Monitoring. The Weyburn-Midale Project

B. Dietiker

Petroleum Technology Research Centre

Geological Survey of Canada

ptrc Petroleum Technology Research Centre

CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

IEA GHG WEYBURN-MIDALE CO_2 MONITORING AND STORAGE PROJECT

Natural Resources Canada / Ressources naturelles Canada

Canada

Overview

- Introduction:
- Weyburn-Midale: Location, Reservoir, EOR, Storage
- A decade of Research for the Weyburn-Midale Project
- Organisation of the Project

- Theme 1: Geological Integrity
- Theme 2: Wellbore Integrity
- Theme 4: Risk assessment

- Theme 3a: Geophysical Monitoring
- Theme 3b: Geochemical Monitoring

- Summary

Weyburn-Midale Reservoir

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Weyburn

- Discovered 1954
- OOIP ~<u>1.4 Billion</u> BBLs
- Field size 70 sq miles

Midale

- Discovered 1954
- OOIP ~<u>0.5 Billion</u> BBLs
- Field size 40 sq miles

Weyburn-Midale Reservoir

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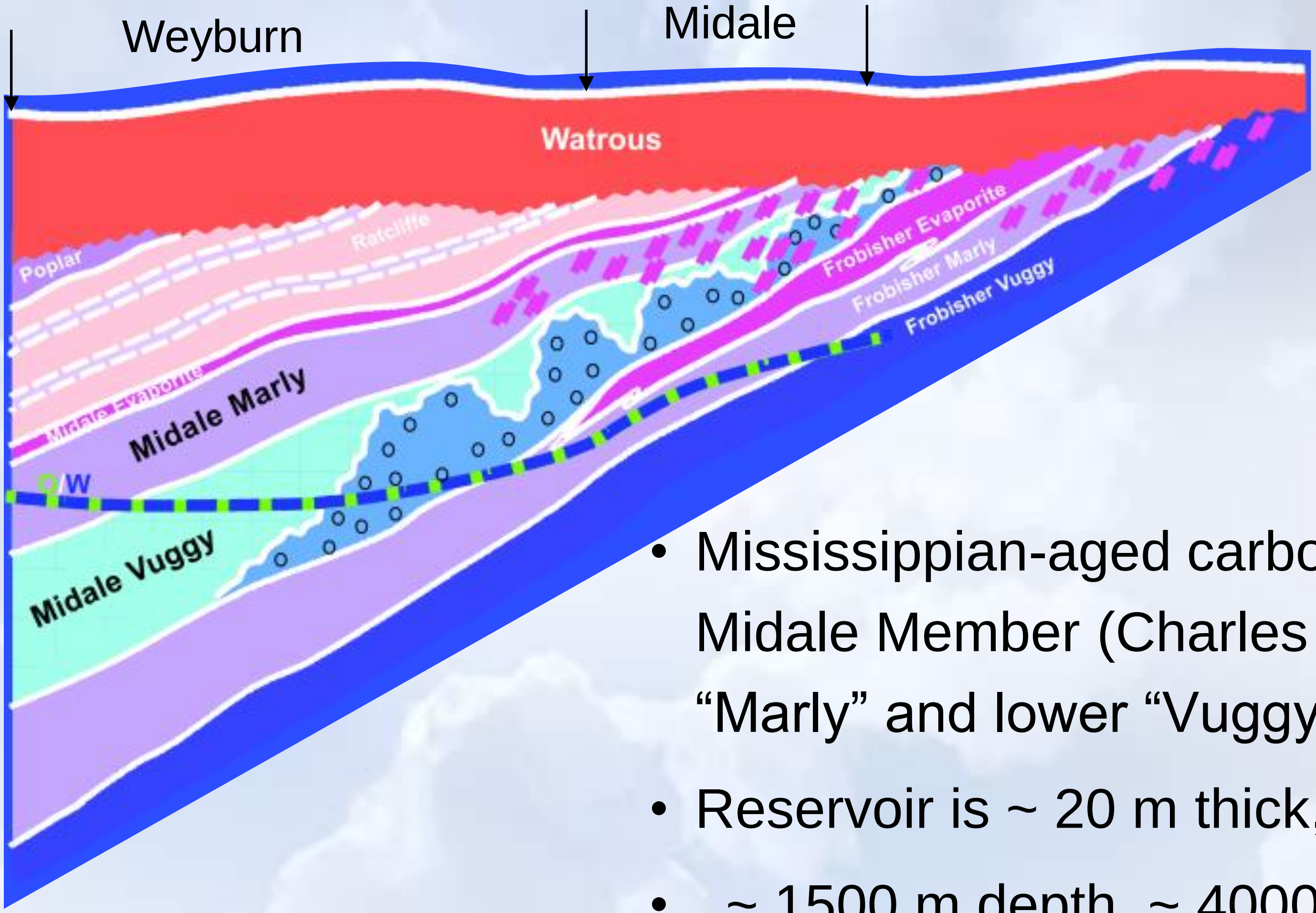
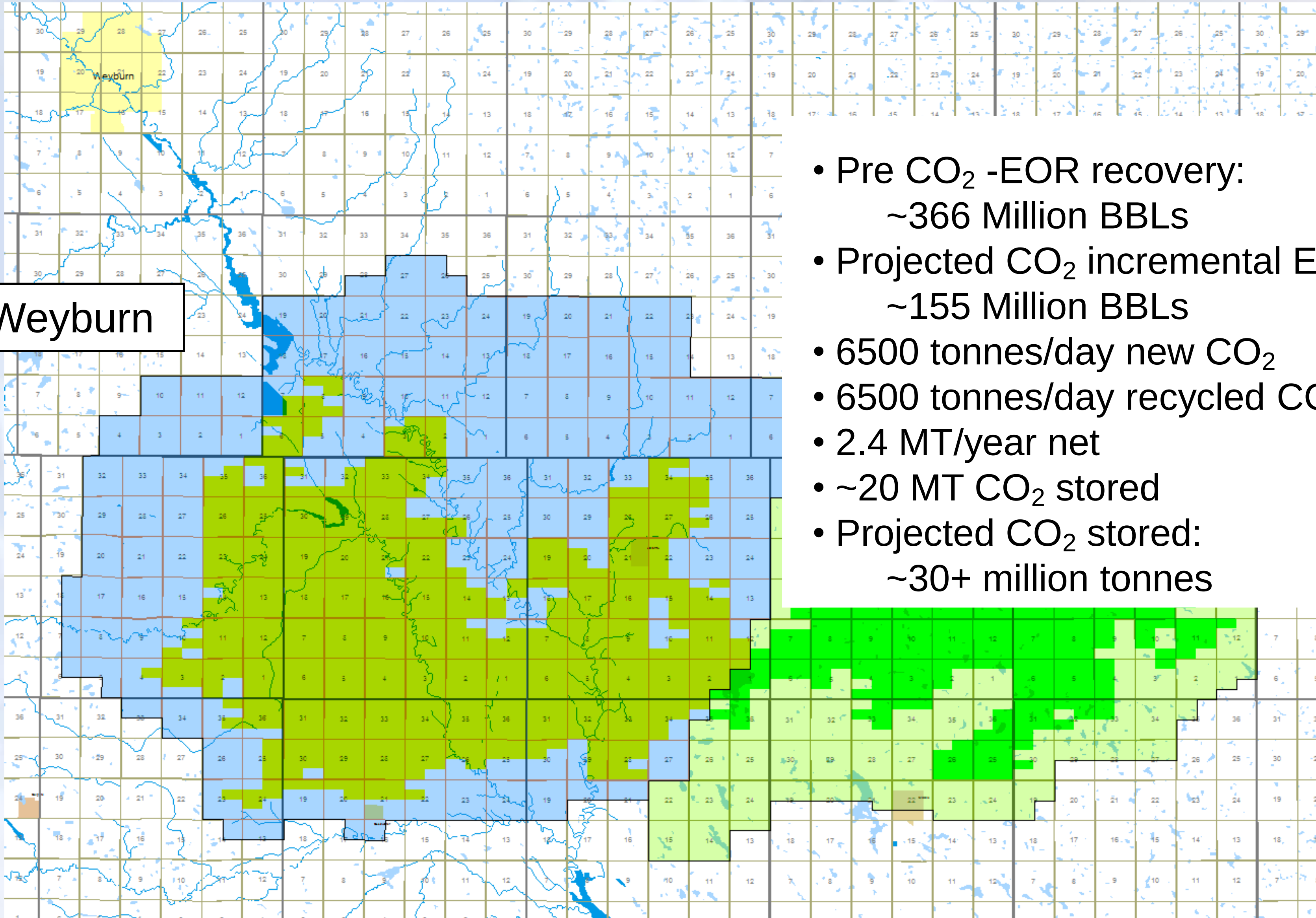


- Mississippian-aged carbonates of the Midale Member (Charles Fm): upper “Marly” and lower “Vuggy”
- Reservoir is ~ 20 m thick, fractured
- ~ 1500 m depth, ~ 4000 wells
- Production: 25-34 API medium sour oil

Weyburn-Midale Area



- Pre CO_2 -EOR recovery:
  ~366 Million BBLs
- Projected CO_2 incremental EOR:
  ~155 Million BBLs
- 6500 tonnes/day new CO_2
- 6500 tonnes/day recycled CO_2
- 2.4 MT/year net
- ~20 MT CO_2 stored
- Projected CO_2 stored:
  ~30+ million tonnes

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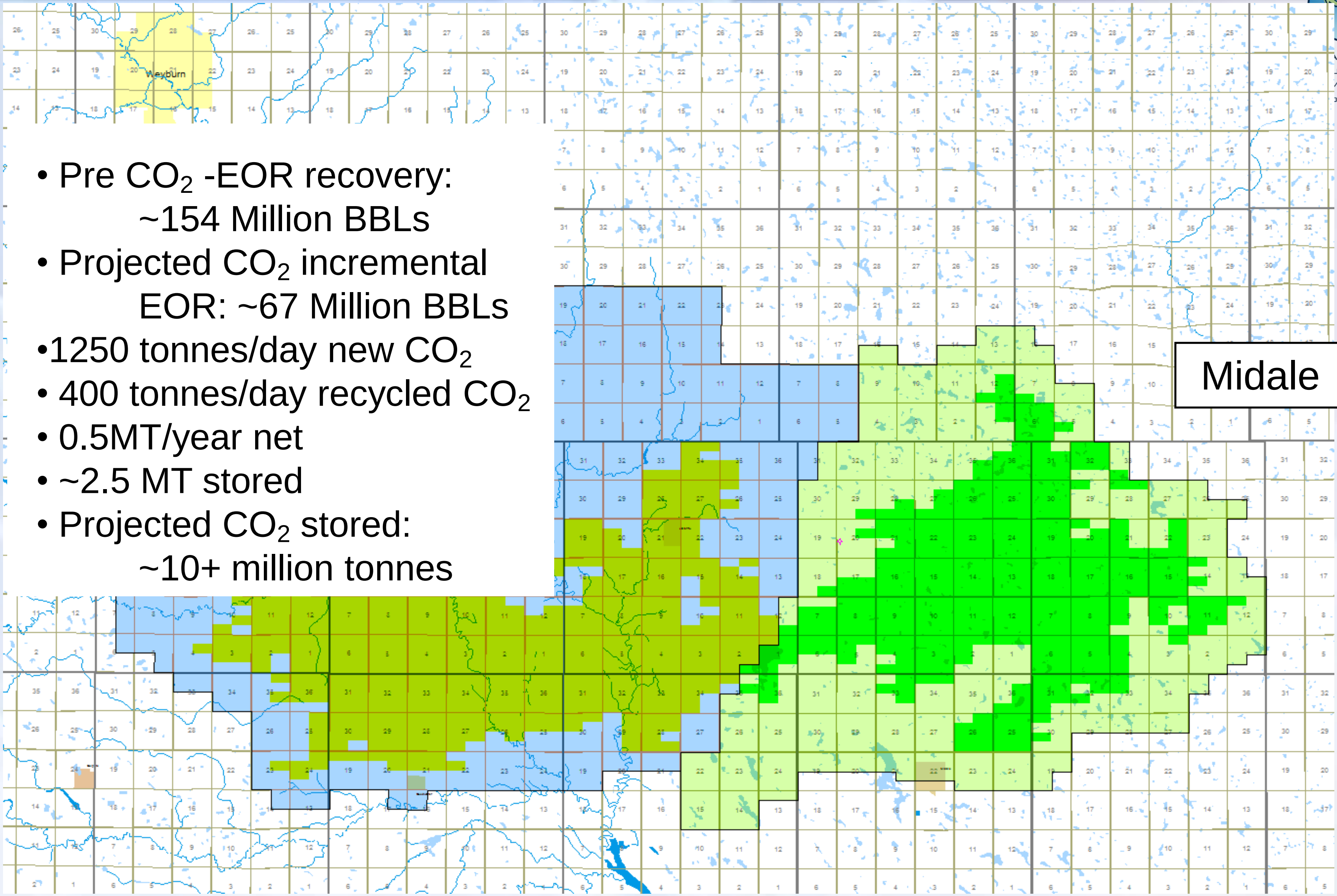
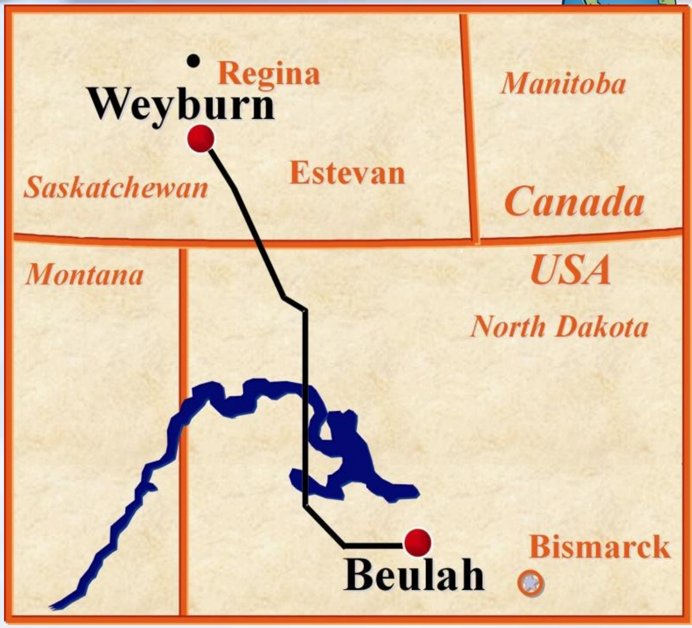
Weyburn-Midale Area



- Pre CO_2 -EOR recovery:
  ~154 Million BBLs
- Projected CO_2 incremental
  EOR: ~67 Million BBLs
- 1250 tonnes/day new CO_2
- 400 tonnes/day recycled CO_2
- 0.5MT/year net
- ~2.5 MT stored
- Projected CO_2 stored:
  ~10+ million tonnes

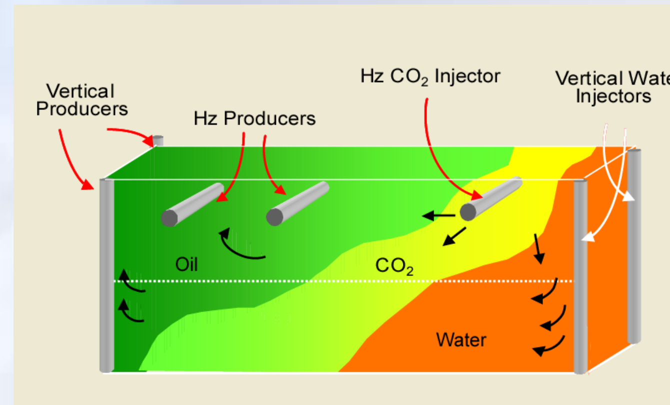
CO_2 Capture

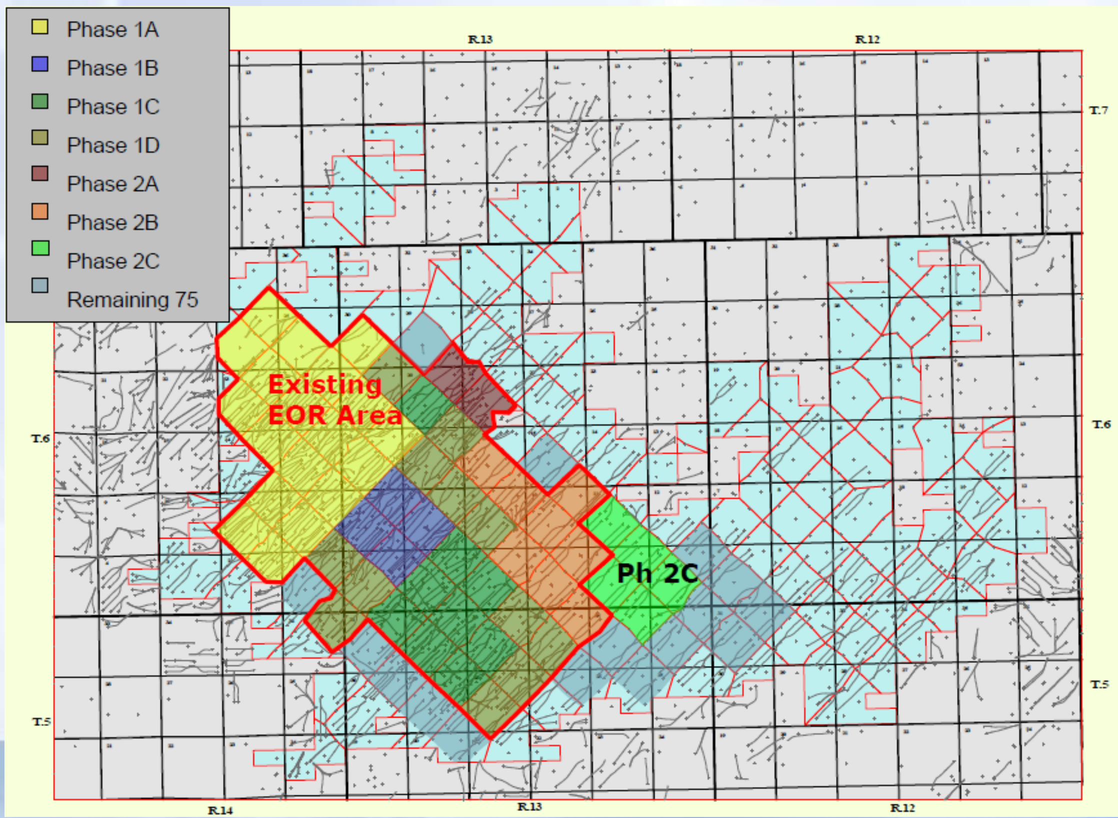
- CO_2 supplied by Dakota Gasification company (Great Plains Synfuels Plant), Beulah, ND, USA
- CO_2-Injection started Oct. 2000
- By End of 2010, 20 million tonnes have been captured



Weyburn CO_2 EOR Project

- combination Horiz/Vert & Prod/Inj
- miscible/near miscible CO_2 injection
- Phase 1A: 19 inverted 9-spot patterns
- Pattern strategies: SSWG, WAG, SGI





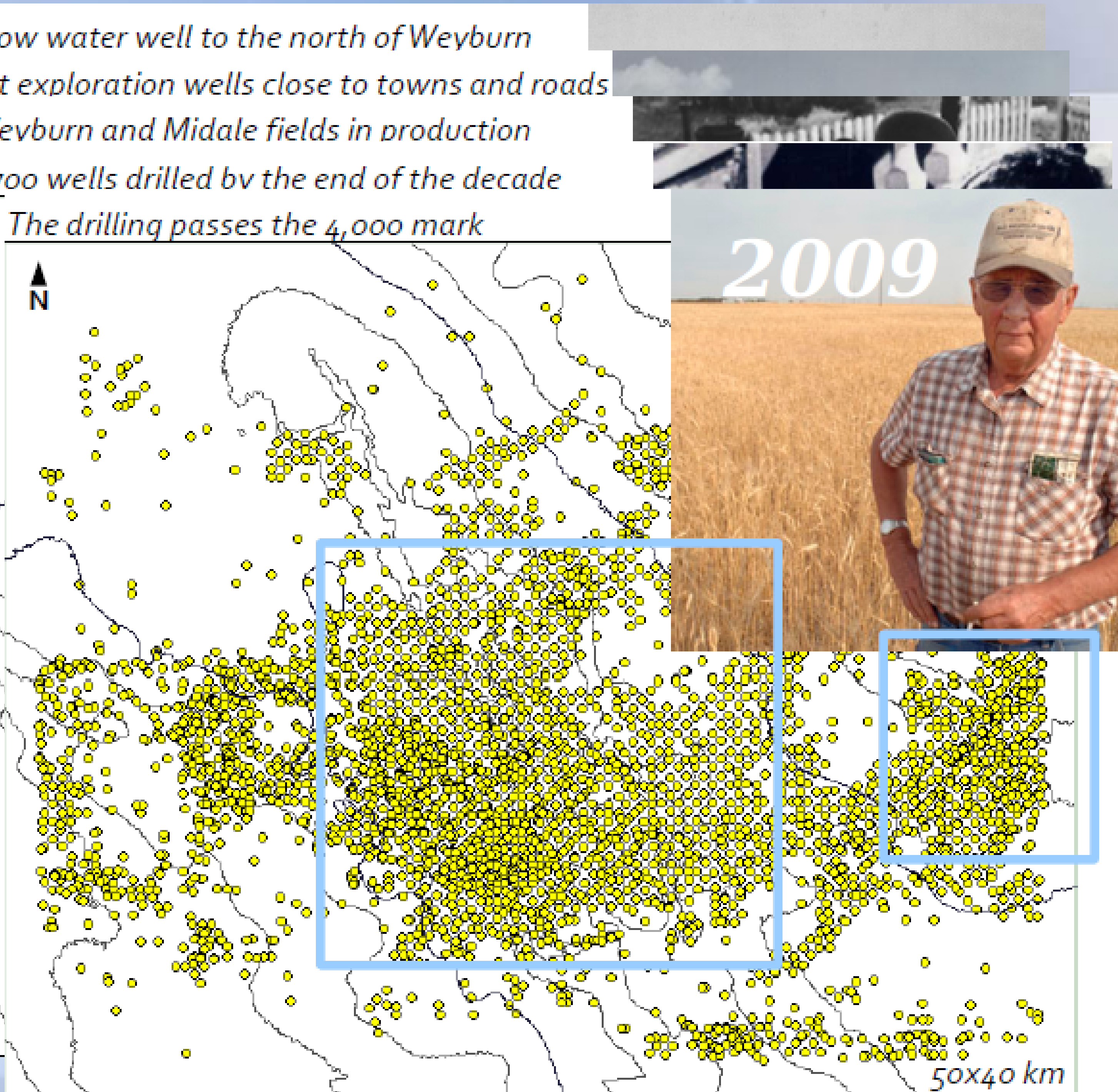
Shallow water well to the north of Weyburn

First exploration wells close to towns and roads

Weyburn and Midale fields in production

700 wells drilled by the end of the decade

The drilling passes the 4,000 mark



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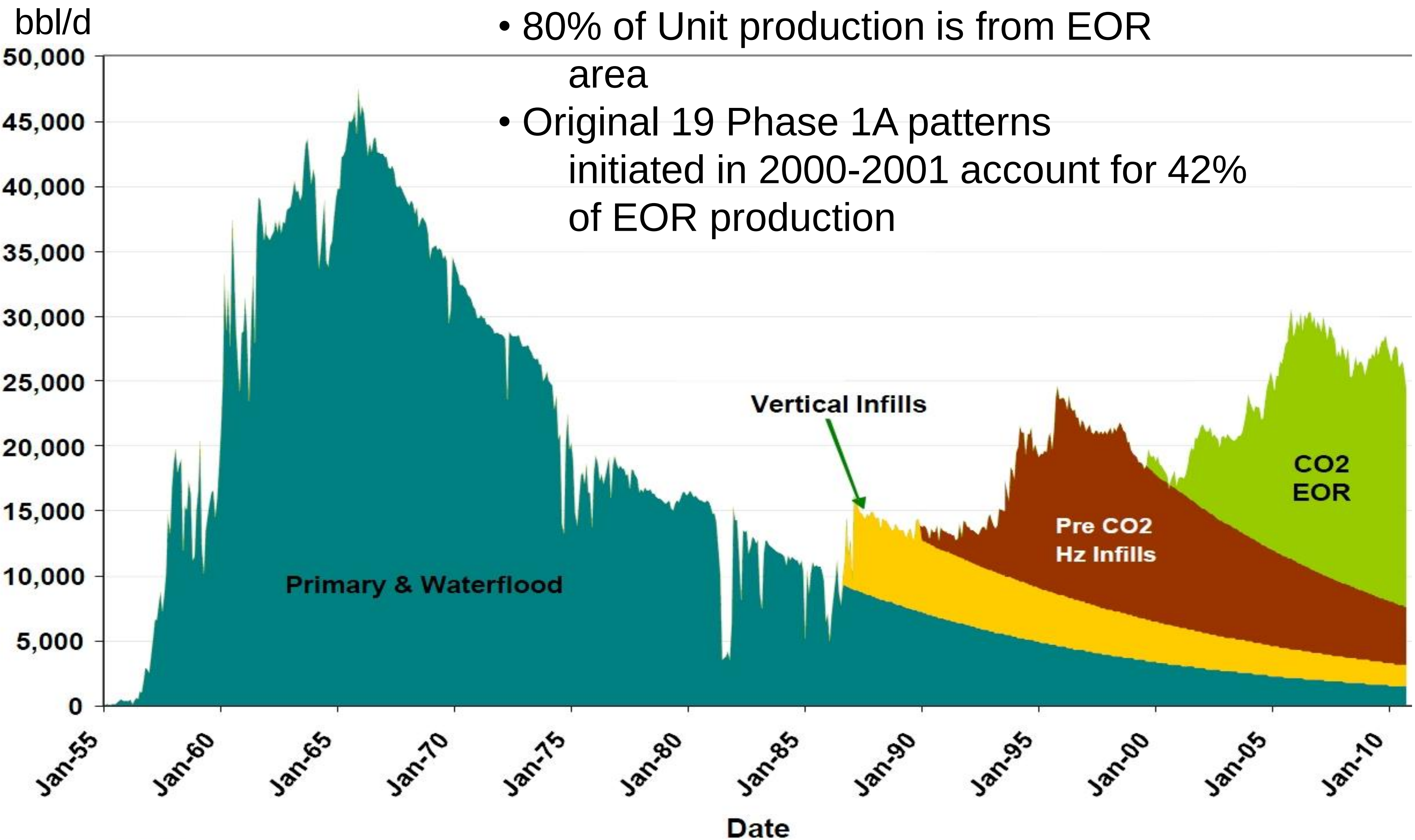
Weyburn Unit Production

- 80% of Unit production is from EOR area
- Original 19 Phase 1A patterns initiated in 2000-2001 account for 42% of EOR production



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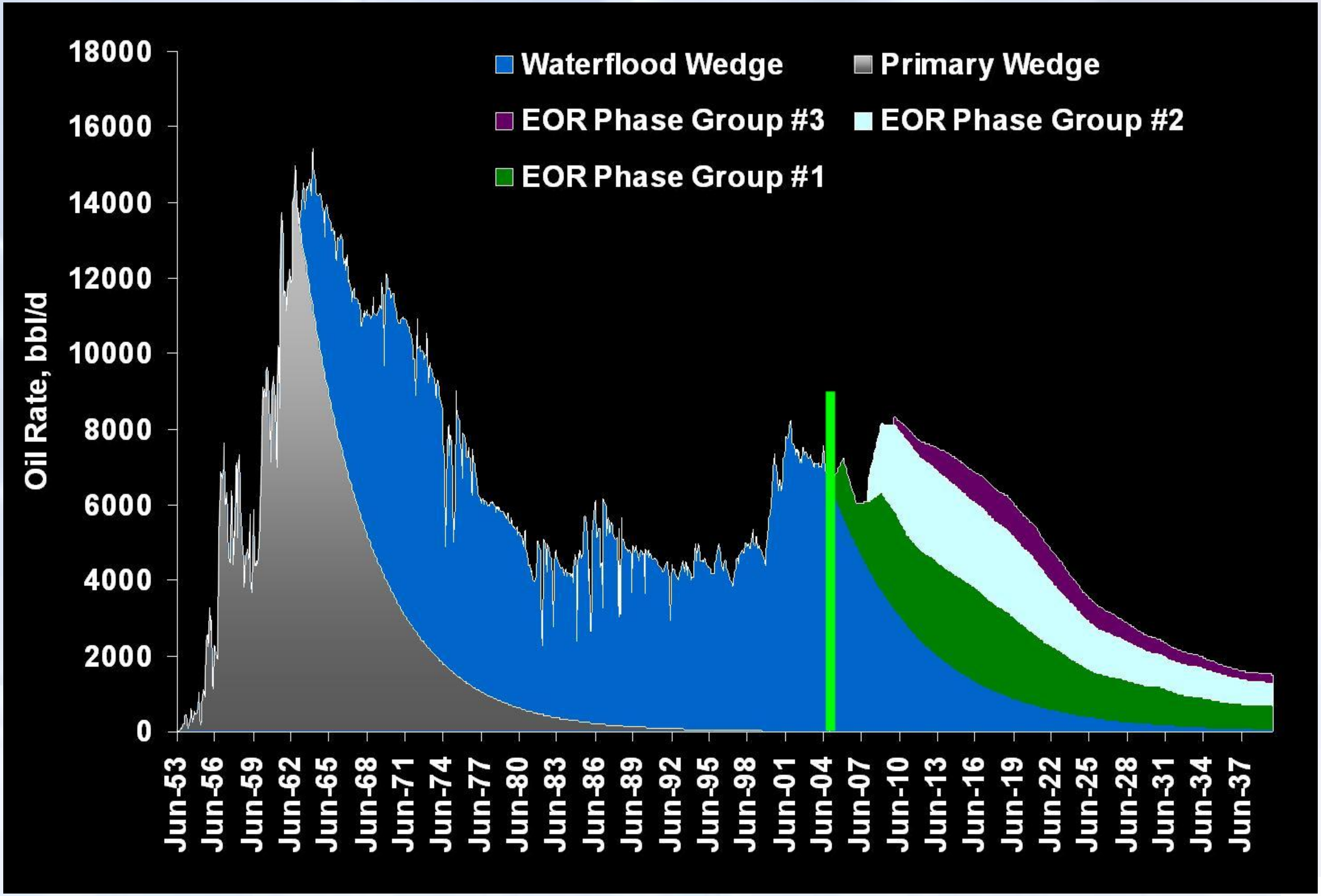
Midale Unit Production



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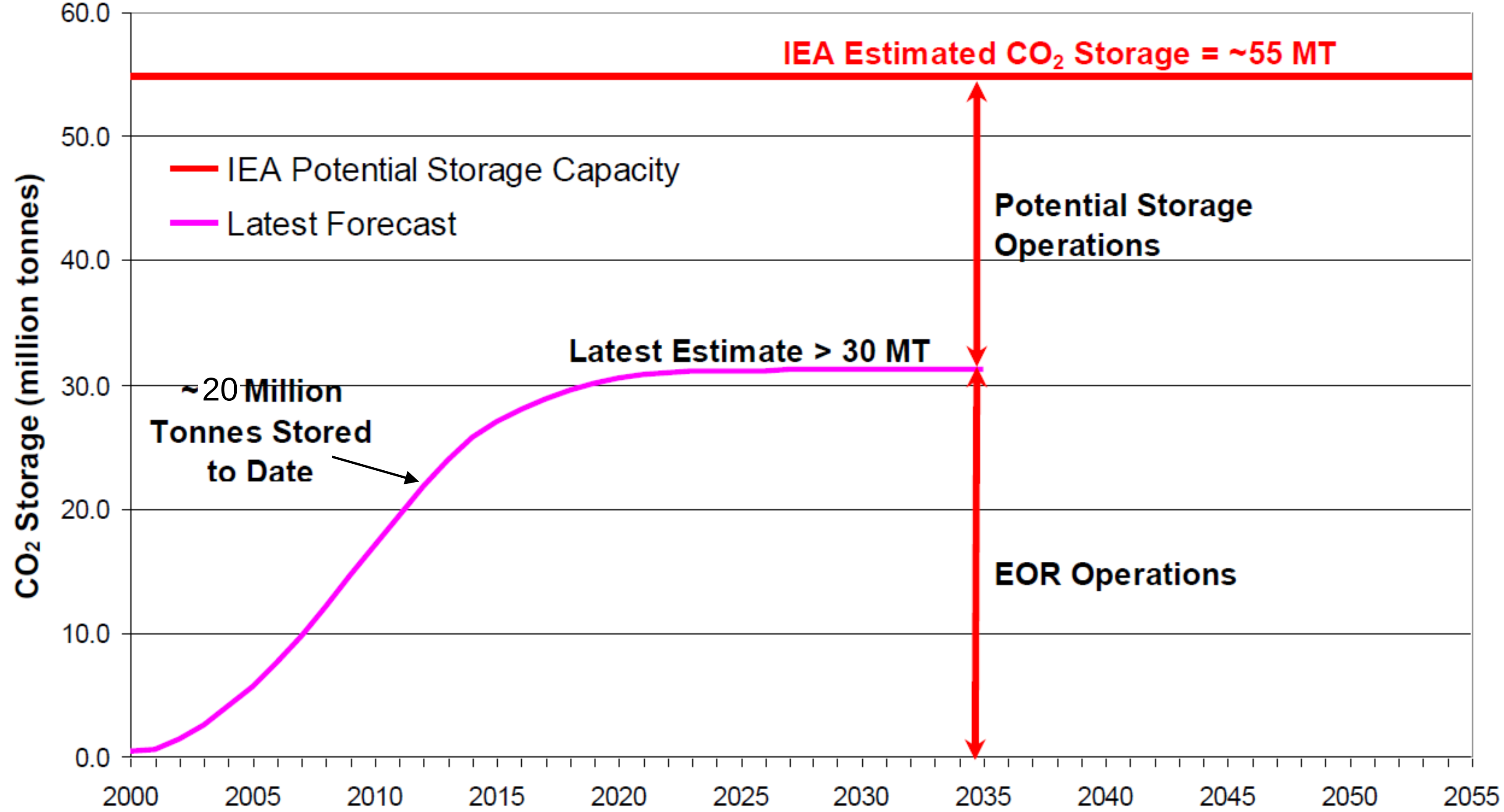
Apache

Storage Estimates



Weyburn & Midale will store CO_2 equivalent to removing about 9 million cars off the road for a year

IEA-GHG Project Overview

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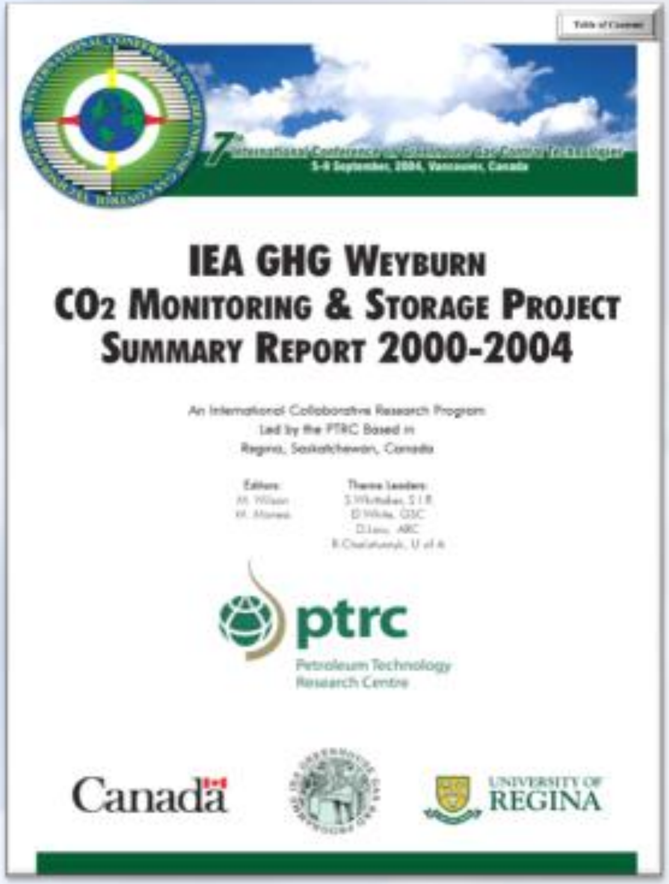
AND STORAGE PROJECT

- Launched in July 2000 by PTRC in collaboration with EnCana
- Assess technical and economic feasibility of CO_2 geological storage
- Funded by 15 industry and government sponsors (Canada, USA, Japan, European Union)
- Employed 24 technology organizations and some eighty specialists in six countries
- Phase I completed September 2004
- Final Phase: initiated 2005

  planned 2008-2012
- Best Practices Manual released this fall


7th International Conference on Greenhouse Gas Control Technologies
5-9 September, 2004, Vancouver, Canada

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CO_2 MONITORING & STORAGE PROJECT
SUMMARY REPORT 2000-2004

An International Collaborative Research Program
Led by the PTRC Based in
Regina, Saskatchewan, Canada

ptrc
Petroleum Technology
Research Centre

Canada

UNIVERSITY OF
REGINA

- download: http://www.ptrc.ca/siteimages/Summary_Report_2000_2004.pdf 15MB

Project Organization

Phase 1: Organized into 4 themes:

- Theme 1: Geological Characterization of the Geosphere and Biosphere
- Theme 2: Prediction, Monitoring, and Verification of CO_2 movements
- Theme 3: CO_2 Storage Capacity and Distribution Predictions and the Application of Economic Limits
- Theme 4: Long Term Risk Assessments of the Storage Site

Final Phase:

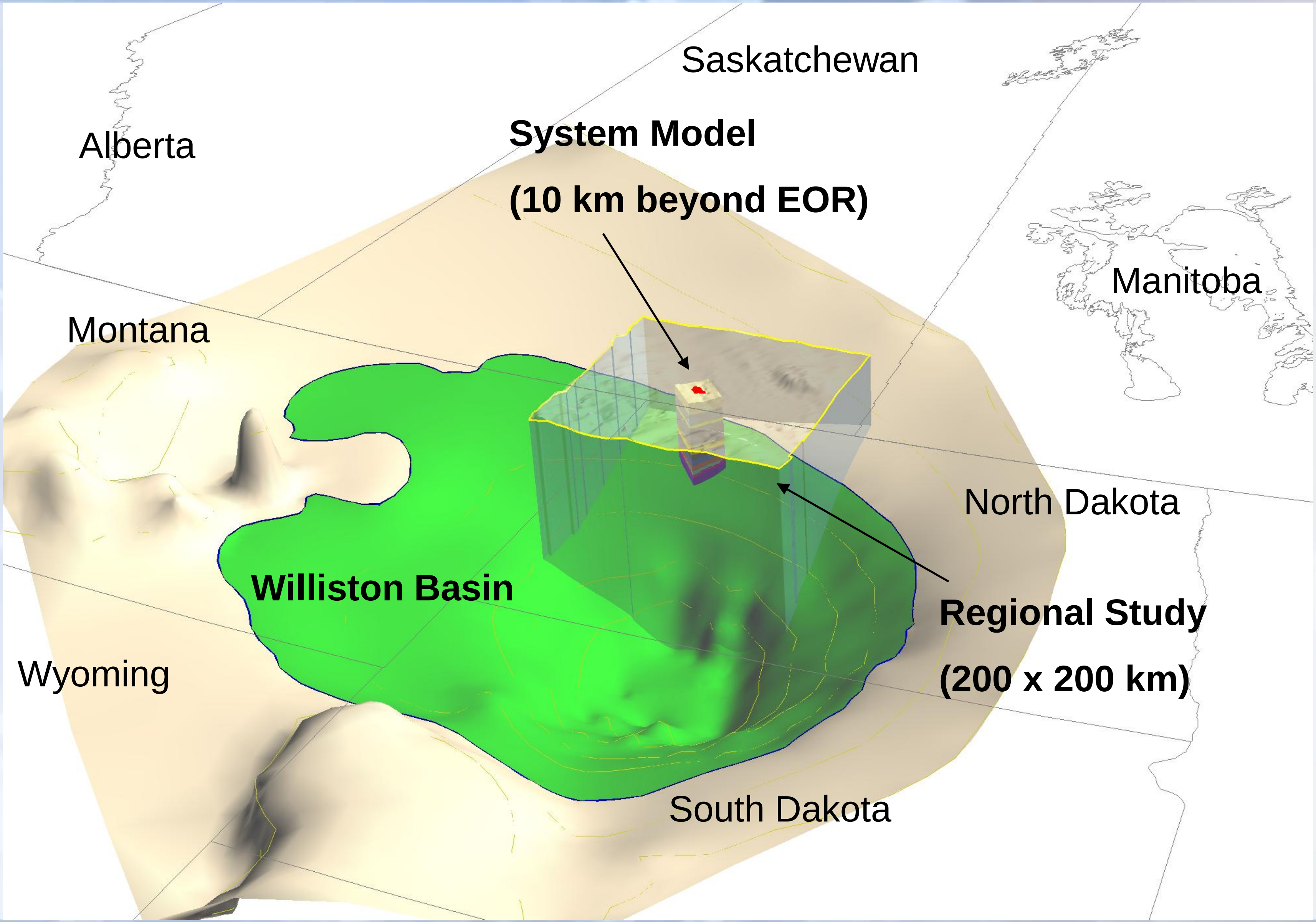
- Non-Technical Component
  - REGULATORY
  - PUBLIC COMMUNICATIONS
  - FISCAL POLICY
- Technical Components
  - GEOLOGICAL INTEGRITY
  - WELLBORE INTEGRITY
  - STORAGE MONITORING METHODS (Geophysics & Geochemistry)
  - RISK ASSESSMENT

Theme 1: Overview

- Phase 1: Geological Characterization
  - Regional Study / Framework
  - System Model / Geological Model

- Final Phase: Geological Integrity
  - what is new?
  - what is important for monitoring?

