3D full-waveform inversion of the Snowflake CO_2 injection VSP data

Hyeong-Geun Ji, Sea-Eun Park, Ju-Won Oh and Kris Innanen

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JEONBUK NATIONAL UNIVERSITY
KETEP Korea Institute of Energy Technology Evaluation and Planning

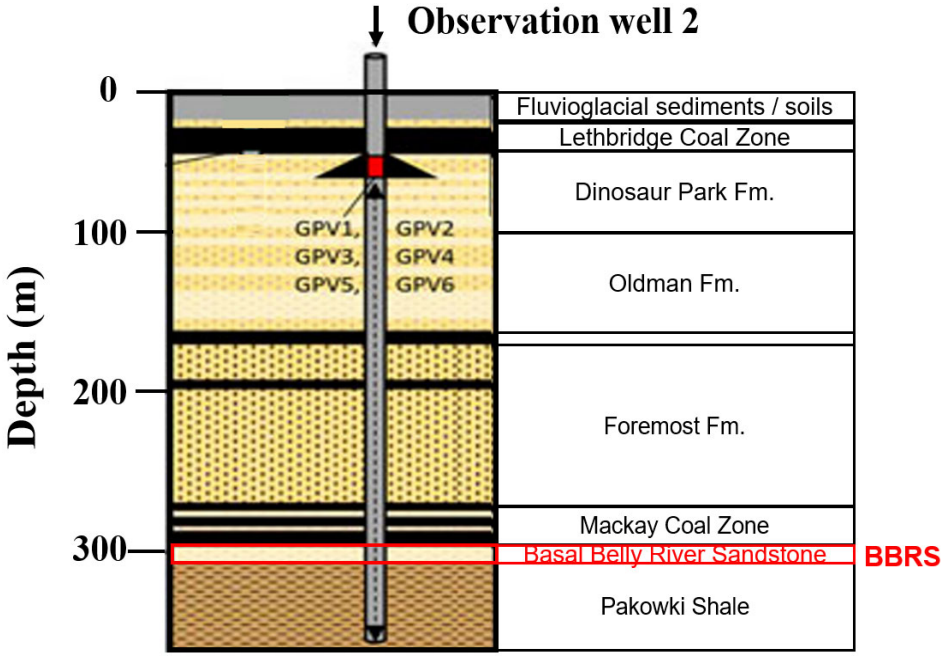
Self-Introduction

- **Name: Hyeong-Geun Ji**
- **Education:** Master's course at Jeonbuk National University (22' 03~24' 08)
- **Lab**: Jeonbuk National University Computational Geophysical Laboratory (JBCGL, https://jbcgl.jbnu.ac.kr/))
- **Duration of visit:** 23' 09 ~ 24' 03.
- **Purpose:** CaMI VSP monitoring demonstration study

Funded by KETEP Korea Institute of Energy Technology Evaluation and Planning

Contents

Overview of CaMI FRS



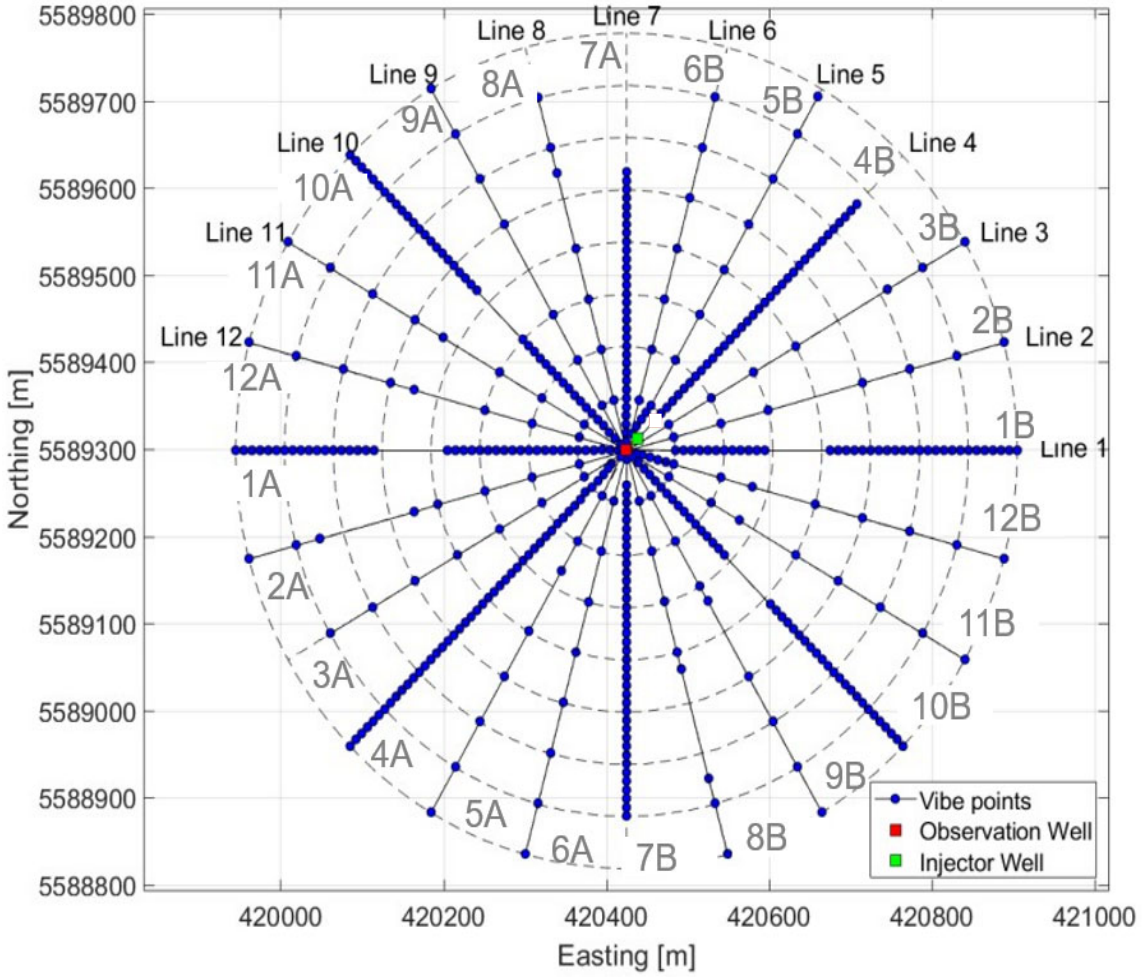
The CaMI FRS is….

- located near Brooks, southern Alberta
- developing and validating monitoring techniques
- targeting the BBRS layer for CO_2 injection

The BBRS layer is ….

- formed during the late Cretaceous period
- an extremely thin layer with a thickness of 7 m
- overlaid by the coals and mixed shale and sandstone units

Snowflake VSP data

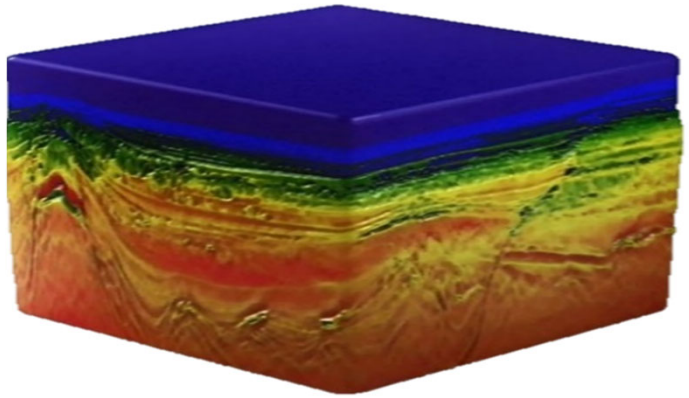


walkaway - walkaround survey

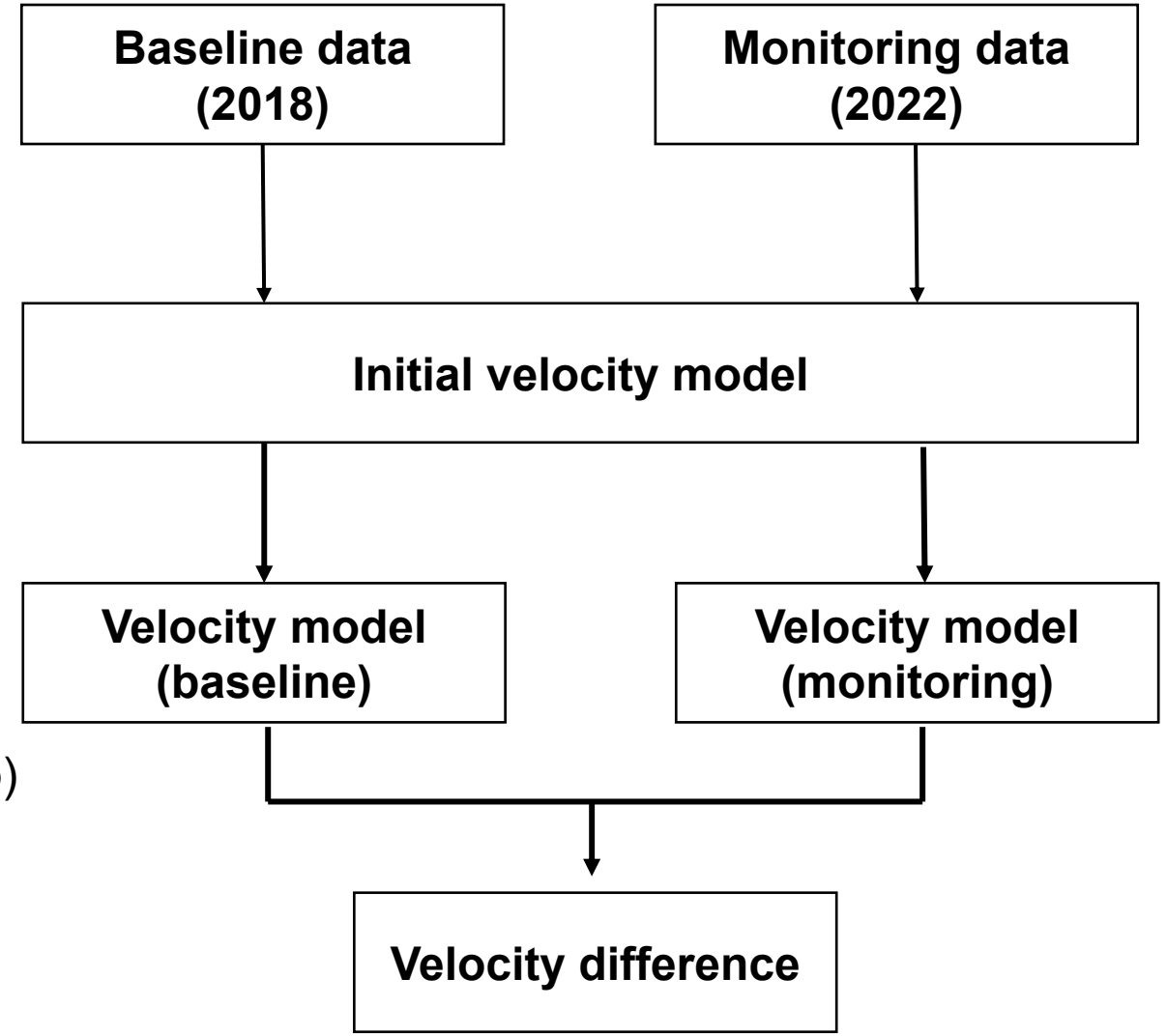
	Number of shot	
	Snowflake I	Snowflake II
Line1	76	74
Line2	15	15
Line3	14	14
Line4	83	82
Line5	20	20
Line6	15	15
Line7	72	71
Line8	15	15
Line9	15	15
Line10	82	82
Line11	16	16
Line12	22	22
	445	441

