Geomechanical Testing and Modeling of Reservoir and Cap Rock Integrity in an Acid Gas EOR/Sequestration Project, Zama, Alberta, Canada

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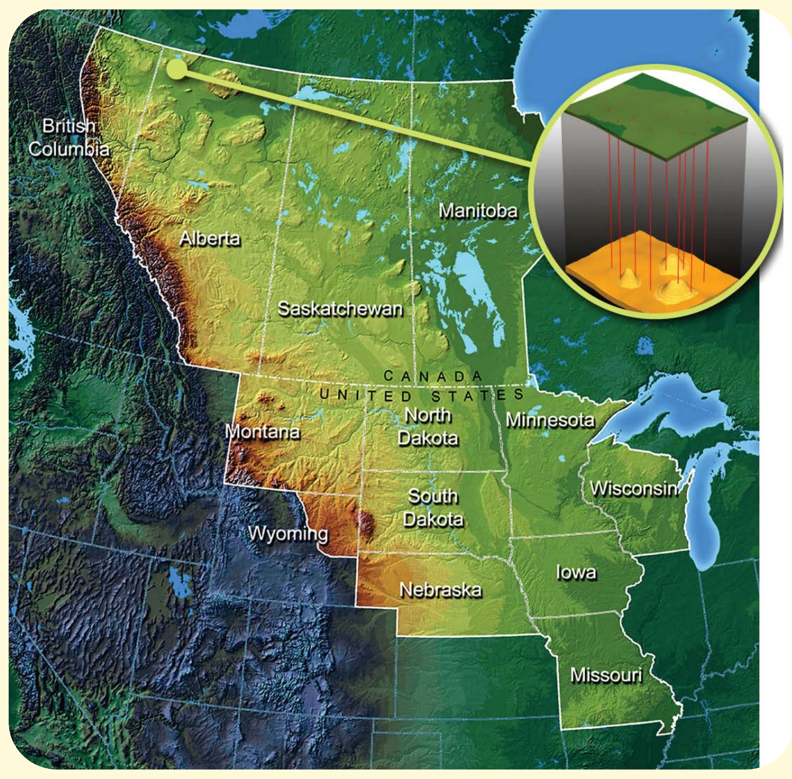


The PCOR Partnership region comprises nine states and four provinces in the central interior of North America. This work is being conducted as part of the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnership (RCSP) Program.

ABSTRACT

Since December 2006, a stream of acid gas (approximately 70% CO_2 and 30% H_2S) has been injected into a Devonian pinnacle reef structure in Apache Canada's Zama oil field in northwestern Alberta, Canada. The injection has been conducted at an average rate of approximately 25,000 m^3 of acid gas per day, which includes approximately 45 tonnes of CO_2 per day. This project includes a variety of efforts focused on examining the effects that high concentrations of H_2S can have on enhanced oil recovery (EOR) and carbon sequestration operations, particularly with respect to monitoring, mitigation, and verification.

As geological sequestration comes to the forefront of technologies aimed at reducing anthropogenic CO_2 emitted to the atmosphere, storage sink integrity becomes a paramount issue to address. One such research activity in the Zama project has been to investigate the geomechanical properties and in situ stresses in the Keg River Formation reservoir and the Muskeg Formation cap rock. Geomechanical testing in the laboratory, log analysis, and numerical modeling will help establish injection pressure thresholds and, hence, the overall integrity of the system. Laboratory tests have been conducted on core samples taken from the Zama Field, including uniaxial and triaxial compressive strength tests, static and dynamic elastic properties, pore volume compressibility, stress-dependent permeability, and compressional and shear wave velocities at varying stress levels. These data sets, along with new information being obtained in ongoing field and laboratory programs, will ultimately form the basis for developing a numerical geomechanical model of the F-Pool pinnacle reef that will be used to assess the long-term integrity of the reservoir/cap rock system.