Study Region - Geoscience



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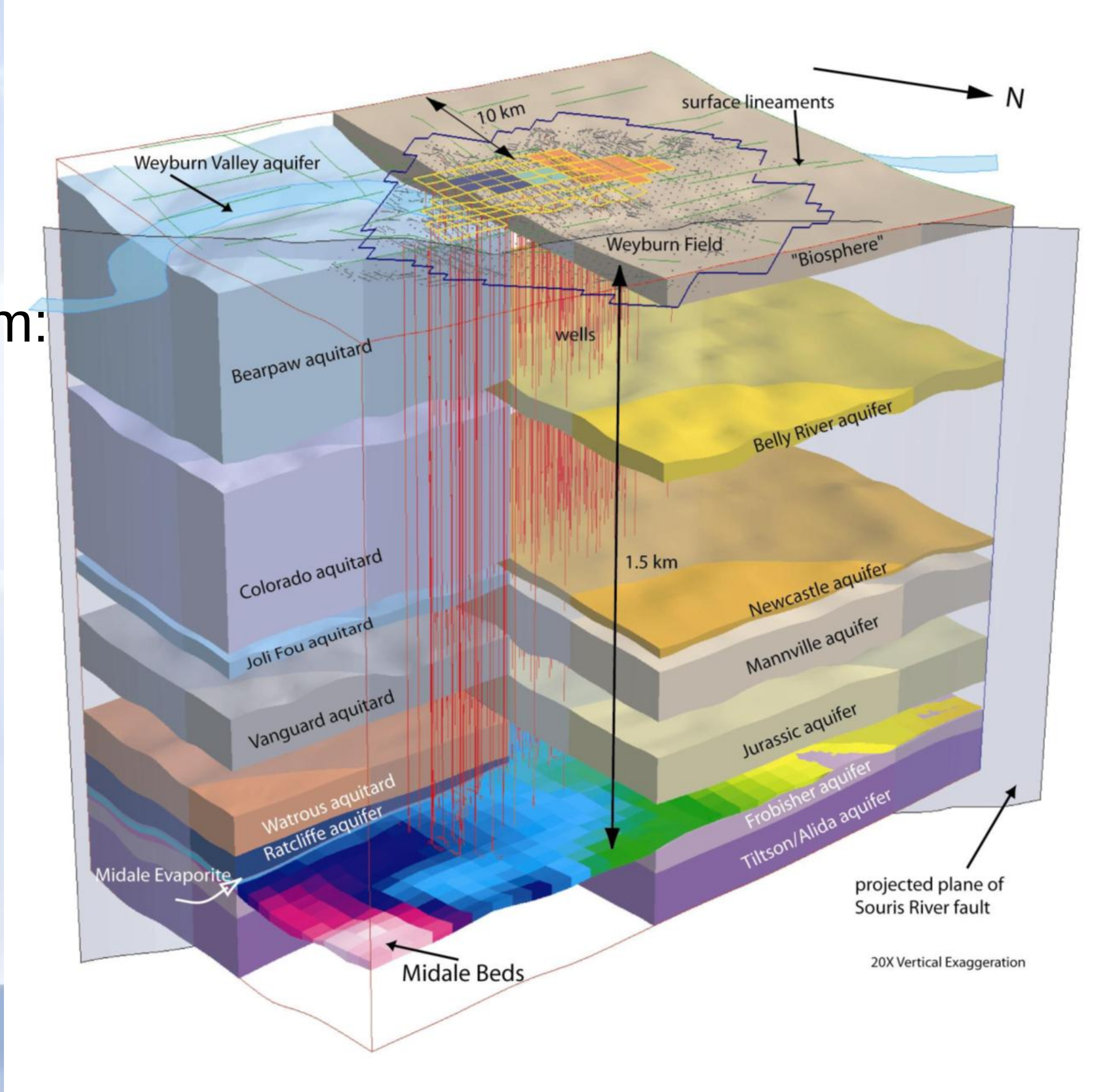
Geological/Hydrogeological Model

- 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system:
  - lithology
  - hydrogeological characteristics
  - hydrochemistry
  - poro/perm
  - faults



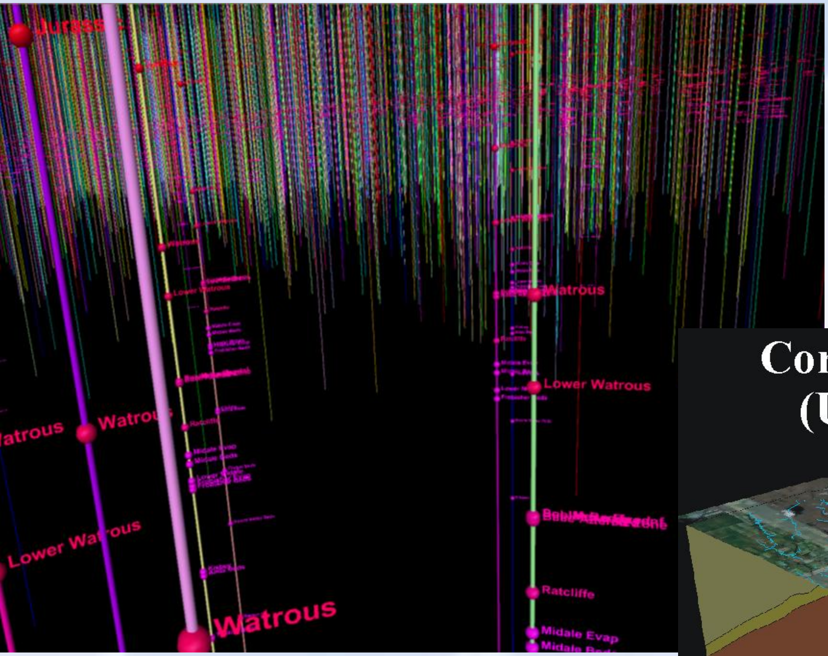
Theme 1: Final Phase

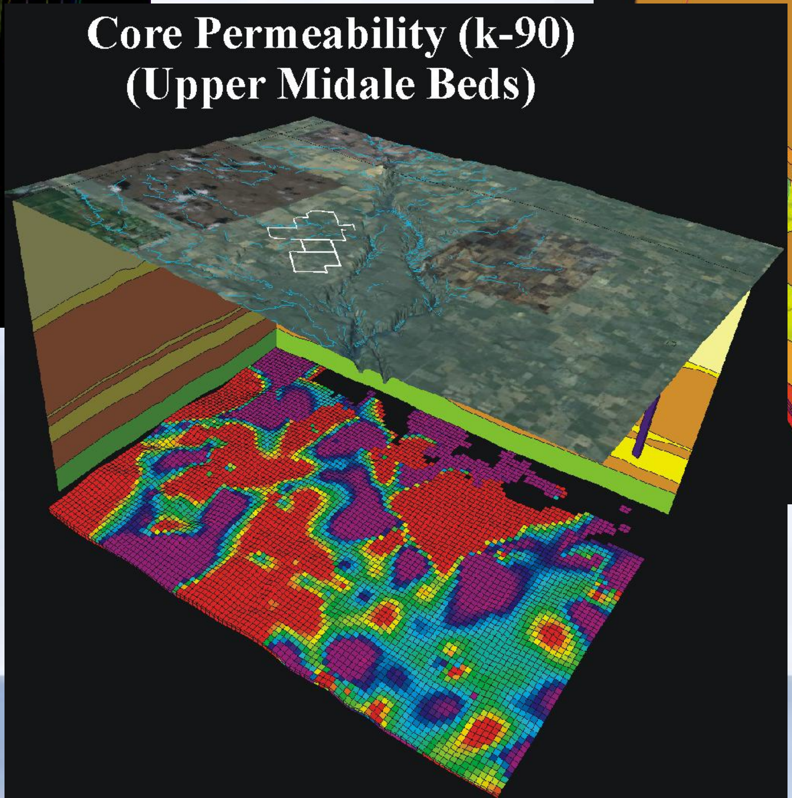
- Overall – assess gaps from Phase I associated with site characterization
- Update Geological Model
- Natural Analogue
- Regional Seismology
- CO_2 Movement above the Watrous: Fill-spill Analysis
- Numerical Simulation

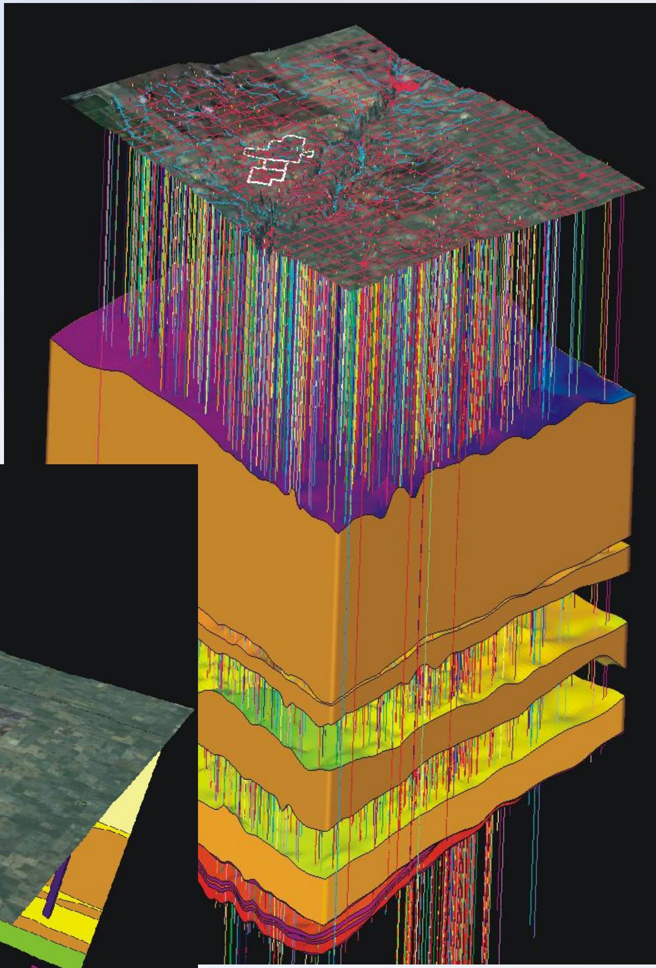
Contribute to Best Practices Manual

Update Geological Model

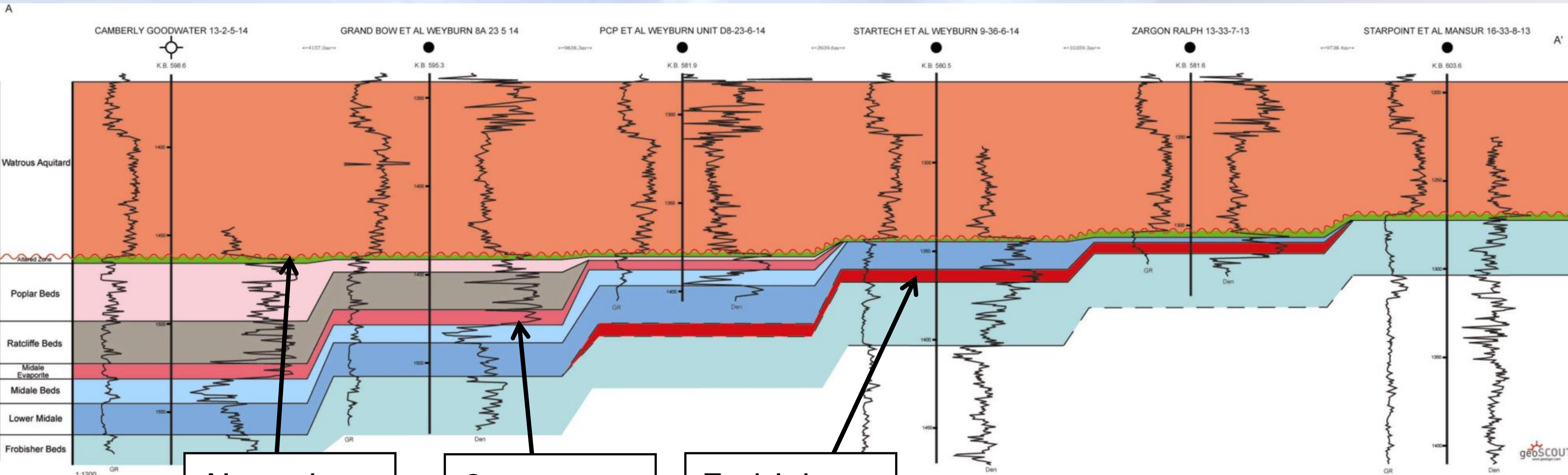
27 Tops picked in each of over 900 wells, all compiled into Petrel.







Update Geological Model: New Horizons



Altered Zone

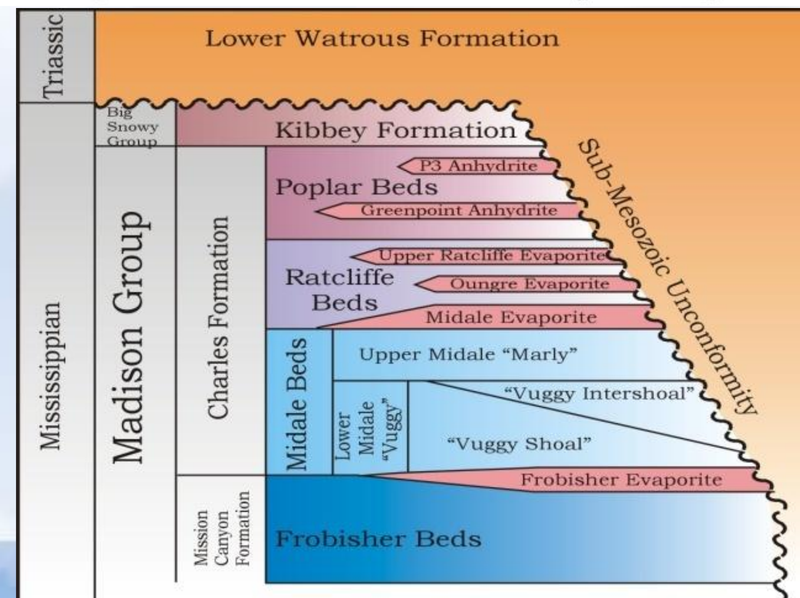
Zone of anhydritization and dolomitization along the unconformity.

Frobisher Evaporite

Lower evaporate sealing unit (where present)

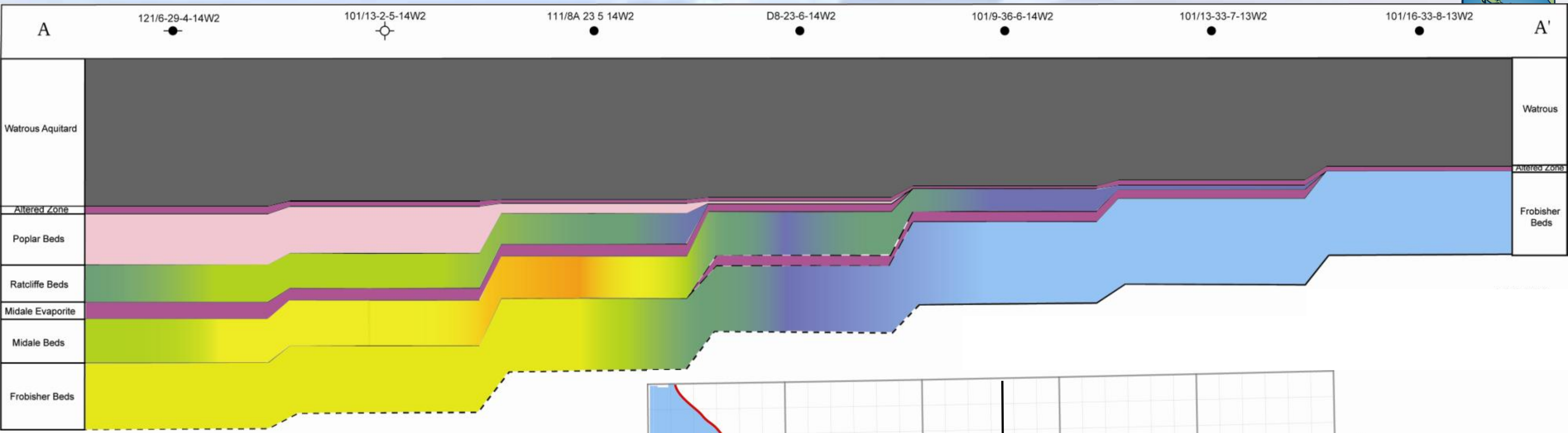
Oungre Evaporite

Pervasive anhydrite unit within the Ratcliffe Beds

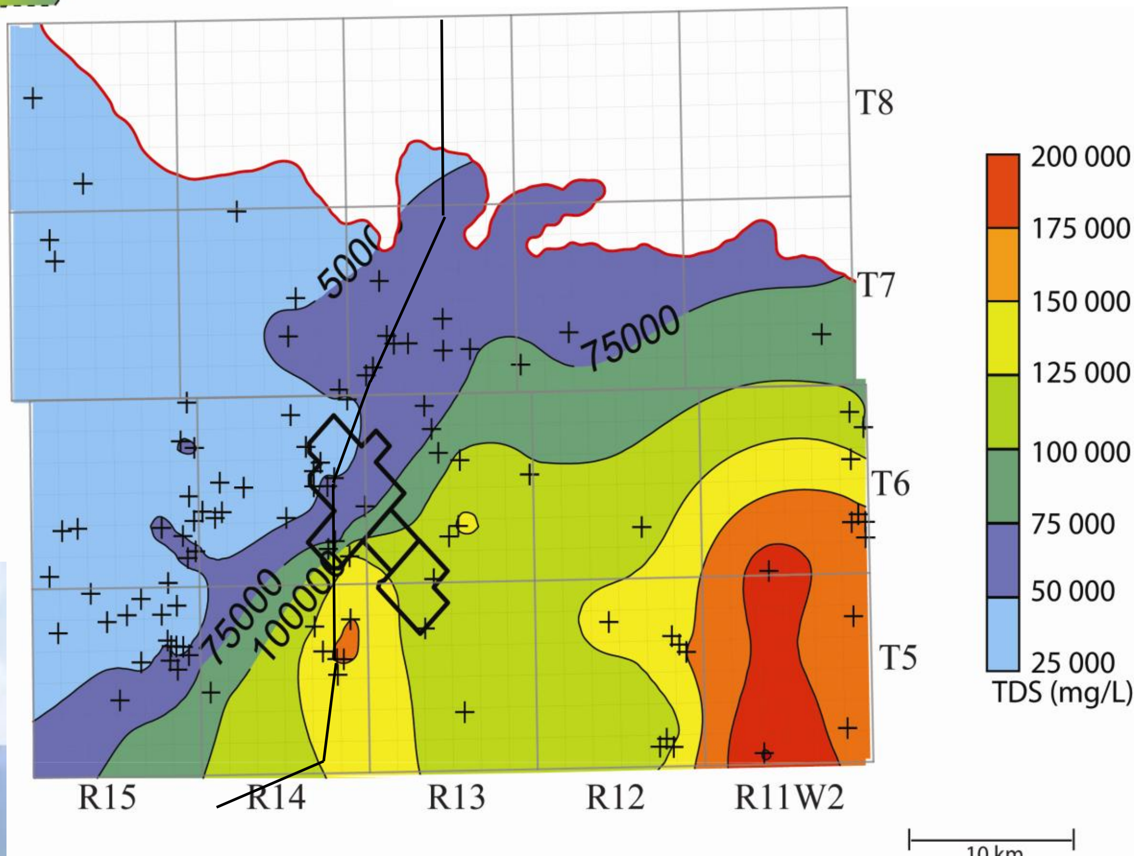


Also: Belly River to surface, well logs

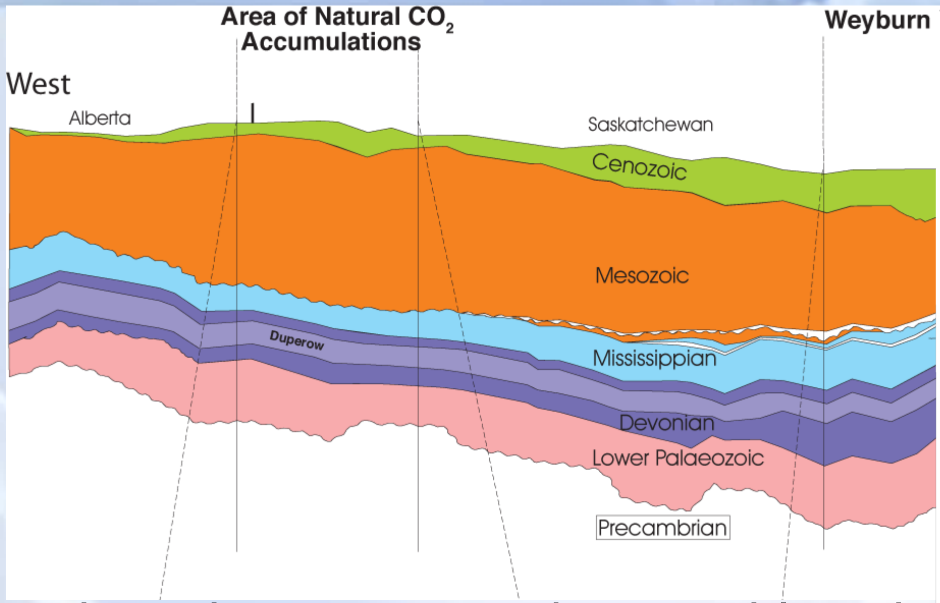
TDS in cross-section

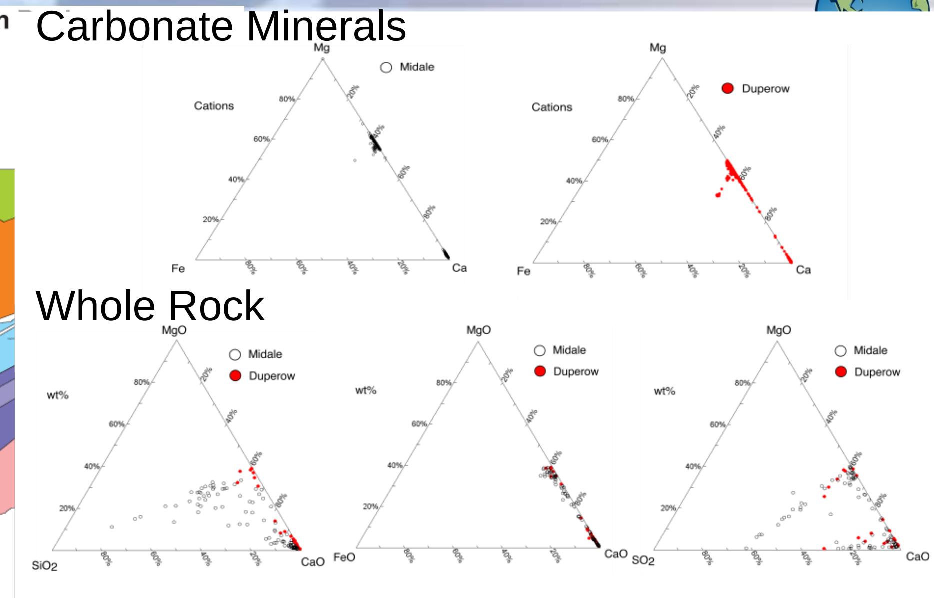


Midale Aquifer



Natural Analogue





The cabonate-caprock assemblage in the eastern portion of the Williston basin have successfully "sequestered" CO_2 for 50 million years. How can natural analog "success" be translated to Weyburn injection?

- Duperow vs. Midale?
- Dinsmore evaporite vs. Midale Evaporite?
- Mineralogy and mineral compositions are indistinguishable.
- Rock types identical with anhydrite-rich lithologies as seals.
- Whole rock chemistry overlaps, except for silica, but silicate minerals present are un-reactive.
- Porosity distributions like the Midale Vuggy.

Regional Seismology

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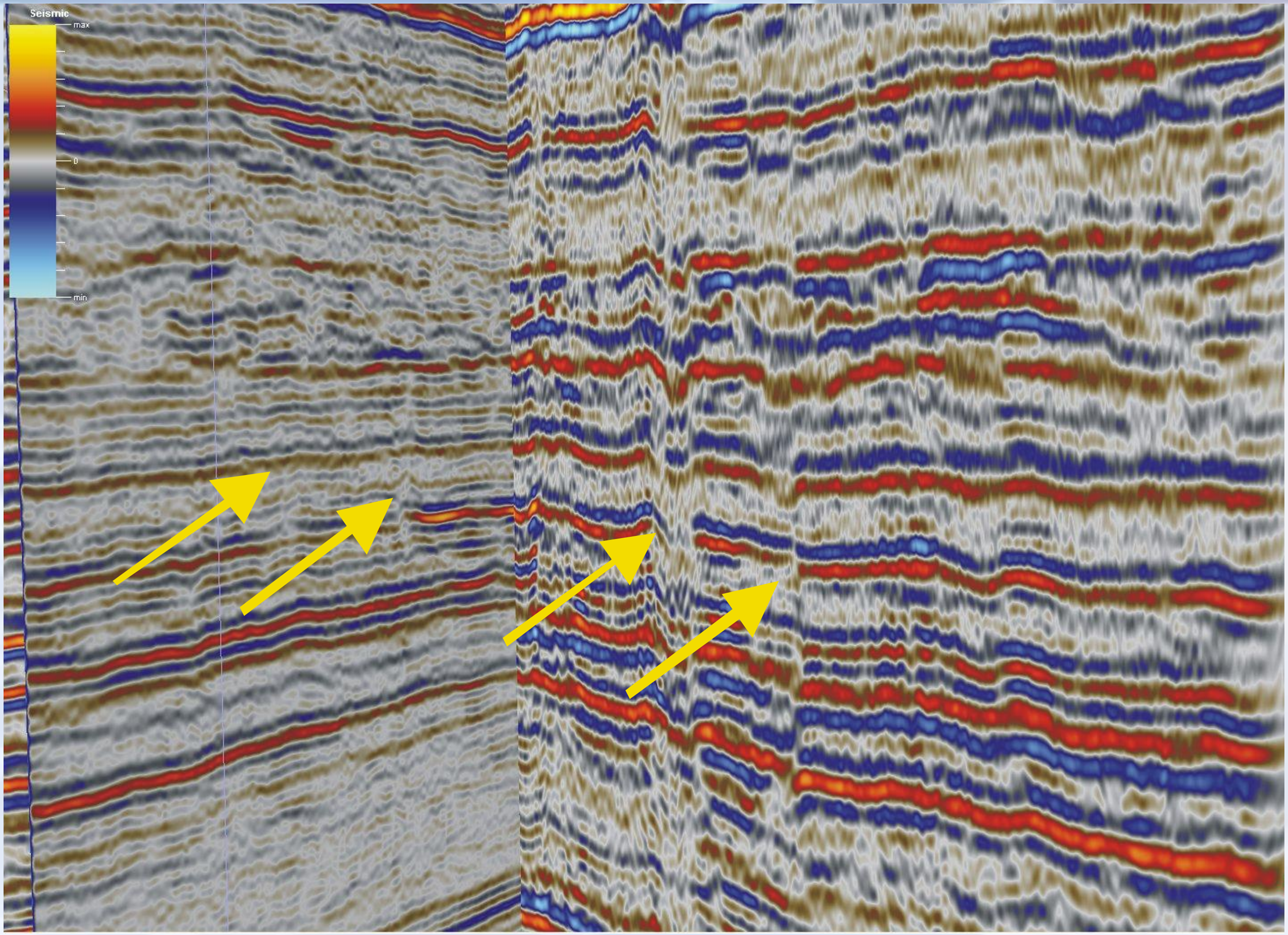
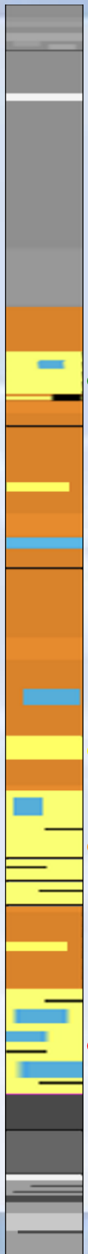
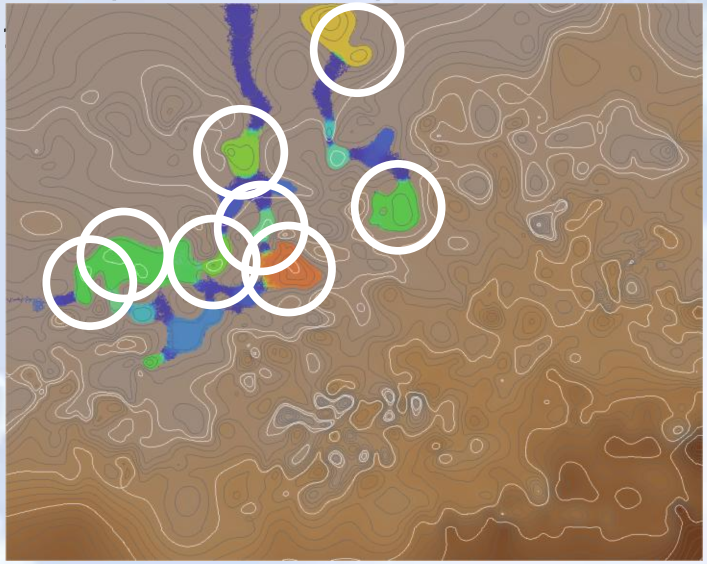


Regional line 'for-910362' (right) and 3D volume cross-line (left).
Wavelet transform of both datasets, balanced both frequency spectra, providing accurate tie between the recent and vintage seismic information and enhanced the near–vertical structural disturbances.