Full waveform inversion

Full waveform inversion (FWI)



- Estimate the underground properties ($\mathbf{V_P}$, V_S, ρ)
- High resolution
- Require huge calculation costs
- Vulnerable to noise
- Can used for CO_2 monitoring



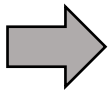
< Individual FWI >

Methodology

- **Objective function**

$$E(\mathbf{m}) = \sum_s \sum_r \left[-\hat{u}(s,r,\mathbf{m}) \cdot \hat{d}(s,r) \right] \qquad (1)$$

$$\hat{u}(s,r,\mathbf{m}) = \frac{u(s,r,\mathbf{m})}{\left\| u(s,r,\mathbf{m}) \right\|} \quad , \quad \hat{d}(s,r) = \frac{d(s,r)}{\left\| d(s,r) \right\|} \qquad (2)$$



Matching phase rather than amplitude

- **Gradient direction**

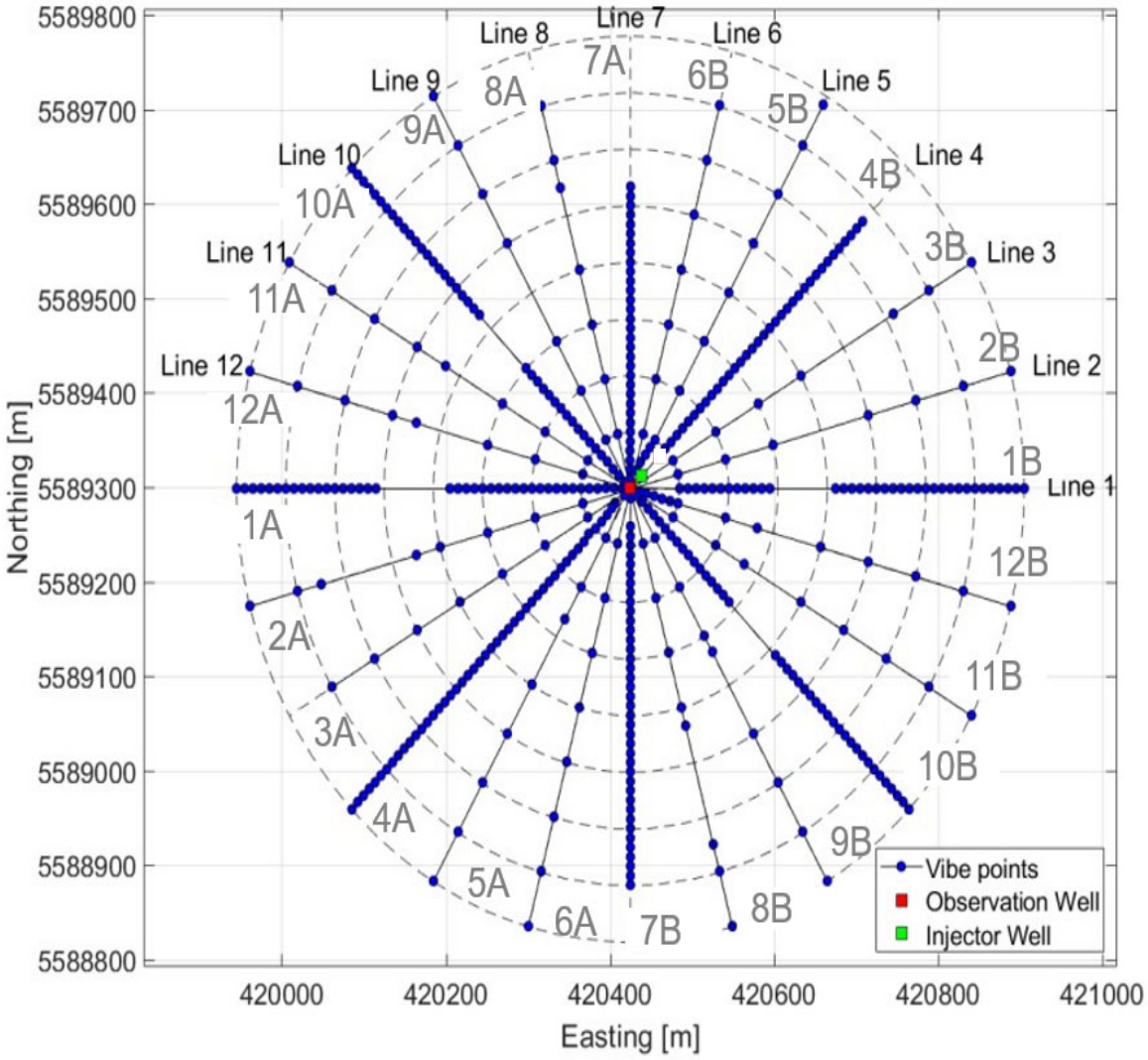
$$\frac{\partial E(\mathbf{m})}{\partial m_i} = \sum_s \sum_r \left[\frac{\partial u(s,r,\mathbf{m})}{\partial m_i} \cdot b(s,r,\mathbf{m}) \right] \qquad (3)$$

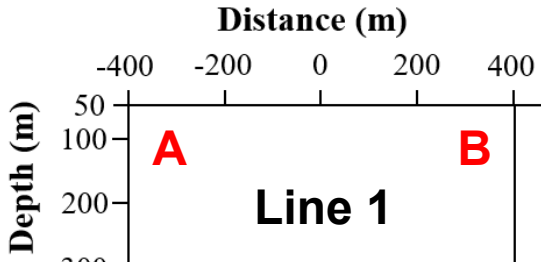
s : source u : modelled data
r : receiver d : field data
$\mathbf{m}$: model parameter

- **Adjoint source**

$$b(s,r,\mathbf{m}) = \frac{1}{\left\| u(s,r,\mathbf{m}) \right\|} \left\{ \hat{u}(s,r,\mathbf{m}) [\hat{u}(s,r,\mathbf{m}) \cdot \hat{d}(s,r)] - \hat{d}(s,r) \right\} \qquad (4)$$

