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CO_2-Based Enhanced Oil Recovery

CO_2 Geological Storage and EOR Workshop
Mexico City, Mexico
March 21–23, 2012

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NATIONAL ENERGY TECHNOLOGY LABORATORY

PCOR Partnership

Presentation Outline

- The Plains CO_2 (PCOR) Partnership
- Carbon management
- Enhanced oil recovery (EOR)/carbon capture and storage (CCS)
- Projects: Zama and Bell Creek
- Presentation wrap-up

U.S. Department of Energy (DOE) Regional Carbon Sequestration Partnership (RCSP) Program

- Seven partnerships, all tasked with regional characterization and site-screening activities.
- Screening along with economic drivers have resulted in several large-scale demonstration projects.

The PCOR Partnership

The PCOR Partnership region includes nine states and four provinces, covering over 1.4 million square miles.

The PCOR Partnership has brought together the key stakeholders to make large-scale geologic CO_2 sequestration a near-term reality.

Carbon Management

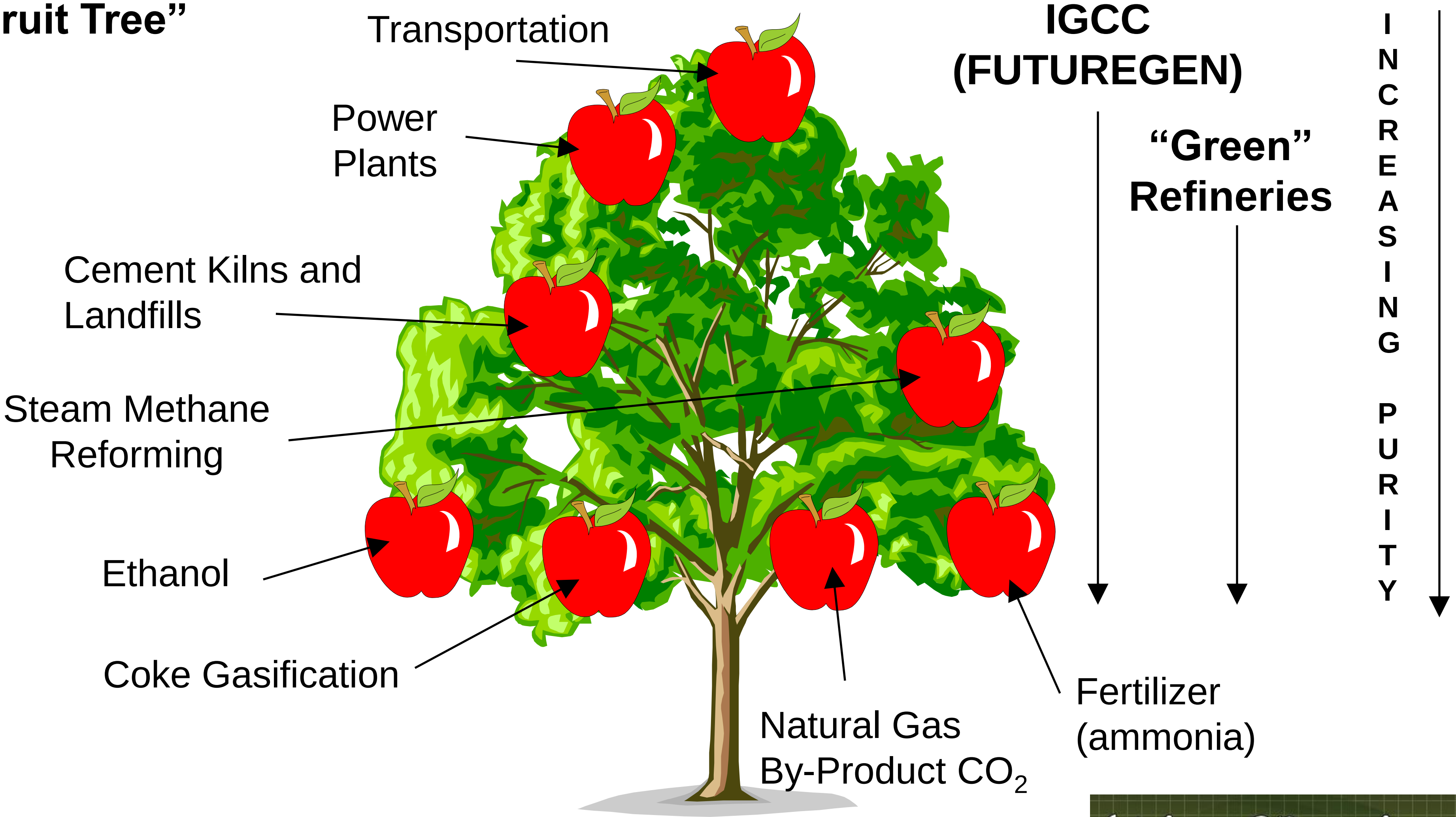
Typically, carbon management considerations include:

- An overview of carbon dioxide (CO_2) capture technologies, dehydration, and compression.
- Pipeline transportation.
- Geologic sequestration options.
- Terrestrial sequestration options.
- Environmental and commercial risks.
- Carbon markets.
- Economics.

Carbon Capture

Industrial CO_2 Sources

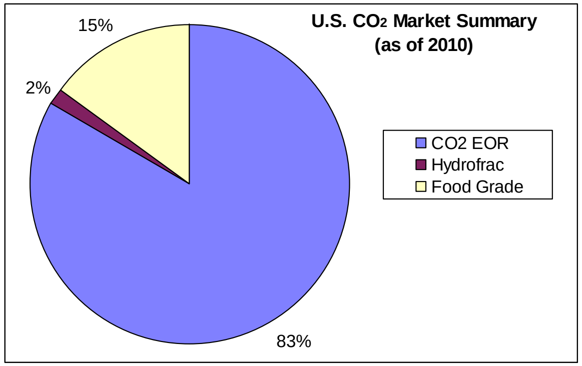
“The CO_2 Source Fruit Tree”



Melzer CO2nsulting

What Are the U.S. Markets for CO_2?

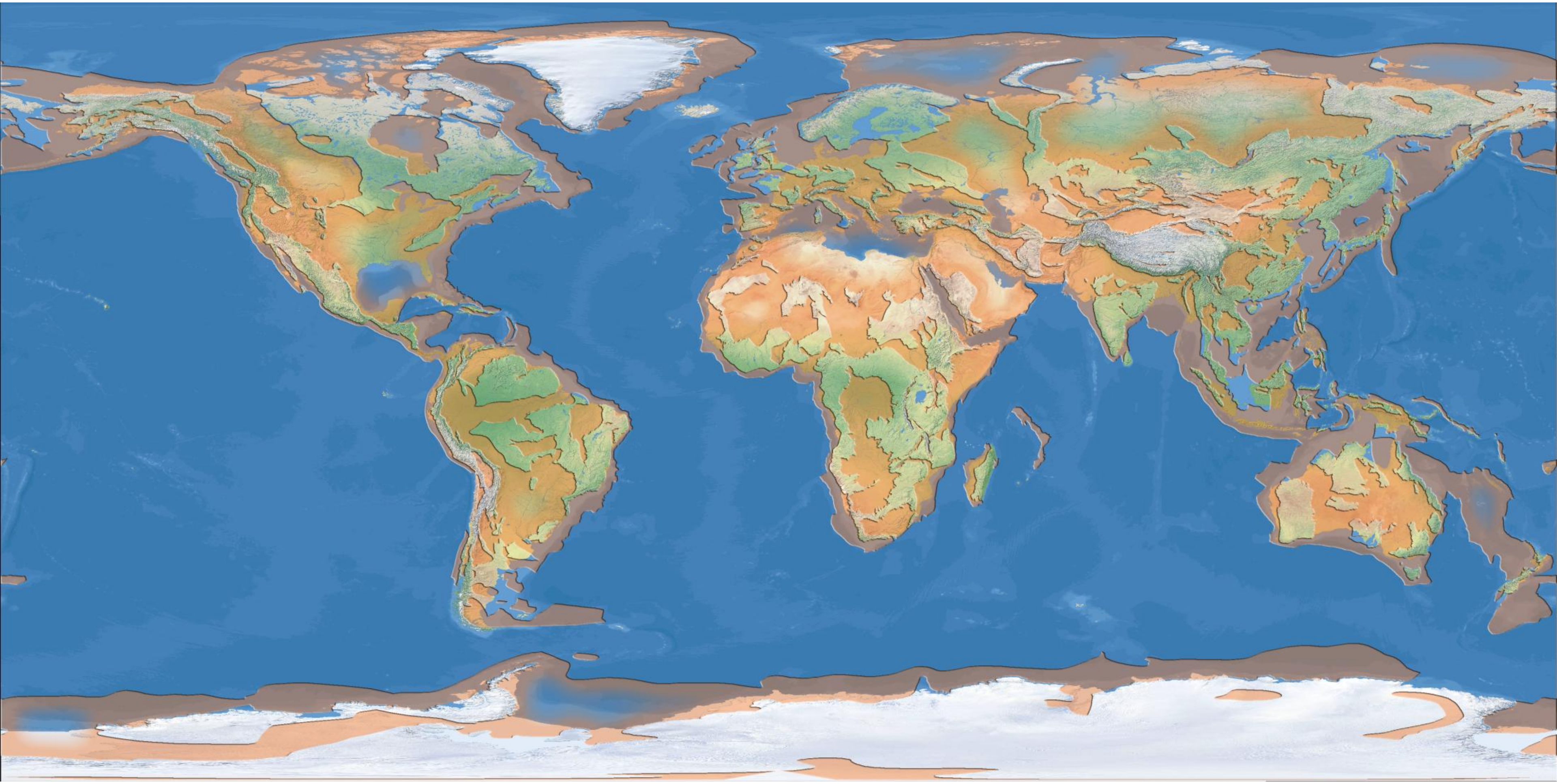
- Existing
  - CO_2 EOR (3.0 billion cubic feet per day [Bcfd])
  - Shortages of CO_2 exist today – probably could use 50% more right away!
- Merchant CO_2
  - Hydrofracturing services (60 million cubic feet per day [MMcfd])
  - Food grade (550 MMcfd)
    - Food, beverage, wastewater treatment
- Potential
  - Enhanced coalbed methane
  - Enhanced gas recovery



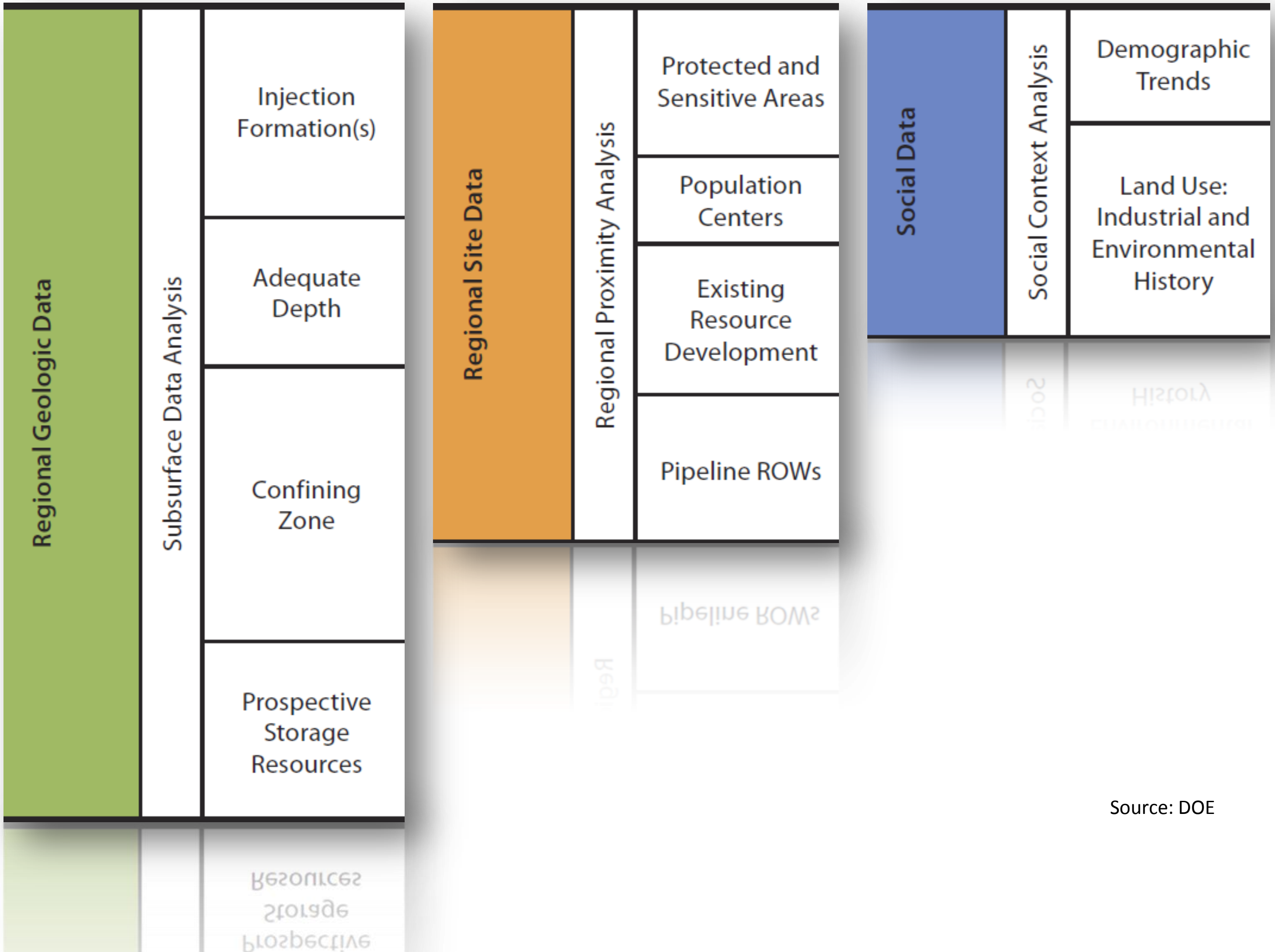
CO_2 Storage Options

- Saline formations
- Oil and gas fields:
  - Storage in association with CO_2-based EOR
  - Storage in depleted oil and gas fields

Global Sedimentary Basins



Guidelines for Site Screening



Source: DOE

North American Oil Fields

CO_2 EOR Opportunities

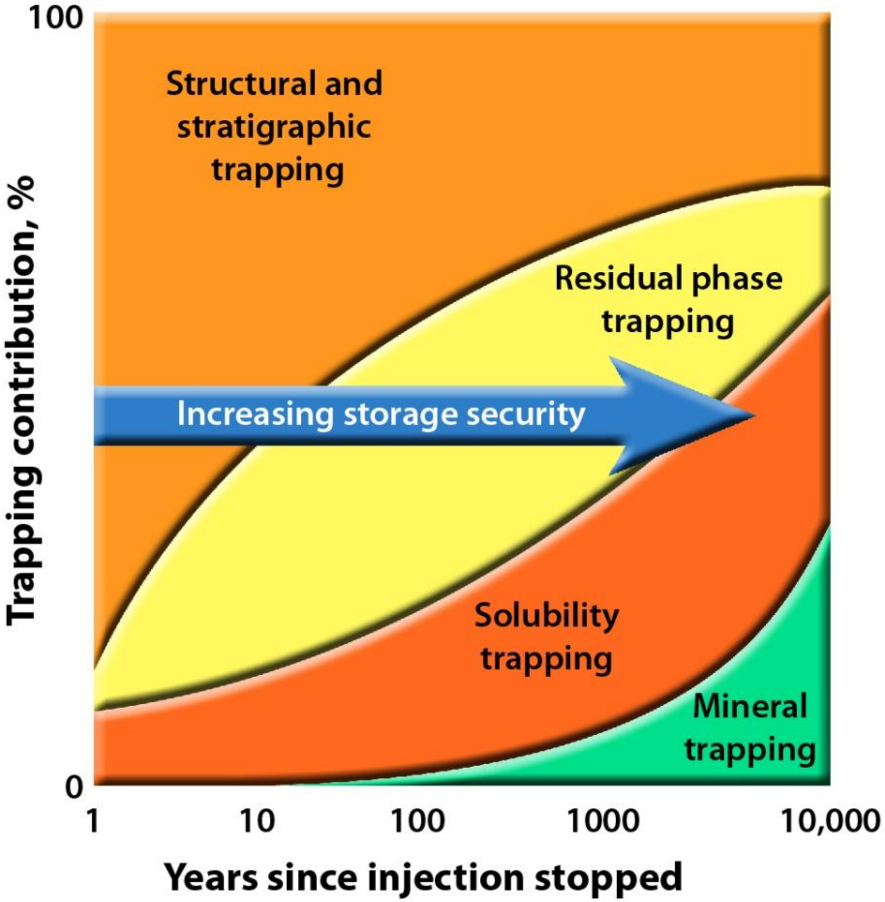
Permian Basin

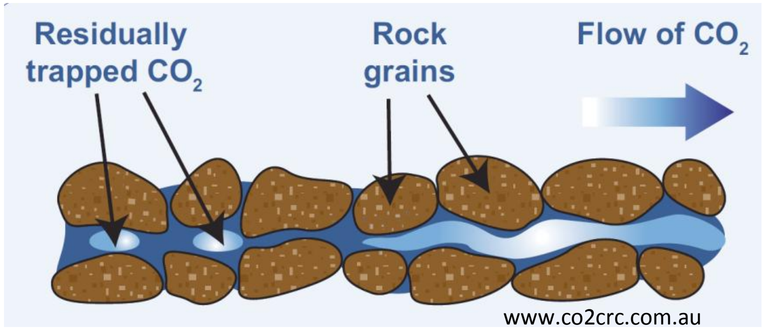
- New Mexico, Texas.
- Production since early 1900s.
- Considered a “mature” basin with respect to petroleum production.
- CO_2 flood EOR began in the 1970s.
- Over 1 billion barrels (bbl) of incremental oil from CO_2 injection have been produced from dozens of fields.

