「未来社会を支える温暖化対策技術
シンポジウム in 関西 2019」

CO_2地中貯留技術実用化に向けての安全管理技術開発の取り組み

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

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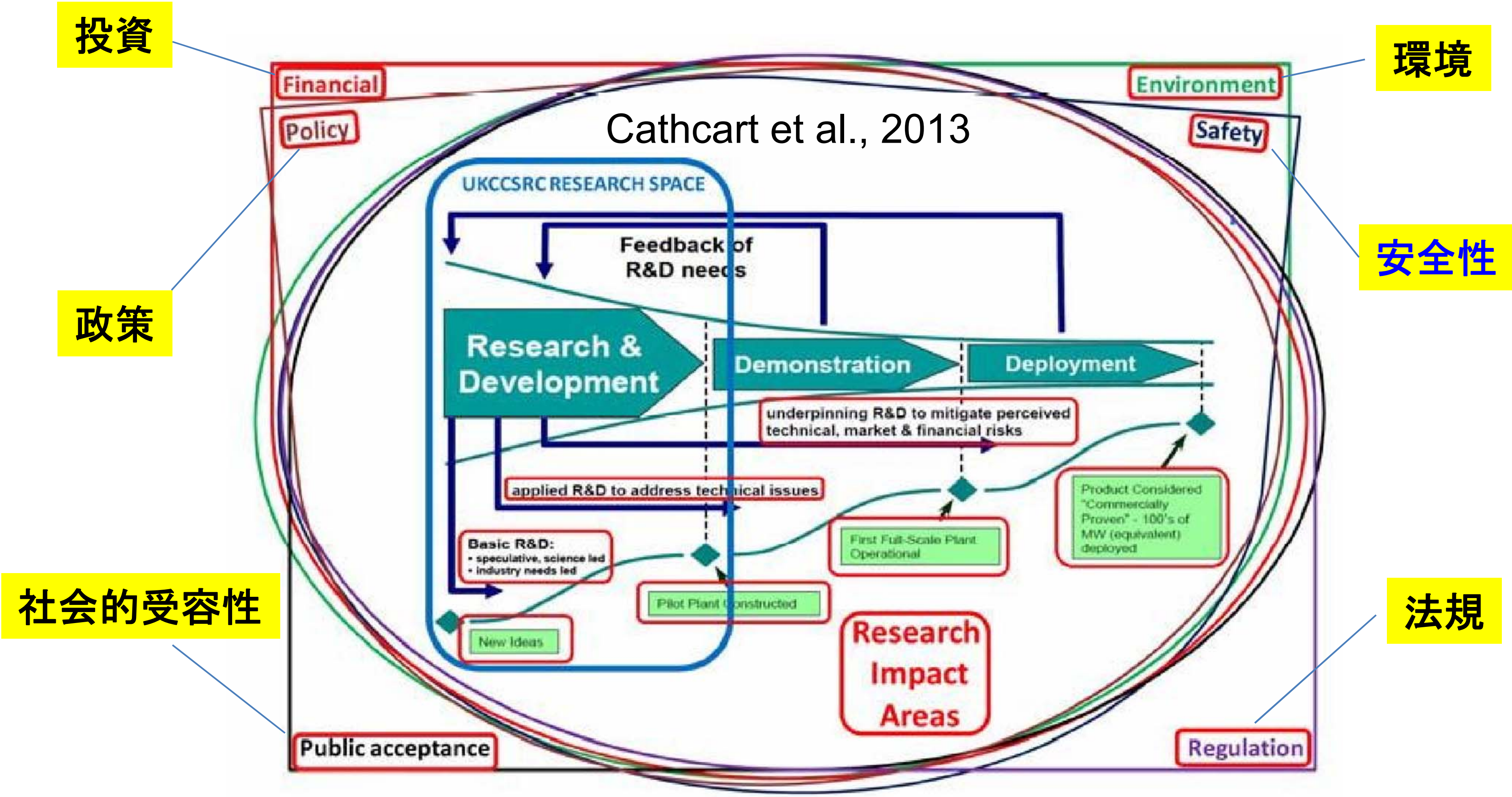
地中貯留技術の実用化・事業化へ



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）

➢大規模CO_2地中貯留の実用化に向けて

- ✓油ガス田開発技術・経験・ノウハウを活用しても、取り組むべき技術課題がある
- ✓ 安全性（リスクマネジメント）、経済性（コスト削減）、社会的受容性の向上

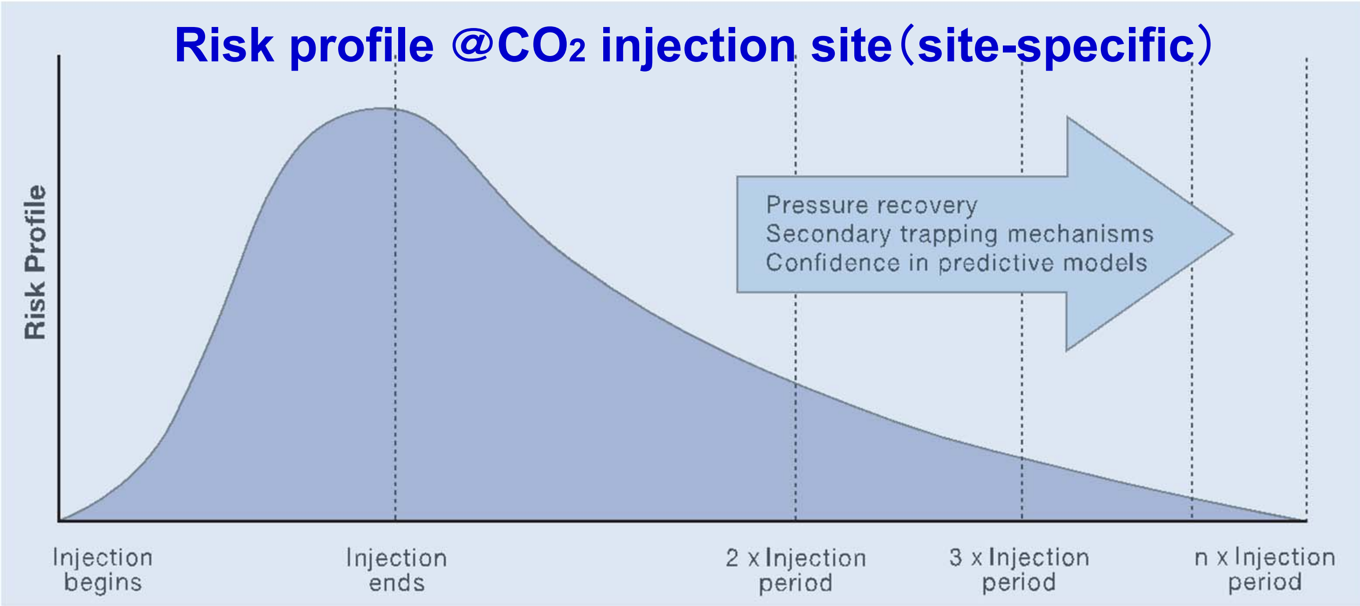
社会実装

A Social Licence for Carbon Dioxide Capture and Storage: How Engineers and Managers Describe Community Relations

Anne Maree Dowd & Mallory James

➢Safety/Risk Assessment in CO_2 Storage

・Potential Risks（不確実性による）



[Illustration source: Benson, 2007]

Losses of Injectivity, Capacity and Containment, Induced Seismicity, Environmental Impacts

地下への流体圧入

（地熱開発、水圧破砕、非在来型資源開発）

↓

地層の間隙水圧力（pore pressure）増加、

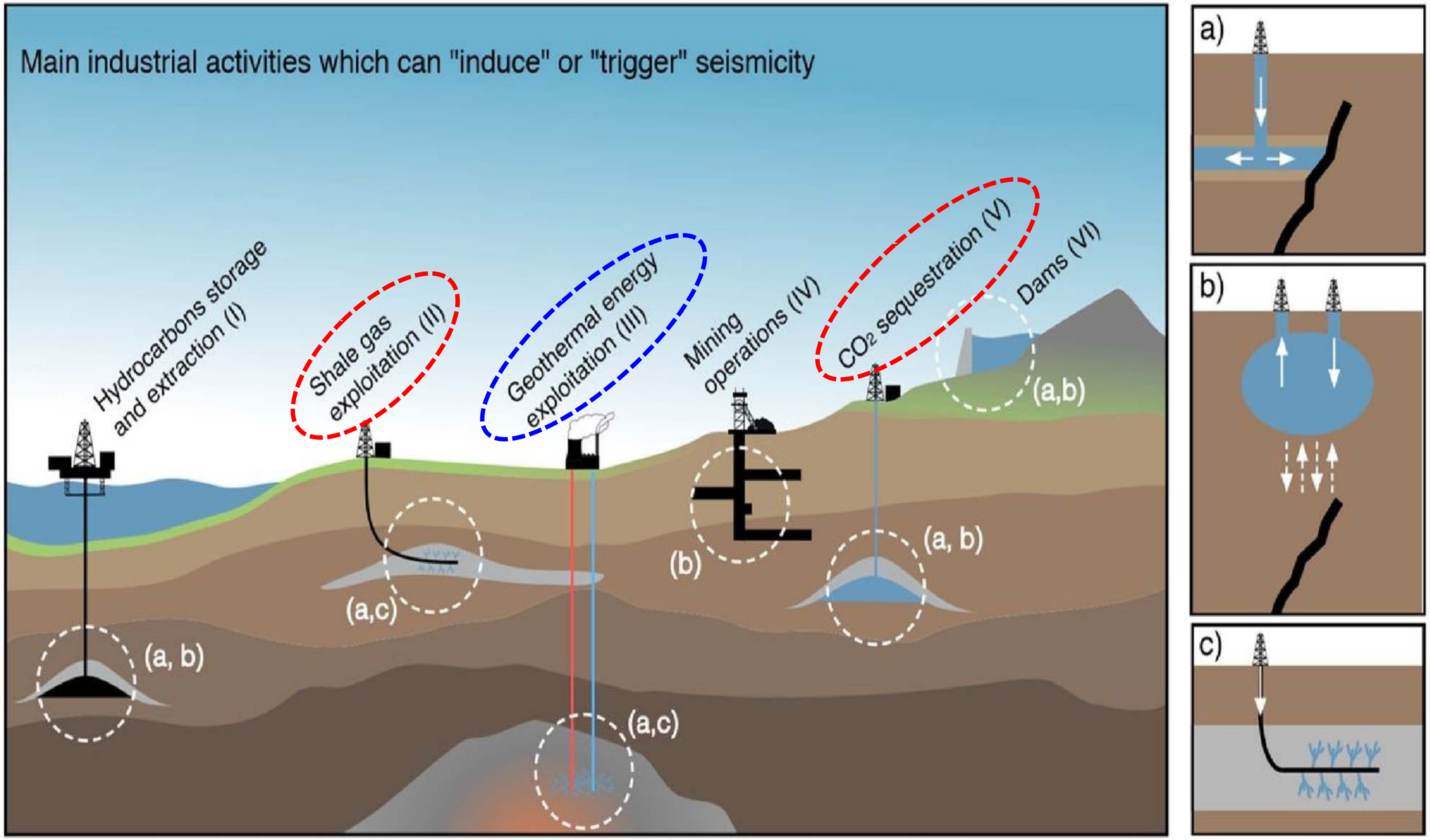
有効応力（effective stress）減少

↓

Injection-Induced Seismicity

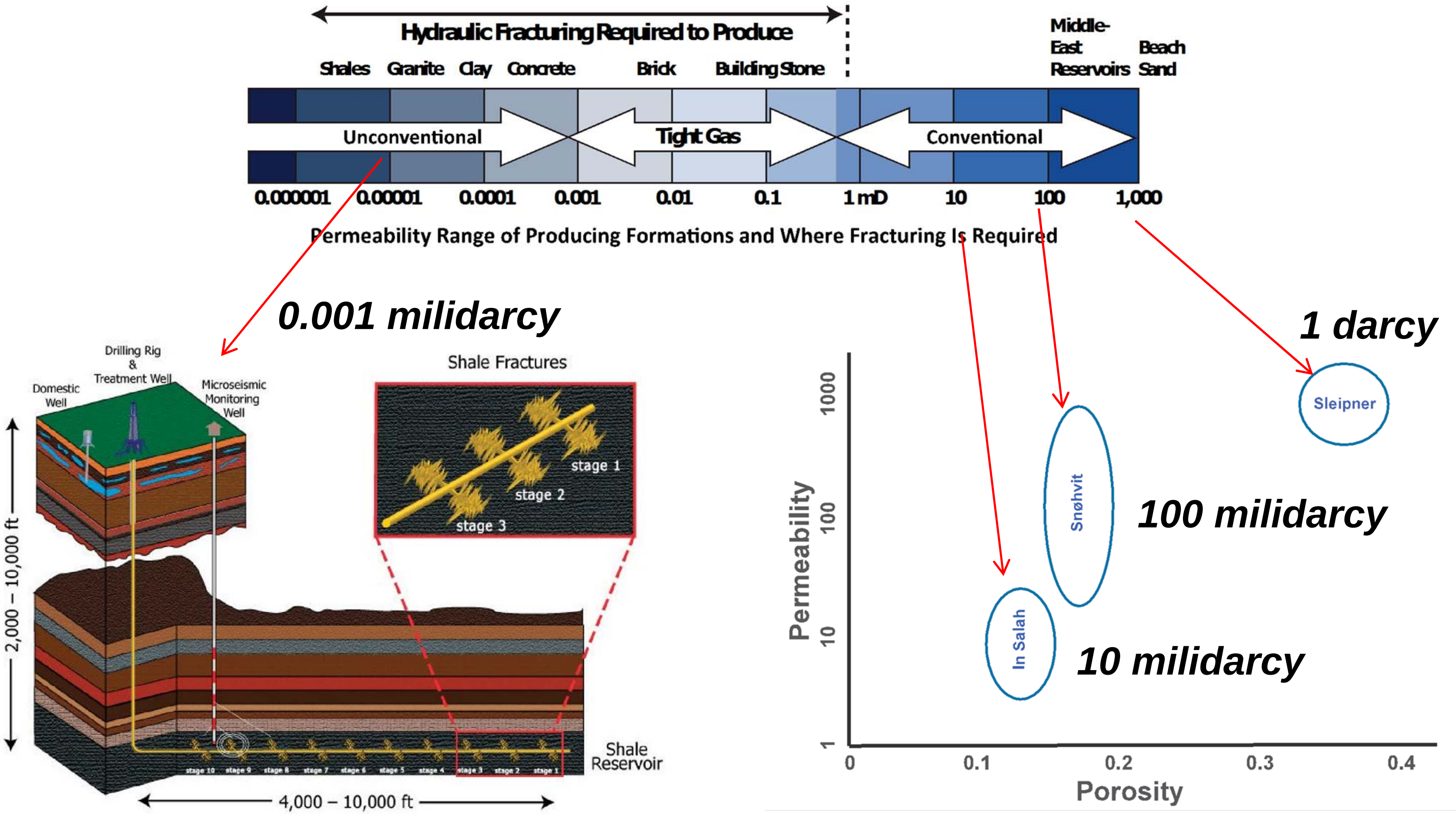
地下資源開発、CO_2地中貯留

人類の産業活動に係わる minor earthquakes and tremors



A variety of anthropogenic activities can trigger minor earthquakes and tremors.

