BELL CREEK TEST SITE – SITE CHARACTERIZATION REPORT

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 4 – Deliverable D64

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BELL CREEK TEST SITE – SITE CHARACTERIZATION REPORT

EXECUTIVE SUMMARY

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Resources Inc. (Denbury) to determine the effect of a large-scale injection of carbon dioxide (CO_2) into a deep clastic reservoir for the purpose of simultaneous CO_2 enhanced oil recovery (EOR) and to study incidental CO_2 storage associated with EOR at the Bell Creek oil field, which is operated by Denbury Onshore, LLC. A technical team that includes Denbury, the EERC, and others is conducting a variety of activities to determine the baseline characteristics of the Muddy and overlying formations in the Bell Creek field area, which will facilitate assessment of various migration pathways, guide monitoring strategies, and aid in determination of the ultimate fate of injected CO_2.

CO_2 is being injected into an oil-bearing sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately 4500 feet. The Muddy Formation within the boundaries of the Bell Creek oil field is characterized by high permeability (150–1175 mD) and high porosity (25%–35%), with reservoir pressures and temperatures that will maintain injected CO_2 in a supercritical state and at conditions required for miscibility of CO_2 in the oil. The activities at Bell Creek will inject an estimated 1 million metric tons of CO_2 annually, essentially all of which will be permanently stored.

Denbury is carrying out the injection and production operations in a phased approach as part of a commercial EOR project, while the EERC is providing support for the site characterization; modeling and simulation; risk assessment; and monitoring, verification, and accounting (MVA) activities to aid in assessing CO_2 migration and to study the relationship between incidental CO_2 storage and EOR. The PCOR Partnership has developed an approach that integrates site characterization, modeling and simulation, assurance monitoring, and performance MVA into an iterative process that will demonstrate that 1) incidental CO_2 storage can be safely and permanently achieved on a commercial scale in conjunction with a commercial EOR operation; 2) oil-bearing sandstone formations are viable sinks for CO_2; 3) MVA methods can be established to effectively monitor incidental CO_2 storage during a commercial EOR project and provide the technical framework to account for CO_2 stored; and 4) the lessons learned and best practices employed will provide the data, information, and knowledge needed to develop similar MVA plans for CO_2 storage projects across the region. A thorough understanding of site characterization of the Bell Creek oil field and its surrounding area is critical to achieve these objectives.

Specific goals of the characterization program include 1) understanding seal integrity; 2) understanding effective storage capacity, storage efficiency, and sweep efficiency; 3) understanding phase behavior of injected CO_2, fluid, and rock matrix; 4) guide assurance monitoring, performance monitoring, and accounting efforts; 5) provide inputs for geologic modeling and predictive numerical simulation; 6) understand the ultimate fate of injected CO_2. To accomplish these goals, the EERC technical team conducted a robust characterization of the reservoir and surrounding subsurface strata of the Bell Creek oil field from 2010 to 2013.

Bell Creek characterization efforts included the following:

- Review and interpretation of existing data
  - Three 2-D seismic lines
  - One 3-D vertical seismic profile (VSP)
  - Six hundred thirty-two well files
  - Logs from 748 wells
  - Core analysis data from 25 wells
  - Review of the existing body of technical work and geologic studies of the Bell Creek Field, Muddy Formation, and Powder River Basin

- Collection and interpretation of new data sets
  - Bottomhole pressure surveys from 156 wells
  - Forty-square-mile 3-D seismic acquisition
  - Two 3-D 50-level VSPs
  - Pulsed neutron logs (PNLs) in 35 wells
  - Continuous downhole pressure and distributed temperature profiles since April 2012
  - Review, description, and analysis of 66 cores at the U.S. Geological Survey and Bureau of Economic Geology
  - Collection of a 75-square-mile lidar survey
  - Collection and extensive analysis of approximately 200 feet of new 4-inch-diameter core from three wells (05-06 OW, 33-14R, and 56-14R)
  - Collection of modern high-resolution well logs from four new wells
  - Examination and analysis of Muddy Formation outcrop

Existing reservoir data were interpreted to provide a baseline understanding of the geologic structure, mineralogy, and properties of the reservoir and overlying sealing formations within the Bell Creek oil field. This preliminary geologic interpretation was utilized to target additional data acquisitions where key knowledge gaps existed. The new data were used to reinterpret formation properties in order to decrease uncertainties in predictive simulations which provide insight into EOR and CO_2 storage performance and guide monitoring efforts. Operations data such as production and injection volumes coupled with monitoring data will be utilized to periodically update characterization efforts to improve the overall understanding of project performance.

BELL CREEK TEST SITE –SITE CHARACTERIZATION REPORT

INTRODUCTION

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Resources Inc. (Denbury) to determine the effect of an approximately 1-million-ton/year injection of carbon dioxide (CO_2) into a deep clastic reservoir to study incidental CO_2 storage associated with CO_2 enhanced oil recovery (EOR) at the Bell Creek oil field, which is operated by Denbury Onshore, LLC. Denbury is carrying out the injection and production operations as part of the commercial EOR project, while the EERC is providing support for the site characterization, modeling and predictive simulation, assurance monitoring, and development of performance monitoring, verification, and accounting (MVA) plan to study the interrelationship of CO_2 EOR and incidental CO_2 storage associated with EOR activities.

The Bell Creek oil field in southeastern Montana is an initially subnormally pressured reservoir with significant hydrocarbon accumulation that lies near the northeastern corner of the Powder River Basin (PRB) (Figure 1). Exploration and production activities for mineral and energy resources in the area over the last 55 years have yielded a significant amount of information about the geology of southeastern Montana and the northern PRB. Over the course of decades, oil and gas production through primary and secondary recovery (waterflood and polymer flood pilot tests) has resulted in reservoir decline and has now led to the planned implementation of a CO_2 injection-based tertiary oil recovery project. CO_2 will be delivered to the site via pipeline from the ConocoPhillips operated Lost Cabin gas plant, where CO_2 is separated from the process stream during refinement of natural gas. The plant is located in Fremont County, Wyoming (Figure 1) and is delivering around 50 million cubic feet of CO_2 per day to the Bell Creek oil field.

CO_2 will be injected into the oil-bearing sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately 4500 feet (1372 meters). CO_2 injection will occur in a staged approach (nine planned CO_2 development phases, designated as Phases 1 to 9) across the field (Figure 2). It is expected that the reservoir will be suitable for miscible flooding conditions, with an incremental oil production target of approximatley 30 million barrels. The activities at the Bell Creek oil field will inject an estimated 1 million tons of CO_2 annually, much of which will be permanently stored at the end of the EOR project.

There is growing recognition that EOR operations utilizing CO_2 as the injectant can have additional value for the public and the environment by taking advantage of the normal situation that commonly takes place in any EOR operation utilizing an outside substance to increase oil production from a reservoir. The fluid being injected, including saltwater when utilized in a secondary recovery project, ultimately occupies some of the pore space vacated by the produced oil. At the time of depletion and the closure of the EOR project, the injectant remains stored. This project is directed at taking advantage of the opportunity to monitor and account for this incidental storage of CO_2 that occurs during normal oil field operations.

