

未来社会を支える

温暖化対策技術シンポジウムin 関西 2021

CO₂地中貯留技術実用化に向けての取り組み

— 研究開発から実用化・事業化への推進 —

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)

CO₂貯留研究グループリーダー

せつ じきゅう

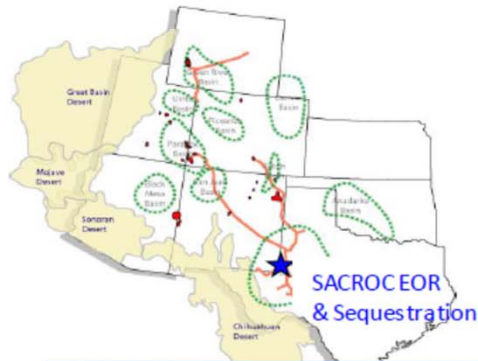
薛 自求

Ziqiu Xue (xue@rite.or.jp)



1. 温故知新 – CO₂-EOR/ CO₂地中貯留

Before looking ahead, let's review the journey so far



Enhanced Oil Recovery - US

(DOE, 2020)

- First US patent for CO₂ EOR issued in 1952
- First field test in 1964
- First commercial project (SACROC) in 1972

実用化？



Sleipner Project- Norway

- CO₂ removed from natural gas produced on production platform in North Sea
- Injection into saline reservoir under sea
- Started 1996

圧入規模: 100万トン/年



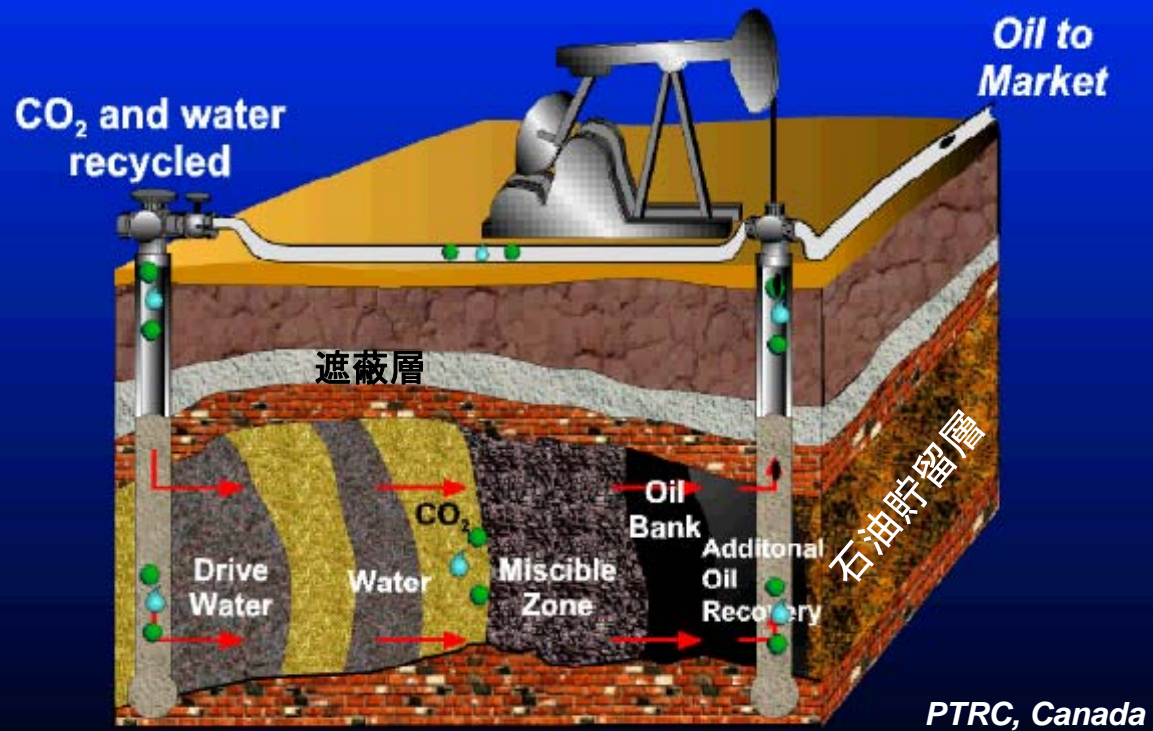
Weyburn – Saskatchewan

- EOR project with 50 wells
- Uses CO₂ from coal gasification plant
- Started 2000

日本: 長岡CO₂圧入実証プロジェクト始動

米国: テキサスFrioプロジェクト始動

Carbon Dioxide Flooding

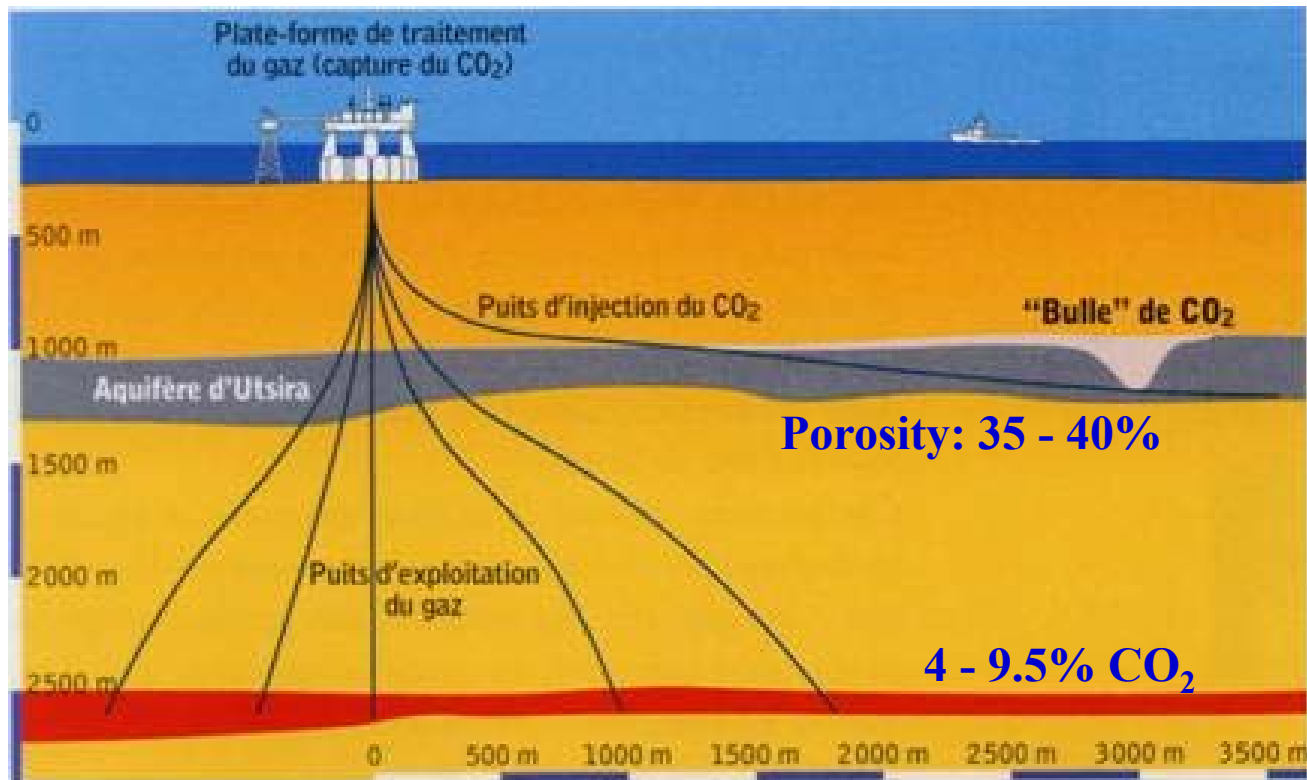


- ▶ 40-70% of CO₂ injected stays in reservoir

Associated CO₂ Storage in CO₂-EOR

SACS (Saline Aquifer CO₂ Storage)

North Sea, Norway (Statoil), Sleipner



Porous Sand
(Net sand:80-100%)

High Permeability
(1 - 3 darcy)

Temp: 37 °C
Pressure: 8 - 11MPa

1 million ton/year
(3% of Norway)

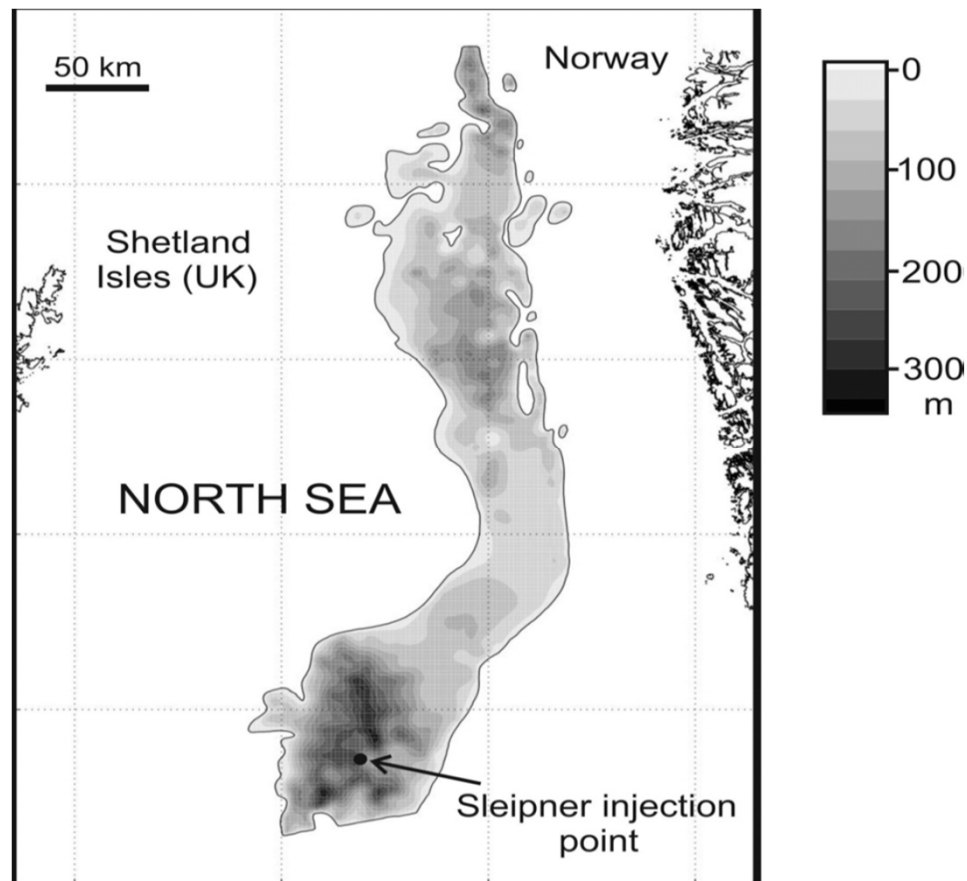
Carbon Tax: 7,000 yen/ton → 6.6 billion/year *20 year

44 billion+0.86 billion*20 year

北海（ノルウェー領） Sleipner での地中貯留

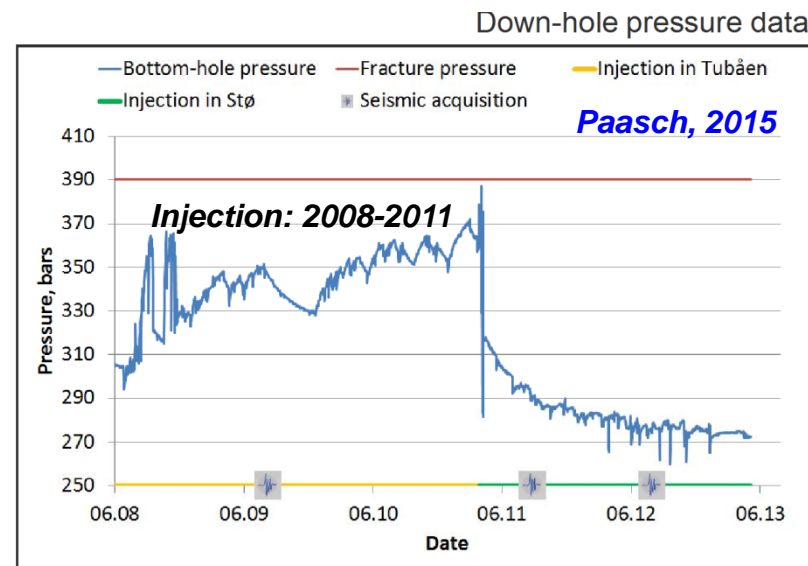
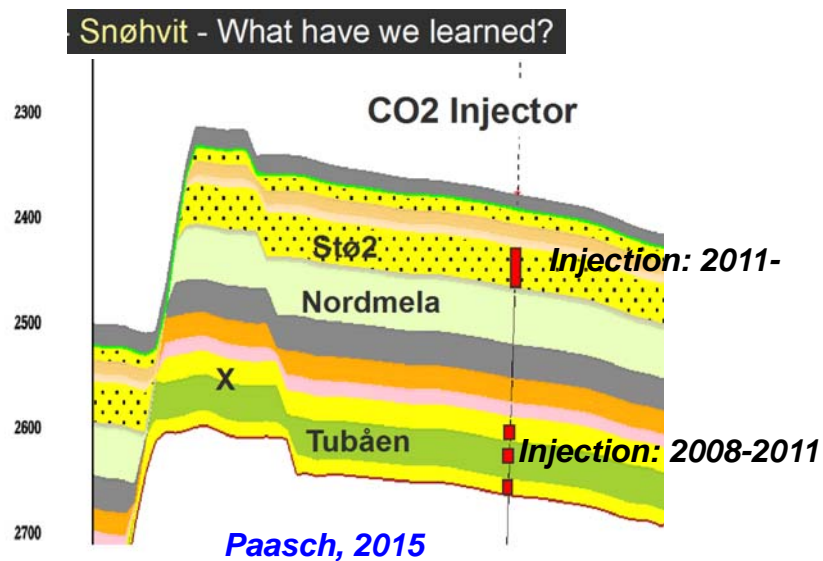
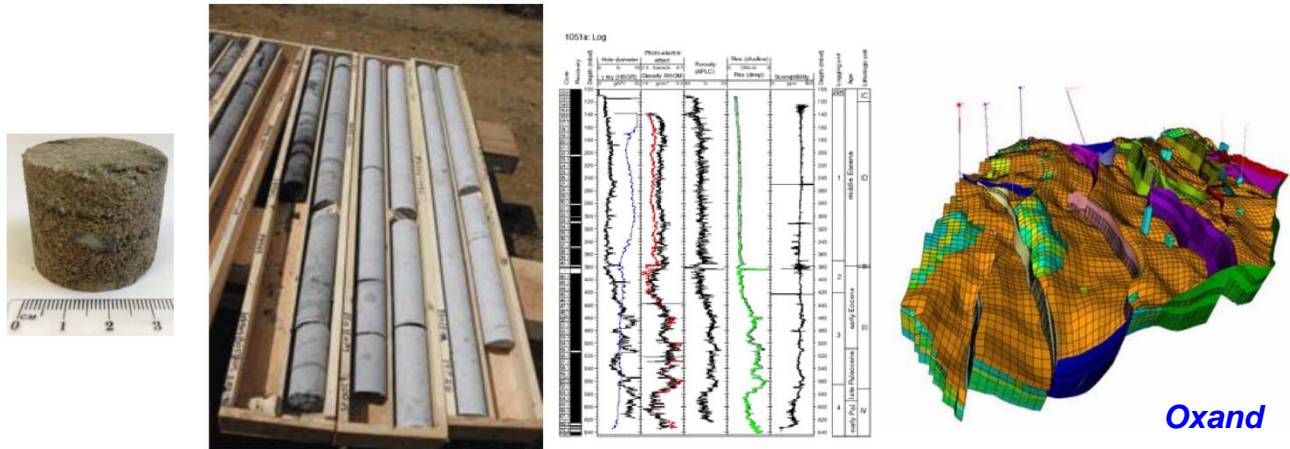


Utsira Sandへの圧入
Chadwick et al. (2004)
空隙率: 32~42%



Limits and thickness of the **Utsira Sand** and location of the Sleipner injection point.

➤ Reservoir characterization: Heterogeneity and Injectivity



Stratigraphy and Depositional Environment

@ Snøhvit

	Age	Formation	Hammerfest Basin
Jurassic	Late	Volgian	
		Kimmeridgian	Hekkingen
		Oxfordian	
	Middle	Callovian	Fuglen
		Bathonian	
		Bajocian	Stø
		Aalenian	
	Early	Toarcian	
		Pliensbachian	Nordmela
		Sinemurian	
	Hettangian	Tubåen	
Triassic	Late	Rhaetian	
		Norian	Fruholmen
			Snadd

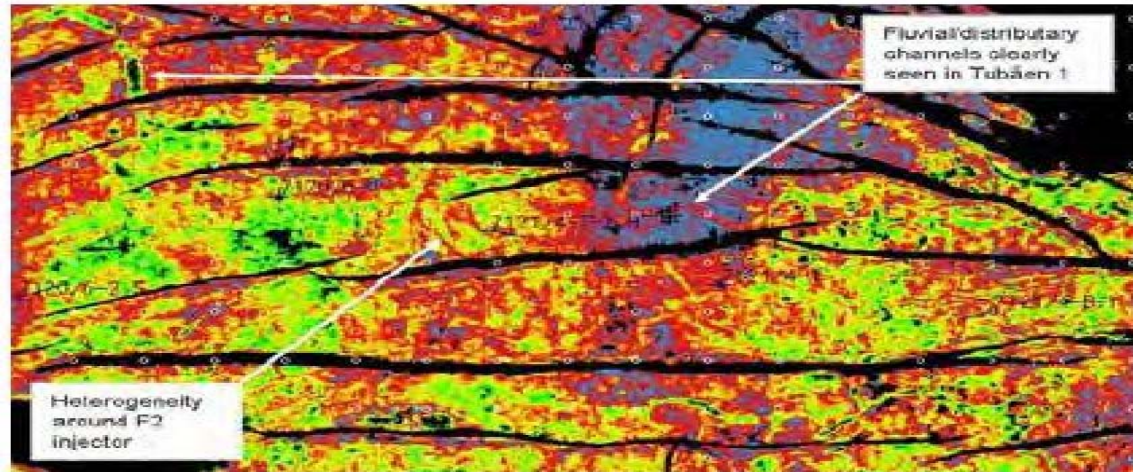


Figure 3: Amplitude map of the base Tubåen Fm reflection. Green colours are high amplitudes and blue colours low amplitudes.