地熱、非在来型油ガス、CO_2地中貯留における流体圧入

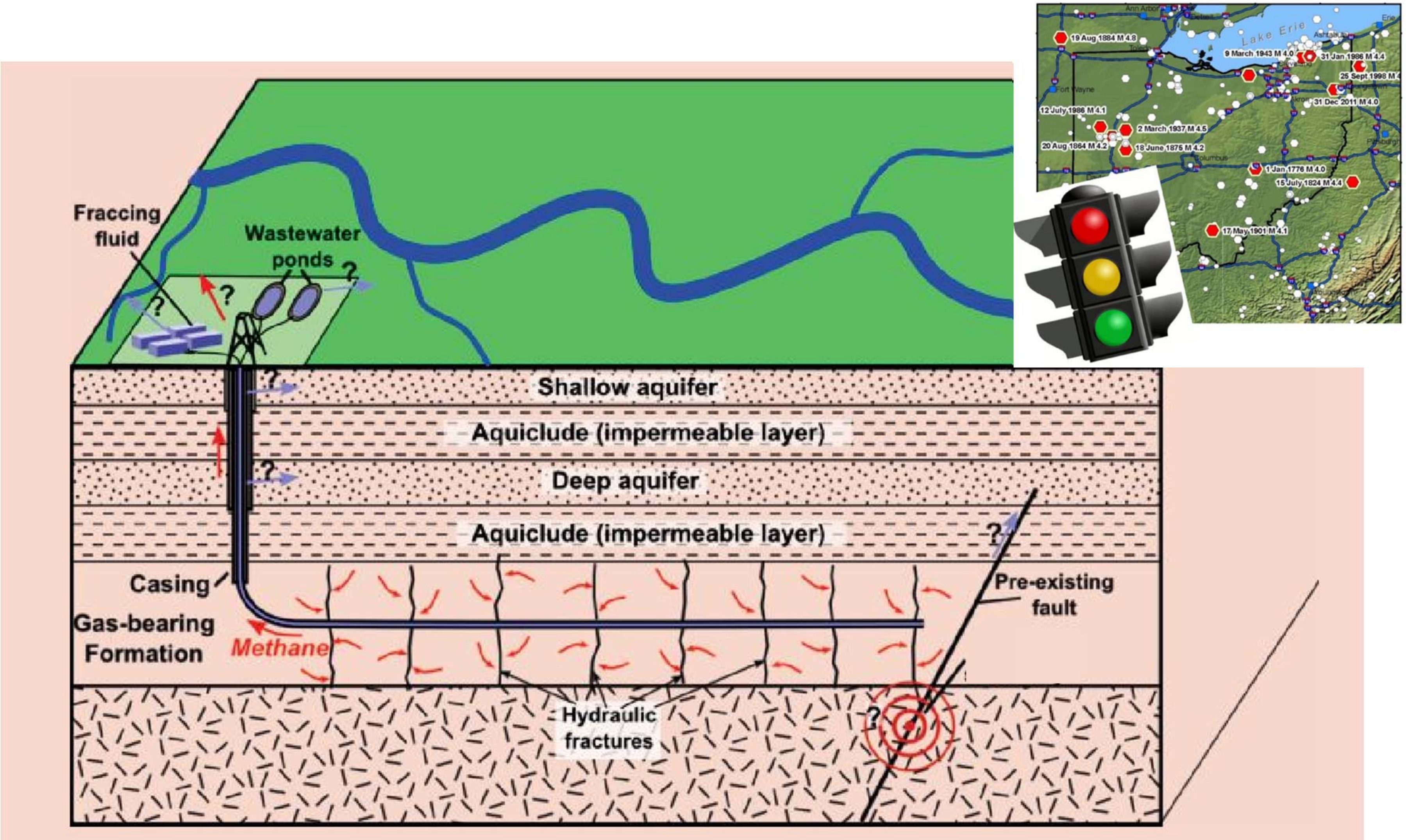


米国の非在来型油ガス田サイトの例

水圧破砕によって、低浸透性貯留層から油ガスを生産する

Shale gas drilling has a visual impact on the landscape, as seen here in Wyoming,

Induced and Triggered Events in Fluid Injection



Stage 1 began at 13:04:48 UTC on July 7th and ended at 15:01:09 UTC on July 7th.
Depths: ~ 3.53 km – 3.44 km (11547 ft. – 11295 ft.)
Stage 2 began at 23:32:18 UTC on July 7th and ended at 01:30:15 UTC on July 8th.
Depths: ~ 3.43 km – 3.35 km (11230 ft. – 11005 ft.)
Stage 3 began at 16:35:32 UTC on July 8th and ended at 18:34:56 UTC on July 8th.
Depths: ~ 3.34 km – 3.23 km (10971 ft. – 10826 ft.)
Stage 4 began at 22:16:20 UTC on July 8th and ended at 00:22:24 UTC on July 9th.
Depths: ~ 3.29 km – 3.22 km (10797 ft. – 10558 ft.)

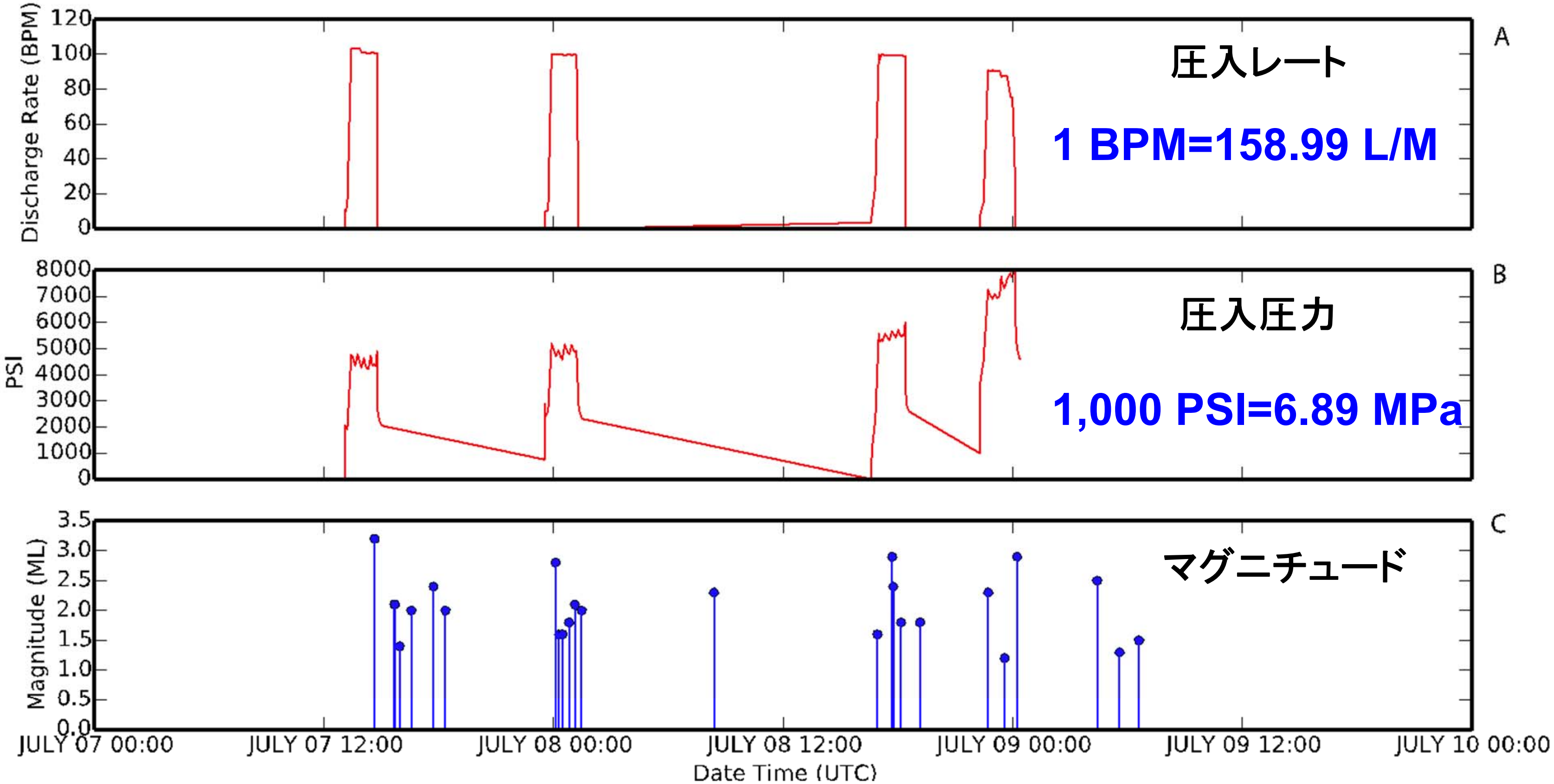
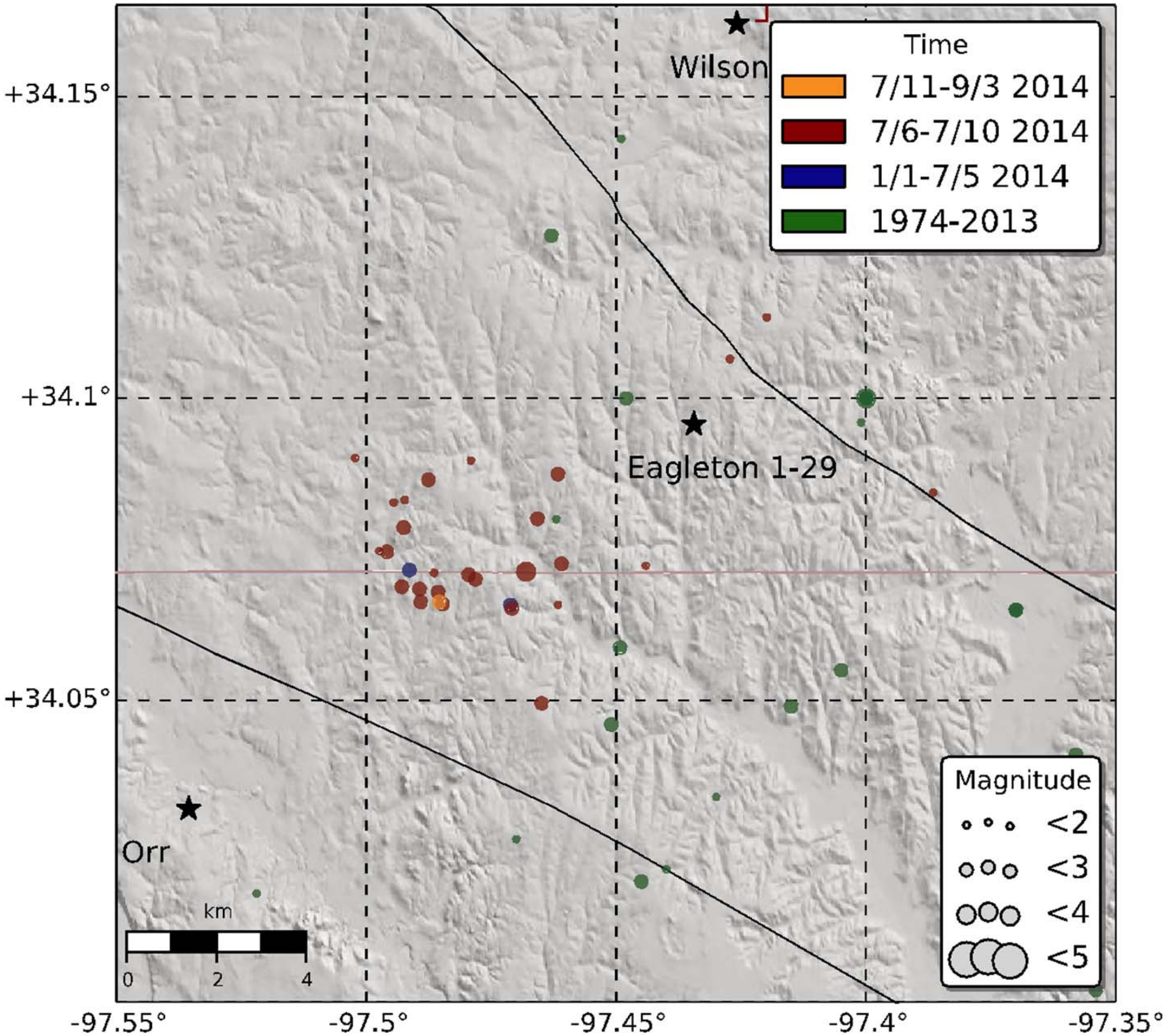


Figure 4. The plots span, in UTC time, the four fracking stages of Eagleton 1-29 well between July 7th 2014 and July 9th 2014. Plot A shows the discharge rate in BPM, or rate of injection, through time, plot B shows the pressure in PSI through time and plot C shows magnitude of earthquakes occurring within 7.0 km of the Eagleton well through time.

Microseismic Monitoring in Hydraulic Fracturing @Oklahoma



米国内のエネルギー開発分野における有感地震の報告

Energy Technology	Number of **Current** Projects	Number of **Historical** Felt Events	**Historical** Number of Events M≥4.0	Locations of Events M≥2.0
Geothermal				
Vapor-dominated (The Geysers)	1	300-400 per year since 2005	1 to 3	CA
Liquid-dominated	23	10-40 per year	Possibly one	CA
EGS	~8 pilot	2-10 per year	0	CA
Oil and gas				
Withdrawal	~6,000 fields	20 sites	5	CA, IL, NB, OK, TX
Secondary recovery (water flooding)	~108,000 wells today	18 sites	3	AL, CA, CO, MS, OK, TX
EOR	~13,000 wells today	None known	None known	None known
Hydraulic fracturing for shale gas recovery	~35,000 wells today	1 sites	0	OK
Waste water disposal wells (Class II)	~30,000 wells today	8 sites	7	AR, CO, OH,TX
Carbon capture and storage (small scale)	2	None known	None known	None known

National Academy of Sciences, 2013

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

Table 1
Summary of seismicity observations at recent CO_2 injection operations.

Project	Category	Monitoring design	Observations [a]	Seismicity Type[b]	References
Aneth USA	CO_2-EOR	Borehole Array M-1.2 to M0.8	Magnitudes: **M**-1.2 to **M**0.8 Frequency: 3800 events over 1 year. Two fault-like clusters.	II	Rutledge (2010), Zhou et al. (2010), Soma and Rutledge (2013)
Cogdell USA	CO_2-EOR	Regional Network M4.4, M3+	One **M**4.4 event and 18 magnitude 3+ events over a 6 year period. No major seismicity at nearby, similar operations.	I	Gan and Frohlich (2013), Davis and Pennington (1989)
Weyburn Canada	CO_2-EOR	Borehole Array M-3 to M-1	Magnitudes: **M**-3 to **M**-1. Frequency: 100 events over 7 years. Diffuse locations.	II	Whittaker et al. (2011), White et al. (2011), Verdon et al. (2010, 2011)
Decatur USA	Dedicated Storage	Borehole Arrays Surface Stations M-2 to M1	Magnitudes: **M**-2 to **M**1 Frequency: 10,123 events over 1.8 years. Multiple fault-like clusters.	I	Will et al. (2014), Couëslan et al. (2014), Kaven et al. (2014, 2015)
In Salah Algeria	Dedicated Storage	M-1 to M1	Magnitudes: **M**-1 to **M**1. Frequency: 5500 events over 2 years. Indications of fracture stimulation.	I & II	Oye et al. (2013), Goertz-Allmann et al. (2014), White et al. (2014b), Verdon et al. (2015)

[a] **M** = moment magnitude.

