Evaluation of Geologic Information in the CTV II CO_2 Sequestration Project Class VI Permit Application

This site characterization evaluation report for the proposed CTV II Class VI Sequestration Project summarizes the geologic evaluation and data submitted by Carbon TerraVault Holdings LLC (CTV) in their permit application narrative dated February 2, 2023, submitted per 40 CFR 146.82(a). This report describes and evaluates the available data on which the UIC Class VI permit application is based and identifies uncertainties that EPA recommends be addressed via the pre-operational testing that will be performed before the applicant will receive authorization to inject CO_2. Clarifying questions for CTV are provided in blue in the text below. Additional objectives for pre-operational testing to address identified data gaps are identified at the end of the evaluation text. While some of the needed testing is described in the narrative or the pre-operational testing plan, CTV did not submit procedures for all needed testing. Evaluating these testing procedures is outside of the scope of this site characterization review; however, approval of testing procedures will be needed prior to well construction and testing.

Project Background

CTV plans to develop the CTV II CO_2 storage site in San Joaquin County near Stockton, California. CTV proposes to construct and operate five CO_2 injection wells (including three existing wells to be converted to Class VI wells and two newly drilled wells) to be completed in the Winters Formation (the injection zone) at a depth of approximately 9,500 feet true vertical depth (ft TVD). The combined Sawtooth Shale, Tracy Formation, and Starkey Formation (i.e., Starkey-Sawtooth) comprise the upper confining zone, and the Delta Shale will serve as the lower confining zone. CTV plans to inject 0.97 million tonnes of CO_2 annually for a period of 23 years, for a total injection volume of 22.31 million tonnes. At the proposed injection site, the base of the lowermost underground source of drinking water (USDW) is contained within undifferentiated non-marine sediments at a depth of approximately 2,400 feet below ground surface (bgs). CTV is not requesting an injection depth waiver or aquifer exemption expansion for this project.

Site Characterization

CTV utilized literature review and available 2D and 3D seismic data, core data, well logs, and reservoir performance data to characterize the proposed injection site. Core and porosity data was available from 37 wells drilled within and near the Area of Review (AoR) as shown in Figures 2.2-1 and 2.4-1. Regional wells with log data are indicated in Figure 2.1-7. Wireline log data included measurements such as spontaneous potential, natural gamma ray, borehole caliper, compressional sonic, resistivity, neutron porosity, and bulk density. X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) data is available for cores from two wells located approximately 6 miles north of the AoR (Figure 2.4-1).

Figure 2.2-2 contains a type log from well Union_Properties_2 located on the western edge of the AoR boundary showing average rock properties used in CTV's site model for the injection and confining zones. Traces of the available seismic data and well ties are shown in Figure 2.2-3 (including 3D seismic throughout and beyond the AoR, acquired in 1998 and reprocessed in 2013; and several 2D seismic lines acquired between 1980 and 1985, including one that transects the AoR), where CTV tied merged 3D data to 2D data to create the structural model for the project site.

Regional Geology, Hydrogeology, and Local Structural Geology [40 CFR 146.82(a)(3)(vi)]

Regional Geology

The proposed project site's AoR overlaps the Union Island Gas Field, which ceased production in 1988, where CTV plans to repurpose the Cretaceous-aged Winters Formation dry gas reservoir for CO_2 storage. The Union Island Field lies within the Sacramento Basin, the northern, asymmetric sub-basin of the larger Great Valley Forearc. The sedimentary formations of the Great Valley range in age from Jurassic to Holocene age. The basin is constrained on the west by the Coast Range Thrust, on the north by the Klamath Mountains, on the east by the Cascade Range and Sierra Nevadas, and on the south by the Stockton Arch Fault (which forms the eastern boundary of the AoR). Sedimentation thickens southward towards the Stockton Arch Fault due to the southern tilt of the basin. Figure 2.1-2 displays the Sacramento Basin regional study area, and Figure 2.1-1 shows the location of the proposed AoR in the context of the southern half of the Sacramento Basin.

Formation Summary

Figure 2.1-6 is a schematic NW-SE cross section representing the local stratigraphy of the project area. The major stratigraphic intervals comprising the injection and upper and lower confining zones are Upper Cretaceous to lower Paleogene in age within the AoR. Above the upper confining zone is a major unconformable surface at the base of the Valley Springs Formation, which separates the more deformed Mesozoic and lower Paleogene strata below from the less deformed uppermost Paleogene and Neogene strata above, within which is the base of the lowermost USDW.

Available data about geologic formations within the AoR are summarized in Table 1 below. Average depths and thicknesses for the injection and confining zones were provided in Table 2.4-2, and the values for units overlying the upper confining zone were estimated from Figures 2.2-2 and 2.2-4.

Table 1. Formation Summary.

Unit	Depth within the AoR (ft TVD)	Thickness Across the AoR (ft)	Total Dissolved Solids (mg/L)	Average Porosity (%)	Average Permeability (millidarcies, mD)
Undifferentiated non-marine sediments (lowermost USDW)	2,400 ft bgs	--	3,000 – 10,000 (calculated based on an unspecified number of salinity logs)		
Nortonville Shale	3,957	750	--		
Domengine Sandstone	4,707	500	--		
Capay Shale	5,207	250	--		
Mokelumne River Formation	5,457	1,875	--		
H&T Shale	7,332	125	--		
Starkey-Sawtooth Shales (upper confining zone)	7,457 (mean); ranges from 7,208 to 7,776 ft	2,288	--	23.0 (16 wells with porosity logs)	0.59 (16 wells with porosity logs)

Unit	Depth within the AoR (ft TVD)	Thickness Across the AoR (ft)	Total Dissolved Solids (mg/L)	Average Porosity (%)	Average Permeability (millidarcies, mD)
Winters Formation (injection zone)	9,713 (mean); ranges from 9,492 to 9,995 ft	256	15,595 (2015 water sample from 1 well within the AoR)	18.9 (19 wells with porosity logs)	13 (19 wells with porosity logs)
Delta Shale (lower confining zone)	9,969	157	--	14.7 (13 wells with porosity logs)	0.04 (13 wells with porosity logs)

Maps and Cross Sections of the AoR [40 CFR 146.82(a)(2), 146.82(a)(3)(i)]

CTV's proposed injection wells are depicted in Figure 2.2-6. The injection wells are spaced between 1,735 ft and 4,390 ft apart. The confining Stockton Arch Fault is depicted on the figure as the eastern boundary of the delineated AoR (see Faults and Fractures below).