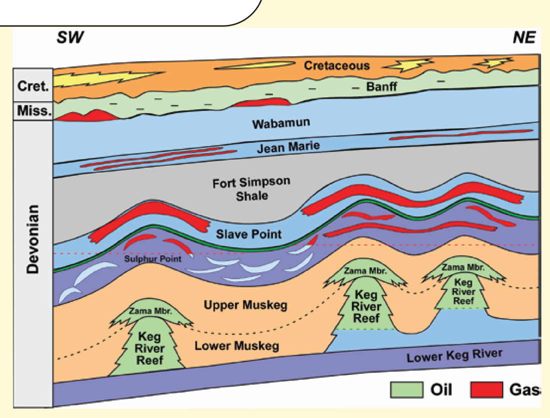
Numerical and analytical geomechanical modeling have also been used to examine perturbations in the reservoir pressure and, hence, in situ regimes in the reservoir and cap rock throughout the history of the field's initial oil production, water flooding and, most recently, acid gas injection. Findings and recommendations for monitoring and modeling carbon storage operations in this geological environment will be described. Initial results from this program indicate that the Muskeg Formation anhydrite cap rock has a high mechanical strength, high stiffness, low compressibility and very low permeability.

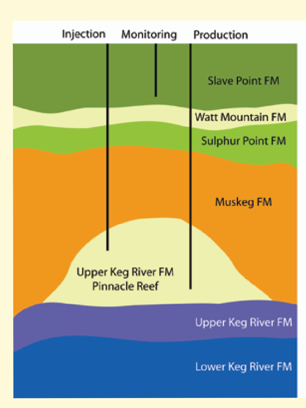
PCOR Partnership 2003–Present

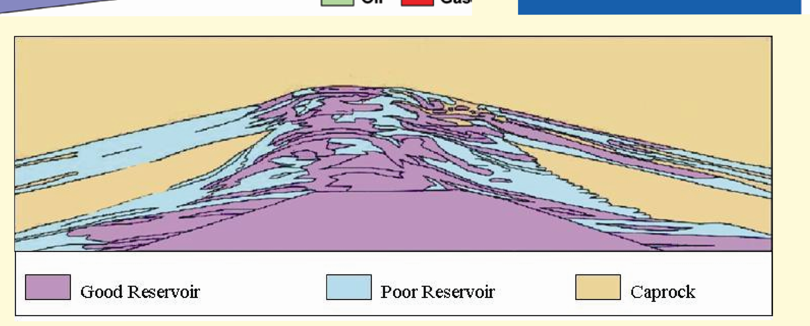
Project Participants
Apache Canada Ltd.
Weatherford/Advanced Geotechnology
University of Saskatchewan
RPS Energy
Natural Resources Canada
Energy Resources Conservation Board Alberta Geological Survey
U.S. Department of Energy National Energy Technology Laboratory
Energy & Environmental Research Center
University of North Dakota

PCOR Partnership

BACKGROUND



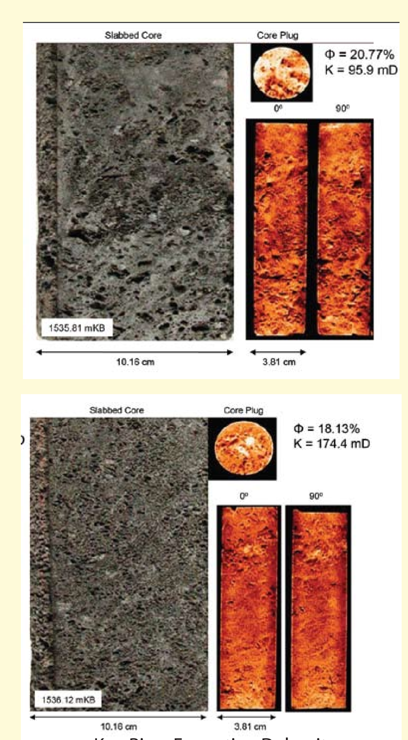




Injection occurs at a depth of approximately1500 meters into pinnacle reef structures as shown. Geomechanical integrity at the interface between the Muskeg anhydrite and Keg River reservoir is a primary research element in the project.

