Seismic Monitoring of CO_2 Injection at the IEA Weyburn CO_2 Monitoring and Storage Site: Summary of Phase I Results

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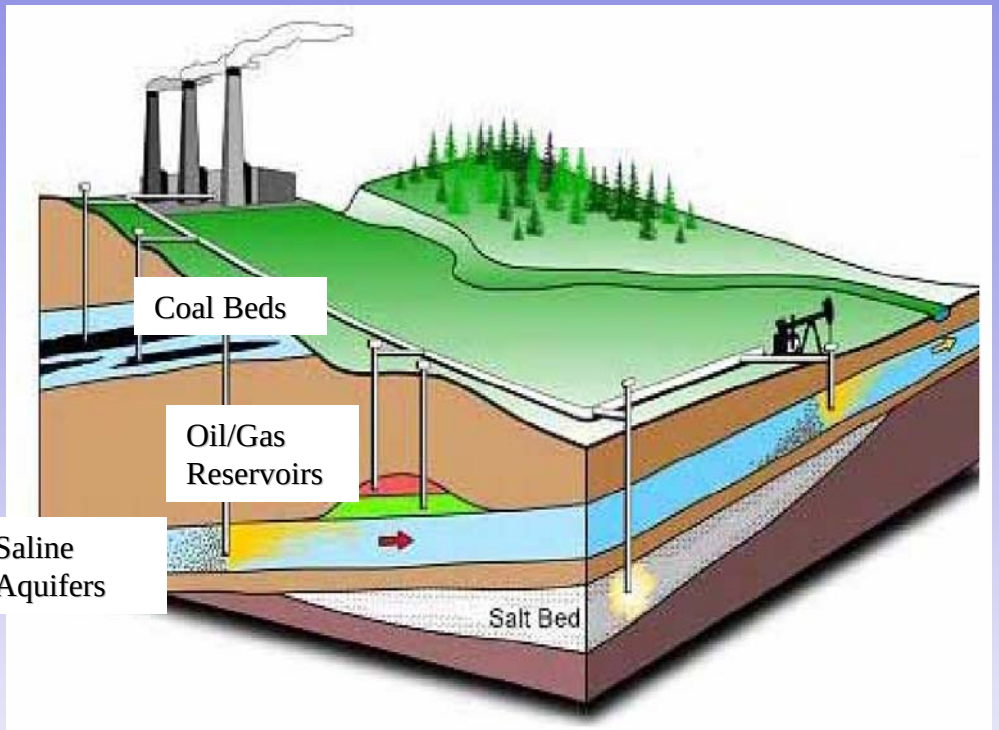
Outline

- Geological Storage of CO_2 in Canada
- The Weyburn CO_2 Flood
- Prediction of CO_2 Movement
- Seismic Monitoring
- Volumetrics
- Conclusions

Geological Storage

Sedimentary Basins

- Depleted oil and gas reservoirs
- Coal beds
- Saline aquifers
- Gas hydrates*

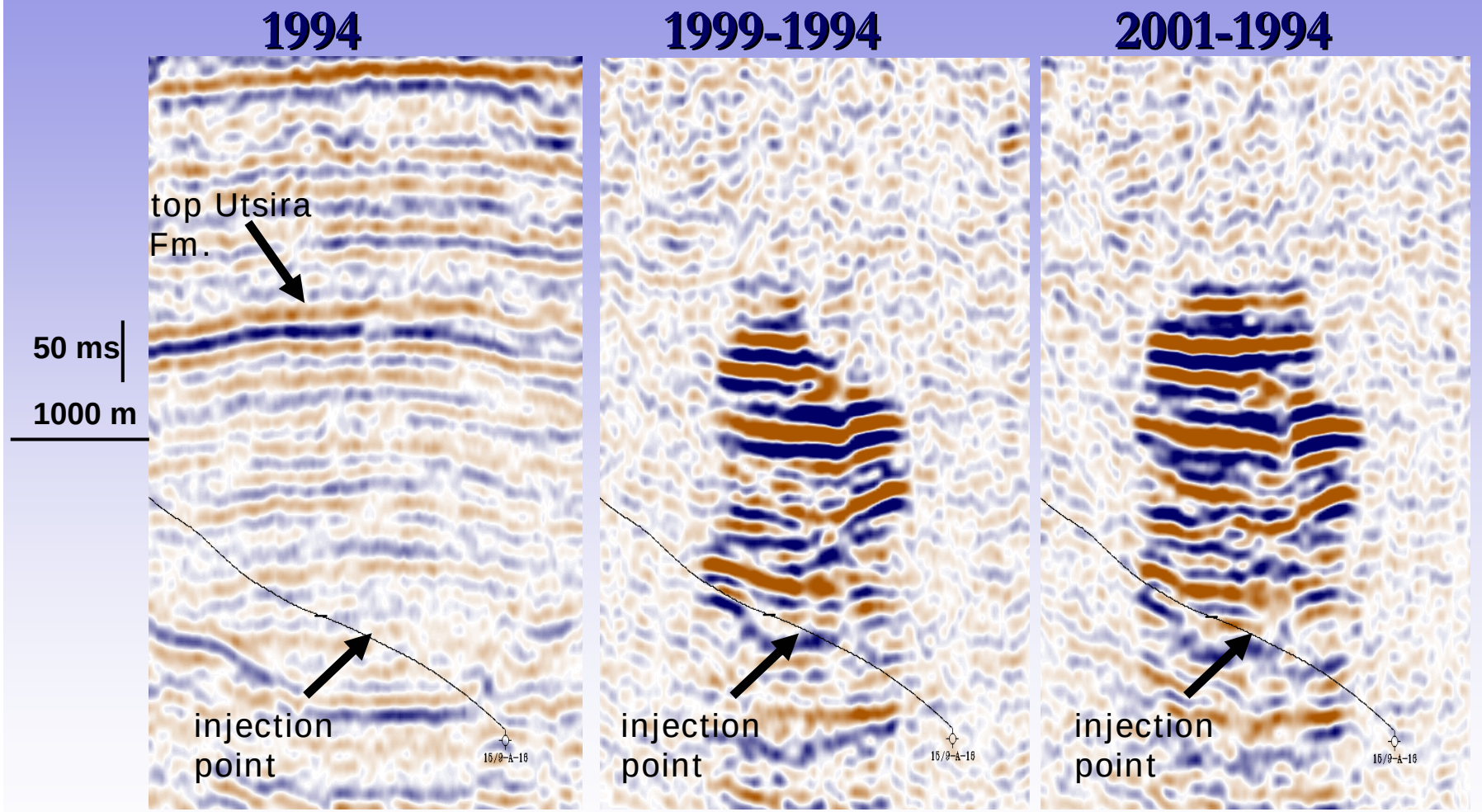


Other

- Deep Ocean
- Marine sediments
- Ultramafic rocks

*** Arctic Canada, East and West Coasts**

Sleipner Time-Lapse Seismic



From Eiken et al. 2004

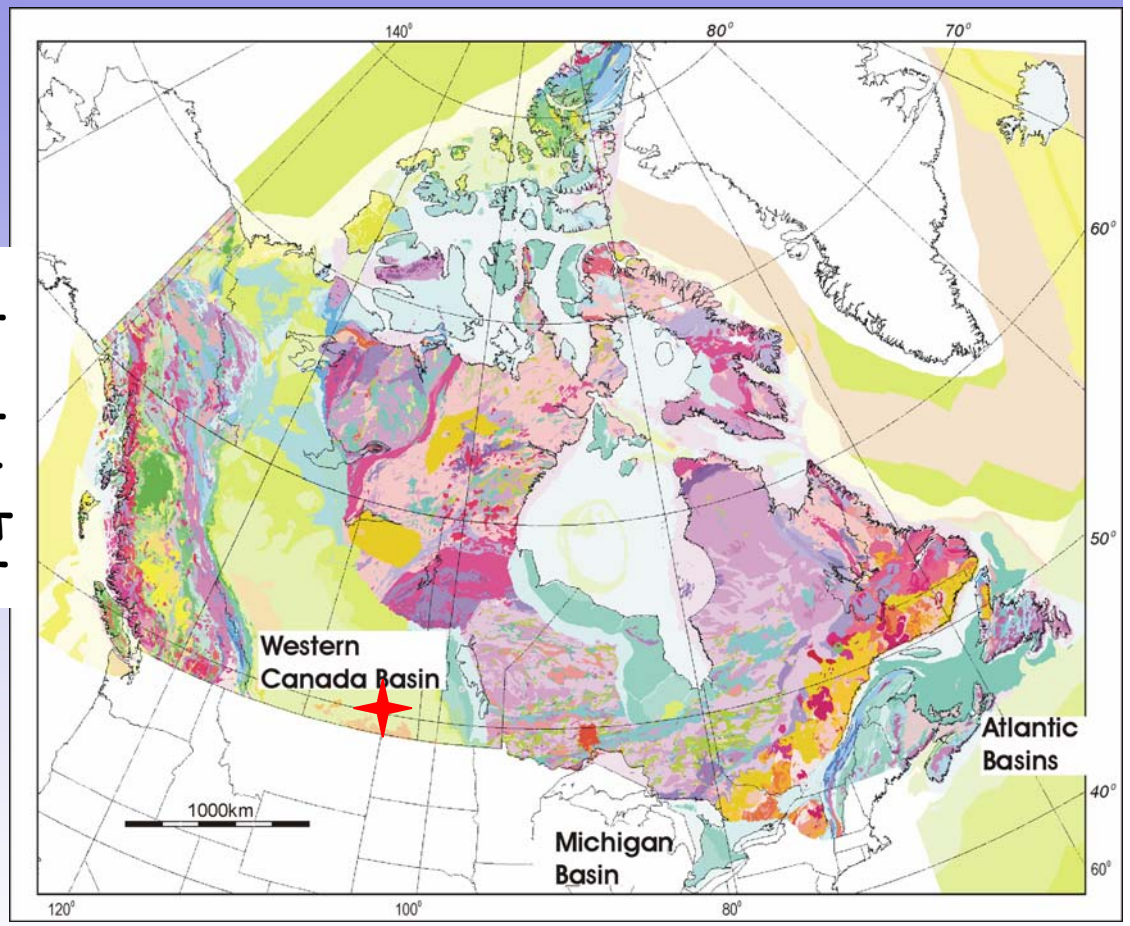
Examples of CO_2 Volumes

- Average auto: 4 t/yr
  - 98 Mt annually (Canada)
- 250 MW generator: 10 Mt/yr
- Weyburn Capacity (20-30 Mt)

Inventory of Storage Capacity

WCSB Storage – Estimates:

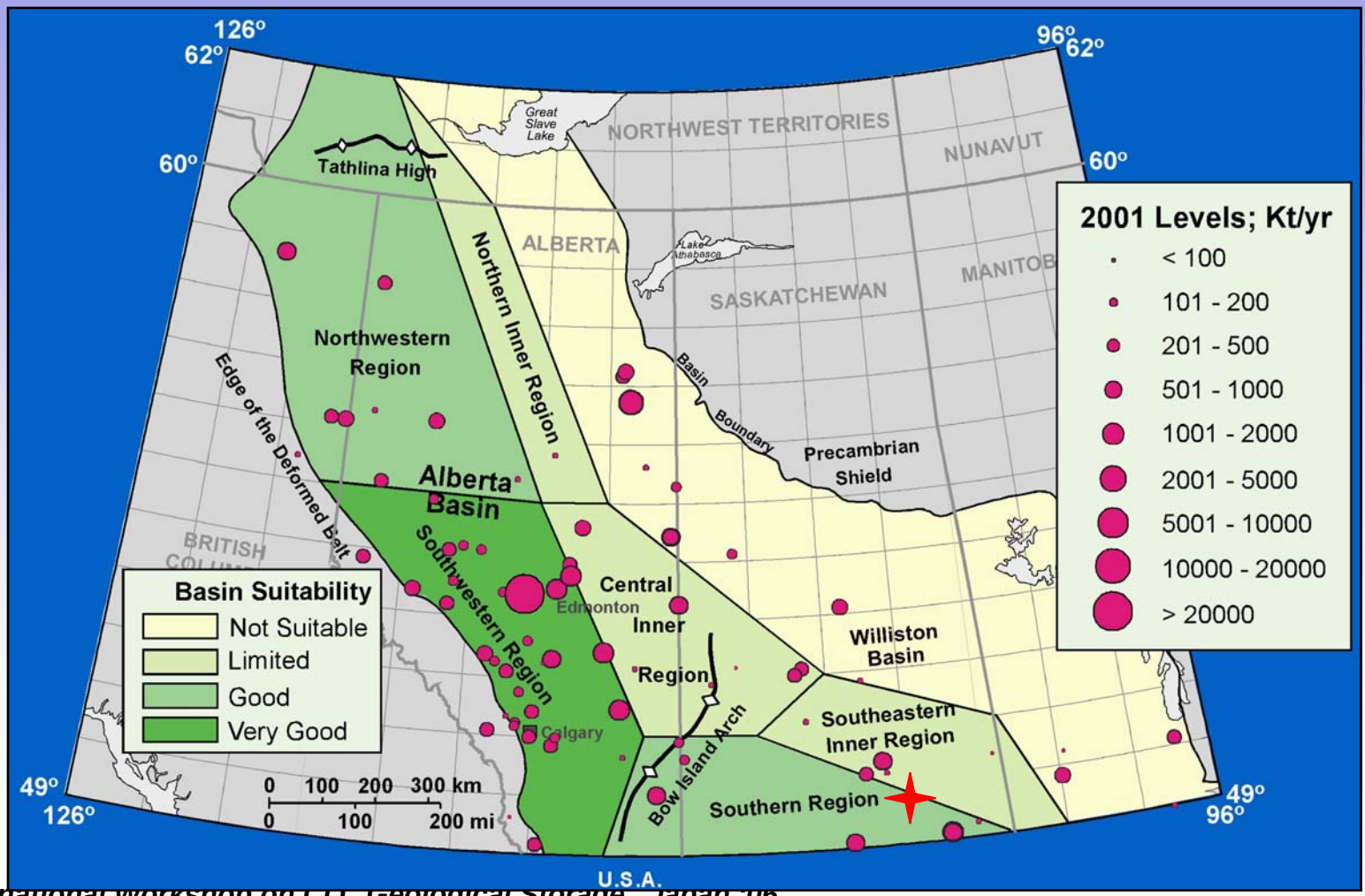
CO_2 EOR	450 MT
Depleted Reservoirs	
Oil:	111 MT
Gas:	13,200 MT
ECBM	100,000 MT
Saline Aquifers	1,000,000 MT