Shot line slices for comparison 2D and 3D FWI results

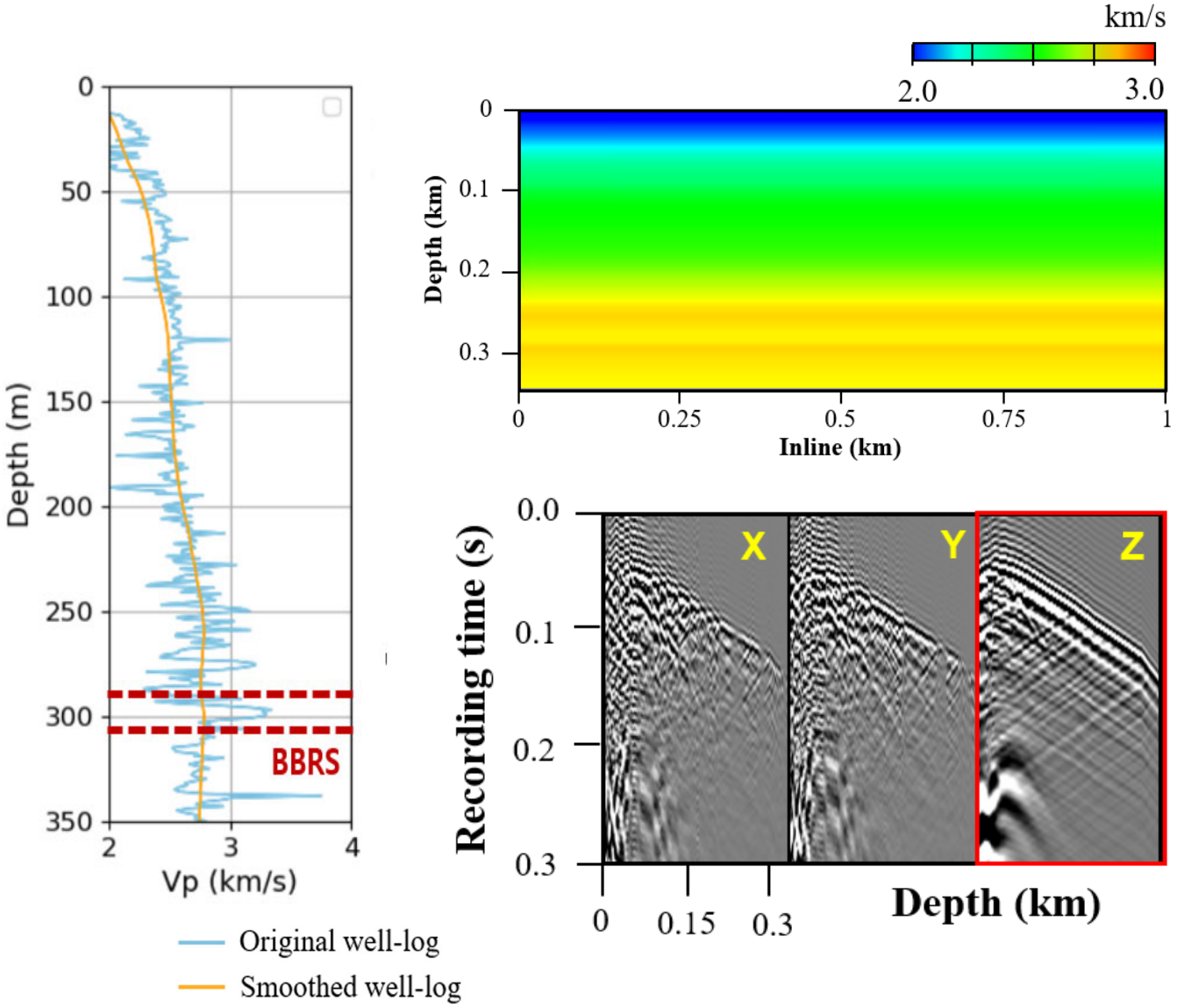




Line 1	Line 2	Line 3
Line 4	Line 5	Line 6
Line 7	Line 8	Line 9
Line 10	Line 11	Line 12

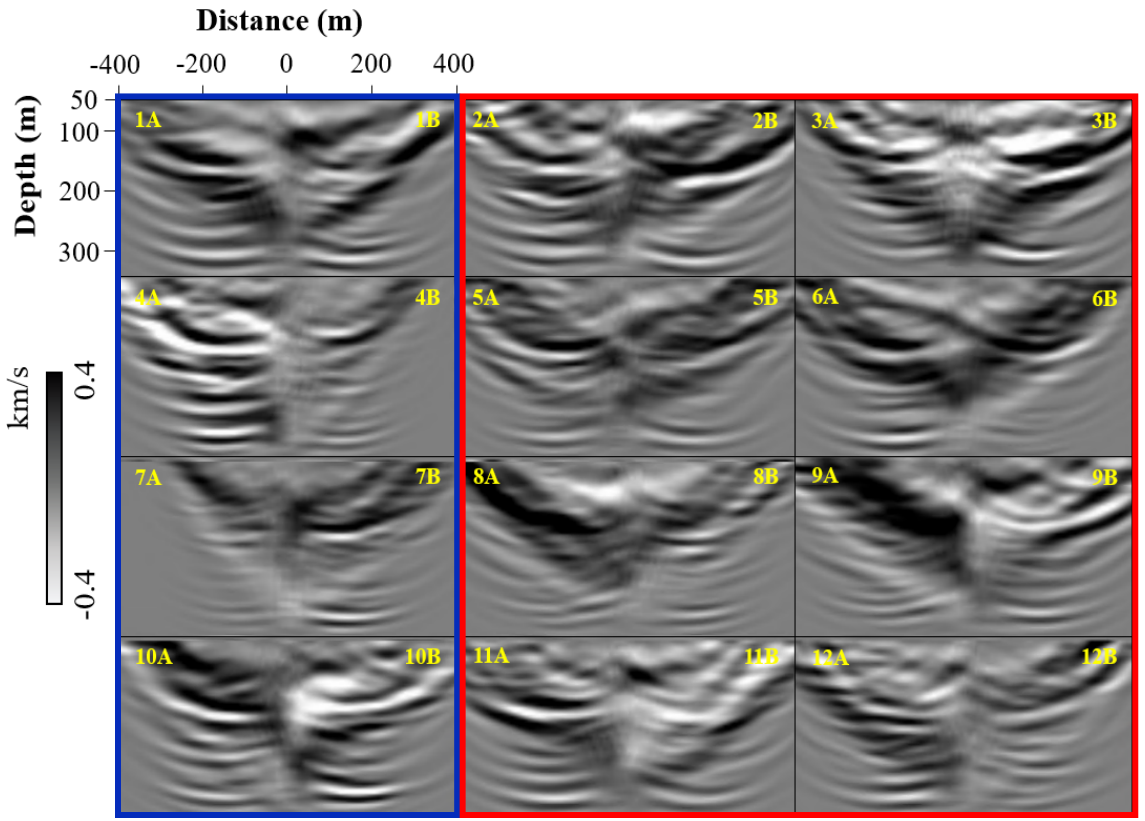
For 2D-3D comparison, we sliced FWI results along the shot line

Setting of 2D FWI



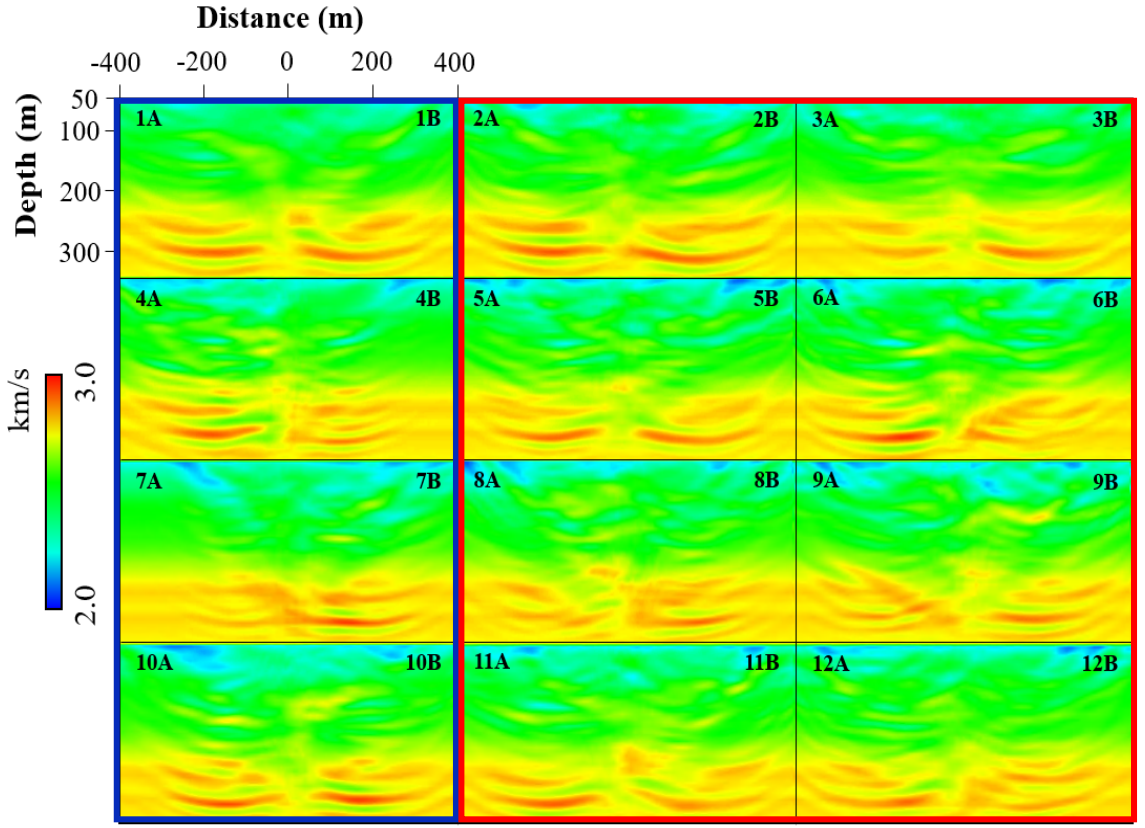
	2D FWI
Number of space grids	200 * 70
Total recording time (s)	0.3
Space grid sampling (m)	5 * 5
Time grid sampling (ms)	0.5
Maximum frequency (Hz)	200
Source wavelet	ricker
Source wavefields storing method	Memory
Smoothing gradient (m)	25
Objective function	GCN
Number of iterations	15
Step length (km/s)	0.02

Inversion results – Snowflake I (2D)



