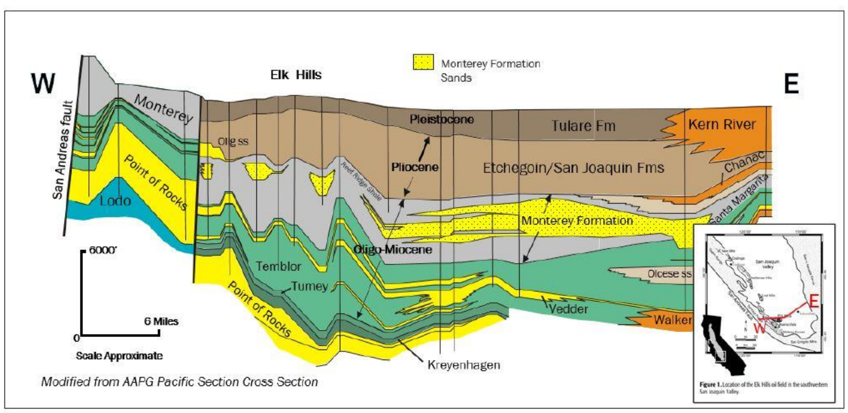
Computational and Static Modeling Evaluation of CTV A1-A2 Permit Nos. R9UIC-CA6-FY21-1.1 and R9UIC-CA6-FY21-1.2

This Computational and Static Modeling Evaluation report for the proposed Carbon TerraVault 1 LLC (CTV) Elk Hills A1-A2 Class VI geologic sequestration project summarizes EPA's review of the computational modeling performed by CTV as described in the Area of Review and Corrective Action Plan (AoR CA), which is Attachment B Version 3 (submitted November 4, 2022). This report also summarizes EPA's review of the geologic narrative submitted as Attachment A Version 3 (submitted June 20, 2022) of the permit application. Clarifying questions or requests for additional information are provided below in ***bold, italic*** text.

Static Modeling Comments and Geologic Site Conditions

This portion of the review assessed whether the information presented in Attachments A and B of the application could be independently verified with the data presented. The review evaluated whether statements and claims made in the text were supported by data. The comments below include requests that are necessary to determine if the statements made in the text are accurate.

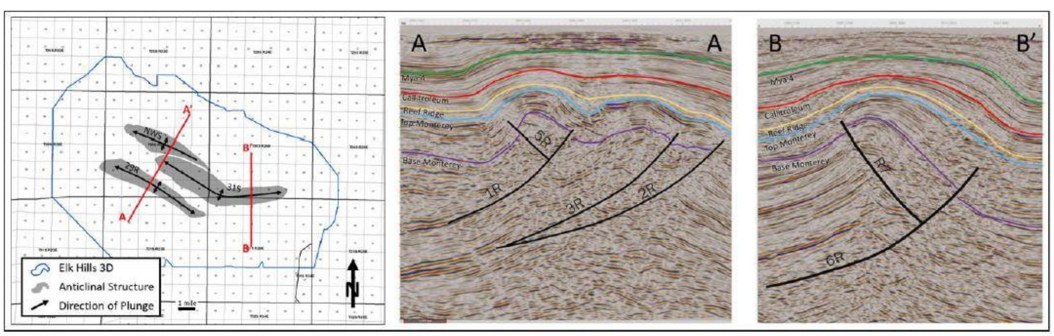
Figure 3: Cross-section across the southern San Joaquin Basin showing the lateral continuity of the major formations (Zumberge, 2005).



- Figure 3 in Attachment A, shown above, suggests that the Reef Ridge and Monterey Sands are time equivalent formations.
  - ***Please add a description to clarify that the Reef Ridge Formation is at the very top of the Monterey Formation.***
- Page 8 of Attachment A describes the San Joaquin Formation and Etchegoin Formation.
  - ***Is the base of the San Joaquin Formation an unconformity?***
  - It is stated that "This depleted Mya gas reservoir would effectively dissipate any possible CO_2 leakage before it could reach the Upper Tulare USDW". However, there is no

