Quantifying CO_2 Mass in Subsurface from Seismic Data

地震波探査データに基づくCO_2貯留量評価技術の開発

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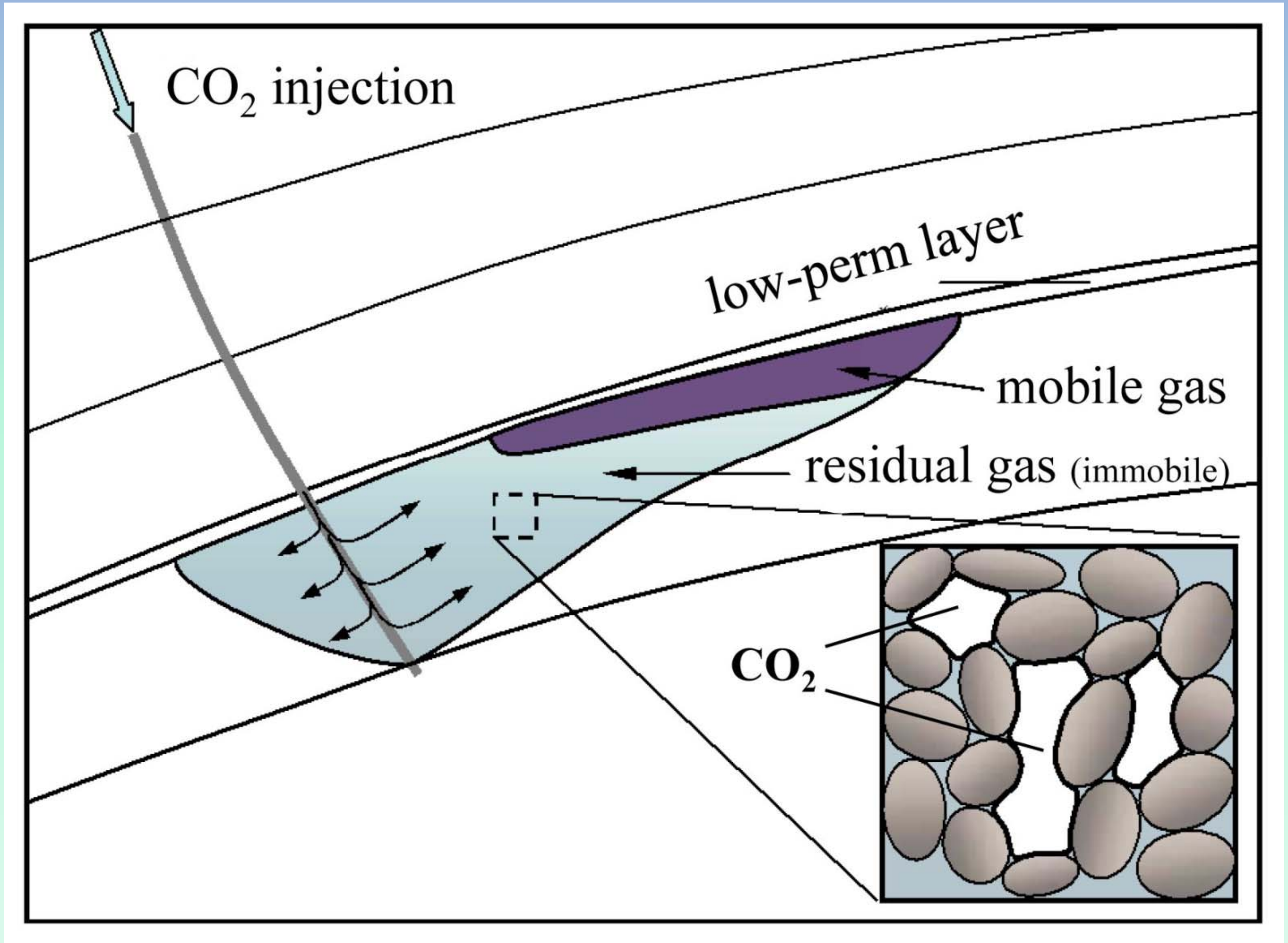
CO_2 Stored in Saline Aquifer



Juanes et al., 2006

Geological Sequestration of CO_2

- Mobile phase trapped by seal
- Dissolution in water
- Precipitation as a mineral
- Immobile phase as residual, nonwetting saturation

Objectives of CO_2 Monitoring

Map the movement of CO_2 & CO_2 is being safely contained in reservoir.

CO_2 sequestration is a safe and verifiable mitigation technology option

Monitoring, **M**easurement and **V**erification : MMV

Monitoring, **E**valuation, **R**eporting and **V**erification : MERV

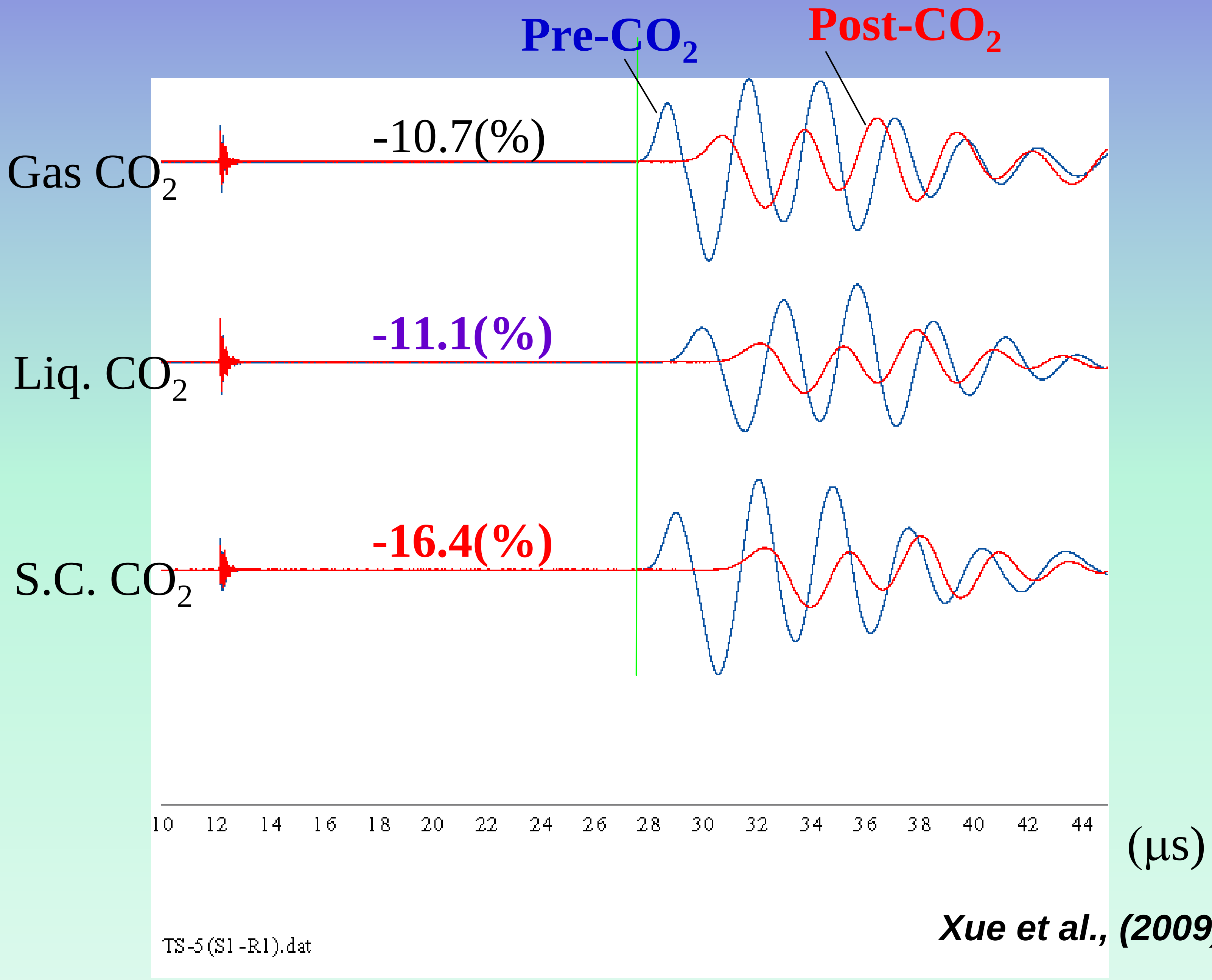
Examples from CO_2-EOR & CO_2 storage projects

Cross Well Seismic and Electromagnetic (EM)

- McElroy oil field, West Texas, USA (Harris et al.,1995)
- Lost Hills oil field, South California, USA (Hoversten et al., 2003)