Enough shots Fewer shots

< 1st iteration gradient direction >

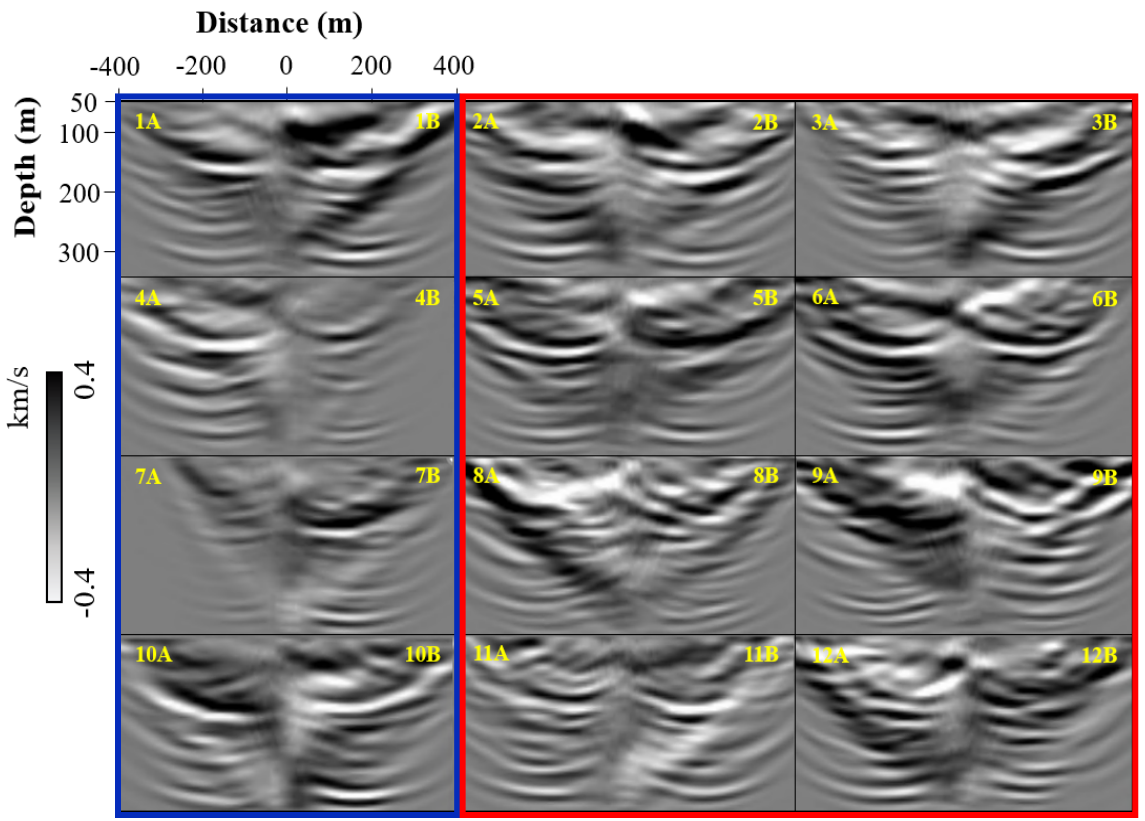


Enough shots Fewer shots

< final inverted model >

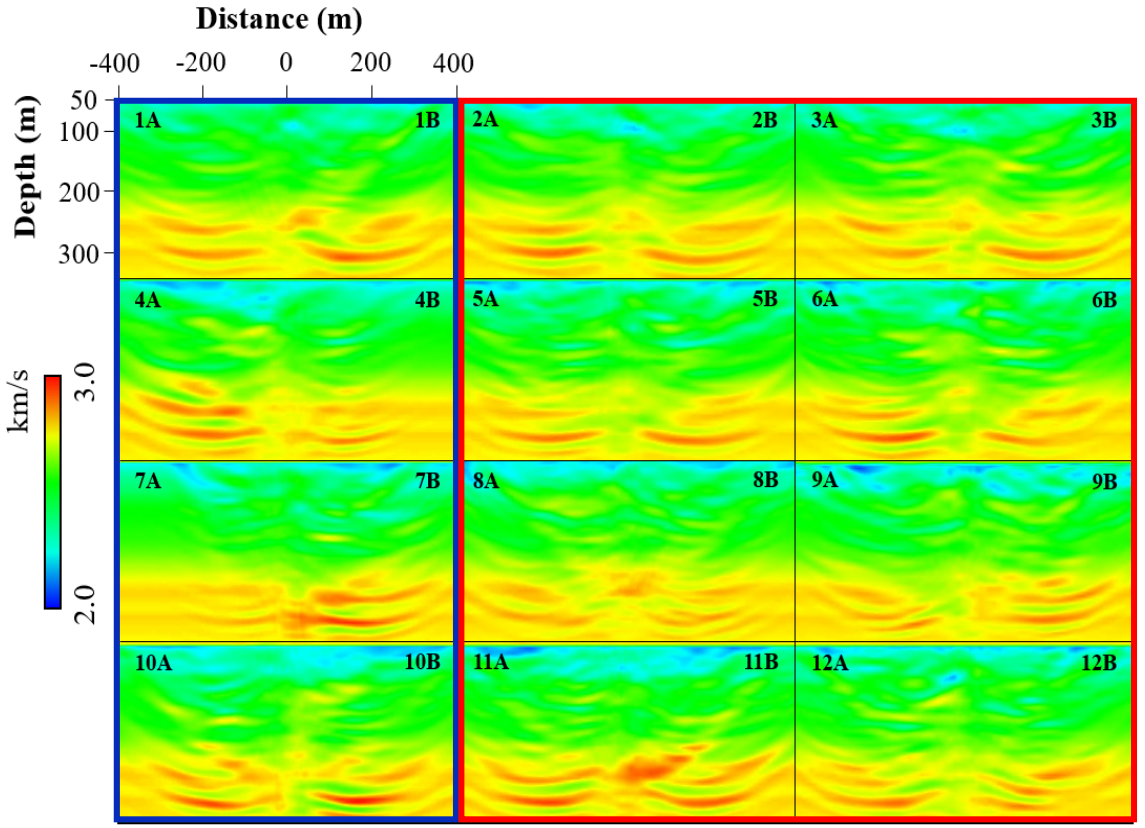
- X Lines with fewer shots exhibit unsatisfactory results
- X The migration isochrone is significantly emphasized
- X Poor continuity of layers

Inversion results – Snowflake II (2D)



