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Marcellus Field Development Optimization: Multi-Bench Evaluation in Bradford County, PA

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Abstract

This paper uses a case study to describe an approach for optimizing the economic development of one of the most prolific areas in the Marcellus shale, located in Bradford County, PA. A project was built to optimize well spacing, landing, completion design, and conduct uncertainty evaluations for upcoming pad developments by utilizing a fully integrated hydraulic fracturing, reservoir, and geomechanics numerical simulator. One of the key questions addressed in this study was whether single or multiple benches are optimal for maximizing economic value.

Our structured modeling process is: (a) define the area of influence, (b) identify and model the physics of a pad representative of the area of influence, (c) establish history match objectives and input parameter uncertainty ranges, (d) calibrate the model to selected objectives, (e) employ a multigenerational algorithm for economic development optimization, and (f) evaluate potential outcomes using a Monte Carlo uncertainty analysis. This multidisciplinary effort integrates static/dynamic data, completion diagnostics, and Marcellus formation production. The fully-coupled 3D model allows for physics-based estimates of fracture propagation, production, and economics for each scenario. Robust optimization ensures our development aligns with current industry and gas market dynamics.

The current case study successfully matched fracture and production observations for a five well pad, including a parent-child situation, which had almost ten years of production data. Proper pad selection, calibration, and uncertainty analysis, grounded in a physics-based model, provided a robust understanding of reservoir architecture and performance. In our specific case, the pads developed in the area consisted only of a single bench, and despite partial information in the calibration data, our evaluation yielded multiple attractive economic development options. Findings from this model were applied to other pads in the area in an iterative process of refining models. We treat simulation models as evergreen and continue to re-evaluate and update as new field data are available.

The case study presented showcases an effective methodology for optimizing unconventional reservoir development. Our integrated modeling approach, incorporating geology and dynamic data, enriches our

reservoir characterization and is a powerful tool for economic reservoir optimization. The multi-bench evaluation and criteria for pad selection is an added utility of our learnings. The novelty lies in the multi-disciplinary phase project design, ensuring a comprehensive and iterative optimization process. This methodology may be applied broadly to enhance stimulation strategies and optimize pad development in unconventional reservoirs.

1. Introduction

Unconventional resource field development is often guided by stochastic analysis of static reservoir properties and well performance. The stochastic approach relies upon the analysis of large reservoir and well performance datasets to identify empirically and pragmatically what works and what does not work in the field.

Stochastic evaluations often attempt to use methods that aim to decouple the impact of geology, geophysics, rock mechanics, completion design, landing, and spacing on well productivity and estimated ultimate recoveries. However, the subsurface is highly complex, and decoupling these effects using a purely stochastic approach can be extremely challenging. Some statistical approaches often overlook fundamental physical constitutive relations for fracture propagation, proppant transport, and fluid flow in porous media, leading to potentially unrealistic and unreliable results if the analysis is not properly constrained.

Stochastic field development analysis necessitates significantly large datasets with extensive tests in completion designs and well spacing in areas sharing similar subsurface characteristics, including geology, geophysics, petrophysics, and rock mechanics. These large datasets are crucial for guiding field decisions with confidence. However, it is often challenging to determine which data serves as an appropriate analog and what should be included in the analysis without introducing bias.

Some operators approach field development statistically, relying solely on stochastic methods. While stochastic methods may be suitable and adequate in later stages of field development, early- and mid-stage development can pose challenges due to lack of data abundance, including analogs. The authors believe that the two approaches, stochastic and physics-based modeling, are mutually inclusive, and their integration provides operators with a competitive advantage.

Integrated reservoir modeling can complement stochastic reservoir evaluations providing answers to several key questions crucial for effective field development. Those include: (a) What are the key physical factors impacting well performance?, (b) What spacing and completion designs should be tested while extensive datasets are still under construction?, (c) How do we reduce the number of tests while optimizing the value needed to assess well performance?, (d) How can we accurately consider subsurface variability and evaluate its impact on well performance?, and (e) What surveillance is necessary for addressing critical development questions?

During early and mid-life field development, the authors believe that properly calibrated reservoir models should guide the path forward to effectively develop different reservoir areas in a field. Building and calibrating a few integrated models in strategically selected reservoir areas provide a competitive advantage to operators and offers a more efficient way to define what to test in the field. Testing and guiding field decisions on paper would lead to more efficient field development.

Many basins exhibit significant areal variations, necessitating different stimulation designs for economically developing various field areas. Integrated reservoir modeling can provide fit-for-purpose answers for maximizing economic benefit for different field regions.

2. Field development methodology:

Comprehensive studies were conducted in strategically chosen locations to complement and better understand the findings of our stochastic evaluations. The main objectives of these studies were to optimize well placement, completion designs, well spacing, and flowback processes. The proposed field development methodology follows these high-level steps:

1. Identify areas with distinct petrophysical and geomechanical properties with a high variance in static properties and/or well performance. Type decline curve regions may be a useful starting point for evaluation.
2. Determine the area of influence (AOI) for necessary studies. More than one study may be necessary in each high variability region.
3. If no production wells are yet available, a model may be constructed, and an uncertainty analysis conducted to determine possible outcomes. Once wells start production, the model may be revisited and uncertainty ranges refined.
4. When producing wells are available, a representative pad should be used for calibration. In a later section, we will discuss the criteria we utilized for selecting a representative pad for integrated reservoir modeling.
5. Calibrated models are then used for production forecasts, to evaluate outcomes for different spacing and completion designs, and for running economic optimization analyses for the field development (spacing, completion, and landing).
6. Monte Carlo simulation is used to estimate range of outcomes expected for an optimized completion design within the variability observed in the AOI.
7. Utilize the Monte Carlo simulation for determining if additional surveillance data is necessary to reduce uncertainty and enhance development design.

In general, areas identified for integrated reservoir modeling include:

- New development regions or those with limited data for stochastic analysis.
- Areas with limited variability in completion design to allow for empirical evaluation.
- Locations requiring deeper analysis to comprehend key performance drivers and assess the cost-effectiveness of additional surveillance measures.
- Zones with legacy completions, requiring the evaluation of applying new completion designs for the remaining inventory.
- Locations where relationships between parent and child wells, or scenarios involving simultaneous development, necessitated further evaluation.
- Evaluation of landing zone targets and multi-bench configurations.

3. The West Liberty Case Study

This case study focuses on the methodology used for evaluating multi-bench development in a prolific area in West Bradford County, Pennsylvania, defined as the West Liberty area in Figure 1. Earlier pad developments in the West Liberty area targeted a single bench, the lower Marcellus, and utilized completion designs intended to maximize recovery for that zone.

A calcite rich zone called the Cherry Valley Member (CVM) divides the upper and lower Marcellus zones. The CVM is known to act as a hinderance to vertical fracture growth due to its contrasting lithological and geomechanical properties. East of Bradford County, the CVM thickness can reach up to 40 feet and thins considerably towards the west of the play. The CVM is approximately 15' thick in the West Liberty area, where there are no analogue multi-bench developments. Multi-bench developments exist further east, but those wells were drilled and completed in regions where the Cherry Valley is significantly thicker (to up to ~40'), making them poor analogues, and their use in a stochastic evaluation a challenged assumption. The key question is whether we can access the upper Marcellus (UMRCL) resources by stimulating the lower Marcellus (LMRCL) zone with large completion designs, or if a multi bench development is necessary for maximizing economic value.

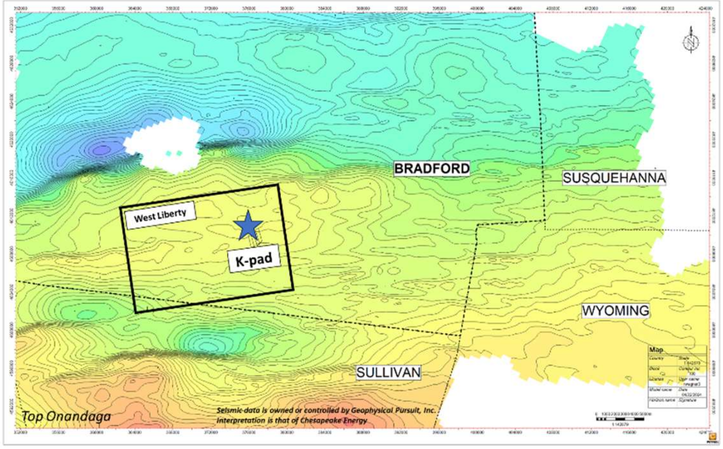


Figure 1. Bradford County and The West Liberty area

The specific goals of this case study were: (i) Maximize the economic value of the remaining upper and lower Marcellus locations through optimizing well spacing, landing zone, completion design, and fracture order, (ii) Assess potential outcomes of different pad development strategies, (iii) Estimate expected resource degradation due to depletion for future infill wells.

The results of this study guided capital investment decisions related to a large planned upper Marcellus and lower Marcellus co-development test and will help guide the future development strategy for the West Liberty area.

3.1 Background

Variations in commodity prices and cost of services directly impact development decisions and require the evaluation of multiple options to determine the best economic decision for that time.

