Methods for the Prediction, Monitoring and Verification of CO_2 Movement: The IEA GHG Weyburn CO_2 Monitoring and Storage Project

Don White, Geological Survey of Canada

Acknowledgement of Sponsors

Natural Resources Canada

Ressources naturelles Canada

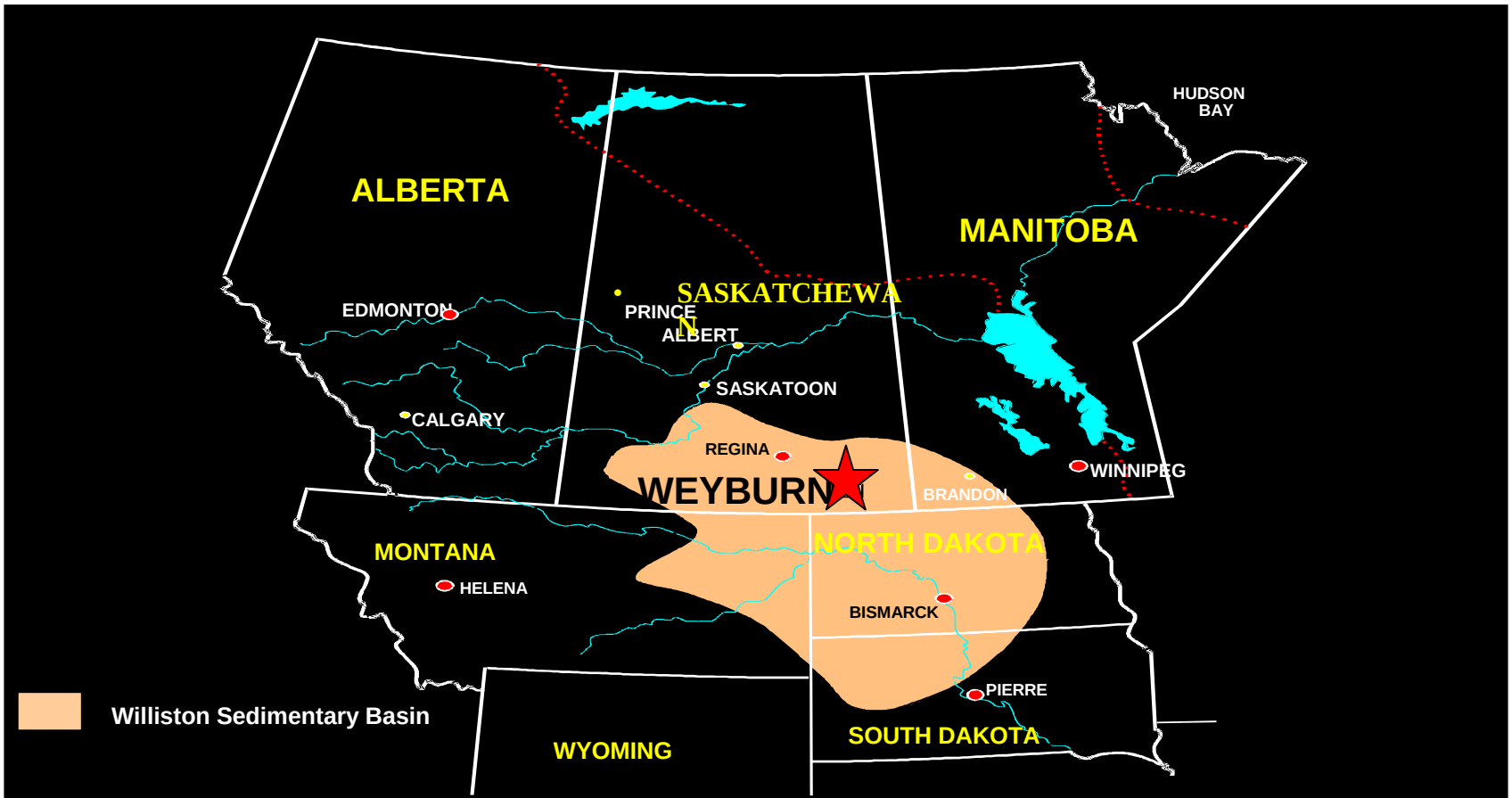
- **Other Sponsors**
- SaskPower
- Nexen Canada Ltd
- TotalFinaElf
- BP
- Dakota Gasification Co.
- TransAlta Utilities
- ENAA (Japan)
- European Union
- Saskatchewan Industry & Resources
- Alberta Energy Research Institute

Acknowledgements

- **Tom Davis**, Colorado School of Mines
- **Ernie Majer**, Lawrence Berkeley National Laboratory
- **Keith Hirsche**, Hampson-Russell Software
- **Ian Hutcheon, Maurice Shevalier**, U. Calgary
- **Ernie Perkins, David Law,** Alberta Research Council
- **Roberto Bencini**, INGV, Italy
- **Shawn Maxwell**, Engineering Seismic Group
- **Geoff Burrowes, Sandy Graham, Ryan Adair, David Cooper, David Hassan, Guoping Li**, EnCana

1. The IEA Weyburn Project

Weyburn Field



Weyburn Unit:

Field Size: 70 sq. miles

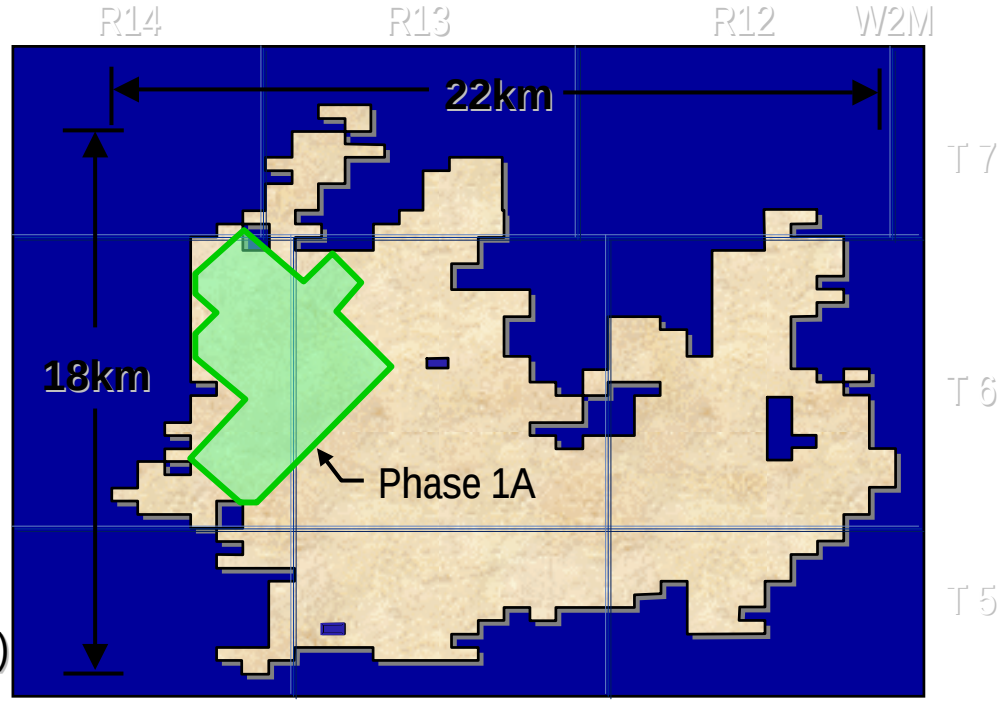
Oil Recovered: 370 million bbls

OOIP: 1.4 billion bbls

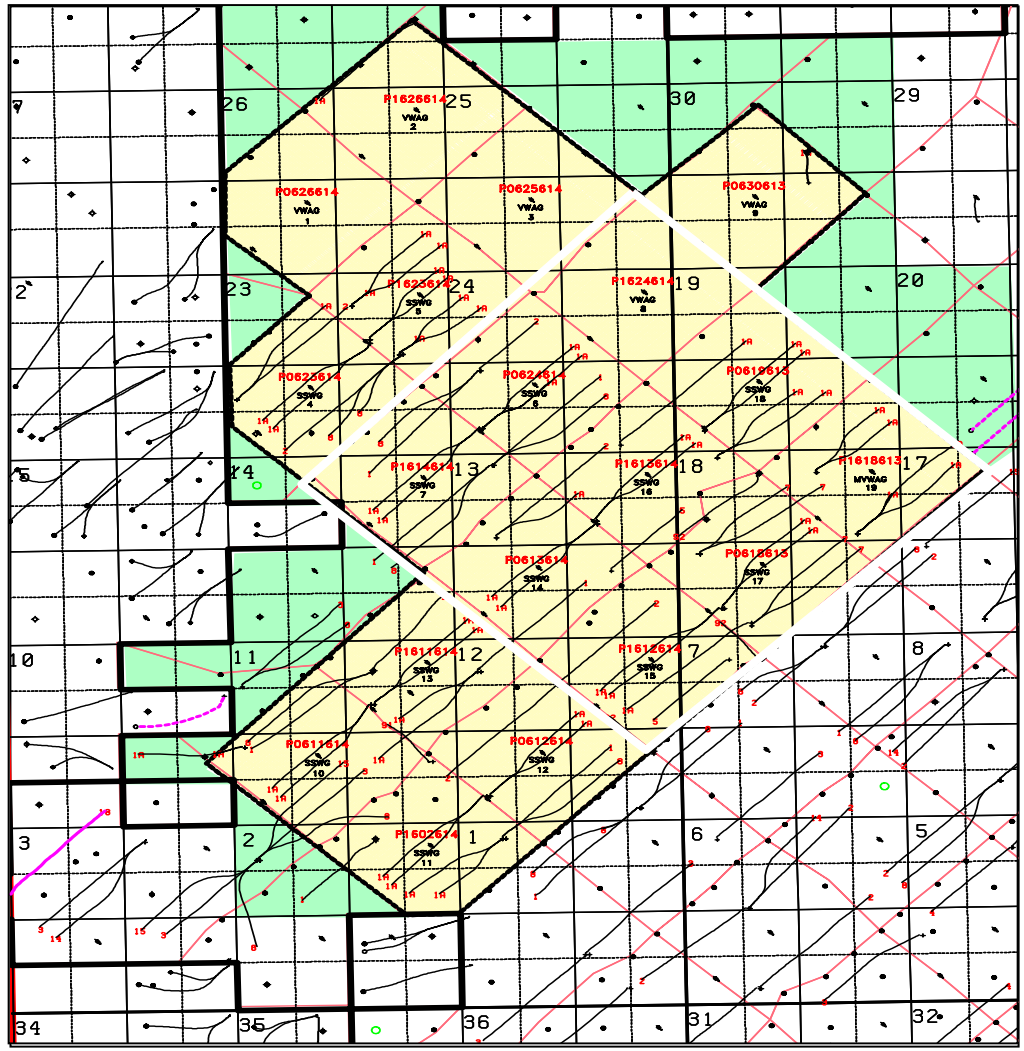
CO2 IR: 130 million bbls

Weyburn Field: Phase 1A EOR Area

Producing Fm.	Mississippian, Midale
Discovered:	1954
Area:	70 sq. miles
Current oil rate:	22,000 BOPD
Number of wells:	1072 total
	660 vert. oil
	200 hz. oil
	197 vert. inj.
	15hz. inj.
Sour crude:	25-34 API
Depth:	1450m (4760 ft)
OOIP:	1,400 MMbbls
Cum. Prod. (02/01):	360 MMbbls
Total recovery to date:	26%