Core Samples that have been selected and analyzed are from zones representative of the anhydrite cap rock and dolomitic reservoir of the Zama Field.

Muskeg Formation Anhydrite



Keg River Formation Dolomite

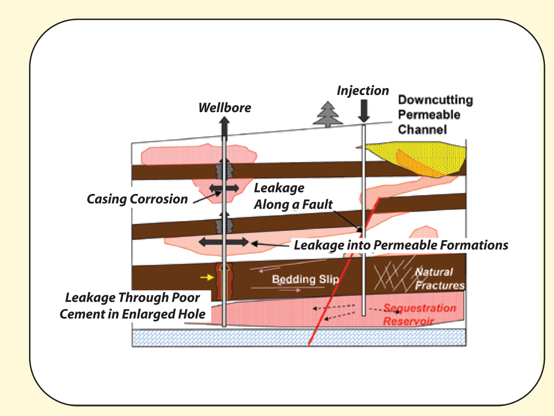
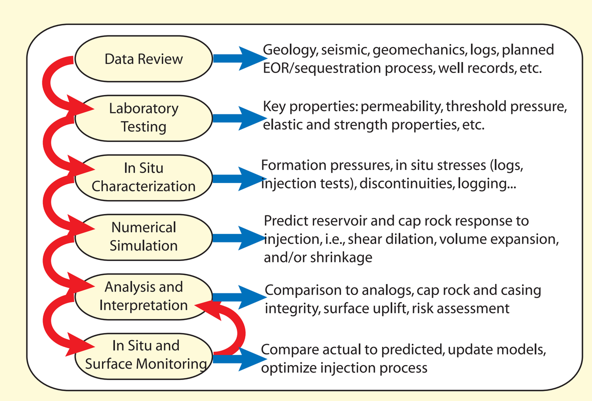


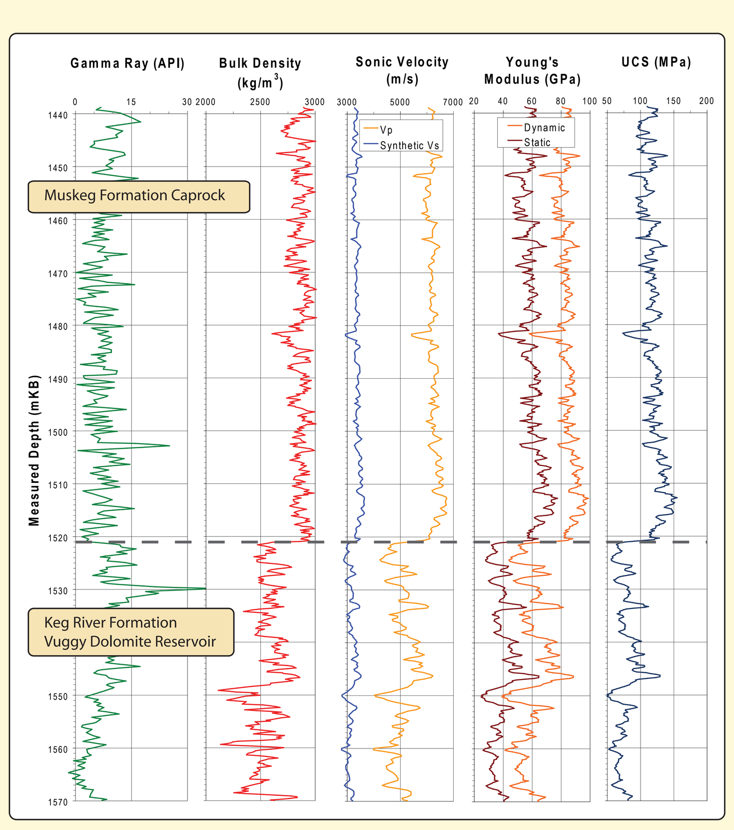
Illustration of the possible leakage pathways due to geomechanical failure. Their likelihood of occurrence due to the injection of acid gas at Zama is being evaluated through a rigorous testing, analysis, and interpretation process.