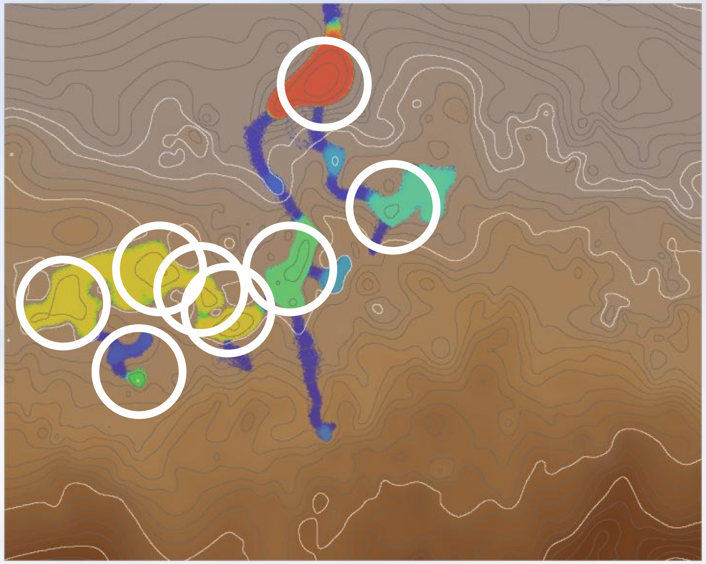
CO_2 Movement above the Watrous: Fill-spill Analysis

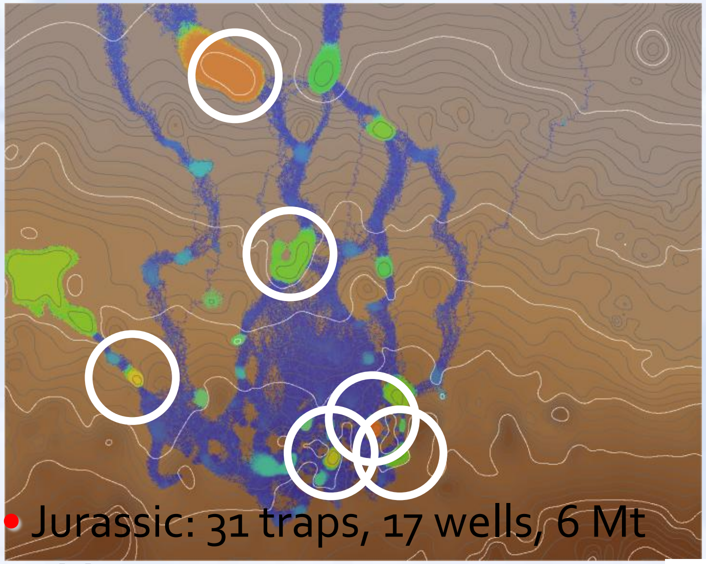


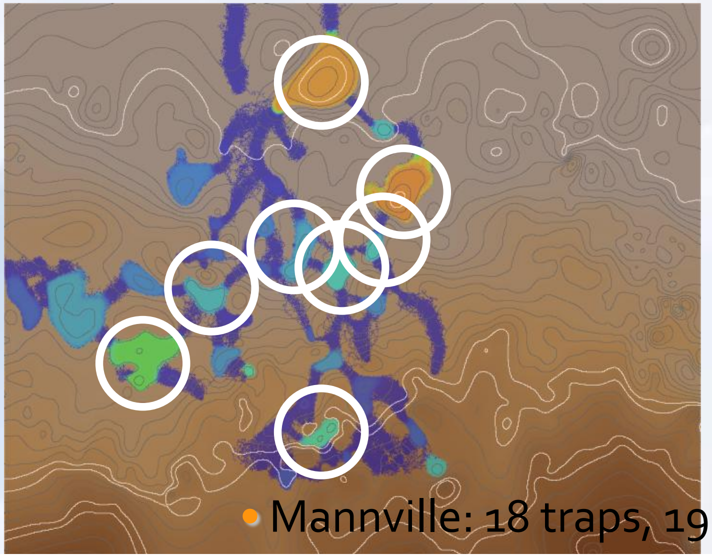
- Belly River: 11 traps, 14 wells, 40 kt



- Newcastle: 13 traps, 12 wells,







- Jurassic: 31 traps, 17 wells, 6 Mt
- Mannville: 18 traps, 19 wells,

12 Mt

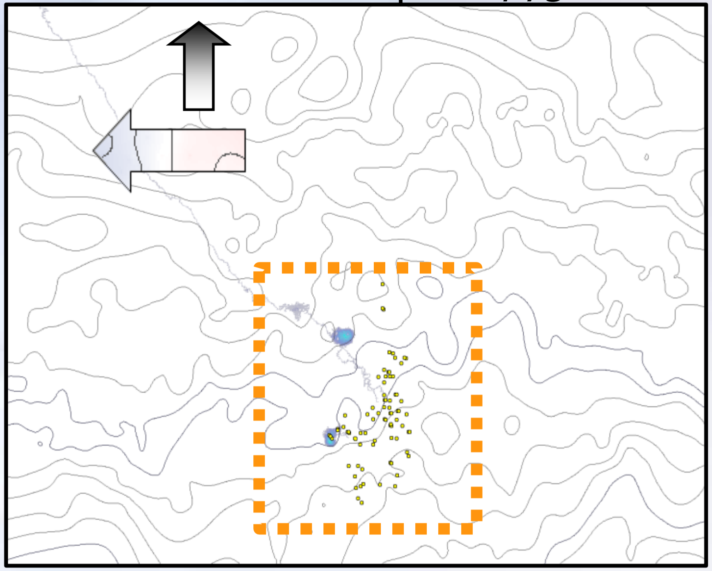
Migration Scenarios

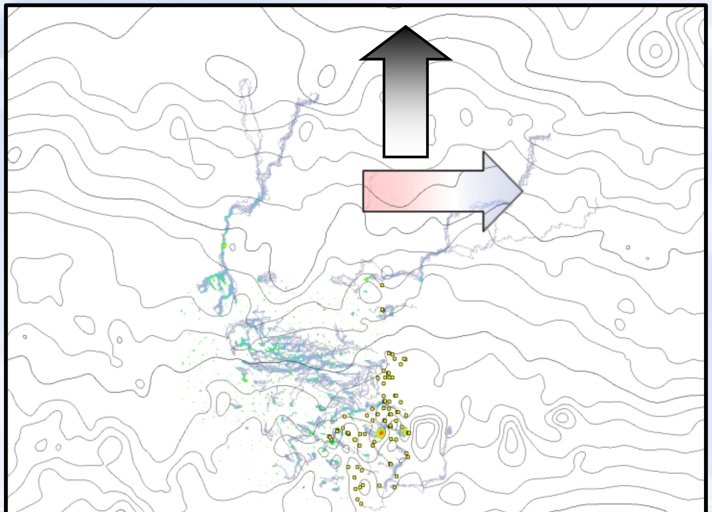
Very leaky wells: 8 microns (5mD)

Breach:	*Colorado, 75 wells*
Capacity:	*2.8 Mt*
Newcastle:	*60 kt*
Mannville:	*2.4 Mt*
Jurassic:	*340 kt*

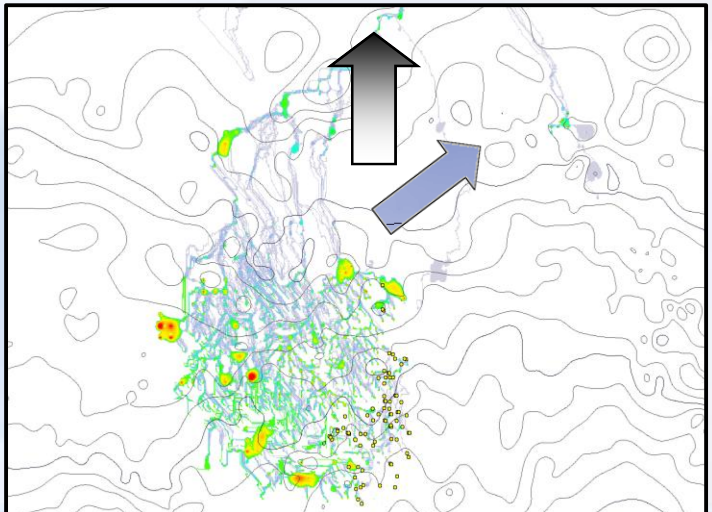
Newcastle:	*2 small pools, 60 kt*
Mannville:	*19 of 20 largest pools, 1.7 Mt*
Jurassic:	*18th largest pool, 59 kt*

- Newcastle: 2 pools, 75 wells breach





- Jurassic: small pools, breach locally

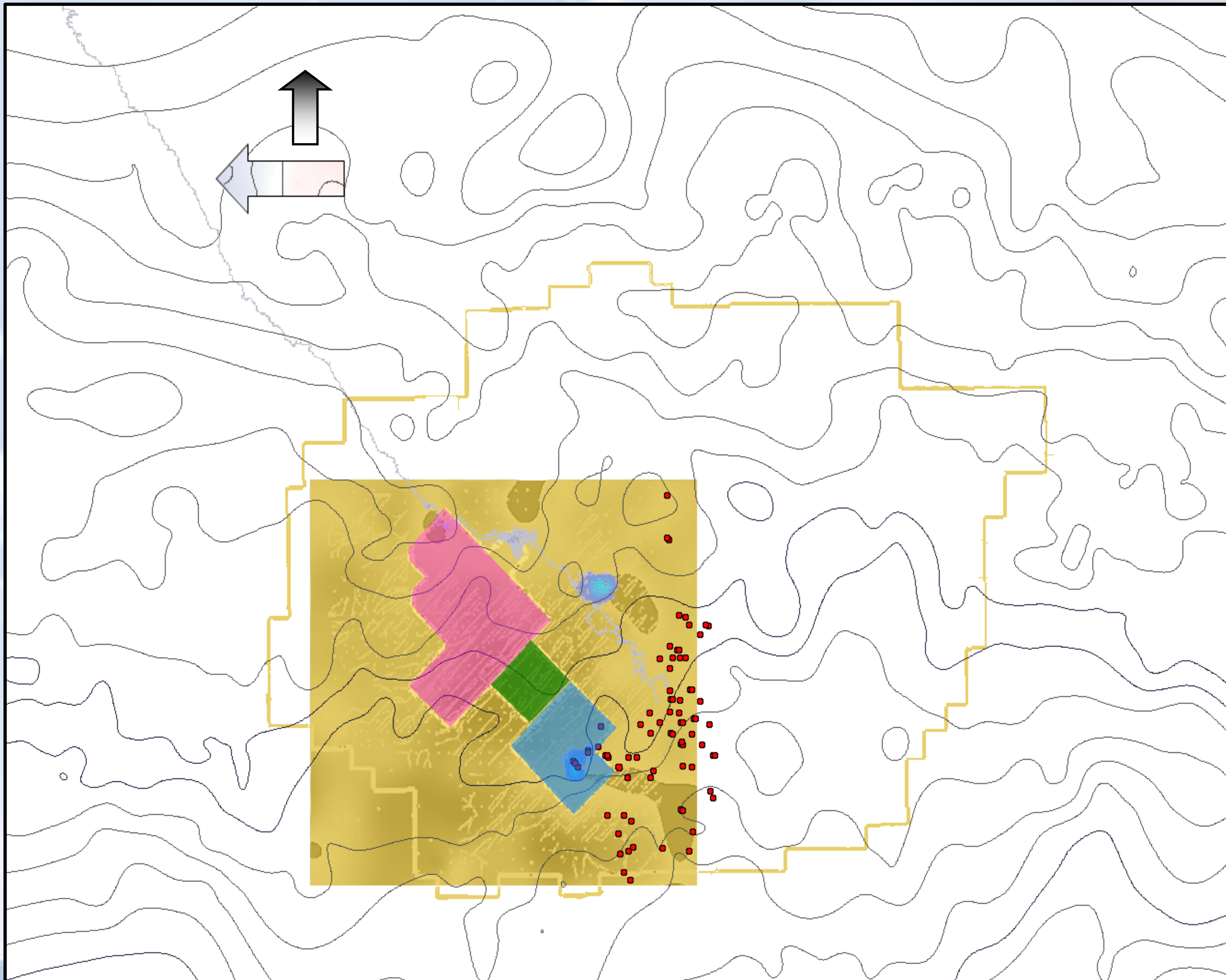


- Mannville: 20 pools, N-NE

permeability, threshold pressure, porosity, gas saturation added to the model

Migration Scenarios

- Newcastle: 2 pools, 75 wells breach



Numerical Simulation: SSWG Pattern 1 (P1612614)

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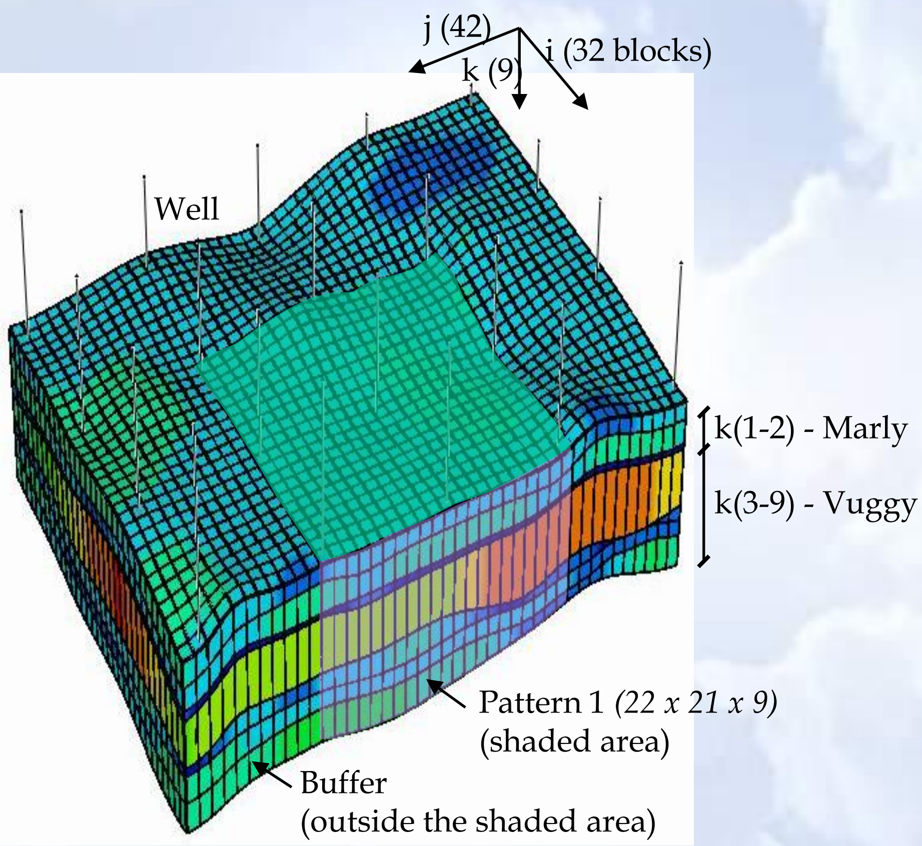
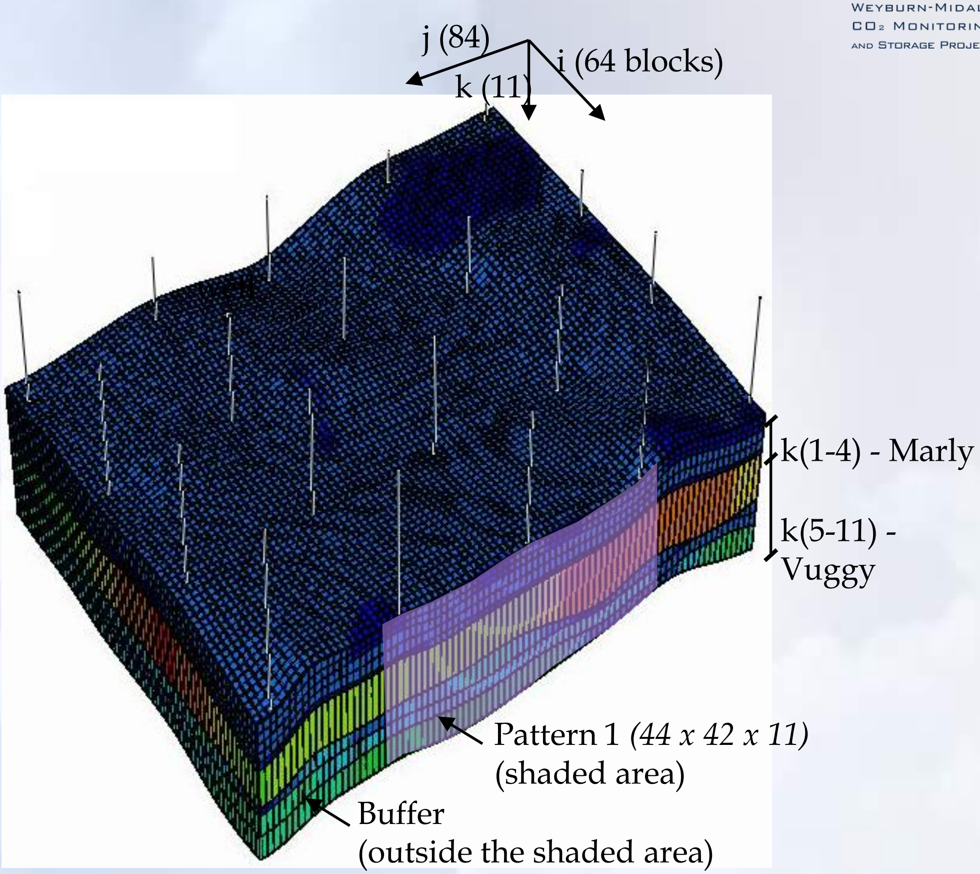
Model I and Model II



3D view for the base case simulation field



3D view for the simulation field

History Match Simulations

Overall Field Productions - Base Model-I vs. Fine Grid Model-II

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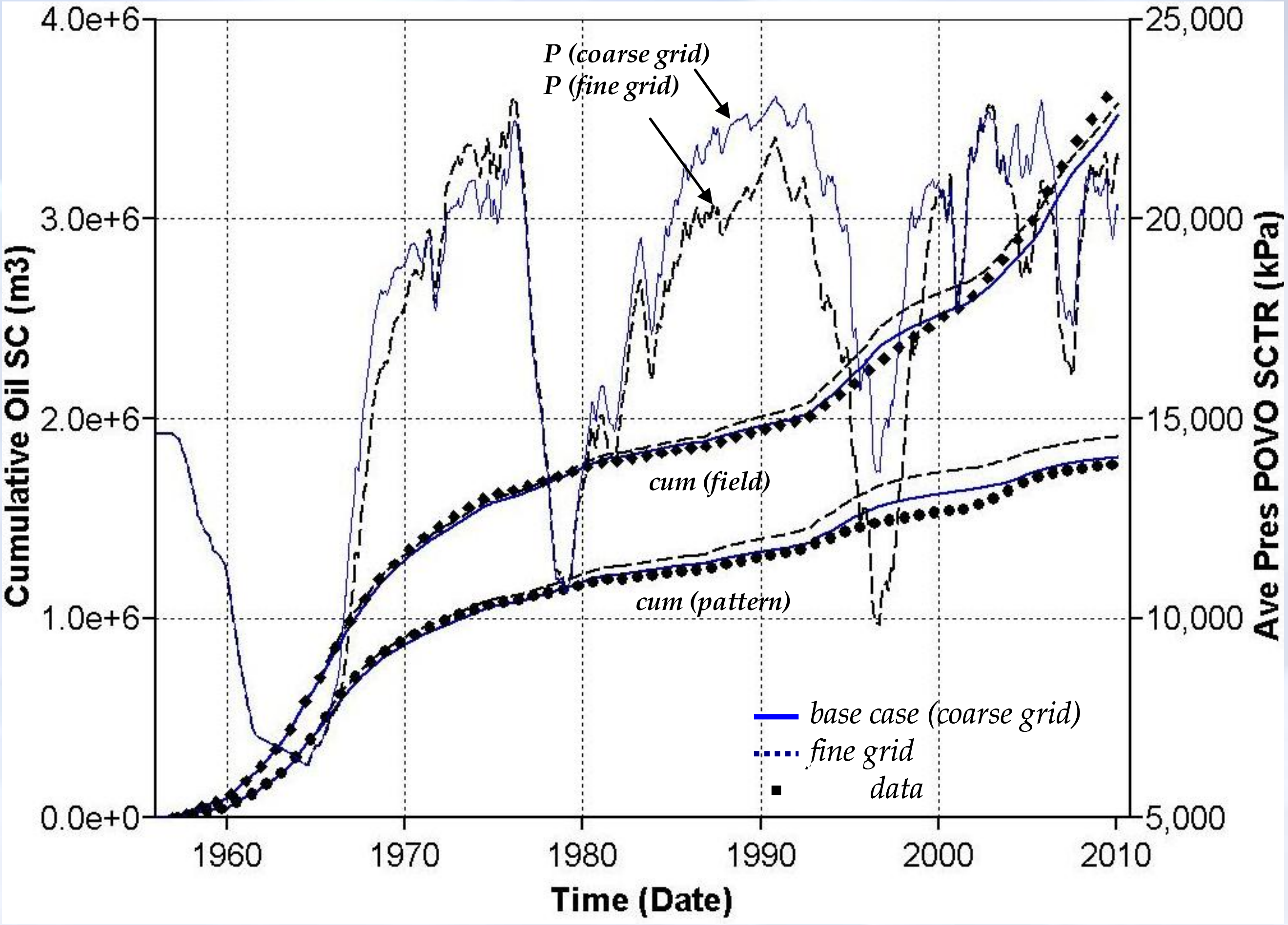

- Grid effect is clearly noticeable on the overall field production and pressure data

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History Matching Simulations

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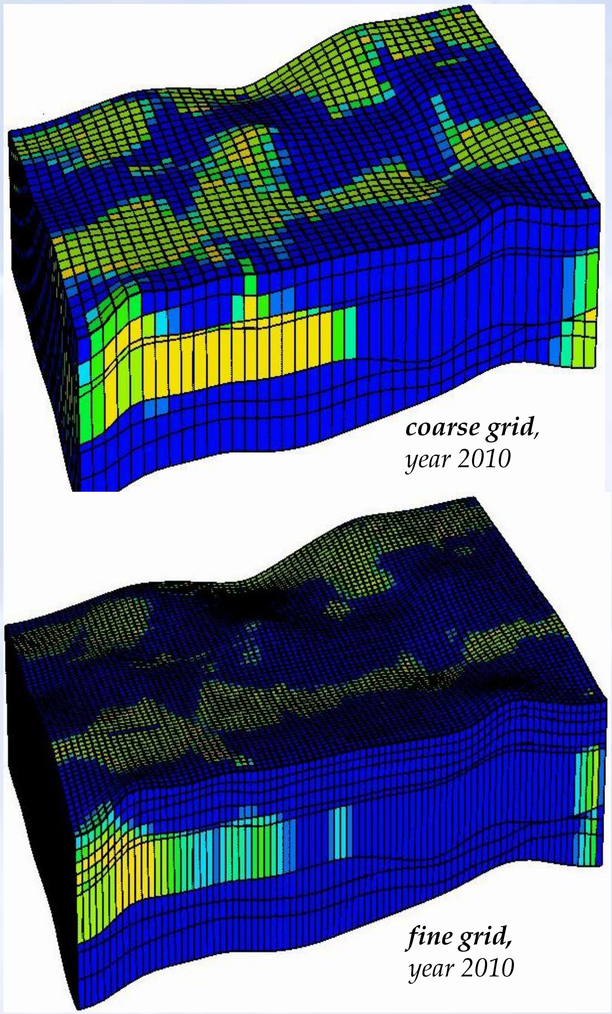
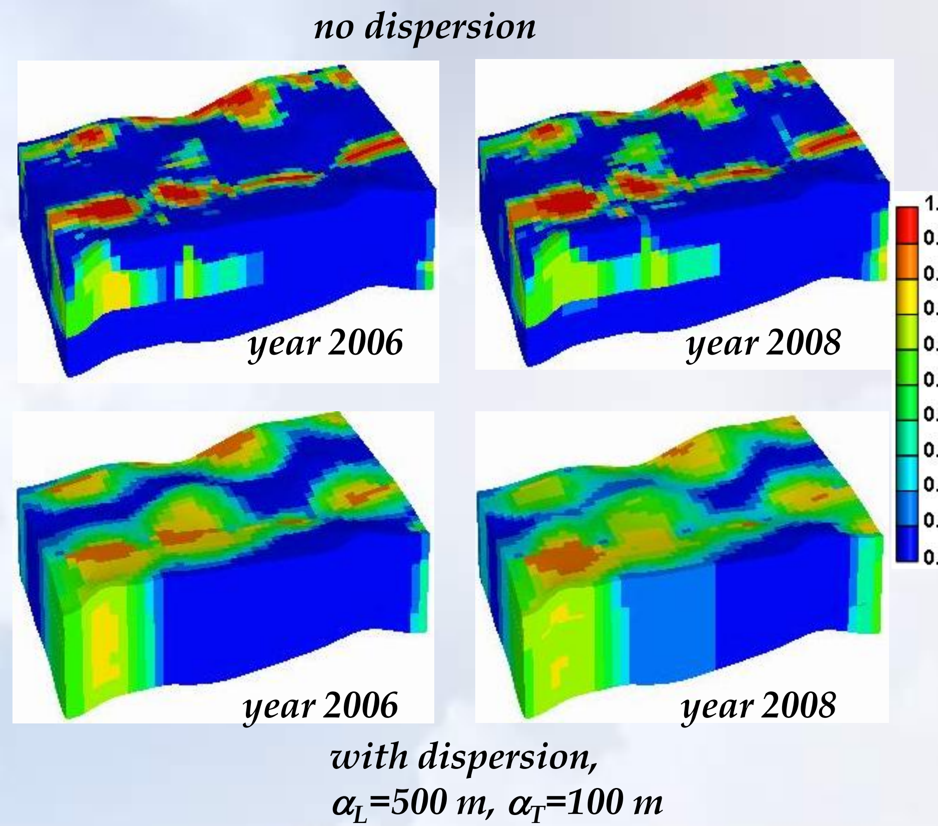
Role of Gride Size and Mechanical Dispersion on CO_2 Distribution in Oil Phase





- CO_2 spreads larger area in the coarse grid model
- Grid effect is clearly noticeable
- Mechanical dispersion plays a significant role

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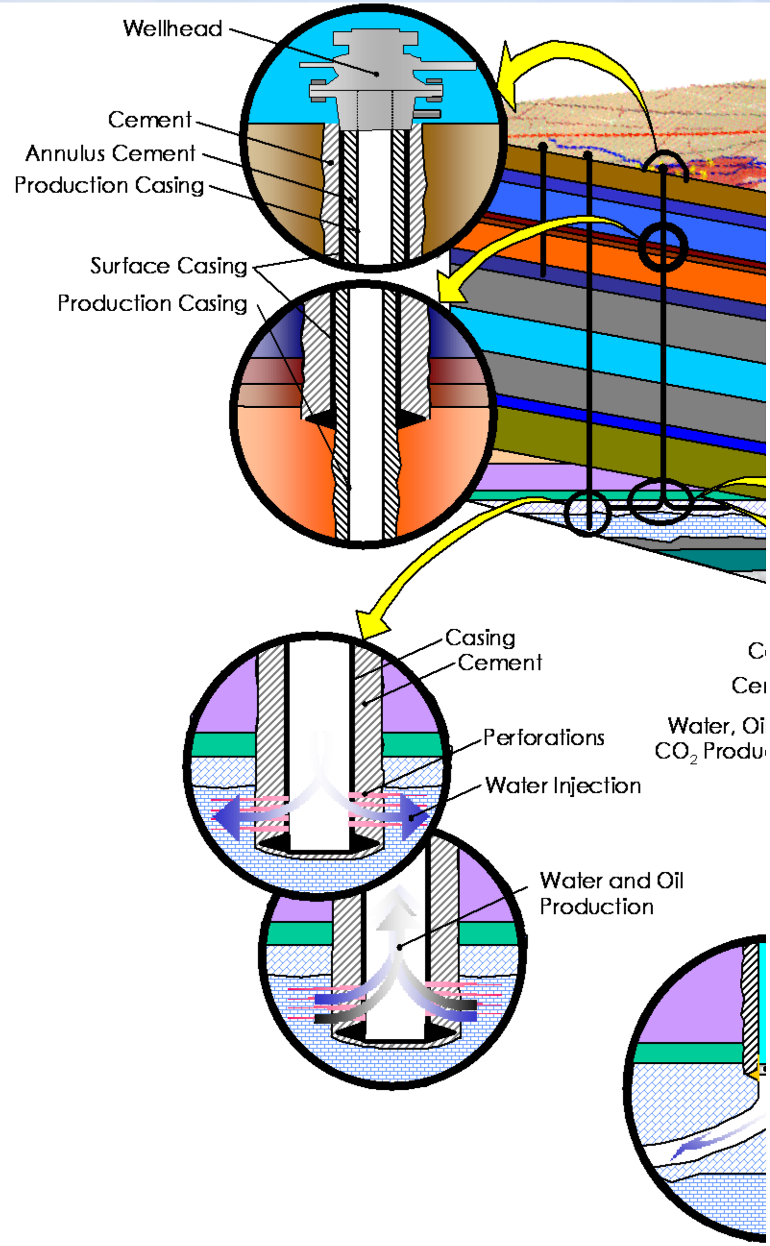
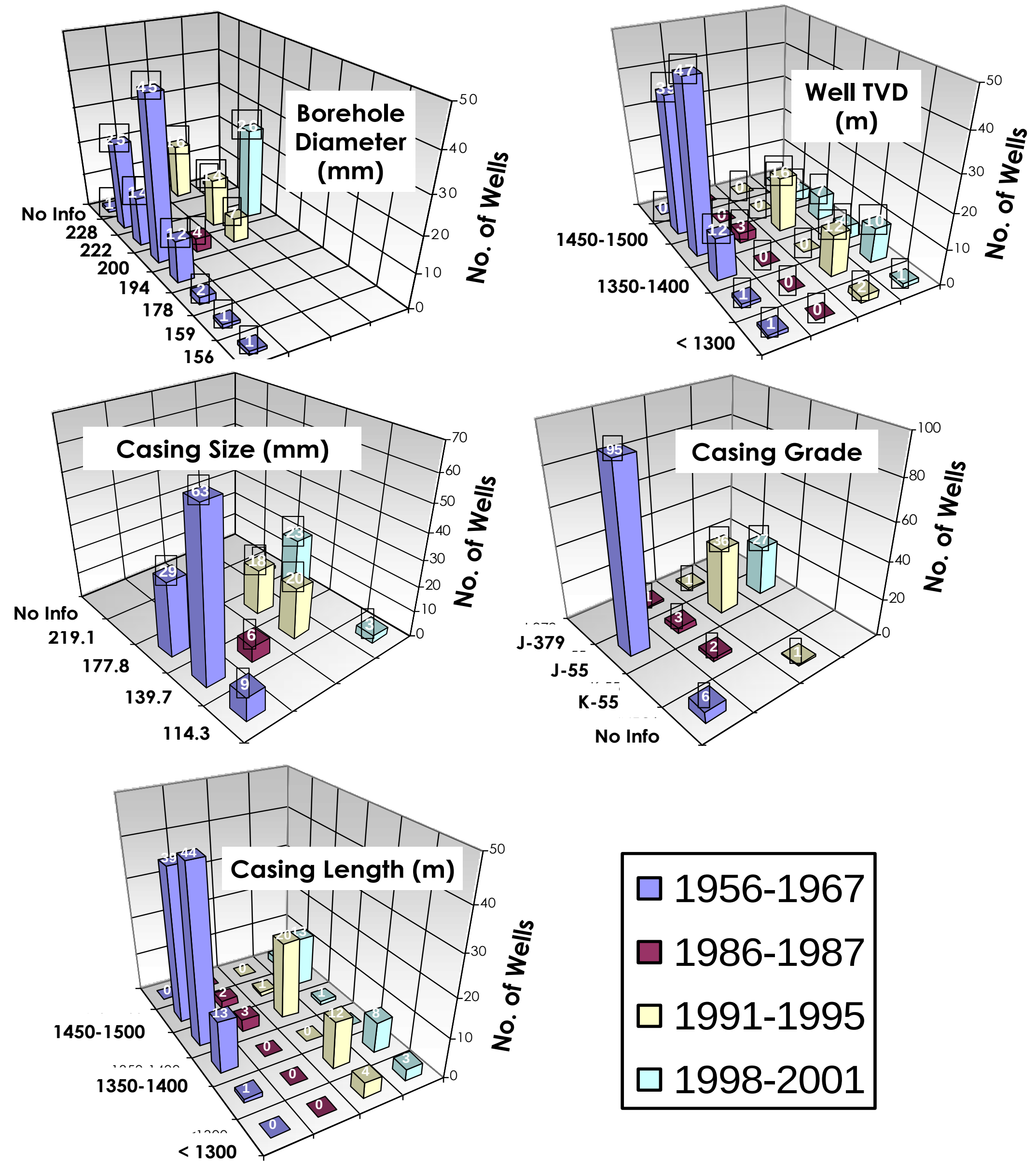
Theme 2 – Wellbore Integrity: Overview

Task	**RP**
Weyburn wellbore database	UofA
Numerical simulation of wellbore systems	UofA
Compilation/Review of existing practices, CO_2/EOR (etc.)	T.L. Watson & Assoc.
Casing corrosion study	Ohio U. (Institute for Corrosion & Multiphase Tech.); RAE Inspection
Well integrity - Downhole testing program → Tool development → Program implementation	Opsens Solutions

Wellbore Database





Cement Details Report

Well Identification

101011100614W200 LICENSE # : 87G007

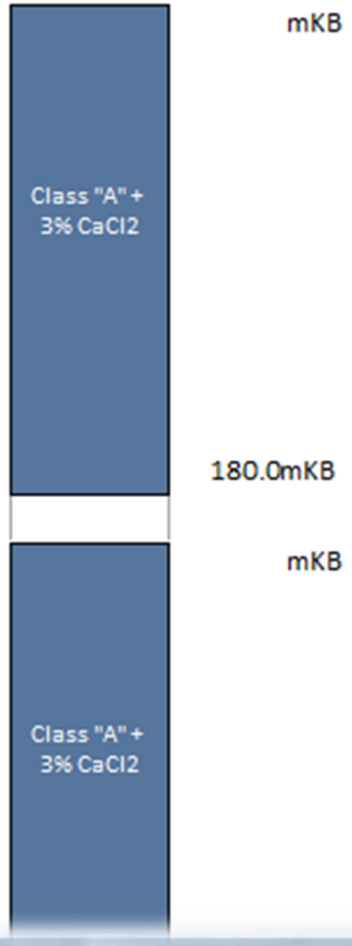
SPUD: 13/07/1987

LEAD SHOE INTEGRITY - SURFACE CASING @ 180 mKB CMTSLUR ID: 554

Class "A" + 3% CaCl2

Detailed Calculations

Slurry Mass X 1000kg/	14.00	tonnes	**Bore Hole Diameter**	311	mm
Slurry Density	1869	kg/m3	**Casing Diameter**	219	mm
			Average Annular Area	0.0383	m2
Calculated Slurry Volume	7.49	m3	**Calculated Cement Base**	180	mKB
Is Slurry Volume Directly From Well File?	☐		**- Calculated Cement Column Length**	(/ 0.0383) -	mKB
Well File Slurry Volume		m3	**Calculated Cement Top**		mKB



LEAD SHOE INTEGRITY - SURFACE CASING @ 180 mKB CMTSLUR ID: 554

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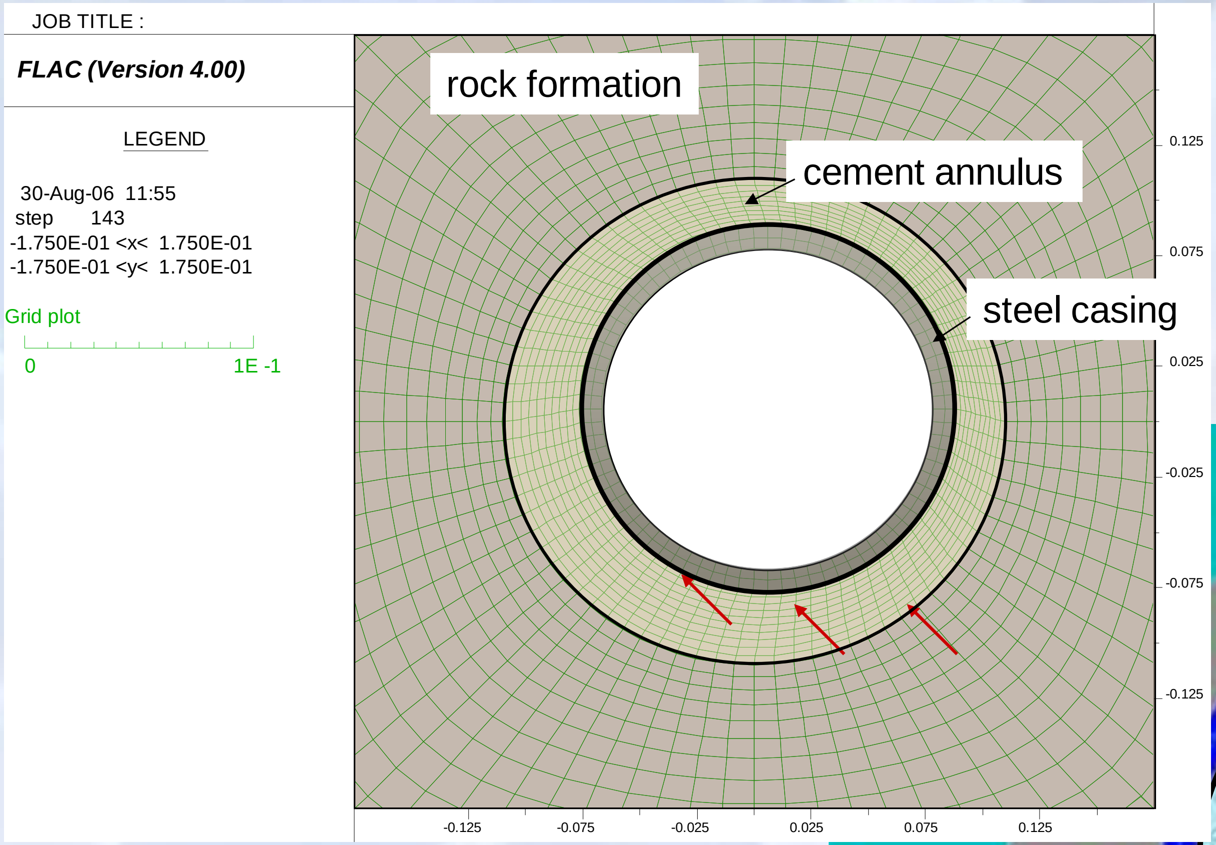
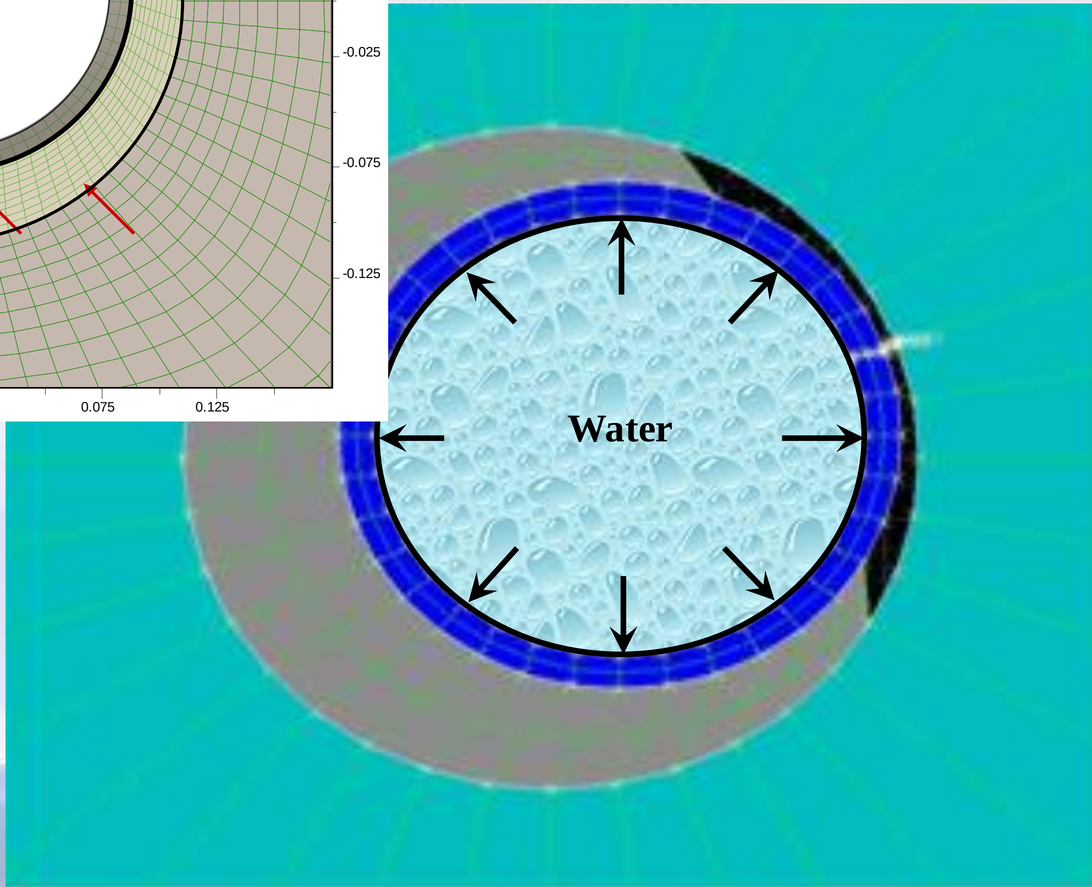
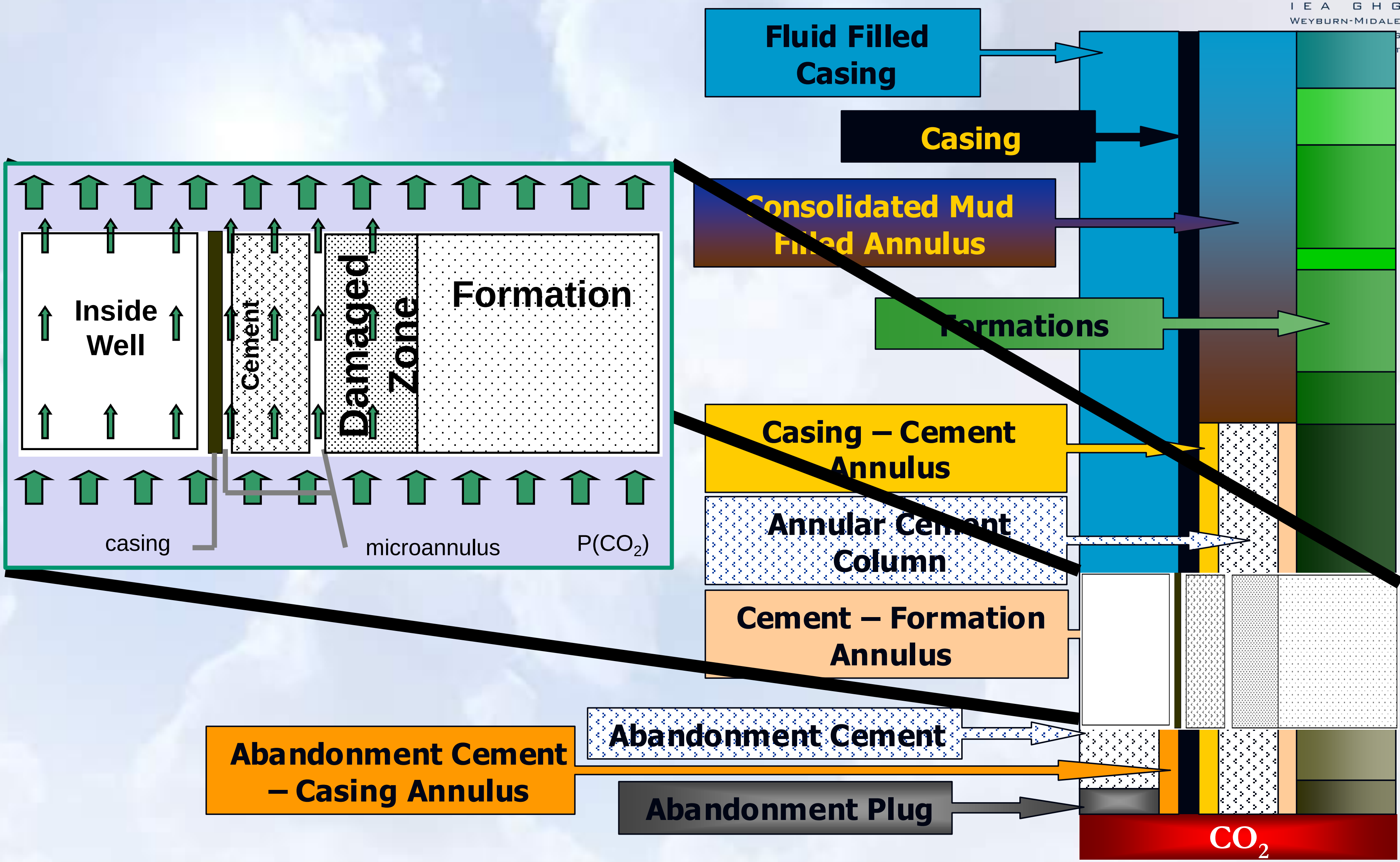
Is Slurry Volume Directly From Well File?	☐		**- Calculated Cement Column Length**	(7.49 / 0.0383) -	mKB