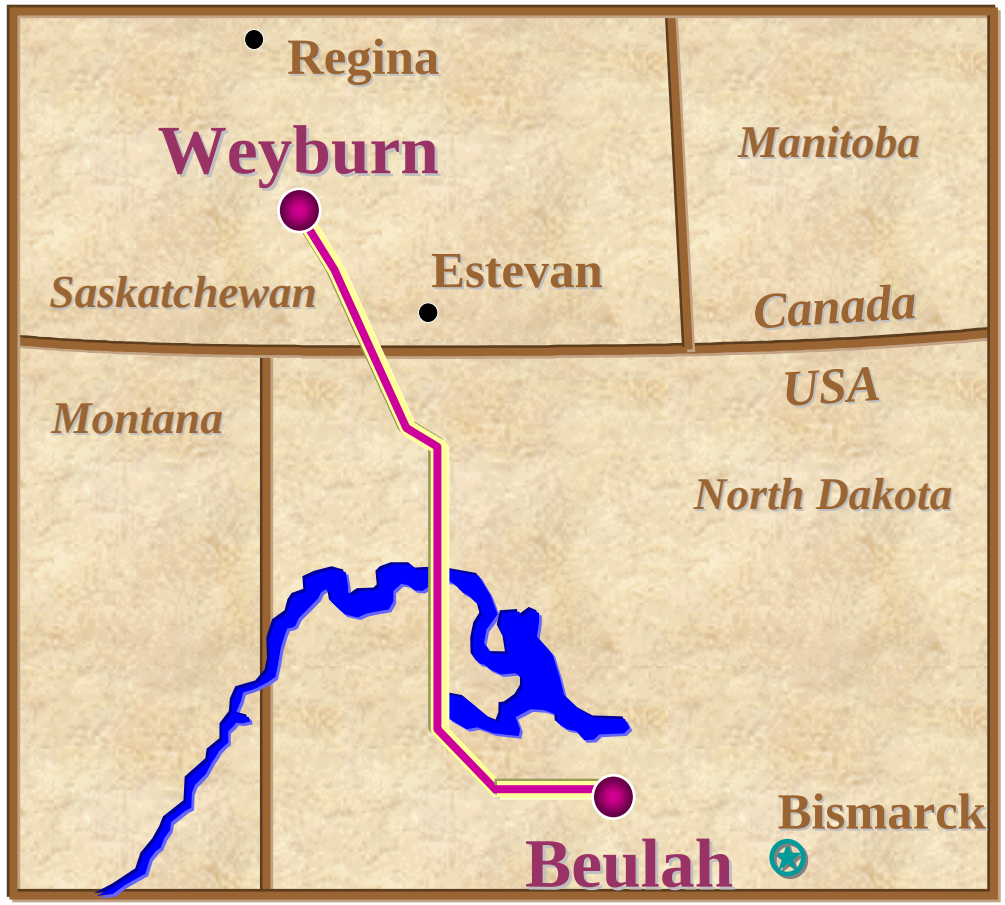


Weyburn Field: Phase 1A EOR Area

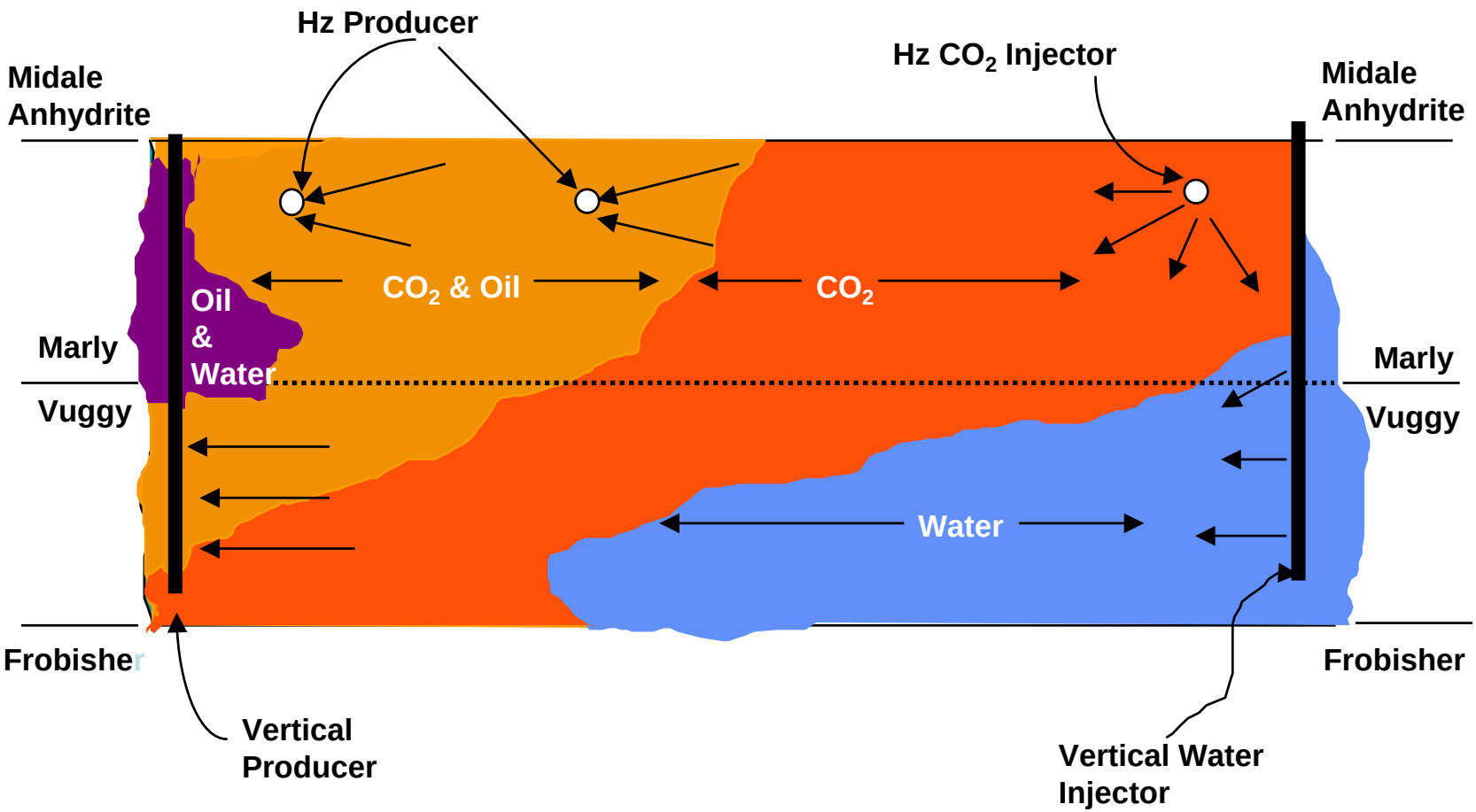


The Source of CO_2

- 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)



The CO2 Flood

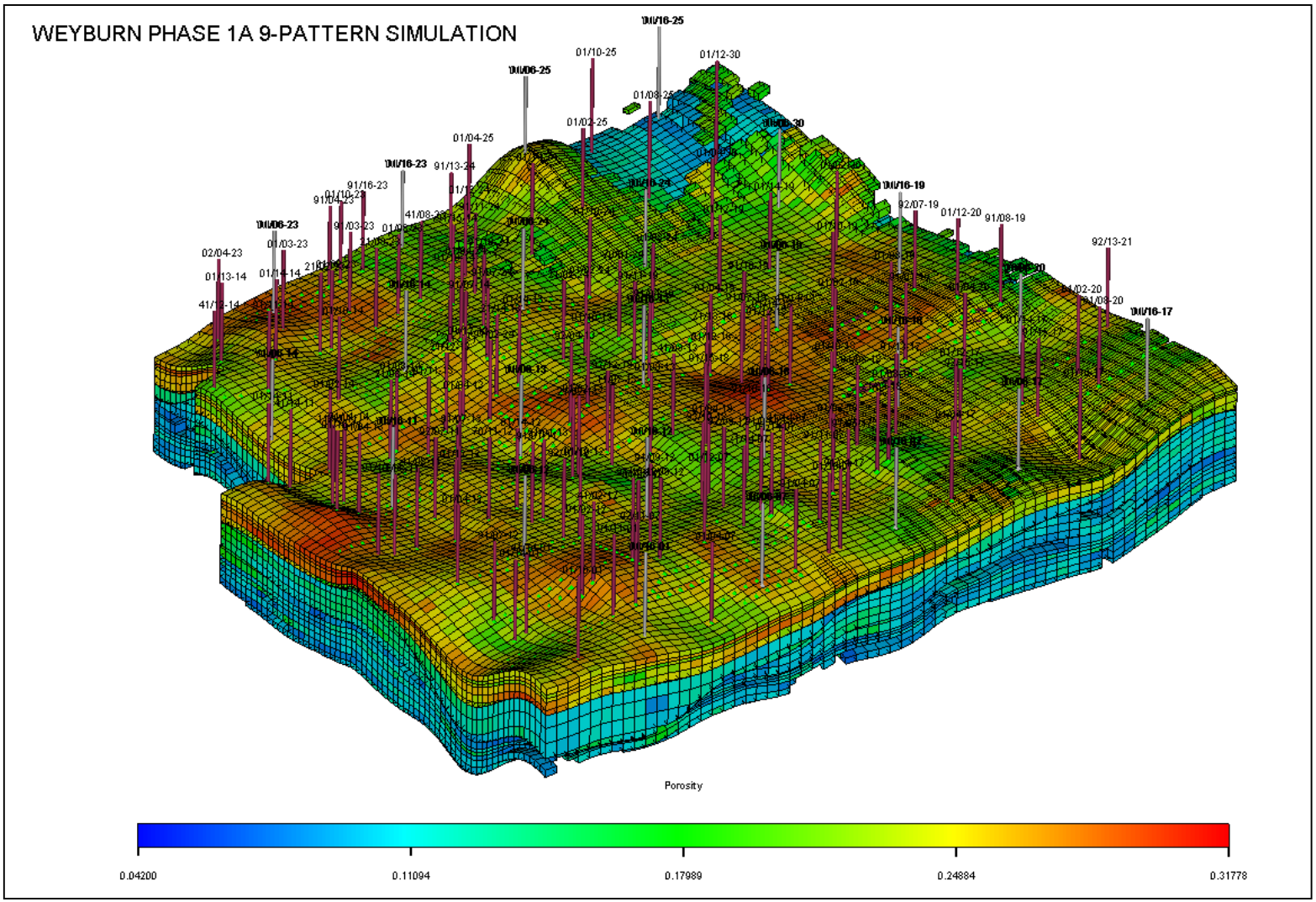


Objectives

- Test and develop methods for monitoring CO_2 injection.
- Enhance conformance control through improved reservoir characterization and prediction.
- Verify volumes of CO_2 in the subsurface.
- Establish safety and containment of injected CO_2.

