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Data request for Majiata DCL plant site characterization for geological sequestration - explanation of purpose and need

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Jeff Wagoner and Julio Friedmann

Abstract

Detailed and accurate geological assessment of the proposed CO2 pilot injection and commercial project associated with Shenhua's DCL plant is central to project success and US-China collaboration. The best result requires access to multiple data types and in the highest abundance available for the site and region. Insufficient data access will result in inaccurate simulations, poor drilling recommendations, high uncertainty in understanding new data from the site, and would increase the chance of technical failure or poor outcome. Examples from prior successful project discussed here are provided to demonstrate the need for full access to individual data types, access to multiple data types, and ability to correlate and integrate between these data sets.

1-Overview

The sequestration effort associated with Shenhua's DCL plant is a flagship project associated with the historic agreements between Presidents Hu and Obama in Nov. 2009. Under Annex II, as agreed between Shenhua and the West Virginia University, a collaborative research program in support of the site will feature advanced simulation, risk assessment, and monitoring recommendations associated with and following initial site characterization. Earlier pre-feasibility and feasibility studies have demonstrated the need for sharing data from site characterization and outlined the benefits resulting from access to this information.

The purpose of this document is to outline the types of information that are necessary to provide that support and accurately evaluate an area for geologic carbon storage (GCS). Geologic and engineering data come in many forms and it is important that the appropriate data be available to the geoscientist and engineer performing the evaluation.

The most important component to successful development and operation of any GCS project is site characterization and assessment. This work not only serves as the basis for future simulation and risk assessment, but also provides the operators with critical design information and operational constraints. Critically, access to all available data can dramatically reduce uncertainty, can increase confidence in drilling and monitoring program designs, and aid in interpretation of newly acquired data. Harmonious, integrated interpretation and understanding of the subsurface benefit from multiple wells, multiple seismic lines, availability to core samples and interpretations, stratigraphic and structural interpretations, and geochemical samples and analyses. The more wells, seismic data, core, and analyses, the better the interpretation. These are critical for proper and accurate initialization of simulations used to predict site performance, design monitoring surveys, and avoid hazards that could lead to undue risk

In order to successfully characterize the subsurface, teams must first get access to and collect the appropriate technical data. Secondly, we need to put the geologic data into a framework that allows analysis and interpretation of the subsurface structure, called a geomodel. Finally, we populate this spatially realistic geomodel with physical properties that will allow the geoscientist to simulate the movement of gas and fluids in the subsurface environment.

The following is a list of data types that are essential in constructing detailed regional and site-specific geologic models and property models:

Surface topography (DEM)
Geological maps and cross-sections
Structure location maps
Structure contour maps
Borehole data
plan map of boreholes
collar location
collar elevation
stratigraphic Data (tops)
Borehole geophysical logs
resisitivity
induction
long normal
short normal
natural gamma
density
caliper (oriented?)
temperature
SP
dipmeter
neutron
fracture logs
downhole photography
Geological logs
stratigraphic tops
lithology logs
mudlogs

Borehole samples
sample locations (well location and depths)
core descriptions (lithology, bedding attitude, faults/fractures)
cuttings descriptions
sidewall core descriptions
sample analysis
Surface geophysical surveys
Seismic surveys
seismic reflection (2D/3D)
refraction
VSP
Aerial photography
Log correlation (interpretive data)
detailed geophysical log correlation between boreholes
Hydrology
Reservoir pressure measurements
Maps of potential groundwater barriers
Hydrologic head maps
Surface outcrop studies (if applicable)
understand sedimentary architecture

2-Description of data types required for subsurface characterization

Surface topography (DEM)

A digital elevation model (DEM) is a digital representation of ground surface topography or terrain. 10m, 30m, or 90m digital elevation models are all widely available in the United States, while only the coarser DEMs are likely available in other parts of the world.

Geological maps

A geologic map is a special-purpose map designed to show the spatial distribution of geological features. Rock units or geologic strata are shown by color or symbols to indicate where they are exposed at the surface. Bedding planes and structural features such as faults, folds, foliations, and lineations are shown with strike and dip symbols that give these features three-dimensional orientations. These features can be projected into the subsurface, based on this surface expression. Separate fault, fracture, or surface lineament maps are also generally available. The geologic map is generally one of the first sources of data to collect in evaluating a potential GCS target.

Boreholes

A boreholes is in many ways the most valuable asset for the geologist. The borehole provides both rock samples and geophysical measurements of the material encountered during the drilling process. Collection of borehole data is typically one of the first things done in the characterization process.

Plan maps (and associated tables) of borehole locations are critical to site characterization, since so much of the valuable information comes from the well. The well locations can also be plotted on the geologic maps for reference purposes. Additional important information should be provided in table format including:

Collar location
Collar elevation
Stratigraphic Data (tops)

Well completion, abandonment, and drilling history reports should be available for each borehole. Directional surveys are important in areas where directional drilling is encountered.

Borehole geophysical logs

Geophysical logs are very valuable for identifying different lithologies and formations, as well as correlating the rock section between boreholes. Importantly, geologists and geophysicists improve their assessment and characterization of the subsurface through access to logs from as many wells as possible at a location – this reduces the range of possible interpretations and allows for proper initialization of models.