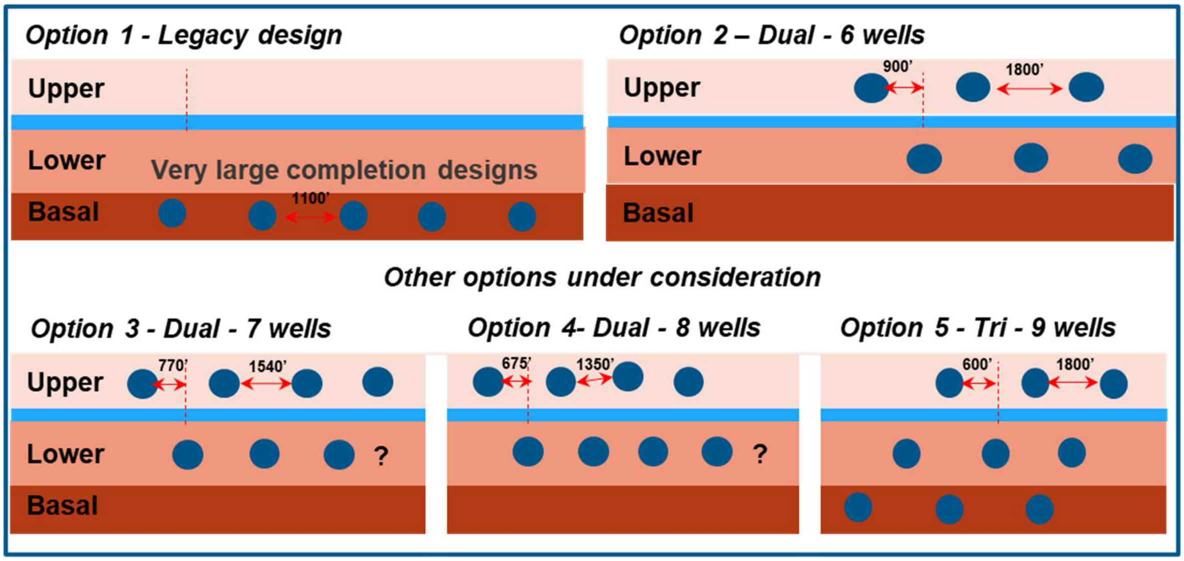


Figure 2. Some development configurations of interest

Multiple options were evaluated for a major pad development, including:

1. Large completion designs targeting the basal portion of the lower Marcellus.
2. Two-bench upper and lower Marcellus development.
3. Three-bench development with two in the lower Marcellus and one in the upper Marcellus.

Figure 2 summarizes these well configurations. Integrated reservoir modeling was utilized to determine the best completion option for each option.

3.2 Definition of the Area of Influence (AOI) for the West Liberty case study area

The area of influence (AOI) for reservoir modeling was defined using well and seismic data, addressing key factors: (1) Assessment of spatial variability in petrophysical and geomechanical properties such as porosity, permeability, stresses, etc. Variograms were utilized to quantify the spatial correlation and variability of these properties across the reservoir domain, helping to delineate areas of high and low continuity. This was accompanied by the corresponding dynamic synthesis, which is explained below. (2) Definition of structural domains, particularly the presence of mappable faults and folds, which play a crucial role in reservoir behavior.

The K-pad wells were used for calibration as they are the nearest to an upcoming development. Details regarding the criteria for selecting a representative pad are outlined below in section 4a.

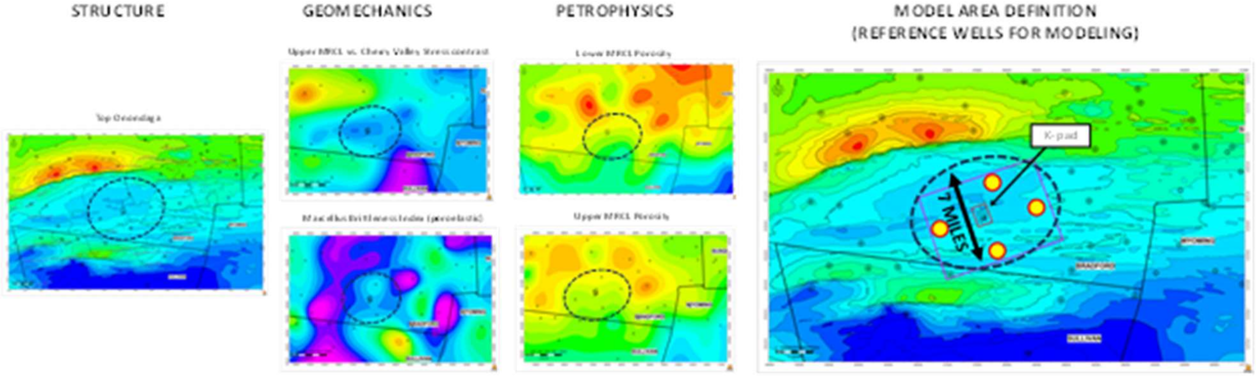


Figure 3. Area of influence (AOI) defined from well and seismic data. Structural (left), geomechanics and petrophysics (middle). Polygon is defined from available data and spatial variability (right).

The structural domain of the K-pad is characterized by a gently dipping large synclinal structure, as depicted in Figure 3 (left). The AOI is a 7-mile polygon centered on the K-pad that is limited to the north and south by a large salt-cored asymmetrical anticlinal structure with thick salt core. The AOI is also informed by the spatial analysis and the trend of petrophysical and rock mechanics properties. Four wells around the K-pad inside the 7-mile are included in the AOI. These wells serve as primary sources of data and provide insights into the subsurface characteristics within their vicinity. Beyond the defined AOI, uncertainties may arise due to extrapolation beyond the known data points and could produce end points that fail to capture the specific physics and heterogeneity.

3.3 Geological background

The Marcellus Formation is a middle Devonian organic-rich shale and a prolific natural gas reservoir. It is underlain by the limestone rich Onondaga Formation deposited in a shallow marine environment. The lower unit of the Marcellus, above the Onondaga Formation, consists of a transition zone of calcareous mudstone with an increase of interbedded calcareous content from the bottom (basal Marcellus) to the upper part (lower Marcellus). This lower unit has the highest gas saturation within the Marcellus Formation. The sequence is then followed by the Cherry Valley Member (CVM), a distinctive, calcite-rich layer with minor limestone beds. The CVM plays a critical role in the mechanical stratigraphy of the region as it often acts as a barrier to vertical fluid migration, thus localizing hydraulic fracturing within the Marcellus itself. Above the CVM, the upper Marcellus continues with similar black shale characteristics but is slightly less organic-rich compared to the lower sections. The sequence is capped by the Stafford or Hamilton Group that consist of interbedded shale, limestone, and sandstone. The mechanical stratigraphy of these formations influences drilling and fracturing operations, as the variations in rock strength and composition across these layers affect the propagation of fractures and thus the efficiency of hydrocarbon extraction (Zagorski W., et al., 2017; Higley D., et al., 2019).

3.4 Petrophysical Model

An existing petrophysical model covering the Marcellus Shale was used to populate the geomodel used in the base case of the integrated reservoir model discussed below. The petrophysical model utilizes a deterministic approach to solve for the rock components using a series of equations defined by input constants or observed trends between core data and well logs. First, an iterative loop is used to solve for the bulk volumes needed to estimate hydrocarbon pore volume: clay, organic matter, pyrite and other remaining bulk mineralogy, porosity, and saturations. Then fluid properties, equation of state and methane adsorption models are incorporated to calculate original hydrocarbon in place. Absolute permeability is calculated from phie-ka relationship and is corrected for gas slippage. Finally, net effective stress is calculated using parameters from a separate mechanical properties model (discussed below) and applied to a stress dependent permeability relationship to estimate the in-situ permeability.

The key core measurements used to calibrate the petrophysical model include X-ray diffraction, Leco Total Organic Carbon, retort porosity, pressure-decay permeability, and total gas content from methane adsorption isotherms. Using the relationships defined in the core calibrated model, we were able to interpolate and extrapolate 1D petrophysical analyses to over 140 locations in northeast Pennsylvania and southern New York using a minimum well log suite comprised of Gamma Ray (GR), Neutron Porosity (NPHI), Bulk Density (RHOB), and Deep Resistivity (RESD) curves. Figure 4 illustrates the inputs and outputs of the 1D petrophysical model. Interval statistics of petrophysical properties are then gridded to create maps used in subsequent reservoir and development planning.

3.4.1 Petrophysical Model Uncertainty Analysis

Sources of uncertainty within petrophysical models are known but are often difficult to quantify and sometimes ignored in integrated reservoir modeling. We utilized a Monte Carlo uncertainty analysis on the petrophysical model, which 1) highlighted areas of the petrophysical model that have the highest uncertainty, allowing us the flexibility to make reasonable adjustments to the base case model during the history matching process and 2) provided insights needed to generate petrophysical property ranges for the sensitivity workflow discussed later in this paper.

We investigated the potential uncertainty of key inputs to the regional Marcellus petrophysical model. This included well logs, formation temperature, initial pore pressure and 17 other key input parameters. A commercial petrophysical software package with a built-in Monte Carlo module allowed us to run simulations on our internal petrophysical code in a batch process. The module allowed us to set high and low shifts to the inputs and output a variety of statistical curves, particularly probability curves P10 and P90 for porosity, Sw, gas-filled porosity, and in-situ matrix permeability (figure 4). The shifts applied to logs that are sampled in counts applied gaussian distributions (i.e., GR, NPHI, and RHOB), while the other constants and coefficients used triangular distributions defined by the high and low shift values.