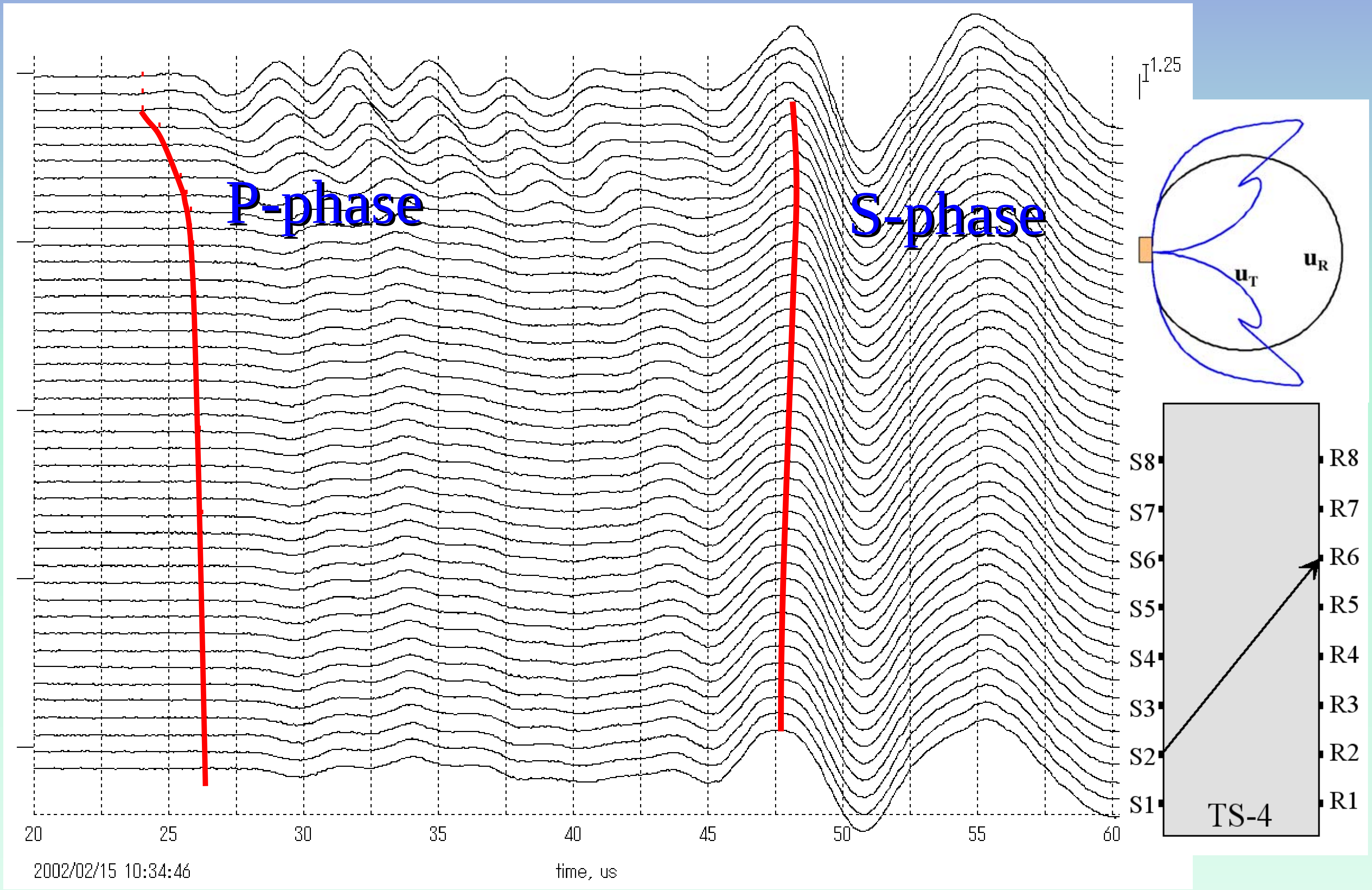
Time-lapse 3D Seismic Survey (4D Seismic)

- Weyburn oil field, South Saskatchewan, Canada (White, 2004)
- Sleipner, ***aquifer***, North Sea, Norway (Art et al., 2004)

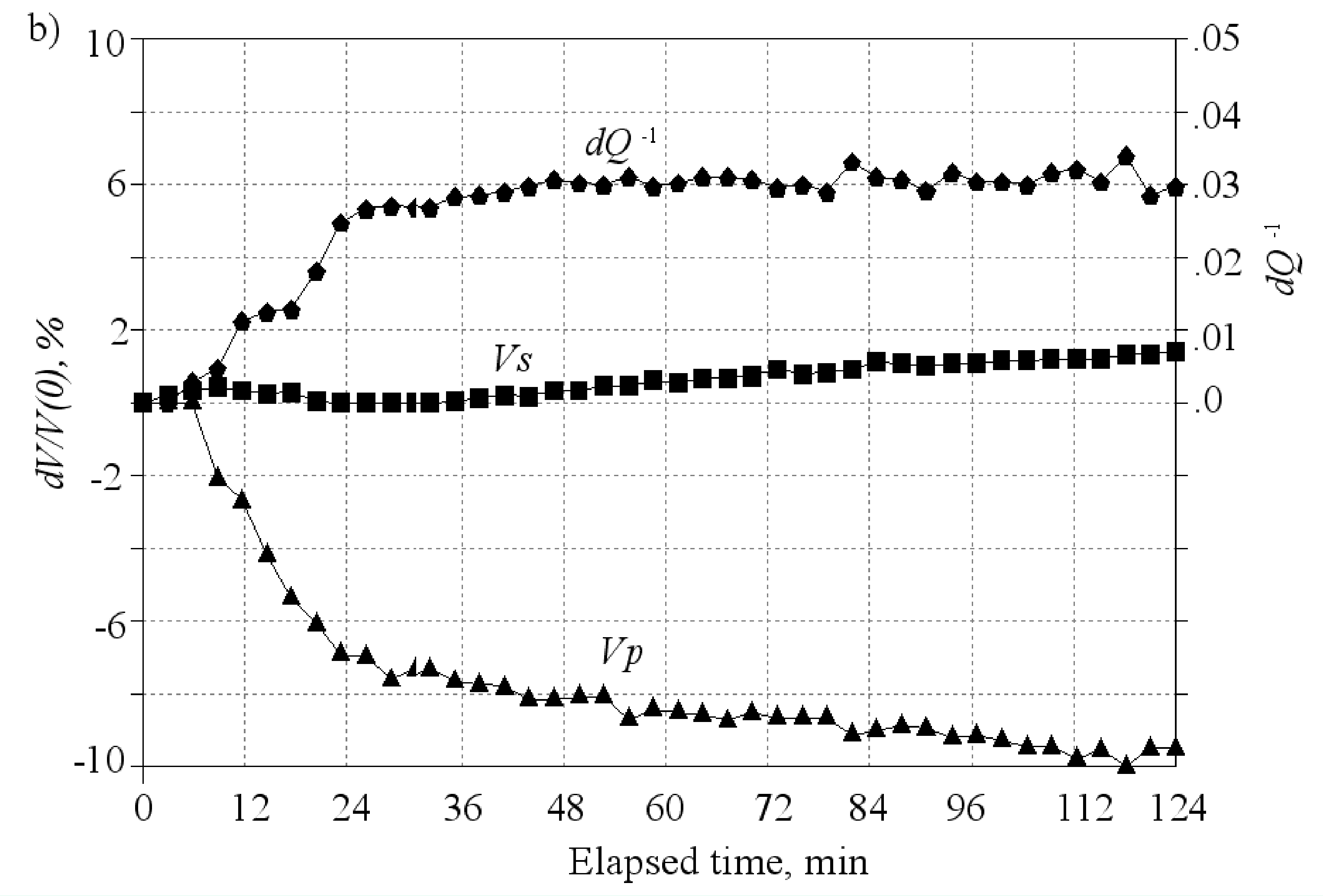


Xue et al., (2009)

