Energy and Environmental Systems Group
Institute fo Sustainable Energy, Environment and Economy (ISEEE)

Executive Summary

WABAMUN AREA CO_2 SEQUESTRATION PROJECT (WASP)

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Background

The geologic storage of carbon dioxide (CO_2) could enable Canada to exploit its fossil energy resources while simultaneously managing its CO_2 emissions. Developing cost-effective, environmentally sound and publicly acceptable CO_2 storage depends on building the public's understanding of the long-term safety and storage capacity for underground CO_2 storage. Knowledge must be in the public domain, because only then can it assure policy makers, regulatory agencies and the public that these operations are safe and that CO_2 has been permanently removed from the atmosphere. Both safety and capacity are important. Without assurances for environmental safety, storage makes little sense and without public confidence, sufficient storage capacity will not be made available to make a meaningful impact in economy-wide CO_2 emissions removal. If these situations exist, it makes little sense to invest in scaled-up storage capacity.

The WASP study was conducted by a group of 16 University of Calgary (U of C) researchers and industry consultants over a period of 16 months from March 2008 to August 2009. The study performed a comprehensive characterization of large-scale CO_2 storage opportunities over a large 5000 km^2 area (Figure 1) in central Alberta. It also analyzed potential risks. As a benchmark, the project examined the feasibility of storing 20 Mt-CO_2/year over 50 years. This gigaton-scale storage project is more than ten times larger than the commercial projects that are currently under review. It fills a gap between the province-wide capacity estimates (which do not involve site-specific studies of geology, flow and geomechanics) and the detailed commercial studies now being performed for individual CO_2 storage projects. Unlike commercial projects, this study is a public non-confidential project lead by the U of C in cooperation with Alberta Geological Survey.

A number of large stationary CO_2 emitters are located in central Alberta with cumulative CO_2 emissions of 30 Mt annually. This includes four coal-fired power generation plants in the Wabamun Lake area, which is located southwest of Edmonton. Emissions from these plants range from 3 to 6 Mt-CO_2/year. Although significant CO_2 storage capacity exists in depleted oil and gas reservoirs within the Wabamun area, these may not be available in the near future because most of the reservoirs are still producting. Moreover, the large Pembina Cardium oil fields located just south of the Wabamun Lake area are now producing through the assistance of mature waterflood systems and many are in the initial stages of investigating the use of CO_2 as a miscible flooding agent to further enhance oil recovery (EOR). Commercial scale use of CO_2 for this purpose is still a few years away and until then, these pools will require only pilot-scale volumes of CO_2 for reservoir characterization and testing purposes. As a result, CO_2 storage in deep saline aquifers is a likely near-future scenario for large scale CO_2 sequestration. While it is certainly possible to move CO_2 from the Wabamun area to distant storage locations, it is of considerable interest to public policy makers to determine if large-scale storage is feasible in the immediate vicinity of the power plants.

Early in the study, the Nisku aquifer was selected as the primary target for CO_2 sequestration. About a quarter (12 townships over the top northeast diagonal) of this area has current oil and gas exploration and production activity occurring in the Nisku formation, and represent a less desirable location for CO_2 injection in the short term. The remaining 38 townships were assessed as a possible repository for current CO_2 storage. Wells drilled in the area over the past 50 to 60 years enabled the study team to access geological and petroleum engineering information. Data was available primarily from two sources: public domain databases and oil and gas seismic data for the study area.