Williston Basin

- North Dakota, Montana, Saskatchewan, Manitoba, South Dakota.
- Production since 1950s.
- Considered a less mature basin.
- Two CO_2 flood EOR projects since 2001.

Geologic CO_2-Trapping Mechanisms





PCO2R Partnership

Key Reservoir Characteristics

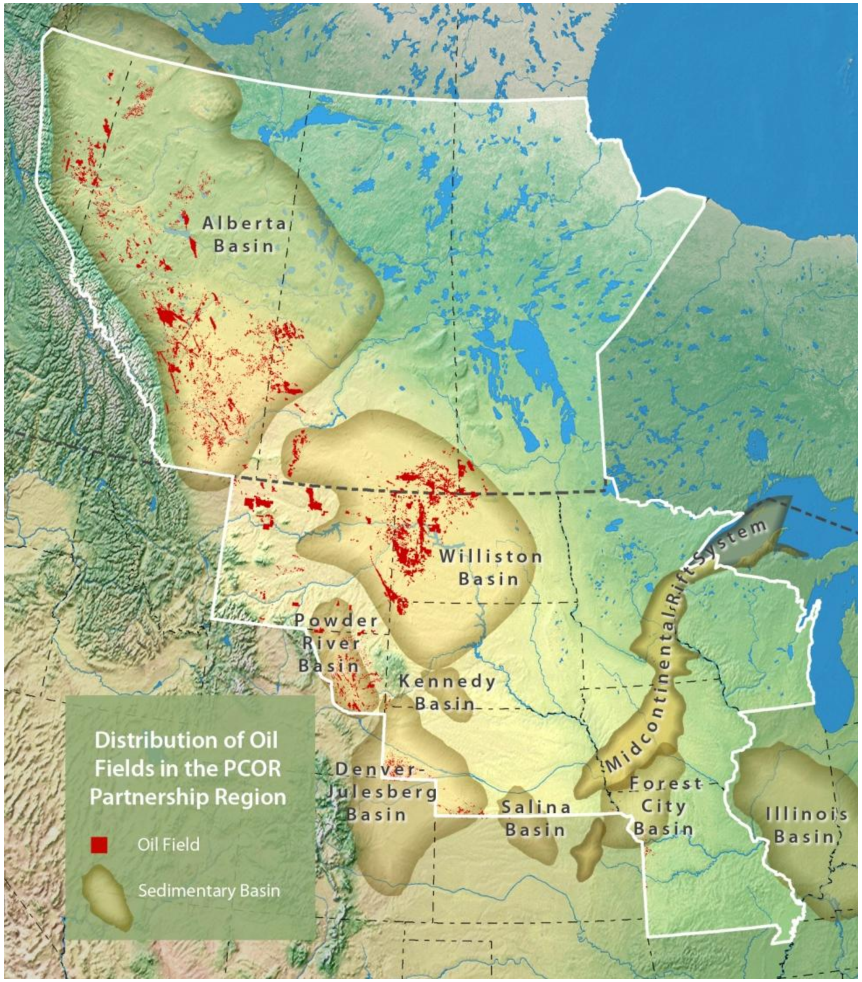
- Minimum reservoir pressure of 1100 psi desirable for dense-phase operations and miscibility (miscibility is also oil property-dependent).
- Reservoir temperature between 90° and 250°F.
- Oil gravity between 27° and 48° API.
- Waterflood residual oil saturation greater than 25%.
- Nature of porosity and permeability for lateral fluid communication.
- A good waterflood performance suggests a successful CO_2 flood (establishes needed measures for reservoir sweep efficiency).

Tertiary EOR Background

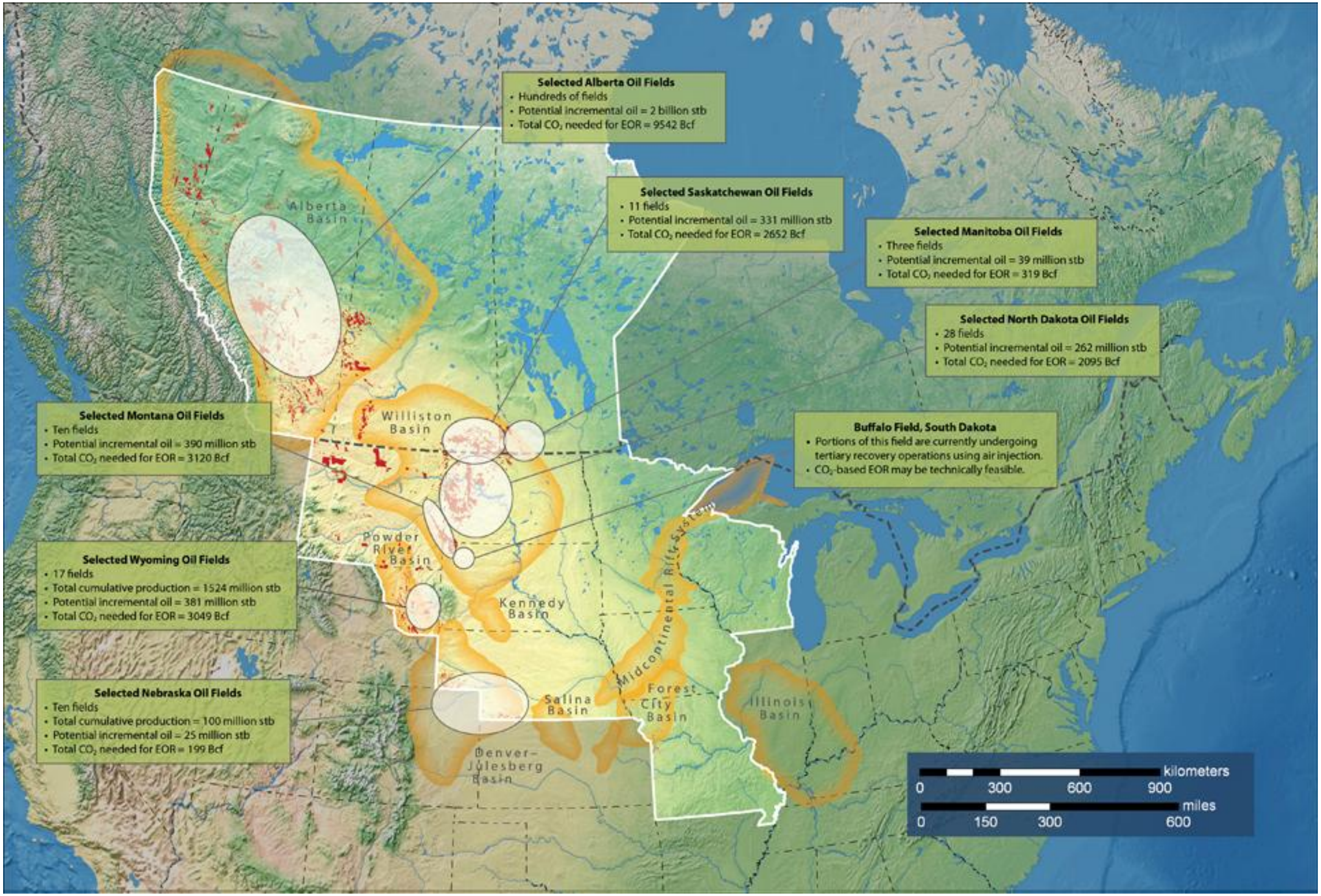
- Roughly 17 thousand cubic feet (Mcf) per ton of CO_2.
- Assumed 8 Mcf (net) of CO_2 needed for every barrel of incremental oil (13 Mcf/bbl initial purchase) for PCOR Partnership projections. What will Weyburn tell us?
- The PCOR Partnership initially used Nelms and Burke (2004) screening criteria to select North Dakota fields for detailed evaluation.
  - Subsequent collaboration with producers
  - Subsequent collaboration with North Dakota Department of Mineral Resources Oil and Gas Division
    - Waterflood performance
    - Original oil in place (OOIP) updates
    - Unitization activity

Oil Fields

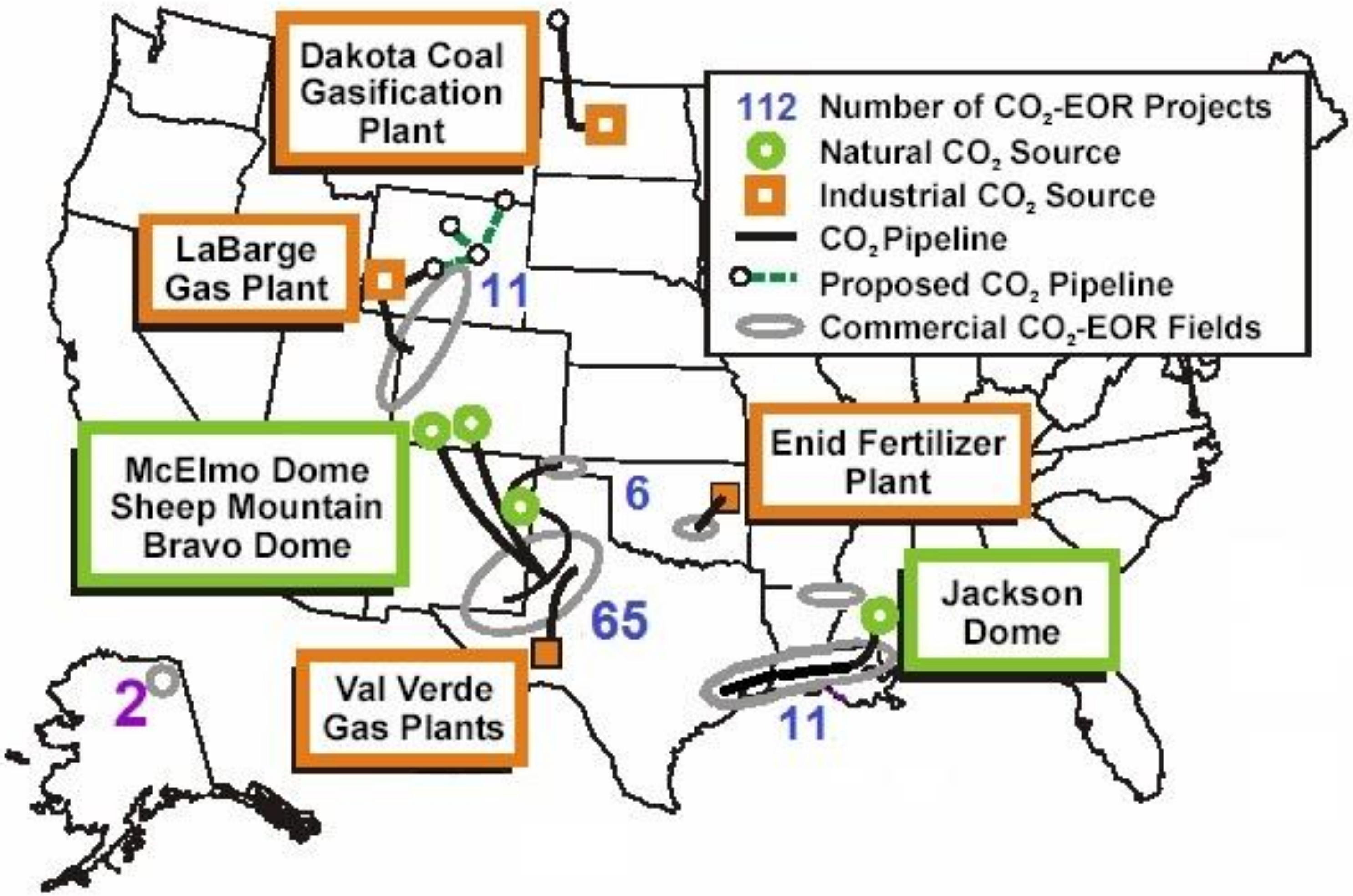
- Over 6000 fields evaluated in the Williston, Powder River, Denver−Julesberg, and Alberta Basins.
- Used two methodologies:
  - EOR approach
    - 160 fields
    - Sequestration capacity of about 1 gigaton (Gt)
    - Over 3 billion bbl of incremental oil production
  - Volumetric approach
    - Thousands of fields
    - Storage capacity over 10 Gt



EOR Recovery Potential



Expanding Interest in CO_2 EOR



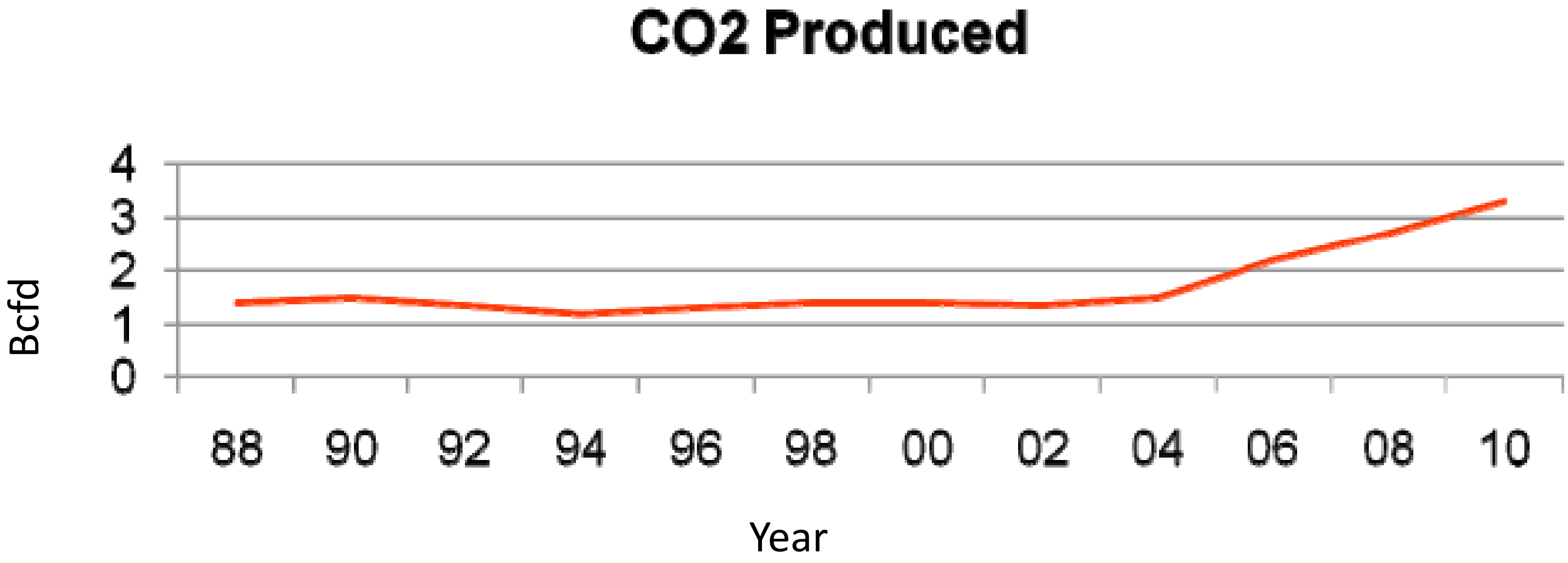
How Big Can the CO_2 Business Become?