[b] Type I = seismicity concentrated within overpressured zone. Type II = seismicity outside overpressured zone.

圧力増加域内、あるいは域外　→→　イベントの位置評定（location）が重要！

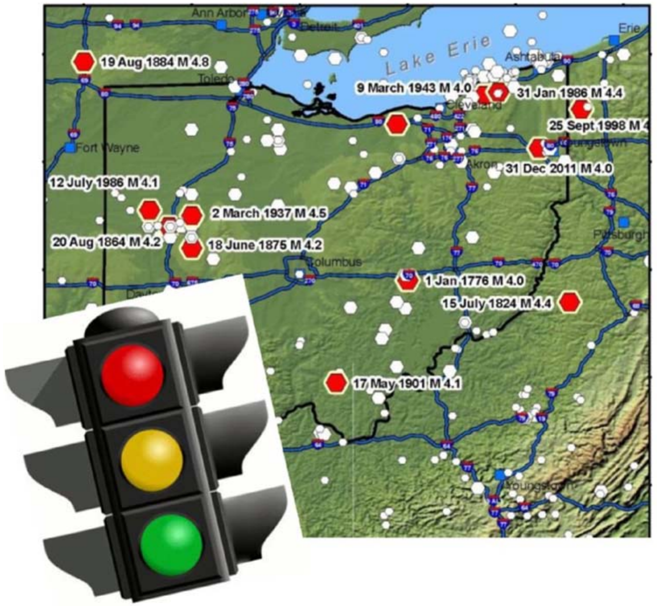
Earthquake and Micro-Earthquake Comparison

Magnitude	Equivalent TNT Radiated Energy	Energy Comparison
+3	480 kilograms	Large potash mine earthquake
+2	15 kilograms	Small potash mine earthquake
+1	480 grams	10 ton trucks collide
0	15 grams	Jump off a tall building
-1	0.5 gram	30-30 rifle bullet
-2	15 miligram	Drop a large dictionary
-3	0.5 miligram	Break a small stick

（微小地震：Micro-seismicity; 微小振動: Tremors?）

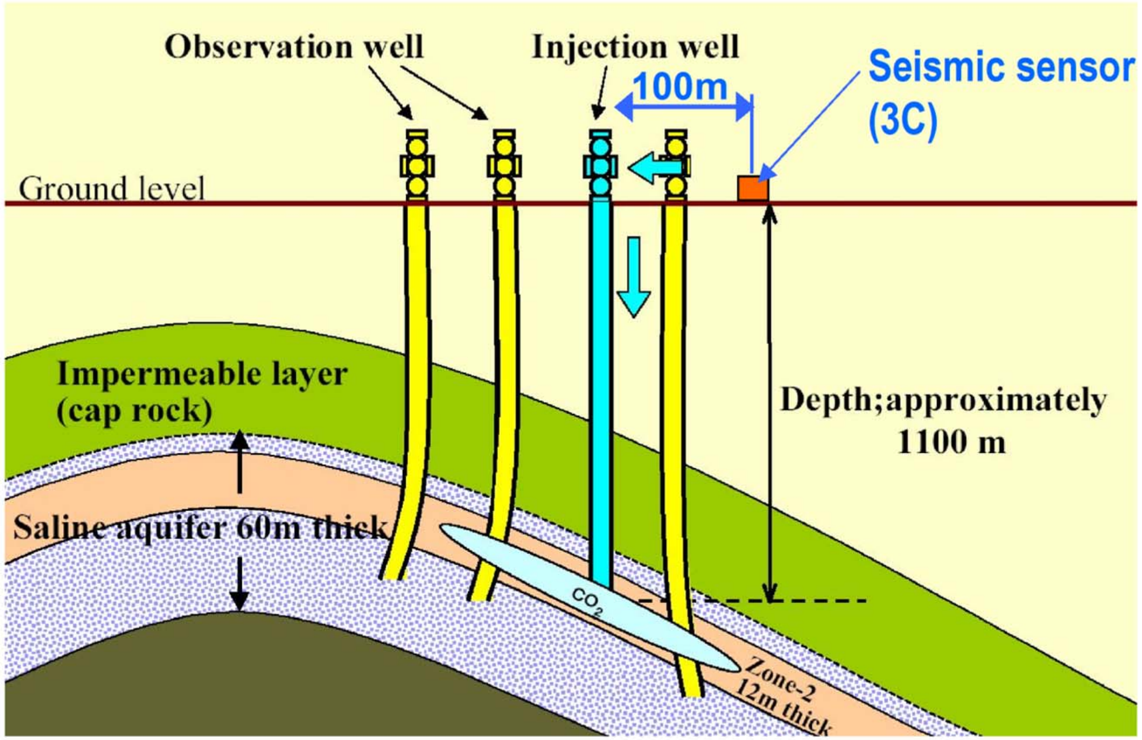
CO_2圧入サイトの安全管理技術開発

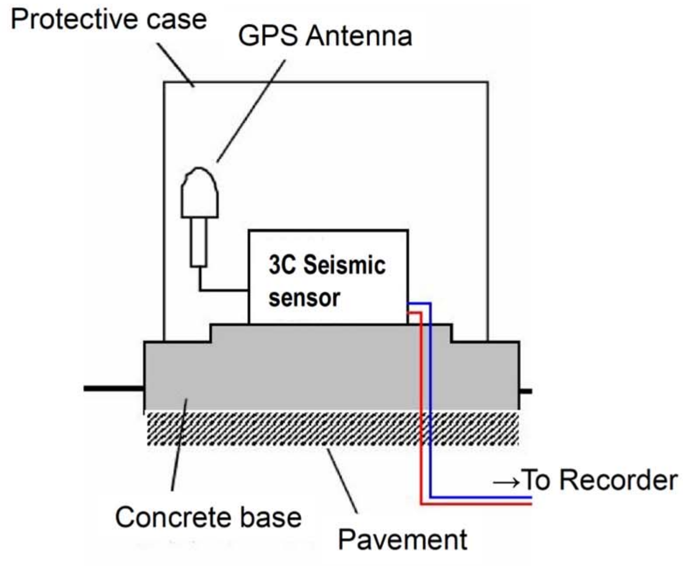
ATLS: Advanced Traffic Light System



CO_2地中貯留サイトの観測事例
ATLSの実用化に向けて

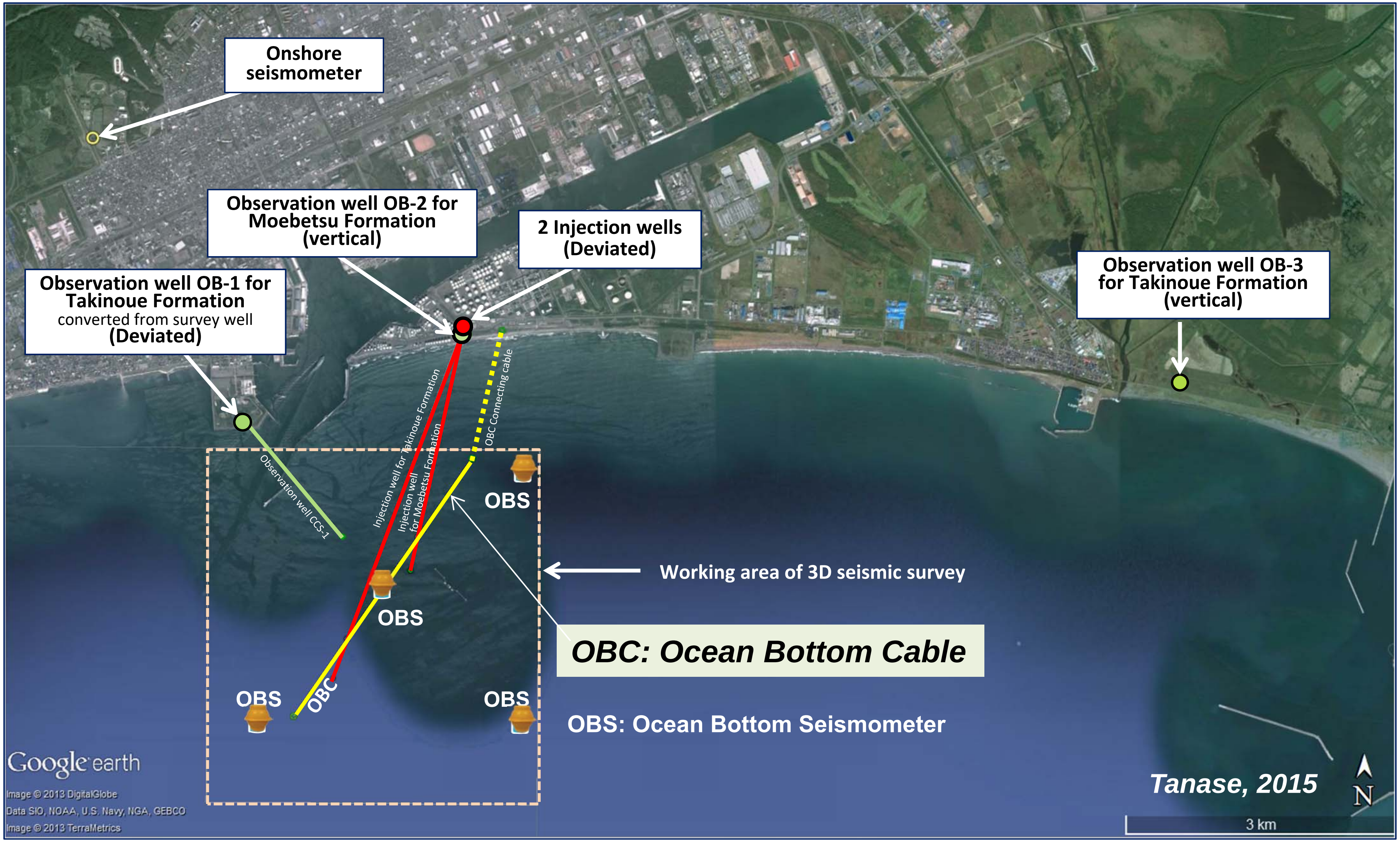
Microseismic Monitoring at Nagaoka Site





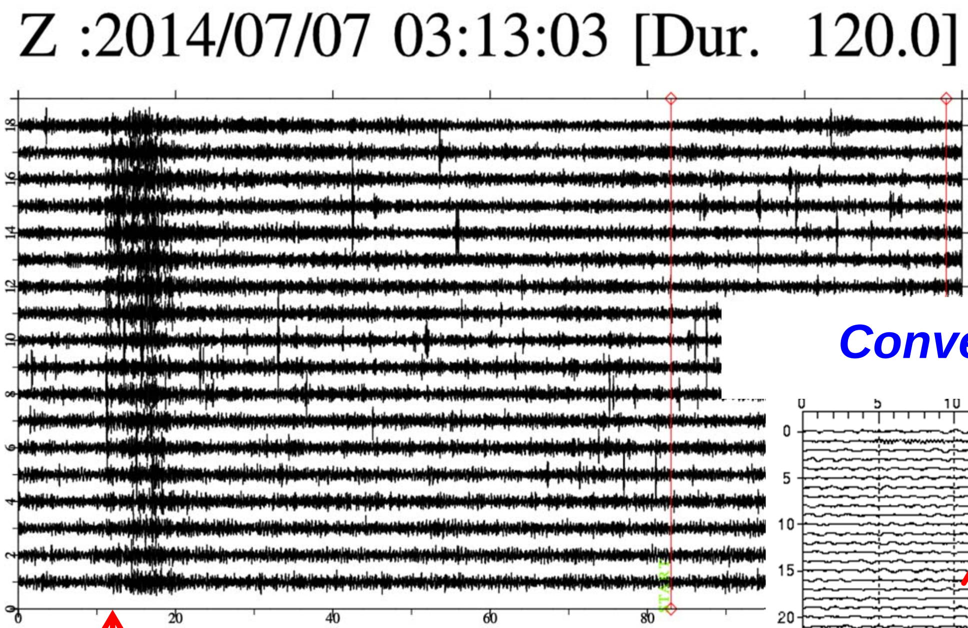
長岡実証試験サイトにおける微小地震観測
（CO_2圧入：2003.7 – 2005.1、約1万トン）

A Dense Microseismic Monitoring Network @Tomakomai



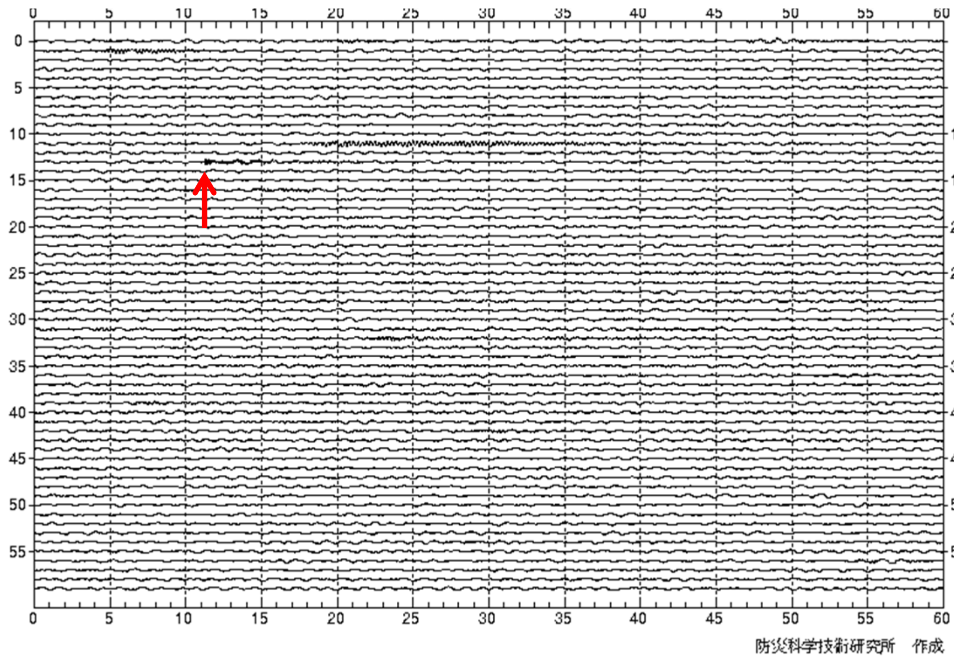
Microseismicity (M<1) detected by OBC and Conventional seismometer @ Tomakomai