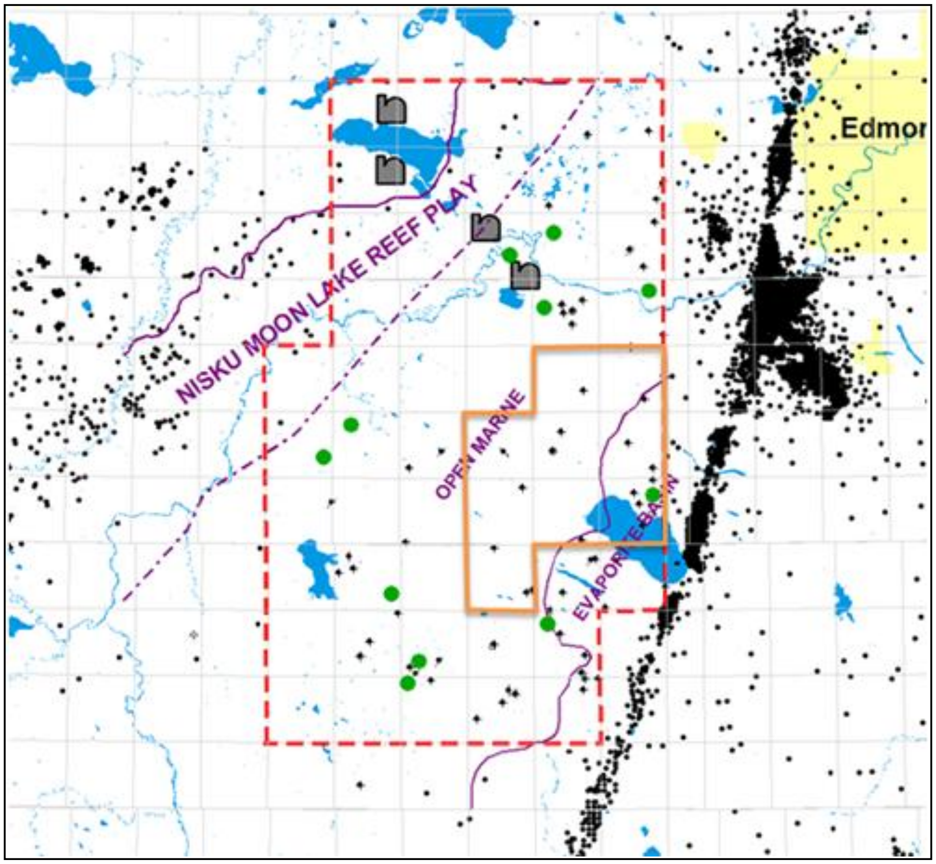

Figure 1: WASP Study Area

The WASP study was unusual in the aerial extent of the study area and the 1 Gt-CO_2 notional target for CO_2 injection. This scale raised new challenges with respect to available data. The most difficult challenges were as follows:

1. Only 96 wells (an average of 2 wells per township) have penetrated the Nisku aquifer's primary geological horizon.
2. Only two of these wells are active. One serves as a water source well and the other as a water injection well. Both are used in an up-hole waterflood operation. With so few wells, the team's ability to obtain fluid samples or use pressure measurements to test large-scale connectivity within the Nisku aquifer was limited.
3. Seismic data was plentiful, however, it was acquired for a variety of purposes over many decades. This resulted in the data being heterogeneous, which necessitated careful re-interpretation to maximize its value for characterizing the Nisku aquifer. In addition, the depth, thickness, and impedance contrast of the formation makes it a challenging target for seismic analysis.
4. Available core samples are very old (30 to 60 years) and not appropriate for geomechanical experimentation.
5. Well tests with limited duration were conducted using old pressure-measurement technology.
6. The Nisku is a marine carbonate reservoir, which makes the application of geo-statistical tools more difficult than for clastic sedimentary formations.

The challenge of sparse data relative to large study areas is likely to be inherent in any gigaton-scale CO_2 storage study. The WASP team exploited existing Nisku data to develop a range of models that were used to make initial assessments regarding favourable locations for further assessments. Uncertainties can be reduced in local areas, if reservoir evaluations for specific injection locations are performed. The WASP study has provided recommendations for prospective locations for CO_2 storage within the WASP study area, as well as site-specific evaluation methodologies (see the impedance analysis of the Geophysical Analysis and the porosity and permeability estimations in the Geological Modelling sections).

In addition to site-specific results, the WASP study has generated insights into how to manage large-scale CO_2 storage studies that aim to simultaneously evaluate secure large-scale storage while identifying prospective locations for storage sites.

Geological Characterization of the Nisku Aquifer for CO_2 Sequestration

Although other geological formations in the Wabamun Lake area have CO_2 storage capability, the Nisku aquifer was selected because of its depth, good reservoir qualities, and lack of oil and gas plays in the area of interest. The Nisku formation also scored well on the delicate balance between the availability of data (number of penetrating wells) and the risk of well leakage. One other deep reservoir, the Basal Cambrian sandstone, exists below the WASP study area. Unfortunately this horizon suffers from a lack of well penetration and associated data. Therefore, the WASP evaluation was limited to the Nisku aquifer.

Findings from the study include the following.