analysis to support this statement. ***Please provide an analysis or data to support this statement.***
  - When describing the Etchegoin Formation it is stated "Between sand reservoirs are laterally continuous shales that are sealing and prevent hydraulic communication from above and below". ***What well data supports this statement? Please provide data to support this claim.***
- Page 9 of Attachment A describes the Monterey Formation.
  - It is stated that "Within the AoR there is no evidence of faults that transect the Monterey Formation or penetrate the Reef Ridge confining layer." ***What data was used to reach this determination?***
  - In the Summary section for the Monterey Formation, it is claimed "Both datasets support the geological framework establishing sand continuity and as well as vertical confinement by the Reef Ridge Shale and lateral reservoir confinement." The sentence is unclear and seems to be a circular reasoning. The statement also lacks supporting data and information. ***Please provide well correlations, seismic correlation and well communication data from previous production/injection to support the claim that static and dynamic data sets are consistent and prove sand continuity and vertical confinement.***
- Page 9 of Attachment A describes the A3-A11 reservoir.
  - ***Will there be concurrent operations between the A3-A11 reservoir waterflood and the A1-A2 reservoir CO2 injection? If yes, please describe the potential impact of having two concurrent operations.***

Figure 11: EHOF Showing location of NWS and 31S anticlines with 3-D seismic boundary and line of cross sections. (Right) Cross Section A-A' and B-B' showing structure of EHOF anticlines with reverse faults.

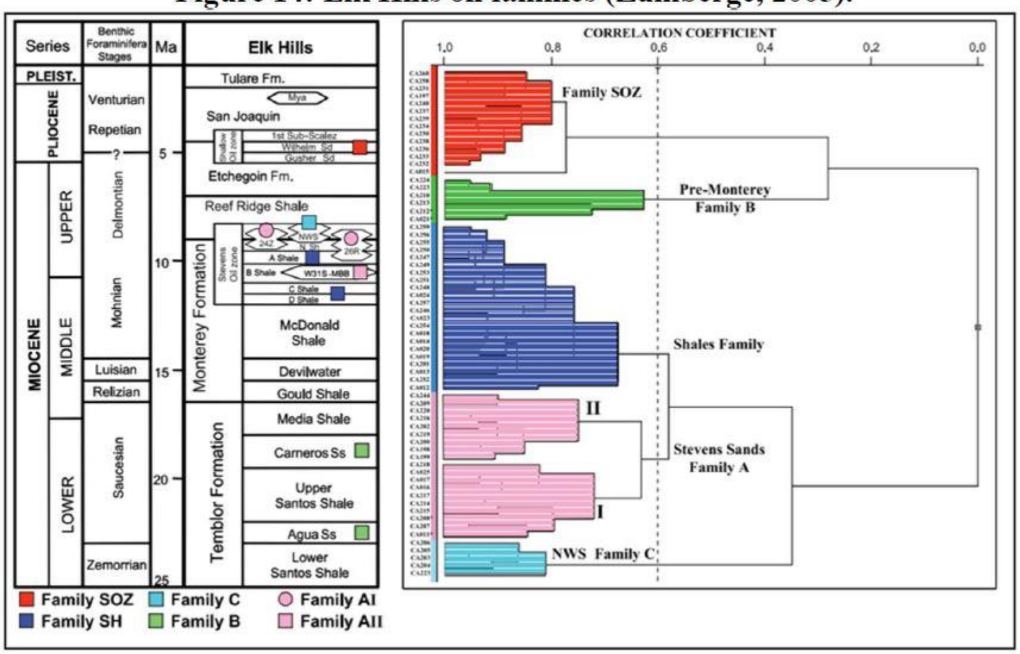


- Figure 11 in Attachment A, shown above, depicts the structure of the Elk Hills Oil Field (EHOF) anticlines.
  - ***Are there any wells that could be depicted in the cross section for reference? If so, please include the wells in the figure.***
  - ***Please include a scale on the figure.***

- *The A' symbol is missing from the A-A' cross section. Please indicate which side of the cross section is A'.*
- ***Is the sharp kink in the top of the Monterey Formation in the A-A' cross section evidence of a fault? Please include reasoning as to why or why not.***

