◆ CCS Technical Workshop 2021 ◆

CO_2地中貯留技術開発と実用化への取組

～マイクロバブルCO_2圧入、光ファイバーセンシング技術～

R&D Achievements on Microbubble CO_2 Injection and Fiber Optic Sensing Technologies

二酸化炭素地中貯留技術研究組合・技術部長

(公財)地球環境産業技術研究機構（RITE）
CO_2貯留研究グループリーダー

せつ　じきゅう
薛　自求

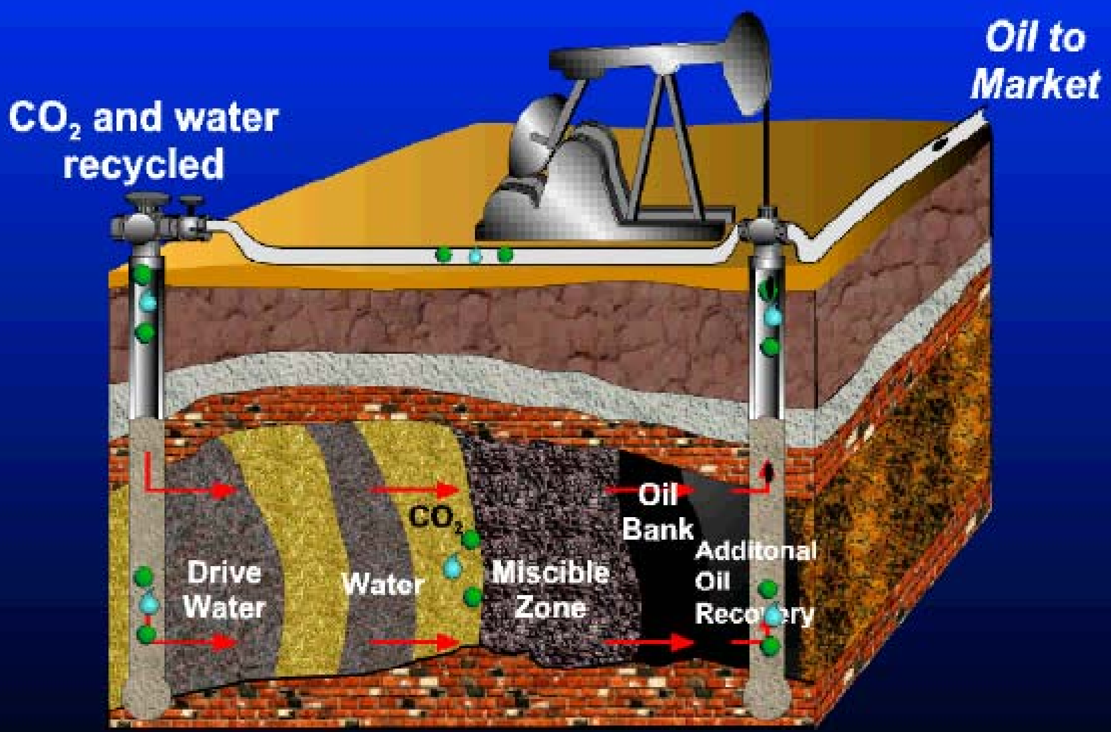
Ziqiu Xue (xue@rite.or.jp)

RITE Research Institute of Innovative Technology for the Earth

１．CO_2地中（深部塩水層）貯留について

Geologic Carbon Dioxide Storage: The Way Forward

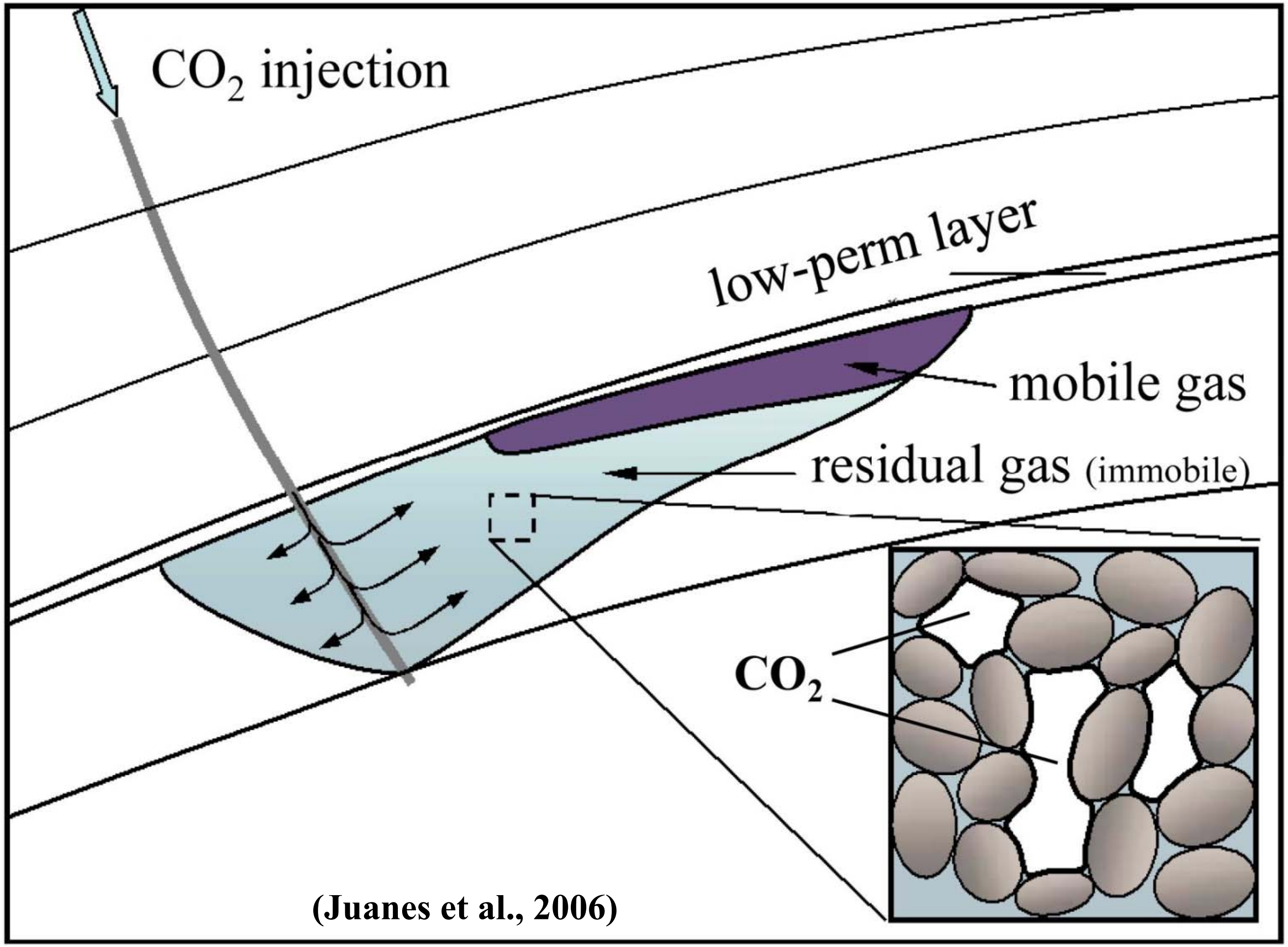
Carbon Dioxide Flooding



- 40-70% of CO_2 injected stays in reservoir

Associated CO_2 Storage in CO_2-EOR

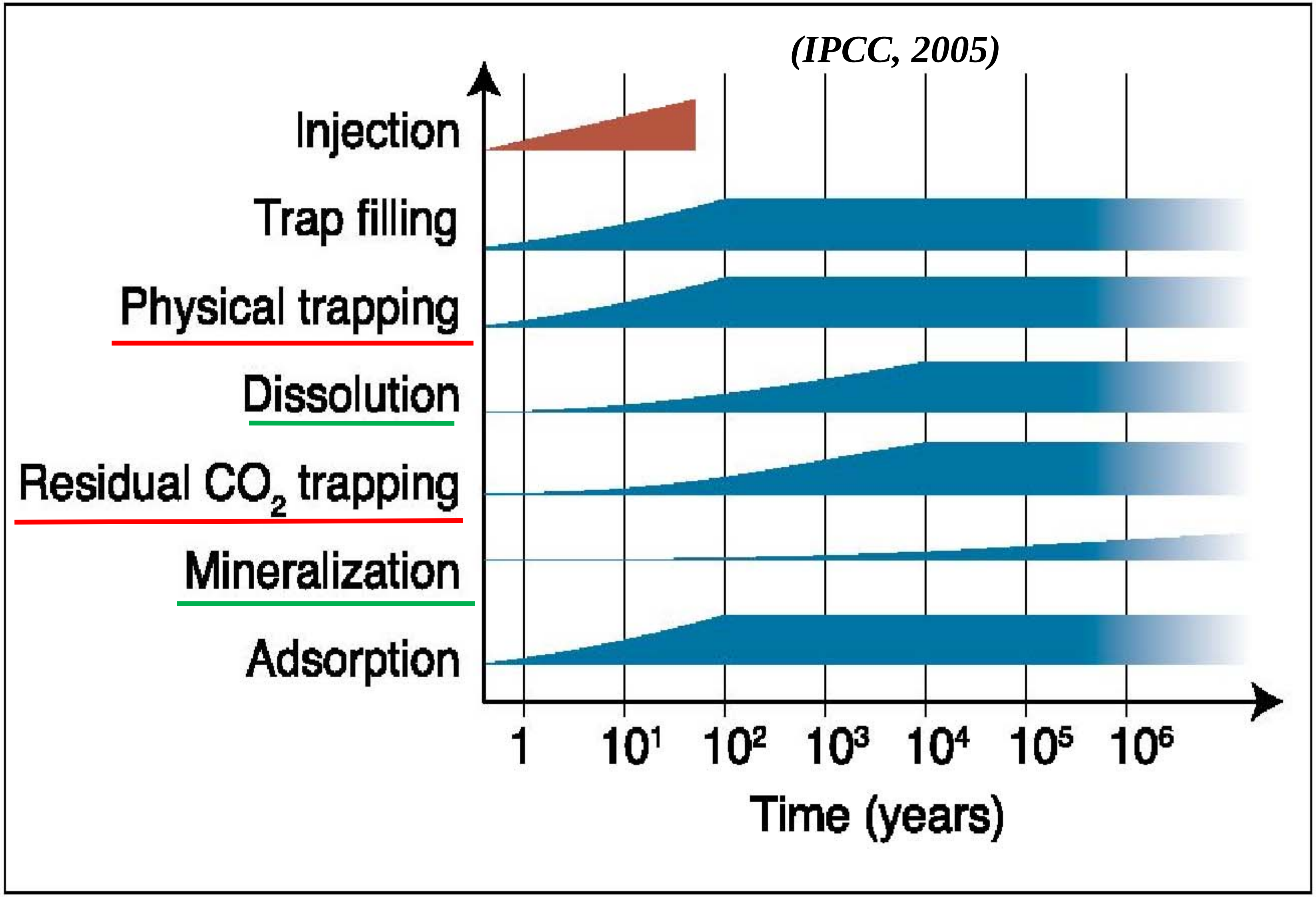
Geologic CO_2 Storage in Deep Saline Aquifer



Permanently Storing CO_2 in the Subsurface

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

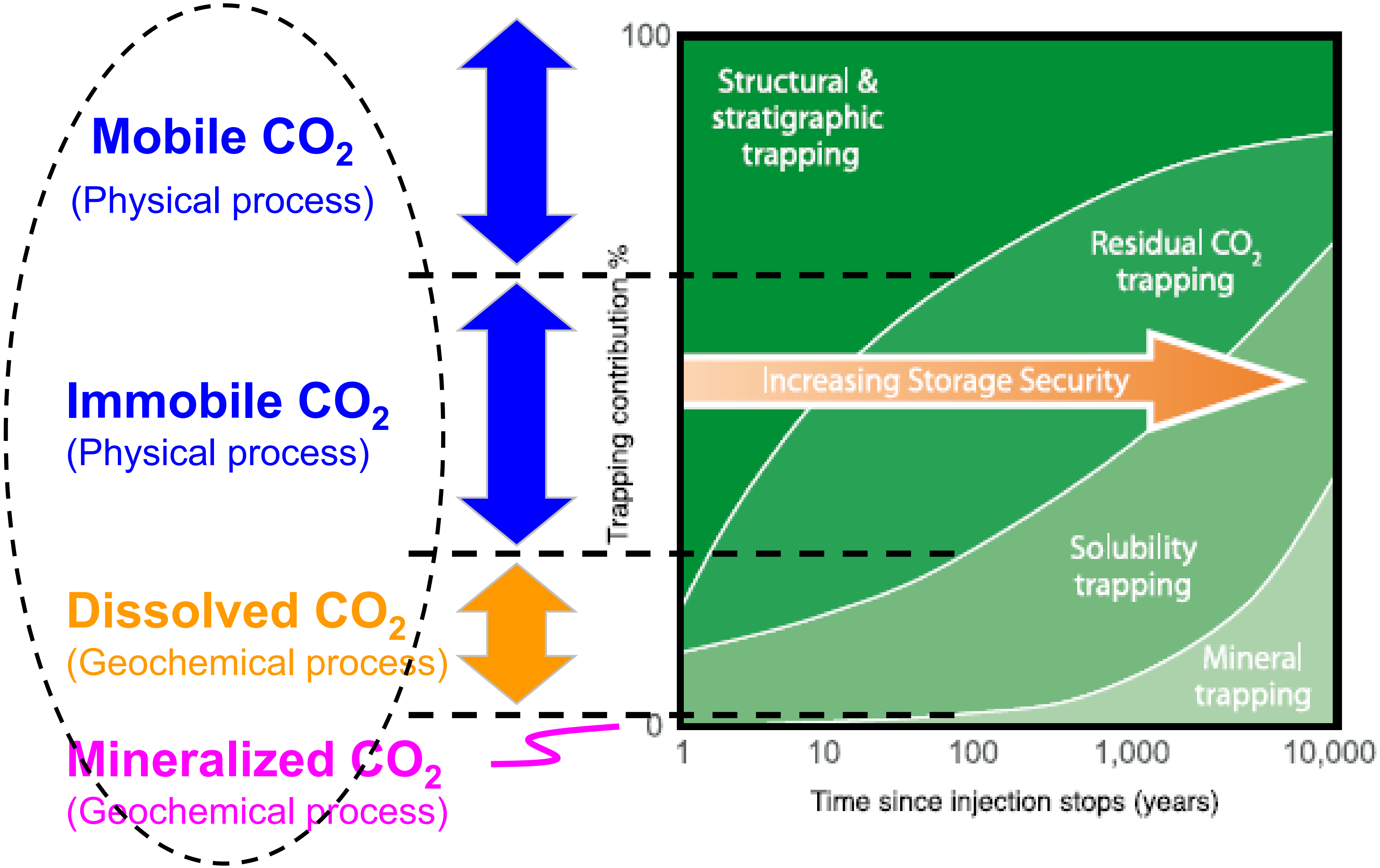
CO_2 Trapping Mechanisms: long term security
(how long is enough long?)



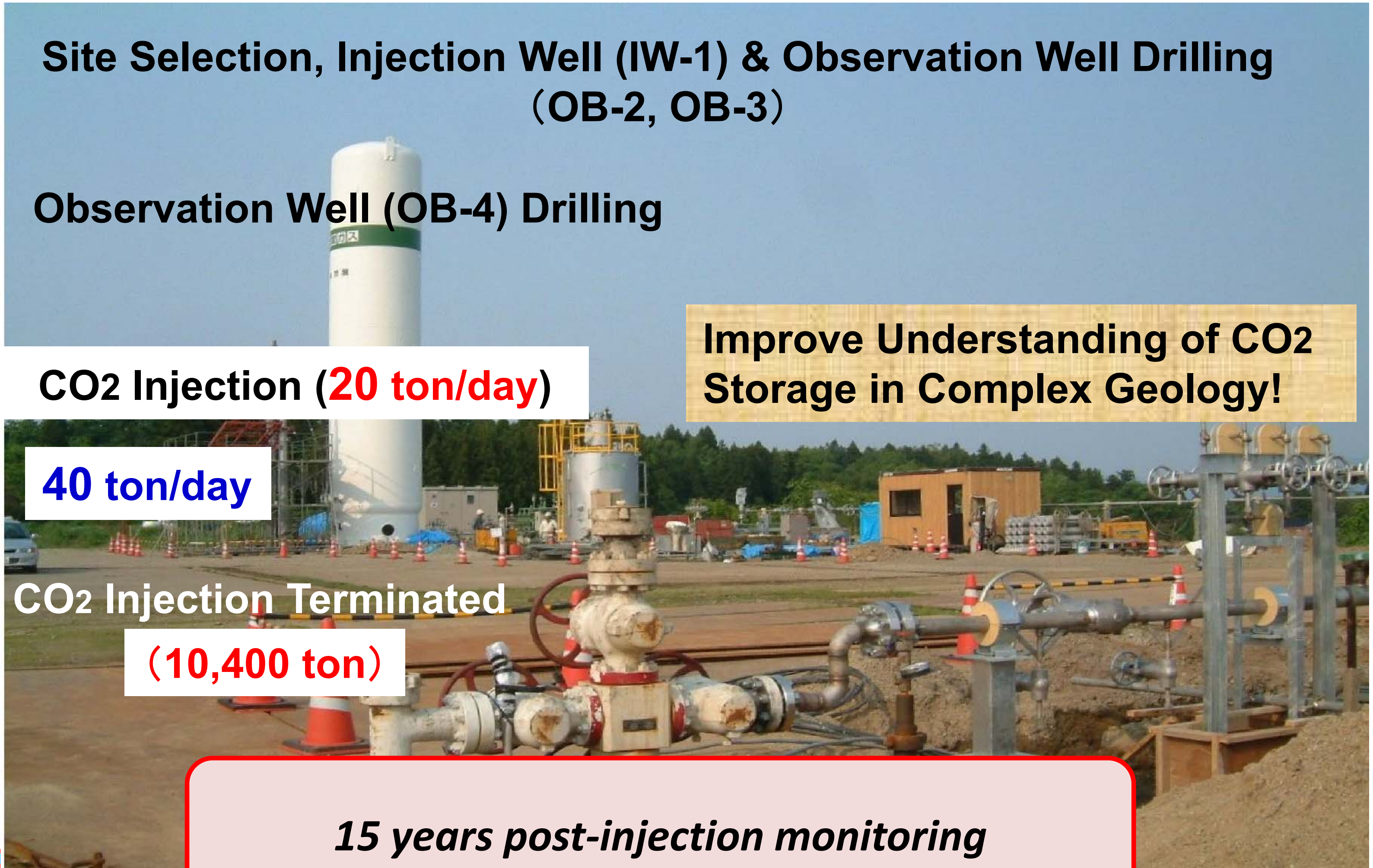
: lab data

: field data

Trap Mechanism & Long-term Behavior of Injected CO_2 in Deep Saline Aquifer



Overview of Nagaoka Project



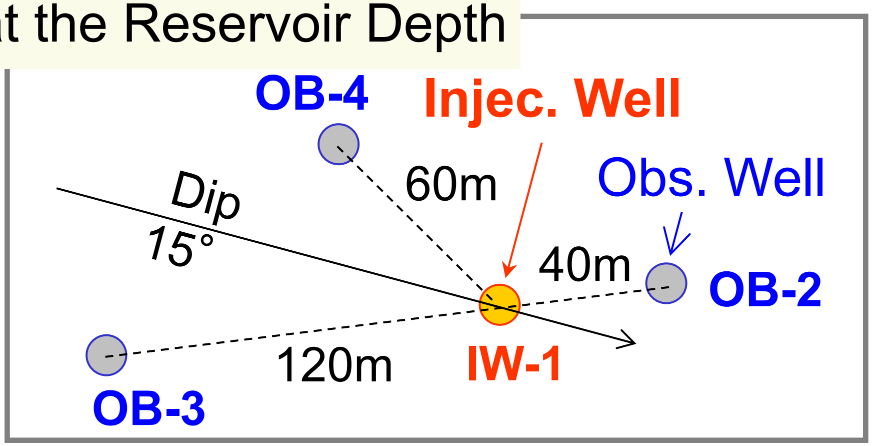
- **2000** Site Selection, Injection Well (IW-1) & Observation Well Drilling (OB-2, OB-3)
- **2001**
- **2002** Observation Well (OB-4) Drilling
- **2003** CO_2 Injection (20 ton/day)
- **2004** 40 ton/day
- **2005** CO_2 Injection Terminated (10,400 ton)
- **2010**
- **2020**