- If we view through the old “lens”:
  - Oil prices averaging $12–$25/bbl.
  - CO_2 source and transportation infrastructure expensive and limited.
  - Not many more reservoirs pass muster.
- The new “lens”:
  - Oil prices above $70/bbl.
  - CO_2 capture more ubiquitous.
  - Revenue streams for both oil production and storage.
  - Many, many more reservoirs are profitable.
- Targets expanding into residual oil zones.

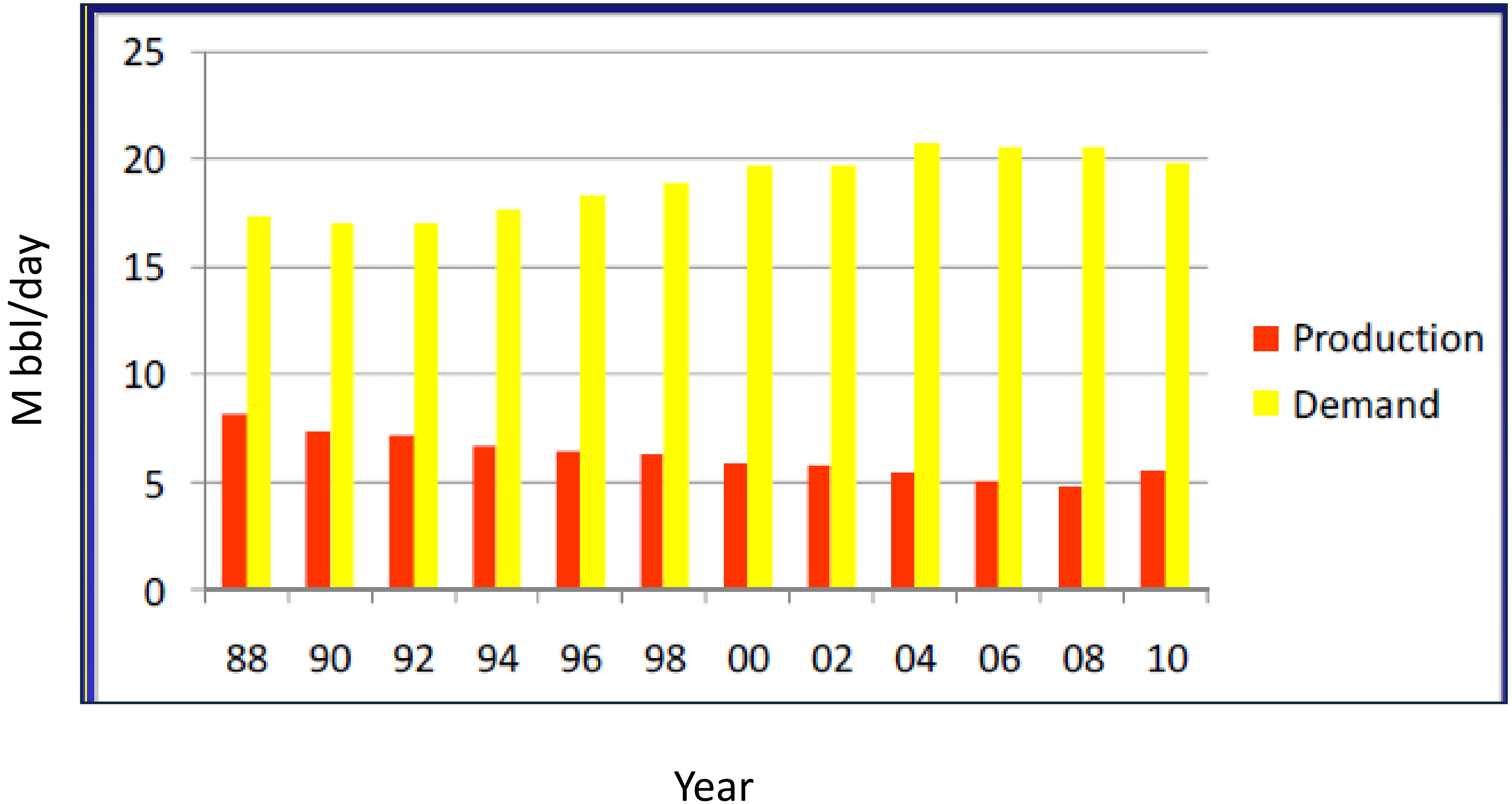
Can We Do It? – Current Analogs

- CO_2 EOR
  - 177,000 tons/day of “new” CO_2 = 3.1 Bcfd
    ~110 MMbbl/yr
- Natural gas storage
  - 450 state-permitted natural gas injection sites
- Strategic petroleum reserve
  - 700 million barrels of oil (MMbo) in storage as of 2008
  - Current storage capacity: 727 MMbo

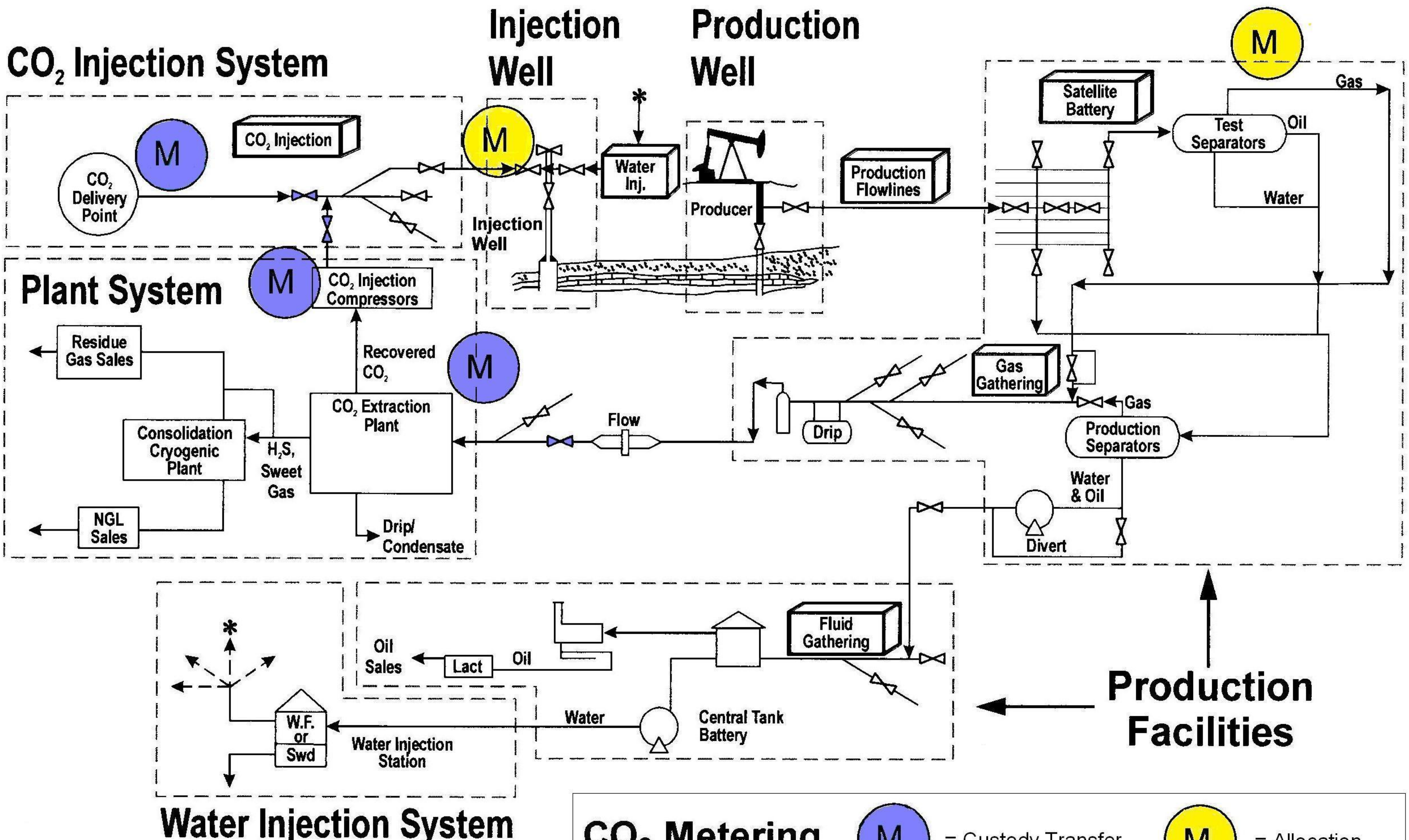
U.S. CO_2 Sales for EOR



U.S. Crude Oil Production and Demand



CO_2 Flood Production Systems

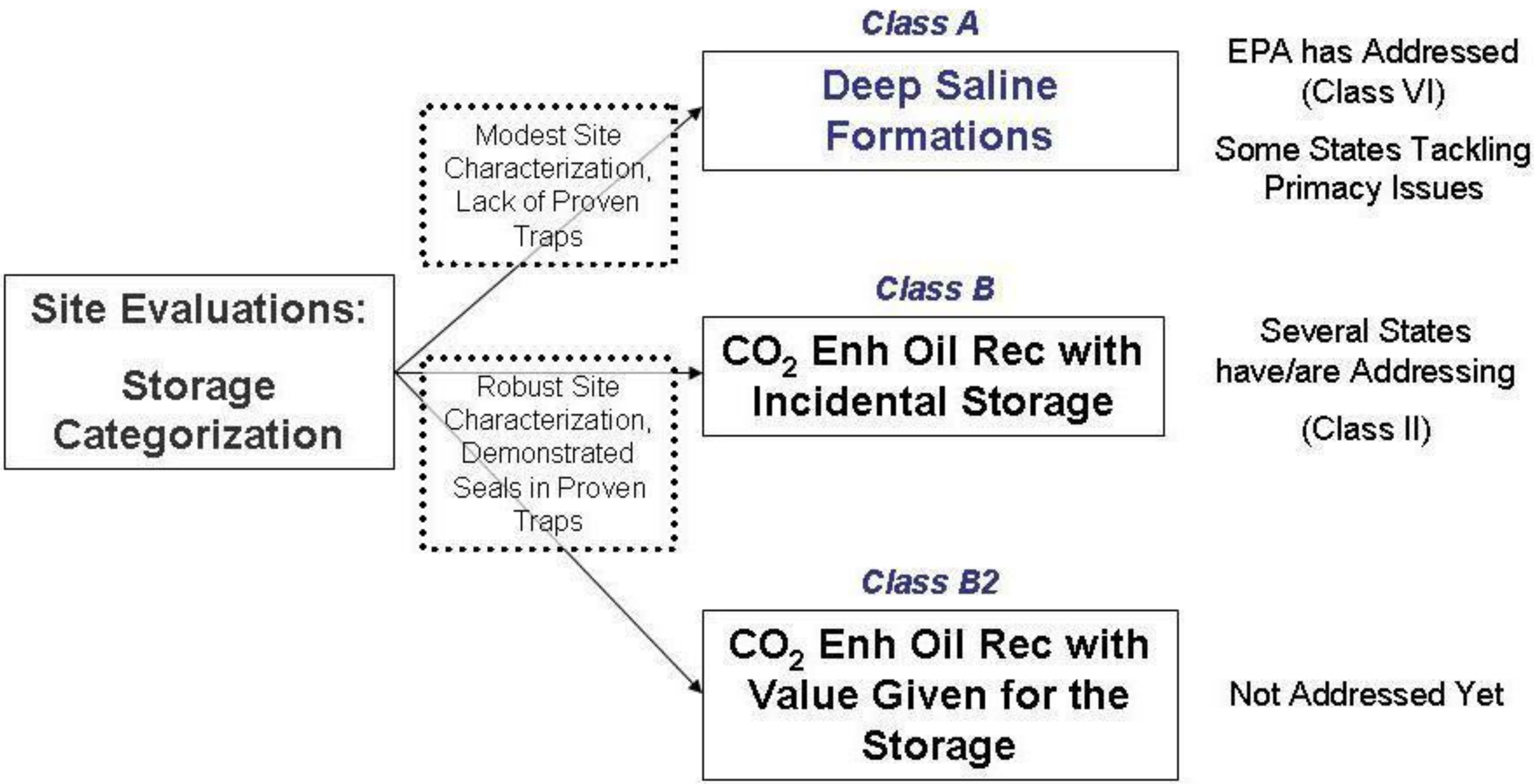


CO2 Metering M = Custody Transfer M = Allocation

Source: Practical Aspects of CO_2 Flooding, Figure 5.1

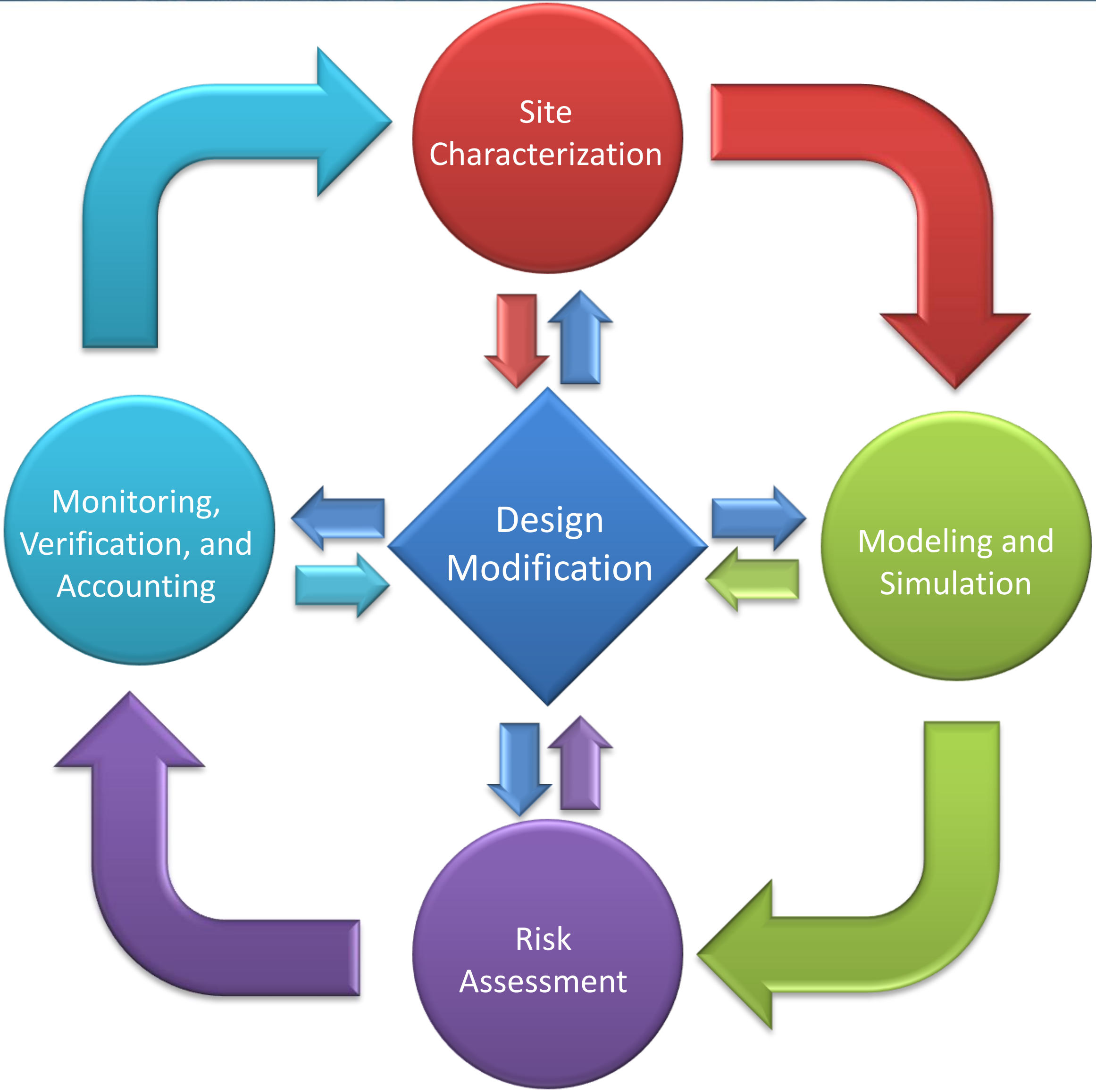
Figure 8:

Regulatory Frameworks for CO_2 Storage



PCOR Partnership Technical Approach

- Risk-based approach to define monitoring, verification, and accounting (MVA) strategy.
- Cost-effective MVA plan.
- Minimal disruption of operations at the project sites and for the partners.