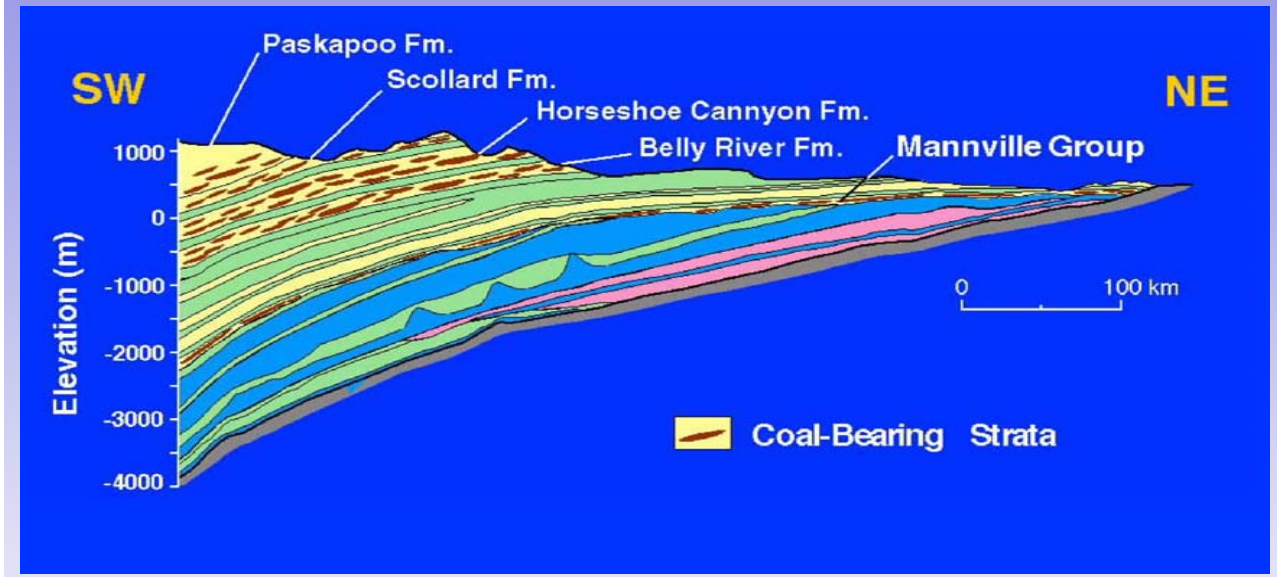
900 m depth ⟶ supercritical gas

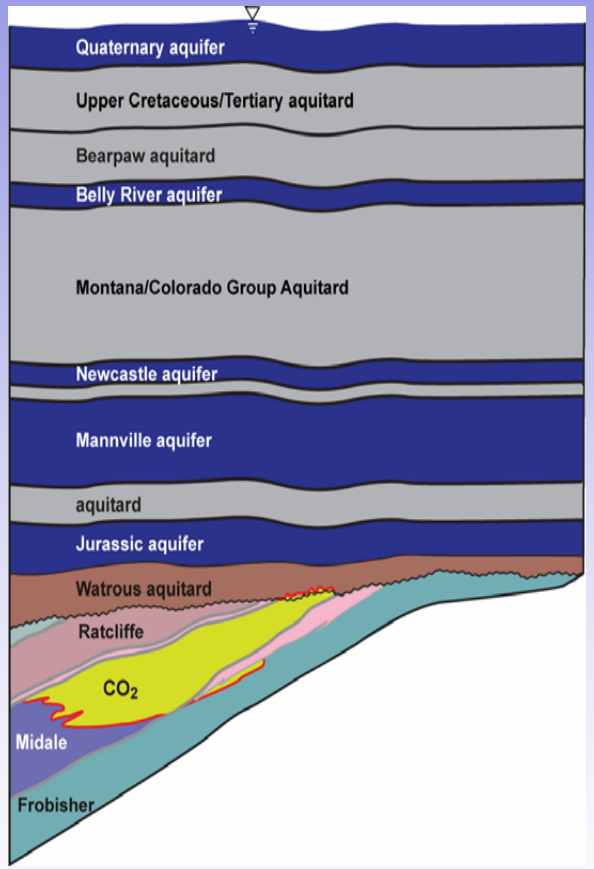
Good Geographic Match Between Best Storage Areas and Major Sources

AGS/EUB - Inventory of CO_2 Sources in WCSB



WCSB Saline Aquifers, Coal Beds

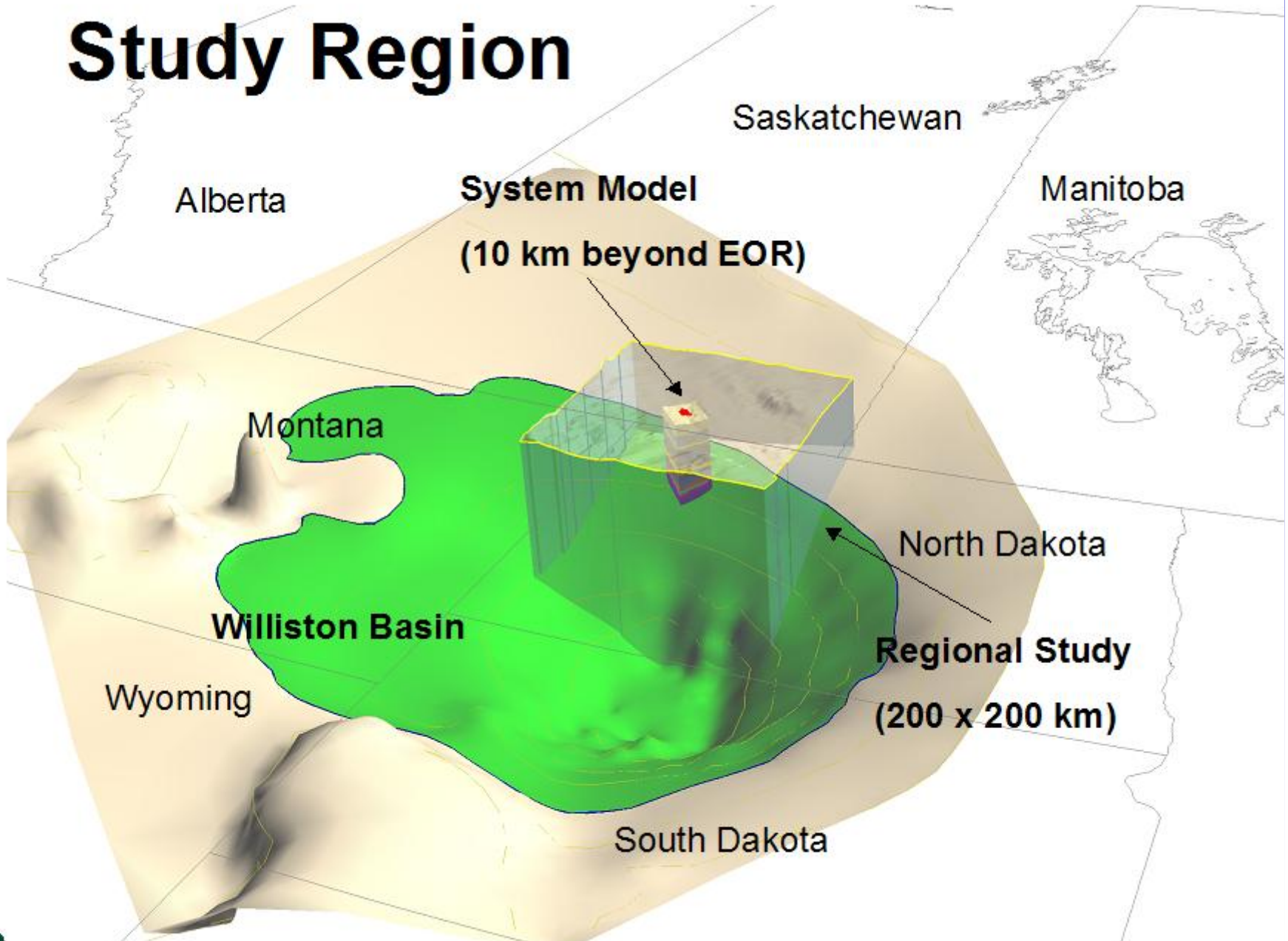




- **Regionally extensive (100's km)**
- **Large volume**
- **Isolated by aquitards/aquicludes**

1. The IEA Weyburn Project

Study Region



Objectives

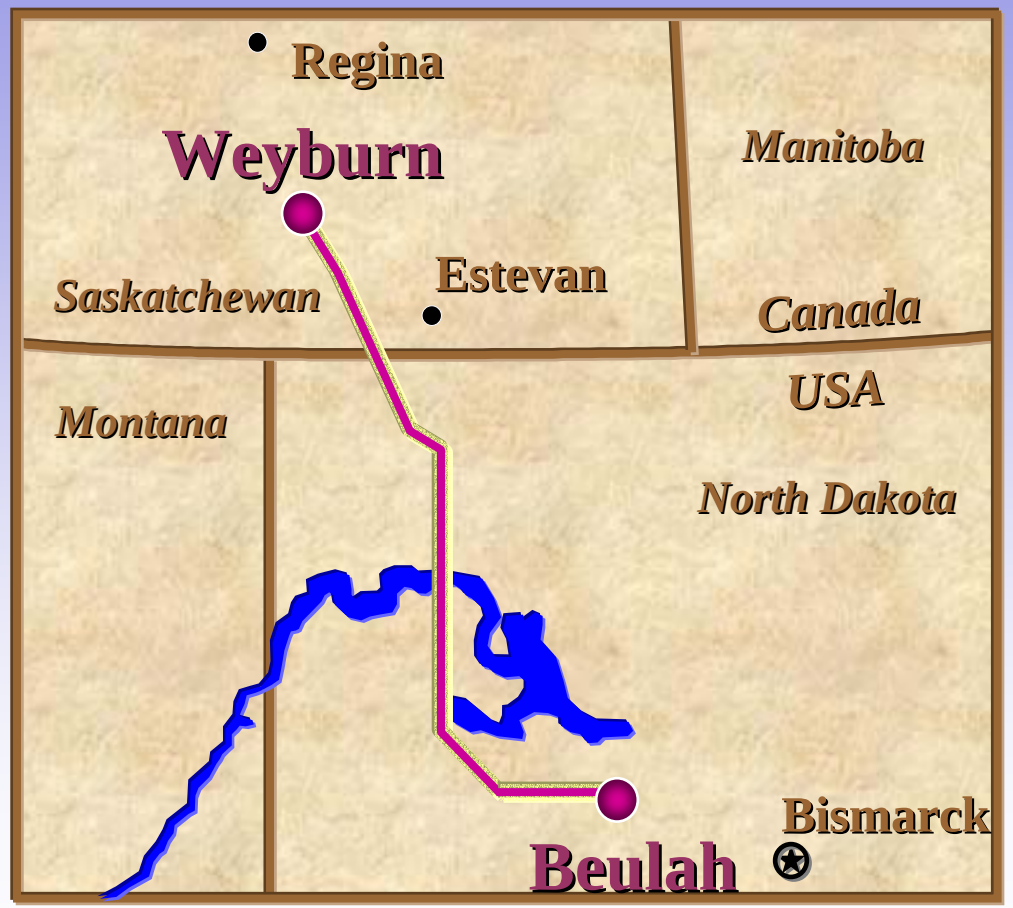
- Develop methods for **monitoring** CO_2 injection.
- Improve **reservoir characterization** to enhance conformance control and prediction .
- **Verify volumes** of CO_2 in the subsurface.
- Establish **safety** and **containment** of injected CO_2.

