PCO$_2$R Partnership
Plains CO$_2$ Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

BEST PRACTICES MANUAL (BPM) FOR SITE CHARACTERIZATION

Plains CO$_2$ Reduction (PCOR) Partnership Phase III
Task 4 – Deliverable D35

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EXECUTIVE SUMMARY

The purpose of this best practices manual (BPM) is to describe lessons learned and best practices for site characterization of carbon dioxide (CO_2) geologic storage (herein “storage”) projects. Information presented is derived from field and laboratory storage project activities conducted by the Plains CO_2 Reduction (PCOR) Partnership. Site characterization is one of four technical elements of the adaptive management approach (AMA) formalized by the PCOR Partnership for storage project development. The other technical elements are modeling and simulation; risk assessment; and monitoring, verification, and accounting (MVA) of injected CO_2.

Site characterization is defined here as the acquisition and analysis of data to develop an understanding of critical properties and characteristics of storage project-relevant surface and subsurface environments. Lessons learned and recommended best practices are applicable to both dedicated storage (typically in deep saline formations [DSFs]) and associated storage (most commonly resulting from CO_2 enhanced oil recovery [EOR]) projects. This document is intended to 1) provide guidance to non-technical specialists including project developers, regulators, and others interested in evaluating and developing CO_2 storage opportunities and 2) serve as a reference for CO_2 storage technical specialists.

During screening of candidate storage sites, interrogation of existing information and data such as geologic maps and reports, well records, and seismic surveys is typically the main site characterization activity. Data acquired that describe potential storage formations and project sites are compared to generic or project-specific criteria to identify, screen, and rank sites with the potential capacity, injectivity, and containment to meet project requirements. Recommended best practices for screening-phase site characterization include:

- Early establishment of a rigorous data management system capable of handling data from all life cycle phases of a project.
- Understanding the project area regulatory environment, since regulations may affect the selection of storage targets.
- Working with regional geologic knowledge centers and/or government–industry storage characterization programs to access data and information. Available geologic data (and often information regarding regional sociopolitical issues and attitudes) can be of sufficient relevance and quality to use as a basis for early project investment decisions.

As a project moves from site screening to feasibility assessment of one or more selected candidate sites, increasing requirements for data to support progressive iterations of modeling/

simulation and risk assessment may require new data acquisition via exploration wells, seismic surveys, and other fieldwork. As a project advances to the design phase, site characterization data will be used to develop detailed plans for CO_2 injection, infrastructure installation, and MVA to support permit applications and final investment decisions. Modeling and simulation will be used to determine an optimum injection plan, with predictions of CO_2 migration and pressure effects used to inform definition of the storage complex and area of review (AOR). Risk assessments will be refined to demonstrate that the project will have an acceptable risk profile and to provide context for the MVA plan. Key feasibility assessment- and design-phase recommended best practices derived from PCOR Partnership experience include the following:

- The cost-effectiveness and risk of any new data acquisition efforts should be carefully evaluated and methods for their execution strategically planned. With good planning, new site characterization data can be incorporated into an MVA program, and low-cost data acquisitions can often be used to derisk or optimize subsequent higher-cost data acquisitions.

- Because operations associated with injecting and monitoring CO_2 are closely analogous to and/or derived from oil and gas operations, site characterization exercises should—to the extent possible—follow oil and gas industry standard protocols. In addition to offering significant economic and reliability benefits, oil/gas industry methods are generally well understood and accepted by regulatory communities.

- A screening-level assessment of all wellbores within a project AOR is a key feasibility assessment component. In addition to identifying potential leakage pathways and associated risks, the assessment will serve as the basis for estimating level of effort and cost associated with further evaluation and/or mitigation/remediation plans.

- Seismic survey data are often critically important to accurately assessing the viability of a candidate storage complex, but seismic data acquisition is a major undertaking in terms of logistics, cost, and time. If affordable, hiring a qualified expert to act as a general contractor to assemble the required participants and coordinate the overall work effort is the most convenient, efficient, and effective way to execute a seismic survey.

- Because of high budget and schedule impacts, well-drilling decisions have the potential to be disruptive to feasibility- or design-phase activities. If site screening has indicated that a candidate project site will likely need one or more wells drilled, the project team should develop a set of criteria and guidelines for 1) assessing the need for each new well, 2) establishing the type of well needed (exploration or infrastructure), and 3) siting each new well.

The scope and intensity of site characterization activities will tend to progressively diminish during the construction/operation and closure/postclosure phases of a project as routine MVA, history-matching of predictive models, and updating of risk assessments become the main technical elements. However, installation of wells during construction activities is likely to yield considerable characterization data that should be used as appropriate to inform the other technical elements. Similarly, any unexpected behavior of injected CO_2 or other operational anomalies detected by the MVA program may require additional site characterization to support development of mitigation strategies.

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BEST PRACTICES MANUAL (BPM) FOR SITE CHARACTERIZATION

1.0 INTRODUCTION

In 2003, the U.S. Department of Energy (DOE) established the Regional Carbon Sequestration Partnerships (RCSP) Initiative to help develop technology, infrastructure, and regulations needed to facilitate large-scale carbon dioxide (CO_2) geologic storage (herein “storage”) and support deployment of commercial carbon capture and storage (CCS) projects. The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is one of seven partnerships created by this program. The PCOR Partnership includes over 120 public and private sector stakeholders and covers an area of over 1.4 million square miles (3.6 million square kilometers) in the central interior of North America, including portions of Canada and the United States (Figure 1).

Figure 1. The PCOR Partnership region (Ayash and others, 2016).

A series of best practices manuals (BPMs) is being published for each of the four PCOR Partnership-defined primary technical elements of a storage project:

- Site characterization
- Modeling and simulation
- Risk assessment
- Monitoring, verification, and accounting (MVA)

These BPMs are derived from extensive PCOR Partnership regional characterization and field demonstration experience acquired via activities conducted throughout the PCOR Partnership region. An additional BPM is also being developed that encompasses best practices for integrating these technical elements into an iterative, fit-for-purpose adaptive management approach (AMA) for commercial storage project deployment. This document is intended to provide guidance to project developers, regulators, and others interested in evaluating and developing CO_2 storage opportunities and serve as a useful reference for CO_2 storage technical specialists.

This BPM describes site characterization activities and their application throughout the five PCOR Partnership AMA-defined life cycle phases of a storage project:

- Site screening
- Feasibility assessment
- Design
- Construction/operation
- Closure/postclosure

For the purpose of this BPM, site characterization is defined as the acquisition and analysis of data to develop an understanding of critical properties and characteristics of storage project-relevant surface and subsurface environments. The technical terms used in this document are in general agreement with the definitions of Canadian Standards Association (2012) CSA Group Standard Z741-12, a joint Canada–U.S. initiative, with the exception of "site characterization" (see Section 4.0).

2.0 GEOLOGIC STORAGE

Storage projects can be broadly divided into two types. ***Dedicated storage*** involves the underground injection of anthropogenic CO_2 solely for the purpose of greenhouse gas (GHG) mitigation. The Sleipner project in the Norwegian North Sea has been injecting approximately 1 million tonnes of CO_2 per year since 1995 into a deep saline formation (DSF), and several other dedicated storage projects are now operating at a similar large scale around the world (Global CCS Institute, 2017). ***Associated storage*** occurs as a result of CO_2 injection for other purposes, most commonly CO_2 enhanced oil recovery (EOR). CO_2 EOR was first undertaken in Texas in the 1970s, and over 100 CO_2 EOR sites are now operational in the United States (Oil & Gas Journal, 2014). The technology is also being deployed in other countries, including Canada, Brazil, Mexico, and Saudi Arabia (Global CCS Institute, 2017).

Although predominantly linked to CO_2 EOR, associated storage could also result from enhanced coalbed methane (ECBM) or enhanced gas recovery (EGR) operations; however, these scenarios remain unproven at industrial scale. Despite associated storage being a direct result of CO_2 EOR, in many cases, operators of such sites might not seek recognition of GHG mitigation benefits because of various economic, regulatory, or legal factors. CO_2 EOR projects are driven by the economic benefit of producing oil that may otherwise not be recoverable by primary or secondary production methods. Storage of CO_2 is a consequence of the EOR process, rather than the process goal. During EOR operations, a significant portion of injected CO_2 is produced along with oil, separated and purified as needed, and reinjected for additional oil recovery. As a result of the separation and recycle operations applied at EOR sites, CO_2 storage accounting may be more complex than in dedicated storage scenarios.

The PCOR Partnership region encompasses significant storage resources, with large-scale operational CCS projects including both dedicated and associated storage (Peck and others, 2016). Extensive regional and site characterization activities for both storage scenarios have been undertaken by the PCOR Partnership, and this experience has informed the writing of this BPM. While the best practices described herein have been drawn from lessons learned in the PCOR Partnership region, many of the recommendations are applicable to other storage environments and scenarios, including offshore projects.

3.0 PCOR PARTNERSHIP AMA

The PCOR Partnership has formalized and implemented an AMA for assessment, development, and deployment of commercial storage projects (Ayash and others, 2016). The AMA represents a fit-for-purpose approach that can be tailored to the needs of each project, ensuring that the necessary technical elements are appropriately and cost-effectively applied to generate the knowledge needed to enable project implementation. The AMA architecture is shown in Figure 2. The core of the AMA consists of four key technical elements (Table 1), conducted with varying scopes and levels of intensity as a project moves through each of the five life cycle phases of commercial development (Table 2).

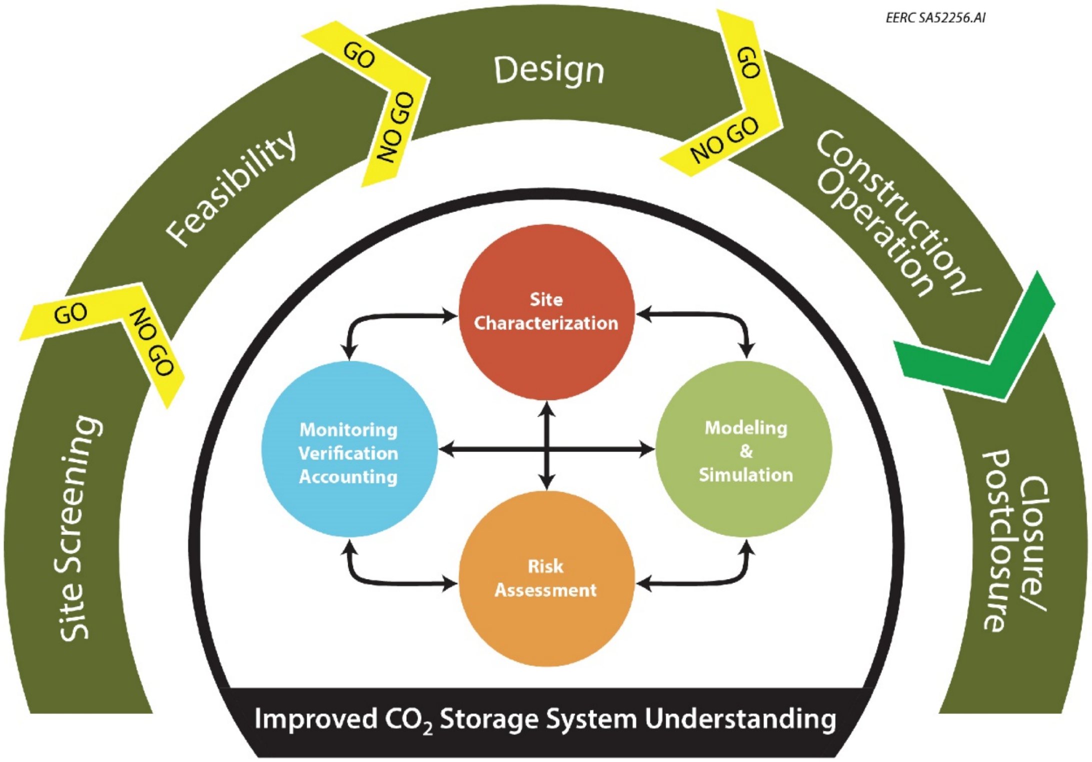


Figure 2. PCOR Partnership AMA for CO_2 storage project development (Ayash and others, 2016).

