from selected tops values for the four formations selected for carbon sequestration potential. These calculations were performed in wells with picks specified from IHS in the surrounding area of Pueblo and El Paso counties and in the wells in our study area. Isopach thicknesses were calculated by simple subtraction of formation interval depths from the selected raster log picks of formation tops.

An isopach contour map was then generated from the calculated isopach thicknesses of the well locations and generated across the counties for our four identified targets by stratigraphic depth (Figure A-1). Blank values for thicknesses in the isopach model are due to insufficient well log data for choosing formation tops and the inability of the model to interpret formation thicknesses due to the sparseness of data or may be caused by lacking physical presence from formation unconformities due to regional events such as the Apishapa Uplift in southern El Paso County.

From the generation of isopach formation thickness contour maps, storage potential and formation thicknesses has been modeled and assessed for our area of interest. The primary target, the Lyons formation, has isopach thickness greater than 50 ft across El Paso and Pueblo counties, with increasing storage potential toward the southeast (Fig. A-1a). Isopach thicknesses of greater than 100 ft exists for a large portion of SLB acreage making the Lyons formation a good candidate for CO_2 sequestration operations.

Sequestration potential in our secondary target, the Entrada formation, is higher in Pueblo County with isopach thicknesses greater than 50 ft (Fig. A-1b). Good thickness (>25 ft) for CO_2 storage potential exists in southern and eastern El Paso County as well.

Development of the tertiary target, the Dakota sandstone gross interval, for CO_2 sequestration would be preferential in Pueblo County, but across both counties the thickness of this formation and the large amount of interbedded shale layers makes this formation a good target for sequestration operations (Fig. A-1c). Interbedded shale layers add additional baffles to CO_2 migration between formation intervals and help to ensure permanence of CO_2 storage in the thick sandstone layers of the Dakota group. Average isopach thicknesses are approximately 200 ft in gross formation intervals for sequestration across both counties.

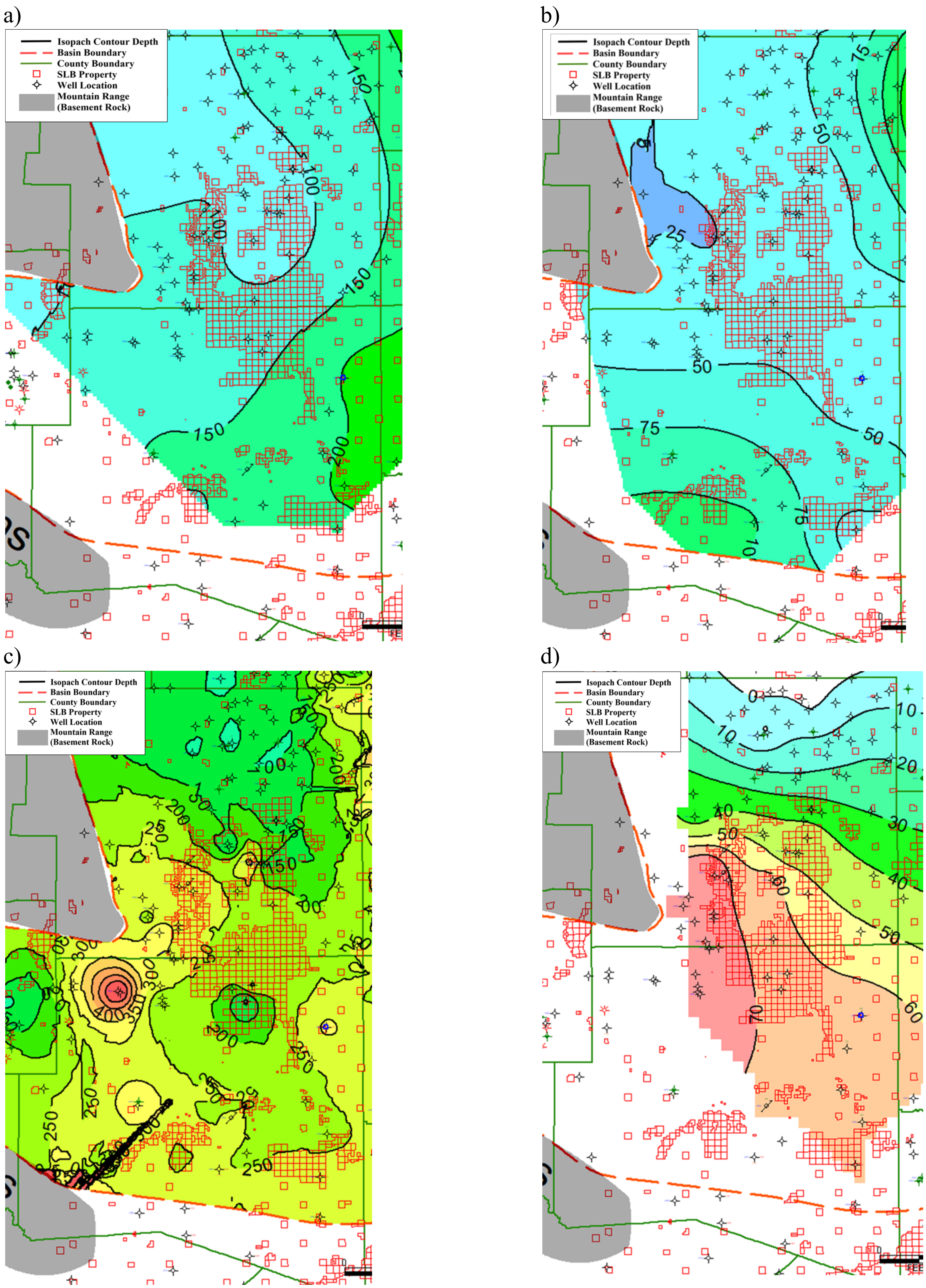

Figure A-1: Isopach contour map (thickness in feet) for Pueblo and El Paso Counties of a) Lyons Sandstone, b) Entrada Sandstone, c) Dakota Group gross interval, d) Codell Sandstone, with Colorado Land Board acreage shown in overlay.