Weyburn Research Themes

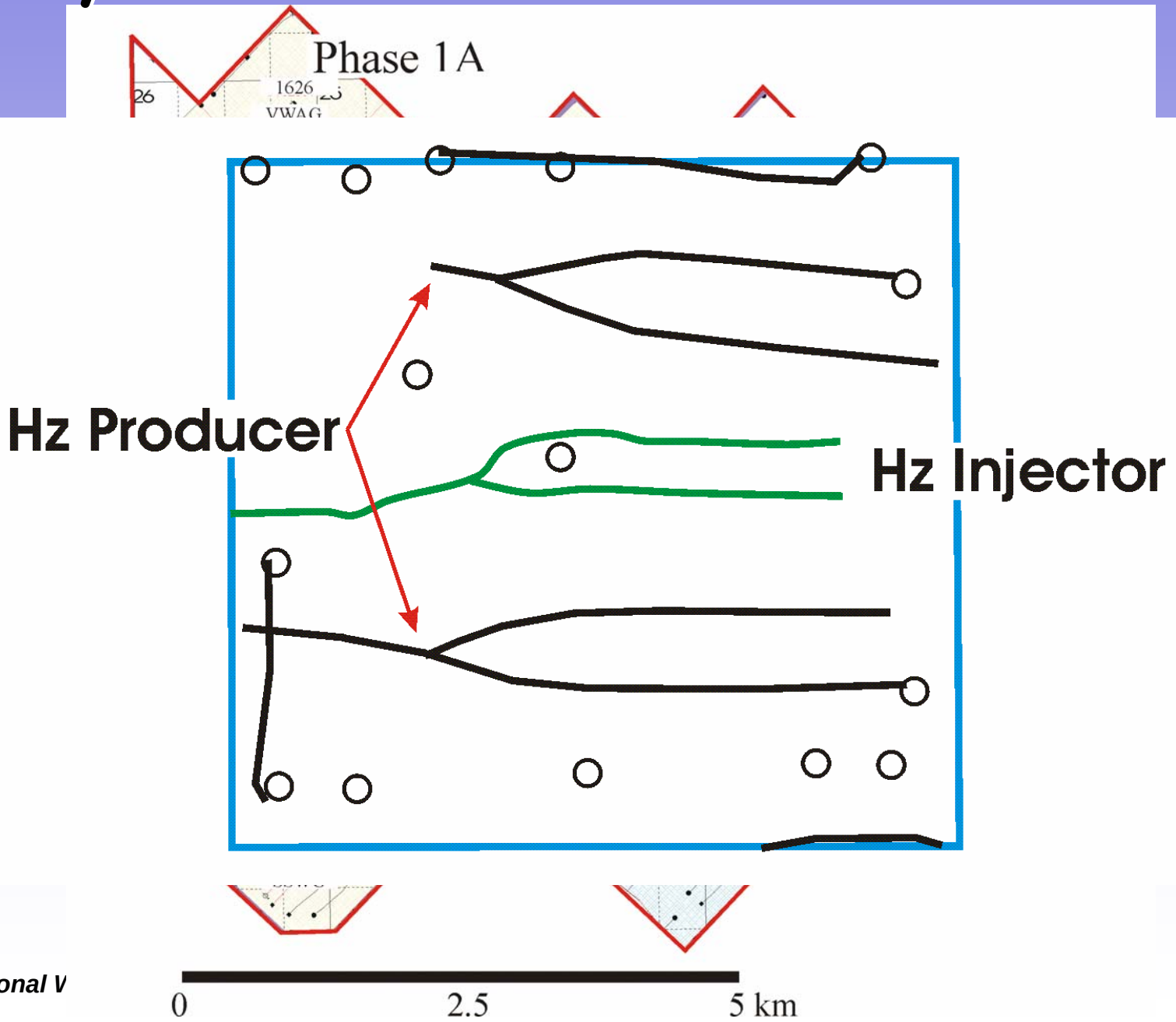
- Geological Characterization
- **Prediction, Monitoring & Verification of CO_2 Movement**
- CO_2 Storage Capacity, Distribution & Economics
- Long-Term Risk Assessment

The Source of CO_2

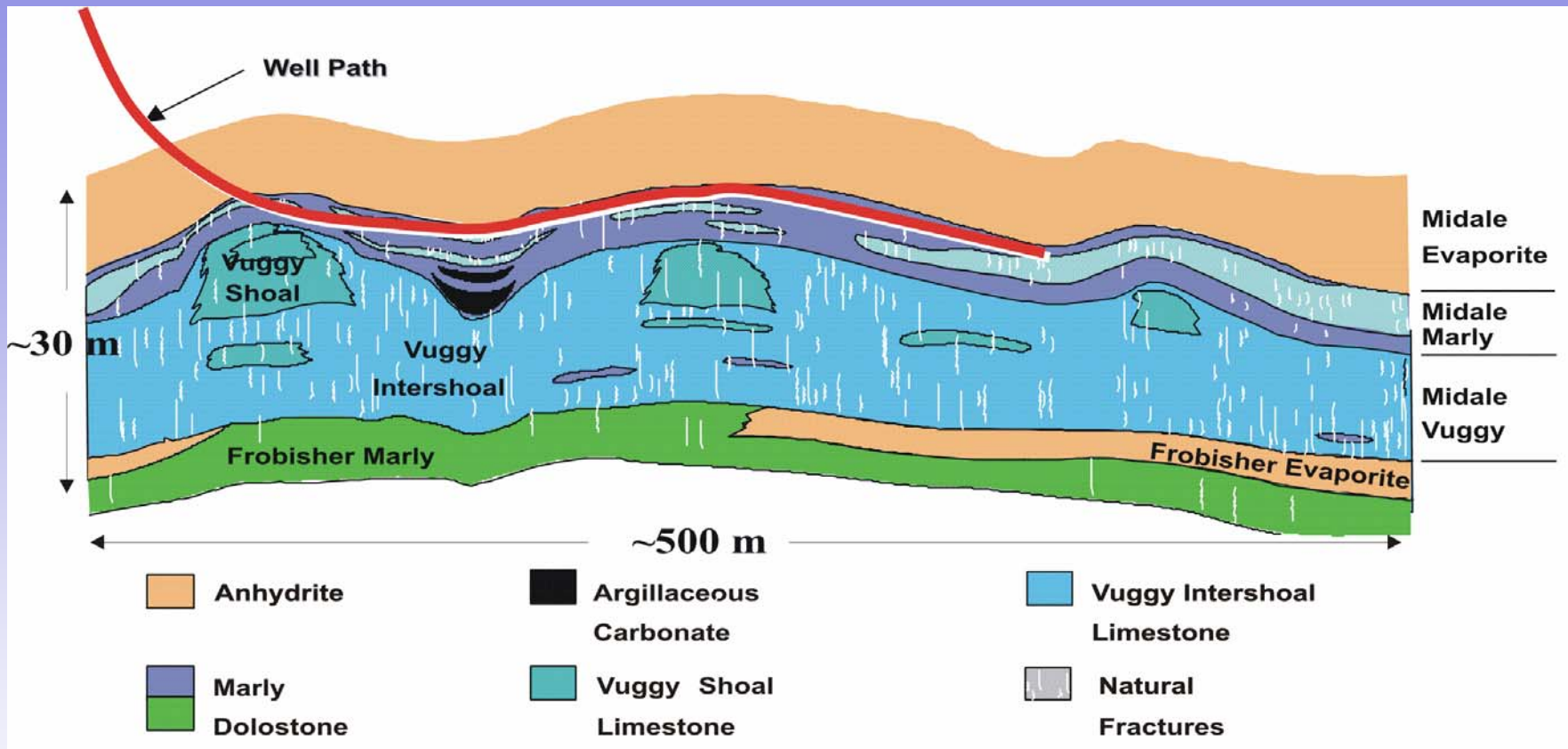
- Dakota Gasification Company
- 250 mmscfd CO_2 by-product of coal (lignite) gasification
- 95 mmscfd (5000 tonnes/day) contracted and injected at Weyburn
- CO_2 purity 95%
- EnCana currently injects 120 mmscfd (i.e. 21% recycle)



Weyburn Field: Phase 1A EOR Area



The Reservoir (Fractured Carbonate)



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

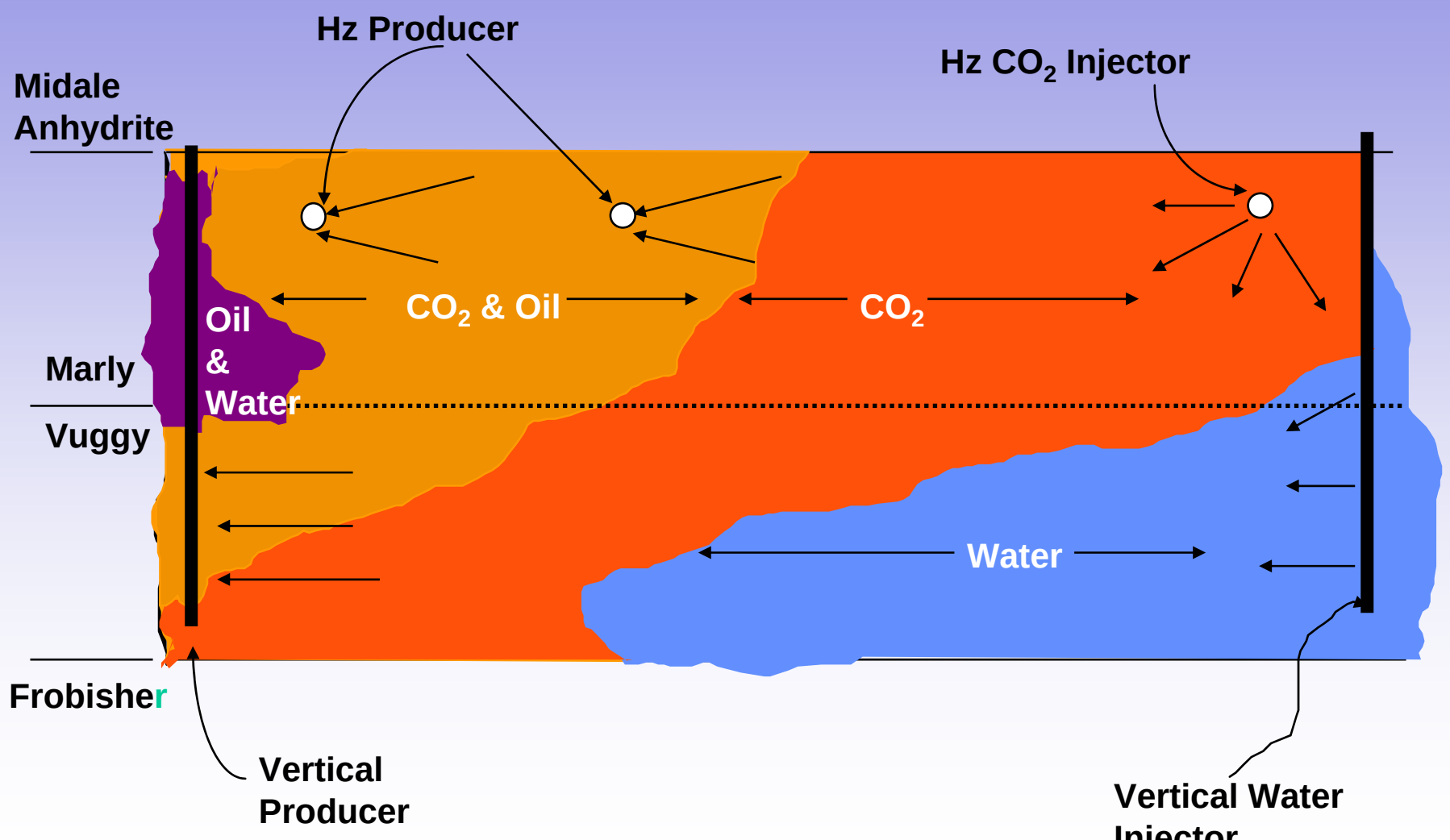
Anhydrite seal

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

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

Intern

The CO_2 (Miscible) Flood



Properties of CO_2

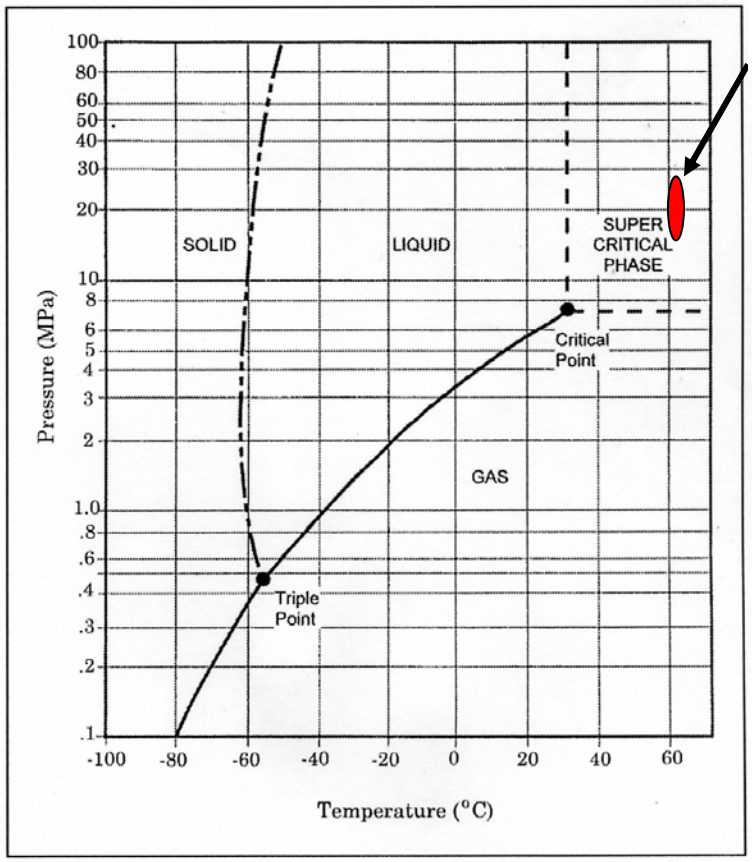


Fig. 4. Phase diagram for carbon dioxide.