Seismic records with identifiable P and S

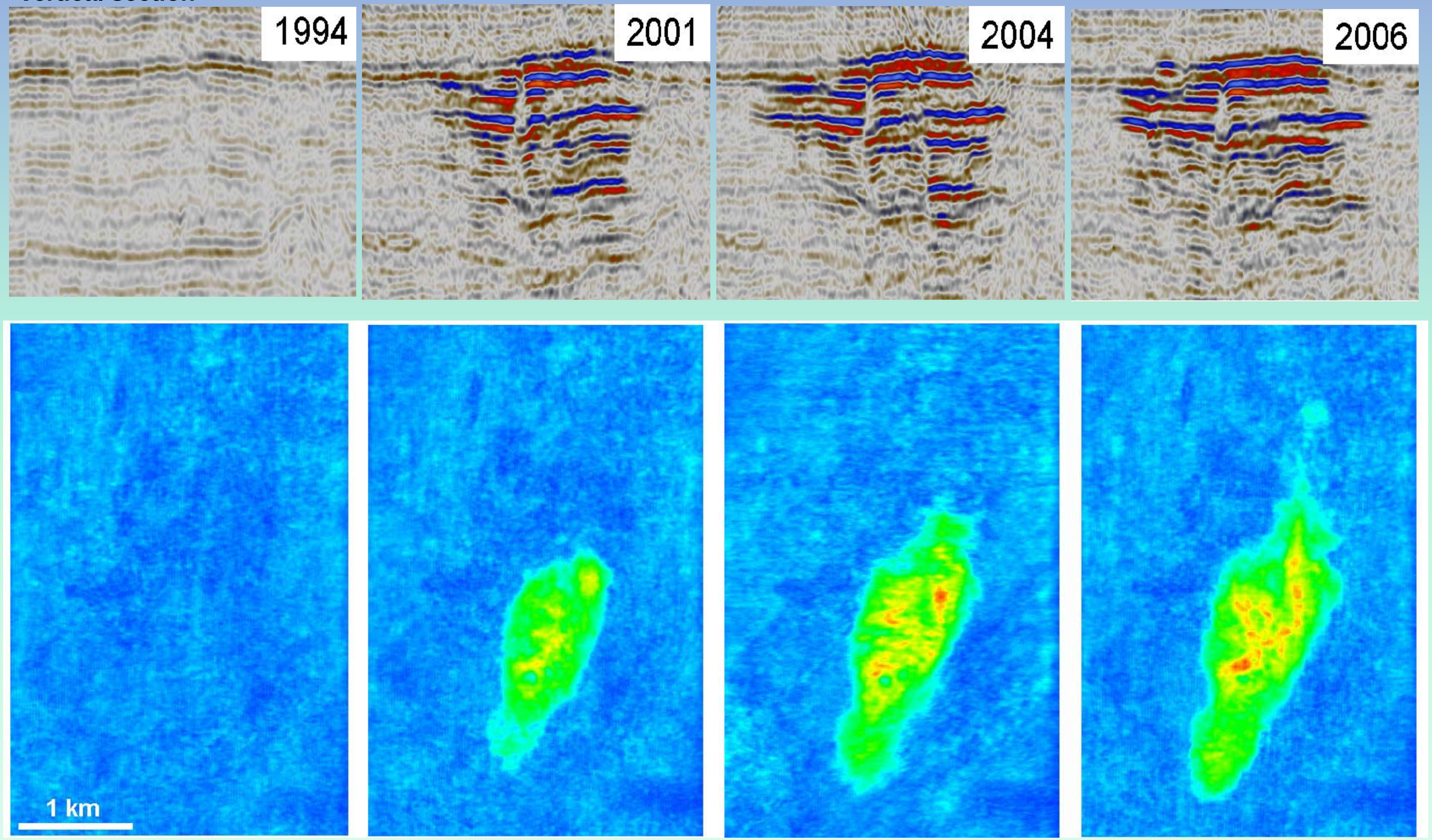


Seismic response to CO_2 replacing water in porous Tako sandstone



Imaging CO_2 in the reservoir @Sleipner

vertical section



plan view

Chadwick (2009)

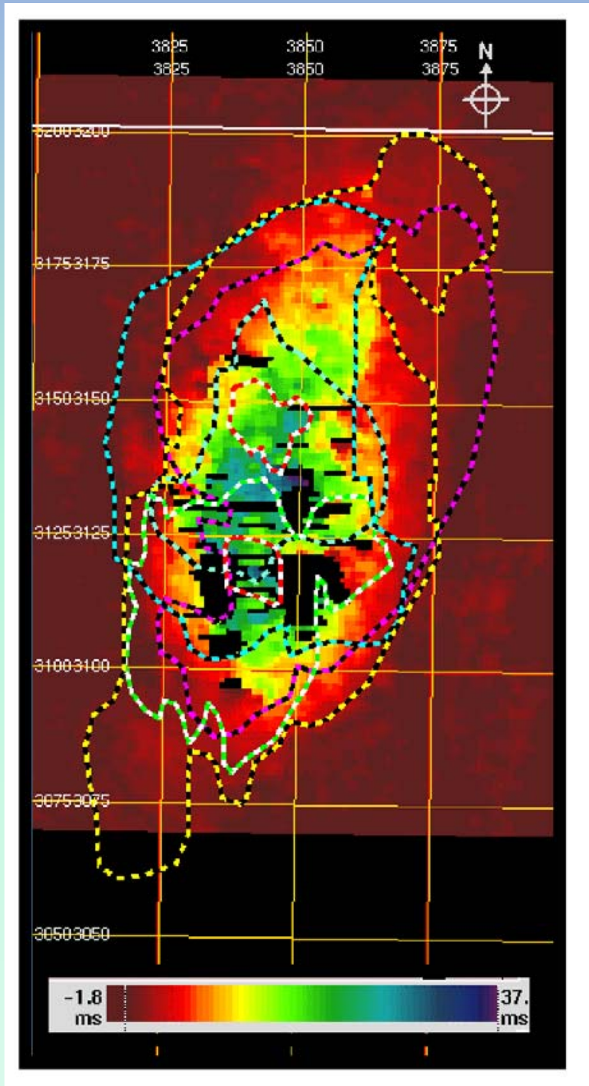
CO_2 Mass Estimation with Seismic Data @Sleipner (Arts et al., 2002)

$$Vol_{CO_2} = \Phi * dx * dy * \int_z \frac{V_{S_W=1} * V_{(1-S_W)}}{2^* (V_{S_W=1} - V_{(1-S_W)})} * (1-S_w) * (TWT_{99} - TWT_{94}) \; dz$$

Gassman factor

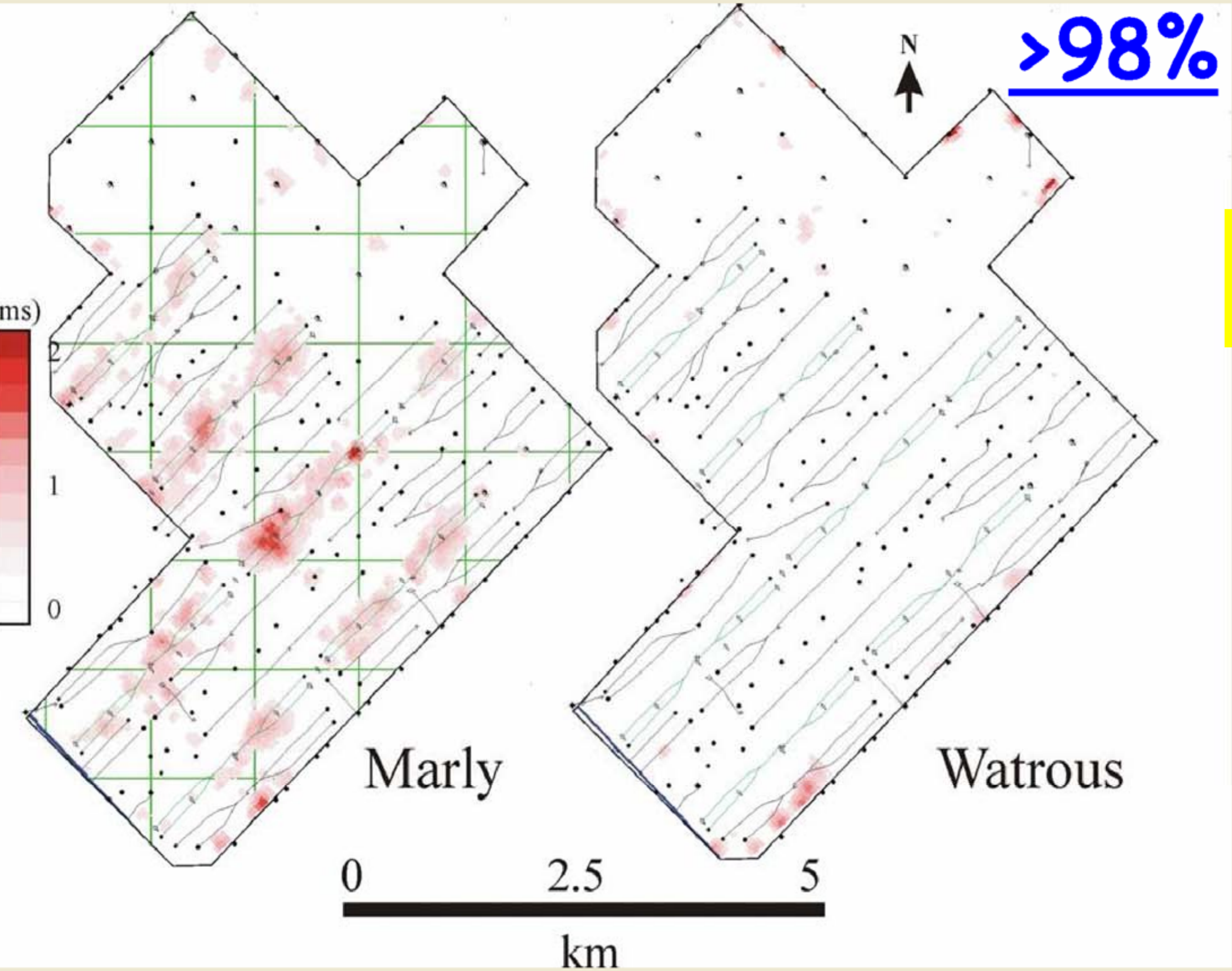
With:

Vol_{CO_2}	is the volume of CO_2 under reservoir conditions (Rm^3)
$V_{S_W=1}$	is velocity in water saturated sandstone ('94) (m/ms)
$V_{(1-S_W)}$	is velocity in CO_2 saturated sandstone ('99) (m/ms)
S_w	is water-saturation and $(1-S_w)$ is CO_2-saturation
Φ	is porosity
dx, dy	are the inline and crossline spacing (product is the bin-size) (m)
TWT_{99}	is an interpreted traveltime picked below the CO_2 after injection ('99) (ms)
TWT_{94}	is the same interpreted traveltime before injection ('94) (ms)



Containment Estimate from Seismic

White (2004)



Estimated CO_2 Mass >98% in reservoir

No Evidence for leakage!