Well Integrity Modelling





Well Integrity Assessment



Literature Review and Data Studies

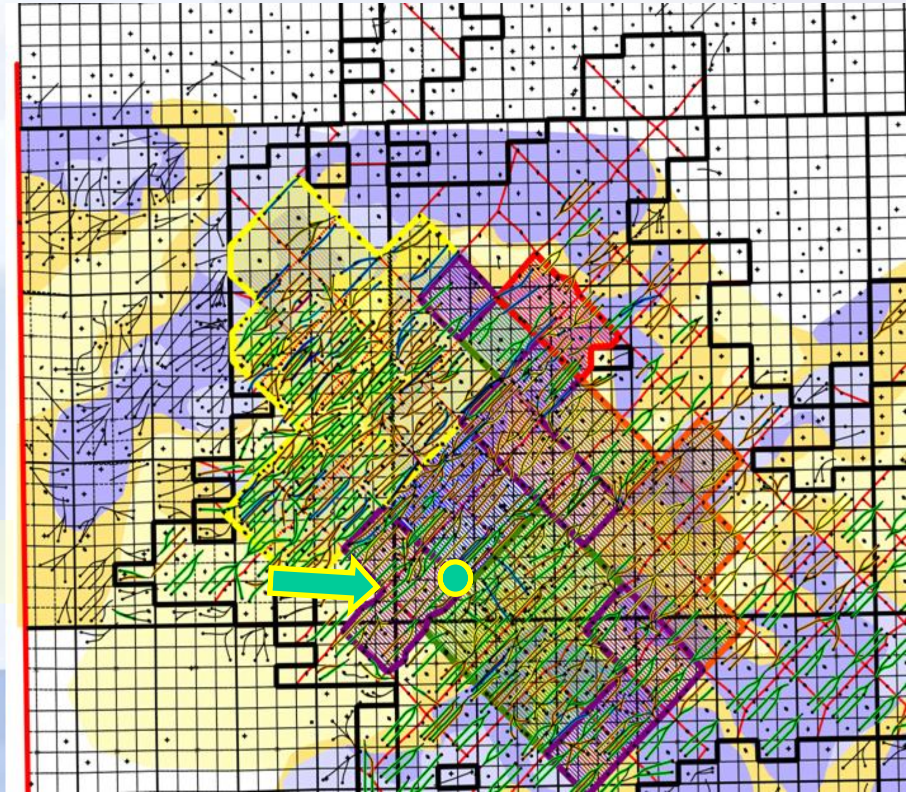
- Best practices for CO_2 storage
- Best practices for Well Abandonment
- Literature Review for Corrosion in Wellbore Steel

Downhole Testing Program

Testing Program Elements

1. Cased-hole logging
2. Pressure transient (vertical interference) tests
3. Cement sampling (with CemCore tool)
4. Mini-frac tests
5. Fluid sample – Gravelbourg

101/08-06-006-13W2



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CemCore Tool

- Dimensions anticipated for the cores are 9.5 mm (3/8 inch) diameter and 38 mm (1.2 inch) length.

- Retained in the tool's cutter then brought to surface.

PPT Tool (pore pressure transmission)

- 4 Isolation Packers
- Feed through N_2 inflation lines
- Flow input ports
- <4in Max OD

- 8 pressure/temp sensors
- 4 Isolation feed through
- Coiled Tubing Super Connector
- 4 independent ¼ inflation lines
- 2 ¼ sensor lines

PPT Tool

Run on Coiled Tubing

Theme 4: Risk Assessment

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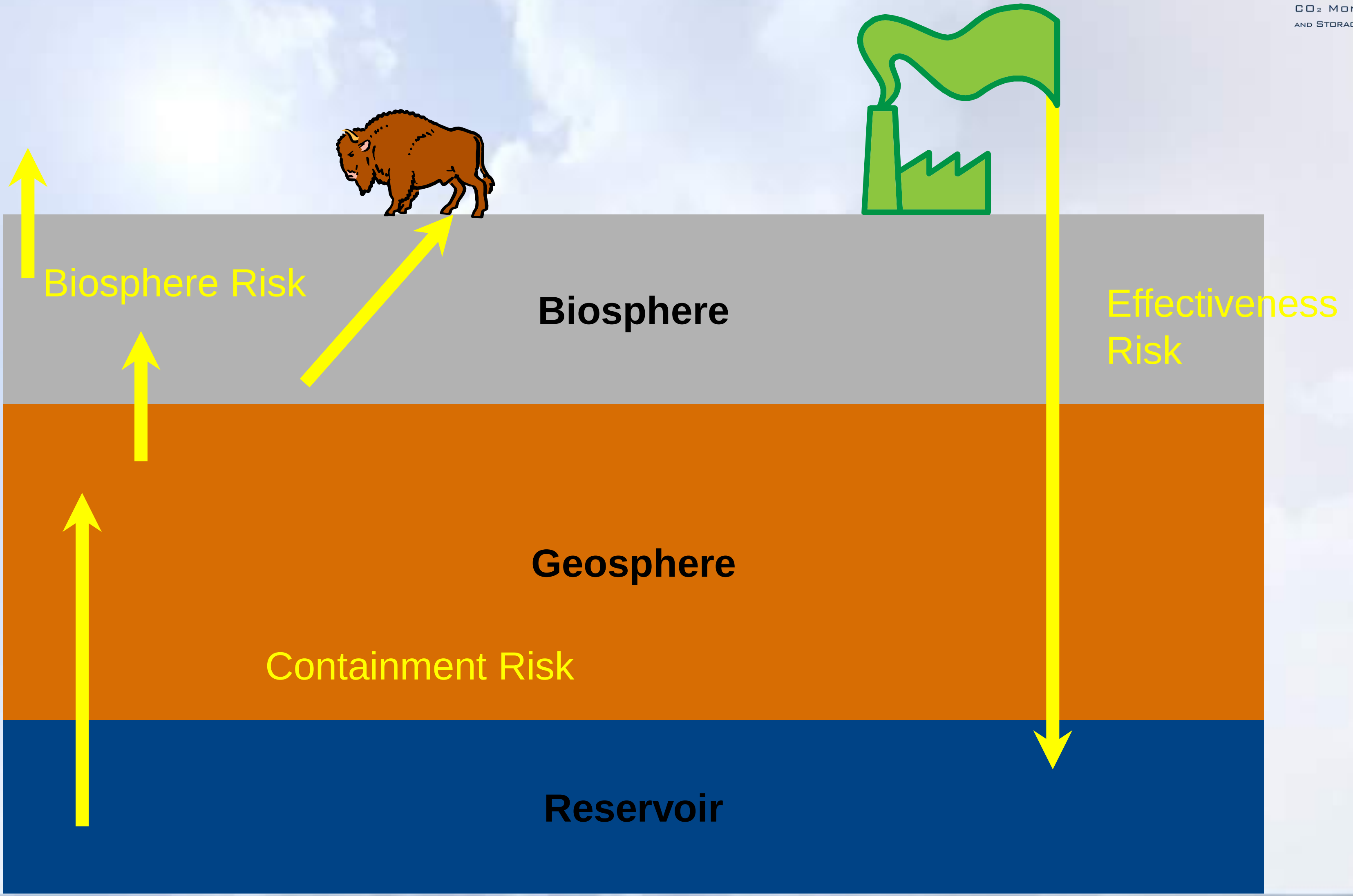
" Risk can be managed, minimized, shared, transferred, or accepted. It cannot be ignored."[1]

"All I'm saying is <u>NOW</u> is the time to develop the technology to deflect an asteroid"

[1] Latham, M. 1994. Constructing the Team. Final report of the government/industry review of procurement and contractual arrangements in the construction industry. HMSO, London.

Terminology



Fundamental CO_2 storage project requirements

The Project has to be able to demonstrate that it will generate greenhouse benefits.

Geosphere risk assessment

- The storage will retain most of the CO_2 injected ← Containment risk assessment
- The storage will receive an adequate volume of CO_2 ← Effectiveness risk assessment

The Project has to be able to demonstrate that it will not pose a threat to the community or its assets.

- The stored CO_2 will pose acceptable risk to:
  - •public safety
  - •community assets (environment, amenity etc)

  ← Biosphere risk assessment

The Project has to be acceptable to the community.

- The community and key stakeholders support the Project ← Community engagement

Geosphere & Biosphere Risk

Technical Inputs
- Wellbore integrity research
- Characterisation of reservoir characteristics & transport of CO_2
- Seismicity of area
- Characterisation of CO_2 reactions in reservoir
- Monitoring techniques & effectiveness

Geosphere Risk Assessment

Outputs
- CO_2 risk events (initiating event & pathway) & ranking
- Mass of CO_2 released if event occurs
- Likelihood of each event occurring & releasing CO_2

Stakeholder Engagement

Stakeholder Values

Building Capacity to Engage

Acceptability of Risks

Biosphere Risk Assessment

Other Technical Inputs
- Characterisation of aquifers
- Characterisation of surface water
- Characterisation of soils / sediments
- Behaviour of CO_2 in soils, sediments, groundwater, surface water
- Receptors in environment
- Toxicology (animal, plant, human)

Outputs
- Risks to biosphere assets (ranking & severity)

Mitigation Measures

Effectiveness Risks

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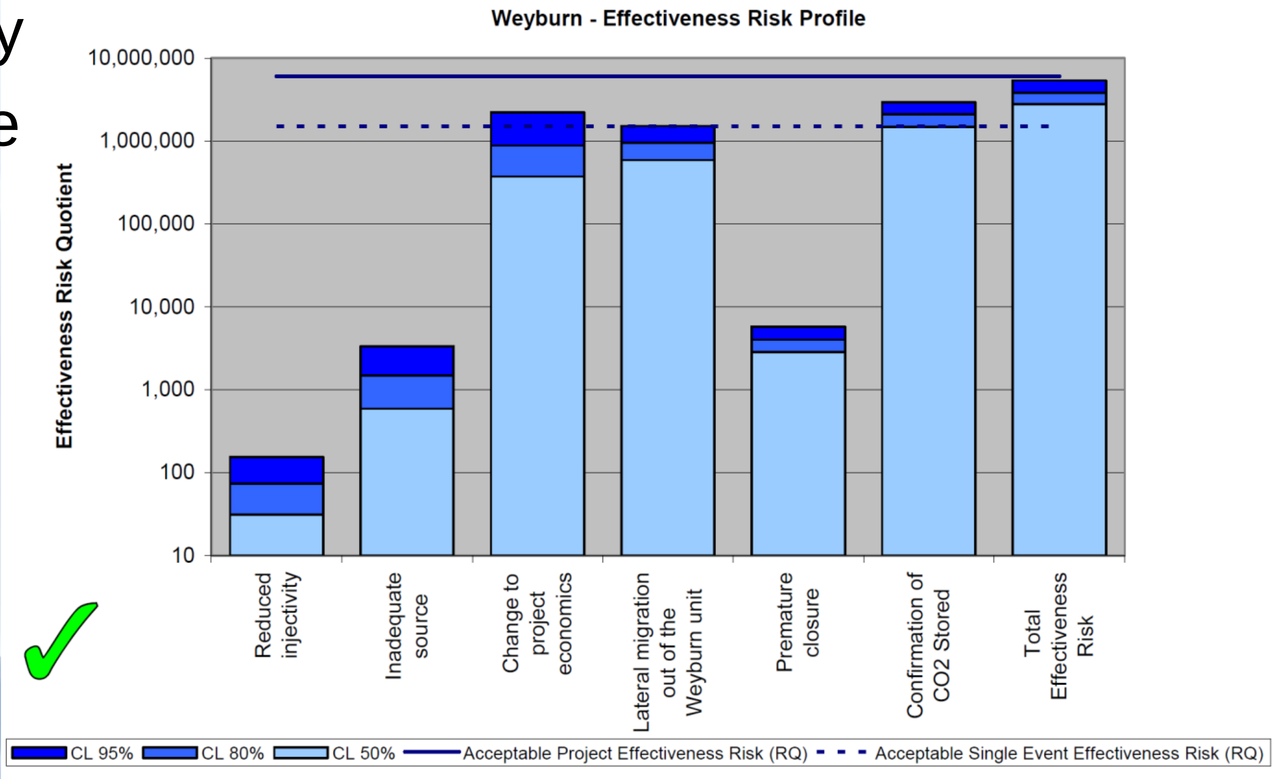
- Change to project economics
- Lateral migration out of the Weyburn Unit
- Change in public perception / regulations
- Ability to verify stored CO_2
- Lack of capacity
- Reduced injectivity
- Inadequate source



Process Towards Community Acceptance

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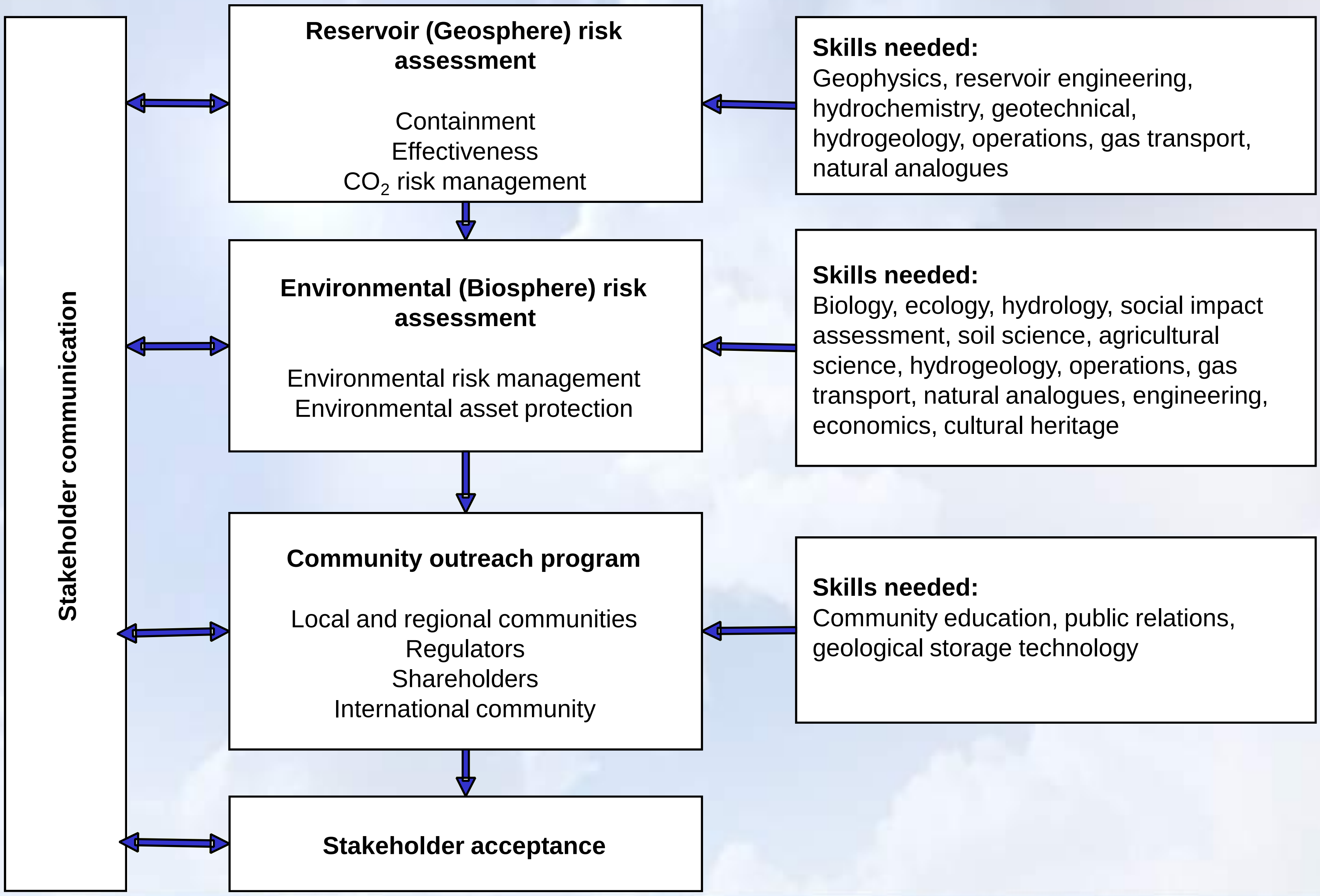

Monitoring: Overview

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and Storage Project

Site Characterization

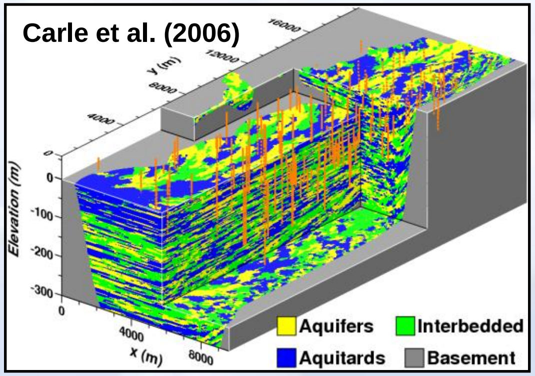
Modeling

Monitoring

define & bdry | **initial conds**

predict performance

measure performance



CO_2 isolation performance

- ✓ Capacity
- ✓ Footprint
- ✓ Containment
- ✓ Risk (CFC uncertainty)

Verification

Compare results: resolve discrepancies & refine MMC capabilities

Geophysical Monitoring: Overview

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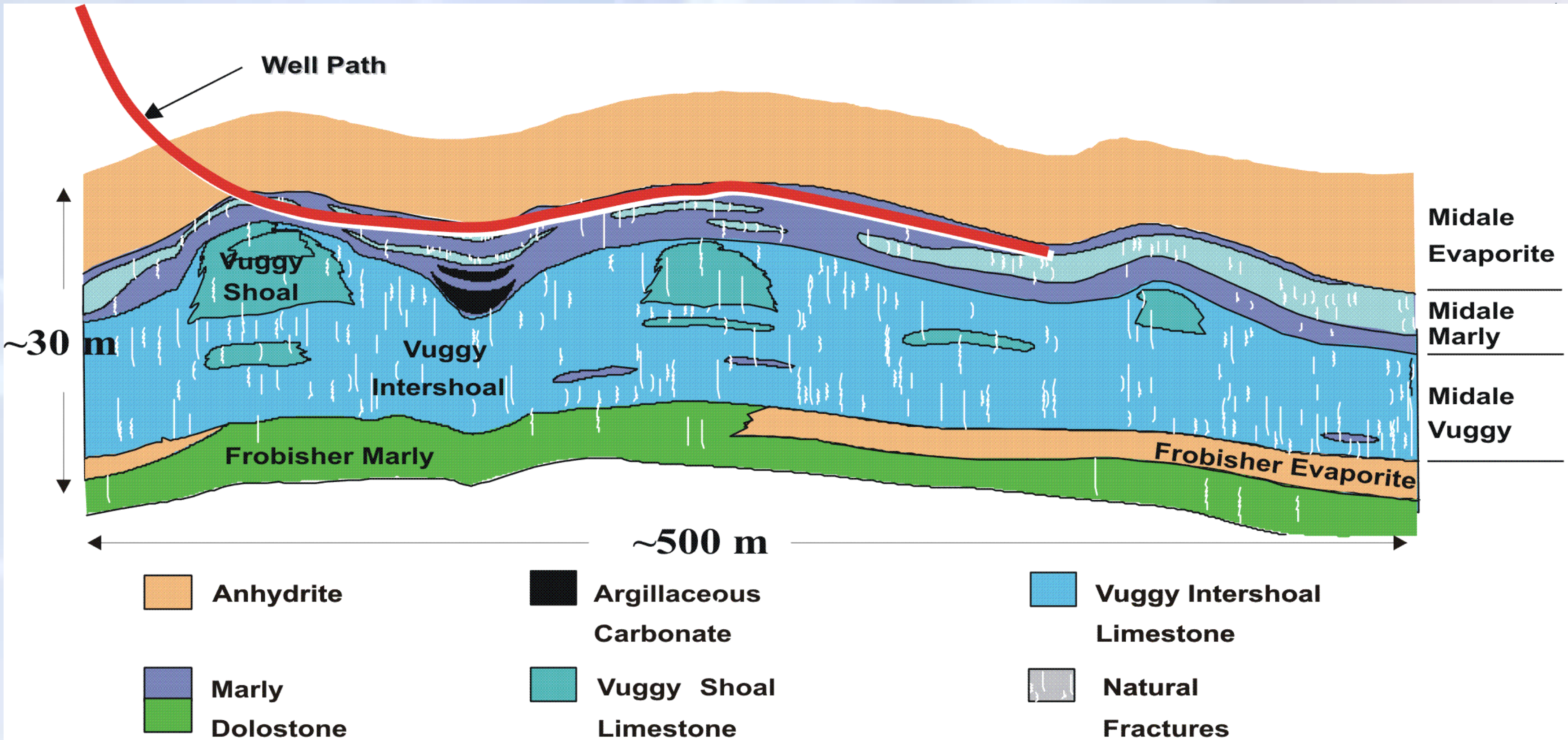
Weyburn-Midale
CO_2 Monitoring
and Storage Project

- Introduction
- Geophysical Characterization of Rock/Fluid System
- Feasibility studies
- Downhole monitoring methods
- 3D Seismic Methods
  - Time-lapse seismic results
  - P vs. S_{CO_2} (prestack seismic inversion)
- Caprock Integrity - seismic anisotropy
- Overburden Monitoring and CO_2 inventory estimates
- Microseismic monitoring
- 3D time-lapse seismic monitoring without a baseline
- Seismic constrained simulation/history matching
- Predictive model verification (stochastic inversion)

The Reservoir (Fractured Carbonate)



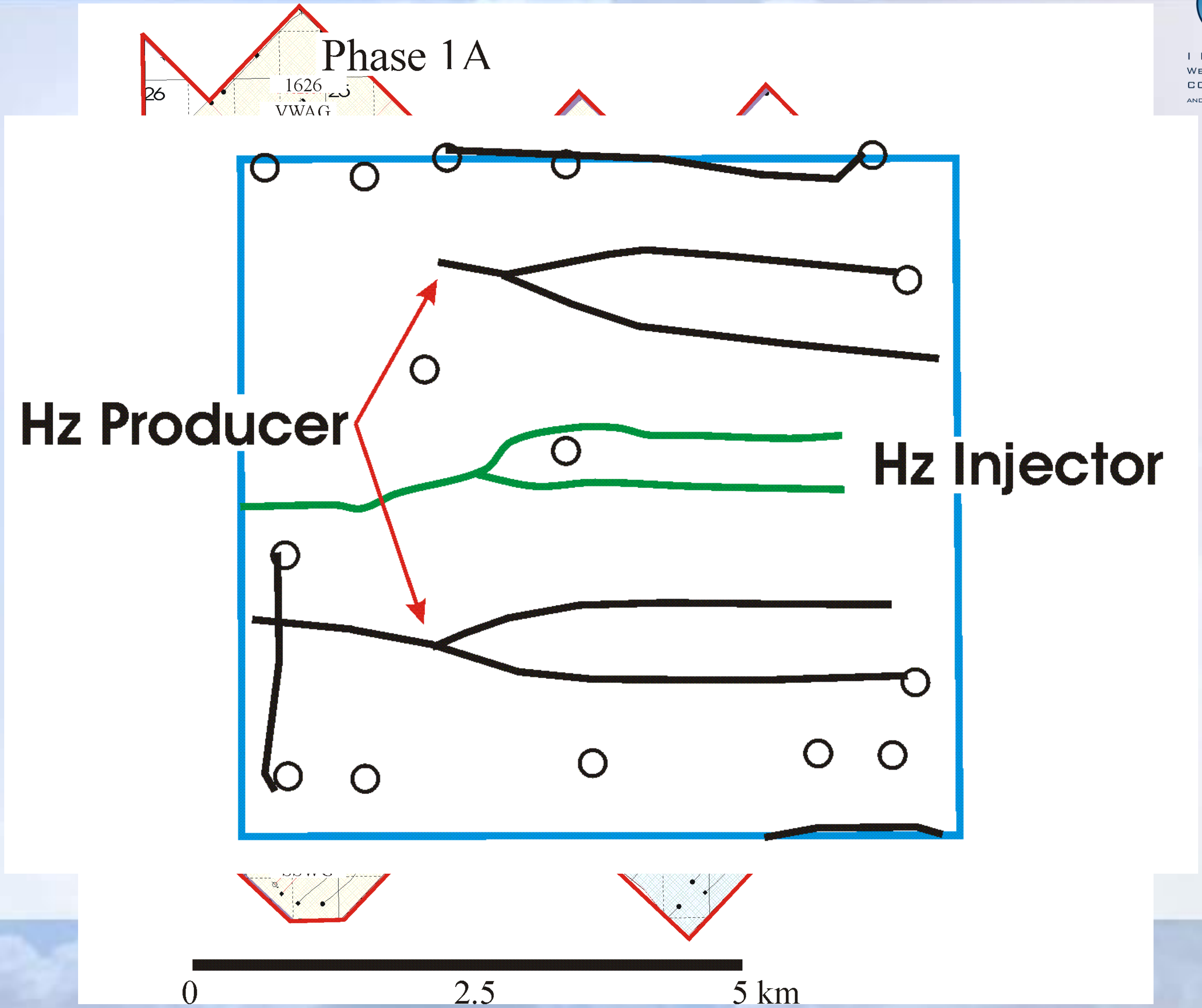
Reservoir: 1450 m depth, <30 m thick, T=63° C, P=14 MPa

Anhydrite seal

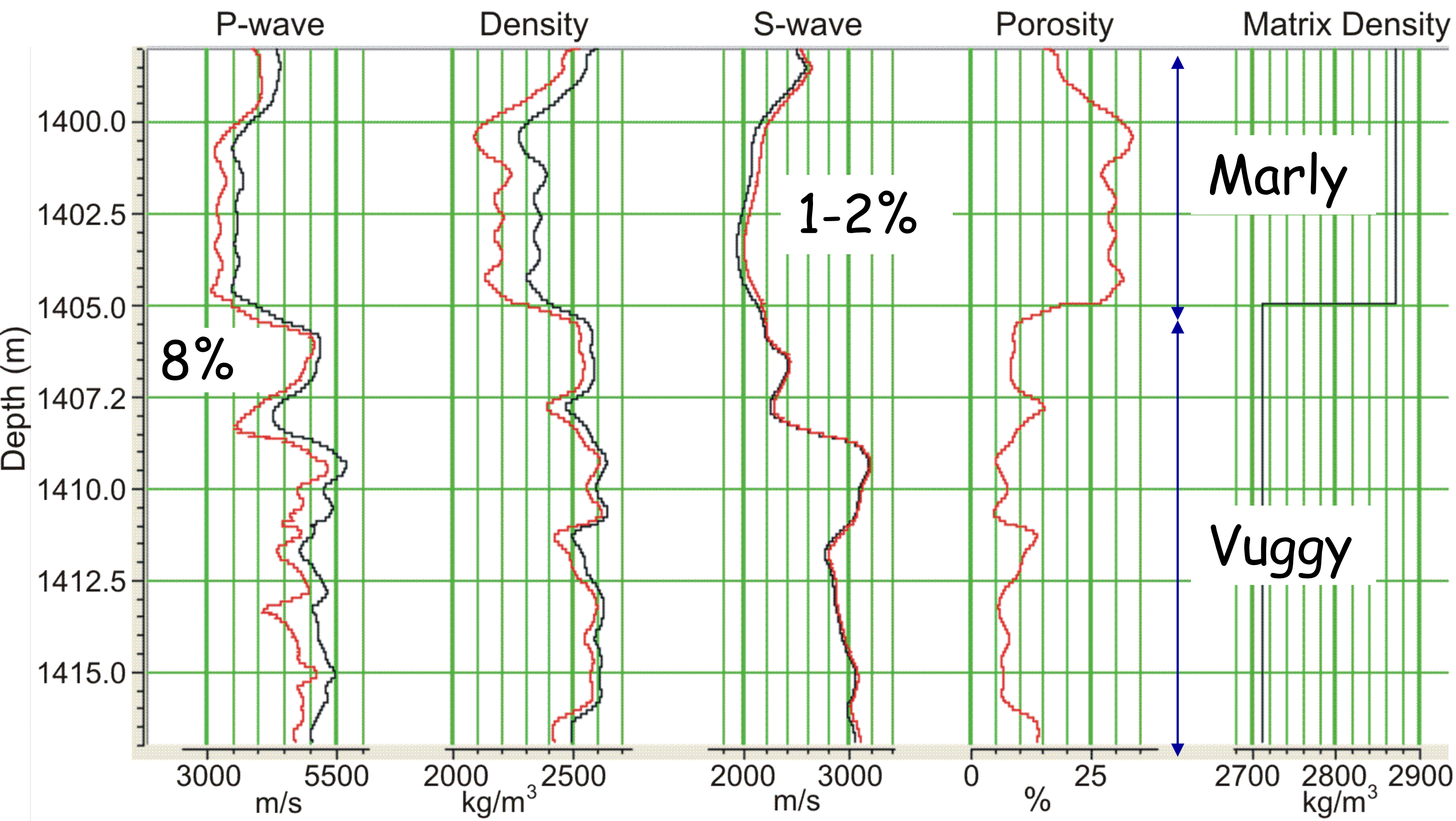
Marly Dolostone: 6 m thick, 16-38% porosity, 1-50 mD perm

Vuggy Limestone: 17 m thick, porosity 8-20%, 10-300 mD perm

Weyburn Field: Phase 1A EOR Area



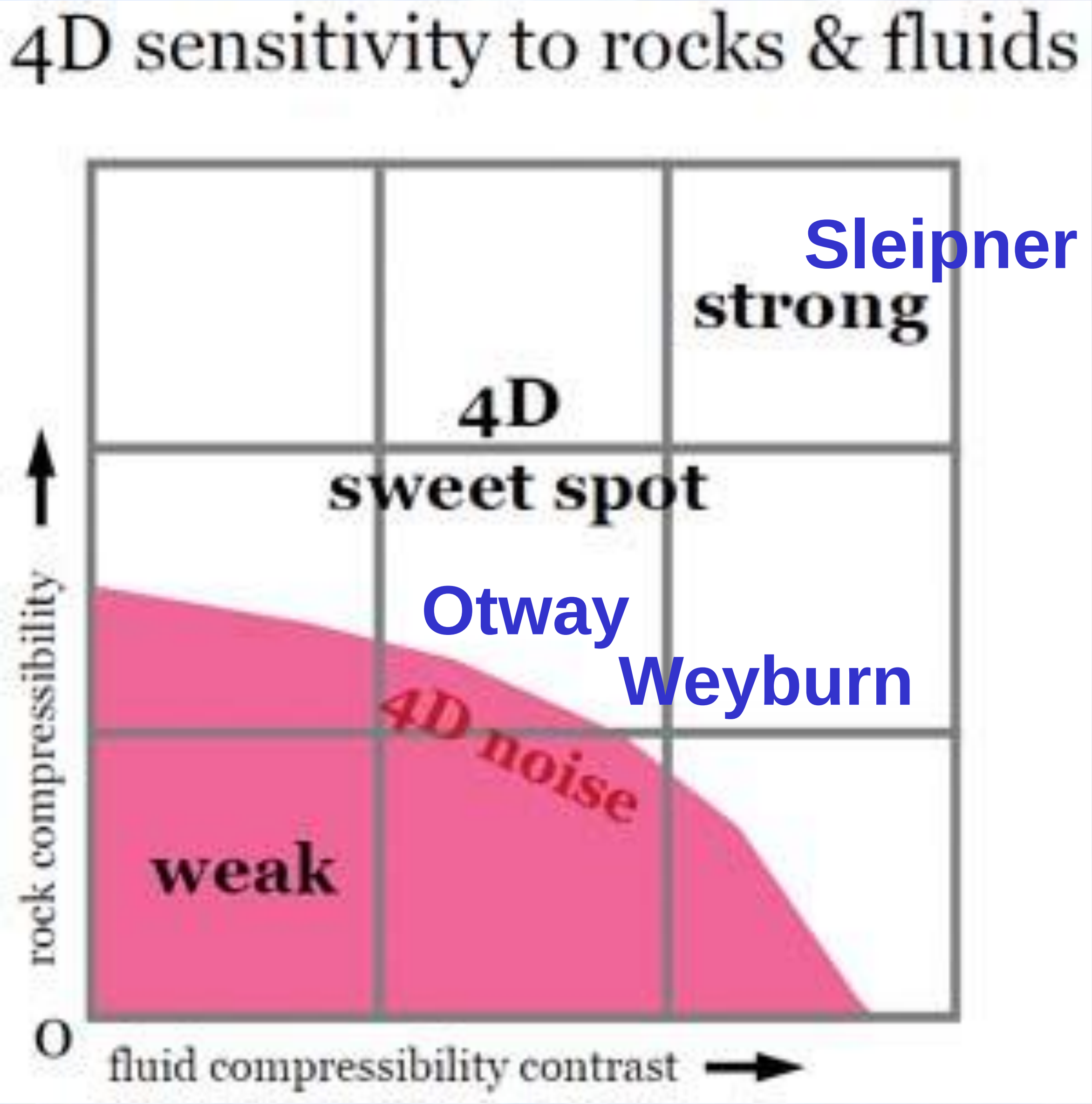
Characterization: Modelled Field Properties



Post-injection (100% brine replaced by 70% CO_2+30% brine)

Pre-injection

Weyburn Field: Phase 1A EOR Area



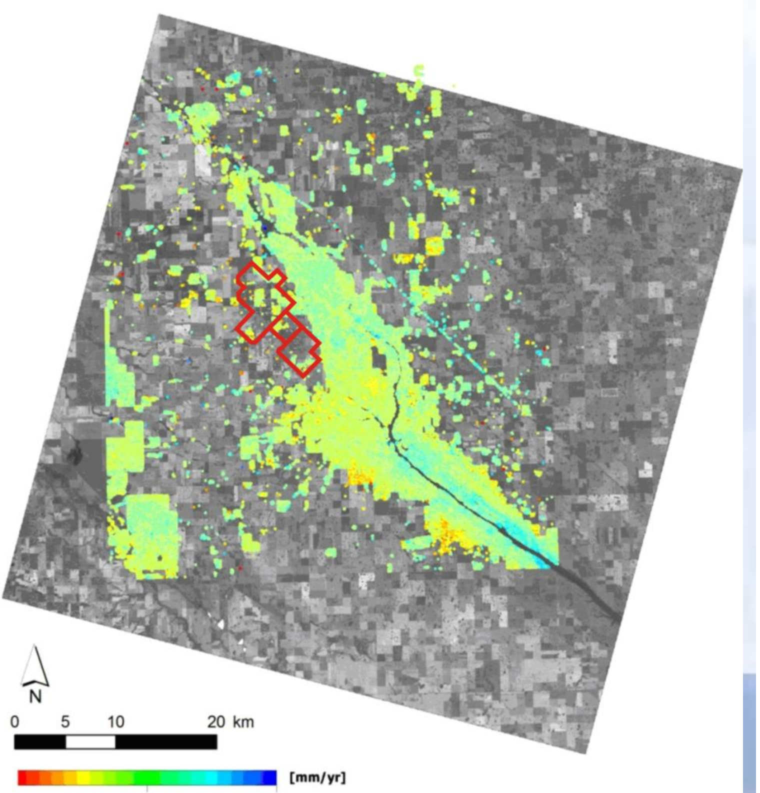
After Lumley (2010)

Recommendations: Characterization

- Characterizing the local rock/fluid/stress system is essential to the design and understanding of geophysical monitoring.
- Variations in the composition of the CO_2 injectant can have significant effects.
- Lab measurements on core samples is the most practical means of characterization.
- Supplemental in situ measurements are highly desirable (static and time lapse logging, pressure, and fluid saturation).