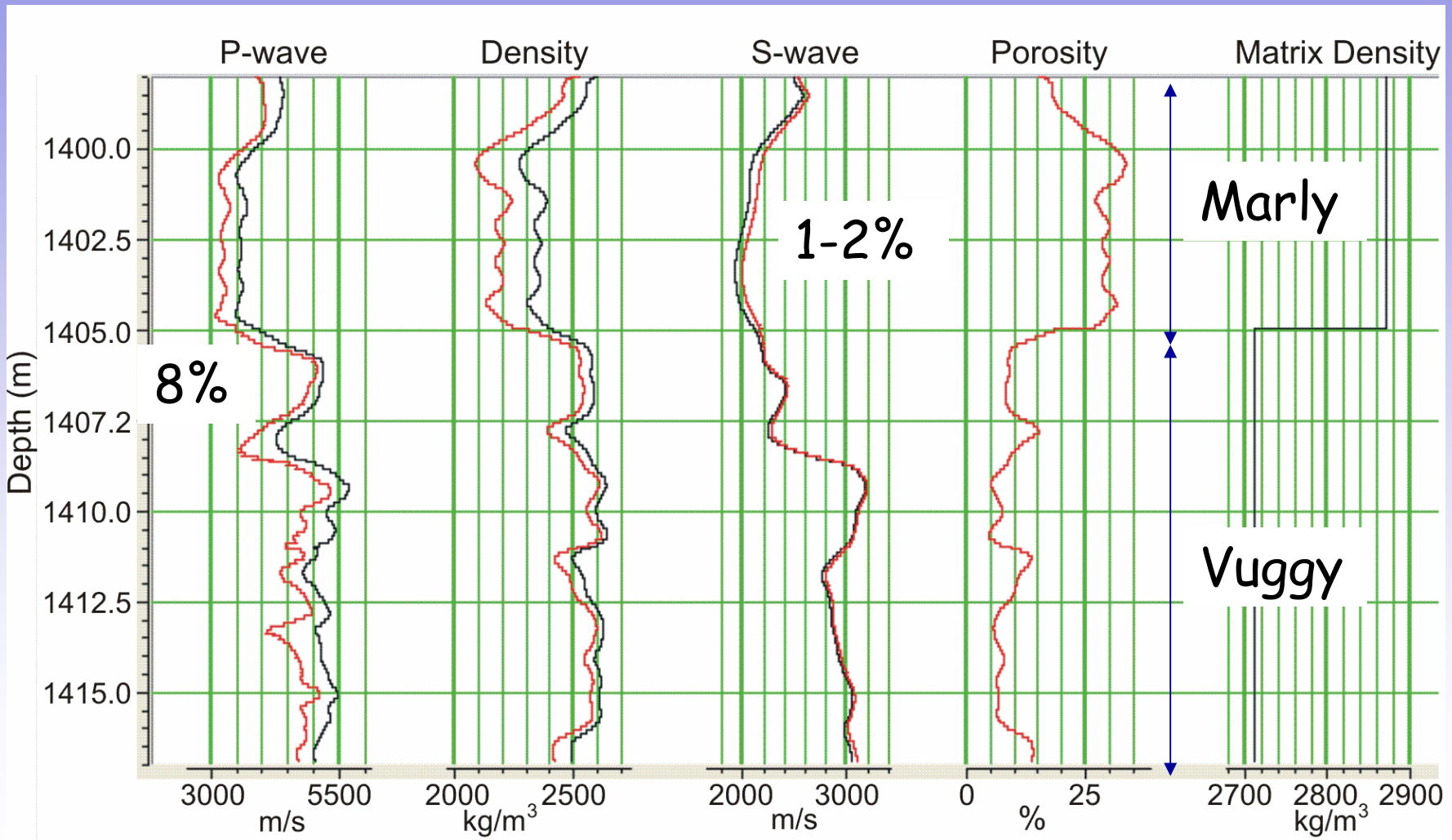
Weyburn

Reservoir fluid properties (for P=15-25 MPa; T=63 deg C) summarized from Brown (2002).

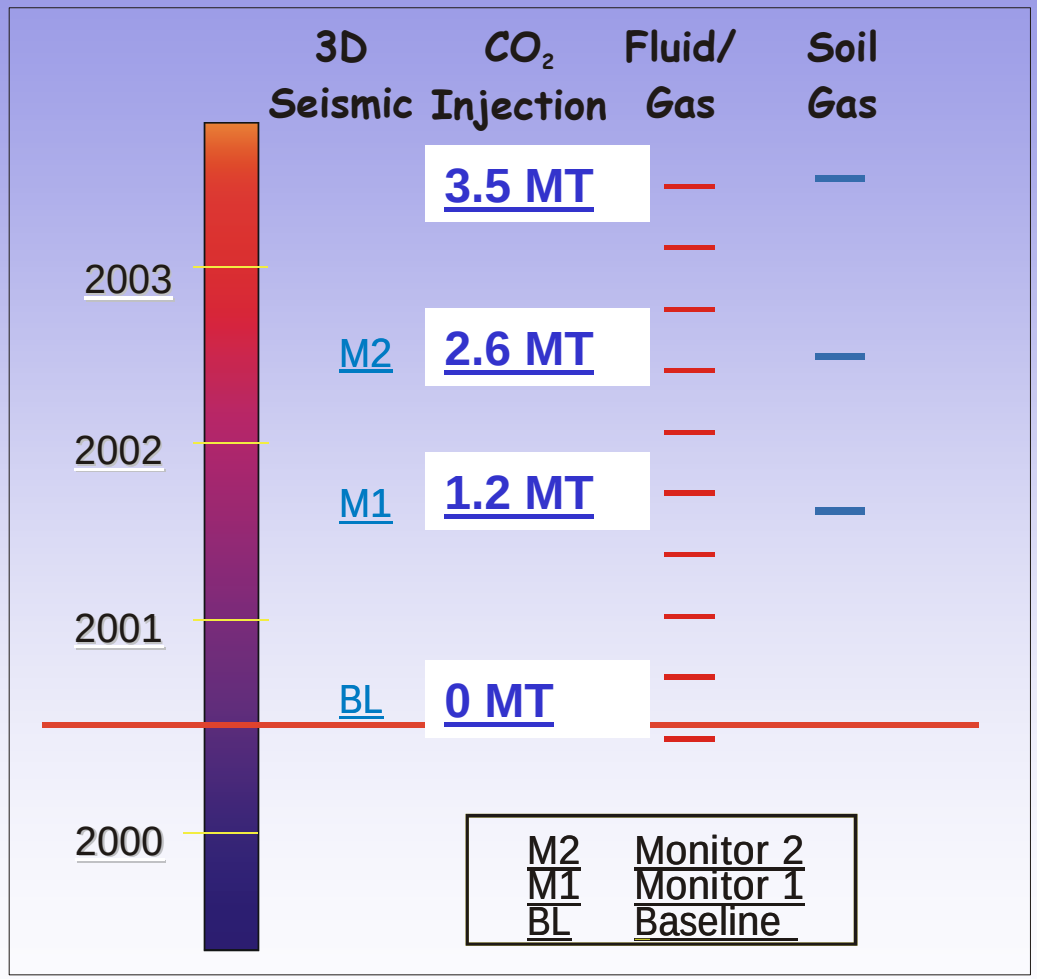
Fluid	Bulk Modulus (GPa)	Density (gm/cc)	Viscosity (relative to oil)	Solubility of CO2 (molar %)
Oil	1.2-1.7	0.80-0.88	1	66
Brine	2.7-3.2	1.02-1.08	~1/10	1-2
CO_2	0.05-0.18	0.58-0.76	1/70	100

Reservoir: T=63^0 C, P>15 MPa

Model Response (Gassmann)