Detailed Site Characterization

Hydrogeology

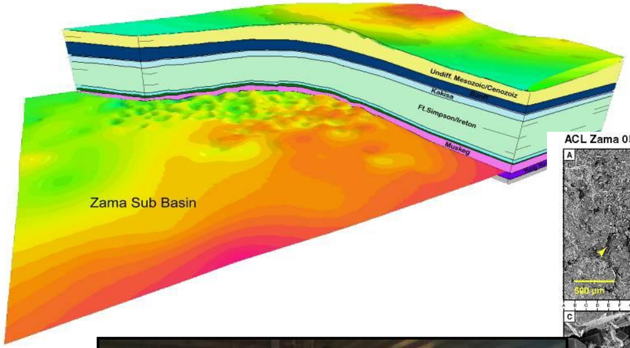
Geomechanics

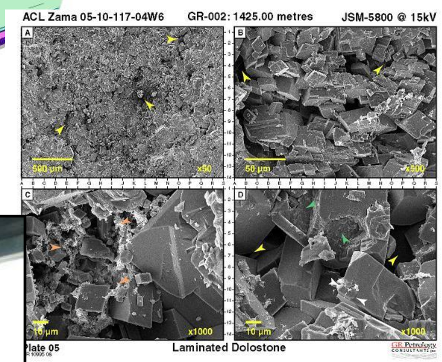
Geochemistry

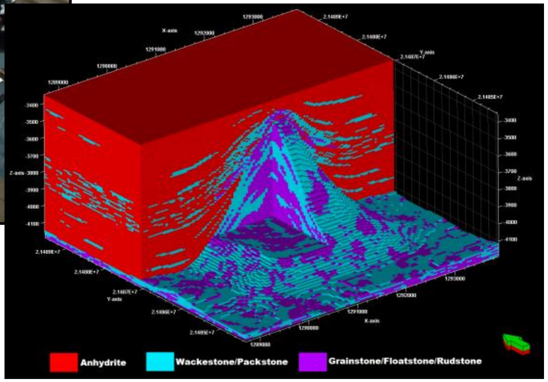
Engineering

Modeling

Risk analysis

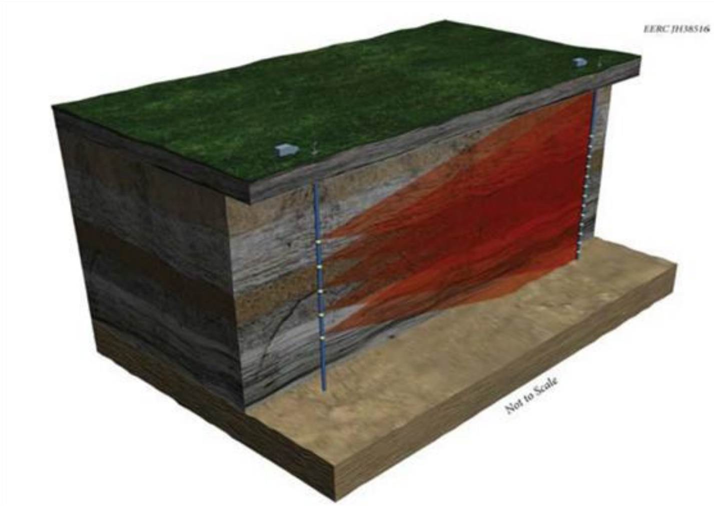




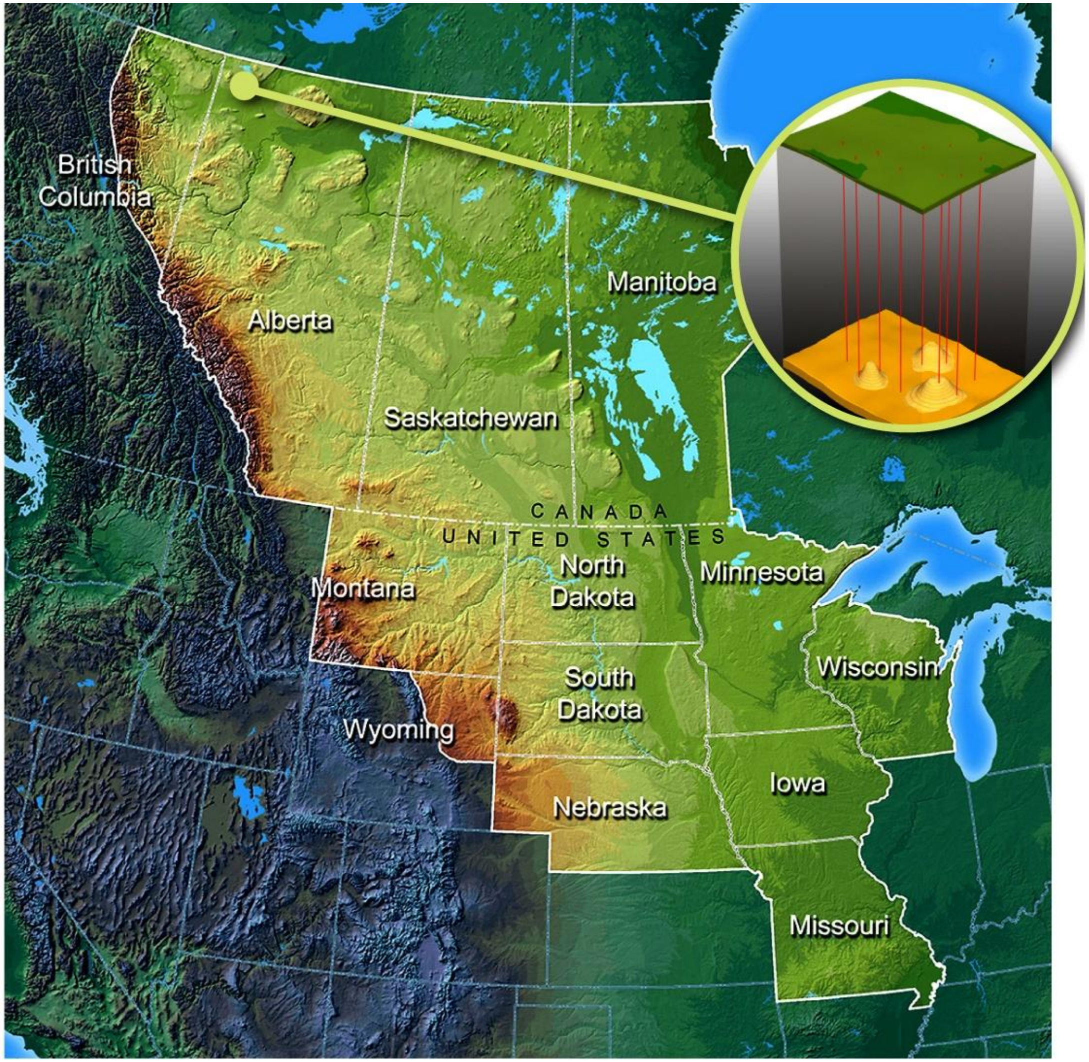


MVA

- Based on site characterization, modeling and simulation, and risk assessment
- Two parts – surface/near-surface and deep monitoring
- Goals
  - Verify site security
  - Assess variances within predicted injection program
  - Establish preinjection conditions
  - Track movement of CO_2
  - Evaluate efficiency of the CO_2 EOR and storage program
  - Identify fluid migration pathways
  - Determine ultimate fate of CO_2



Energy & Environmental Research Center (EERC) Work at Zama



Apache Canada teamed with the EERC to examine the relationship between EOR and CCS.

- One of five PCOR Partnership demonstration sites.
- Cost-effective MVA.
- Basis for establishing and monetizing carbon credits.
- Internationally recognized.

Apache CANADA LTD.

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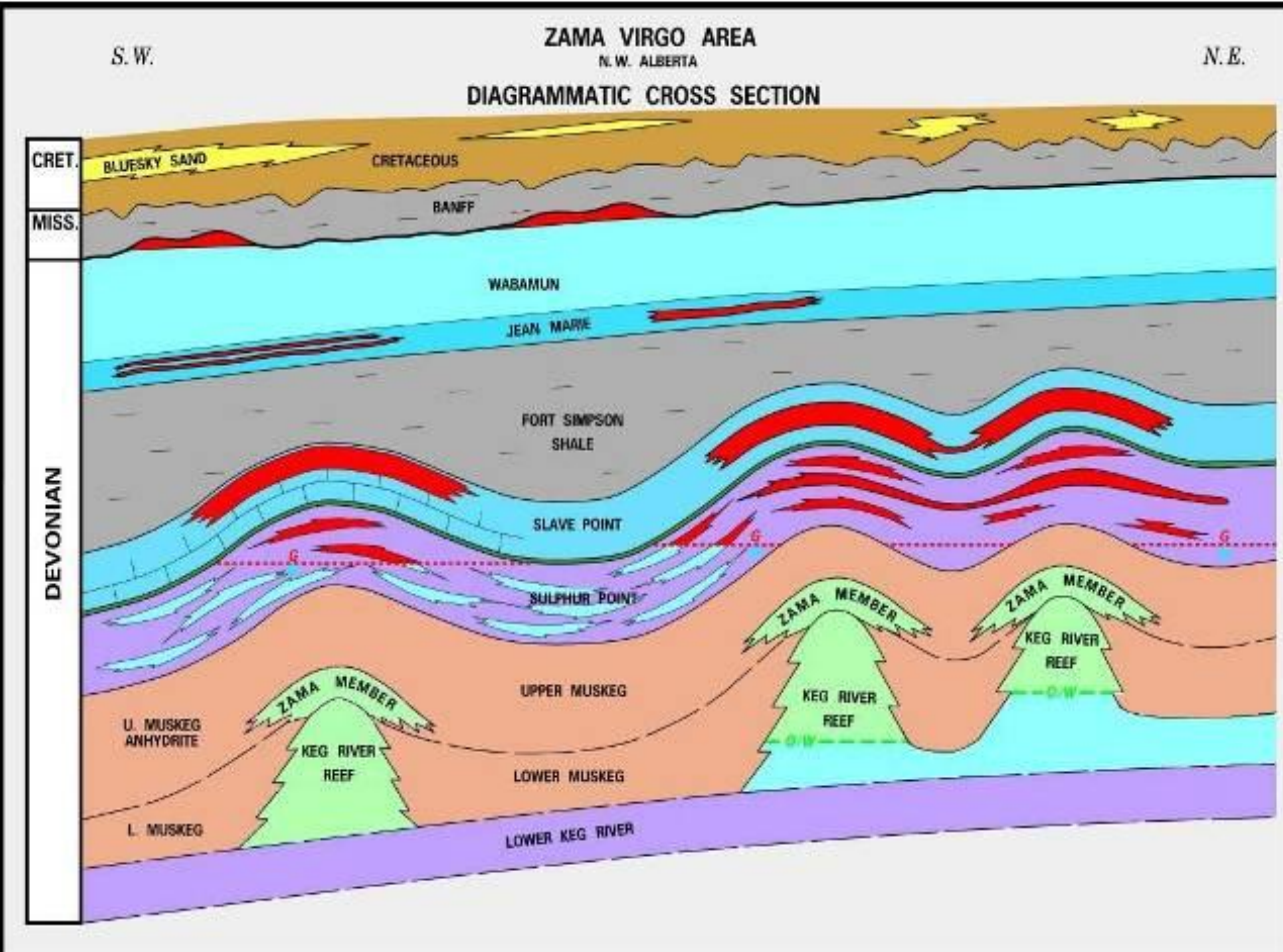
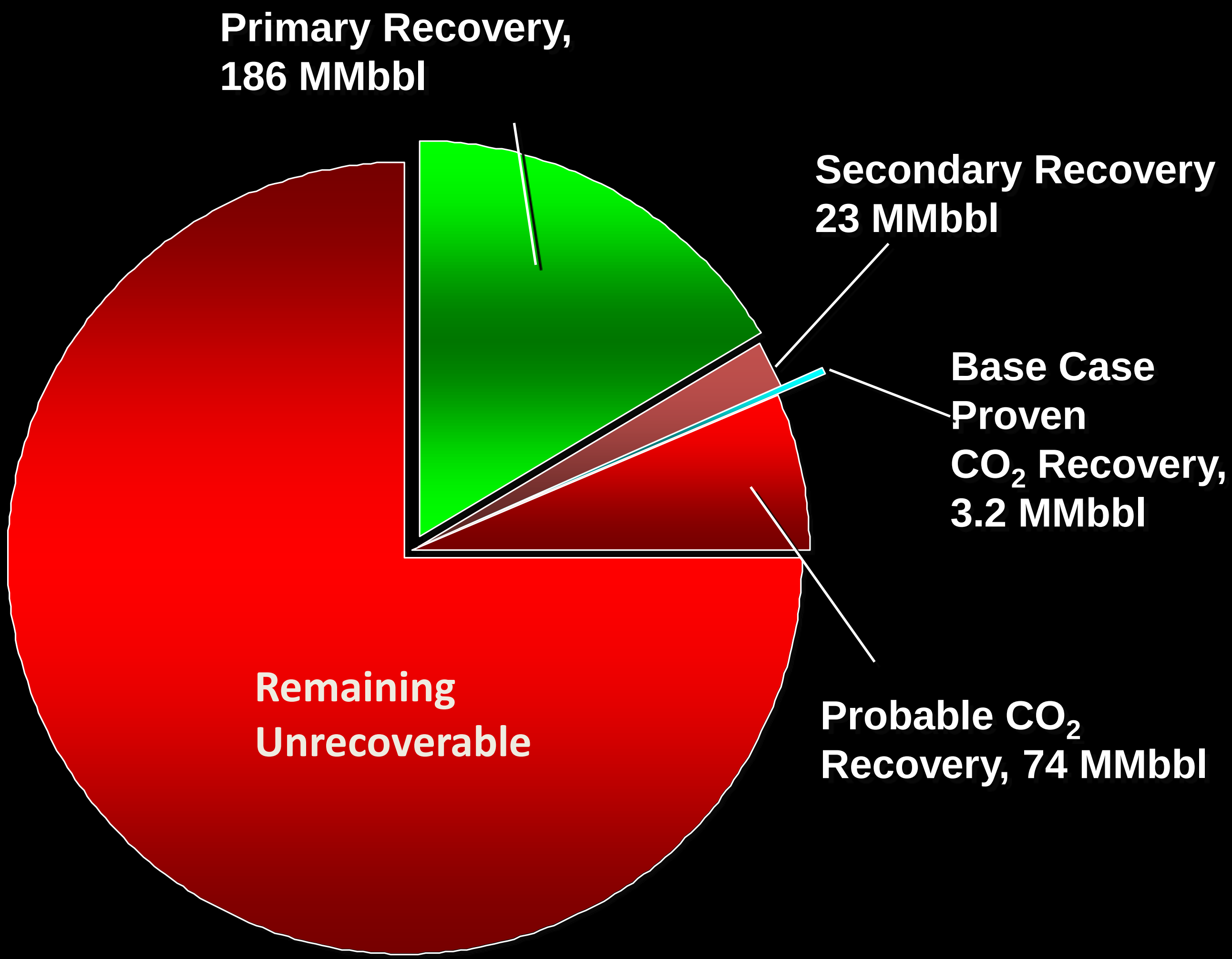
PCO_2R Partnership


ZAMA VIRGO AREA
N.W. ALBERTA
DIAGRAMMATIC CROSS SECTION
S.W.
N.E.
CRET.
MISS.
DEVONIAN
BLUESKY SAND
CRETACEOUS
BANFF
WABAMUN
JEAN MARIE
FORT SIMPSON
SHALE
SLAVE POINT
SULPHUR POINT
G
ZAMA MEMBER
KEG RIVER
REEF
O/W
UPPER MUSKEG
U. MUSKEG
ANHYDRITE
LOWER MUSKEG
L. MUSKEG
LOWER KEG RIVER

Zama Field History

- Currently operated by Apache Canada, Ltd.
- Discovered in 1967.
- Primary well development took place in the ‘60s and ‘70s.
- Waterflooding of selected pinnacles began in the ‘80s and is ongoing.
- 850 pools discovered to date.
- Cumulative production through August 2006 is 209 million stock tank barrels (stb) (17.4%).
- Currently producing approximately 5800 barrels of oil per day (bopd) @ 80.1% water cut.