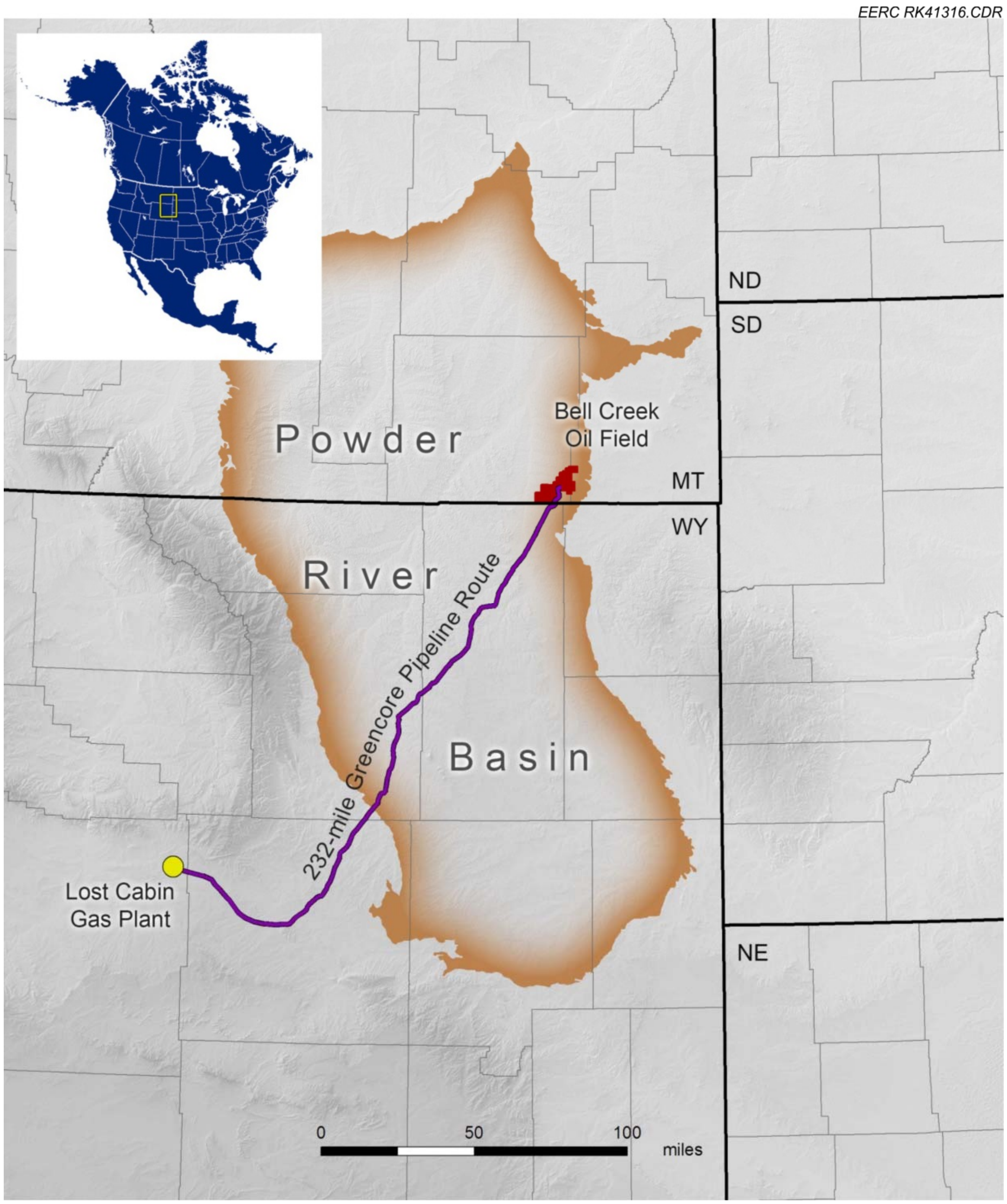

Figure 1. Location of the Lost Cabin Gas Plant and Bell Creek oil field in Wyoming and Montana (modified from Gorecki and others, 2012).

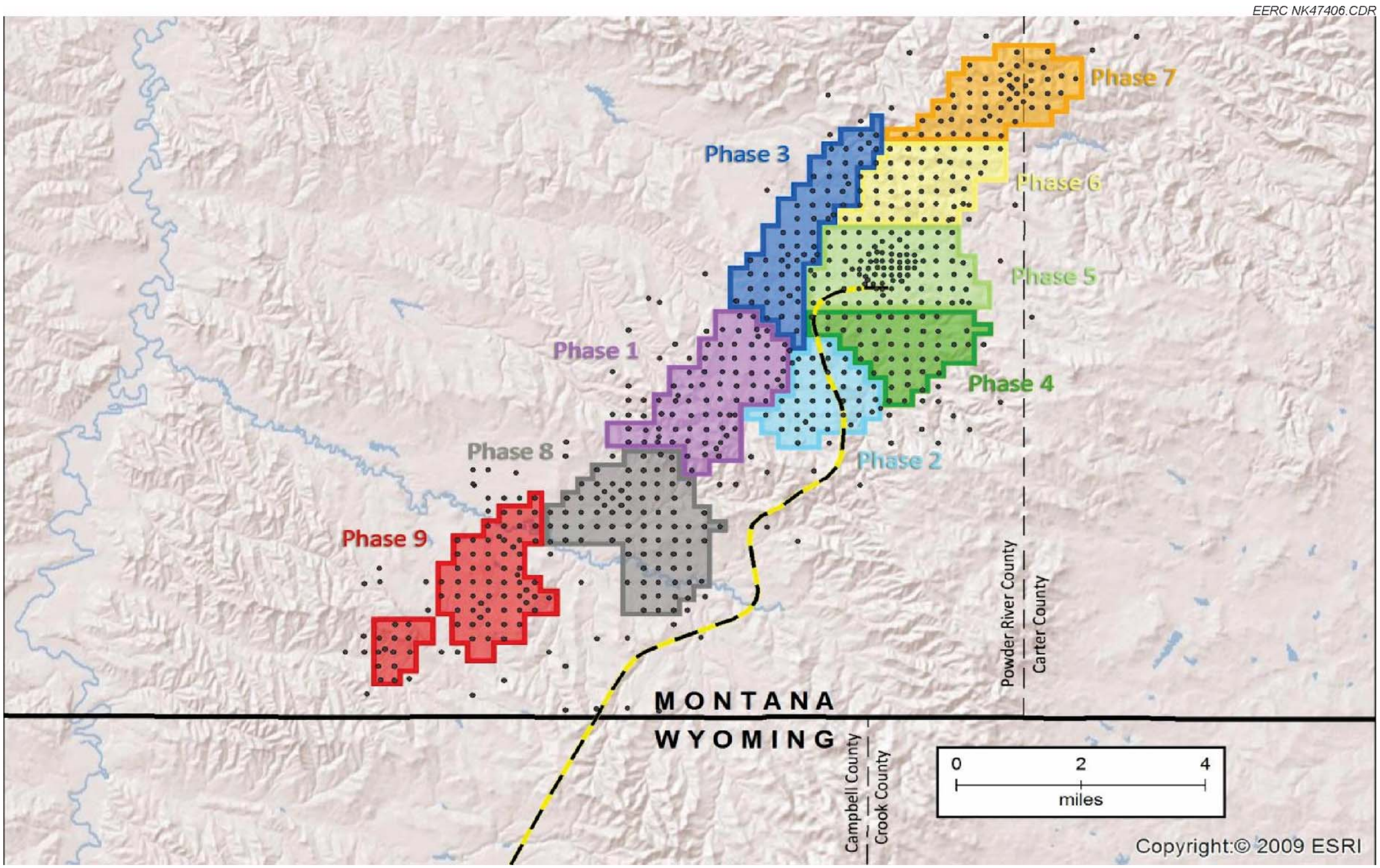

Figure 2. Bell Creek CO_2 EOR development phases.

Geologic Overview

Within the Bell Creek oil field, the Muddy Formation is dominated by high-porosity (25%–35%), high-permeability (150–1175-mD) sandstones deposited in a near-shore marine environment (Encore Acquisition Company, 2009). The initial reservoir pressure was 1200 psi at the time of discovery, which is significantly lower than the regional hydrostatic pressure regime (2100 psi at 4500 ft) (Saini and others, 2012). The existence of a stable, underpressured system in the Bell Creek oil field provides additional support for the suitability of the reservoir as a CO_2 storage reservoir. It demonstrates that both the overlying and underlying sealing formations are competent and capable of maintaining a sustained pressure differential. The oil field is located structurally on a shallow monocline with a 1°–2° dip to the northwest and with an axis trending southwest to northeast for a distance of approximately 20 miles. Stratigraphically, the Muddy Formation in the Bell Creek oil field features an updip facies change from sand to shale that serves as a trap. The barrier bar sand bodies of the Muddy Formation strike southwest to northeast and are overlain by a deltaic siltstone that strikes perpendicularly to the Muddy Formation and finally are partially dissected and somewhat compartmentalized by intersecting shale-filled incisive erosional channels.

The overlying Upper Cretaceous Mowry Formation shale will provide the primary seal, preventing fluid migration to overlying aquifers and to the surface. On top of the Mowry Formation are several thousand feet of low-permeability shale formations, including the Belle Fourche, Greenhorn, Niobrara, and Pierre shales, which will provide redundant layers of protection in the unlikely event that the primary seal fails to prevent upward fluid migrations fieldwide (Figure 3).

Site Characterization Activities

The Bell Creek project provides a unique opportunity to develop methods to monitor and account for CO_2 incidentally stored in association with a complex, large-scale (>1 million tons/per year) CO_2 EOR operation. A detailed site characterization was conducted to provide a solid foundation for critical activities necessary to complete project objectives.

The EERC's site characterization activities served as essential and direct inputs into geocellular modeling activities (geologic, geomechanical, numerical, and predictive simulation) to determine 1) the capacity of the target formation (i.e., Bell Creek Field oil reservoir); 2) the mobility and fate of the CO_2 at near-, intermediate-, and long-term time frames; 3) potential storage efficiency of the reservoir; and 4) ability of the formation to permanently retain injected CO_2 and reservoir fluids. Characterization activities, at the time of this report, consisted of collecting, evaluating, and interpreting data sets throughout the field such as 1) historic core analyses, outcrop analysis, and analyses of new characterization wells core-drilled in development Phases 1 and 2 of the Bell Creek oil field; 2) all available historic well logs; 3) all available well files which include data on drilling, completion, and stimulation/workover records; 4) geological and geophysical information including maps, cross sections, and geophysical surveys;