Monitoring Feasibility Studies

- **INSAR**: regional monitoring of injection-related surface deformation.
- **Gravity** monitoring: monitoring large injection volumes or shallow leakage monitoring.
- Require models to interpret what observed changes mean in terms of subsurface fluid distribution and stress changes.
- Best applied in conjunction with other higher resolution monitoring methods.
- **LEERT** currently falls into the category of a research method.



LEERT = Long-Electrode Electrical Resistivity Tomography

- Steel casings as electrodes, inject current and measure electric field.

- Numerical modeling study

- more resistive the overburden

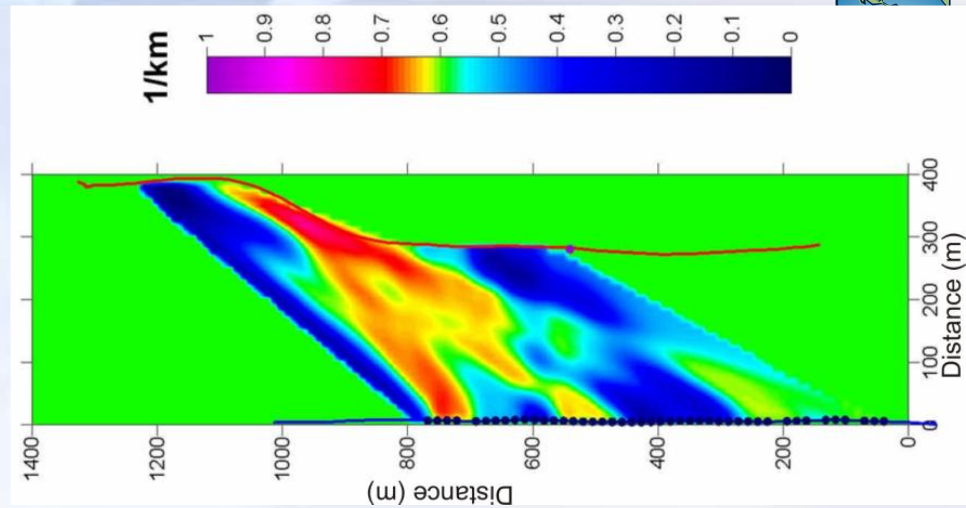
- and/or the reservoir is significantly shallower

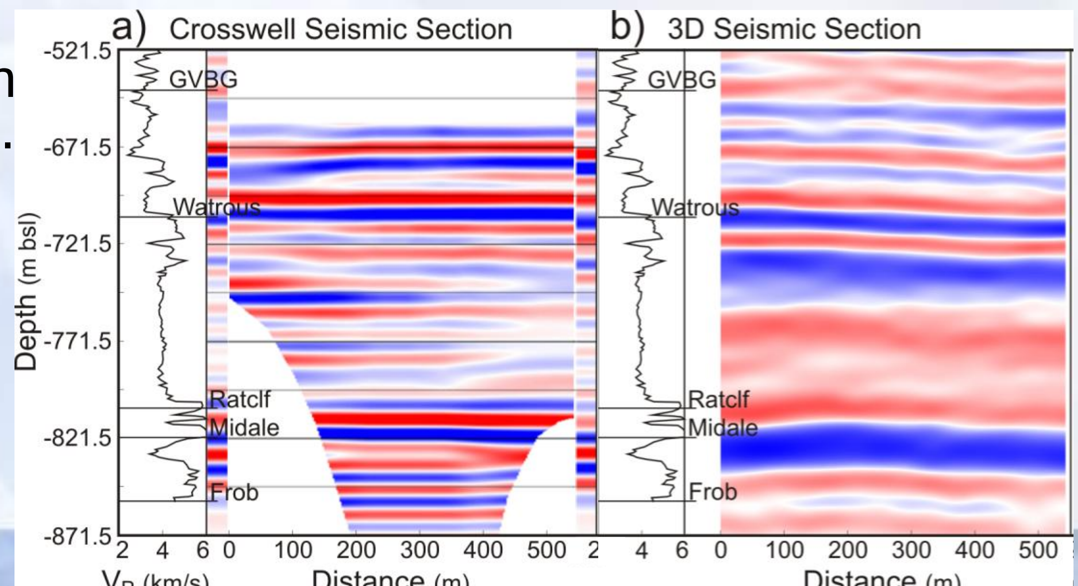
- Small inter-well distances are required;

- likely have fewer well casings

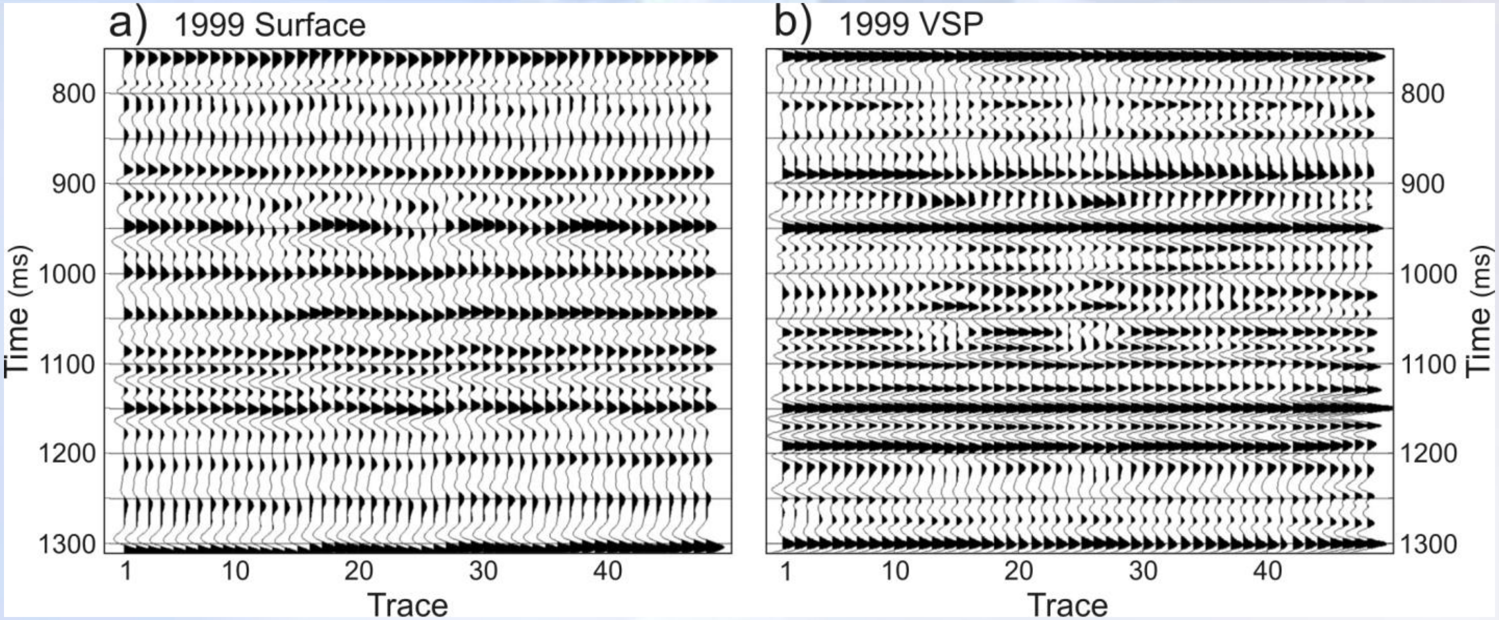
Downhole: Cross-well geophysical methods

- Crosswell methods can provide higher resolution images of the subsurface.
- Limited by required access to boreholes, the geometry of existing boreholes, and provide limited spatial coverage.
- In an EOR setting, borehole access requires interruption of production in active wells or access to abandoned wells.
- Usually wellbores do not extend through the reservoir limiting the imaging aperture for transmission tomography at the reservoir level.
- Crosswell techniques are best suited for monitoring above the reservoir. In a non CO_2 -EOR environment, there may be few wells, and monitoring wells will have to be provided.





Downhole: VSP



- Time-lapse VSP data are capable of producing somewhat higher resolution images of changes in the reservoir over a subset of the area covered by the surface time-lapse seismic data.
- Cover a small area of the reservoir compared to the area of surface shotpoints used to generate the VSP;
- Recording fidelity issues are common either due to sensor coupling in the wellbore or casing coupling to the wall of the wellbore;
- The data provide low fold coverage of the subsurface.
- These factors make AVO analysis of the VSP data unstable.

Downhole: Recommendations

- Active-source downhole seismic methods (X-well and VSP) provide higher resolution imaging, but are limited by their deployment complications and their limited areal coverage.
- Best used for experimental purposes or support/calibration of surface time-lapse seismic.

- Permanent passive monitoring array has been very successful in providing assurance monitoring and constraints on deformation near the reservoir.
- Not suited for tracking CO_2 plume.

3D-3C Time-Lapse Seismic Data Acquisition

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Survey Dates

Date	Area A	Area B
1999	**Baseline**	-
2001	**Monitor I**	Baseline
2002	**Monitor II**	-
2004	Monitor III	Monitor I
2005 (May)	-	Monitor IIa
2005 (Nov)	-	Monitor IIb
2007	Monitor IV	Monitor III
2008	Monitor V	Monitor IV
2009		Monitor V

Blue: IEA Weyburn Phase I Data

Black: EnCana surveys

cenovus ENERGY

Time-Lapse Seismic: Depth Slice at the Reservoir

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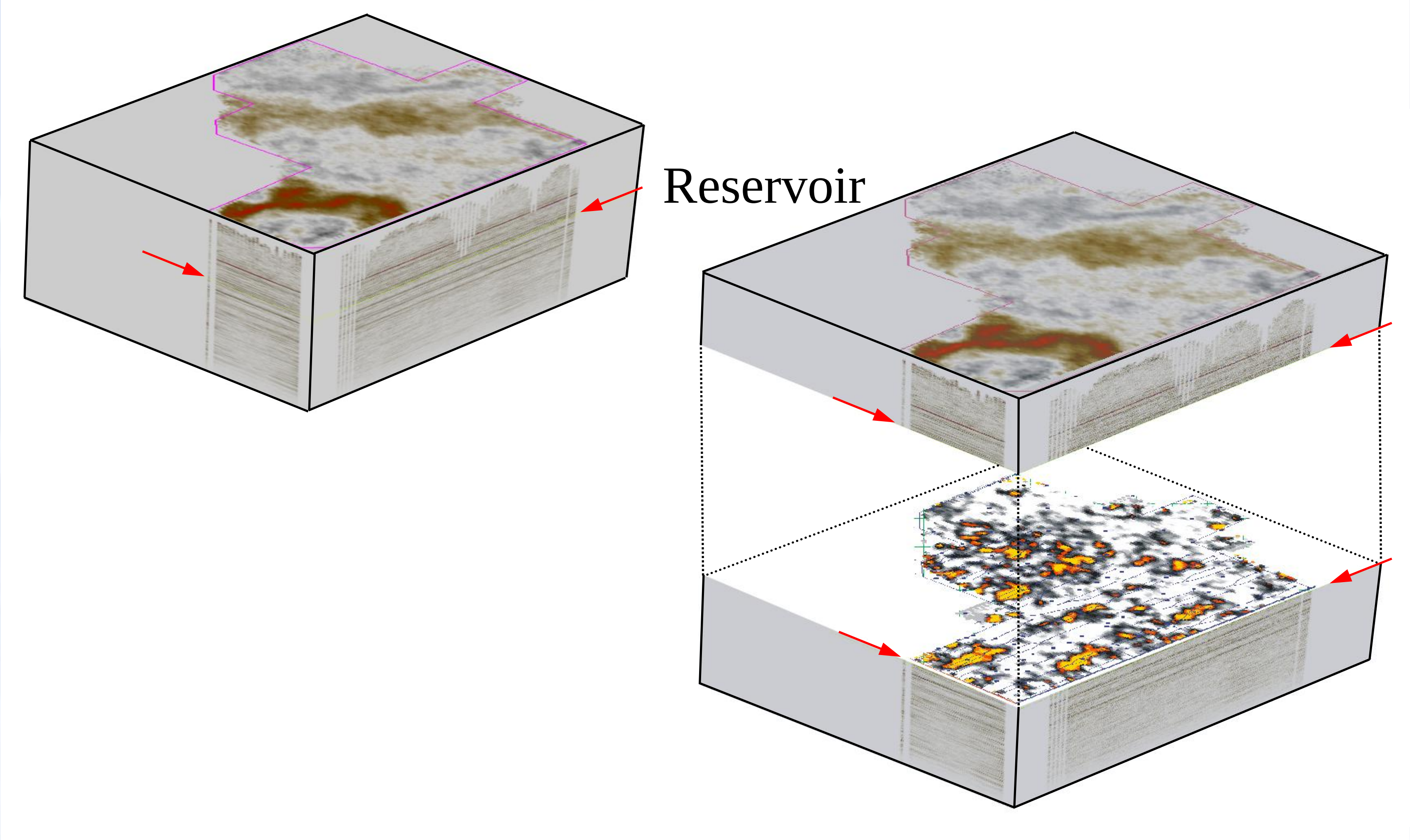

Marly Amplitude Differences

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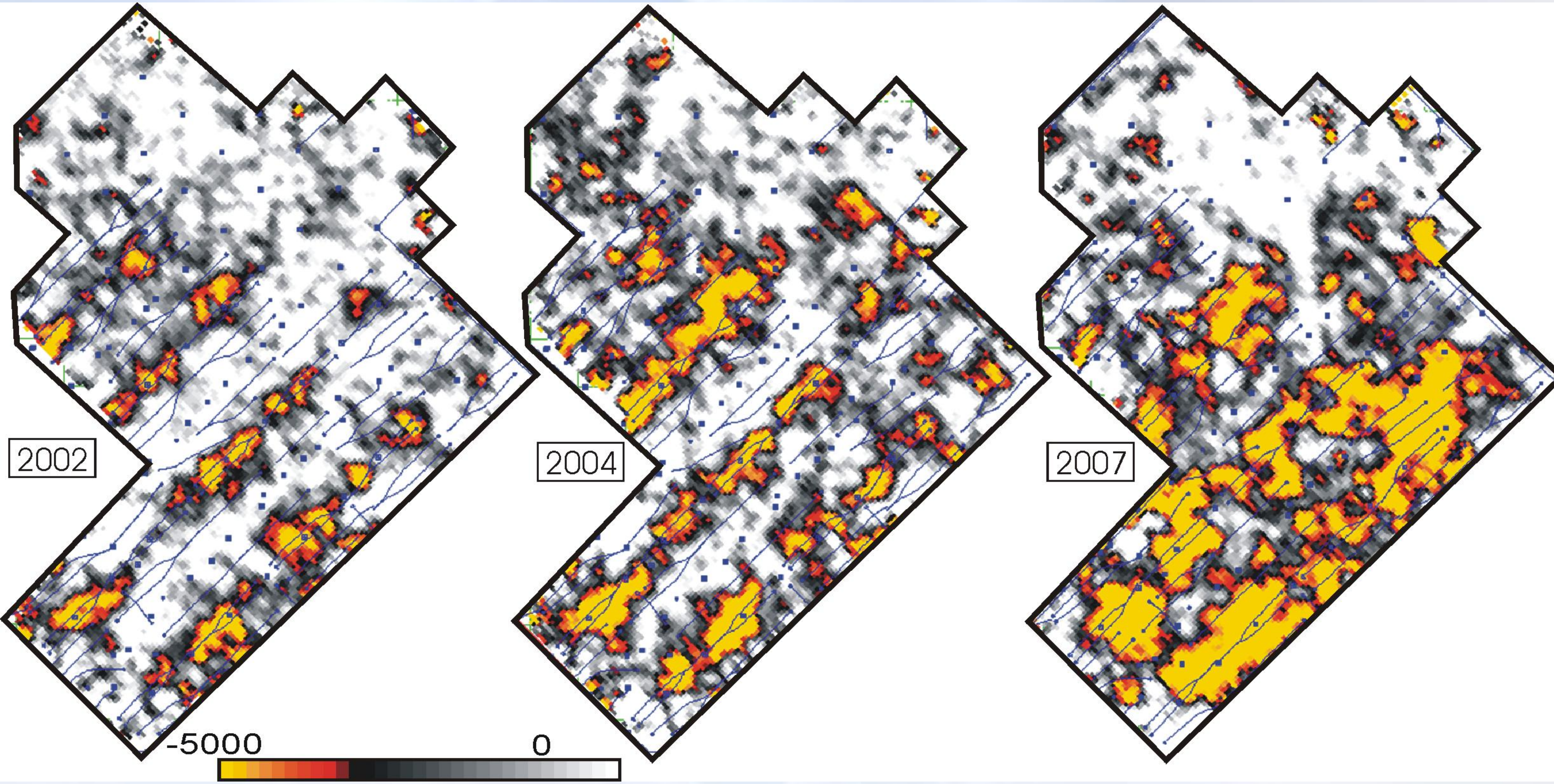
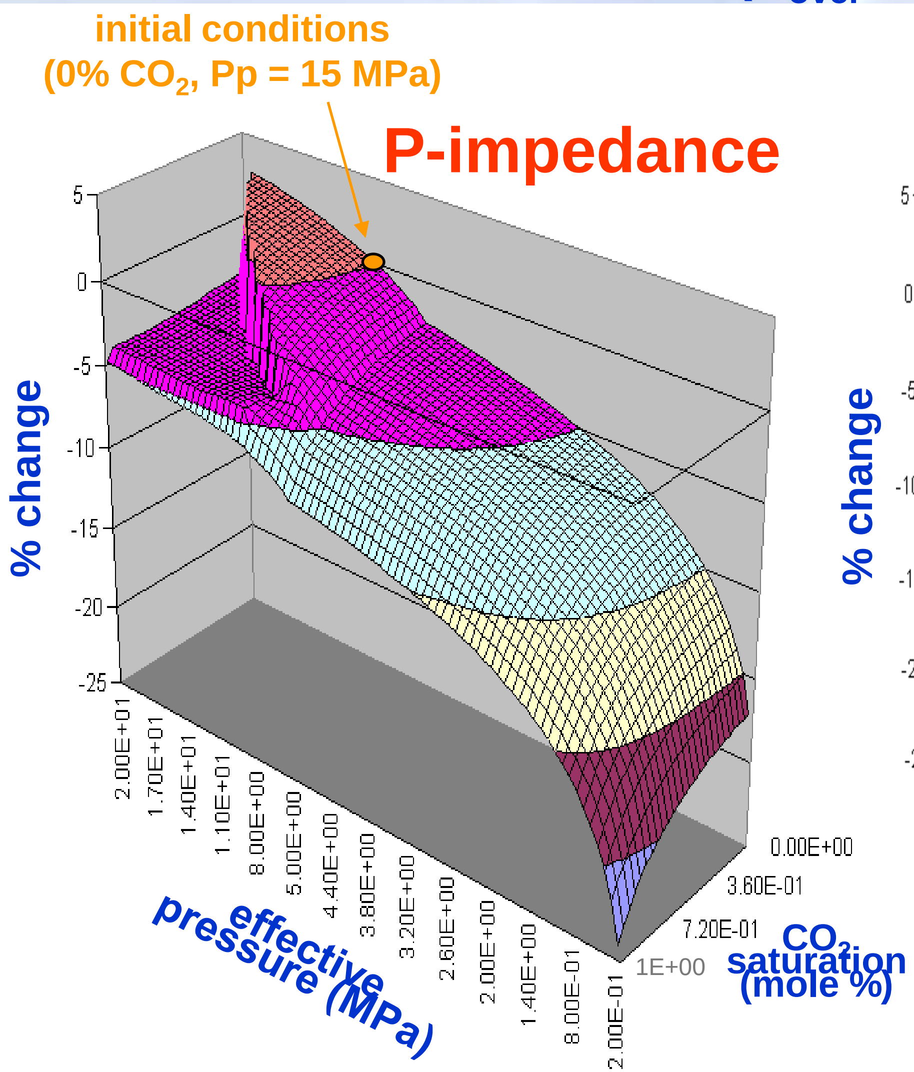
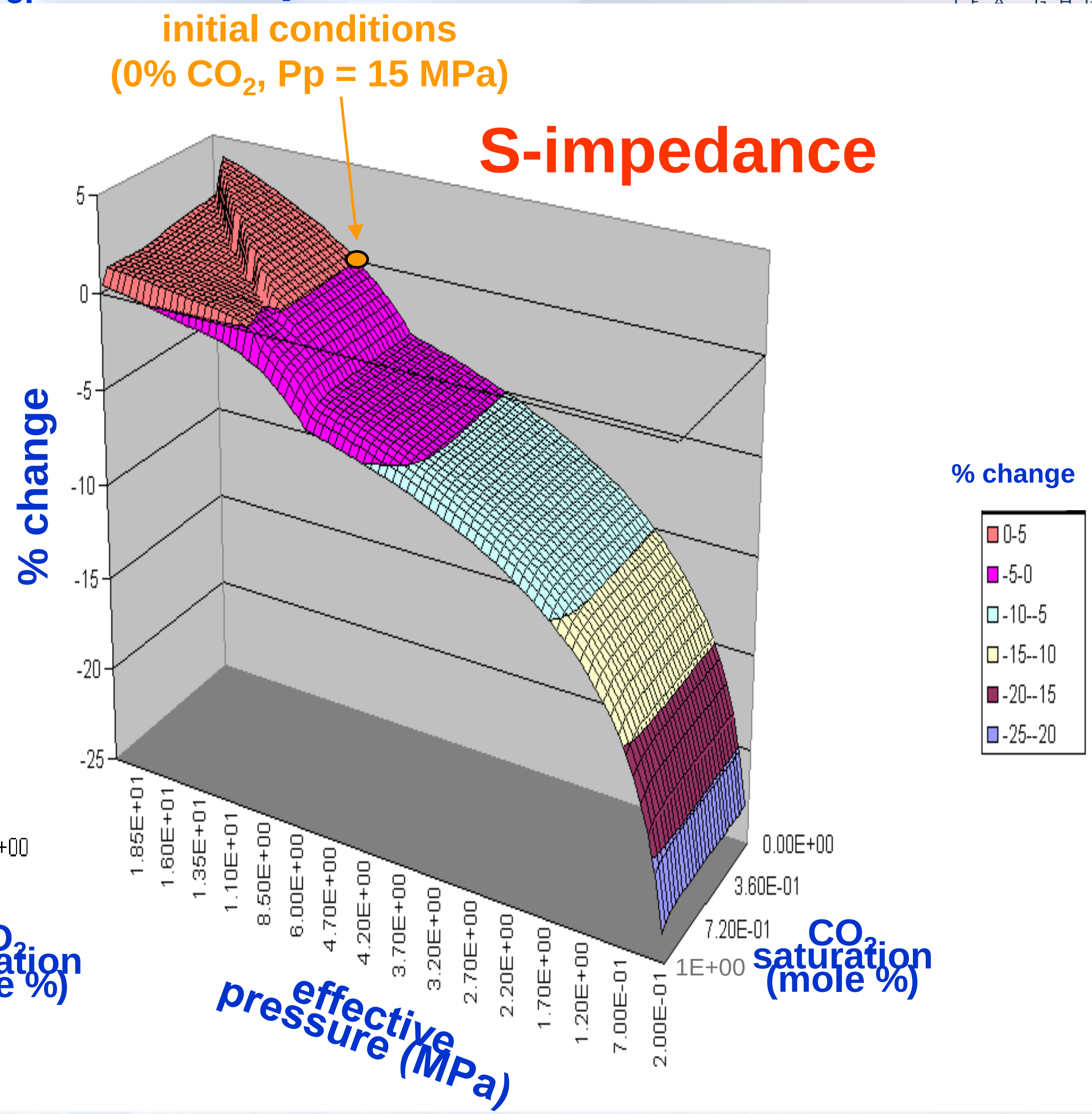
2.8 MT CO_2 | **3.7 MT CO_2** | **7.4 MT CO_2**



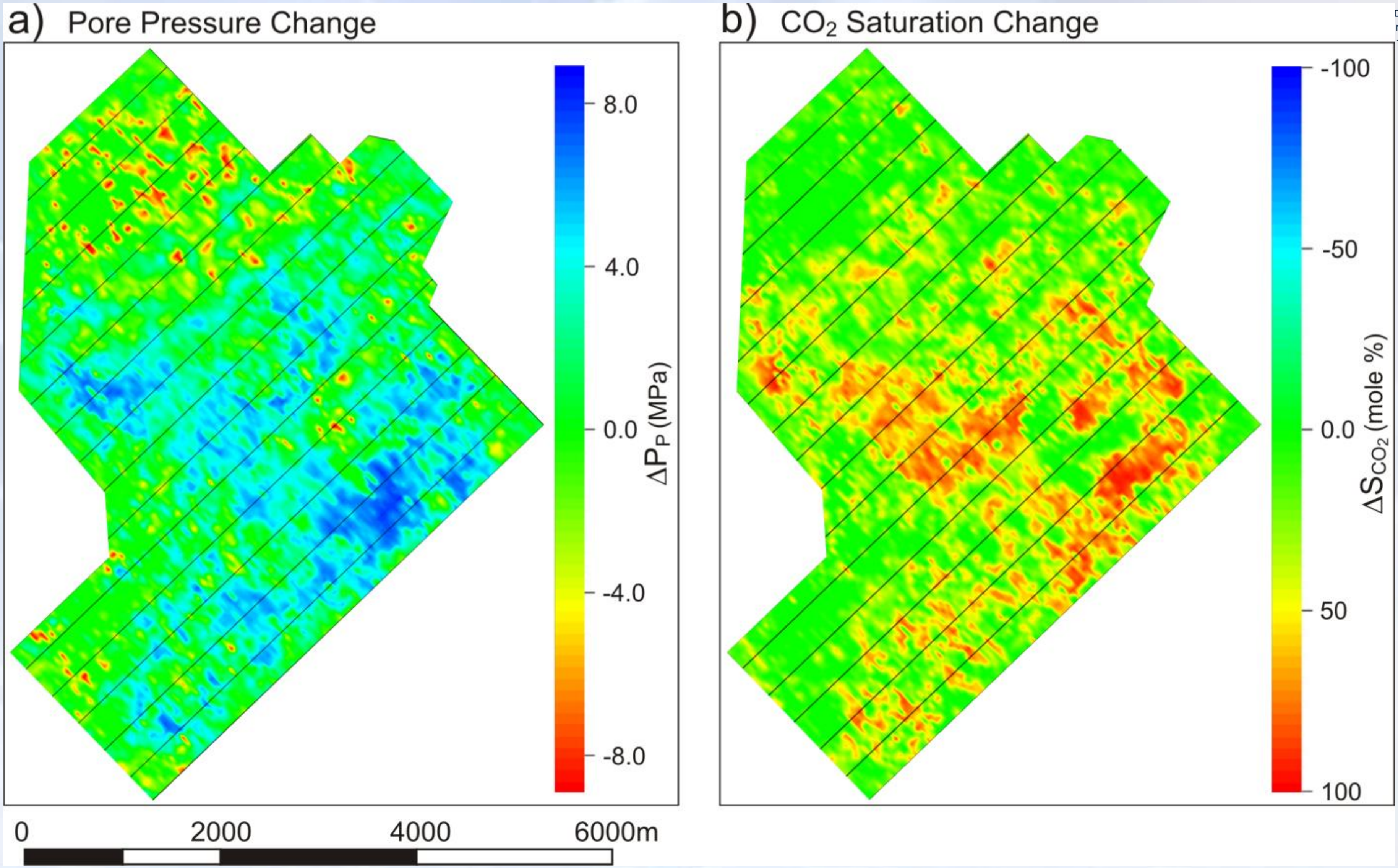
P vs. S_{CO_2} (prestack inversion)

(P_{over} = 24 MPa)

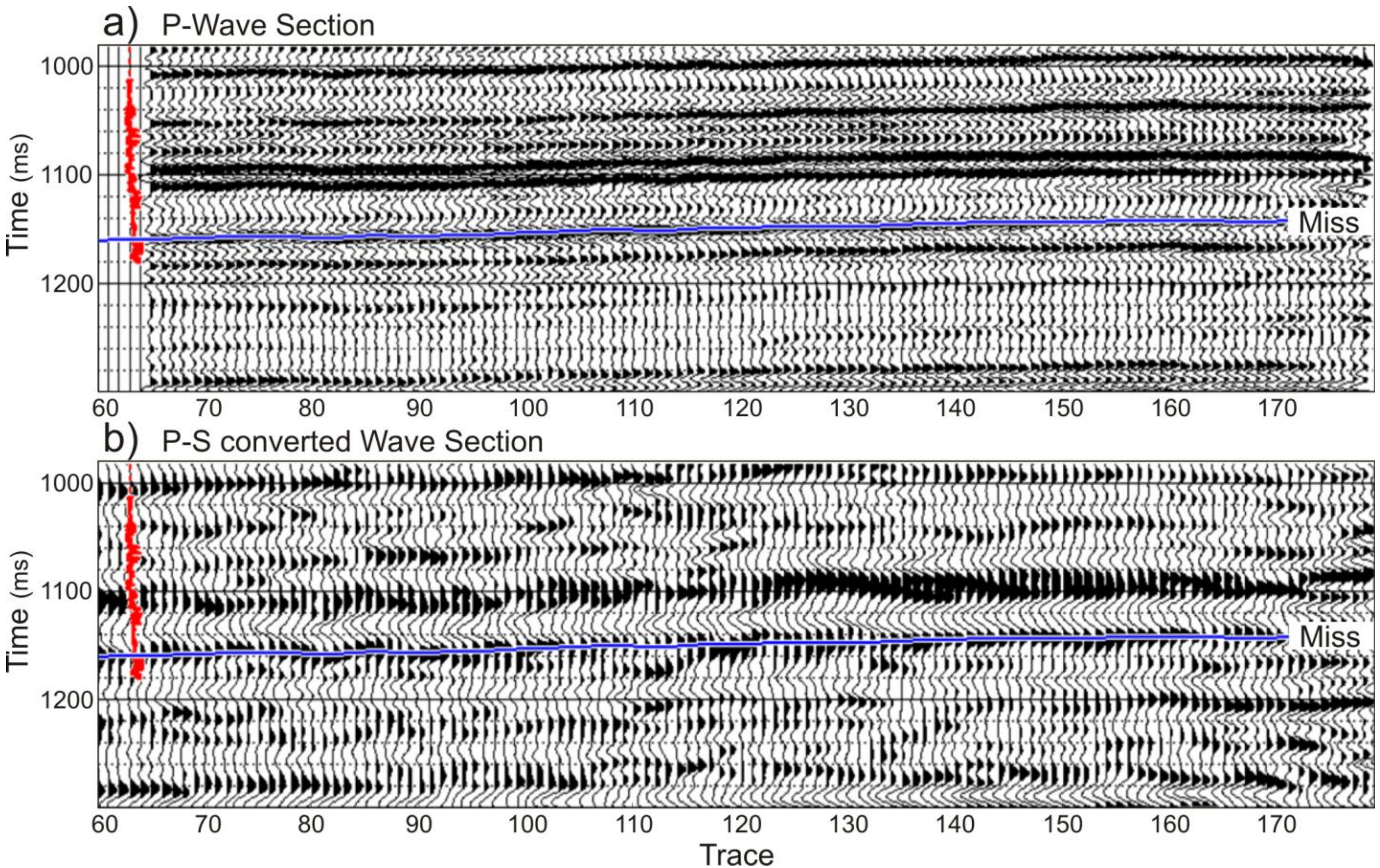




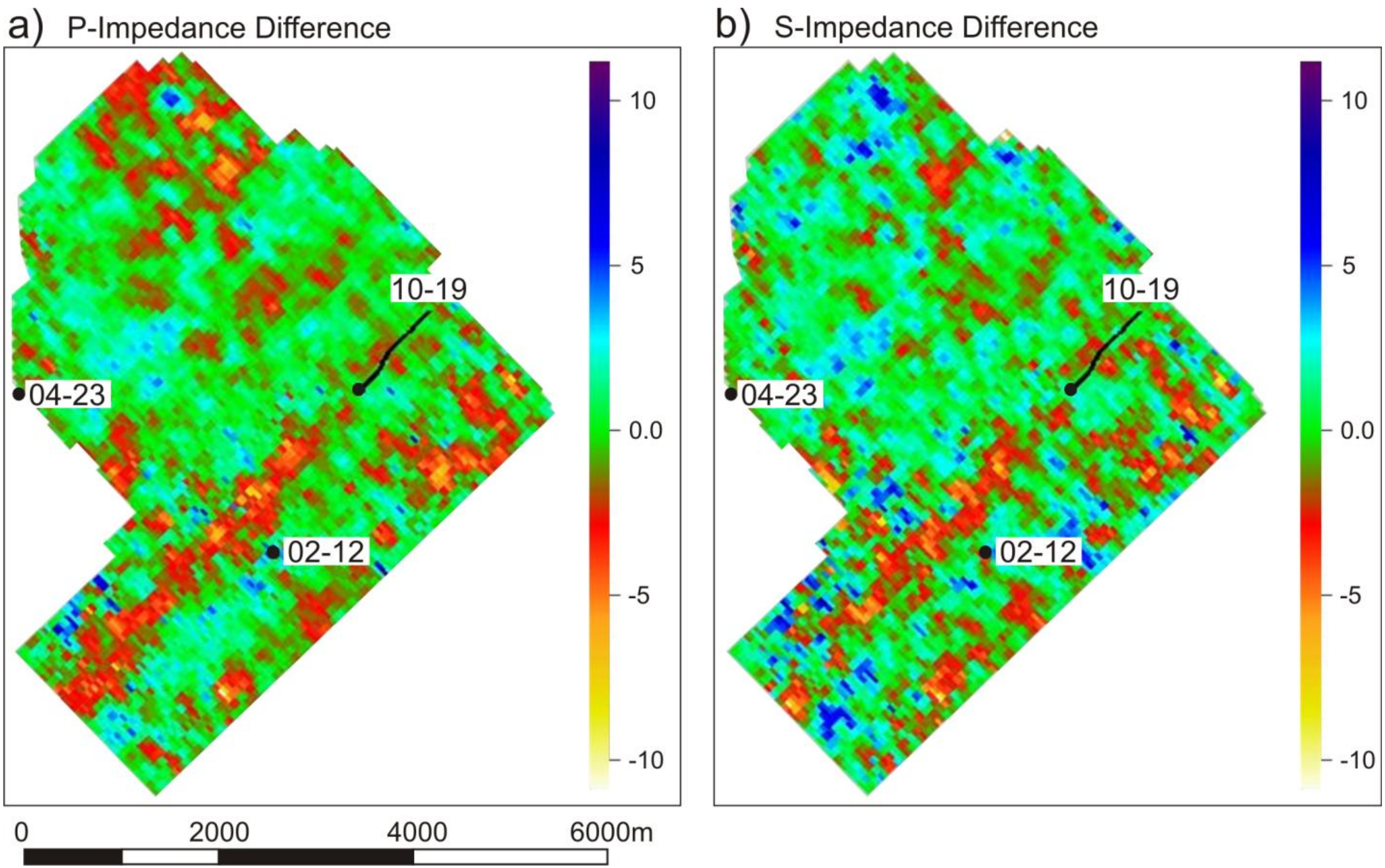
P vs. S_{CO_2} (prestack inversion)



P vs. S_{CO_2} discrimination



P vs. S_{CO_2} discrimination



Assessment of Data Repeatability

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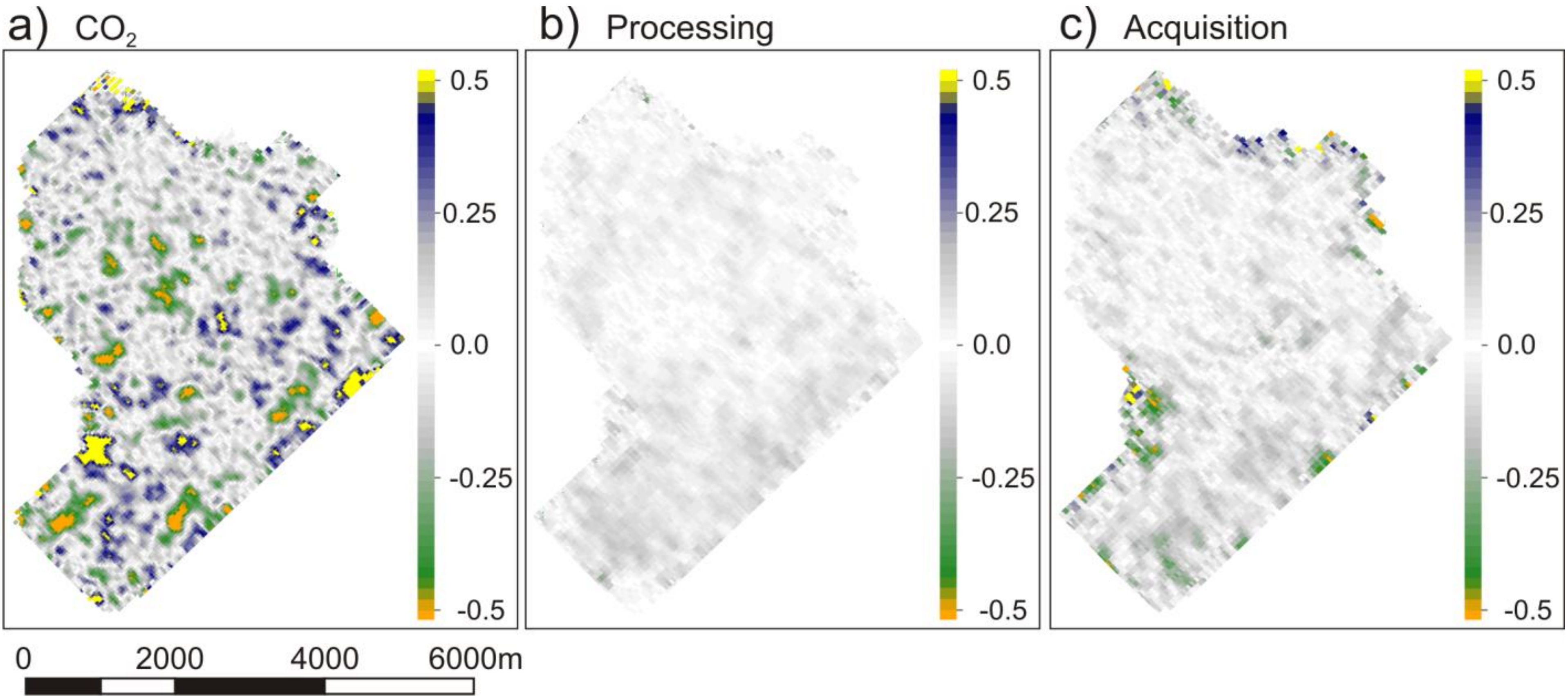
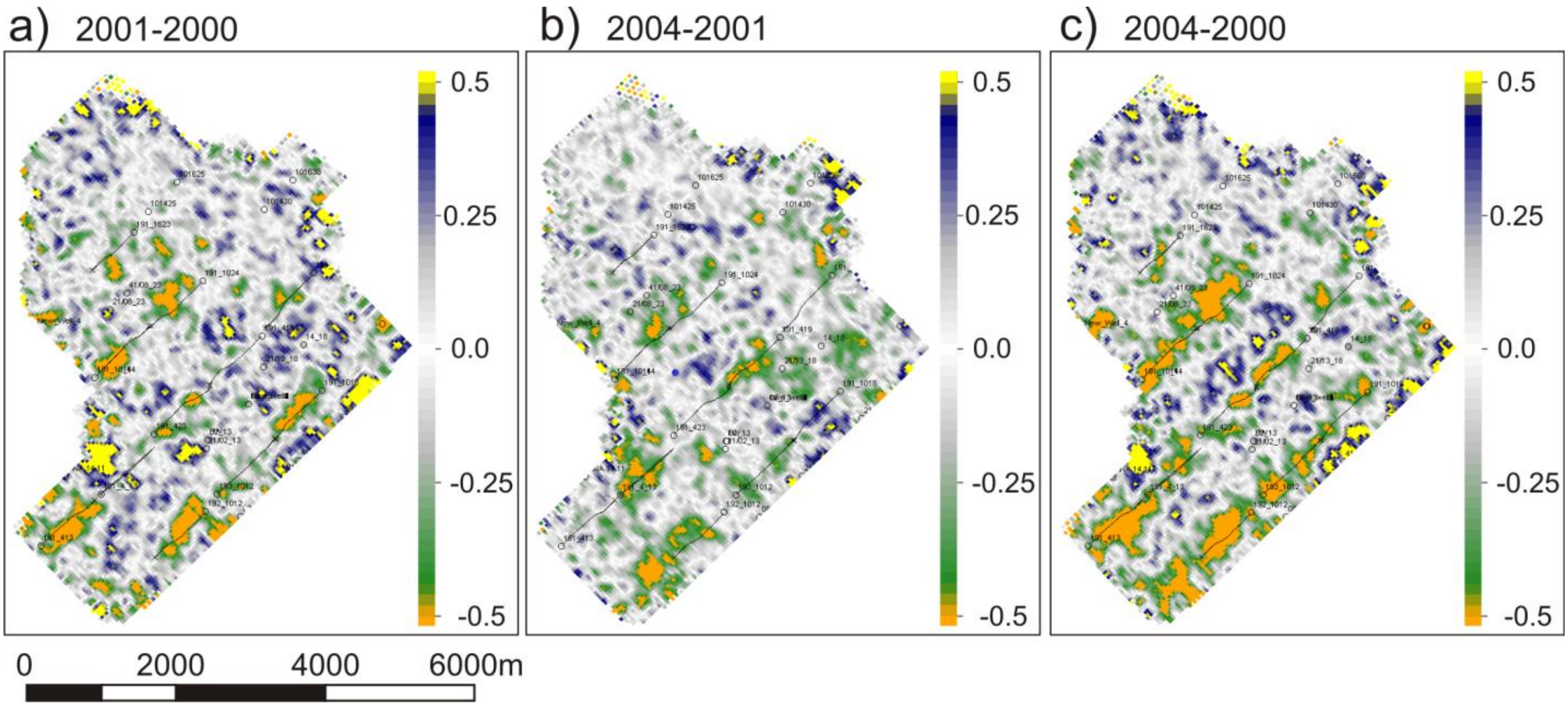


3D time-lapse seismic monitoring without a baseline



3D Seismic Methods: Recommendations

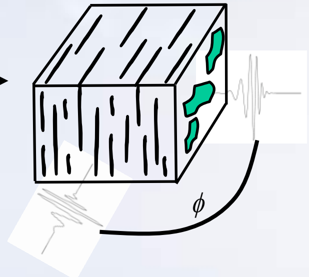
- Overall, provide the most effective means of monitoring the CO_2 distribution over a large area.
- Provide depth resolution capable of imaging/detecting CO_2 in the reservoir and overburden.
- Applicability will depend on local geology.
- Effective use in a qualitative sense is demonstrated, but semi-quantitative use is still limited.
- Pressure vs. CO_2 saturation discrimination is feasible.
- Value of multi-component data acquisition is arguable.