15 years post-injection monitoring

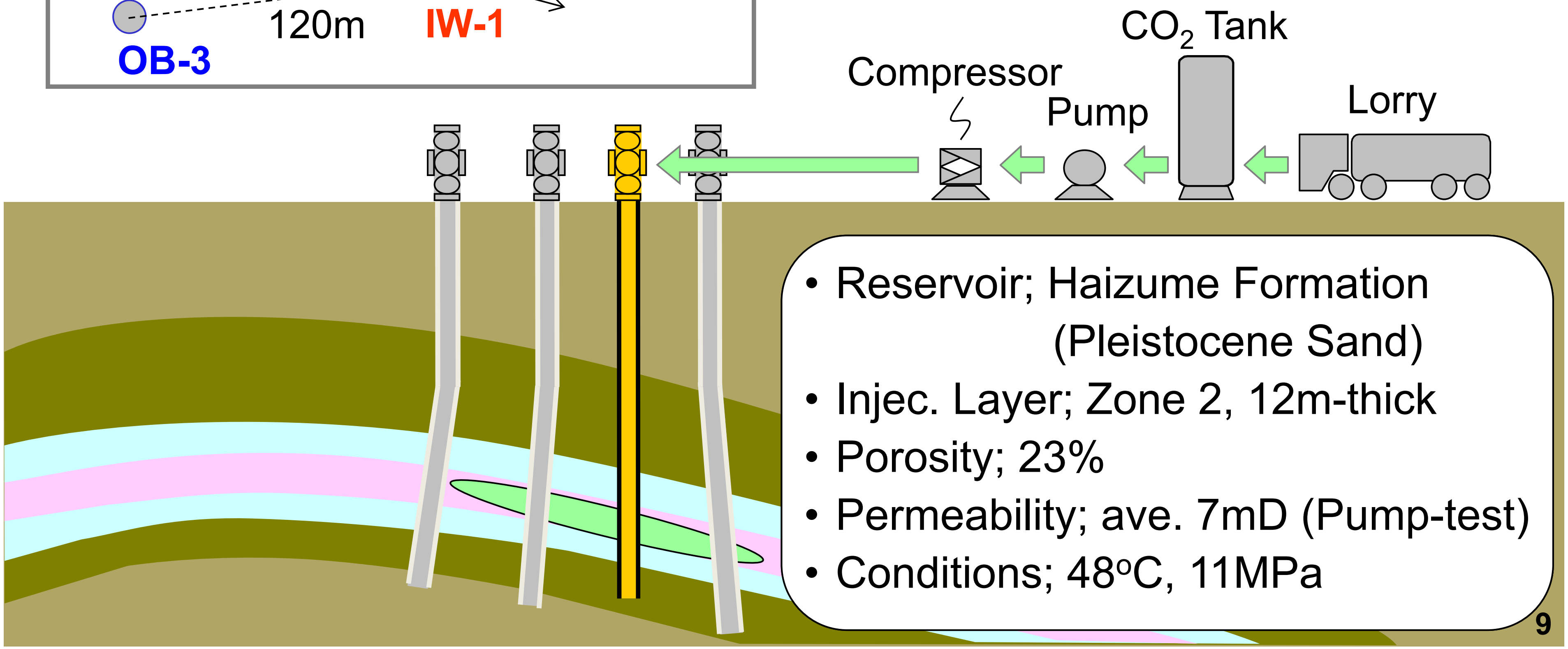
Improve Understanding of CO_2 Storage in Complex Geology!

Overview of the Nagaoka Site

Well Configuration
at the Reservoir Depth

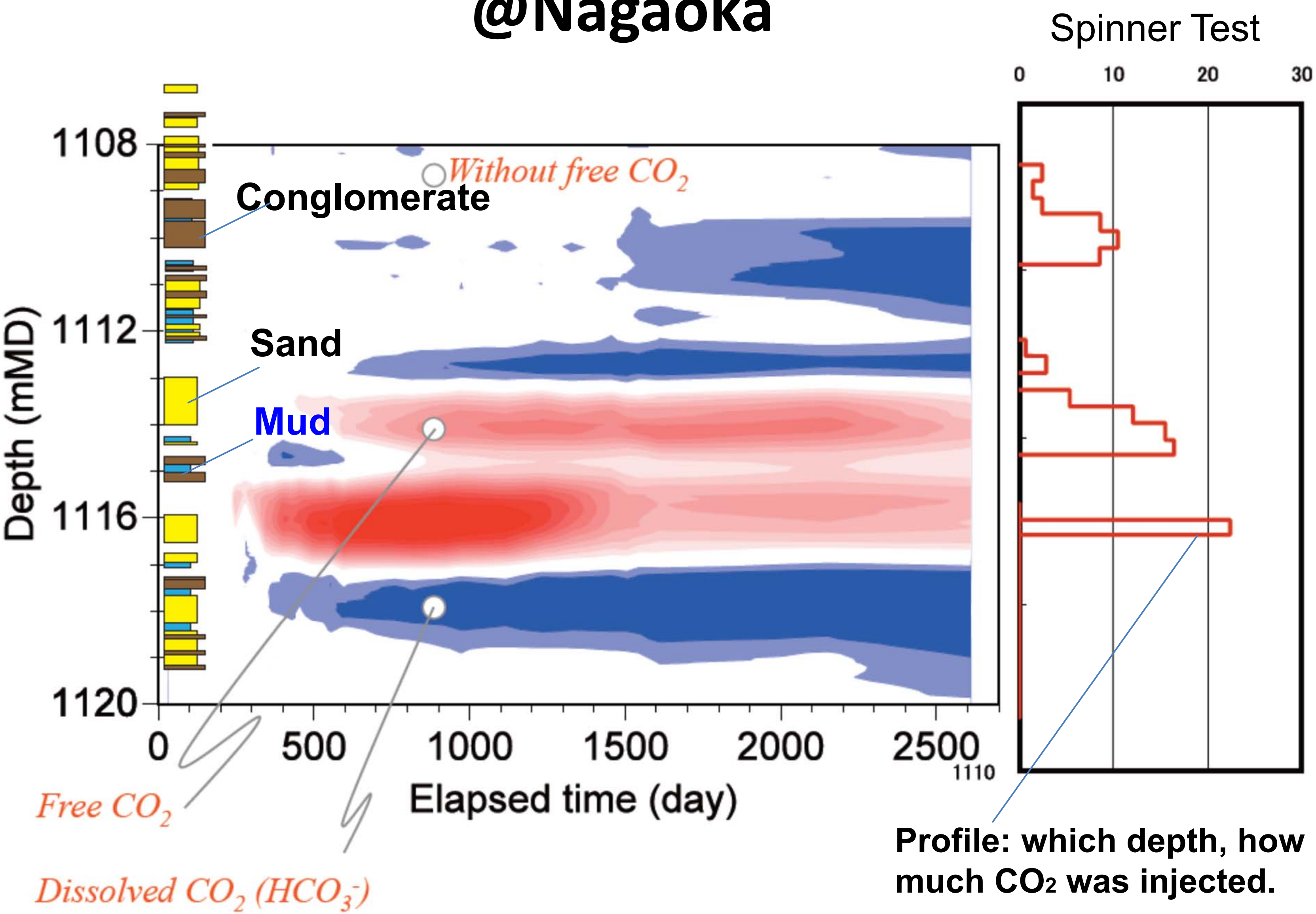


- Injec. Period; Jul. 2003~Jan. 2005
- Total amount; 10,400 ton CO_2
- Rate; 20~40 ton/day



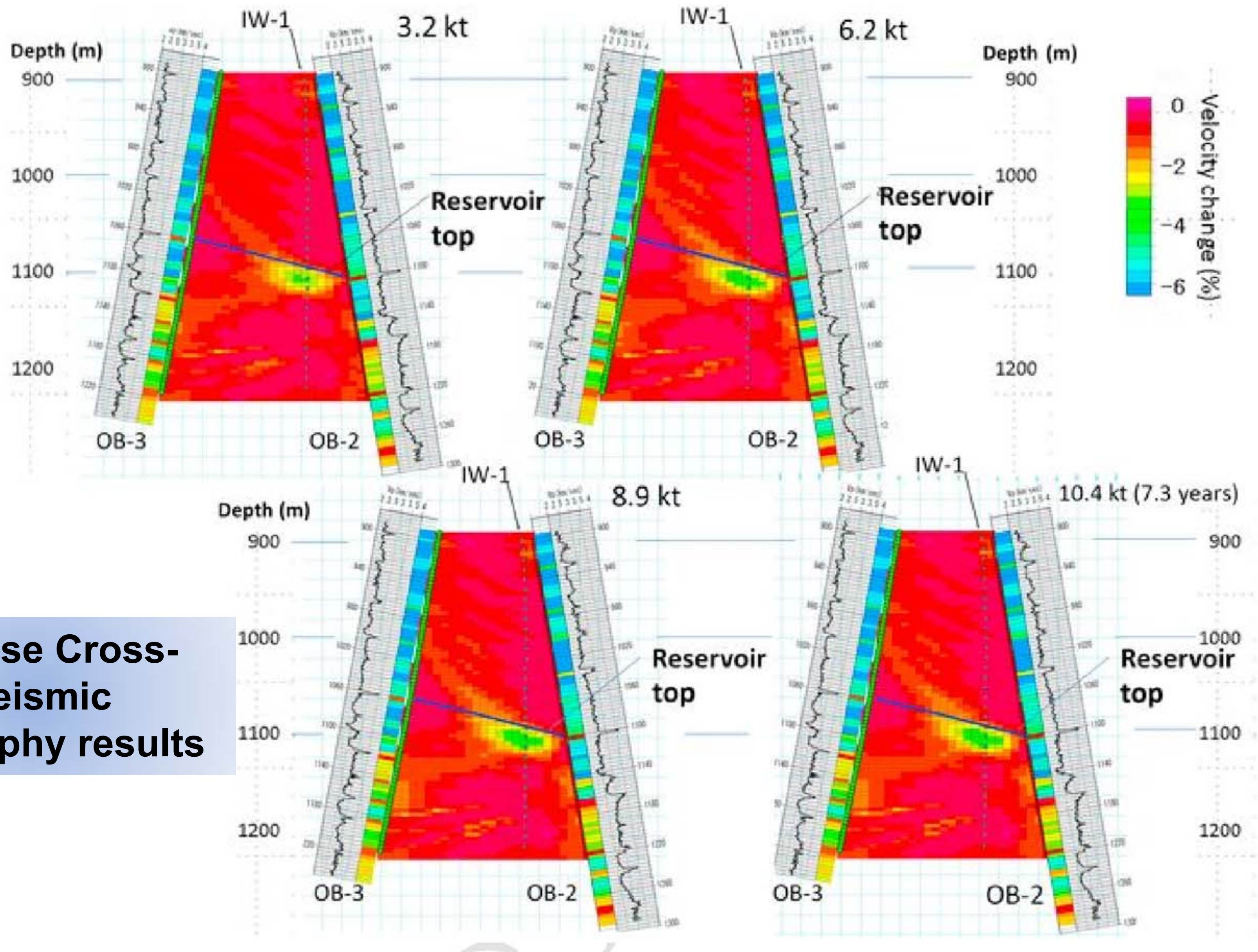
- Reservoir; Haizume Formation (Pleistocene Sand)
- Injec. Layer; Zone 2, 12m-thick
- Porosity; 23%
- Permeability; ave. 7mD (Pump-test)
- Conditions; 48^{o}C, 11MPa

Injection Profile and CO_2 Distribution @Nagaoka



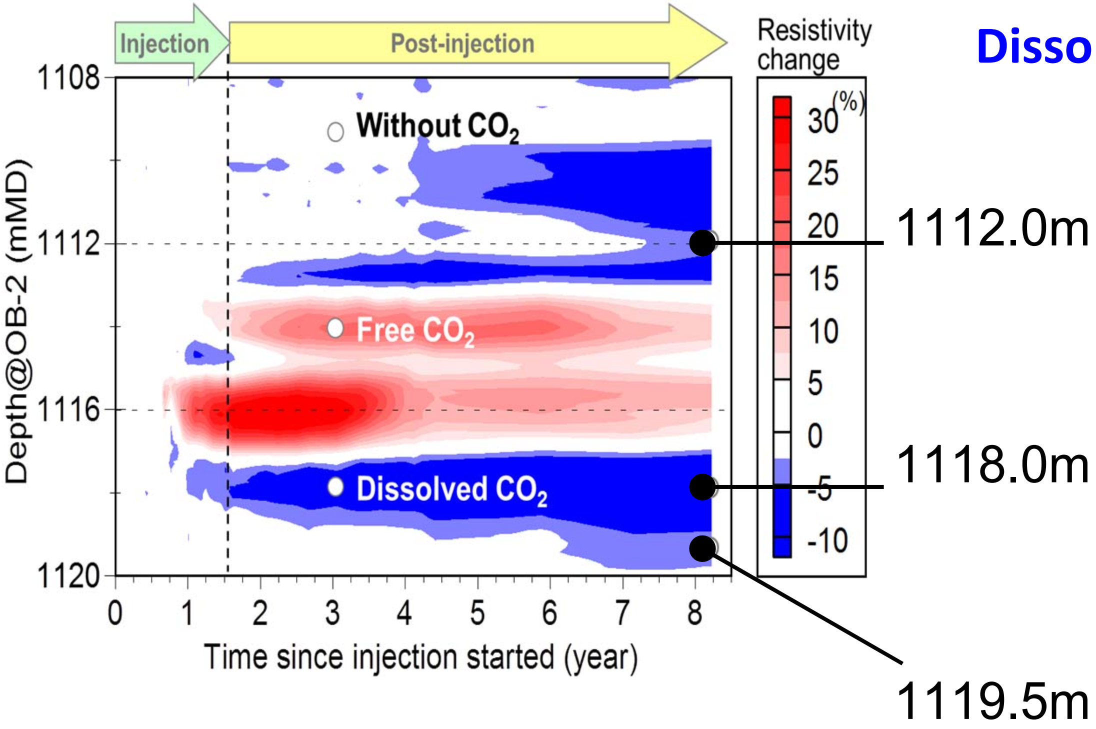
Profile: which depth, how much CO_2 was injected.

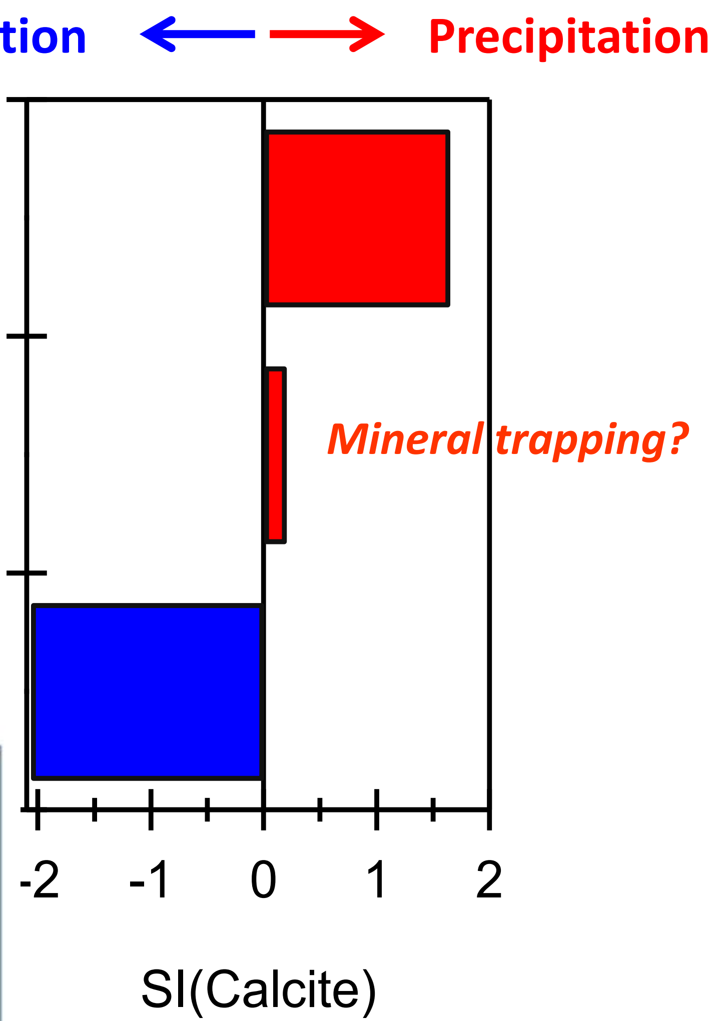
Tracking CO_2 Injected in Subsurface

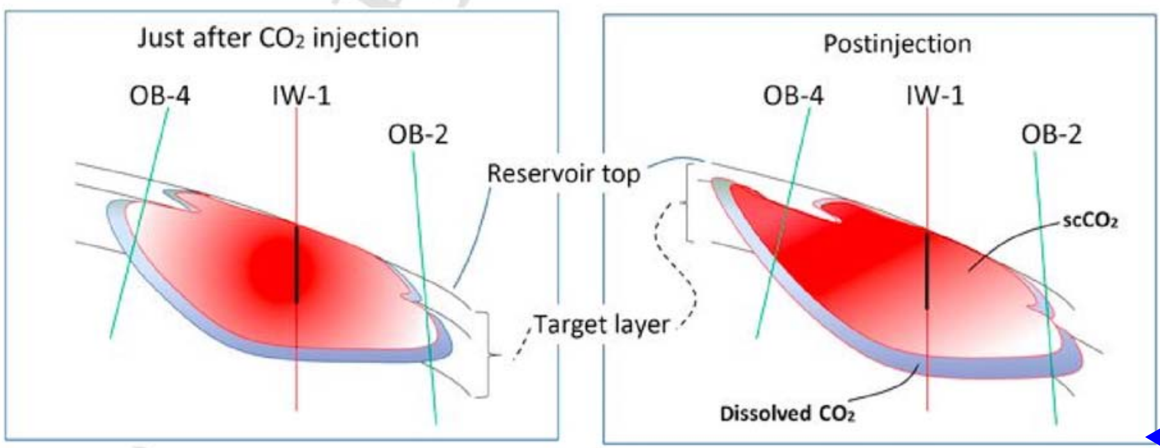


Time-lapse Cross-well seismic tomography results

Saturation Index (SI) of Calcite ($CaCO_3$)