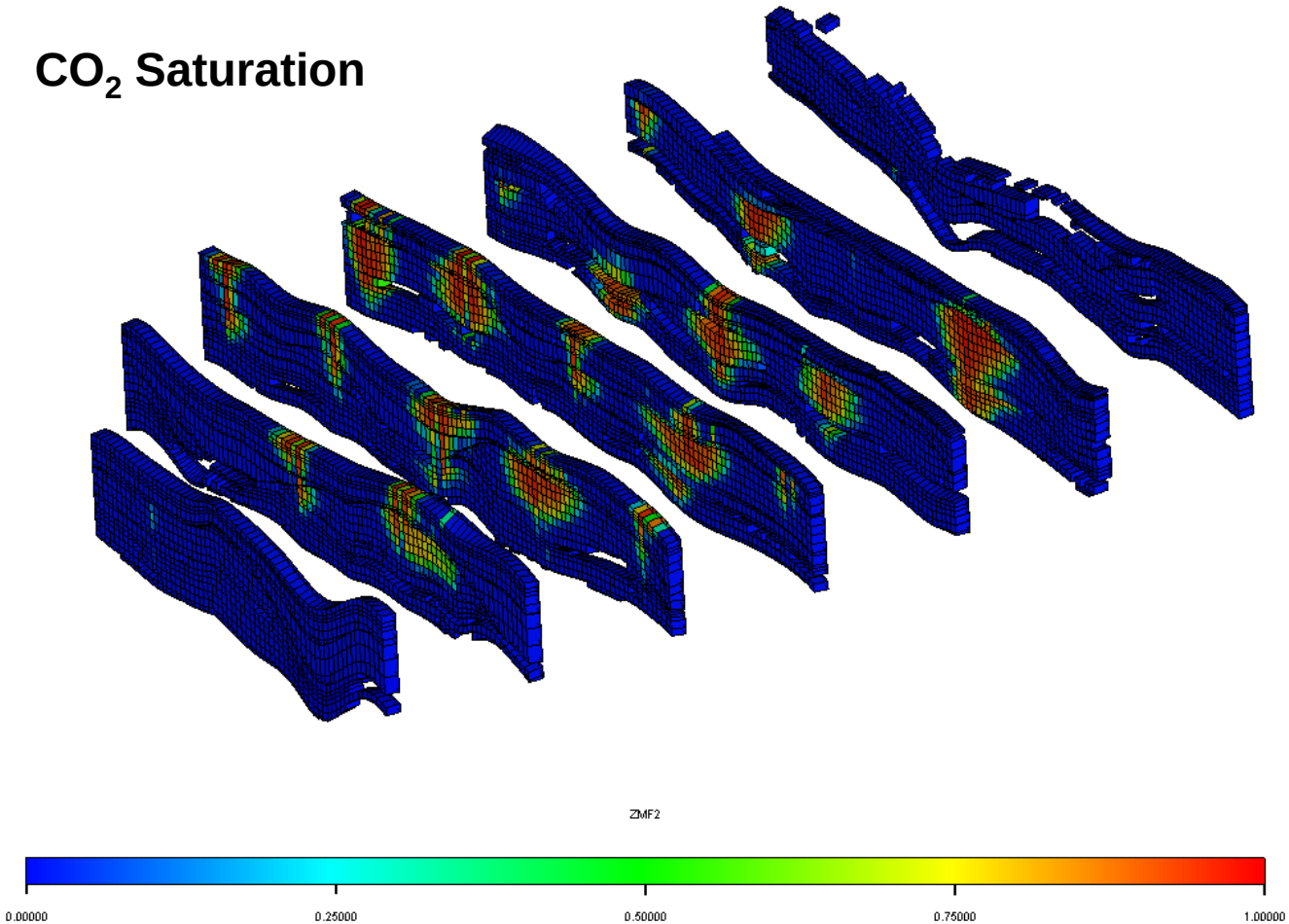
2. Pre-Injection Prediction

Pre-injection Prediction 1

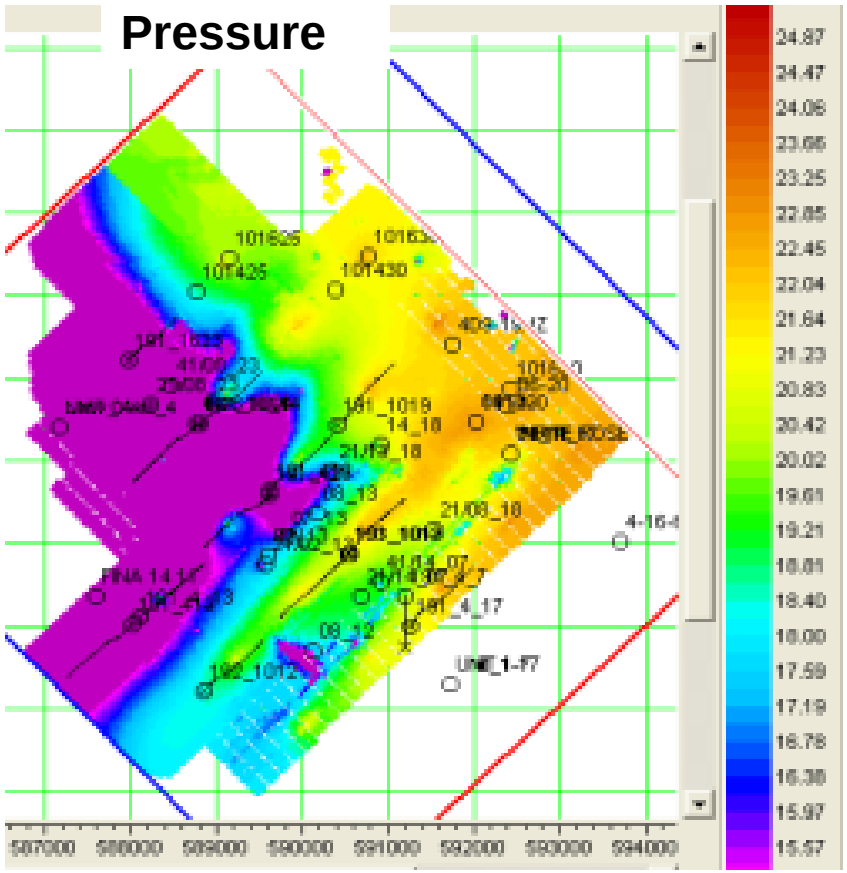


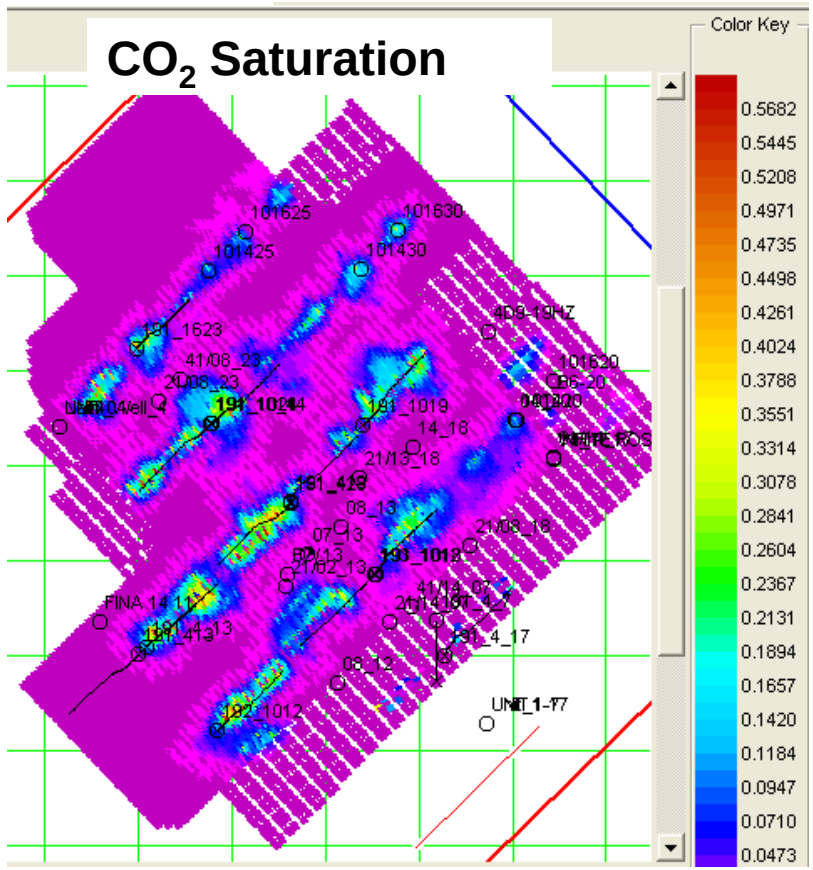
Pre-injection Prediction 2

WEYBURN PHASE 1A 9-PATTERN SIMULATION

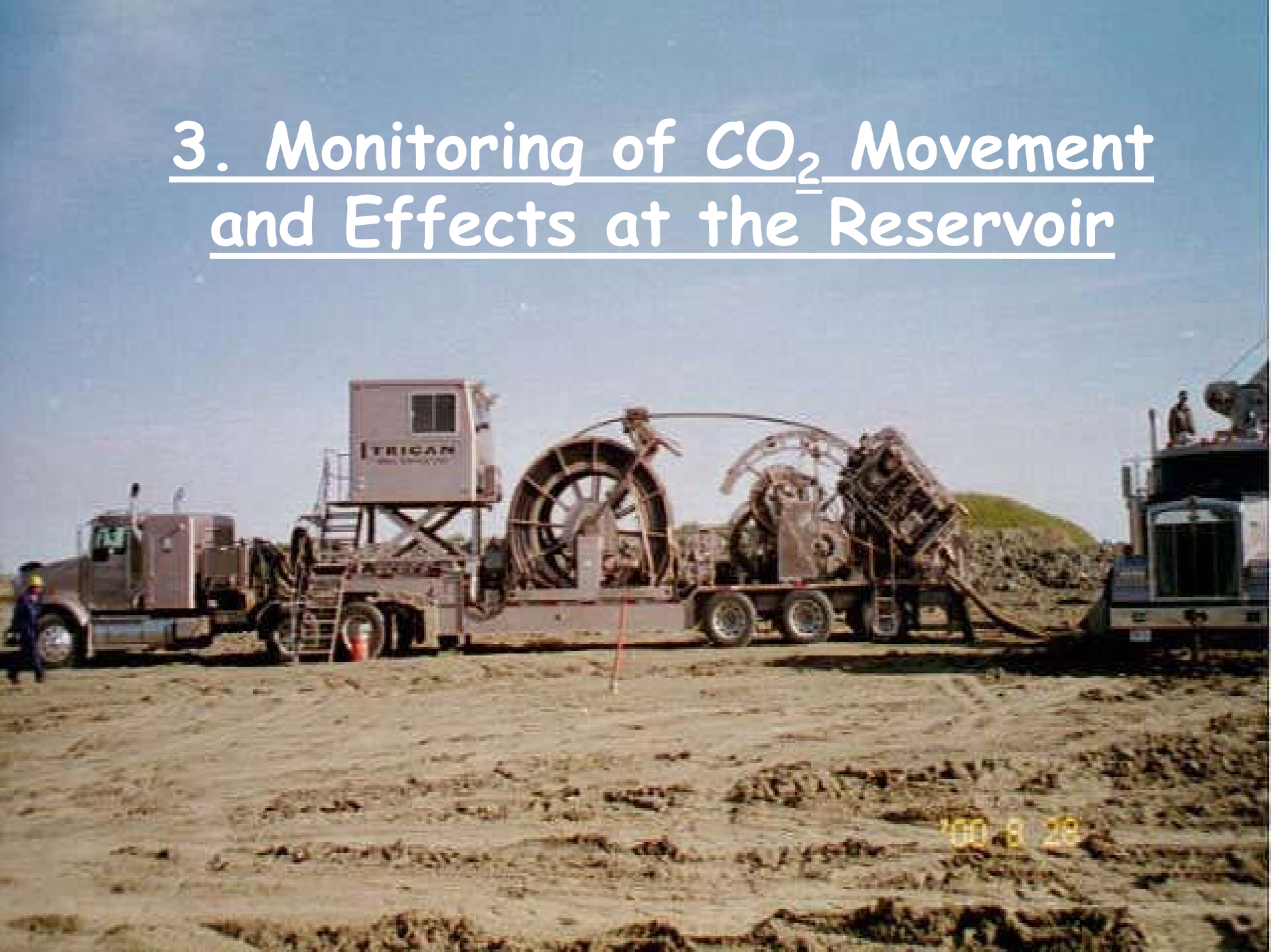


Pre-injection Prediction 3





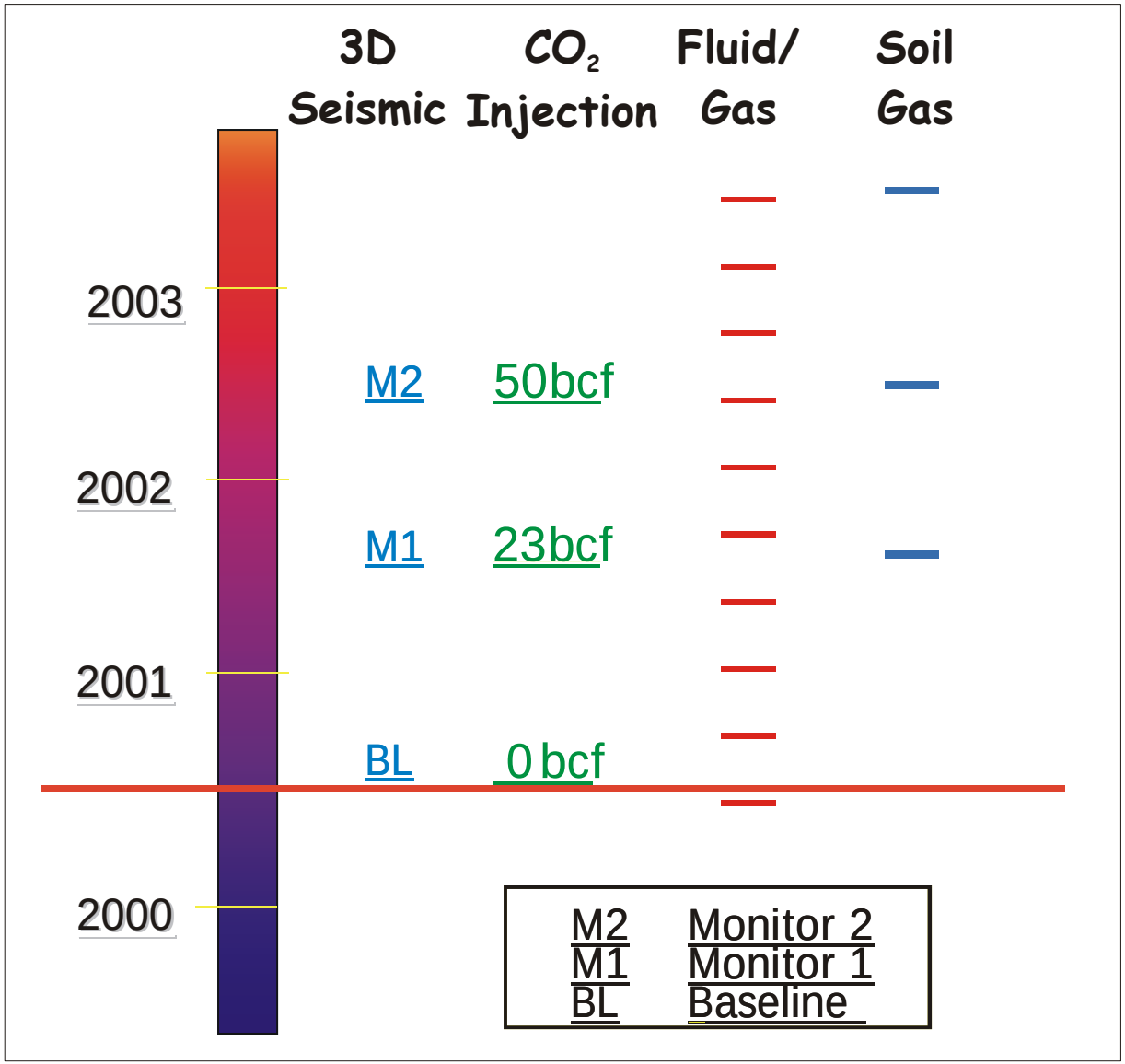
3. Monitoring of CO_2 Movement and Effects at the Reservoir