Storage Security: Caprock Integrity - Seismic Anisotropy

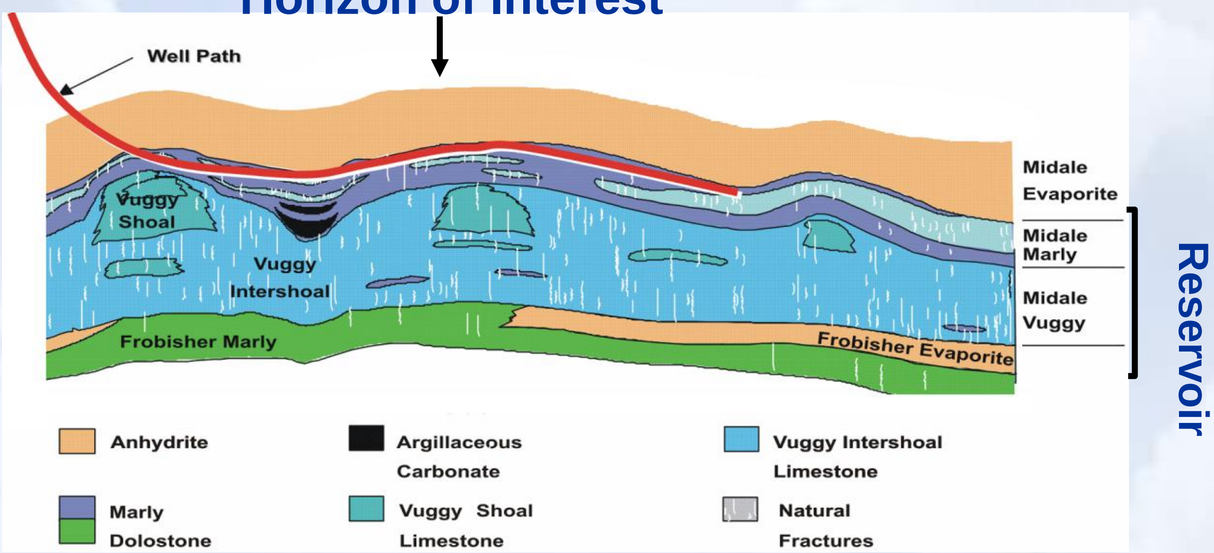
Possible sources:

- **Horizontal stress field**
- **Mineral fabrics**
- **Faults, fractures or micro cracks**

HTI anisotropy (aligned vertical fracture set) →

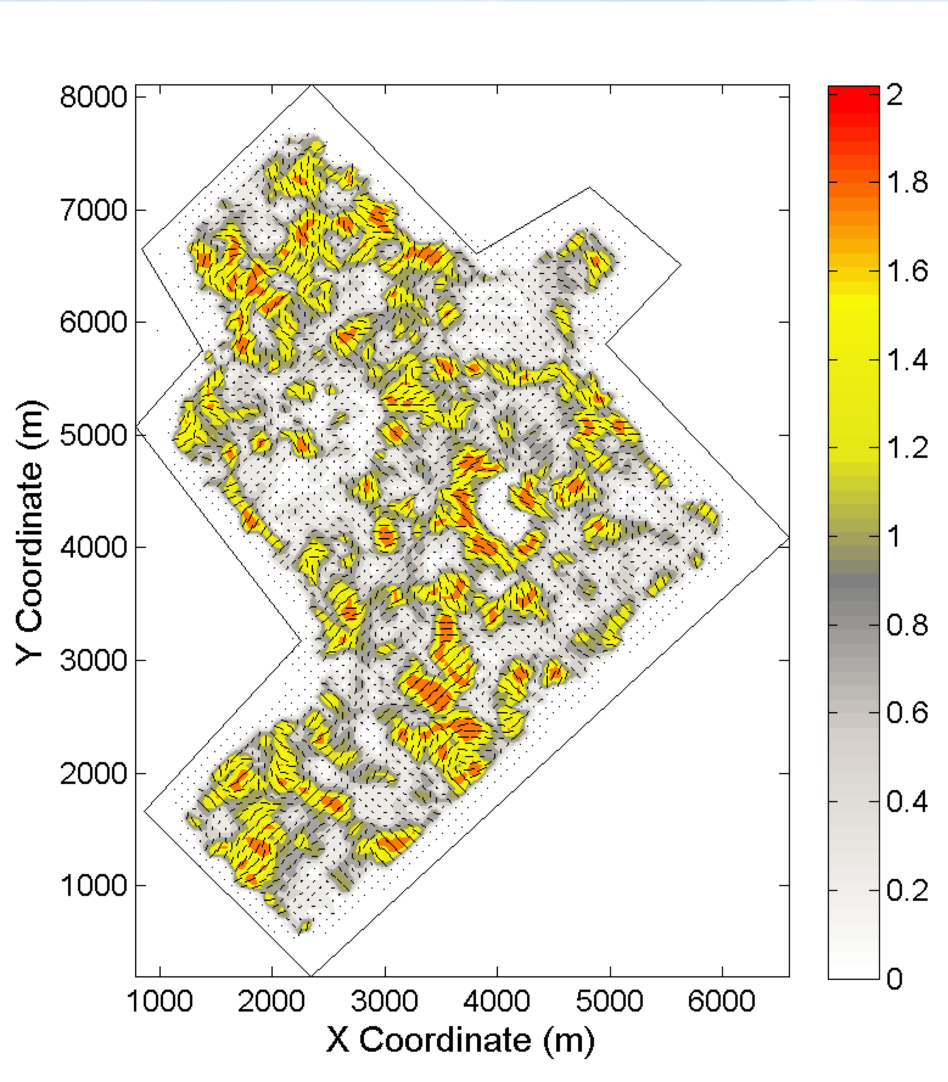


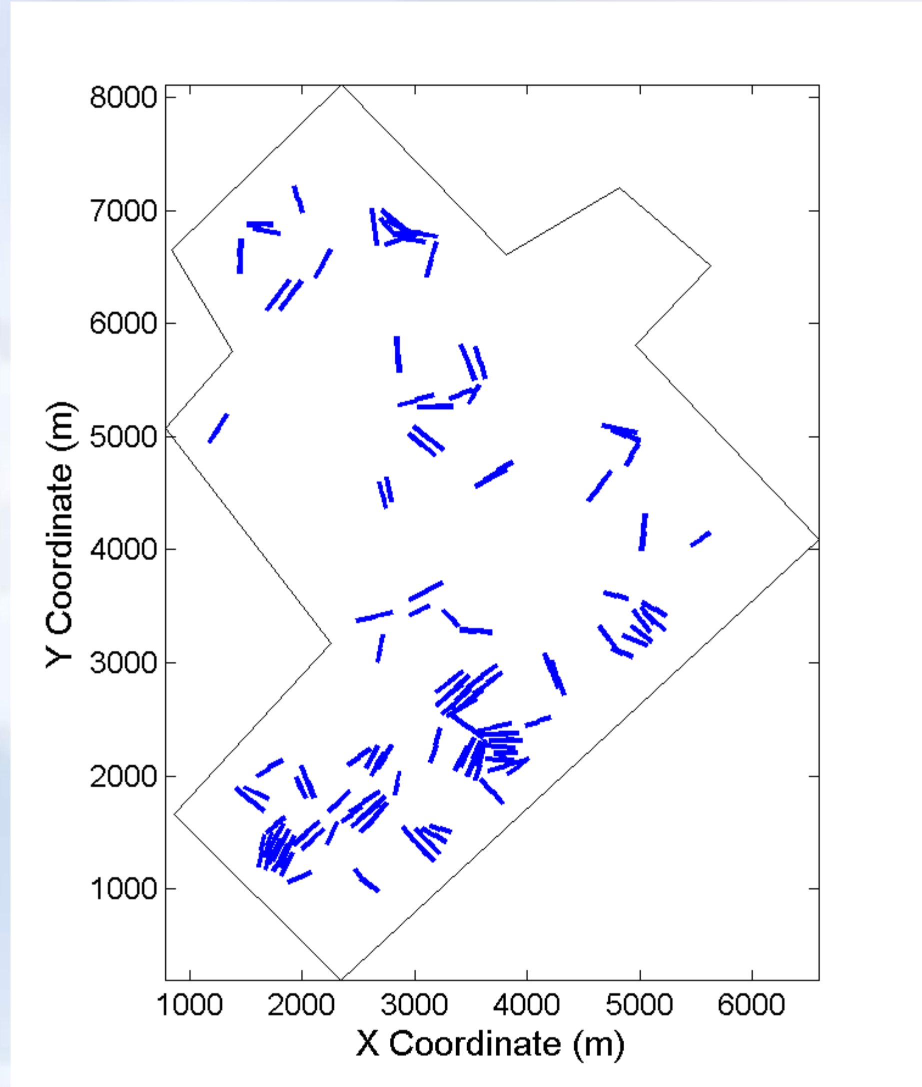
Horizon of Interest



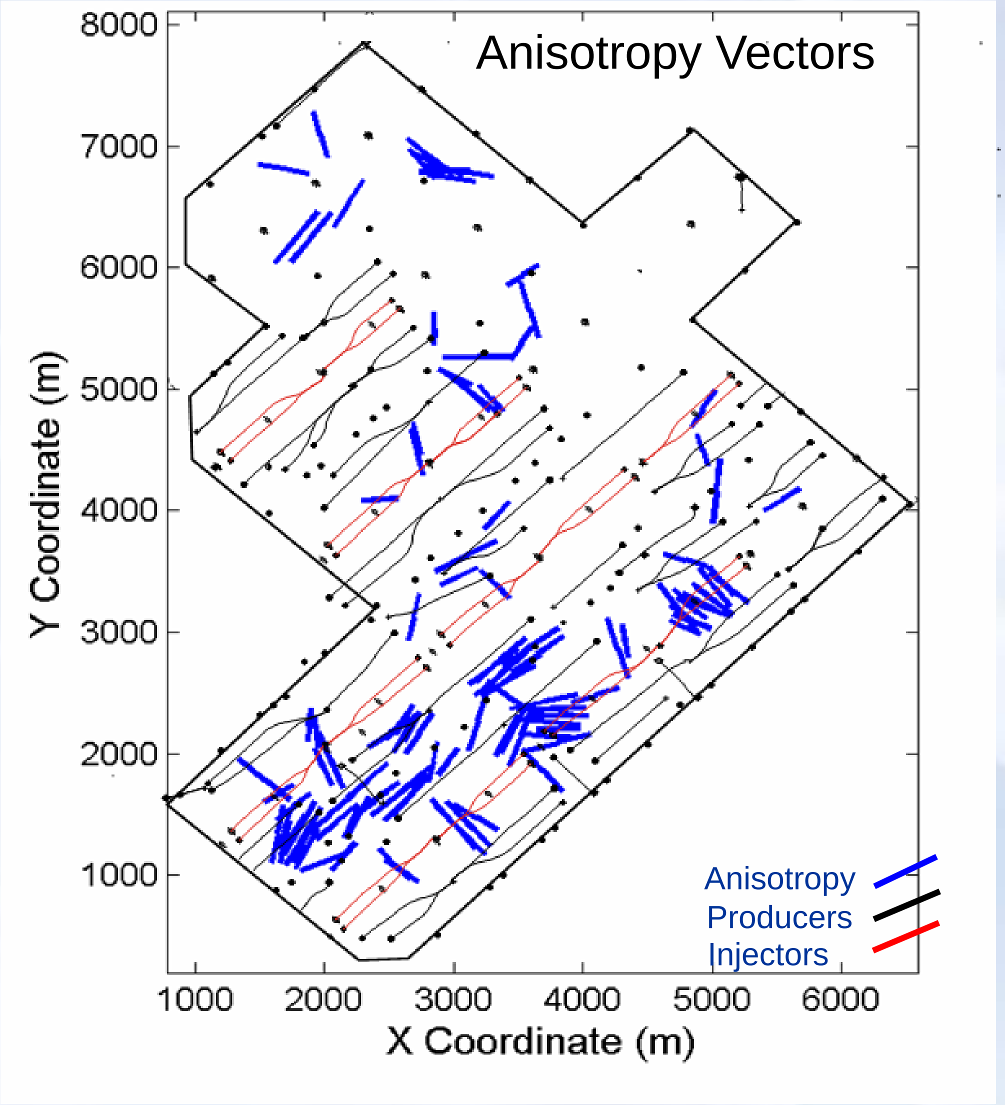
A. Duxbury

Caprock Integrity - Seismic Anisotropy

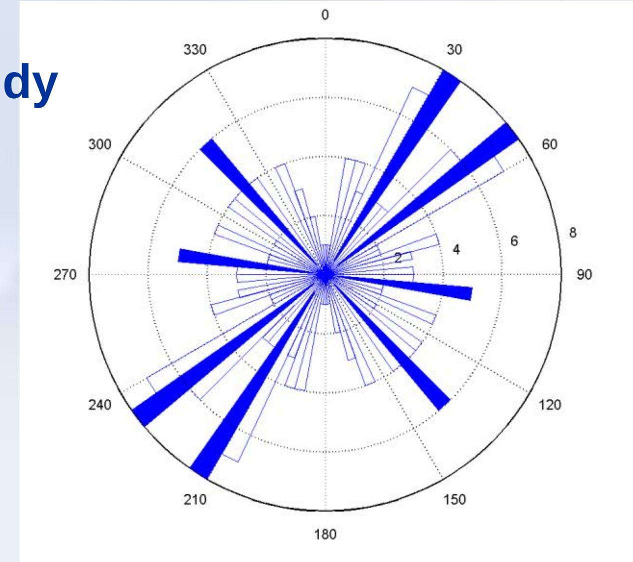




AVOA Results: Correlation With Other Studies

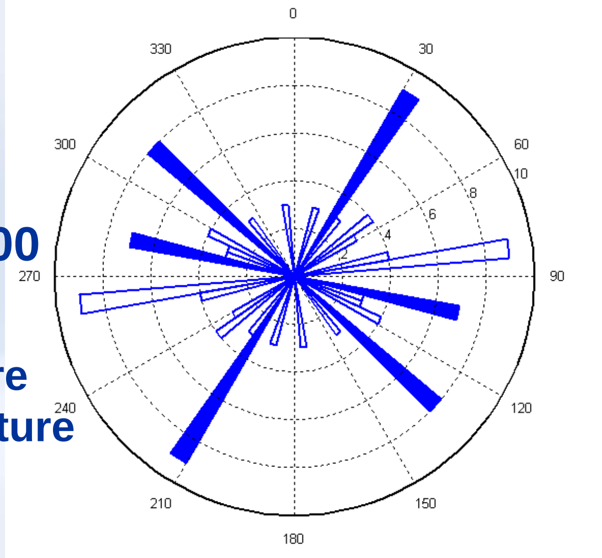


This Study



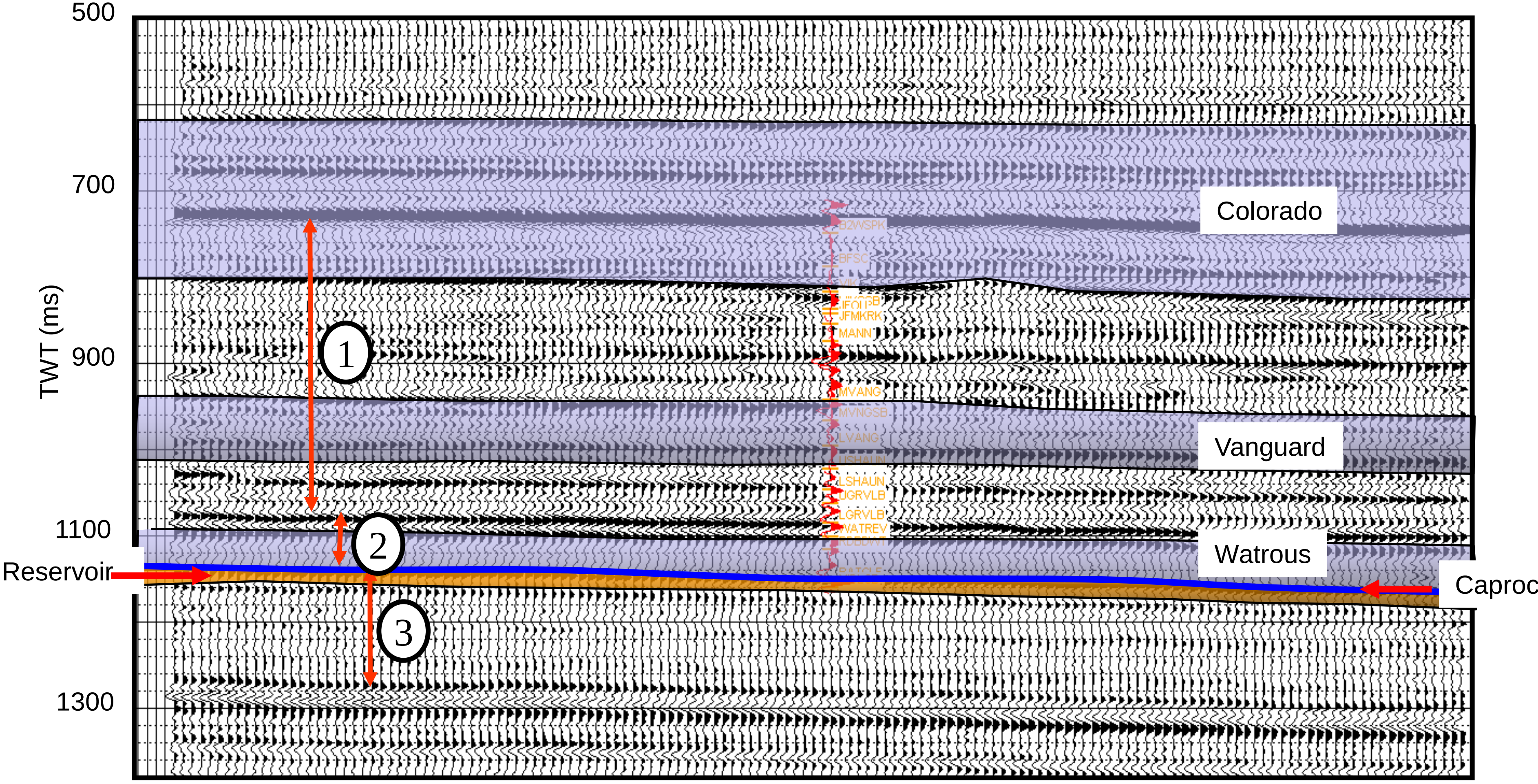
Bunge, 2000

Reservoir oriented core sample fracture analysis

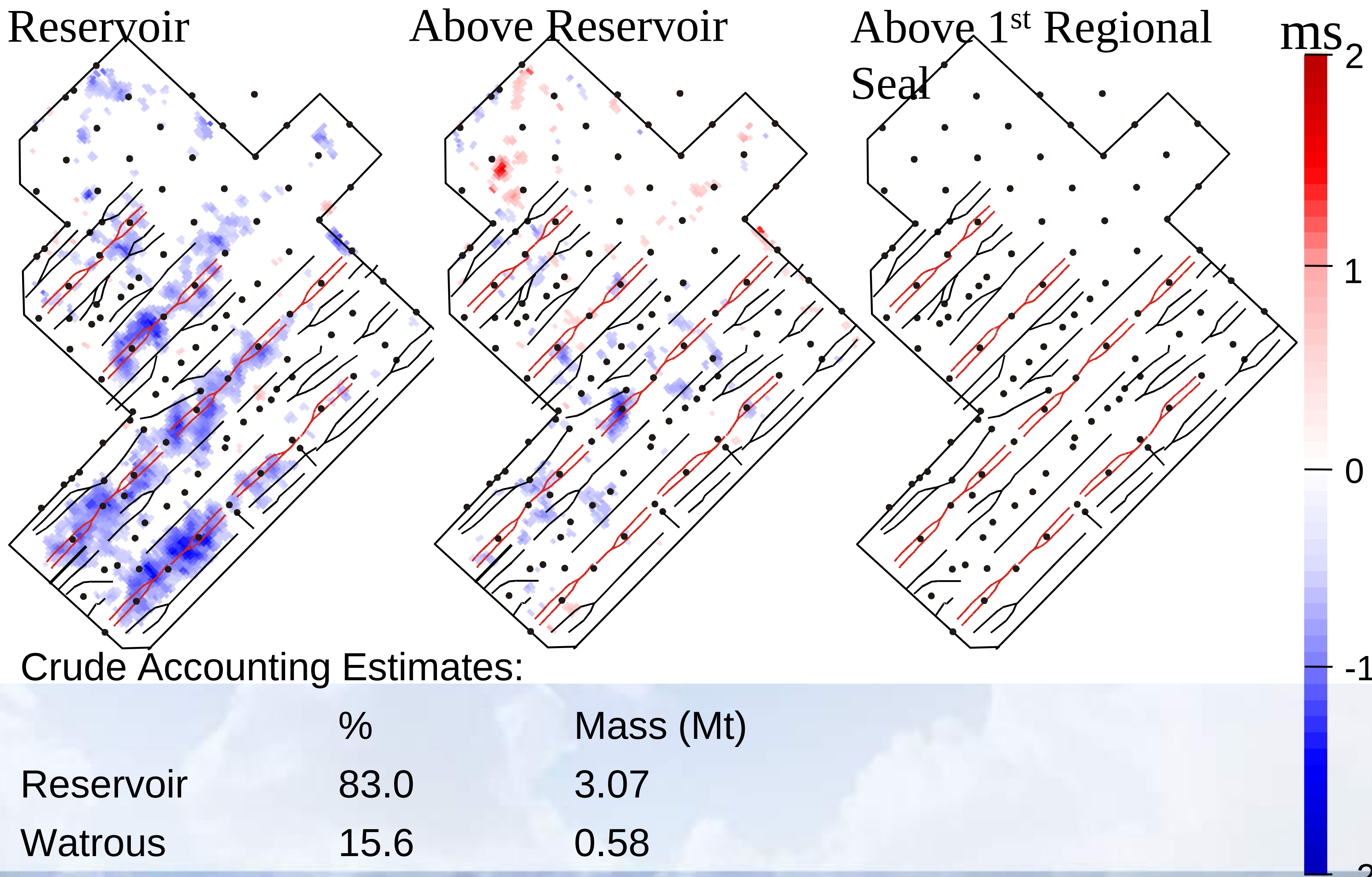


Overburden Monitoring: CO_2 Inventory Estimates

Regional Seals



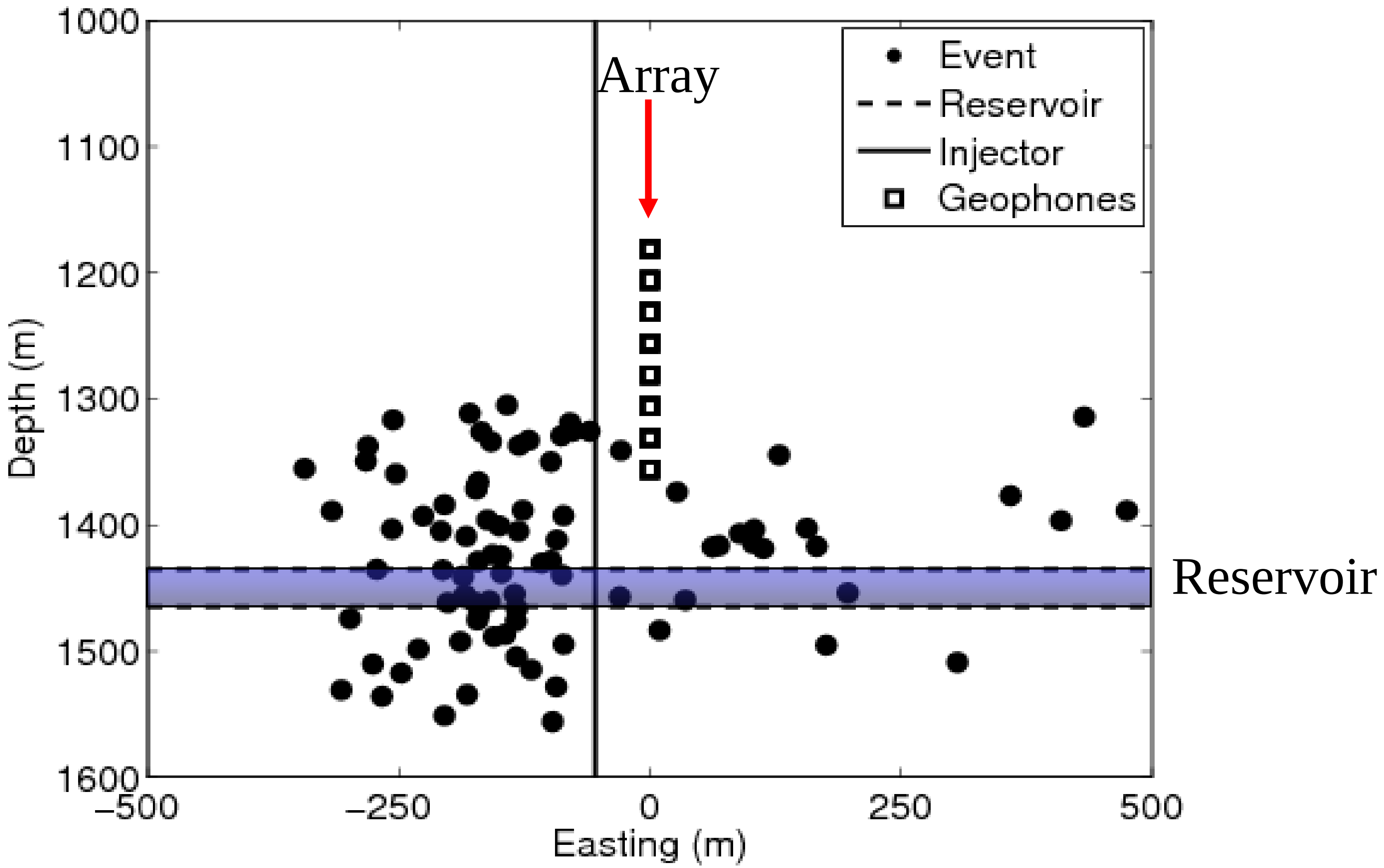
2004-2000 Interval travel time differences



Crude Accounting Estimates:

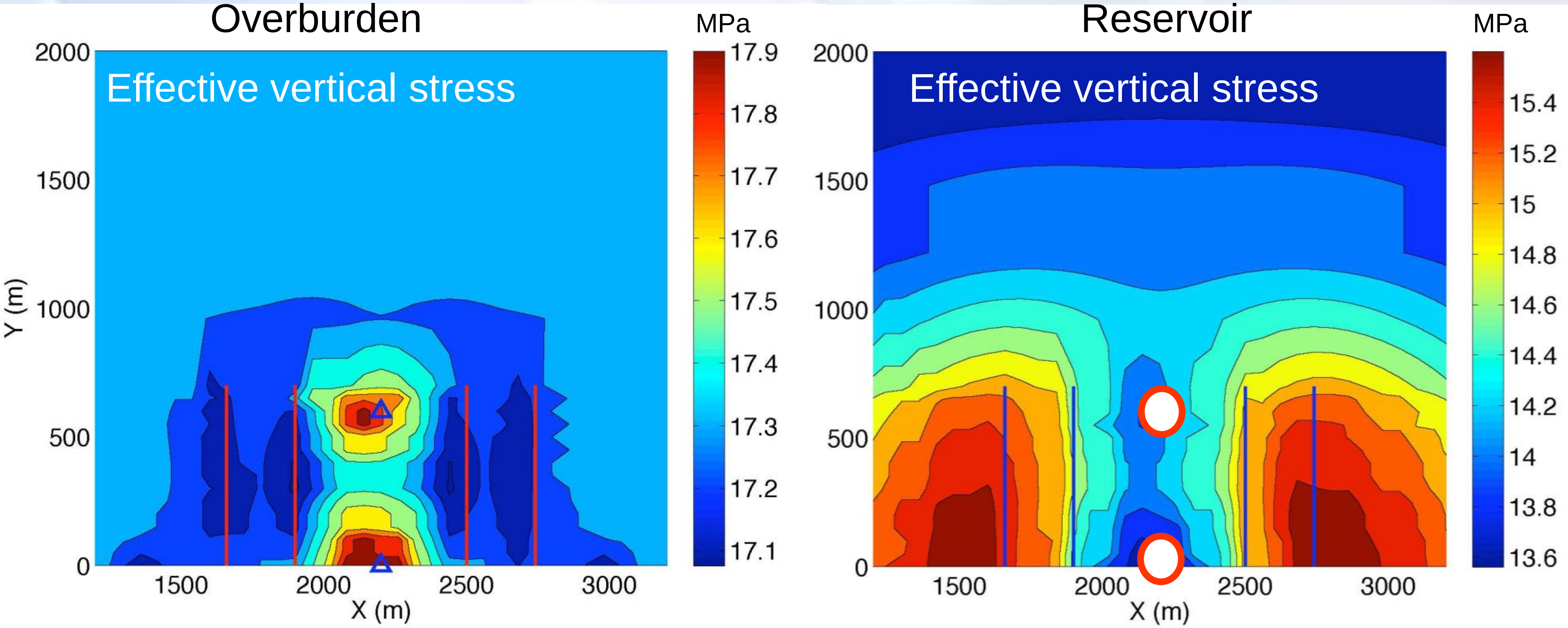
	%	Mass (Mt)
Reservoir	83.0	3.07
Watrous	15.6	0.58
Above Watrous	1.4	0.05

Microseismicity



Stress Distribution: Vertical Injectors

Small moment magnitudes (-3 to -1)
Low rate of seismicity: aseismical deformation
Modelling to assess significance of observation
Events likely due to stress transfer



Overburden: $\sigma_{V\text{-}EFF}$ ↑, Vp ↑

Verdon et al. 2010

Summary

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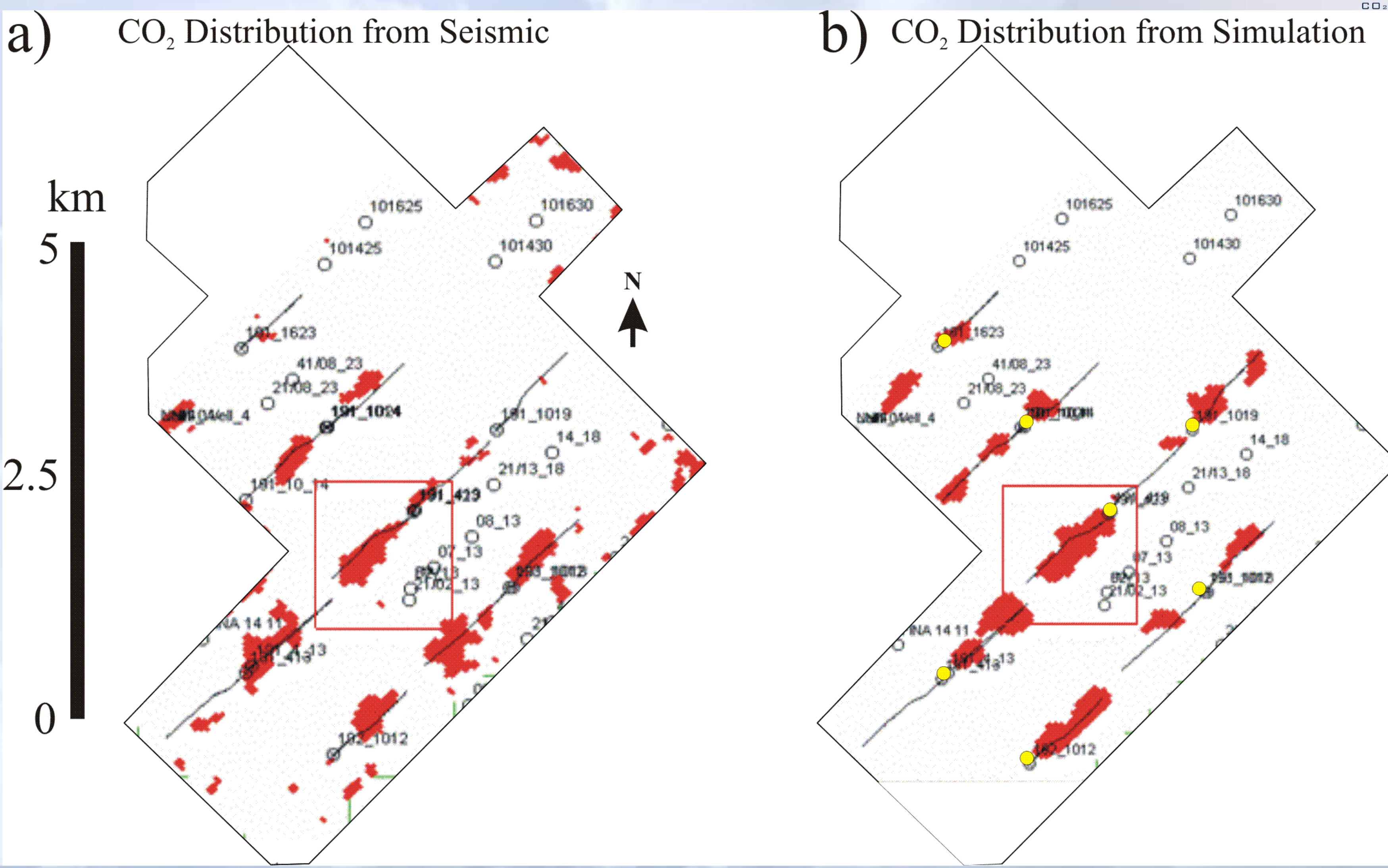
CO_2 MONITORING
AND STORAGE PROJECT

- **<u>Reservoir Monitoring</u>**
  - P vs. CO_2 discrimination: ΔP_{pore} up to 7-8 MPa, S_{CO_2} up to 60%.
  - Predictive model verification: stochastic algorithm tested.
- **<u>Caprock Integrity</u>**
  - Isolated anisotropic regions.
  - May be associated with vertical fracturing; however, seismic alone can't discriminate.
- **<u>Overburden Monitoring</u>**
  - No significant travel time changes observed above the regional seal; 0-1% of injected CO_2 based on seismic.
  - Small travel time (& amplitude) changes are observed just above the reservoir caprock (~1380 m) at the base of the storage complex. Likely associated with OOZ CO_2.
  - OOZ CO_2 is likely the direct result of EOR injection operations rather than upward migration of CO_2 from the reservoir.
  - Microseisms observed within the immediate overburden, are likely due to stress-arching effects in the overburden.