1. Mean porosities for the Nisku interval range from 3 to 5%, with localized zones in excess of 10%. These findings were determined from available core analyses and petro-physical wireline logs.
2. Permeability from core measurements (air permeabilities) yielded a median of 10 mD, but values are strongly heterogeneous with some intervals having values in excess of 1000 mD.
3. Geostatistical methods successfully made use of the more abundant wireline log information to create best-efforts-basis mapping of the distribution, connectivity, and size of the better porosity/permeability intervals. New statistical correlations were exploited between wireline resistivity and conductivity measurements, and porosity and permeability values were determined using core analyses. These correlations were then used to estimate porosity and permeability when core data was unavailable. Although these correlations are informative, further research is necessary for validation. This work is described in detail in this report (see Using Resistivity/Conductivity to Estimate Permeability in the Geological Modelling section).
4. Zones of high porosity (8% or higher) found from logs were distributed unequally in depth, with the lower third of the reservoir showing a higher than expected number of high permeability zones. Unfortunately, most of the core samples were only available for the upper third of the interval. This highlights the importance of using analyses that derive porosity/permeability data from wireline measurements.
5. A geostatistical method using “Geo-bodies” or “objects” was successfully employed to model the connectivity of high and lower porosity and permeability regions. Statistical information about geo-body distribution was gathered from satellite imagery of modern analogs for the Nisku aquifer. A large amount of uncertainty remains about the nature and extent of high porosity/permeability zones within the Nisku interval.

6. Geological models were generated and exported successfully for use in fluid-flow simulators. These simulators suggest potentially good injection volume capability is available in the Nisku aquifer (see summary of numerical modelling results below).

Geophysical Characterization of the Nisku Aquifer

The study area was explored using vintage surface seismic data that had been acquired as hydrocarbon exploration over many decades. The WASP team had access to approximately 200 seismic lines (2432 km total length) and seven 3D seismic volumes (419 km^2 total area). The datasets have varying acquisition and processing specifications. Therefore prior to interpretation, inversion and attribute analysis, two primary steps were taken. One was data calibration and the second amplitude normalization. While a catalog of seismic data was made covering the entire WASP region, detailed analyses was concentrated on the proposed CO_2 injection region.

The following are the most important findings.

1. There was no sign of faulting in the WASP study area.
2. The time structure map for the Nisku aquifer is smooth and consistent with the NE-SW regional dip orientation.
3. Several localized anomalies were detected in the focus area. The WASP team concluded that these were probably caused by dissolution (karsting) in the overlying Wabamun formation that occurred while it was near the surface. These locations should be avoided until further characterization can be completed to establish the level of connectivity between the Nisku and the Wabamun formations as a result of these features.
4. Several favourable zones of low acoustic impedance and high bulk porosity were identified in the study area. Ambiguity remains around how much the increase in shale content has impacted these measurements. Nevertheless, these zones are prospective as high permeability/porosity possibilities.
5. The use of surface seismic as a method of mapping the development of a Nisku CO_2 plume was difficult because of the thin nature of the Nisku formation. Therefore, other methods of monitoring CO_2 movement within the formation will be necessary.

Geochemical Characterization of the Nisku Aquifer for CO_2 Sequestration

The WASP study has compiled a baseline of geochemistry data for the Nisku formation using public domain data. This information was used in the geochemical modelling of the CO_2 injected into the Nisku formation over a 50-year period. The key findings of this model are as follows.

1. Nisku bines are “sour” in that they contain potentially significant concentrations of dissolved H_2S.
2. Small amounts of dolomite and calcite will be dissolved and/or precipitated in the reservoir. According to the simplified model, mineral trapping will likely only play a minor role in CO_2 sequestration.
3. For sulfur-containing species, there are no significant observable differences in the chemical or mineralogical reactions between H_2S and non-H_2S containing aquifers.
4. A further significant finding is the potential for H_2S to be exsolved into the advancing pure CO_2 plume. This point is discussed further in the reservoir modelling section below.

5. ToughReact is a 1D reservoir simulator with full geochemistry and was used to study the injection process. Please note that the differences between the results from ToughReact and the reservoir modelling sub-group have not been resolved. The preliminary results of the ToughReact simulations are as follows.
    a. Between 34% (after 1 year) and 56% (after 50 years) of the injected CO_2 that dissolves in the brine will convert to bicarbonate (HCO_3^-) in a process called "solubility trapping".
    b. Approximately 26 times more CO_2 will be sequestered in the brine compared to mineral trapping.
    c. CO_2 injection will likely create a dehydrated region around the injection wellhead with the radius increasing from ~ 20 m after 1 year to 140 m after 50 years.