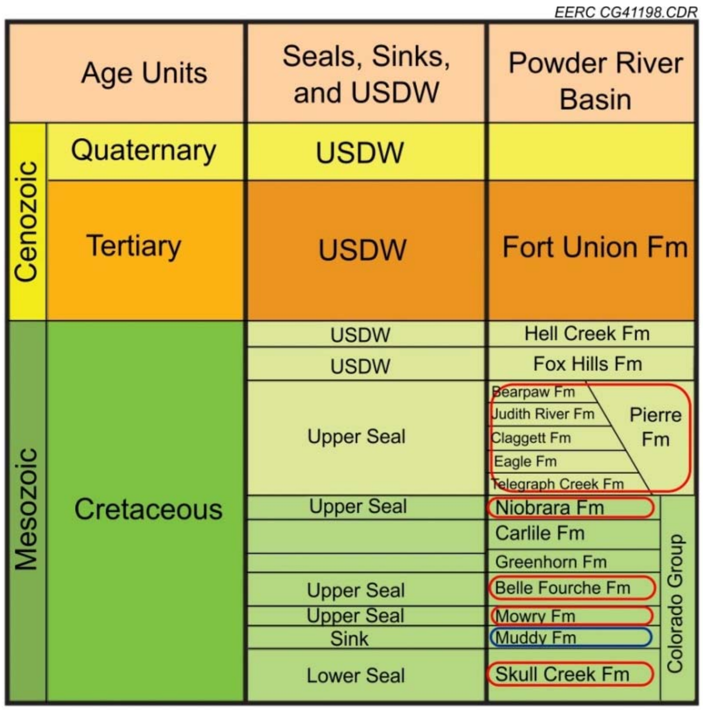

Figure 3. Late Cretaceous to Quaternary stratigraphic column of the PRB. Sealing formations are circled in red, and the primary oil-producing and sink formation is circled in blue. Formations bearing underground sources of drinking water (USDW) are also identified.

and 5) a 75-square-mile lidar survey. Additional characterization work is being completed as part of the iterative process of site characterization, modeling, predictive simulation, assurance monitoring, and performance MVA, including collection, interpretation, and integration of 1) modern high-resolution well logs in over 35 wells, 2) bottomhole pressure (BHP) survey data in over 156 wells, 3) continuous downhole pressure and temperature data, 4) additional modern core analysis on historic and newly acquired core, 5) two 3-D vertical seismic profiles (VSPs), and 6) a 40-square-mile 3-D seismic survey.

The majority of characterization data is derived from targeted characterization activities designed to produce data pertinent to key aspects of the field's geology. Characterization data can also be derived from the CO_2-monitoring activities deployed in the field (a value-added proposition for certain monitoring activities, such as wellhead pressure monitoring). These data not only stand on their own in the form of geological field assessments or CO_2-monitoring reports but are also fed directly into a variety of geocellular modeling activities. The production of geologic models and subsequent dynamic simulations provide a primary means of data integration and interpretation. Modeling and simulation activities provide an opportunity to evaluate characterization data in a holistic sense and appraise the interrelatedness of various data sources and identify key variables. In addition, inefficiencies or inaccuracies uncovered in the modeling and simulation process can identify knowledge gaps requiring additional or modified characterization activities.

PURPOSE

The PCOR Partnership has developed a philosophy that integrates site characterization, modeling, simulation, risk assessment, and MVA into an iterative process to produce meaningful results for large-scale CO_2 storage projects (Figure 4). Elements of any of these activities are crucial for understanding or developing the other activities. For example, as new knowledge is gained for site characterization, it reduces a given amount of uncertainty in geologic reservoir properties. This reduced uncertainty can then propagate through modeling, risk assessment, and MVA efforts. Because of this process, the PCOR Partnership Program is in a strong position to refine characterization, modeling, risk assessment, or MVA efforts based on the results of any of these activities (Gorecki and others, 2012).

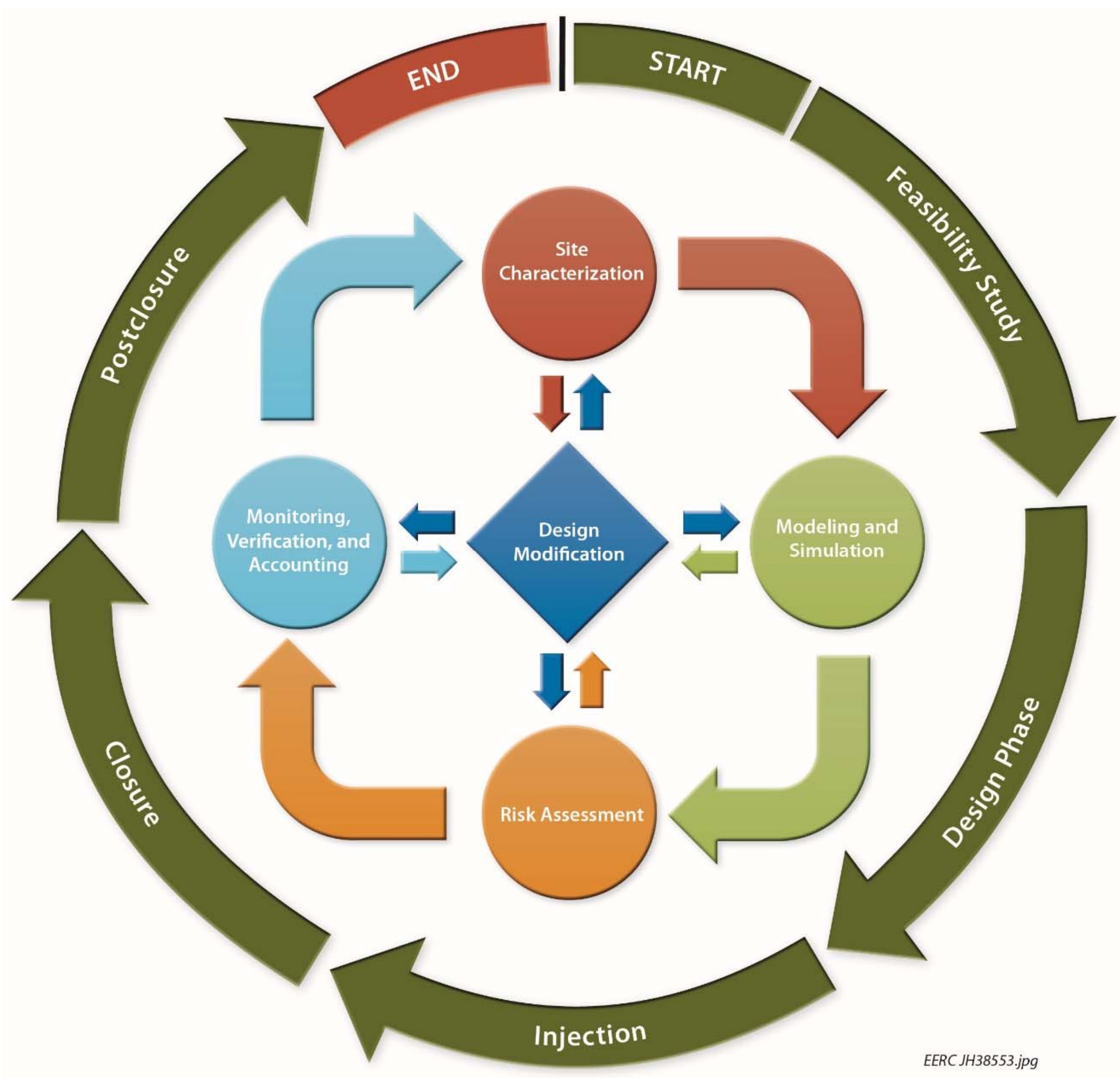

Figure 4. Project elements of the Bell Creek study. Each of these elements feeds into another, iteratively improving results and efficiency of evaluation (Hamling and others, 2012b).

The EERC's geological characterization activities conducted throughout the Bell Creek oil field provide a direct input into modeling and simulation activities. Knowledge gained from site characterization reduces a given amount of uncertainty in geologic reservoir properties, leading to more accurate predictions during simulation and modeling. More accurate simulations and models are then propagated through risk assessment and guide MVA. Modeling and simulation activities identify knowledge gaps to guide and target future characterization efforts and monitoring activities. The data acquired through each synergistic process is guided by the characterization component of the Bell Creek study.

The goal of the characterization plan is to provide the necessary geological foundation to understand the interrelationship between EOR and incidental CO_2 storage and to develop monitoring programs capable of tracking and accounting for injected CO_2. The results and experience gained at the Bell Creek oil field will provide insight and knowledge that can be directly and readily applied to similar projects within the PCOR Partnership region and throughout the world (Saini and others, 2012).

PROJECT OBJECTIVES

The PCOR Partnership has developed an approach that integrates site characterization, modeling and simulation, assurance monitoring, and performance MVA into an iterative process that will demonstrate that 1) incidental CO_2 storage can be safely and permanently achieved on a commercial scale in conjunction with a commercial EOR operation; 2) oil-bearing sandstone formations are viable sinks for CO_2; 3) MVA methods can be established to effectively monitor incidental CO_2 storage during a commercial EOR project and provide the technical framework to account for CO_2 stored; and 4) the lessons learned and best practices employed will provide the data, information, and knowledge needed to develop similar MVA plans for CO_2 storage projects across the region. A thorough understanding of site characterization of the Bell Creek oil field and its surrounding area is critical to achieve these objectives, and the characterization activities completed provide a critical foundation necessary to demonstrate these goals.

To gain a better understanding of the CO_2 storage reservoir and seal, geological site characterization activities have been and continue to be conducted at the Bell Creek oil field to 1) predict CO_2 movement with modeling and simulation, 2) identify areas of risk and potential migration pathways, 3) develop an effective MVA plan for both CO_2 EOR and CO_2 storage aspects of this project, and 4) to evaluate CO_2 sweep and effective storage efficiency.