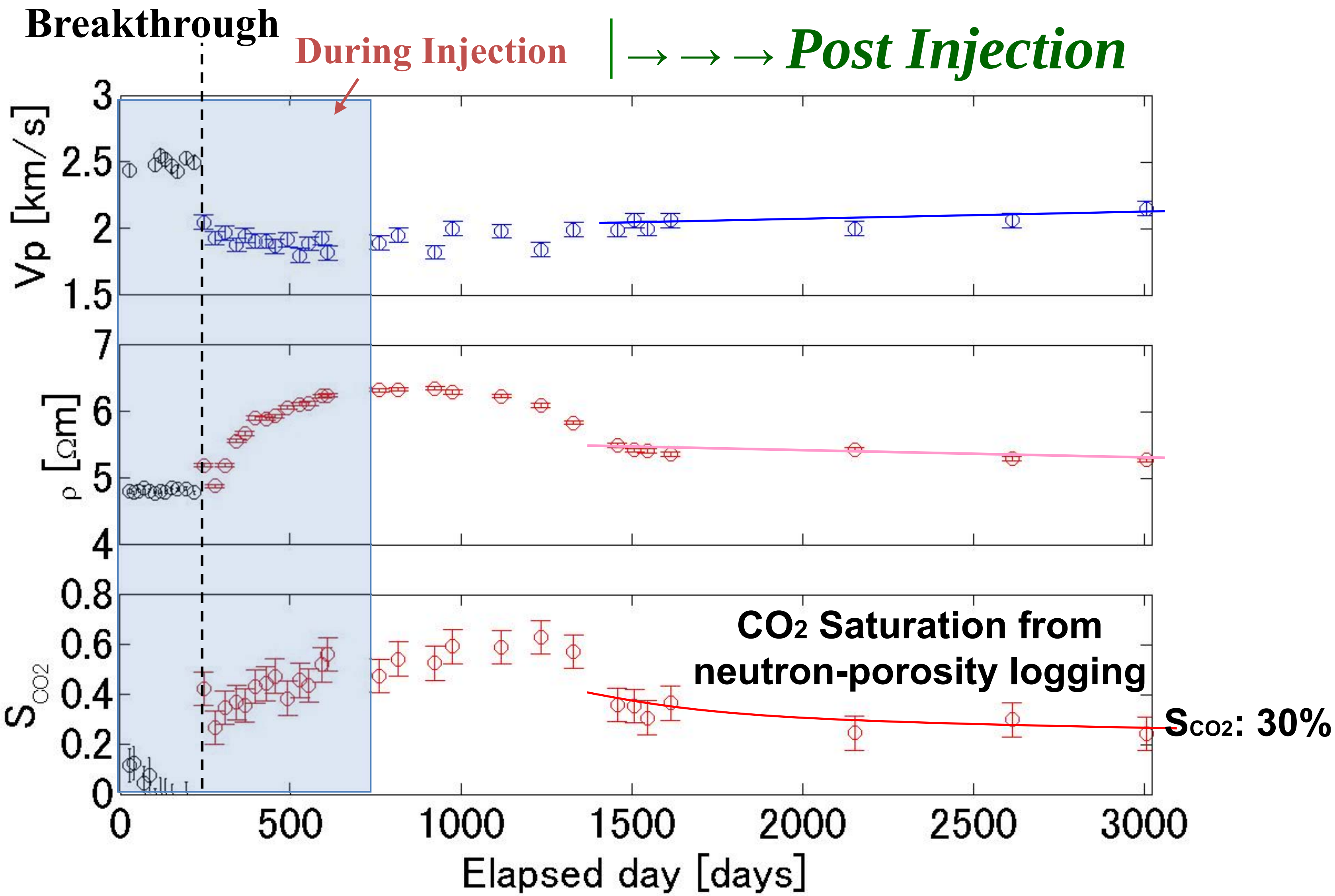


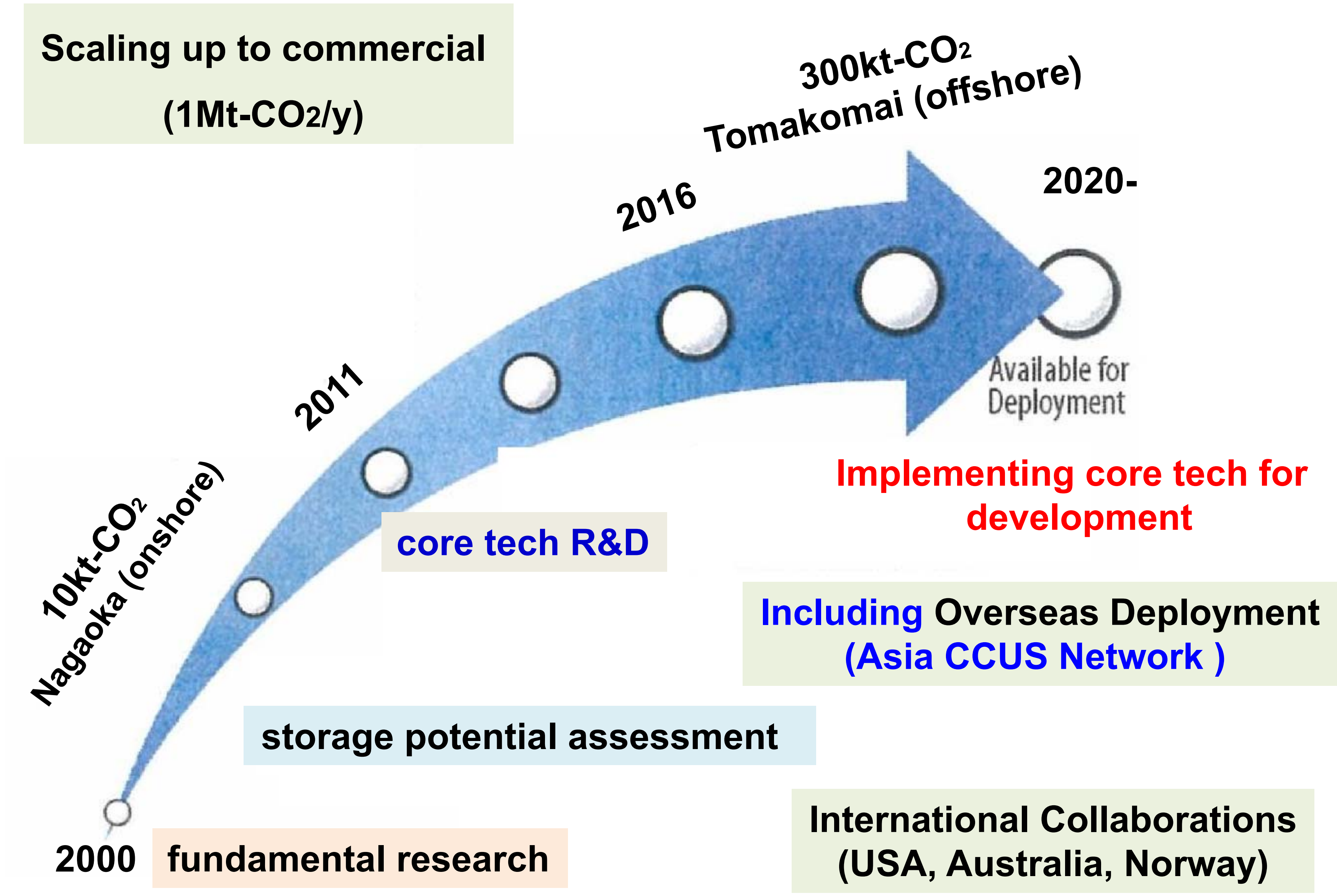




Long term prediction of injected CO_2 in subsurface

Time-lapse Changes at（1116.0m @OB-2）




Scaling up to commercial
(1Mt-CO_2/y)
300kt-CO_2
Tomakomai (offshore)
2020-
2016
2011
Available for
Deployment
10kt-CO_2
Nagaoka (onshore)
Implementing core tech for
development
core tech R&D
Including Overseas Deployment
(Asia CCUS Network)
storage potential assessment
International Collaborations
(USA, Australia, Norway)
2000
fundamental research

2．CO_2地中貯留技術開発から、実用化（運用・検証・普及）へ

Research, Development and Deployment of CO_2 Storage

(Up-Scaling Injection and Down-Sizing Costs)

Carbon Sequestration Leadership Forum
www.cslforum.org

CARBON SEQUESTRATION LEADERSHIP FORUM (CSLF)

TECHNICAL GROUP

TASK FORCE ON

IMPROVED PORE SPACE UTILISATION

貯留効率

Storage Efficiency

経済性

（economics）

Improved Pore Space Utilisation: Current Status of Techniques

The pore space of a CO_2 storage system is the 'resource' to a CO_2 storage site operator. Presently, the efficiency of the storage resource is quite low, with only 1 to 4% of the bulk volume being utilised to store CO_2 in saline formations. A poor utilisation of this pore space resource means that the resource is wasted, and the opportunity to reduce the cost per tonne of CO_2 stored is significantly hindered. Conversely, a resource that is effectively utilised is likely to significantly improve the economics of CCS projects.

➢ Recommended Technologies for Improved Pore Space Utilisation:

P	Technology Type	Prior R&D and application	Technology Readiness Level (TRL)	Technology Prospectively
1	Microbubble CO_2 Injection	Laboratory and Modelled, prototype	TRL 4	High potential
2	Swing Injection	Laboratory and Modelled	TRL 3	High potential
3	Increased Injection Pressure	Laboratory and Modelled	TRL 3	High potential
4	Active Pressure Relief (increase sweep & reduce lateral spread)	Enhanced Oil Recovery (EOR), planned for Gorgon CO_2 injection project	TRL 6	High potential
5	Foams (block high permeability pathways)	EOR	TRL 6	Reasonably well understood
6	Passive Pressure Relief	Modelled	TRL 4	Limited effectiveness
7	Polymers (increase formation water viscosity)	EOR	TRL 7	Reasonably well understood
8	Surfactants (reduce residual saturation of formation water)	EOR	TRL 7	Reasonably well understood
9	CO_2 saturated water injection & geothermal energy	Laboratory and Modelled	TRL 3	Site specific & lower volume

* minor modelling and laboratory investigations may be required prior to commercial scale application

What's Microbubble?

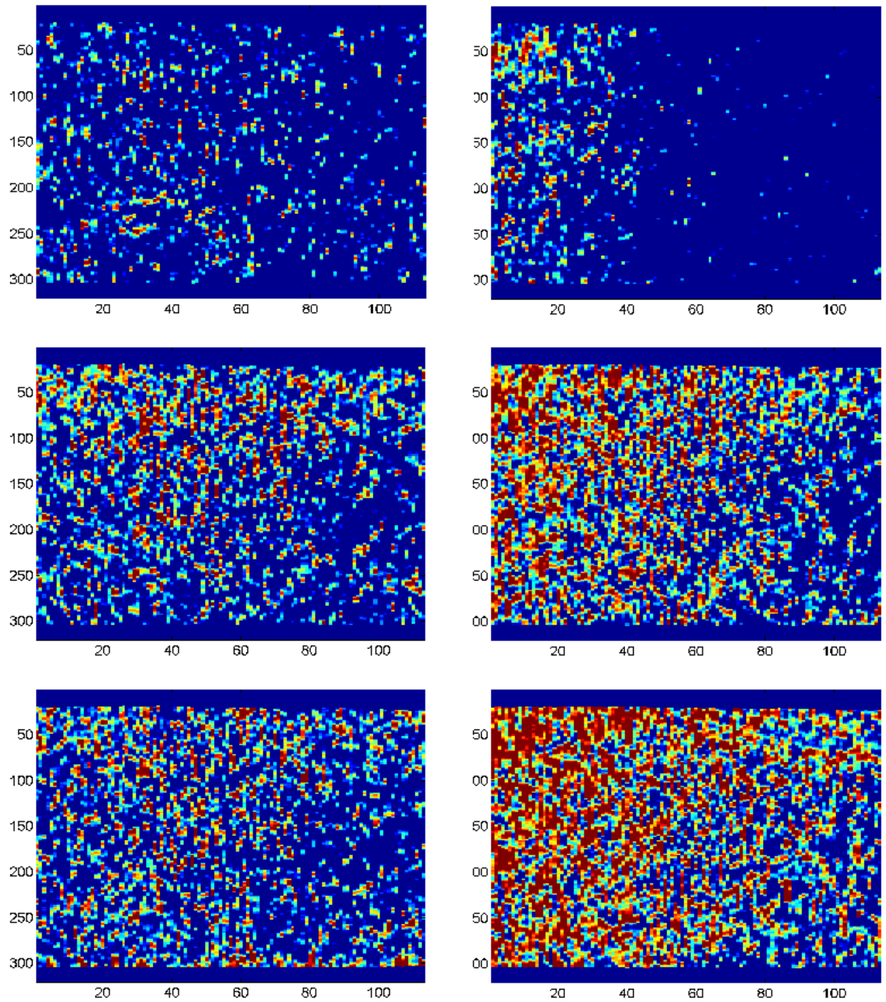
Microbubble CO_2 Injection for Improving *Storage Efficiency & Enhanced Dissolution*

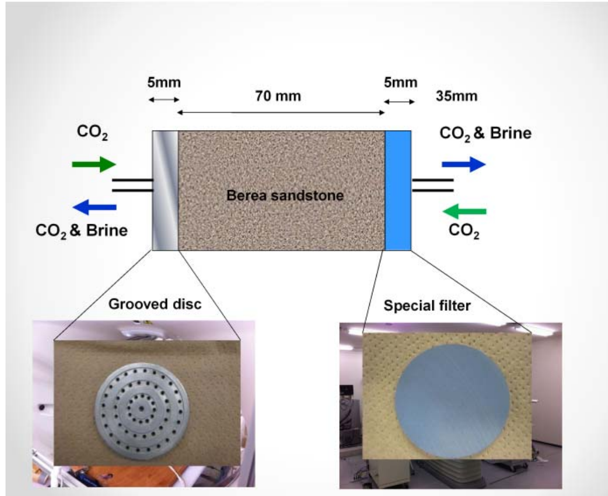
CO_2 distribution
(left: grooved disc; right: special filter)

0.045 PV

0.68 PV

8.18 PV

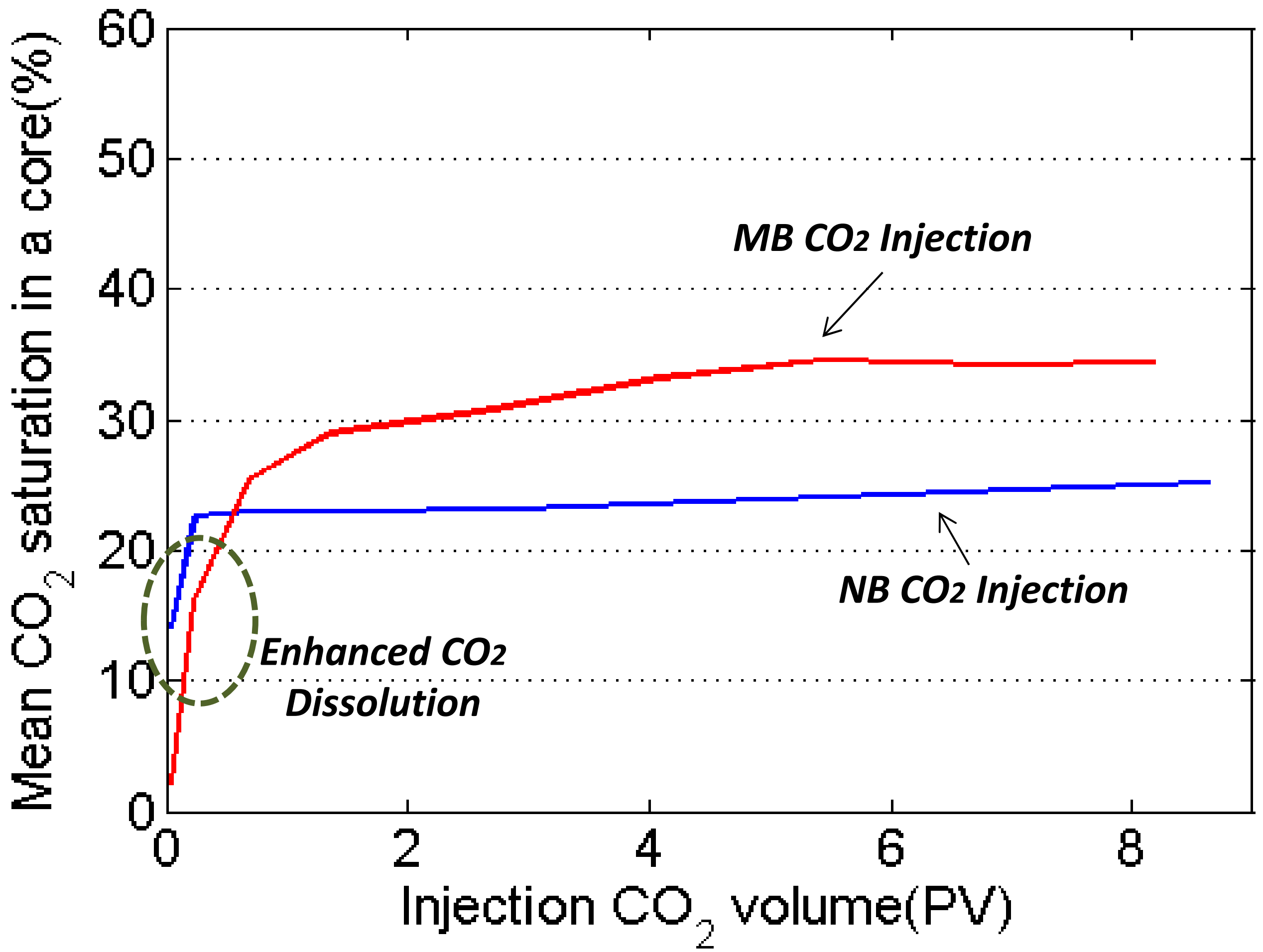




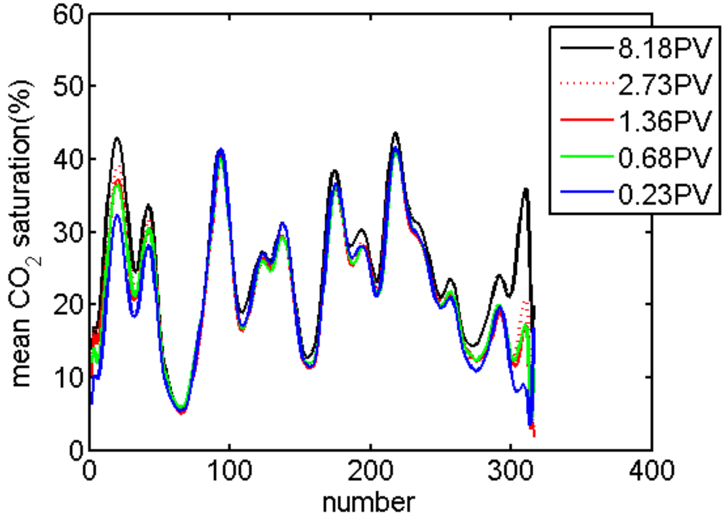
Visualization of MB CO2 injection using X-CT

(Patent: PCT/JP2009/064249)