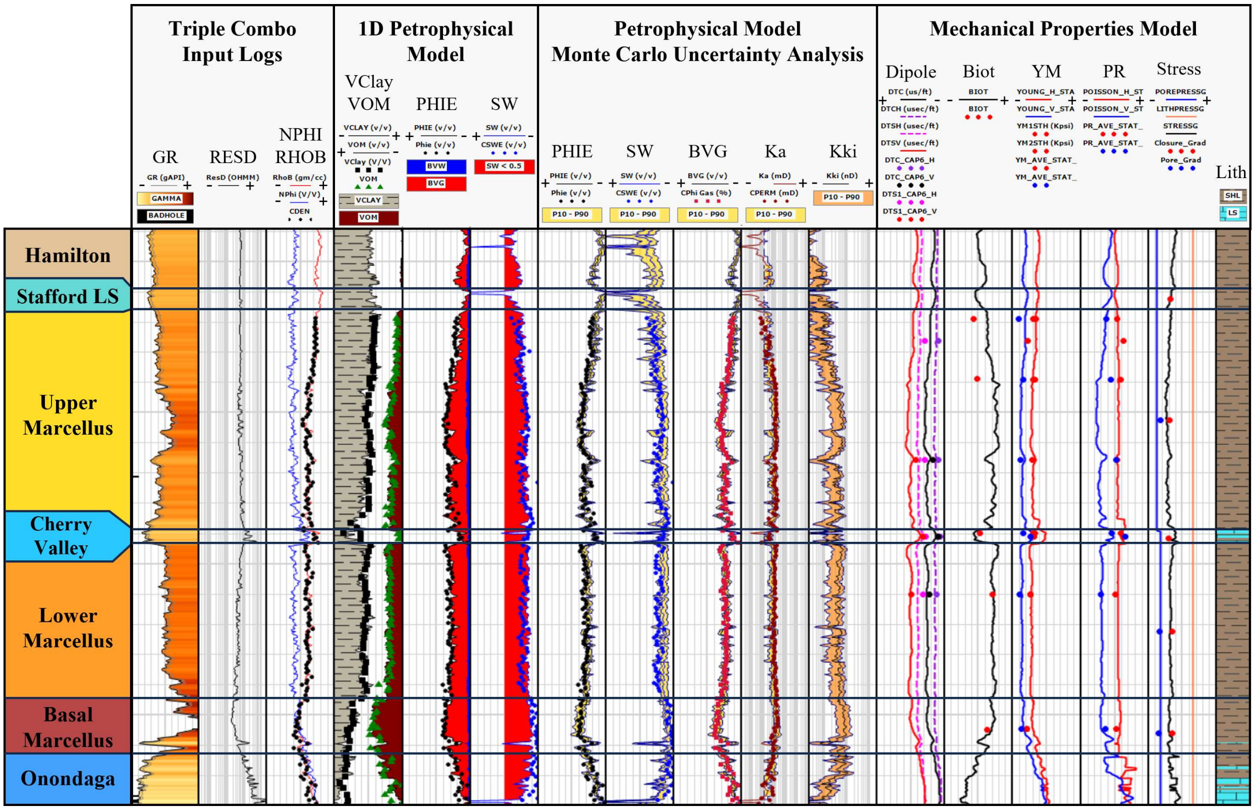


Figure 4. Petrophysical log plot showing conditioned triple combo logs, outputs from the 1D petrophysical model, probability curves from the Monte Carlo uncertainty analysis, and outputs of the calibrated geomechanical model.

3.5 Geomechanical Modeling

The geomechanical workflow presented considers well, core, and empirical data as well as operational observations. This approach was developed based on the work of Murphy et al. (2015) and modified to incorporate updated lab measurements conducted at the Reservoir Technology Center (RTC) on the Chesapeake Energy campus. A key component of this workflow is the use of an empirical equation to generate a Biot Coefficient curve, and an internally developed methodology to calculate effective strain based on core calibrated elastic properties. The core calibration was performed using data from a nearby well, with vertical, horizontal, and 45-degree plugs taken from eleven different depths spanning the Onondaga Limestone through the upper Marcellus Shale. In addition, four Diagnostic Injection Tests (DFIT) were conducted to calibrate reservoir and closure pressures.

4. Integrated Reservoir Modeling workflow

Integrated Reservoir Modeling is utilized as a valuable tool for refining reservoir characterization and delineating effective field development strategies. We aim to maximize production yield and economic returns of each distinct area in a field by utilizing state-of-the-art tools and industry-leading practices (McClure et al., 2024). Below, we detail the steps that encapsulate our comprehensive approach for integrated reservoir modeling.

a. Identify a pad representative of the AOI.

b. Base model construction and calibration.

  - Observations and data available for calibration.
  - Utilize the base model for preliminary scoping the impact of different development options.

c. Evaluate potential outcomes using a Monte Carlo uncertainty analysis.

  - Both petrophysical and geomechanical properties may vary across the AOI. We recommend evaluating the potential outcomes for the AOI based on the uncertainty of key variables. Pressure, Shmin, Permeability, Water Saturation, and to a lesser extent, porosity of the UMRCL target were defined as key variables for this study.

d. Perform economic field development optimization.

  - Create an economic model and define the key variables for optimization. Net Present Value (NPV10) was the key optimization variable for this study.
  - Employ a multigenerational algorithm for economic development optimization.

4.a Identification and modeling the physics of a pad representative of the AOI

The goal of the modeling exercise is to characterize the reservoir, enabling the submission of scenarios that explore outcomes using different spacing, landing, and completion designs. Hence, choosing a representative pad that reflects the main physics in the Area of Interest (AOI) is crucial. We recommend the following criteria for selecting the pad or well sets for integrated reservoir modeling in the Marcellus shale.

- Availability of petrophysical and geomechanical logs within the Area of Interest (AOI).
- Production wells demonstrating boundary-dominated flow conditions.
- Well performance aligned with type curve expectations.
- Preferably, a parent-child scenario where the parent well has reached boundary-dominated flow (BDF) before the children wells are brought online, allowing assessment of well interactions.
- Avoid features like faults or extensive natural fracture regions that may not be representative of the majority of the development, to ensure pad performance accuracy.
- Wells with similar completion fluid type, perforation design, and overall completion design across wells if available.

The chosen pad for calibrating an integrated numerical model in the West Liberty area is about three miles from an upcoming large development (K-pad). The K-pad development comprised five wells. The pad's development commenced with a parent well in October 2012, followed by the co-development of four additional wells in August and September 2014. The wells had been producing for over ten years and were in boundary-dominated flow regime for over eight years when the current study was conducted.

All wells within this development were drilled to the bottom of the lower Marcellus, specifically targeting the basal Marcellus zone. The parent well was completed with four clusters per stage, 54’ cluster spacing, and approximately 97,000 pounds of sand per cluster (1,800 #/ft), while the four child co-developed wells were completed with three clusters per stage, 54’ cluster spacing, and around 150,000 pounds of sand per cluster (2,800 #/ft).

Figure 5 provides an aerial view cross-section layout of the wells at the approximate landing point. As depicted, the parent well had significantly depleted its stimulated rock volume (SRV) area by the time the co-developed wells were drilled and completed. Figure 6 showcases production profiles for all wells within the unit.

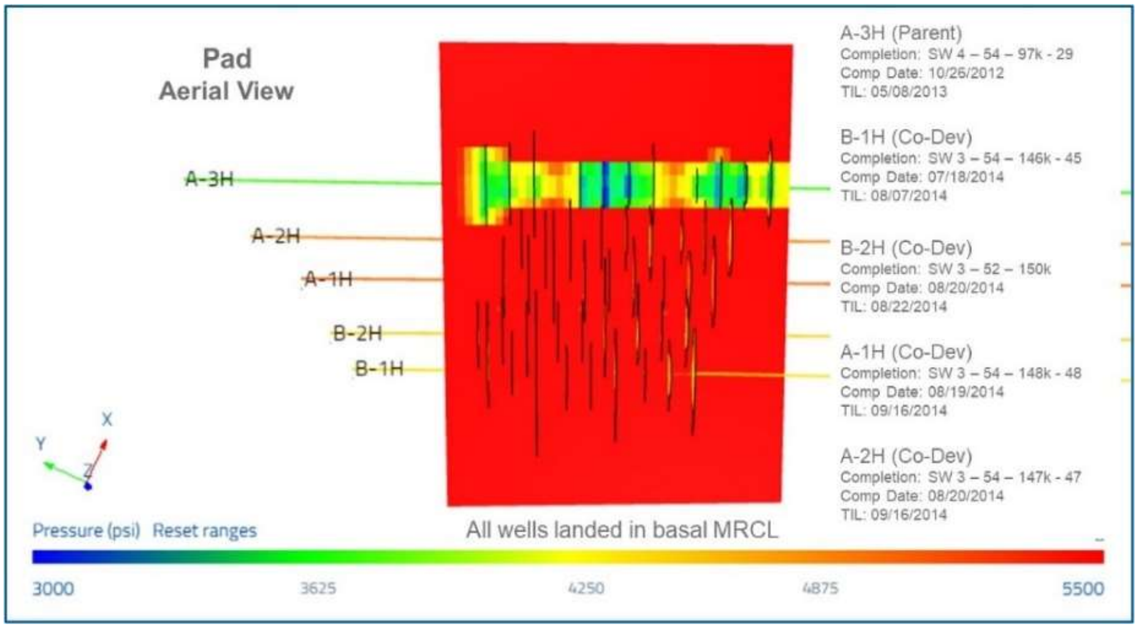


Figure 5. Aerial view of pressure depletion when child wells are put on production (basal MRCL landing)

Neighboring wells near the selected pad have experienced significant fracture interactions from nearby developments. Production data also indicates that the parent well's productivity was influenced by the adjacent co-development of the children wells, and that overlap exists between parent and child Stimulated Rock Volumes (SRV).