Enough shots Fewer shots

< 1st iteration gradient direction >

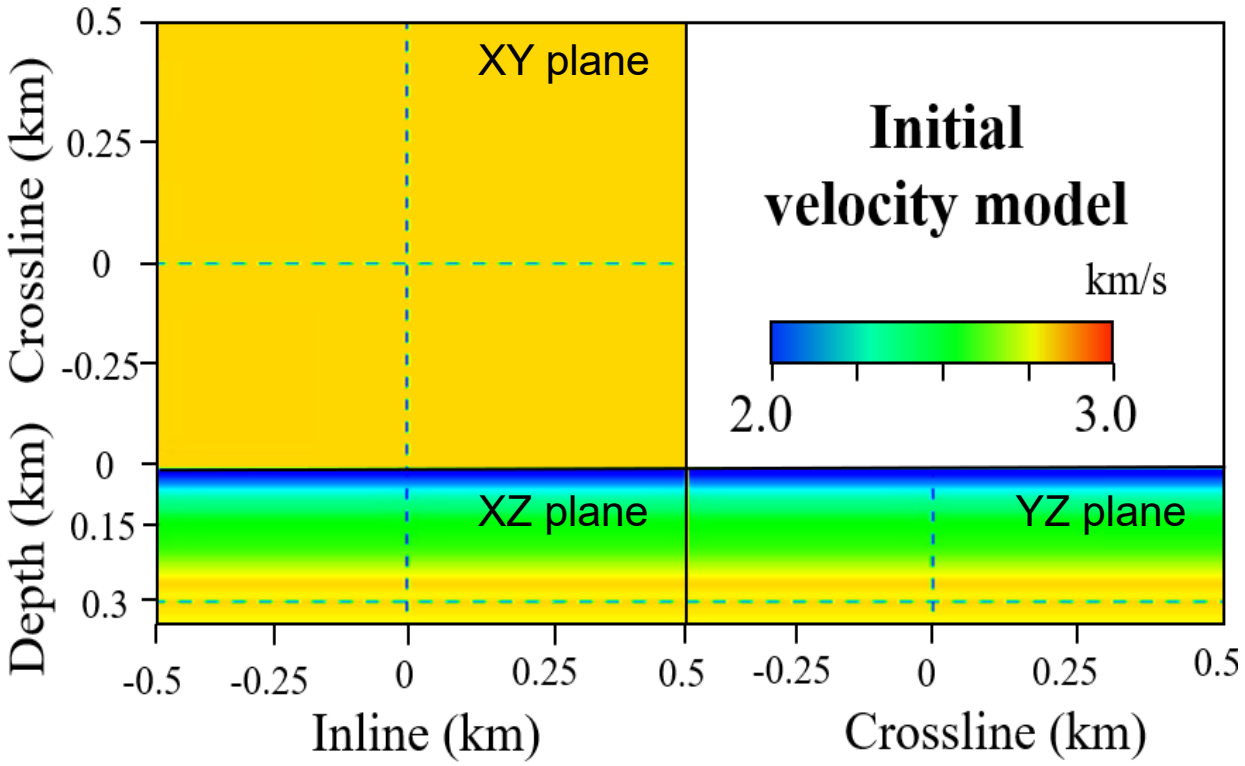


Enough shots Fewer shots

< final inverted model >

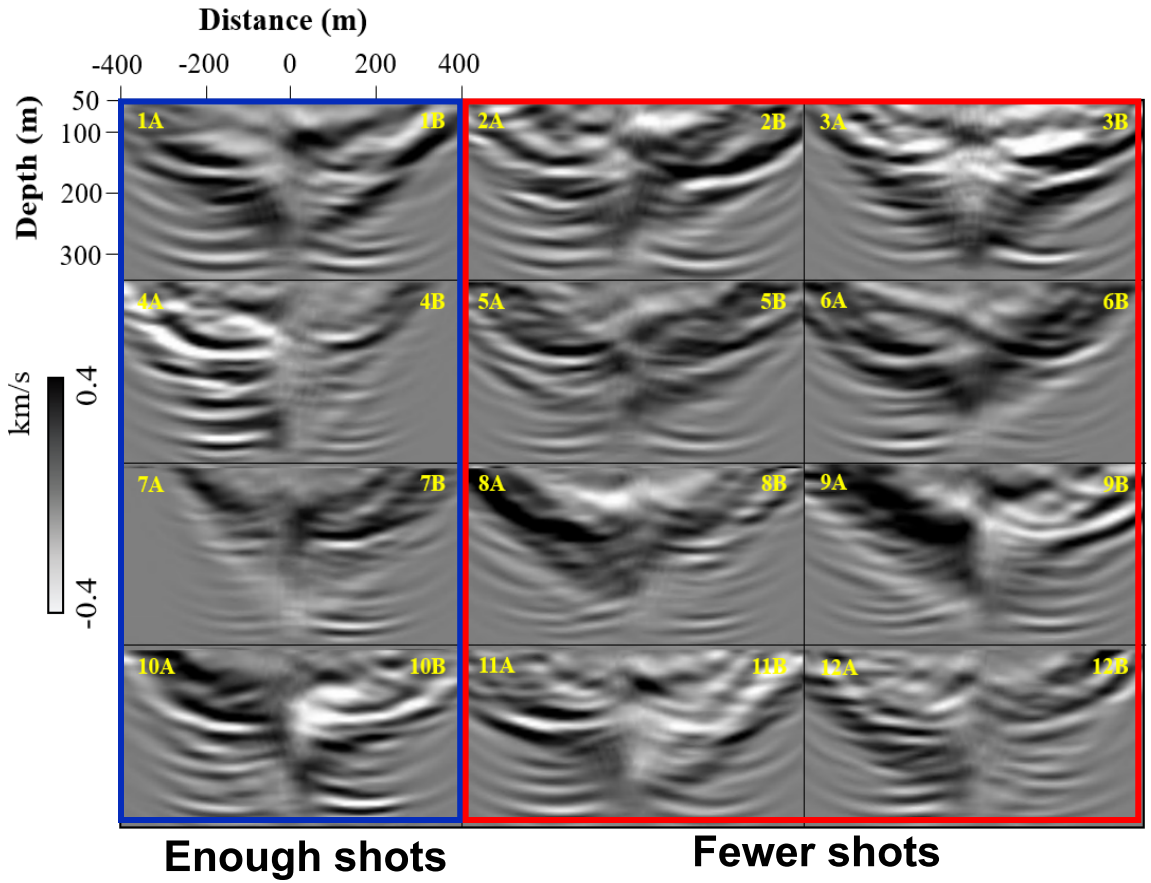
- X Velocity structures between the baseline and monitoring results are different
- X Some lines updated more rapidly in the injection layer than the baseline (Line 4, 7, 11)
- X The velocity change due to CO_2 injection is not detected well

Setting of 3D FWI

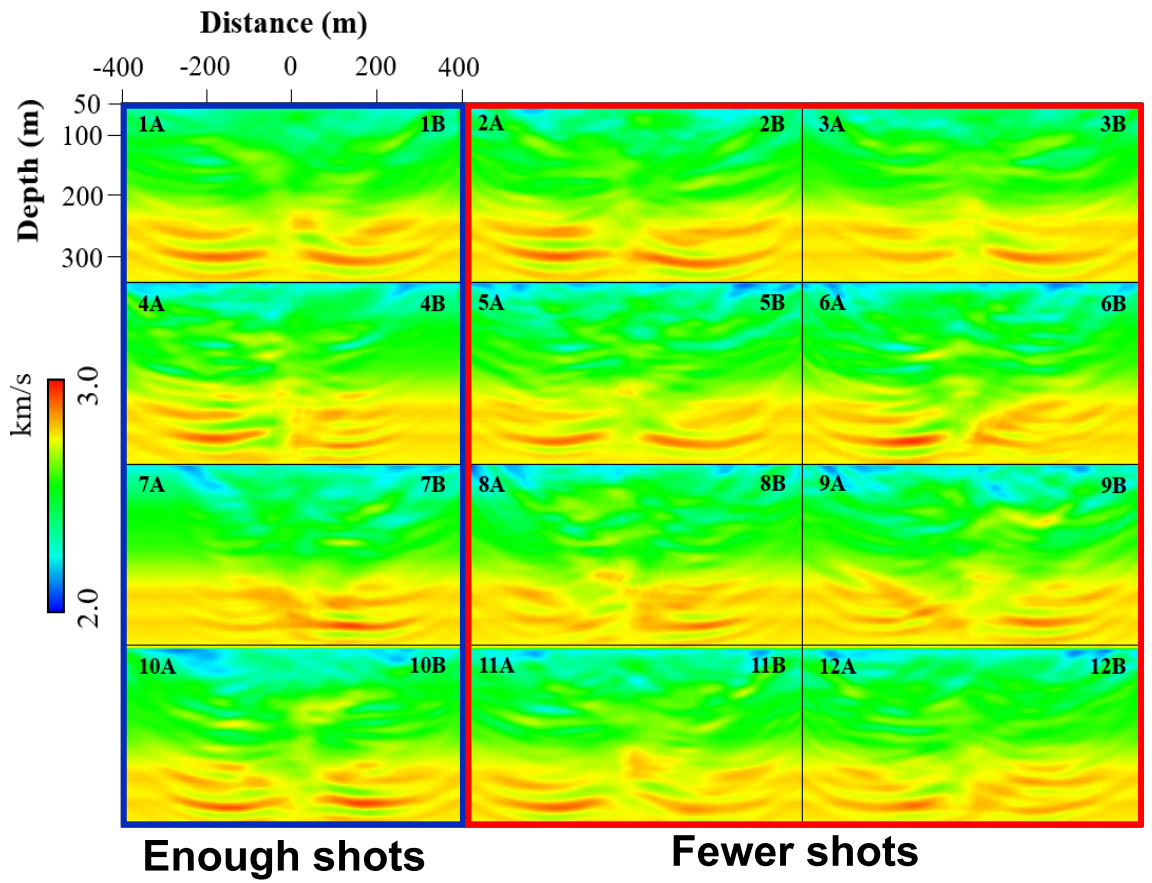


	3D FWI
Number of space grids	200 * 200 * 70
Total recording time (s)	0.3
Space grid sampling (m)	5 * 5 * 5
Time grid sampling (ms)	0.3
Maximum frequency (Hz)	200
Source wavelet	ricker
Source wavefields storing method	Boundary saving
Smoothing gradient (m)	25
Objective function	GCN
Number of iterations	15
Step length (km/s)	0.02

Inversion results – Snowflake I (2D)