自然地震記録の一例



OBC Record

Conventional Seismometer Record



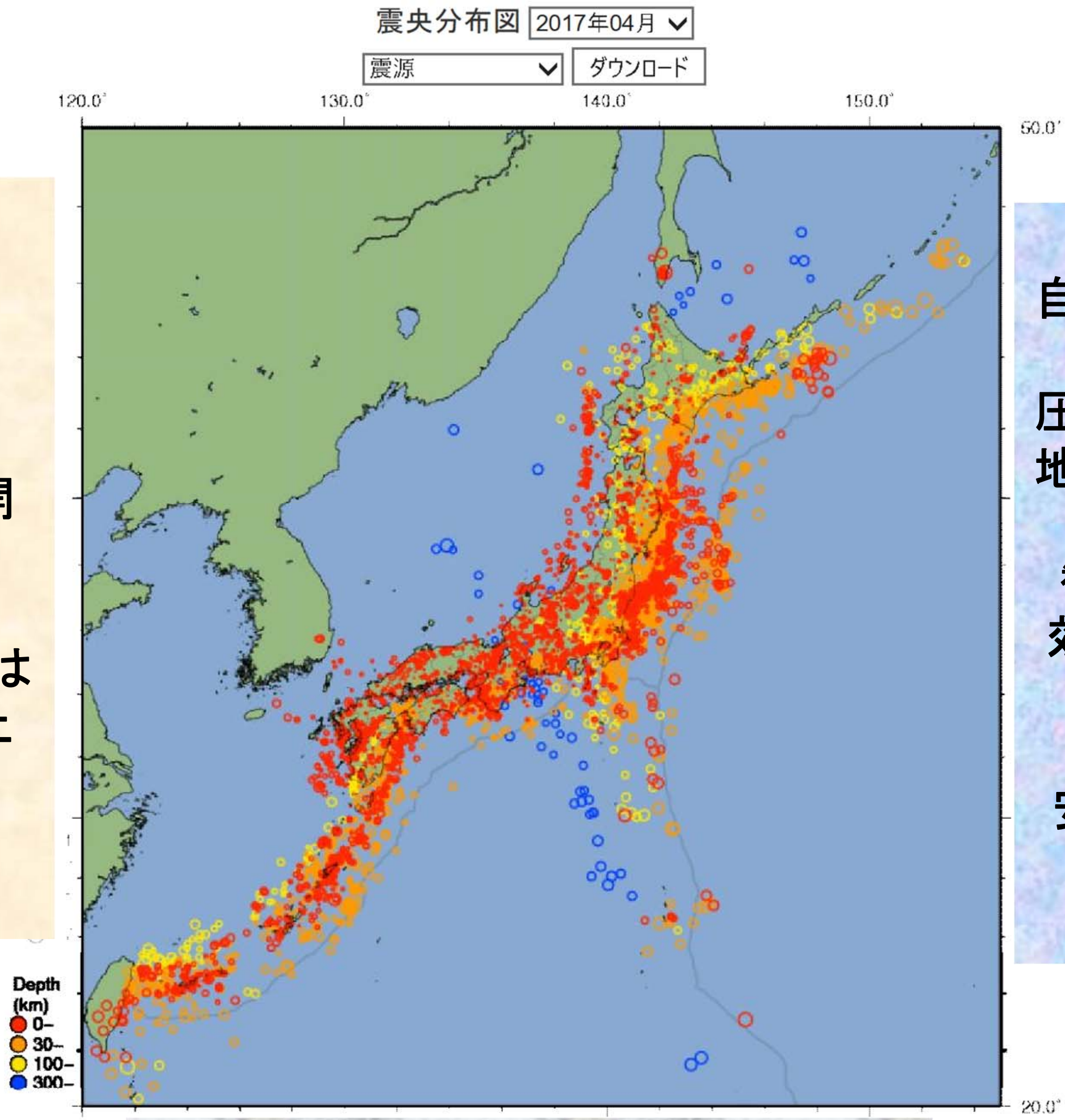
"Two birds (2D/3D Seismic, Microseismic) with one stone (OBC)"

気象庁｜地震月報(カタログ編)

自然地震が多い！

2017.４以降
地震月報が未公開

圧入サイト周辺では
震源決定精度向上
が欠かせない



自動処理・省力化

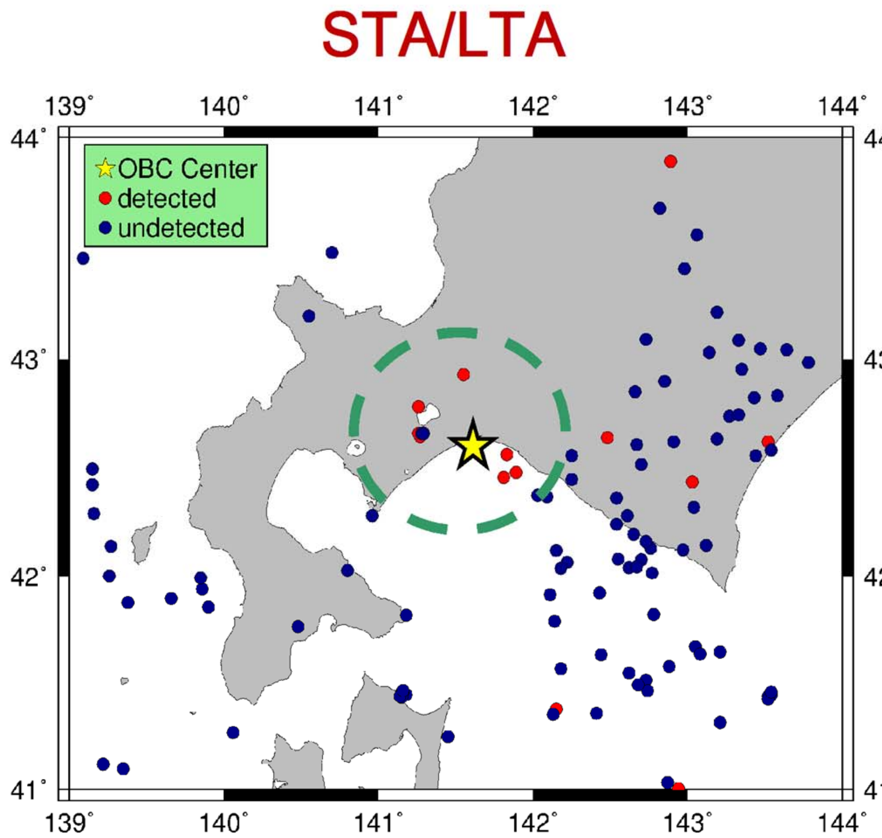
圧入サイト周辺の
地震カタログ整備

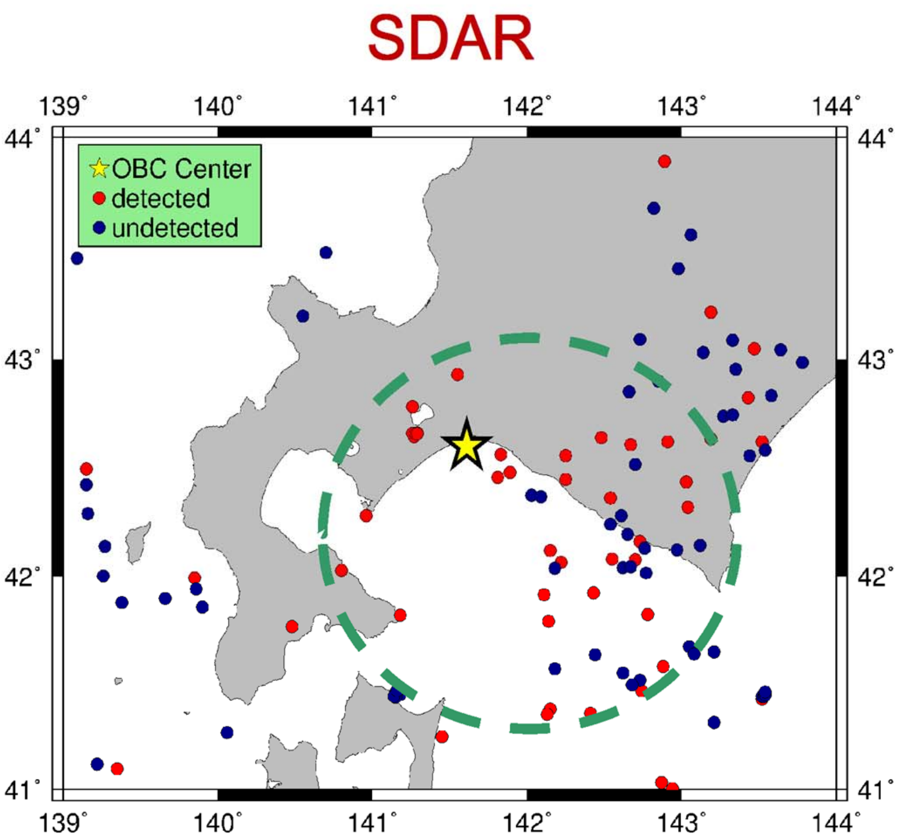
観測・解析結果を
効果的に公開及び
有効活用

安全管理、不安や
疑念の解消へ

圧入サイト周辺：どこまでの範囲？

OBCの観測データからイベントを効果的に検出

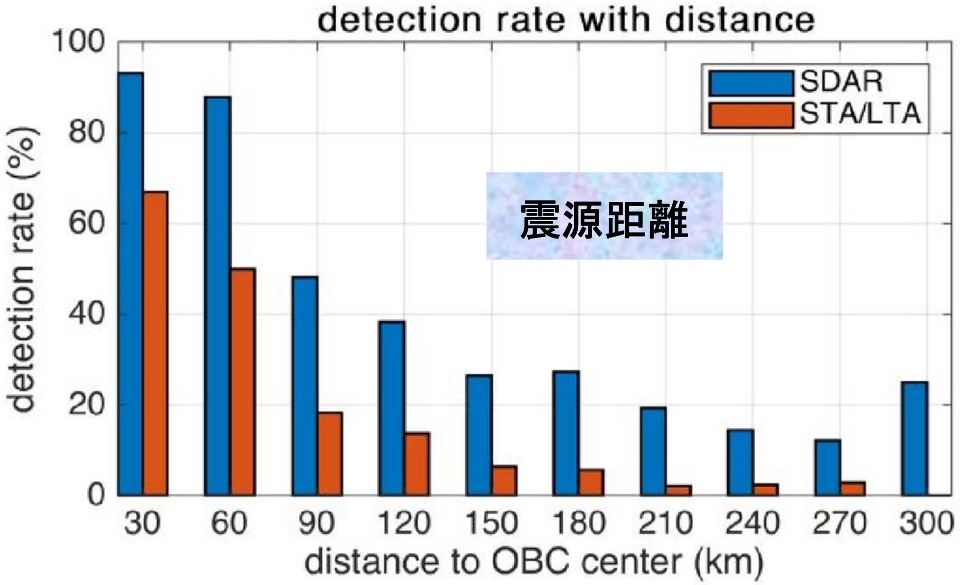




圧入前の自然地震の観測データ：　2015.02.01 -- 2015.02.28

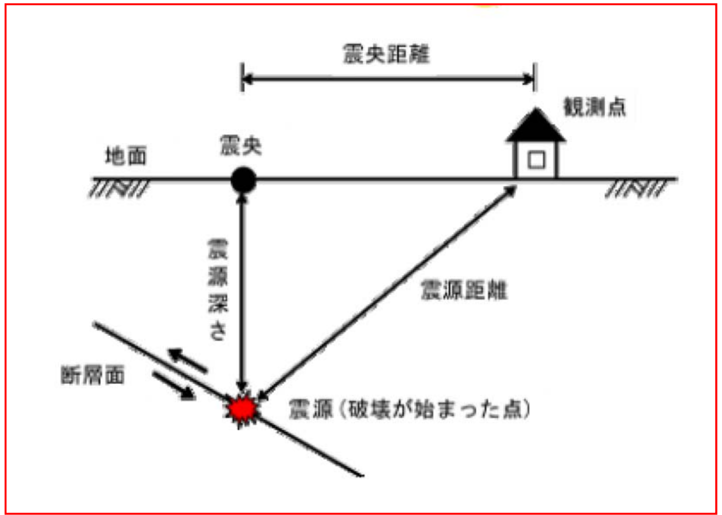
従来のSTA/LTA法と新しいSDAR法の有効性の検証

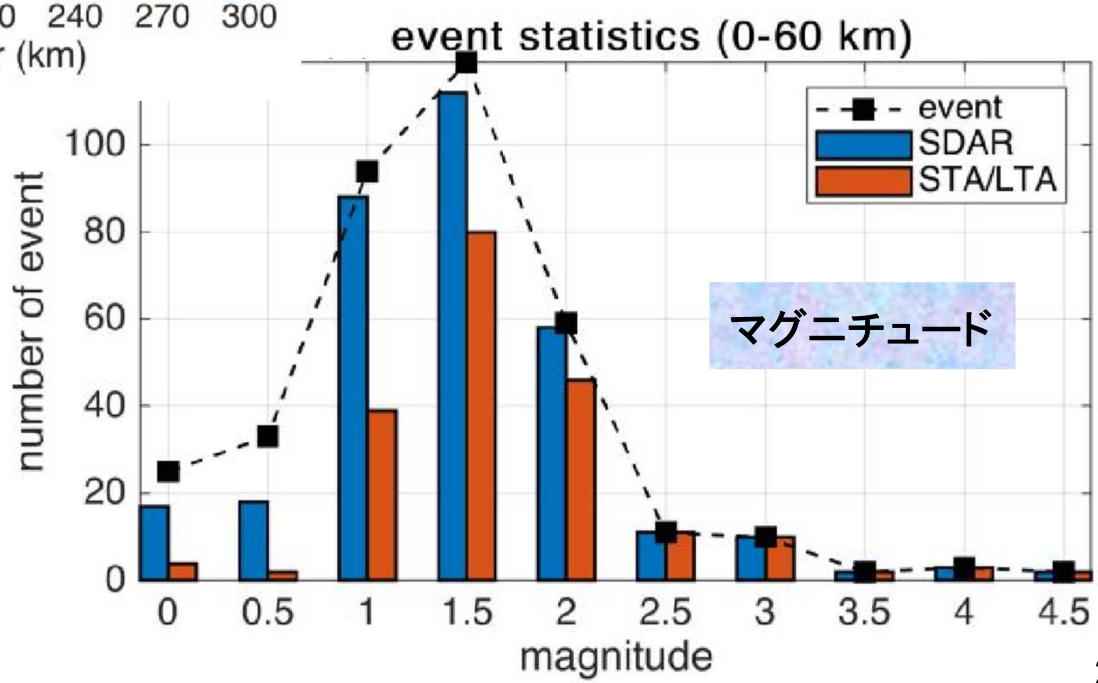
SDAR and STA/LTA on OBC data (2015.02-2016.01)