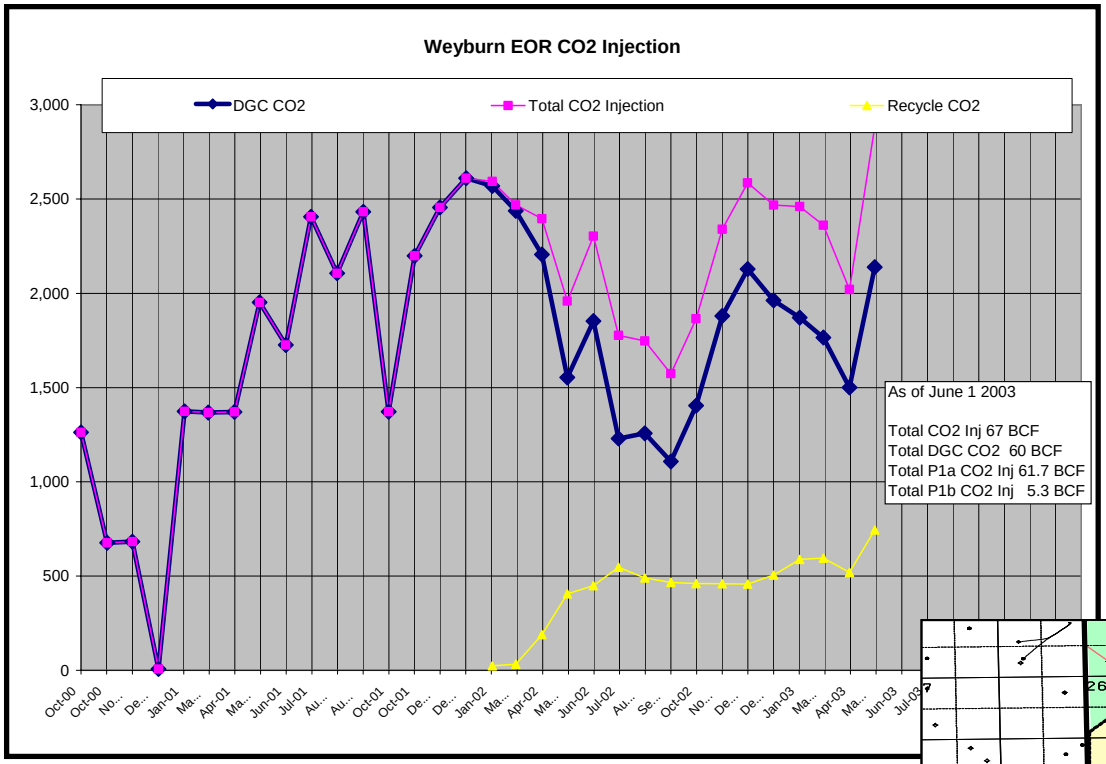
Monitoring Techniques

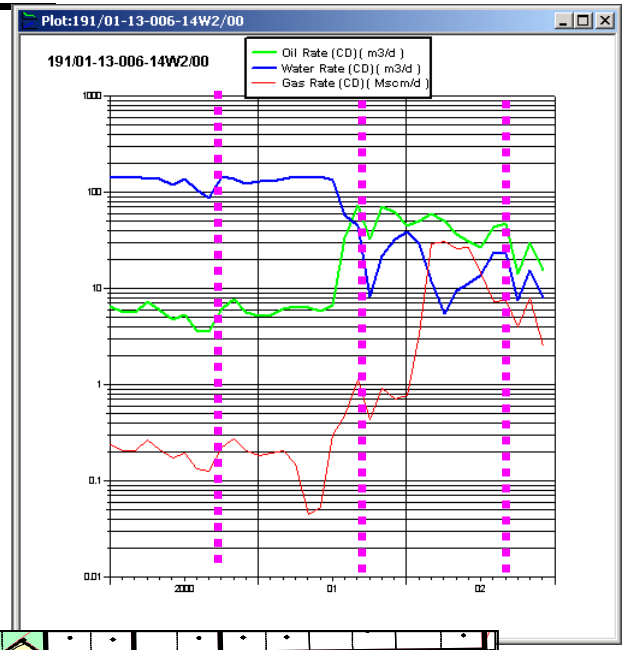
- Production Data
- Geochemistry of Production Fluids/Gases
- 3D Multi-component Time-Lapse Seismic
- Passive Microseismic Monitoring
- Soil Gas Sampling

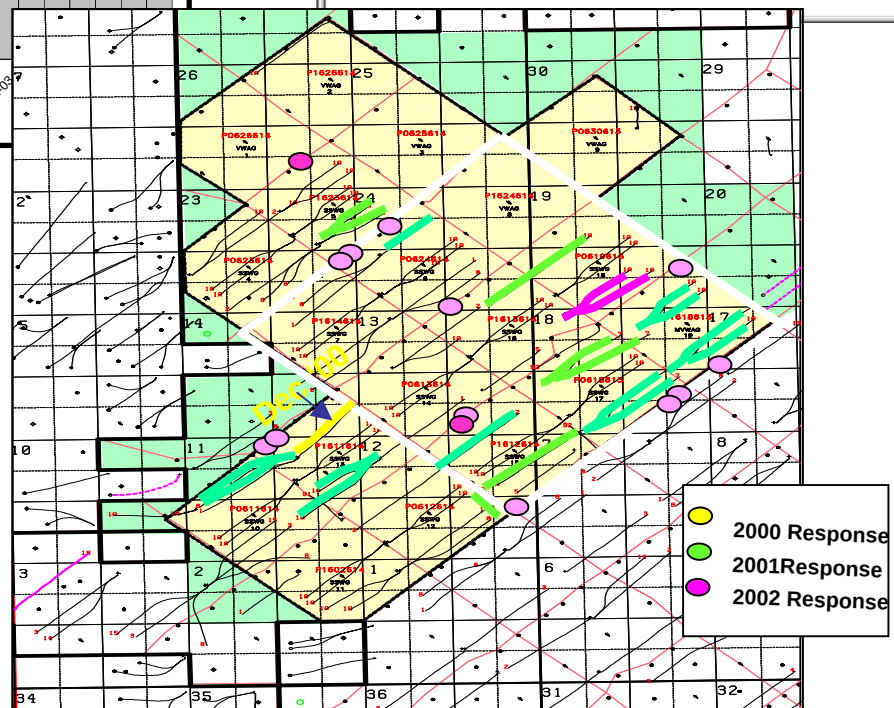
Monitoring Schedule



Production Data





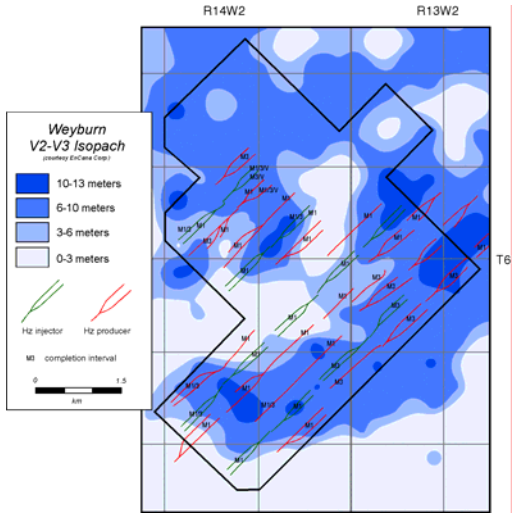


Geochemistry of Production Fluids

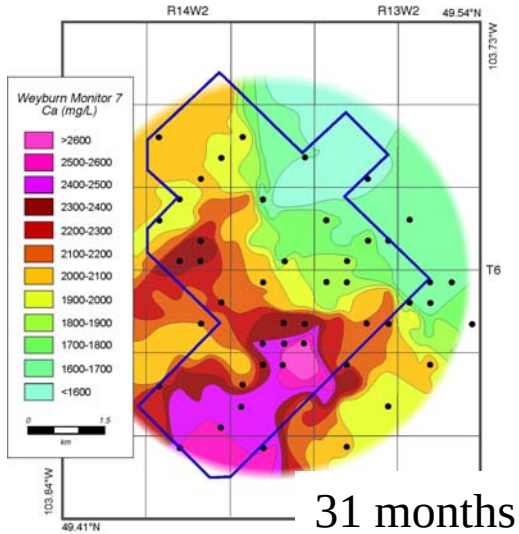
Average values of selected geochemical parameters for the Weyburn pilot injection area.

	Pre-Injection (n=41)		930d of Injection (n=63)		
	avg.	*s.d.*	*avg.*	*s.d.*	% change
measured pH	6.7	0.2	6.7	0.3	-1
Total Alk. (mg/L)	428.8	103.9	1093.8	375.2	155
Ca (mg/L)	1371.9	186.0	1912.8	298.0	39
Mg (mg/L)	373.8	27.2	597.2	69.3	60
Resist. (ohm m)	0.149	0.023	0.104	0.014	-43
$d^{13}C$-HCO_3	-2.8	2.7	-5.7	4.7	n/a
Cl (mg/L)	38443.0	7929.8	39534.1	7410.4	3
SO_4 (mg/L)	3464.5	206.7	3595.7	251.6	4

Injected CO_2 and Reservoir Reaction
Follow the Vuggy



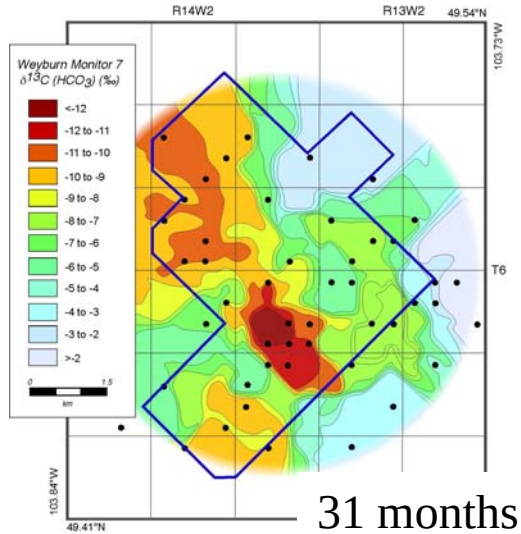
V2+V3
Vuggy Shoal



31 months

Ca Distribution

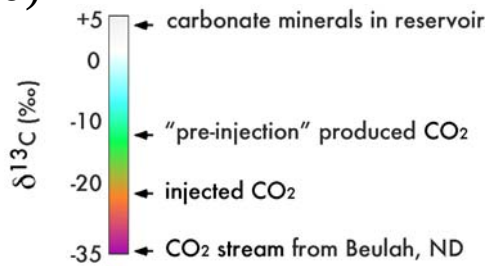
Calcite and dolomite dissolution increases the Ca^{2+} and Mg^{2+} concentrations in produced fluids.



31 months

δ ^{13}C Distribution

Injected CO_2 dissolution (decreasing $\delta^{13}C$ in produced fluid)

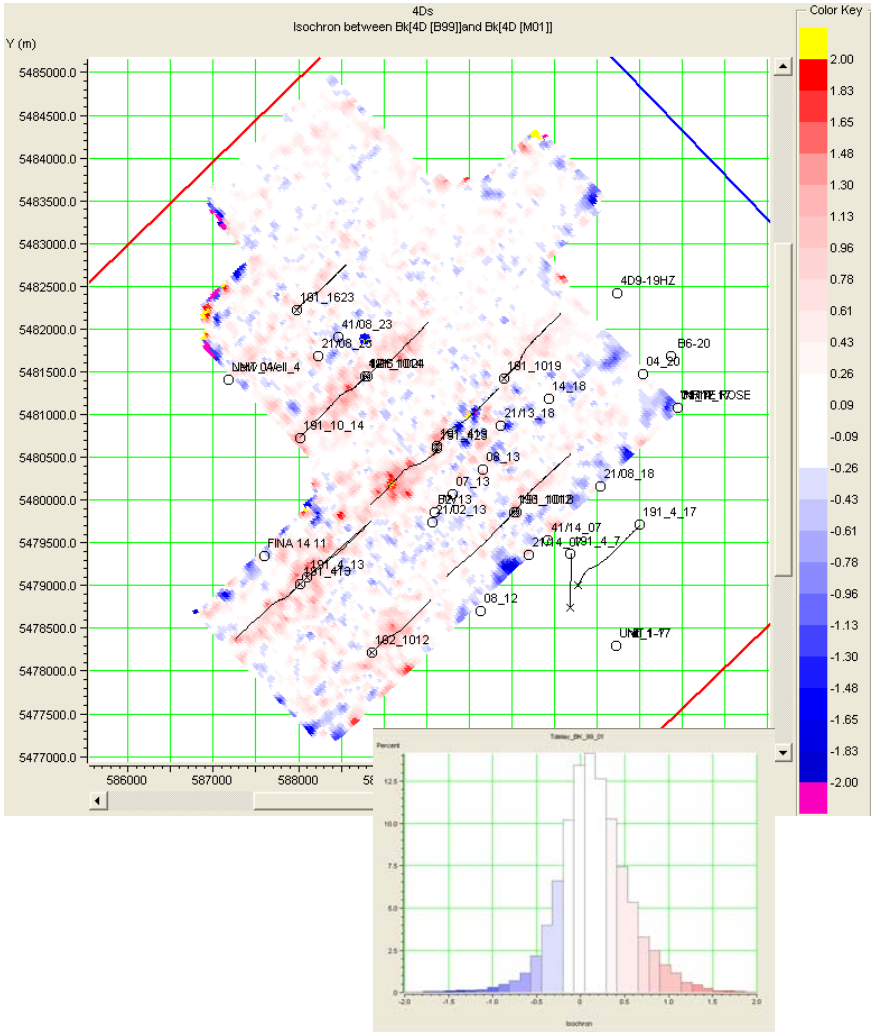


Time-Lapse Seismic

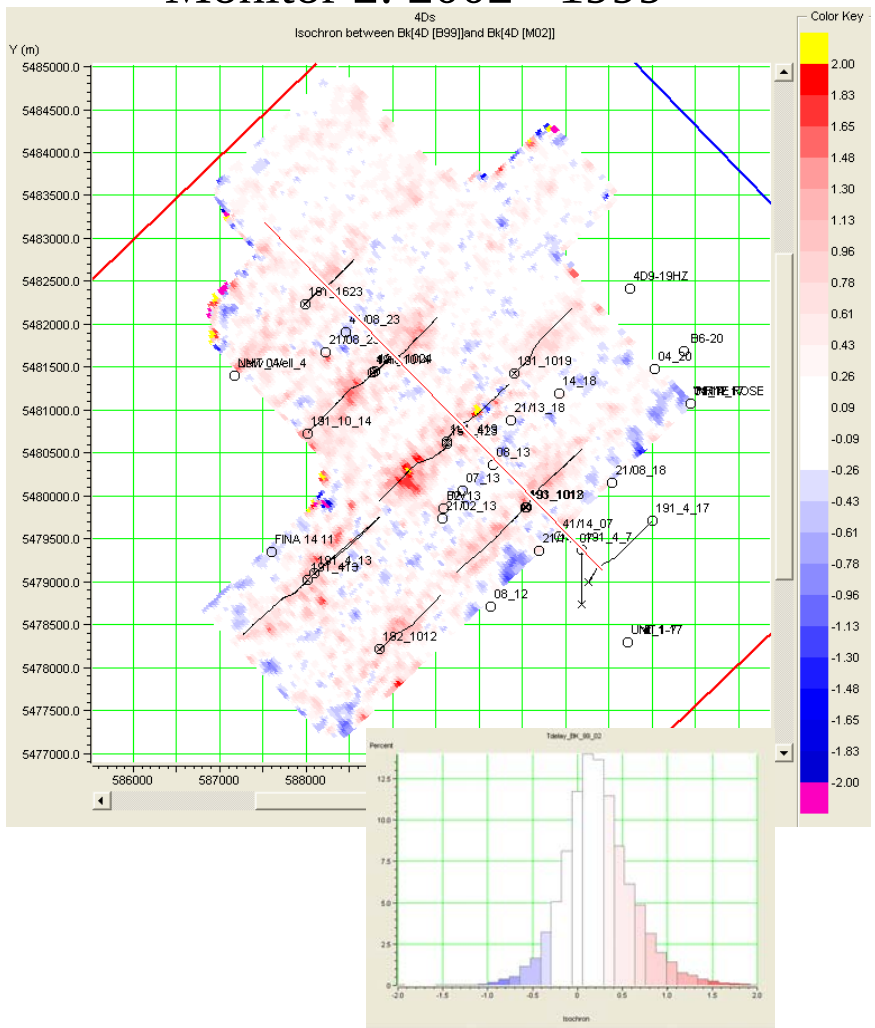
- P- and S-Wave
- Time delays
- Amplitude differences