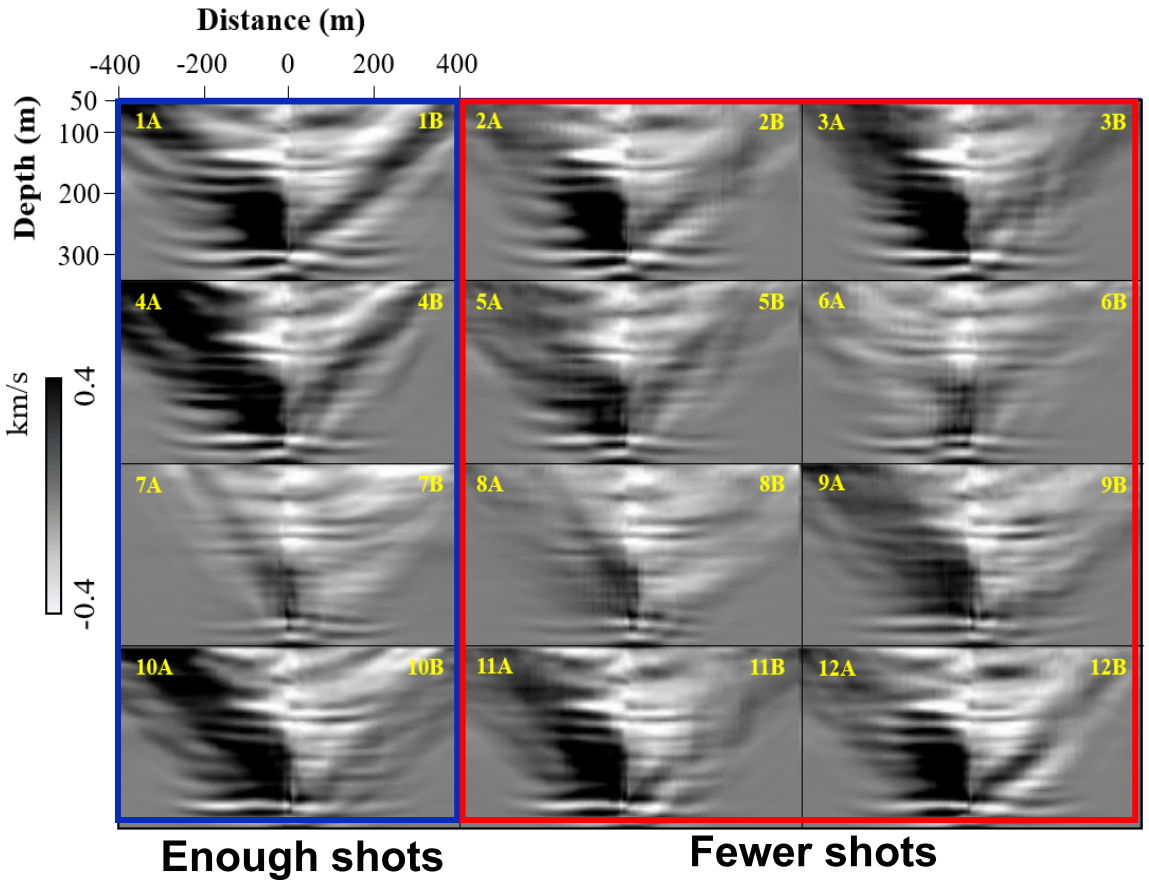


< 1st iteration gradient direction >

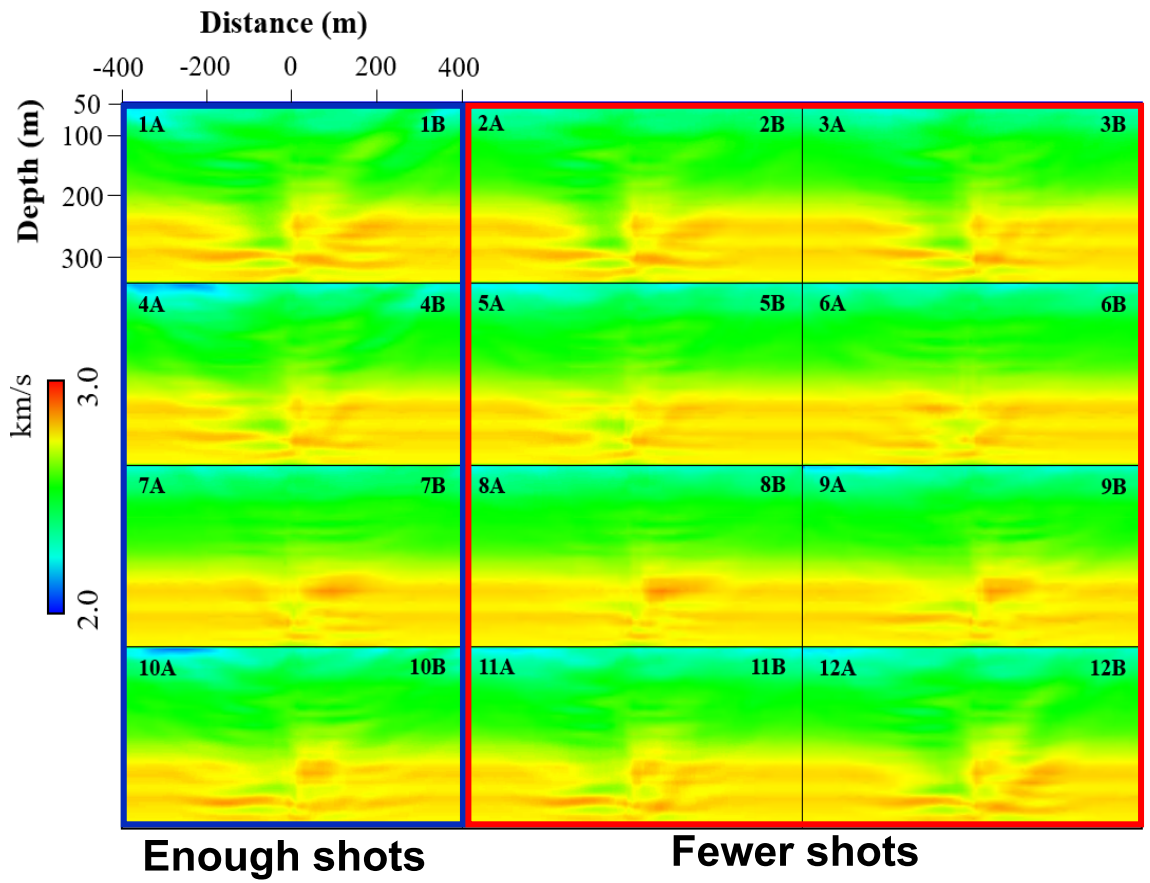


< final inverted model >

Inversion results – Snowflake I (3D)



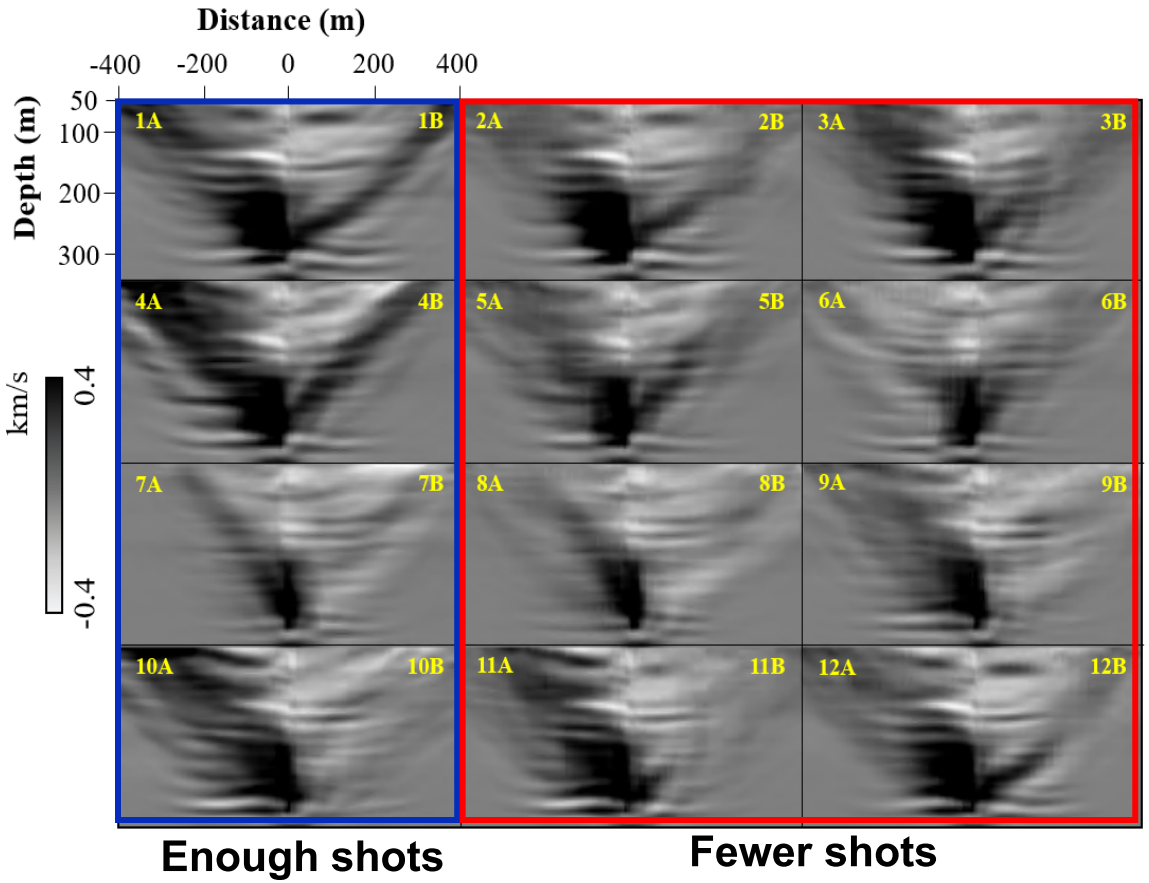
< 1st iteration gradient direction >



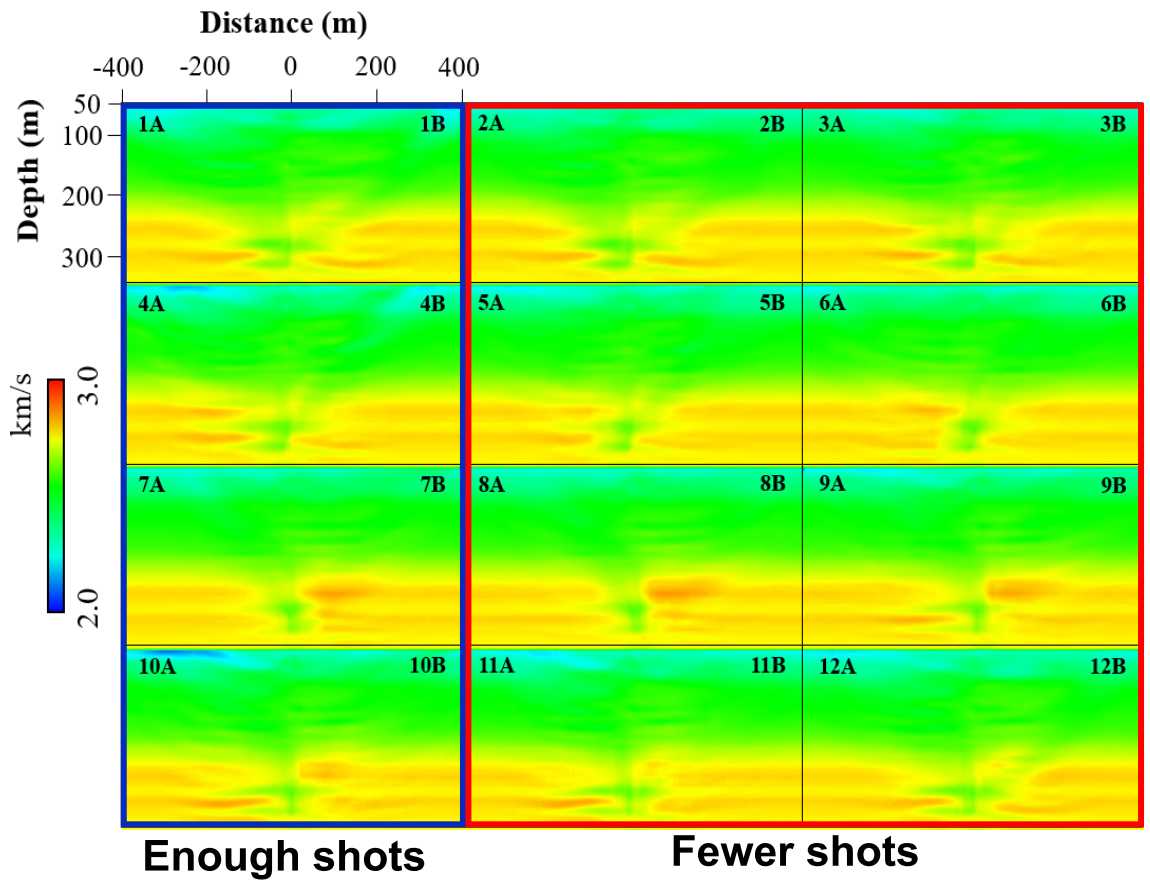
< final inverted model >

- X Stronger long wavelength components are implemented
- X The BBRS layer has been updated relatively weaker
- ✓ The continuity of the layer has been improved
- ✓ Even in layers with limited sources, there are horizontal variations

Inversion results – Snowflake II (3D)