Biot – Gassmann - Domenico Theory

Two phase (partial saturation)

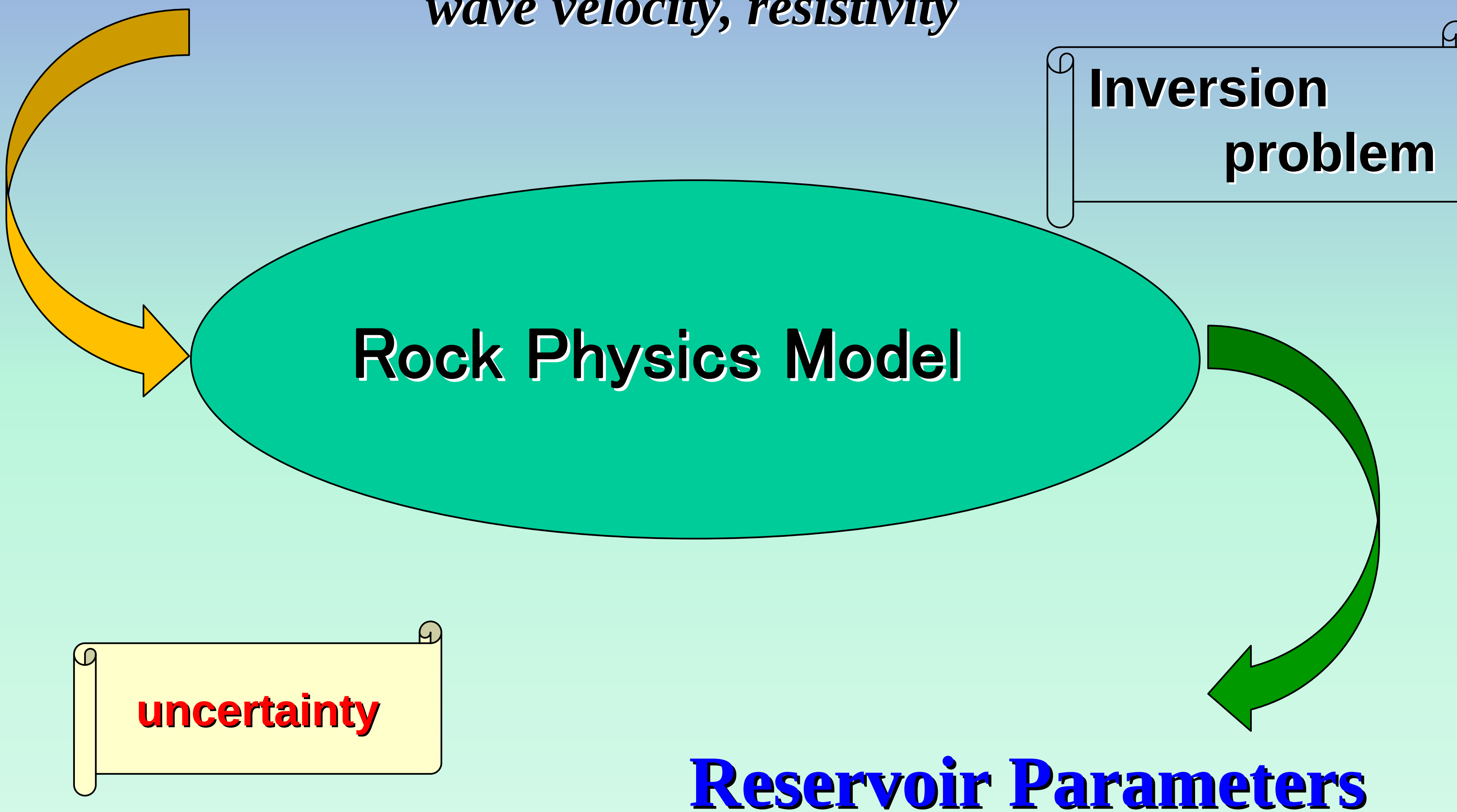
$$V_p = \sqrt{\frac{K + \left(\frac{4}{3}G\right)}{\rho}} \qquad V_s = \sqrt{\frac{G}{\rho}}$$

$$K = K_d + \frac{\left(1 - \frac{K_d}{K_s}\right)^2}{\frac{\phi}{K_f} + \frac{(1-\phi)}{K_s} - \frac{K_d}{K_s^{\,2}}}$$

S_w	Water saturation	---
φ	Rock porosity	---
ρ	Material density	kg/m^3
ρ_s	Solid framework density	kg/m^3
ρ_w	water bulk density	kg/m^3
ρ_c	CO_2 bulk density	kg/m^3
K	Bulk modulus	GPa
K_d	Dry rock bulk modulus	GPa
K_s	Solid framework bulk modulus	GPa
K_w	Water bulk modulus	GPa
K_c	CO_2 bulk modulus	GPa
K_f	Pore fluid bulk modulus	GPa
G	shear modulus	GPa
G_d	Rock shear modulus	GPa