A typical downhole log suite may include any of the following wireline logs:

- resisitivity
    - induction
    - long normal
    - short normal
- natural gamma
- density
- caliper (oriented?)
- temperature
- SP
- dipmeter
- neutron
- fracture logs

These logs need to be available in either hardcopy or digital (LAS) format. Downhole logs are extremely useful to characterize the subsurface, as they provide a continuous record of the stratigraphic section from the surface to total depth of the hole. Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, nuclear magnetic resonance, and other properties of the rocks and their contained fluids. Downhole geophysical logs have historically been output as a blue line hardcopy, generally as a long strip of paper. Standard digital log output files are in Log ASCII Standard (LAS) format. These LAS-format files are suitable for use in geophysical-log-analysis software systems.

Electric logs can also be divided into three general types based on what physical properties they measure; resistivity, porosity, and imaging. Resistivity logs (about 17 types) measure some aspect of the specific resistance of the geologic formation. Porosity logs (usually acoustic or nuclear) measure the fraction or percentage of pore volume in a volume of rock. Nuclear logs include density logs and neutron logs, as well as gamma ray logs which are used for correlation. Increasingly, companies have also used imaging logs (e.g., FMI logging) to identify subtle sedimentary structures, drilling induced fractures, and pre-existing faults and fractures. All these logs, and even downhole photography, can play an important part in primary characterization of seals, reservoirs, faults, fractures, and fluids.

Geological logs and borehole samples

Geological logs use data collected at the surface, rather than by downhole instruments. The geological logs document the lithology, based on samples collected downhole (cuttings, core, sidewall, etc.).

There are several types of rock samples that can be collected during drilling of a borehole. The most common samples are called cuttings samples, which are bits of rock circulated to the surface by the drilling mud in rotary drilling. The cuttings travel up the wellbore suspended in the drilling fluid or mud that was pumped into the wellbore via the drill string/pipe and they return to the surface via the annulus. Cuttings are then separated from the drilling fluid and are sampled at regular depth intervals. The samples are collected are stored in containers, with the appropriate depth interval labeled on the container. Access to cuttings allows for improved statigraphic and geochemical characterization of reservoir and sealing units.

Core samples are generally more useful (although more expensive) than cuttings in that they represent a continuous intact sample of the formation. There are several types of core techniques, including continuous and side-wall coring. Cores are typically analyzed in the lab, measuring petrophysical properties such as porosity, permeability, and saturation. In addition, direct measurements of residual phase saturation, strength, and sealing capability can be measured with special core analyses. Critically, continuous cores can unambiguously resolve many uncertainties in interpretation of well logs and prediction of stratigraphic continuity and character. All of these data are valuable to the characterization of a potential GCS site.

Surface geophysical surveys

Surface geophysical surveys such as gravity, magnetics, and electrical methods are useful to document the spatial variability of subsurface properties across the project area. These surveys can locate faults and fracture zones, as well as estimating the depth to basement rock. Such data can dramatically improve the identification of possible site hazards and large risk elements.

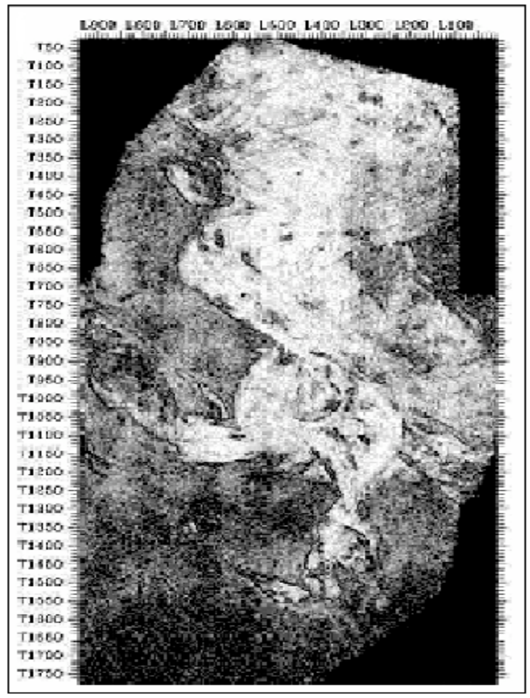
Seismic surveys

Seismic reflection

Seismic reflection (2D/3D) surveys are probably the most useful tool to define the continuity of sedimentary layers and subsurface structures (faults and folds). Reflection seismology is a method of exploration geophysics that uses the principles of seismology to estimate the properties of the Earth's subsurface from reflected seismic waves. The method requires a controlled seismic source of energy. By noting the time it takes for a reflection to arrive at a receiver, it is possible to estimate the depth of the feature that generated the reflection.

3D seismic interpretation is a form of seismic interpretation that provides visualizations of structures in three dimensions. In seismic surveys, controlled explosions are generated and the reflections of these explosions are read to generate data about the subsurface structure. With 3D seismic interpretation, these data are rendered in a three dimensional representation. Rather than visualizing a site in the form of a flat elevation map or cross section, 3D seismic interpretation allows the geologist to manipulate the angle of view and to visualize a site interactively. It can also provide information about the surrounding area that may not be readily apparent with other mapping techniques.

Because it is also possible to show the features along a single stratigraphic horizon, 3D seismic also greatly improves the recognition of porous areas within the survey and trends of permeability.This 3D seismic image from the In Salah reservoir (Riddiford et al. 2004) reveals high porosity and permeability regions (white) and low porosity and permeability regions (dark). This was critical to plan the three CO2 injection wells, each operating at 300,000 tons CO2/year.