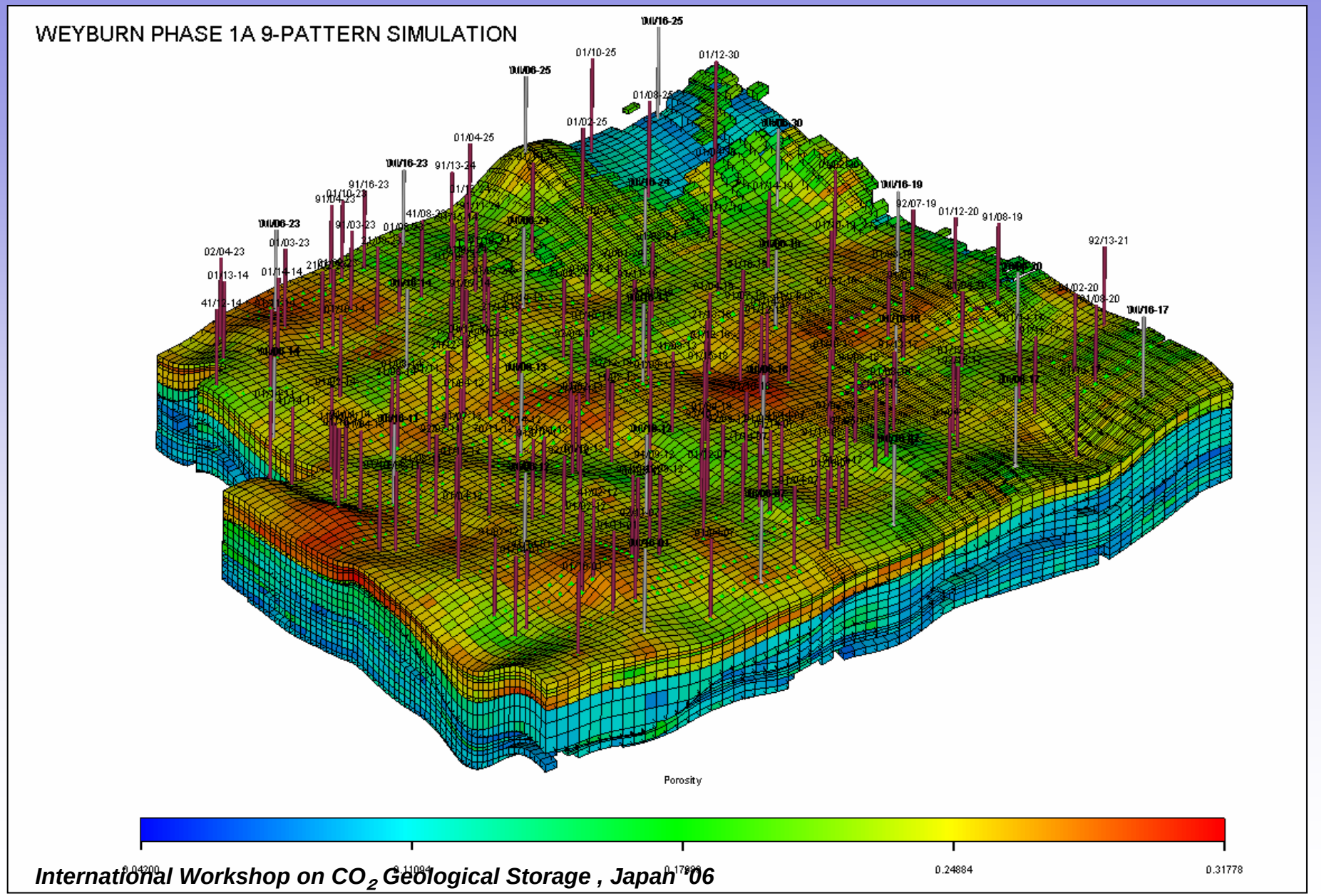


Monitoring Schedule

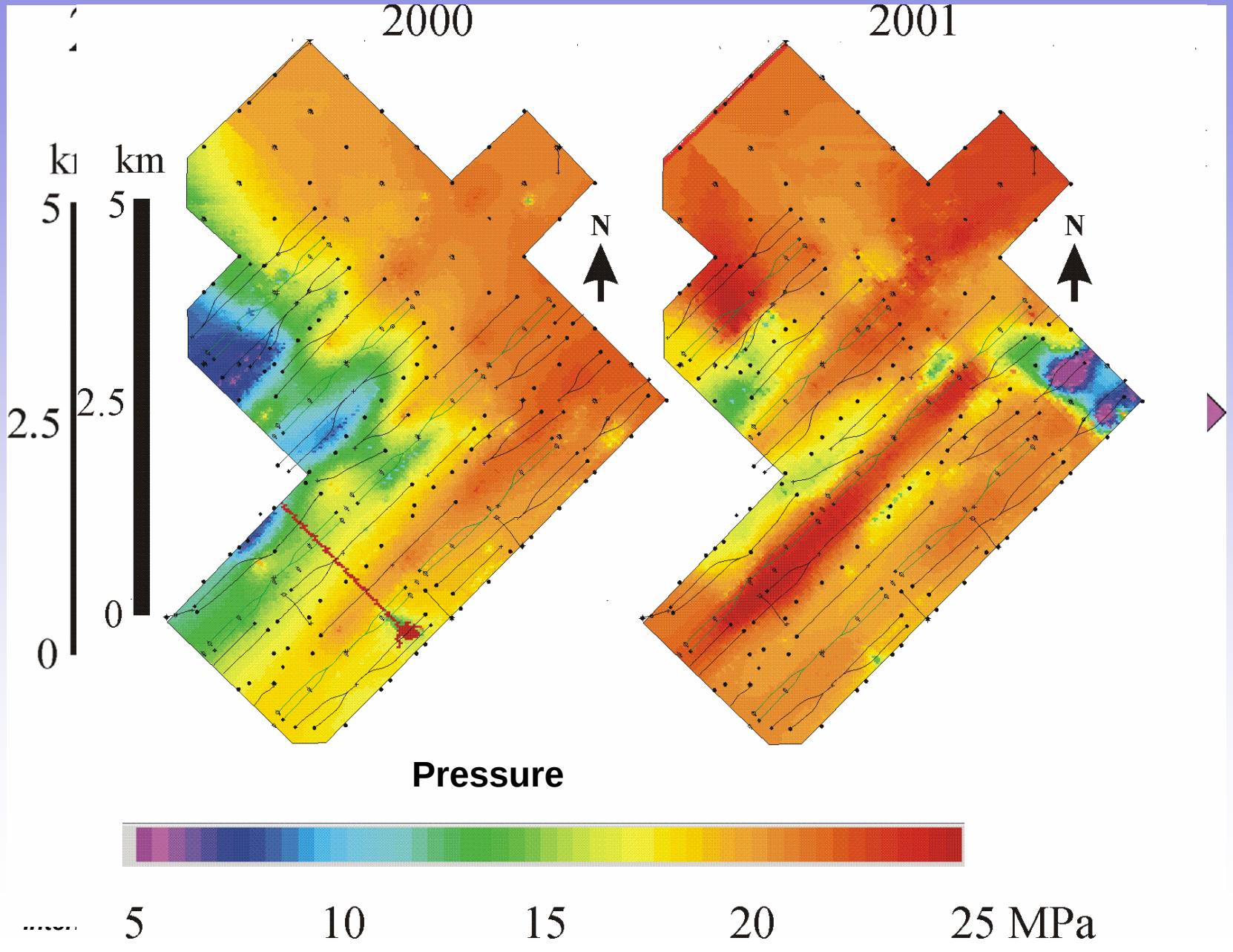


2. Pre-Injection Prediction

Pre-injection Prediction



Pre-injection Prediction



3. Monitoring of CO_2 Movement and Effects at the Reservoir

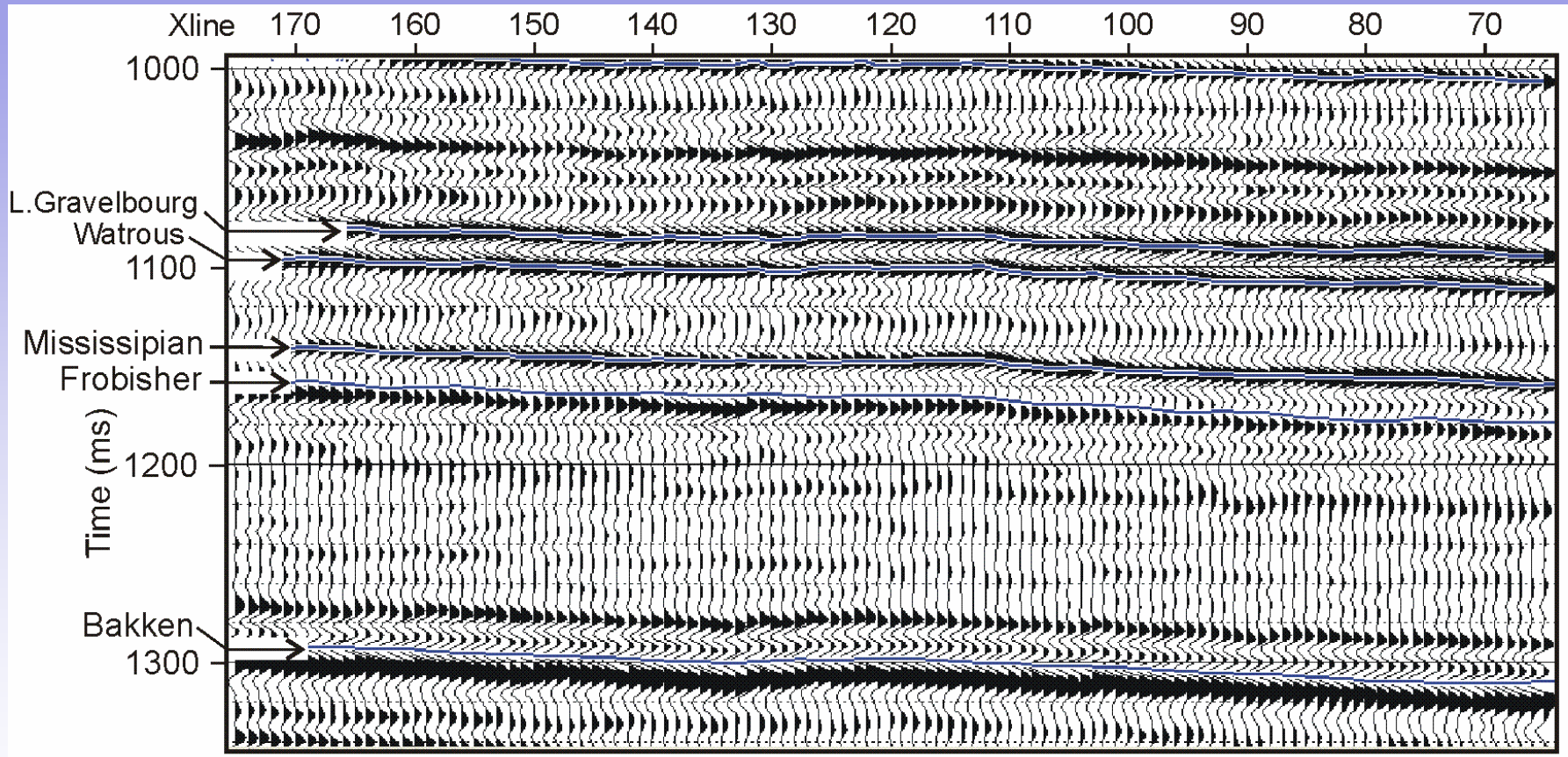
Monitoring Techniques

- Production Data
- Geochemistry of Production Fluids/Gases
- 3D Multi-component Time-Lapse Seismic
- Passive Microseismic Monitoring
- Soil Gas Sampling

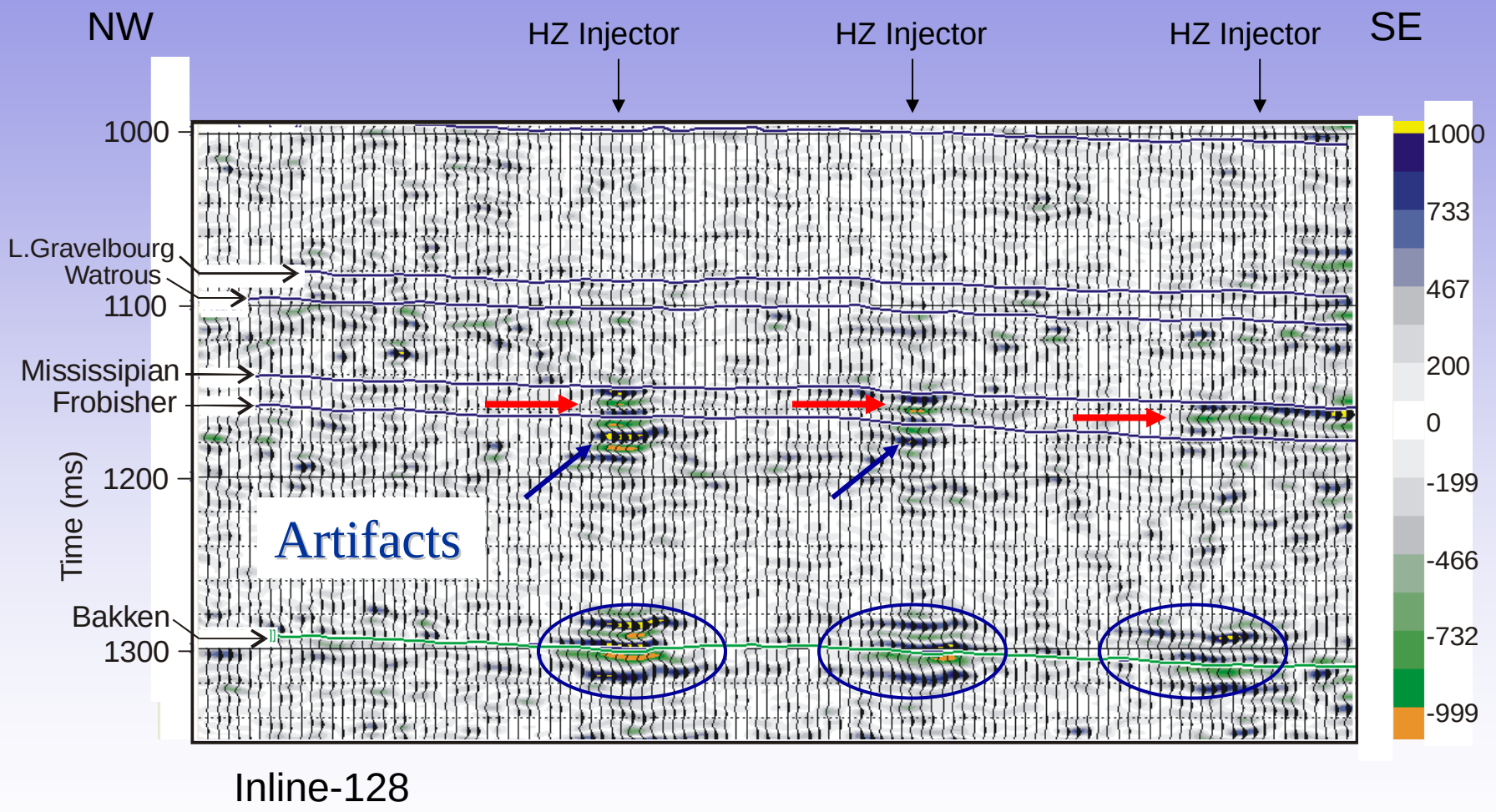
Time-Lapse Seismic

- **P- and S-Wave**
  - pressure vs. saturation
  - fractures (S-wave splitting)
- **Time delays & Amplitude differences**
  - vertical discrimination