Seismic constrained simulation/history matching

Trial-and-error history matching

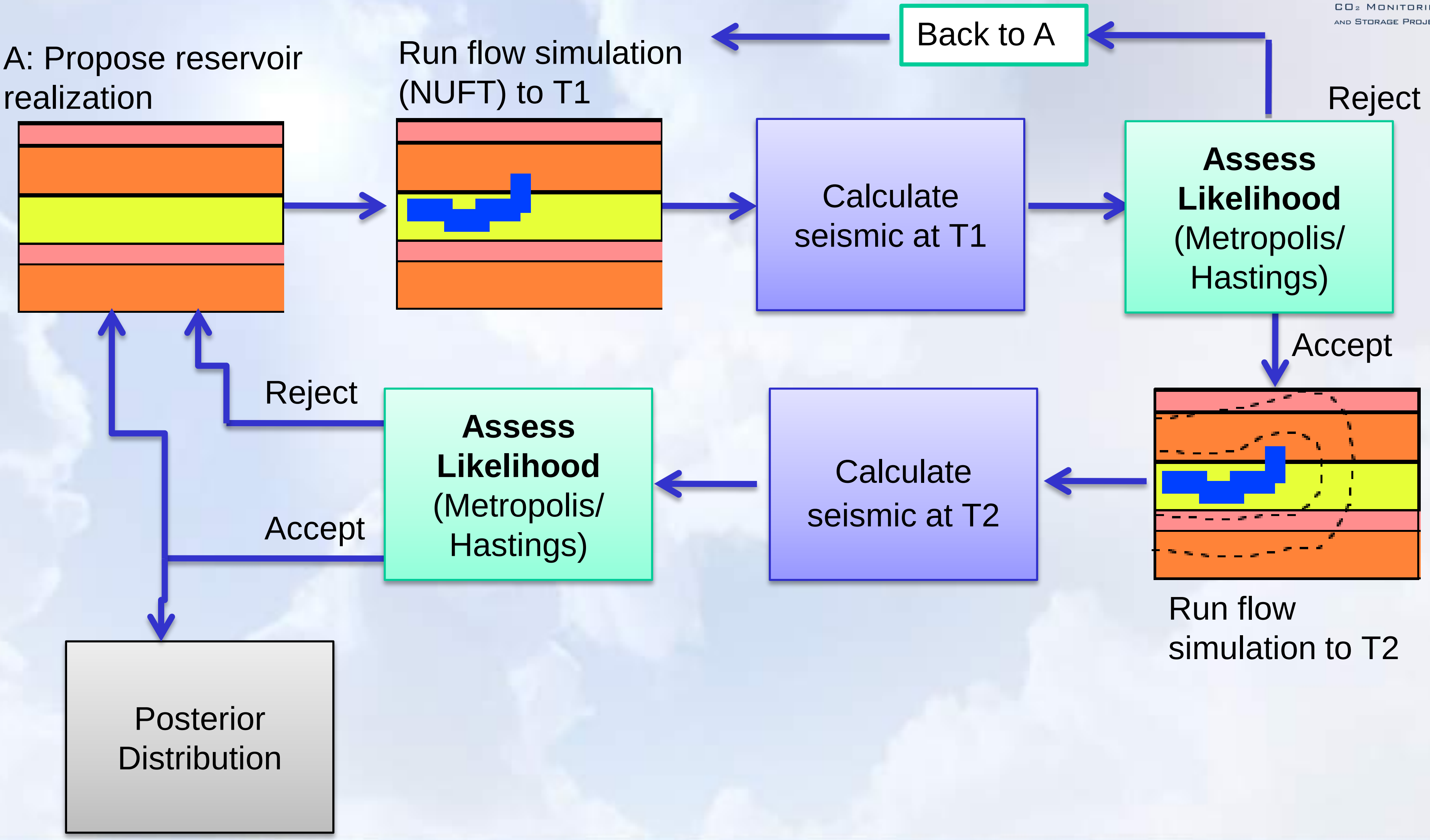


Recommendations: Seismic constrained simulation/history matching

- Primary means of integrating monitoring observations with geological model.
- Trial-and-error forward modelling provide time-tested methodology, but is labour intensive.
- Stochastic inversion (or other comparable methods) in principle provide an objective way forward, but are developmental.

Approach is based on the Monte Carlo Markov Chain (MCMC) method (Mosegaard and Tarantola, 1995)

IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project



Seismic Inversion Test (Single Injection Pattern)

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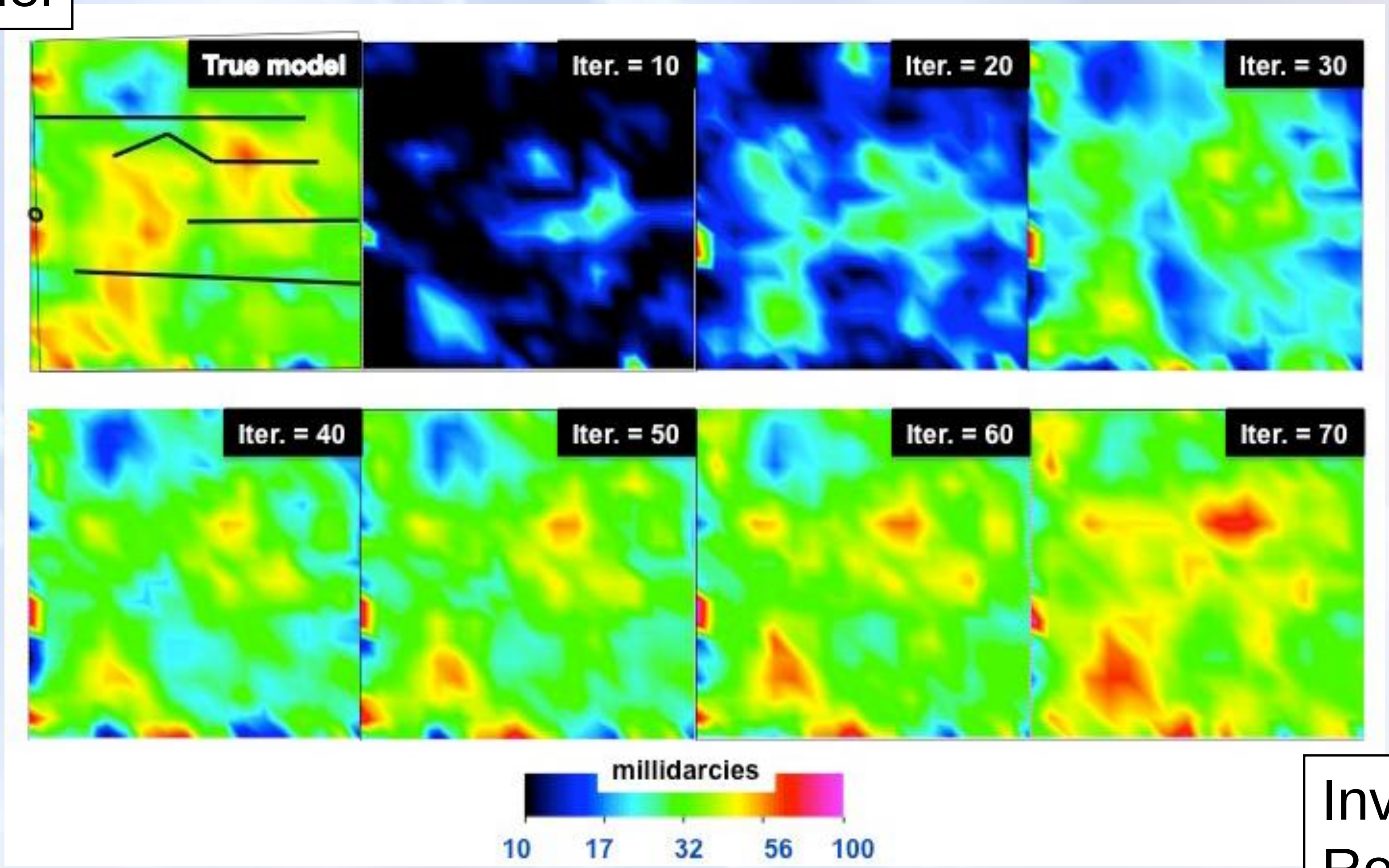
True Model



Inversion Result

Improved site characterization & storage prediction through stochastic inversion of t-lapse geophys & geochem data

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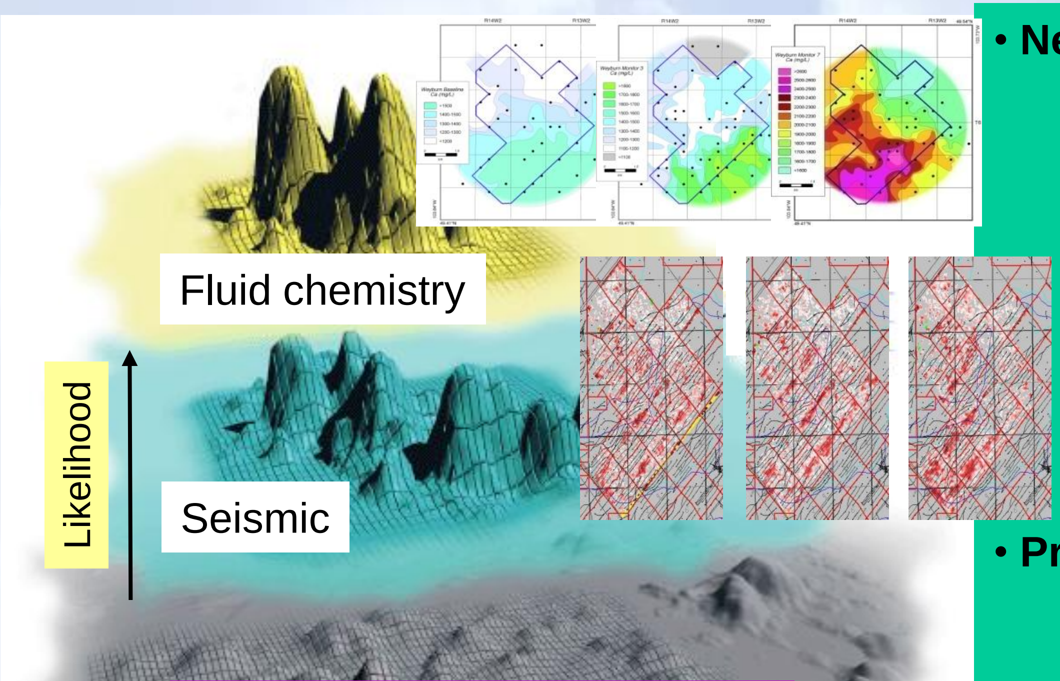
CO_2 MONITORING
AND STORAGE PROJECT

Research Provider: Abe Ramirez et al. (LLNL)



- Inaugural attempt to integrate seismic & fluid chemistry data
- Fundamental elements of storage monitoring programs
- Thus, proposed methodology is new & broadly applicable

- **New data**
  - Seismic: images CO_2 migration paths
    - Controlled by perm distribution
    - Defines spatial framework of phys/chem trapping mechanisms
  - Fluid chem: documents compositional evolution within this framework
    - Controlled by CO_2-aq-min rxns
    - Define mass partitioning among phys/chem trapping mechanisms
- **Prior data**
  - CO_2/H_2O injection; HC/H_2O production
- **Models embedded w/in MCMC algorithm**
  - Extended reactive transport model
  - Lithologic transitional probability model

- **Fundamental goal**
  - Optimize agreement between observed & predicted storage perf per refined
  - Permeability distributions
  - Mineral volume fraction & kinetic data

Overview: Inverting Geochemical Parameters

- Objectives
  - Quantify rates of key dissolution/precipitation reactions
  - Assess heterogeneities in distributions of reactive mineral phases/rates
- Challenges
  - Limited spatial resolution of brine compositional data
  - Extensive influence of injected water
  - Excessive computational burden
- Approach
  - Construct realistic synthetic problem to understand key constraints on water-rock reactions and effects of heterogeneity
  - Apply the inversion algorithm to a small-scale test problem (e.g., Pattern 16)
  - Apply the inversion algorithm across the larger scale

Dissolution / precipitation modeling of various Minerals

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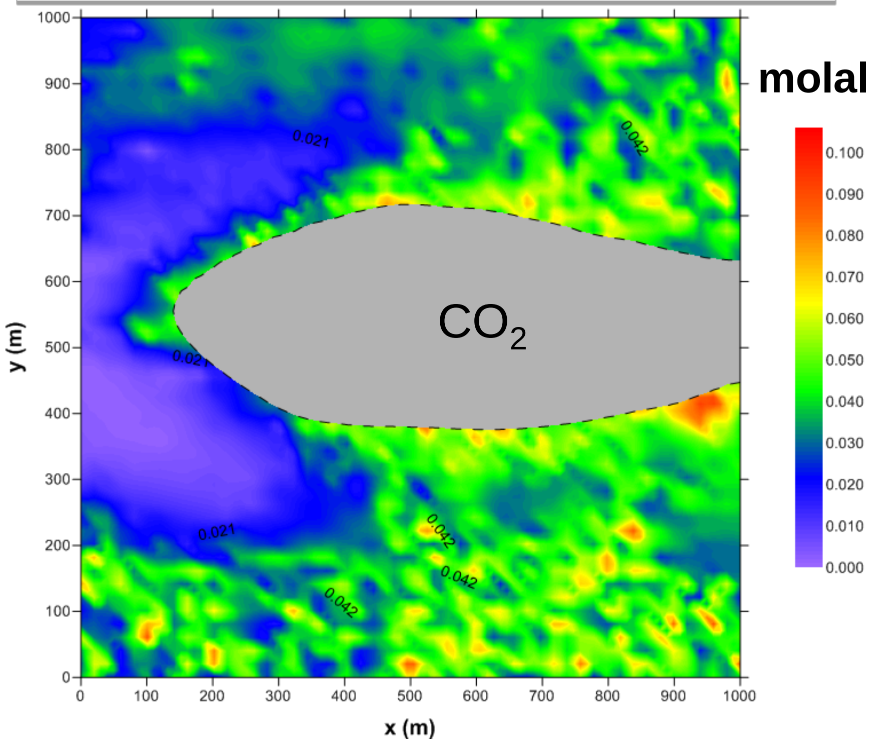
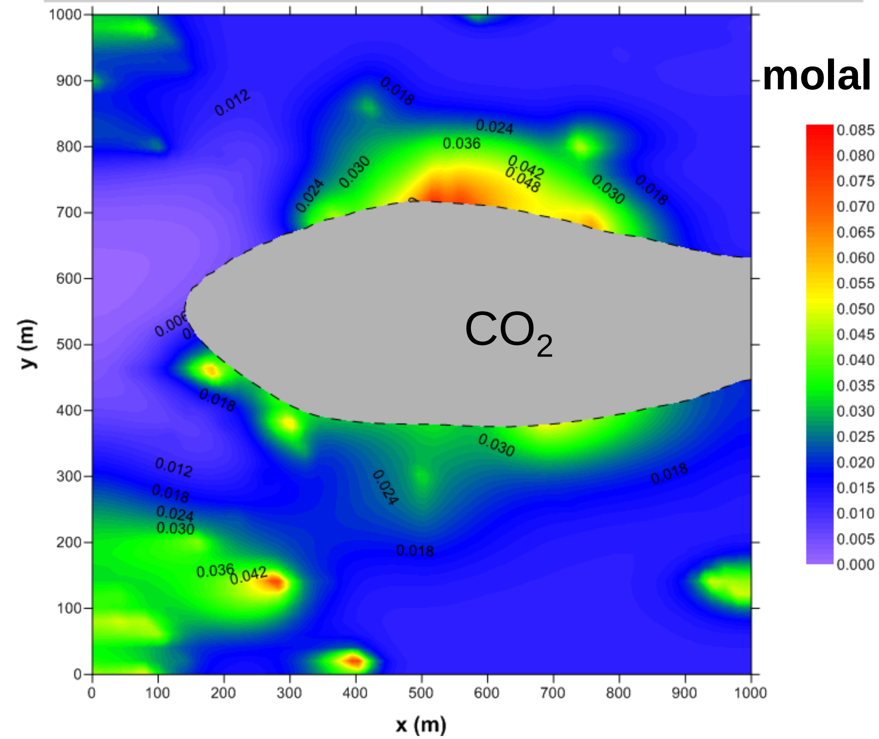
and Storage Project

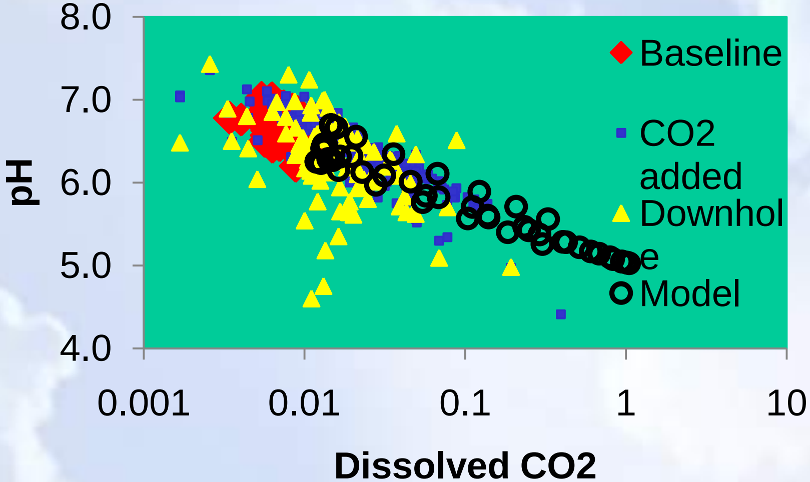
Ca^{2+}, 1,000-days of CO_2 Injection

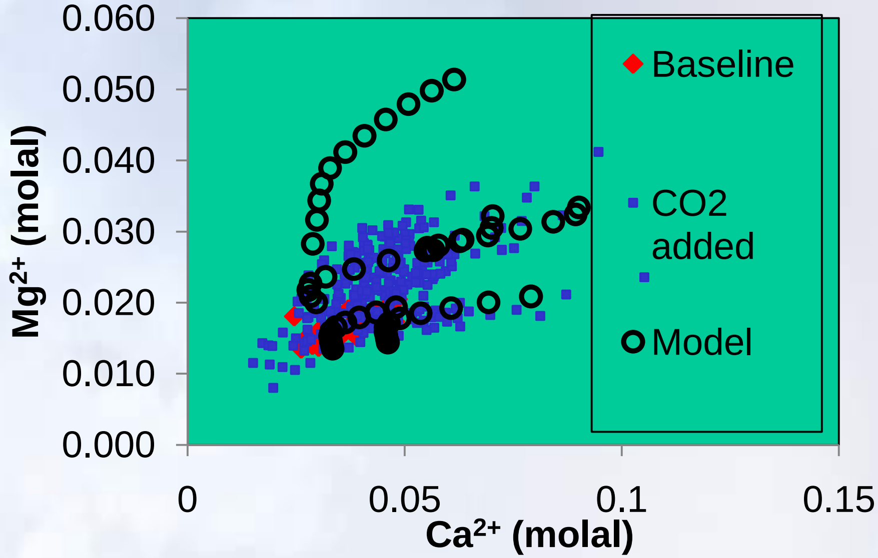


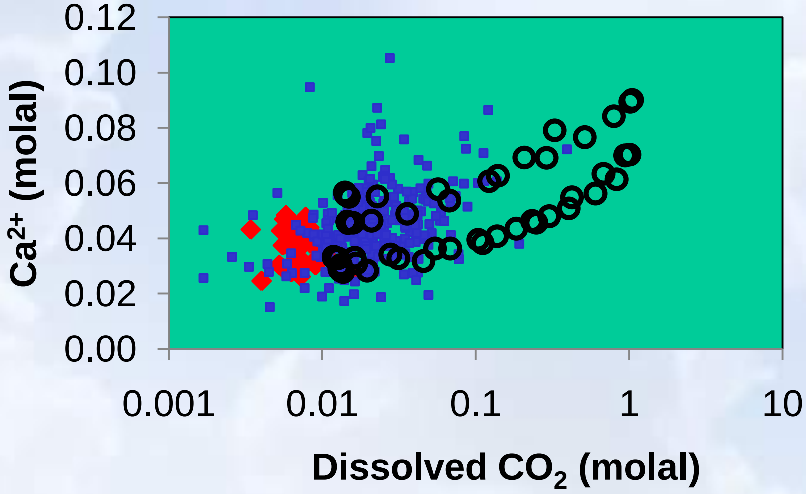
Mg^{2+}, 1,000-days of CO_2 Injection

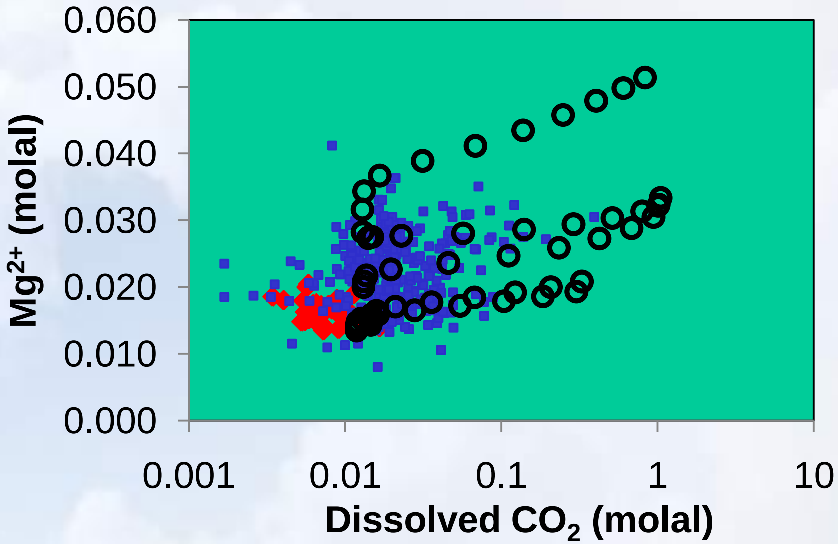


Geochemical indicator modeling



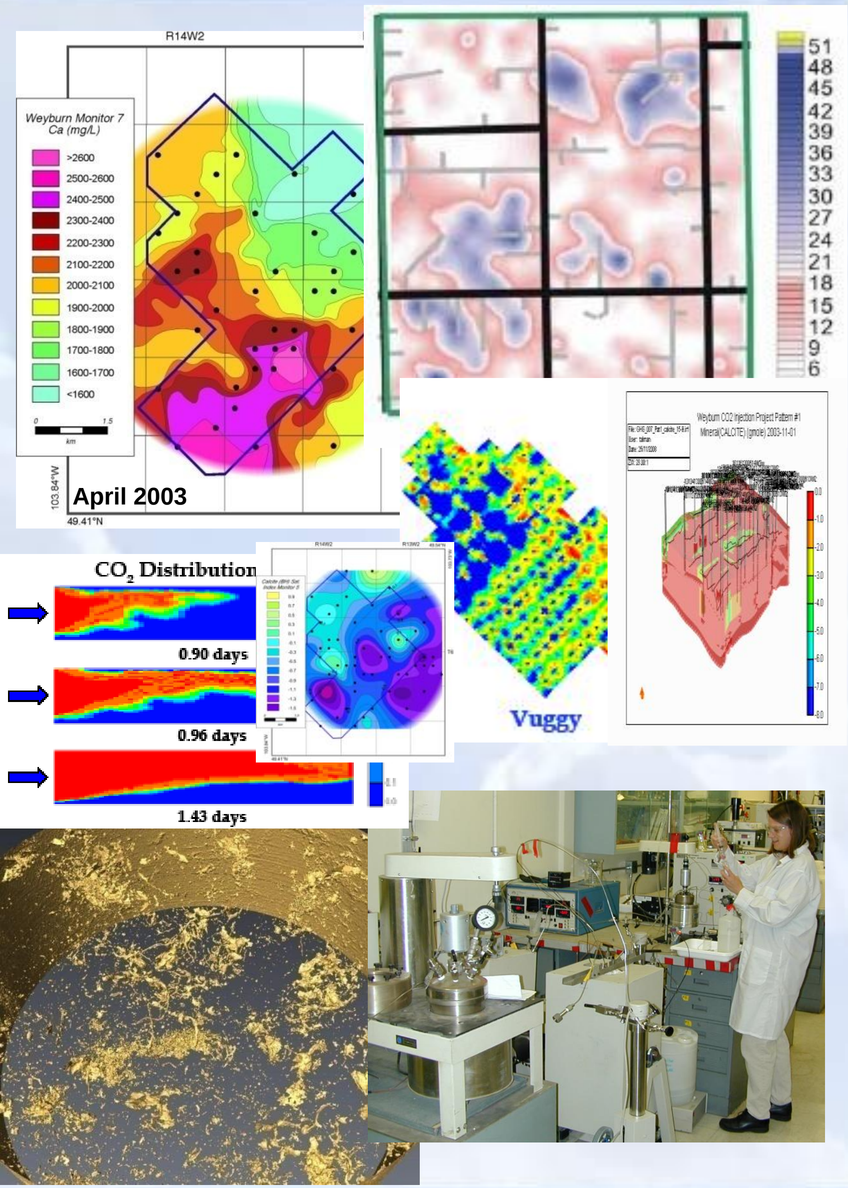






Trends in geochemical indicators are reproduced by heterogeneous reactive mineral model: pH, Ca, Mg

Geochemical Monitoring: Overview



Storage Monitoring

Reservoir fluids (brines, gases)

Reservoir fluids (hydrocarbons)

Shallow groundwater

Soil gas

Storage Prediction

Reactive transport modeling (AITF)

Reactive transport modeling (SLB)

Hydrocarbon EOS

Process/Property Studies

CO_2-brine-rock interactions

Pore-scale matrix analysis

Fracture transport

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Reservoir fluid sampling (brines, gases)

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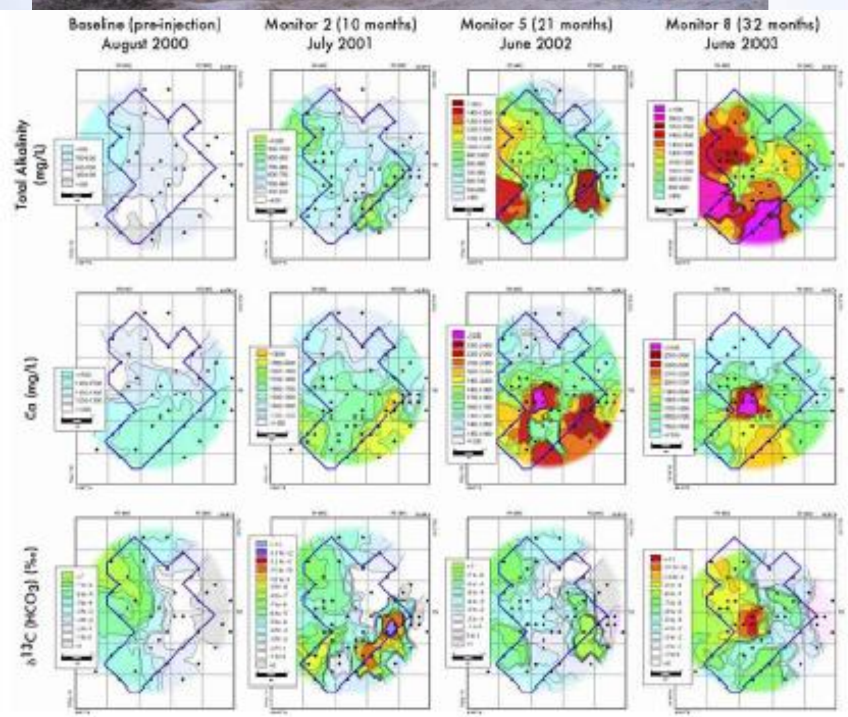
CO_2 Monitoring
and Storage Project



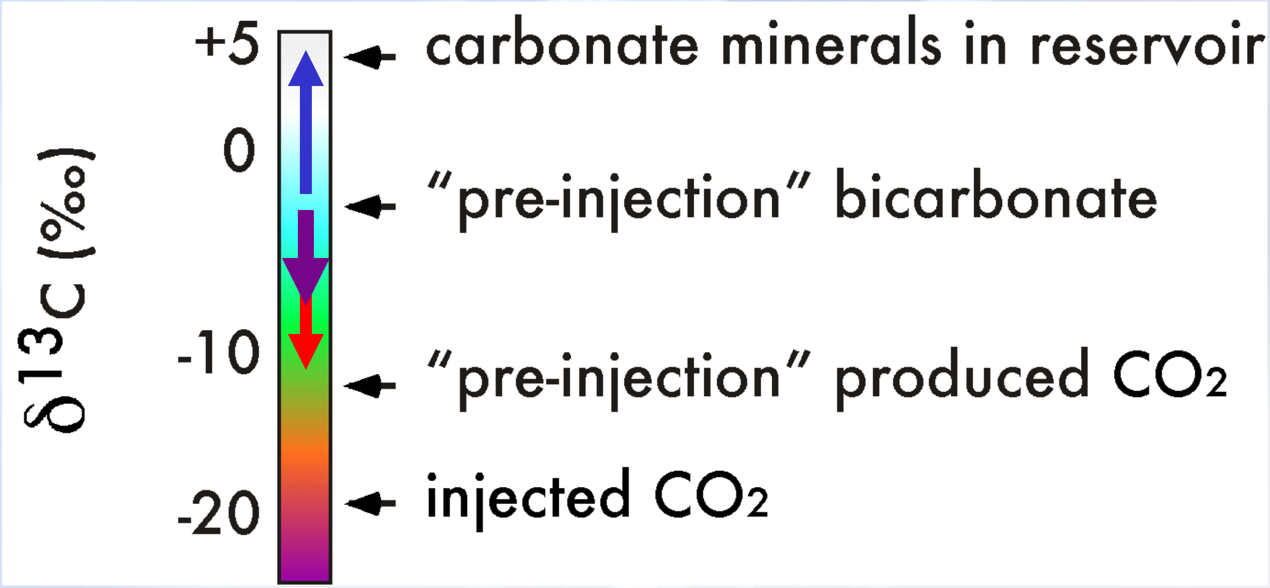
Research Provider

- ✓ Bernhard Mayer, Maurice Shevalier, et al. (Applied Geochemistry Group, Univ. Calgary)

Project scope

- ✓ Continue Phase-1 monitoring of CO_2-fluid-rock reactions & the intra-reservoir fate of injected CO_2 by periodic fluid sampling of 40-60 production wells within & nearby the Phase 1A/1B area
- ✓ During Phase 1, a baseline (Aug 2001) & 11 syn-injection monitoring trips (3/year, M1-M11, Mar 2001 – Sep 2004) were completed
- ✓ During Final Phase, 5 monitoring trips (2/year, M12-M16: Oct 2008 – Oct 2010) address the same well suite sampled during M11 (Sep 2004); data continuity
- ✓ 40+ geochemical & isotopic parameters measured; comprehensive database: ~30k entries to date
- ✓ Unique, invaluable history-matching resource for reactive transport modeling programs

CO_2-brine-rock reactions: isotopic evolution

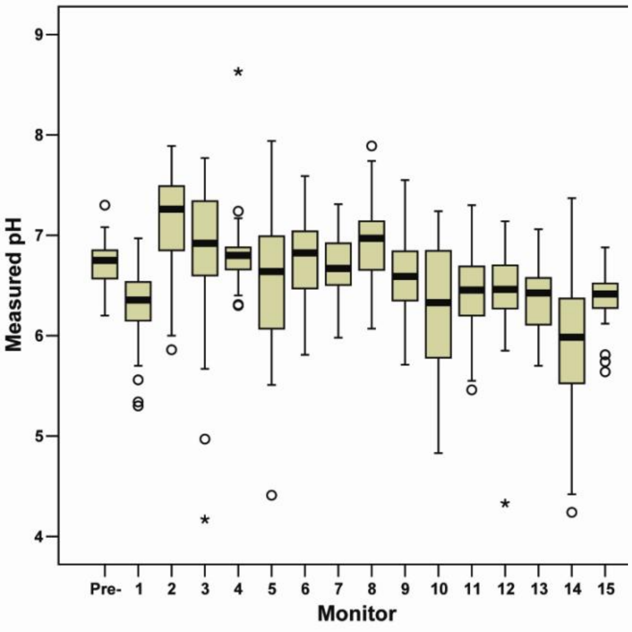


- CO_2 dissolution increases TDC, lowering produced $\delta^{13}C_{HCO3}$.
- dissolution of carbonate minerals increases HCO_3^- & produced $\delta^{13}C_{HCO3}$
- both reactions take place, but net result is lowering of $\delta^{13}C_{HCO3}$-

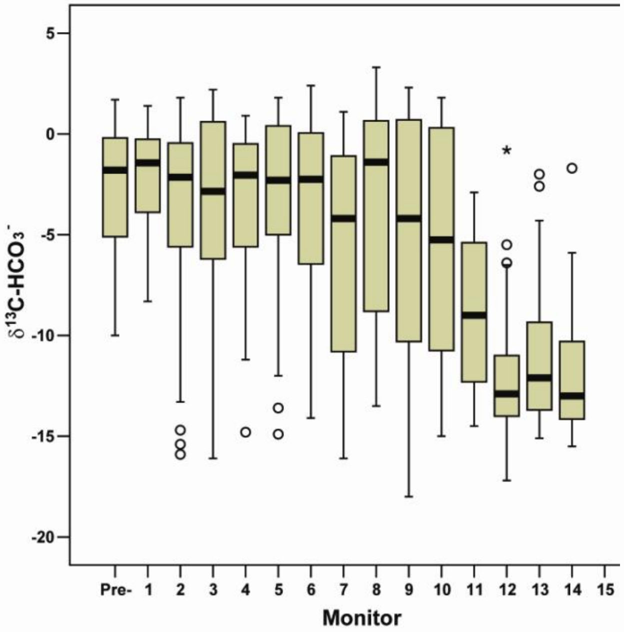
$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^-$	One $\delta^{13}C$-HCO_3^- ratio
$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$	Second $\delta^{13}C$-HCO_3^- ratio
$CO_2 + H_2O + CaCO_3 = Ca^{2+} + 2HCO_3^-$	Mixed $\delta^{13}C$-HCO_3^- ratio

Evolution of field-average pH, Alkalinity, δ13C

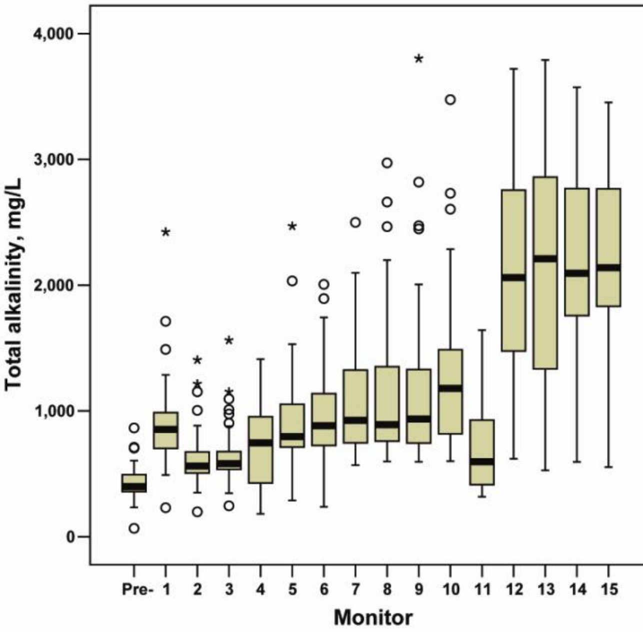
pH



δ13C

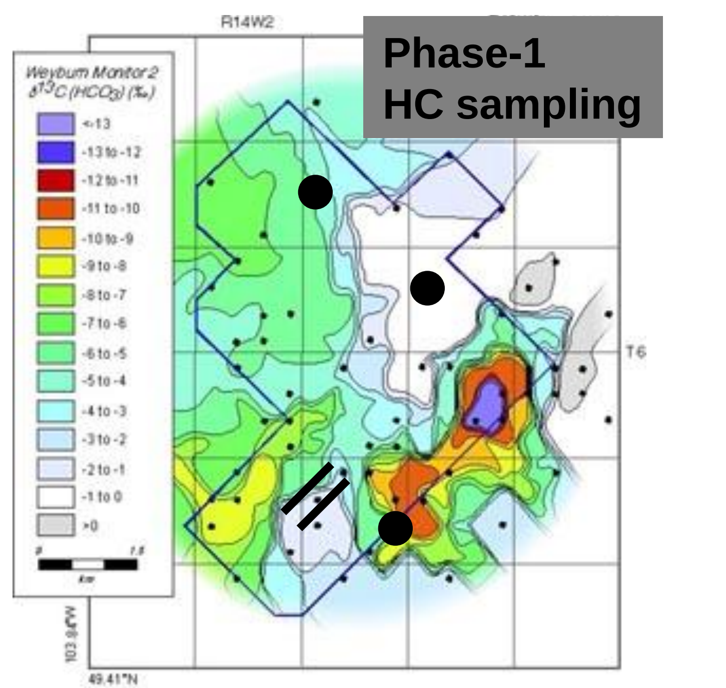


Alkalinity



- Evidence of solubility trapping: decrease in pH & $\delta^{13}C\text{-}HCO_3^-$
- Evidence of calcite & dolomite dissolution: significant increase in Ca & Mg concentrations

Reservoir fluids (hydrocarbons)



Research Provider

- ✓ Mars Luo et al. (SRC)

Project scope

- ✓ Continue Phase-1 effort:
  - ❖ Sample & analyze hydrocarbons from selected production wells (Phase 1A/1B)
  - ❖ Develop Weyburn-tuned HC EOS
  - ❖ Determine MMP

- Collect & mix separator oil & gas samples at GOR; measure PVT properties of reconstituted live oil & live oil-CO_2 system at reservoir conditions

- ✓ Fit PVT data with phase behavior modeling code to further **tune 7-component PR-EOS formulation for incorporation into GEM & NUFT**
- ✓ Redetermine MMP (rising bubble apparatus)
- ✓ Updated HC EOS & MMP required to refine reactive transport modeling work
- ✓ Analytical data required for continuity of valuable history-matching resource

Shallow groundwater sampling

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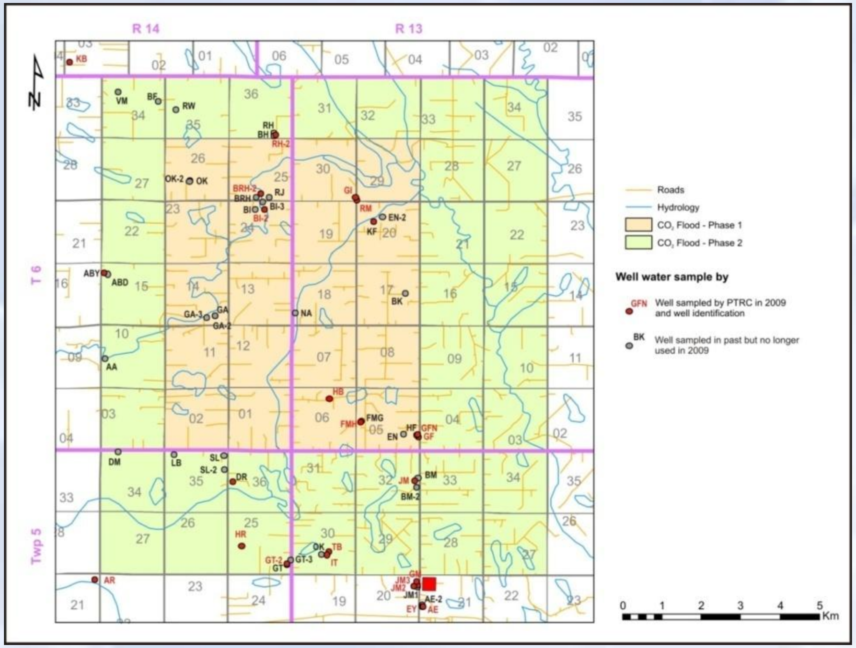

- 24 private (active) wells could be sampled in 2009
- Number of active wells has declined significantly over time
- Reasons for decline:
  - owners moving off site
  - Weyburn Utility Board pipeline

Research Provider

✓ Harm Maathuis et al. (consultant)

Project scope

✓ Continue Phase-I sampling/analysis program
✓ Re-visit domestic wells sampled previously; determine current status; sample active wells
✓ Compare water quality results of 2009 with those of previous surveys
✓ Make recommendations for future surveys
✓ Long-term continuous “clean” record is critical from public acceptance standpoint
✓ Sampling trip July-Aug 2009

Conclusions / Recommendations

Since 2000, little change in water quality; changes in major ions concentrations (nitrate) have been observed in shallow wells located near barns.