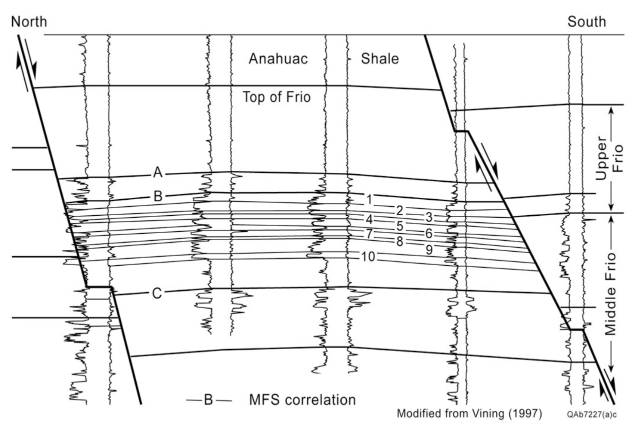


Aerial photography

Aerial photography is required for all project areas, allowing for correlation of surface features with the subsurface interpretation. Photos provide visual confirmation of surface lineaments, rock outcrops, etc.

Log correlation (interpretive data)

Any interpretive data that has been generated in the project area of interest is valuable to the characterization process. This can include any detailed geophysical log correlation between boreholes, cross sections, and plan map interpretations. The example below from the Frio Brine Pilot (Hovorka et al. 2001) used five wells within the pilot injection area and some seismic information to correlate key stratigraphic units and identify faults. This information is critical for proper estimation of risks and initialization of simulations. If applicable, surface outcrop studies can greatly improve understanding of sedimentary architecture, reservoir continuity, and rock properties between wells.



3-Building the Geomodel

Fundamental to geologic characterization is the integration of spatial geologic information, such as stratigraphy, lithology, structure, and rock physical properties. Historically, geoscientists have generally relied on two-dimensional visualizations for analyzing geological data. Traditional geologic maps contain projected information about the subsurface in the form of strikes, dips, fold axes, fault traces, etc., as well as implicit information like the distribution and apparent thickness of stratigraphic units. Geological maps typically include a cross-section that provides an interpretation of the subsurface. But because of the complexity of the spatial relationships, a three-dimensional model of geology is better suited for integrating different types of data, providing a more realistic characterization of a site than a two-dimensional view. Being able to easily manipulate a large, complex data set provides the geoscientist with the opportunity to detect and visually analyze the spatially correlated data, which leads to an increased understanding of the subsurface.

Three-dimensional geologic models can be regional in scale, covering thousands of square kilometers. Regional-scale models remain somewhat limited in their development, due in part to the challenges presented by construction of high-resolution grids that are based on sparse structural, lithologic, and stratigraphic data. Smaller site-specific 3D models can be very well constrained in areas where seismic and borehole data are available. Models can be continuously revised as new data are progressively added or as the interpretative understanding of the geology evolves. New data are often slowly acquired over time during which this "living" model evolves.

Map-derived data, along with geophysical, borehole and other data, can be assembled into a realistic 3D model as a set of surfaces, with the volumes defined by those surfaces. Faults are represented by 2D grids, which intersect and displace the volumes. This type of geologic framework is critical to the understanding and identification of faults, fracture zones, and facies changes in the caprock, reservoir, and time-equivalent deposits in the surrounding basin.

There are 2 types of geologic models that are important to characterizing a potential CO_2 sequestration site. The most common type of model is the geologic framework model in which a framework of time-stratigraphic layers is constructed. These stratigraphic units are generally “named” formations, many of which can be laterally extensive and extend across entire basins. The second type of model is the lithofacies model, in which lithologies are modeled within the stratigraphic framework. Both require substantial information from multiple data sets, and increased data quality and volume greatly improves simulation accuracy and decreases uncertainty.

Table 1 provides examples of static geomodels that were the basis for complex simulations and in some cases pilot and large-scale CO2 injections.

Table 1: Data set availability for geological model construction

	Southern Nevada Basin	Southern San Joaquin basin	In Salah Project	Frio Brine Pilot
Survey purpose	Nuclear weapons testing	Oil and gas exploration and regional CO2	Gas production and large-	Oil production and pilot CO2 injection

		capacity assessment	scale CO2 injection	demonstration and field experiment
Number of wells	950	2970	17	25
Number of seismic lines	28	9	3D survey	unknown
Number of well logs	400	40	17	20
Number of cored wells	50		3	Regional input
Used regional data for constraints	Yes	Yes	Yes	Yes

Framework Geomodels: Examples from the southern San Joaquin Basin and southern Nevada

The first step in building a geologic framework model is to define the node structure to create a topographic surface. The free surface is generally based on a 10-30 m lateral resolution DEM, which is converted to a 2D grid within Earthvision. Stratigraphic tops for all of the major stratigraphic units are collected and digitized. These data are converted to elevation and 2D grids are generated for the top of each mappable unit.

Figure 1a is an example of a highly faulted basin in the Basin and Range Province of Nevada. The basin geology is structural complex, yet stratigraphically simple. The yellow zone is the youngest formation, non-marine basin-fill alluvium. The underlying light brown zone consists of a series of volcanic deposits, mainly air-fall and ash-flow tuffs. The lower blue zone represents the pre-Tertiary basement rocks. Figure 1b is the same plot but with the alluvium stripped off. This allows for a better view of the highly normal faulted, extended basin. The dark vertical lines represent all of the boreholes that have been drilled in this area. Each borehole represents a data point that has been used to define and refine the structure as seen in this image.