< 1st iteration gradient direction >



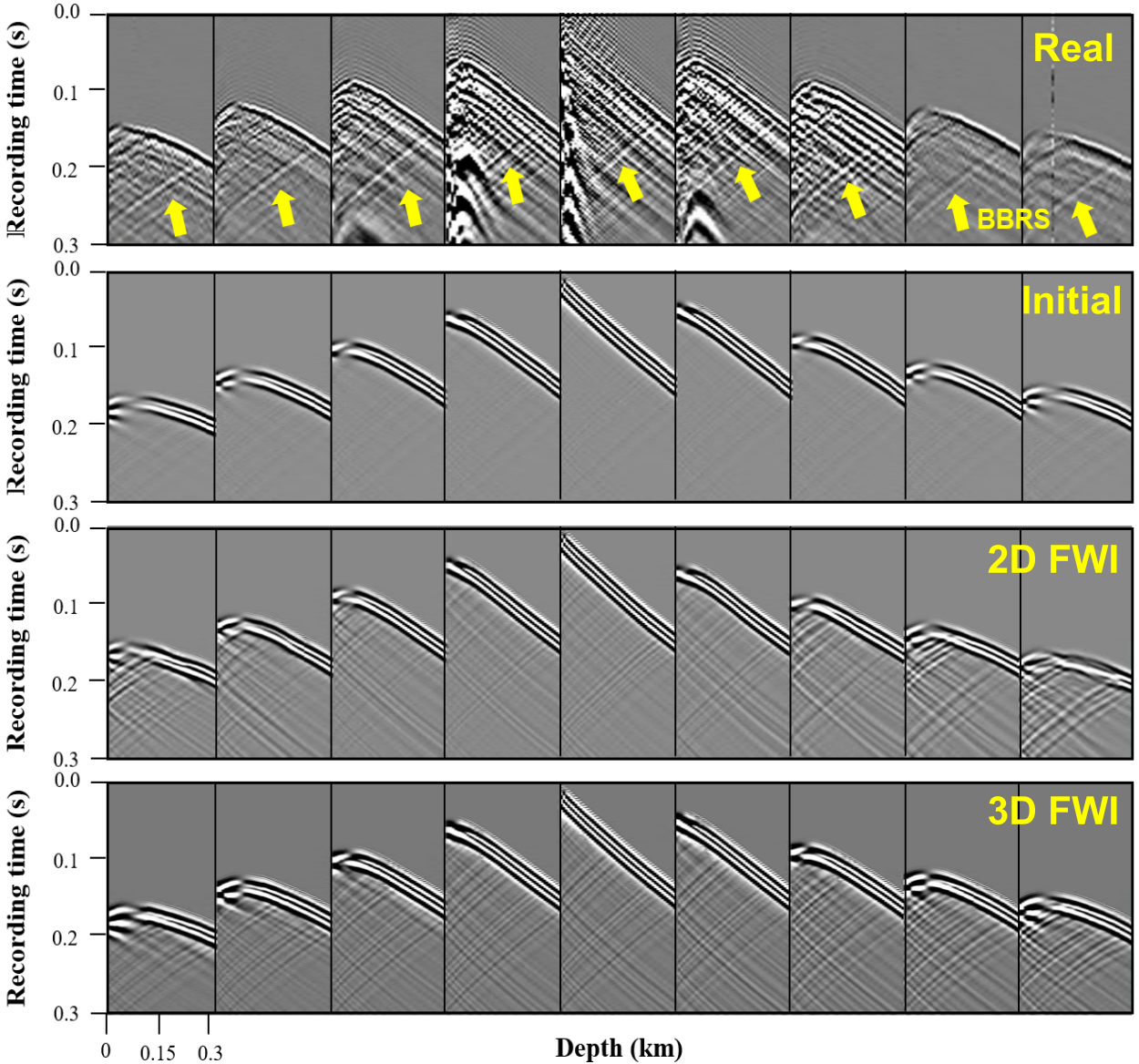
< final inverted model >

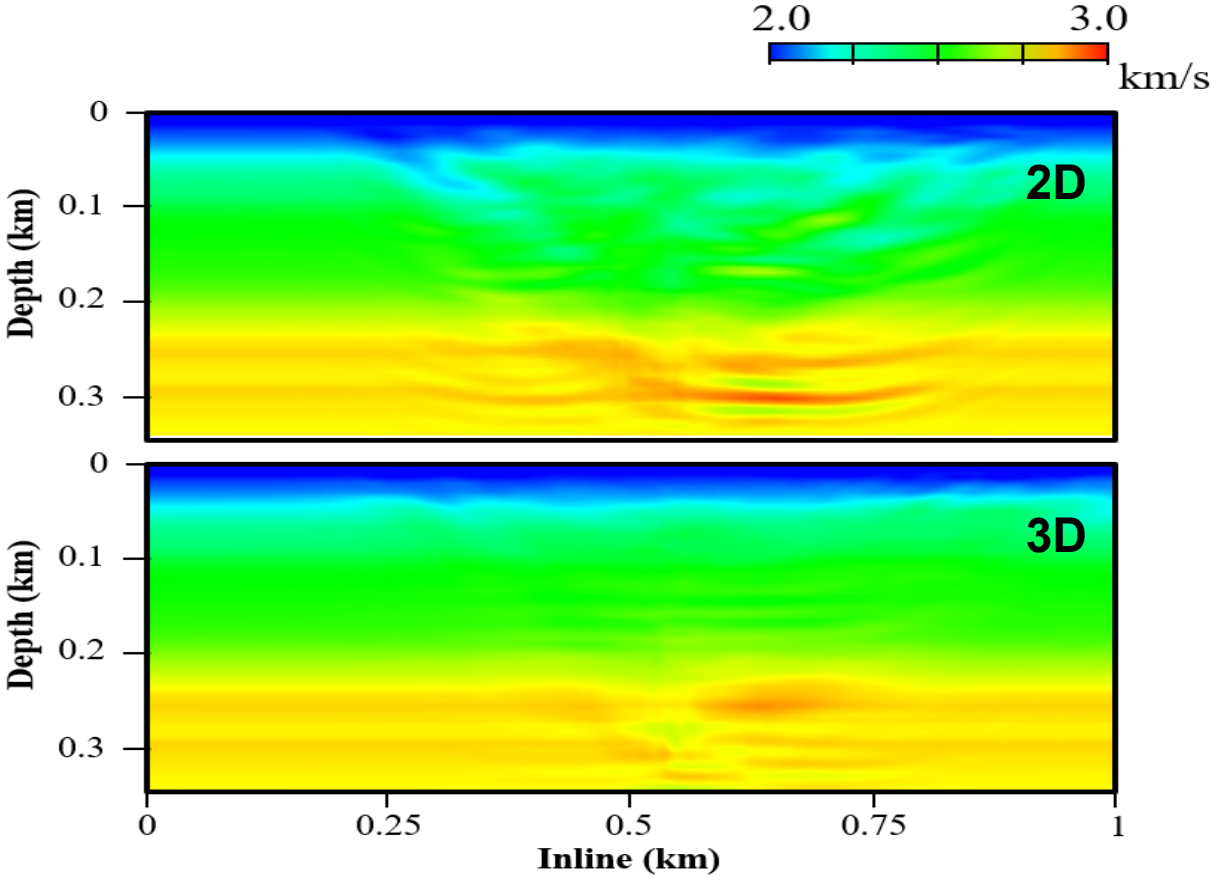
- The gradient trends are similar, but stronger updates occur in the baseline
- The continuity of the layer has been improved
- The velocity change in the BBRS layer has been detected
- The structure between the baseline and monitoring implemented consistently

→ **Advantageous for CCS monitoring**

Comparison between observed and modelled data (Baseline)