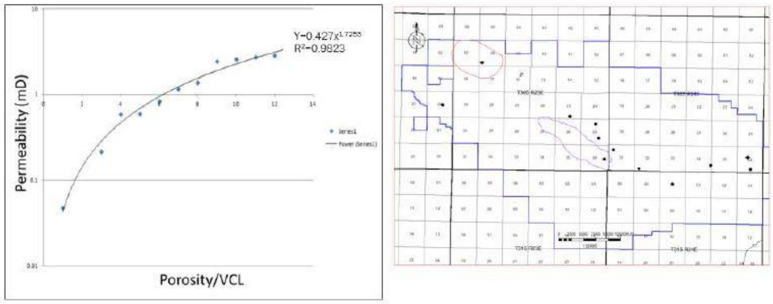
- The seismic control of the formation is described on page 13 of Attachment A.
  - It is stated that "The Reef Ridge is a thick continuous shale over the San Joaquin Basin." ***Please include a regional seismic diagram to verify the statement and Figure 12.***
  - Page 13 includes the statement "In the EHOF, the thickness averages 1,100 feet (Figure 12) and is well resolved within seismic. Analysis of the three-dimensional seismic and well data provides no evidence that the faults either transect the Monterey Formation or penetrate the confining Reef Ridge Shale." ***Please provide or explain the well data and seismic analysis that led to this determination.***

Figure 14: Elk Hills oil families (Zumberge, 2005).



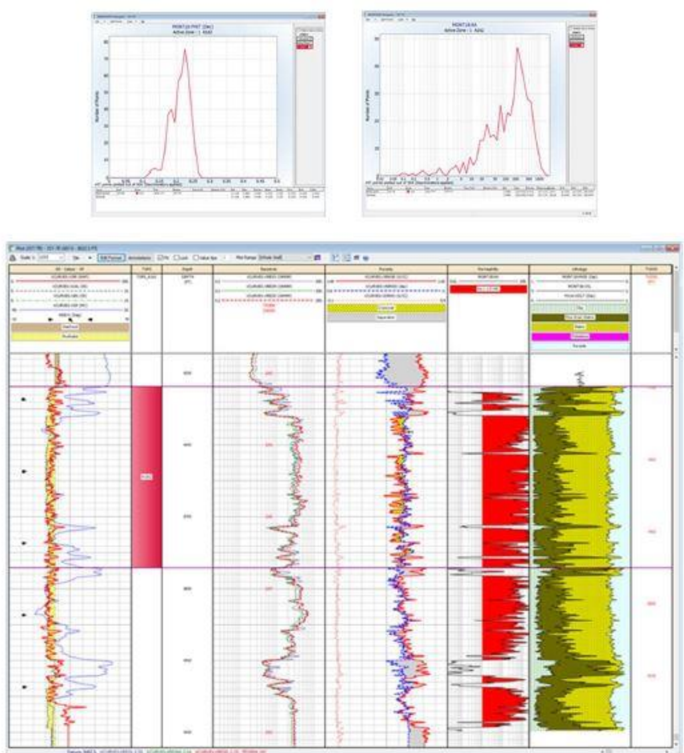
- Figure 14 in Attachment A (above) depicts the oil analysis performed in the Monterey and overlying formations.
  - ***Please provide the geochemical cross-plots to identify the hydrocarbon families***
  - ***Please include a discussion on how the geochemical data compares to the pressure plots.***

Figure 19: Permeability function developed based on mercury injection capillary pressure data and calculated from log derived porosity and clay volume. Map shows the locations for wells with Monterey Formation sand core data used in the function.



- Figure 19 in Attachment A, show above, includes a permeability curve, however there is little context, and it is difficult to interpret.
  - ***Does Figure 19 show an example or subset of the total data used to derive the permeability function in the figure?***
  - ***Please explain how the data in the figure relate to the permeability range of 3 mD to 1,500 mD and the average permeability of 45 mD?***
  - ***What location and depths were the permeability data collected from?***

Figure 20: Porosity and permeability for well 357-7R, showing the distribution and the input and output log curves.



- Figure 20 in Attachment A, shown above, describes the porosity and permeability for well 357-7R. The lithology log shows no difference between the Reef Ridge Shale and the Monterey Sand.

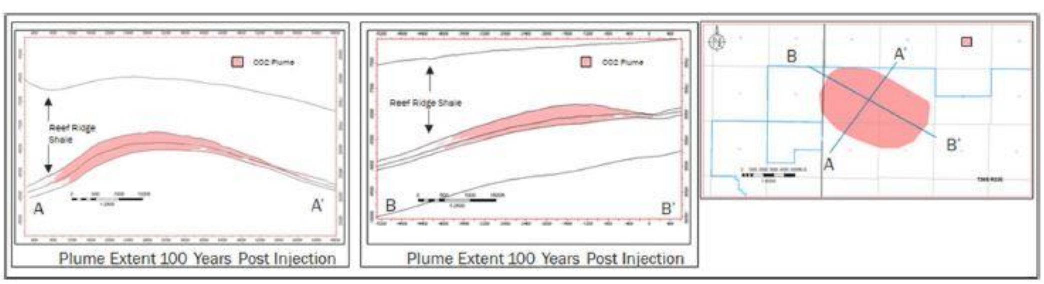
- *Please described how the lithology log was created.*
- ***Are the percentages of clay, fine grain matrix, matrix, and porosity very similar for the Monterey Formation and Reef Ridge Formation?***
- ***Why does the lithology porosity percentage appear so similar between the two formations when the average porosity for the Monterey Formation is 21% and the average porosity for the Reef Ridge Formation is 7%?***