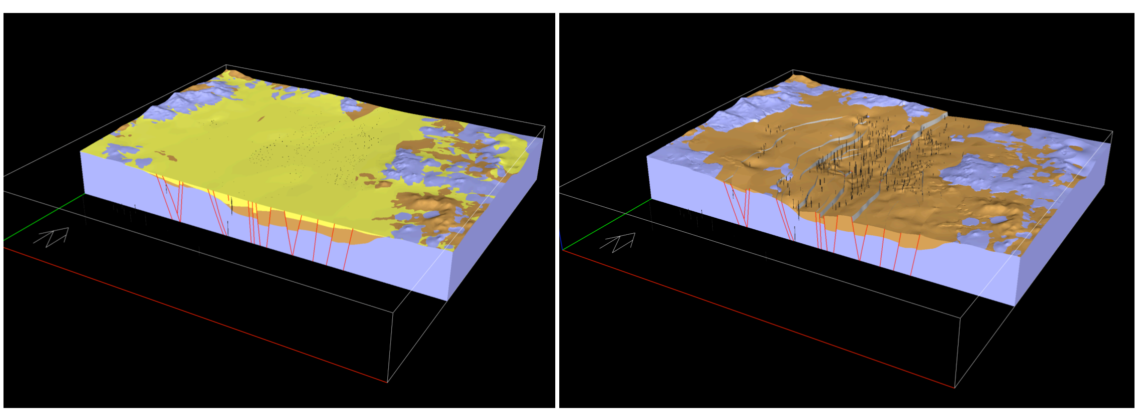


Figure 1: A highly faulted static geomodel in the Basin and Range Province of Nevada. The right image is the same model as the left one but with the alluvial basin fill (yellow layer) stripped off.

The faults are generally defined by seismic data, surface geophysical measurements, stratigraphic data, and surface expression. The faults can represent either transmissive pathways or permeability barriers, which prevent the movement of gas and fluids. To understand which faults are transmissive vs. sealing, one must know both the orientation of the fault and the region stress direction; this cannot be estimated without BOTH pieces of information.

This type of 3D geological model is necessary to understand the interpreted complex relationships of the fault structure to the stratigraphy and drilled boreholes. This complex model can be converted to a 3D property grid and/or mesh and can then be linked to other simulator codes for additional simulations. Accurate population of these models requires large amounts of borehole, core, porosity, and permeability data. The resulting grids and meshes will honor the complexity of the geological model, which is critical for producing realistic simulations.

Figure 2 is an example of a regional model that was developed to improve our understanding of the location and character of potential sequestration targets in the southern part of the San Joaquin basin. This regional framework model is about 50 km x 50 km in size; smaller models of any size can be easily extracted within this range, using the same basic data sets (e.g., Figure 3). The smaller model reveals the detail of the geology in the potential injection area and was used to initialize and constrain further flow and transport simulations as well as understand potential risks and hazards of the site. These extracted submodels also are necessary to focus on the details of a specific site and its associated the technical issues such as well planning, monitoring design, and avoiding risk and hazards. Both models require multiple wells and multiple data streams to condition the models for accuracy and provide constraints on rock type, continuity, porosity, permeability, composition, and structural features (see figure 6 below).

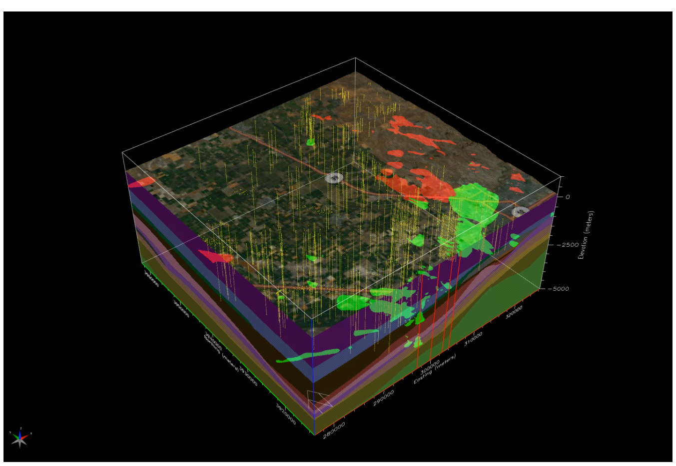


Figure 2. This regional model was developed to access CO2 storage capacity and help select potential pilot sites in the southern part of the

San Joaquin basin. This model is 50 km x 50 km and shows the location of and locations of oil and gas fields.

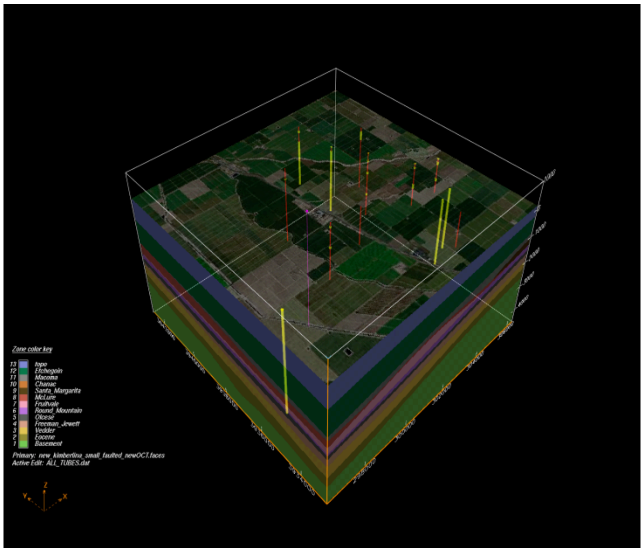


Figure 3. This 10 km x 10 km submodel was extracted from the regional model in Figure 2. This figure shows the oil and gas wells located near a potential CO_2 injection site (purple symbol). The yellow columns are areas where the hole has been plugged with cement. The red areas of the well are either open or filled with drilling mud.