Natural earthquake hypocenters come from:
Japan Meteorological Agency (JMA)

http://www.data.jma.go.jp/svd/eqev/data/bulletin





ATLSにおける観測データ解析フロー

イベントの抽出 → 地震カタログとの対比 → 自然地震は除く

・微小振動を取りこぼさない
・ノイズを抽出しない

震源位置
・設定範囲内 or not

振幅
・設定値より大 or not

評価

設定範囲外
設定値より小
＝対象からはずす

対象として残す

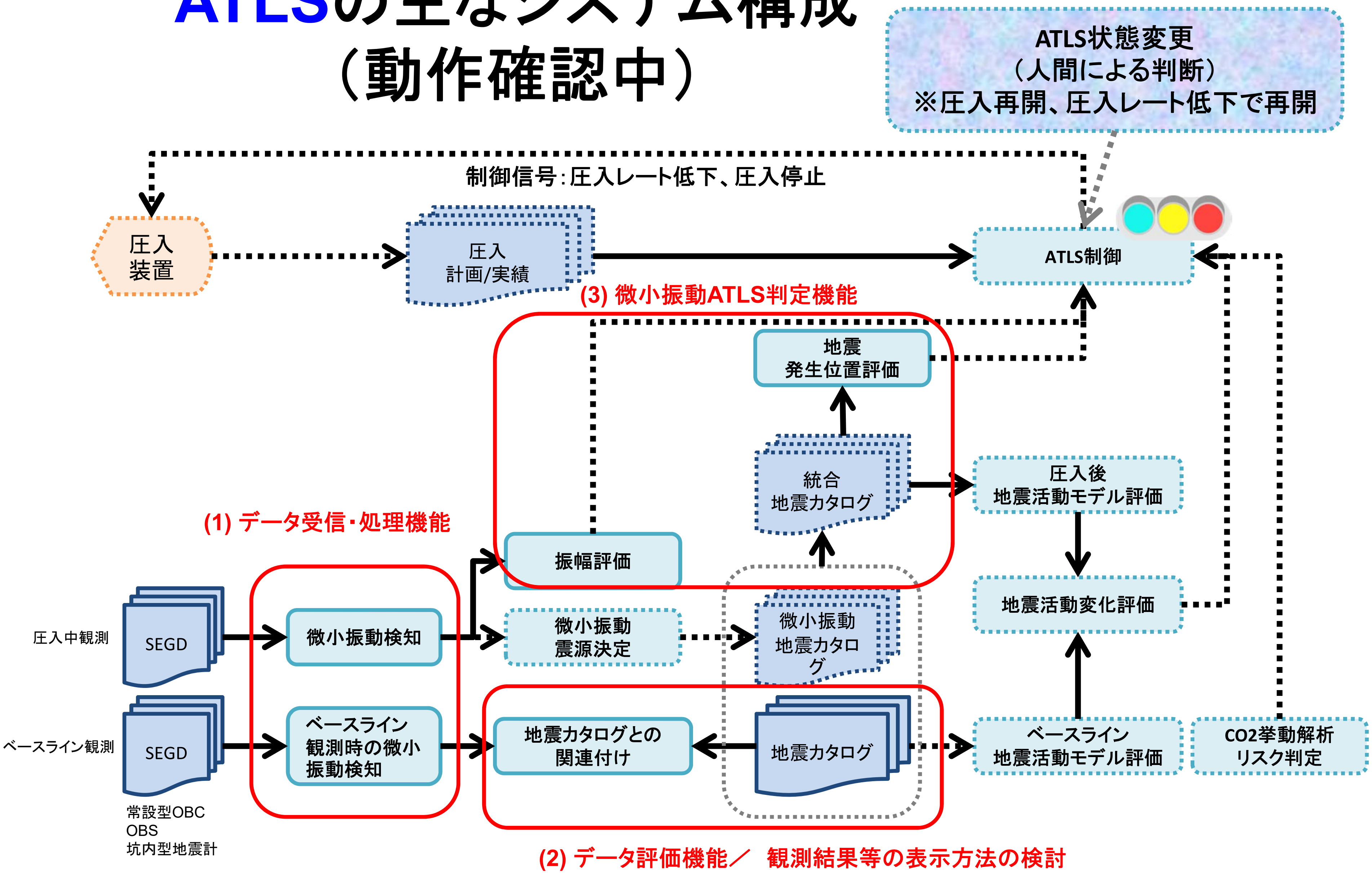
判定

SDAR: Sequential Discounting Auto Regressive

STA/LTA: Short Term Average / Long Term Average

他の観測結果も含めて、
総合的に判定する！

ATLSの主なシステム構成
（動作確認中）



ATLSシステムの完成に向けて

- 気象庁の地震観測情報(データベース)を活用して、解析対象イベントの絞り込み

- 信号機の色(判断基準)や圧入再開条件等の検討
  (他分野の事例や知見を参照)

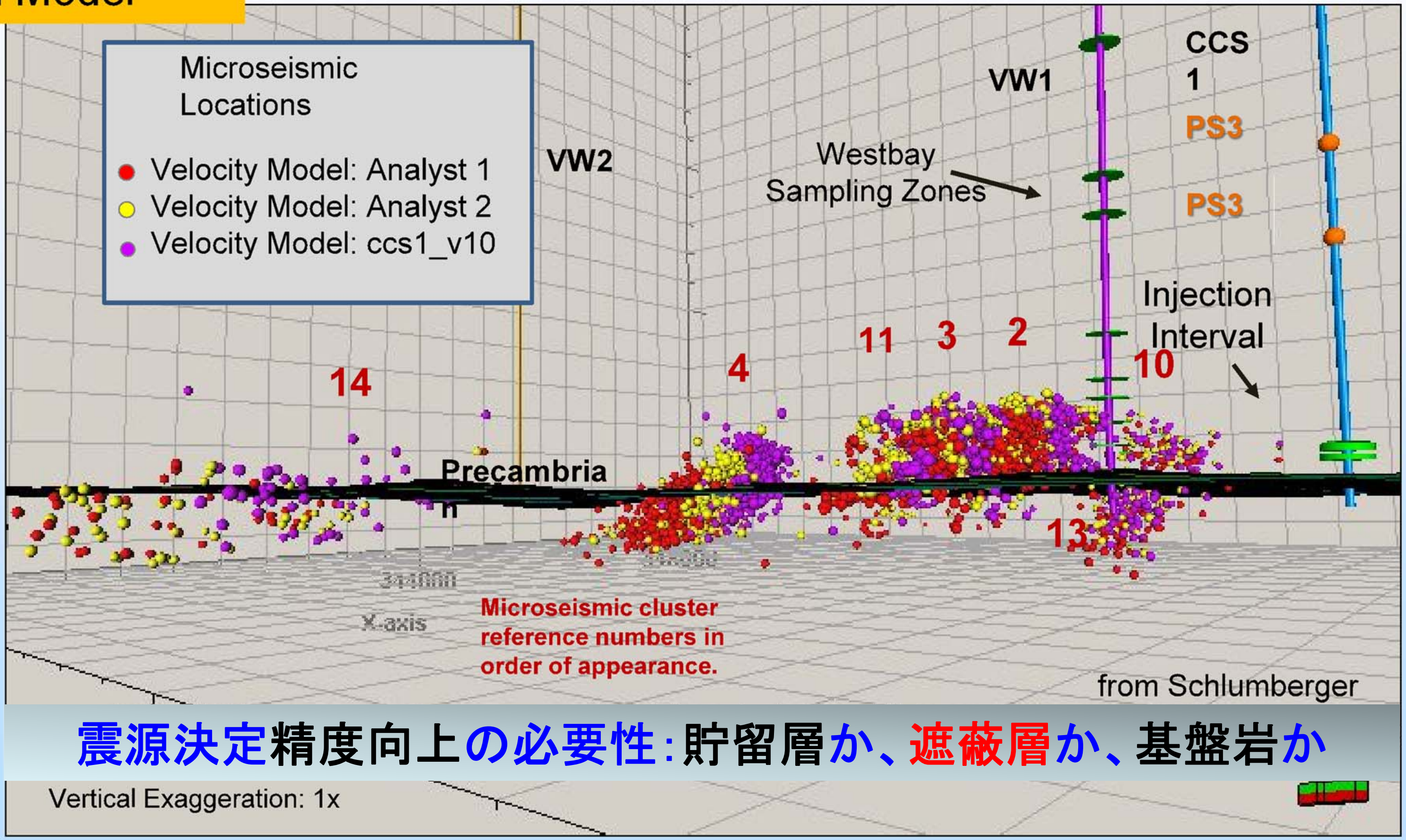
- 圧入サイトにおいて、どの範囲(Area of Review)まで重点的に監視するか

- 圧入時の観測データを有する海外機関との協力

- Science-basedのリスクコミュニケーション
  (社会的受容性向上の手法論からの転換)

米国イリノイのDecaturサイトの観測事例(1/2)

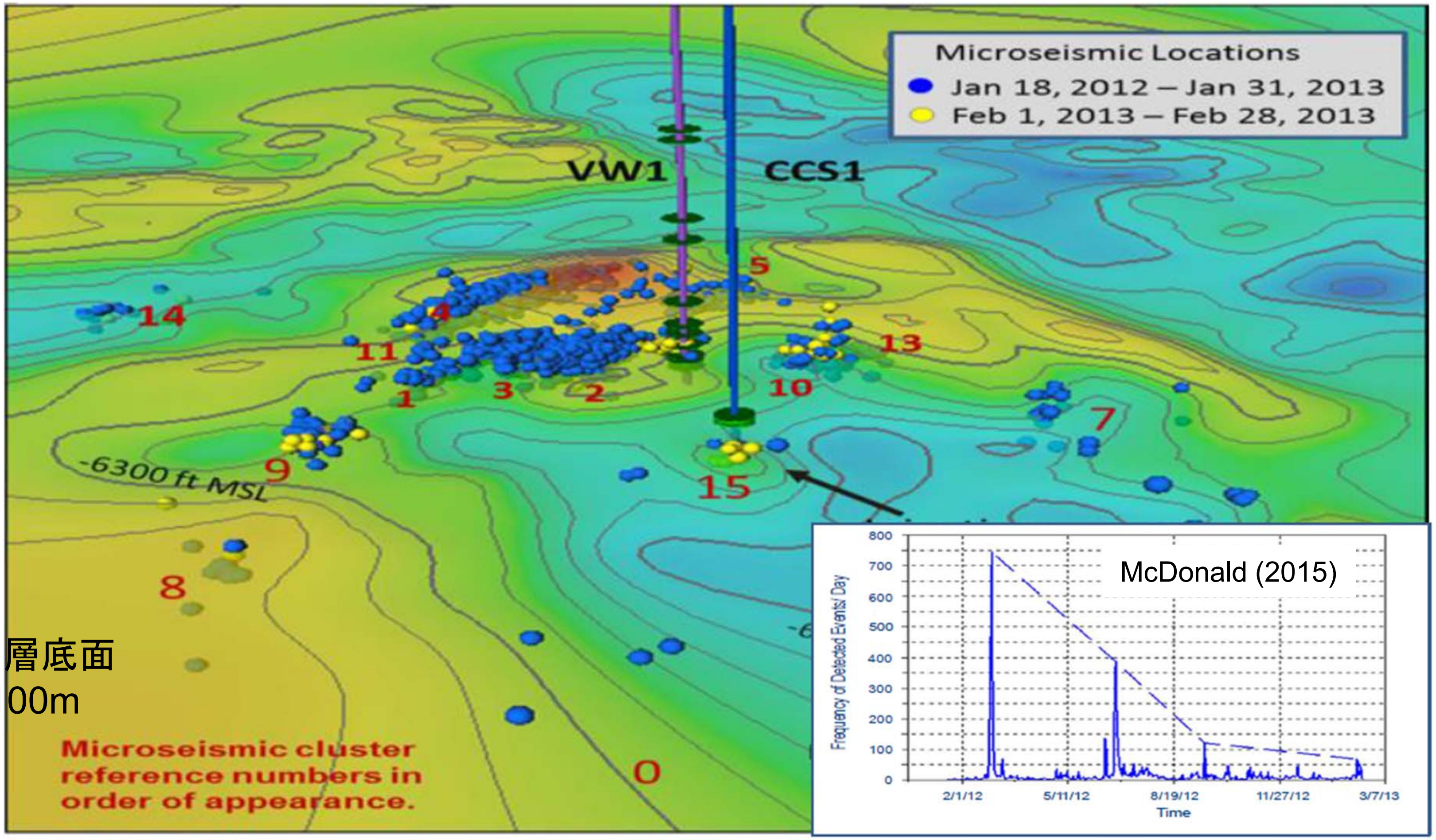
Inject, Monitor, and Model



震源決定精度向上の必要性:貯留層か、遮蔽層か、基盤岩か

Microseismic Events at Decatur, Illinois

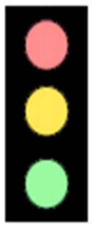
米国イリノイのDecaturサイトの観測事例（2/2）



貯留層底面
～2100m

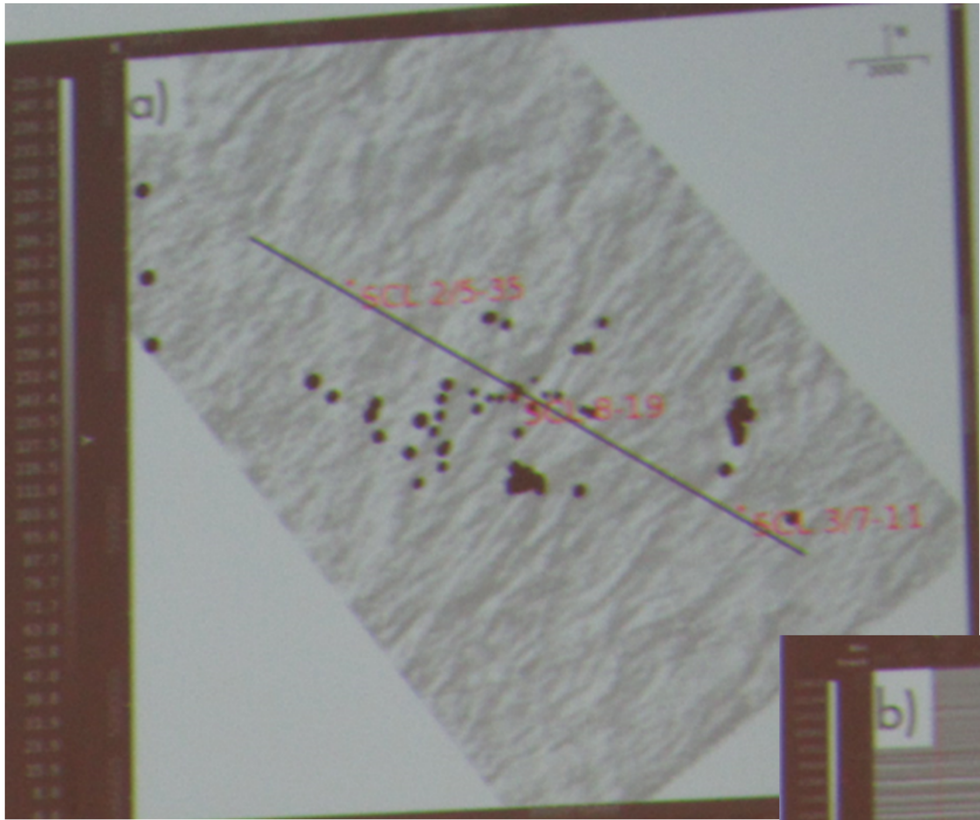
- 微小振動が多発する時期がある
- クラスター状に震源域が分布する
- 下位の基盤と圧入対象層で発生

AoRは12.8km



>M2.0かつ地表で被害: 圧入中止
>M2.0で有感 : 圧入レート低減
>M2.0で無感 : 関係機関報告、関連調査
>M1.5が1月以内に5回 : 関係機関に報告
<M1.5 : 継続