The percent of exceedance (Saskatchewan standard/objectives) of constituents in the Weyburn area is consistent with those observed elsewhere in Saskatchewan.

Determining if shallow groundwater is being affected by EOR will be difficult at best.
Lowering of pH and increase in the bicarbonate concentration expected. However, pH might be buffered. $\delta^{13}C$ of bicarbonate might be indicative but not available.

Recommendations:

• For long-term monitoring of the groundwater quality conducting surveys every three (3) or five (5) years will be sufficient

• To establish baseline data, any future sampling events should include the determination of the $\delta^{13}C$ values

• Since the number of private wells likely will decline further and monitoring may be conducted over decades, consideration should be given to constructing a network of monitoring wells strategically located throughout the Phase I and II areas.

Soil gas monitoring

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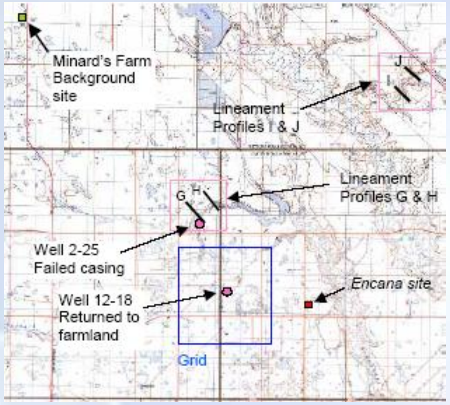
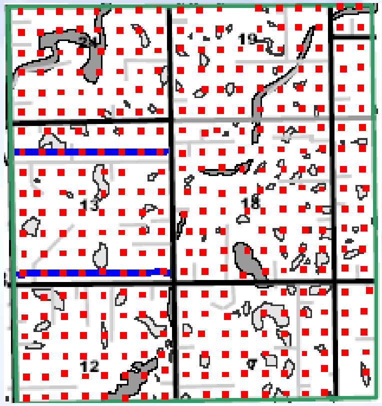
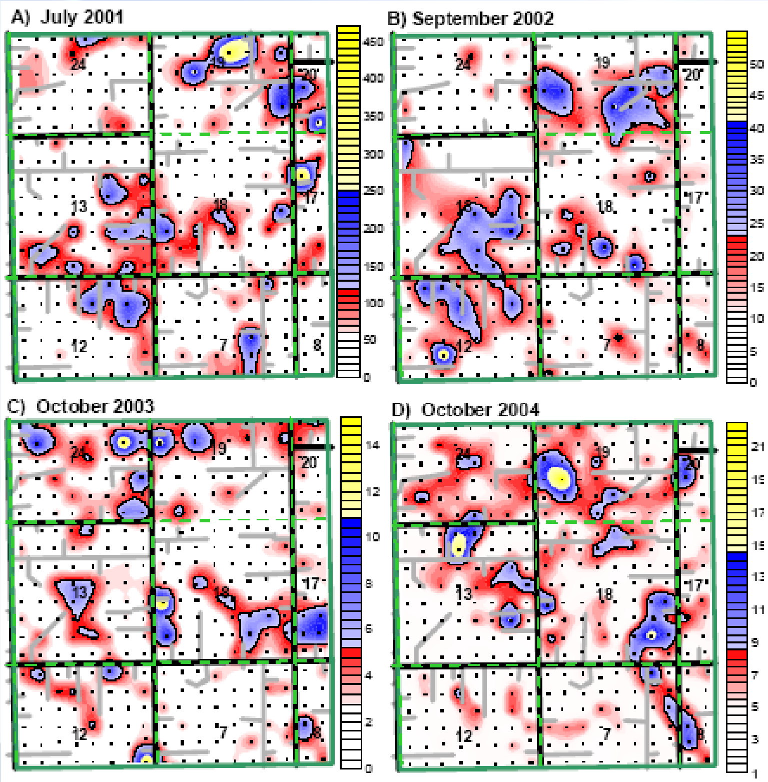






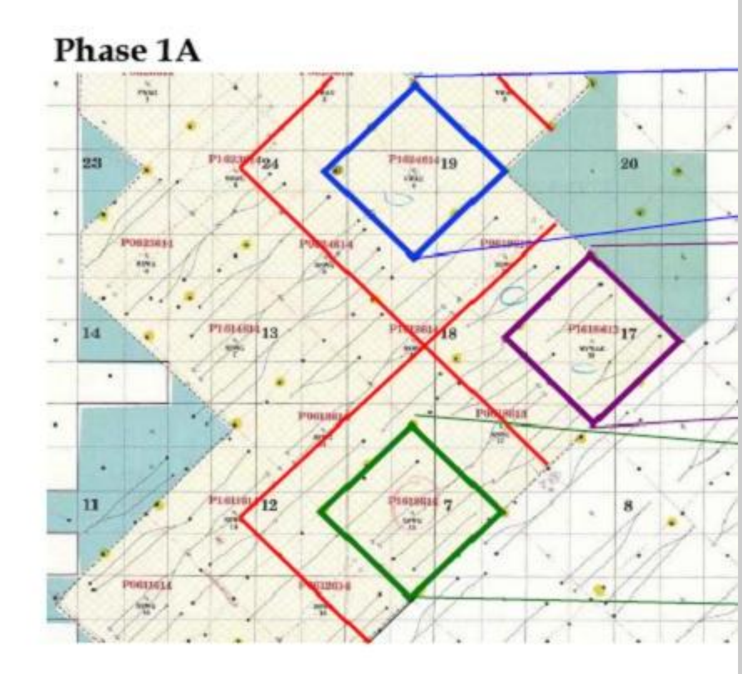
Research Provider

- ✓ David Jones et al. (BGS, SUR, BRGM)

Project scope

- ✓ Continue Phase-1 & interim Phase 1-2 effort (2001-2005) [background & Weyburn]
- ✓ Identify/extract background seasonal variations
- ✓ Source actual anomalies, if identified
- ✓ Long-term continuous “clean” record is critical from public acceptance standpoint
- ✓ Leverages CO_2ReMoVe funding, incorporates advanced techniques (e.g., continuous monitoring station), & potentially extends scope to include near-well locations
- ✓ Scheduled sampling trips Oct 2009 & Oct 2010

Reactive transport modeling: AITF, SLB, LLNL



Research providers:

- ✓ Stephen Talman, Ernie Perkins (AITF)
- ✓ James Johnson (SLB)
- ✓ Tom Wolery, Yue Hao, John Nitao (LLNL)

Project scope

- ✓ History match produced water compositions & observed isotopic evolution
- ✓ Predict reservoir/seal por/perm evolution & storage partitioning among distinct physical/chemical trapping mechanisms
- ✓ Augment NUFT to include a Weyburn-tuned Peng-Robinson EOS for hydrocarbons (Zhao et al., 2002; Freitag et al., 2004)

Accurate history matching requires

- ✓ Initial fluid-rock chemistry
- ✓ Injected water compositions
- ✓ Fractured reservoir model

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Expt'l/modeling study CO_2-brine-rock reactions

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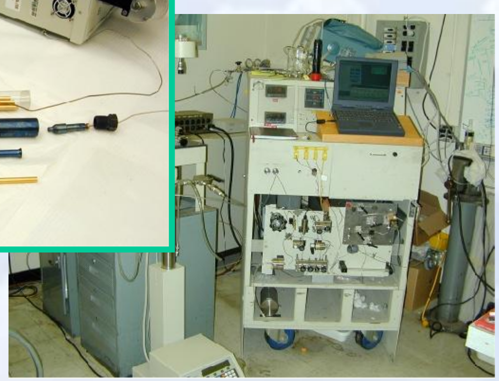
Research Provider

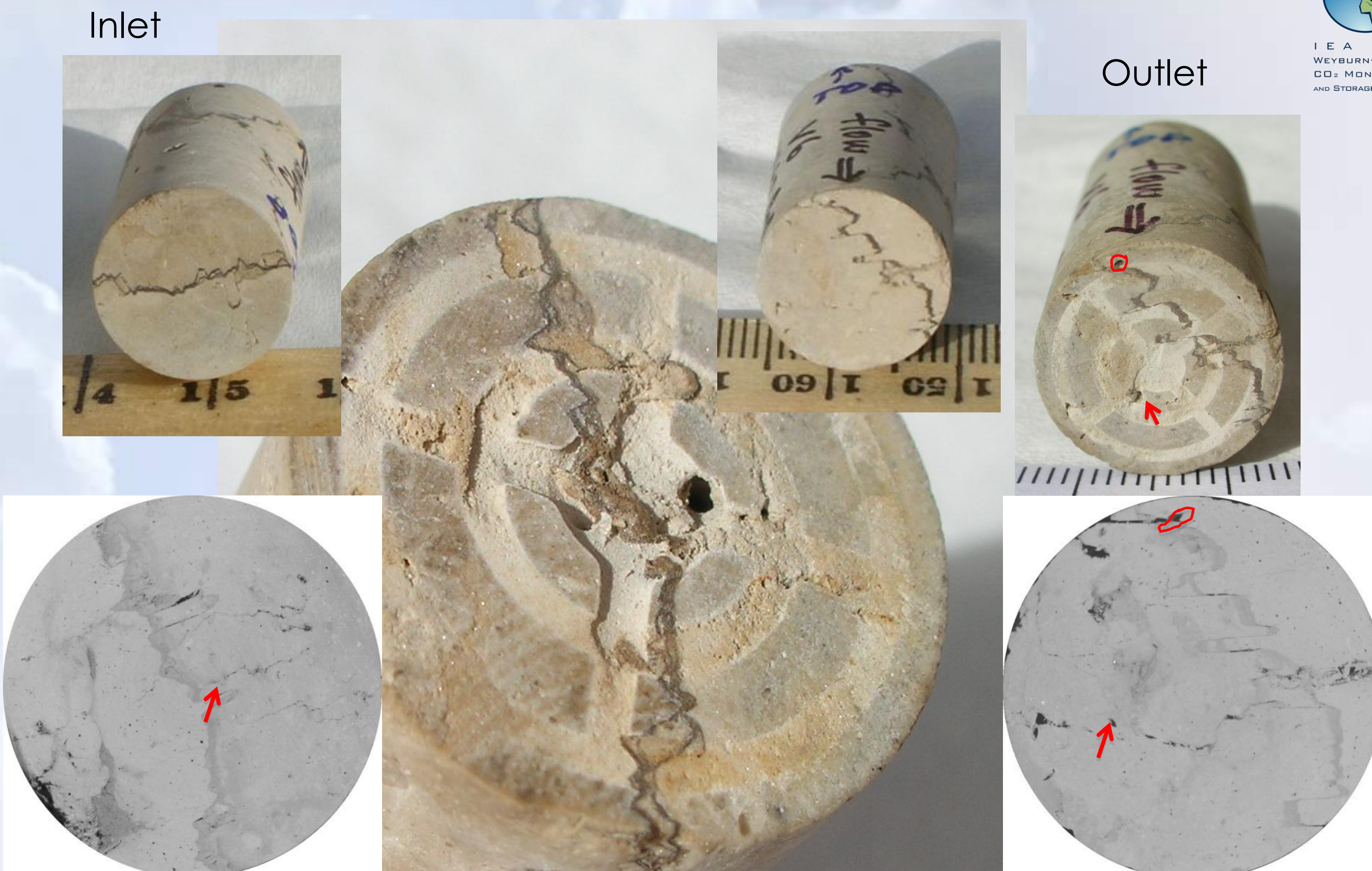
- ✓ Susan Carroll, Yelena Sholokhova, Megan Smith, and Yue Hao (LLNL)

Project scope

- ✓ Investigate the impact of injecting CO_2 on reservoir/cap-rock integrity using open (flowing) system experiments designed per lab-scale RTM (reactive transport modeling)
- ✓ Reservoir & cap-rock samples from Phase 1A/1B will be used; P-T will represent reservoir conditions
- ✓ This study will greatly improve our understanding of reservoir/cap-rock permeability evolution as a function of carbonate diss/pptn in the presence of CO_2
- ✓ It will also help calibrate & refine our reactive transport models



V6 pCO_2 = 3 MPa (1462.8 m)



Micron-scale reservoir matrix analysis

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Research Provider

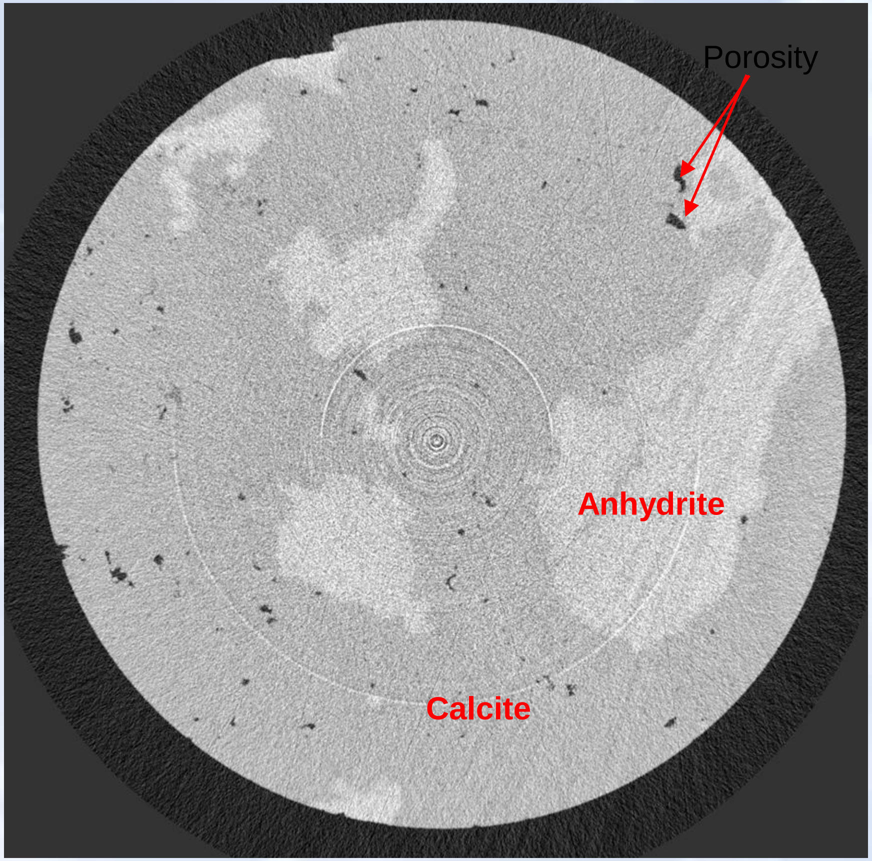
- ✓ Tom Kotzer, Chris Hawkes, Ted Mahoney, Michael Bird, and Samuel Butler (Univ. Sask.)

Project scope

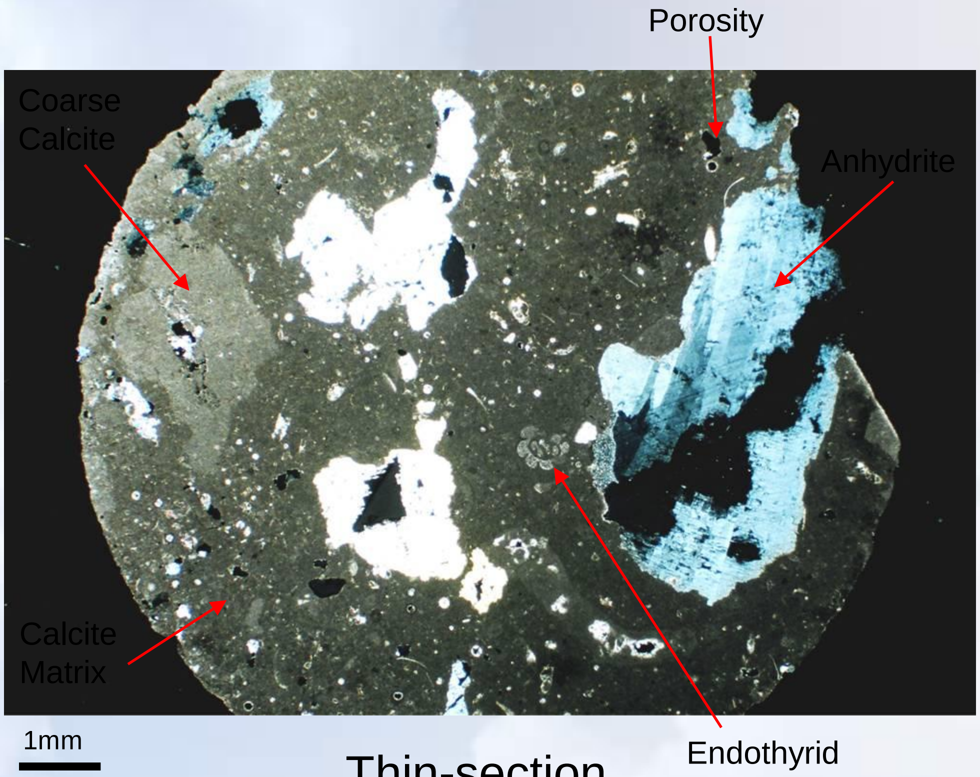
- ✓ Use micro-beam techniques (conventional & synchrotron) on pre- & post-CO_2 flood core from Weyburn to examine the micron-scale 3D pore-space network & distribution of pore-lining minerals
- ✓ Focus is on identifying incipient mineral & petrophysical alteration effects associated with CO_2 injection
- ✓ Core samples subjected to CO_2 at reservoir P-T in the laboratory (Carroll, et al.) will also be analyzed using this approach
- ✓ Micro-beam techniques potentially fill a critical gap in our current monitoring arsenal: the ability to detect CO_2-induced mineral diss/pptn effects at typical reservoir conditions over relatively short time frame; e.g., first few years of a CO_2 storage project
- ✓ Such detection of incipient mineral alteration effects will help calibrate & constrain reactive transport models.

Synchrotron CMT

Midale Vuggy (V2)



2-D CMT Slice



Thin-section

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Brine/CO_2 exposure, sample 1E-1

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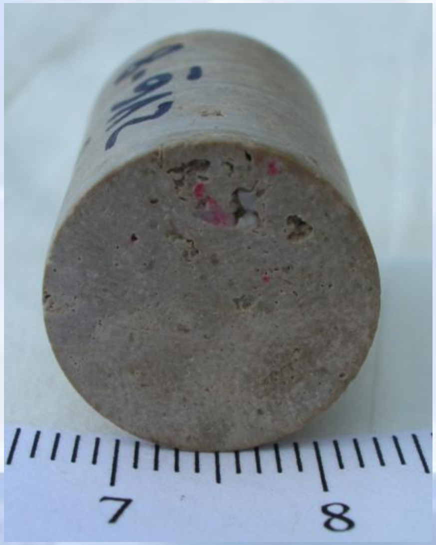
Before exposure | **After exposure**

Inlet

Distinct dissolution features (wormholes)

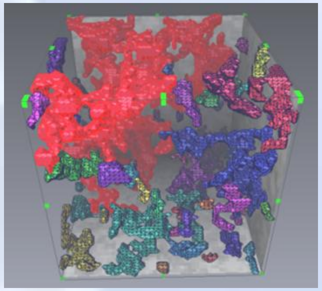
Outlet



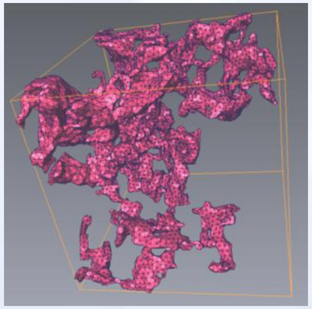
Subtle, diffuse dissolution features; CMT imaging required to assess extent & character.

Micro-scale numerical modeling of flow

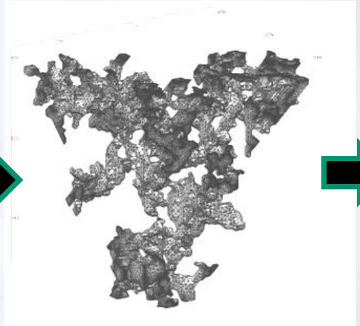
- Refinements of pore space filtering and meshing has enabled flow modeling of larger sub-volumes
  (35μm × 35μm × 35μm)



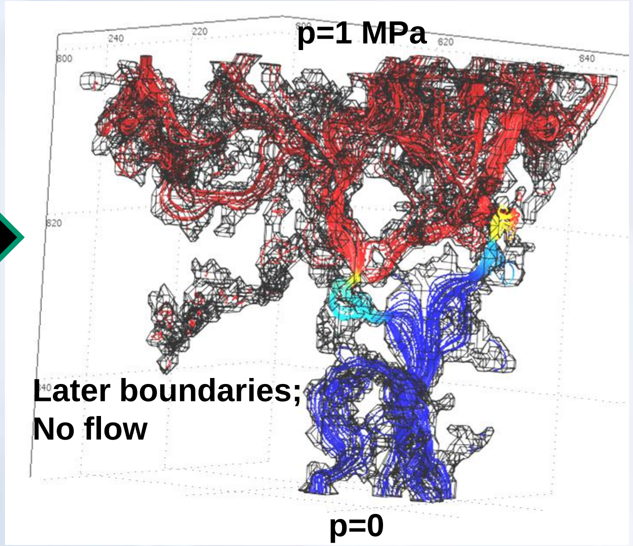
The largest connected region in the sub-sample was isolated, as highlighted in red.



The sub-sample was first *surface* meshed in 3D.



Geometry was extracted for full 3D tetrahedral meshing.



The solution to the steady state Navier-Stokes equation.
The color profile represents the pressure gradient (Red, pressure =1 : Blue, pressure = 0).

Fracture transport

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Research Provider

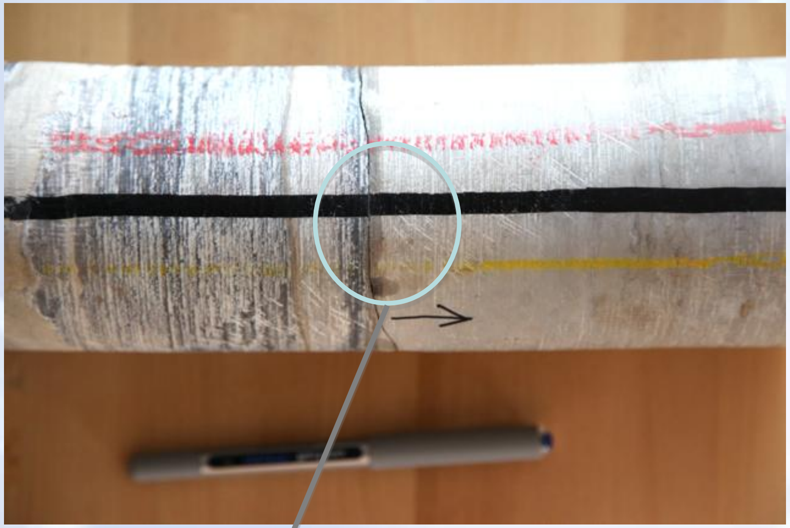
- ✓ Russ Detwiler, Jean Elkhoury, and Pasha Ameli (University of California -- Irvine)

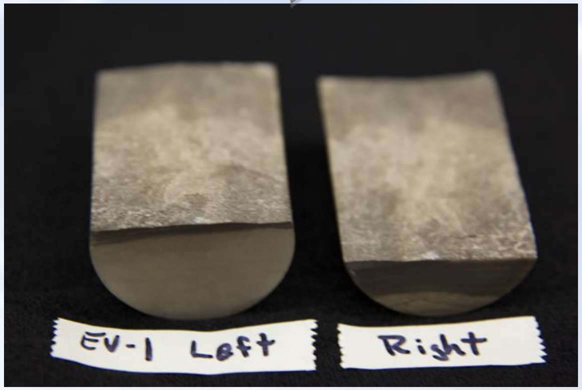
Project scope:

- ✓ Experimental/modeling study to measure & predict the CO_2-induced evolution of fracture permeability in Weyburn core
- ✓ Explicit integration of hydrological, geochemical, geomechanical processes
- ✓ Explore the scaling behavior of these processes using a computational model that couples geomechanical deformation & geochemical alteration of fracture perm during reactive flow
- ✓ Before & after the reactive flow experiments, characterize fracture surface roughness through measurement of asperity heights using a high-resolution profilometer & surface mineralogy using SEM
- ✓ *CO_2-induced alteration of the fluid transport properties of natural fractures within Weyburn core has yet to be characterized*

Experiment EV-1 – Experimental conditions

Original core with open bedding-plane fracture





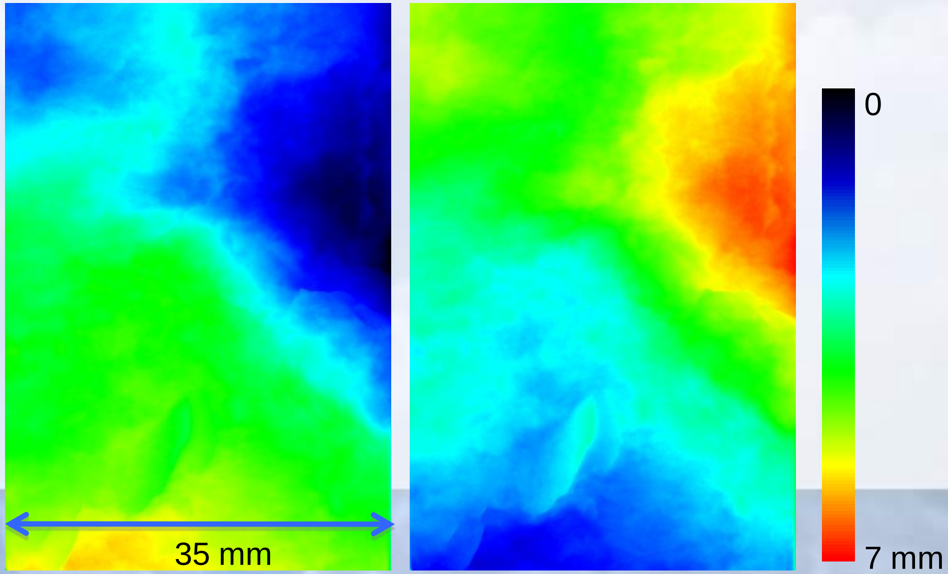
Sub-core prepared for flow-through experiment

Experimental conditions:

- Confining pressure = 28.6 MPa
- pCO_2=14.3 Mpa
- Constant flow rate = 0.003 mL/min
- Pressure control at inlet
- Duration 29 days

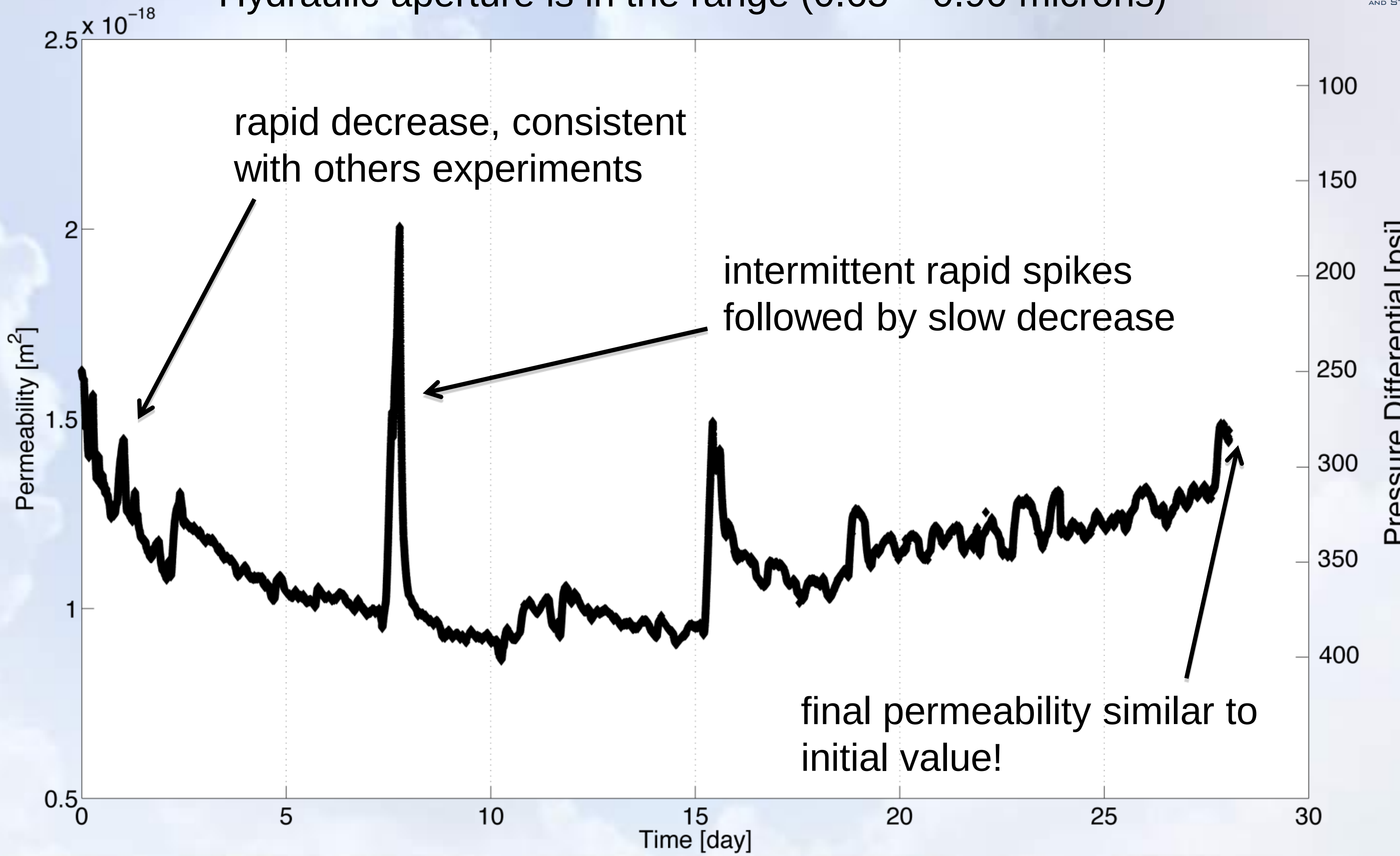
Optical surface profilometry

Measured surface topography

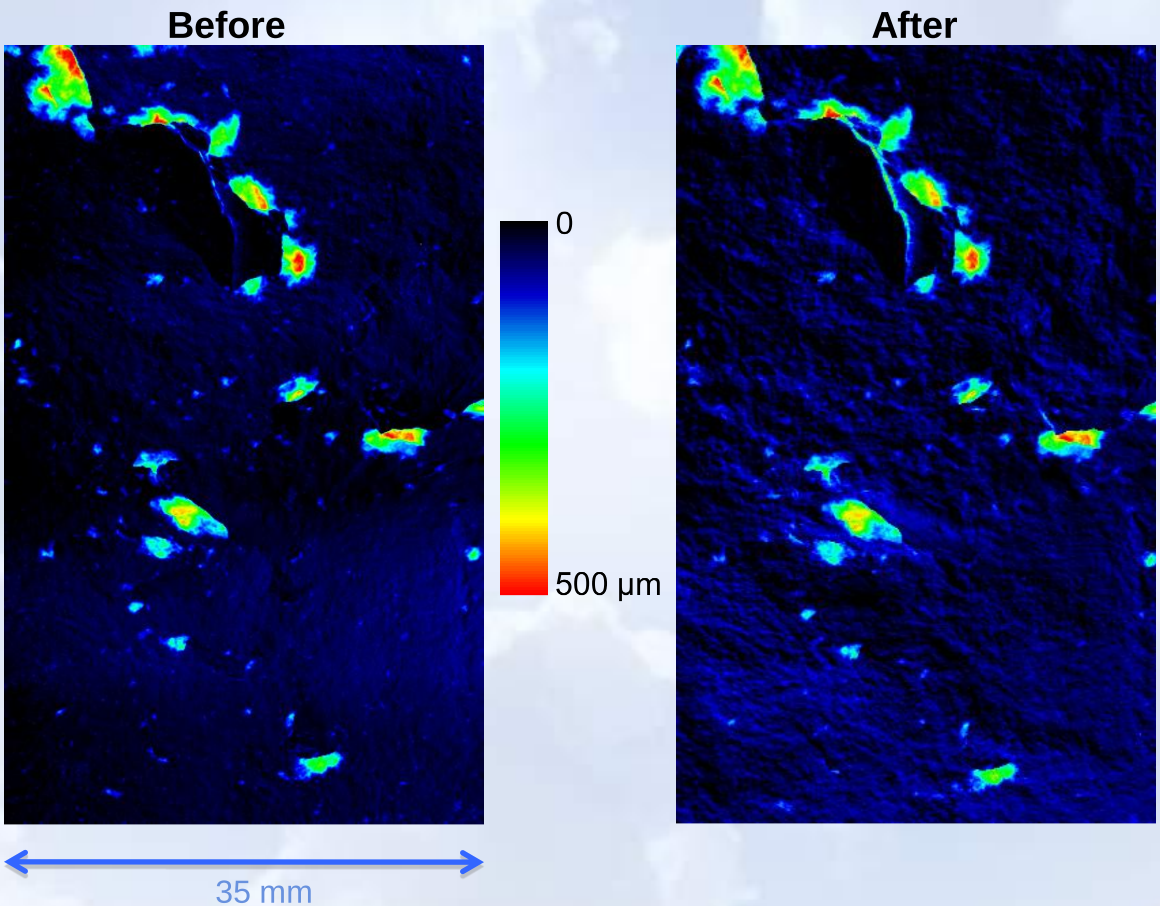


Permeability alterations observed during experiment

EV-1 Permeability evolution and differential pore pressure
Hydraulic aperture is in the range (0.65 – 0.90 microns)



Experiment EV-1: Aperture maps



Small differences between before and after maps:

- ✓ likely a result of registration artifacts with ‘after’ measurements

or

- ✓ no measurable alteration of the fracture aperture distribution

So, what caused permeability fluctuations?

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An International Collaborative Research Program Led by the PTRC Based in Regina, Saskatchewan, Canada

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- Sask Industry and Resources
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- Shell

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- ECOMatters (ECOM)
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- Permedia Group
- Saskatchewan Research Council (SRC)

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www.ptrc.ca
http://ptrc.ca/weyburn_overview.php
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