Monitor 1 and 2 Time delay map

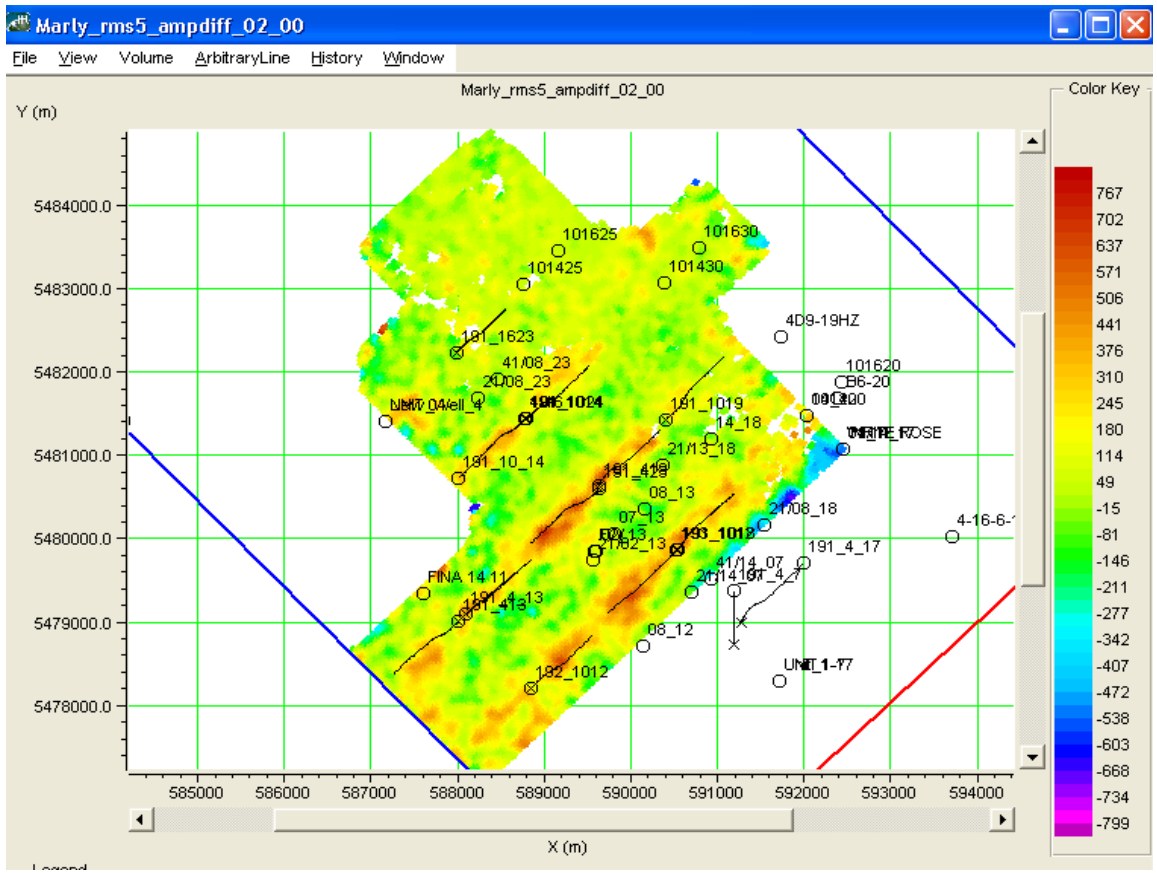
a) Time delay map at 1300 ms
Monitor 1: 2001 - 1999



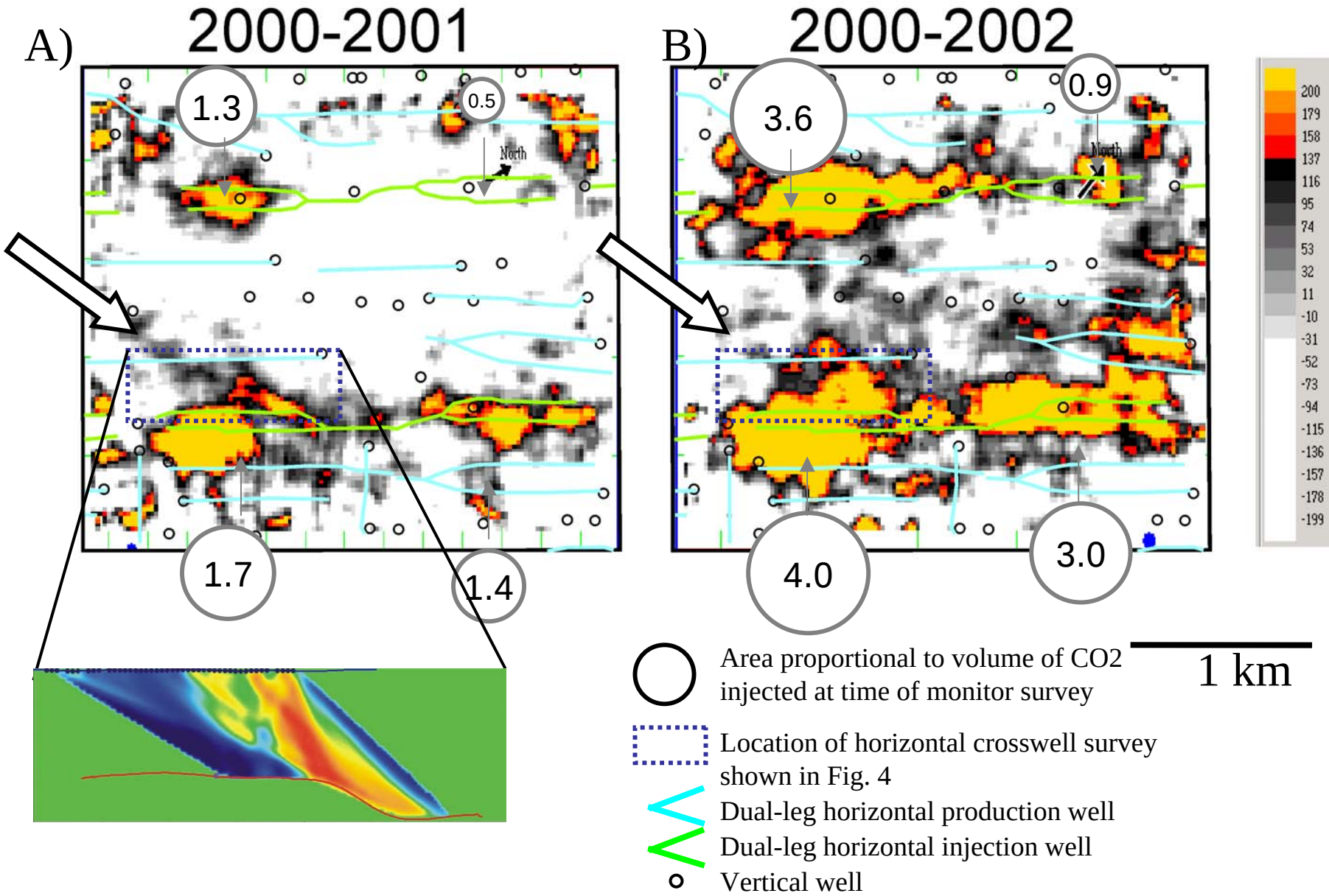
b) Time delay map at 1300 ms
Monitor 2: 2002 - 1999



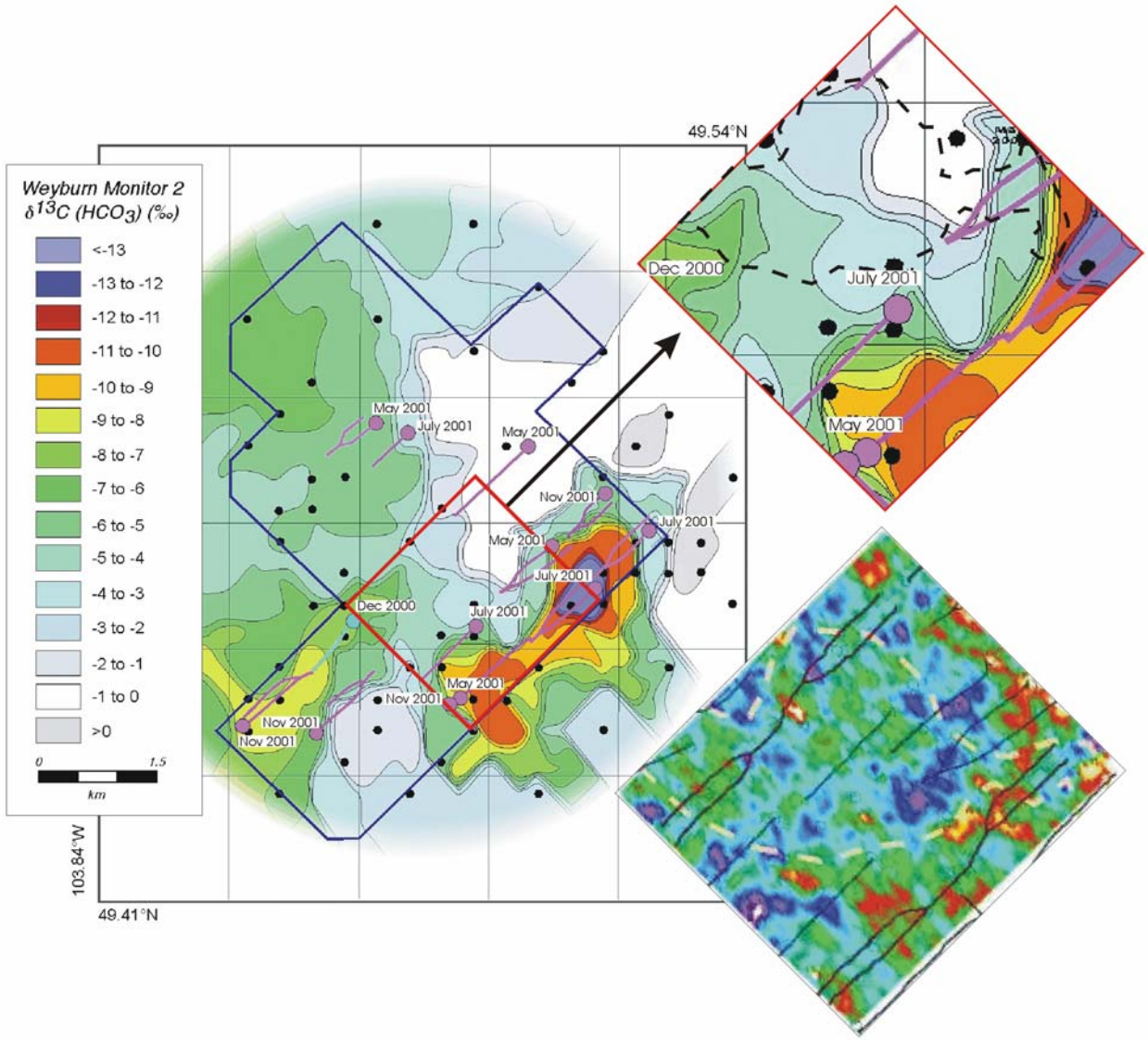
Monitor 2 (2002-2000) Amplitude difference at Marly



