Geomechanical Characterization of an Acid Gas EOR, CO_2 Sequestration and Monitoring Project, Zama Field, Alberta

Pat McLellan, Queena Chou, Jordan Gao, *Advanced Geotechnology-Weatherford*, Calgary

Chris Hawkes, *University of Saskatchewan*, Steve Smith, *Energy & Environmental Research Center, University of North Dakota*

Contact: 403.693.7531 mclellan@advgeotech.com

ADVANCED GEOTECHNOLOGY – A Weatherford Company

Integrated Petroleum Geomechanics Solutions

www.advgeotech.com

Abstract

A comprehensive monitoring, mitigation and verification (MMV) plan is critical to the success of any geological carbon sequestration project utilized as a method of reducing CO_2 emissions to the atmosphere. Beginning in October, 2005 and running through September, 2009 the Zama Oil Field in northwestern Alberta, Canada has been the site of acid gas (approximately 70% CO_2 and 30% H_2S) injection for the simultaneous purpose of enhanced oil recovery (EOR), H_2S disposal, and sequestration of CO_2. The Plains CO_2 Reduction (PCOR) Partnership has conducted MMV activities at the site throughout this period while Apache Canada Ltd. has undertaken the injection and hydrocarbon recovery processes. This project has been conducted as part of the US Department of Energy (USDOE) and National Energy Technology Laboratory (NETL) Regional Partnership Program and includes the participation of Natural Resources Canada, the Alberta Department of Energy, the Alberta Energy & Utilities Board and the Alberta Geological Survey.

In an effort to research caprock integrity and the risk of leakage during these field operations a first order geomechanical characterization has been undertaken of the injection reservoir, comprising the Keg River Formation and its Zama Member, and the overlying Muskeg Formation caprock. This poster will summarize key data obtained from a laboratory and wireline log-based analysis of the petrophysical and mechanical properties, and the in-situ stress state in this setting.

Vertical stress estimates were determined by integrating bulk density logs in the area, while accounting for the unlogged portion above the surface casing shoe. Horizontal stress magnitudes in the caprock and reservoir were estimated from regional and local stress data for this part of Alberta. Dedicated stress tests such as a mini-frac, a microfrac profile, or an extended leak-off test have not been conducted in the caprock to date in this field. Minimum and maximum in-situ horizontal principal stress orientations in the Zama field and surrounding area, measured within and above the injection interval, were determined from borehole breakouts.

Vertical and horizontal in-situ stress changes have occurred within the reservoir and surrounding caprock due to initial production in the pinnacle reef, subsequent water flooding, and most recently acid gas injection. The prediction of these stress changes is a complex function of the reef geometry, the poro-elastic response of the reservoir, pore pressure changes over time in the reef and reservoir, and possibly temperature changes. For this poster, only the horizontal stress changes due to poro-elastic effects have been considered. 3D geomechanical modelling will be used to simulate the more complex problem once the mechanical properties and in-situ stresses are adequately constrained.

Basic porosity and unstressed permeability distributions from two cored intervals through the Zama Member and Keg River Formation in two pinnacle reefs in the setting are summarized. Ultrasonic shear and compressional wave velocity measurements have been made under unconfined and confined stress conditions on anhydrite and dolomite from the Muskeg Formation caprock. Triaxial rock strength and unconfined compressive strength (UCS) tests are summarized using Mohr Coulomb and Hoek Brown failure criteria. Static and dynamic elastic properties measured under anisotropic stress conditions are compared. A Schmidt rebound hammer was used to develop a profile of pseudo-static Young's moduli and UCS though the Muskeg Formation caprock and portions of the Keg River Formation in two wells.