Figure 2.2-7 shows surface bodies of water, surface features, and infrastructure and political boundaries in San Joaquin County. Major surface water bodies in the area are Clifton Court Forebay, Victoria Canals, Grant Line Canal, and the Salmon Slough. State and EPA subsurface cleanup sites are depicted in Figure 2.2-8.

Questions for CTV:

- ***Please provide a map that contains all of the elements required at 40 CFR 146.82(a)(2).***

Faults and Fractures [40 CFR 146.82(a)(3)(ii)]

The Stockton Arch subdivides the Great Valley Forearch into the Sacramento and San Joaquin Basins, bounding the Sacramento Basin in the south. Eocene-Miocene uplift of the Stockton Arch separated the Sacramento Basin from the San Joaquin Basin and created a series of high-angle reverse faults known as the Stockton Arch Fault Zone. Near the project site, this feature is represented by the Stockton Arch Fault, a reverse fault trending NE-SW which bounds the AoR to the southeast. It produces a slight anticlinal structure in the injection zone as displayed on Figures 2.2-4 and 2.10-1. Based on Figure 2.1-6, the Stockton Arch Fault juxtaposes the Winters Formation injection zone with the Lathrop Sand with an estimated throw of approximately 1,000 ft (Figure 2.2-4).

Figure 2.3-1 displays the Stockton Arch Fault and local well ties used to map structural features, and Figure 2.3-2 is the corresponding NW-SE structural cross section which shows this fault cutting across the local stratigraphy. A secondary fault is located across the Stockton Arch Fault on its hanging wall to the east of the project site, but CTV asserts that the main fault is sealing for the project site and thus does not discuss the secondary fault further. Additional site-specific data collection using EPA-approved methods will be necessary to eliminate uncertainty about the presence of faults in the AoR. The Stockton Arch Fault is cut off at the top by the Base Valley Spring unconformity, and some folding of strata above the unconformity may be related to the structural overprint of the fault beneath it.

CTV asserts that the Stockton Arch Fault will provide a seal to stratigraphically trap injected CO_2 and contain formation pressure increases due to injection. Among the available lines of evidence for fault sealing as described in EPA's Class VI Site Characterization Guidance are the juxtaposition of the injection zone against the Lathrop Sand (as described above) and pressure compartmentalization.

To support the assertion of pressure compartmentalization, CTV notes that the fault has trapped natural gas for millions of years, and prior to production in the natural gas field, formation pressure was 5,040 psi (measured in 1972), and natural gas production drew down that pressure to 1,200 psi (where it remains underpressured at present). The narrative does not specify when this reservoir pressure measurement was collected or describe the source of the statement. CTV predicts that CO_2 injection activities will increase reservoir pressure to 4,500 psi, which is lower than pre-gas production levels. Thus, CTV asserts, the fault will be sealing for the proposed injection activities, and those activities will not adversely impact fault stability. CTV also reviewed mud logs from wells drilled on both sides of the Stockton Arch Fault to demonstrate pressure isolation within the Winters Formation injection zone. Mud logs from wells drilled in the late 2000's indicated normal hydrostatic or lower pressure in the confining zone and other zones above the Winters Formation injection zone. CTV states that none of the wells showed any pressure losses despite gas depletion in the Winters Formation due to production activities; however, no specific pressure data were provided in the application, so CTV should provide documentation of historical pressure measurements for the Union Island Gas Field and the mud logs used as the basis to assert pressure compartmentalization and/or pressure data derived from the mud logs.

Based on the recommendations of EPA's Class VI Site Characterization Guidance and to address potential public concerns about faults and risk, CTV should provide additional evidence of fault sealing, e.g., of the juxtaposition of units by the Stockton Arch Fault; calculation of shale gouge ratio, a characterization of catalysis and diagenesis.

Questions for CTV:

- ***Please provide documentation of historical pressure measurements in the Union Island Gas Field; the mud logs used to assert pressure compartmentalization and/or pressure data derived from the mud logs (including the locations of the wells) or other data about the mud logs that show different pressures in the Winters Formation on opposite sides of the Stockton Arch Fault.***
- ***When and where was the "current" 1,200 psi pressure measurement taken? If it was not within the past 2-3 years, please provide evidence that field operations since the pressure measurement have not affected pressures in the reservoir, and the data are therefore still accurate.***
- ***Please provide any other site-specific evidence that the Stockton Arch Fault is sealing, e.g., Allan charts demonstrating the juxtaposition of units by the Stockton Arch Fault; and any other available data to support the fault sealing assertion including calculation of shale gouge ratio, a characterization of catalysis and diagenesis, and pore pressure measurements on both sides of the fault. See Section 3.5.2 of EPA's Class VI Site Characterization Guidance for acceptable lines of evidence and associated data.***

Injection and Confining Zone Details [40 CFR 146.82(a)(3)(iii)]

Figure 2.4-1 shows the locations of wells with mineralogy data relative to the AoR, along with wells with porosity data and wells used for CTV's ductility calculation (see Geomechanical and Petrophysical Properties below). There appear to be 20 wells with porosity data (mostly within the AoR), 6 wells with core data (four are within the AoR, two are 5 miles or more to the north of the AoR), and 4 wells with data for the ductility calculations (all of which are within or immediately southwest of the AoR).