Table 1. AMA Technical Element Summary

Technical Element	Goal/Purpose	Example Methods
Site Characterization	Develop an understanding of surface and subsurface environment properties and characteristics relevant for storage project.	Collect, analyze, and interpret existing data, and acquire field data (e.g., logs) and/or samples (e.g., cores, fluids) for analysis or experimentation.
Modeling and Simulation	Model key subsurface features, and predict movement and behavior of injected CO_2.	3-D geologic base models can be developed to support numerical flow models for various injection scenarios.
Risk Assessment	Identify, monitor, and manage project risks.	Risks can be assessed and prioritized using qualitative or semiquantitative frameworks based on expert panel judgment.
MVA	Track behavior of injected CO_2, and monitor for potential changes in surface and subsurface environments.	Seismic surveys, pulsed-neutron logs, production data, pressure monitoring, and groundwater sampling.

Table 2. AMA Project Phase Summary

Project Phase	Goal/Purpose	Typical Technical Activities
Site Screening	Identify one or more candidate storage project sites.	Primarily site characterization, informed and supported by modeling/simulation and risk assessment as appropriate.
Feasibility	Assess technical/economic viability of candidate storage sites; identify viable site(s) for advancement to design.	Site characterization, modeling/simulation, and risk assessment.
Design	Complete detailed design to derive definitive project cost and time line estimates, secure required permits, and make go/no-go decision on construction.	Detailed modeling/simulation, risk assessment, and MVA design to support regulatory permit applications and investment decisions.
Construction/ Operation	Build and operate facilities to achieve project CO_2 injection and storage objectives.	MVA plan implementation including baseline data collection prior to injection, routine history-matching of MVA data with simulation results, and regular review of risk assessment.
Closure/ Postclosure	Cease CO_2 injection, and demonstrate CO_2 containment in the storage complex.	MVA program continuance (in line with simulation and risk models) to demonstrate compliance with regulatory requirements prior to permit surrender.

As shown in Figure 2, multiple go/no-go decision points along the development pathway illustrate where the developer may review project status and confirm that progress is adequate to advance to the next phase. The goal of the AMA is to efficiently deploy and integrate the four technical elements as needed throughout a storage project to cost-effectively meet the technical, economic, and regulatory objectives and requirements of each phase, thereby maximizing potential for successful project implementation. Summary descriptions of the five project phases are presented in Table 2, and additional information can be found in Ayash and others (2016).

4.0 SITE CHARACTERIZATION OVERVIEW

As one of the four AMA core technical elements, site characterization comprises collection, analysis, interpretation, and application of data and information for the purpose of understanding storage potential and assessment of factors that could impact project performance. Data collection methods can range from accessing records, reports, and other documents available from public and private sources to utilizing a wide array of field technologies for determining or measuring various geologic/physical/chemical properties of subsurface and surface environments. Data collected are used to build a conceptual model of a candidate storage complex (i.e., the target storage reservoir[s] and surrounding seal formation[s]) for use in assessing storage potential.

As an AMA component, site characterization objectives and associated activities are largely driven by project- and site-specific risk and uncertainty and the need to inform site design and operation. This fit-for-purpose approach allows for tailoring site characterization activities to address the needs of each unique storage project. For example, a dedicated storage project targeting a DSF may have few (if any) wells penetrating the storage formation, so an exploration well may be required to acquire essential information. Conversely, an oil field being considered for a CO_2 EOR associated storage project will likely have numerous well penetrations and extensive production experience, reducing the need for acquisition of new reservoir data but possibly requiring significant wellbore integrity assessment.

5.0 PROJECT DEFINITION

Prior to initiating any site evaluation or development work for an envisioned or proposed storage project, the project should be adequately defined. The following are examples of key project elements to define:

- Overall goal
  - What is the desired project outcome?
- Scope
  - What are the key project objectives and steps/procedures to be utilized in achieving the objectives?
- CO_2 source
  - How much CO_2 is being produced and captured?
  - What is the CO_2 stream composition?

  - Will the CO_2 amount and composition be relatively consistent throughout the anticipated project duration or subject to significant fluctuation?

- Storage target
  - What storage capacity is required?
  - Is the project team interested in dedicated or associated storage or is a combination a viable option?
  - If associated storage (i.e., CO_2 EOR) is a viable option, can the project handle fluctuating demand from the partner oil company?

- Finances
  - What level of financial commitment is available?
  - Is the project trying to get credit for stored CO_2?
  - Who are the partners contributing financially to the project?
  - Are the sources of income stable in the short and long term?

- Time line
  - Are there key regulatory requirement deadlines that need to be met?
  - If targeting associated storage, when is the partner company expecting CO_2 to be available for delivery?

6.0 SITE CHARACTERIZATION PROGRAM DEVELOPMENT AND PHASE-BASED APPLICATION

This section provides guidance on how to develop and deploy a strategy for addressing the AMA site characterization technical element throughout the five phases of a generic storage project. Although primary emphasis is on DSF-based dedicated storage projects, many of the lessons learned and recommended best practices cited are also relevant to associated storage projects.

6.1 Site-Screening Phase

6.1.1 Goal

The goal of site screening is to identify—primarily on the basis of existing accessible data and information—one or more suitably located candidate storage sites that may offer sufficient storage capacity and the geologic structure necessary for safe, long-term containment of injected CO_2. Site characterization activities during the site-screening phase represent a first pass at collection, analysis, and interpretation of existing data sets that lay the foundation for additional investigation during subsequent project phases. Questions to be addressed during the site-screening phase include the following:

- What quantity and quality of relevant data are available, and what level of effort is required (based on a cost/benefit analysis) to support site screening?

- What are the storage targets with adequate potential capacity, injectivity, depth, and containment?
- What is the distance between the CO_2 source and the potential storage targets?
- Are sealing formations present?
- Are there culturally or environmentally sensitive features that may impact a potential project?

Recommended Best Practice – Data Management System

Collection and review of existing data are the primary site characterization activities of the site-screening phase. Because storage projects are likely to continue for decades and personnel may change, development of a rigorous data management system is critical to ensuring long-term accessibility to all data collected over the life of the project.

6.1.2 Site-Screening Approach

Site-screening characterization activities will comprise accessing and reviewing publicly (and possibly non-publicly) available data needed to assess, qualify, and rank candidate storage sites based on screening criteria (see Section 6.1.3). Sources of data will vary by location; however, since site screening focuses on initial assessment of the geology of an area, the initial search for data will often lead to geological surveys/organizations. Examples of these data sources in the United States are shown in Table 3. State regulatory entities, universities, geology graduate degree theses, and public consortia can also yield relevant data.

Table 3. Examples of Site-Screening Data Sources in the United States

Source	Web Site	Content
U.S. Geological Survey (USGS) or State Geological Surveys	www.usgs.gov	Various reports or data sets detail the information that has been collected on geologic formations.
USGS Groundwater Atlas	https://pubs.usgs.gov/ha/ha730/	Series of print publications describing the location, extent, and geologic and hydrologic characteristics of the important aquifers of the nation.
DOE NETL NATCARB[1] Database	http://natcarb.netl.doe.gov/	A national view of carbon storage potential, with data from the RCSPs and other sources.
DOE NETL Carbon Storage Atlas	https://www.netl.doe.gov research/coal/carbon-storage/ natcarb-atlas/data-download	A coordinated update of carbon capture and storage potential across the United States and other portions of North America.

[1] National Energy Technology Laboratory National Carbon Sequestration Database and Geographic Information System.

Recommended Best Practice – Regional Geologic Data Centers

Working with regional geologic knowledge centers and/or government–industry storage characterization programs is often a time/cost-effective way to access existing geologic and other project-relevant data and information. Available geologic data (and in some cases, information regarding regional sociopolitical issues and attitudes) can be of sufficient relevance and quality to use as a basis for prefeasibility assessment project investment decisions.

6.1.3 Site-Screening Criteria

Basic evaluation criteria should be established to enable ranking candidate storage sites. Criteria unique to each potential storage project can be generated, or criteria can be selected from existing publications that describe generic screening criteria (Det Norske Veritas, 2013; International Energy Agency Greenhouse Gas R&D Programme, 2009). Depending on project goals, objectives, and assets, acceptable storage targets may vary significantly between projects in the same area. For example, project financial considerations could limit the potential length of a CO_2 pipeline or a utility may be interested in project opportunities for associated storage, resulting in very different project dynamics. For these reasons, a thorough project definition and establishment of site-screening evaluation criteria are imperative to ensuring a quality site-screening process and dictating the site characterization data that need to be gathered. Typical criteria that may be established include the following:

- Target storage formations must offer the necessary storage capacity and injectivity to store the projected quantity of CO_2 at the required rate. More specifically, the storage formation must have:
  - Sufficient depth to achieve CO_2 dense-phase conditions, typically 800 m or greater.
  - Sufficient thickness, porosity, and permeability as defined by project-specific criteria. It should be noted that significant reservoir heterogeneity can affect project risk through greater uncertainty regarding injectivity and capacity.

- Target storage sites must show prospective geologic features for containment, including:
  - Presence of sealing layers above the target storage formation(s).
  - Absence of major faults, fractures, or other features that could compromise containment.
  - A relatively low number and/or reliable records indicating high quality of legacy wells intersecting the target storage formation(s).

- Low or acceptable risks—in accordance with project criteria and goals—to sensitive environmental receptors, including groundwater resources and ecosystems.

- Low or acceptable risks to other subsurface resources, including oil and gas reserves.

- No significant impediments to storage or transport such as natural or anthropogenic features (population centers, national parks, sensitive areas).

- Target storage formation is within an acceptable distance from the CO_2 source.

6.1.4 Selection of Storage Target Candidates

Based on the project definition and upon establishing a list of storage target criteria, site characterization activities can start to answer questions that will guide the project forward. During the site-screening phase, characterization activities focus on collection, analysis, and interpretation of existing geologic data sets. Key site-screening activities for a dedicated storage project are summarized below:

- Establish potential geographic extent for potential projects – This activity may be based on various factors, including suitable geology, political or other geographical boundaries, and economics (e.g., pipeline distances).

- Understand applicable rules and regulations – Different jurisdictions may have separate and differing guidelines for underground injection. For example, in the United States, aquifers with total dissolved solids (TDS) levels of less than 10,000 mg/L are typically not considered viable storage targets.

- Collect geologic data sets for identification of potential storage targets – Gather geologic information needed to assess which geologic formations may offer the necessary properties (i.e., porosity, permeability, thickness, seals) to store the projected quantity of CO_2. Geologic databases and published reports (i.e., USGS Groundwater Atlas, NATCARB) are often consulted as a first step in assessing formation suitability. If possible, these data sets should be used to construct a geologic model to help in storage target evaluation.

Recommended Best Practice – Data Confidence
Establish confidence levels in available site-screening data, and assess the impact of any knowledge gaps on screening process outcomes.

- Identify potential project barriers – The goal is to evaluate any remaining factors that could affect the selection of a storage target, including surface features such as national/state parks, rivers, lakes, population centers, wildlife management areas, or any other environmentally or culturally sensitive features. Nearby oil and gas production or other subsurface resource recovery operations could also represent barriers because of risks associated with:

  - Storage operations interfering with hydrocarbon production or sterilization of reserves.

  - DSF overpressurization as a result of brine disposal.

  - High numbers of wellbore penetrations with significant potential for compromising storage security.

  - Interference or trespass with regard to resource recovery.

Recommended Best Practice – Preliminary Understanding

Develop sufficient understanding of pertinent geologic resources, subsurface and surface access rights, and the sociopolitical environment to gauge whether at least one suitable candidate project site and storage complex can be identified.

Recommended Best Practice – Regulatory Environment

Understand the regulatory environment of the project area. Regulations may affect the selection of storage targets.

Recommended Best Practice – Preliminary Leakage Potential

Based on available data, assess potential leakage pathways, and estimate reasonable likelihood of CO_2 migration beyond the storage complex and—assuming pathway transmissivity—extent and impact of migration.