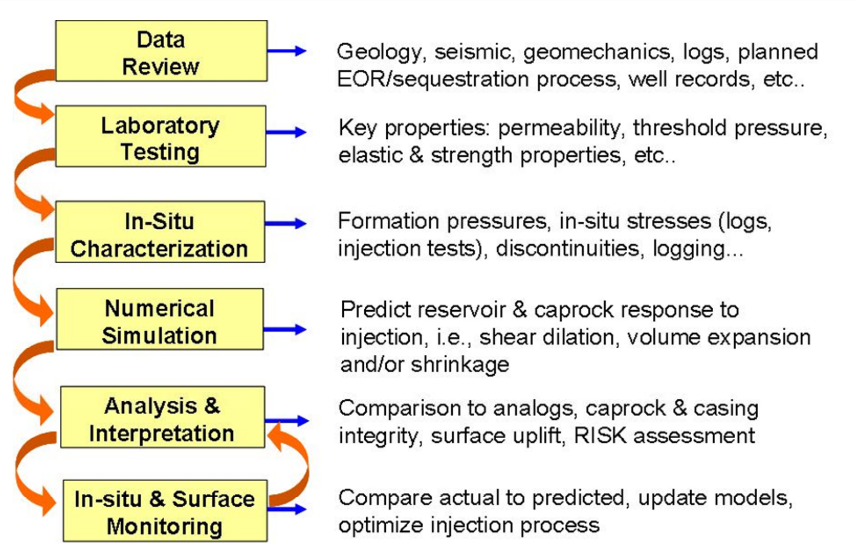
Dynamic log-derived elastic properties and their static equivalents were determined for the Muskeg and Keg River Formations in two wells. In order to do this a synthetic shear velocity relationship was developed using recent data from an offset well in the region. These log-derived properties are compared to the static laboratory and Schmidt hammer derived data. Pore volume compressibility tests were also made on a select number of core plugs of the Keg River Formation under relevant reservoir pore pressure and stress conditions, along with stress-dependent permeability and elastic properties. Statistical relationships describing the petrophysical and mechanical properties of the rocks investigated in this study are presented. Key learnings with regard to the heterogeneity of the vuggy dolomitic reservoir versus the evaporitic caprock are highlighted.

The data presented in this poster have a variety of applications to EOR and CO_2 sequestration in pinnacle reefs of the type being investigated in the Zama field. In addition to caprock integrity, the data can be used to assess optimal injection strategies, design well drilling, completion and stimulation programs, develop and interpret reservoir monitoring data, and conduct coupled geomechanical-reservoir simulation studies of acid gas injection.

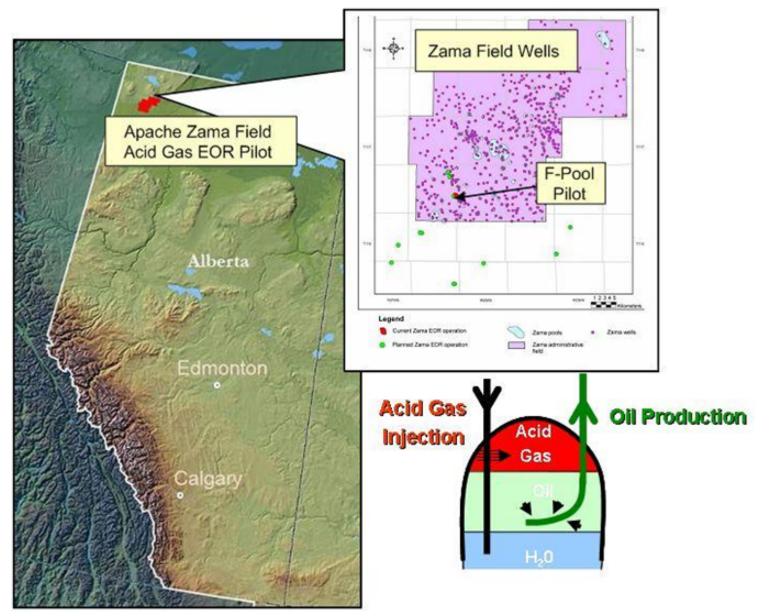
Acknowledgements:

We would like to thank individuals in the following organizations for their assistance in the preparation of this poster: Apache Canada, Omni Laboratories, University of Saskatchewan, Weatherford Canada, Natural Resources Canada, Alberta Geological Survey, RPS Energy, and CalPetra Research and Consulting.

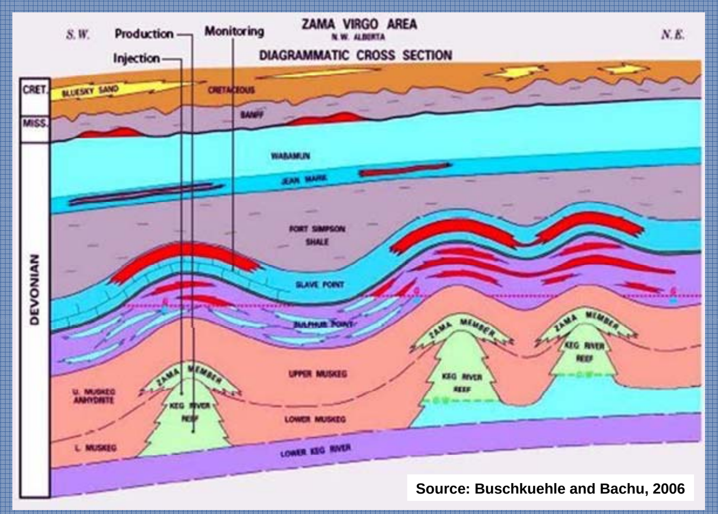
Typical Methodology for a Geomechanical Caprock Integrity Assessment