CTV states that quantitative mineralogical data is unavailable from within the AoR, so the mineralogical data presented in the application is from two wells located approximately 5 to 6 miles outside the AoR. These core data are presented in Table 2.4-1. Formations, sample depths, and the quantities of minerals are provided in the table as derived from XRD and FTIR. However, due to the well locations, they do not provide the site-specific data points for the injection and confining zones that are needed to reduce uncertainty in the site characterization and modeling inputs that will be needed for final approval/authorization to inject. **Cores collected during construction will need to be analyzed to confirm site-specific properties, including porosity, permeability, capillary pressure, pore pressure, mineralogy, etc.**

CTV determined formation porosities from bulk density using a matrix density of 2.65 g/cc as calibrated from core grain density and core porosity data, and from compressional sonic logs using 55.5 µsec/ft matrix slowness and the Raymer-Hunt equation. Formation clay volumes were determined by spontaneous potential and calibrated to core data. CTV then estimated log permeability by applying a core-based permeability transform that utilizes capillary pressure, porosity, and permeability with clay values from XRD and/or FTIR. The permeability transform is based on 13 core data points from two wells, and an example transform for Sacramento Basin zones is provided in Figure 2.4-2. Figures 2.4-3 and 2.4-4 are example porosity and permeability data for the location of proposed injection well Sonol_Securities_6. CTV verified the transform by comparing core porosity and permeability to values calculated from the transform (Figure 2.4-5). These values appear to correlate well (and include some data from within the AoR).

Figure 2.4-6 is a map of wells within the AoR from which available porosity and permeability data was collected. Capillary pressure data for the injection zone were obtained from core samples from well Sonol_Securities_5 in the Union Island Gas Field, though CTV notes that no capillary pressure data are available for the upper confining zone. **Collection of capillary pressure data for the upper confining zone is stated as an objective for pre-operational testing; this data will be needed to reduce uncertainty in model inputs and confirm these estimations.**

CTV determined formation depths and thicknesses from structural and isopach maps based on wireline logs. Gross thickness and depth maps within the AoR for the injection and upper confining zones are provided in Figure 2.4-8. CTV asserts that variability in the thickness and depth of the injection or confining zones will not impact containment. Because the upper confining zone is at least 2,000 ft thick, there is no concern about confinement. **Pre-operational testing data will need to be collected to reduce uncertainty in model inputs and confirm these estimations.**

Injection Zone Properties

The Winters Formation injection zone is an upward-fining deep-water sandstone with thinly interbedded sandstone and shale deposited as coalesced channels at the base of the slope on the upper channelized portion of a sandy suprafan. The mean depth to the top of the injection zone within the AoR is 9,713 ft, and ranges from 9,492 to 9,995 ft, as shown on Table 2.4-2. The injection zone is at a depth of approximately 9,500 ft TVD in the footwall of the Stockton Arch Fault.

The formation has a gross average thickness of approximately 256 ft. The average porosity of the injection zone is 18.9% (based on 19 wells with porosity logs and 8,518 individual logging data points), and its average permeability is 13 mD (based on 19 wells with porosity logs and 7,993 individual logging data points). Figure 2.2-5a is an isochore map showing Winters Formation injection zone thicknesses at the location of each proposed injection well (showing thicknesses between 250 and 350 ft near the wells), and Figure 2.2-5b is a structure map demonstrating the regional 2° dip to the west. Downdip to the southwest of the AoR, the Winters Formation thickens and fans out towards the basin. Updip to the northeast of the AoR at the base of the slope, the Winters Formation injection zone pinches out, providing for a second stratigraphic trapping mechanism in addition to the Stockton Arch Fault.

Qualitative core data from 3 wells within the AoR describe the mineralogy of the injection zone as consisting of "quartz, feldspar (plagioclase & K-spar), mica, ferromags, and lithics" with additional calcite cemented intervals. XRD data is available from the well GP_Dohrmann_1_RD1 located approximately 6 miles north of the AoR. Reservoir sand from two samples in this well averaged 67% quartz, 14% plagioclase and potassium feldspar, and 12% total clay (primarily kaolinite and smectite). Calcite and dolomite were reported to make up less than 3% of the samples. CTV's capillary pressure curve for the injection zone is presented in Figure 2.4-7. Capillary pressure data was obtained from a core sample from well Sonol_Securities_5 within the AoR. **Additional data collection during pre-operational testing will be useful to confirm its representativeness of the entire AoR.**

Confining Zone Properties

Starkey-Sawtooth Formation (Upper Confining Zone)

CTV asserts that the combined formations of the Sawtooth Shale, Tracy Formation, and Starkey Shale will provide primary upper confinement due to their low permeability, thickness, and regional continuity that extends beyond the AoR. Figure 2.2-4 is a cross section interpreted from well logs spanning the AoR which demonstrates that the confining zones are laterally continuous across the AoR. CTV states that this cross section is representative of formations and sand continuity for all five injection well locations, and this appears accurate based on the trend of the injection wells along strike across the structure maps shown in Figure 2.4-8.

- The Starkey Formation is an inter-channel shale overlying the Tracy Formation.
- The Tracy Formation is deep-water sandstone on the east-west trending south-facing depositional slope. It overlies the Sawtooth Shale and thickens southward into the San Joaquin Basin. On the west side of the Stockton Arch Fault in the AoR, the Tracy Formation is very shale rich with minor interlaminations of low-quality sands.
- The Sawtooth Shale directly overlies the injection zone in the AoR and provides a regional seal that is 100 to 500 ft thick, averaging approximately 100 ft across the AoR. The average porosity is 18.5%, and the average permeability is 0.15 mD. CTV notes that the Sawtooth Shale has contained gas operations within the Winters Formation for 50 years and the natural gas deposits for millions of years.

The combined average porosity of the formations that comprise the upper confining zone is 23.0%, based on data from 16 wells with porosity logs and 50,563 individual logging data points, and the average permeability is 0.59 mD, based on data from 16 wells with porosity logs and 49,662 individual logging data points. The mean depth to the top of the confining zone within the AoR is 7,457 ft, and ranges from 7,208 to 7,776 ft, as shown on Table 2.4-2. The mean thickness of the Starkey-Sawtooth upper confining zone is 2,288 ft, and its thickness varies across the AoR from approximately 2,150 to 2,650 ft due to the deposition of the Winters Formation injection zone, where the shale minimum thickness corresponds to depositional highs in the Winters Formation injection zone (Figure 2.4-8). CTV notes that no representative mineralogy data are available for the upper confining zone.