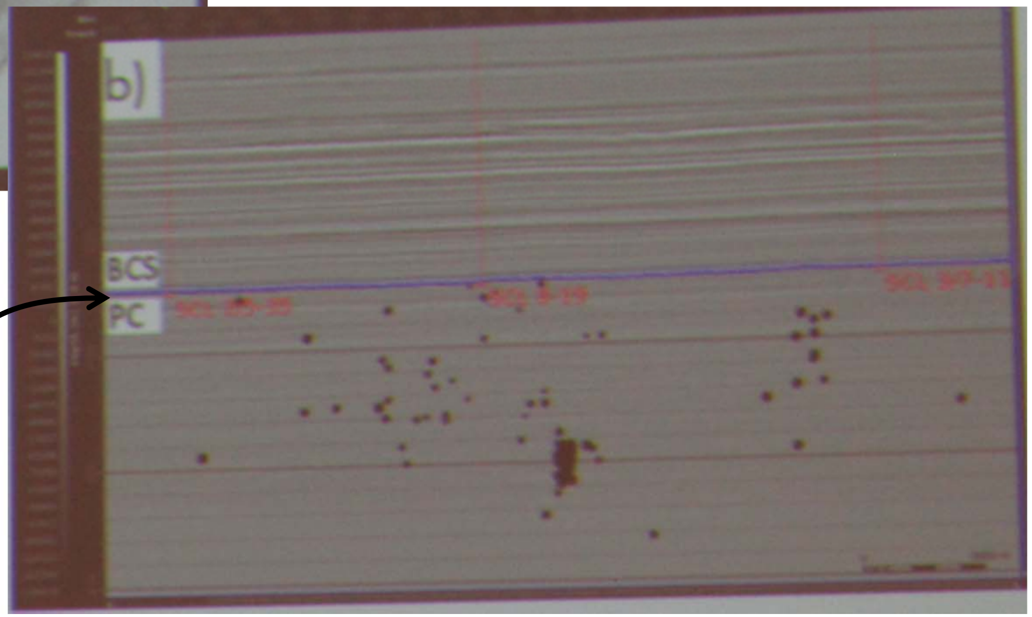
QUESTサイトの微小振動観測結果



>M4.0: 圧入中止
>M2.0: 関係機関に報告
<M2.0: 継続

- 貯留層内のM-2程度の地震まで検知
- Area of Review（AoR）は10km
- 2018年（圧入開始後1年5月後）から年回100回程度微小振動が発生
- これまでの最大M=0.1

O’Brien (2018)



貯留層下部

Micro seismicity monitoring

Performances of the network, Alarms thresholds

- Very good performance of whole network

Detection sensitivity map
-3 : near the injection wellbore
-2 : near the shallow wells

フランスの警報･警告の運用事例（閾値設定）

In 2010, with subsurface network	Since April 2011, micro-seismic events detected by the deep seismic array in the injection well
Very near seismic event : 6	
Magnitude : -1.1 to -0.2	Magnitude : -3.1 to -1.4

- French administration asked for alarms thresholds

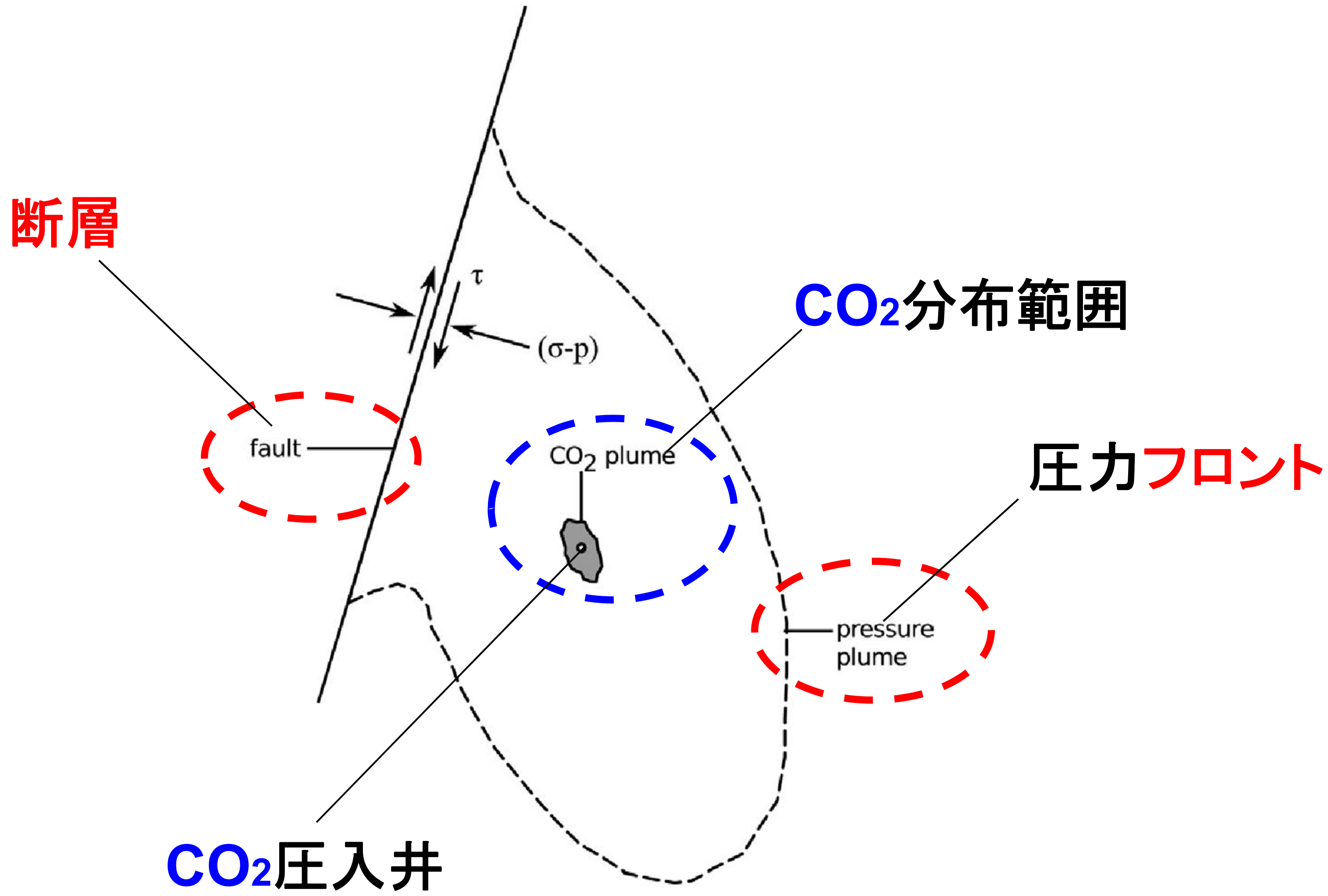
Official alarms thresholds

According to magnitude and number of events, alarm procedure is activated

- For seismic events with magnitude above 2, in the circle given by the subsurface network
- For magnitude above -1, if there is evidence of propagation in space and in time of seismic events external to the reservoir

Billiot (2011)

圧入サイト周辺の地震観測: どこまでの範囲？



米国EPAの観測範囲決定概念図

EPA United States Environmental Protection Agency

Area of review (AoR): The region surrounding the geologic sequestration project where USDWs may be endangered by the injection activity. The area of review is delineated using computational modeling that accounts for the physical and chemical properties of all phases of the injected carbon dioxide stream and displaced fluids, and is based on available site characterization, monitoring, and operational data as set forth in §146.84.

地質モデルを用いた
数値解析結果

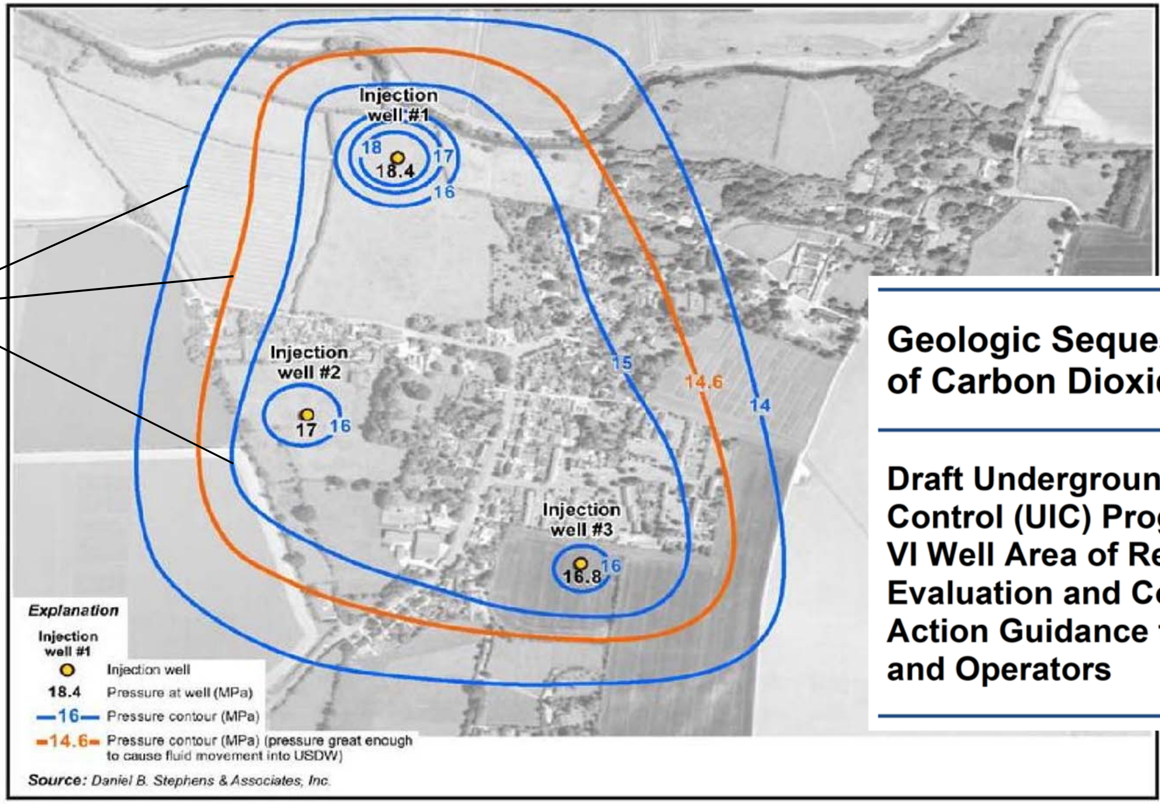


Figure 3-3: Hypothetical Geologic Sequestration Site: Model Predicted Maximum Pressure Within the Injection Zone

Geologic Sequestration of Carbon Dioxide

Draft Underground Injection Control (UIC) Program Class VI Well Area of Review Evaluation and Corrective Action Guidance for Owners and Operators

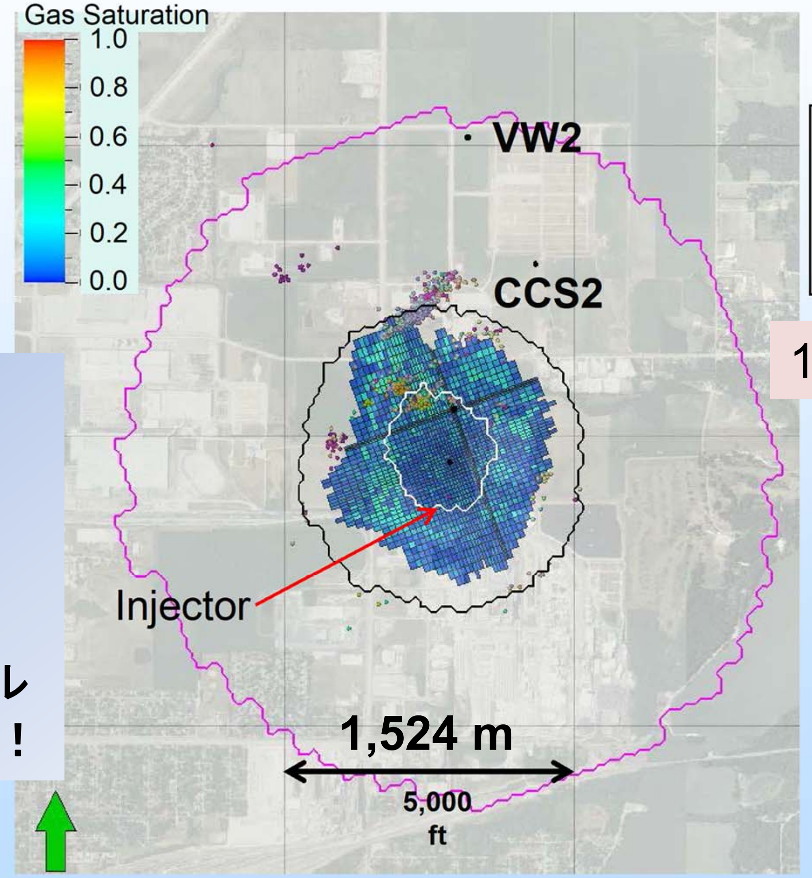
Cluster Development in Relation to Pressure Plume

January 2013

Inject, Monitor, and Model

約100万トン圧入
終了後の予測結果

予測精度は地質モデル
の完成度に大きく依存！



50 psi front
100 psi front
150 psi front
200 psi front

100 psi＝0.69 MPa

from Schlumberger Carbon Services

S1. No Flow Barriers

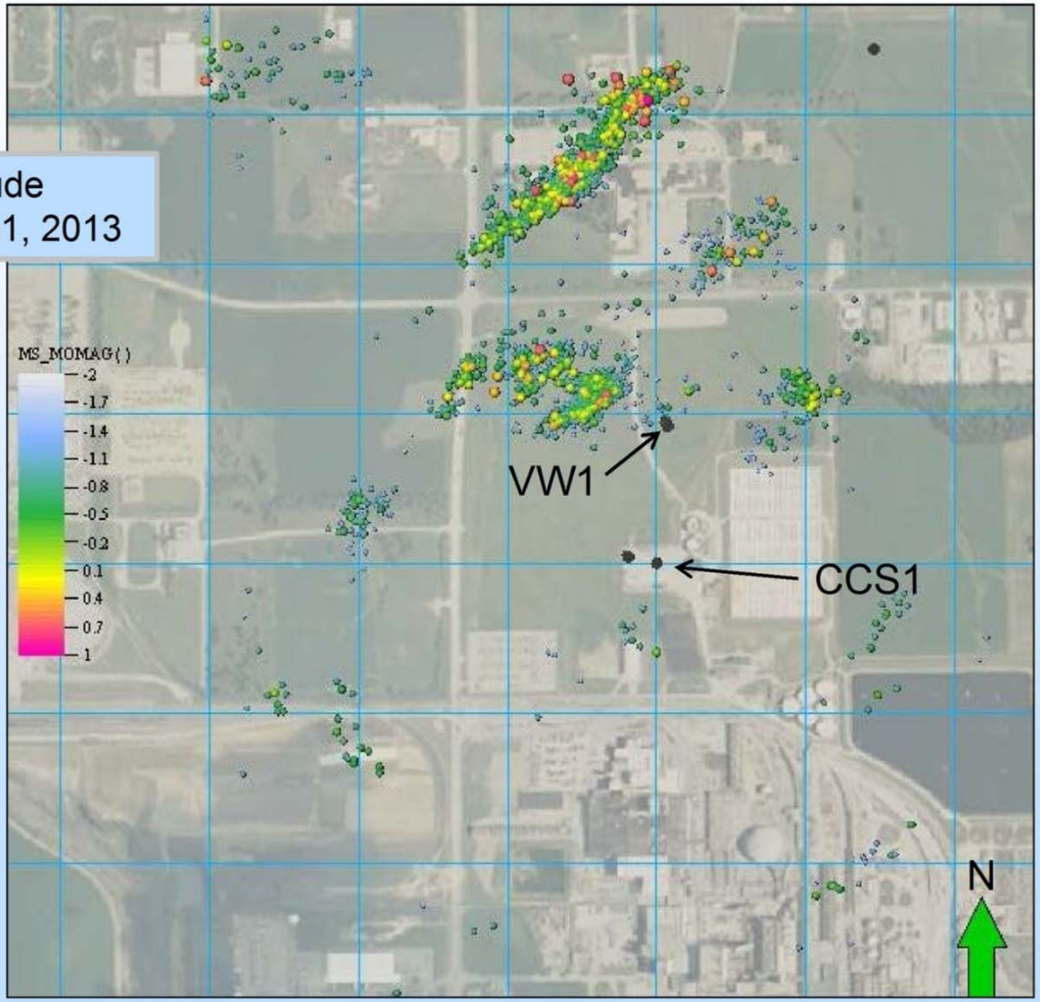
Plume and Pressure Fronts at Decatur, Illinois