Stø (main reservoir)

- Shallow-marine environment
- Good lateral and vertical communication

Tubåen

- Densely stacked fluvial channels
- Poor lateral and vertical communication

Paasch, 2015

Integrating aspects from both 3D seismic and sequence stratigraphy

Carbon Storage Program

Improving and Optimizing Performance

US/DOE (2020)

Regional Carbon Sequestration Partnerships (RCSPs)

地域特性を考慮



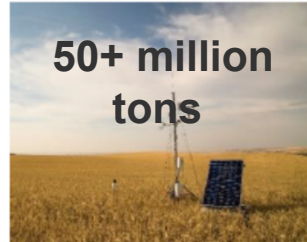
2005-2011
1 million tons

Advancing monitoring and measurement tools: improving characterization and reducing the uncertainty about the CO₂ and pressure fronts.



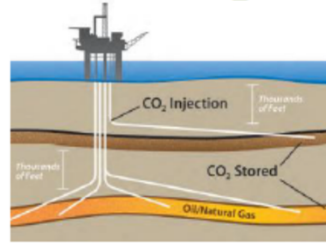
Fiber Optic Distributed Acoustic Sensing (DAS)

CarbonSAFE



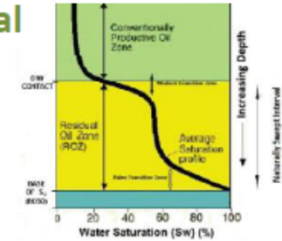
50+ million tons

Offshore Storage

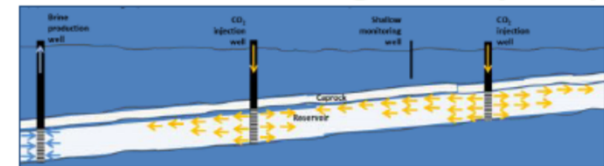


Unconventional EOR

Shale Oil EOR

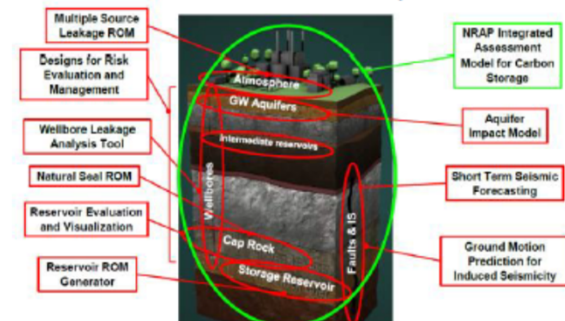


Brine Extraction Storage Tests (BEST)



地層水汲み上げによる圧力緩和法

National Risk Assessment Partnership (NRAP) is developing toolsets to reduce uncertainty and quantify potential impacts related to release of CO₂ and induced seismicity

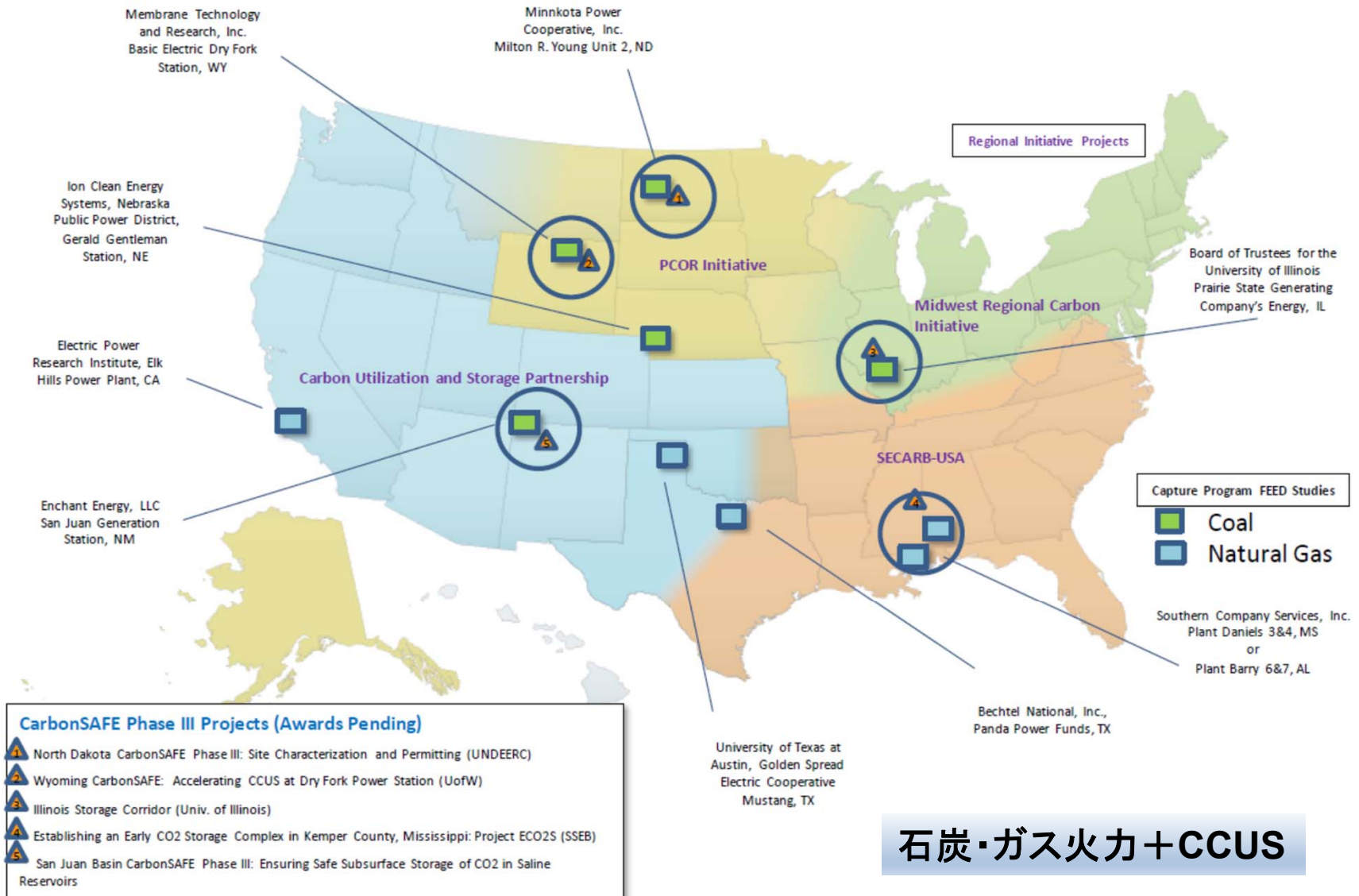


CARBON STORAGE PROGRAM



光ファイバーセンシング技術
(分布式音響測定 - DAS)

Carbon Storage Assurance Facility Enterprise (CarbonSAFE)

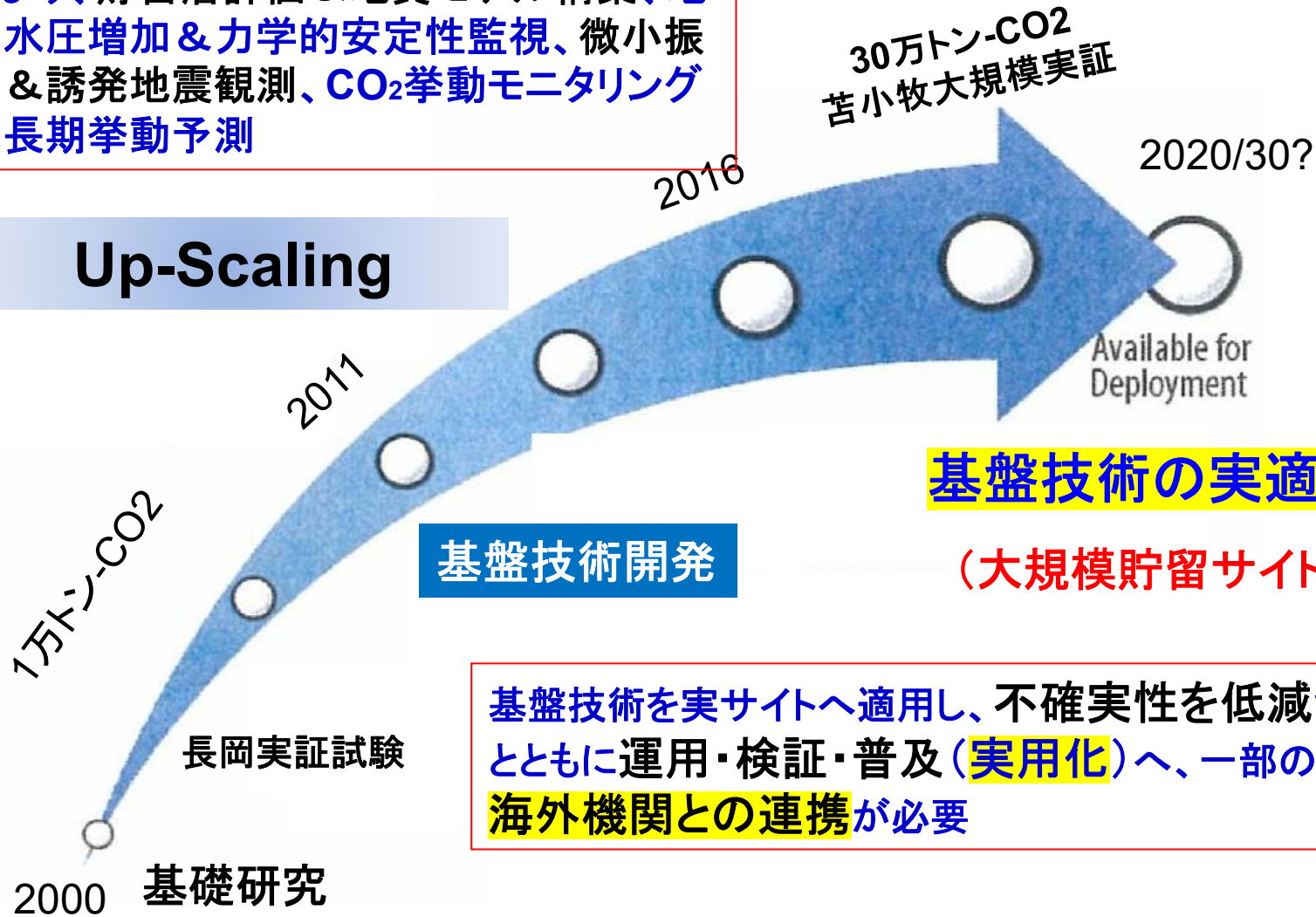


石炭・ガス火力+CCUS

貯留層規模／CO₂圧入規模のUp-scalingにより、貯留層評価&地質モデル構築、地層水圧増加&力学的安定性監視、微小振動&誘発地震観測、CO₂挙動モニタリング&長期挙動予測

国内においては、これまでの取り組み

Up-Scaling



基礎技術の実適用

(大規模貯留サイト)

基礎技術を実サイトへ適用し、不確実性を低減させるとともに運用・検証・普及(実用化)へ、一部の技術は海外機関との連携が必要

実用化: 不確実性の低減・安全性&経済性の向上

二酸化炭素地中貯留技術研究組合の概要 (2021年6月14日時点)

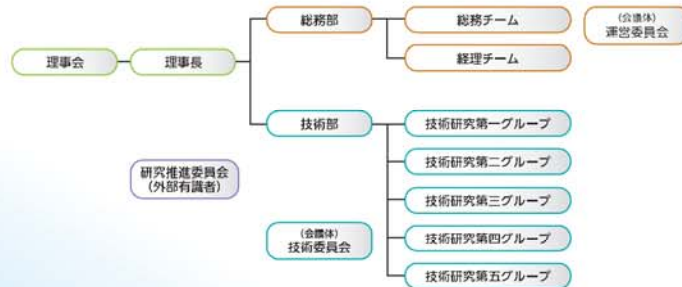
設立年月日

2016年4月1日

組合員

- ・応用地質株式会社
- ・株式会社INPEX
- ・石油資源開発株式会社
- ・大成建設株式会社
- ・国立研究開発法人産業技術総合研究所
- ・公益財団法人地球環境産業技術研究機構
- ・JX石油開発株式会社
- ・電源開発株式会社
- ・伊藤忠商事株式会社
- ・伊藤忠石油開発株式会社

組織構成



二酸化炭素地中貯留技術研究組合
Geological Carbon dioxide Storage Technology Research Association
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E-mail: inquiry@co2choryu-kumiai.or.jp
TEL: 050-3757-2989
<http://www.co2choryu-kumiai.or.jp>



2021.6



二酸化炭素地中貯留
技術研究組合
Geological Carbon Dioxide Storage
Technology Research Association



二酸化炭素地中貯留技術研究組合
Geological Carbon dioxide Storage Technology Research Association

設立年月日

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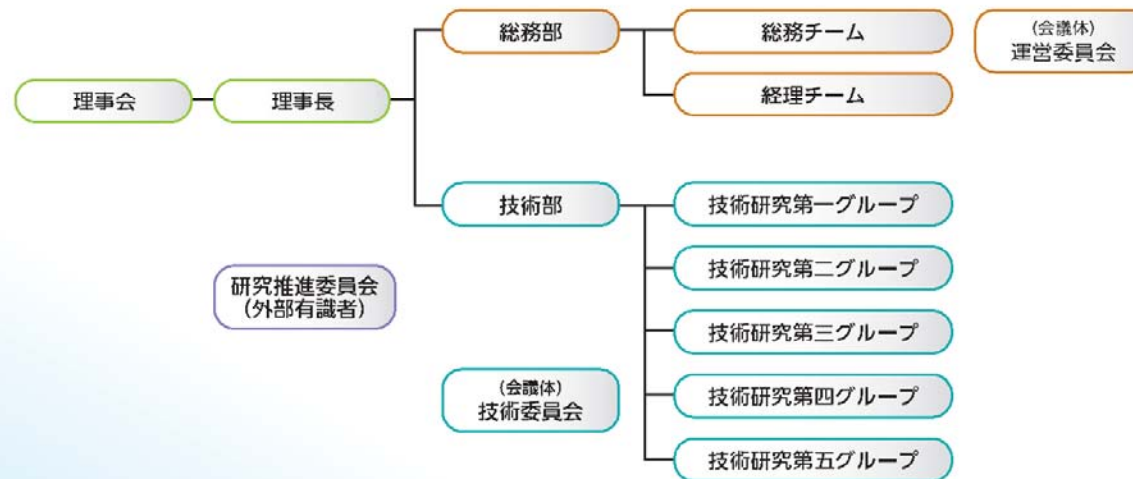


二酸化炭素地中貯留技術研究組合

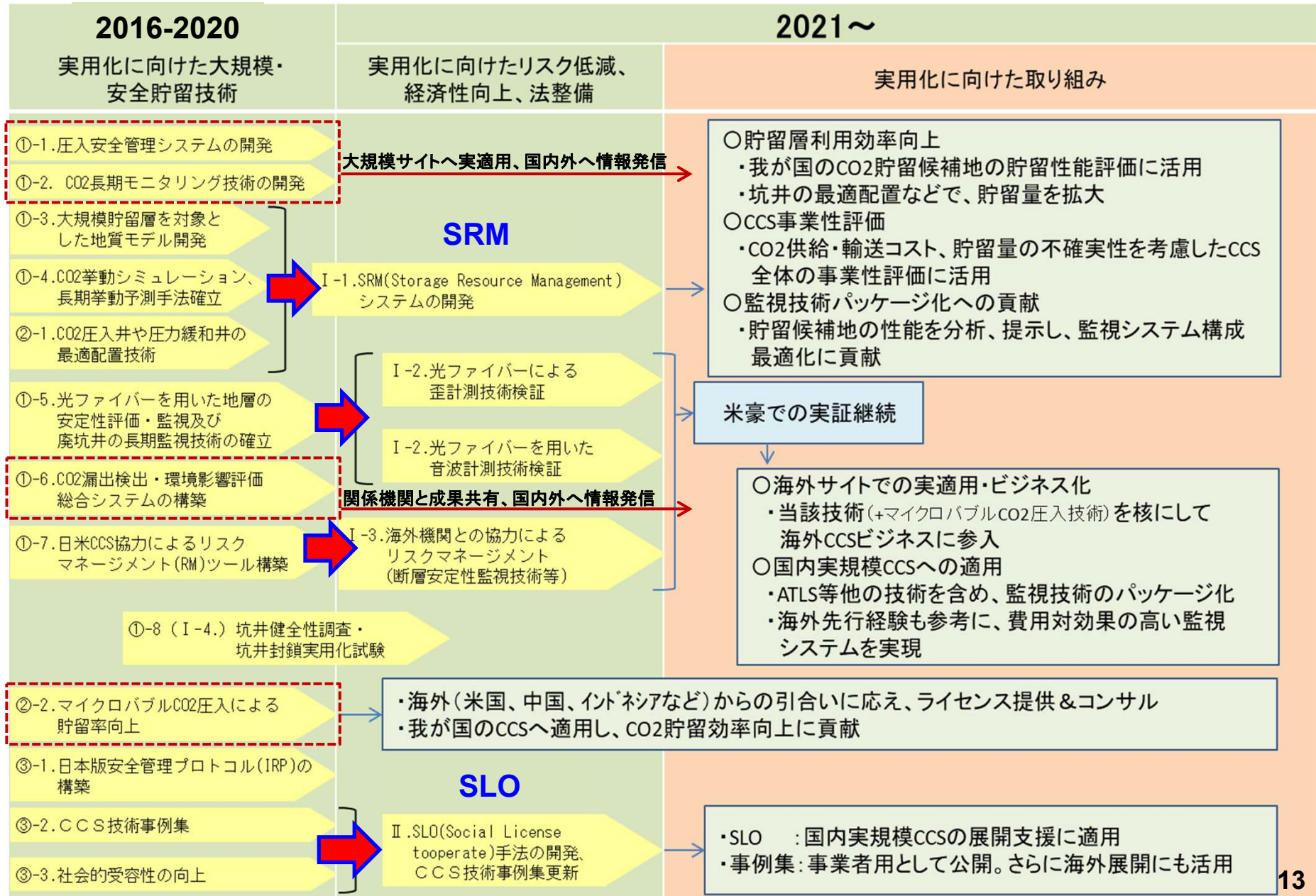
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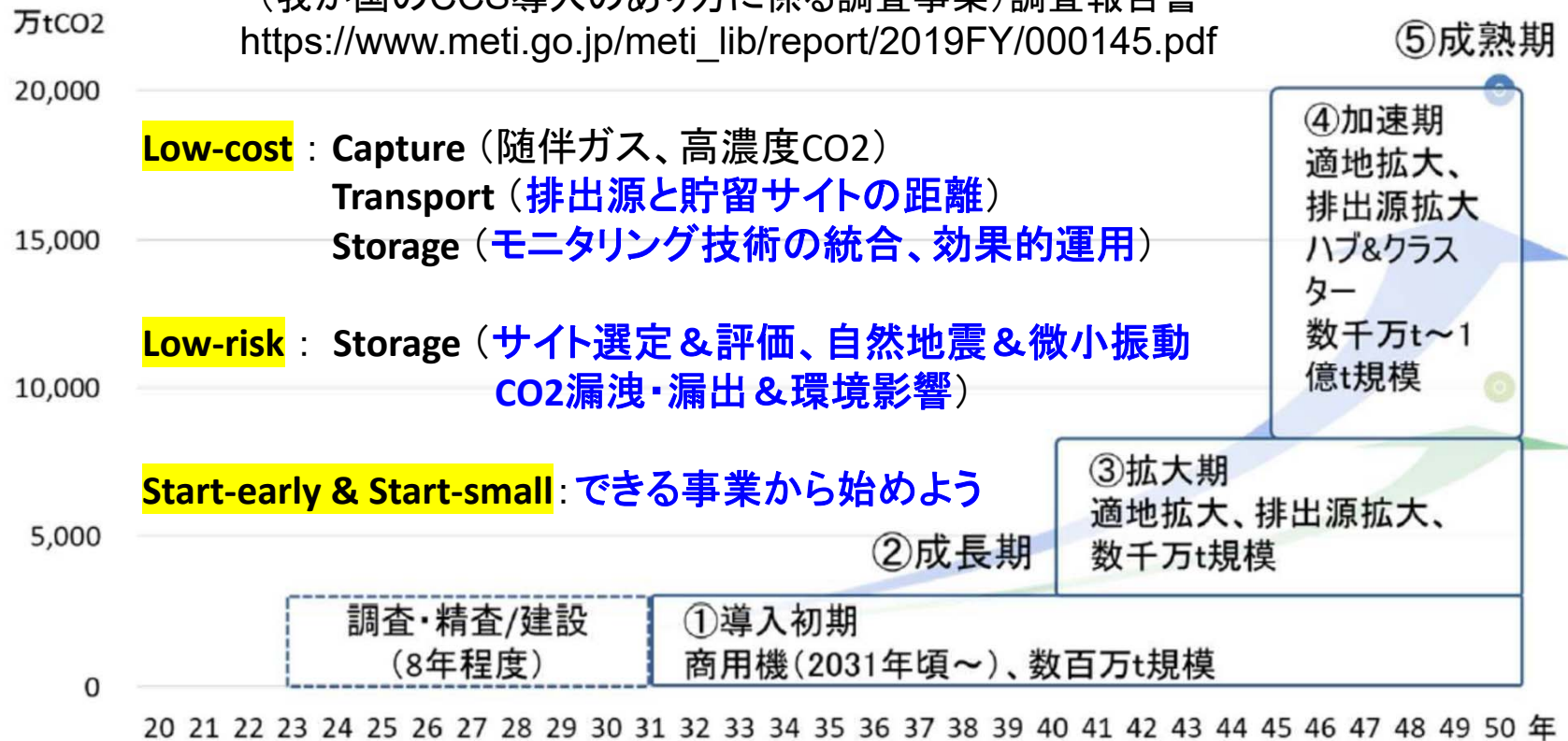
5ヶ年の研究成果の総括および2021年度以降の取り組み (中間評価資料抜粋)