6.1.5 Transition Between Site-Screening and Feasibility Phases

Site screening-phase site characterization activities typically comprise gathering existing data for a potential storage project area and evaluating relevant geologic and surface environments, as described in Case Study 1. The site-screening phase aims to reduce the potential storage targets to a subset of possibilities, which can then be evaluated in greater detail in the feasibility phase. The transition between these two project phases will vary by project, as each project will have unique circumstances and goals. Most often, however, the transition from site screening to feasibility assessment is defined based on financial investment.

As a project team and financial sponsors narrow the search and one or more sites are selected for further evaluation, field activities may be required to gather site-specific data. This may entail more detailed data reconnaissance, model generation, or data acquisition via drilling, sampling, and testing new wells; collecting and/or analyzing core and fluid samples from existing wells; or conducting 3-D seismic surveys. These types of activities are generally associated with feasibility-phase site characterization and are addressed in the following section of this document.

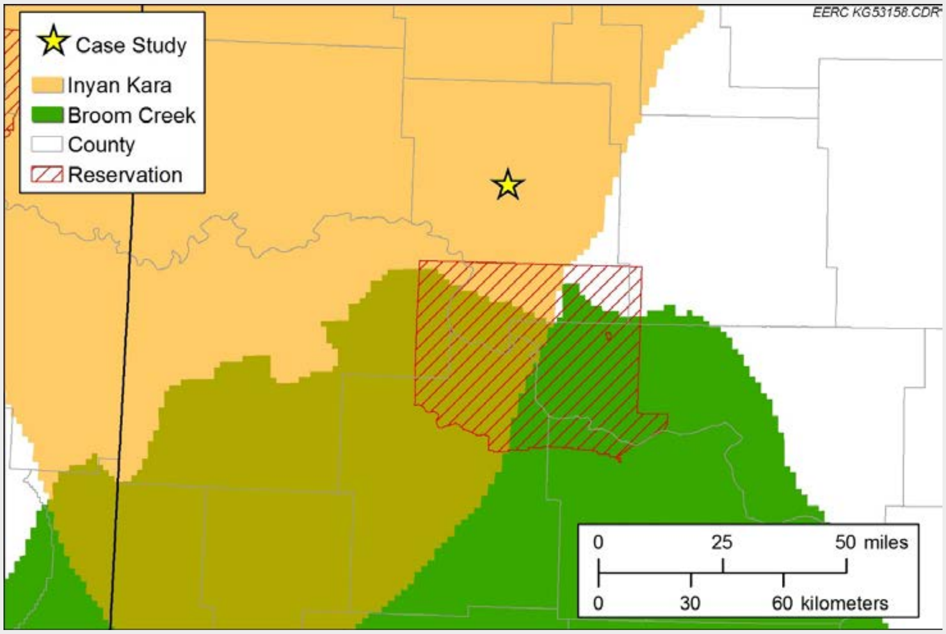
Case Study 1 – Site Screening

This case study is presented as an example of a site-screening characterization effort for a new project. The operator of an industrial facility in western North Dakota was looking to capture and store at least 1 million tonnes of CO_2 a year. The company was interested in both associated and dedicated storage options and established a feasible transport distance of up to 100 kilometers for dedicated storage. Upon establishing a set of evaluation criteria, potential dedicated storage sites were screened using the following approach:

- Available data sources and maps were used to indicate the areal extent of DSFs in western North Dakota. Four candidate reservoir DSFs were identified, including, in order of increasing depth, the Inyan Kara, Broom Creek, Mission Canyon, and Deadwood (Basal Cambrian), as shown in the table and figures below and on page 12. The northern edge of the Broom Creek Formation is about 40 kilometers south of the CO_2 source facility.

DSF Characteristics in Order of Increasing Depth (not all formations shown in the figure below)

Formation	Thickness, m	Rock Type	Oil/Gas
Inyan Kara	50–200	Sandstone	No
Broom Creek	Up to 100	Sandstone	No
Mission Canyon	50–200	Limestone/dolomite	Yes
Deadwood	50–300	Sandstone	Yes



Map showing case study region
(colors denote areas with subsurface storage potential).

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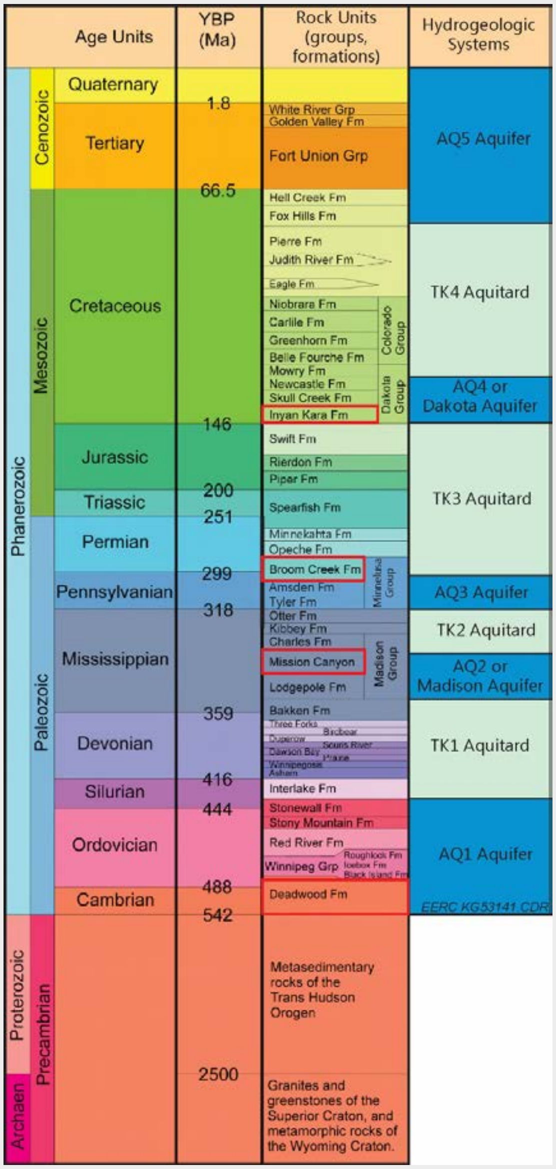
- Data obtained from USGS and the North Dakota oil and gas regulatory agency revealed that these formations all have sufficient salinity (i.e., greater than 10,000 mg/L TDS) and depth (greater than 800 meters) to be considered for DSF storage.
- This initial screening revealed that the Deadwood Formation may be the most suitable storage target, with significant storage resource potential and greater depth than the other candidate DSFs, thereby avoiding potential conflicts with other subsurface resources and enhancing containment potential.
- Further investigation into oil and gas activity revealed significant regional brine disposal in the Inyan Kara Formation.
- The nearby presence of commercial oil fields indicated potential for EOR sales and associated storage. Rights-of-way for existing pipelines could provide routes for a new CO_2 pipeline. Detailed discussions with oil and gas industry representatives were warranted to further assess associated storage options.
- Resulting from significant Bakken oil production in the area, the presence of multiple wellbore penetrations could represent potential leakage pathways for any storage in the overlying Inyan Kara and Mission Canyon Formations.
- Assessment of environmentally and/or culturally sensitive areas identified the Missouri River and Fort Berthold Indian Reservation as significant project-planning factors.



North Dakota stratigraphic column (modified from Peck and others, 2014).

Screening Outcome

This case study illustrates how gathering and assessing relevant data sources can enable rapid screening of potential storage targets. As a result of this screening, the Deadwood Formation was selected for further evaluation.

6.1.6 Site-Screening Outcomes

Although site-screening-phase site characterization activities are typically limited to accessing and interpreting existing data, some regions may present only limited or inadequate available data on the subsurface or specific formations of interest. Depending on the perceived value of assessing a particular region or formation, investment in acquisition of new data may be required to complete the screening effort. Such data acquisition methods are discussed in Section 6.2 below. In addition to assessing the viability of candidate storage sites, data/information packages generated via screening-level site characterization activities can also be used as inputs for development of preliminary models for simulating injected CO_2 behavior and/or conducting preliminary project risk assessments, both of which represent major feasibility- and design-phase work efforts.

At the conclusion of site-screening activities, one or more candidate dedicated storage sites may be ranked sufficiently high to warrant feasibility assessment. In the absence of favorably ranked sites from the screening process, project goals and objectives may be reevaluated and/or the project may be terminated.

6.2 Feasibility Assessment and Design Phases

Site characterization comprises a major portion of feasibility- and design-phase work efforts. Although these two phases have different objectives and workflows, project-specific circumstances may dictate overlap or seamless transition between them, and site characterization activities in both phases may be similar. Consequently, the following section provides an aggregated description of site characterization activities that could take place in either or both project phases.

Feasibility and design phases will also require significant efforts in the technical elements of modeling/simulation and risk assessment, and MVA requirements will need to be considered, especially in the design phase where permit applications will be prepared and submitted. The iterative nature of AMA technical elements means that simulation and risk assessment activities may result in evolving site characterization requirements as the workflow progresses.

6.2.1 Goal

The primary feasibility assessment goal is to establish the viability of any selected candidate project site(s) at a confidence level sufficient to support decisions on whether and how to proceed with the project. Assessing storage site viability in the feasibility phase is supported by acquiring the site characterization data needed to build a representative model of the site geology and surrounding environment. The geologic model is then used to conduct predictive dynamic simulations and support risk assessments that provide an optimal understanding of three critical factors:

- CO_2 storage capacity
- CO_2 injectivity
- CO_2 containment

Key questions to be addressed by feasibility- and design-phase site characterization activities—grouped into the three categories of data adequacy, design considerations, and risk considerations—are listed below:

Data Adequacy

- Are the available site characterization data relevant and of sufficient quality to address model building and other feasibility assessment and design needs, and if not, what additional data are needed and how will they be acquired?

- Is acquisition of new data (e.g., well logs, mechanical integrity tests, reservoir testing, seismic data reprocessing or acquisition, aeromagnetic surveys) needed to address uncertainty, risk, or knowledge gaps?

- Are additional or new core/rock or fluid samples needed for conducting laboratory tests of reservoir and seal properties (e.g., porosity, permeability, relative permeability, mineralogy, and mechanical properties) or rock–fluid chemical interactions?

- Should an exploratory well (or wells) be considered for additional data acquisition? Exploratory wells may be plugged and abandoned after data acquisition or, alternatively (and more expensively), completed in accordance with more rigorous standards as infrastructure wells and maintained for potential later injection or monitoring purposes.

- If new wells are needed, where should they be positioned?

Design Considerations

- Will the storage complex comprise a single reservoir–seal pair or will secondary seals and reservoirs be used in the project design?

- Will issues relating to site access and pore space ownership, or nearby subsurface resource interests such as oil and gas, affect design of the storage project?

- How big is the likely project area of review (AOR), and does it contain regions likely to require additional site characterization to reduce geologic risk or uncertainty to an acceptable level? The AOR encompasses the full 3-D extent of predicted CO_2 plume migration, and anticipated significant pressure propagation as defined by applicable regulations, thereby delineating the project boundaries that need to be considered in the MVA plan.

- Can additional data acquisition be used to estimate preliminary design considerations, project sizing, or operating conditions (e.g., maximum injection pressure, injection rates, well sizing, compression requirements)?

- Do the geologic data provide any indication of potential lateral and/or vertical CO_2 migration pathways—including pathways based on hydraulic connectivity or communication between geologic formations—within the storage site or wider AOR?

- If needed, is there a potentially viable location for injection of produced/extracted water to manage pressure or migration of a CO_2 plume?

Risk Considerations

- Based on interpretation of the acquired geologic data, what are the major risks, key risk indicators, and potential impacts of realized risks?

- What are the key environmental or other receptors that need to be considered for risk assessment purposes? How can potential impacts be assessed?

- Does the AOR contain deep wells and/or other potential leakage pathways, and if so, what is the best approach to adequately assessing leakage potential? Can appropriate well records be accessed?

- Do the geologic data provide any indication of over- or underpressurization of the storage formation or overlying geologic zones?

- Are there any known drilling issues/challenges/risks in the region, and if so, are there offset well data available for use in well design?

- Do the geologic data indicate any potential for induced seismicity as a result of CO_2 injection, and if so, how great is the risk?