BASELINE CHARACTERIZATION

Targeted characterization data acquisitions and interpretation of preexisting data are integrated into modeling and simulation activities that provide accurate evaluation of a potential storage reservoir and surrounding strata. The characterization program enhances and supplements data originating from the commercial EOR project, providing direct and immediate benefit for both the site operator and Bell Creek study. Integration of site characterization data will provide a means of developing and optimizing an economically viable monitoring strategy to accomplish the key project objectives.

Both new and existing data were collected, analyzed, and interpreted between November 2010 and May 2013 (Table 1).

SCOPE OF WORK

To accomplish project objectives, the following site characterization activities were conducted throughout the Bell Creek study:

- Baseline geology of Muddy Formation and surrounding strata within and around the Bell Creek oil field
- Geochemistry of rock fluid compositions of the Muddy Formation and surrounding strata
- Baseline hydrogeology regime
- Rock and fluid properties of the reservoir and surrounding strata
- Mechanical rock properties, stress regime, and fluid regime
- Wellbore integrity and sealing potential of overlying strata
- Seasonal variations in groundwater and soil gas chemistry
- Reservoir properties, storage efficiency, and original oil in place (OOIP)

Key characteristics affecting the long-term mobility and fate of the injected CO_2 were evaluated at three different scales.

Work at the **pool scale** focused on a specific development phase within a specific area unit of the Bell Creek oil field. Phase 1 will be the initial pool targeted for injection. Stratigraphic characterization activities at this scale only included the reservoir and seals directly overlying and underlying the reservoir.

Work at the **field scale** covered the entire Bell Creek oil field. Stratigraphically, the entire sedimentary succession from the basement to the surface was evaluated locally.

Work at the **regional**, or **subbasin**, **scale** evaluated relevant data and information on key geologic formations over the northeastern portion of the PRB. Hydrogeological systems and the regional continuity of key sealing formations were the focus of studies at this large scale.

All characterization activities followed the plan outlined in Hamling and others (2011), which contains further detailed methodologies.

Table 1. Bell Creek Baseline Site Characterization Overview

Site Characterization Activity	*Activity Description*	*Location*	*Purpose*
Geophysical Data	• 40-square-mile 3-D surface seismic survey acquisition • Two 3-D VSP acquisitions • Three vintage 2-D seismic lines interpreted • One vintage VSP interpreted	• All of Phases 1, 2, 4, 5,and 8; parts of Phases 3, 6, 7, and 9; and areas updip and downdip of the reservoir • Part of Phases 1 and 2 • Transecting middle and western portions of the Bell Creek oil field • Central portion of the Bell Creek oil field	• Guide future characterization activities • Input for structural interpretation • Basis to conduct 4-D measurements to track CO_2 movement
Well File Review	• 632 historical well files reviewed	• Entire Bell Creek oil field and surrounding area	• Assess regional geologic properties
Core and Outcrop Analysis	• Review of existing body of technical work and geologic studies • Outcrop characterization • 66 cores examined, described, and analyzed at USGS[1] and BEG[2] • Collection and extensive analysis of approximately 200 feet of new 4-inch core from three wells (05-06 OW, 33-14R, and 56-14R) • Collection and extensive analysis of 47 rotary sidewall cores from the 05-06 OW well and 22 rotary sidewall cores from the 56-14R well • Existing core data from 25 wells	• Entire Bell Creek oil field, Muddy Formation, and PRB • Muddy Formation (located in the PRB, northeastern Wyoming) • Entire Bell Creek oil field and surrounding area • Phases 1 and 2 • Entire Bell Creek oil field and surrounding area	• Assess local geologic properties – Sealing formation(s) – Reservoir interval – Groundwater aquifers
Other Data Interpretation	• 35 pulsed neutron logs (PNLs) • 156 BHP surveys • Continuous downhole pressure and distributed temperature profiles • Logs from 748 wells • Acquisition of modern high-resolution data sets in four wells • 75-square-mile lidar survey	• Within and around Phase 1 • Centered on Phase 1 and surrounding areas • Phase 1 • Entire Bell Creek oil field and surrounding area • Phases 1 and 2 • Entire Bell Creek oil field and surrounding area	• Establish baseline reservoir conditions – Track CO_2 plume movement – Monitor fluid saturation changes along wellbore • Data integration • Predictive simulation

[1] U.S. Geological Survey.
[2] Bureau of Economic Geology.

WELL FILE REVIEW

Existing completions and formation property data (core analysis, well test, well log, etc.) were extracted and analyzed from well files for the Bell Creek oil field. A total of 632 historical well files were evaluated from the Denbury archives and the Montana Board of Oil and Gas. The acquired data were utilized to evaluate the range of completions (casing types, cement types, perforated zones, top of cement, etc.) present throughout the Bell Creek oil field and surrounding areas which help assess well integrity risk to guide MVA strategies (Hamling and others, 2012a, b). The rock and fluid property data collected were used to establish baseline geologic characteristics for initial reservoir characterization activities and geologic model development and to help more fully understand previous interpretations of the site. Well logs extracted from 748 well files and log archives were digitized and analyzed for inclusion into model development. Data gaps identified in the well files were used to guide the acquisition of new characterization data.

GEOPHYSICAL ACQUISITION

Geophysical data such as the 2- and 3-D surface seismic surveys and VSPs aid in the structural interpretation of the reservoir and allow for increased accuracy in geologic model development and serve as a possible mechanism of statistical distribution of model properties. Baseline geophysical data comprised both previously existing data including three 2-D seismic lines and one VSP as well as new data collected during 2012–2013. New data included a 40-square-mile 3-D seismic survey centered on the Phase 1 development area (Figure 5) which was collected in August 2012. In addition, two 3-D VSPs were collected in April 2013 via a removable 50-level, three-component geophone array in the 05-06 OW well and a permanently installed 50-level, three-component geographic array in the 04-03 OW well (Figure 6).

Value will also be derived from the baseline geophysical data set in the form of utility to future monitoring activities. When subsequent time-lapse seismic survey data are acquired, they can be compared to the baseline data set to monitor CO_2 distribution in the subsurface. More details will be provided in the 3-D seismic and characterization report to be published at a later date.

Applications for geophysical acquisition activities being pursued at the time of this report include the following:

- Structural and geological interpretation for the updated framework utilized in the 3-D Version 3 model.

- Geomechanical transform over the reservoir area (calibration of seismic attributes with well log data to derive Young’s modulus and Poisson’s ratio from seismic data away from wells).

- Geobody interpretation (combining well data with inverted seismic impedances to derive 3-D facies).

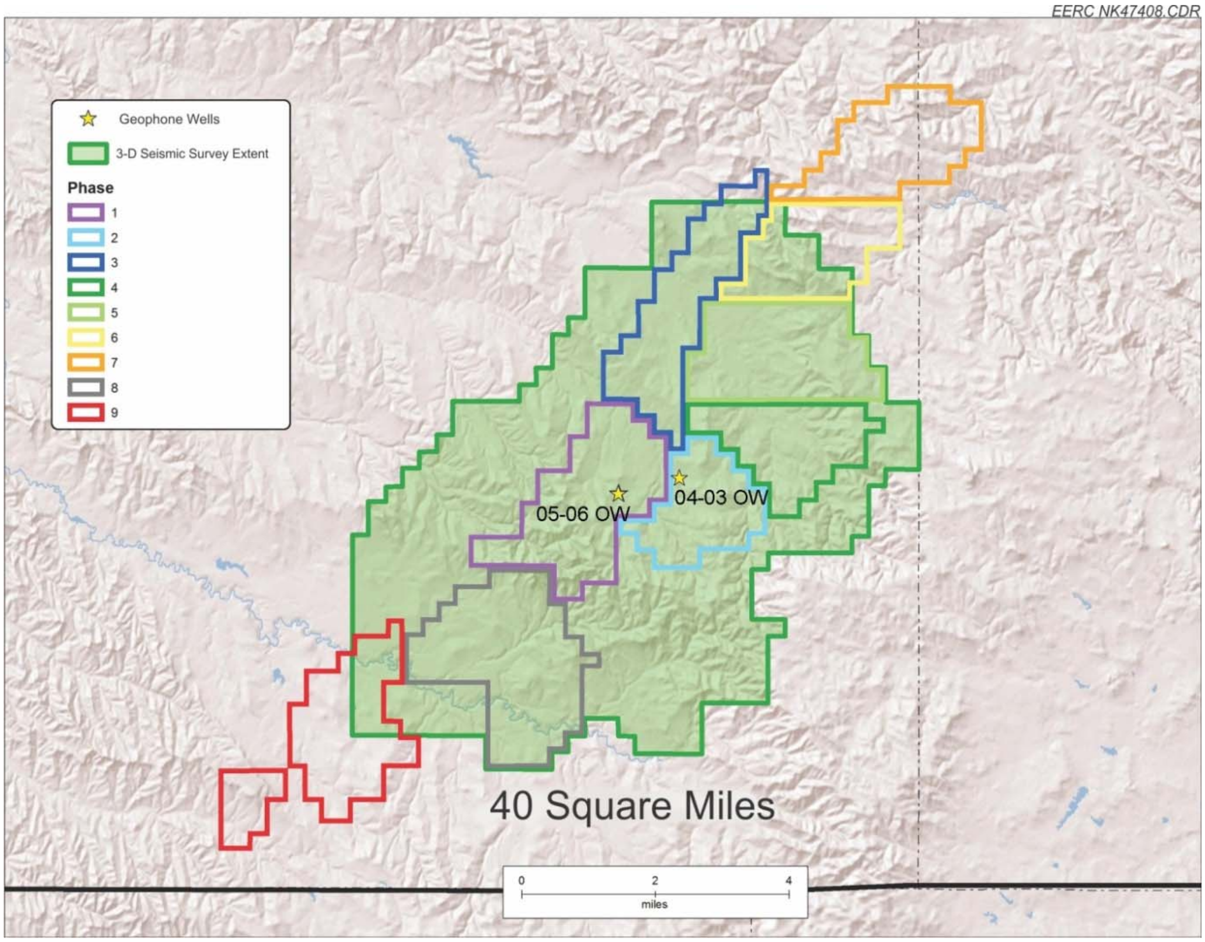

Figure 5. Baseline 3-D surface seismic survey outline.