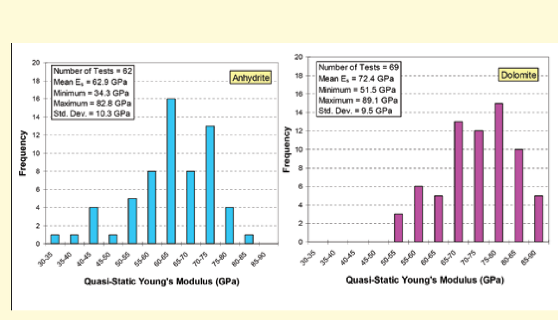
Geomechanical testing has followed a prescribed workflow proven effective through work conducted in conjunction with oil and gas exploration and production activities.

RESERVOIR AND CAP ROCK INTEGRITY TESTING

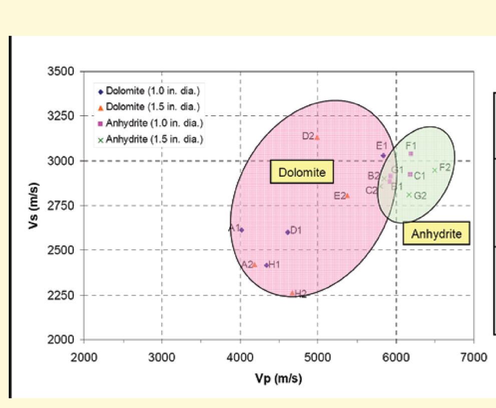
ELASTIC AND STRENGTH PROPERTIES



Log-derived rock and strength elastic properties profile in the Muskeg and Keg River Formations. Shear sonic velocity was derived from Vp–Vs relationships calculated from adjacent wells in the field. Dynamic to static and modulus–UCS empirical relationships were selected from Advanced Geotechnology's ROCKSBank mechanical properties database (2008).



Histograms of quasi-static Youngs modulus measured with the Schmidt rebound hammer on whole diameter core of the Muskeg Formation cap rock.

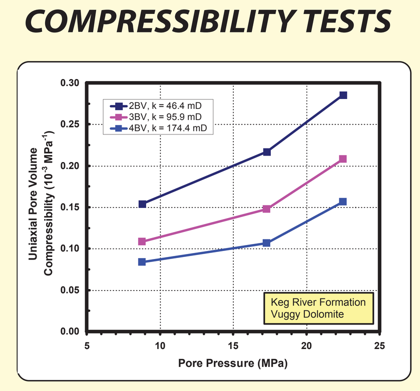


Summary of Calculated Dynamic Elastic Rock Properties From Unstressed Ultrasonic Velocity Apache Zama 6-4-116-6W6

Lithology	Plug Diameter (mm)		Dynamic Young's Modulus (GPa)	Dynamic Bulk Modulus (GPa)	Dynamic Shear Modulus (GPa)	Dynamic Compres-sibility (GPa^{-1})
Dolomite	25.4	Mean	49.73	37.75	19.76	0.055
		Std. Dev.	13.56	10.98	6.19	0.017
	38.1	Mean	49.91	36.38	19.92	0.052
		Std. Dev.	12.53	17.97	4.20	0.010
Anhydrite	25.4	Mean	65.84	76.30	24.31	0.041
		Std. Dev.	2.58	11.46	0.83	0.001
	38.1	Mean	67.84	73.57	25.20	0.040
		Std. Dev.	2.58	3.99	1.00	0.002

Cross-plot of measured Vp–Vs data from unstressed ultrasonic compressional and shear velocity testing of 14 Muskeg Formation and Two Keg River Formation core plugs.

UNIAXIAL, TRIAXIAL, AND COMPRESSIBILITY TESTS



Relationship between PVC and pore pressure during uniaxial pore volume compressibility testing of vuggy dolomite from the Keg River Formation reservoir. Sample porosities range from 18% to 21%, and confining pressure was held constant at 31.9 MPa.