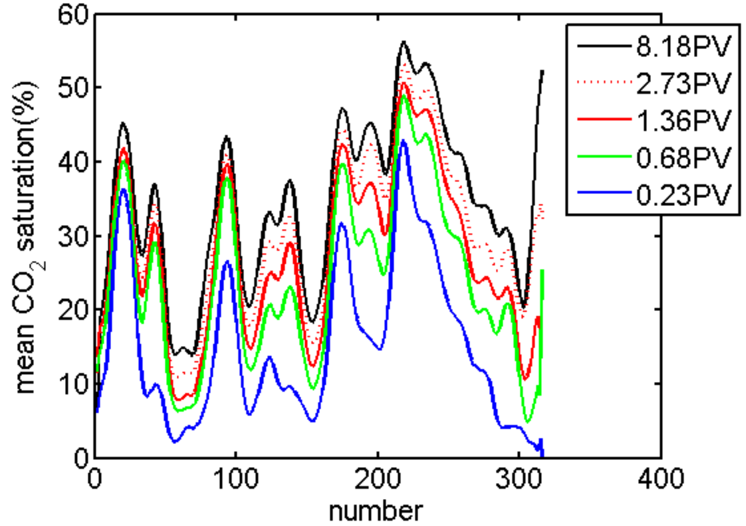
CO_2 Saturation: NB vs MB Injection

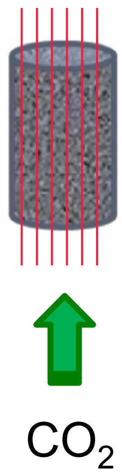


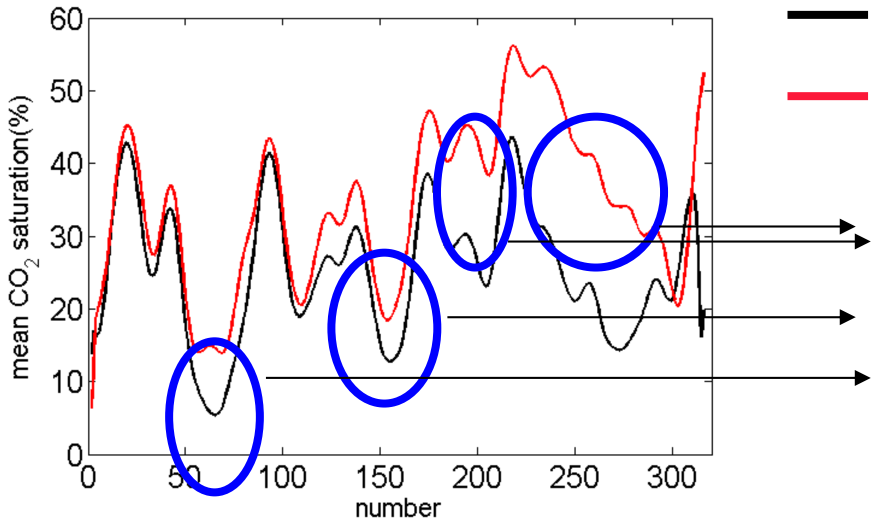
NB CO_2 Injection



MB CO_2 Injection







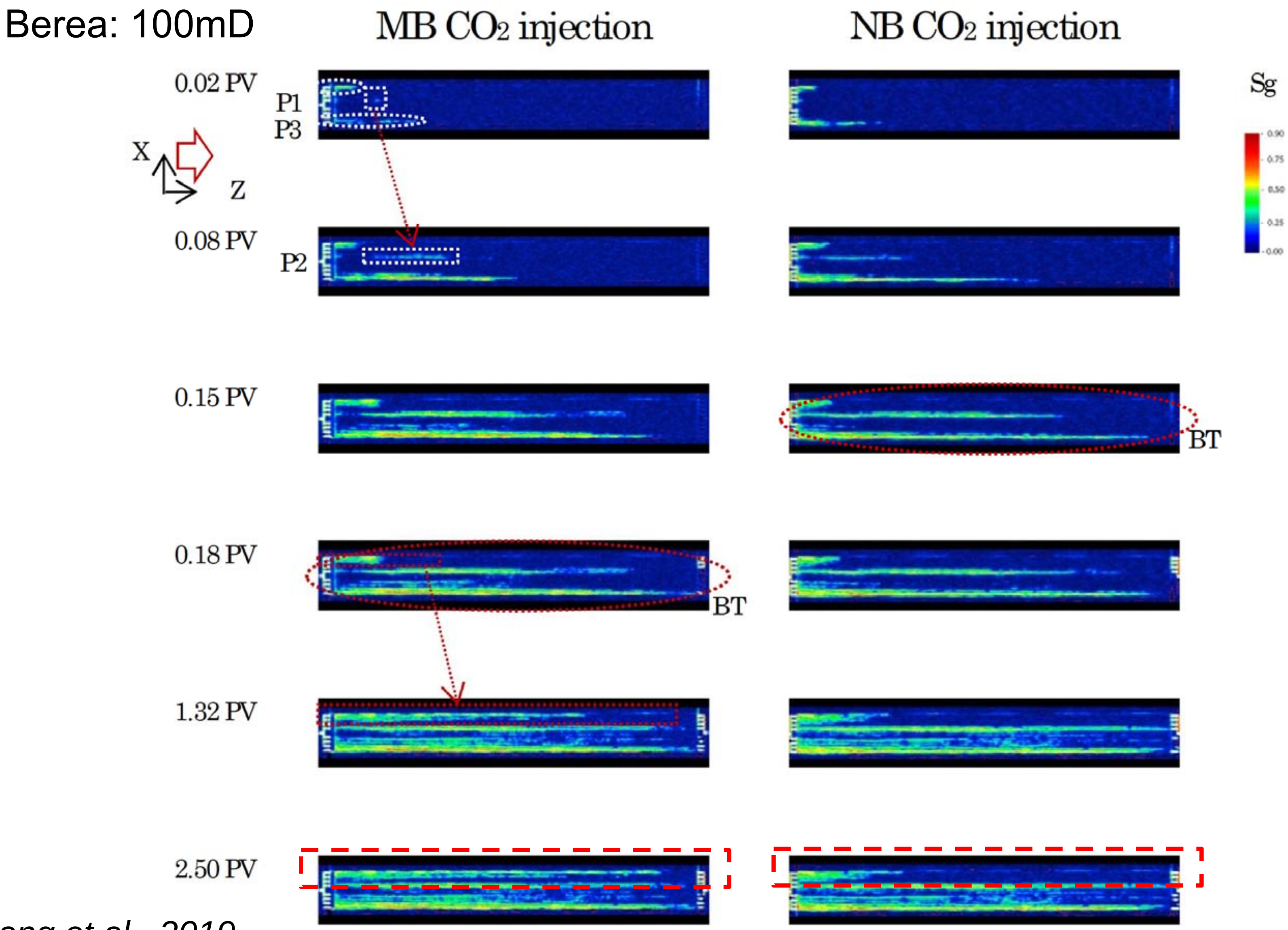
NB CO_2 Injection

MB CO_2 Injection

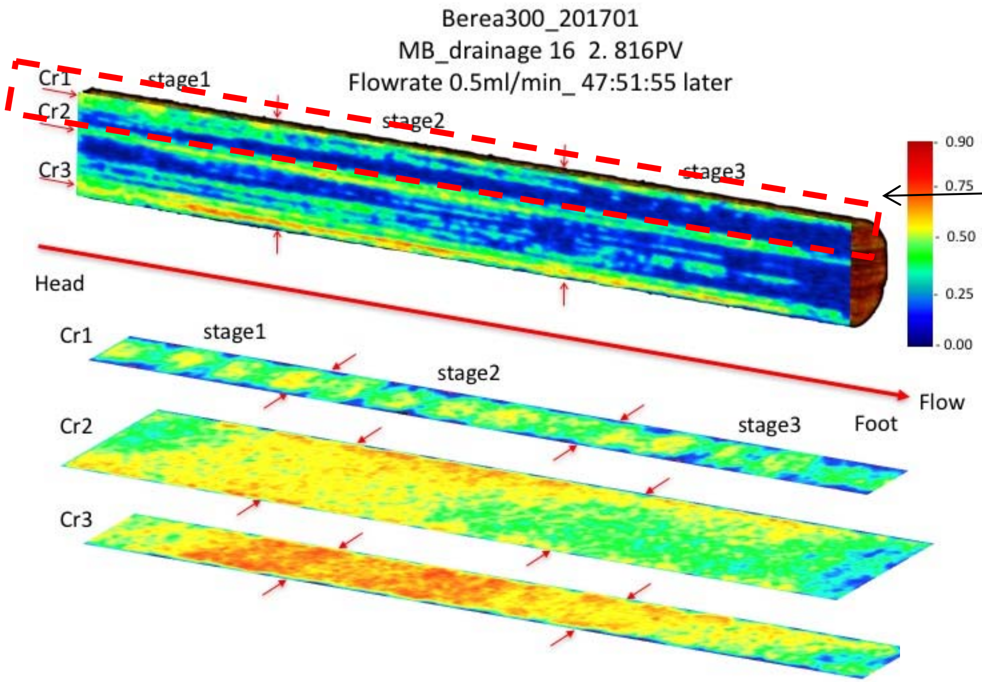
Low permeable zone

penetrated by injected MB CO_2

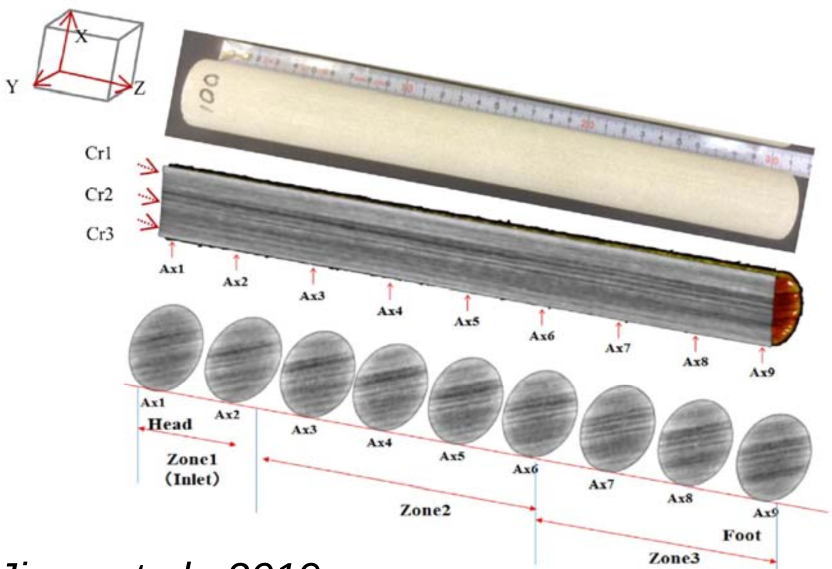
Comparison of MB CO_2 and Conventional CO_2 Injections in High Permeability Sandstone

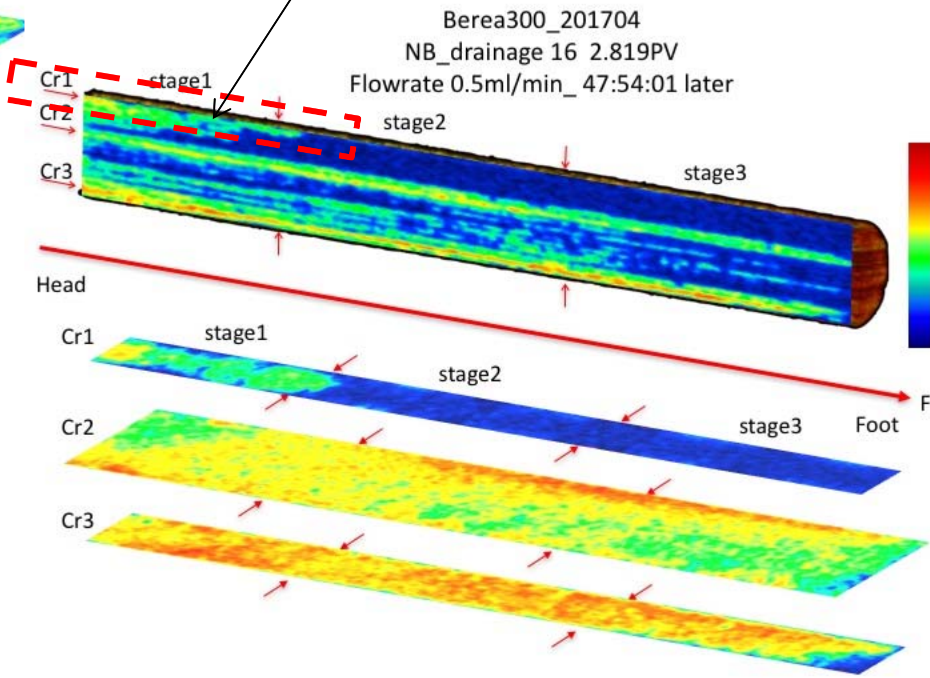


Jiang et al., 2019



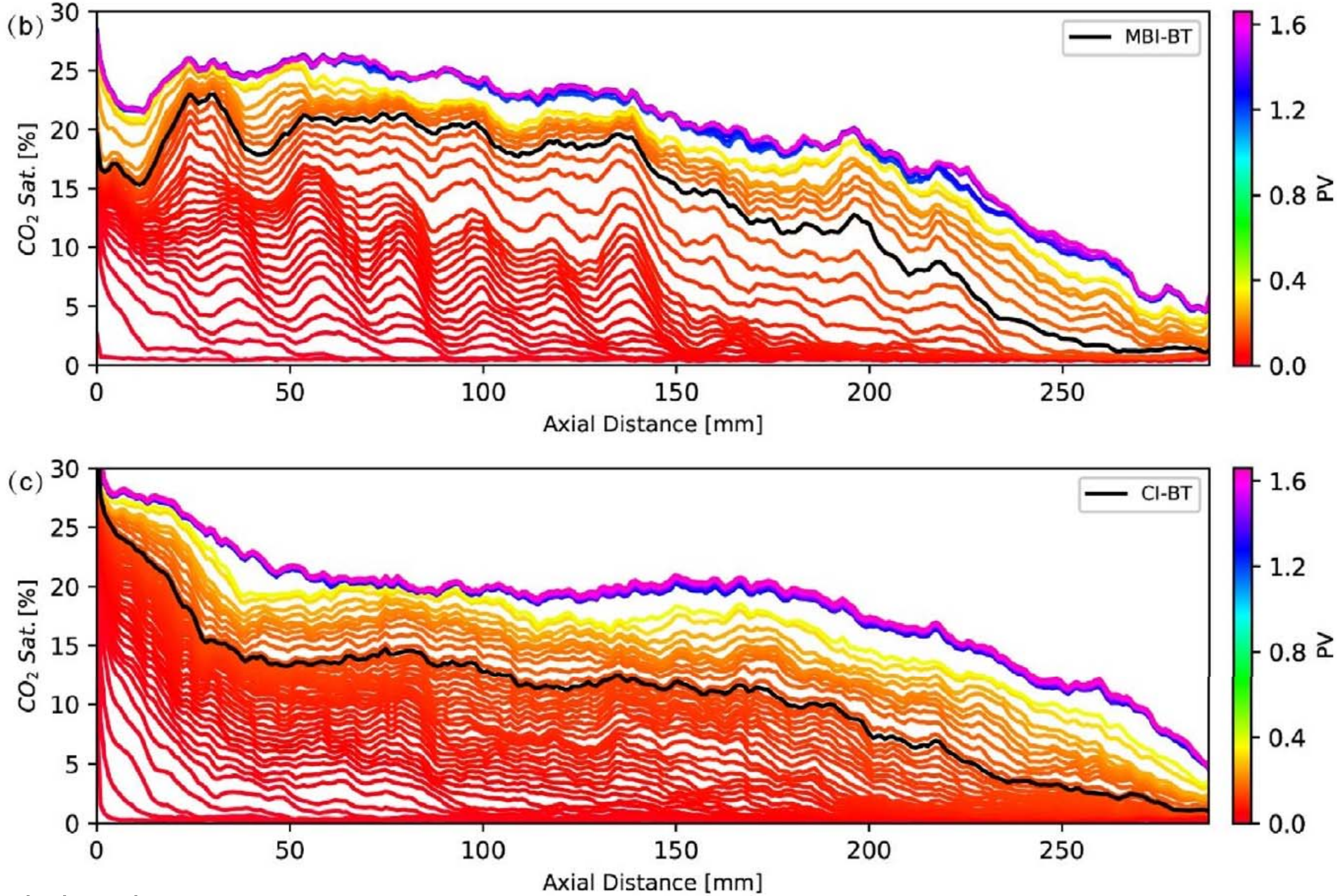
A big difference in low permeability layer