6.2.2 Creation of Geologic Models

While some of the above issues and questions may have been addressed during site screening, refining and augmenting screening evaluations and estimates are often necessary to improve understanding of storage potential and project risks. Geologic models provide a means to aggregate, interpret, and evaluate multiple data sets in context with one another. Models also provide a means to evaluate the performance of physical geologic systems under various operating scenarios, yielding key design criteria. In doing so, more informed and defensible decision making will be possible regarding whether and how to advance the project. In support of this objective, a primary goal of site characterization activities is to provide essential inputs to geologic modeling and simulation activities that assess:

- Pressure distribution in the storage complex.

- Maximum allowable injection pressure.

- Storage reservoir capacity.

- Storage reservoir injectivity.

- Migration of injected CO_2 in the subsurface over various timescales.

- Storage reservoir efficiency (i.e., the percentage of available pore space that will actually be occupied by CO_2).

- Ability of the storage complex to retain injected CO_2 and reservoir fluids.

- Limits or boundaries of the AOR.

6.2.3 Support Risk Assessment and Design of MVA Plan

Other goals of site characterization activities are to provide data for use in combination with modeling activities to 1) conduct an initial project risk assessment and 2) evaluate applicability of MVA technologies to the particular injection site and injection scenario and inform development of an MVA strategy, including the type, timing, extent, and parameters of MVA data acquisition.

6.2.4 Feasibility/Design Approach

The quality of predictive model outputs depends on the accuracy of the base geologic model, which is directly related to the quality of the site characterization data used to build it. Assembling the site characterization database needed to build an accurate model requires:

- Collating all accessible existing data with potential relevance to building a static geologic (geocellular) model of the storage complex and wider (e.g., AOR) environment.

- Reviewing data for relevance and quality.

- Sound workflow processes for interpreting and/or processing data for use as inputs into model building.

- Identifying data gaps, and developing and executing a site characterization plan to fill these gaps, which may entail purchasing and processing/interpreting additional existing data and/or acquiring new data via field and laboratory activities.

In particular, sufficient information should be sought regarding:

- Stratigraphy.

- Geologic structure, including faults and other physical features that could impact CO_2 injectivity and migration.

- Porosity, permeability, and pressure of reservoir and seal formations.

- Mineralogy of reservoir and seal formations.

- Composition of reservoir fluids.

- Baseline hydrogeology and hydrological flow regime within the storage complex and AOR.

- Mechanical rock properties and stress regime of the reservoir and seal formations.

- Nature of potential geochemical interactions between storage reservoir formation fluids, injected fluids, reservoir rock, and seals.

- Nature of wellbore integrity for wells within the AOR.

Examples of existing data sources include:

- Well records, including:
  - Well logs.
  - Analyses of core, drill cuttings, and fluid samples and results of any laboratory experimental activities conducted with these samples.
  - Well completion records.

- Seismic surveys.

- Hydrocarbon production operations data, including offset well-drilling reports, production/injection records, and bottomhole pressure (BHP) readings.

- Permit applications.

Figure 3 summarizes, at a high level, a protocol for acquiring the site characterization data needed for building a representative geologic model, conducting an initial risk assessment, and establishing MVA plan elements. Acquisition of new data may be required because of:

- Inadequate depth, placement, and/or concentration of existing wells.

- Inadequate suitability and/or number of existing well logs and/or seismic surveys.

- Insufficient data contained in existing well files due to inadequate number and/or type of samples collected, inadequate sample characterization, or other shortfalls.

The following subsections describe approaches, methods, and techniques for implementing the site characterization protocol presented in Figure 3, along with case studies, lessons learned, and recommended best practices.

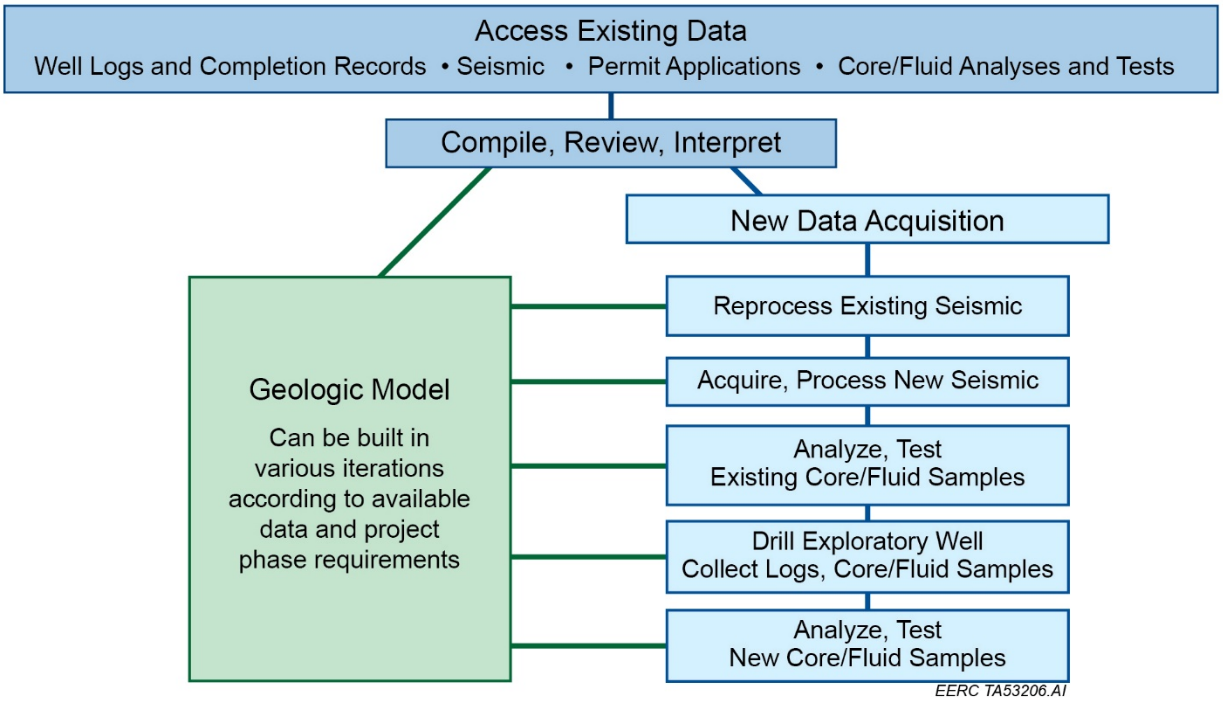


Figure 3. Generalized approach for assembling site characterization data needed to build geologic model.

Recommended Best Practice – Oil and Gas Operations

Because operations associated with injecting and monitoring CO_2 are closely analogous to and/or derived from oil and gas production (especially CO_2 EOR) operations, site characterization and modeling exercises should—to the extent possible—follow oil and gas industry standard protocols. In addition to offering significant economic and reliability benefits, oil/gas industry methods are generally well understood and accepted by regulatory communities.

Acquisition and Interpretation of Data Contained in Existing Well Records

A comprehensive set of historical data for existing wells within and near the AOR should be collected and interpreted. The focus should be on oil and gas exploration/production or brine disposal wells, particularly where potential storage formations have been penetrated. Data for groundwater wells and other shallow wells should be collected where available, as these wells may be integral to permitting and MVA efforts.

Well record data/information to be assessed for relevance and quality may include:

- Well logs of various types (see Appendix A – Well-Logging Techniques and Applications) acquired during drilling and after completion.

- Descriptions and results of any injection tests conducted during drilling (see New Wells for Site Characterization Data Acquisition, page 27).

- BHP and continuous downhole pressure/temperature data.

- Analyses of cores, drill cuttings, and/or fluids collected during and/or after drilling.

- Well drilling, completion, and stimulation/workover records, which provide information related to well depth, perforation placement and technique, and materials and method used for well completion. In addition to providing geologic information, well completion records are of critical importance in assessing wellbore leakage potential, as described in Case Study 2.

Case Study 2 – Assessment of Wellbore Leakage Potential

Using existing legacy data, the PCOR Partnership conducted a wellbore integrity evaluation to rank relative wellbore degradation potential for over 600 wells in an oil field being used for EOR and associated CO_2 storage. The evaluation started with compiling data on wellbore characteristics, including the following:

- Cement type
- Cement additives
- Completion technique
- Well depth
- Well casing

These data were then used to derive a relative leakage potential score using methods modified from Faltinson and others (2011). Concurrent with the PCOR Partnership study, the oilfield operator conducted an independent and comprehensive wellbore integrity evaluation based on data sources used in the PCOR Partnership study and new data, including results of mechanical integrity tests, casing and cement evaluation logs, production and injection profiles, and wellhead pressures. Comparison of outputs from the two studies confirmed the utility of legacy data for cost-effective screening of wellbore leakage potential.

Recommended Best Practice – Wellbore Screening

A screening-level assessment of all wellbores within the project AOR is a key feasibility assessment component. In addition to identifying potential leakage pathways and providing an initial estimate of wellbore leakage risk, the assessment will serve as the basis for estimating level of effort and cost associated with any needed further evaluation and/or mitigation/remediation plans.

Seismic Survey

Well logs and core analysis techniques can be used to develop a detailed understanding of near-wellbore geologic features and properties to support assessments of capacity, injectivity, and seal effectiveness. However, correlation and interpretation between wells may be challenging, since discrete samples represent an extremely small portion of the subsurface and may not be representative of the storage formation. By pairing well-based measurements (which can be regarded as 1-D) with geophysical investigations such as surface-based 2-D and 3-D seismic surveys, extensive information regarding spatial variations in subsurface geology between and beyond wells can be ascertained.

2-D vs. 3-D

2-D and 3-D surface seismic surveys (Figure 4) frequently constitute a major element of site characterization by providing data for large tracts or volumes of the subsurface. When subsurface structure is gentle, 2-D seismic lines can be used to produce vertical slice images of geologic structure and formation continuity. In more complex structural domains, 3-D seismic surveys allow detailed geological analysis in any direction or orientation within the subsurface volume encompassed by the survey. A third method—3-D vertical seismic profile (VSP)—is sometimes used to provide a detailed image around a specific well. Although VSPs are limited in ability to see away from the well, they can provide significant information where larger surface seismic surveys are impractical.

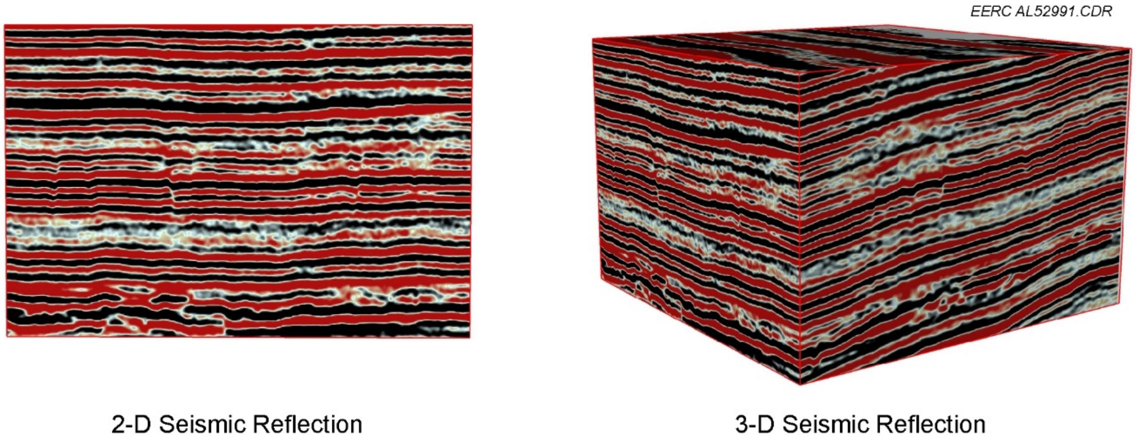


Figure 4. Examples of 2-D and 3-D seismic reflections.

Lesson Learned – Surface 3-D vs. 3-D VSP

The question of whether to use surface 3-D seismic survey or 3-D VSP to characterize the subsurface of a site requires an analysis of the cost/benefit trade-offs and geometry concerns that affect lateral coverage and imaging away from the well. A potential drawback to 3-D VSP is that the associated data processing is a specialty service, with fewer available vendors, resulting in pricing that is not competitive relative to 3-D data processing.