- Seismic inversion over the zone of interest (converting seismic waveforms to lithology).
- Amplitude versus offset prestack processing to derive reservoir properties.
- Calibration and enhanced processing of the time-lapse 3-D surface seismic data.
- Seismic characterization of subsurface structure.
- Time-lapse seismic images of CO_2 saturation changes.
- Passive seismic monitoring of the field during injection.
- Interpretation of 2-D lines purchased from PacSeis and additional publically available data from the USGS.
- Processing and interpretation of two separate but overlapping VSP surveys in and around the Phase 1 area.

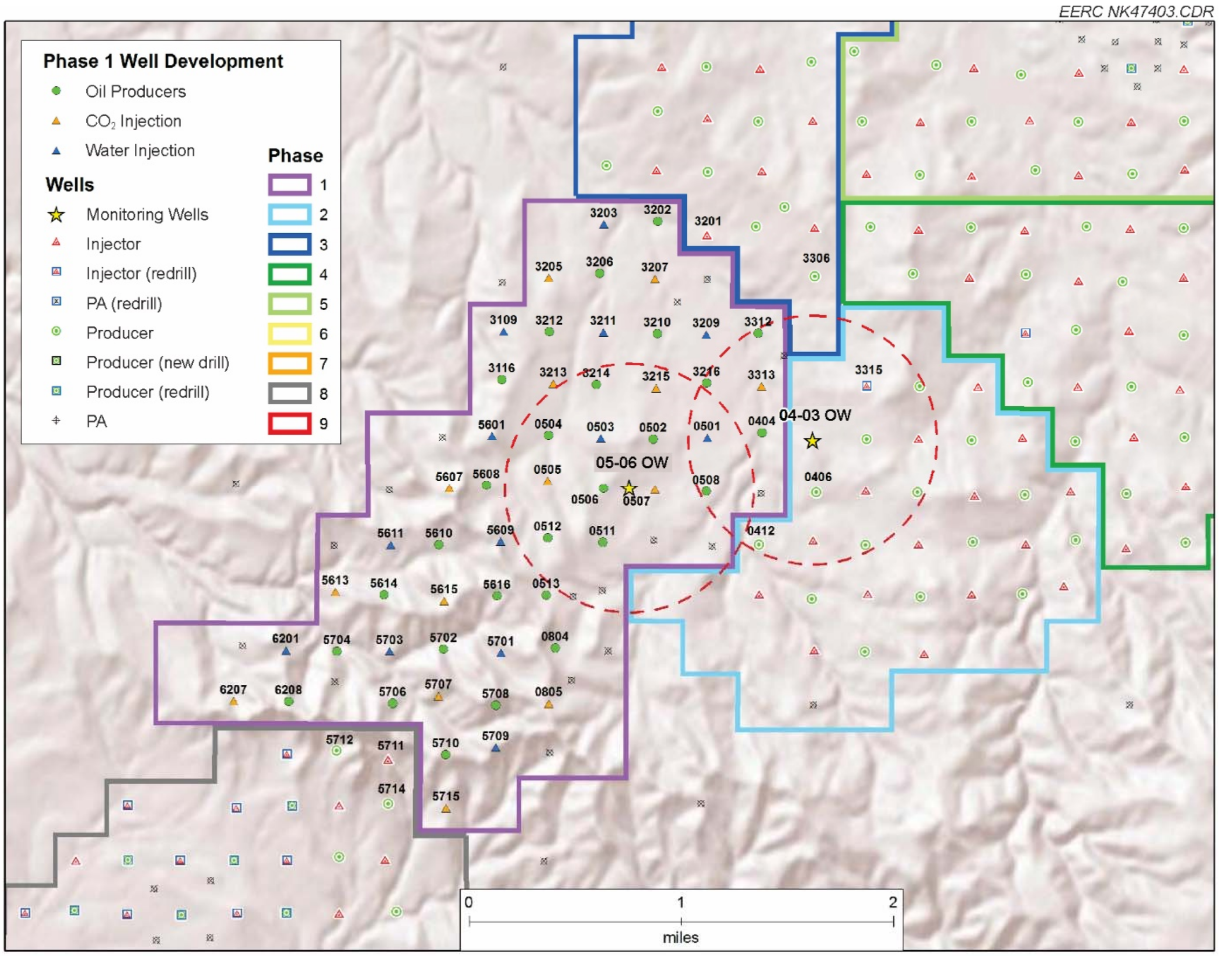

Figure 6. Survey design of the 3-D VSP seismic surveys. Red circles illustrate modeled maximum illumination at reservoir depth.

ROCK ANALYSIS

Outcrop Characterization

Outcrop activities have been conducted within the Bell Creek oil field and surrounding areas to understand the nature of heterogeneities in both horizontal and vertical subsurface structures. A Muddy Formation outcrop, located in the PRB, northeastern Wyoming, was examined and characterized in July 2011 to provide insight into the regional structure and facies distribution which can be correlated to observations made in the reservoir. This enables a better understanding of zones of high flow and flow-restrictive barriers built into the 3-D geocellular models. Additional outcrop characterization is planned in August 2013 to develop an understanding of previously unavailable outcrop exposure.

USGS and BEG Core Sample Evaluation

Both historic and recently collected core data were directly integrated into the geocellular modeling workflow to enhance the Bell Creek study project objectives. Historic core data from 25 wells within the Bell Creek oil field were examined and reviewed to improve understanding of the mineralogical distribution, depositional regimes, and structural settings within the reservoir and sealing formations. Newly collected and interpreted core datasets include 66 total cores: 58 at the USGS Core Research Center and eight at the BEG Core Sample Repository. A select subset of the USGS cores (21) were sampled for porosity, permeability, petrographic, x-ray diffraction and fluorescence, and scanning electron microscopy analyses, which are essential inputs for the geocellular modeling workflow (Figure 7).

Characterization Well Core Evaluations

Approximately 200 feet of 4-inch-diameter core has been recovered from three characterization wells (05-06 OW, 33-14R, and 56-14R) in Phases 1 and 2 (Figure 8) as well as 47 sidewall cores from 05-06 OW and 22 sidewall cores recovered from 56-14R. The newly collected core is ideal to accomplish the following: 1) correlate with new acquisition of modern high-resolution well logs, 2) aid in correction of vintage well log and core analysis, 3) understand variability in reservoir and cap rock, 4) petrographic and mineralogical evaluation, and 5) well tie with dipole sonic for time-depth transform needed for 3-D seismic interpretation.

Additional special core analysis (SCAL) data were acquired from the full-diameter core of well 05-06 OW. These data have been analyzed to enhance the following aspects to the Bell Creek study:

- Determine capillary pressure and relative permeability curves for dynamic simulation purposes.

- Develop a better understanding and modeling of reservoir behavior (wettability) for depletion stages.

- Utilize electrical properties to gain insight into the effect of clays on initial water saturation estimation.

Drill cuttings from well 05-06 OW were utilized to conduct a laboratory study investigating potential CO_2–rock interactions. The goal of that effort was to provide geochemical and mineralogical data sets before and after exposure to CO_2. The laboratory experiments exposed the cuttings from aquifer depths and samples of groundwater from regional aquifers to CO_2 at relevant temperatures and pressures. The goal of the study was to provide geochemical and mineralogical data sets as well as develop an understanding of the following:

- Mineral dissolution/precipitation trends.

- Groundwater chemistry changes as a result of interaction of CO_2 with the groundwater zone overlying the Bell Creek oil and gas reservoir.