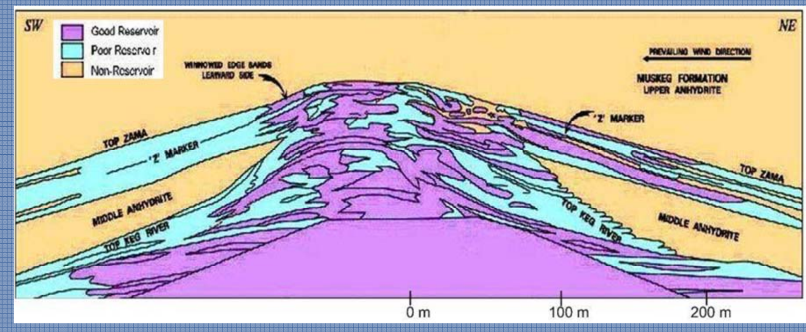
Location of the Zama Field, NW Alberta



Stratigraphic Cross-Section, Zama Area, NW Alberta

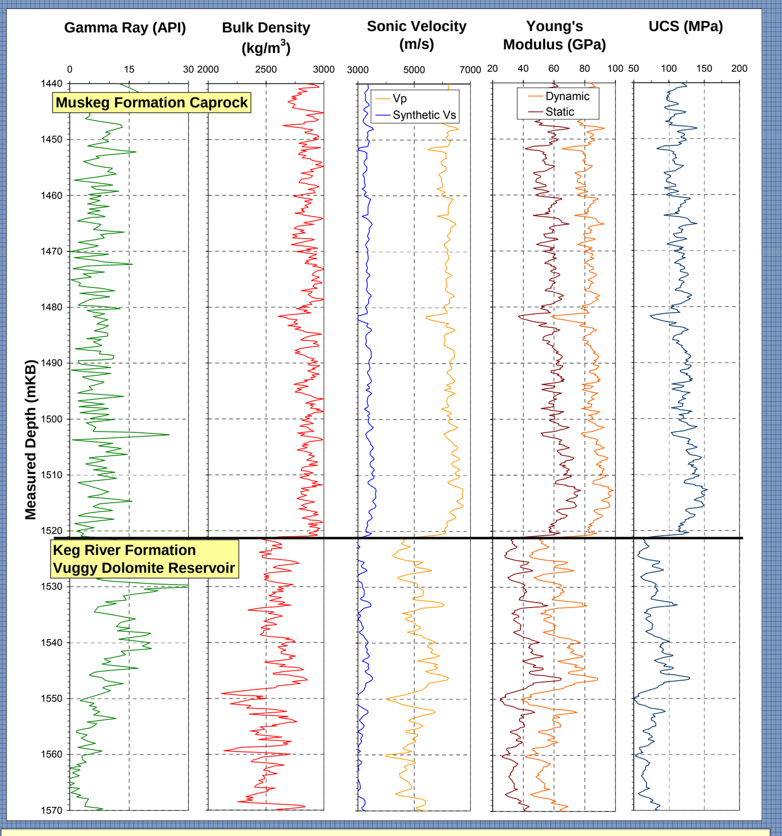


Cross-Section of a Typical Zama Devonian Keg River Formation Pinnacle Reef



A schematic southwest-northeast cross-section of a typical Devonian pinnacle reef in the Zama field, northwest Alberta. This figure shows the three strata of interest in this study: the Muskeg Formation (caprock), the Zama Member (dolomite) denoted as the "Z" marker, and the Keg River Formation (reservoir). Source: Apache Canada Ltd.

Log-derived Elastic and Strength Properties ACL Zama 6-4-116-6W6

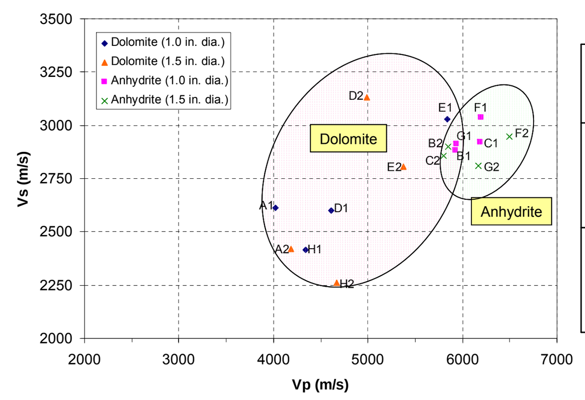


Log-derived rock and strength elastic properties profile in the Muskeg and Keg River Formations from ACL Zama 6-4-116-6W6 (1440 - 1570 mKB MD). Shear sonic velocity was derived from Vp-Vs relationships calculated from ACL Amber 8-7-116-6W6. Dynamic to static and modulus-UCS empirical relationships were selected from Advanced Geotechnology's ROCKSBank mechanical properties database (2008).