- The Reef Ridge ductility is described on page 23 of Attachment A.
  - ***If there is a leak-off test, or formation-integrity test data to demonstrate seal integrity of the Reef Ridge Formation, please submit it***.
- In the seismic risk section, the statement on page 31 "Has a geologic system free of known faults and fractures and capable of receiving and containing the volumes of CO_2 proposed to be injected." This statement is misleading since the field was created by faults.
  - ***Please revise the statement to read accurately. For example, "free of known earthquake-prone faults" or "free of known active faults".***
- The statement on page 31 of Attachment A "There are no faults or fractures identified in the AoR that will impact the confinement of CO_2 injectate." This statement is misleading since the anticlines in the area are fault controlled.
  - ***Please revise the statement to represent that faults will contribute to the containment of CO_2 injectate.***

Model Design

This section of the review evaluated how the computational modeling was designed and incorporated the injection zone and confining zone geology. The review evaluated the appropriateness of assumptions, boundary conditions and choice of grid spacing. The comments below include requests to design the model with greater detail and provide information on assumptions made.

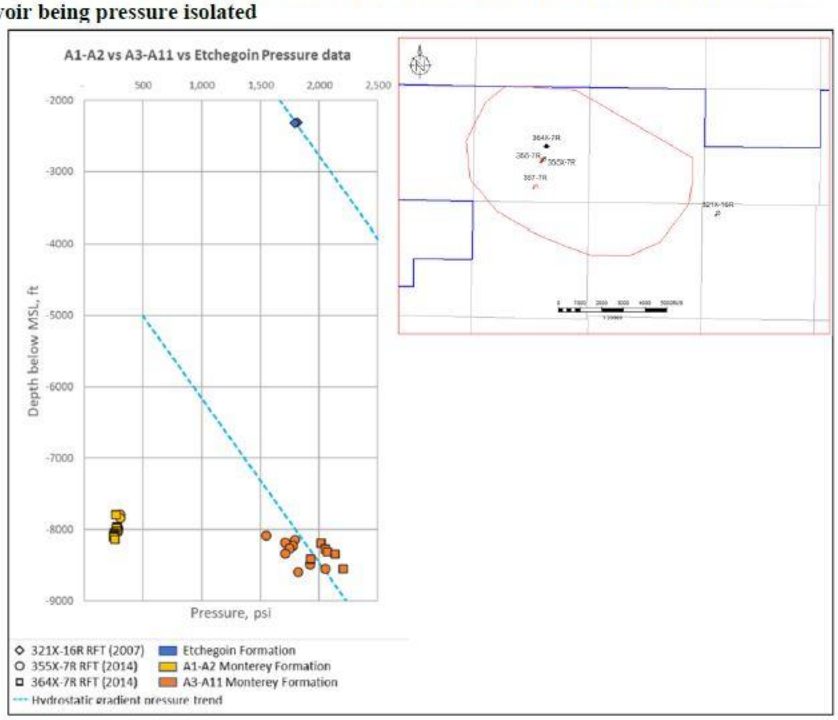
Figure 38: Plume modeling results showing lateral confinement of the CO2 plume by the edges of the anticline structure.



- Figure 38 in Attachment A, shown above, depicts the plume modeling results in the A1-A2 formation.