米国Decaturサイトの観測事例

Microseismic Cluster Activity: Cluster Locations with Relation to Surface

Moment Magnitude
Jan 18, 2012 – July 31, 2013

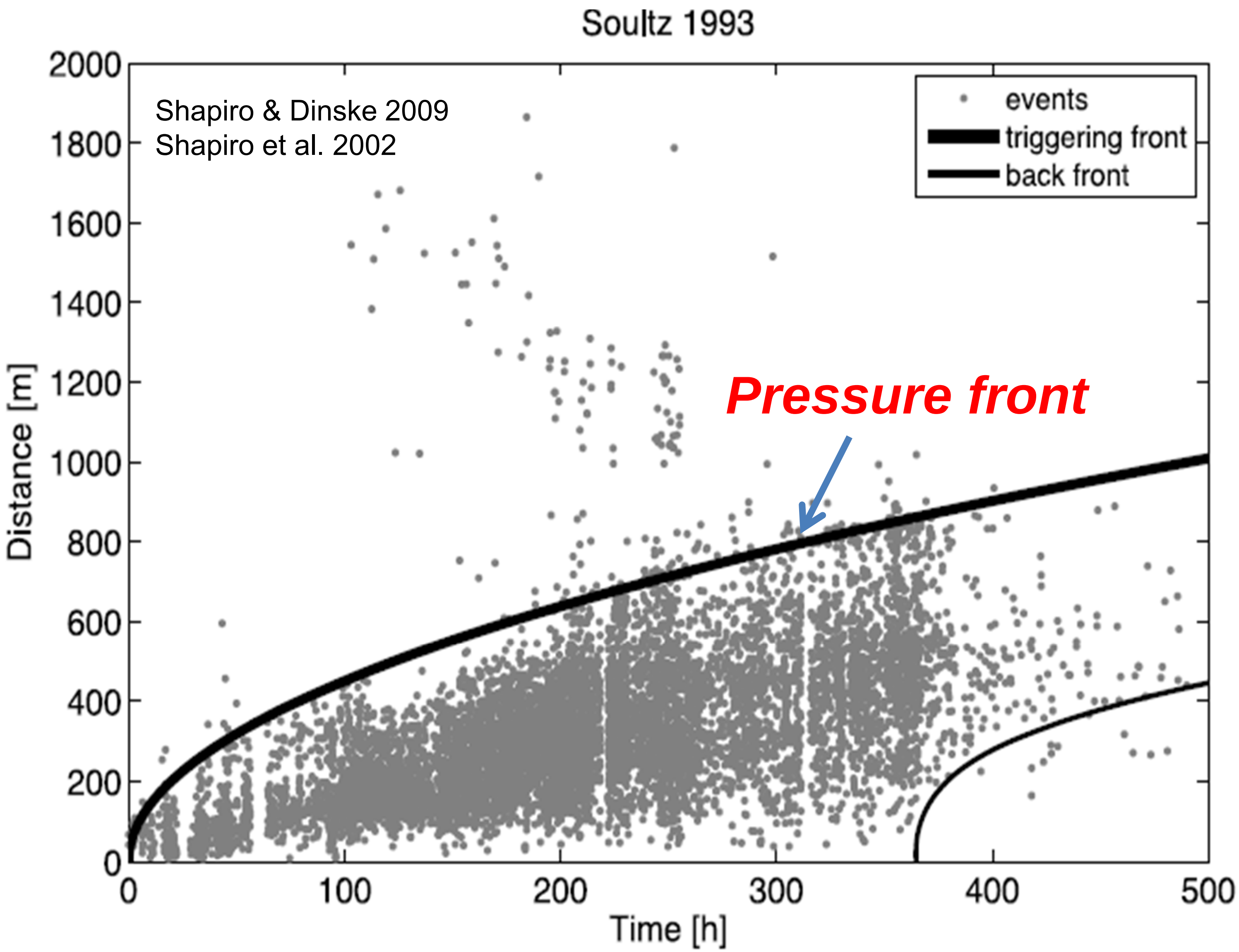
Inject, Monitor, and Model



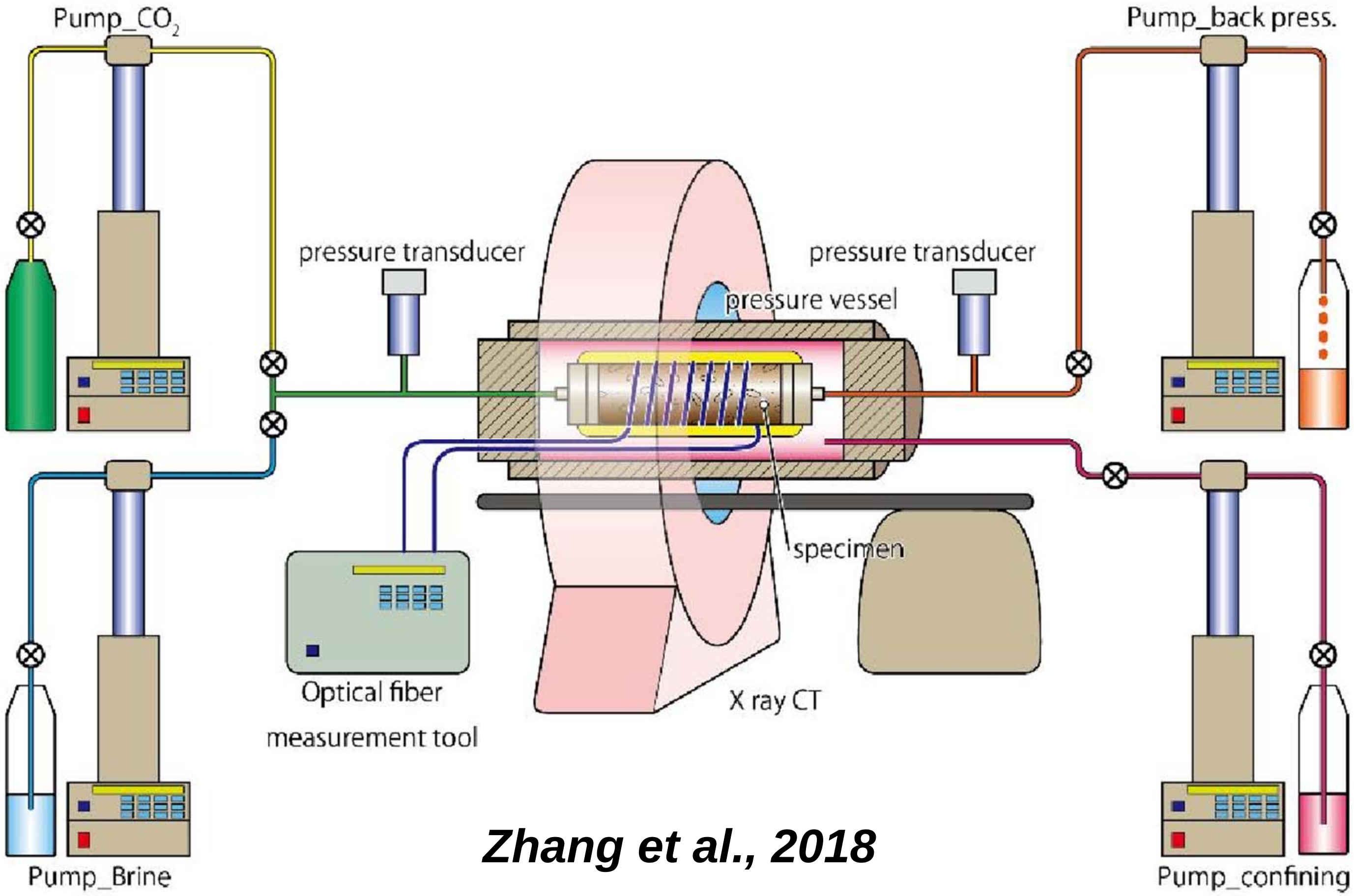
Greenberg, 2015

from Schlumberger Carbon Services

事例：地熱開発における微小地震eventとpressure frontの関係



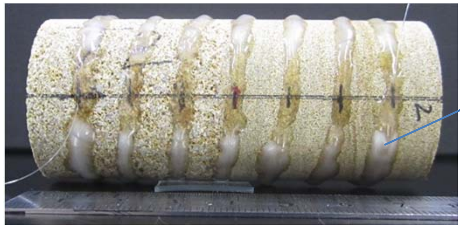
CO_2 Plume Front and Pressure Front
-- *Insights from a lab experiment* --