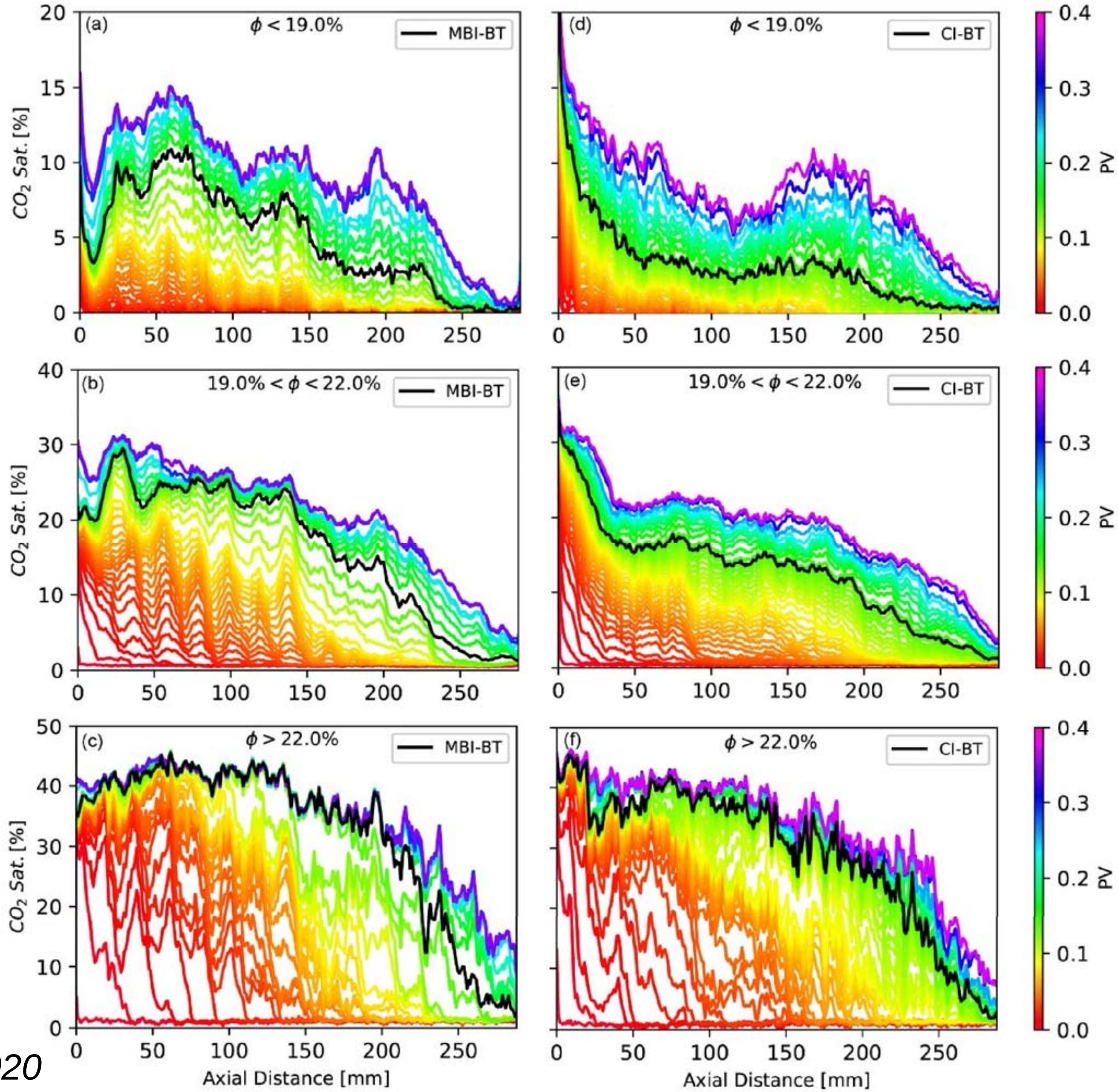
Jiang et al., 2019

CO_2 Saturation profile along Berea longitudinal direction



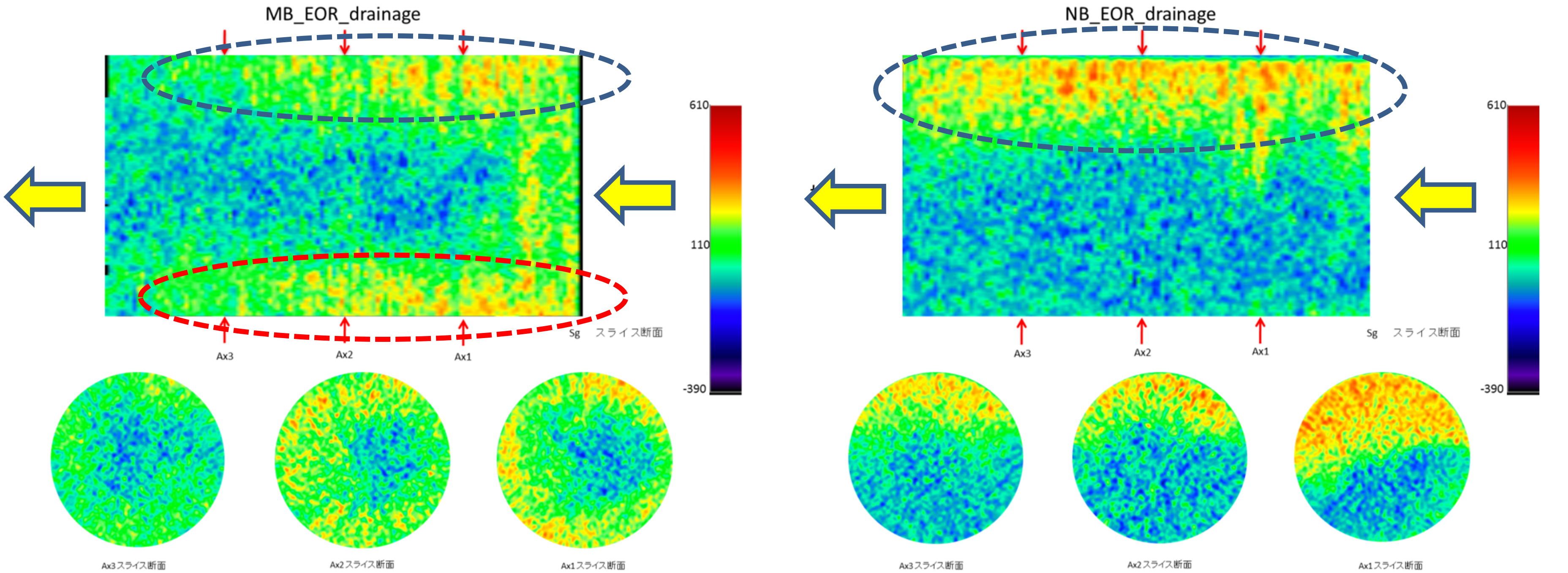
Zhai et al., 2020

CO_2 Saturation in heterogenous porous zones



Zhai et al., 2020

Gravity Override of the Injected CO_2 In high permeability reservoir

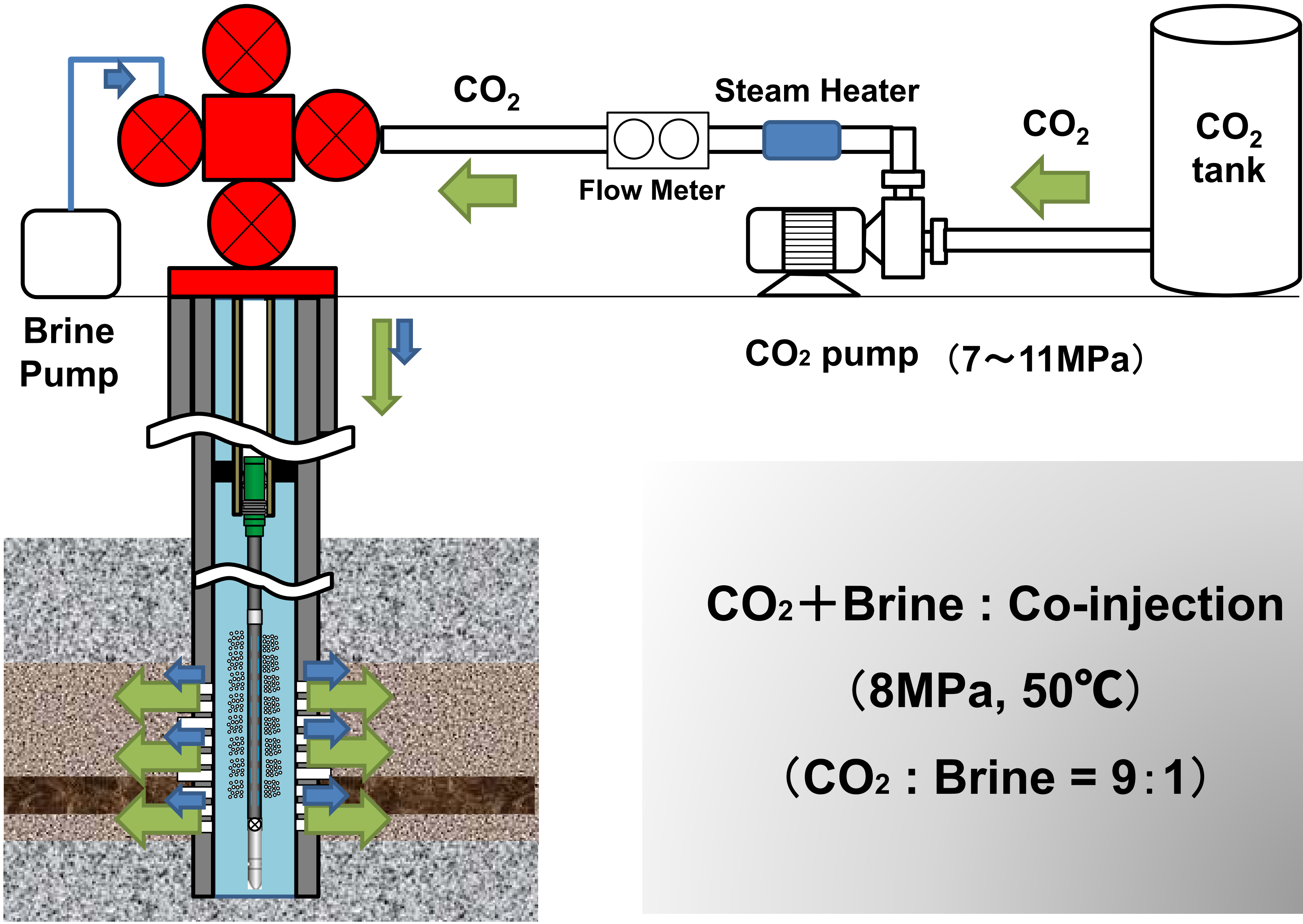


Elapsed time: 40 min; Left: MB-EOR; Right: NB-EOR

(Xue et al., 2014)

Microbubble CO_2 Injection Pilot Test at the JAPEX field site

27



CO_2＋Brine : Co-injection

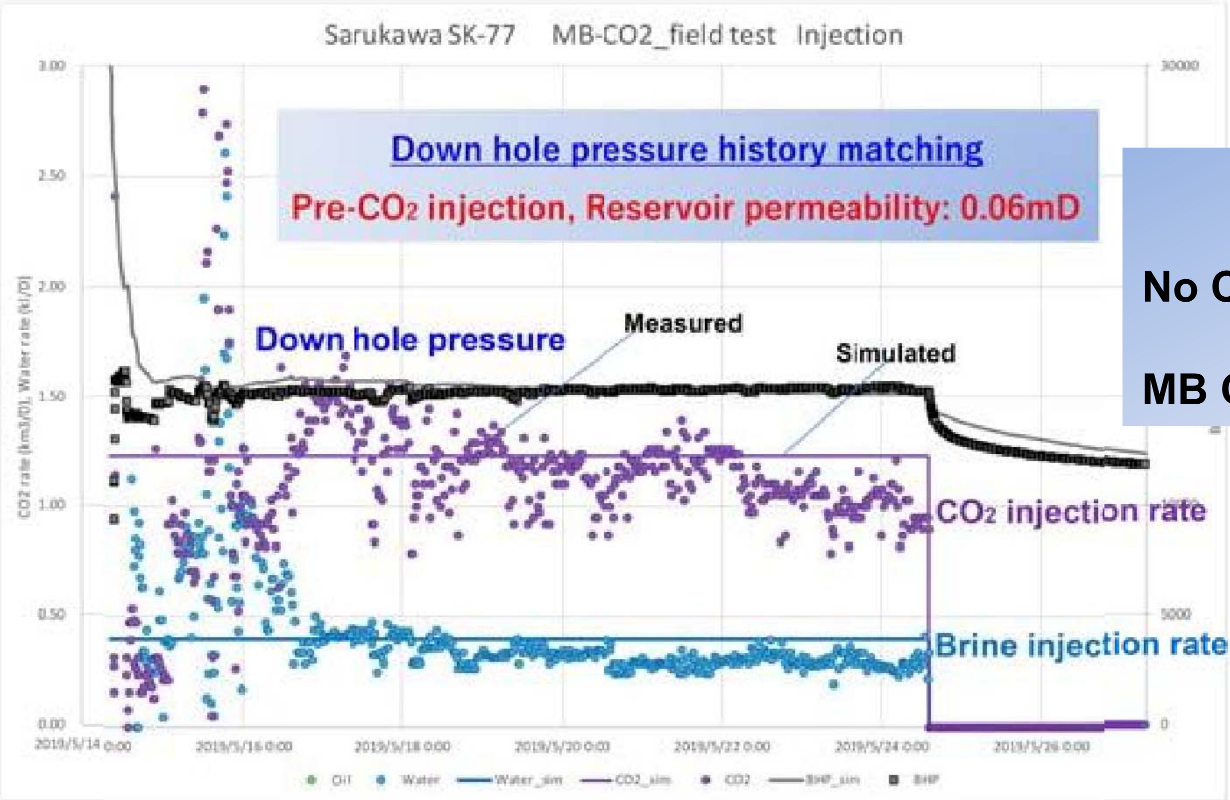
（8MPa, 50℃）

（CO_2 : Brine = 9：1）

上田ほか、2020; Xue et al., 2021)

Table 1 Results of the injection and production tests

	Injection		Production			CO_2 stored	Injection index
	tonne	KL	tonne	KL	KL		
Microbubble injection	CO_2	brine	CO_2	brine	oil	80%	0.39 tonne/D/MPa
	20	4	3.9	1.2	0.6		
Conventional injection	CO_2	brine	CO_2	brine	oil	63%	0.09 tonne/D/MPa
	5.8	1.2	2.1	0.35	0		

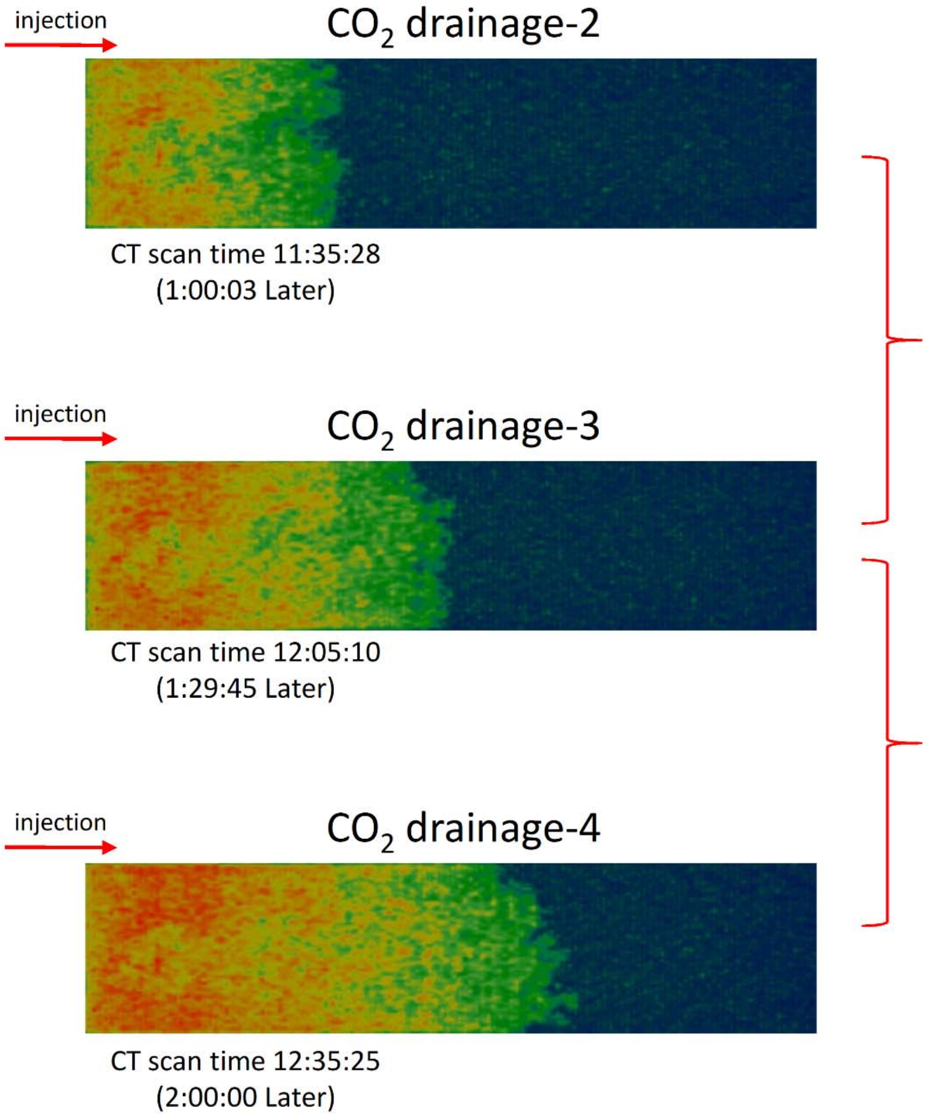


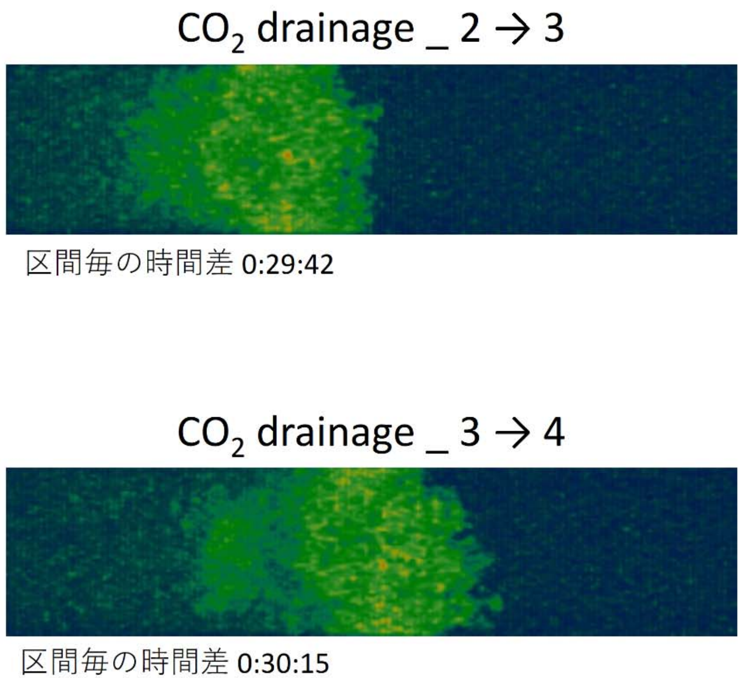
Oil Production

No CO_2 injection: 60 Liter

MB CO_2 injection: 600 Liter

Visualization of Normal bubble CO_2 Injection in low permeability (0.01mD) sandstone with X-CT





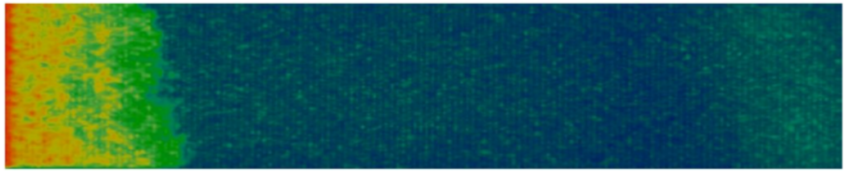
Xue et al., in preparation

Visualization of Microbubble CO_2 Injection in low permeability (0.01mD) sandstone with X-CT

Xue et al., in preparation

injection

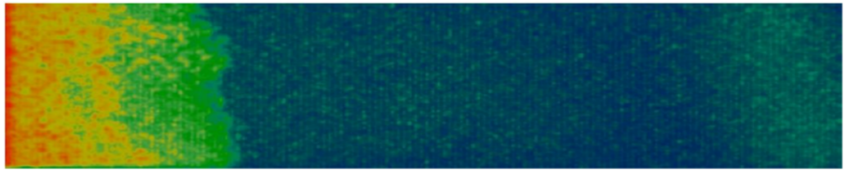
CO_2 drainage-2



CT scan time 14:00:09
(1:00:07 Later)

injection

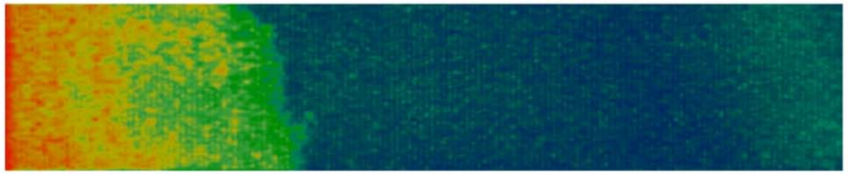
CO_2 drainage-3



CT scan time 14:30:24
(1:30:22 Later)

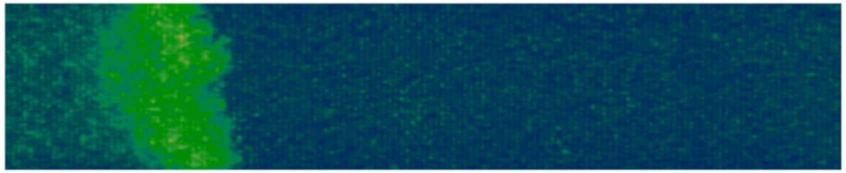
injection

CO_2 drainage-4



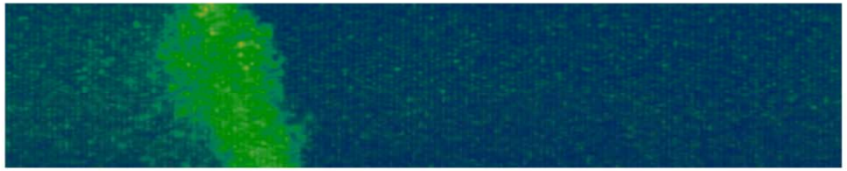
CT scan time 15:00:20
(2:00:18 Later)

CO_2 drainage _ 2 → 3



区間毎の時間差 0:30:15

CO_2 drainage _ 3 → 4



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Injecting MB CO_2: Penetrate and Flood low permeability zones, Improve Sweep Efficiency !

➢ Recommended Technologies for Improved Pore Space Utilisation:

P	Technology Type	Prior R&D and application	Technology Readiness Level (TRL)	Technology Prospectively
1	Microbubble CO_2 Injection	Laboratory and Modelled, prototype	TRL 4	High potential
2	Swing Injection	Laboratory and Modelled	TRL 3	High potential
3	Increased Inje			igh potential
4	Active Pressur sweep & redu			igh potential
5	Foams (block pathways)			easonably well understood
6	Passive Pressure Relief	Modelled	TRL 4	Limited effectiveness
9	geothermal energy	Laboratory and Modelled	TRL 3	volume

* minor modelling and laboratory investigations may be required prior to commercial scale application

Microbubble CO_2 Injection Technology

TRL 4 ➔➔➔ TRL 7

High potential ➔➔➔ Highly Recommend

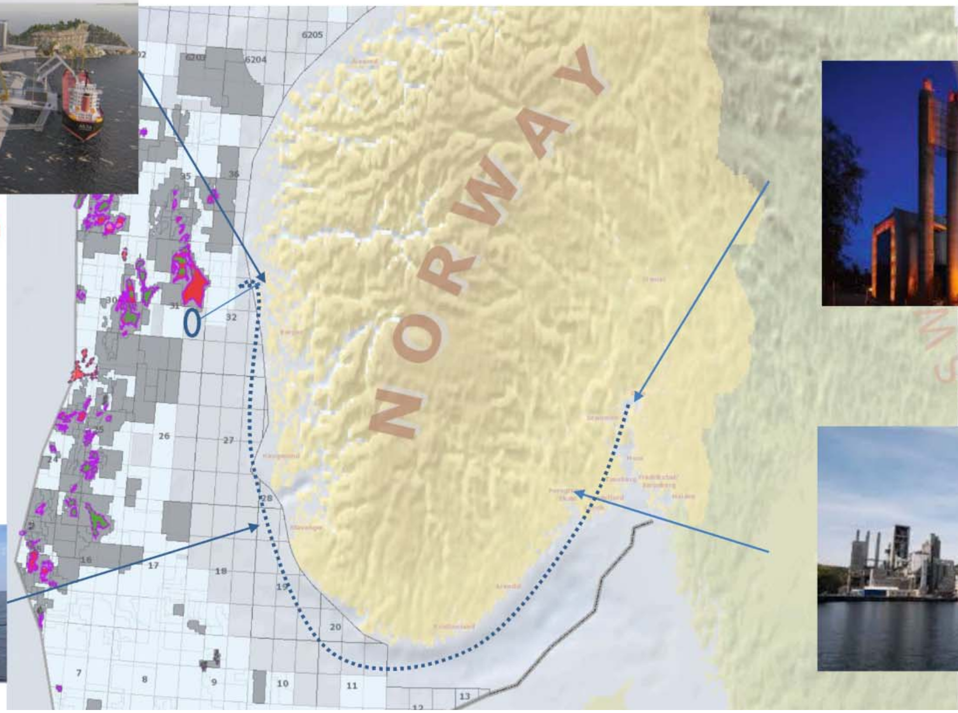
Microbubble CO_2 Injection ➔➔➔ Improving Storage Efficiency

Storage Efficiency: 63% up to 80% ➔➔➔ More Economical

The Norwegian CCS demonstration project

equinor TOTAL

Ship transport from capture to storage terminal – pipeline to offshore storage complex



fortum

Waste-to-energy 400 000 tonnes CO_2 per annum

NORCEM HEIDELBERGCEMENT Group

Cement production 400 000 tonnes CO_2 per annum

Olje- og energidepartementet

23 years experience with CCS and CO_2 Storage offshore Norway

"...realise a cost-effective solution for full-scale CCS in Norway, provided that this incite technology development in an international perspective".