➤ Scaling up to Commercial-scale

2050年に向けて、徐々に拡大するケース

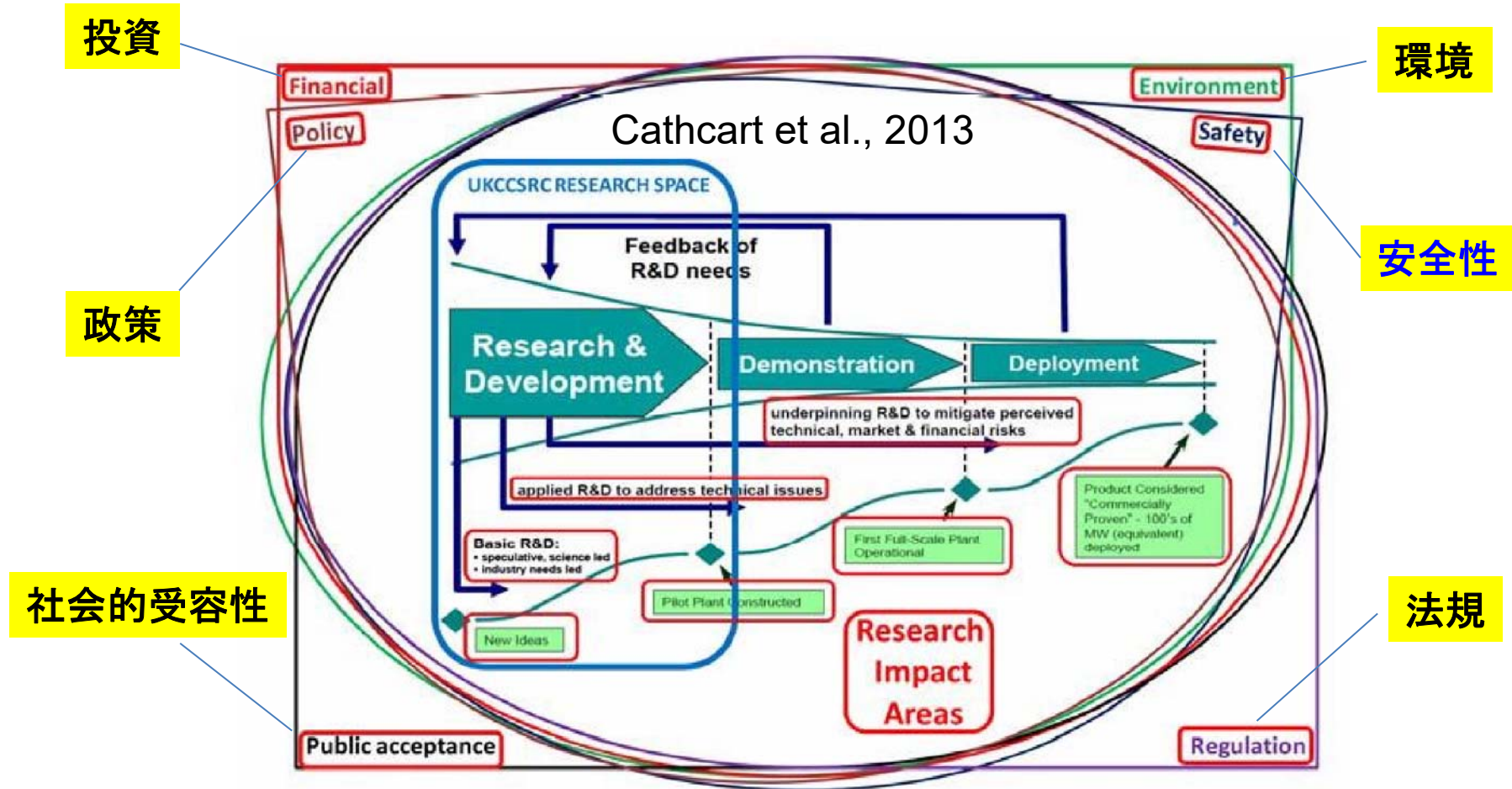
(我が国のCCS導入のあり方に係る調査事業)調査報告書
https://www.meti.go.jp/meti_lib/report/2019FY/000145.pdf



50年にカーボンニュートラル(実質排出ゼロ)を実現するために、今から毎年、同じ削減量で減らしていくと計算すると、30年時点では45.9%の削減が必要になる。この計算で割り出された数字を意識して、新目標が決まったとみられる。



2. CO₂地中貯留技術の実用化・事業化へ



技術開発や知見の提供

Research & Development → Demonstration, Deployment

実用化には、技術開発以外の要素(安全性、経済性、社会的受容性、法整備)

「二酸化炭素を地下に埋める」注目の技術“CCS”が抱える期待と課題【脱炭素とはなにか#5】

<https://www.businessinsider.jp/post-234099>



三ツ村 崇志 [編集部]

Apr. 30, 2021, 03:00 PM | TECH INSIDER 9,929



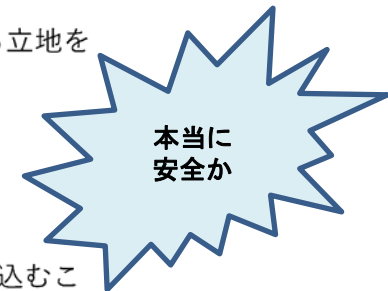
2020年12月に発表された、日本の脱炭素に向けたロードマップであるグリーン成長戦略でも、電力部門で排出している二酸化炭素の30~40%分の削減を、原子力発電と火力発電にCCUS（CCS含む）を組み合わせた技術で達成するとしている。

仮に40%すべてをCCSで達成するには、年間1.8億トンもの二酸化炭素を処理しなければならない計算となる。



日本近海で二酸化炭素1400億トン分の容量

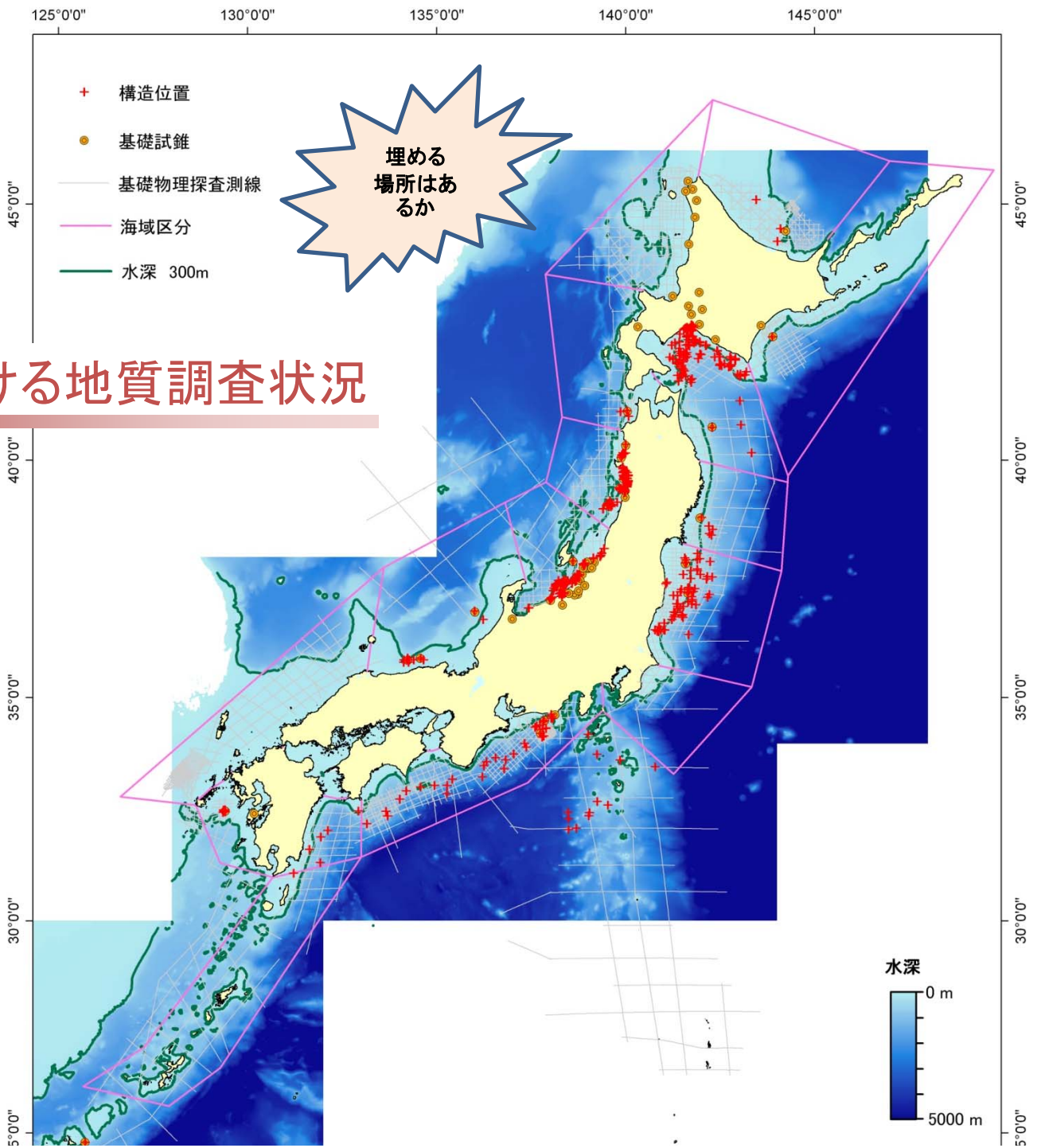
日本CCS調査では、貯留層と遮蔽層を兼ね備えた1億トン以上の二酸化炭素を貯留できる立地を3カ所程度選定することを目指し、日本近海の調査を進めている。



コストの壁をどうクリアするのか？

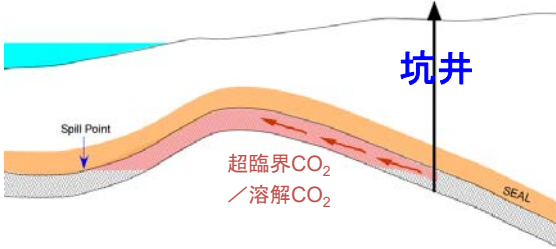
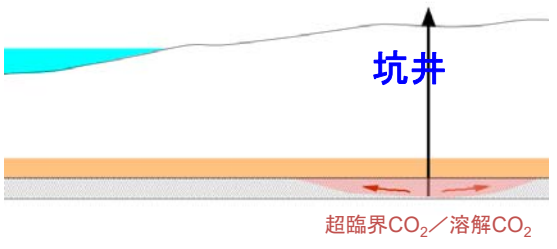
海外では、二酸化炭素を単純に地中に埋め戻すCCSではなく、二酸化炭素を油田に送り込むことで石油の生産を増やす「原油増進回収法（EOR）」という手法を用いている企業が多い。

長期安全性(貯留メカニズム)、地域社会の理解(地震や漏洩への懸念解消)



国内における地質調査状況

カテゴリー分類と貯留ポテンシャル試算(M1)

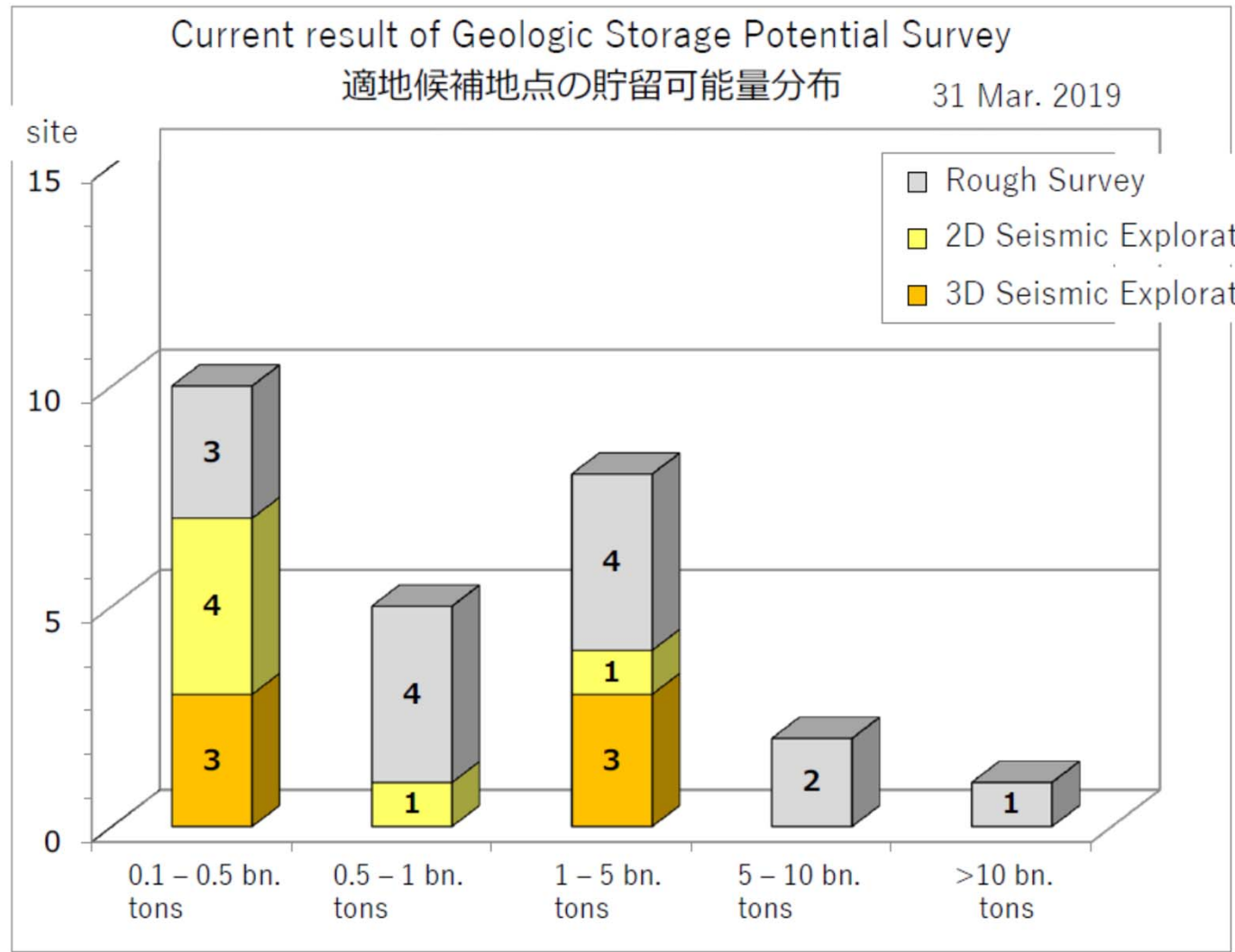
地質データ		カテゴリーA	カテゴリーB
油ガス田	坑井・震探データが豊富	A1 (旧1) 35億t-CO ₂	B1 (旧3) 275億t-CO ₂
基礎試錐	坑井・震探データあり	A2 (旧2) 52億t-CO ₂	
基礎物探	坑井データなし、震探データあり	A3 (旧4の一部) 214億t-CO ₂	B2 (旧4) 885億t-CO ₂
貯留概念図			
(参考) 実施状況		Weyburn(カナダ)等 長岡プロジェクト	Sleipner(ノルウェー)等
計		約300億t-CO ₂	約1,160億t-CO ₂