Geophysical Parameters

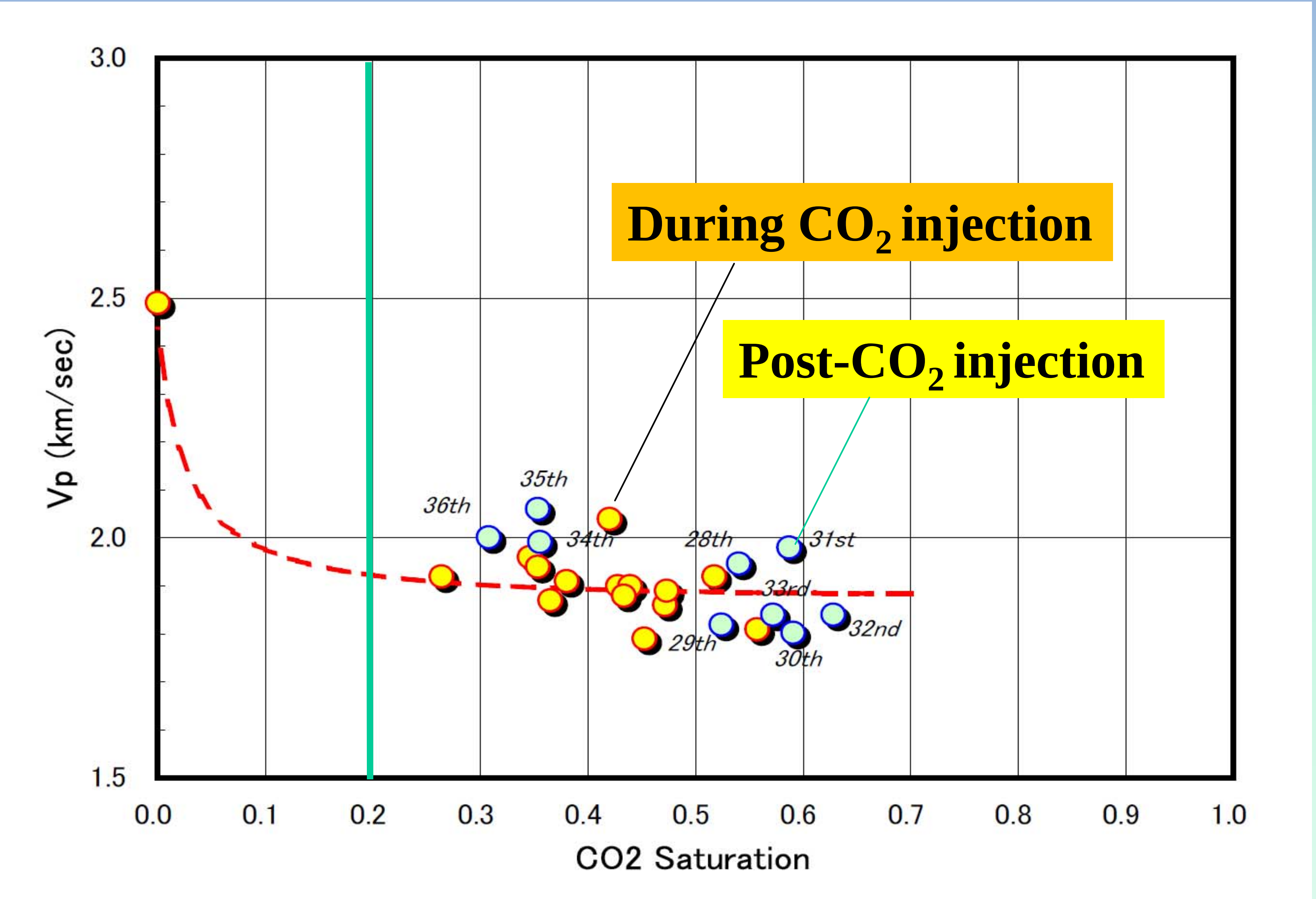
wave velocity, resistivity



Reservoir Parameters

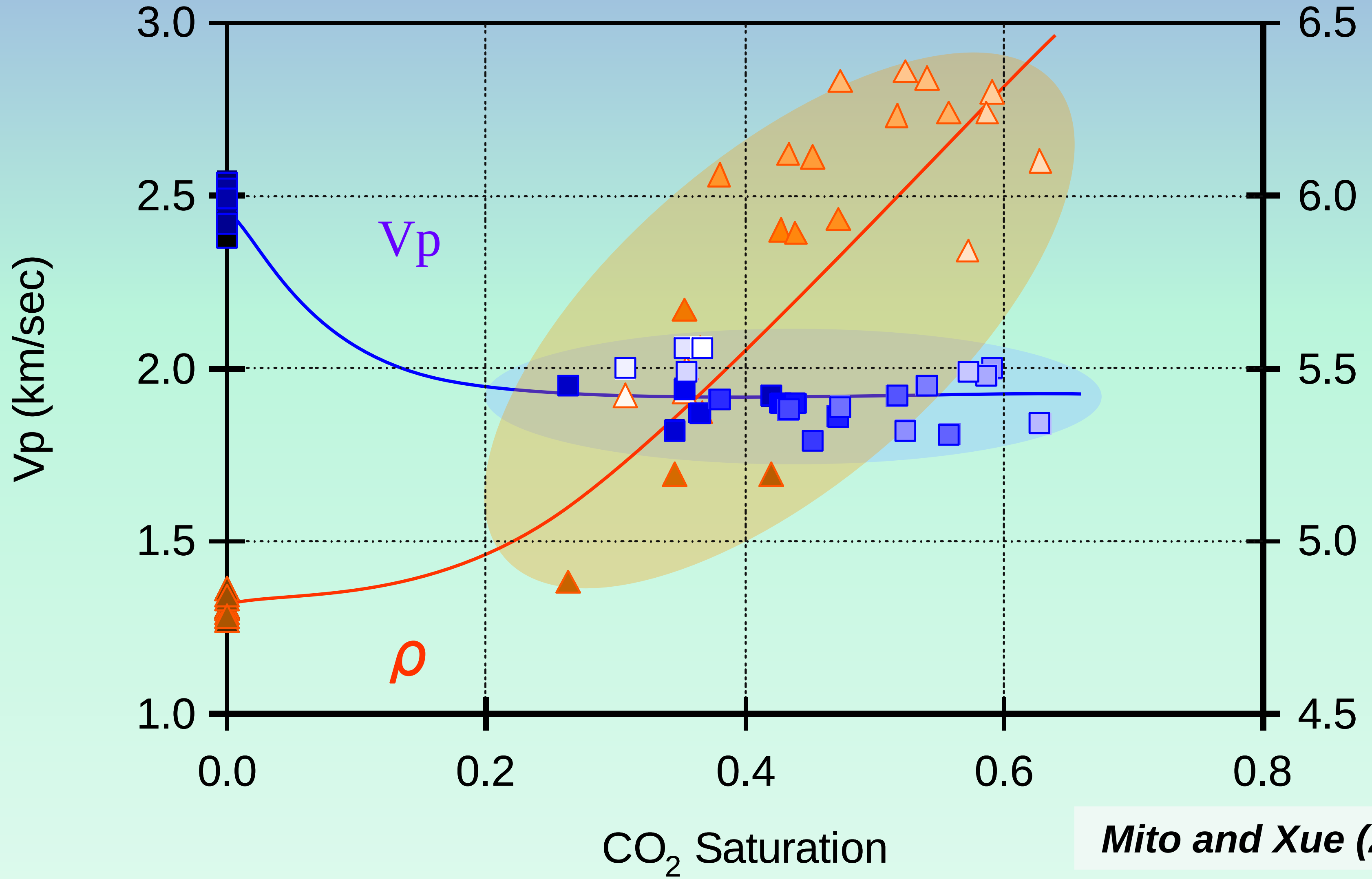
fluid, gas saturation

Sonic Vp *vs* CO_2 Saturation@ Nagaoka



Sonic Vp and resistivity vs CO_2 saturation

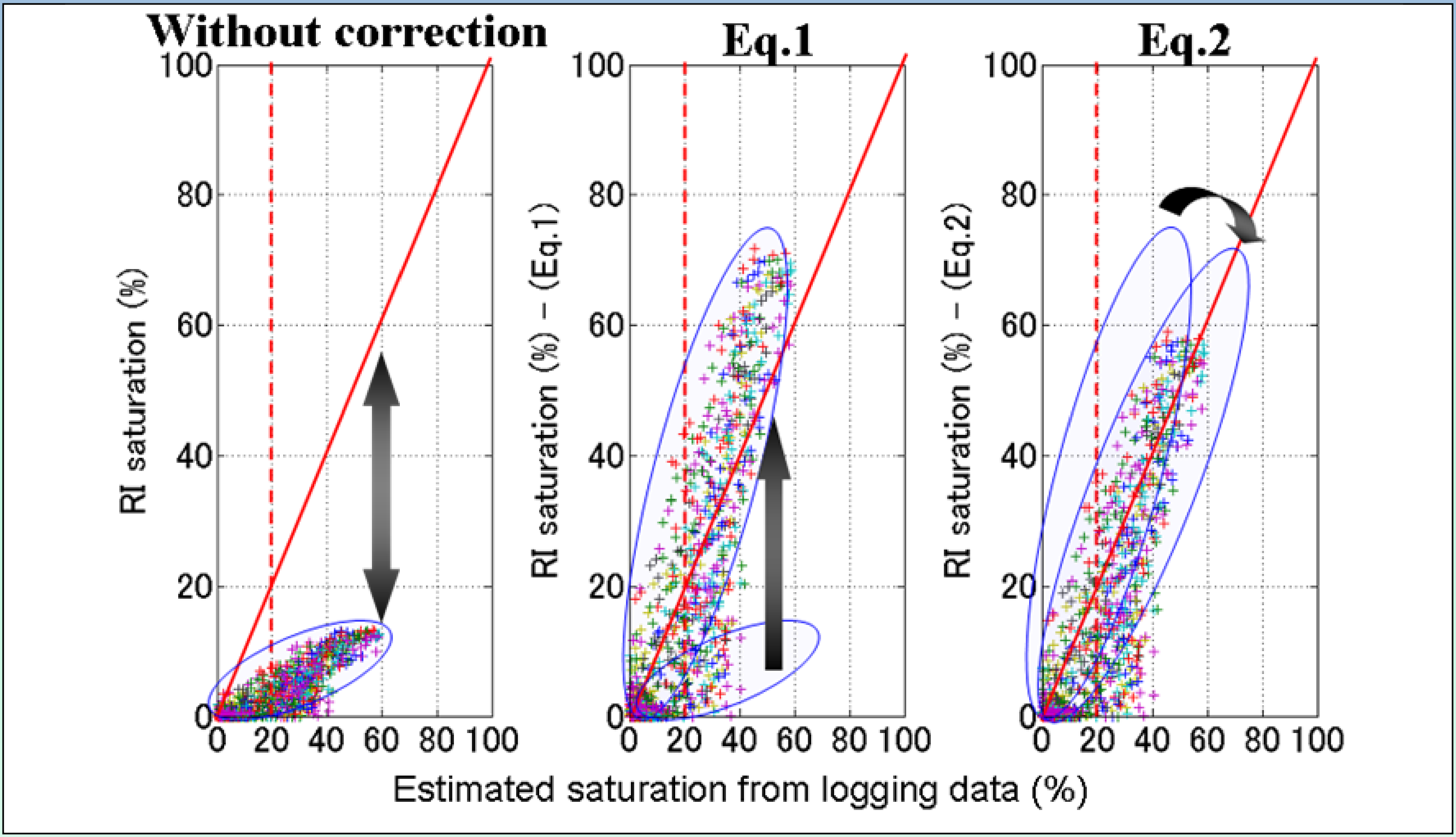
(1116.0m @ OB-2, Nagaoka)