Start FEED - summer2018

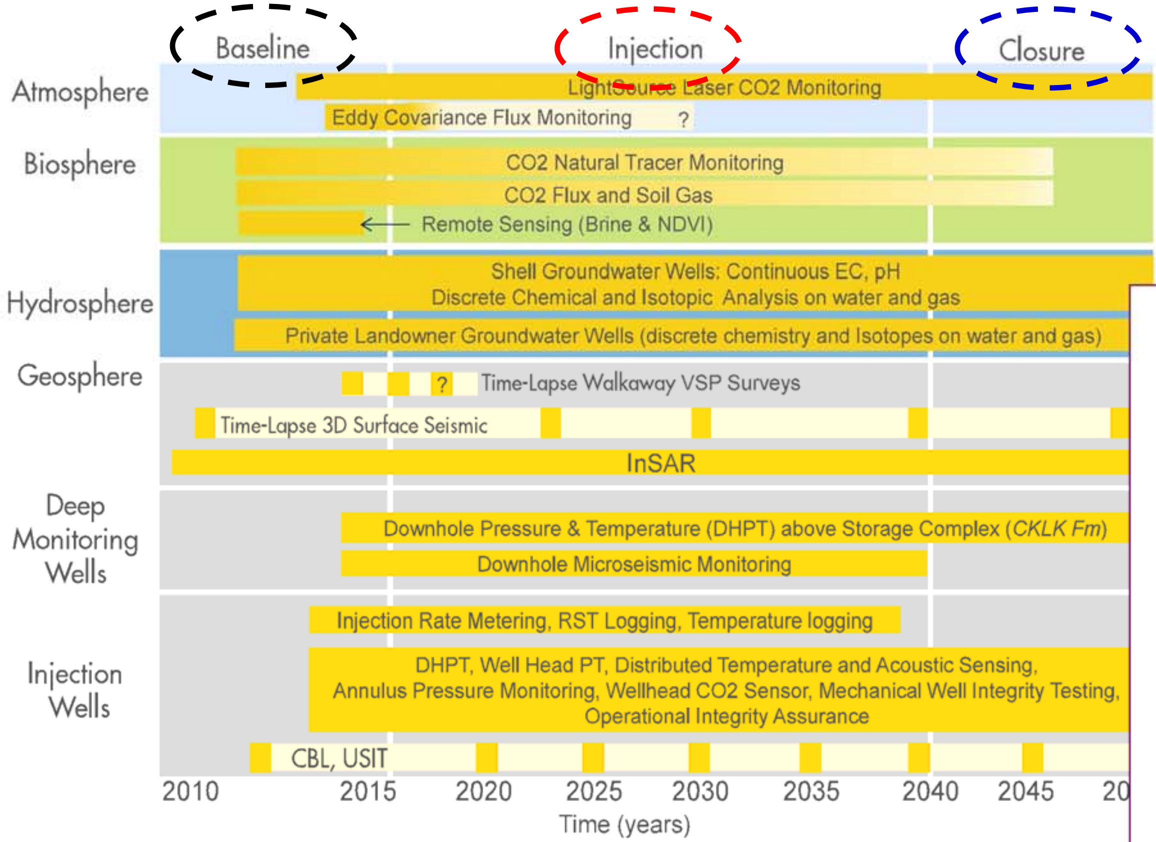
QA - prepare investment decision – 2019/2020

Investment decision 2020/2021

Development 2020/2021→

Operation - 2023/2024

MMV plan throughout the project life @QUEST



(based on ISO standard)

- First o f a kind – conservative approach
- Comprehensive: from atmosphere to geosphere
- Risk-based
- Site-specific
- Independently reviewed
- Combination of new and traditional technologies
- Baseline data collected before start-up

MMV: Measurement, Monitoring and Verification

➢ Advanced Monitoring by US/DOE

- Monitoring at a carbon storage site is necessary to **track the movement** of CO_2 and **assure permanence** for geologic storage.

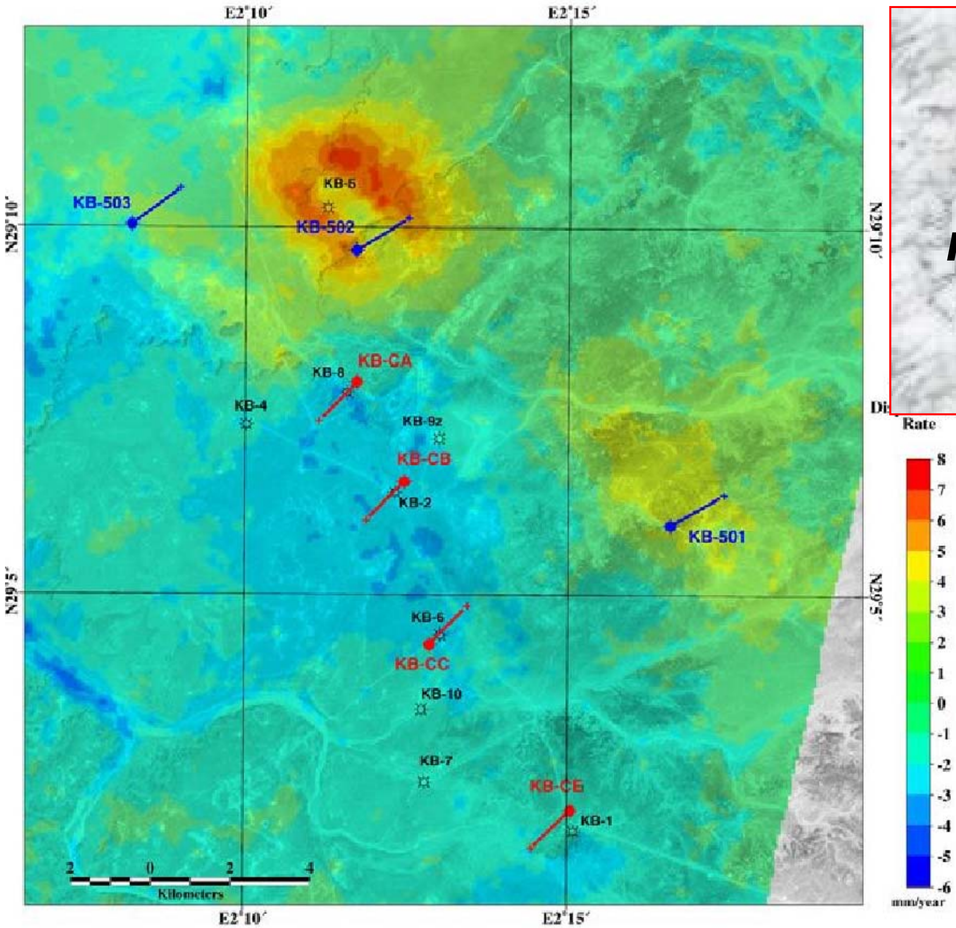
- **Advanced monitoring** technologies are needed to **decrease the cost and uncertainty** in measurements and satisfy regulations.

- Giving site operators the ability to: (1) measure **critical subsurface parameters** associated with the injected CO_2, (2) provide measurements of **down-hole** and reservoir conditions for **real-time decision making** and **process optimization**, and (3) provide **long-term** post-injection monitoring of the fate of injected CO_2.

- **Transformational sensor** to support demonstration and deployment of advanced coal power with CCS **beginning in 2025**.

Fiber Optic Sensing: temperature, pressure, strain, acoustic, fluid chemistry

Uplift at In Salah CO_2 Injection Site



Pressure buildup depending on

reservoir porosity & permeability,

CO_2 injection rate & volume.

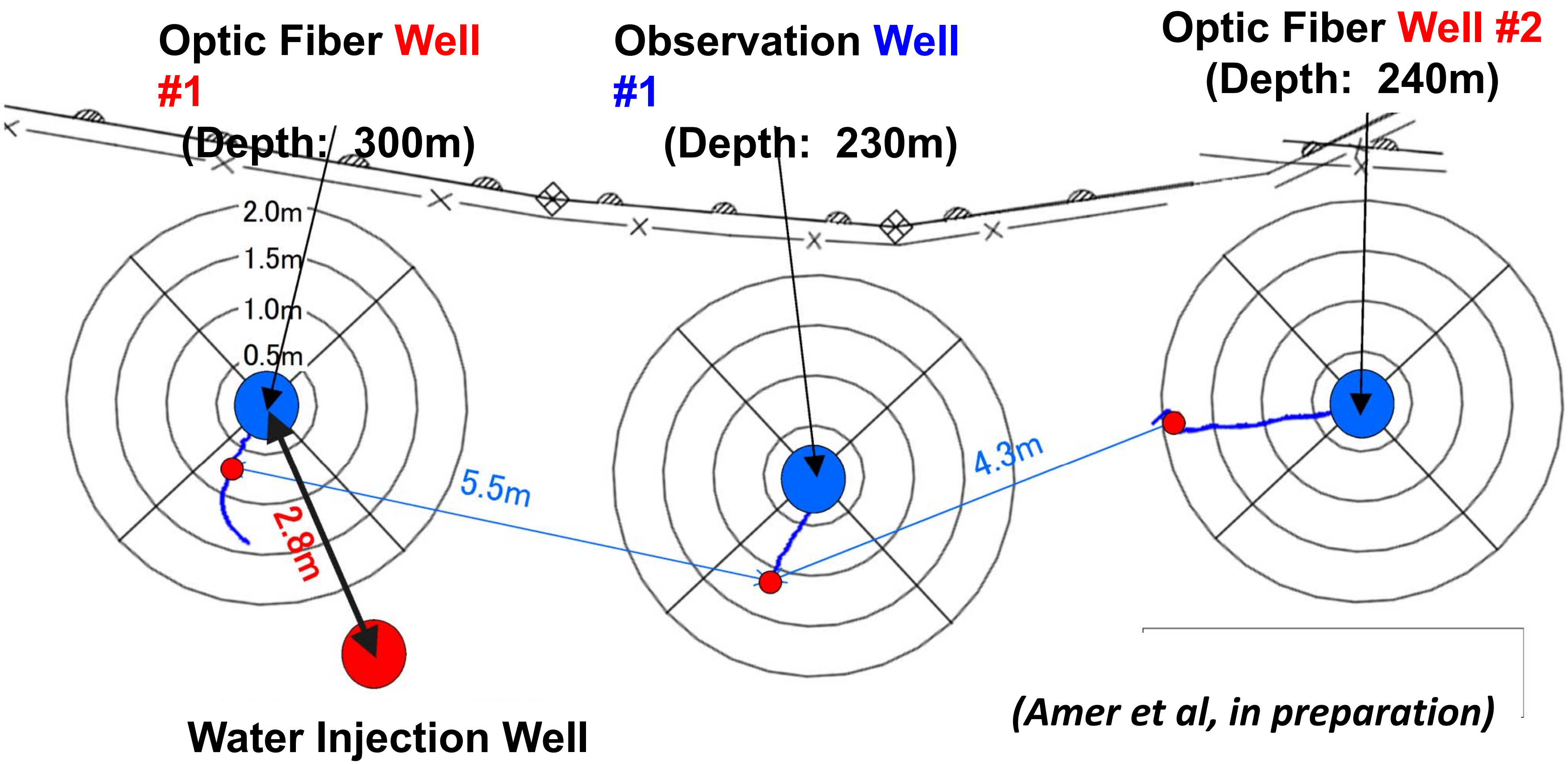
Uplift at ground surface

How to interpret?

Pressure buildup at subsurface

Need continual strain data along depth?

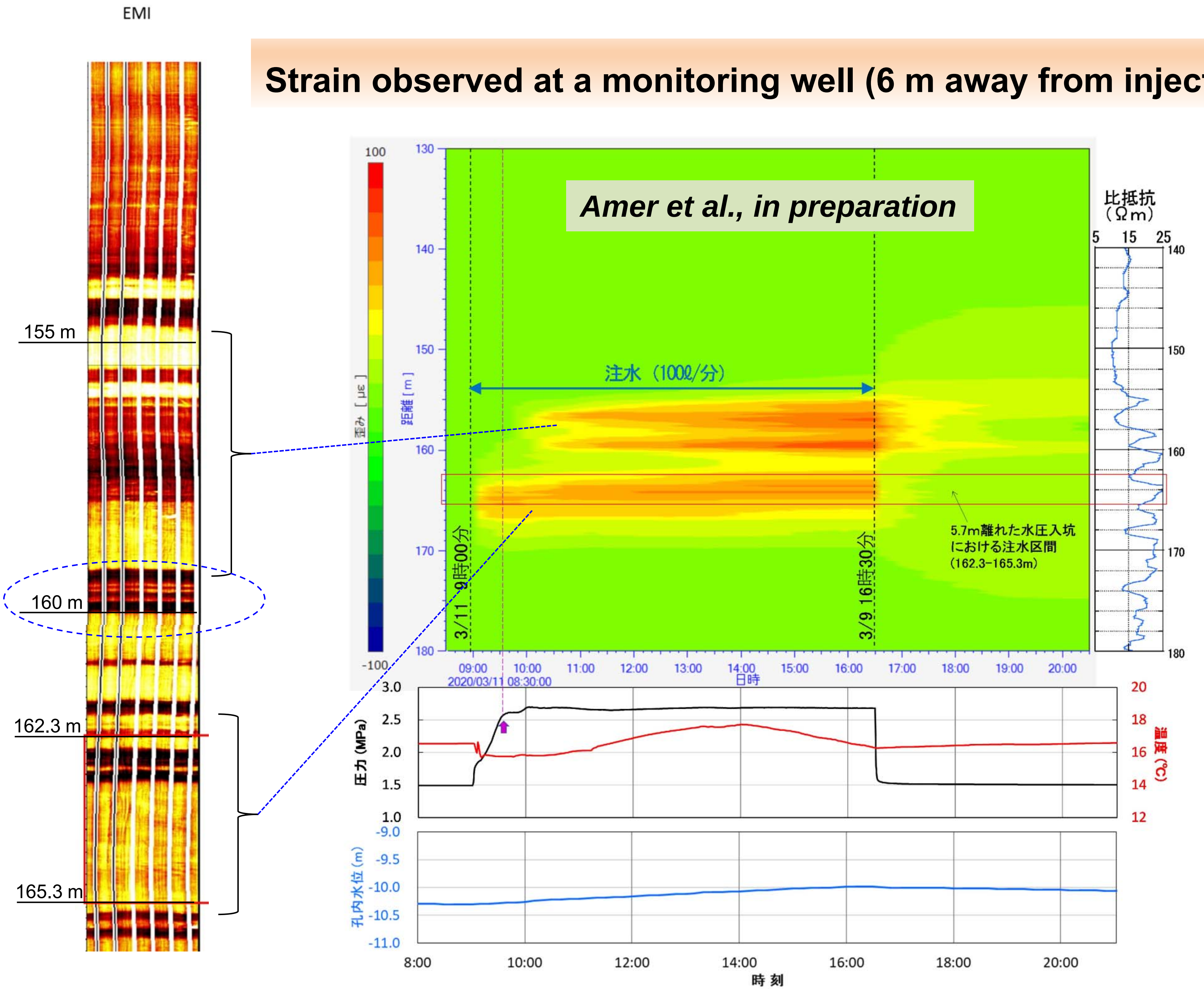
Field Experiments on Well Integrity Monitoring with Distributed Fiber Optic Strain (DFOS) Measurement



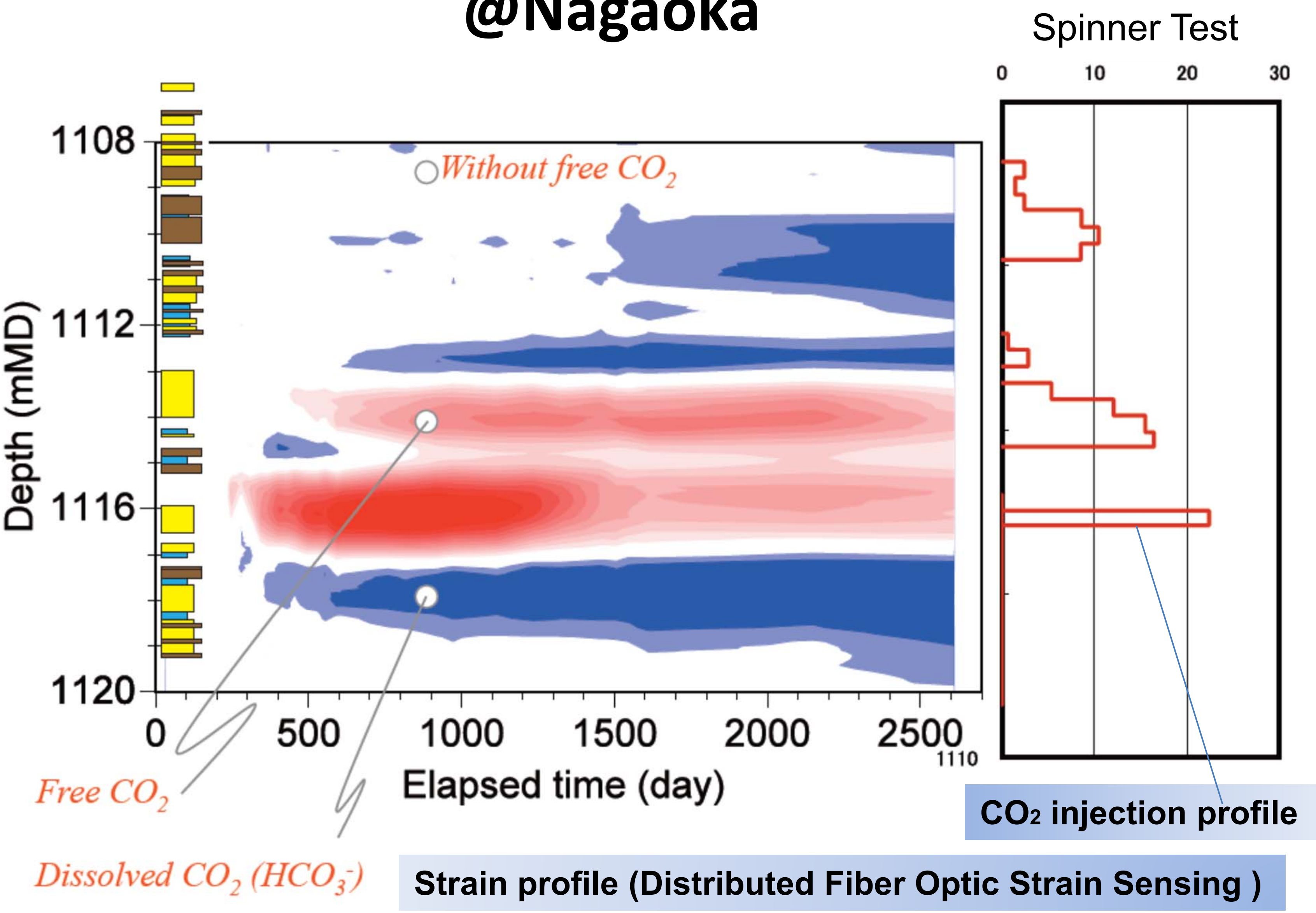
(Amer et al, in preparation)

How optic fiber responses to deformation in alternate layers of sand and mud during water injection?