- *Please add the injectors and monitoring wells to the figure or create a new figure to help illustrate where the penetrations in the injection zone are located with respect to the predicted CO_2 plume modeling results.*
- Page 5 of Attachment B states "Well data, open-hole well logs and core (Figure 2), define the subsurface geological characteristics of stratigraphy, lithology, and rock properties."
  - ***Was seismic data used to create the static model? If so, please describe how the data was incorporated.***
- Figure 4 in Attachment B states "The stratigraphic units either pinch-out up-dip or reservoir sands transition to shale."
  - ***Please provide either a seismic section, well correlation panel, or both to support the statement made. Please show the pinchout and transitions to shale in both the dip and strike direction.***
- The Constitutive Relation section in Attachment B states "Material Balance is a well accepted method to determine the average saturations and fluid contacts in an oil and gas reservoir over time".
  - ***When was the last test or measurement that allowed for the determination of the gas-oil contact and oil-water contact at that time?***

Figure 11: Formation pressure data in the area gathered in 2007 and 2014, after the blowdown of the A1-A2 reservoir, showing large pressure differentials between the A1-A2 and the underlying (A3-A11) and overlying (Ethcegoin) reservoirs, which supports the conclusion of the A1-A2 reservoir being pressure isolated



- Figure 11 in Attachment B, shown above, presents pressure data from 2007-20014 in the AoR between different formations.

- ***This data was obtained during production operations. Is there any data representative of the initial project conditions, when production has ceased, that can demonstrate pressure isolation?***

Figure 112: Plan view showing the plume development through time for layer 15. Red dots ae the injectors, Blue dots are monitoring wells. Sections 8 and 17 have CO_2 in small quantities due to minor potential connected sand lenses, as the reservoir becomes shale dominated up-dip. It is highly unlikely that CO_2 will migrate to these areas.

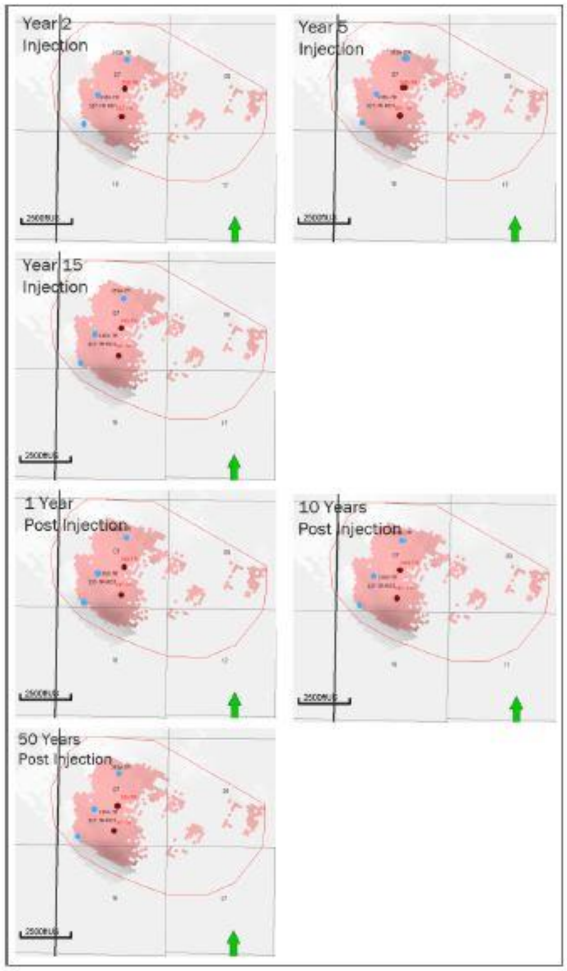
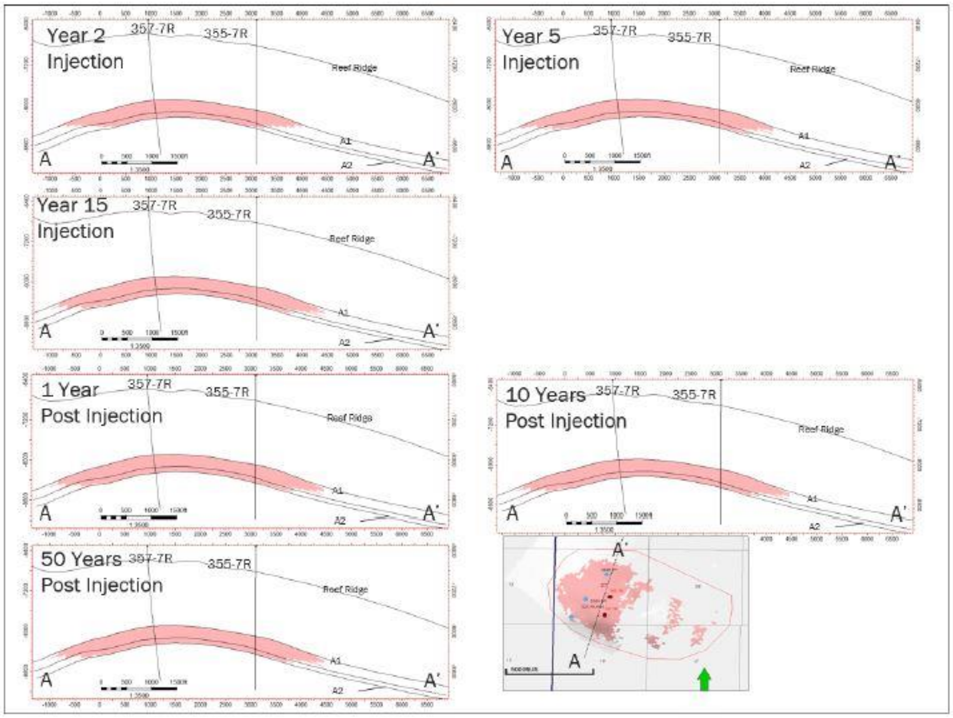