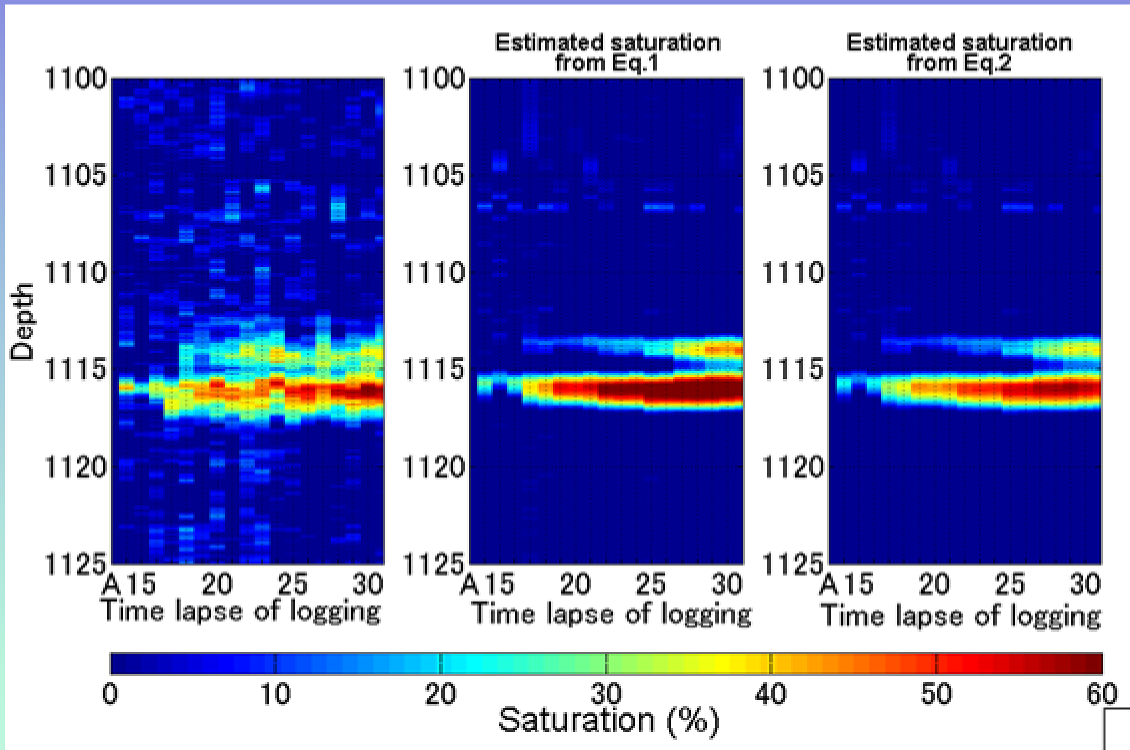
Mito and Xue (2009)

Estimating CO_2 Saturation from Induction Log Data

(1116.0m @ OB-2, Nagaoka)



Nakatsuka et al. (2010)



Suggested Eq.1 and Eq.2

RI: Resistivity Index

Eq.1

$$S_{CO_2} = \left(1 - \left(\frac{1}{RI}\right)^{\frac{1}{n}}\right) \times \frac{1}{V_{clay}}$$

Eq.2

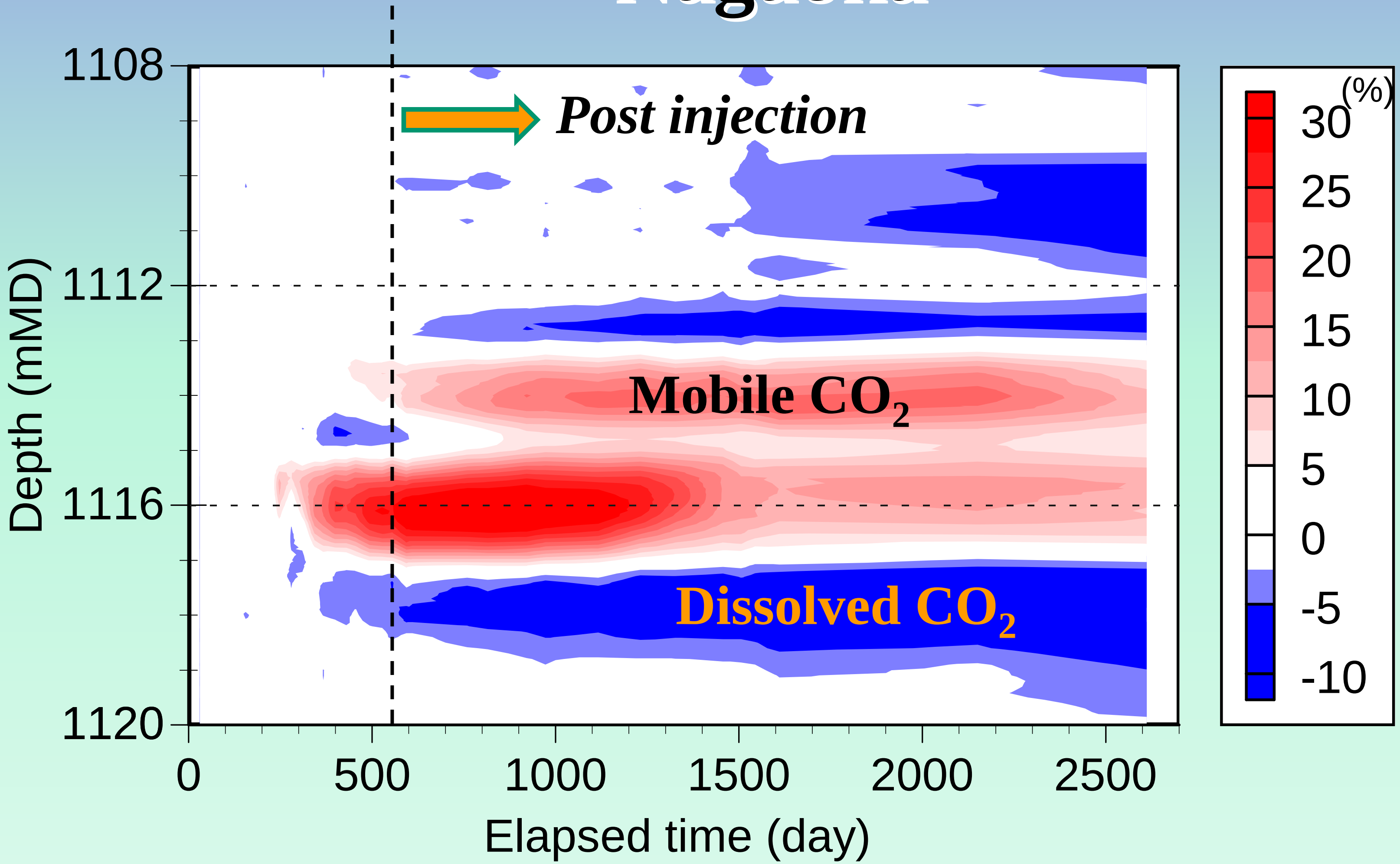
$$S_{CO_2} = \left(1 - \left(\frac{1}{RI}\right)^{\frac{1}{n}}\right) \times \frac{\left(1 - V_{clay}\right)}{V_{clay}}$$

$$\left(V_{clay} \neq 0\right)$$

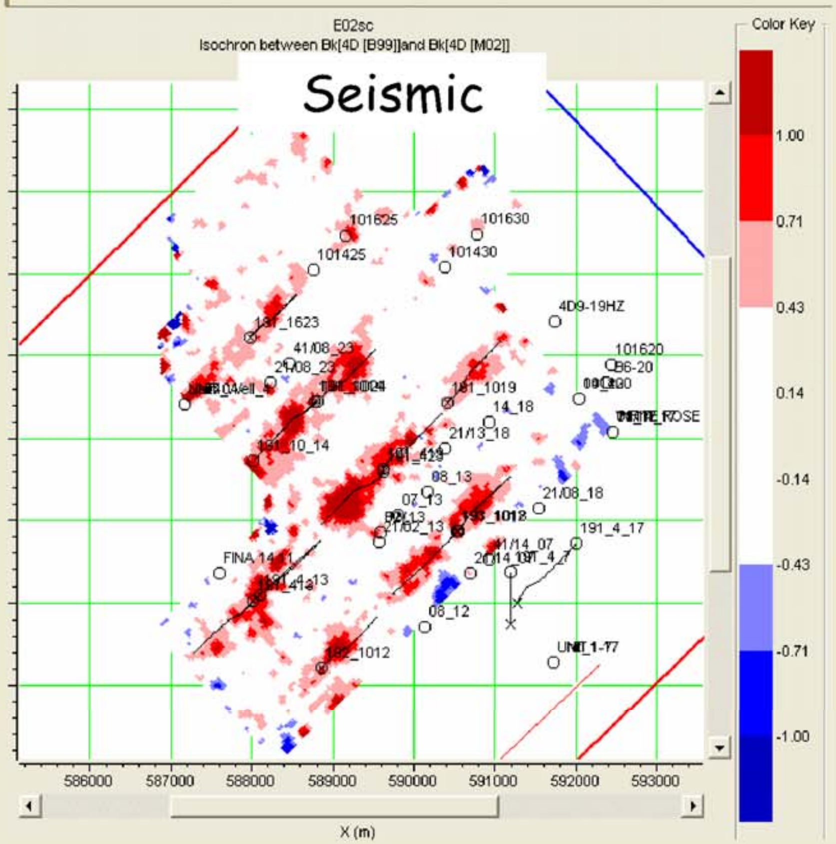
Results of estimated CO2 saturation with suggested Eq.1 and Eq.2