Muskeg Formation Typical Core Section Apache Zama 6-4-116-6W6

Schmidt Rebound Hammer For Young's Modulus and Unconfined Compressive Strength Determinations

Ultrasonic Velocity Testing and Dynamic Elastic Properties

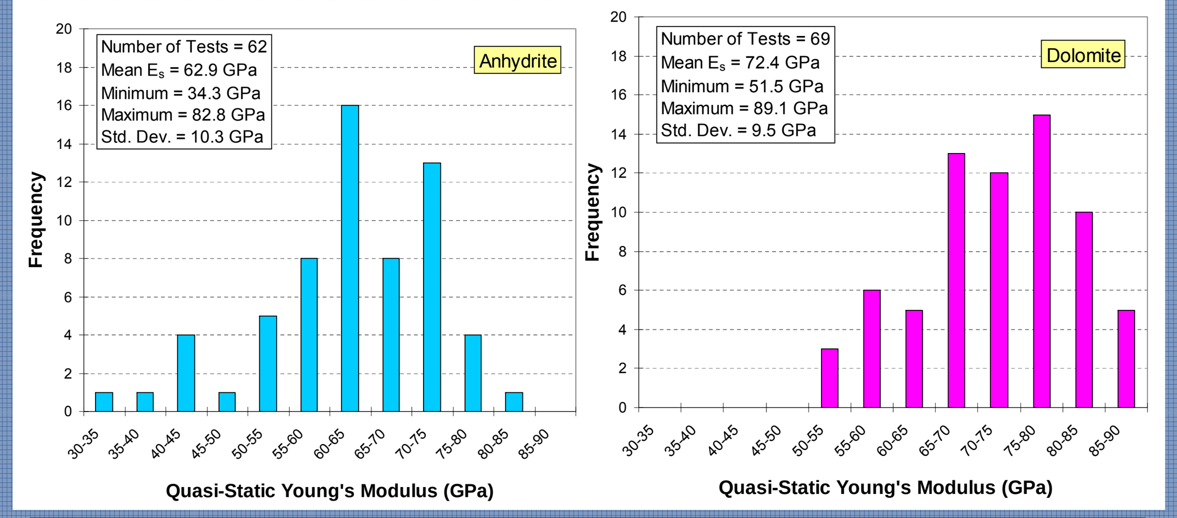


Cross plot of measured Vp/Vs data from unstressed ultrasonic compressional and shear velocity testing of 14 Muskeg Formation and 2 Keg River Formation core plugs of dolomite and anhydrite lithologies taken from ACL Zama 6-4-116-6W6 (1510.16 – 1522.70 mKB MD). AG sample number for each data point is shown.

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

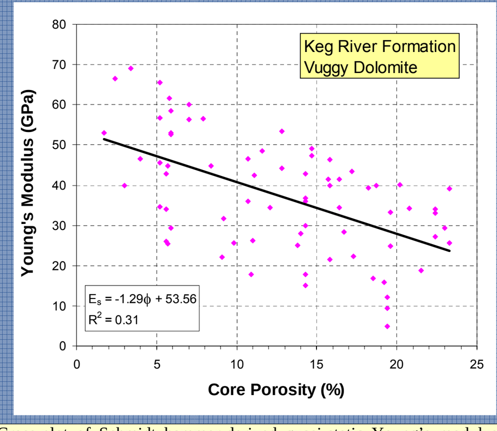
Lithology	Plug Diameter (mm)		Dynamic Young's Modulus (GPa)	Dynamic Bulk Modulus (GPa)	Dynamic Shear Modulus (GPa)	Dynamic Compressibility (GPa⁻¹)
Dolomite	25.4	Mean	49.73	37.75	19.76	0.055
		Std. Dev.	13.56	10.98	6.19	0.017
	38.1	Mean	49.91	36.38	19.92	0.052
		Std. Dev.	12.53	17.97	4.20	0.010
Anhydrite	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

Schmidt Rebound Hammer – Young's Modulus



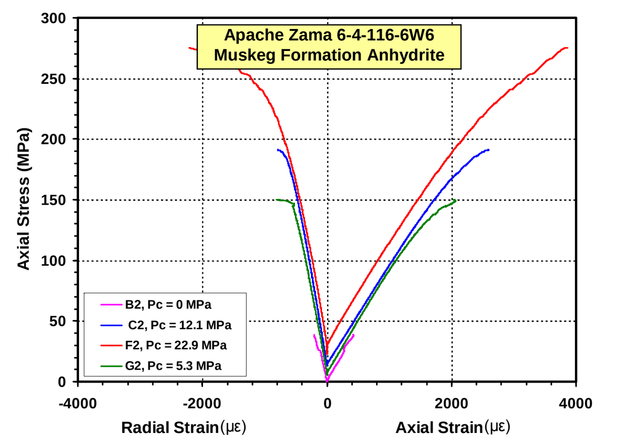
Histograms of quasi-static Young's modulus measured with the Schmidt rebound hammer on whole-diameter core of the Muskeg Formation caprock from ACL Zama 6-4-116-6W6. Depth interval 1508.81 to 1522.16 mKB.