Carbon sequestration operations developed in the quaternary target, the Codell sandstone, might be preferential in the southern-most acreage in El Paso County and across Pueblo County. In these locations, the Codell thickness is greater than 50 ft and has larger storage potential in these thicker sections (Fig A-1d).

In these outlined formations, isopach thickness can be used as a metric for estimating the carbon storage capacity. The generated isopach contour maps can be used to model total storage capacity in each respective formation types with thicker intervals being more amenable to storage of CO_2, with larger reservoir volumes as a result. Note that isopach maps should be refined using more and site-specific data with careful assessment of net-to-gross thickness assessments.

A total gross thickness map of the 4 primary targets summed together are shown in Figure A-2a and is used as an indicator of locations across SLB properties in Pueblo and El Paso counties that would be good targets for sequestration. Higher summed gross thicknesses of the 4 formations of interest in SLB properties indicate higher potential CO_2 storage volumes for CCS projects.

Using the summed isopach thicknesses from the formations of interest, a ranking system has been developed for SLB surface estate locations in Pueblo and El Paso counties (Figure A-2b). Here, we have defined SLB surface estate acreage with isopach thickness of the summed formations of less than 100 ft as having low CCS potential, isopach thickness of 100-200 ft is defined as having fair CCS potential, 200-300 ft is defined as having moderate CCS potential, 300-400 ft is defined as having good CCS potential, 400-500 ft is defined as having very good CCS potential, and greater than 500 is defined as having excellent CCS potential.

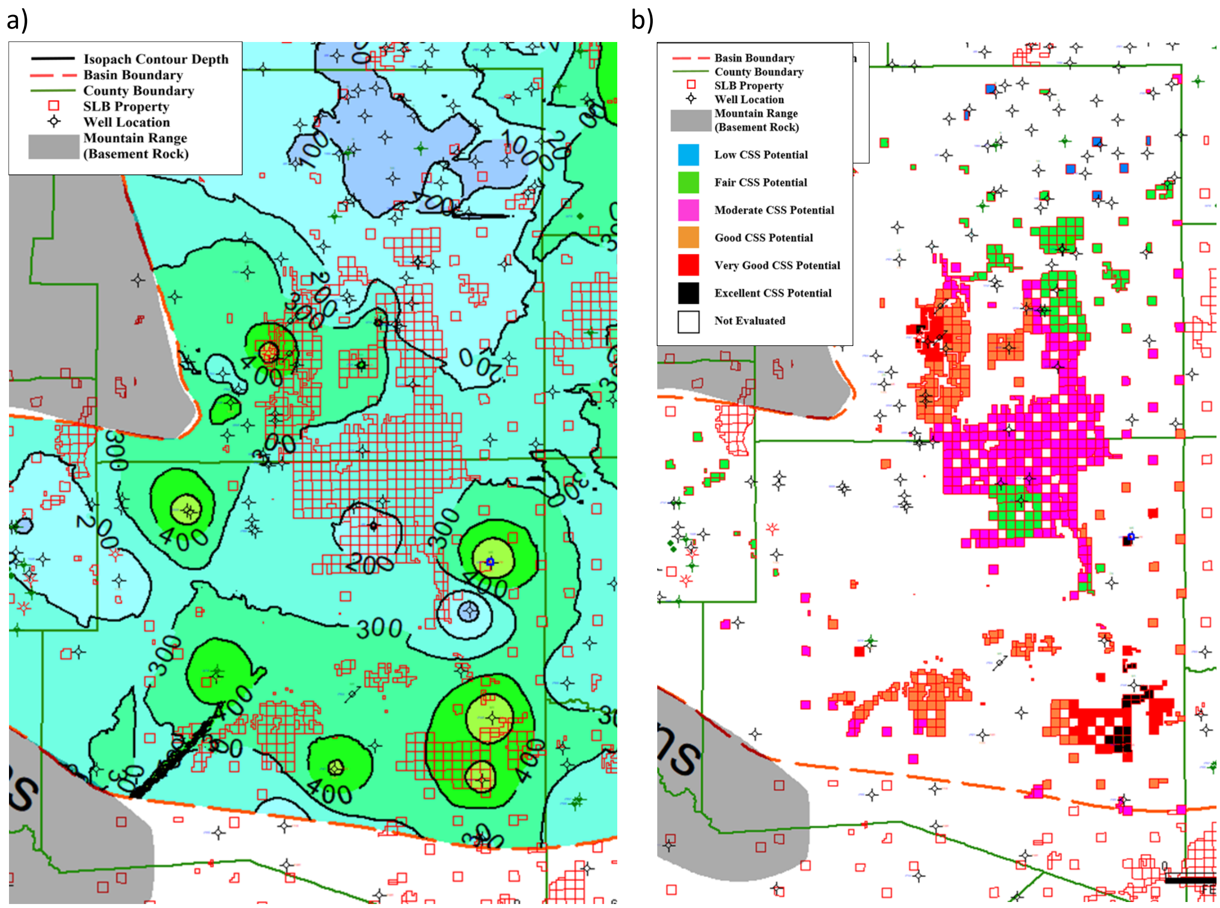

Figure A-2: a) Summed isopach contour map (thickness in feet) of the gross thickness of the formations of interest (Lyons, Entrada, Dakota Group, and Codell) in Pueblo and El Paso counties, Colorado; b) Ranked SLB surface estate acreage for potential for CCS projects.