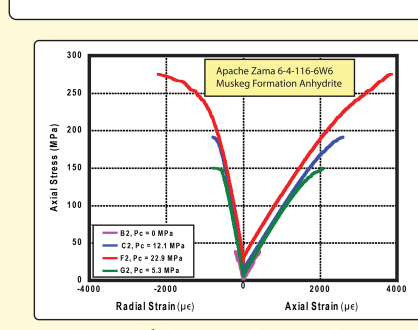
Definition of Uniaxial Pore Volume Compressibility

$$PVC = C_{pp} = +\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_p}\right)\Bigg|_{\sigma}$$

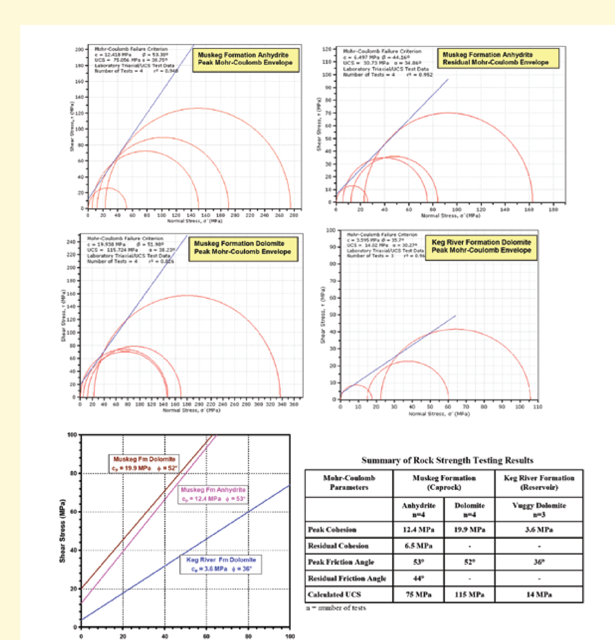
where V_p = pore volume
P_p = pore pressure
σ = total stress

This laboratory test measures the change in pore volume per unit change in pore pressure with the total axialstress, equal to the overburden stress, maintained constant.

PVC is used for many purposes, including: reserve calculations, well test analyses, prediction of formation compaction and surface subsidence, and the prediction of dilation or expansion with reservoir injection or production. There are many different PVC test configurations and stress paths possible depending upon the problem being solved.



Triaxial Stress–Strain Curve



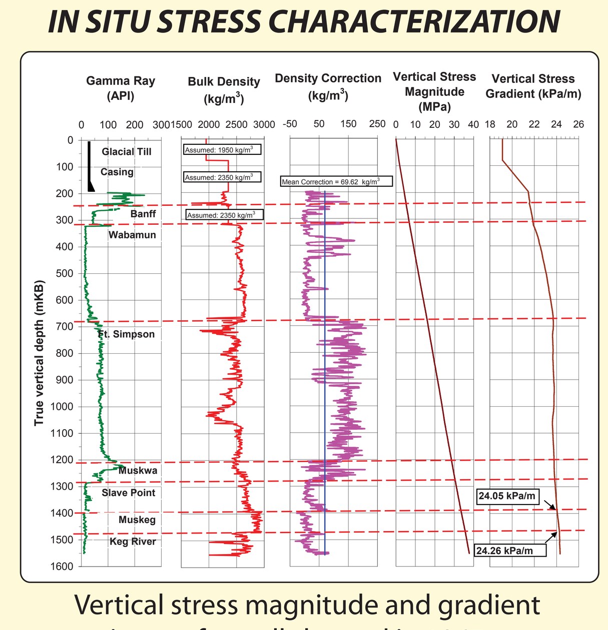
Summary of Rock Strength Testing Results

Mohr-Coulomb Parameters	Muskeg Formation (Caprock)		Keg River Formation (Reservoir)
	Anhydrite n=4	Dolomite n=4	Vuggy Dolomite n=3
Peak Cohesion	12.4 MPa	19.9 MPa	3.6 MPa
Residual Cohesion	6.5 MPa	-	-
Peak Friction Angle	53°	52°	36°
Residual Friction Angle	44°	-	-
Calculated UCS	75 MPa	115 MPa	14 MPa