Separating the Mokelumne River Formation and Capay Shale is a basin-wide unconformity, which CTV asserts will create a secondary seal between the injection zone and base of the lowermost USDW.

Delta Shale (Lower Confining Zone)

The Delta Shale directly underlies the Winters Formation injection zone in the AoR and will serve as the lower confining zone for the CTV II project. The Delta Shale consists of approximately 157 ft of shale barrier. The average porosity of 14.7% of the lower confining zone is based on data from 13 wells with porosity logs and 2,983 individual logging data points; and its average permeability of 0.04 mD is based on data from 13 wells with porosity logs and 2,906 individual logging data points.

CTV notes that there are sparse well penetrations in the Delta Shale lower confining zone, resulting in a lack of available log data from which the formation can be mapped. Therefore, CTV mapped the lower confining zone using available seismic data. XRD data from well GP_Dohrmann_1_RD1 (located approximately 6 miles north of the AoR) is available for two Delta Shale samples, which average 46% total clay, with smectite and kaolinite being the major clay species. They also contain 40% quartz, 10% plagioclase and potassium feldspar, and 1% calcite and dolomite.

Questions for CTV:

- ***Are any porosity and permeability data available for the Tracy Formation confining zone?***
- ***Does CTV have core data from drilling in any wells in nearby oil fields or from any other research on GS in the state of California that can provide porosity, permeability, capillary pressure, pore pressure, mineralogy, etc., data about the injection or confining zones to increase the number of data points on which the site characterization is based?***
- ***Based on stratigraphic maps in the application, the Tracy Formation occurs between the Starkey and Sawtooth Shales. Are the Starkey, Tracy, and Sawtooth (i.e., all three formations) intended to serve as the primary confining zone together?***

Geomechanical and Petrophysical Information [40 CFR 146.82(a)(3)(iv)]

CTV acquired data from 4 wells (shown as pink squares in Figure 2.4-1) comprising 9,633 individual logging data points within the AoR that had compressional sonic and bulk density data to determine upper confining zone ductility, and CTV acquired data from 16 wells (black circles in Figure 2.4-1) comprising 59,014 individual logging data points within the AoR that had data to determine upper confining zone unconfined compressive strength (UCS). Based on this data, the Starkey-Sawtooth Shale upper confining zone was determined to have an average ductility of 2.0, with 65% of the shale having a ductility below 2.0. The average rock strength of the confining zone was determined to be 4,593 psi as calculated using a log derived UCS methodology (Ingram et. al., 1997). Figure 2.5-1 presents log-based unconfined compressive strength and ductility calculations from well Sonol_Securities_6; **however, EPA recommends that CTV perform a triaxial load test as part of pre-operational testing, consistent with EPA's Class VI Site Characterization Guidance.** Based on calculations performed for well Sonol_Securities_6 located in the northern portion of the AoR, the brittleness index (RBI) decreases to a factor of ≤ 2.0, which CTV considers to be ductile and less prone to fracturing.

CTV states that the AoR has a strike-slip/reverse fault regime based on studies conducted within the Sacramento Basin. The maximum principal horizontal stress orientation is estimated to be N40°E±10° which is consistent with regional data (Heidback et al., 2016) and is shown on Figure 2.5-3.

No site-specific fracture pressure or fracture gradient is available for the Winters Formation injection zone or the upper confining zone, or pore pressure data for the confining zones, but CTV intends to collect this information via pre-operational step rate testing. Fracture gradients are available for other shallower formations such as the H&T Shale and Mokelumne River Formations. These gradients are based on formation integrity testing from other wells within the AoR. Fracture gradient range was observed to be from 0.75 to 0.84 psi/ft from these wells. CTV applied a fracture gradient of 0.7 psi/ft for their computational modeling. CTV states that the overburden stress gradient in the reservoir and confining zone is 0.94 psi/ft.

Question for CTV:

- ***Please clarify where the 0.94 psi/ft overburden stress gradient was referenced, or state how it was determined.***

Seismic History [40 CFR 146.82(a)(3)(v)]

CTV researched historical seismic events within the vicinity of the project site via the USGS earthquake catalog. Figure 2.6-2 shows the locations of the events, and Table 2.6-1 summarizes the events, including their date, depth, and magnitude. Eleven events have occurred between 1866 and 2010. The depth of the events ranged from 2.9 to 14.6 km and earthquake magnitudes ranged from 3.1 to 6.0. The most recent event occurred in 2010 at a depth of 14.6 km having a magnitude of 3.1. This happened to be the closest event as well, occurring right on the northeast edge of the AoR. The shallowest event occurred in 1976 at a depth of 2.9 km and having a magnitude of 3.3, over 17 miles from the southern edge of the AoR. The highest magnitude earthquake (M 6) occurred in 1866 approximately 11 miles to the southwest of the AoR boundary; the depth for this event is unknown.

CTV states that the Stockton Arch Fault, which is the closest fault system to the site, is only identified within the subsurface with no evident surficial expressions. The fault trace is consistent with mapping developed by the California Geologic Survey (CGS) and the U.S. Geologic Survey (USGS). The fault extends upward, and is eventually cut off by the base of the Valley Springs Formation (which is present above the injection and confining zones). No evidence of significant offset is observed above this formation according to available seismic interpretation data (California Department of Conservation of Oil, Gas & Geothermal Resources Oil & Gas Technical Reports).