Reservoir Modelling of the Nisku Aquifer for CO_2 Sequestration

A number of reservoir models are discussed in this report. They range from generic assessments of CO_2 plume development using Nisku parameters to a full 3D areal model of the entire Nisku aquifer that assesses the long-term fate of a large scale 20 Mt/yr over 50 years CO_2 injection project. The following are the most important results from the reservoir modelling activity.

1. The primary limit to CO_2 storage capacity in the Nisku is the buildup of pressure at the injection wells. On the 50-year injection timescale, the entire WASP study area will be pressurized, so one cannot treat individual injection operations independently.
2. Although the large-scale pressure field is controlled by the total rate of injection into the Nisku, the pressure at the injection wells will be substantially higher than the large-scale background pressure. It is a requirement that injection well pressure be below fracture pressure, which will provide the first order of constraint on storage volumes.
3. Methods to increase near-well injectivity can significantly reduce near-well pressure and increase overall storage capacity. For example, horizontal injection wells and the use of modern methods to stimulate these wells (i.e., controlled multiple vertical fractures), can increase total storage capacity by ~ 50% while maintaining a given maximum wellbore pressure.
4. Available pore space is not a significant limitation in the 50-year scenario with no brine production.
5. The CO_2 saturation plumes associated with large-scale multiple injection projects do not show interference and are limited to radii of about 4 or 5 km, assuming injection rates of 0.25 to 0.5 Mt/yr/well.
6. Managing reservoir pressure by removing brine from the Nisku formation may substantially increase overall storage capacity.
7. H_2S dissolved in the Nisku aquifer brine may pose an additional risk when the gas front passes by existing wells. Maximum H_2S saturation in the gas phase is located at the leading edge of the advancing CO_2 plume; and the composition of the gas at the edge can be dominated by H_2S even for relatively low-dissolved H_2S concentrations in the brine. This is an important and unique finding for the WASP study that underscores the importance of proper geochemical characterization of the formation fluids prior to initiating a CO_2 sequestration project. Knowledge of these phenomena enables engineers to properly plan for the existence of H_2S in potential produced fluids associated with future plume management programs.

One of the most significant finding is that plume pressure management will be required to increase CO_2 storage capacity in large-scale CO_2 sequestration projects. Members of the WASP team have previously published studies on the engineering methods needed to “manage” the placement of CO_2 plumes to mitigate the saturation plume radius using methods that force CO_2 dissolution. It is almost a certainty that these approaches will eventually be required once many large scale CO_2 sequestration projects are underway and competing for aquifer storage space. If these methods are employed and they involve brine production from a target reservoir, it will be very important to be aware of any increase in H_2S concentrations in the advancing CO_2 plume.

Geomechanical Data Analysis of the Nisku Aquifer for CO_2 Sequestration

In-situ stress fields for the subsurface of the Wabamun CO_2 storage area where established based on existing analyses. These analyses provided guidance for determining maximum injection pressure and acted as boundary conditions for further geomechanical modelling efforts.

A table of geomechanical properties for the subsurface at the Wabamun CO_2 storage area was created. Well logs were used to establish dynamic deformation properties (Young’s modulus, Poisson’s ratio and bulk modulus) and correlations were used to determine static deformation properties. The unconfined compressive strength (UCS) was established for each lithology based on correlations with log properties. The created database was used as input data for the geomechanical modelling component of the WASP study. The lower sedimentary succession within the Nisku aquifer and Calmar cap rock is very competent stiff rock.

When new cores become available from future drilled CO_2 sequestration wells, it will be important to perform a modern suite of geomechanical tests on these samples. For example, tri-axial laboratory tests are recommended to confirm the accuracy of the UCS correlations for the site and to adjust the dynamic-to-static conversion factors. Because of the age of the existing cores, they are not suitable for this kind of laboratory analysis.

Geomechanical Modelling of the Nisku Aquifer for CO_2 Sequestration

Potential surface heaving and hydraulic-induced fracturing because of a large scale CO_2 injection project were investigated using GEOSIM, a state-of-the-art coupled flow and geomechanical modelling program. Injection of CO_2 into the Nisku aquifer (premised on bottom hole injection pressures being below fracture pressures) is not likely to cause any significant surface heave or environmental impact associated with surface deformation.