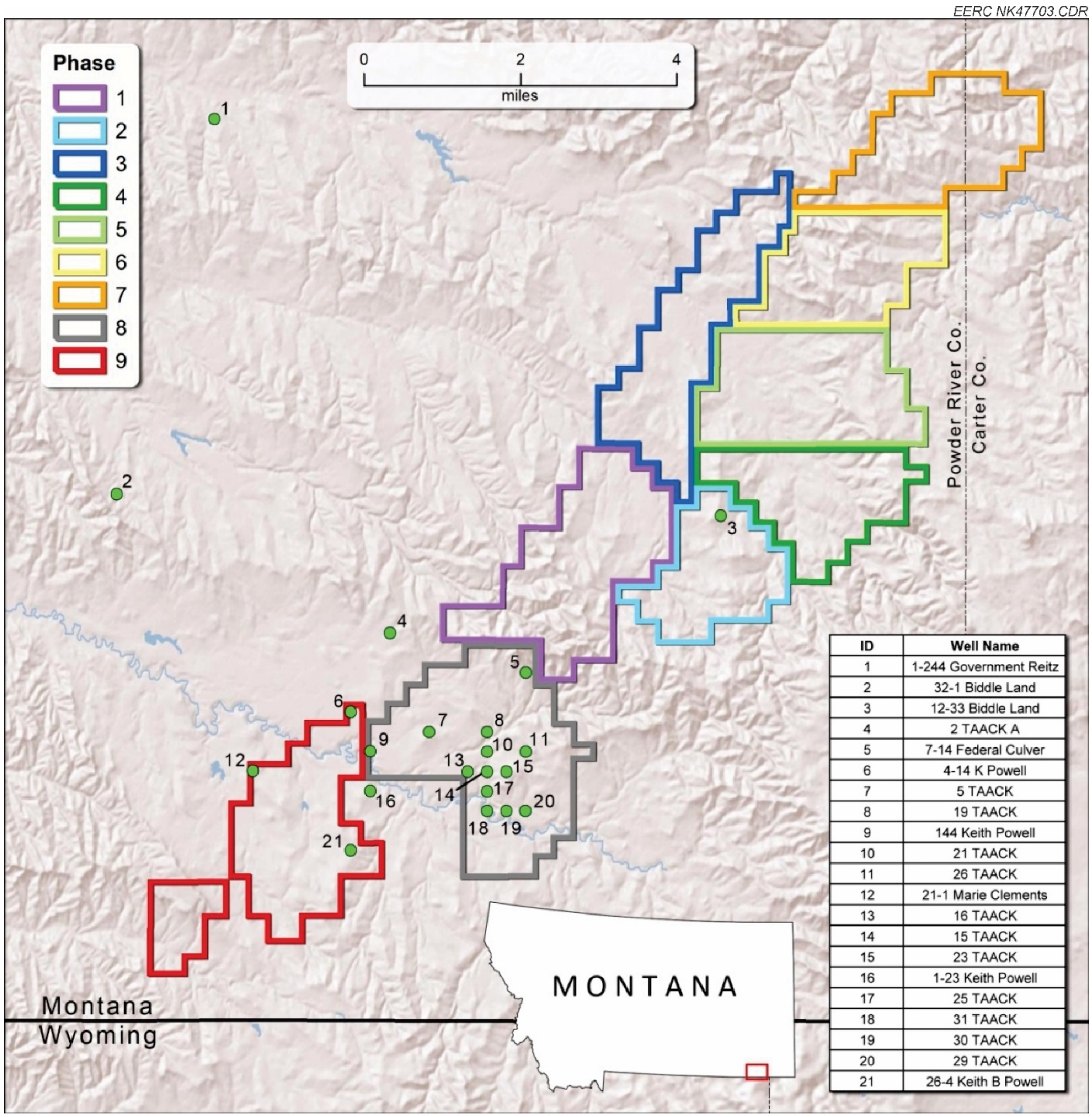

Figure 7. Select subset of USGS collected core throughout the Bell Creek oil field submitted for mineralogical, petrographic, porosity, and permeability analyses.

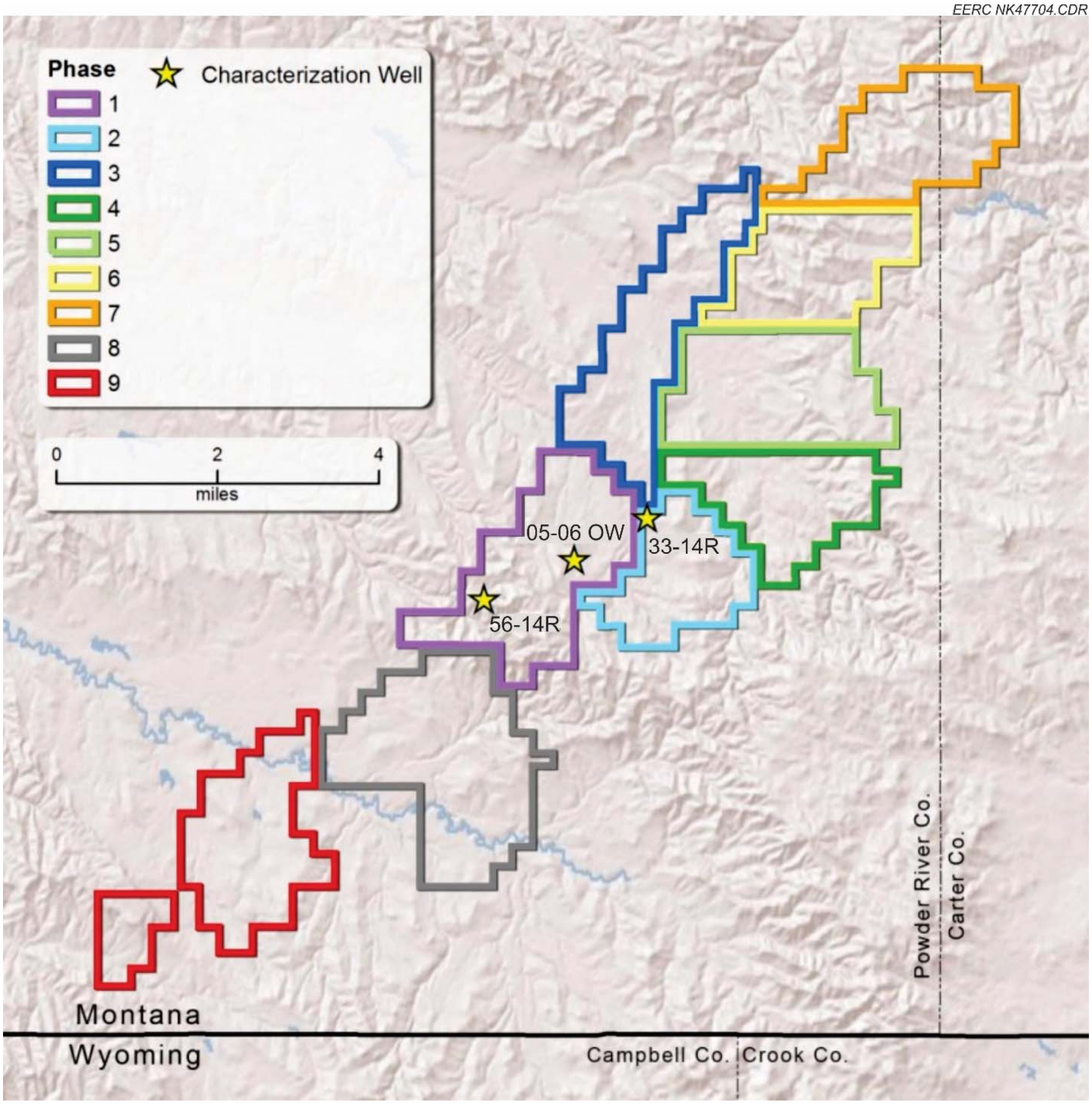

Figure 8. Site characterization wells utilized for core collection and analysis.

ADDITIONAL CHARACTERIZATION ACTIVITIES

Additional ongoing characterization dataset acquisition activities being deployed throughout the Bell Creek oil field that also contribute to the Bell Creek study project goals include the following:

- A 75-square-mile lidar survey was conducted to provide elevation data at a spatial resolution of 3 feet. Additionally, aerial imagery was collected simultaneously at a spatial resolution of 1 foot. The high-resolution data allow for a detailed evaluation of the landscape (Figure 9), including the identification of well pads and accurate ground elevation for wells. By being able to identify well pads, wellbore locations were accurately identified, and accurate ground elevations were determined for each well.

The lidar survey also helped with quality assurance and quality control (QA/QC) of actual well locations and associated ground elevations during modeling and simulation activities as well as correction of depths of existing core and well log data.

- Casing-conveyed permanent downhole monitoring (PDM) consisting of three downhole pressure gauges and a distributed fiber optic temperature system were installed during completion of well 05-06 OW. PDM yields critical real-time temperature and pressure from the reservoir during baseline and operational conditions and serves to provide value in evaluating the integrity of the Muddy Formation seal.

- PNLs were collected in 35 wells within and along the boundaries of the Phase 1 development area. A Sigma log was collected spanning from total well depth to within 200 ft of surface to provide porosity, gamma ray, lithology, and fluid/gas saturation data. A carbon/oxygen inelastic scattering log was collected over the reservoir interval to provide high-resolution water/oil/gas saturation data to better distinguish oil vs. water saturation in-reservoir due to the low water salinity.

- One hundred fifty-six periodic BHP surveys were collected fieldwide from 14 data acquisition events (April 2010 – January 2013) as part of the commercial EOR project to provide a means to monitor reservoir pressure (Kalenze and others, 2013). BHP data are utilized to assess reservoir performance during pressure maintenance and potential fluid flow barriers and compartmentalization of the reservoir.