Figure 13: Cross-sections showing the plume development through varying times through the project.



- Figures 12 and 13 in Attachment B, shown above, illustrate plume development though various times of the project.
  - ***Please display the plume results to quantitatively show the saturation. Please include cross-sectional and plan view contour plots for both gas saturation and CO_2 saturation at various times in the project timeframe. Please include figures of the simulated pressure plume over time, both in plan and cross-sectional views.***
- Figure 13 in Attachment B (above) depicts the CO_2 plume reaching the upper boundary of the model.
  - ***Please explain how the spatial extent of the model is sufficient if the CO_2 plume reaches the boundaries.***
  - ***Please explain how no-flow boundary conditions are appropriate if the CO_2 plume reaches the boundaries.***
- The Model Calibration and Validation section in Attachment B describes the different sensitivities that were run.
  - ***Please describe any uncertainty there might be with the interpretation and imaging of the structure bounding faults.***
- The AoR Delineation section in Attachment B did not discuss whether there will be any concurrent operations in the area during the project timeframe.
  - ***Please include a description of known operations that will take place during the project timeframe and how that could affect the AoR delineation.***

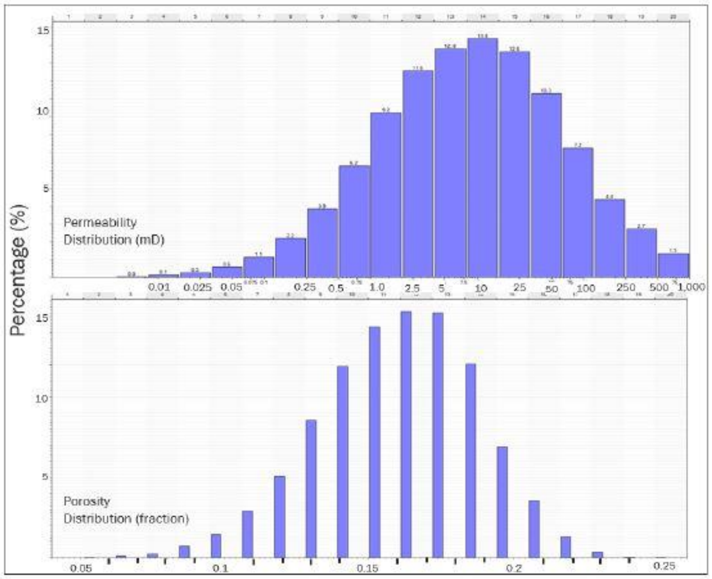
- The current x-y grid spacing around the injectors is too large to determine any near-field pressure effects.
    - ***Please analyze the reservoir with finer grid spacing around the injectors to illustrate near-field pressure buildup and determine that the maximum bottomhole pressure is accurately represented.***
- Attachment B does not describe how permeability anisotropy was incorporated.
    - ***Please discuss whether, or how permeability anisotropy was included in the model. Was any analysis done to determine differences between vertical and horizontal permeability?***
- Table 8 in Attachment B provides a summary of sensitivity cases. Case numbers 4 – 8 were run with increasing or decreasing the parameter by 10%. The 10% change appears to be arbitrary.
    - ***Please use a stochastic model to simulate sensitivities.***

Incorporation of Site-Specific Conditions

This section of the review verified that the geologic description provided in Attachment A was accurately incorporated in the computational model. This included reviewing the incorporation of initial site conditions and operating information. The comments below include requests that are necessary to understand the incorporation of the initial site data and ensure consistency.