(注) 内陸盆地、湾(瀬戸内海、大阪湾、伊勢湾など)は対象外。B1、B2は水深200m以浅を対象。

〔 カテゴリーA: シール層が期待され、かつクロージャーが想定される帯水層
 カテゴリーB: 連続的なシール層が期待される帯水層 〕

CO2 Storage potential in Japan

METI(2020)

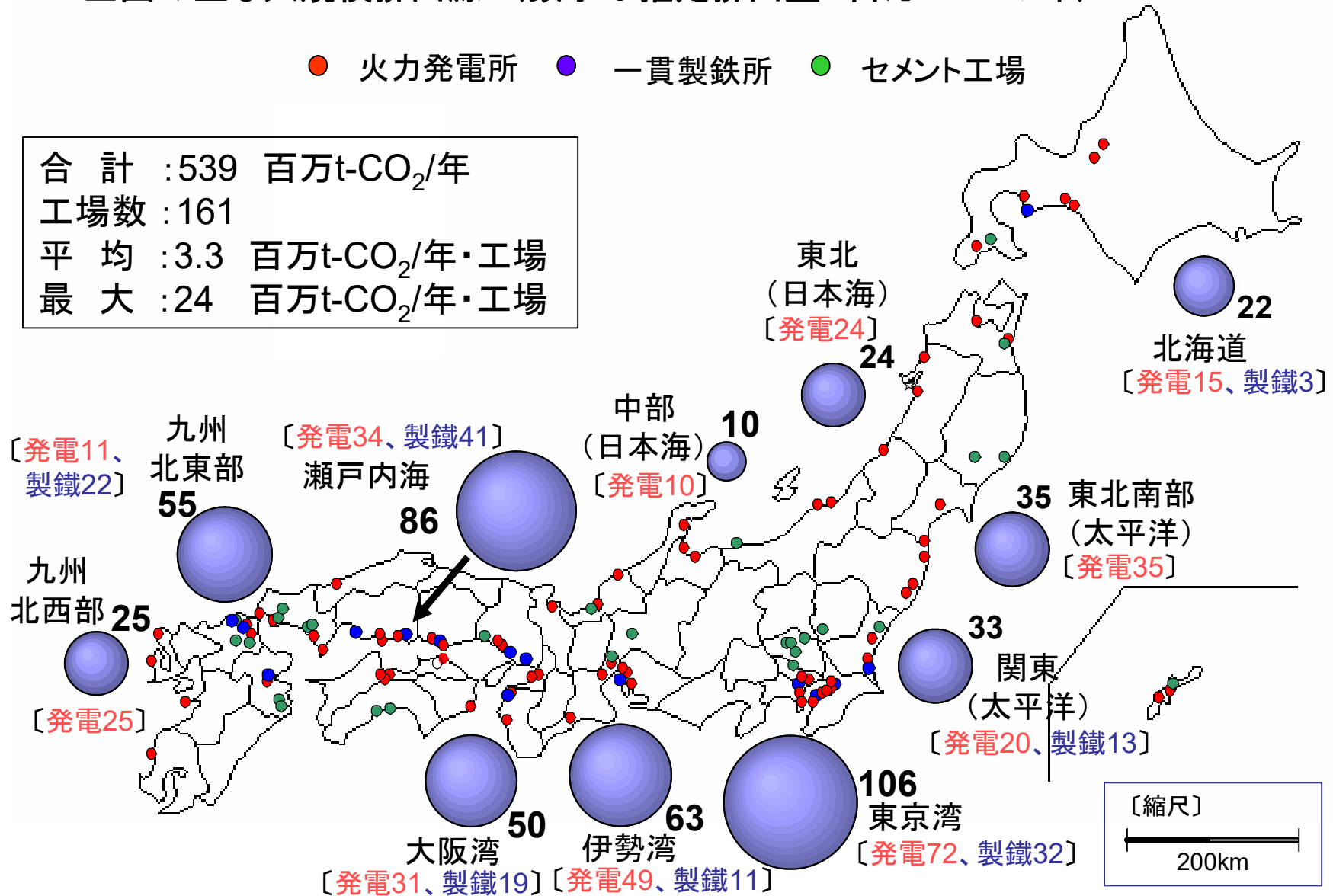


課題：排出源と貯留サイトのマッチング

全国の主な大規模排出源（数字は推定排出量 百万t-CO₂/年）

● 火力発電所 ● 一貫製鉄所 ● セメント工場

合計 : 539 百万t-CO₂/年
 工場数 : 161
 平均 : 3.3 百万t-CO₂/年・工場
 最大 : 24 百万t-CO₂/年・工場

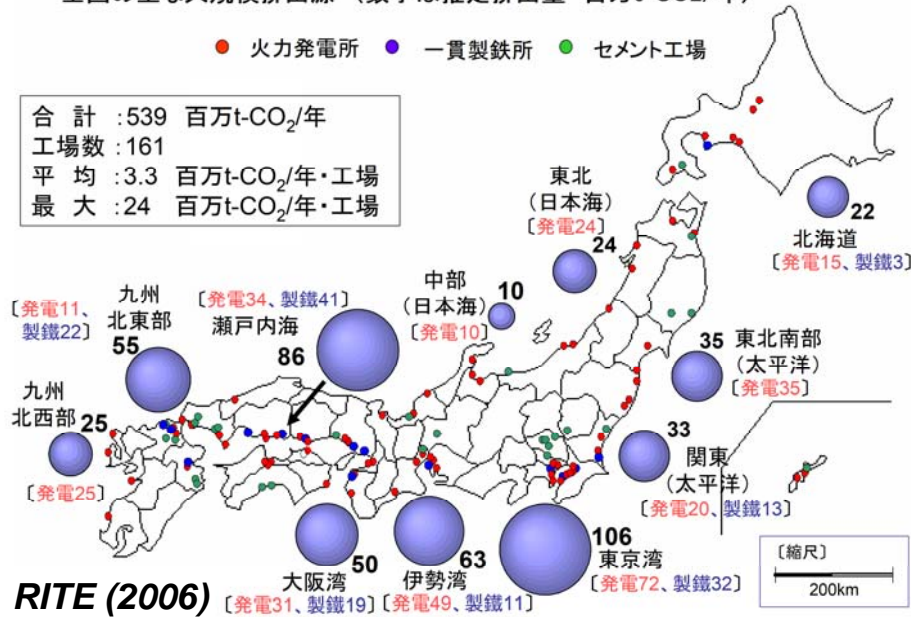


SRM: CO₂ Storage Resources Management (経済性評価込み)

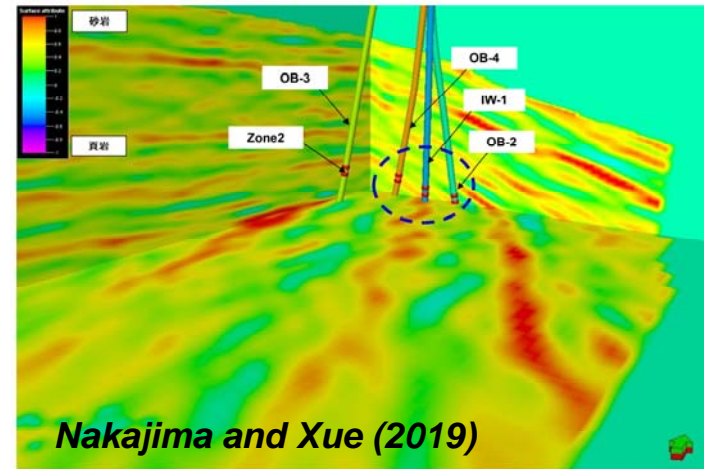
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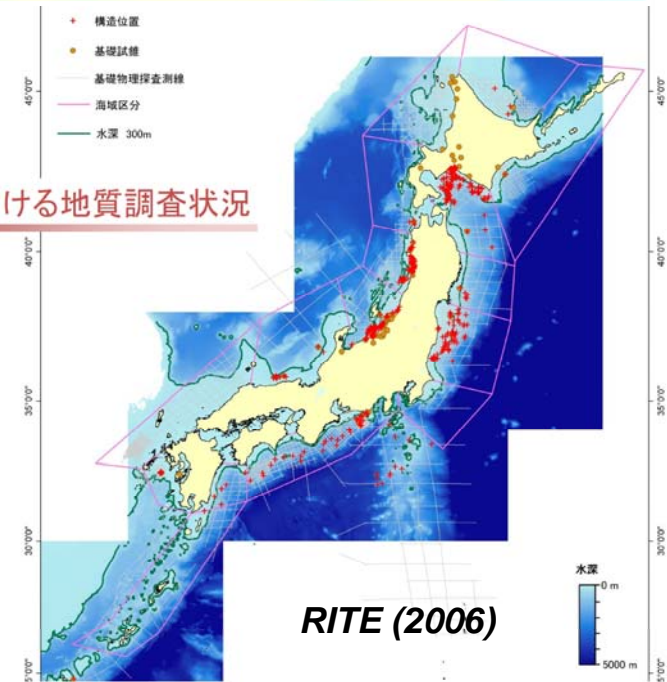


RITE (2006)



Nakajima and Xue (2019)

国内における地質調査状況



RITE (2006)

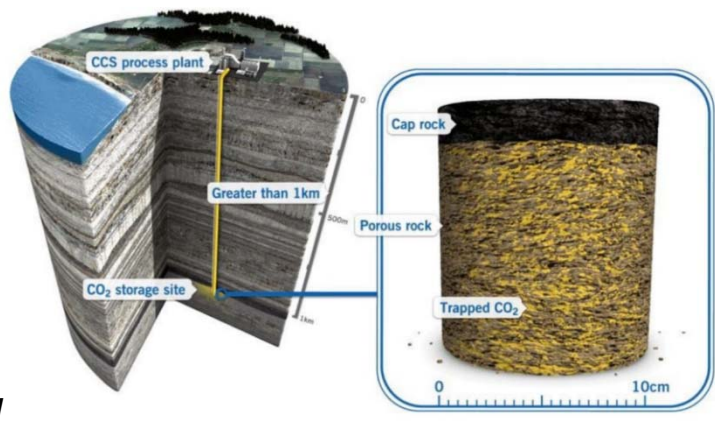
1. Depth: > 1 km

2. Location:

- reservoir and containment
- accessible

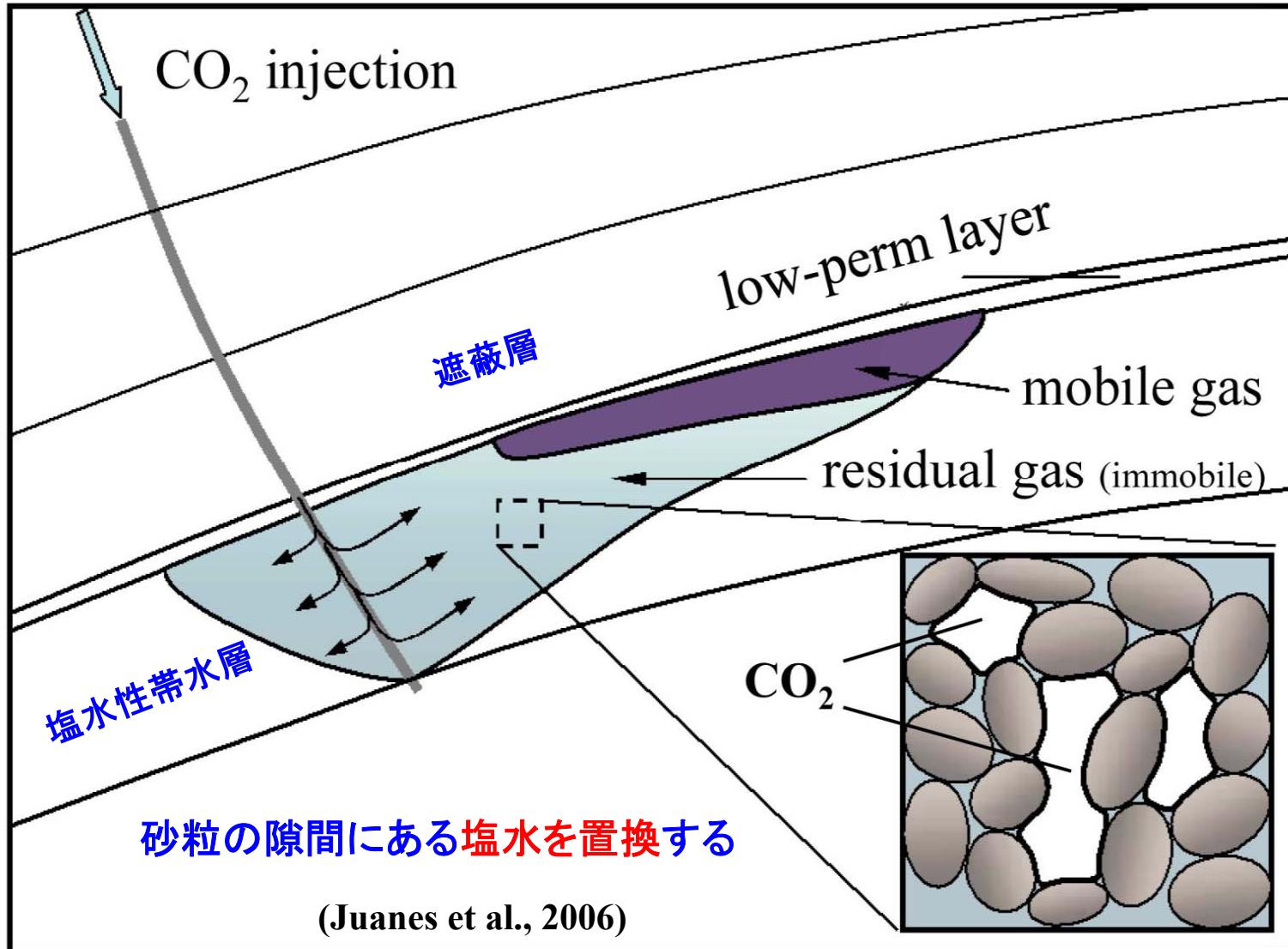
3. Capacity:

Space to hold all the planned CO₂

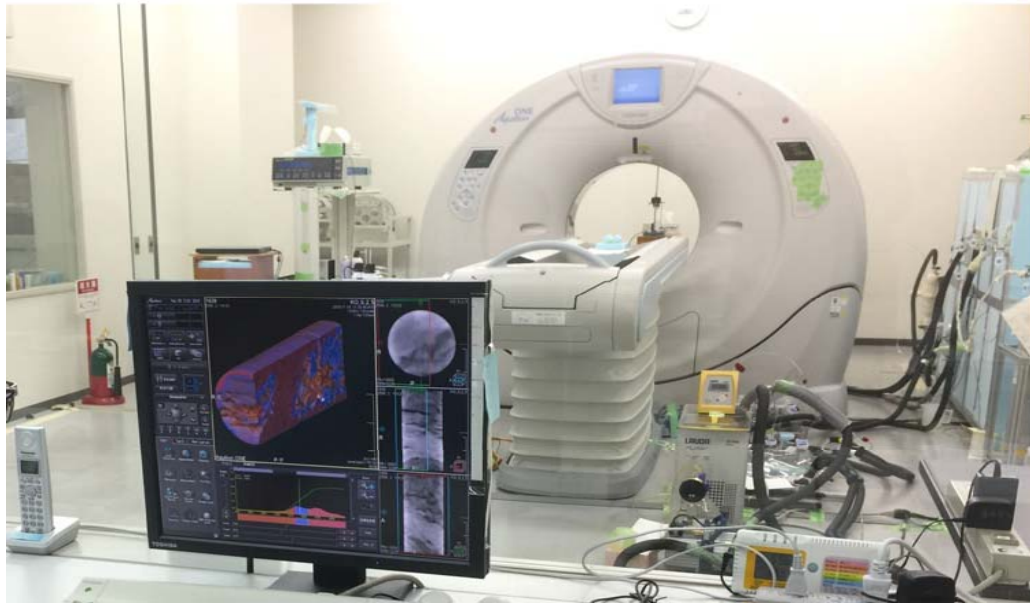


Source: GCCSI

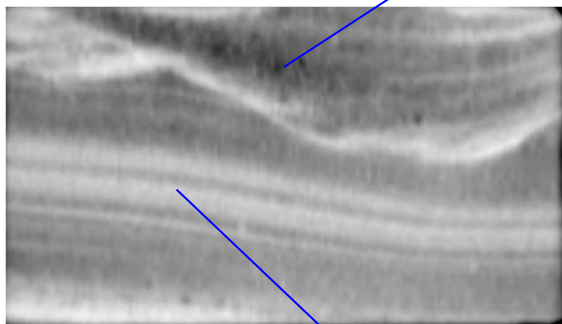
CO₂ 地中貯留メカニズムの模式図



医療用X-CTによる砂岩中のCO₂挙動の可視化



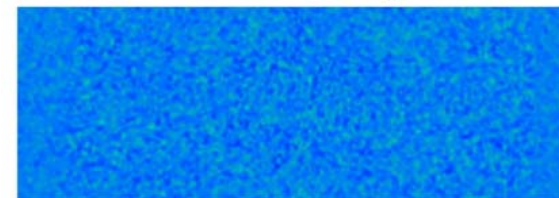
灰色-黒色域: 密度が低い(隙間が多い)



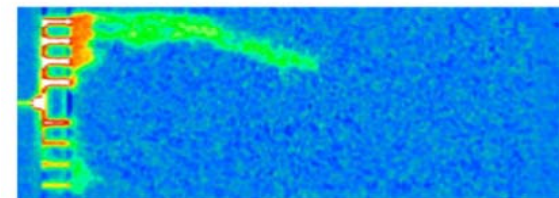
白色域: 密度が高い(隙間が少ない)