ϕ vs. Young's Modulus

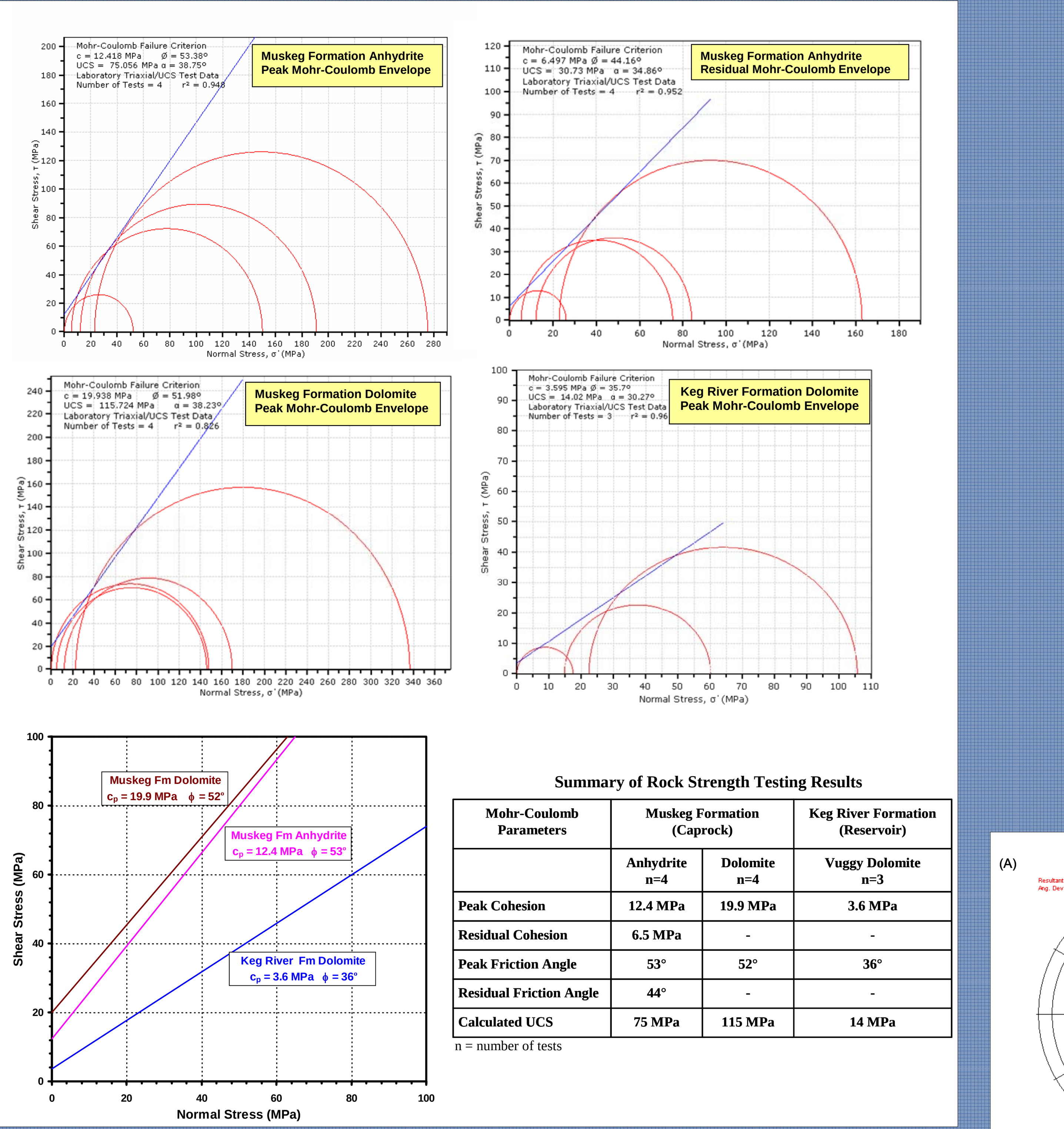


Cross-plot of Schmidt hammer-derived quasi-static Young's modulus against routine core porosity in the Keg River Formation vuggy dolomite. Depth: 1525.37 to 1546.25 mKB.