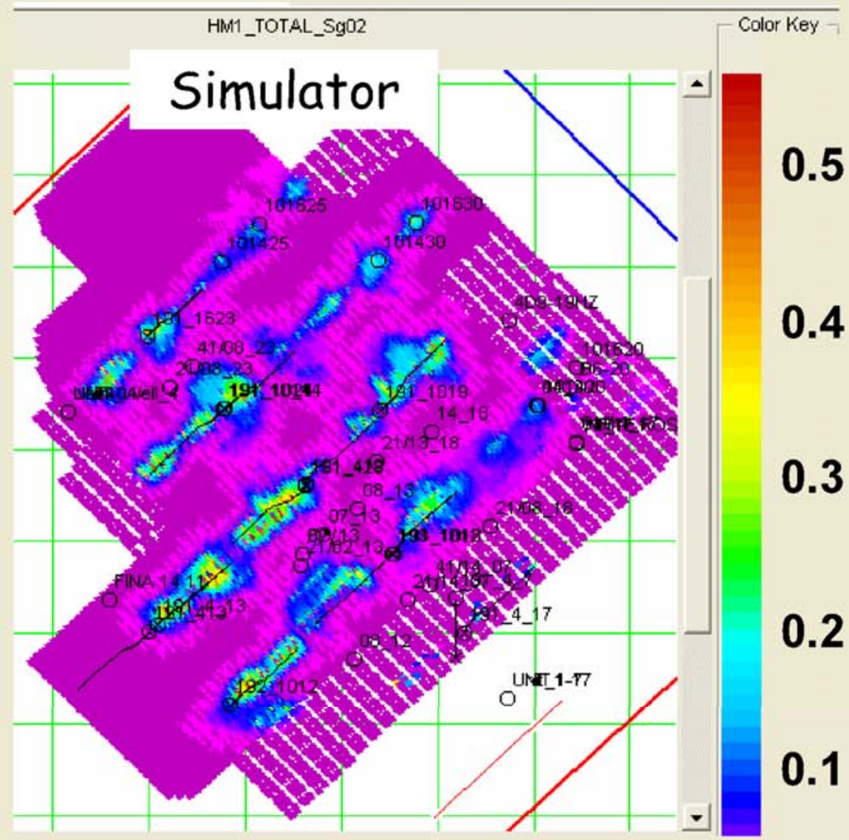
Nakatsuka et al. (2010)

CO_2 Derived from Induction Log @ Nagaoka



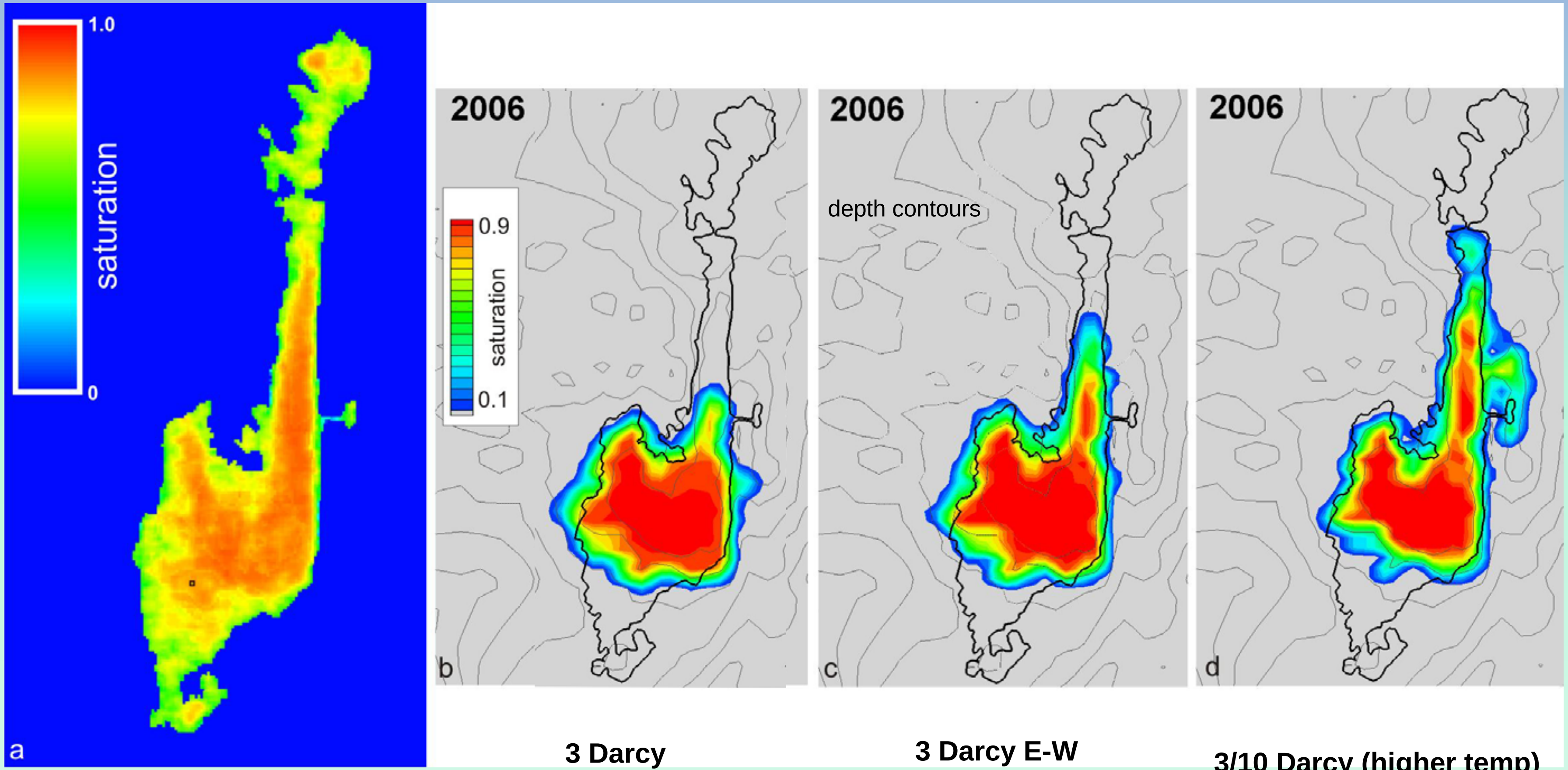
CO2 distributions from Seismic and Simulator, 1st iteration (Monitor 2 Survey)





White (2004)

3D flow simulation of topmost layer growth by 2006



3 Darcy

3 Darcy E-W
10 Darcy N-S

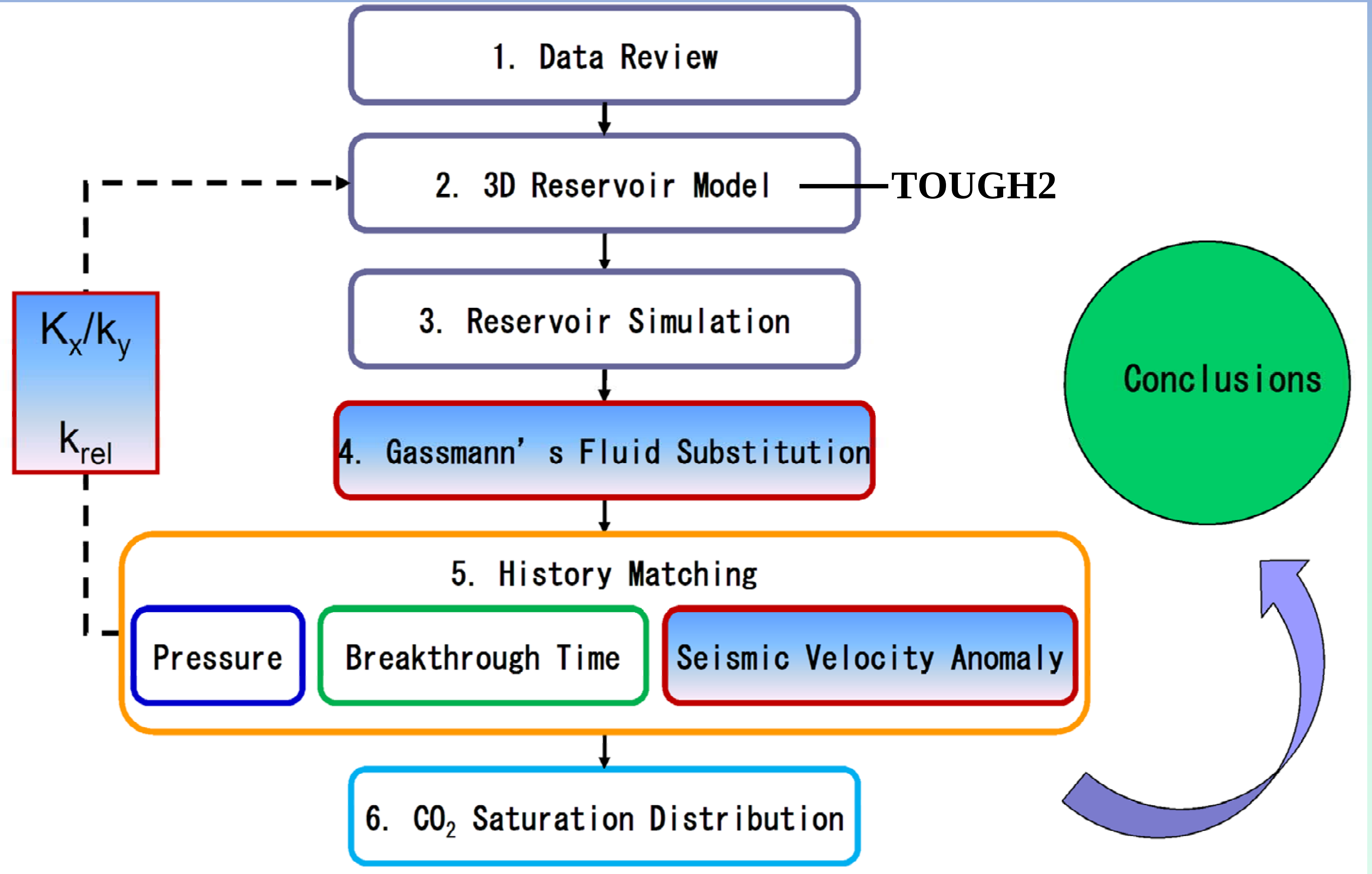
3/10 Darcy (higher temp)