Figure 4 is a structural contour map on top of the target reservoir built with 9 seismic lines and over 100 wells. It shows the character of this surface, identifying locations of faults. These faults were identified on regional seismic lines that constrained the location, orientation, offset, and continuity of the fault, which was used to understand project risk for geological sequestration. This type of presentation is extremely valuable in all site characterizations, since it provides physical constraints for the location and continuity of important layers over a model domain. Similar maps would normally be generated for potential reservoirs, seals, and key market units.

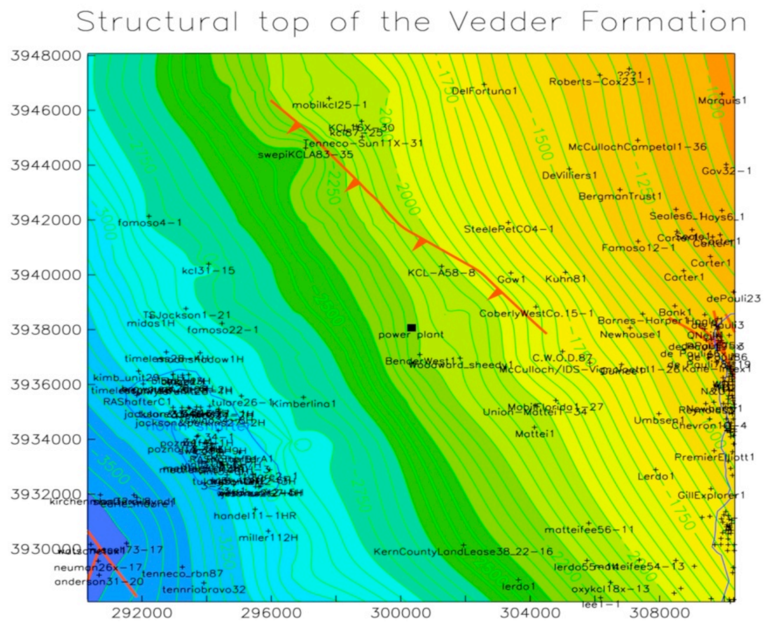


Figure 4. Structural contour map of the top of the target reservoir formation.

Figure 5 is a 2D cross section through the 3D model shown in Figure 3. These sections include detailed correlation of the downhole geophysical logs run in each well. These logs show the variation in the stratigraphic section, as well as the locations of possible offsetting faults in the area.

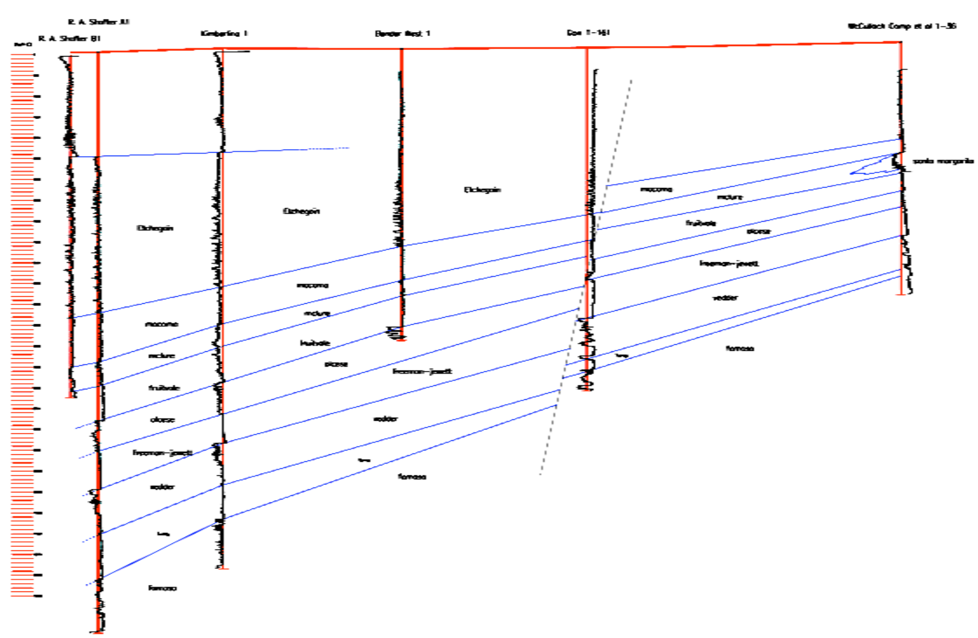


Figure 5. Example cross section trending SW-NE through the site-specific model shown in Figure 3. The correlated geophysical logs are SP logs.

Lithofacies Geomodels

Lithofacies modeling, in which different lithologies are modeled within the stratigraphic framework model, are critical to understanding the spatial distribution of physical properties. Detailed lithologic analysis is done by interpretation of downhole geophysical logs. These models are particularly important because the lithology of the major stratigraphic units can vary significantly and it is the lithology that generally determines the physical properties of the rock. Figure 6 is an example of a basin-scale lithofacies model and shows the variation of lithologies across the basin in southern Nevada. More than 1100 geotechnical boreholes were logged across the basin and the lithologic units intersected in these holes were documented. Each rock type has a typical range of physical properties identified from core and well-log analysis; these data can be used to create a 3D model of selected properties. Smaller site-specific models area extracted from this dataset, allowing for a detailed view of the distribution of lithologies within the project area and accurate initialization of flow simulations, geomechanical simulations, and geochemical responses to perturbations (like CO2 injection).