In characterizing the risk of induced seismicity associated with CO_2 injection, CTV asserts that there is no clear link to the proposed injection site, citing no correlation between induced seismicity and historical oil and gas production. None of the seismic events have occurred within the Winters Formation injection zone and many of the events occurred at depths greater than 19,500 feet (5.9 km), well below the proposed injection interval. CTV states that injection operations will result in a final formation pressure of 4,500 psi, which is lower than the pre-gas-production historical reservoir pressure of 5,050 psi that was exerted on the Stockton Arch Fault. Fault reactivation (as a normal fault) to a degree that would offset thousands of feet would be required to pose a risk due to the proposed injection zone being offset from older strata with the same confining zones above. Figure 2.6-3 of the Narrative shows the proposed injection site in an area of low relative stress magnitude and minimal clusters of stress inversions.

CTV intends to monitor for pressure changes and associated seismicity as part of the Testing and Monitoring during operation. CTV's seismic hazard mitigation is detailed in Section 2.6.2.

Questions for CTV:

- ***Regarding the statement there is no correlation between induced seismicity and historical oil and gas production, does this include evaluation of fields where injection (e.g., in Class II wells) was occurring?***
- ***Please provide data to support statements in the narrative about past (i.e., 5,050 psi) and predicted (i.e., 4,500 psi) reservoir pressures.***

Hydrologic and Hydrogeologic Information [40 CFR 146.82(a)(3)(vi), 146.82(a)(5)]

The CTV II project site is located within the central area of the Tracy Subbasin, in the San Joaquin Valley Groundwater Basin (Figure 2.7-1). Surface water sources in the area include the San Joaquin River, Old River, and Middle River. Man-made hydrological features include the California Aqueduct, Delta-Mendota Canal, and other irrigation canals.

CTV identifies both the base of fresh water (BFW) and the base of the lowermost USDW (Figures 2.7-2 and 2.2-4, respectively). The base of the lowermost USDW is estimated to be contained within undifferentiated non-marine sediments at a depth of 2,400 ft, based on evaluation of geophysical logs and salinity calculations; the USDW is depicted in Figure 2.2-4. The four-step process CTV used to conduct salinity calculations is described in Subsection 2.7.2.2; however, it is unclear if this represents wells within the AoR.

Formations containing USDWs were identified as alluvium deposits, flood Basin/intertidal deposits, alluvial Fan Deposits, the Modesto Formation, the Tulare Formation, and undifferentiated non-marine sediments. These formations are depicted in Figure 2.7-1. The non-marine sediments, at a depth of 2,400 feet, are identified as the lowermost USDW, and have a total dissolved solids (TDS) range of 3,000 to 10,000 mg/L. The occurrence of groundwater is linked to the layers of sand and gravel from river channels and flood deposits that are bound by lower permeable clays and silts, in particular the Corcoran Clay which separates the Upper and Lower Aquifer zones, which are principal aquifers within the subsurface.

Hydrogeologic cross sections of the Tracy Subbasin are provided in Section 2.7.4. Cross Section B-B' in Figure 2.7-4 runs northwest-southeast through the non-Delta and Delta portions of the Tracy Subbasin. Cross Section C-C' in Figure 2.7-5 runs northeast-southwest across the Delta area. These cross sections demonstrate the principal aquifers of the Tracy Subbasin – the Upper and Lower Aquifer zones – and their separation from the injection zone by the Corcoran Clay, a lakebed deposit within the Tulare Formation. The Upper Aquifer is an unconfined to semi-confined aquifer existing in the Alluvial Fan Deposits, Intertidal Deposits, Modesto Formation, Flood Basin Deposits, and the upper portions of the Tulare Formation. CTV reports that the Upper Aquifer is used by community water systems and for agriculture. The Lower Aquifer is mainly comprised of the lower portions of the Tulare Formation below the Corcoran Clay and extends to the base of fresh water, and it is typically used by community water systems and agriculture. The estimated thickness and lateral extent of the separating Corcoran Clay is shown in Figure 2.7-3. Where the Corcoran Clay pinches out in the southern end of the AoR, the Upper and Lower Aquifer zones merge. A schematic profile is provided in Figure 2.7-6.

Potentiometric maps for the Upper and Lower Aquifer zones are provided in Figures 2.7-7 and 2.7-8, respectively. Data on groundwater levels were obtained from the Tracy Subbasin GSP (GEI 2021), which included groundwater level measurements from over 226 wells across the Tracy Subbasin. From these data, a groundwater gradient was established, the details of which are provided in Section 2.7.6. The gradient is typically downward in the aquifer zones. In the non-delta areas, the gradient ranges from a few feet bgs to 70 feet bgs, and groundwater levels are 10 to 30 feet higher in the Upper Aquifer than the Lower Aquifer. In the delta areas, groundwater levels are at sea level.

CTV identified 35 water supply wells within one mile of the AoR using California State Water Resources Control Board Groundwater Ambient Monitoring Assessment Program (GAMA), Department of Water Resources (DWR), California Statewide Groundwater Elevation Monitoring (CASGEM), and other public databases. Water wells are depicted in Figure 2.7-9 and listed in Table 2.7-1. Table 2.7-1 includes known water well depths and other available information. CTV notes that water wells were identified solely through well logs contained within public records; thus, wells that were not recorded or wells whose records may not have survived are not included in CTV's tabulation of wells. However, CTV asserts that all local water supply wells are completed in intervals much shallower than the injection zone. Available data of Table 2.7-1 supports this assertion, as all water wells are completed above a depth of 482 ft.