Core testing 2 - 3 Darcy
Well testing 1 - 8 Darcy

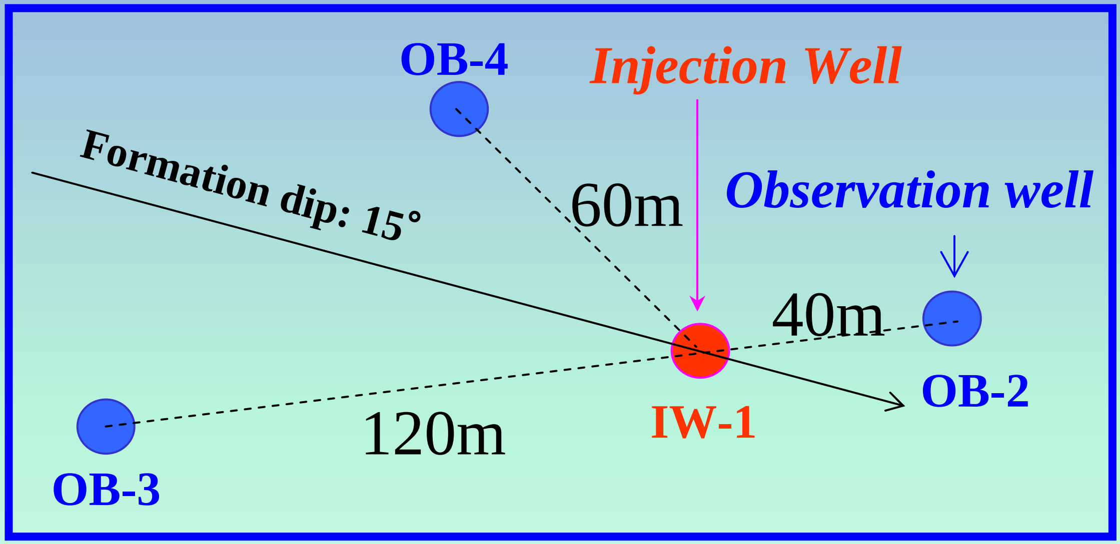
Model 3 Darcy

Chadwick (2009)

Methodology



Breakthrough Time Matching



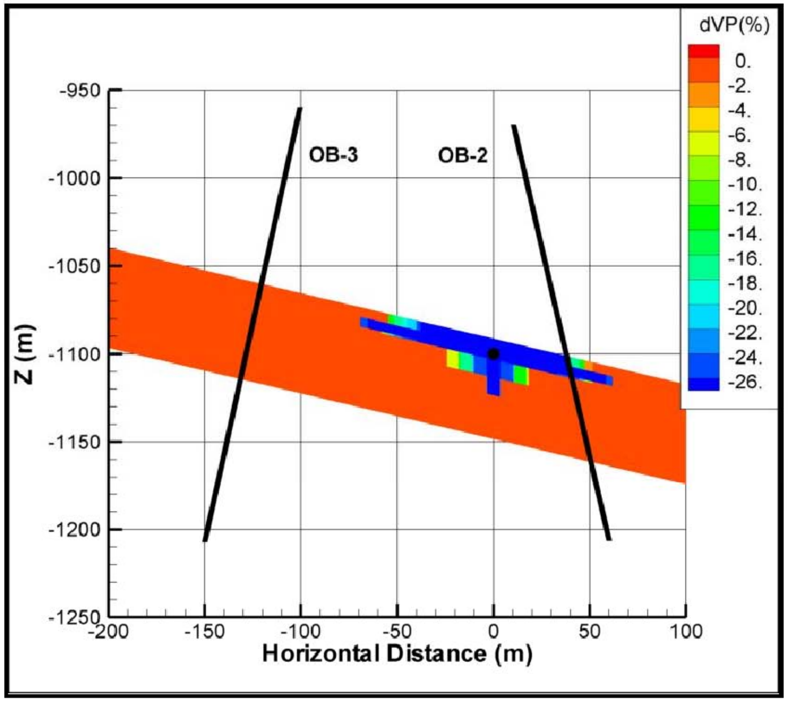
Breakthrough time	Logging Data (Days)	Sim. RP1 (Days)	Sim. RP2 (Days)	Sim. RP3 (Days)
OB-2	232-259	154	200	234
OB-3	No detected	No detected	No detected	No detected
OB-4	325-359	201	259	342

Good Match!

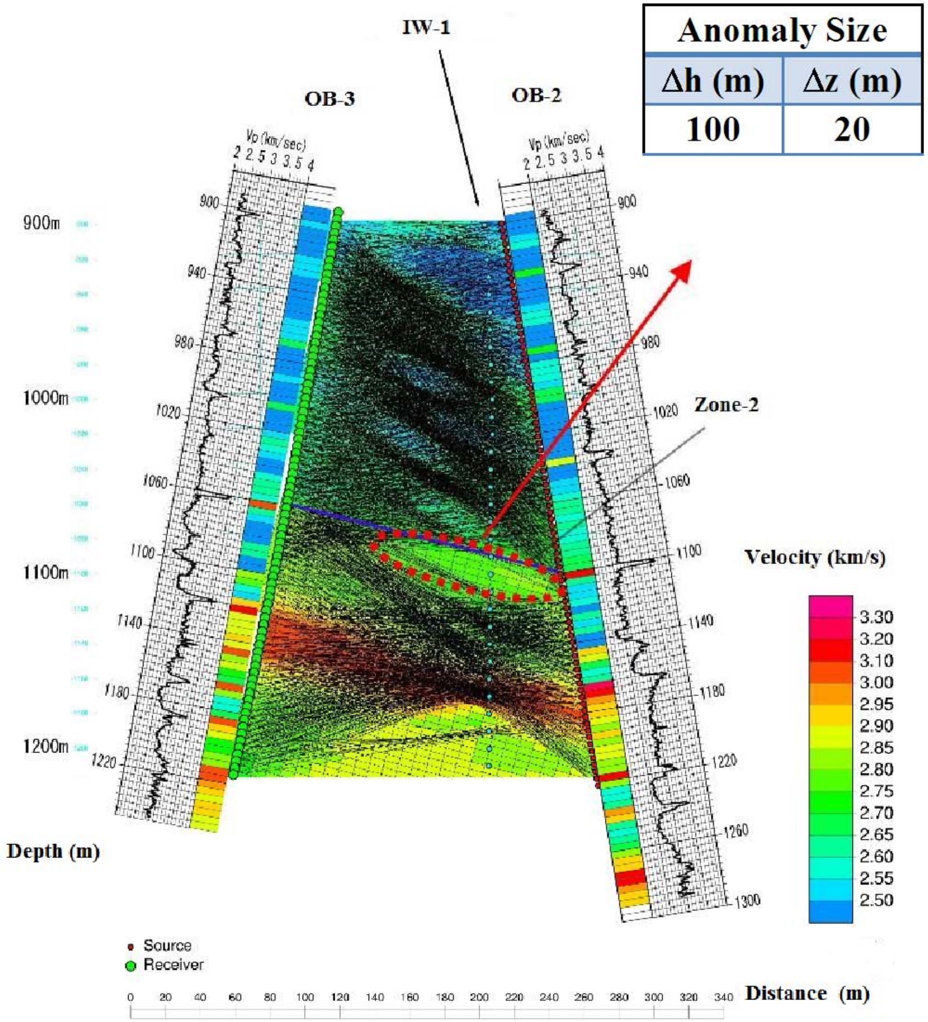
Velocity Anomaly Matching

Sim. RP3

Anomaly Size	
Δh (m)	Δz (m)
105	22



Anomaly Size	
Δh (m)	Δz (m)
100	20



Conclusion

- P- and S-wave clearly response to CO_2 injection into porous sandstones and strongly support monitoring and quantification of CO_2 mass stored in reservoir.
- Joint inversion of seismic wave velocity and resistivity is helpful for improving understanding and modeling on CO_2 migration in subsurface.
- History matching results from CO_2 flow simulation and monitoring provides insights to quantifying mass of CO_2 injected in reservoir.

Acknowledgements

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