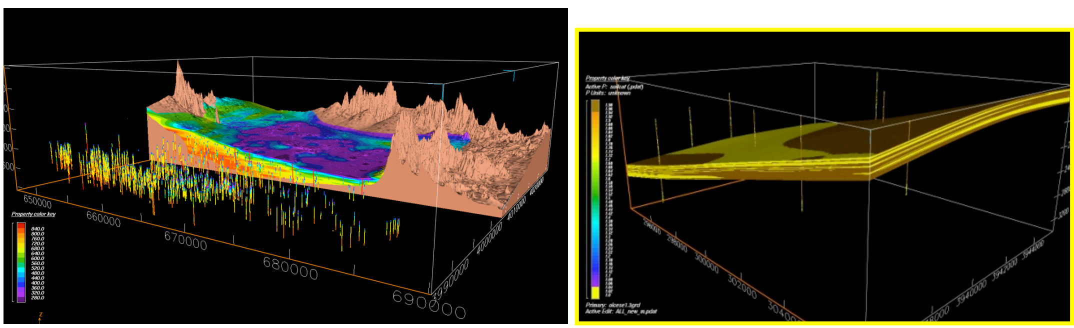


Figure 6. Two examples of lithofacies models: Left: The southern Nevada basin: the model shows the variation of several lithologies within the basin defined by the hundreds of wells (shown as vertical multicolored lines). Right: Lithofacies and porosity models of the Olcese formation, derived from 7 wells within the 10 km x 10 km extracted model, Southern San Joaquin. All available core and well-log data were required for accurate model calibration.

4-Populating the geomodel with measured physical properties

Example from the In Salah CO_2 sequestration project (Krechba Field)

The In Salah project in Algeria is an industrial-scale CO_2 storage project that has been in operation since 2004. CO_2 from several gas fields, which have a CO_2 content of 5-10%, is removed from the production stream. Rather than vent the separated CO_2 to atmosphere (as was normal industry practice for such gas plants), BP and its joint venture partner invested an incremental $100 million in a project to compress, dehydrate, transport, and inject that CO_2 into a deep saline formation down-dip of the producing gas horizon. The injection formation is a 20-m thick Carboniferous sandstone, 1900 m below ground with around 15% porosity and 10 mD permeability. Three state-of-the-art horizontal CO_2 injection wells were drilled perpendicular to the stress field, and therefore the dominant fracture orientation, to maximize the injection capacity. By the end of 2008, over 2.5 million tonnes of CO_2 have been stored underground.

Using detailed geological characterization and reservoir modeling, the investigators were able to model the likely consequences of CO2 injection and design their injection wells accordingly. This integrated analysis illustrates the geological controls on the movement and dispersion of the CO_2 plume, giving invaluable insights into the long-term performance assessment of this storage site. Eighteen wells intersect the Carboniferous reservoir and aquifer zone and have been used to create a detailed reservoir characterization of the storage system. In addition to conventional wireline and core data, three wells have image log data and two have detailed geochemical gas analyses. Together with the seismic data, these data have been used to construct geological and reservoir models of the reservoir, aquifer, and cap rock system. The structural geological setting for the storage site has been assessed using regional geological analysis, seismic data, image logs, and core data.

The Krechba field is located in Algeria and consists of a low relief anticline. The main reservoirs are Carboniferous sandstones at a depth of 1700 m, and Devonian sandstones from 2800 – 3000 m (Figure 7). The areal extent of the field is about 130 km^2. The reservoir is influenced by strike-slip faults propagating up from the underlying Devonian sequence. The structural character at the reservoir level is illustrated in Figure 8, with CO_2 injection on the margins of a gentle anticlinal structure. Image log and core analysis show the presence of conductive fractures aligned with the present-day stress field (NW-SE), with fracturing locally controlled by fault and fold architecture (Figures 9, 10). Three-dimensional seismic data surveys were conducted at In Salah and these data are critical to constrain the geological interpretation. Along with lithologic data collected from core, 3D seismic data can be used to construct three-dimensional models of the subsurface (Figure 12). Multiple seismic surveys (4D) are invaluable to track changes in the subsurface resulting from injection of the CO_2.

Accurate simulation of CO_2 injection at the Krechba gas field (In Salah, Algeria) requires multiple data sets to inform multiphase flow modeling, the hydrogeomechanical response of the subsurface environment to elevated fluid pressures arising from injection, the geochemical reactions associated with CO_2 injection which can impact porosity and hence permeability over long time scales. These data sets range in scale from major structural features apparent at the reservoir scale to individual faults within given formations to the distribution of mineralogy at the pore scale.

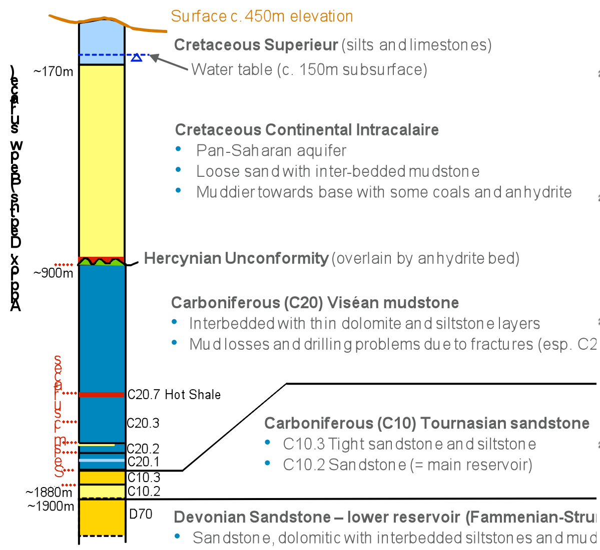


Figure 7. Krechba stratigraphic column.