CTV's permit application narrative includes substantial information on USDWs. **Additional characterization of the lowermost USDW to satisfy the requirements of 146.82(a)(5) is required.**

Questions for CTV:

- ***Is any information available about the TDS content of the non-marine sediments that contain the USDW?***
- ***Where are the wells on which the geophysical logs used for the salinity calculations are based?***
- ***Please confirm the total completion depths of the wells showed as "NA" in Table 2.7-1.***

Confining Zone and Injection Zone Geochemistry [40 CFR 146.82(a)(6)]

The permit application narrative indicates that no quantitative mineralogy information exists for the injection or confining zones within the AoR, and that this data will be acquired during pre-operational testing across all zones of interest. Core descriptions from three wells within the AoR and two wells about six miles north of the AoR characterize the Winters Formation injection zone as consisting of quartz, feldspar, mica, ferromags, and lithics. Table 2.4-1 summarizes XRD measurements from the GP_Dohrmann_1_RD1 well (6 miles north of the AoR) including two reservoir sand samples. CTV evaluated the mineralogy of the H&T shale from the Speckman_Decarli_1 well and the Delta Shale from the GP_Dohmann_1_RD1 well (both wells are 6 miles to the north of the AoR). **Because this data from 6 miles outside the AoR form the basis of the geochemical modeling (as described further in CO2 Stream Compatibility below), collection of site-specific data during pre-operational testing is needed to eliminate uncertainties about CO_2-rock-fluid compatibility.**

No mineralogy data are available for the Starkey-Sawtooth upper confining zone; however, data are available from the H&T Shale, a similarly aged shale that lies directly above the upper confining zone. Data from the Starkey-Sawtooth upper confining zone should be analyzed during pre-operational testing for comparison to the available XRD data. Mineralogy data from GP_Dohrmann_1_RD1 for the H&T shales and the Delta Shale lower confining zone are summarized in Table 2.4-1. The H&T Shale upper confining zone consists of clay (46%), quartz (23%), plagioclase and potassium feldspar (29%), pyrite (2%), and calcite and dolomite (1%). The Delta Shale lower confining zone consists of a higher quartz content (40%) and a lower plagioclase and potassium feldspar (10%). Installation of a stratigraphic well and core sample analysis would provide a more representative characterization of the minerology for the Starkey-Sawtooth formation within the AoR.

Fluid samples collected in 2015 from the Winters Formation injection zone were evaluated from the Sonol_Securities_4 well (located within the AoR) and gas chromatography analysis were evaluated from the Sonol_Securities_5 well in the Union Island Gas field. These wells are located within the central portion of the AoR (Figure 2.8-3). The formation consists of saline water and gaseous hydrocarbons. Laboratory water chemistry and gas chromatography analytical results are summarized on Figure 2.8-1 and Figure 2.8-2, respectively, and in Table 2.8-1. The results indicated a TDS concentration of 15,595 mg/L, elevated concentrations of chloride and sodium, and a strong calcium and bicarbonate signature. Methane and nitrogen were the dominant analyte compositions of the gas analysis.

No fluid geochemistry analysis was available for the upper or lower confining zones. CTV states that fluid for analysis will only be extracted from the shale if stimulation is performed. CTV does not anticipate any CO_2 compatibility issues with the formation fluids within the confining zones due to their low permeability and carbonate content. **Additional collection of site-specific data during the pre-operating phase will be necessary to confirm assumptions of site parameters and reduce uncertainty in modeling inputs.** Injection formation fluid compatibility is discussed further in CO2 Stream Compatibility below.

Site Suitability [40 CFR 146.83]

Facies Changes

The Winters Formation injection zone is a silica rich formation. CTV states that regional thickness and lateral continuity will allow the reservoir to accommodate the injection of CO_2. This appears to be the case based on information provided in the application (including some cores taken within the AoR); **however, CTV should provide evaluations based on pre-operational core sampling of the Winters Formation injection zone to confirm these assertions and reduce uncertainties in the characterization of facies changes and allow final approval of the AoR.**

Structural Information

The injection zone gently dips 2° west in a slight anticlinal structure. The only notable structural feature in the AoR is the Stockton Arch Fault, which demarcates the southeastern edge of the AoR. The location of the site is situated in a structural-stratigraphic trap region with the Stockton Arch Fault and Winters Formation pinching out updip to the northeast. CTV asserts that these structural features, and the confining nature of the shale formations above and below the injection zone, will contribute to the local immobilization and containment of the CO_2 injectate.

These assertions about regional structural features appear to be supported by available regional data. **However, additional characterization of the Stockton Arch Fault during pre-operational testing is needed to confirm these assertions.** CTV should provide additional evidence of fault sealing, i.e., data to clarify the juxtaposition of units, potential for leakage along faults, catalysis, diagenetic sealing, shale gouge ratio, and/or additional pressure compartmentalization per EPA's Class VI Site Characterization Guidance as described under "Faults and Fractures" above.

CO_2 Stream Compatibility

CTV does not anticipate any CO_2 compatibility issues with the injection zone due to the dominant quartz and feldspar content, limited dissolution, and minimal calcium and magnesium cations associated with the Winters Formation injection zone formation water. CTV does not anticipate any CO_2 compatibility issues with the confining zones due to their low permeability and carbonate content.

CTV conducted geochemical modeling using PHREEQC software and assumed parameters to estimate the compatibility of the injectate with the injection and confining zones (the modeling is described in Appendix 3).

CTV's modeling approach applied available formation minerology from outside the AoR, injection zone geochemical data from the within the project site, and two potential injectate chemical compositions. Thermodynamic data for the prominent minerals within the injection zone and confining zone were obtained from the Lawrence Livermore National Laboratory (LLNL.dat) which includes data for the minerals characterized (i.e., quartz, feldspar, and various clay minerals). The calculation of saturation indices appears to be sufficient and consistent with EPA guidance recommendations, applying XRD data for the various minerals and assumptions for dissolution and precipitation reactions. The input parameters summarized in the associated tables (Tables 1 through 4) reflect other information in the narrative and the results summarized in Tables 5 through 7 are consistent with the modeling conclusions.

Predicted reactions include mineral dissolutions and precipitations, including carbonate formation and CO_2 dissolution into the formation brine. The results of the geochemical modeling support CTV's assertion and appear to indicate that there are no concerns for injectivity and that CO_2 injection will not cause significant reactions that will affect the containment of CO_2. **However, given the limited amount of geochemical and mineralogic data on the injection and confining zones from within the AoR, geochemical modeling inputs will need to be updated with site-specific data collected within the AoR during pre-operational testing to reduce uncertainty about the geologic characterization of the site and ultimately approve the AoR delineation before CTV is authorized to inject CO_2.**

Storage Capacity

CTV asserts that historical gas production in the Winters Formation at Union Island Gas Field demonstrates the storage capacity of the Winters Formation injection zone. Cumulative historical production was 292 billion cubic feet of gas and 3.4 million stock tank barrels of water. CTV asserts that this capacity is sufficient to contain CTV's proposed injection volume of 22.31 million tonnes. However, it is unclear what information factored into this assertion, such as the area of the Winters Formation within the gas field relative to the anticipated CO_2 plume and how this relates to the volume of supercritical CO_2 at anticipated temperature and pressure conditions during and after injection operations.