Triaxial Stress-Strain Curves



Triaxial and Unconfined Compressive Strength Results



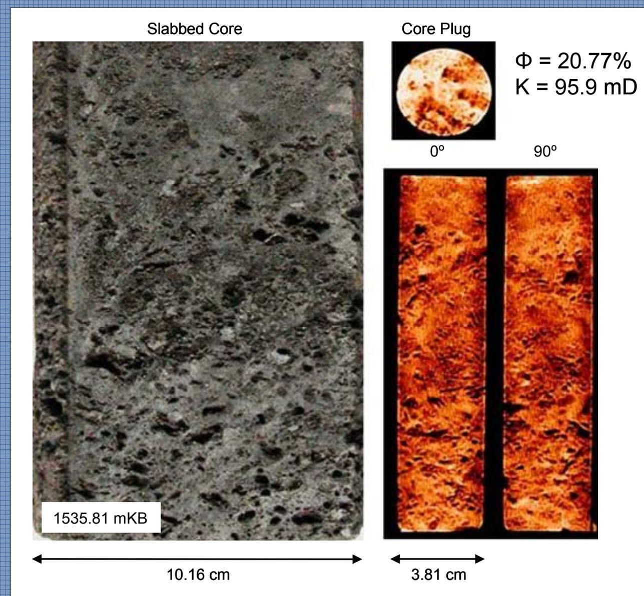
Summary of Rock Strength Testing Results

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

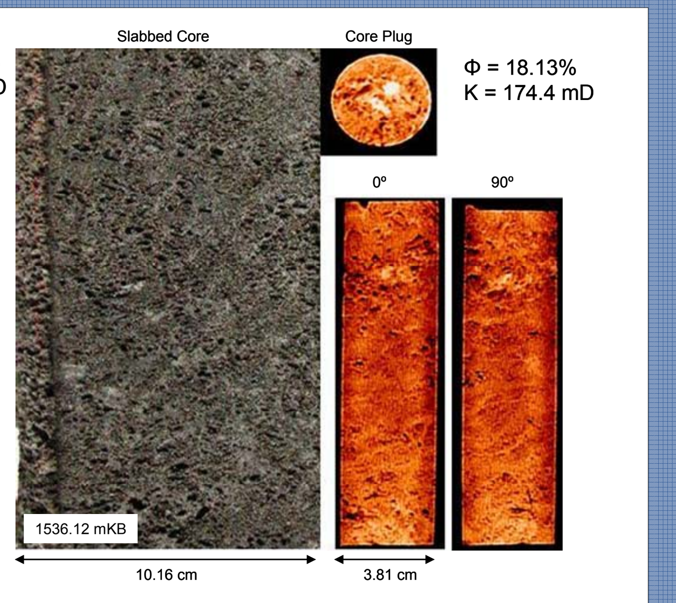
n = number of tests

Apache Zama 6-4-116-6W6, Keg River Formation

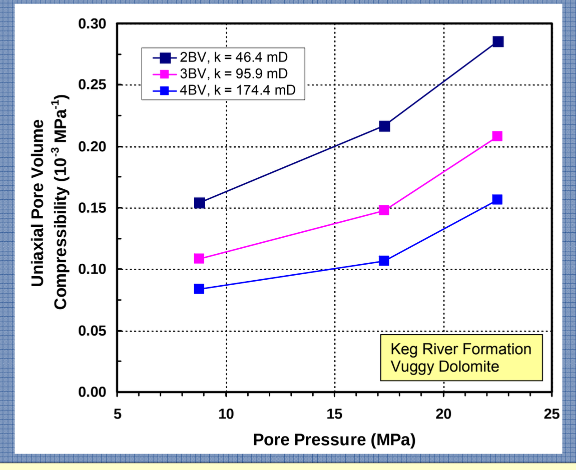
Vertical Core Plug 3V-RM, Mid-plug Depth 1535.75 mKB



Vertical Core Plug 4V-RM, Mid-plug Depth 1536.06 mKB



Uniaxial Pore Volume Compressibility (PVC)



Relationship between PVC and pore pressure during uniaxial pore volume compressibility testing of vuggy dolomite from the Keg River Formation reservoir, Apache Zama 6-4-116-6W6. Sample porosities 18-21%. Confining pressure held constant at 31.9 MPa.