Interpretation

Accurately interpreting and deriving the most useful information from a seismic survey requires correlation with data from wells that intersect the survey. This is done by using borehole sonic and other well logs to tie geologic layers and horizons (which are known with certainty) to seismic reflection data (that would otherwise be ambiguous), as shown in Figure 5. Once identified, reflections can be tracked away from the well to reveal much useful information. 3-D surface seismic that intersects a well location provides lateral visibility away from the well, e.g., at 25-meter intervals, and aids in interpretation of changes in stratigraphic sequence, rock types, and structure, which, in turn, supports assessment of capacity, seal character, and communication pathways. 2-D surface seismic that intersects a well is less expensive and provides lateral visibility only along the line trace. While 2-D can also support a storage assessment with similar interpretation, uncertainty is increased because of the need to interpolate between widely spaced line traces.

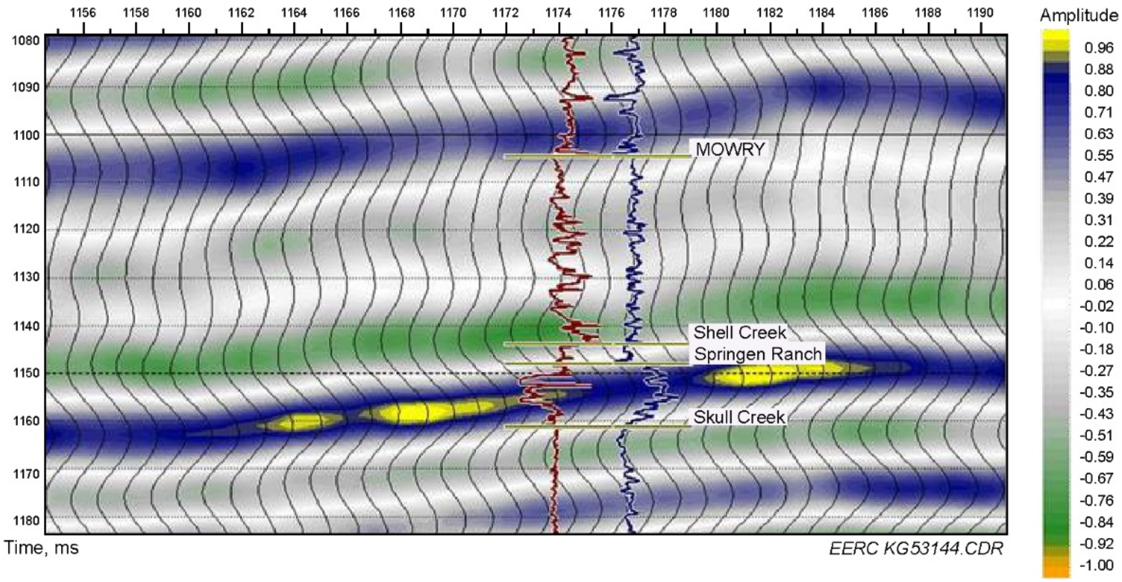


Figure 5. Reflection seismic data showing color-coded amplitude varying spatially along the line passing through a well. Gamma ray (GR) and sonic P-wave velocity well logs are overlaid, with formation tops labeled. The GR trace (red) overlays the well location. The P-wave trace (blue) is slightly offset for clarity (modified from Burnison and others, 2014).

Well spacing in developed oil fields is typically on the order of 0.5 km, while in undeveloped areas, wells may be many kilometers apart. Seismic data can provide information at lateral intervals as short as tens of meters, and data can be aggregated to yield highly informative subsurface geology snapshots encompassing large areas covering many square kilometers. Seismic reflections can be used to generate maps of subsurface geology (Figure 6) and vertical sections that identify and illustrate the approximate extent of significant geologic features. These maps can be used to deduce other information regarding:

- Potential CO_2 migration pathways such as fractures and faults.
- Stratigraphic boundaries between formations.
- Formation dip.
- Thickness of potential storage and sealing formations.
- Changes in lithology.
- Presence and geometry of structural features that may serve as CO_2 traps.
- Zones of differing porosity.

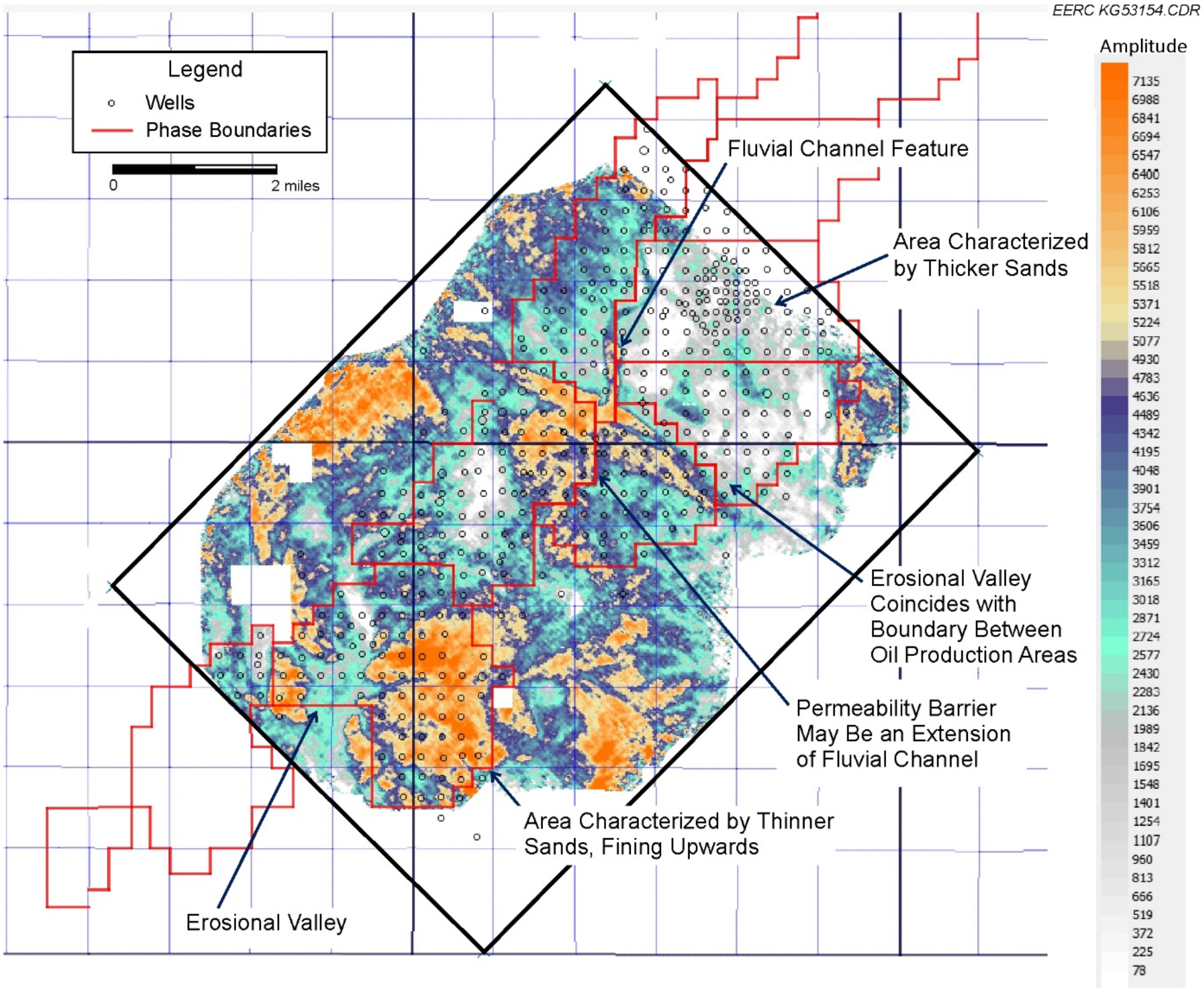


Figure 6. Plan view of seismic reflection amplitudes in an oil reservoir undergoing CO_2 EOR. Variations in the amplitudes of seismic reflections allow interpretation of geologic features, including fluvial channels, permeability barriers, erosional valleys, and sand deposits. Solid lines indicate boundaries between areas for separate phases of oil production. Small circles indicate wells. It should be noted that gaps in data coverage are due to licensing restrictions (modified from Burnison and others, 2014).

Purchase of Seismic Data

In cases where the openly available seismic data are insufficient/inadequate, purchasing licensed data may be possible. Large quantities of existing seismic data have been collected into libraries for relicensing or sale by data aggregation companies. If no data are available for the specific study area (a distinct possibility, since seismic surveys are typically concentrated in oil exploration areas), data proximal to the study area can provide an economical alternative to acquiring new data. Either 3-D or 2-D surveys may be available. If seismic data acquisition has occurred within the last 30 years, data quality is likely to be good. With recent advances in seismic data-processing methods, even older data may yield helpful information via reprocessing with modern algorithms to provide a more interpretable data set.

Recommended Best Practice – Seismic Data Purchase

Because commercial seismic data vendors are often reluctant to allow extensive data review and interpretation prior to purchase, data quality and usability should be assessed by a subject matter expert before purchase.

Additional Considerations

Additional considerations regarding seismic data applications include the following:

- Acquisition of new 3-D seismic surveys over a target area can further improve model resolution and simulation accuracy, especially for predicting effects of various CO_2 injection strategies, e.g., injection into additional or alternative formations.
- 3-D seismic data are critical to ensuring an accurate understanding of important subsurface geologic features where structure is significant.
- Following a positive decision on project feasibility and an official decision to advance the project to the design phase, acquisition of new 3-D data around planned injection well locations is a good way to establish a baseline for use in monitoring impacts of CO_2 injection.

Lessons Learned – New 3-D Seismic

Acquiring new onshore 3-D seismic survey data is a significant undertaking in terms of expense and land/landowner impact, because thousands of source and receiver locations are needed. Many months of lead time may be required for permitting if more than a few landowners are affected. Weeks or months will be needed for data processing and expert data interpretation. Total effort for a new seismic survey typically requires several experts in survey design, permitting, surveying, field gear provision, acquisition and sourcing, survey and crew oversight, monitoring for damage, and data processing and interpretation.

Lesson Learned – 3-D vs. 2-D

If 3-D seismic survey costs are deemed prohibitive, an alternative is to collect multiple 2-D lines, the trade-offs being less subsurface coverage and reduced interpretive certainty, which becomes more significant as geologic structure increases in complexity.

Recommended Best Practice – Seismic General Contractor

If affordable, hiring a qualified expert to act as a general contractor to assemble the required participants and coordinate the overall work effort is the most convenient, efficient, and effective way to execute a seismic survey.

Permit Application Review

Permit applications to regulatory authorities for drilling, production, and/or injection operations can be valuable sources of characterization data, often including geologic data, reservoir properties, maps, and detailed descriptions of previous operations in the area.

Hydrogeological Regime Characterization

The term hydrogeological regime refers to the 3-D direction and rate of fluid flow within a geologic system comprising a rock formation or group of formations. Consideration of the regional and local hydrogeological regimes affecting a storage complex is required for models to predict both the migration of injected CO_2 and the dissipation of pressure within and throughout the storage complex and AOR. Understanding the hydrogeological regime is also important for identifying possible pathways between the storage complex and surrounding formations, and assessing risks associated with any identified leakage pathways. The existence and nature of any hydraulic connectivity or communication between different rock units can often be determined using formation pressure gradients and reservoir fluid chemistry, as shown in Case Study 3. These data can also support storage capacity estimation.

Case Study 3 – Assessing Hydrogeological System

Understanding natural or baseline flow within a hydrogeological system proposed for dedicated CO_2 storage is always important, but especially so in situations where CO_2 injection and subsequent migration and pressure effects have the potential to impact ongoing or potential future oil and/or gas production operations. The PCOR Partnership undertook a feasibility assessment for a dedicated storage project located near an operating natural gas field. Extensive site characterization activities were conducted, including the following:

- Downhole pressure measurements and formation fluid analyses to investigate hydrogeological flow patterns in project-relevant formations
- Drilling, logging, and injection-testing an exploratory well

These and other site characterization data were used to create a geologic model and conduct a preliminary risk assessment. Predictive modeling–risk assessment iterations determined that use of the initially planned CO_2 injection point resulted in a significant risk of impacting nearby gas production operations. The risk derived from indications of hydraulic connectivity between the candidate storage reservoir and actively producing gas pools. To investigate the possible presence of interformation communication, the project team undertook a comparative analysis of historical well pressure and associated well log data. A key outcome of the analysis was significant evidence of extensive vertical and lateral communication between storage and gas-producing formations. In response to this evidence, an alternative injection well location was identified.