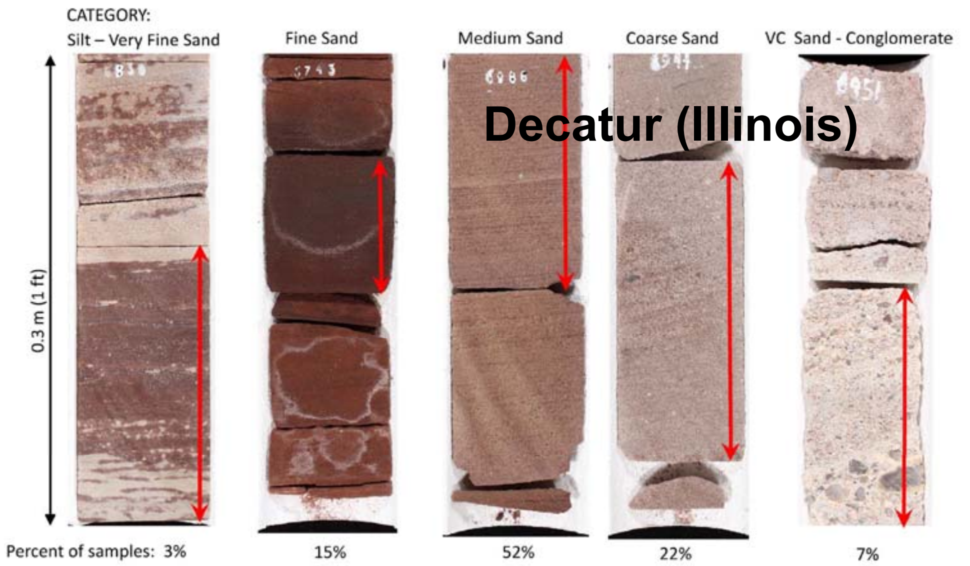
Strain observed at a monitoring well (6 m away from injector)

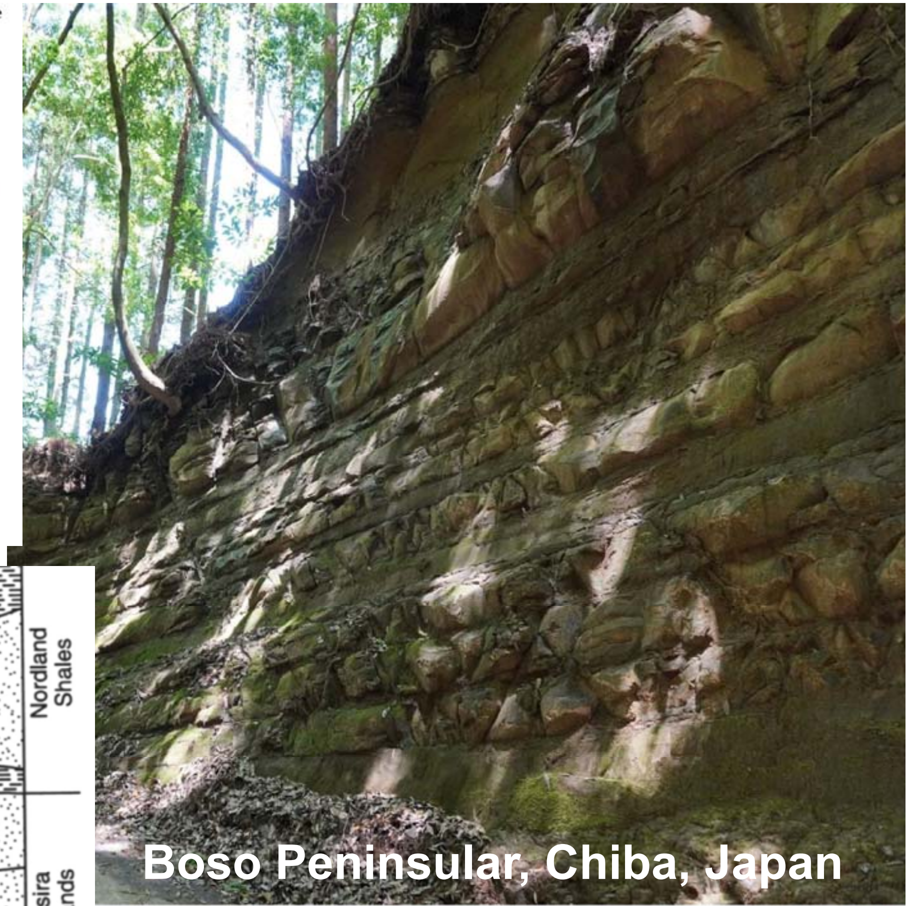


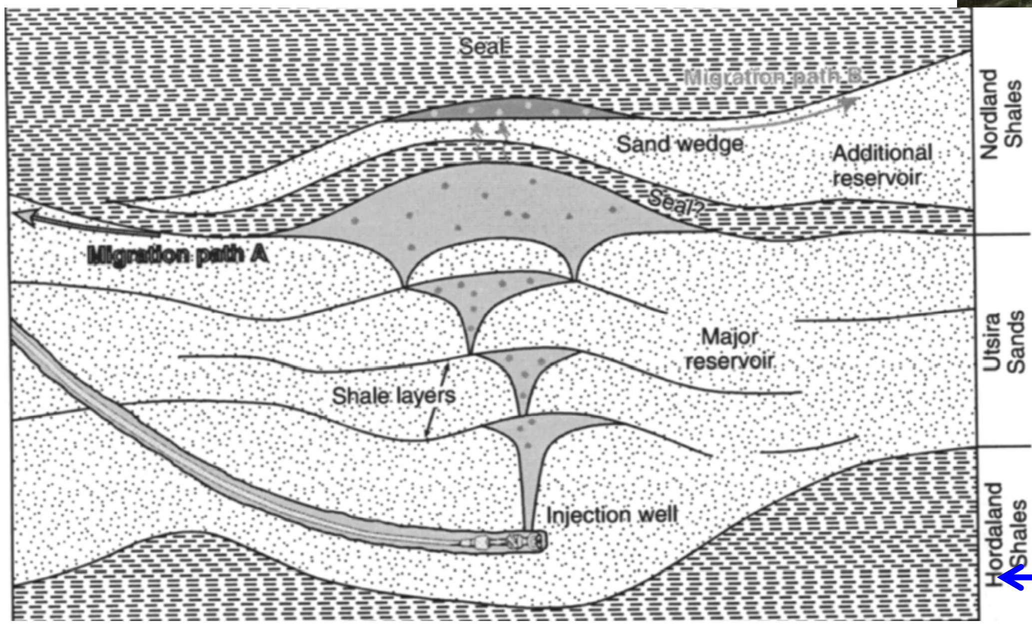
Injection Profile and CO_2 Distribution @Nagaoka



Alternation of Sand and Mud ➔➔ Heterogeneity & Anisotropy of Sand

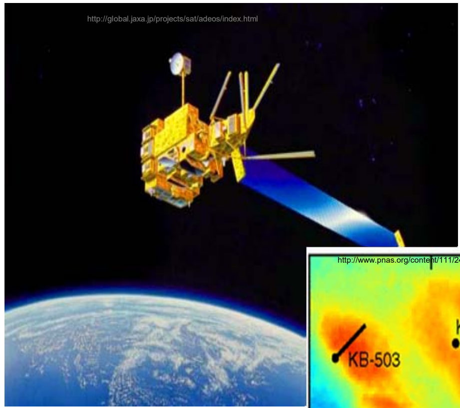




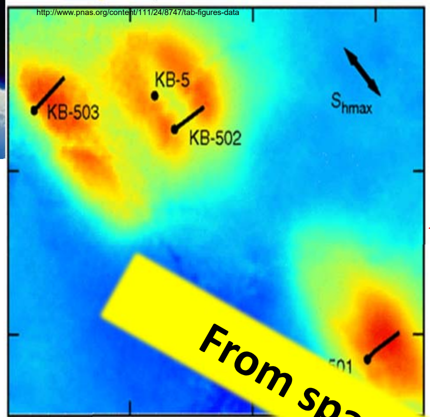


Schematic representation of the Sleipner storage system

International Collaboration on Fiber Optic Sensing



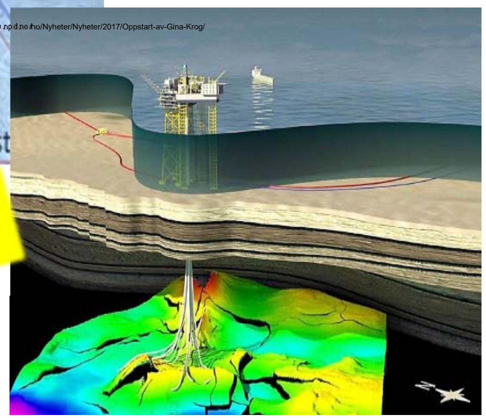
Satellite measurements+ GPS and geodesy for onshore sites



Demonstration of concept and methods: onshore surface heave (e.g. In Salah)

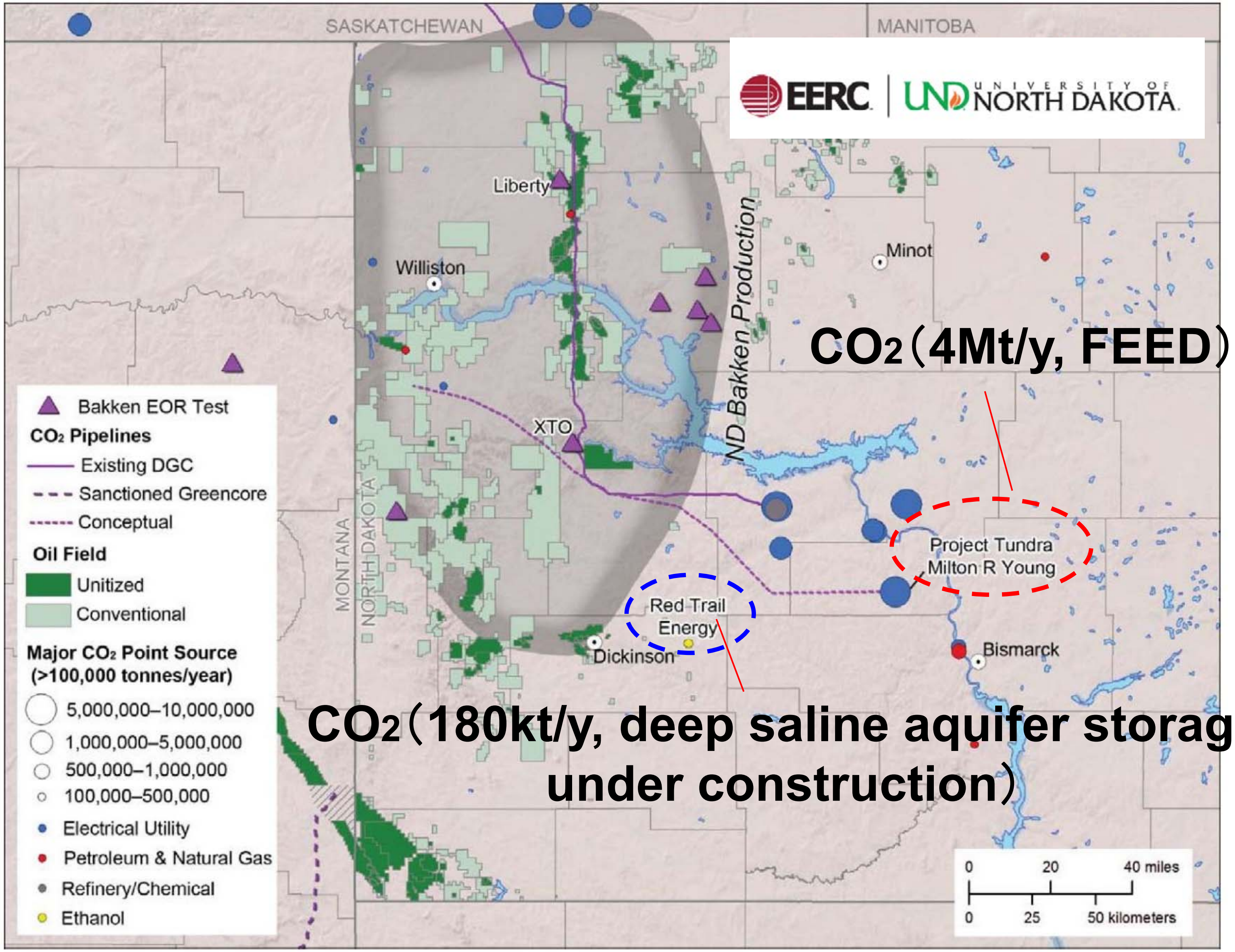
Onshore: North Dakota Univ. /US

Offshore: NGI /Norway

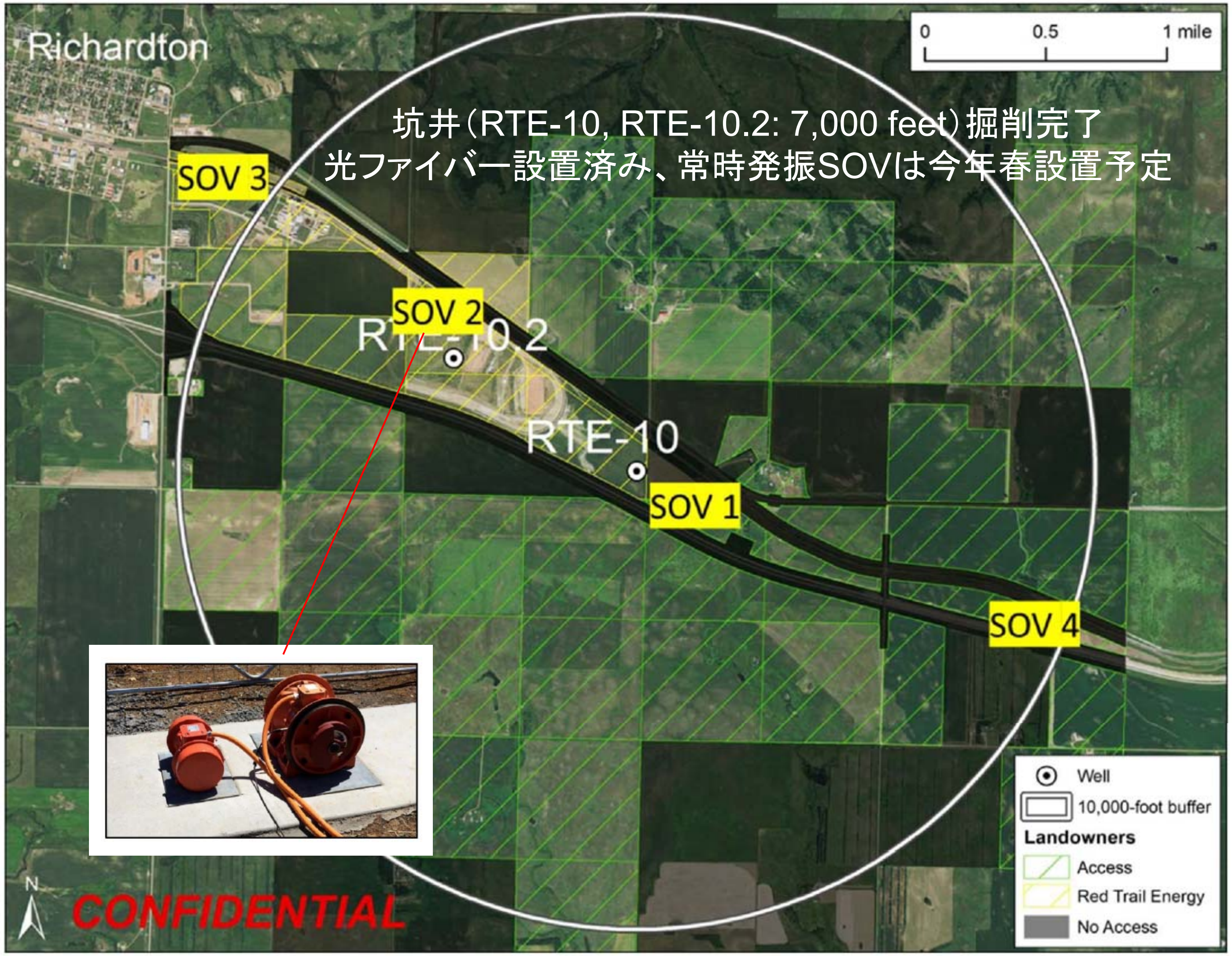


A fully-coupled Surface-Sub surface Distributed Geomechanical Monitoring has been scheduled at North Dakota, USA.

US-Japan CCUS Collaboration at North Dakota

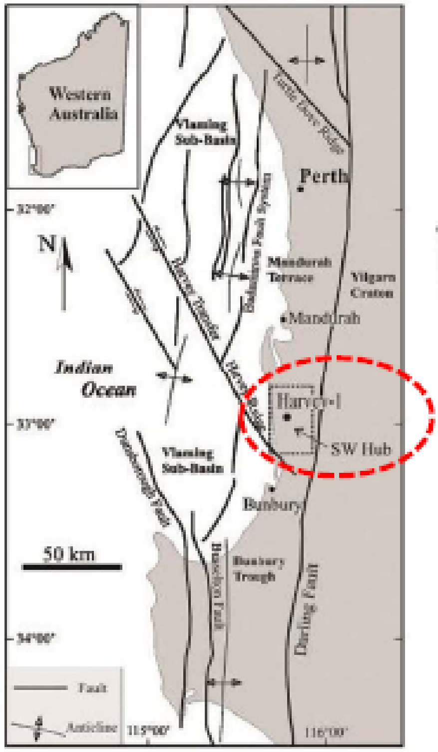


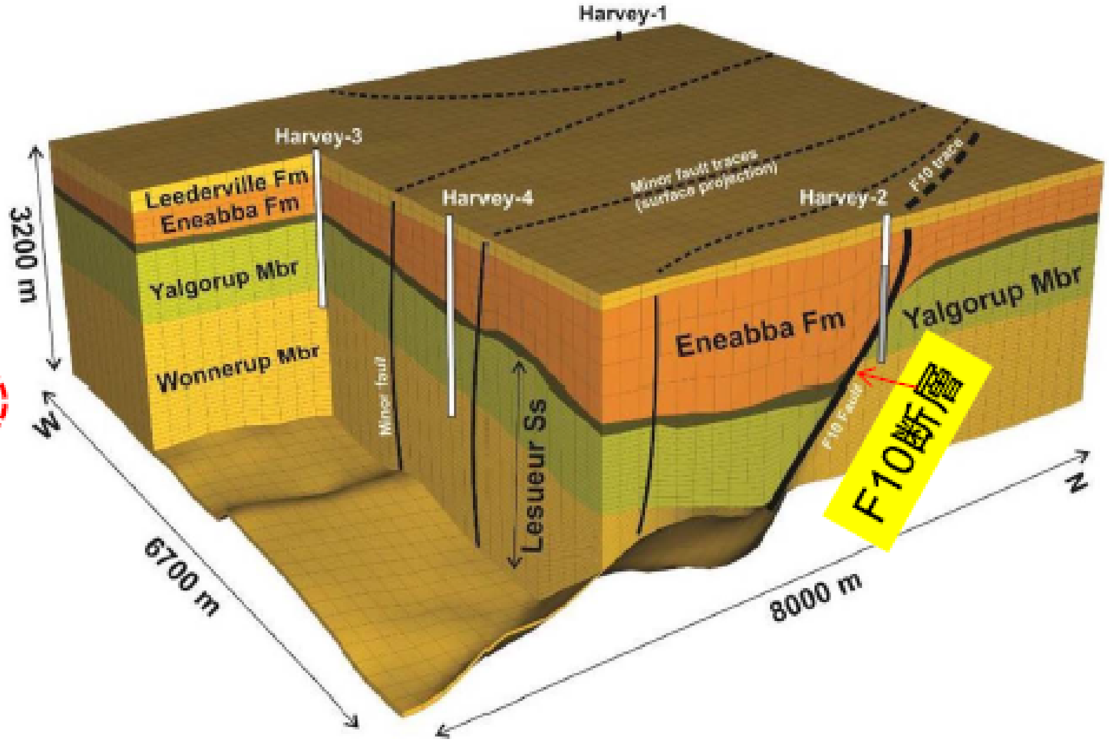
DAS/VSP for CO_2 Monitoring and Distributed Strain Sensing for Geomechanical Monitoring at North Dakota



A New Collaboration on Fault Integrity Monitoring between Australia and Japan at In-Situ Lab

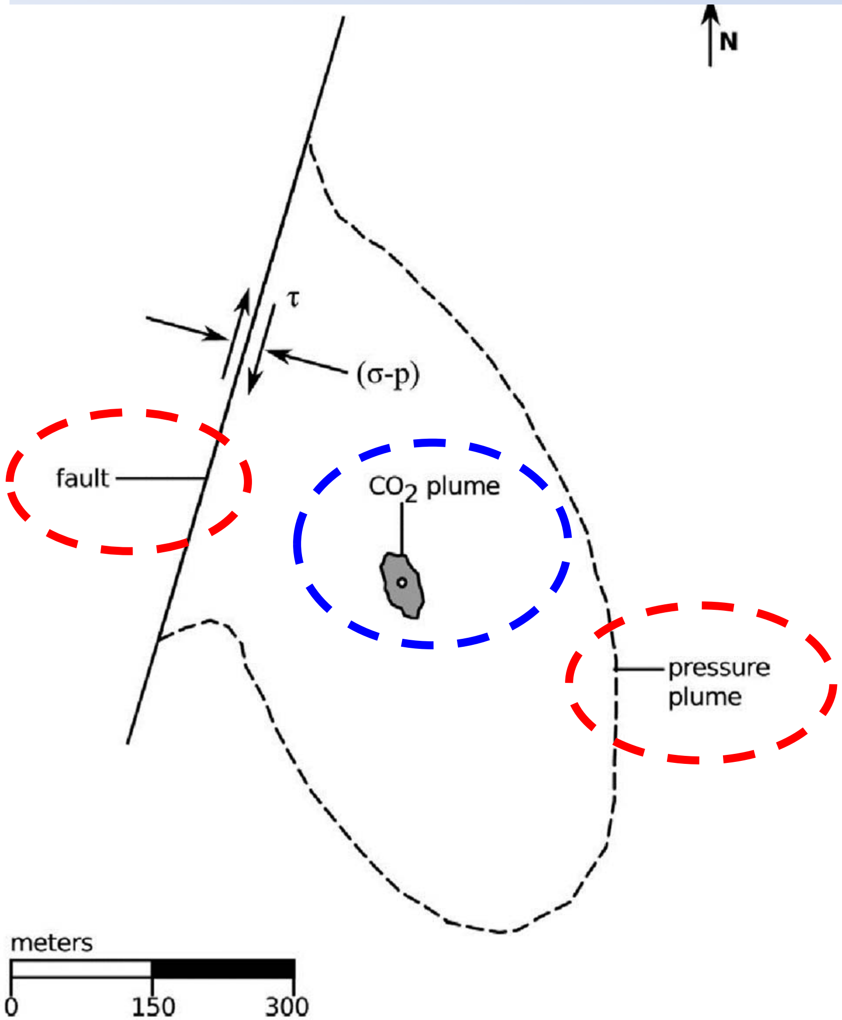
The South West Hub In-Situ Laboratory – A Facility for CO_2 Injection Testing and Monitoring in a Fault Zone