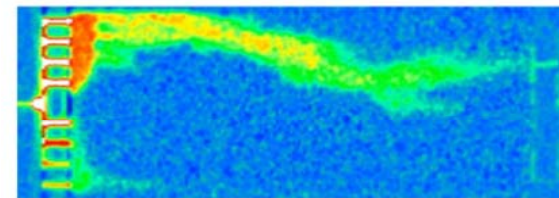
MB CO₂ Injection



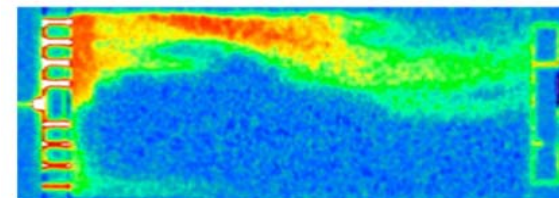
initial



0.03PV

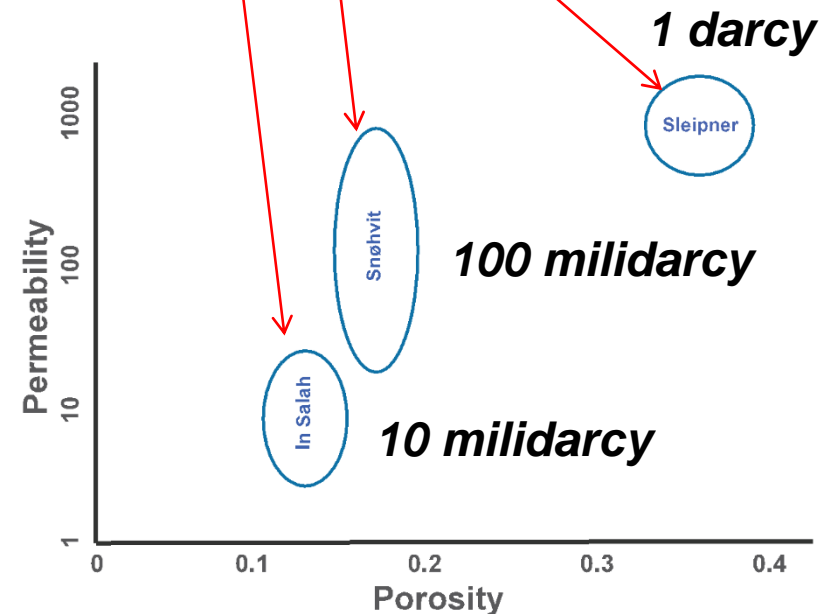
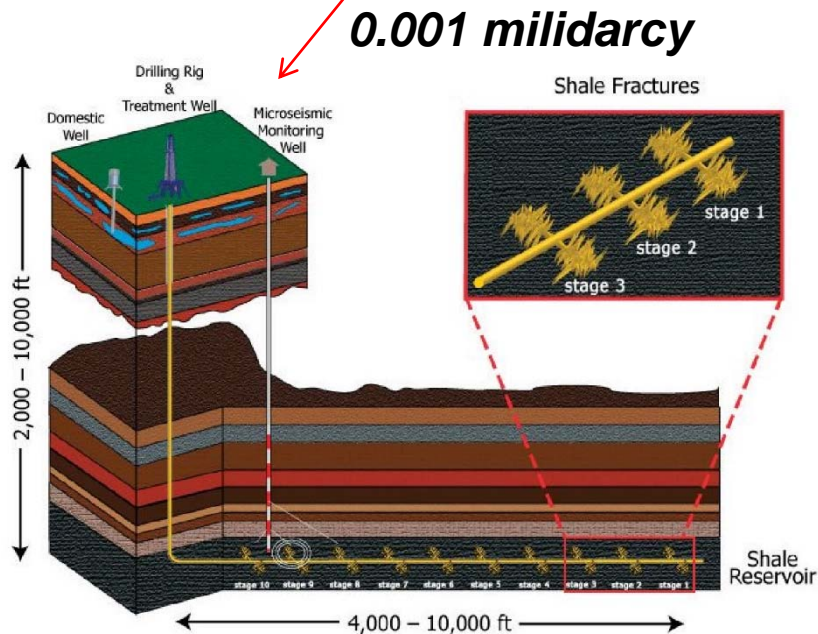
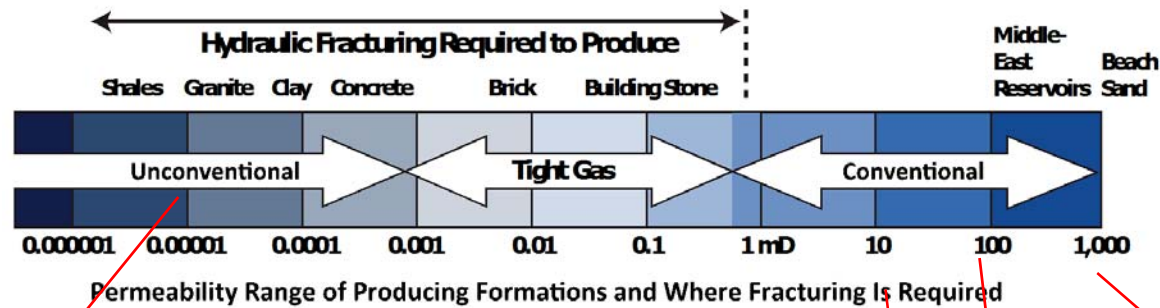


0.07PV
_BT



0.28PV

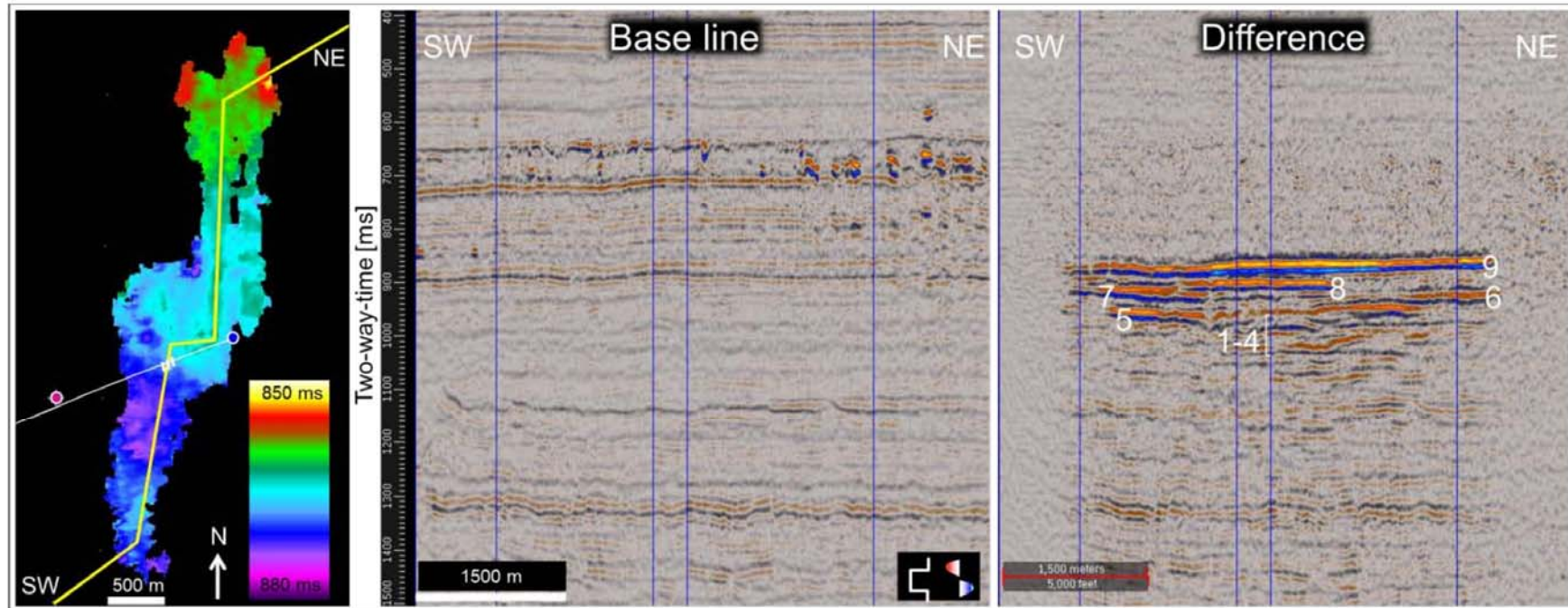
非在来型油ガス開発、CO₂地中貯留 における流体圧入地層の違い



CO₂ high buoyancy in high permeability and thick formation (1/2)

Low storage factor at Sleipner, North Sea

Furre et al., 2017

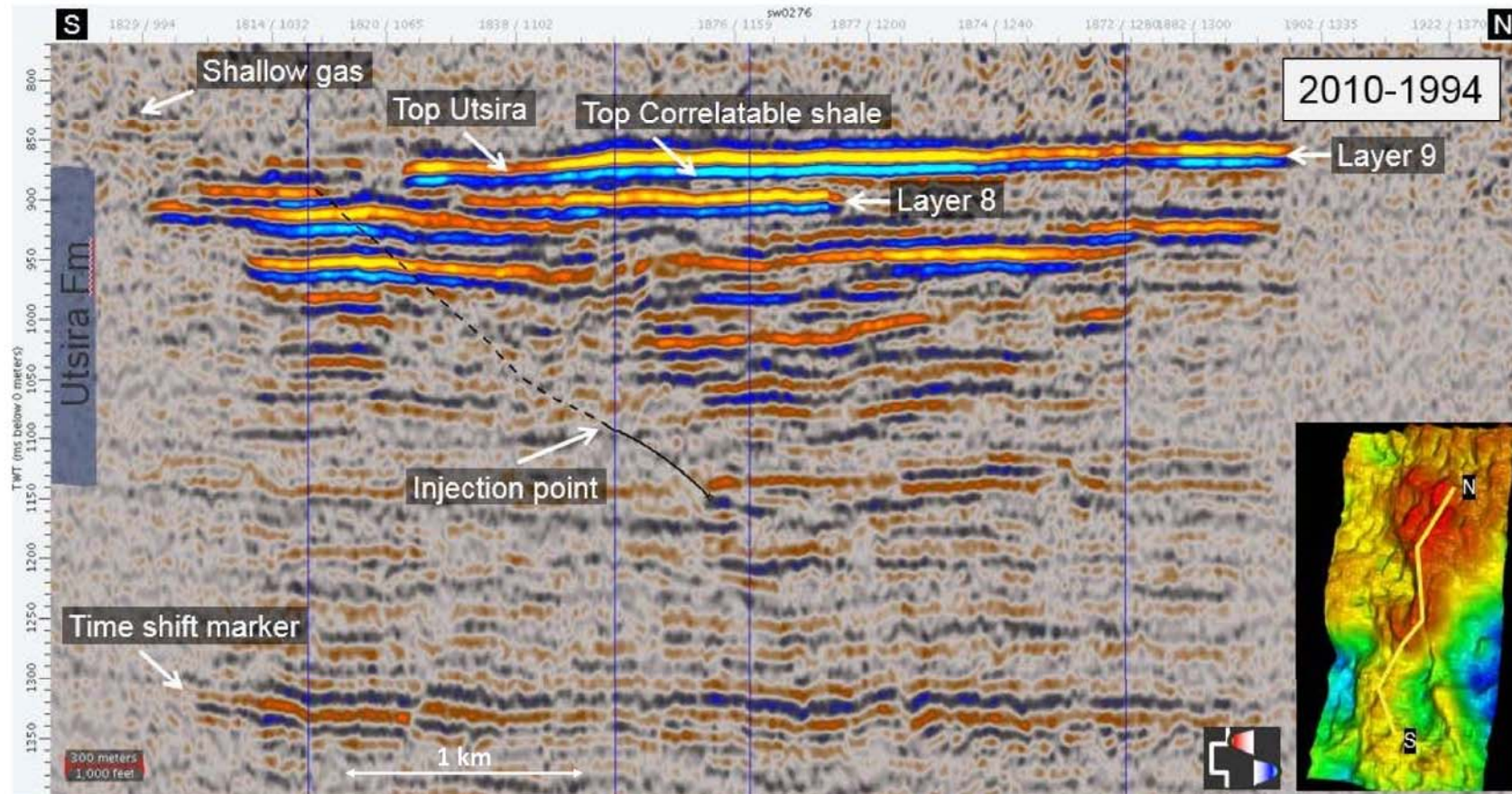


Map of the two-way time interpretation of the CO₂ plume in Utsira sand

(Utsira sand: a giant sand body with high permeability and large thickness)

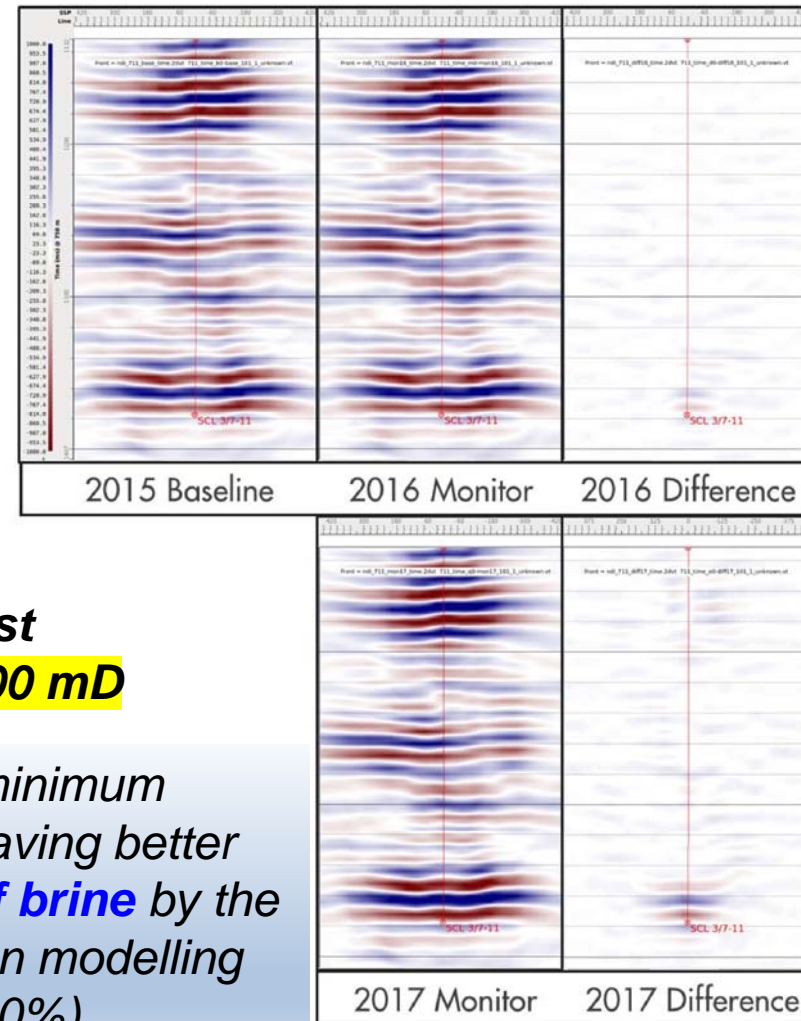
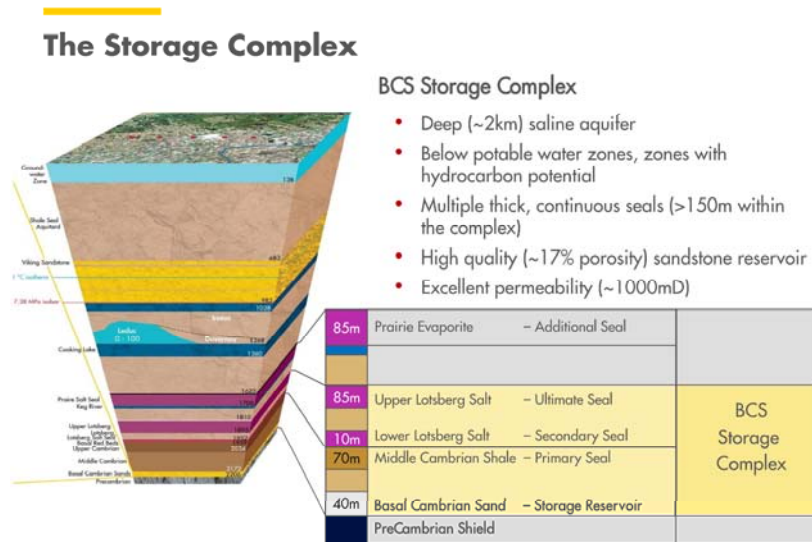
In the early years the CO₂ signatures in the shallower layers (6-9) were spatially small, and in more recent data, imaging is better for layers 5-9, whereas layers 1-4 are challenging to interpret.