Laboratory Techniques for Detailed Reservoir and Seal Characterization

If necessary to reduce uncertainty regarding reservoir and seal properties, laboratory testing of core and fluid samples may be performed. Core samples may be available from previous wells or collected from new wells drilled as part of the storage project (see New Wells for Site Characterization Data Acquisition, page 27). Detailed descriptions of laboratory characterization techniques are provided in Sorensen and others (2014); an abbreviated summary is provided here.

For potential reservoirs, data are needed to determine injectivity and geomechanical integrity thresholds for injection design and to support estimates of storage capacity. For candidate seals, potential to act as a barrier to vertical migration of injected CO_2 under anticipated reservoir conditions should be assessed. Characterization methods for gathering these data and information include:

- Petrographic assessment, which encompasses a variety of x-ray and electron microscopy techniques to assess rock properties relevant to CO_2 storage and containment.

- Geomechanical testing to assess mechanical integrity and potential for fracturing during CO_2 injection.

- Permeability testing to support determination of injectivity and capacity of reservoirs and containment integrity of sealing formations. Permeability can be determined via tests conducted using core and reservoir fluid (or simulated reservoir fluid) samples.

- Pore network geometry determination to provide permeability distribution data, which enable calculation of CO_2 breakthrough pressure and are useful as inputs to dynamic simulation models for predicting CO_2 injection behavior and plume movement.

- Relative permeability testing which, for dedicated storage projects, generally refers to brine permeability relative to permeability of supercritical CO_2. This testing supports modeling and simulation efforts.

- Geochemical characterization, including assessment of reservoir mineralogy and laboratory analysis of fluid chemistry, to support predictive simulation.

Geochemical Effects

CO_2 injection into storage formations has the potential to trigger geochemical reactions with both native fluids and/or constituent solid minerals. Reactions, which may occur over a variety of timescales and could affect storage performance in a number of ways, can be arbitrarily divided into two categories:

- Short-term or relatively rapid reactions that can result in changes to reservoir porosity and permeability by precipitating mineral matter in pore spaces. Such changes, especially in the near-wellbore environment, could negatively affect injectivity and, ultimately, capacity. The presence of impurities in CO_2 may be an important factor in determining injectivity risks associated with rapid injected fluid–native fluid reactions.
- Longer-term reactions can affect the migration and ultimate form of injected CO_2 through secondary trapping mechanisms such as dissolution or mineral precipitation. Geochemical reactions could also affect containment by altering seals or wellbore materials. Long-term geochemical effects are difficult to model because of various factors including reaction kinetics, and so predictions need to be carefully framed in terms of uncertainty.

Carbonate formations may be particularly prone to geochemical effects since calcite and dolomite may both react with formation waters acidified by dissolution of CO_2. In most instances, characterization of reservoir and seal geochemistry will be challenging since securing representative native fluid samples from DSFs may be hard or impossible without access to exploration or injection/monitoring wells. Subject to the representativeness of available core samples, characterization of mineralogy is possible for reservoirs and seals to support geochemical testing and modeling.

Lesson Learned – Value of Geochemical Studies

Properly structured laboratory geochemical studies can be used to predict potential for reactions that could adversely affect CO_2 injectivity and storage capacity. For maximum predictive accuracy, studies should utilize:

- Storage- and seal-representative well cuttings and core samples.
- Actual or synthetic (formulated based on analysis of actual formation fluids) formation fluids.
- CO_2 streams representative of actual source CO_2.
- Reservoir temperature and pressure, based on downhole-measured values.

Lesson Learned – Storage Reservoir Heterogeneity

Candidate storage reservoirs and complexes that encompass wide variation in depositional environments and therefore significant heterogeneity in rock fabric, texture, and geochemistry can often exhibit a wide variability in porosity and permeability distribution—leading to difficulty in accurate characterization. Dealing with these characterization challenges may require:

- Correlation and integration of characterization data from wells with data from seismic surveys and hydrogeological studies to reduce uncertainty levels of injectivity and storage capacity estimates.
- Iterative data acquisition, analysis, and experimental activities that build on initial findings and reduce inherent geologic data interpretation uncertainty.

New Wells for Site Characterization Data Acquisition

Wells provide the only means to directly sample and test (in situ) reservoir and seal formations. A majority of dedicated storage sites will require drilling an injection well (or wells) and possibly one or more monitoring wells. In some cases, these may be the only wells drilled into the storage reservoir(s) at the site and for some distance beyond. In contrast, associated storage sites may not require drilling new wells because of the presence of numerous existing wells and extensive available site characterization data acquired during hydrocarbon exploration and production operations. If needed, injection and monitoring wells are most likely to be drilled in the construction phase of a project, but may be drilled at other times subject to project-specific circumstances.

If insufficient data are available to equip project decision makers with an adequate level of certainty regarding the suitability of a candidate storage site, the drilling of one or more exploration wells may be required. In addition to precisely targeted geologic data acquired during drilling and well-logging activities (Figure 7), exploration wells enable acquisition of core, drill cutting, and fluid samples. These samples are often needed for use in laboratory analytical and experimental activities to improve understanding of storage reservoir and seal properties and potential geochemical interactions that could impact storage complex capacity, injectivity, and containment capability (as described in Laboratory Techniques for Detailed Reservoir and Seal Characterization, page 25, and Geochemical Effects, page 26).

Exploration wells are typically cheaper than injection or monitoring wells (commonly referred to as “infrastructure wells”) and should have no long-term maintenance costs if plugged and abandoned following their use for data acquisition. In deciding what type of well to drill and when, the relatively lower cost of single-purpose exploration wells must be balanced against the higher cost of a dual-purpose (exploration and injection or monitoring) infrastructure well. In addition to cost, financial risk must also be considered. Drilling an infrastructure well early in a project may involve significant risk due to the uncertainty regarding storage potential (and by extension, project site viability) and optimal well location. Factors that can impact any well-drilling decisions include:

- Sparseness or lack of existing wells within or near the storage reservoir and/or AOR.
- Significant uncertainty—based on the totality of existing site characterization data—regarding geologic sequence or structure within and near the storage reservoir and/or AOR.
- Identified need for an infrastructure well.

Because of the typical depth requirement (for storage) of 800 meters or greater, wells represent one of the largest expenditures during the design and construction of a storage site. Exploration wells will typically cost on the order of a million U.S. dollars or more, and infrastructure wells may cost several million U.S. dollars. As a result, decisions regarding whether, when, where, and what type of well to drill are typically only made after careful evaluation of all existing and relevant site characterization data. To ensure maximum return on any well-drilling investment, careful planning and management of drilling operations are required to gain the maximum amount of characterization data within budget constraints. Well placement can be dependent on practical issues (e.g., rig access), geologic structure or reservoir properties, outputs from injection scenario predictive modeling exercises, or a combination of these. Interpretation of seismic survey data can significantly aid well placement decisions.

Since most management and technical aspects of drilling programs are covered by standard practices largely derived from the oil and gas industry, they are beyond the focus of this BPM. However, some issues of particular importance to CO_2 site characterization are discussed below.

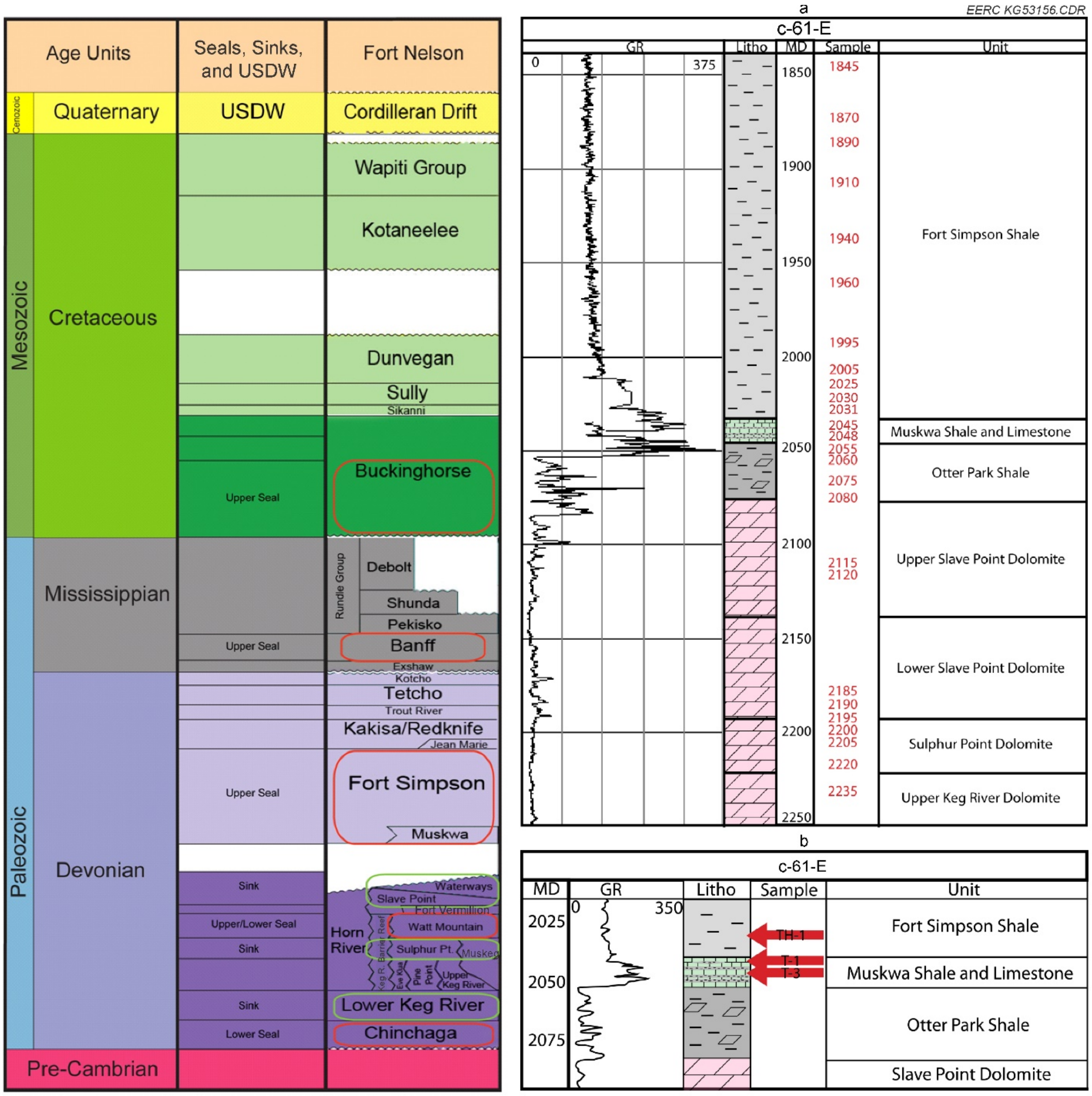


Figure 7. Comparison of two stratigraphic columns (built for a PCOR Partnership dedicated storage project) showing increased precision with project progression (left column built using regional geologic data acquired during site screening; right column used logs from project-drilled test well, seismic survey, and other detailed site characterization data acquired during feasibility assessment) (modified from Sorensen and others, 2014).

With respect to sampling of wells for geologic characterization data:

- Techniques that can improve quantification of fracture initiation pressure (i.e., maximum permitted injection pressure) could allow for greater operational flexibility in injection operations.

- Cores represent a significant expense within the drilling program and need to be carefully targeted to ensure critical sections are sampled (for example, the seal–reservoir interface) without excessive cost. Well control and offsets can be used to help pick core points or intermediate logging runs may be used to support coring decisions.

- Sidewall cores can be obtained as a cost-effective alternative to full cores, e.g., where coring has missed important sections. However, the small sample sizes restrict the types of laboratory testing that can be undertaken.