The well set selected is one of the most productive in the Marcellus and perhaps in North America. We believe that the wells were landed in a sweet spot of the field. Estimated Ultimate Recoveries (EUR) for the wells within the pad are expected to fall within the P3 distribution of the type curve.

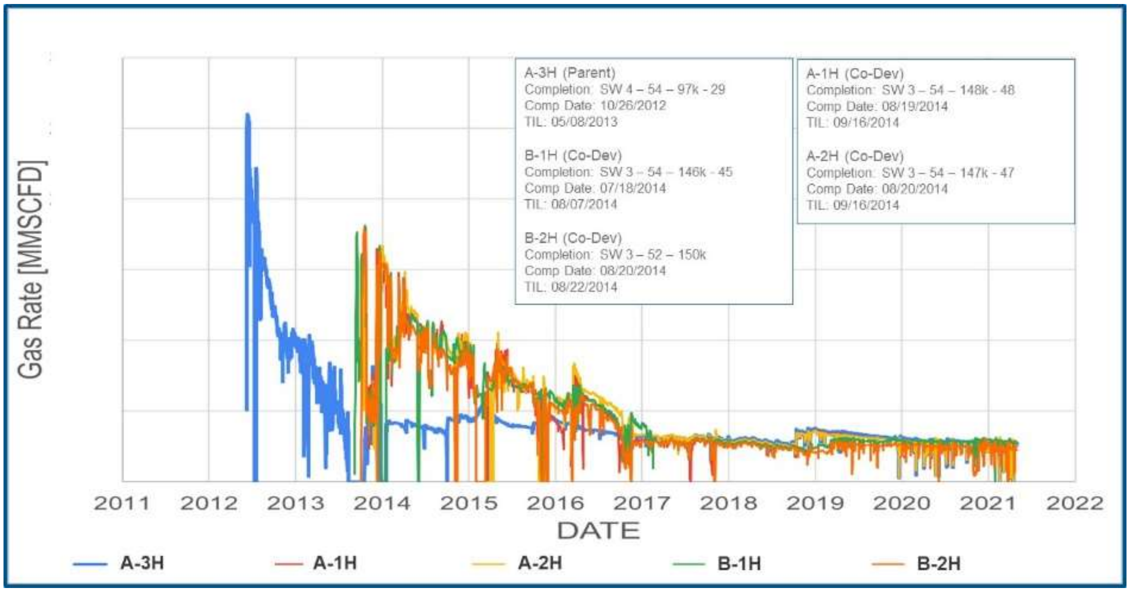


Figure 6. Production profile for the wells in the model

4.b Base model construction and calibration

The static input for the reservoir simulator comes from a geomodel built from the four wells defined within the Area of Interest (AOI). Given that the K-pad is almost equidistant from all four (approximately three miles), a stochastic modeling approach was adopted. This involved utilizing property distributions and spatial analysis obtained after upscaling the 1D models defined in the preceding section. This step laid the foundation for a subsequent stage, for generating high and low cases required for uncertainty analysis in the 3D space. The upscaling process from 1D to 3D was meticulously conducted to ensure that relationships between the two dimensions were accurately transformed while preserving the resolution of main 1D heterogeneities within the 3D layers. This precision in upscaling was particularly significant for factors such as fracture growth and the role of Cherry Valley in containment evaluation. Once all properties were modeled, synthetic logs were extracted at K-pad location and used as input for a Layer Cake model into the coupled simulator (Figure 7).

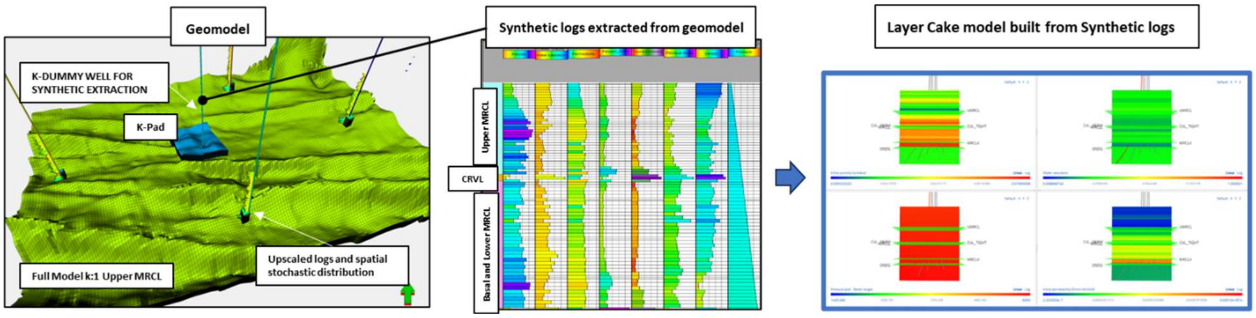


Figure 7. Workflow for Reservoir model input. Layer cake model input (right) come from synthetic logs (middle) extracted at K-pad location from the geomodel (left) built using four vertical wells that cover the AOI.

The layer cake model now integrates the reservoir characterization and is used to calibrate well performance and capture the intricate interactions between the wells within the pad. This model encompasses five wells and simulates three stages for each well, comprising one parent well and four co-developed children. The model's layout features an unbounded eastern side and a bounded western side, necessitated by the interactions with offsetting wells on the pad. The no-flow boundary was implemented on the western side to effectively capture interaction with an offsetting pad.

Figures 8 and 9 offer a gun barrel view of the pad's wells, while showing reservoir petrophysical and geomechanical properties. The tops of the Stafford (SFDL), Upper Marcellus (UMRCL), Cherry Valley (CVL), Lower Marcellus (LMRCL), Basal Marcellus (MRCLX), and Onondaga (ONDG) formations are identified in the figures.

Figure 8 illustrates the petrophysical properties across different reservoirs, highlighting key insights: 1. MRCLX exhibits superior porosity and permeability with lower initial water saturation. 2. LMRCL showcases consistent quality. 3. CVL, although present, contributes limitedly as a reservoir. 4. The best part of the UMRCL is found in the 60’ above the CVL. 5. Porosity and permeability diminish significantly towards the top of the UMRCL. 6. Zones beyond UMRCL's top exhibit near-zero permeability. 7. The current model assumes very small difference in pressure gradient between the LMRCL and UMRCL. Pore pressure in the UMRCL is one of the biggest uncertainties in the Petrophysical model. There is no DFIT data in the AOI for the UMRCL, while there are several pressure estimates from DFITs conducted at the LMRCL.

Figure 9 shows reservoir minimum horizontal stress (Shmin) and poroelastic reservoir properties, offering the following mechanical insights: 1. ONDG exhibits substantial stress contrast with MRCLX, serving as a strong stress barrier. 2. The model indicates minimal contrast between LMRCL and MRCLX stresses. 3.

A notable stress contrast (~600 psia) is evident within the thin CVL (~15 feet). 4. UMRCL showcases lower stress levels. However, pressure and stress remain relatively uncertain in UMRCL due to the absence of DFIT measurements for calibrating the static model.

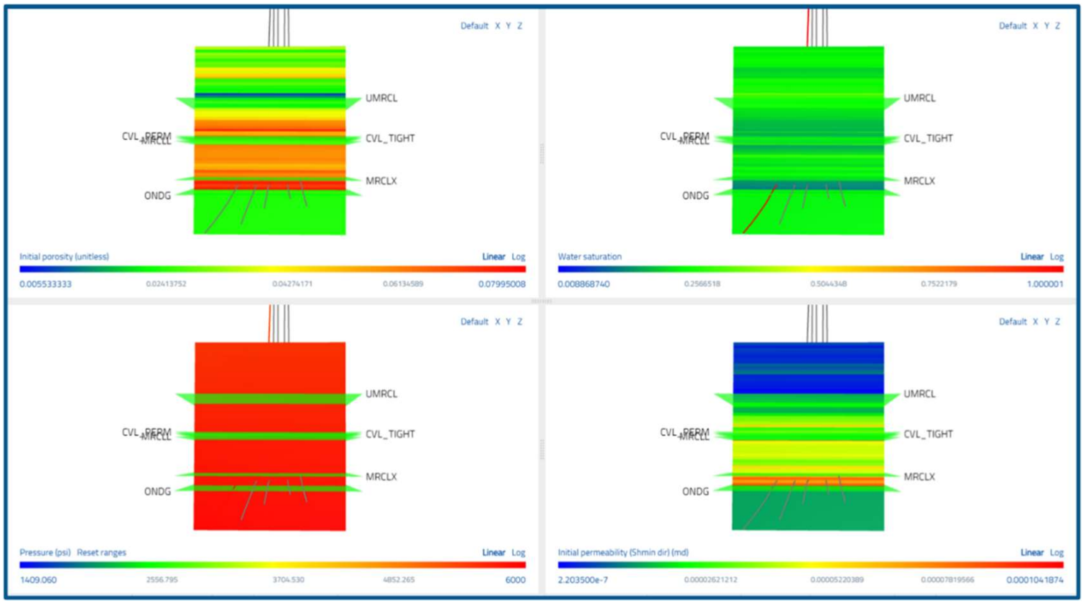


Figure 8. Petrophysical properties in the static reservoir model

The following data and interpretations were utilized for calibration: (a) Treatment pressures and ISIPs, (b) Fracture treatment pressures, (c) Production history for all 5 wells (Up to 9 years of production), (d) RTA evaluation suggesting some of the volume produced is from the UMRC, (e) Observed interference in neighboring wells.