CO₂ high buoyancy in **high** permeability and **thick** formation (2/2)
at the Sleipner site



the high storage factor at Quest (high CO₂ saturation)

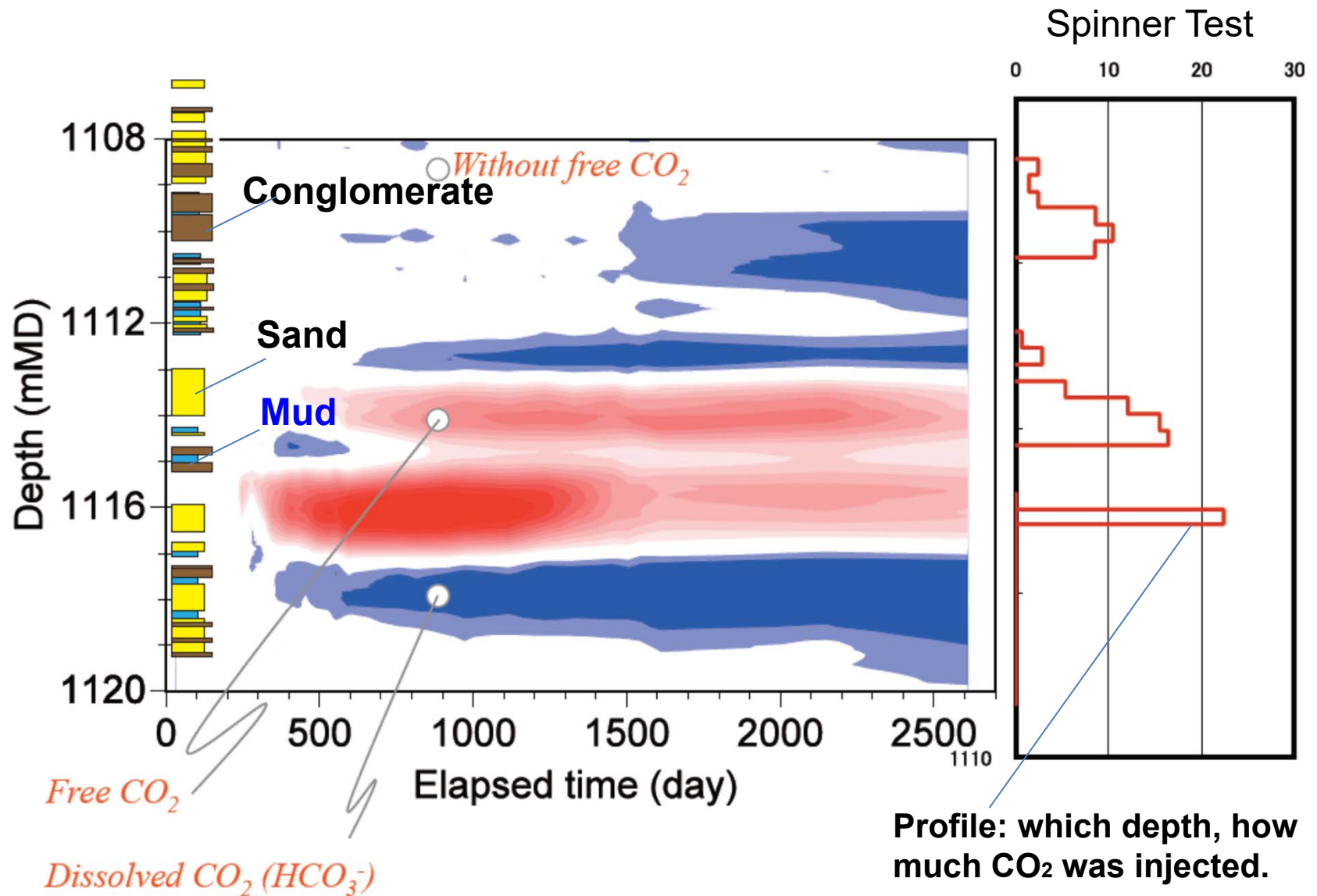
1 Mt/year, started in 2015



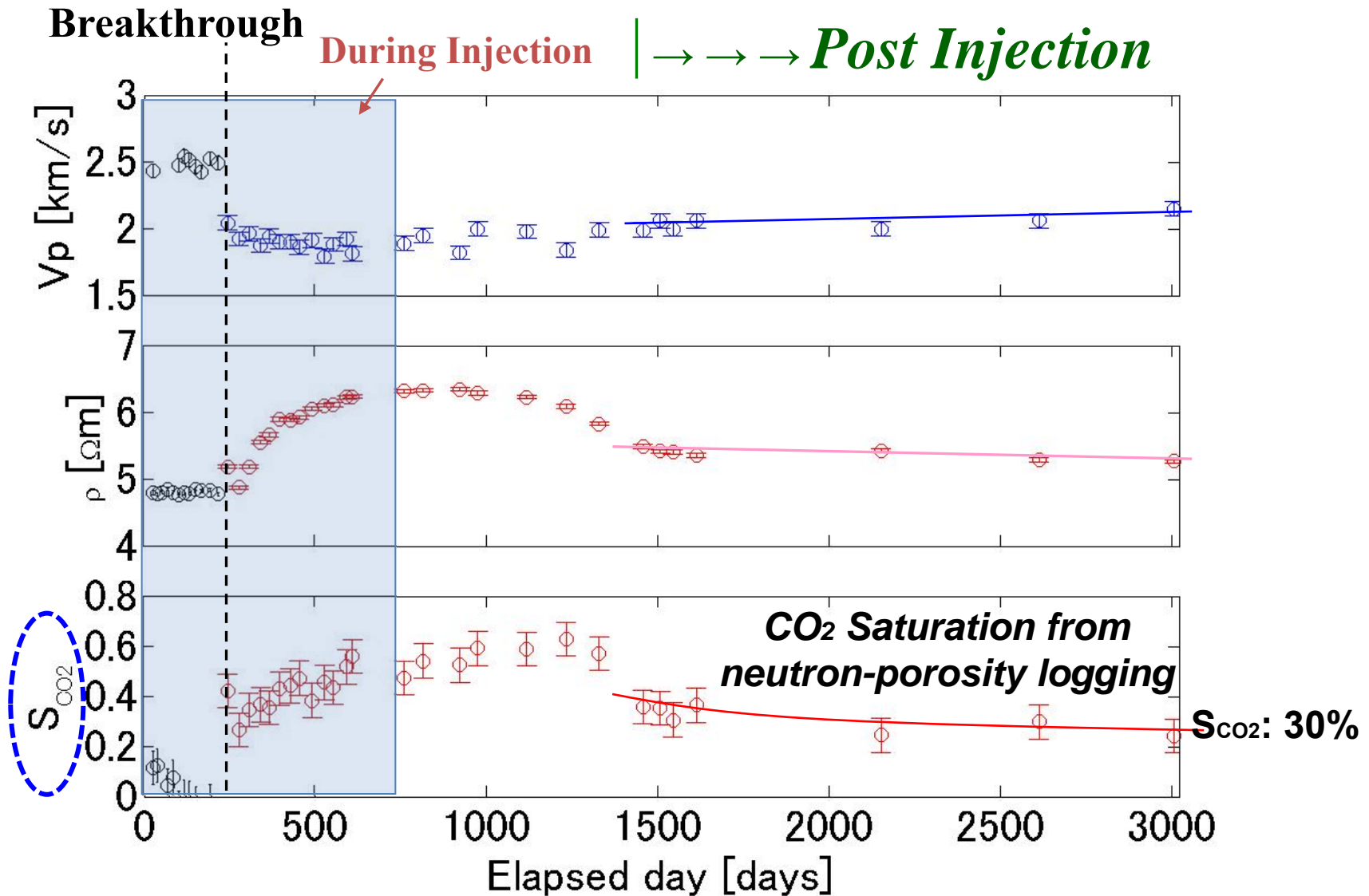
Sandstone reservoir property Quest
thickness: 40m; permeability: ~ 1,000 mD

the plume extent is closer to the theoretical minimum is another indication that the reservoir is behaving better than expected, and that the **displacement of brine** by the CO₂ may be **more effective** than pre-injection modelling predicted. (CO₂ saturation assumed up to 100%)

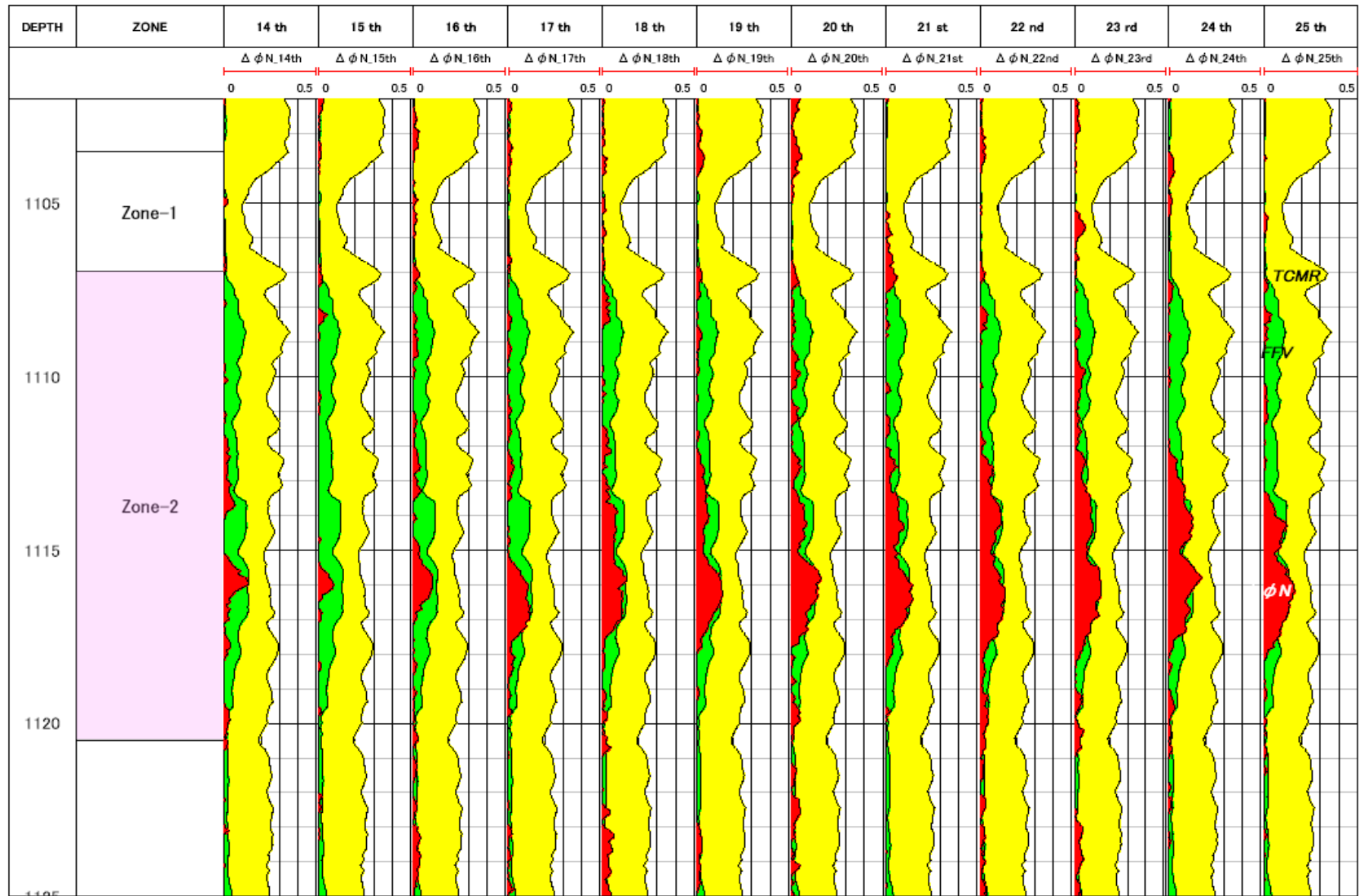
CO₂ Distribution @Nagaoka, Japan



Time-lapse Changes at (1116.0m @OB-2)



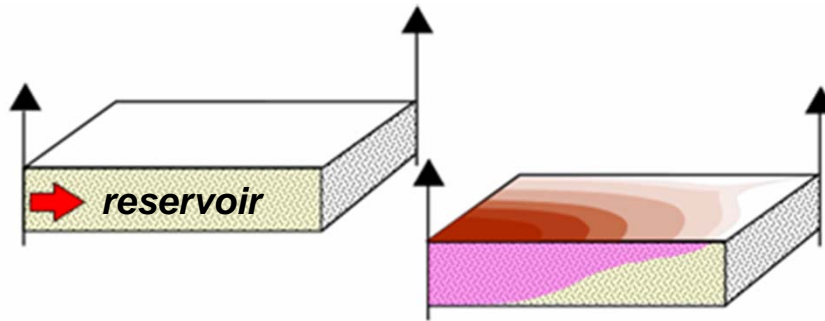
中性子孔隙率(CO₂含有率)変化図 (OB-2)



Estimating Volumetric Storage Capacity

Sf: Storage efficiency

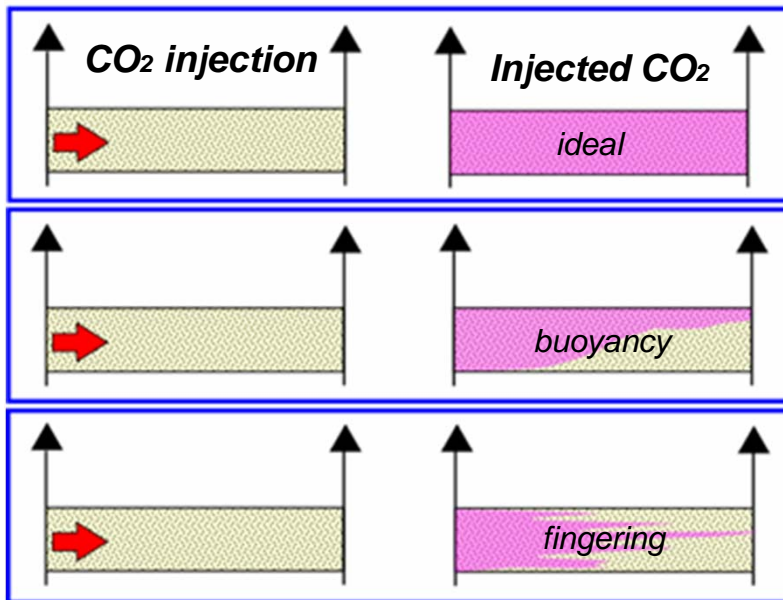
(RITE, 2006; Ogawa et al., 2011)



To calculate the CO₂ storage capacity of a deep saline aquifer, the following equation may be used:

$$\text{CO}_2 \text{ storage capacity (mass)} = \frac{S_f \times A \times h \times \phi \times S_g \times \rho}{B_g \text{CO}_2}$$

where A , h and ϕ are aquifer area, effective aquifer thickness and porosity respectively, so that the product $(A \times h \times \phi)$ represents the total pore volume within the aquifer volume under consideration. S_g is the supercritical CO₂ gas-phase volume fraction in the injected CO₂ plume. ρ is CO₂ density at standard conditions (=1.976 kg/m³), and $B_g \text{CO}_2$ is the CO₂ volume factor, which depends on local pressure and aquifer temperature. Therefore, the term $(\rho/B_g \text{CO}_2)$ represents the in situ density of pure CO₂ at the local pressure and temperature. S_f represents a “storage factor”, the ratio of immiscible CO₂ plume volume to total pore volume, which incorporates the combined effects of trap heterogeneity, CO₂ buoyancy and displacement efficiency and so on. In the calculation, the entire aquifer below a depth of 800 m is considered.



S_f : a “storage factor”, the ratio of immiscible CO₂ plume volume to total pore volume, the combined effects of trap heterogeneity, CO₂ buoyancy and displacement efficiency.

Storage Factors in Different Regions

Comparisons of storage efficiency factors.

0.25 0.5

(Ogawa et al., 2011)

	Efficiency*	Comments*
Australia	19 %	Geodisc, Bradshaw et al., 2004
Japan	12.5 %	$S_f \times S_g \simeq E (DOE) \text{ or } Cc (CSLF)$
Alberta	$\simeq 9 \%$	Bachu & Adams, 2003 (Dissolution)
USA	1 — 4 %	DOE Atlas, 2008 (Monte Carlo Simulation)
Norway offshore	$\simeq 4.4 \%$	Joule II, 1996

*Note: After Thibeau and Mucha (2007).

Storage potential

$$= A \times h \times S_f \times \phi \times S_g / BgCO_2 \times \rho$$

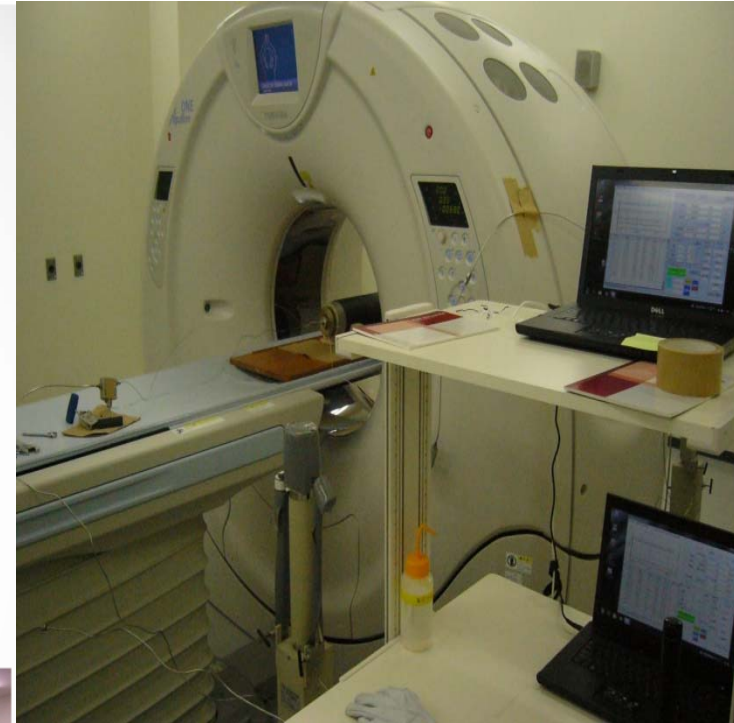
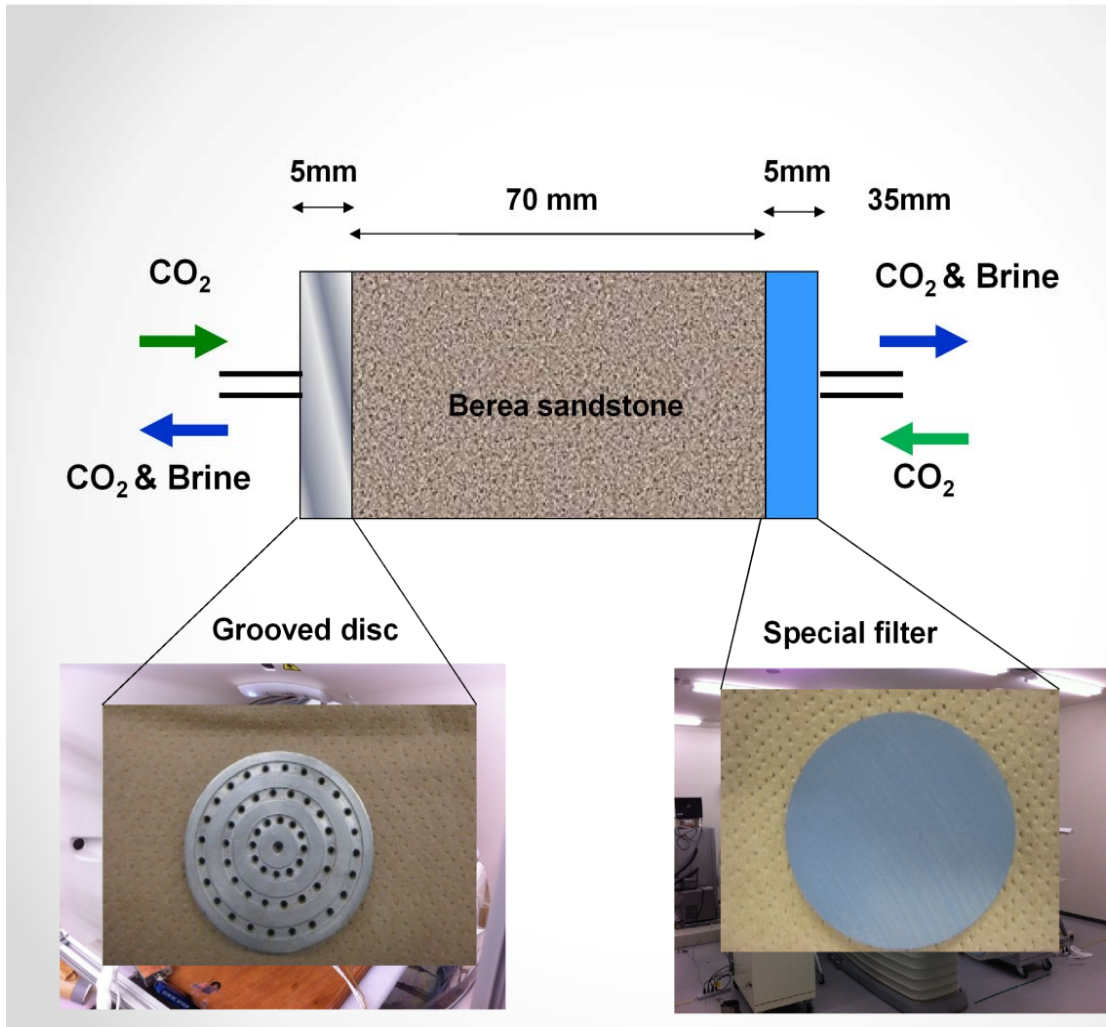
- A : aquifer area
- h : effective thickness
- S_f : storage efficiency factor
- φ : porosity
- S_g : CO₂ saturation
- BgCO₂ : CO₂ volume factor 0.003m³/m³, depth: 2000m, 70°C
- ρ : CO₂ density 0.001976 (t/m³)