Zhang et al., 2018

Doi :10.1029/2018WR023415

不均質砂岩試料を用いた流動と変形の同時測定実験

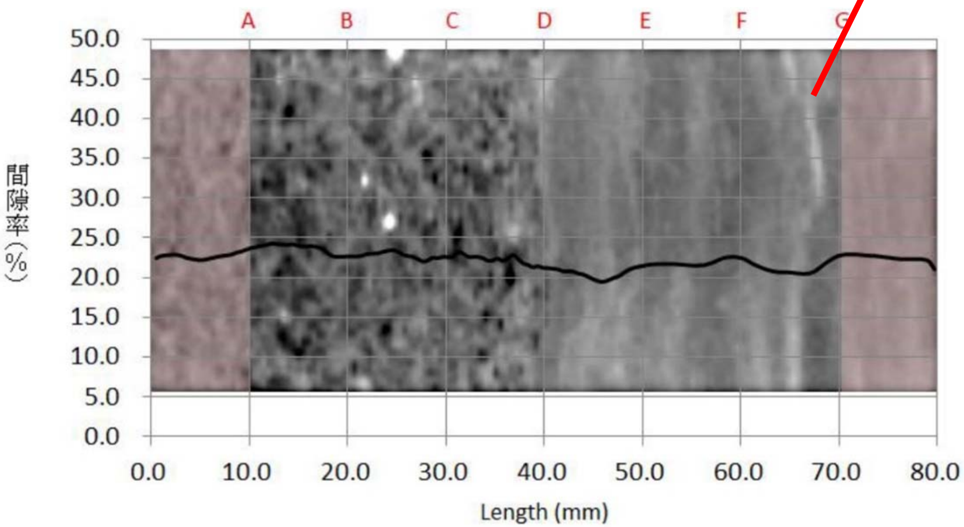


巻き付けた光ファイバー

貯留層（粗粒）

遮蔽層（細粒）

X-CT画像

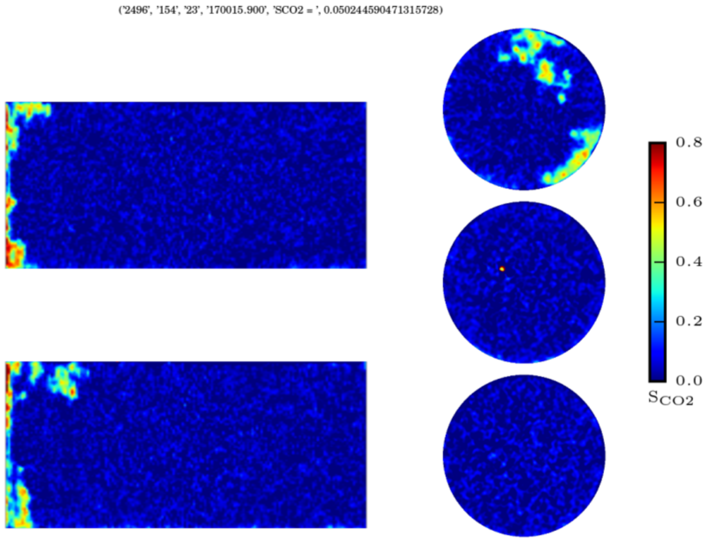


Zhang et al., 2018

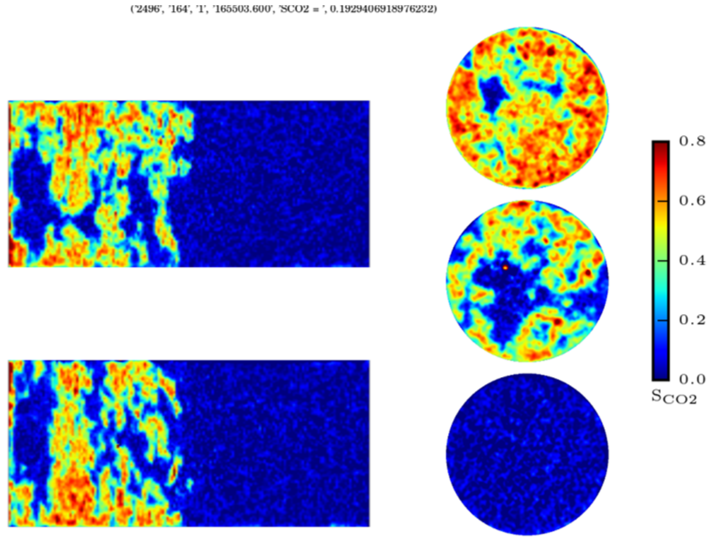
遮蔽層の安定性監視、圧力フロントの観測

粗粒部（貯留層）内のCO_2分布状況（X-CTイメージ）

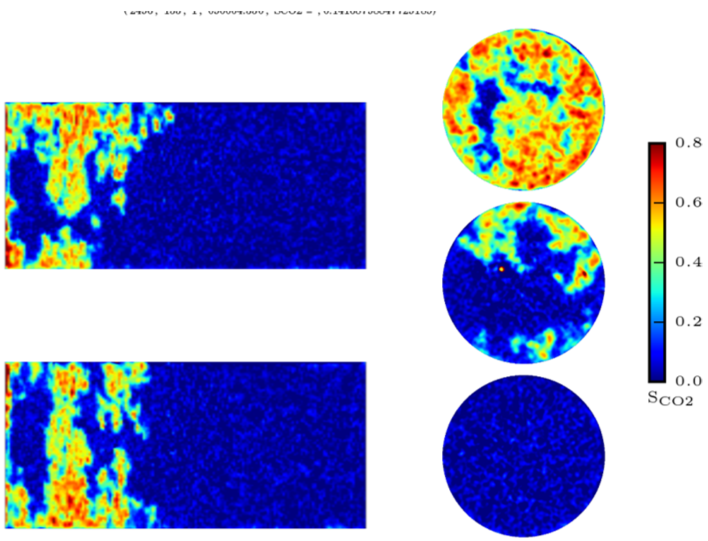
①



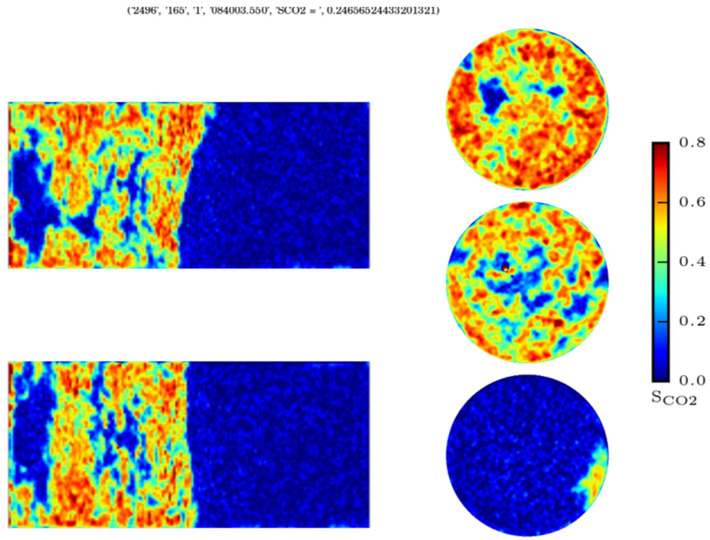
③



②

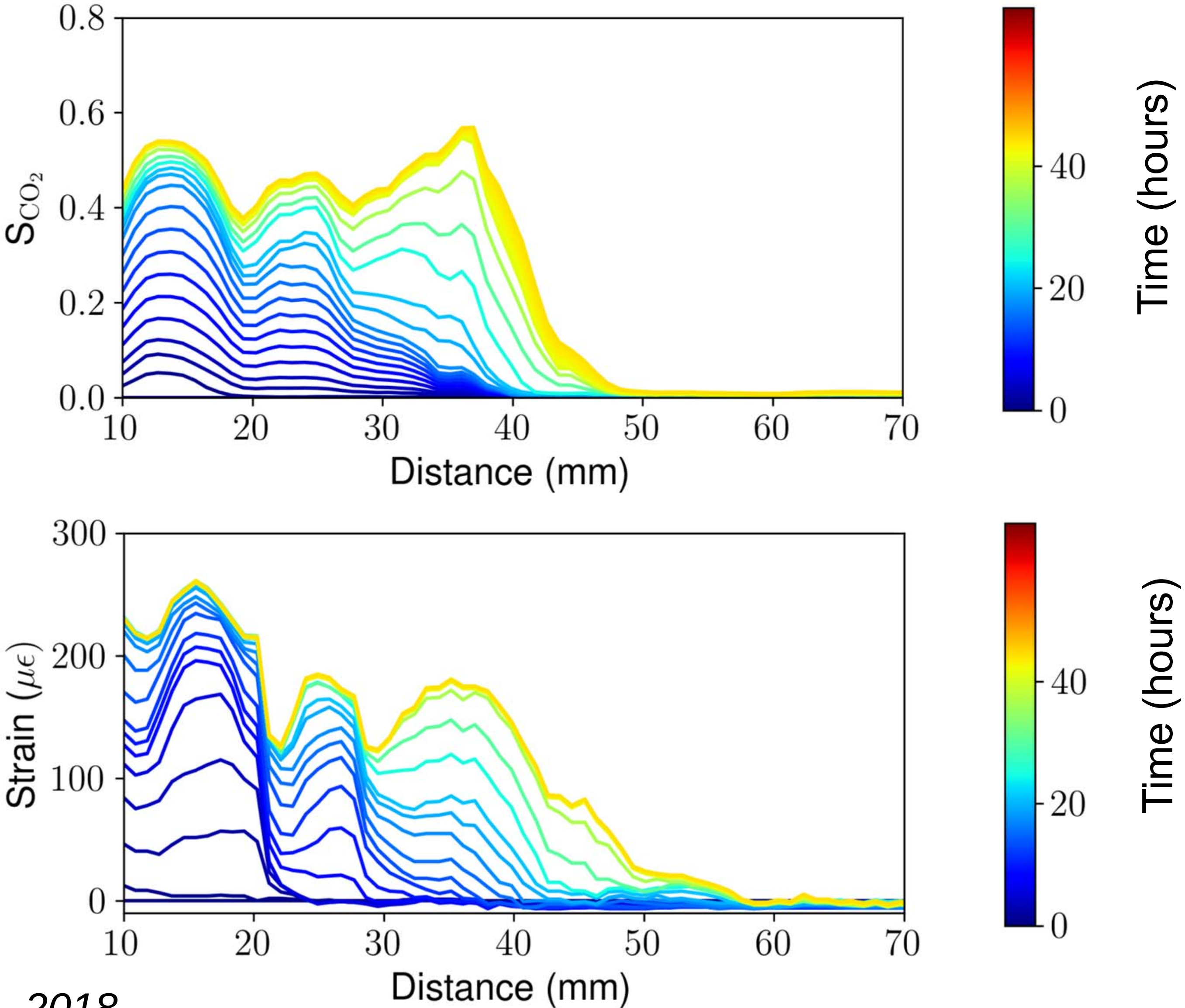


④



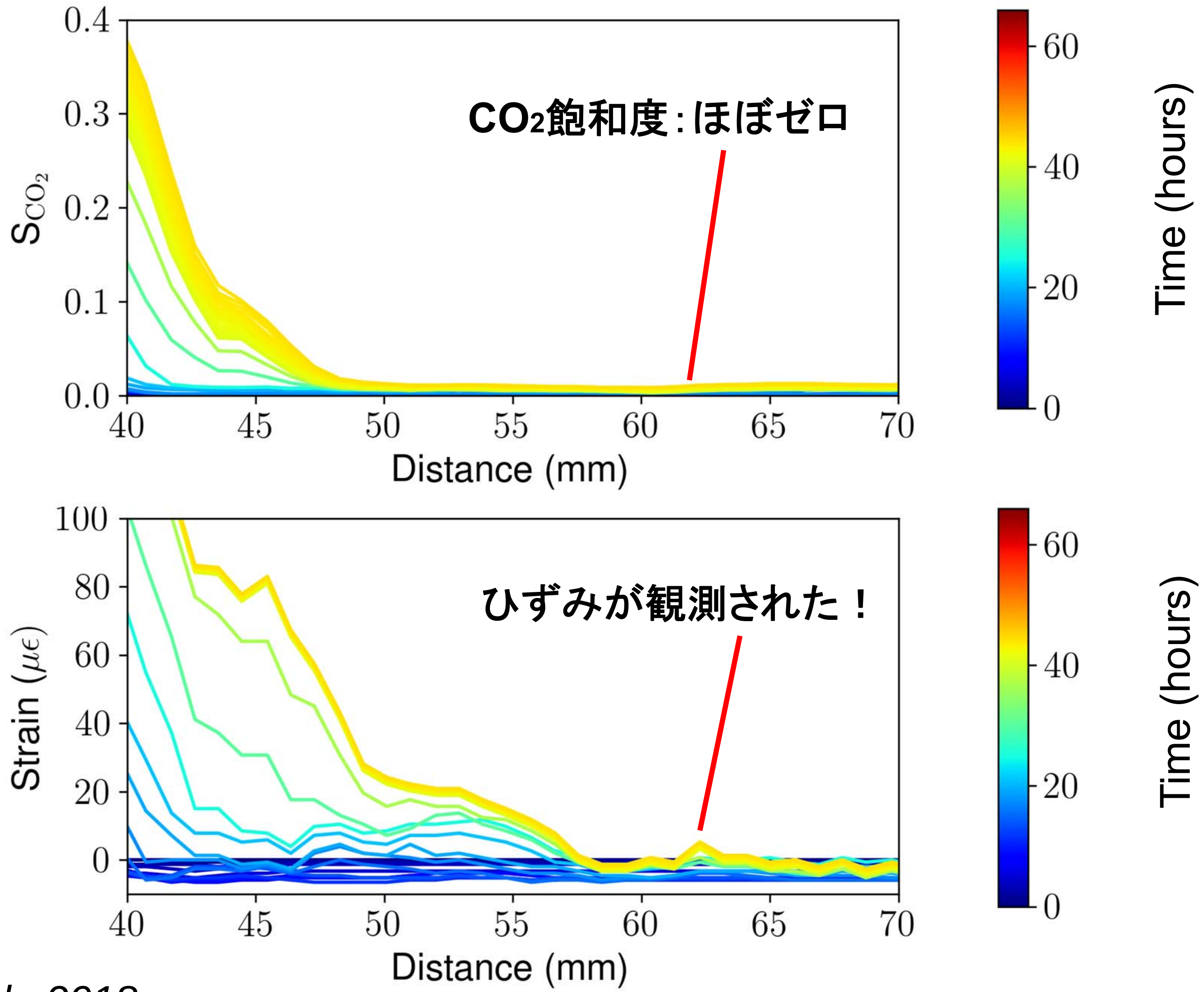
Zhang et al., 2018

粗粒部（貯留層）におけるCO_2飽和度とひずみの対応関係



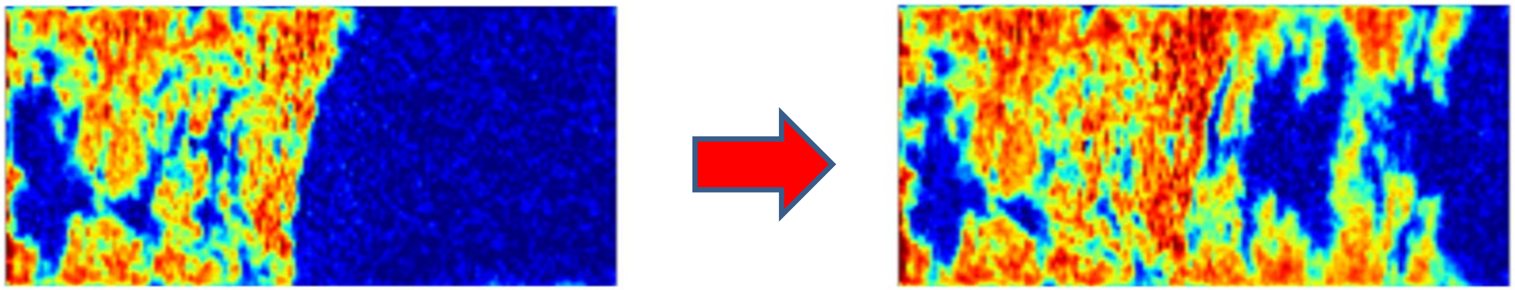
Zhang et al., 2018

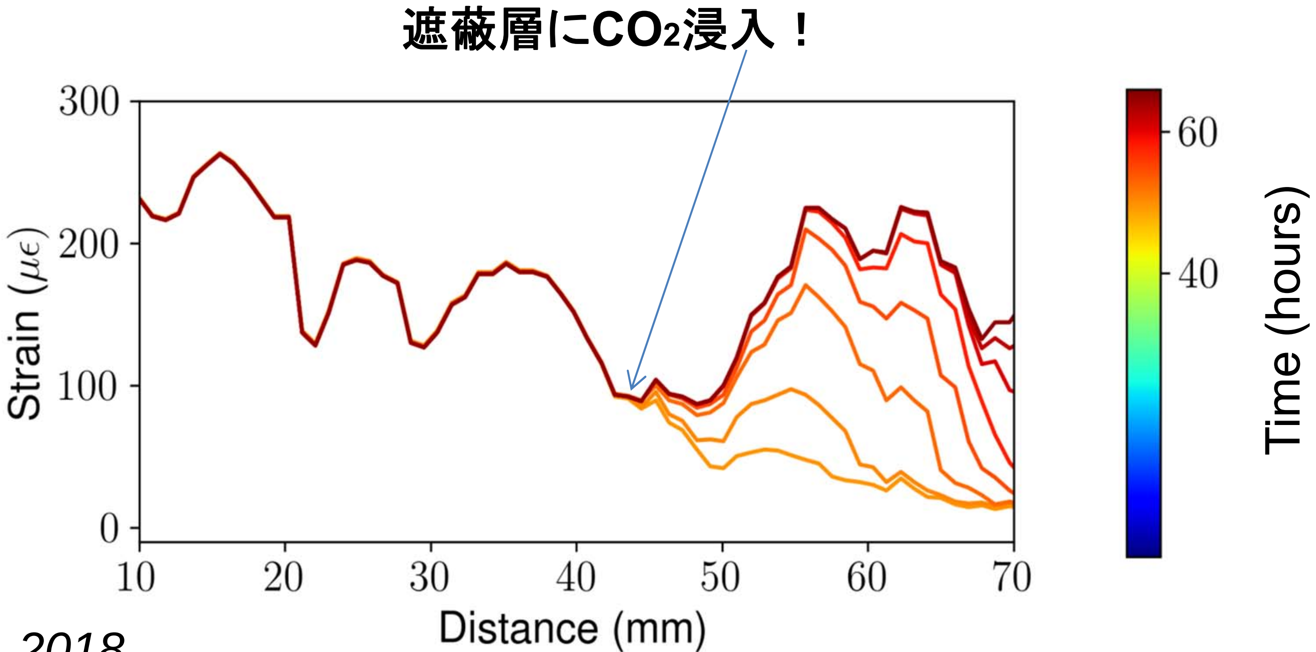
粗粒部のCO_2飽和度が増える過程で、細粒部のひずみ発生状況



Zhang et al., 2018

粗粒部から細粒部にCO_2浸入した後のひずみ発生状況



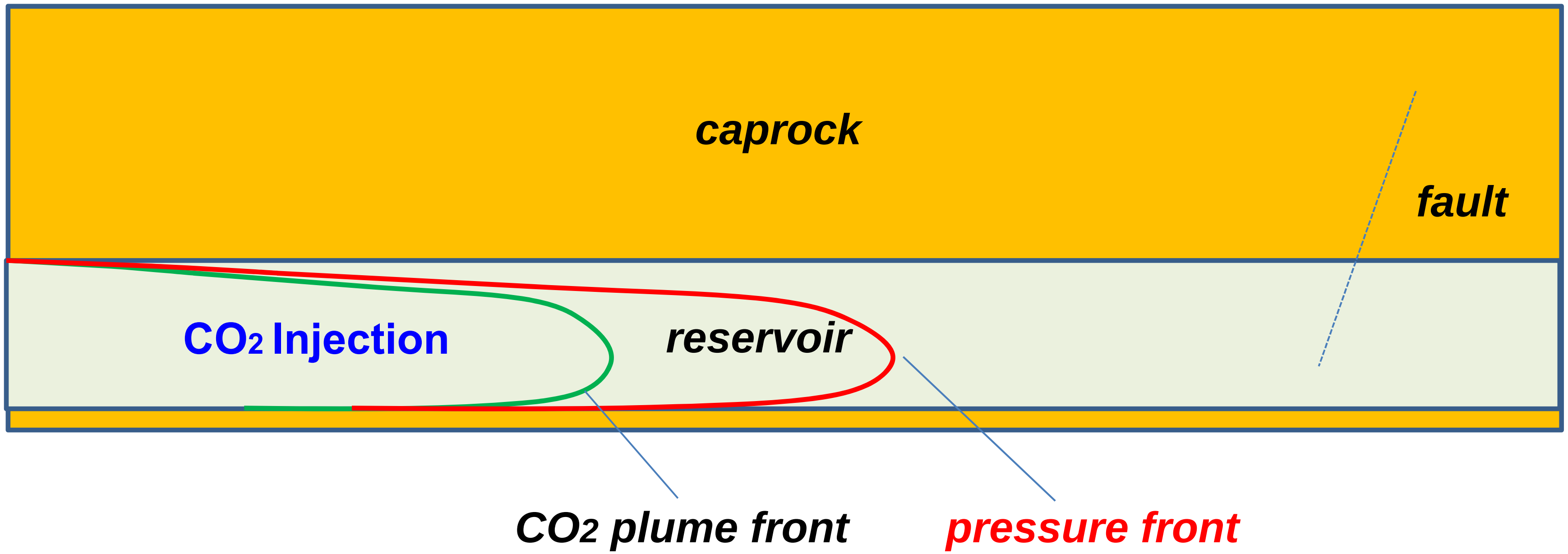


Zhang et al., 2018

- ➢ 砂岩試料の測定実験結果より、*CO_2 plume front* と *pressure front* が区別できた。

- *Geomechanical simulation*より、*pressure front* と貯留層物性の関連性に関するヒストリーマッチング

- 光ファイバーによる断層安定性モニタリング（海外機関と協力も）



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