Zama Keg River Estimated Recoveries

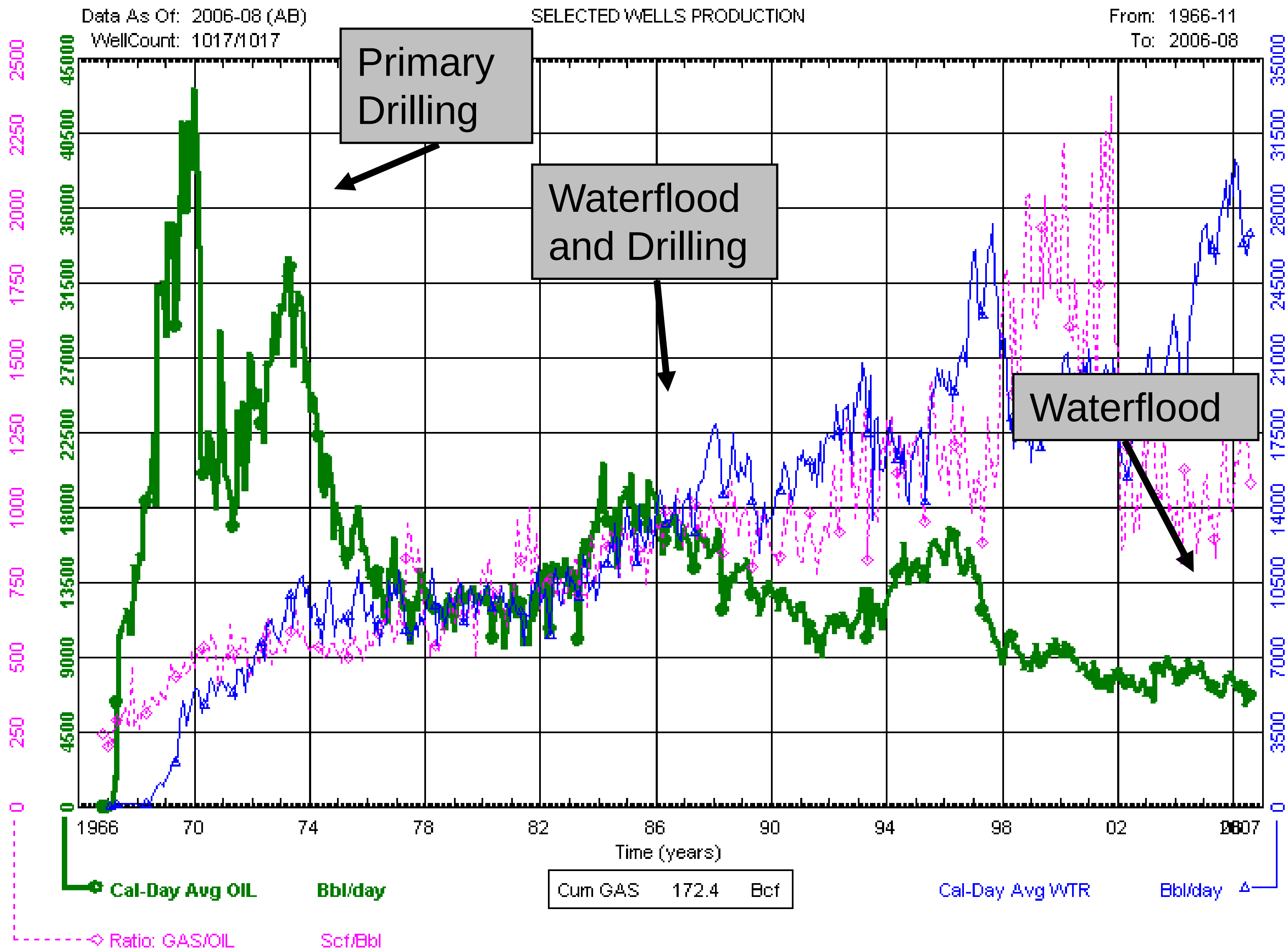


Technical evaluation based on 61MM$ demonstration project in operation since 2004.

Incremental pool recovery @ 15%

OOIP = 1,200 MMbbls

Zama Field – Production History



Zama Acid Gas EOR Project

- Unique approach combining acid gas disposal and CO_2 EOR.
- Acid gas is obtained from EOR recycle and additional field production passed through the on-site gas plant.
- Shut down the sulfur plant and eliminated CO_2 venting.
- Six pinnacles currently accepting acid gas for EOR.
- Potential for expansion into hundreds of additional pinnacles.

Plant Throughputs and Capacities

Plant

- Raw gas inlet capacity = 112 MMcfd
- Peak throughput = 112 MMcfd
- Hydrogen sulfide (H_2S) = 1.6%, CO_2 = 5.4% (7%)

Compression

- Five acid gas plant compressors ~8.8 MMcfd

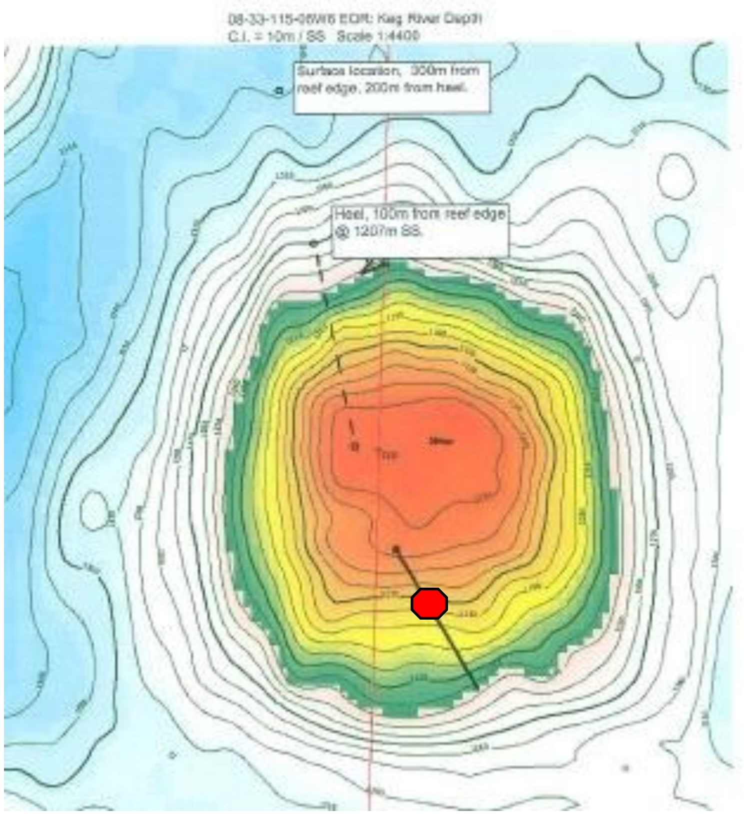
KR Z3Z Pool – Acid Gas Disposal to EOR

Zama Keg River Z3Z Reservoir Parameters

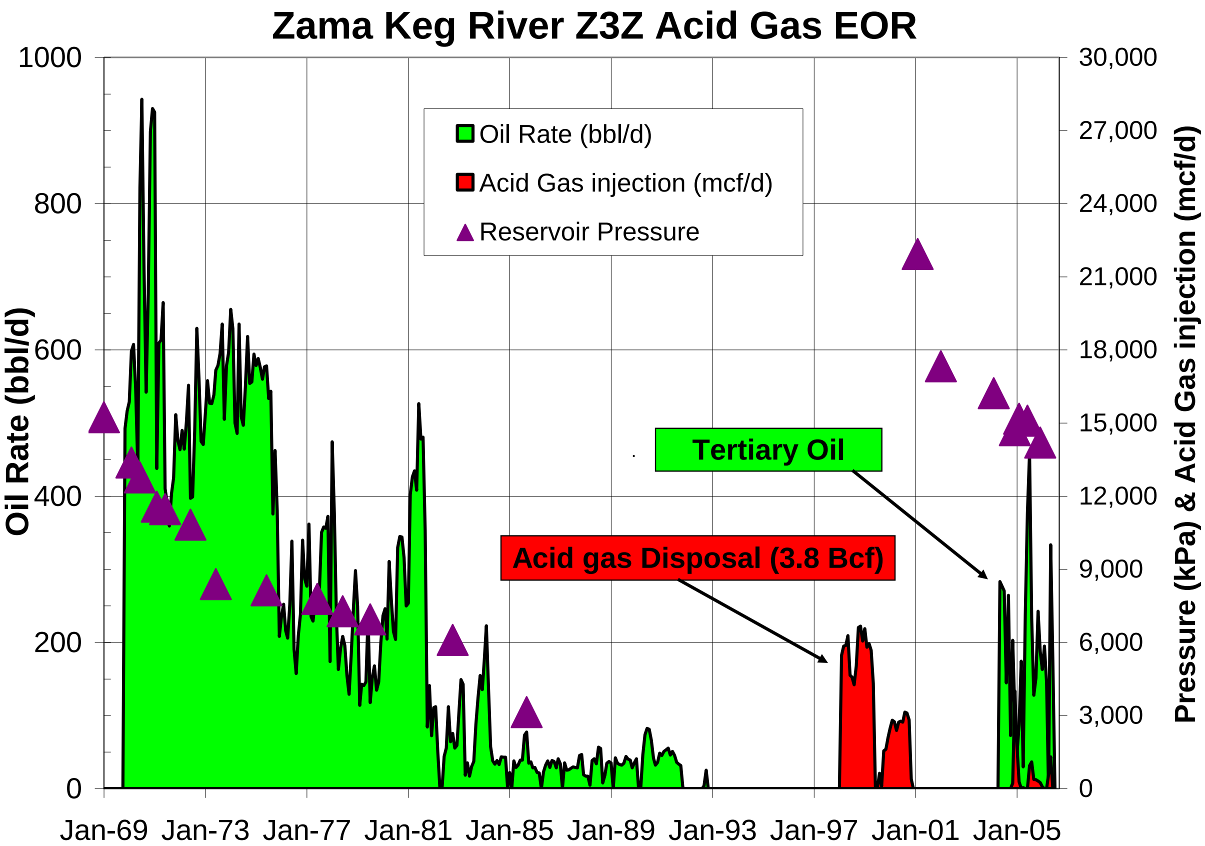
Initial Reservoir Pressure	15.3 Mpa (2210 Psi)
Reservoir Temperature	174 F
Initial Water Saturation	15% (from logs)
Porosity	8% (from logs)
Initial GOR	105.3 m^3/m^3 (591 scf/bbl)
Initial Formation Volume Factor	1.34 rb/stb
Bubble Point Pressure	12.5 Mpa (1802 Psi)
Oil Gravity	37.4 API

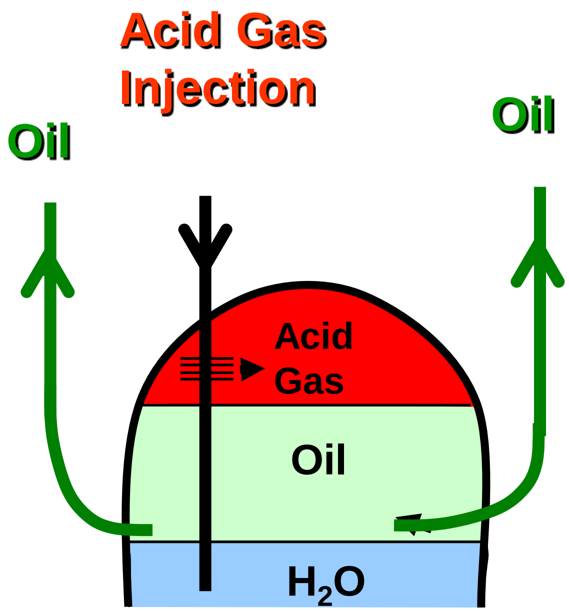
Injected Gas composition	67% CO2, 32% H2S
Minimum Miscibility Pressure	~15 Mpa (2175 Psi)

Original Oil in Place	377 E3m3 (2374 mbbl)
Cum Oil Prior to CO2 injection	143 E3m3 (904 mbbl)
Recovery Factor prior to CO2	38.0%



KR Z3Z Pool – Acid Gas Disposal to EOR

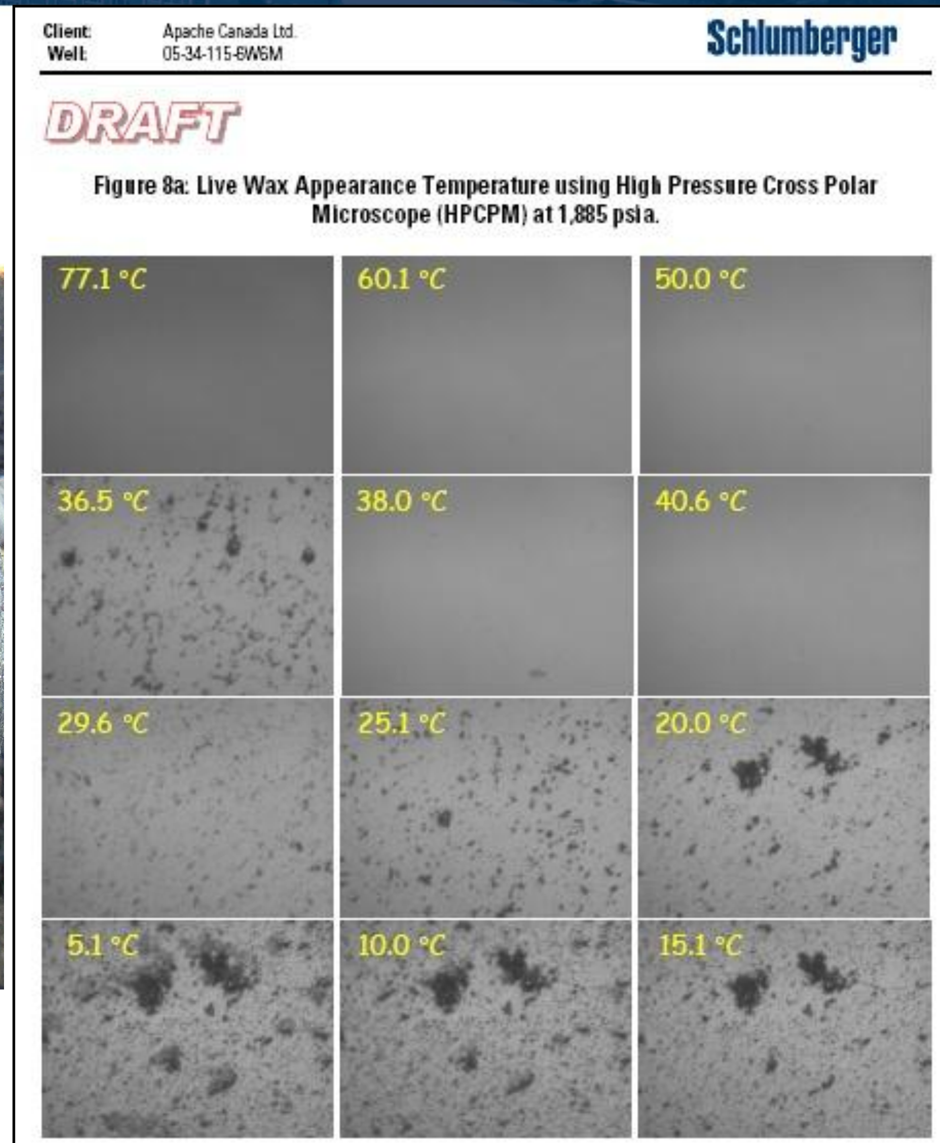




- **Current RF = 44.2%**

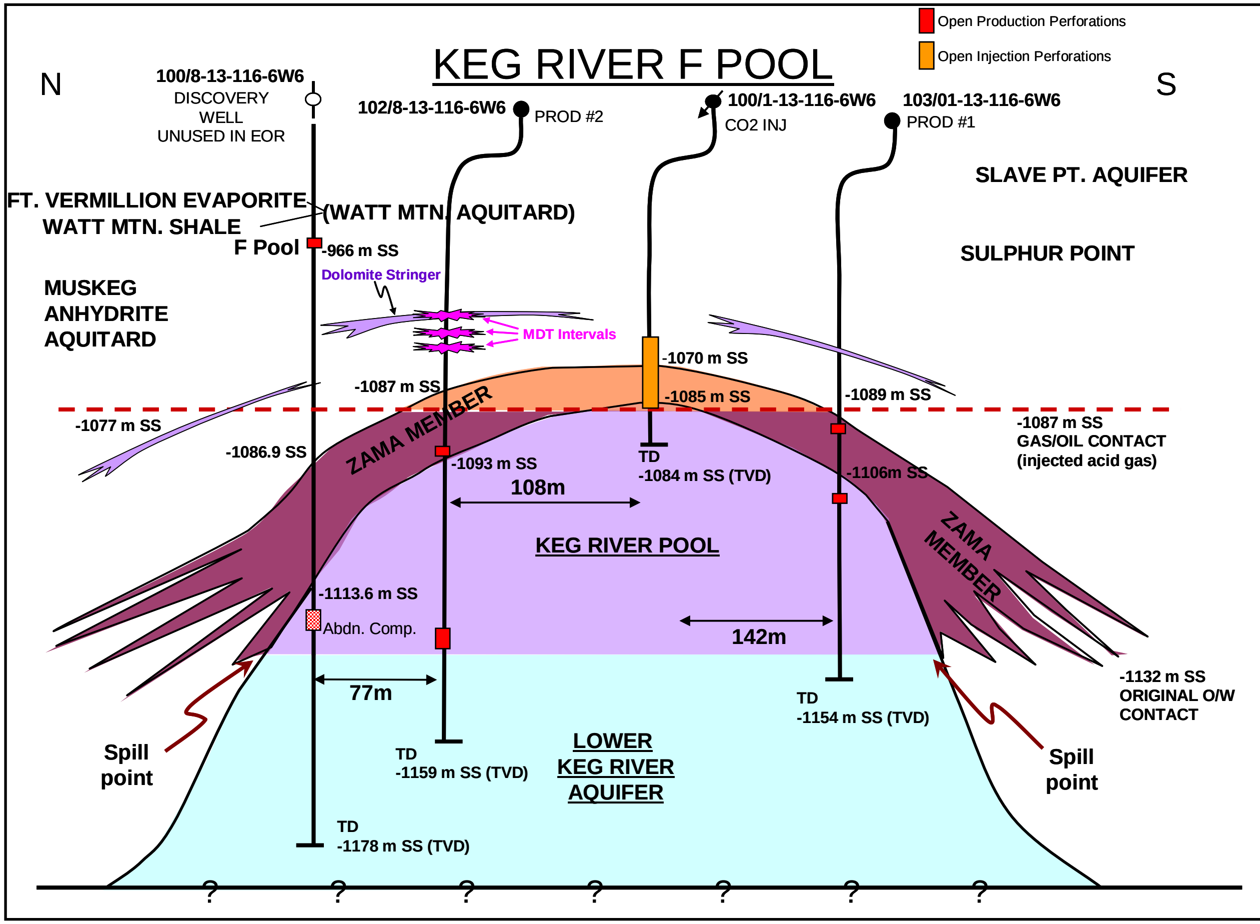
Zama Keg River Z3Z – Operational Challenges

Wax and asphaltenes precipitated in the pipeline during production.