➤ 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

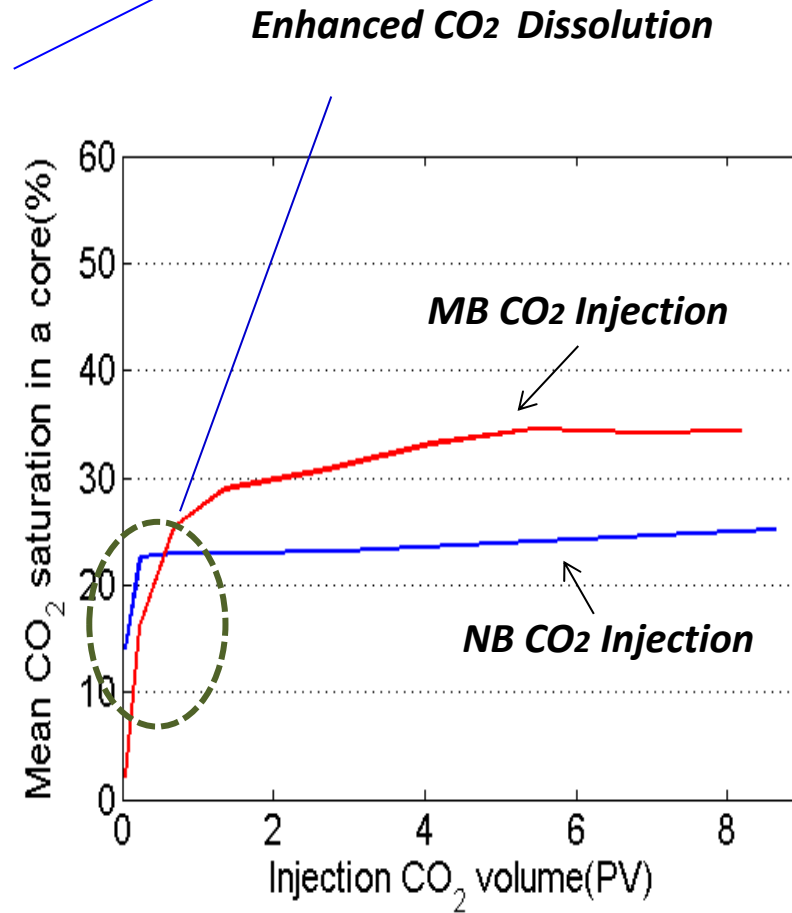
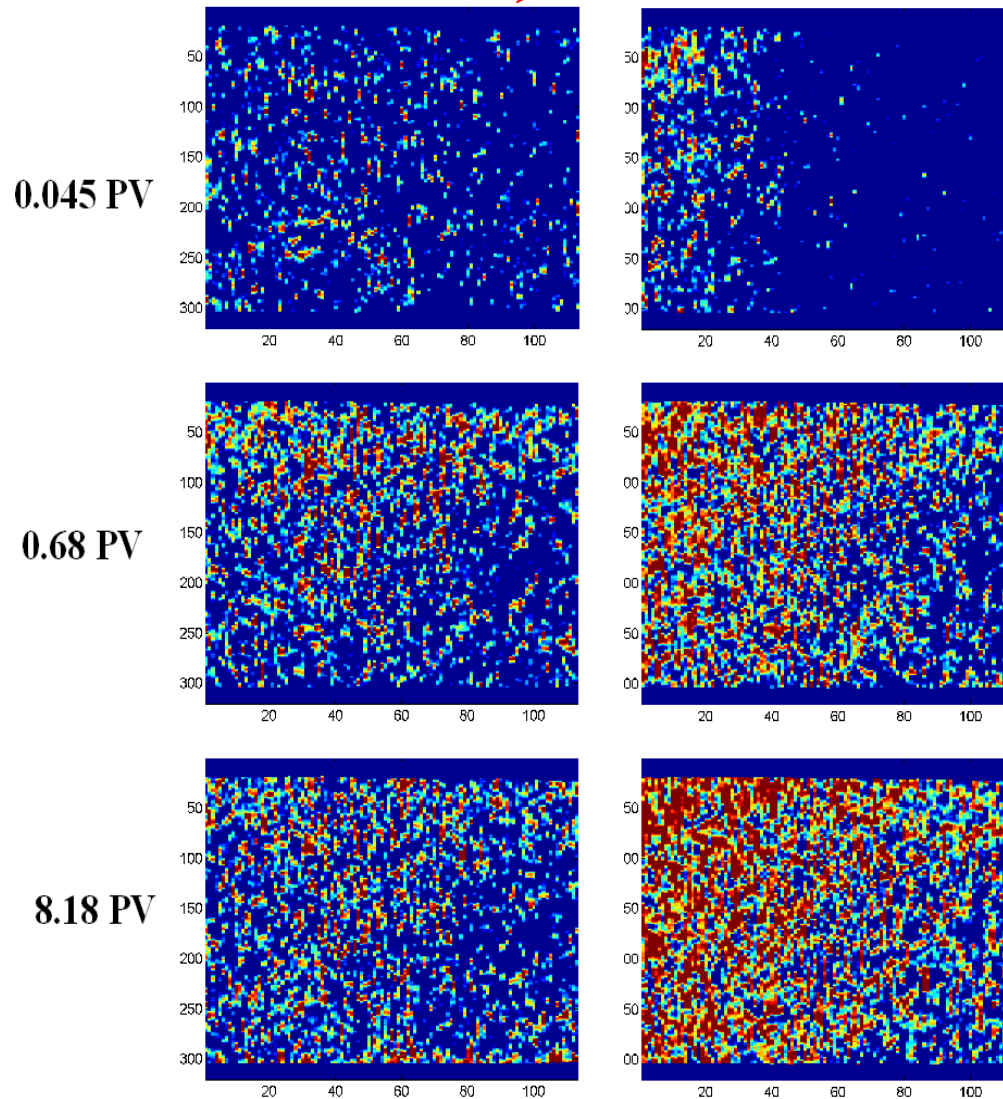
* minor modelling and laboratory investigations may be required prior to commercial scale application

Sample arrangement for X-CT imaging

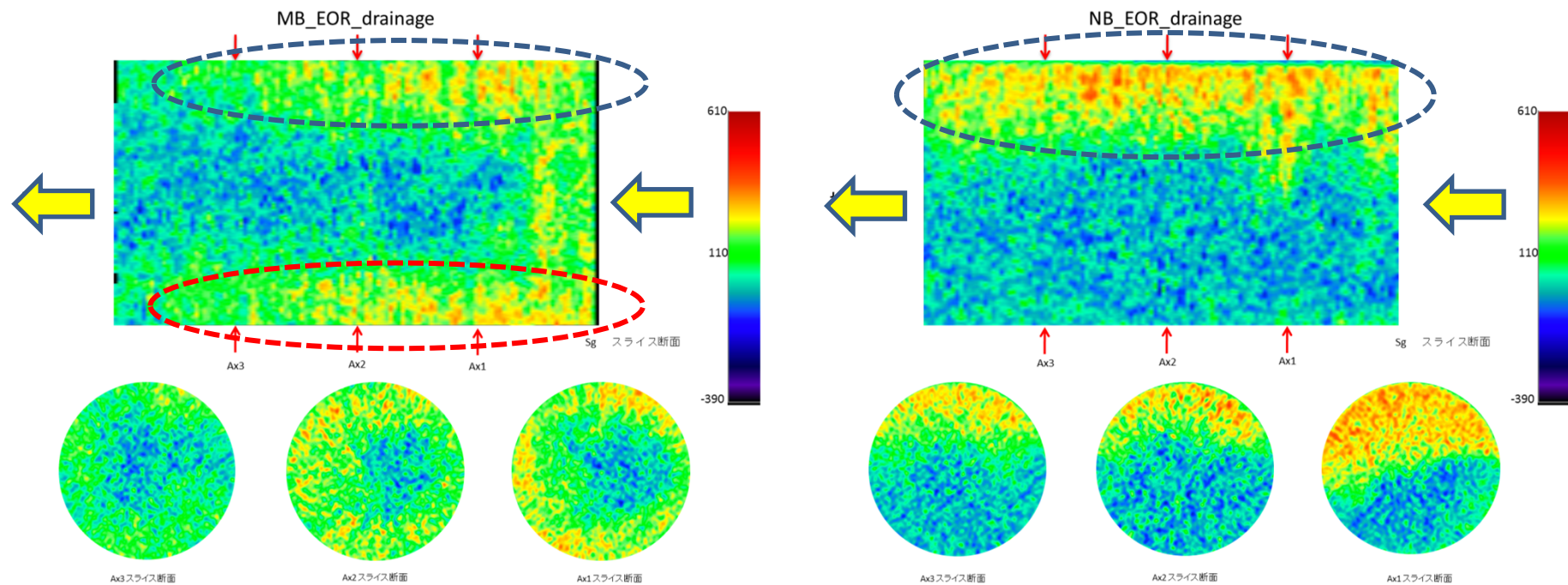


Confining pressure: 12MPa
Pore pressure: 10MPa
Temperature: 40°C

CO₂ distribution (left: grooved disc; right: special filter)

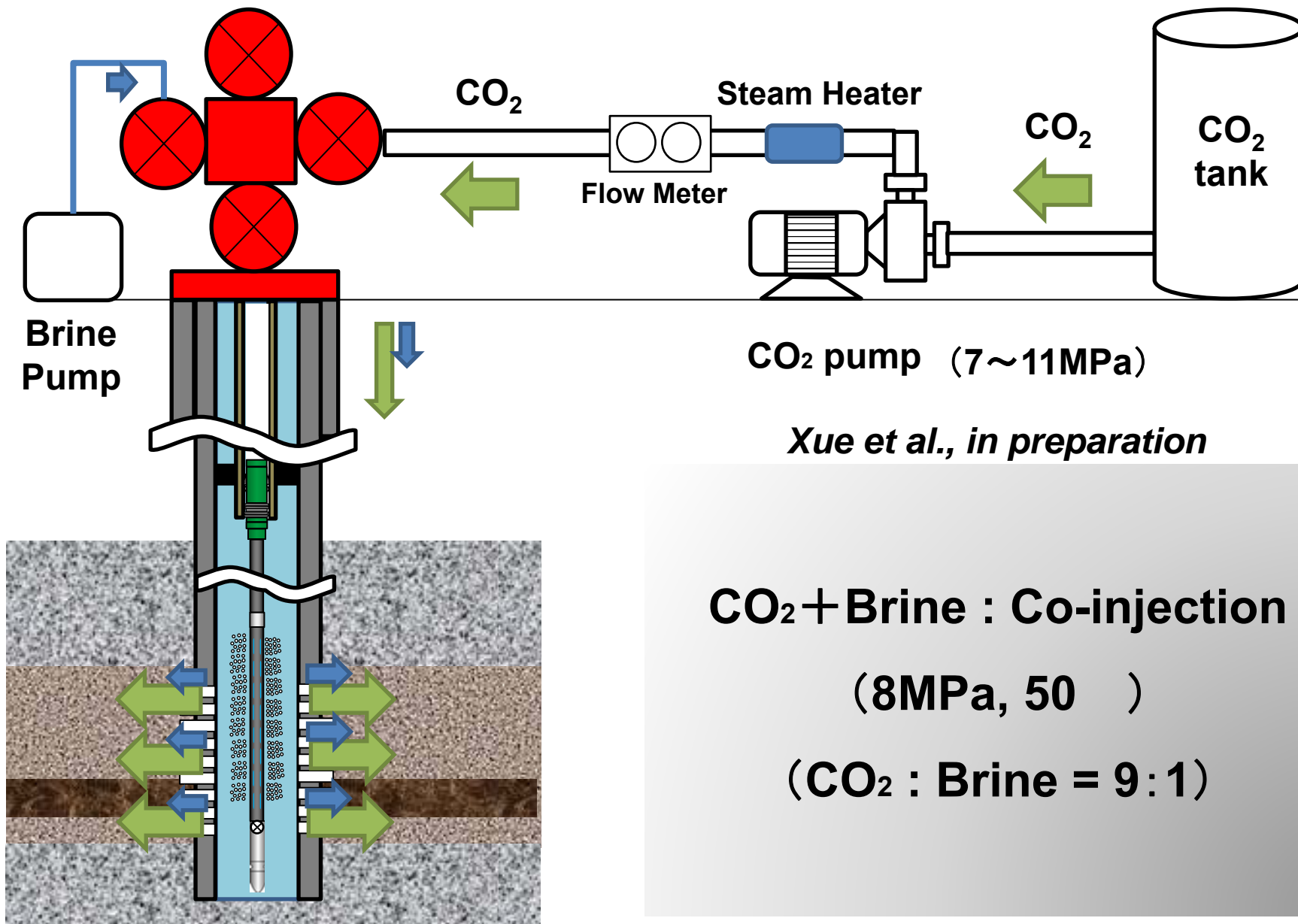


Gravity Override of the Injected CO₂ In high permeability reservoir

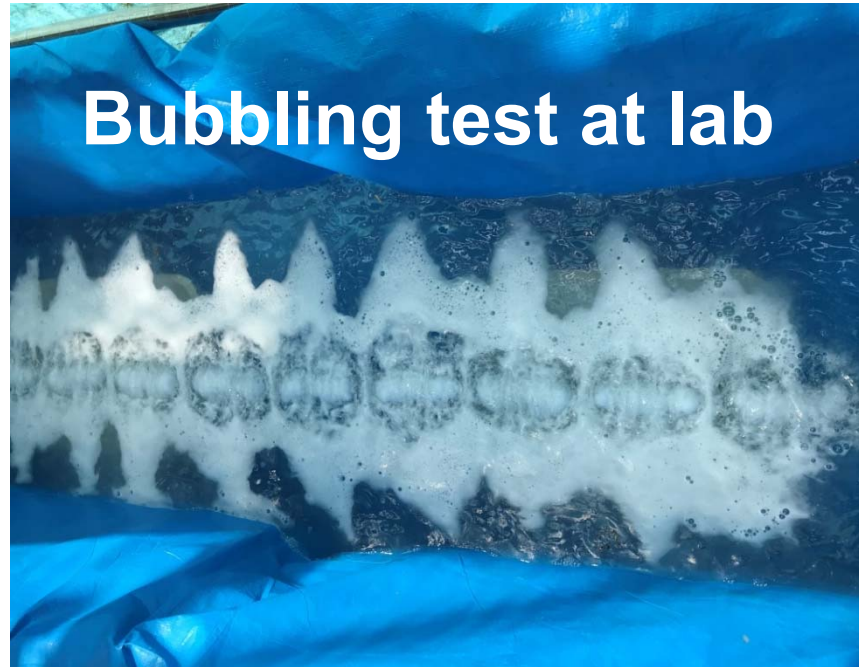


Left: マイクロバブル圧入; Right: 従来法によるCO₂圧入

(Xue et al., 2014)



上田ほか、2020; Xue et al., 2021)