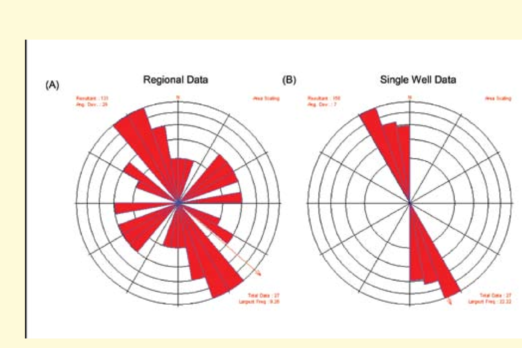
n = number of tests

Triaxial and Unconfined Compressive Strength Results

IN SITU STRESS CHARACTERIZATION

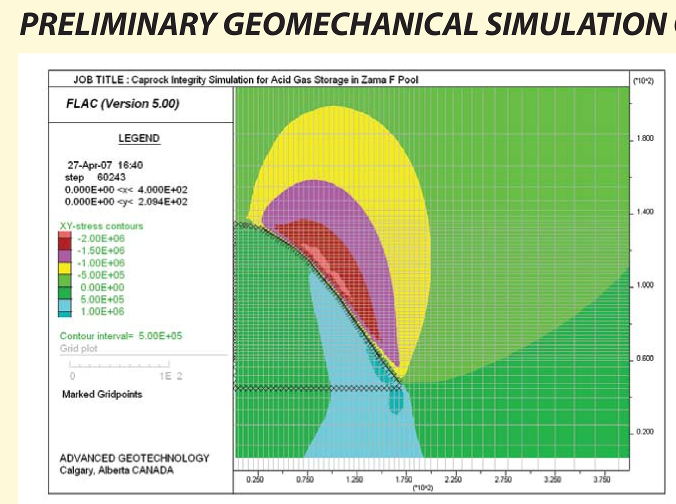


Vertical stress magnitude and gradient estimates for wells logged in 1967.



(A) Rose plot of regional minimum horizontal stress orientation as determined from borehole breakouts in the Zama area. Source: Geological Atlas of the WCSB (Bell et al., 1994). (B) Rose plot of local borehole breakouts corresponding to the orientations of the minimum horizontal stress in Fort Simpson Formation shales.

PRELIMINARY GEOMECHANICAL SIMULATION OF ACID GAS INJECTION



In situ stresses, formation pressures, and mechanical properties described in this poster are used to make deterministic predictions of deformations, induced normal and shear stresses, and to assess the propensity for fault reactivation or movements on natural fractures. This figure shows a preliminary model of shear stresses which develop adjacent to the F pool pinnacle reef at a reservoir pressure of 28 MPa.

KEY CONCLUSIONS TO DATE

- Old core from initial wells drilled in the Zama Field (circa 1967) can be used to measure representative rock mechanical and acoustic properties in the laboratory for these relatively stiff reservoir and cap rock strata.
- Correlation between log-derived dynamic, static laboratory, and dynamic laboratory elastic and strength properties have been developed for the reservoir and cap rock units of interest in this setting.
- Based on data analyzed to date, cap rock leakage potential due to a geomechanical mechanism appears to be very low.

RELATED WORK IN PROGRESS OR PROPOSED

- Small volume microfrac in situ stress tests in the Muskeg cap rock and, ideally, the Keg River Formation reservoir.
- Geochemical, mineralogical, and mechanical property investigations of Slave Point Formation dolomite that was previously affected by acid gas disposal.
- Mechanical property characterization of intersecting fault or fracture properties in the candidate reservoir and cap rock units (shear strength, stiffness, and stress-dependent permeability).
- Coupled reservoir–geomechanical simulation of the F-Pool reservoir, including history matching of prior production and injection activities.