CTV provided some limited information regarding regional gas production, most notably the location of oil and gas fields as shown on Figure 2.1-1. Most of these oil fields are located miles away from the project site to the north and northwest. Production from the oil fields began in 1976 and extended through 1988. Figure 2.1-6 illustrates a stratigraphic cross section that includes the location of select oil fields and extends through the AoR.

Confining Zone Integrity

The Starkey-Sawtooth and Delta Shale formations provide upper and lower confinement of the injection zone, respectively. The Starkey-Sawtooth upper confining zone is approximately 2,288 ft thick within the AoR and the Delta Shale lower confining zone is approximately 157 feet thick, and both are laterally extensive across the AoR.

CTV asserts that both upper and lower confining zones are free of transecting faults or fractures within the AoR, with the exception of the local Stockton Arch Fault (see discussion and questions under Faults and Fractures [40 CFR 146.82(a)(3)(ii)]). Information on faults in the project area is based on 2D and 3D seismic data (shown on Figure 2.2-3). Both 3D surveys, which cover an extensive area within and beyond the AoR, were acquired in 1998 and reprocessed in 2013. The 2D seismic data were acquired between 1980 and 1985; one east-west seismic line runs through the southern portion of the AoR.

Additionally, step-rate testing to determine fracture pressure will be needed to ensure that operating pressures are appropriate to confining zone geomechanical properties.

Secondary Confinement

CTV did not define a secondary confining zone, citing that the Starkey-Sawtooth is a suitable upper confining zone to capture and contain CO_2 within the Winters Formation injection zone. However, they did identify other shale barriers above the Mokelumne River Formation that could contribute to containment, including the H&T Shale, the Capay Shale, Domengine Sandstone, Nortonville Shale, and the basin-wide unconformity. CTV asserts that each will contribute to separation of the injection zone from the USDW and provide additional upper confinement.

To reduce uncertainty, it is recommended that CTV fully characterize H&T Shale, the Capay Shale, Domengine Sandstone, Nortonville Shale as secondary confining zones using any available data for the pre-construction phase of the project, pursuant to 40 CFR 146.83(b).

Questions for CTV:

- ***Please provide additional information and calculations regarding how CTV determined the storage capacity of the injection zone, and how site-specific properties of the injection zone from within the AoR and operational conditions were factored into this evaluation.***
- ***Please provide information about the resolution of the 3D seismic surveys used to characterize faults near the project. Specifically, given the large area surveyed, what information exists that smaller faults would be identified?***
- ***Please characterize the H&T Shale, the Capay Shale, Domengine Sandstone, Nortonville Shale as secondary confining zones to satisfy the requirements of 40 CFR 146.83(b).***

Site Geomodel

CTV developed a static 3D representation of site geology in Schlumberger's Petrel software using well data and 3D seismic data rendered into a geo-cellular grid. The Area of Review and Corrective Action Plan (AoR/CA) document describes the static geomodel created for the AoR delineation. CTV's geomodel appears to be consistent with the site characterization data as described in the narrative document, and there are no initial concerns with the methodologies used to construct the geomodel. All concerns regarding the geomodel reflect the concerns about the deficiencies in site-specific characterization data as described in this evaluation. Details of the geomodel are discussed below.

- The model domain is described in Table 3.2. Figure 3.3 displays the geomodel boundary and geo-cellular grid used to define the CO_2 plume extent and delineated AoR. CTV rotated the model 40° to align it with local structural and depositional trends. CTV notes that grid sizes were initially 100 by 100 feet across the entire domain, then grid sizes were upscaled to 200 by 200 feet. The static geomodel grid is displayed in Figure 3.4. Cells were modeled with heights of 20 ft to provide vertical resolution for identification of sand vs. shale layers; this appears to represent vertical facies distribution when compared to open hole log data from well Sonol_Securities_8 (Figure 3.5). **As data are collected from within the AoR during pre-operational testing, the grid inputs should be revised as necessary to reflect any heterogeneities identified and reduce uncertainty in the model inputs.**
- CTV used Sequential Gaussian simulation with porosity and permeability measurements and calculations (as described in Injection and Confining Zone Details [40 CFR 146.82(a)(3)(iii)] above) to calculate porosity/permeability distributions for the static geomodel. Histograms of the porosity/permeability distributions are provided in Figure 3.8, and the distribution of these properties is displayed in cross section view in Figure 3.9. Core data used for these distribution calculations are consistent with data collected from wells outside of the AoR as described in the narrative (Figure 3.6).
- CTV references the results of geochemical modeling provided in Appendix 3: CTV II Geochemical Modeling (described in CO2 Stream Compatibility above) for potential geochemical reactions in the injection zone. CTV excluded reactive transport from the site geomodel, citing the IPCC Special Report on Carbon Dioxide Capture and Storage (2005), which shows that mineralization trapping has minor effects on the AoR, to assert that excluding reactive transport modeling will not adversely affect the computational modeling.
- CTV set no-flow boundaries on all sides in the geomodel. This is based on the characterization of the upper confining zone as described in the narrative, and historical performance data indicating the maintained formation underpressure of 1,200 psi. This is consistent with the site characterization, as the Starkey-Sawtooth Shale is characterized as an upper confining layer in the site characterization. No lower boundary is defined in the geomodel, given the buoyant nature of the CO_2 plume. CTV also considers the Stockton Arch fault as a no-flow boundary for the eastern edge of the geomodel domain. This assumption is consistent with the site characterization narrative, but substantial pre-operational testing information is needed to confirm that the fault will be pressure sealing within the AoR (see Faults and Fractures [40 CFR 146.82(a)(3)(ii)] above). CTV modeled the northern and the remainder of the eastern edges of the geomodel as open boundaries; this is consistent with information in the narrative, given the lack of bounding structural features in these directions as described in the narrative.
- Initial reservoir conditions are described in Table 3.4. At an elevation of 9,600 ft MSL, formation temperature is 218°F based on fluid analysis; pressure is 1,200 psi based on a pressure test; fluid density is 61 lbs/ft^3; and salinity is 15,000 ppm. Fluid density and salinity are consistent with the summary of formation fluid properties measured from well Sonol_Securities_4 (located within the AoR) in Table 2.8-1 of the site characterization narrative.