Definition of Uniaxial Pore Volume Compressibility

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

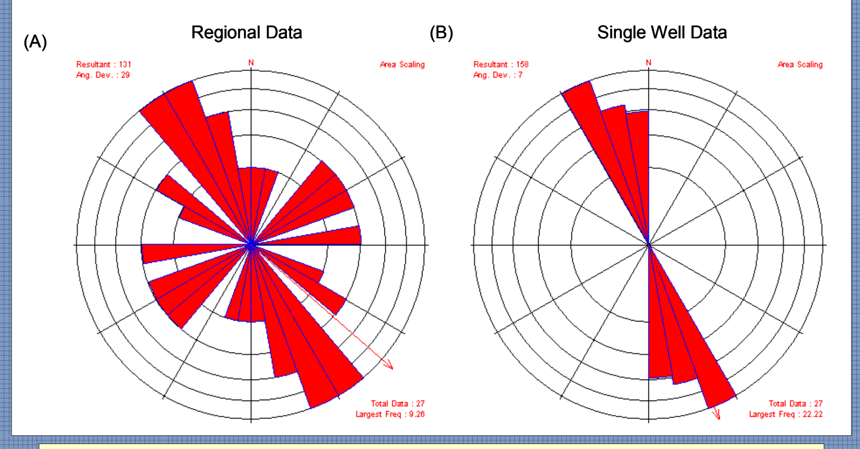
where V_p = pore volume, P_p = pore pressure, σ = total stress

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

PVC is used for many purposes including: reservoir 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.

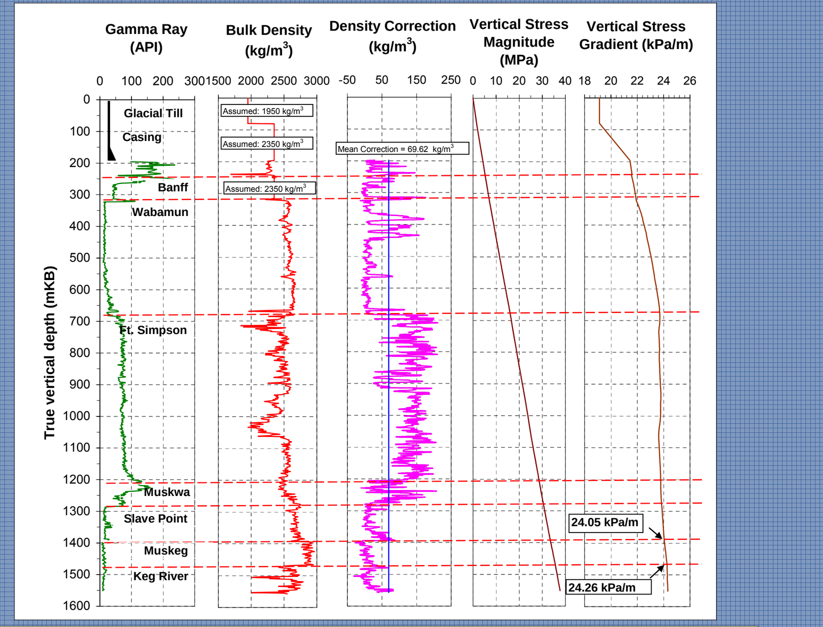
In-Situ Stresses in the Zama Area

Minimum Horizontal In-Situ Stress Orientation



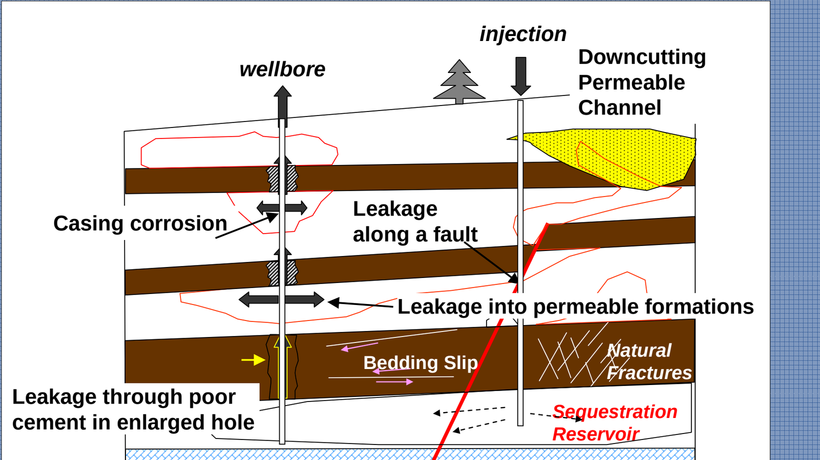
(A) Roseplot of regional minimum horizontal stress orientations as determined from borehole breakouts in the Zama area. Source: Geological Atlas of the WCSB (Bell, McLellan and Price, 1994). (B) Roseplot of borehole breakouts corresponding to the orientations of the minimum horizontal stress in the Fort Simpson Formation shales, Dome Zama 11-24-116-6W6, 1075 to 1444 mKB TVD.