Weyburn Seismic

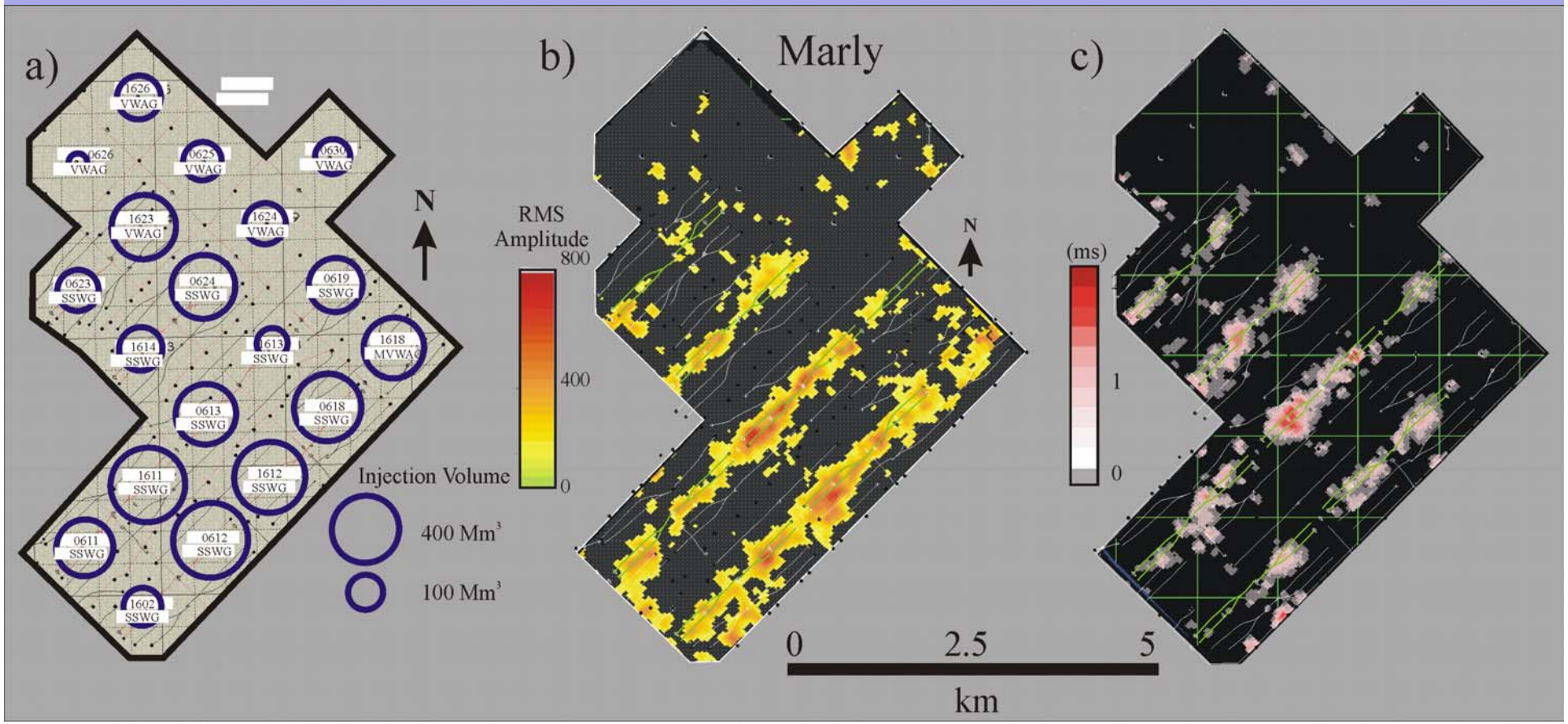


Monitor 2 Time-Lapse Amplitude Difference



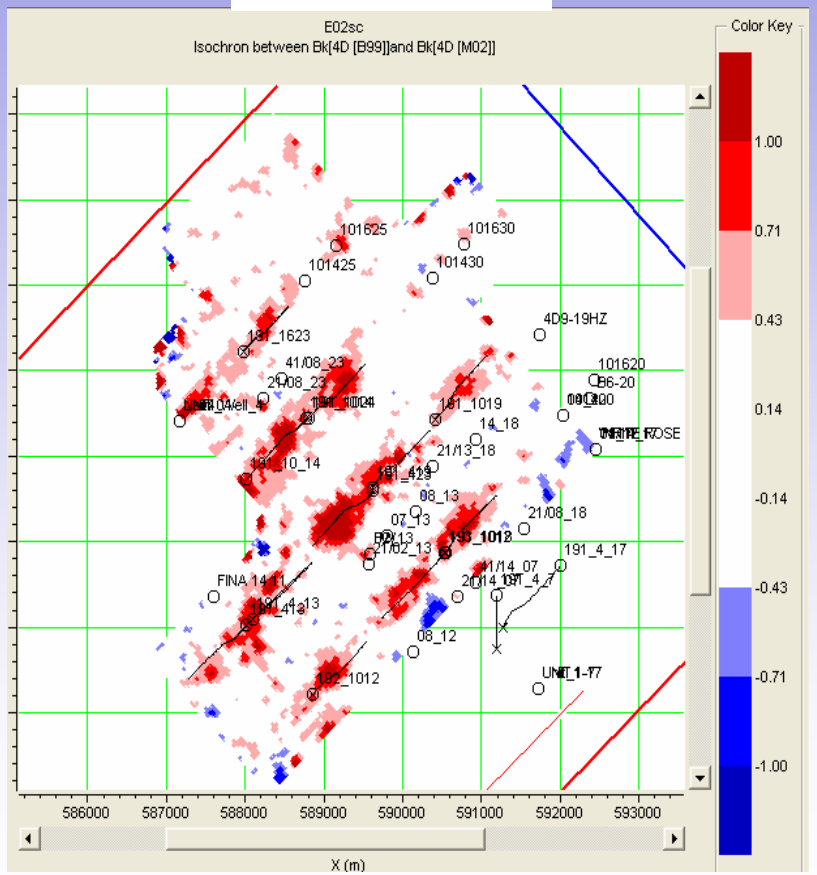
Inline-128

Monitor 2 Production-Seismic Comparison

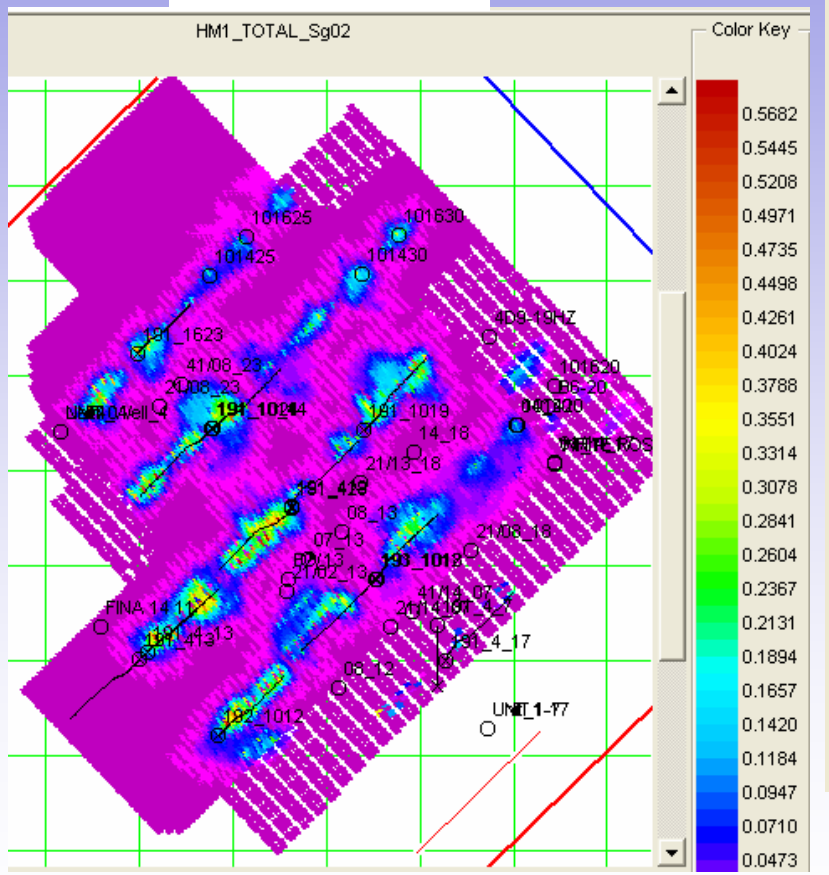


CO2 distributions from Seismic and Simulator, 1st iteration (Monitor 2 Survey)