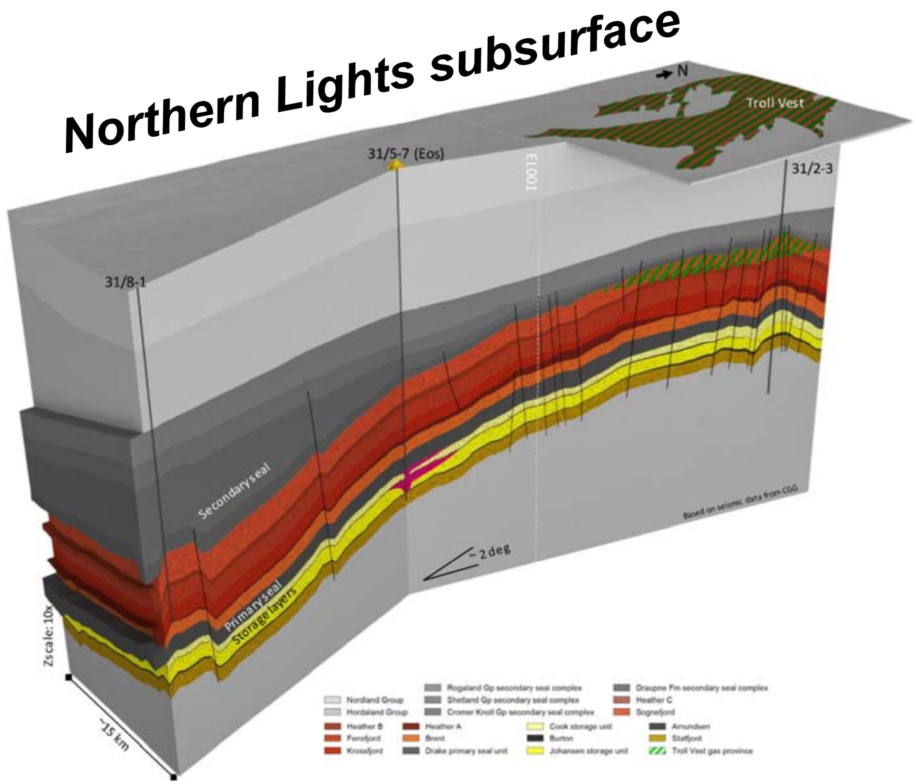




CO_2 plume front *vs* pressure front

(Geomechanical Modeling)





Schematic of the subsurface going from south to north through the 31/5-7 (Eos) CO_2 confirmation well. The CO_2 plume extent after 37.5 Mt injection is illustrated in magenta.

https://www.equinor.com/en/news/20201019-sharing-data-northern-lights.html

J.A. White, W. Foxall / International Journal of Greenhouse Gas Control 49 (2016) 413–424

３．大規模CO_2地中貯留の実現に向けて

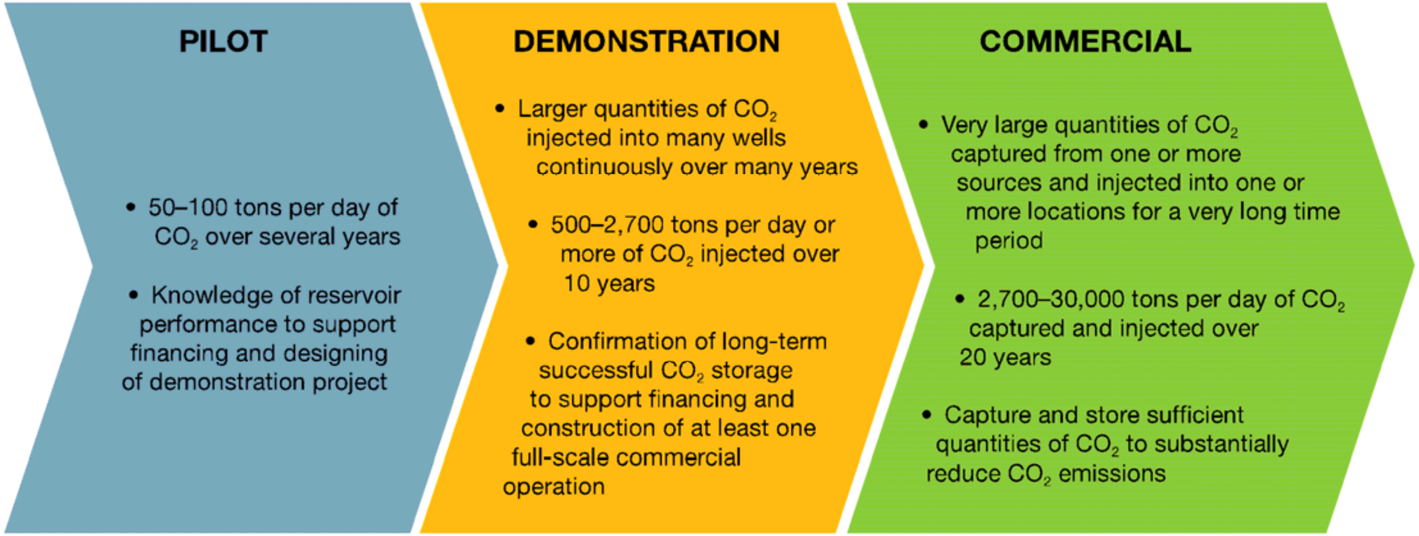
Can We Achieve Gigatonne CO_2 Storage?

Norwegian/US CCS collaboration opportunities

Stages of Carbon Capture and Storage Development

LEARNING* by *DOING !

Source: ADB, 2013



***Most* CCS/CCUS projects operating in North America and Europa and main operators are major oil and gas companies.**

***Some* projects in East Asian countries (China, Japan, South Korea), Australia and Middle East, but *less* in Southeast Asian countries.**

Norwegian/US CCS collaboration opportunities

"...realise a cost-effective solution for full-scale CCS in Norway, provided that this incite technology development in an international perspective".

Carbon Storage Program

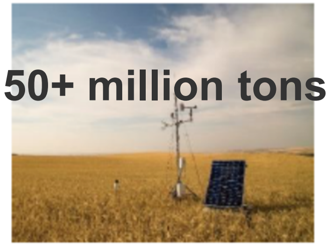
Improving and Optimizing Performance

US/DOE(2019)

Regional Carbon Sequestration Partnerships (RCSPs)

2005-2011
1 million tons

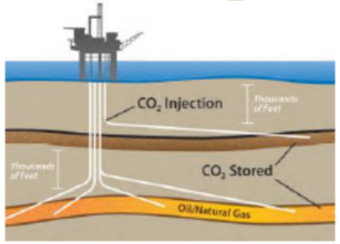
CarbonSAFE



50+ million tons

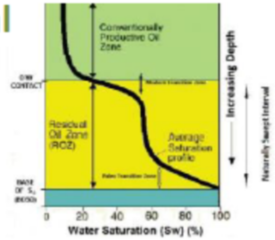
2011- (new regional initiative)

Offshore Storage

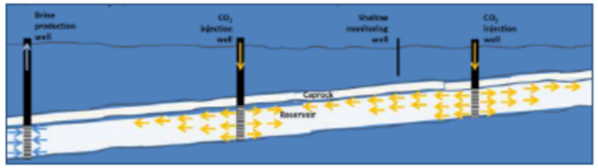


Unconventional EOR

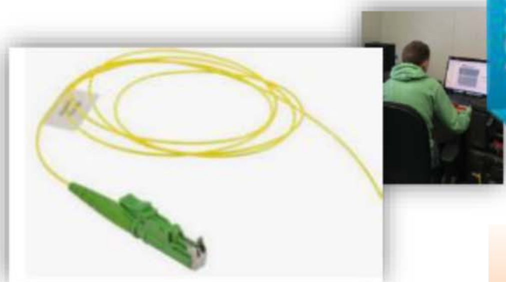
Shale Oil EOR



Brine Extraction Storage Tests (BEST)



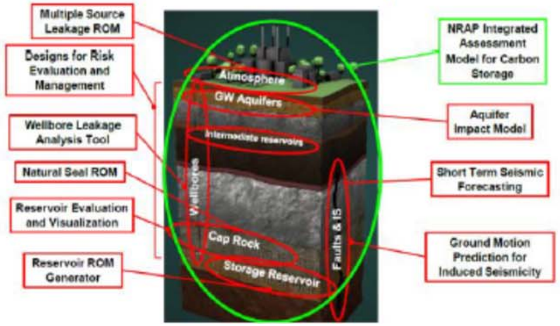
Advancing monitoring and measurement tools: improving characterization and reducing the uncertainty about the CO_2 and pressure fronts.



Fiber Optic Distributed Acoustic Sensing (DAS)

光ファイバーセンシング技術
（分布式音響測定 - DAS）

National Risk Assessment Partnership (NRAP) is developing toolsets to reduce uncertainty and quantify potential impacts related to release of CO_2 and induced seismicity



US/DOE：RCSP（計1MT）➔➔ CarbonSAFE（目標:50+MT）
➔➔ New Reginal Initiative

New Regional Initiative CCUS Selections

Awardee	Project
Battelle Memorial Institute	Regional Initiative to Accelerate CCUS Deployment in the Midwest and Northeastern USA
New Mexico Institute of Mining and Technology	Carbon Utilization and Storage Partnership of the Western United States
Southern States Energy Board	Southeast Regional Carbon Utilization & Storage Partnership (SECARB-USA)
University of North Dakota	Plains Carbon Dioxide Reduction (PCOR) Partnership Initiative to Accelerate CCUS Deployment

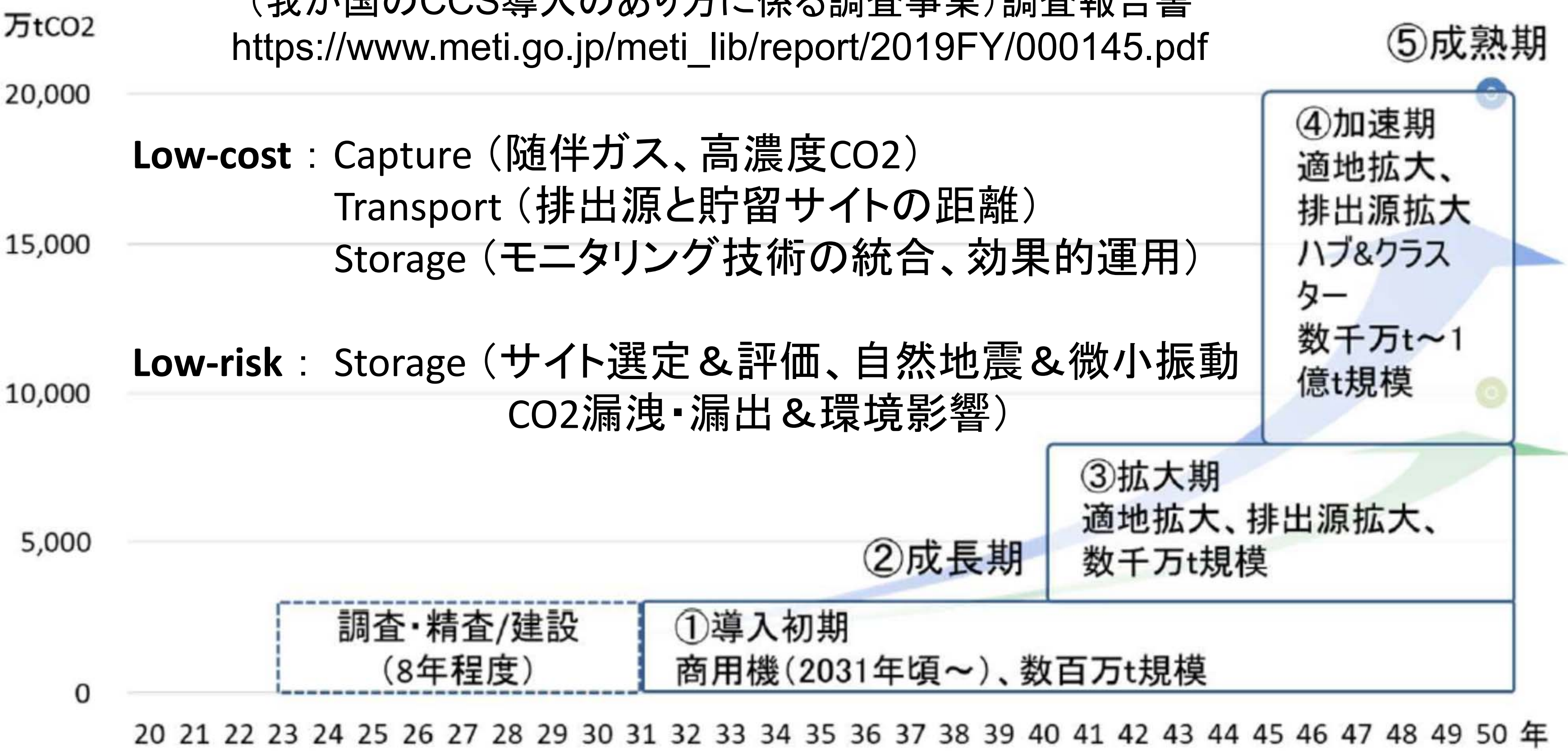
- To identify and address knowledge gaps under a new Regional Initiative to Accelerate CCUS Deployment.
- To identify and promote potential infrastructure and/or carbon utilization/ storage projects that will help enable low emission coal-based facilities of the future.

➢ Scaling up to Commercial

（我が国のCCS導入のあり方に係る調査事業）調査報告書
https://www.meti.go.jp/meti_lib/report/2019FY/000145.pdf

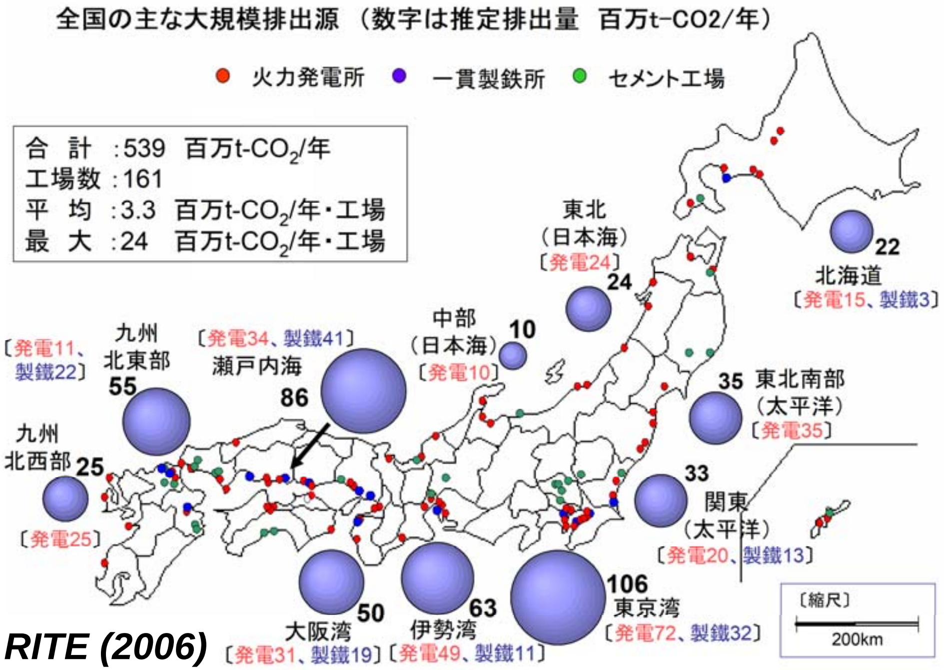
Low-cost：Capture（随伴ガス、高濃度CO2）
Transport（排出源と貯留サイトの距離）
Storage（モニタリング技術の統合、効果的運用）

Low-risk：Storage（サイト選定＆評価、自然地震＆微小振動
CO2漏洩・漏出＆環境影響）

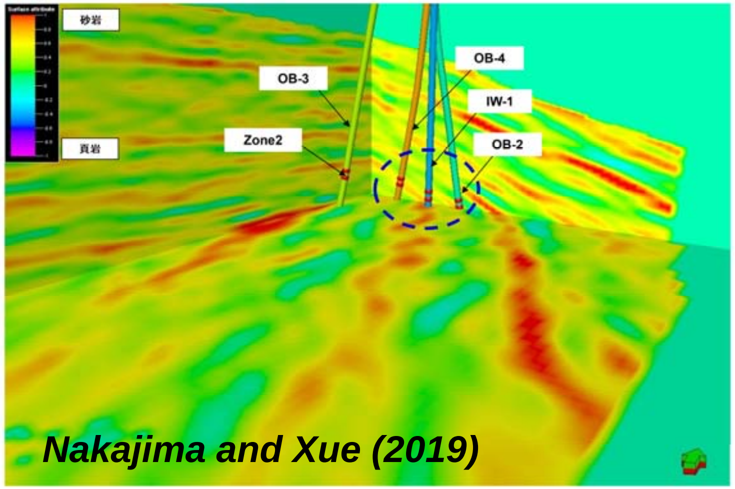


2050年に向けて、徐々に拡大するケース

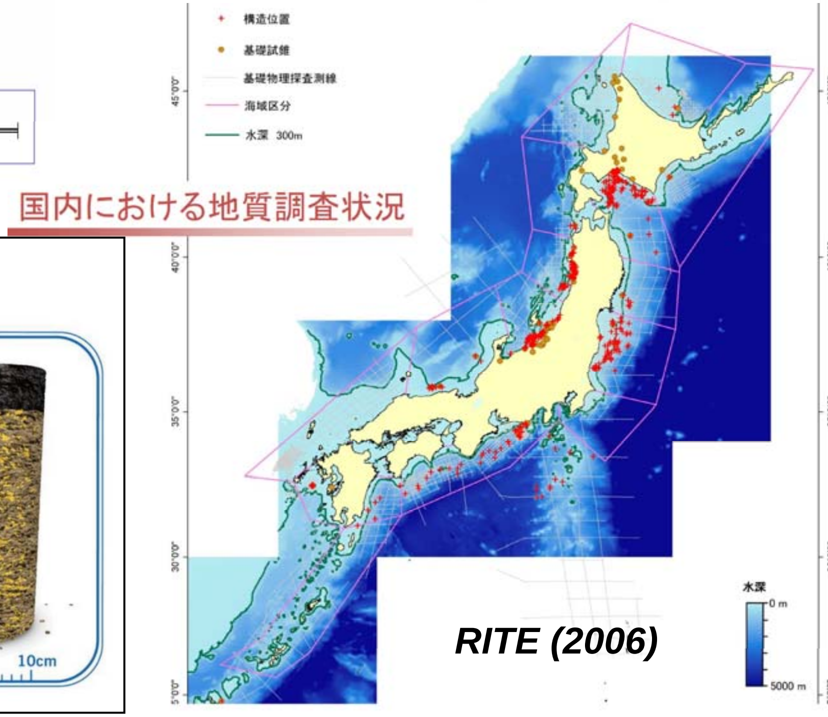
SRM: CO_2 Storage Resources Management（経済性評価込み）



RITE (2006)



Nakajima and Xue (2019)



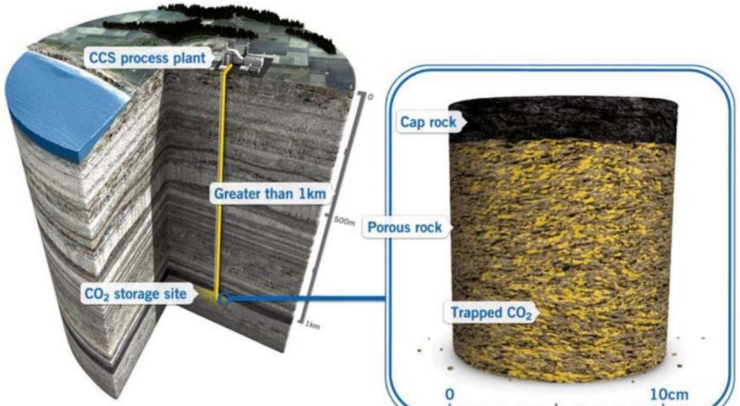
RITE (2006)

1.Depth: > 1 km

2.Location:

- reservoir and containment
- accessible

3.Capacity:
Space to hold all the planned CO_2



Source: GCCSI

謝 辞

この成果は、国立研究開発法人新エネルギー・産業技術総合開発機構（NEDO）の委託業務の結果得られたものです。ご協力いただいた関東天然瓦斯（株）、（株）物理計測コンサルタント、サンコーコンサルタント（株）、東京ガス（株）、ニューブレクス（株）にも感謝申し上げます。

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