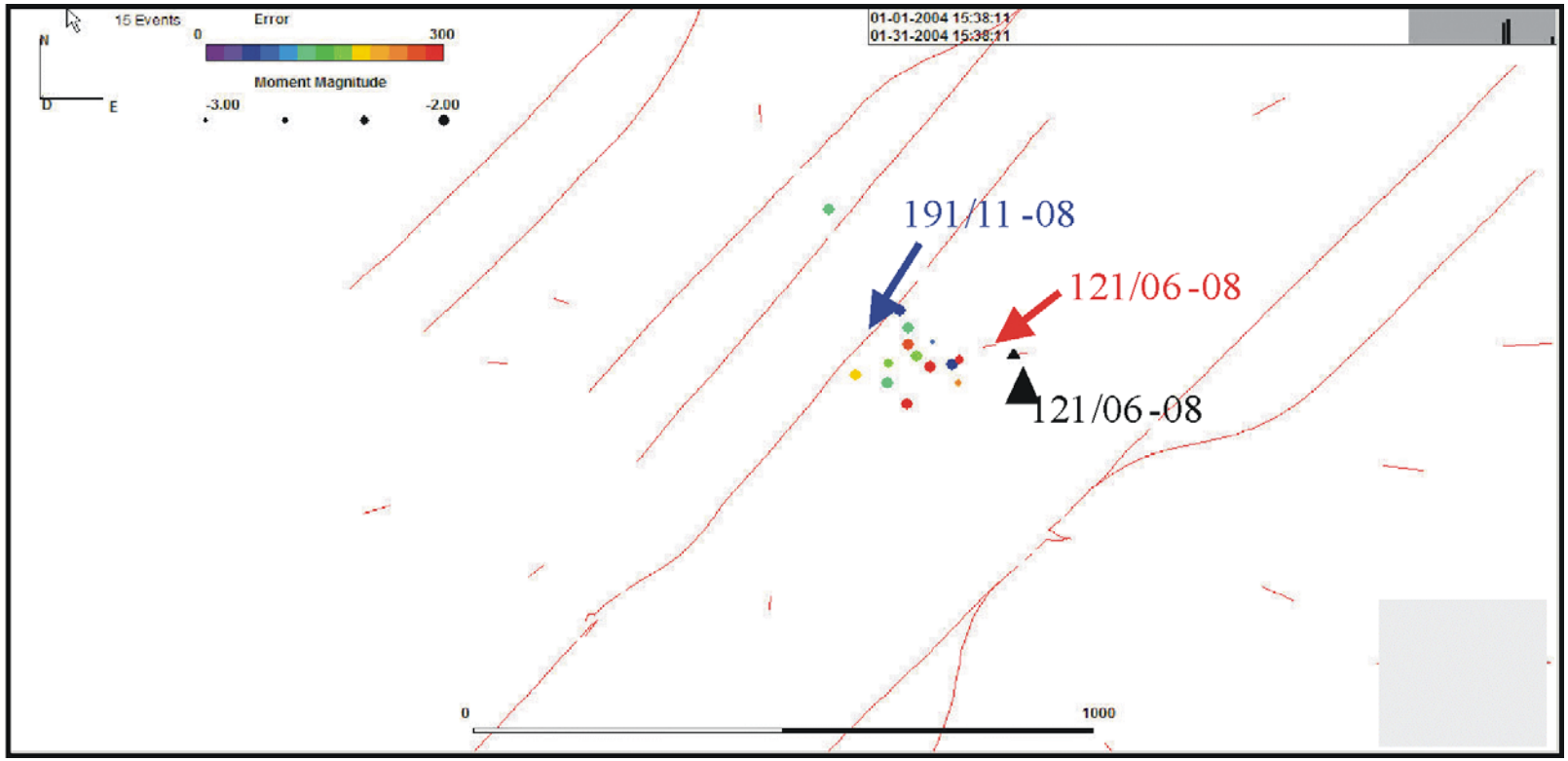
Amplitude Anomalies at the Reservoir

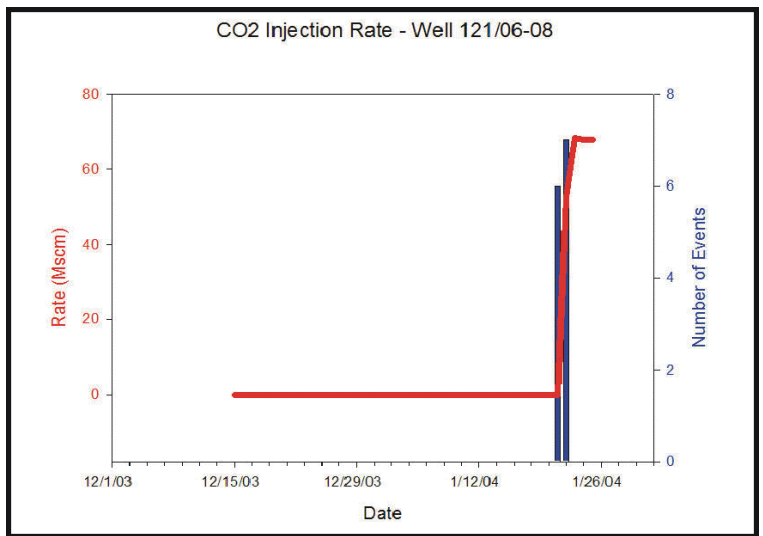


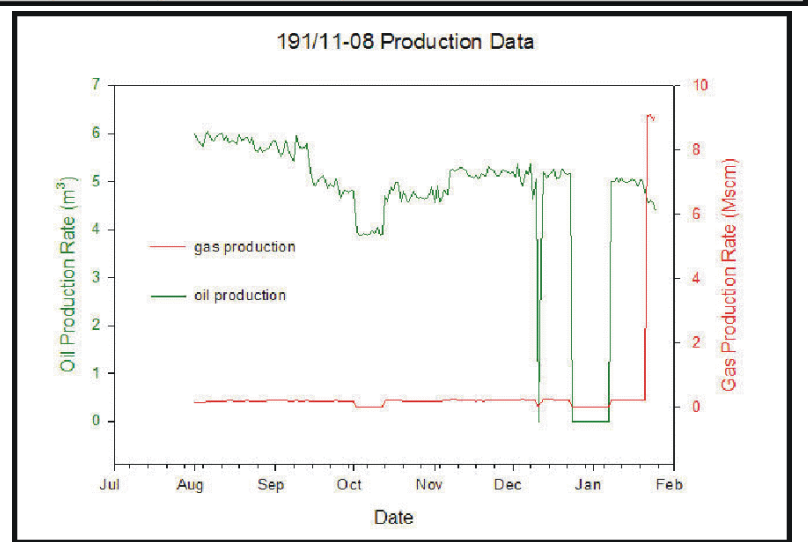
S-wave and Geochemical Anomalies



Microseismicity: Plan View







Soil Gas Survey

Is CO_2 leaking to the surface?

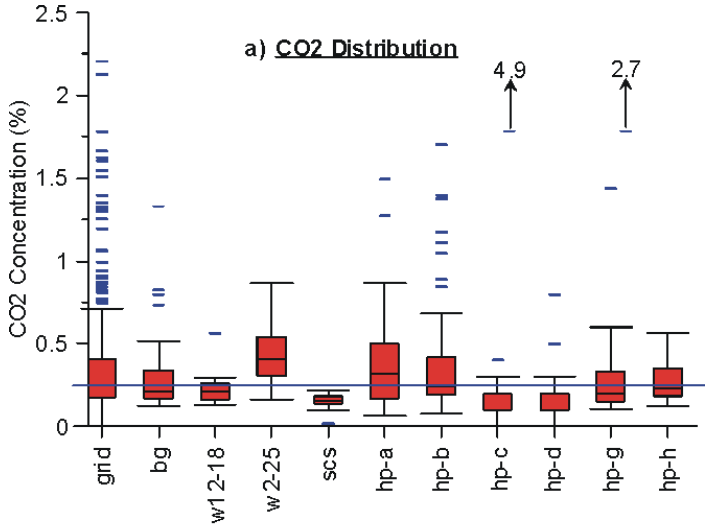
- Injection Site: detailed sampling over 3 years

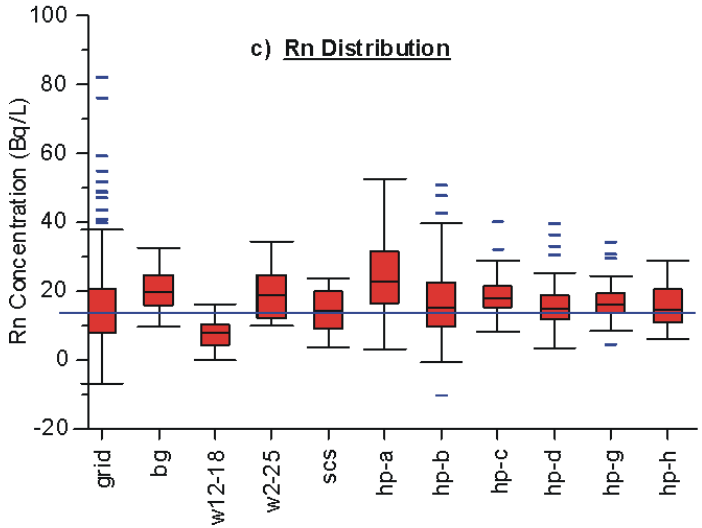
- Remote background Site
- Potential pathways: abandoned wells, river lineament, and salt collapse structure

Other Sites

- CO_2, O_2 and CO_2 flux values in the range of natural soils

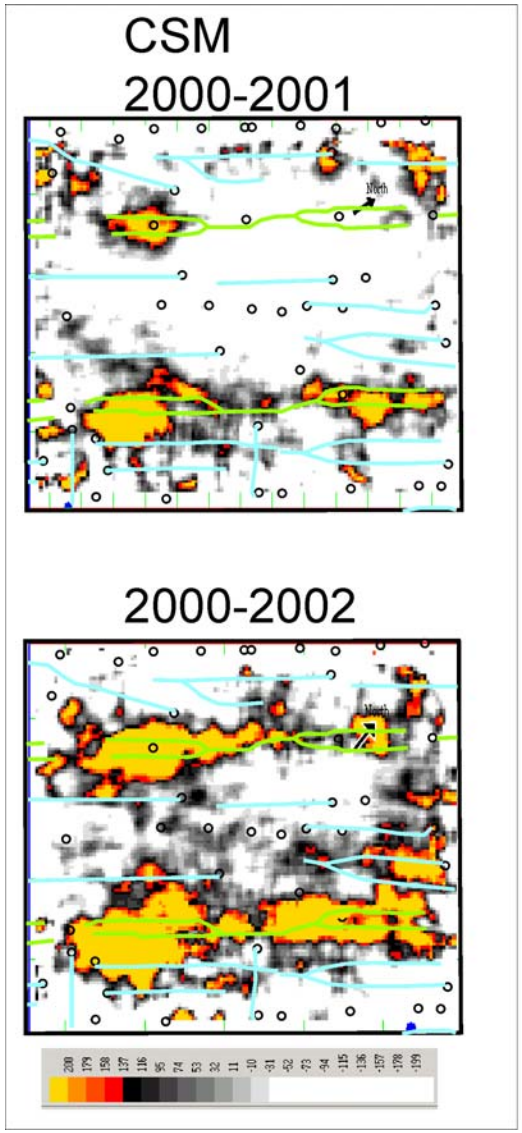
- Injection site has similar statistical distribution to background site.