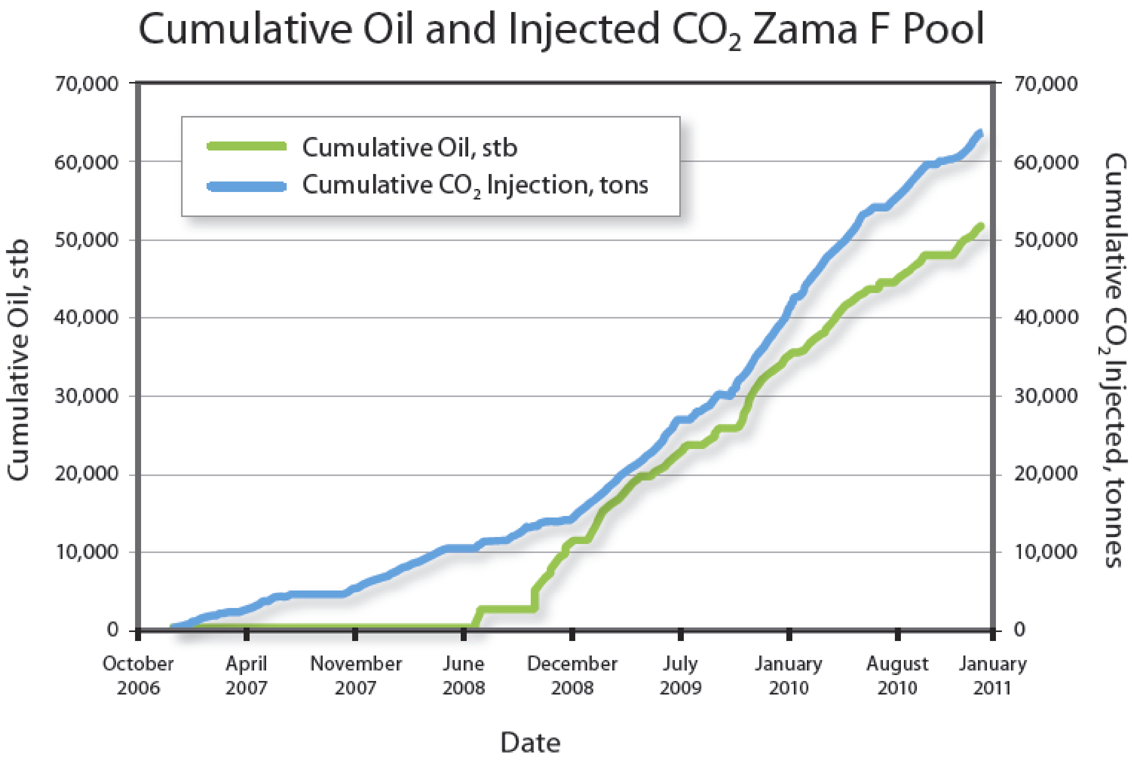
“F Pool” Operational Configuration

- Top-down injection scheme through one wellbore.
- Injected gas stream is approximately 70% CO_2 and 30% H_2S.
- Two production wells.
- Observation well completed in the Sulphur Point Formation.



"F Pool" Acid Gas Injection

- Began injection December 15, 2006.
- Average injection rate around 1 MMcfd.
- Second production well completed June 2008.
- Cumulative CO_2 injection over 60,000 tonnes.
- Cumulative production over 50,000 bbl.



Philosophy of Monitoring

- Maximize the use of existing data sets in an effort to characterize the baseline conditions of the site.
- Minimize the use of invasive or disruptive technologies to acquire new data.
- MVA data acquisition is coordinated with routinely scheduled operation activities.
- Ensure that the monitoring operations are as transparent as possible to the day-to-day field operations.

The Zama MVA program was developed using current Alberta regulatory framework for acid gas injection. Characterization activities were added to fully describe the system and provide confidence in the safe and secure storage of injected fluids.

MVA Operations

Monitor the CO_2–H_2S plume through:

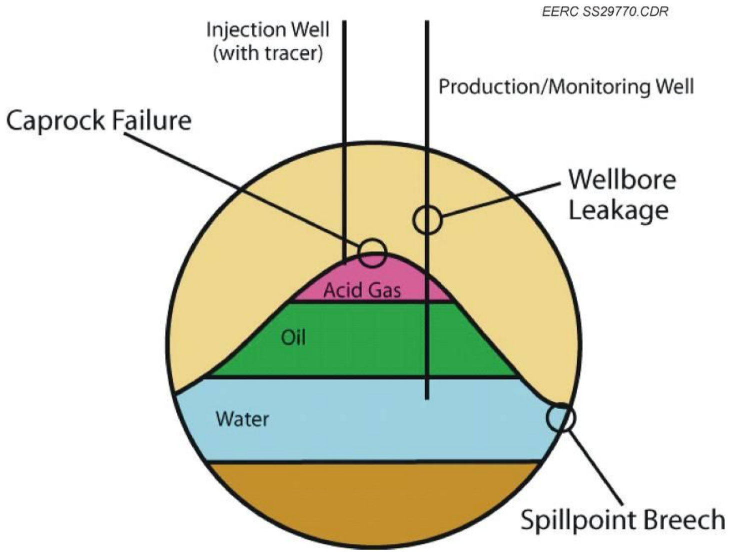
- Perfluorocarbon tracer injection and fluid sampling.
- Reservoir pressure monitoring.
- Wellhead and formation fluid sampling (oil, water, gas).

Monitor for cap rock failure through:

- Pressure measurements of injection well, reservoir, and overlying formations.
- Fluid sampling of overlying formations.

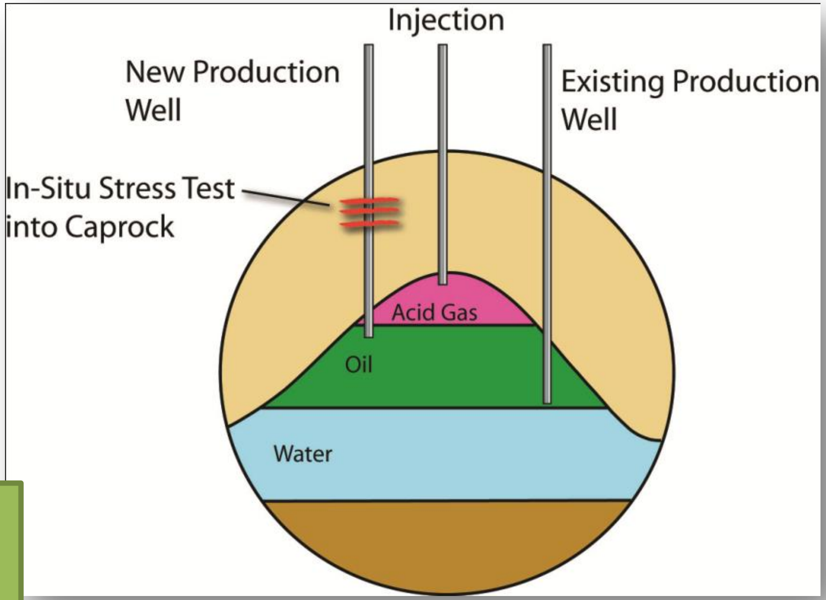
Determine injection well conditions through:

- Wellhead pressure gauges.
- Well integrity tests.
- Wellbore annulus pressure measurements.



Mechanical Integrity

- **Modular Dynamics Test – July 2008**
  - Performed to obtain horizontal stresses in reservoir cap rock.
  - Tested three intervals:
    - Two anhydrite
    - One dolomite stringer (encased in anhydrite)
- Unable to fracture anhydrite!
- Fracture attained in dolomite at over 5000 psi.
  - Allowable injection pressure is approximately 2100 psi.



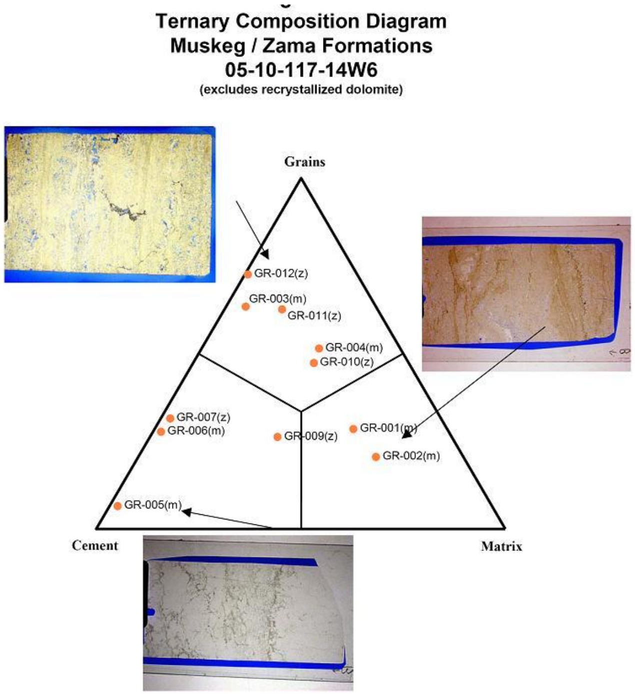
Conclusion:
All results to date indicate that cap rock leakage potential due to a geomechanical mechanism appears to be very low.

Geochemistry

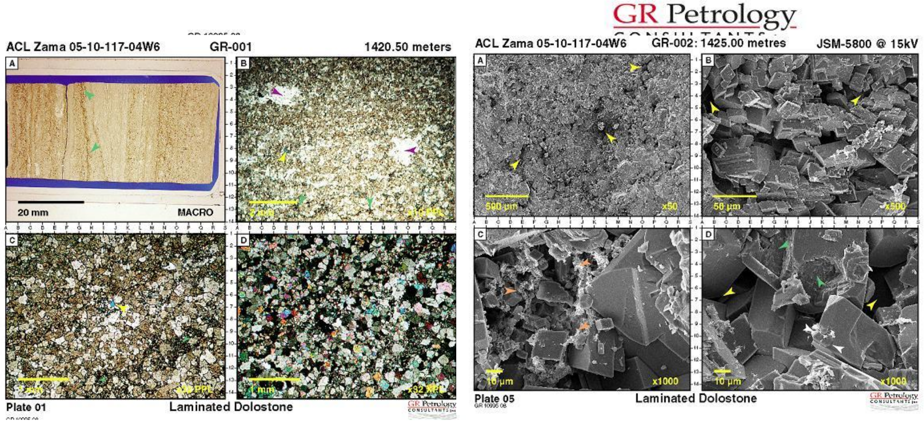
Petrophysical Evaluation
- Injection zone, cap rock, and overlying porous intervals.

Laboratory Work
- EERC acid gas soak test to determine rates of mineral reactions in carbonates and evaporites.

Modeling
- To evaluate reactions in carbonates with respect to:
  - Acid gas.
  - Formation fluids.
  - Formation minerals.



Conclusion:
Cap rock is very tight.
The reactivity of the reservoir is low.



Zama Key Findings

Hydrogeology: Pinnacle geometry, excellent cap rock, and extremely slow groundwater flow preclude migration**.**

Geomechanics: Reservoir and cap rock have more than adequate geomechanical integrity. Standard operating practices are sufficient to protect cap rock integrity.

Geochemistry: The reactivity of the reservoir is low. The primary form of acid gas trapping was solution trapping.

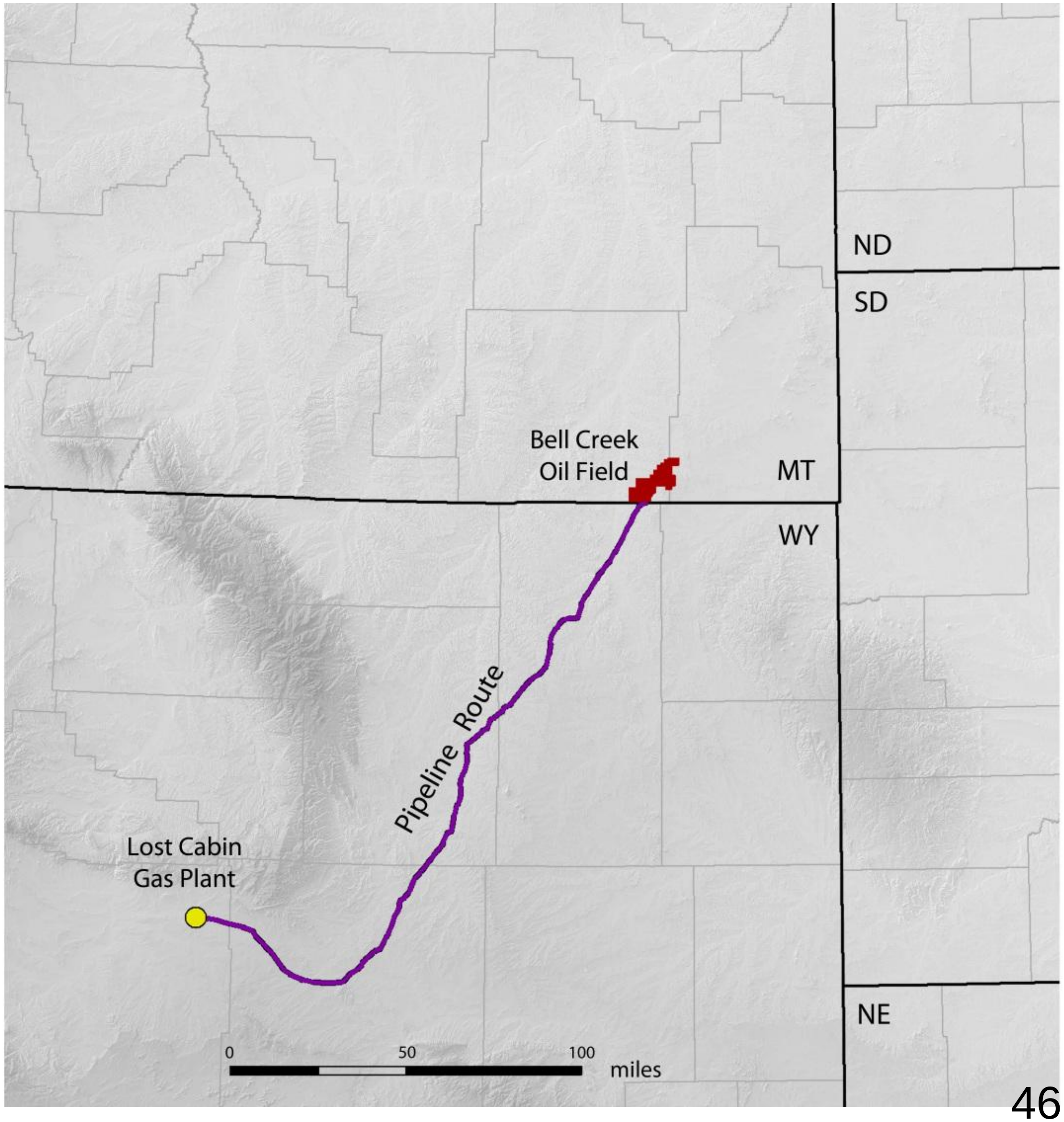
Engineering: Comprehensive planning using proven oil field practices.