- To enhance the geocellular modeling and simulation workflow activities, QA/QC was performed on 748 wells with geophysical logs fieldwide. Modern high-resolution well log datasets were acquired from four wells: 05-06 OW, 04-03 OW, 33-14R, and 56-14R. These well logs will improve model accuracy and help correlate existing logs.

- Assessment of the near-surface environment was conducted through soil gas and groundwater sampling activities. Samples were collected and analyzed on a quarterly basis beginning November 2011 – April 2013 to provide a baseline data set of chemistries in the vicinity of wellbores within and around the injection area. These data sets provide a valuable correlation to the wellbore integrity and risk assessment analysis components to the Bell Creek study. Further detailed methodologies and measured analyses of conducted soil gas and water monitoring activities are outlined in Kalenze and others (2013).

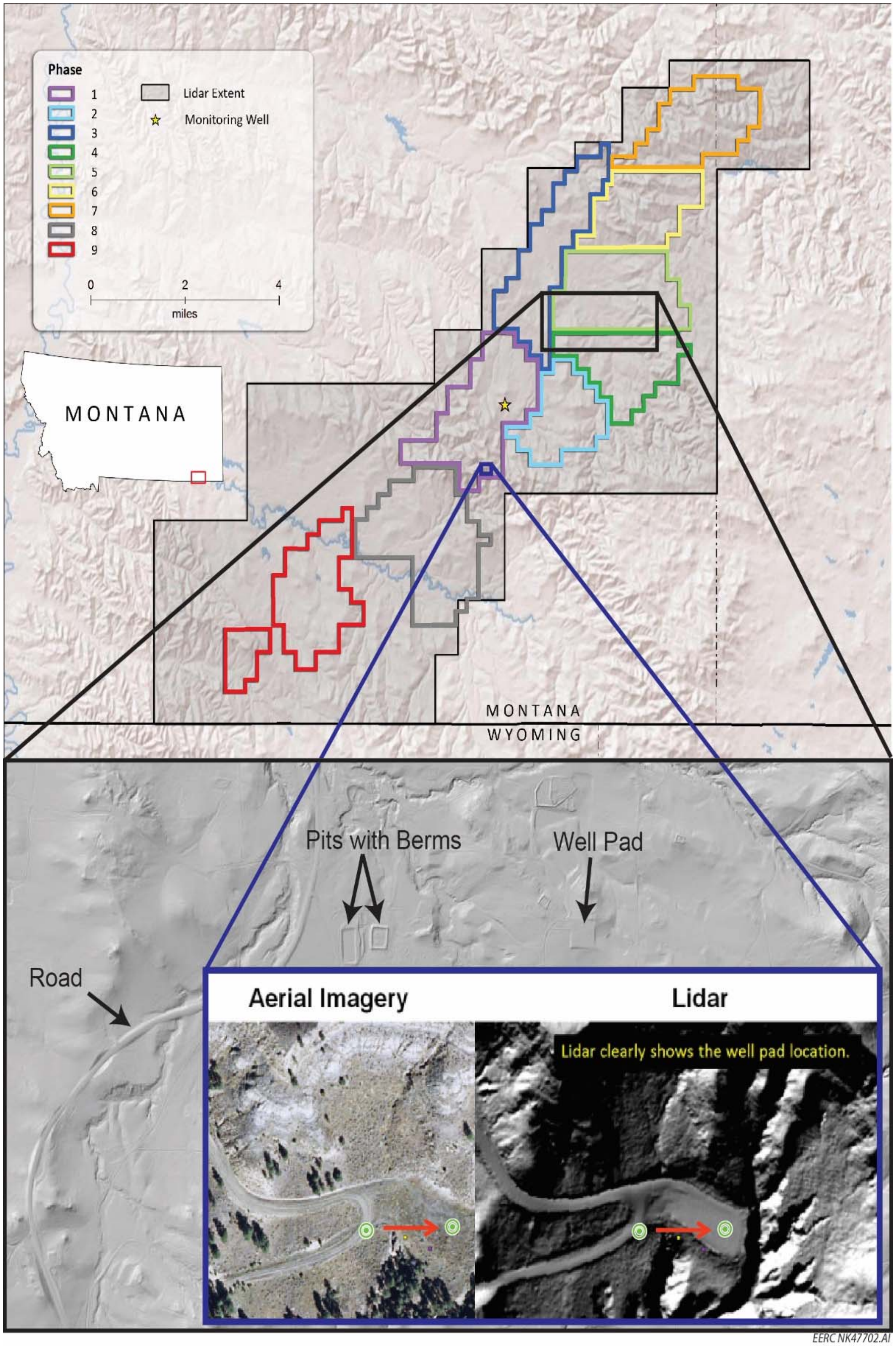

Figure 9. Lidar imagery used to identify and correct surface features within the geospatial database.

MODELING AND SIMULATION

Modeling and numerical simulation are being utilized with the goal of providing a comprehensive assessment of CO_2 storage behavior based on specific knowledge gained from the following Bell Creek site characterization activities (Figure 10): literature review of geologic reports; special core and fluid analysis; pressure, volume, and temperature studies; and well logs. These data enabled the development of a detailed static geologic and dynamic flow model for the field and its surrounding area to assess the impact of various operating conditions on miscibility, flow dynamics, and other reservoir properties (Saini and others, 2012).

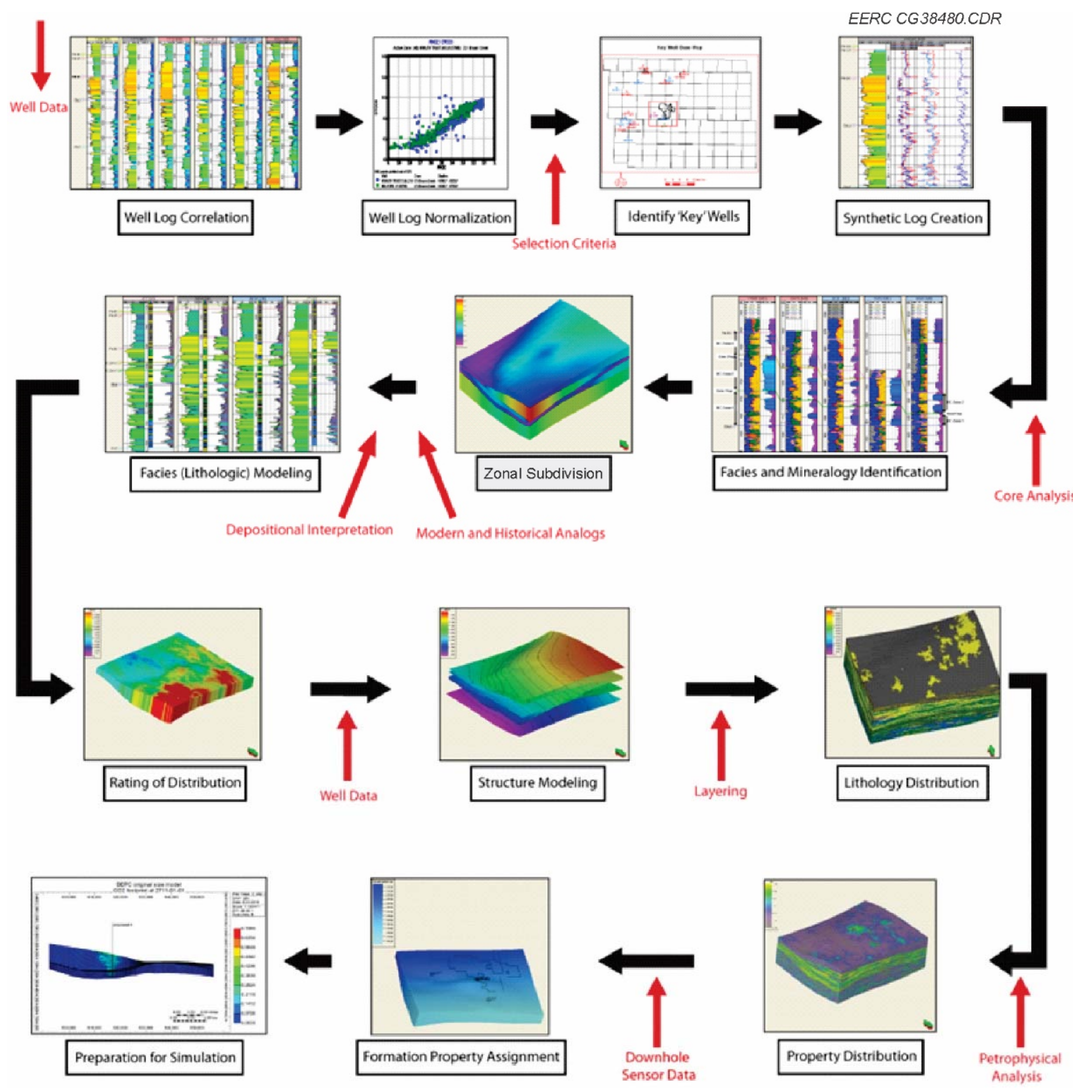

Figure 10. Geocellular modeling workflow constructed for Bell Creek project.