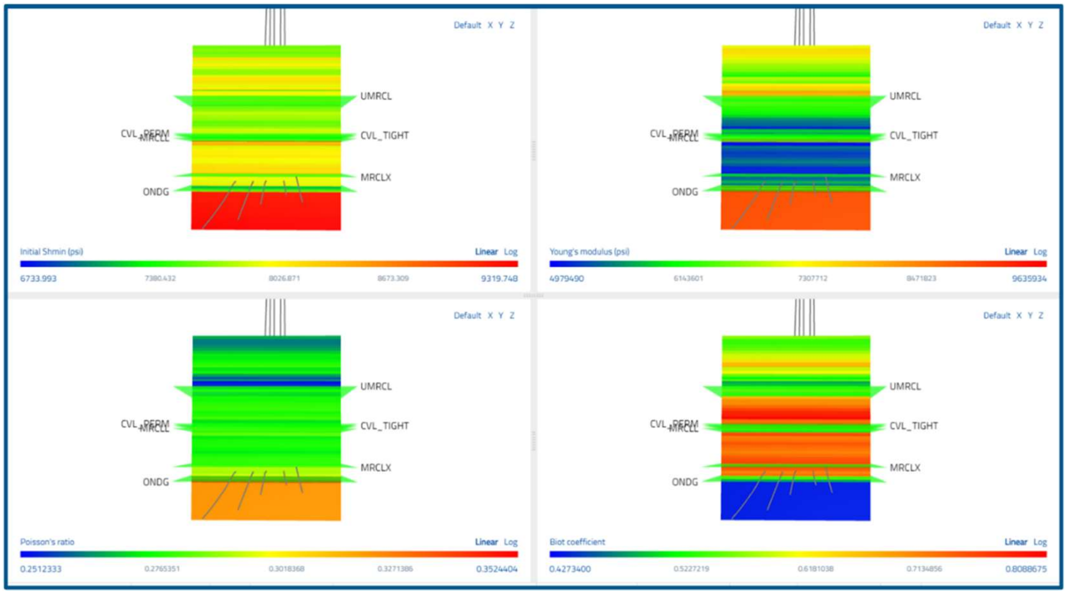


Figure 9. Mechanical properties in the static reservoir model

4.b.1 Model calibration methodology

The comprehensive model calibration workflow integrates all observations and interpretations within the field. Figure 10 provides a visual representation of each step, highlighting the multidisciplinary collaborative nature of the process.

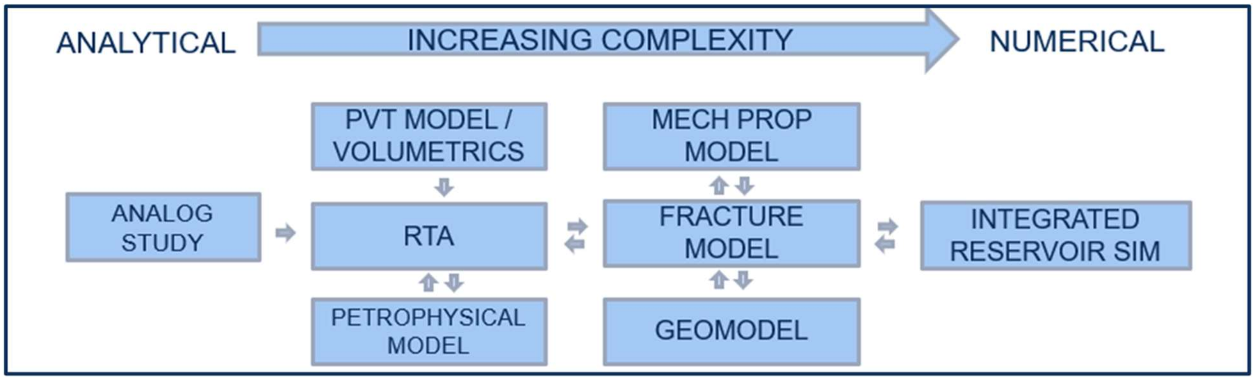


Figure 10. Integrated modeling workflow

<u>Analog review:</u>

The analysis process commences with a review of the performance of all existing wells within the West Liberty area. The objective of this review is to estimate well recovery using strictly Decline Curve Analysis (DCA) and to ascertain whether the selected well set for calibration is representative of the type curve area's performance. Additionally, this step involves documenting observed fracture interactions, pressure interference, and changes in well productivity throughout their operational lifespan.

The analog review of the West Liberty area indicates that the wells chosen for modeling rank among the top performers within the type curve area. Their performance places them within the top 3% of West Liberty, as depicted in Figure 11. The Estimated Ultimate Recoveries (EUR) for the model's wells is substantially greater than the P50 type curve recoveries.

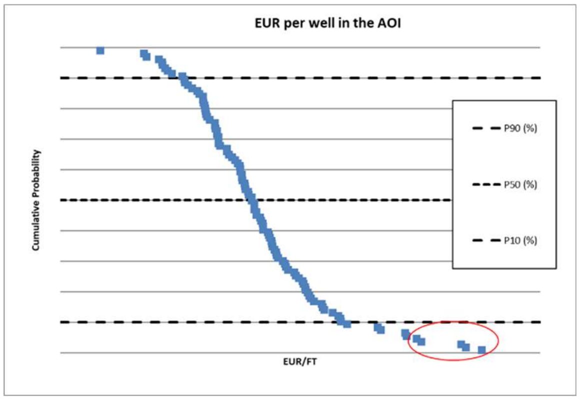


Figure 11. EUR for wells in the AOI – probit plot

The calibration wells (K-pad) were drilled in a sweet spot characterized by favorable Upper Marcellus formation properties, making it a superior reservoir compared to many other locations within the type curve area. Notably, there appears to be substantial variability in pore pressure, stress, and permeability toward the upper section of the Upper Marcellus.

Although these wells are situated near an upcoming pad development, directly extrapolating the results may lead to overly optimistic outcomes. Nonetheless, through model calibration and field development optimization, we can derive directional guidance regarding suitable completion and spacing designs for field testing.

Ideally, the selected pad for model calibration should exhibit performance closer to that of a P50 well within the type curve area. Following optimization runs, it is recommended to explore the uncertainty space by conducting Monte Carlo simulations and further refining potential outcome expectations.

Overall, the model calibration and field development optimization process will provide valuable directional guidance regarding optimal completion and spacing designs for field testing, along with their potential benefits.

Rate Transient Analysis:

In the Marcellus, Rate Transient Analysis RTA provides reasonable starting points for model calibration (FCD, Ksrv, and Propped surface area). The initial estimates speed up the integrated reservoir model calibration process. Figure 12 illustrates the workflow employed for our Rate Transient Analysis interpretation. This workflow is an adaptation of the one published by Clarkson (2021). We have tested and implemented the proposed workflow for hundreds of wells in the Marcellus with consistent results.

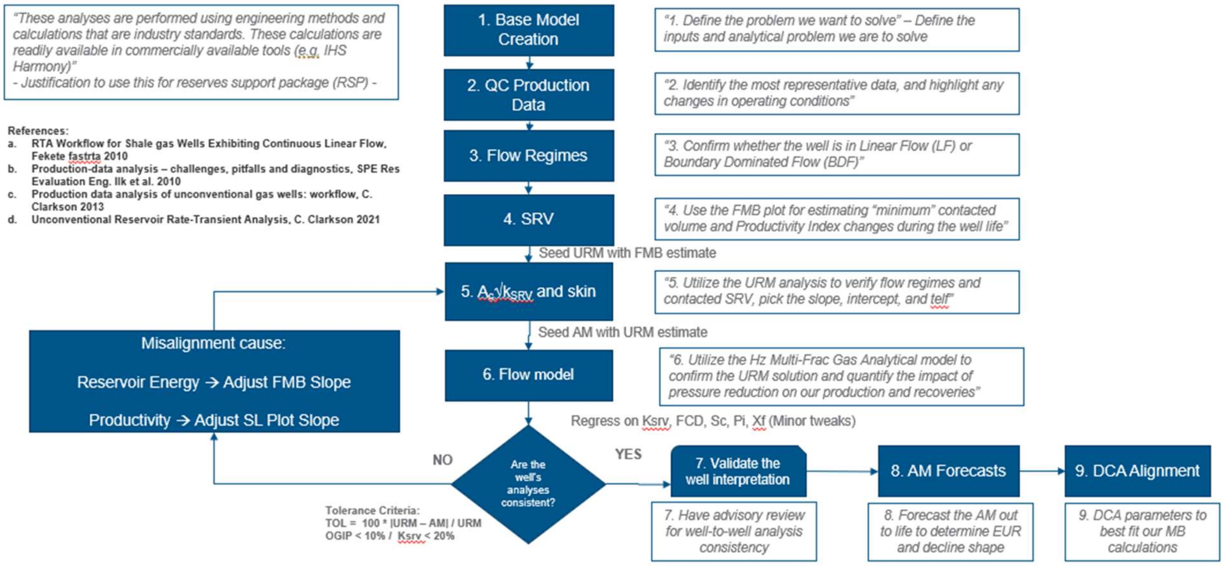


Figure 12. Rate Transient Analysis workflow

Table 1. RTA vs detailed Integrated Reservoir Modeling

	RTA	FULLY COUPLED RESIM
Geomodel Heterogeneity	Single layer model	Multi-layer model capturing geologic variability
Flow Unit	Assumes Hf	Calculated from fracture geometries
Cluster Efficiency	Assumed. Identical spaced fractures	Honors fracture model
Landing	Assumes mid point landing	Landing influences fracture geometries
Fracture Model	Simplified box. Assumes identical fractures per cluster	Calculated detailed geometries
Fracture water load	Not honored	Fully included and coupled
Geomechanics	Simplified	Fully included and coupled

The Flowing Material Balance (FMB) calculations conducted for the selected calibration wells indicate that these wells are effectively draining a substantial portion of the Upper Marcellus volume. This observation is subsequently validated by the fracture and integrated reservoir modeling processes.