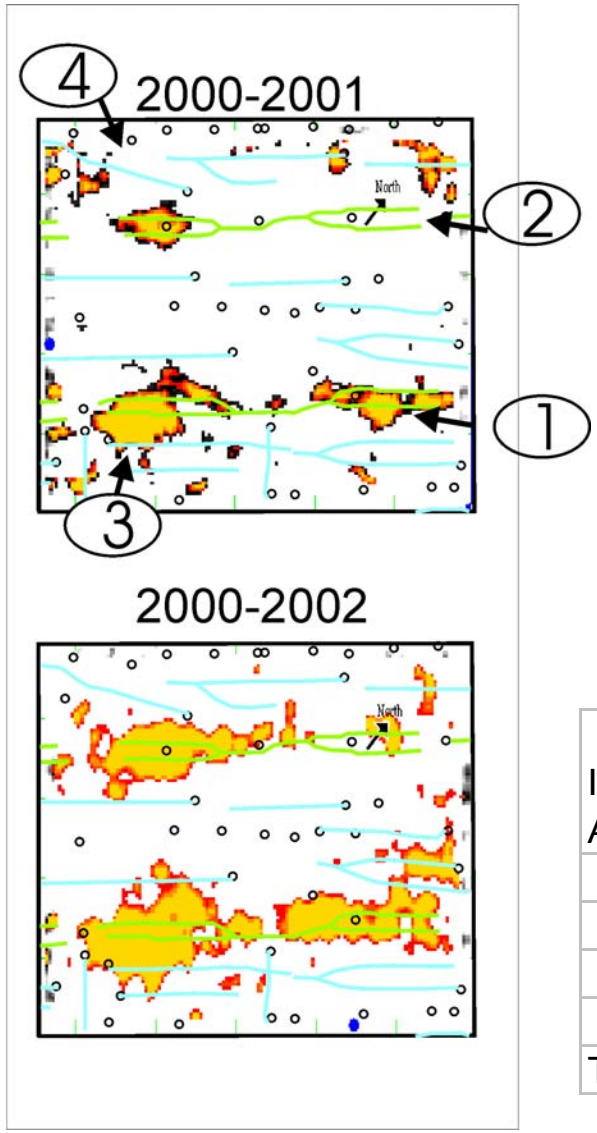




4. Verification & Improved Prediction

Preliminary Volumetrics





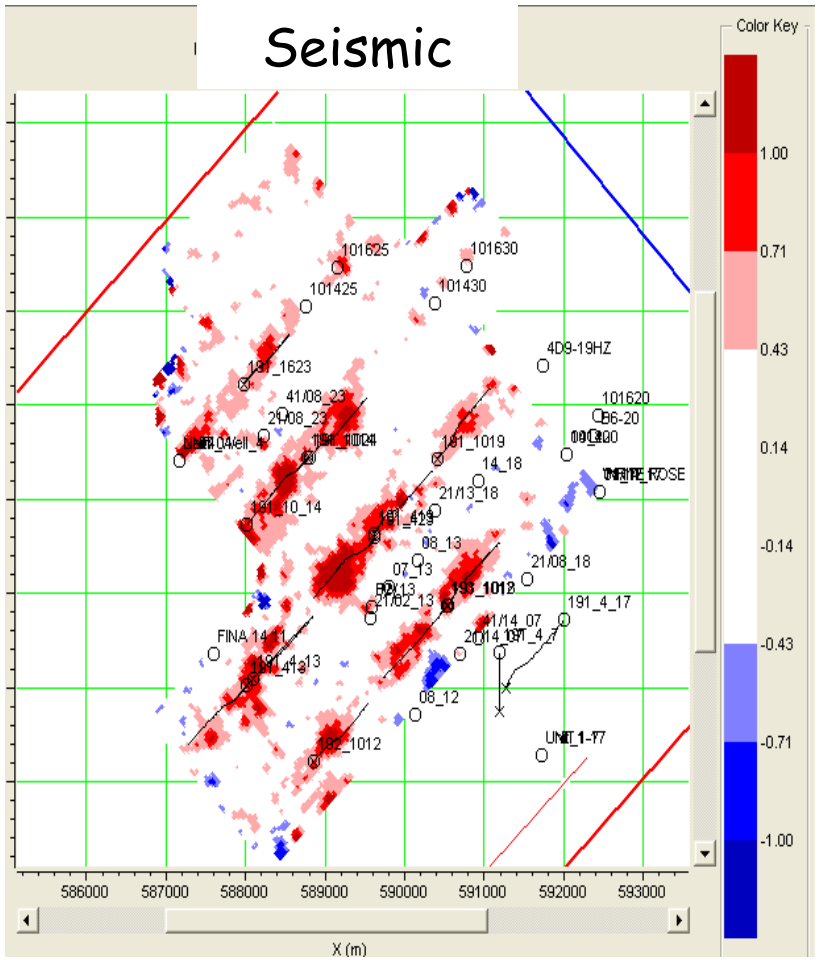
Reservoir Properties Assumed:
T=63 deg C
P=15 Mpa
Porosity=0.17 (vol. Fraction)
Thickness=10 m

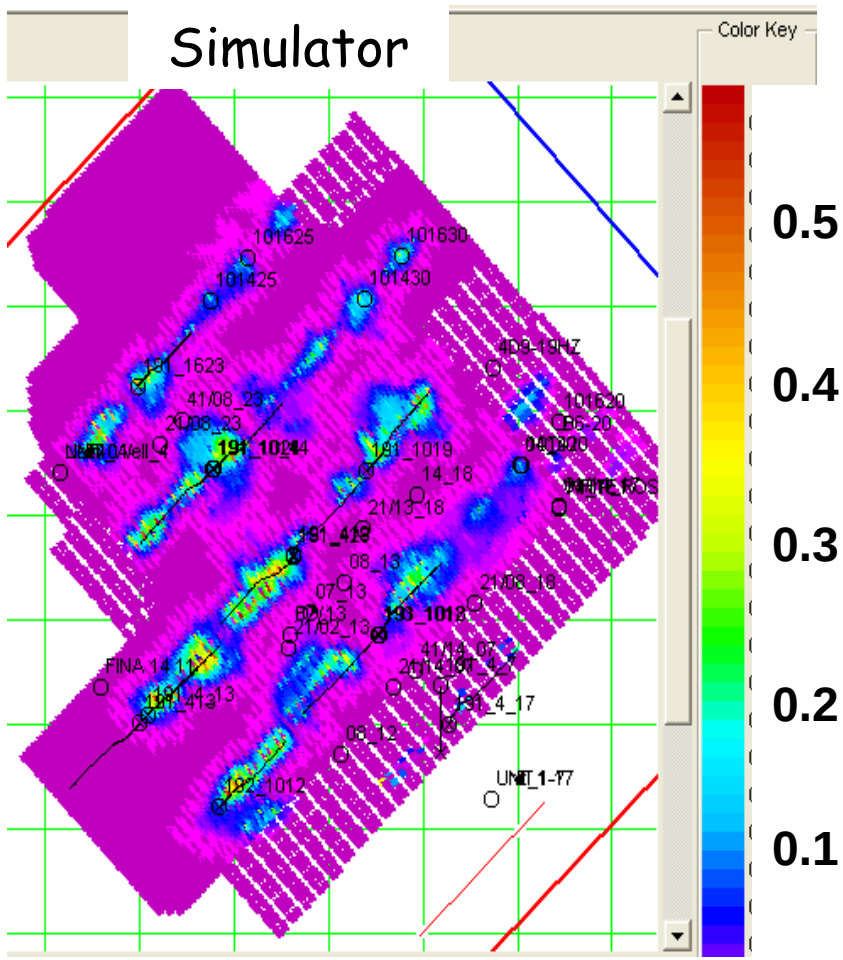
Co2 Injected

Total pore space in CSM area (Mcm)	CO2 injected to 2001 as %pore space	CO2 injected to 2002 as %pore space
16.73	3.6	6.7

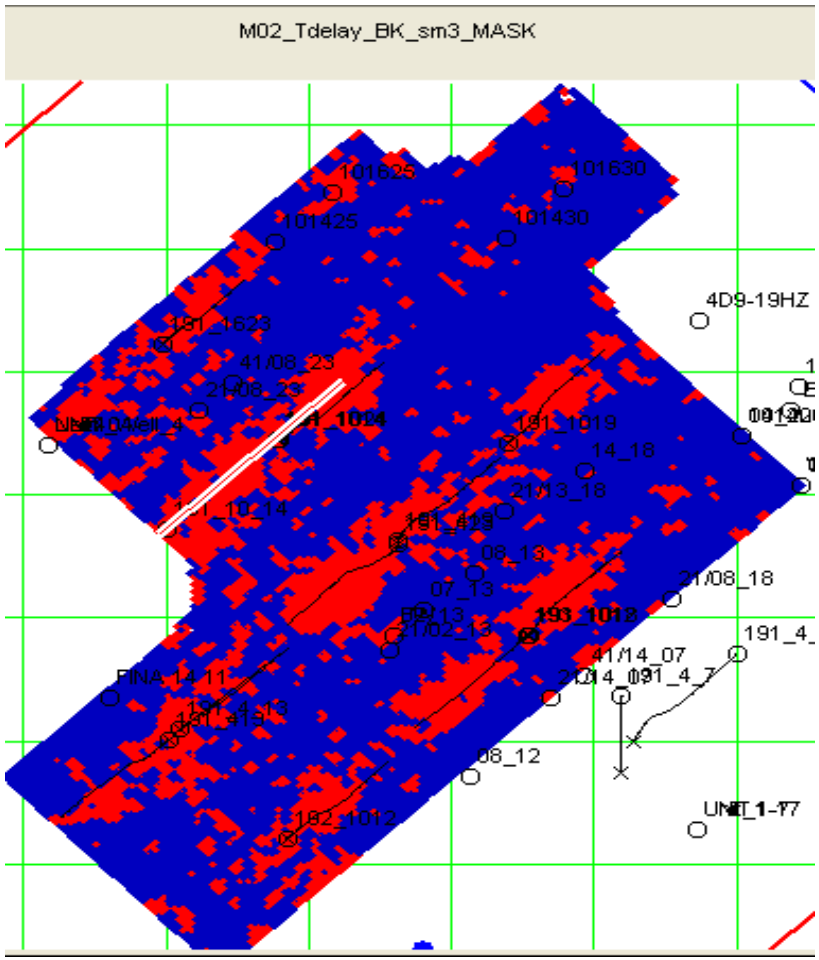
Injector Area	2001 Seismic vol./CO2 vol. Ratio	2002 Seismic vol./CO2 vol. Ratio
1	**0.53**	**0.55**
2	**0.78**	**0.58**
3	**0.56**	**0.51**
4	**0.34**	**0.39**
Total	**0.51**	**0.49**

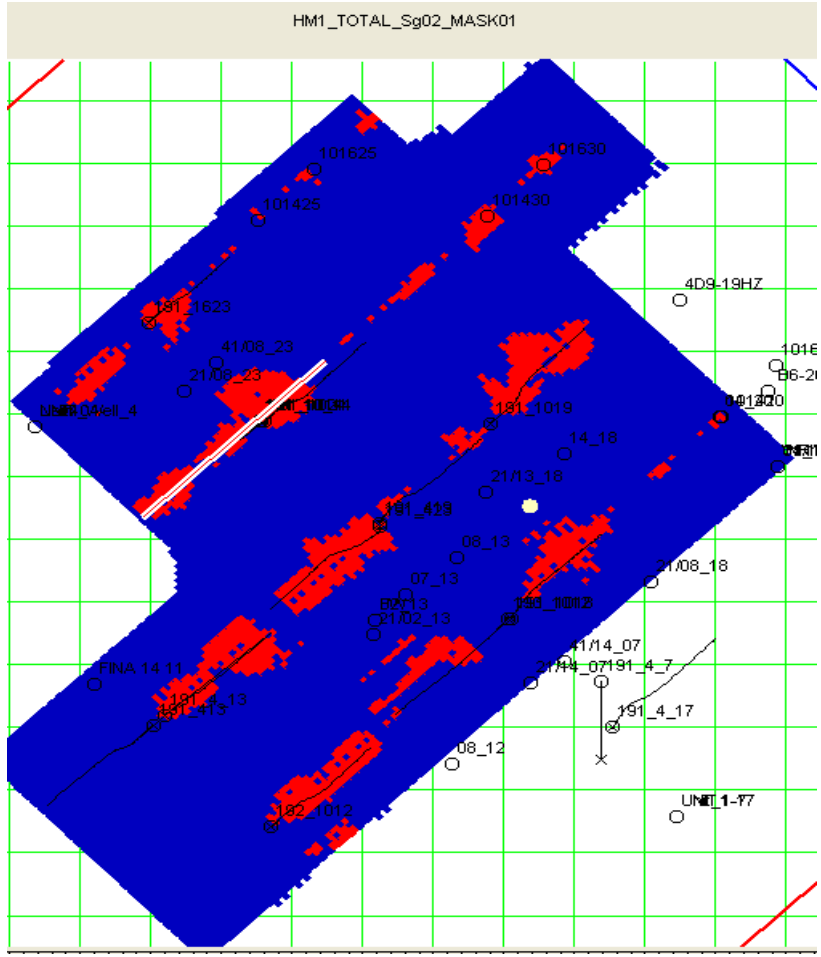
CO2 distributions from Seismic and Simulator, 1st iteration (Monitor 2 Survey)



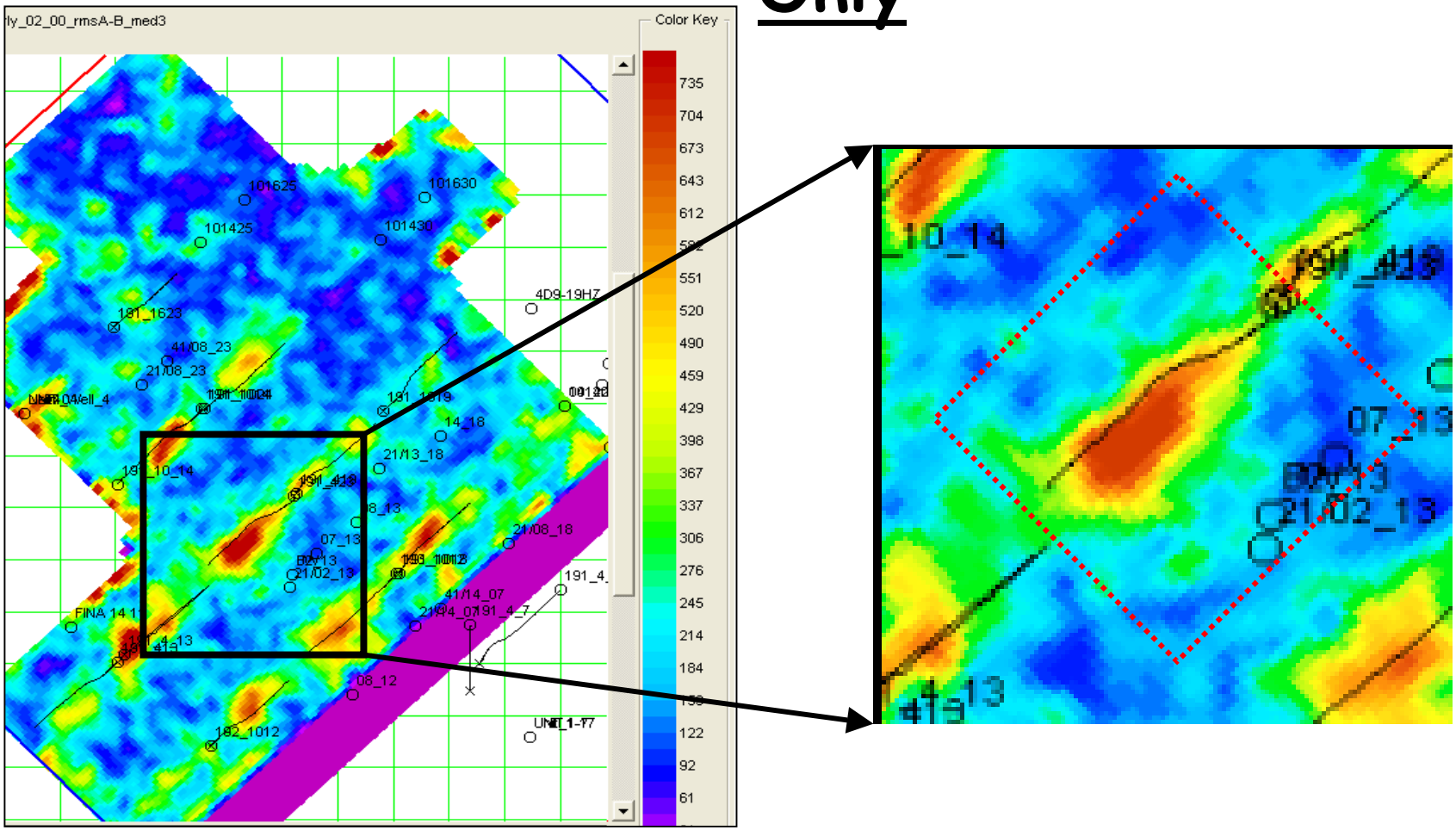


Seismic to Simulation comparison
1st iteration (Monitor 2 Survey)