MVA: All characterization activities and current monitoring results indicate that the Zama Field is an ideal candidate for large-scale CO_2 storage location.

Carbon Credits: Findings were applied toward the establishment of carbon offset credits under the Alberta Environment Specified Gas Emitters Regulation.

Bell Creek CO_2 EOR and Storage Project

- Bell Creek Field is owned and operated by Denbury Resources, Inc. (Denbury).
- CO_2 from ConocoPhillips Lost Cabin natural gas-processing plant.



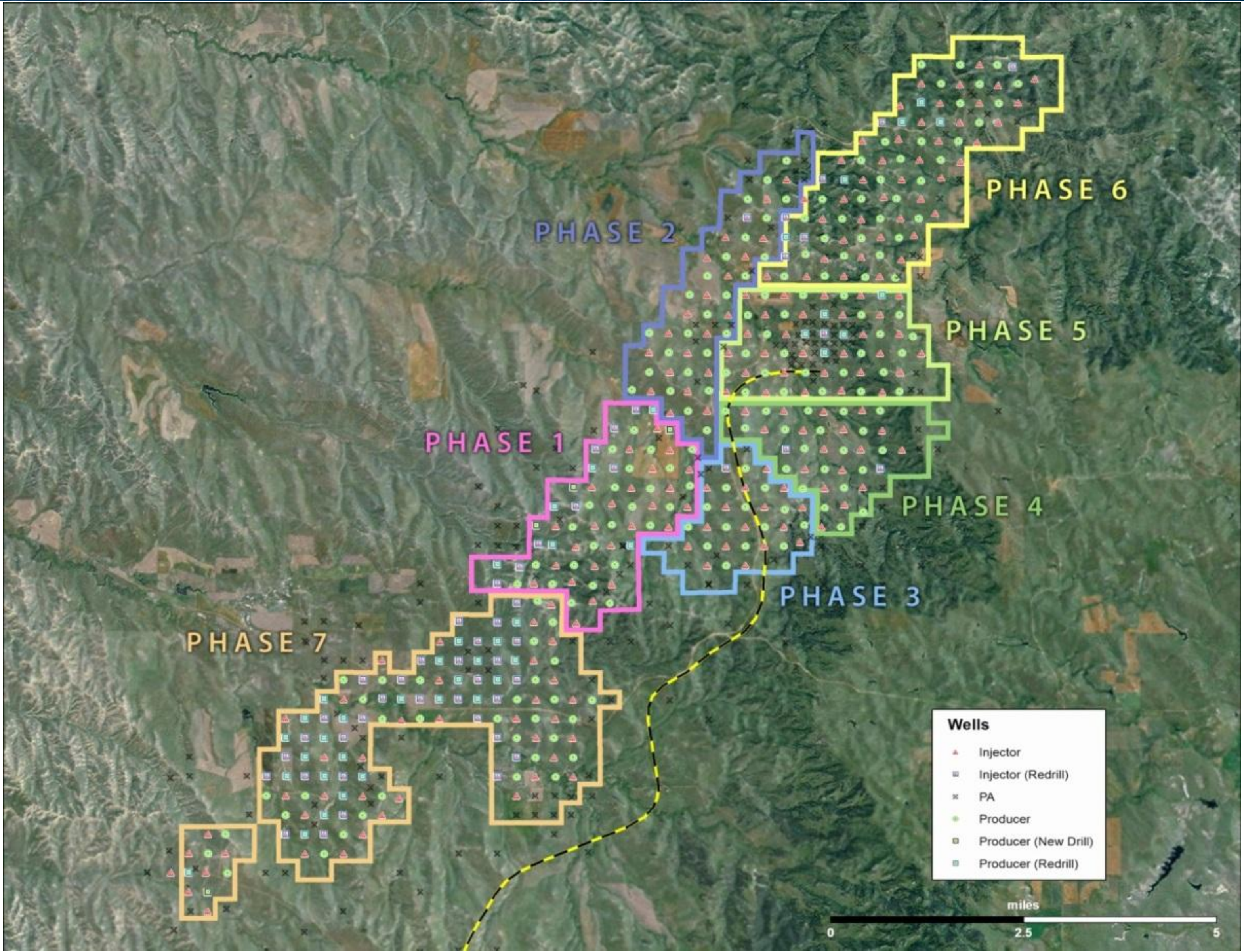
Field History

- Discovered in 1967
- Field developed within 2 years (450+ wells)
- OOIP estimated at 353 MMbo
- Peak production of 56,000 bopd (August 1968)
- Cumulative production total = 133 MMbo (38% recovery)

Current Activities

- Denbury is preparing the field for CO_2 injection.
- Wells are being recompleted, and facilities are under construction.
- Approximately 50 million standard cubic feet per day (MMscfd) of CO_2 will be delivered to Bell Creek.
- Injection scheduled to begin first quarter of 2013.
- An estimated 35 million incremental bbl of oil will be recovered using CO_2 EOR at Bell Creek.

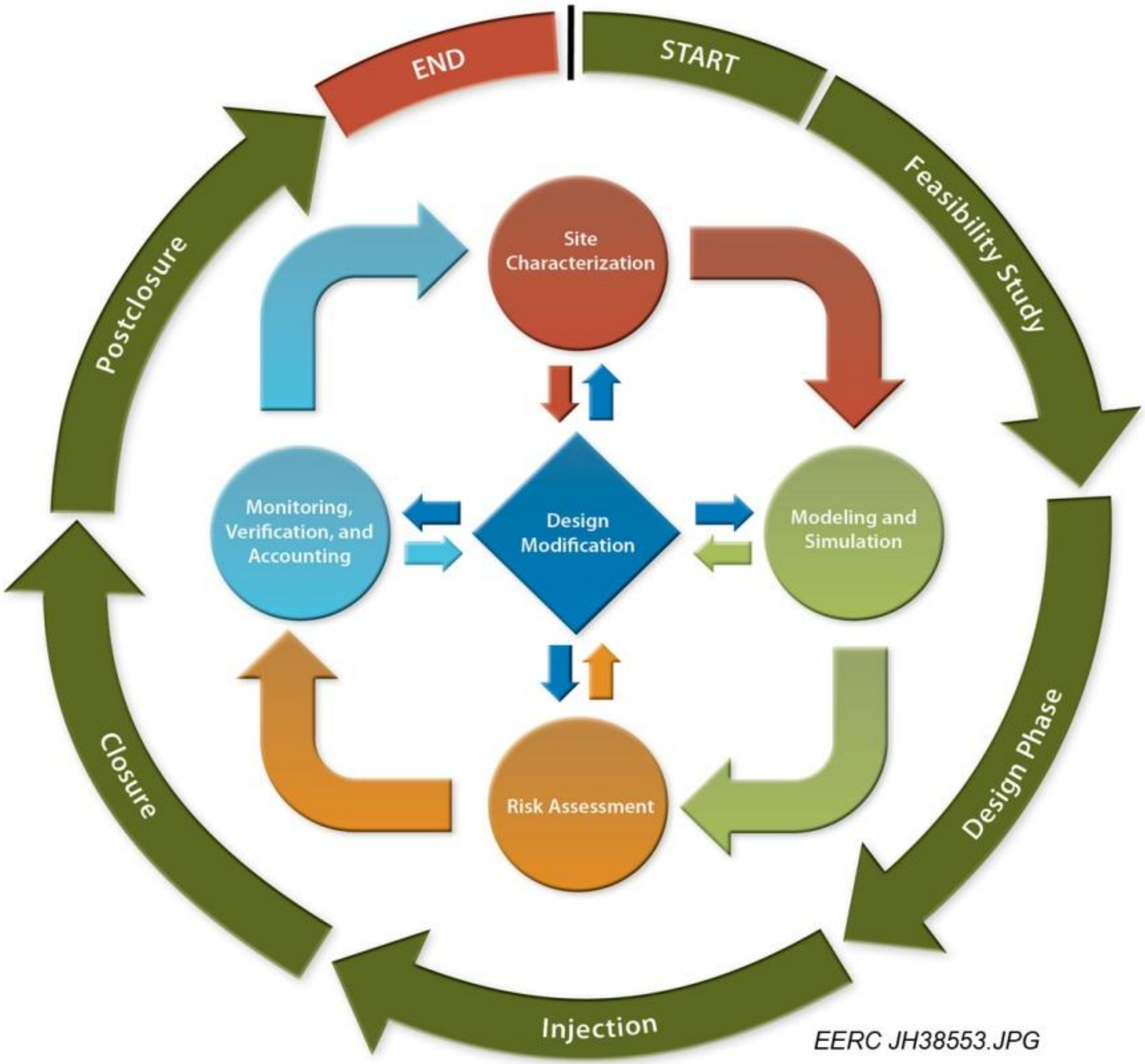
Phased Approach



PCOR Partnership Activities at Bell Creek

- **Developing an integrated approach to MVA.**
- **Focused on site characterization, modeling and simulation, and risk assessment as a guide for developing an MVA strategy.**

Monitoring Philosophy



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Site Characterization

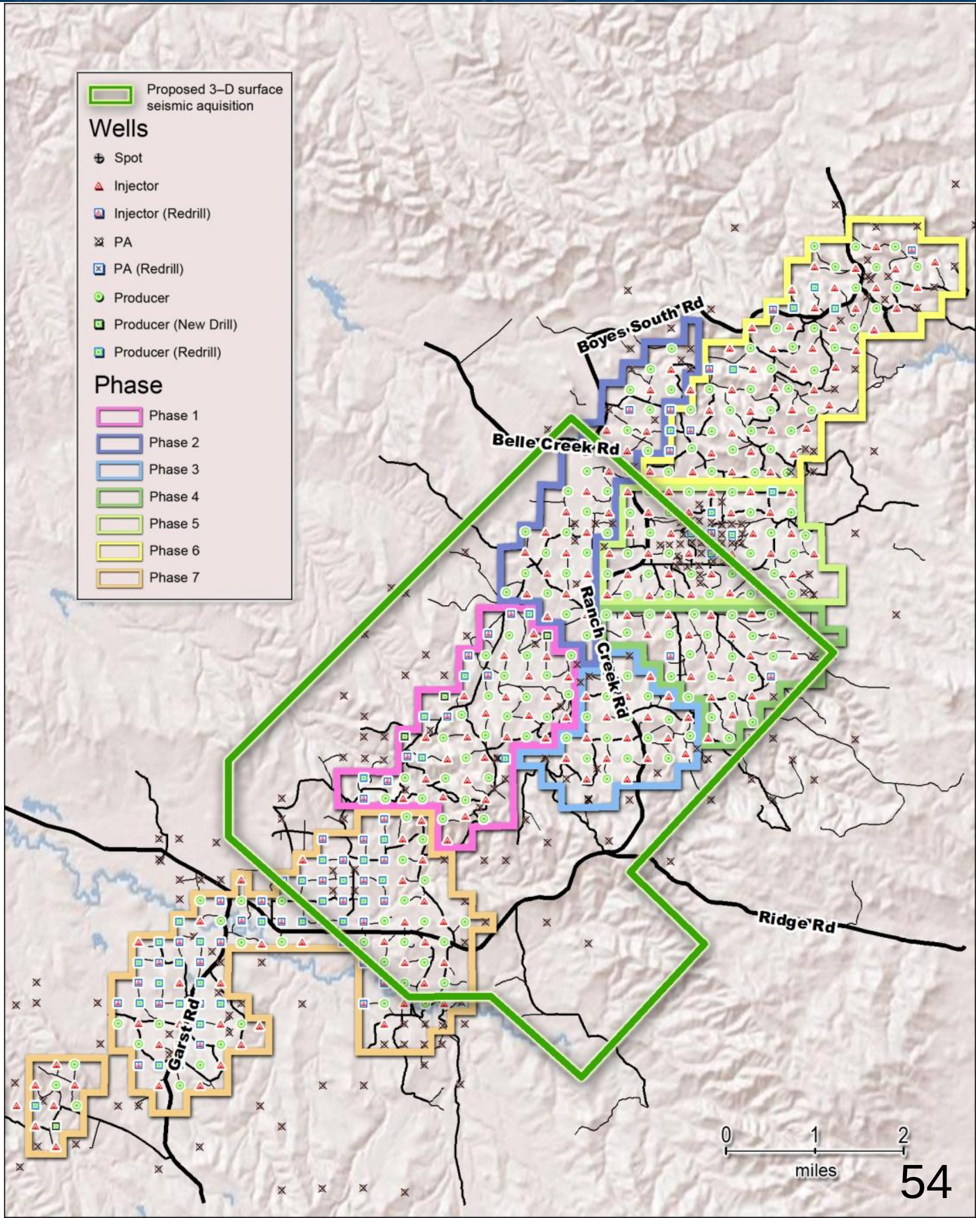
- Conduct outcrop field trip
- Visit core libraries
- Review historic data (well files)
- Drill a new dedicated data collection and monitoring well
- Collect baseline seismic data (2-D, 3-D, crosswell, and vertical seismic profile [VSP])

Site Characterization (geology)

- Muddy sandstone (only producing reservoir):
  - Depth = 4300–4500 ft
  - Gross thickness = 30–45 ft (three to four lenticular zones)
  - Permeability range = 425–1175 mD
  - High porosity = 25%–35% (loosely consolidated)
  - Oil gravity = 32 °–41° API

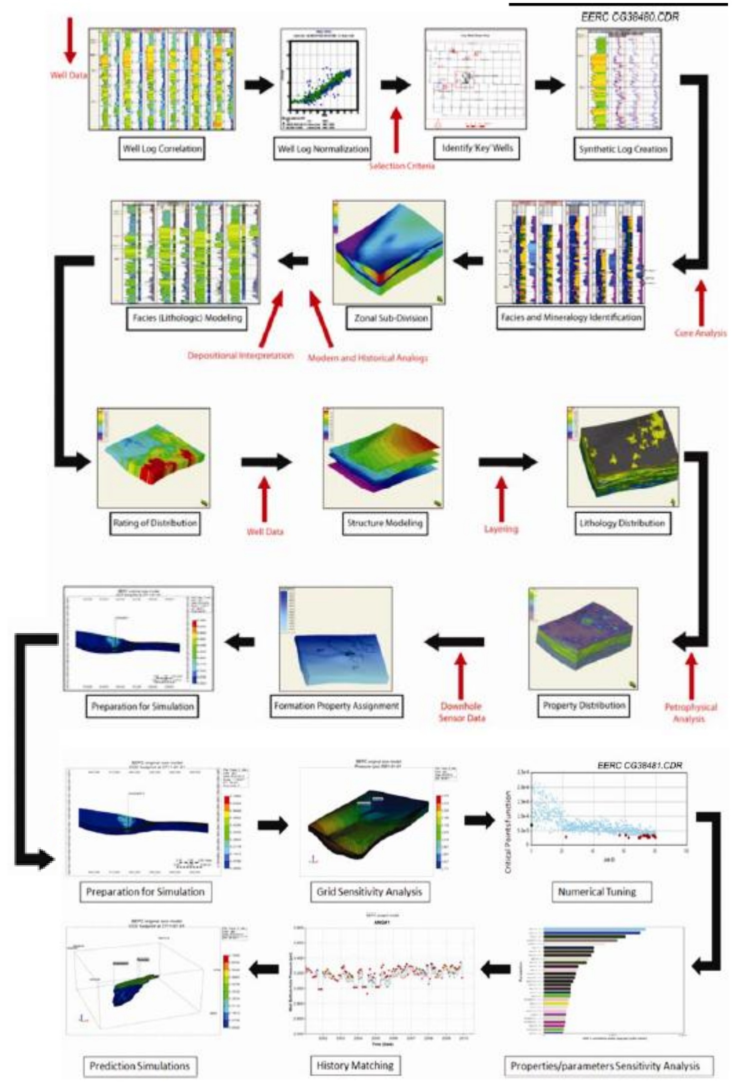
Site Characterization (seismic)

- Assist with updip/downdip boundaries and reservoir structure
- Provide baseline data for time-lapse seismic plume tracking
- Check shot and seismic source testing completed November 2011
  - Optimize seismic survey source parameters



Modeling and Simulation

- Goals
  - Evaluate injection scenarios
  - Predict fluid migration pathways and area of influence at discrete time steps
  - EOR and CO_2 storage efficiencies
  - Predict reservoir response
  - Aid in risk assessment