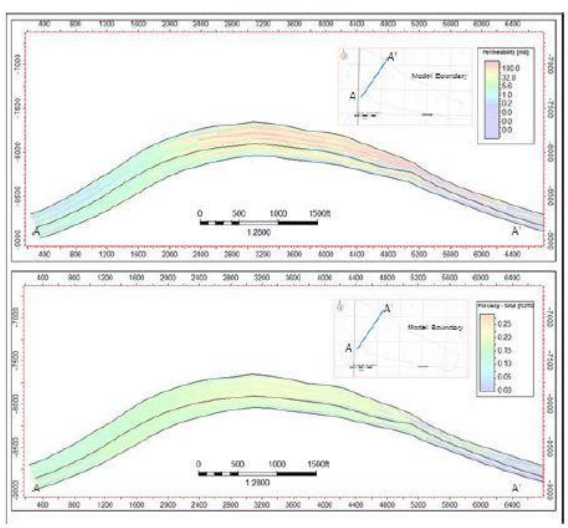
- Page 4 in Attachment B states "Since blow-down, reservoir pressure has remained at 200-300 PSI, indicating a closed reservoir with minimal water influx and/or connection to an aquifer." Recent profiles are important evidence for structural confinement.
    - ***Please provide recent pressure profiles and data.***
- Table 4 in Attachment B lists the initial reservoir temperature but there is no other information on how temperature was represented in the dynamic models.
    - ***Please explain how temperature was incorporated in the dynamic model initially and during injection.***

Figure 7: Monterey Formation A1-A2 sands porosity and permeability distribution in the static model.



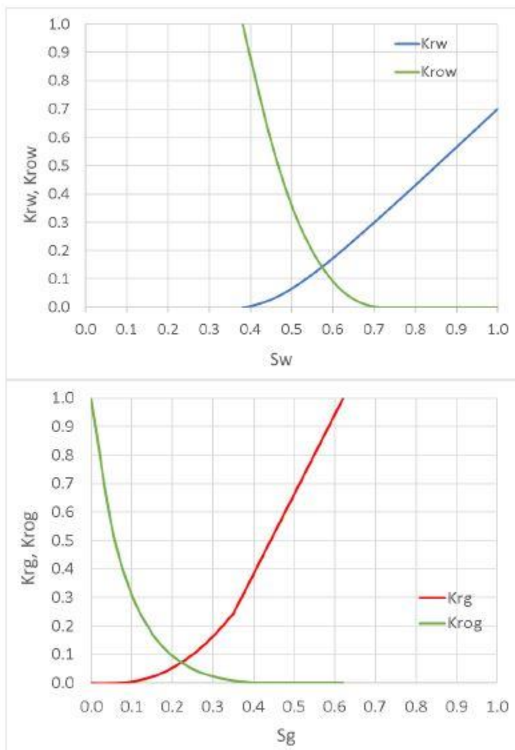
- Figure 7 in Attachment B shows porosity and permeability histograms for the Monterey Formation.
    - ***Please provide additional data (open-hole well log analysis) or other measured data that can be used to verify the permeability and porosity used in the static model.***

Figure 8: Sections through the static grid showing the distribution of porosity and permeability in the reservoir.