Vertical In-Situ Stress Magnitude

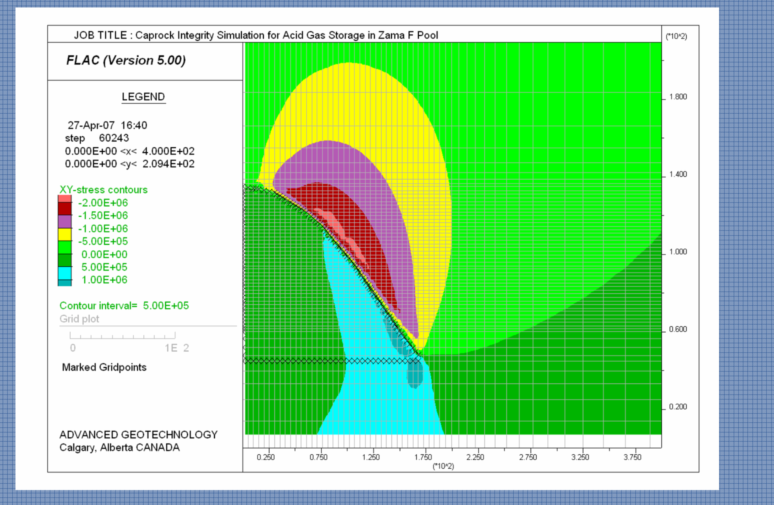


Vertical stress magnitude and gradient estimates for 8-13-116-6W6, Zama, Alberta. Logged in January, 1967.

Possible Caprock Leakage Mechanisms



Preliminary Geomechanical Simulation of Acid Gas Injection



To assess the magnitude of stresses developed in the reservoir and the caprock as a consequence of initial oil production, subsequent waterflooding, and more recently acid gas injection we are using the geomechanical simulation code FLAC developed by Itasca. In-situ stresses, formation pressures and mechanical properties described in this poster are used to model geomechanical responses: deformations, induced normal and shear stresses, and to assess the propensity for fault re-activation or movements on natural fractures. The figure above is a preliminary model of shear stresses which develop adjacent to the F pool pinnacle reef at a reservoir pressure of 28 MPa. Vertical exaggeration is 2:1.

Conclusions/Future Work

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 caprock strata.
- Correlations between log-derived dynamic, static laboratory and dynamic laboratory elastic and strength properties have been developed for the reservoir and caprock units of interest in this setting.
- Caprock leakage potential due to a geomechanical mechanism appears to be very low at the F-Pool pilot setting, based on data analyzed to date.

Related Work in Progress or Proposed

- Additional rock mechanical, relative permeability and capillary threshold pressure measurements in the Muskeg Formation caprock.
- Small volume micro-frac in-situ stress tests in the Muskeg caprock and, ideally, the Keg River Formation reservoir.
- Geochemical, mineralogical and mechanical property investigations of Slave Point Formation dolomite that were previously affected by acid gas disposal.
- Mechanical property characterization of any intersecting fault or fracture properties, in the candidate reservoir and caprock 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

Related References

Advanced Geotechnology, ROCKSBank Rock Mechanical and Petrophysical Database, Version 2.5, March, 2008.

Bell, J.S., Price, P., and McLellan, P.J., In-Situ Stress, Chapter 29 in the Geological Atlas of the Western Canadian Sedimentary Basin, CSPG / ARC / GSC, 1994.

Davison, R.J., Mayer, A., Hladiuk, D.W., Jarrell, J., Zama acid gas disposal/miscible flood implementation and results. Journal of Canadian Petroleum Technology, Vol. 38, No. 2, 45-54, 1999.

Hawkes, C. McLellan, P., Zimmer, U., Bachu, S., Geomechanical Factors Affecting Geological Storage of CO2 in Depleted Oil and Gas Reservoirs, CIPC 2004-258, Presented at the Canadian International Petroleum Conference, Calgary, Alberta, June 8-10, 2004 and published in the Canadian Journal of Petroleum Technology, Vol. 44, No. 10, 52-61, 2005.

McLellan, P.J., Caprock Integrity: What you Need to Know for Thermal Recovery Projects, Presented at "Slugging it Out XVI", 16th Annual One-day Conference on Heavy Oil, Canadian Heavy Oil Association / Petroleum Society of CIM, Calgary, Alberta, April 14, 2008.

Smith, S.A., Dobroskok, A.A., McLellan, P.J., Hawkes, C., Steadman, E.N., and Harju, J.A., Geomechanical Investigations at an Acid Gas EOR Pilot Project in the Zama Oil Field, Alberta, Canada, To be presented at GHGT-9, 9th International Conference on Greenhouse Gas Control Technologies, Washington, D.C., Nov. 16-20, 2008.