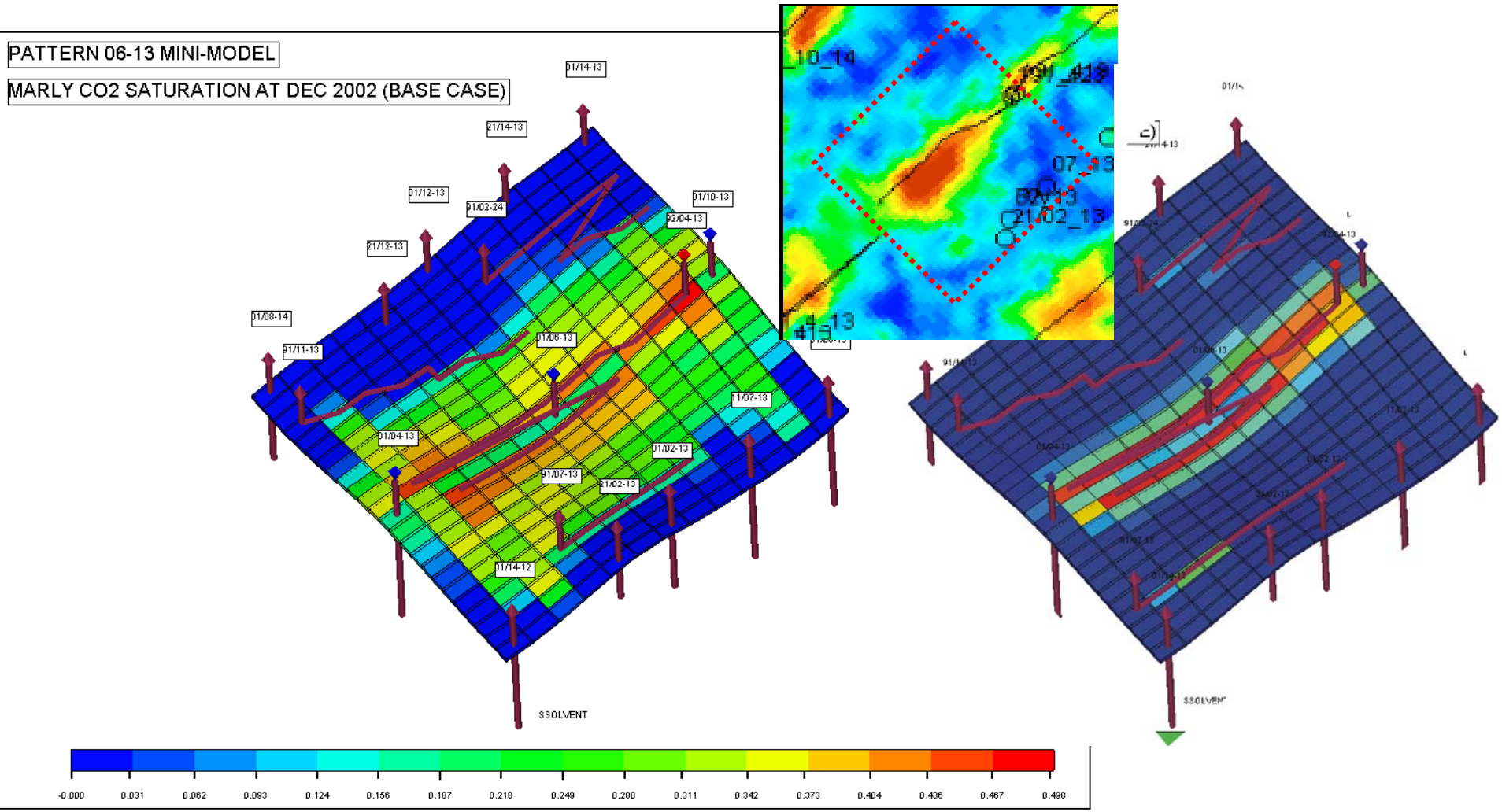




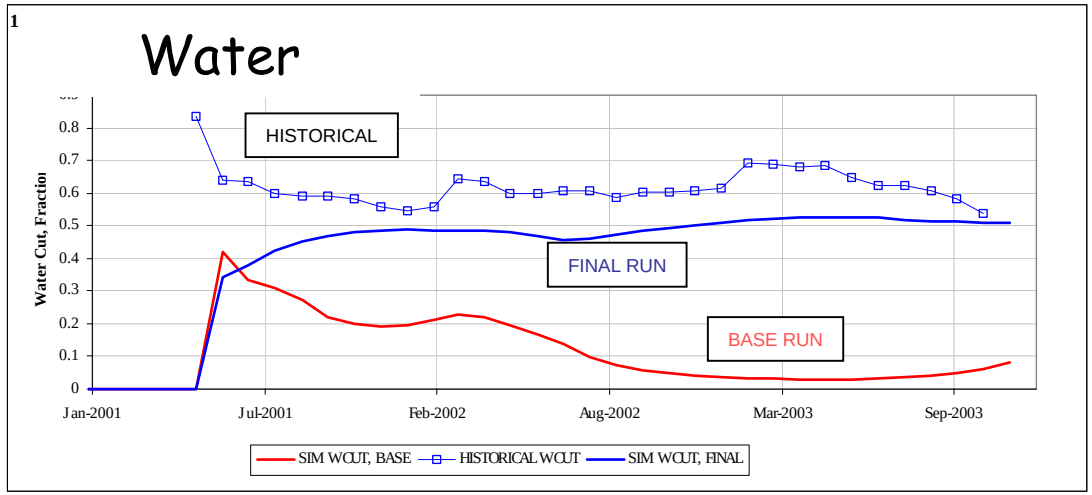
Pattern 06-13-006-14W2 Monitor Amplitude Difference for Marly Unit Only



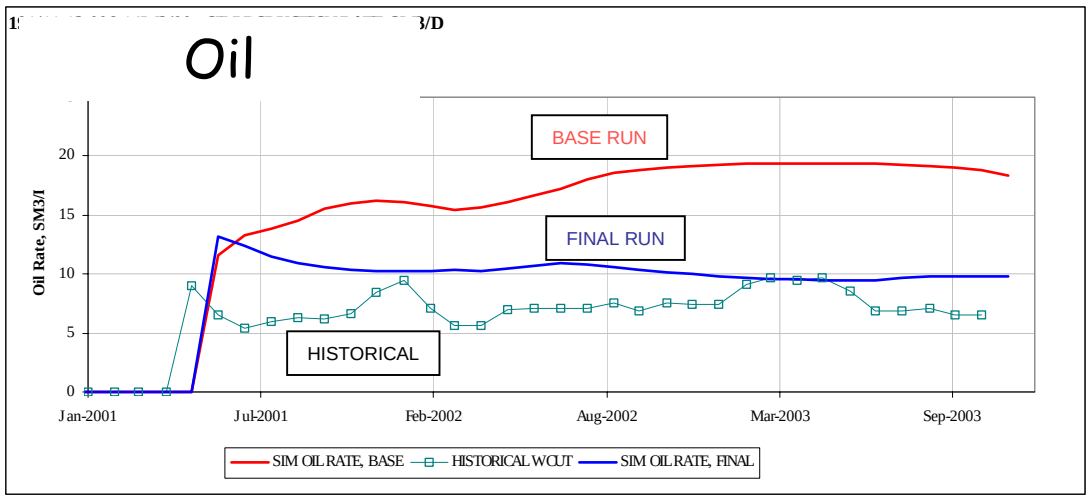
Marly CO2 Saturation for Rev 0 Model



Improved history match

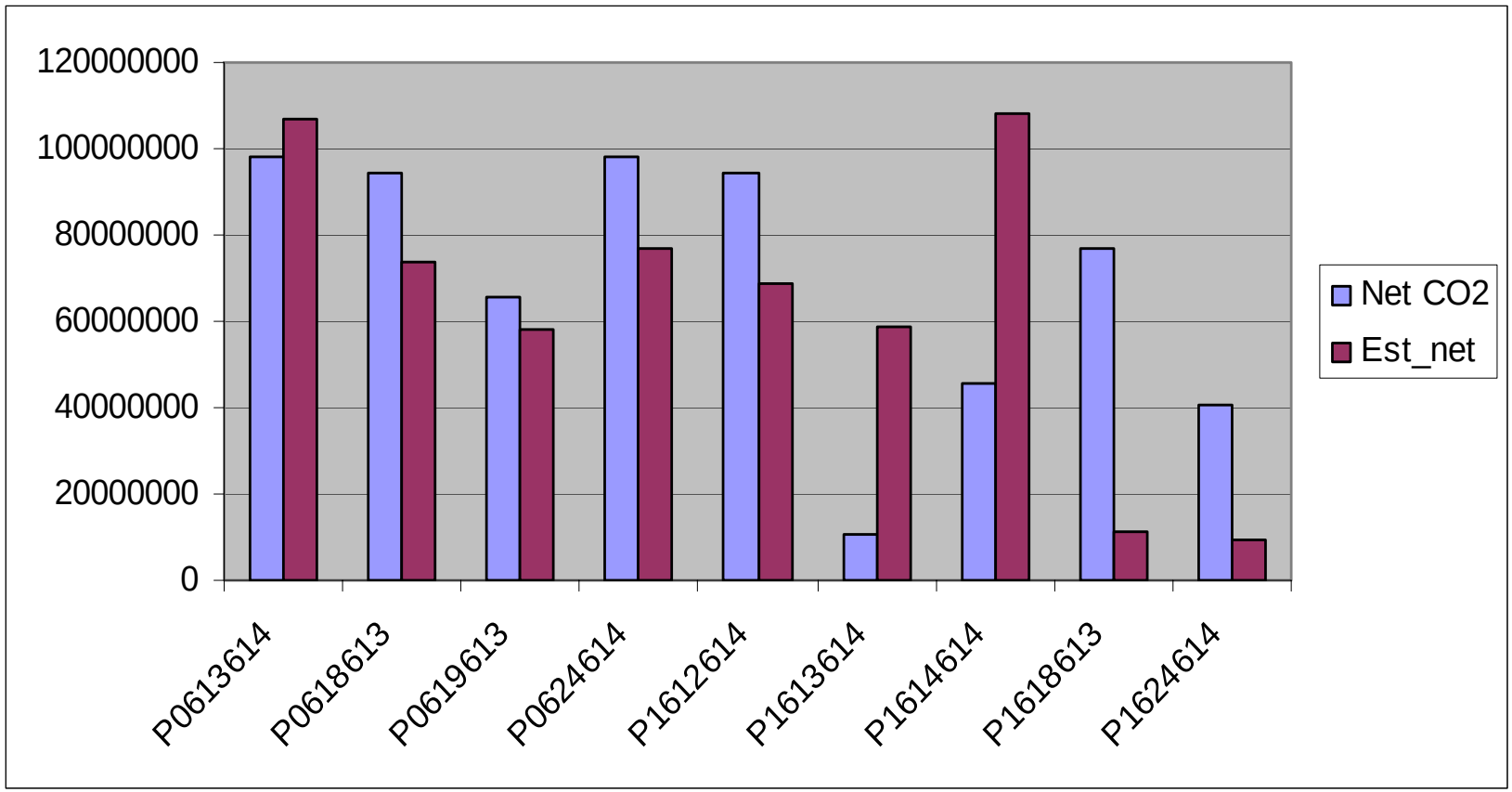


PATTERN 06-13-006-14W2 IMPROVED HM - Water Cut



PATTERN 06-13-006-14W2 IMPROVED HM - Oil Rate

Net CO_2 injected vs seismic estimate



Assumes average Sg of 0.16

Summary & Conclusions

- **Soil gas** levels over the injection area are normal; no evidence for escape of injected CO_2 from depth.
- **Monitoring methods** clearly show physical and chemical effects associated with CO_2 injection.
- **Geochemistry:** chemical processes observed show good spatial correlation with the highest CO_2 injection volumes and with seismic. Processes include:
  - CO_2 dissolution into reservoir brine.
  - Reservoir carbonate mineral dissolution.
  - Increase in total dissolved solids in reservoir brine.

Summary & Conclusions

- **Seismic** methods show robust time and amplitude anomalies.
  - Fractional velocity changes of up to 12%: mainly Sg with secondary P effects (2-3%).
  - No evidence for significant CO_2 escaping from the reservoir.
  - Provide volume estimates currently accurate to ~20%.
  - Illuminate zones of enhanced flow (fractures?).
  - Contribute to more accurate reservoir flow simulations.

- **Microseismicity** is low level.
  - Magnitudes of –3 to –1 are detected.
  - Onset associated with start of CO_2 injection.
  - Located in vicinity of the reservoir.
  - May track flow of gas to nearby producer.