Injection of CO_2 above the fracture pressure will have the potential to increase well injectivity, but may also fracture the caprock. This underscores the importance of acquiring detailed laboratory geomechanical fracture tests on fresh caprock core samples.

Also of significant importance is the need to determine the thermal impact of cold CO_2 injection on the reduction in fracture pressure. Indications from the reported work suggest that cold CO_2 injection may significantly reduce the fracture pressure, while improving the containment of the fracture to the injection zone and reducing the likelihood of fracturing the caprock. This is of particular concern/interest for any large scale commercial CO_2 sequestration projects.

Well Integrity Review of Existing Wells Penetrating the Nisku Aquifer

After a thorough review of the existing wells penetrating the Nisku aquifer, only 4 of the 27 wells in the WASP focus area (smaller region highlighted by an orange boundary in Figure 1) were deemed to require remediation work. This is a welcomed outcome relative to original concerns that abandoned wells drilled through the Nisku aquifer would require significant remediation. More details are reported in the Well Integrity section of this report.

The cost of a properly designed and constructed vertical CO_2 injection well is around $1.3 million CAD. The oil and gas industry already drills and completes this class of well with good results and integrity.

Based on the results of the literature review conducted for the WASP study on the impact of injecting cold CO_2, there is some concern relating to thermal and pressure cycling effects on cement sheath integrity for future CO_2 injection wells. More experimentation using scale models and in-situ testing is needed to fully assess these issues.

Risk Based Leakage Model for the WASP Study

Golder and Associates developed a probabilistic analytical simulator capable of evaluating alternative leakage scenarios associated with legacy wells in multiple formations. The intent of developing this model was to provide a tool that would help with the prioritization of site characterization needs by reducing the overall uncertainty in the ultimate performance of a potential carbon capture site (CCS) site.

Results generated by the model are preliminary. More site-specific information would be necessary to fully utilize the model to establish risk levels that are meaningful for specific projects.

WASP CO_2 Monitoring Measurement and Verification Recommendations

This section of the report is intended to provide a specific set of recommendations relative to a full scale CO_2 sequestration project (i.e., 1 Mt/yr single CO_2 injector). Several stages of development are recommended before an actual full-scale CO_2 injection site is started. In addition, a set of specific monitoring requirements should be implemented for each stage of development.

Given that it was concluded in the geophysical analysis section that surface 3D monitoring of the movement of a CO_2 plume would not be useful, the need to drill monitoring wells (or recomplete existing wells) is stressed. Monitoring wells could be designed as information sources for small CO_2 sequestration projects, and could later be converted to brine injectors or producers for plume management for larger-scale CO_2 sequestration projects.

Although 3D geophysical monitoring of plume movement within the Nisku formation may not be feasible, monitoring of potential CO_2 leakage to the formations above the Nisku (i.e., Wabamun and Banff) may be possible, and would be a sensitive way to detect CO_2 movement. This would ensure the integrity of CO_2 stored in the Nisku. The extent to which baseline surveys are needed to use this method still needs to be resolved.

Full Commercial Scale Economic Summary

The cost for storing large quantities of CO_2 was addressed by developing cost models that reflected several simulated injection scenarios. The storage capacity was evaluated for a time period of 50 years for each injection well development scenario: vertical or horizontal injection wells with or without fractures to stimulate injection. The total volume of stored CO_2 was in the range of 210 to 430 million tonnes. These development scenarios assumed the use of ten vertical injection wells or ten horizontal fracture stimulated wells respectively. The cost model objective was to evaluate only the sequestration costs, which included all costs encountered from the wellhead down into the formation, as well as the costs for a monitoring program. The cost of capturing, pressurizing, and transporting CO_2 to the injection site was not included in the model.

The overall cost for the storage project was in the range of $700 million CAD for the injection scenario with ten vertical injection wells, and up to $1.1 billion CAD for the scenario with 10 horizontal hydraulically fractured injection wells. All values are stated in 2009 dollars. The average cost for storing a ton of CO_2 was estimated to be in the range of $2.7 to $3.4 CAD/ton depending on the type of injection well used. The lowest cost per ton was obtained using horizontal fracture stimulated wells, which also gave the largest amount of stored CO_2. The largest portion of the costs involved monitoring, which accounted for about 75% of the total cost. In addition, 4D seismic acquisition made up the majority of the monitoring costs.