Bubbling test at lab

**Downhole Tool for
Microbubble CO₂ Generation**

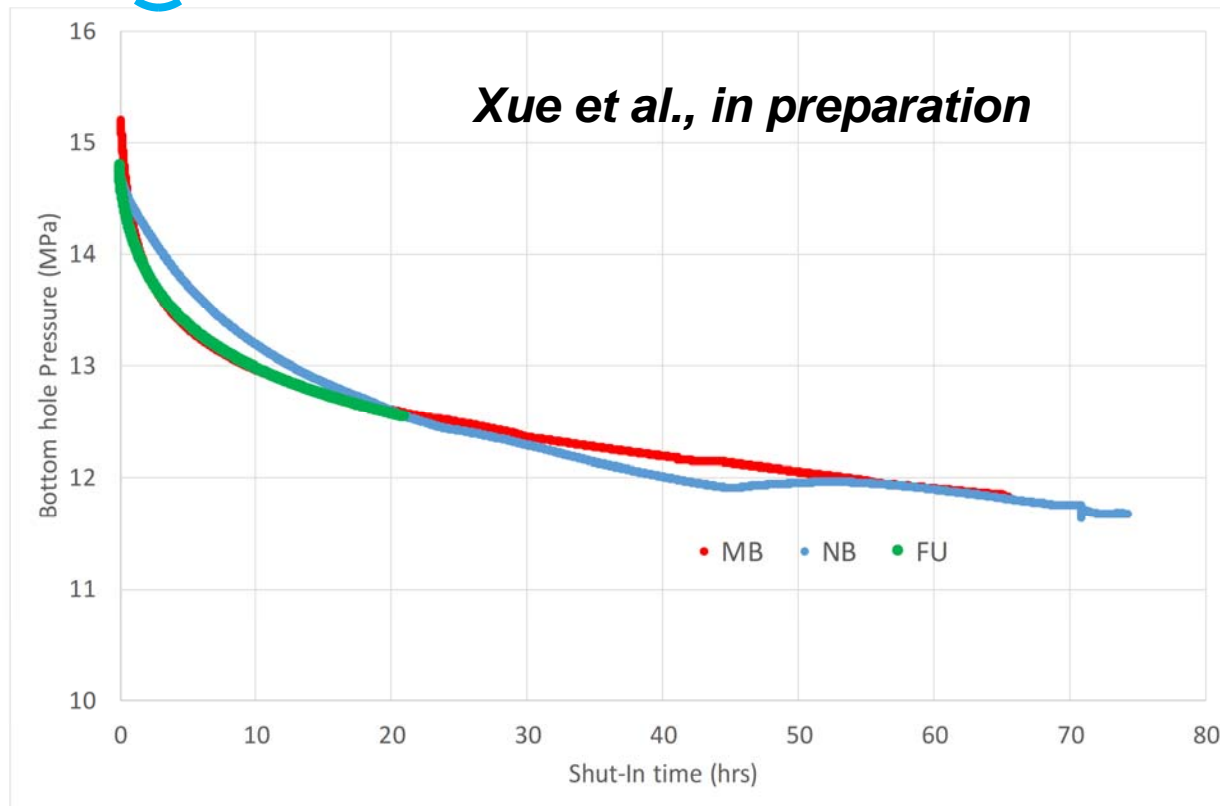


Xue et al., in preparation



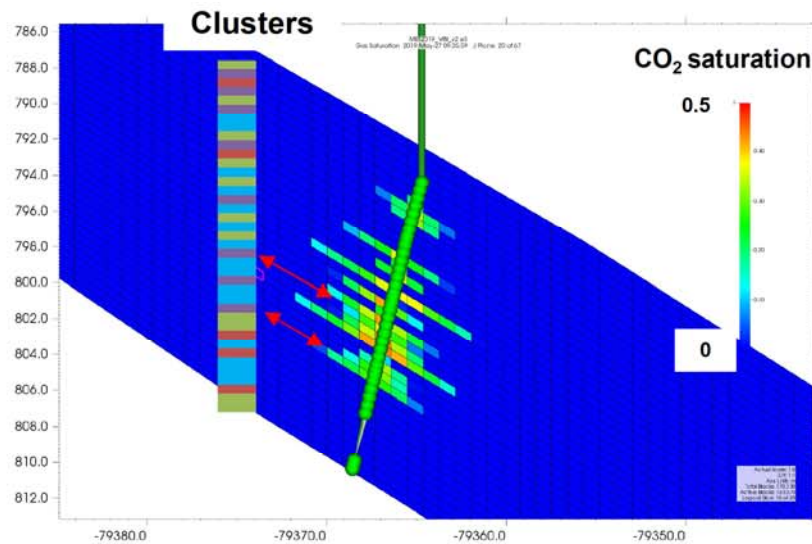
Table 1 Results of the injection and production tests

	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		

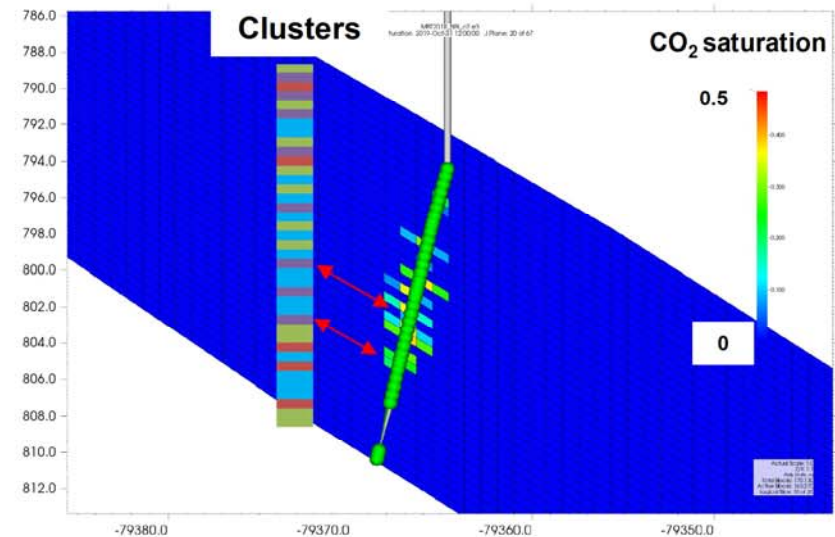


Preliminary Results from CO₂ Injection Simulations (with / without microbubble filter)

Microbubble CO₂ injection



Conventional CO₂ injection

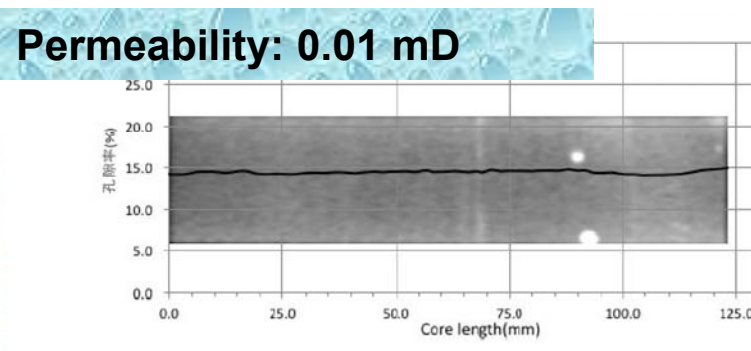
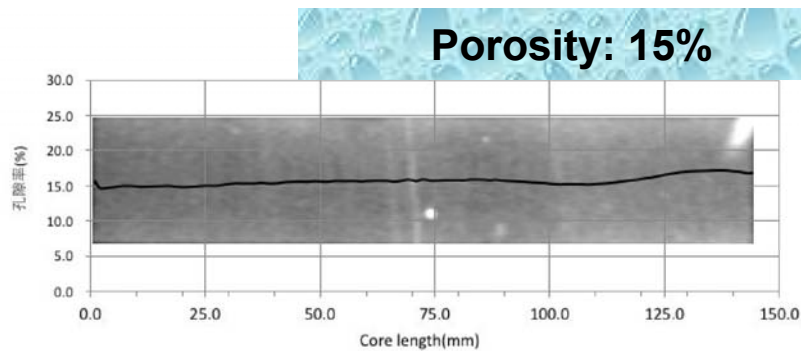
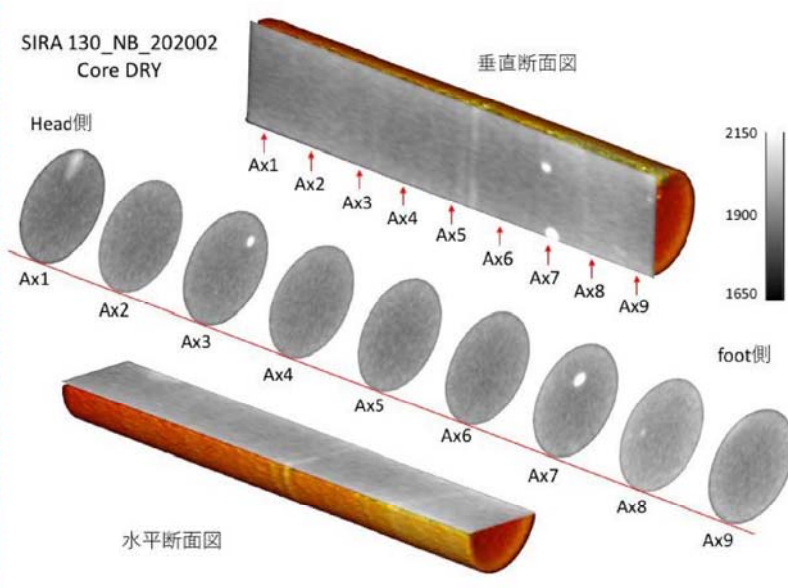
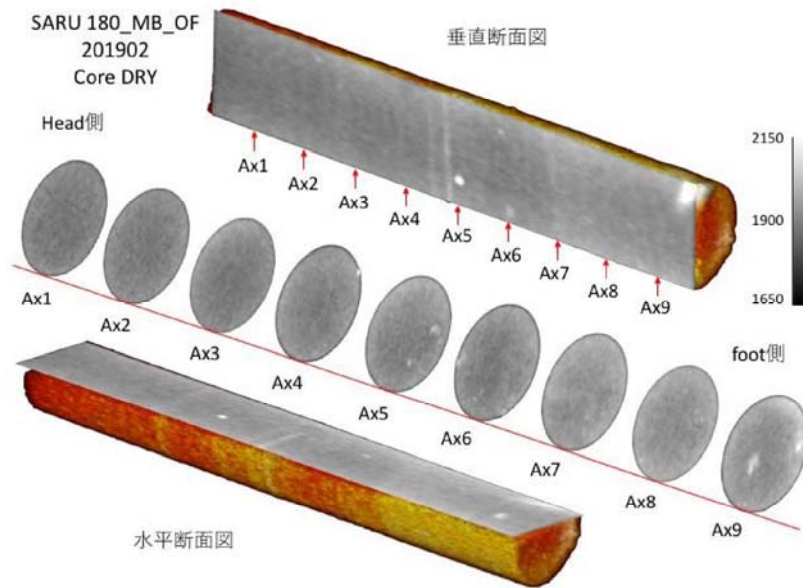


Cluster 1 Cluster 2 Cluster 3 Cluster 4 上田ほか (2020)

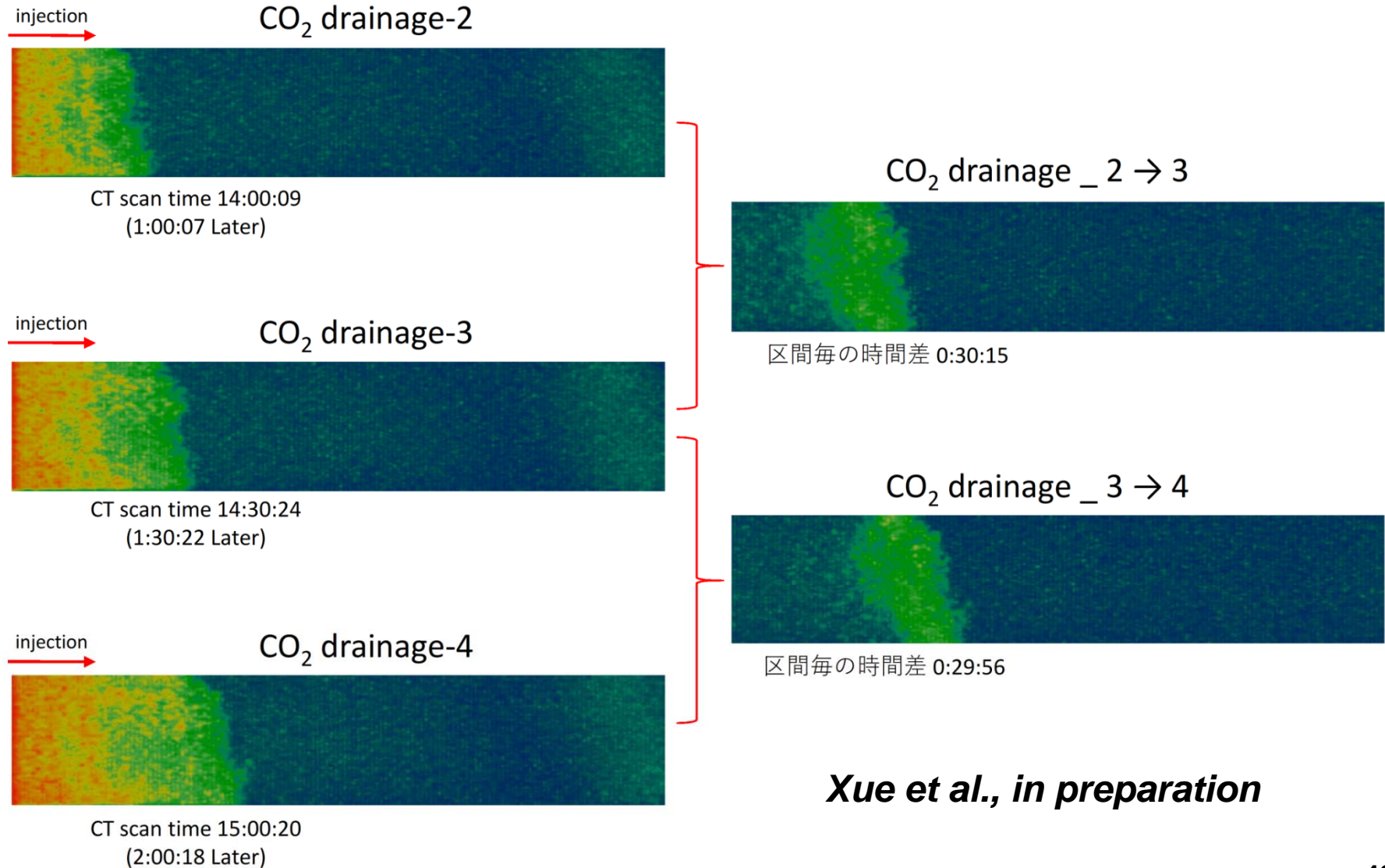
low ← porosity → high

Xue et al., in preparation for Int. J. Greenhouse Gas Control

Microbubble and Normal bubble CO₂ injections in a Japanese **tight sandstone**

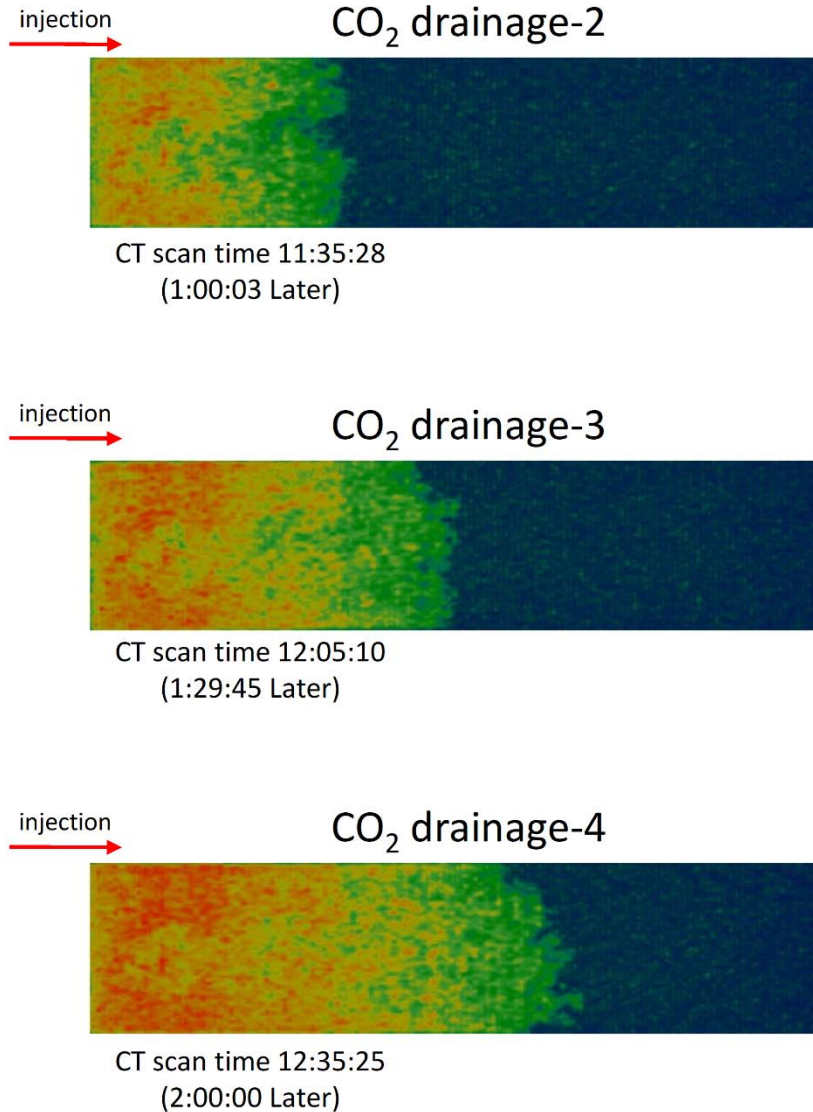


Visualization of **Microbubble** CO₂ Injection with X-CT



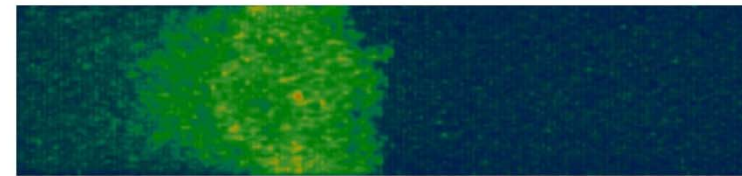
Xue et al., in preparation

Visualization of **Normal bubble** CO₂ Injection with X-CT



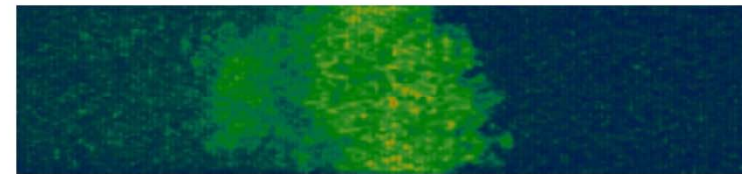
Xue et al., in preparation

CO₂ drainage _ 2 → 3



区間毎の時間差 0:29:42

CO₂ drainage _ 3 → 4



区間毎の時間差 0:30:15

Injecting MB CO₂: Control CO₂ Mobility, Reduce risks of early breakthrough

➤ *Challenges when injecting CO₂ into complex reservoirs*

- **Reservoir Geology and Heterogeneity**

*complex reservoirs with **multi-layer** (alternation of sandstone and mudstone, **strong heterogeneity**), **low permeability** (less than one millidarcy)*

*Injecting MB CO₂: **Penetrate** and **Flood** low permeability zones, Improve **Sweep Efficiency***

Permanently Storing CO₂ in the Subsurface

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

*CO₂ Trapping Mechanisms: **long term** security
(how long is enough long?)*

CCS技術事例集の作成



長岡実証試験 + 海外事例に基づき、Vol.1を完成 →→→ 逐次公開、英訳も



苫小牧大規模実証試験や海外の新規事例を加え、2020年度末までにVol.1を完成

謝 辞

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の委託業務の結果得られたものです。