- Cement mapping tools can be useful in an injection or monitoring well to understand isolation between various injection or monitoring intervals.

- A variety of well-logging techniques can be deployed, as described in Appendix A.

- Wells also provide an important opportunity to test hydraulic properties of various formations and/or formation intervals via injection tests. Tests are typically undertaken prior to well completion and use inflatable packers to isolate sections of the well for injection of fluids (usually water or CO_2,) into near-wellbore environments of specific reservoirs. Key objectives are to assess 1) injectivity, i.e., how easy or hard is it to inject fluids into the formation of interest and 2) CO_2 behavior and interaction with formation fluids and rocks.

Lesson Learned – Core Sample Importance

Because accurate rock-testing data are critical to developing realistic reservoir models, core sample collection, handling, preservation, and analysis activities must be carefully planned and executed. Predicting sampling depths needed to collect cores representative of candidate storage and seal formations requires careful evaluation of historical geologic data.

Recommended Best Practice – Well-Drilling Decision

Because of high budget and schedule impacts, well-drilling decisions have the potential to be disruptive to feasibility assessment activities. If screening has indicated that a candidate project site will likely need one or more wells drilled, criteria and guidelines should be developed for use in:

- Assessing the need for each new well.
- Establishing the type of well needed (exploration or infrastructure).
- Siting each new well.

Lessons Learned – Injectivity Tests

Conducting and interpreting results of injection tests (with water, tubing, and packer) is straightforward and reasonable in cost. Such tests in DSFs also provide direct evidence of stress regimes and allowable injection pressures. However, precaution must be taken to ensure that injection water is compatible with formation water and mineralogy, since significant chemical contrasts between fluids can compromise future wellbore performance (i.e., skin effects such as precipitation of solids and retention of injected chemicals).

Use of CO_2 for injection testing avoids fluid compatibility problems, but analysis of collected data can be more complex, owing to relative permeability and fluid dynamics issues. The cost of delivered CO_2 can be highly variable depending on location and other logistical parameters.

Formation water production tests (in which formation fluids are pumped from the wellbore) can be reliable, but using a submersible (i.e., downhole pump) may limit operating range. Produced water must be stored on-site for licensed disposal, which could add to costs. Reinjection of produced water is an alternative disposal option, but should only be undertaken after reservoir pressure recovery data have been collected. Production tests do not yield information relating to maximum allowable injection pressures.

Drillstem testing is limited in both operation and volumes produced, with a higher probability of operational failures that can be relatively expensive to recover. As with production tests, data pertinent to the assessment of maximum allowable injection pressures are not collected.

Recommended Best Practice – Fluid Compatibility

Prior to undertaking any type of injectivity test, it is necessary to adequately assess the potential for incompatibility between formation and injection fluids. Freshwater can be particularly problematic since high chemical contrasts between injected and native fluids can cause geochemical reactions with the potential to reduce injectivity.

6.2.5 Building the Base Geologic Model

In building a geologic model, optimal-quality site characterization data that represent features and/or conditions at specific locations (wells) serve as control points. Control point conditions are extended between and beyond control points and throughout the storage complex and AOR using seismic survey data, where available. To ensure maximum accuracy of control point data and any subsequently derived model, well log and other downhole-acquired data are corroborated with data acquired via characterization and experimental activities conducted using samples of core, drill cuttings, and fluids (or simulated fluids).

Key inputs for the creation of geologic and simulation models are data points/ranges describing the following:

- Well locations and depths
- Formation top depths
- Formation lithology or rock type(s)
- Formation porosity and permeability
- Formation oil/water/gas saturation points
- Formation fluid composition and salinity
- Pressure and temperature
- Geochemical characteristics of formation fluids and mineralogy that could impact injectivity

Following construction, the geologic model is used as the basis for the dynamic simulation of various injection scenarios to determine factors such as:

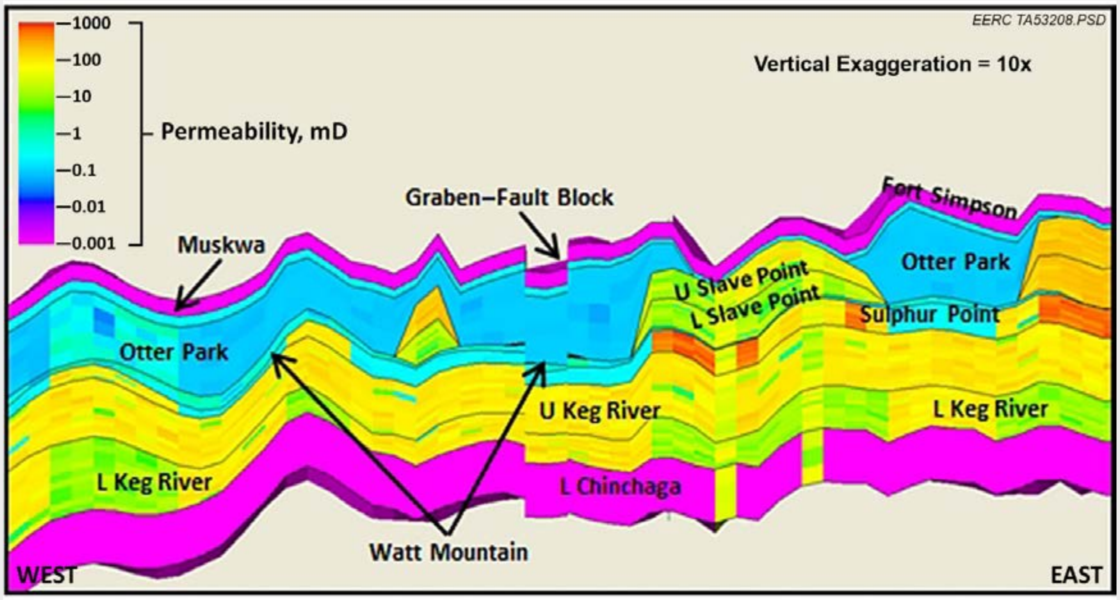
- Storage complex capacity, injectivity, and containment capability.
- Pressure distribution (including minimum and maximum values) in the storage complex prior to, during, and after injection.
- Pressure distribution and allowable injection pressure.
- CO_2 migration and plume evolution.
- Recommended AOR for development of the MVA program and permit application.

Case Study 4 – Using Site Characterization Data to Build a Geologic Model

The PCOR Partnership undertook a feasibility assessment for a dedicated storage project targeting injection of 2 million tonnes/year of CO_2 in a storage complex comprising brine-saturated carbonate (limestone and dolomite) storage formations capped by thick (550-meter) shale sealing formations. Site characterization data collected included:

- Historical well log data from 96 wells.
- Purchased and reprocessed 2-D and 3-D seismic survey data.
- Data acquired from drilling a test well, including logging, injection tests, and laboratory analysis of core, cutting, and fluid samples collected during drilling.

These data enabled determination or estimation of formation lithology (rock type), thickness, porosity, permeability, and other parameters, as well as identification of structural features including hydrothermal sags (localized down-warping of formations caused by intrusion of hot, high-pressure fluids) and faults. Based on an interpreted barrier reef depositional environment as an overall geologic system framework, these data were used to develop structural interpretation and map the tops of major formations within the storage complex. The structural interpretations were then integrated with porosity and permeability distribution data to develop a static geologic model of the storage complex, as illustrated in the cross section below.



West-to-east cross section of a geologic model representing formations and features within the AOR of a dedicated storage project. Potential storage complex comprises sequence of carbonate and shale formations as labeled, with a typical depth range of between 2050 and 2500 meters.

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Of particular significance in this model cross section is the faulted zone (graben–fault block), which was initially identified during site screening and more extensively characterized and accurately positioned via feasibility-phase site characterization activities. The model was used as a basis for CO_2 injection simulation and risk assessment to predict the behavior of injected CO_2 and impacts of any potential out-of-storage-complex migration. Several modeling–risk assessment iterations showed that the originally planned injection site represented an unacceptable risk of injected CO_2 impacting nearby gas production operations. To mitigate this risk, the injection site was moved to the opposite side of the graben–fault block, thereby incorporating the block into the storage complex design as a means of prohibiting migration of injected CO_2 into formations containing producing natural gas pools.

6.3 Construction/Operation and Closure/Postclosure

6.3.1 Site Characterization Within Construction/Operations Phase

Upon completion of the design phase, a final decision will be made to proceed to storage project construction activities, subject to regulatory approval. By this stage, site characterization data will have supported modeling, simulation, and risk assessment efforts, with sufficient data upon which to base key project management decisions.

The construction phase of the project will likely include drilling and completion of injection and monitoring wells, if not previously completed during the design phase. The installation of these infrastructure components will yield major sets of characterization data, which may lead to significant revisions in other technical elements in accordance with the AMA.

The scope of site characterization activities will tend to be progressively reduced in intensity or integrated into the main technical elements of MVA; history matching and predictive modeling; and updating risk assessments during the construction, operation, and closure/postclosure phases of a project. However, installation of wells and baseline MVA activities can yield considerable characterization data that should be used to inform the other technical elements (modeling/simulation and risk assessment) as appropriate. Similarly, any unexpected behavior of injected CO_2 or anomalies detected by the MVA program during operations may require additional site characterization work, with the goal of determining if—and what type of—mitigation strategies are required to address them.

Recommended Best Practice – Data Acquisition Contingency

Discrepancies between MVA observations, operations data, and simulation results serve as a diagnostic to identify areas where additional characterization data can improve alignment between predictions and observations through improved modeling and simulation. In turn, improved simulations can be used to further optimize the MVA program or to show conformance at project closure. This situation can occur at any point in the project life cycle, and as such, project budgets may need to include a contingency for additional site characterization.

6.3.2 Site Characterization Within Closure/Postclosure Phase

Closure/postclosure is the last phase of a CO_2 storage project and is driven by regulatory requirements and issues associated with long-term liability for the injected CO_2. Similar to the construction/operations phase, site characterization activities in this project phase are typically limited to special circumstances. In the event that MVA data and reservoir simulations indicate the reservoir and contained fluids are performing as expected, no additional site characterization data collection will be needed. However, if unexpected/unexplainable MVA data are acquired, a decision may be made (or dictated by regulatory requirements) to collect additional site characterization data for analysis. The possibility of additional data collection will exist for the duration of the project-monitoring program, which will be largely dictated by regulatory requirements.

7.0 STATE OF BEST PRACTICE – SITE CHARACTERIZATION

The PCOR Partnership has formalized an AMA for commercial development of CO_2 storage projects. Site characterization, one of four technical elements underpinning the AMA, may be defined as the acquisition and analysis of data to develop an understanding of site-specific properties and characteristics of the surface and subsurface environments. The other technical elements are modeling and simulation, risk assessment, and MVA. These four technical elements are applied through each life cycle phase of a project (i.e., site screening, feasibility, design, construction/operation, and closure/postclosure) in an iterative fashion to reflect the complexity of storage projects and the need for a flexible approach to address often widely differing individual project needs. This document reports some of the key lessons learned and recommended best practices from site characterization activities undertaken in PCOR Partnership projects, both for dedicated storage (in DSFs) and associated storage (resulting from CO_2 EOR). Many of these findings will also be applicable to storage projects in other geographic regions, regulatory jurisdictions, and geologic or environmental settings (e.g., offshore projects).

Site Characterization vs. MVA

As a project progresses into the construction/operation phase, site characterization and MVA activities may be simultaneously ongoing and/or using the same techniques, leading to significant overlap between these technical elements. Site characterization data offer insight into site-specific properties and characteristics of the surface and subsurface environments. MVA data allow for tracking of the injected CO_2 as the project evolves and surveillance of the environment surrounding the storage complex and site. Similar measurement techniques may be employed in either technical element, but MVA is focused on monitoring CO_2 (i.e., answering the question of where) and any associated impacts, whereas site characterization is focused on understanding the geologic and environmental system (i.e., answering the question of why). Put another way, MVA data will inform ***where*** a CO_2 plume is moving, but site characterization will inform ***why*** the CO_2 plume is moving in that direction.