RTA is reliant on several assumptions and simplifications, some of which are outlined in Table 1. This table compares these assumptions with those made in an integrated reservoir model. Many of the assumptions made in simplified "Analytical" and "Numerical" RTA models are rendered unnecessary in a comprehensive integrated reservoir model.

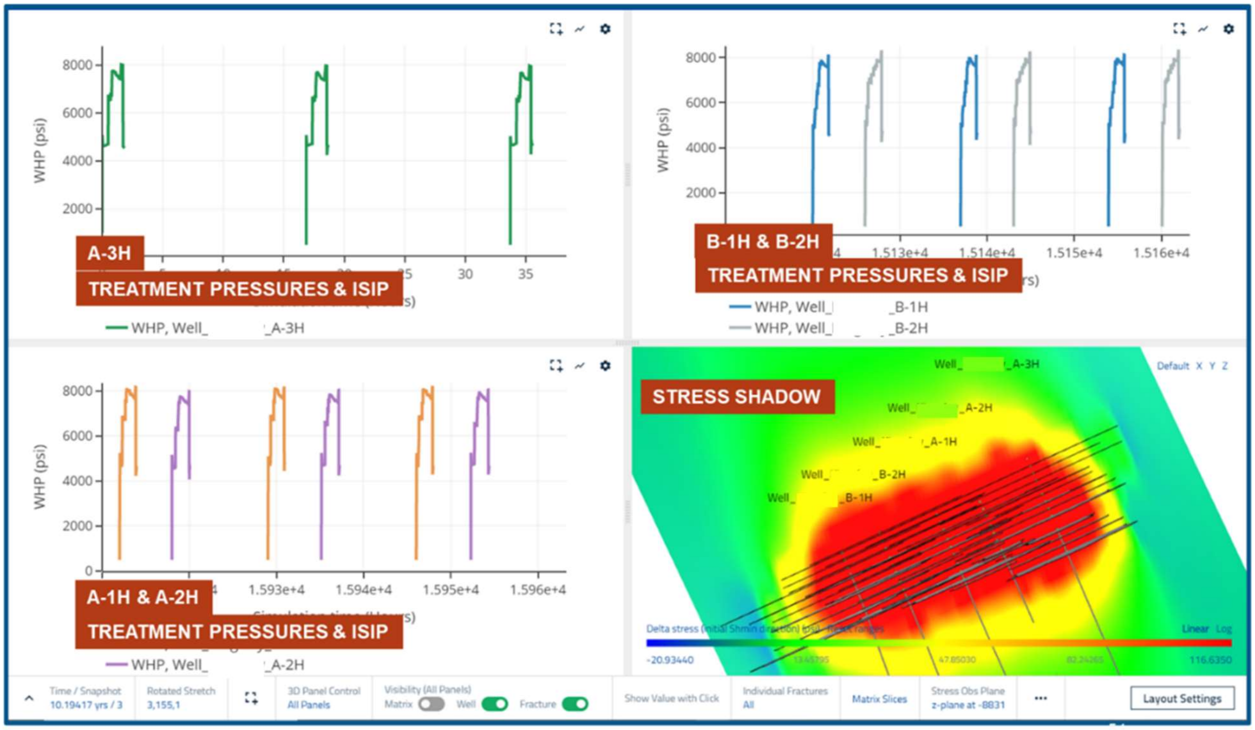
Fully Coupled Integrated Reservoir Modeling:

Fracture modeling and integrated reservoir modeling operate in an iterative loop where disciplines interact to enhance overall model interpretation and reservoir characterization.

When calibrating the model, it's crucial to consider all observations and interpretations. Models should initially adopt a simple approach and incrementally introduce complexity as needed. It is crucial to ensure that variables are adjusted within the agreed-upon uncertainty ranges across all disciplines.

Model Calibration results:

Figure 13 depicts the outcomes of fracture modeling, where treatment pressures and ISIPs align with observed field values.



Time / Snapshot: 10.19417 yrs / 3
Rotated Stretch: 3,155,1
3D Panel Control: All Panels
Visibility (All Panels): Matrix ○ Well ● Fracture ●
Individual Fractures: All
Stress Obs Plane: z-plane at -8831

Figure 13. Treatment pressures and Instantaneous Shut In Pressures (ISIP)

In Figure 14, the dynamic reservoir model calibration is showcased. The model's wells are controlled by gas rates, with minimal to negligible water rates observed after a small fraction of the injected fracture load is recovered, a common trait in Marcellus shale wells. The calculated and estimated flowing bottom hole pressures from the model reasonably match those from all five wells across the almost 10-year production history.

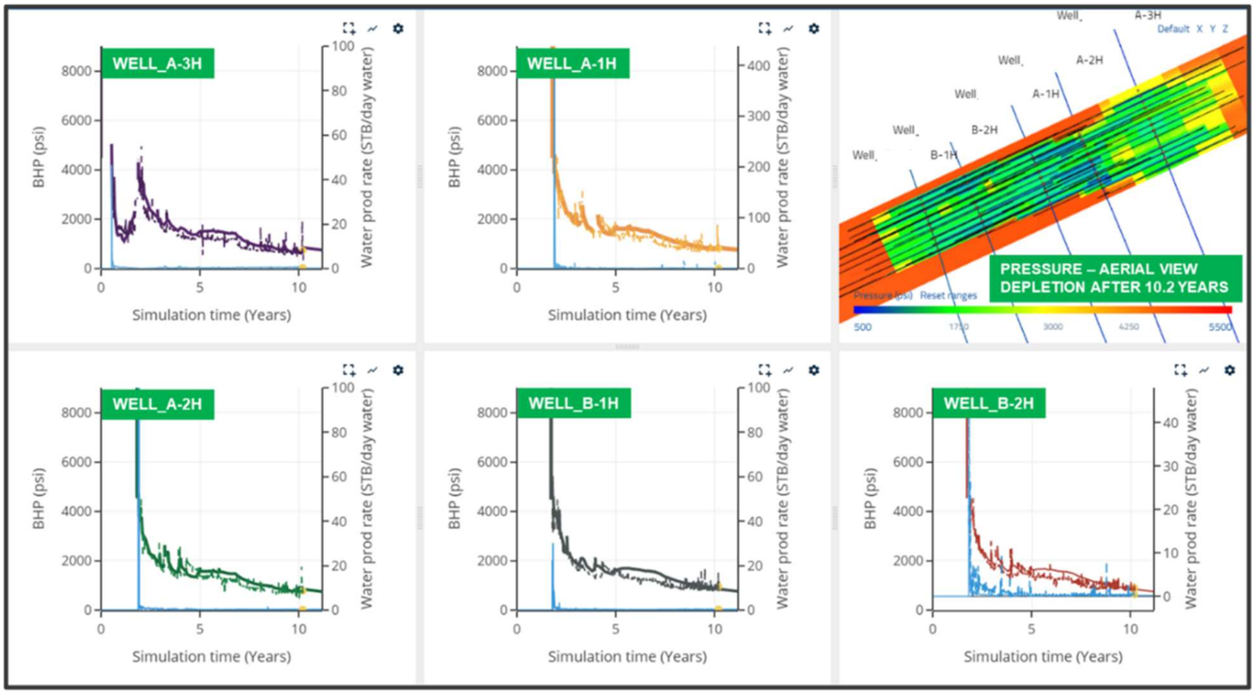


Figure 14. History matched Flowing Bottom Hole Pressures (FBHP)

Through model calibration, we have enhanced our reservoir characterization. The subsequent step involves utilizing this characterized reservoir to assess outcomes for various completion methods, well landing options, and spacing configurations.

4.b.2 Model calibration discussion

These are the primary findings and observations derived from the calibrated model outputs.

1. The Cherry Valley is not an effective barrier at the chosen calibration site, where it measures about 15 feet thick, and there is a stress contrast of about 600 psi compared to the Lower Marcellus.
2. The Cherry Valley member acts only as a hinderance to fracture growth, with roughly 40% of hydraulic fractures penetrating it, despite the use of substantial completion designs, including approximately 150,000 pounds of proppant per cluster (2,800 #/ft).
3. The five wells in the model calibration pad inefficiently drain the upper Marcellus, leaving significant portions of the lateral section relatively undrained in the upper Marcellus.
4. Stimulation jobs produced very large extensional geometries, with hydraulic fractures (Xfs) exceeding 2,500 feet in many instances. This is supported by some observations in the field.
5. Effective propped half lengths (Xfs) vary along the lateral ranging from 400’ to 1,200’. There was significant overlap between the wells stimulated rock volumes.
6. There was some level of asymmetric fracture growth. While most clusters initiated fracture propagation, the inferred cluster efficiency due to the asymmetric fracture growth was closer to 50 to 60%
7. Stress shadow is approximately 150 psi and has some limited impact on asymmetric fracture growth.
8. Irreducible water saturation is approximately 40% and significantly close to connate Sw. Model explains why a a small fraction of the load is produced back to surface.

Reservoir characterization was conducted using a pad where legacy completion designs were implemented over a decade ago. These legacy completion designs featured less clusters per stage, wider cluster spacing, lower perforation friction, and higher proppant intensity per cluster compared to our most recent jobs.