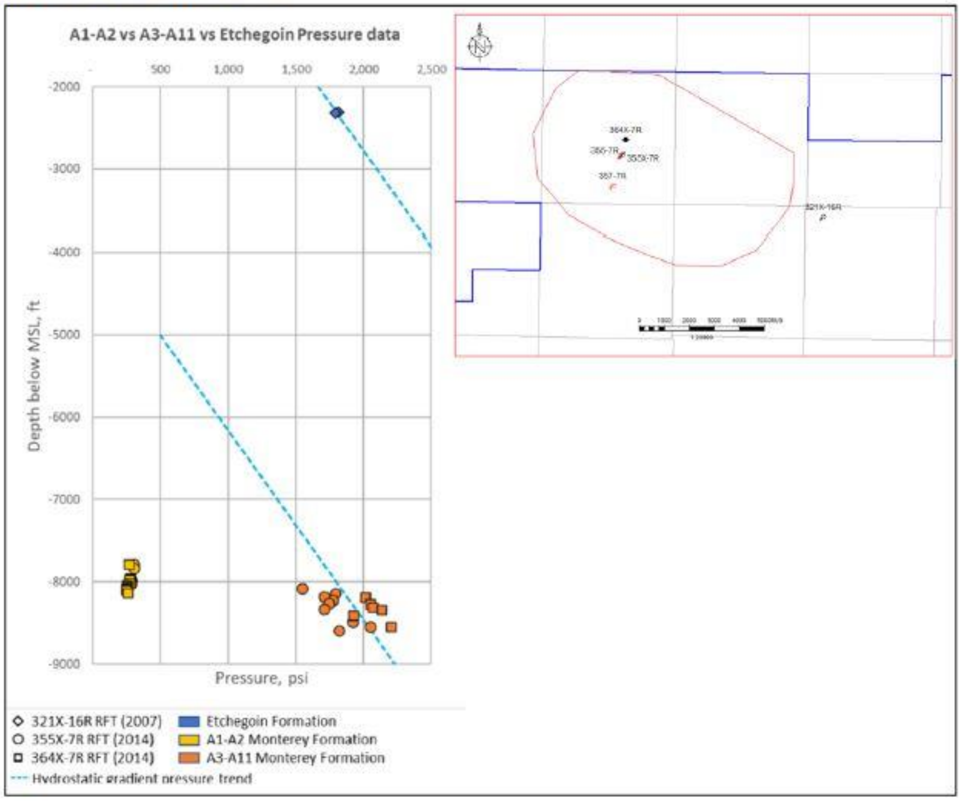
- Figure 8 in Attachment B shows the distribution of porosity and permeability of the reservoir at cross section A-A.
    - ***Additional visuals would help confirm the reservoir properties. Please provide a similar figure from a different cross section.***
- The Maps and Cross Sections of the AoR section in Attachment A mentions a "comprehensive database", however there is not a reference to the database or any other information about it.
    - ***Please include a reference for the database described.***
    - ***Which wells submitted in Figure 5 Attachment A provide the information in the permit application? What are the sources of information?***

Figure 9: Relative permeability curves for Krg-Krog and Krw-Krow used in the computational model study (krow = relative permeability oil in an oil-water system, krg = relative permeability to gas in a gas-oil system, krw = relative permeability to water in an oil-water system, and krog = relative permeability to oil in a gas-oil system).



- Figure 9 in Attachment B shows the relative permeability curves used in the computational modeling.
    - ***Please provide the functional forms that were used to create the curves shown.***
    - ***Please include the data used to create the curves in a tabular form.***

Figure 11: Formation pressure data in the area gathered in 2007 and 2014, after the blowdown of the A1-A2 reservoir, showing large pressure differentials between the A1-A2 and the underlying (A3-A11) and overlying (Ethcegoin) reservoirs, which supports the conclusion of the A1-A2 reservoir being pressure isolated



- Figure 11 in Attachment B pressure data from 2014 for the A1-A2 and A3-A11 reservoirs are shown.
    - Pressure measured at different times is needed to assure there is no migration. ***Is there any measured pressure data over different times? If so, please provide it.***
    - Pressure in the Etchegoin Formation and A3-A11 reservoir is the same even though the y-axis shows their depth is very different. ***Please provide an explanation. If production from the A3-A11 reservoir resulted in pressure depletion, please include that in the explanation.***
- The fracture pressure (0.82 psi/ft) is based on stimulation performed on well 327-7R-RD1. However, no information is provided for the confining zone. It is stated on page 30 of Attachment A, "Injection pressure will be lower than the fracture gradients of the sequestration reservoir and confining layer with a safety factor (90% of the fracture gradient).".
    - ***Is there any data for the confining zone that supports the statement that the proposed injection pressure is lower than the confining zone fracture pressure? If so, please submit it.***
- The Geomechanical modeling section in Attachment A, describes a generic two-dimensional model constructed to represent the reservoir.

    - ***How is the 2-D model with horizontal layering representative of the reservoir? Why was a 3-D model not used for the geomechanical evaluation?***
- Figure 35 in Attachment A shows the fluid composition for the A1-A2 reservoir, however detailed information on the fluid model for the dynamic model was not provided.
    - ***Please provide fluid composition (i.e., mole fraction of each component considered) and relevant model parameters (e.g., binary interaction coefficients for each pair for Peng-Robinson Equation of State (EoS) or adopted EoS, viscosity model and its coefficients).***
    - ***Please provide fluid model information based on results of the lab experiment (e.g., PVT experiment) analyzing up to date fluid sample from the site.***