3-D Geologic Model

A detailed 3-D static geologic model (Version 2) of the Bell Creek oil field was constructed based on the data acquired from the site characterization activities performed as well as insights gained from the first static geologic model of the Phase 1 area (Version 1 model). The Version 2 model covered a 190-square-mile area (Figure 11) encompassing the entire field and was constructed to incorporate a distribution of geological and geophysical properties, commonly referred to as petrophysical properties. These properties were geostatistically assigned throughout the model and included the following (Saini and others, 2012): 1) total porosity, 2) shale volume, 3) effective porosity, 4) net-to-gross ratio, 5) absolute permeability, 6) water saturation, 7) formation pressure, and 8) formation temperature. As mentioned previously, an abundance of vintage geologic data exists in the form of geophysical well logs, lithology descriptions from well files, geologic maps, core data analysis, and cross sections. These data aided the selection of stratigraphic tops across the study area. Newly acquired characterization data were incorporated into the Version 2 model as well, including:

- Lidar survey data.
- A QA/QC analysis performed on 748 wells with geophysical logs.
- Analysis of 25 wells with preserved 2.5- to 4-inch cores.
- Supplemental geological, geomechanical, and reservoir properties acquired from the 05-06 OW monitoring well.

The geologic framework and assigned properties contained within the Version 2 model are necessary components for performing dynamic flow simulations that aid in 1) estimating CO_2 storage and EOR efficiencies, 2) estimating CO_2 breakthrough time at various production wells, 3) studying the long-term CO_2 plume and pressure behaviors and the ultimate fate of injected CO_2, and 4) estimating OOIP and incremental oil recoveries. Various predictive simulation scenarios also provide necessary inputs for preparing and enhancing a monitoring program to track CO_2 movement in the reservoir through targeted monitoring equipment deployments.

Another 3-D geological model is currently under construction as of this writing. The Version 3 model will be complete once all core data analysis (facies model derived from detailed core petrographic analysis of 21 USGS wells and characterization from observation and redrill wells) and seismic data (3-D surface seismic survey, 3-D VSPs, and PNLs) have been acquired and interpreted. This model will follow similar but more robust workflows including advanced interpretations as knowledge of this unique reservoir continues to grow (Saini and others, 2012).

Geomechanical Model

A 3-D mechanical earth model (MEM) is being constructed to assess the state of stress and rock properties with available log data and core data from the field. This model extent will cover the entire Bell Creek oil field and outside the field to the northwest and southeast. The construction process for the 3-D MEM included data collection and auditing, description of the

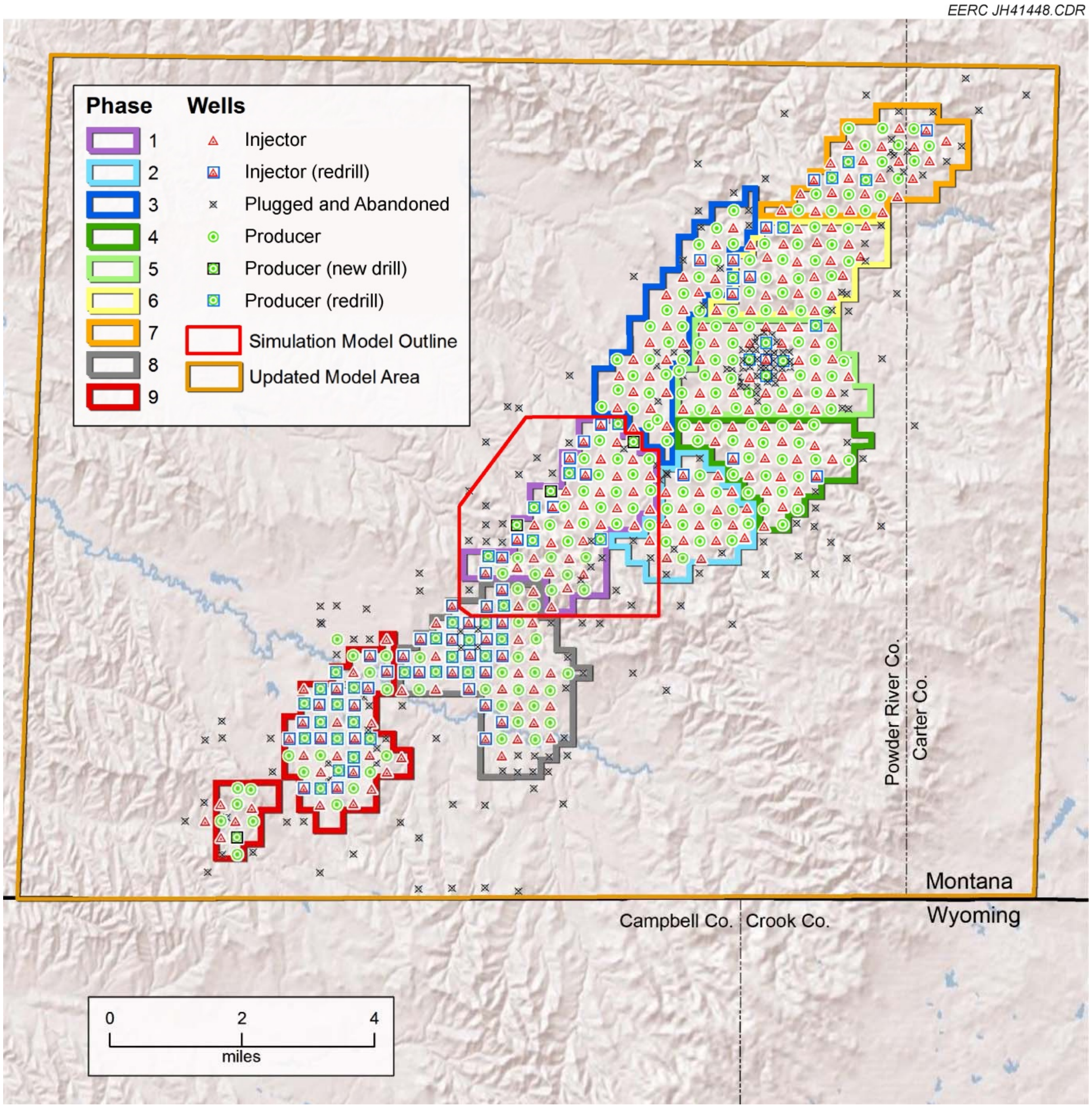

Figure 11. Bell Creek study area boundary for the Version 2 model area (gold) as well as the Version 2 dynamic simulation model boundary (red).

stratigraphic facies, integration of the bulk density to derive the overburden stress, prediction of pore pressure and horizontal stresses, and estimation of the rock mechanical properties such as Young's modulus and Poisson's ratio. The 3-D MEM will include all formations from the reservoir up to the surface and to the bottom of the cap rock below the reservoir. The model will be used for the predictive geomechanical simulation during and after the injection process. The 3-D MEM is constructed with Schlumberger's Techlog and Petrel and will be incorporated into the structural model for the Bell Creek Field.

Following the completion of the 3-D MEM, a comprehensive geomechanical analysis will be performed to match, monitor, and predict the geomechanical response from the reservoir, overlying formations, and surface. Additionally, predictive geomechanical simulations will be designed and performed to help guide and update the MVA plan, evaluate potential risk scenarios, and ensure injected CO_2 remains stored within the reservoir (Ge and others, 2013).

CONCLUSIONS

The PCOR Partnership's philosophy for conducting site characterization activities is to gain as much understanding of the subsurface and near-surface environment as possible from the available datasets and to maximize the utility of any new data sets generated. Baseline site characterization activities serve as direct inputs into the various modeling and simulation activities to better predict CO_2 migration pathways, assess technical subsurface risks, and aid in the monitoring of CO_2 migration in the subsurface. These elements of the project help evaluate various factors of the site's expected and actual performance during commercial-scale CO_2 injection, storage, and EOR.

As part of the Bell Creek study, an EERC technical team conducted a robust characterization of the reservoir and surrounding subsurface strata of the Bell Creek oil field from 2010 to 2013. These site characterization activities were conducted to establish baseline characteristics of the reservoir, assess the viability of the reservoir in the context of CO_2 storage, evaluate and predict reservoir and seal performance and behavior during both the injection and postinjection phases of the project, and guide monitoring efforts to track and account for CO_2 in the subsurface.

The majority of characterization data is derived from historic well data and targeted characterization activities designed to produce data pertinent to key aspects of the field's geology. Characterization data can also be derived from the CO_2-monitoring activities deployed in the field (a value-added proposition for certain monitoring activities, such as wellhead pressure monitoring). These data not only stand on their own in the form of geological field assessments or CO_2-monitoring reports but are also fed directly into a variety of geocellular modeling activities. The production of geologic models and subsequent dynamic simulations provide a primary means of data integration and interpretation. Modeling and simulation activities provide an opportunity to evaluate characterization data in a holistic sense and appraise the interrelatedness of various data sources and identify key variables. In addition, inefficiencies or inaccuracies uncovered in the modeling and simulation process can identify, and have identified, knowledge gaps that, in turn, guide additional or modified characterization activities.

Characterization data acquired as part of an ongoing iterative approach to site evaluation and monitoring are integrated into all facets of the project to develop a better understanding of CO_2 storage efficiency and CO_2 storage in conjunction with commercial EOR. The results and experience gained at the Bell Creek oil field help put the PCOR Partnership in the best technical position to directly and readily apply similar characterization activities to similar projects within the PCOR Partnership region and throughout the world.

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