Baseline

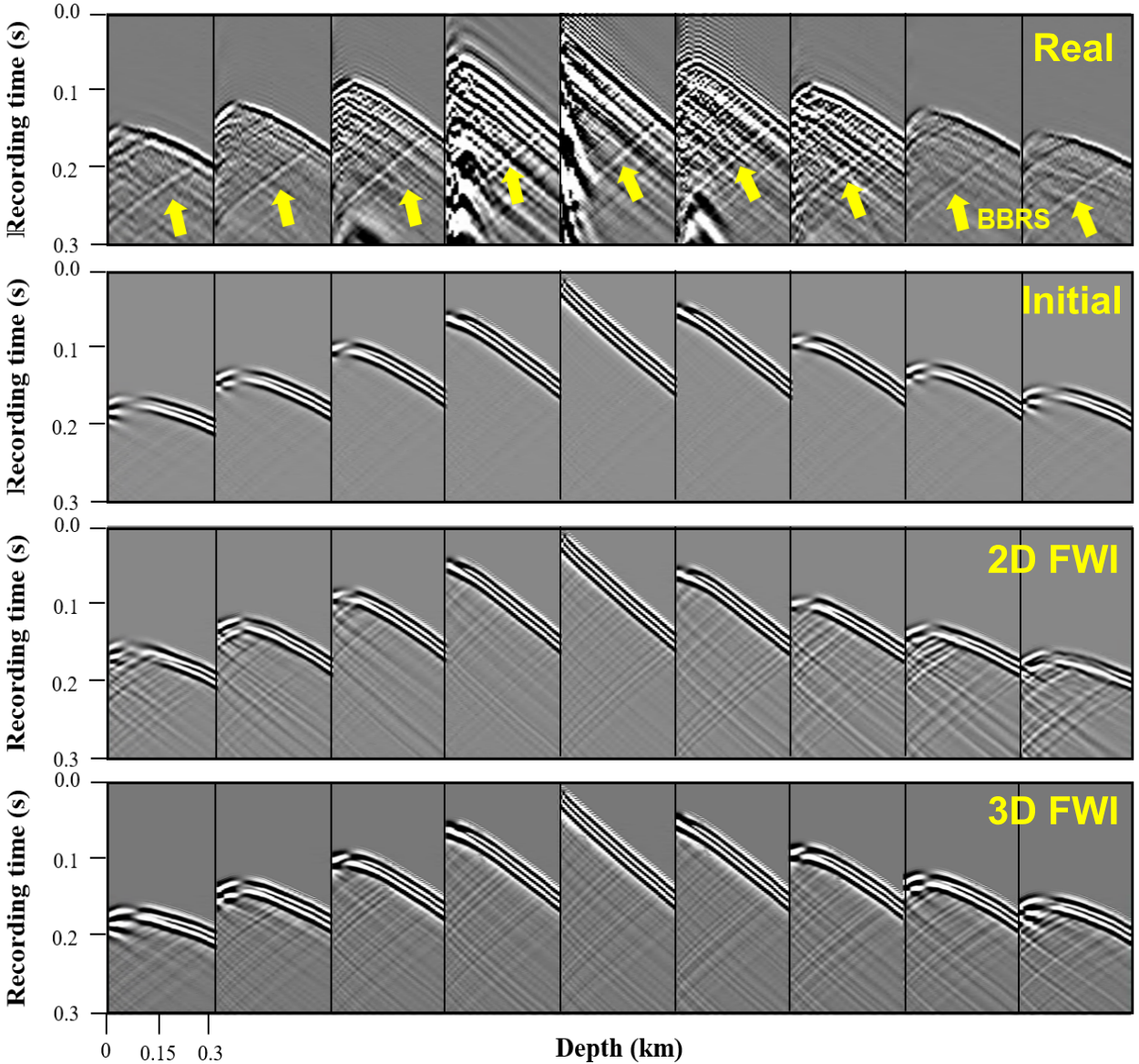


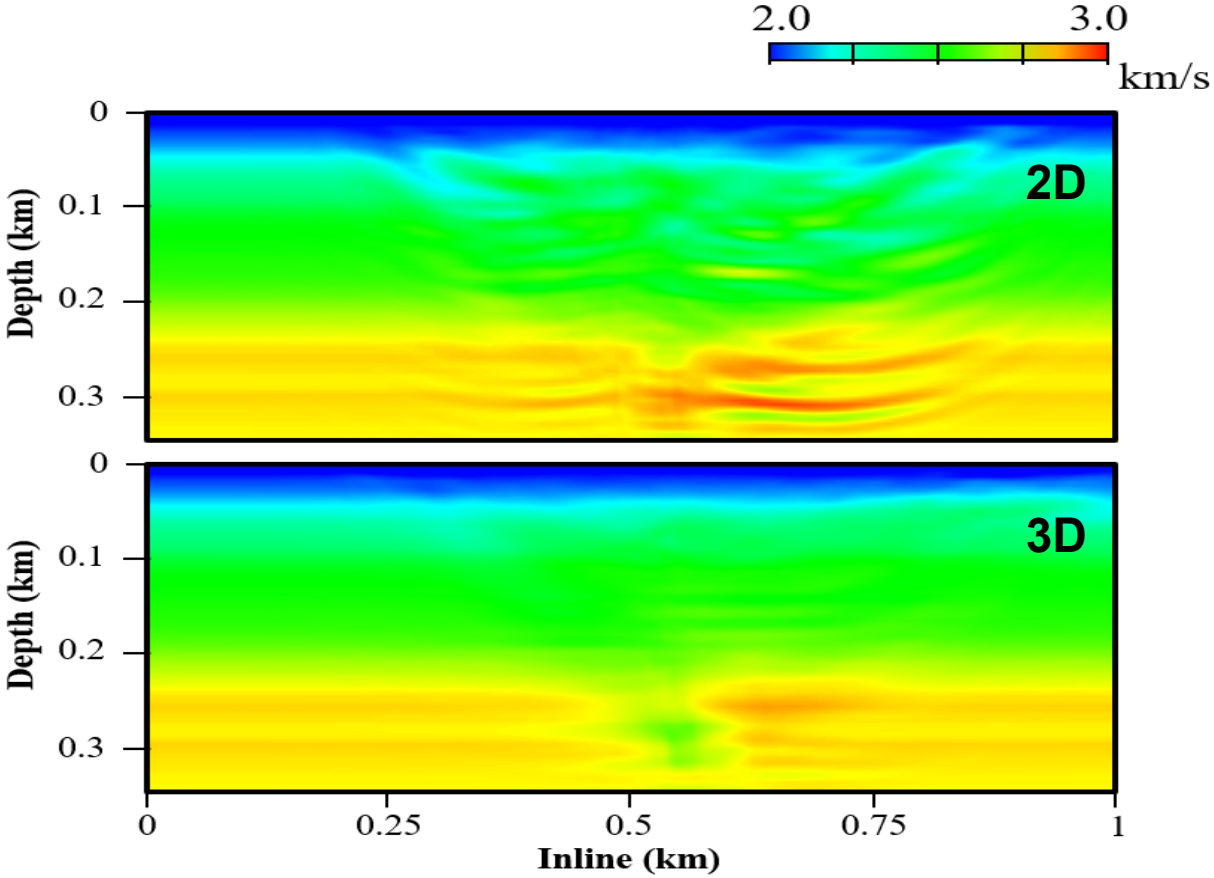


- The direct wave and refracted wave are updated similarly in 2D and 3D
- The reflected wave from BBRS isn't implemented well in 3D

Comparison between observed and modelled data (Monitoring)

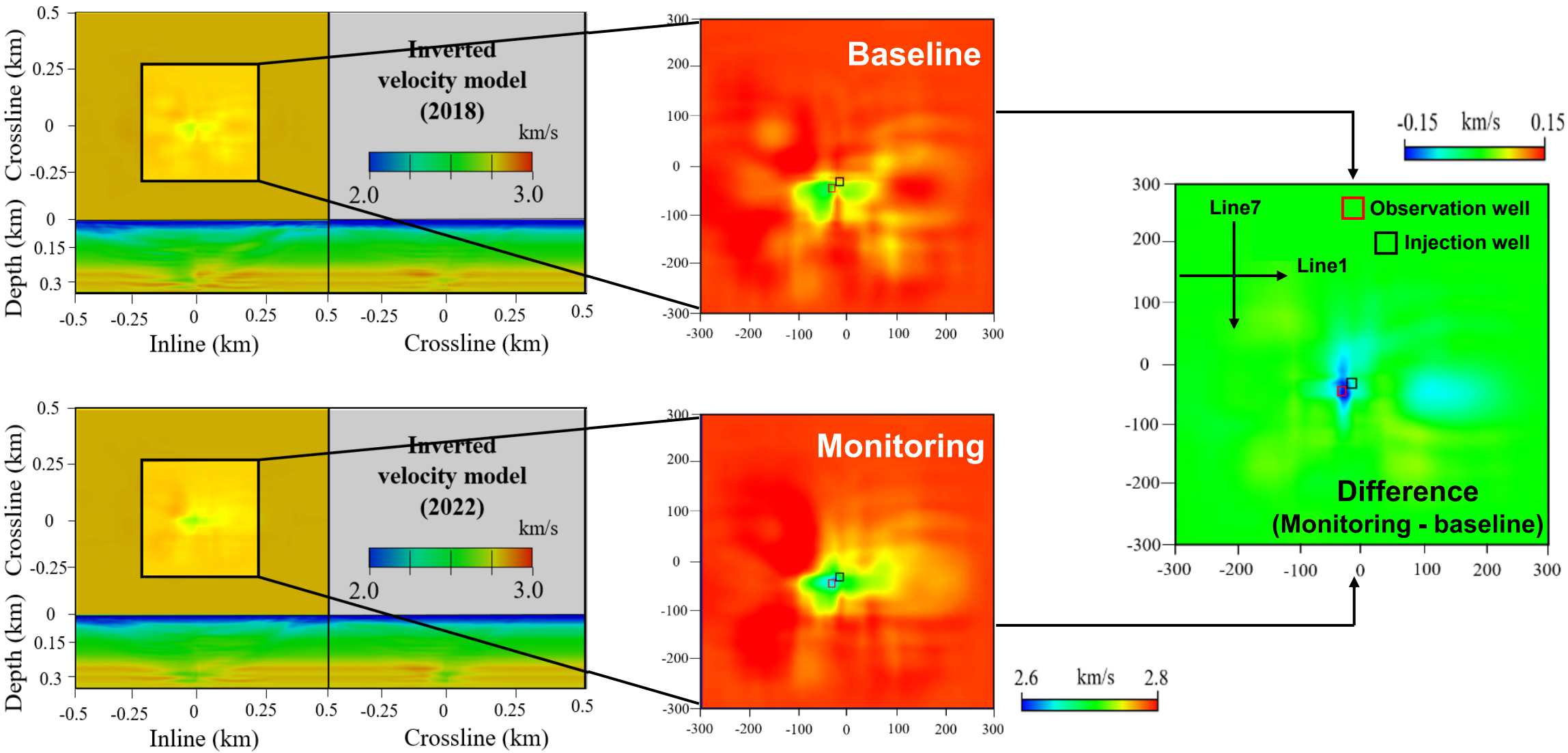
Monitoring





- The direct wave and refracted wave are updated similarly in 2D and 3D
- The reflected wave from BBRS isn't implemented well in 3D

Sliced XY plane of 3D inverted velocity model



Summary

- In this study, we conducted individual 2D and 3D FWI for Snowflake data with nearly same parameters
- We focused on V_P reduction after CO_2 injection, utilizing only Z-component among the 3-components data
- When comparing 2D and 3D results, the continuity of layers has improved in 3D result
- In 3D, changes due to CO_2 injection were detected, and we confirmed that CO_2 spreads along Line 7 in the XY plane

Future study

- Attenuation of vertical long-wavelength component
- Data preprocessing
- 4D regularization for noise reduction
- Implementation of different monitoring strategies (such as common-model strategy)
- Exploring specific approaches to validate the accuracy of FWI results

Acknowledgements

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