Seismic



Simulator



0.5

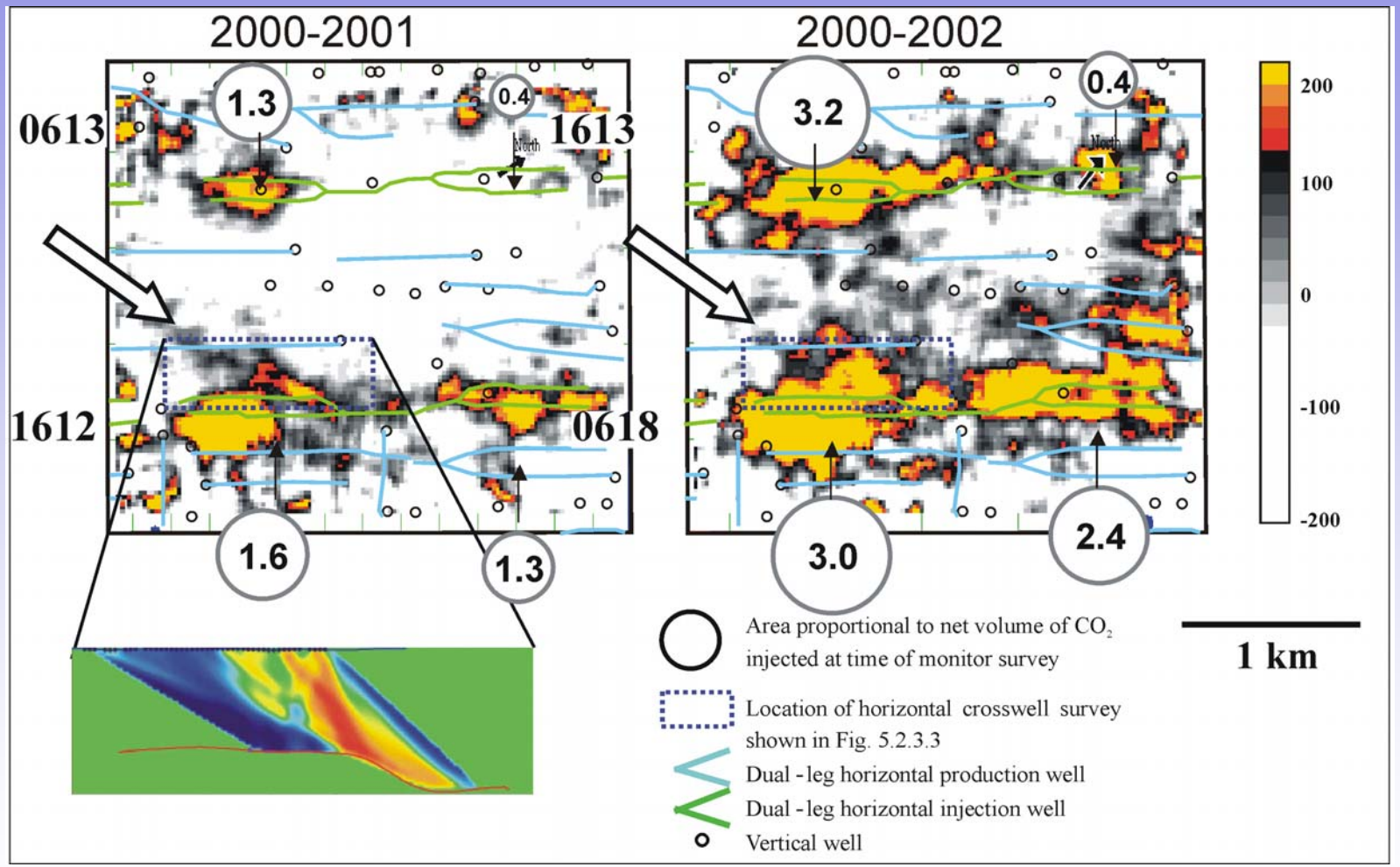
0.4

0.3

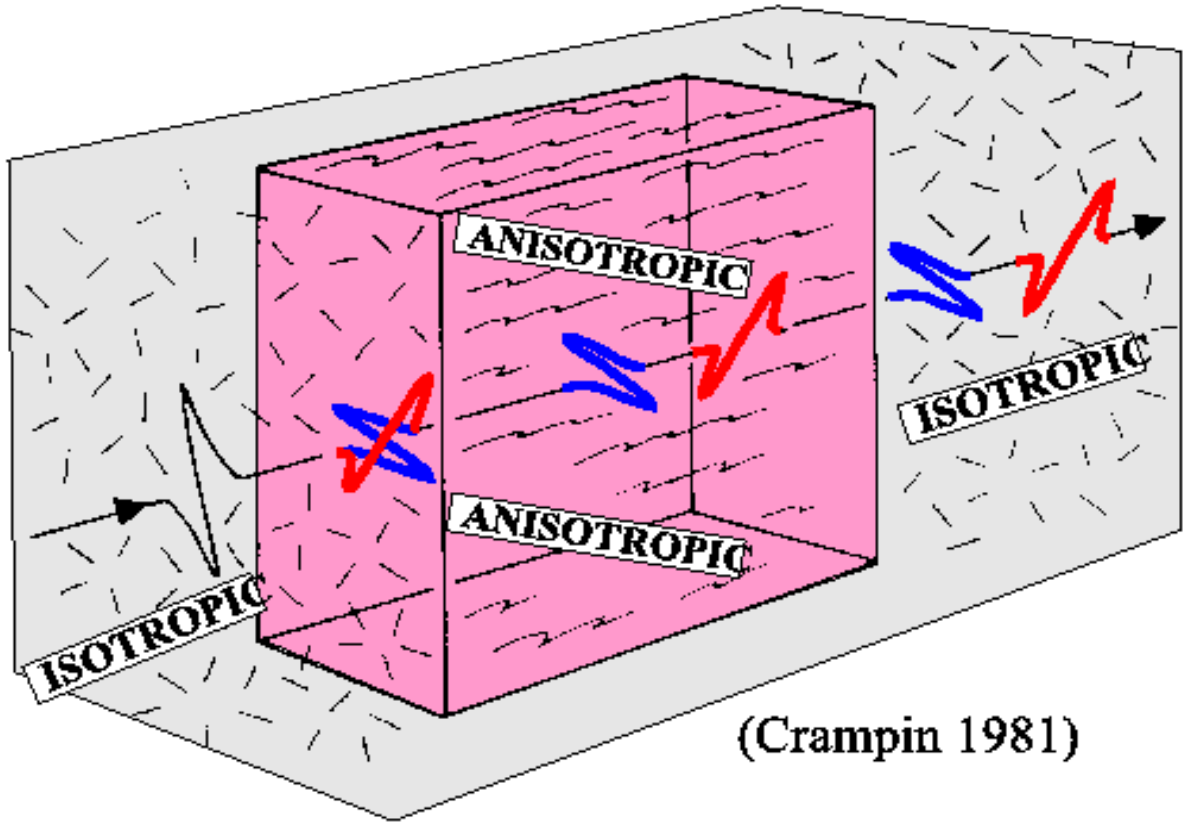
0.2

0.1

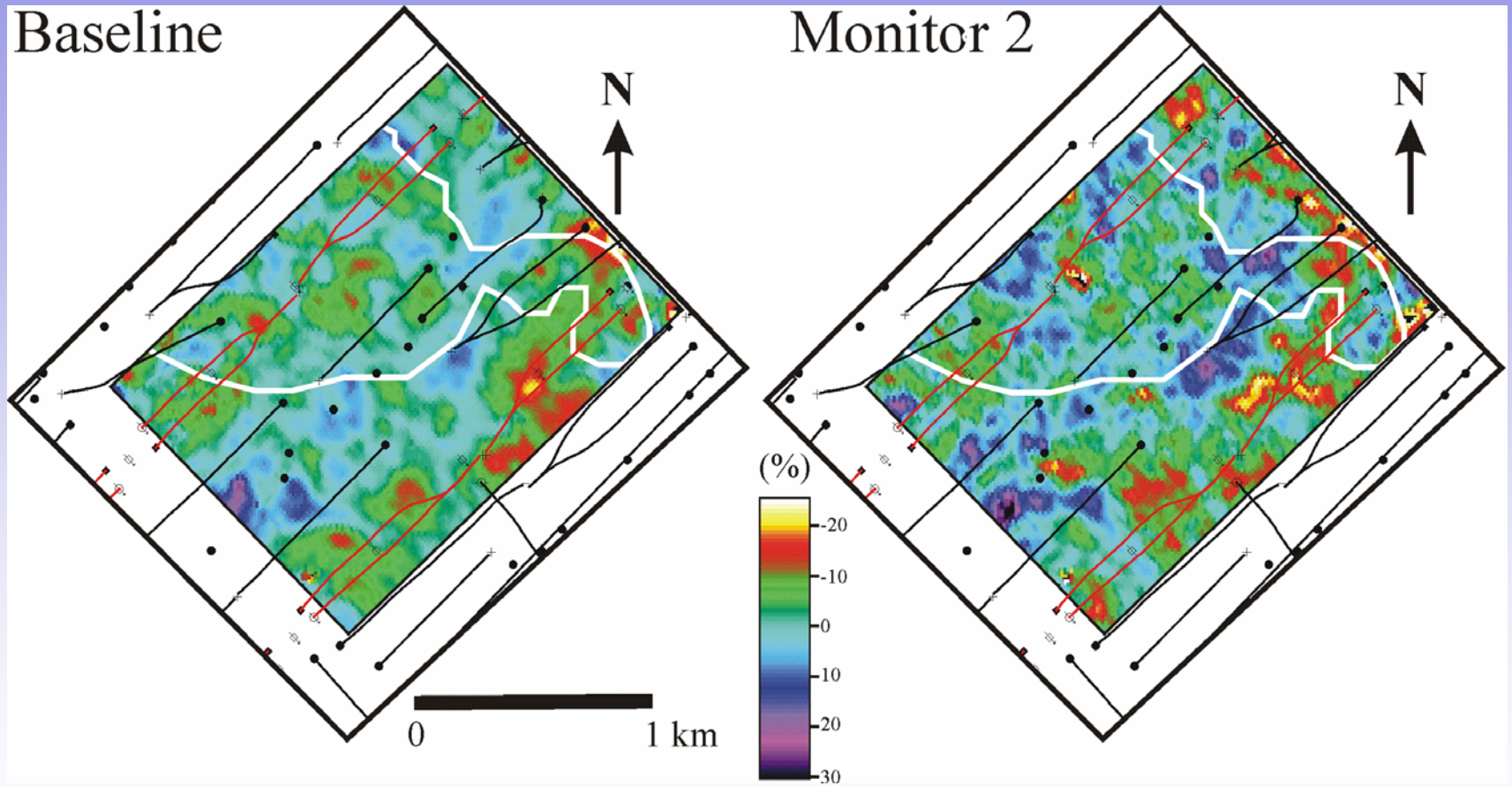
Amplitude Anomalies at the Reservoir



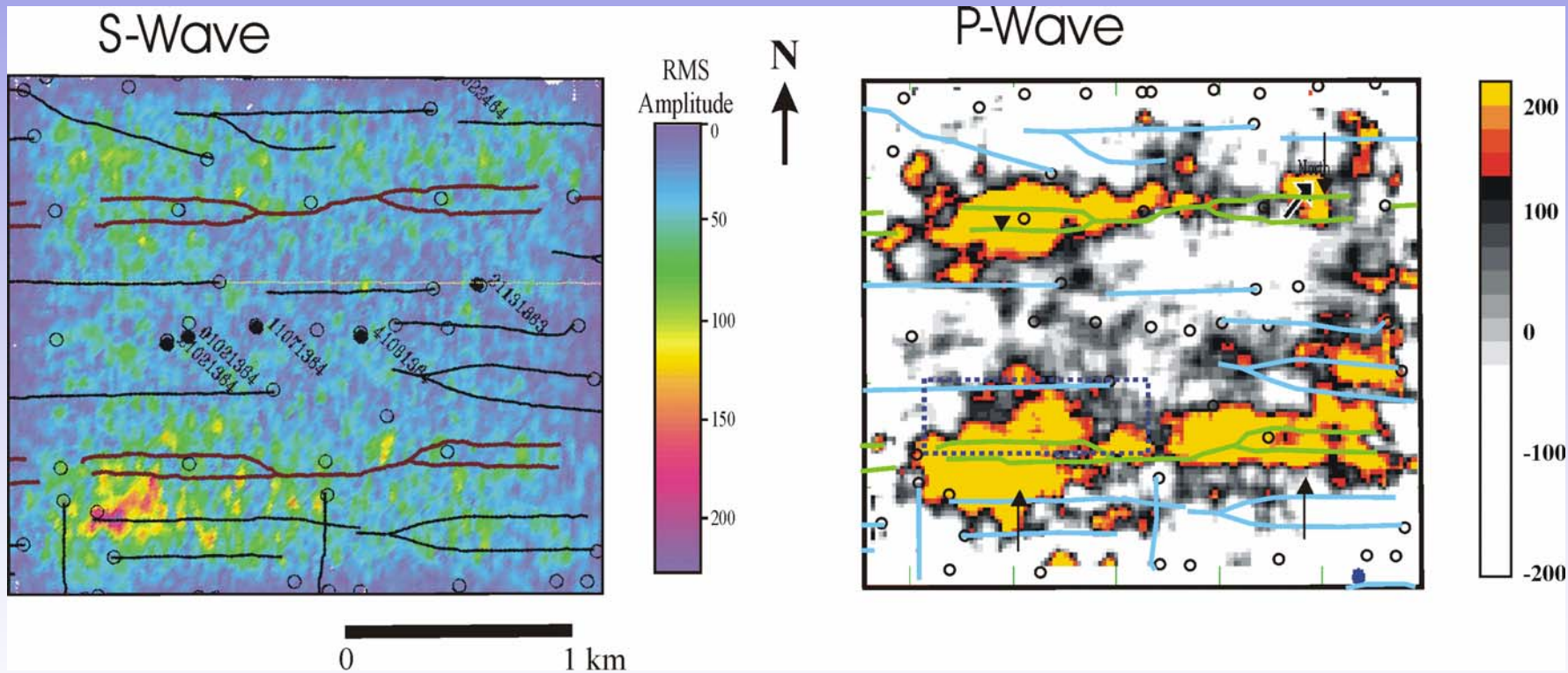
Shear Wave Splitting



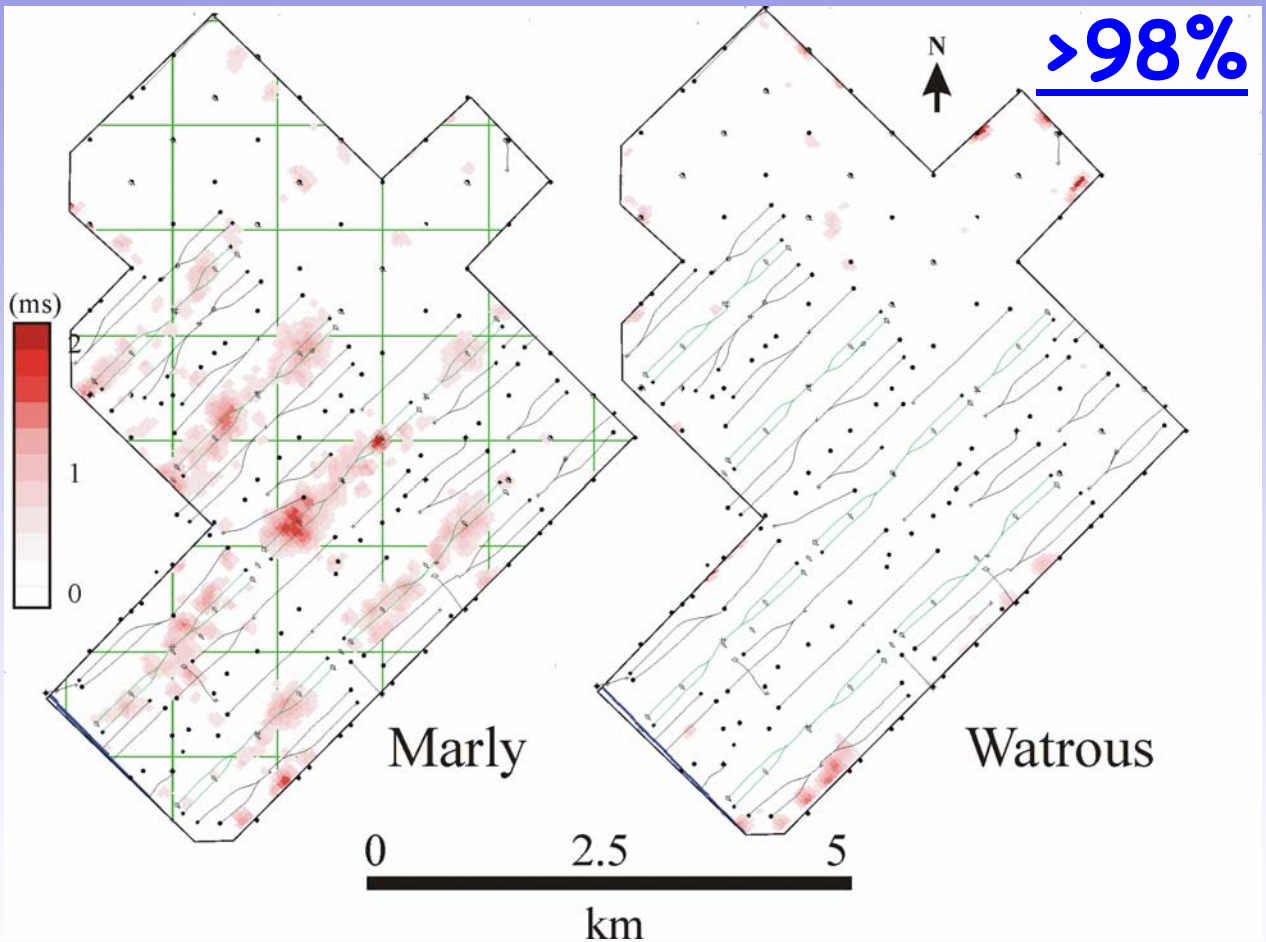
S-Wave Splitting



S-wave vs. P-wave Amplitude Difference Anomalies

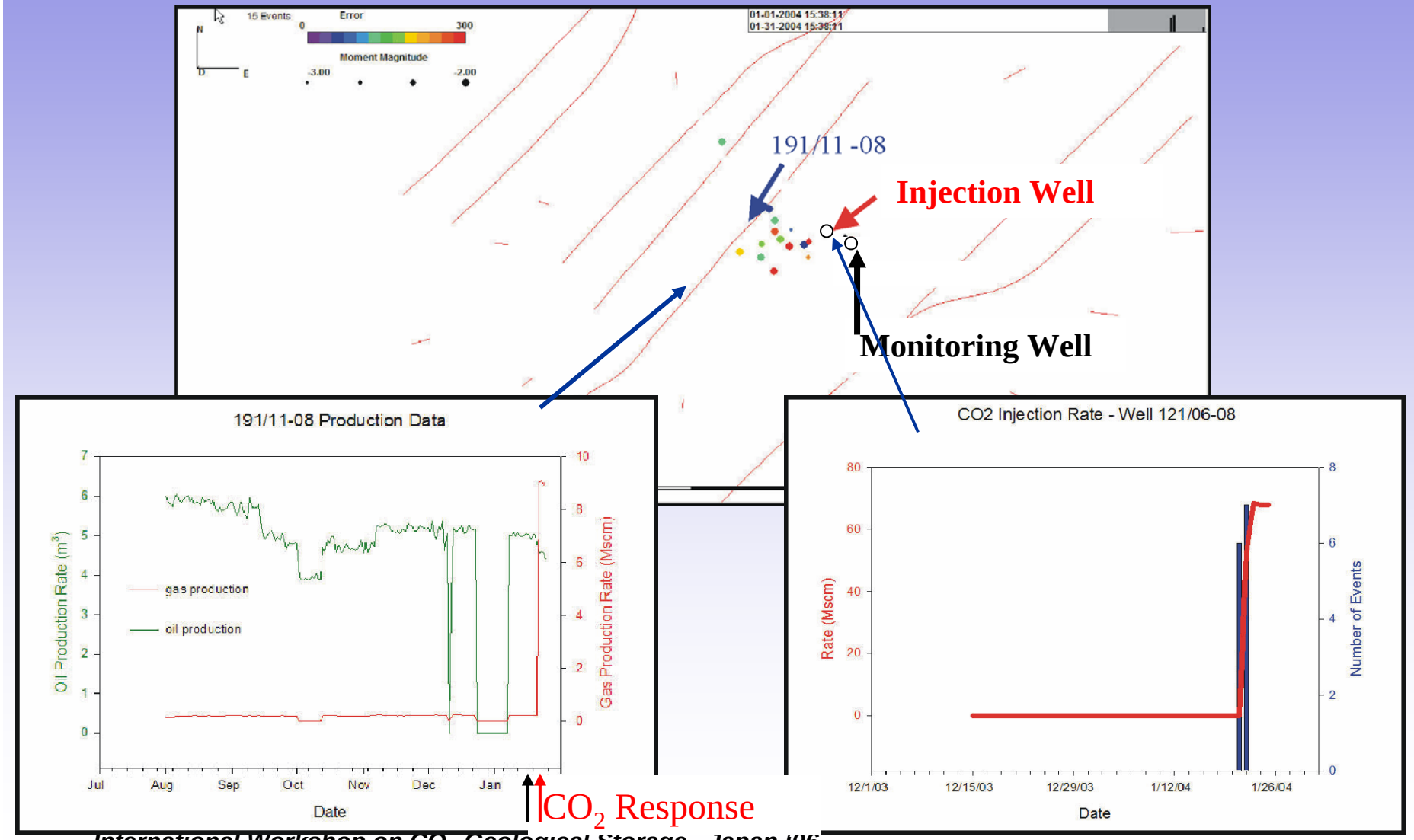


Repeatability



>98%

Microseismicity: Plan View

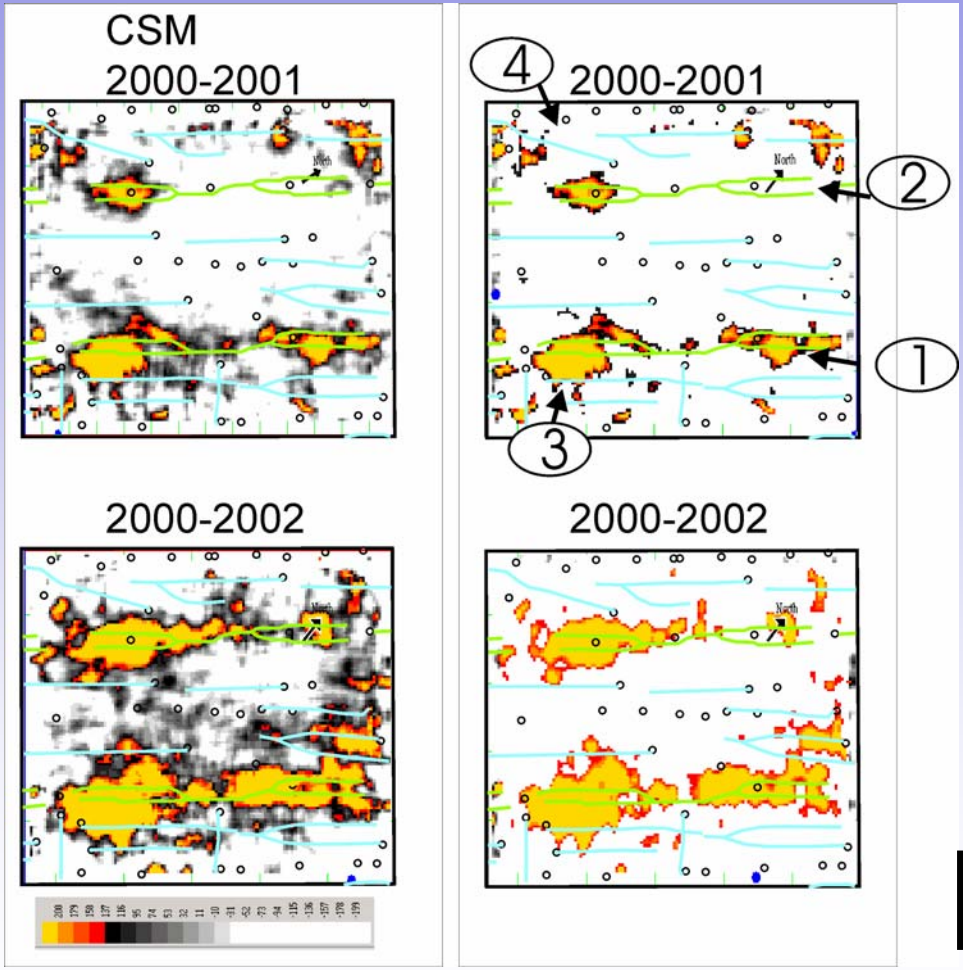


CO_2 Response

Start of Injection

4. Volume Estimation

First-Order Volumetrics



Reservoir Properties:

T=63 deg C

P= 15 MPa

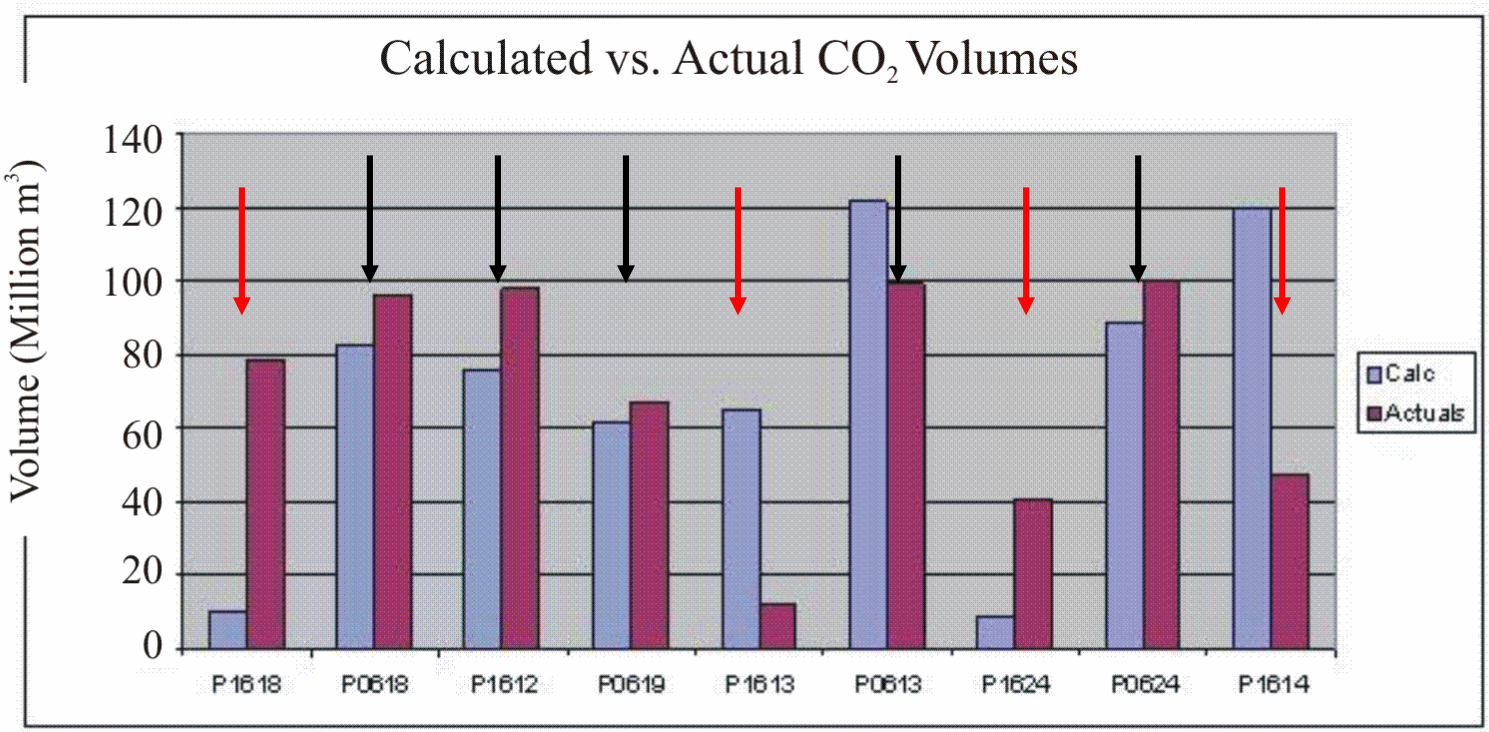
Porosity=0.13

Thickness=23 m

Injector Area	2001 Seismic vol./CO2 vol. Ratio	2002 Seismic vol./CO2 vol. Ratio
1	**5.3**	**6.3**
2	**8.6**	**12.6**
3	**5.4**	**6.2**
4	**3.1**	**4.0**
Total	**4.6**	**5.5**

Mean Saturation=0.19-0.23

Net CO_2 injected vs seismic estimate



Assumes average Sg of 0.20

Summary & Conclusions

- **Monitoring methods** clearly show physical and effects associated with CO_2 injection.
- **Seismic** methods show **robust time and amplitude anomalies**.
  - P-wave amplitudes are highly sensitive to CO_2-rich gas phase at low levels of **saturation (5-10%); good for detection**, but makes volume estimation difficult.
  - Volumetric analysis of seismic anomalies: **mean CO_2 saturation of ~20%**, similar to reservoir simulator results.
  - Vp changes of up to 12%: **mainly Sg** with **secondary P effects (2-3%)**.
  - Off-trend anomalies identify areas of **CO_2 channelling.**
  - Sensitivity of amplitude response to upper reservoir changes (Marly unit) allows **partial discrimination of vertical CO_2 distribution.**

Summary & Conclusions

- **1.4 million m^3 (2500 tonnes)** of CO_2 is the **minimum detectable amount** using time-lapse surface seismic. This estimate may be overly conservative by an order of magnitude.
- **No evidence for CO_2 escaping** from the reservoir. Based solely on the seismic results, the maximum amount of CO_2 that may have migrated above the reservoir is **<2% of the total injected volume.**
- Contribute to more **accurate reservoir flow simulations.**

- **Microseismicity** is **low** level.
  - 60 microseismic events with M=–3 to –1 during 6-months.
  - Events associated with production/injection changes (*e.g.*, water-to-gas) where **pressure transients** might be expected.
  - Induced microseismicity is **less than for water flooding** that has occurred for more than 30 years.

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IEA Weyburn CO_2 Monitoring and Storage Project

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

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Petroleum Technology Research Centre

QUESTIONS ?

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