Reservoir characterization via model calibration enables us to explore the potential impact of more recent completion designs, spacing, and other operational variables on field development. A preliminary evaluation was conducted to assess the impact of landing, completion, and well spacing on pad development. At this stage several discrete scenarios were scoped, evaluated, and ranked. Results are intended to guide decisions on what to test in an upcoming field development.

Below we provide details on some of the most relevant scenarios explored:

- Scenario 1. Low Intensity Completions in the LMRCL. Four wells spaced at 1,200 feet using a newer completion design (105,000 pounds per cluster) landing at the basal Marcellus. This newer design includes five clusters per stage with 35-foot cluster spacing, pumping 105,000 pounds of sand per cluster (3,000 #/ft), and 30 barrels of fluid per foot.

- Scenario 2. High Intensity Completions in the LMRCL. Four wells spaced at 1,200 feet using a newer, larger completion design landing at the basal Marcellus. This design consists of five clusters per stage with 35-foot cluster spacing, pumping 150,000 pounds of sand per cluster (4.200 #/ft), and 45 barrels of fluid per foot.

- Scenario 3. Upper and Lower MRCL Co-development. Seven wells: four lower Marcellus wells landing in the basal Marcellus and spaced at 1,200 feet, and three Upper Marcellus wells spaced at 1,400 feet and landing in the lower portion of the upper Marcellus. All jobs were completed with slickwater and had five clusters per stage. lower Marcellus completions had clusters spaced at 40 feet and pumped 105,000 pounds of sand per foot (3,000 #/ft), while upper Marcellus targets had 35-foot cluster spacing and 90,000 pounds of sand per cluster (2,570 #/ft). In this scenario, the wells landed in the UMRCL are completed with tighter cluster spacing to compensate for lower permeability and enhance initial well productivity.

The model ran in forecasting mode, assuming a drawdown profile similar to other wells in the field. Production forecasts were then used in a detailed economic model to evaluate NPV and DROI for the scenarios. Figure 15 presents the production profiles for the scenarios outlined. The 20-year EUR for the Co-development case is the highest, approximately 22% higher than the case with four wells using a large modern completion design. Adding 45,000 pounds per cluster only increases EUR by approximately 10%.

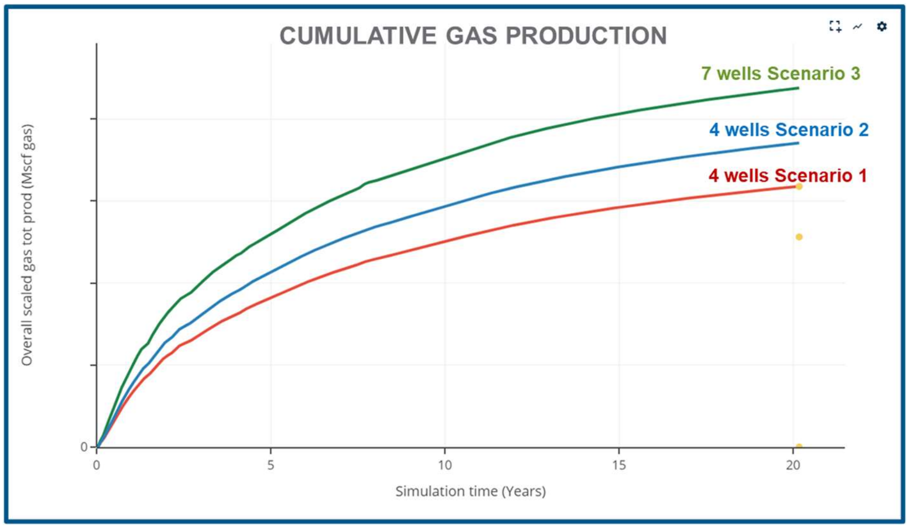


Figure 15. Estimated Ultimate Recoveries (EUR) for some of the most relevant scenarios evaluated.

The economic evaluation depends heavily on commodity prices and cost environment. At higher commodity prices, a 7-well co-development would be the best economic option, while at lower prices, a 4-well development with a larger completion design would be more favorable.

These scenarios evaluated in these discrete runs assume that the Upper Marcellus is as attractive at a prospective pad as it is at the evaluated location. If the upper portion of the UMRCL degrades significantly away from the evaluated sweet spot in the rest of the AOI, it may be preferable to drill only LMRCL wells with larger completion designs from an economic standpoint, as the Upper Marcellus wells may not have enough resources to access.

Other runs in the study evaluated the impact of landing and the order of operations. These are some of our primary observations:

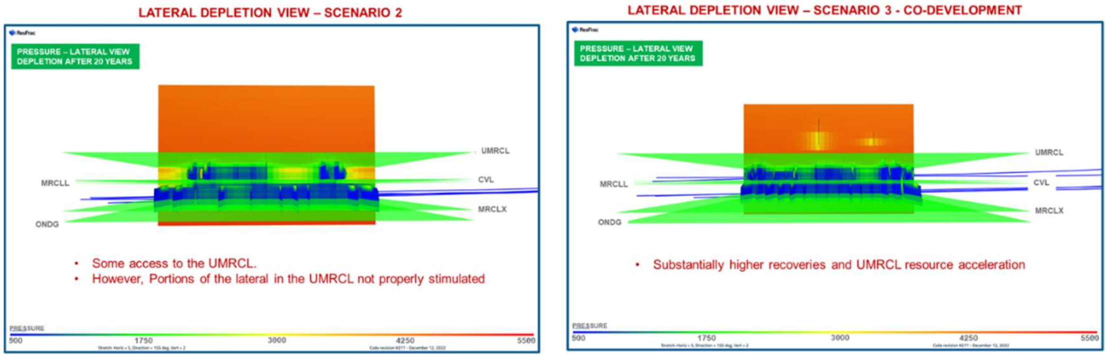
1. Landing wells in the basal Marcellus yields slightly better wells.

2. In the co-development case, completing LMRCL wells first yields better results. This is consistent with the higher stress observed in the LMRCL compared to the UMRCL. In this case, stress shadow reduces the instances of UMRCL breaking into the LMRCL.

3. Wells landed in the UMRCL would likely require slightly tighter cluster spacing as their performance is impacted by the lower permeability in the formation.

Figure 16 illustrates the depletion profiles for scenarios 1 and 2 and shows where additional resources are produced from.

We also used the model to estimate the impact of depletion in cases where UMRCL targets may need to be developed after some time. Results show significant degradation in IP and EUR due to less effective completion. Offset depletion resulted in fracture intersections, reduced effective SRV of the infill completion, and increased interference between wells. Results show the impact ranging from less than 20% infilling after 6 months to almost a 60% degradation if the UMRCL wells are infilled 3 years after starting production from the LMRCL wells. The model proved to be a valuable tool for estimating key operational outcomes and setting expectations.


LATERAL DEPLETION VIEW – SCENARIO 2

- Some access to the UMRCL.
- However, Portions of the lateral in the UMRCL not properly stimulated

LATERAL DEPLETION VIEW – SCENARIO 3 - CO-DEVELOPMENT

- Substantially higher recoveries and UMRCL resource acceleration

Figure 16. Pressure depletion for scenarios 2 and 3 – Lateral Cross Section View

4.c Sensitivity Analysis and uncertainty evaluation workflow

Sensitivity analysis was performed to identify and quantify the uncertainty related to the key control parameters of the reservoir model for the West Liberty area.

The K-pad model is in the middle of four vertical wells with a complete set of core-calibrated logs. The K-wells are amongst the best producers of the AOI. Since the goal is to guide our strategies to develop a full Type Curve, we built an additional conservative model and an optimistic model that not only describes the physics of the K-pad but that reproduces the variability of the geology for the whole AOI. To do that, a four-steps workflow has been defined to address the static and dynamic uncertainty of the area, from log analysis (1D models) to the reservoir model (3D) (Figure 17): 1) The first step, explained before, consisted in a detailed analysis of the parameters that affect the porosity and permeability models: exponents, coefficients, density, correlations; and have a first Monte Carlo simulation on these parameters to provide input to a geomodel. 2) Step two is about upscaling and running stochastic modeling using the high and low cases from the 1D input; synthetics logs and distributions are taken from these models. That guarantees that each log reproduces the geology, definition and granulometry of the broad area. 3) A third step corresponds to a univariate sensitivity assuming distribution on relative impacts of each parameter. A tornado plot allows to rank global uncertainty source. 4) The interaction amongst all key variables is combined in a Monte Carlo simulation to estimate possible outcomes of recoveries. It is based in multiple realizations of all the parameters keeping their relationships. This multivariate analysis is run using two combined sampling functions: Sobol Sequence, efficient design to create evenly spread points with the least error and Centered Composite function, to add samples at the corners of the search space and to get points right up the limits of the sampling (Fang and Lin, 2003).

Probability and cumulative distribution function plots shown on the right of Figure 17 display the estimated ultimate recovery ranges for the potential outcomes in the AOI. The plots also show where the K-pad falls within those distributions. Note that there is a slight difference in the P50 of the well sampled and the model distributions. The Monte Carlo model was performed using the K-pad and the four reference wells within the AOI (for petrophysical and geomechanical input). This resulted in a slight rightward P50 shift in the distribution compared to the actual EUR per well on the Type Curve. While it is possible to match both distributions, they were retained to highlight the disparity between a supervised and unsupervised model, as demonstrated here. Ultimately, this deviation in well sampling raises questions: Is the reservoir (AOI) adequately sampled? Are there other influencing factors at play?

There will be a second part of this paper where the results will be revisited after putting on production wells of an upcoming development in the AOI.