Risk Identification

- Evaluate current wellbores in and around the injection site
- Evaluate risk based on simulation results
- Monitor for high-risk events
- Update simulation and risk analysis based on monitoring results

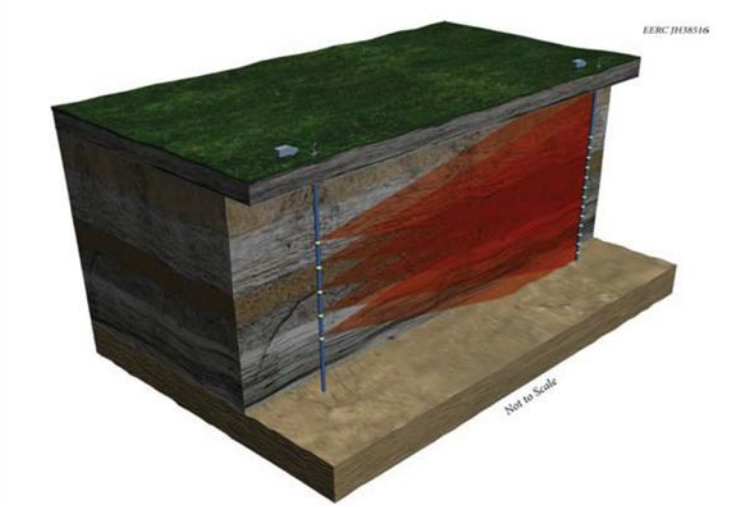
Frequency \ Severity	1	2	3	4	5
5	6	7	8	9	10
4	5	6	7	8	9
3	4	5	6	7	8
2	3	4	5	6	7
1	2	3	4	5	6

Level	Risk Rank	Suggested Action
9-10	High	A.S.A.P: Immediate, short term risk treatment required
7-8	Moderate	Short-mid term risk treatment required, ALARP
5-6	Transition	Uncertainty reduction, ALARP(*), MVA(**), risk treatment whenever possible or affordable
2-4	Low	No immediate action required, continue to monitor. For Risk Rank = 2, look for possibility of cost reduction

(*) ALARP: As Low As Reasonably Possible

MVA

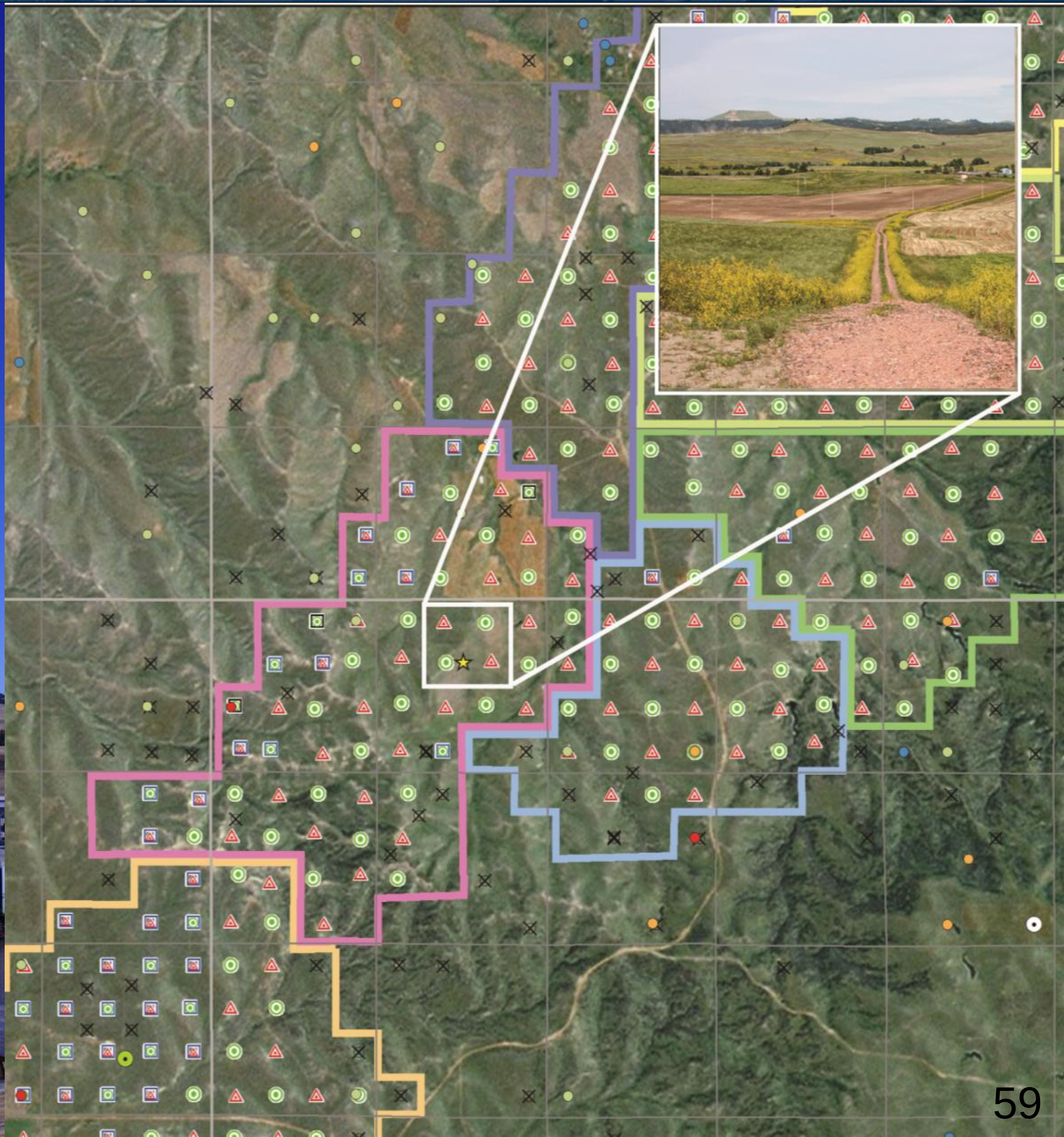
- Based on site characterization, modeling and simulation, and risk assessment
- Two parts – surface/near-surface and deep monitoring
- Goals
  - Verify site security
  - Assess variances within predicted injection program
  - Establish preinjection conditions
  - Track movement of CO_2
  - Evaluate efficiency of the CO_2 EOR and storage program
  - Identify fluid migration pathways
  - Determine ultimate fate of CO_2



Soil Gas and Water Monitoring

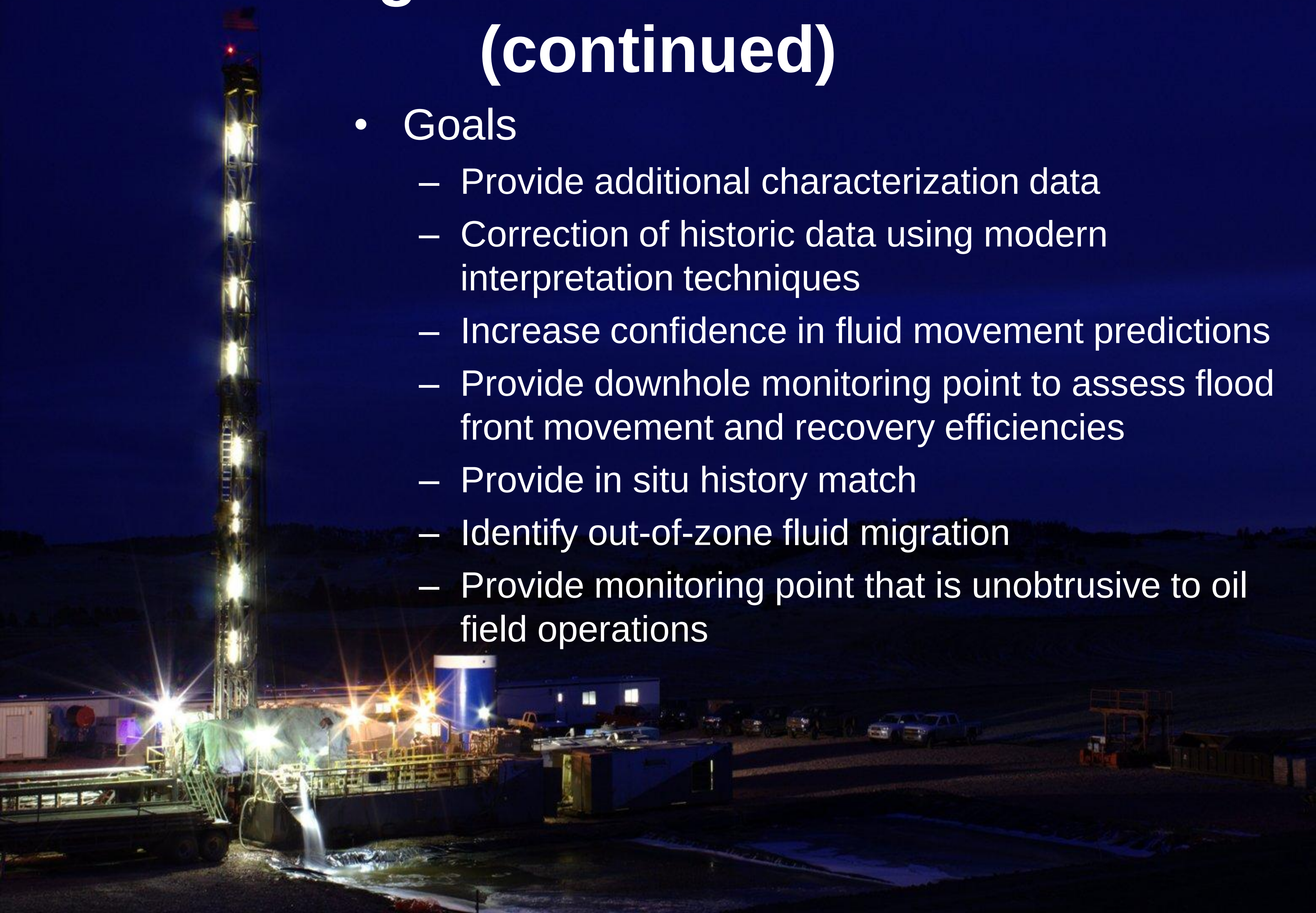
- Provide a baseline data set of seasonal CO_2 flux for comparison throughout the field.
- Determine the source of anomalies through chemical analysis:
  - Natural biological processes
  - Seasonal flux
  - Agricultural practices
- Identify anomalies in a timely manner:
  - Determine source of anomaly.
  - Minimize environmental impact through early identification.
  - Remediation techniques developed for the oil and gas industry exist to correct wellbore integrity problems in a safe and efficient manner.

Monitoring and Characterization Well



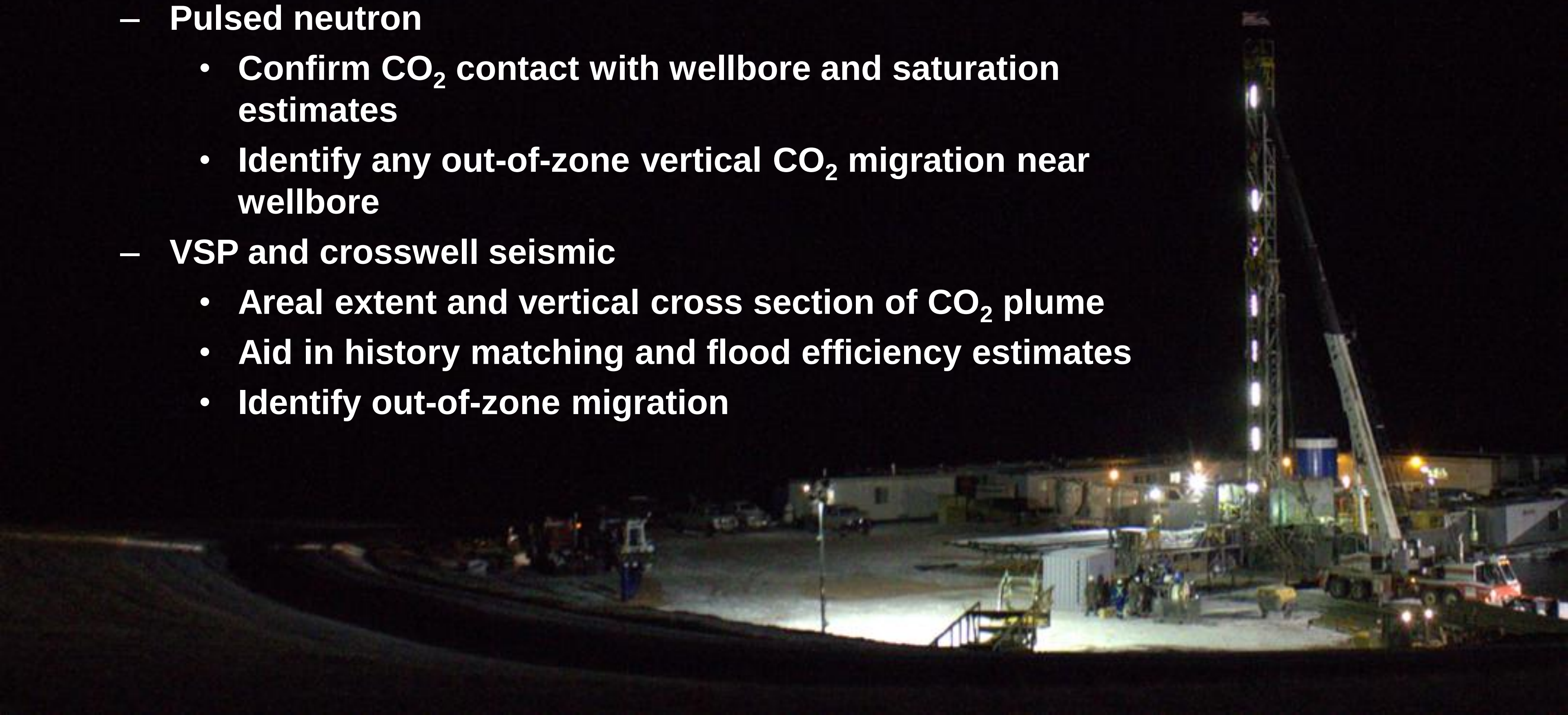
Monitoring and Characterization Well (continued)

- Goals
  - Provide additional characterization data
  - Correction of historic data using modern interpretation techniques
  - Increase confidence in fluid movement predictions
  - Provide downhole monitoring point to assess flood front movement and recovery efficiencies
  - Provide in situ history match
  - Identify out-of-zone fluid migration
  - Provide monitoring point that is unobtrusive to oil field operations



Monitoring Well – Monitoring Plan

- **Staged monitoring program**
  - **Permanent downhole monitoring of continuous pressure and distributed temperature**
    - **Provide in situ history match data**
    - **Provide an indication of CO_2 contact with wellbore**
  - **Pulsed neutron**
    - **Confirm CO_2 contact with wellbore and saturation estimates**
    - **Identify any out-of-zone vertical CO_2 migration near wellbore**
  - **VSP and crosswell seismic**
    - **Areal extent and vertical cross section of CO_2 plume**
    - **Aid in history matching and flood efficiency estimates**
    - **Identify out-of-zone migration**



Monitoring Plan

- Well reentry
  - Goals
    - Supplement characterization data to provide increased confidence in simulation work and predictions of CO_2 and fluid movement
    - Acquire drillstem test (DST) and fracture pressure data in the reservoir
    - Assess compartmentalization of field
    - Provide geomechanical modeling inputs
    - Monitor fluid movement and chemical changes in reservoir

Monitoring Plan (continued)

- Injection and production wells outfitted with real-time sensors
  - Surface casing pressure
  - Production casing pressure
  - Flow line pressure
  - Tubing pressure

Summary

- The PCOR Partnership is working closely with Denbury to characterize the Bell Creek Field and set up for monitoring the CO_2 once injection begins.
- Injection of approximately 50 MMscfd of CO_2 is scheduled to begin first quarter of 2013.
- An estimated 35 million incremental bbl of oil will be recovered using CO_2 EOR at Bell Creek.

Figure 5

CO_2 FLOOD SURVEILLANCE vs. CCGS MONITORING, MEASUREMENT AND VERIFICATION (MMV)

NEEDS

	FLOODING	MMV
1)	INJECTION IN ZONE	INJECTION IN ZONE
2)	FLOW PATHS	FLOW PATHS
3)	PRESSURE CONTAINMENT	PRESSURE CONTAINMENT
4)	WELLBORE INTEGRITY	WELLBORE INTEGRITY
5)	SWEEP EFFICIENCY	N/A
6)	N/A	LONG TERM STORAGE

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Thank You!