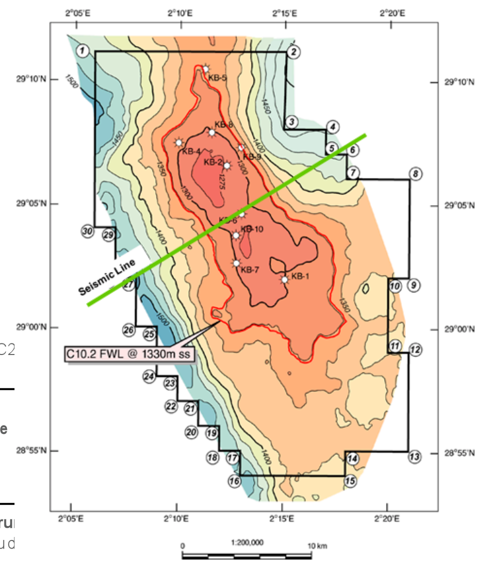


Figure 8. Geologic structure map (depth to the top of the reservoir unit) at Krechba, inferred from a 3D seismic survey.

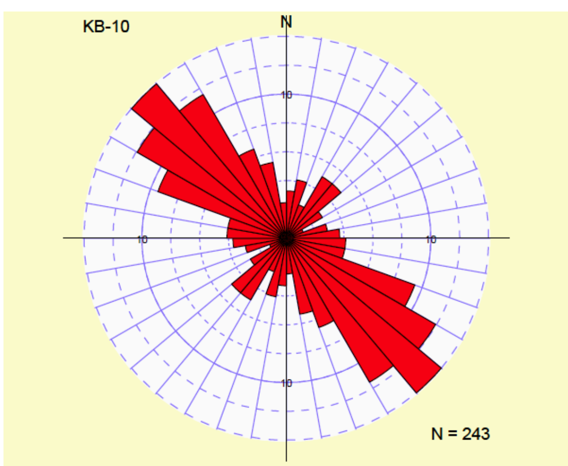


Figure 9. Fracture strike directions as identified from well

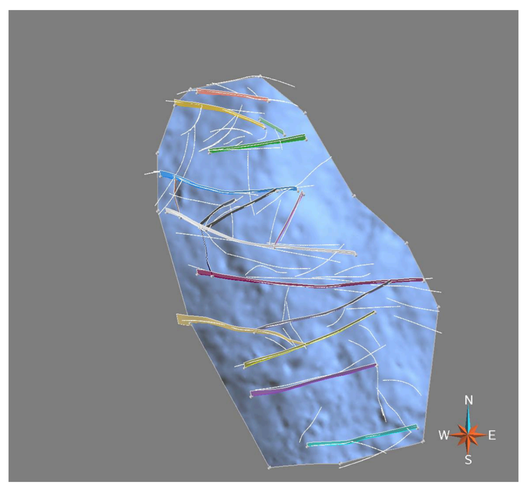


Figure 10. Fault map for the Krechba reservoir, with faults inferred from 1997 3D seismic data.

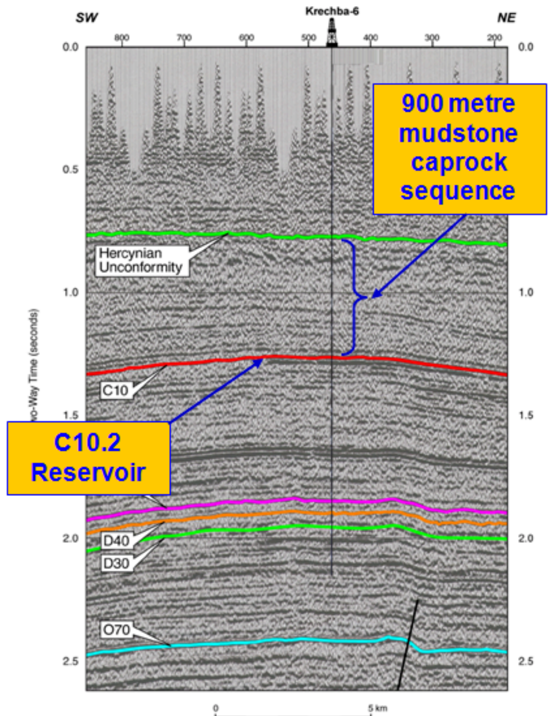


Figure 11. Travel time plot at In Salah.

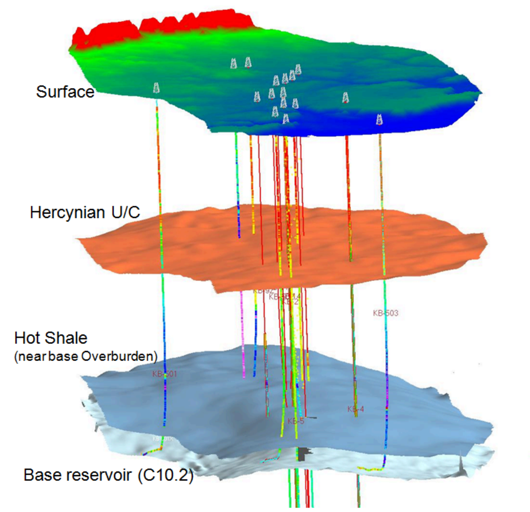


Figure 12. Example shared earth data set for Krechba

Borehole geophysical logs (Figure 13) and core laboratory measurements (Figure 14) provide data which can be used to map laboratory measurements to the reservoir scale using seismic data (Figure 15). Such inferred distributions of permeability and porosity within the formation are a key trial data set with which to inform a calibrated multiphase flow model for CO_2 injection into the reservoir.