- An injection zone fracture pressure gradient was assumed to be 0.70 psi/ft based on the state-approved maximum operating pressure gradient of 0.80 psi/ft for a different formation in the Class II project well GALLI 1. The well appears to be located on the southern edge of the AoR based on Figure 2.5-4. CTV will need to conduct a step rate test for determining the injection zone fracture pressure as part of pre-operational testing. CTV notes that fracture gradient information is unavailable for the Starkey-Sawtooth Shale upper confining zone, so CTV will also conduct a step rate test for the Starkey-Sawtooth as part of the pre-operational testing.
- Table 3.6 contains injection pressure details, including the estimated maximum allowable injection pressures at 90% of the assumed fracture pressure and elevations in each well corresponding to the maximum injection pressure. **The fracture pressure used in the model is assumed, and CTV plans to perform a step rate test to confirm these values as part of the pre-operational testing.**

Overall, the data inputs to the site geomodel are consistent with data collected and described in the narrative document. However, as noted above, many data points require confirmation via pre-operational testing to affirm their appropriateness as modeling inputs to generate a final approvable AoR. CTV states that the simulation and AoR will be updated once site specific core data is obtained during pre-operational testing.

Question for CTV:
- ***Please further elaborate on the data sources listed in Table 3.4 and provide the data that were used to determine formation initial conditions.***
- ***Please provide the data source used to estimate the fracture pressure value used in the geomodel.***

Summarized Objectives for Pre-Operational Testing:

In their pre-operational testing plan (POTP), CTV describes the formation testing to be performed during drilling of the two new injection wells to meet the requirements of 40 CFR 146.87. CTV plans to perform a combination of conventional and open-hole logs including dual induction laterolog, gamma ray, compensation neutron, formation density, and mud log. Electrical logging will be conducted to characterize reservoir rock and fluid properties, and formation pressure testing will be conducted to determine reservoir pressure and permeability.

CTV plans to collect an unspecified number of whole cores during drilling, targeting the confining and injection zones. The POTP states that the whole cores will be collected from one of the newly drilled wellbores within the project area, but does not identify the wellbore location or the number of cores to be taken. The proposed core analysis includes porosity, permeability, saturation, grain density, gamma ray, and general core descriptions. Specialized core analysis will also be conducted and include capillary pressure, XRD, CO_2 to water permeability, confining and injection zone geomechanical measurements, pore compressibility, and scanning electron microscopy (SEM). A pressure fall-off test (FOT) will also be conducted for injection wells UI-Inj-1 and UI-Inj-2. FOT performed on existing wells are provided under separate submittal for each well.

The POTP provides an outline of additional pre-operational testing that will be conducted, including the following:

- Groundwater sample collection and analysis.
- Baseline geochemistry characterization of the USDW and the injection zone.
- Baseline seismicity characterization.
- Facies change analysis of the injection zone.
- CO_2 stream compatibility analysis with subsurface fluids and minerals, confirm AoR delineation model inputs, and confirm analytes for injectate and groundwater monitoring are consistent with the geochemical modeling evaluation.
- Step rate testing to confirm fracture pressure of the injection and confining zones.

The POTP and Testing & Monitoring Plan include general procedures for all of the above referenced tests, except for step rate testing. The POTP does not specify on which wells step rate testing will be performed. **Approval of all pre-operational testing procedures will be needed prior to well construction and testing.**

Based on the data gaps identified in the evaluation as described above, additional pre-operational testing objectives (listed below) can help address the uncertainties identified.

Pre-Operational Testing Objectives:

- **Identify site-specific mineral composition and petrophysical characteristics of the injection and confining zones, in particular to correlate available data from the H&T Shale to the Starkey-Sawtooth upper confining zone.**
- **Clarify formation ductility, principal stresses, pore pressure, fracture gradient, and other petrophysical parameters to confirm geomechanical assumptions.**
- **Determine static fluid levels (per 40 CFR 146.87(c)).**
- **Characterize the hydrogeologic characteristics of the injection zones using a pump test or injectivity test (per 146.87(e)).**
- **Identify potential fractures within the carbonates of the upper confining zone and evaluate their effect on confinement.**
- **Determine precise storage capacity based on site-specific injection zone characteristics.**
- **Confirm the absence of faults that transect the confining zone within the AoR.**
- **Confirm pressure isolation within the injection zone and other stratigraphic intervals across the footwall and hanging wall of the Stockton Arch Fault.**
- **Characterize formation fluid geochemistry and identify potential geochemical reactions and interactions between the injection and confining zone mineralogies and formation brines with the CO_2 injectate to confirm the assumptions and results of the initial geochemical modeling to predict changes in formation water chemistry, mineral precipitation, and dissolution reactions.**
- **Characterize geochemistry in the above confining zone formation to be monitored, including data on CO_2 concentrations and fluxes, to serve as a baseline for comparison to CO_2 levels during and after the operational phase of the project in order to detect any potential leakage.**

Questions for CTV:

- ***On which wells will CTV perform an SRT?***
- ***How many cores does CTV plan to take and analyze from within the injection and confining zones during drilling?***
  Please include triaxial load testing as part of pre-operational testing, consistent with the site characterization guidance.