Conclusion and Recommendations

The most important conclusion of this first phase of the WASP studies is that the Nisku aquifer continues to represent a viable location for the long-term sequestration of CO_2. All available public domain data (and a significant amount of industry seismic data) were used to arrive at this conclusion. Straight CO_2 injection without intentionally managing reservoir pressures (i.e., through brine production and re-injection into a different aquifer or location) will ultimately limit the capacity for CO_2 storage. In the case of the WASP study area, that limitation would be in the range of 0.25 to 0.40 Gt of cumulative CO_2 injection. However, this is a very conservative estimate of the total capacity for the Nisku aquifer's ability to accept CO_2. The total capacity for a "managed" project where net brine withdrawal is used to mitigate the increase in aquifer pressure could easily be 2, 3 or more times this conservative capacity estimate. In other words, the WASP study has identified the lower boundaries of the Nisku formation's storage capacity.

Future studies will need to go further to explore pressure and CO_2 saturation management of the injection plume. This would likely be accomplished with strategically located brine injection and production wells designed to accelerate solution and saturation trapping of CO_2 while maintaining a net total voidage replacement ratio of 1.0 (i.e., an equal reservoir volume withdrawal of fluids relative to the reservoir volume of injected CO_2). This will prevent average reservoir pressure from exceeding the initial pressure at the start of the project. Of course this assumes availability of capacity for re-injection of excess brine production into a suitable brine aquifer either above, below, or adjacent to the aquifer where the CO_2 is being sequestered.

Recommendations for Future WASP Studies

The following is a list of recommendations for future WASP studies.

1. Brine compositions in the WASP database are based on simple sampling methods that do not preserve dissolved gases. Consequently, bottomhole sampling or sampling through surface separators, is required to determine reservoir compositions of dissolved gases. Proper planning of a CO_2 storage project relies on this information.
2. Available seismic data has not been typically shot with the saline aquifer (in this case the Nisku formation) as the primary target. Coverage and vintage issues are also a factor that has limited the options for interpretation and modelling. New seismic programs specifically targeting the Nisku aquifer in the vicinity of a planned CO_2 sequestration site would be useful for the following reasons:
    a. for verification of what is currently being interpreted as karst features to assess the possibility that these features represent possible leakage paths,
    b. for verification of low impedance (higher porosity zones) within the Nisku formation, and
    c. to establish a baseline enabling future seismic to monitor movement of CO_2 to formations above the Nisku in the event of a breach of the cap rock or well seals.
3. Available core from the cap rock (Calmar formation shale) and underlying seal (Ireton formation. shale) are not adequate because of their age—often more than 30 years old and of a highly desiccated nature. Proper geomechanical analysis requires fresh core samples.
4. Various in-situ test programs are needed to assess the geothermal effects on fracturing of reservoir and cap rock and actual leakage rates through compromised cement behind casing and/or poor abandonment. Intentionally designed test wells and testing sites are vital.
5. Pressure management of the injection plume is critical. To that end, DSTs and core samples need to be taken from aquifers that are above and below the target sequestration site. Early on in the development of saline aquifer sequestration sites, characterization needs to address seal quality as much as the actual injection reservoir. Carefully planned and designed vertical pressure transient interference tests to determine the effective vertical permeability are vital for modelling of vertical CO_2 plume movement and evolution.
6. The deepest potential sequestration formations, such as the Basal Cambrian formation sandstone in the WASP region, also need to be appraised as potential CO_2 containers. The lack of financial incentives to explore these possibilities could result in better injection targets being overlooked.

The first phase of the WASP project was about characterization—determining what data is available, interpreting and integrating that data, and predicting system behavior during and after large-scale injection. The next phases of WASP will focus on acquiring data to compensate for the deficiencies listed above. A set of recommended test programs for wells intentionally drilled as test wells and/or CO_2 injectors will be identified and mathematically modelled. The analysis of these tests will facilitate improvements in the design of future large-scale CO_2 sequestration projects. As the rapidly growing industry for the geological storage of CO_2 is nascent, it is necessary and appropriate to define the strategies now to deal with data deficiencies specific to these projects.