Data that support modeling multiphase flow through preferential high permeability conduits include fault maps (Figure 10), again inferred from three-dimensional seismic data, and fracture orientation plots obtained from core samples (Figure 9). Fault maps can be used to delineate features that are explicitly discretized in a numerical flow model such as large faults that may act as conduits or barriers to flow, depending in part on stress orientation. Individual fractures, in contrast, represent features that are too small to discretize explicitly but the effects of which can instead be modeled implicitly using permeability anisotropy or dual continuum simulation approaches.

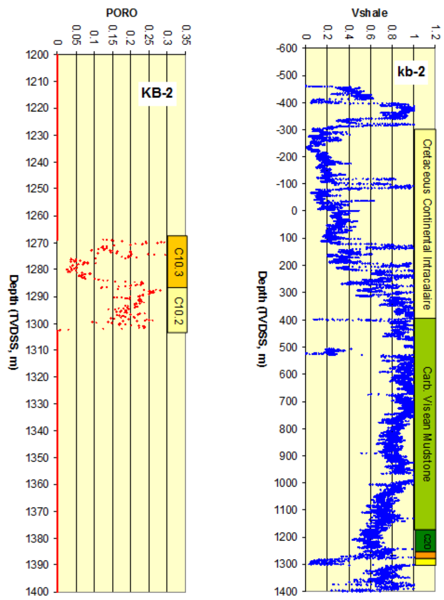


Figure 13. Porosity log (left) and shale log (right) from a Krechba well.

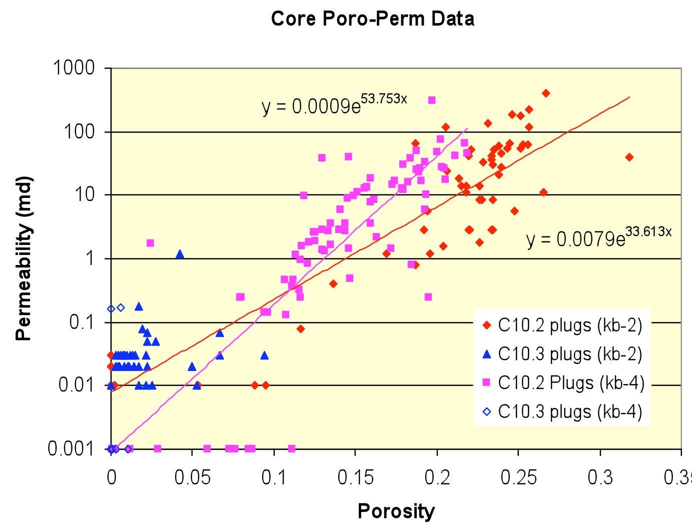


Figure 14. Relationships between permeability and porosity gleaned from core plug experiments.

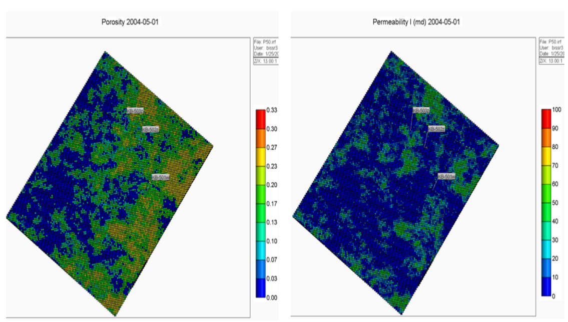


Figure 15. Inferred distributions of porosity (left) and permeability (right), inferred from core plug experiments and mapped to the reservoir scale via borehole geophysics and 3D seismic data.

Geochemical Properties

Realistic simulation of geochemical reactions that may occur in the formation as a consequence of CO_2 injection and dissolution requires brine composition data (major cation and anion concentrations and pH, supported by trace element to help constrain putative reactive mineral phases) in addition to formation mineralogy. At Krechba, insights into the latter have been provided by SEM and XRD studies as well as cathodoluminescence analyses (Figure 16). The values of pertinent equilibrium constants and kinetic rate parameters needed for geochemical modeling are often strongly temperature-dependent, so subsurface temperature data are also required. Temperature data also assist in constraining CO_2 and brine fluid properties such as viscosity.

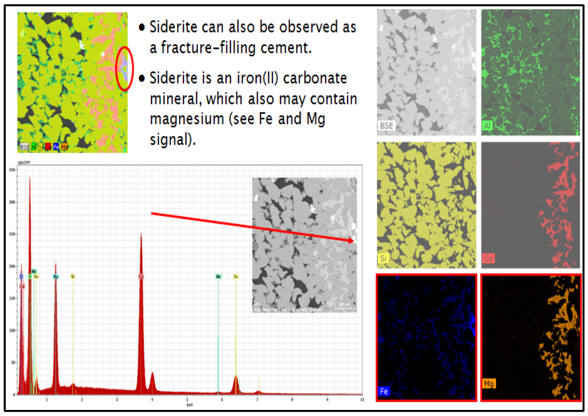


Figure 16. Mineralogical characterization of a core sample from In Salah borehole.

Summary

Development of accurate simulations, well designs, monitoring network developments, and hazard assessments requires access to abundant geological, geophysical, and geochemical data. Increased data access is required to improve the accuracy of models, increase the value of designs, and avoid costly mistakes. It is extremely important to share access to what data is present to avoid high levels of uncertainty and inaccurate simulations.