Interrogation of existing information and data such as geologic maps and reports, well records, and seismic surveys will typically be the main characterization activity during the site-screening phase of a CO_2 storage project. Characterization data can be compared to generic or site-specific criteria (e.g., storage capacity, injectivity, or containment requirements) to identify and rank or screen sites based on their ability to meet project requirements.

The subsequent feasibility assessment of selected candidate storage site(s) will also include a major component of site characterization activity, with existing data used to the fullest possible extent. However, the increasing need for data to support iterations of modeling/simulation and risk assessment will likely require collection of additional data through field investigations, including exploration wells and seismic surveys. The need for field investigation is likely to be greater for dedicated rather than associated storage projects, since the latter will typically be informed through numerous well records and production data. However, associated storage projects may require greater emphasis on collection and appraisal of well records to assess wellbore leakage potential as a major risk assessment component.

The need for accurate site characterization data to inform other technical elements will increase as the project moves into the design phase, where detailed plans for injection, infrastructure, and MVA will be required for permit applications and final investment decisions. Modeling and simulation efforts will be used to determine an optimum plan for injection, with predictions of CO_2 migration and pressure effects used to define the storage complex, AOR, and MVA program sampling locations. Risk assessments will be refined to demonstrate that the project will have an acceptable risk profile and to provide context for the MVA plan.

Site characterization activities will typically decrease during construction, operation, and closure/postclosure phases as routine MVA, history matching of predictive models, and updating of risk assessments become the main technical elements. However, installation of wells during construction is likely to yield considerable characterization data that will, in accordance with the AMA, inform the refinement of other technical elements. Similarly, any unexpected behavior of injected CO_2 or anomalies detected by the MVA program during operations may necessitate additional characterization work.

7.1 Summary of Site Characterization Lessons Learned

Surface 3-D vs. 3-D VSP – The question of whether to use surface 3-D seismic survey or 3-D VSP to characterize the subsurface of a site requires an analysis of the cost/benefit trade-offs and geometry concerns that affect lateral coverage and imaging away from the well. A potential drawback to 3-D VSP is that the associated data processing is a specialty service, with fewer available vendors, resulting in pricing that is not competitive relative to 3-D data processing.

New 3-D Seismic – Acquiring new onshore 3-D seismic survey data is a significant undertaking in terms of expense and land/landowner impact, because thousands of source and receiver locations are needed. Many months of lead time may be required for permitting if more than a few landowners are affected. Weeks or months will be needed for data processing and expert data interpretation. Total effort for a new seismic survey typically requires several experts in survey design, permitting, surveying, field gear provision, acquisition and sourcing, survey and crew oversight, monitoring for damage, and data processing and interpretation.

3-D vs. 2-D – If 3-D seismic survey costs are deemed prohibitive, an alternative is to collect multiple 2-D lines, the trade-offs being less subsurface coverage and reduced interpretive certainty, which becomes more significant as geologic structure increases in complexity.

Value of Geochemical Studies – Properly structured laboratory geochemical studies can be used to predict potential for reactions that could adversely affect CO_2 injectivity and storage capacity. For maximum predictive accuracy, studies should utilize:

- Storage- and seal-representative well cuttings and core samples.
- Actual or synthetic (formulated based on actual formation fluid) formation fluids.
- CO_2 streams representative of actual source CO_2.
- Reservoir temperature and pressure, based on downhole-measured values.

Storage Reservoir Heterogeneity – Candidate storage reservoirs and complexes that encompass wide variation in depositional environments and therefore significant heterogeneity in rock fabric, texture, and geochemistry can often exhibit a wide variability in porosity and permeability distribution—leading to difficulty in accurate characterization. Dealing with these characterization challenges may require:

- Correlation and integration of characterization data from wells with data from seismic surveys and hydrogeological studies to reduce uncertainty levels of injectivity and storage capacity estimates.

- Iterative data acquisition, analysis, and experimental activities that build on initial findings and reduce inherent geologic data interpretation uncertainty.

Core Sample Importance – Because accurate rock-testing data are critical to developing realistic reservoir models, core sample collection, handling, preservation, and analysis activities must be carefully planned and executed. Predicting sampling depths needed to collect cores representative of candidate storage and seal formations requires careful evaluation of historical geologic data.

Injectivity Tests

- Conducting and interpreting results of injection tests (with water, tubing, and packer) is straightforward and reasonable in cost. Such tests in DSFs also provide direct evidence of stress regimes and allowable injection pressures. However, precaution must be taken to ensure that injection water is compatible with formation water and mineralogy, since significant chemical contrasts between fluids can compromise future wellbore performance (i.e., skin effects such as precipitation of solids and retention of injected chemicals).

- Use of CO_2 for injection testing avoids fluid compatibility problems, but analysis of collected data can be more complex, owing to relative permeability and fluid dynamics issues. The cost of delivered CO_2 can be highly variable depending on location and other logistical parameters.

- Formation water production tests (in which formation fluids are pumped from the wellbore) can be reliable, but using a submersible (i.e., downhole pump) may limit operating range. Produced water must be stored on-site for licensed disposal, which could add to costs. Reinjection of produced water is an alternative disposal option, but should only be undertaken after reservoir pressure recovery data have been collected. Production tests do not yield information relating to maximum allowable injection pressures.

- Drillstem testing is limited in both operation and volumes produced, with a higher probability of operational failures that can be relatively expensive to recover. As with production tests, data pertinent to the assessment of maximum allowable injection pressures are not collected.

7.2 Summary of Site Characterization Recommended Best Practices

Data Management System – Collection and review of existing data are the primary site characterization activities of the site-screening phase. Because storage projects are likely to continue for decades and personnel may change, development of a rigorous data management system is critical to ensuring long-term accessibility to all data collected over the life of the project.

Regional Geologic Data Centers – Working with regional geologic knowledge centers and/or government–industry geologic storage characterization programs is often a time/cost-effective way to access existing geologic and other project-relevant data and information. Available geologic data (and in some cases, information regarding regional sociopolitical issues and attitudes) can be of sufficient relevance and quality to use as a basis for prefeasibility assessment project investment decisions.

Data Confidence – Establish confidence levels in available site-screening data, and assess the impact of any knowledge gaps on screening process outcomes.

Preliminary Understanding – Develop sufficient understanding of pertinent geologic resources, subsurface and surface access rights, and the sociopolitical environment to gauge whether at least one suitable candidate project site and storage complex can be identified.

Regulatory Environment – Understand the regulatory environment of the project area. Regulations may affect the selection of storage targets.

Preliminary Leakage Potential – Based on available data, assess potential leakage pathways and estimate reasonable likelihood of CO_2 migration beyond the storage complex and—assuming pathway transmissivity—extent and impact of migration.

Oil and Gas Operations – Because operations associated with injecting and monitoring CO_2 are closely analogous to and/or derived from oil and gas production (especially CO_2 EOR) operations, site characterization and modeling exercises should—to the extent possible—follow oil and gas industry standard protocols. In addition to offering significant economic and reliability benefits, oil/gas industry methods are generally well understood and accepted by regulatory communities.

Wellbore Screening – A screening-level assessment of all wellbores within the project AOR is a key feasibility assessment component. In addition to identifying potential leakage pathways and providing an initial estimate of wellbore leakage risk, the assessment will serve as the basis for estimating level of effort and cost associated with any needed further evaluation and/or mitigation/remediation plans.

Seismic Data Purchase – Because commercial seismic data vendors are often reluctant to allow extensive data review and interpretation prior to purchase, data quality and usability should be assessed by a subject matter expert before purchase.

Seismic General Contractor – If affordable, hiring a qualified expert to act as a general contractor to assemble the required participants and coordinate the overall work effort is the most convenient, efficient, and effective way to execute a seismic survey.

Well-Drilling Decision – Because of high budget and schedule impacts, well-drilling decisions have the potential to be disruptive to feasibility assessment activities. If site screening has indicated that a candidate project site will likely need one or more wells drilled, the project team should—as one of its initial feasibility assessment responsibilities—develop criteria and guidelines for:

- Assessing the need for each new well.
- Establishing the type of well needed (exploration or infrastructure).
- Siting each new well.

Fluid Compatibility – Prior to undertaking any type of injectivity test, it is necessary to adequately assess the potential for incompatibility between formation and injection fluids. Freshwater can be particularly problematic since high chemical contrasts between injected and native fluids can cause geochemical reactions with the potential to reduce injectivity.

Data Acquisition Contingency – Discrepancies between MVA observations, operations data, and simulation results serve as a diagnostic to identify areas where additional characterization data can improve alignment between predictions and observations through improved modeling and simulation. In turn, improved simulations can be used to further optimize the MVA program or to show conformance at project closure. This situation can occur at any point in the project life cycle, and as such, project budgets may need to include a contingency for additional site characterization.

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APPENDIX A

WELL-LOGGING TECHNIQUES AND APPLICATIONS

WELL-LOGGING TECHNIQUES AND APPLICATIONS

Well-logging techniques enable collecting a variety of data for wellbore and near-wellbore environments. In addition to characterizing subsurface formations, logs can be used to characterize well features including pipe, casing, and concrete, making them valuable tools for assessing wellbore leakage potential. Well-logging techniques offer the flexibility to acquire data over the entire extent of a well (from top to bottom) or focus on one or more selected sections based on depth and are useful for both site characterization and MVA activities. Key well log types and applications are summarized below:

- Cement bond
  - Evaluating—via sonic signal—cement compressive strength and cement bond strength.
  - Determining cement bond quality between casing, cement, and formation to confirm zonal isolation.
  - Identifying channeling, microannulus, and partial bonding.
  - Locating areas with direct casing–formation contact (absence of circumferential cement contact with casing).
  - Locating free pipe and top of cement.
  - Indicating need for remediation activities.

- Gamma ray
  - Determining clay mineral content as means of distinguishing rock type, e.g., shale vs. sandstone or limestone.
  - Defining formation boundaries, and enabling correlation of formations between wells.
  - Identifying lithology.
  - Identifying and qualitatively evaluating radioactive mineral deposits.

- Nuclear magnetic resonance (NMR)
  - Quantifying hydrocarbon volume in place.
  - Measuring lithology-independent porosity and associated permeability.
  - Measuring total and effective porosity and porosity and pore-size distribution.
  - Determining free-fluid, capillary-bound, clay-bound, and movable fluids (water and hydrocarbons).
  - Determining fluid viscosity.
  - Determining hydrocarbon type; identifying bitumen, heavy oil, and tar mats.
  - Detecting gas; distinguishing between oil, gas, and water; identifying fluid contacts.
  - Identifying thin, permeable beds in laminated reservoirs.

- Pulsed-neutron/neutron porosity
  - Measuring and monitoring time-based changes in water, natural gas, and CO_2 content.
  - Identifying vertical CO_2 migration channels along the wellbore into overlying formations and/or locating CO_2 accumulations in overlying formations.
  - Providing an indication of cement integrity and/or identifying wells that are candidates for remediation activities.

  - Correlating seismic data with quantitative CO_2 saturation and the vertical distribution of CO_2 within the reservoir.
  - Providing a near-wellbore saturation history for predictive simulation history matching.
  - Detecting horizontal fluid migration.
  - Identifying lithofacies that are not accepting injection.
  - Identifying vertical flow boundaries in the near-wellbore environment.

- Spontaneous potential/induction
  - Detecting the presence of shale in a measured interval.
  - Differentiating potentially porous and permeable reservoir rocks from nonpermeable clays and shales.
  - Defining formation boundaries, and enabling correlation of formations between wells.
  - Providing qualitative indication of formation clay content.
  - Identifying lithology.
  - Determining formation water resistivity (Rw).
  - Estimating formation water salinity.

- Ultrasonic imaging
  - Performing 360° analysis of the cement bond, and determining annulus cement strength.
  - Mapping annulus material (as solid, liquid, or gas), and determining its acoustic velocity.
  - Determining borehole fluid properties.
  - Locating and imaging channels or defects in annular isolation material.
  - Performing casing thickness analysis for collapse and burst pressure analysis.
  - Determining casing internal and external diameters for monitoring purposes and to locate and quantify casing wear damage or metal loss caused by milling, drilling, fishing operations, internal or external scale buildup, casing corrosion, and casing damage or deformation.