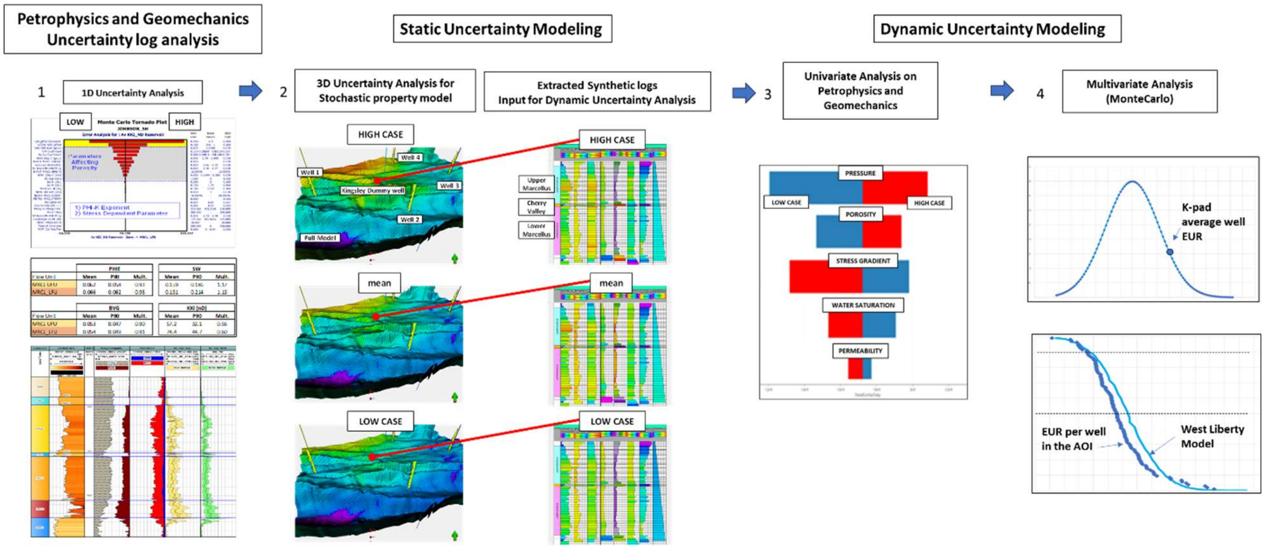


Figure 17. Workflow for static and dynamic sensitivity analysis. Detailed 1D (log) uncertainty analysis (far left) is performed to provide the input to 3D property models (left). High and Low cases are created for all properties as input for a univariate analysis (right). All variables are combined in a Monte Carlo simulation (far right) to estimate possible outcomes of recoveries connecting main geological heterogeneities of the whole AOI.

4.d Completion optimization results

To illustrate the workflow in this paper, an economic optimization evaluation of a potential co-development scenario was conducted. The optimization involved reservoir simulation and the use of a genetic algorithm to assess the impact of cluster spacing and sand intensity per cluster for a co-development scenario involving seven wells. The objective was to maximize NPV.

Figure 18 displays the results of the evaluated cases. The optimization algorithm ran around 100 reservoir simulation iterations to maximize NPV within the model's constraints.

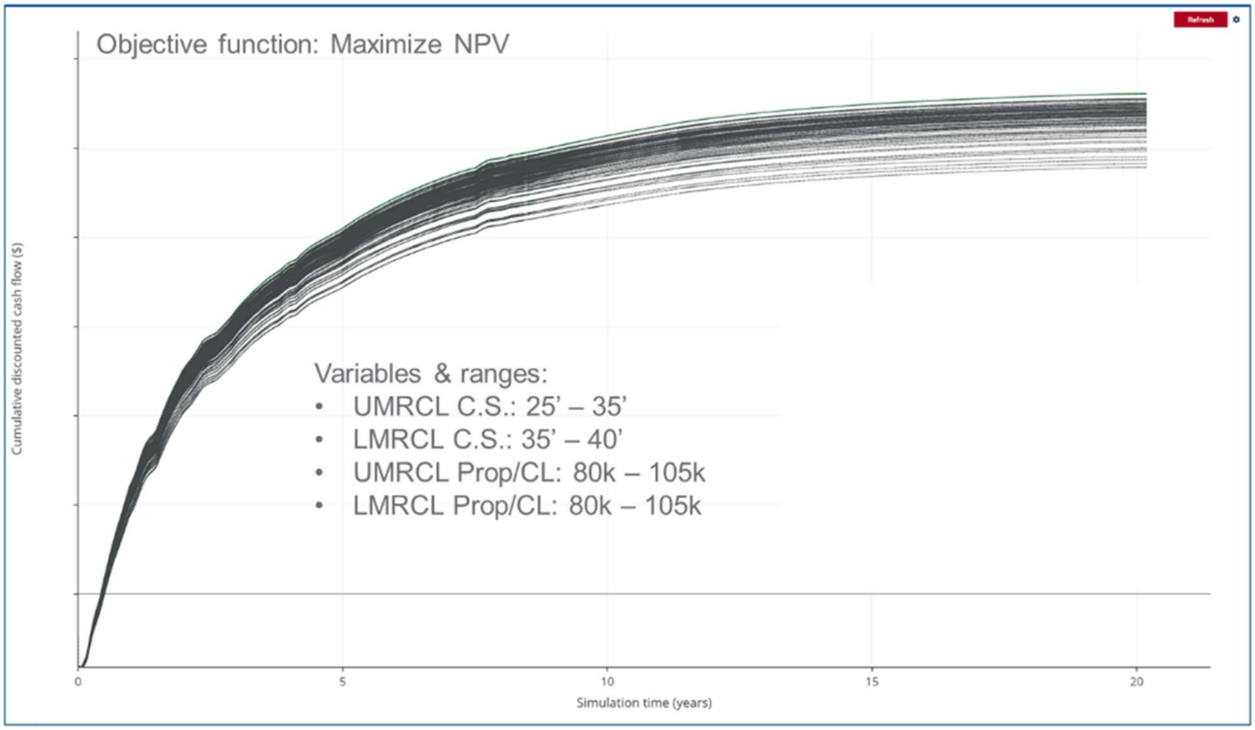


Figure 18. Completion optimization results for the co-development case

The optimized development for the co-development cases resulted in different completion designs for the Upper and Lower Marcellus targets. The Upper Marcellus wells required a cluster spacing of 28 feet and a slightly lower completion intensity of 90,000 lbs per cluster (3,200 #/ft). The Lower Marcellus wells needed a 35-foot cluster spacing and roughly 105,000 lbs of sand per cluster (3,000 #/ft). It's important to note that in these scenarios, well spacing remained constant at 1,200 feet between Lower Marcellus wells and 1,400 feet between Upper Marcellus wells, forming a slightly asymmetric wine rack pattern.

The configuration featuring tighter cluster spacing and lower sand intensity in the Upper Marcellus wells aligned with our expectations, considering the Lower Marcellus targets possess higher permeability and resource density compared to the Upper Marcellus formation.

A similar approach was taken for the 4-well Lower Marcellus scenario to determine the most appropriate completion design for this formation with four wells.

5. Model validation

Our current reservoir characterization relied on calibrating a model that targeted a sweet spot in an area where petrophysical and geomechanical properties vary significantly, particularly in the Upper Marcellus (UMRCL). Unfortunately, there were no Upper Marcellus wells available for calibration. Hence, there is a pressing need to reevaluate and further validate our reservoir characterization and performance forecasts.

We recently developed a pad approximately 2–3 miles away from the calibration pad. This development involved drilling three wells specifically targeting the UMRCL shale. To validate our reservoir characterization, we intend to use the calibrated model as a starting point for calibration in this area. A more thorough evaluation will then follow to confirm the appropriateness of our existing reservoir characterization. We plan to share these validation results and analyses in a separate publication.

6. Conclusions

General workflow conclusions:

1. The proposed approach ensures robust and comprehensive reservoir characterization through the integration of multiple disciplines, thereby accelerating the learning process in field development.
2. Integrated reservoir modeling proved valuable for estimating key operational outcomes. This tool facilitates understanding the primary physics governing performance, determining field testing priorities, and identifying necessary surveillance to reduce reservoir uncertainty cost-effectively.

Specific conclusions from the study of the West Liberty AOI:

1. Lower Marcellus completions with sand intensities greater than 105,000 # per cluster break through the Cherry Valley. The Cherry Valley acts as a hinderance to fracture growth at 15’. In most cases less than 40% of the fractures seem to grow into the Upper Marcellus. Most configurations with LMRCL wells only drain the upper Marcellus inefficiently.
2. Landing has limited impact for developing the resource is a single bench scenario as there is small stress contrast between the Basal and lower MRCL. However, results indicate that landing in the basal MRCL produces slightly higher IP90 and EURs as the basal MRCL has a higher porosity and permeability.
3. In co-development scenarios, the performance of the UMRCL wells is expected to be significantly lower than the LMRCL. That is driven mostly by the lower rock quality, specially reduced thickness and permeability in the Upper MRCL.
4. In co-development scenarios, completing the LMRCL wells first yields slightly better NPV and recoveries. It also reduces fracture growth risk from the UMRCL into the LMRCL.

7. Recommendations

Development options will be heavily influenced by commodity price. At lower commodity prices a development with fewer well locations and larger completion designs is preferable, while a multi-bench co-development will work best in a higher commodity price environment.

Integrated reservoir simulation provided a tool for estimating the economic threshold for the implementation of either single or multi-bench applications.

8. Acknowledgments

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