Safety Assessment Technology

in Deep Saline Aquifer CO_2 Storage

薛　自求

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Research Institute of Innovative Technology for the Earth (RITE)

Research Areas & Program (US/DOE)

Core R&D Research Areas

Key Technology Areas Research Pathways

(DOE, 2015)

Geologic Storage Technology Area
(Storage Technologies and Simulation and Risk Assessment)

- Wellbore construction and materials
- Mitigation technologies for wells and natural pathways
- Fluid flow, reservoir pressure, and water management
- Geochemical effects on formation, brine, and microbial communities
- Geomechanical impacts on reservoirs- seals and basin-scale coupled models; microseismic monitoring
- Risk Assessment databases and integration into operational design and monitoring

Monitoring, Verification, Accounting & Assessment (MVAA) Technology Area

- Atmospheric Monitoring and remote sensing technologies
- Near-Surface Monitoring of soils and vadose zone
- Subsurface Monitoring in and near injection zone

Onshore

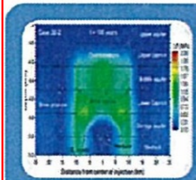
/ Offshore

(Gulf of Mexico)

Carbon Storage Program

Addressing Future Technical Challenges

Offshore Storage Resource Assessment
- Prospective Storage Resource for East Coast and/or Gulf of Mexico
- Depleted Oil and Natural Gas Reservoirs and Saline Formations



Fit-for-Purpose Field Project– Brine Extraction Storage Test (BEST)
- Managing formation pressure and movement of differential pressure and CO_2 plume through brine extraction and treatment of extracted brine for re-use

Intelligent Monitoring Systems and Advanced Well Integrity and Mitigation
- Next generation technologies to monitor, control and optimize CO_2 injection
- Advanced tools and methods for assessing wellbore integrity (identifying and quantifying wellbore leakage) and mitigation

- ***R&D focused on: Cost (Capture) and Confidence (Storage),***
- ***Demonstrations: Integration and Learning***

➢Safety/Risk Assessment in CO_2 Storage (1/3)

･**Definition**, Diversity and Uncertainty

◆ **Risk**: the **possibility** due to **uncertainties and threats** affecting storage process, included in all activities with different degrees

- ✓ **Identifying the risks**
  - ✓ **Analysing the risks**
    - ✓ **Evaluating the risks**
      - ✓ **Monitoring and reviewing the risks**

Controlling the risks (without further risk treatment required)

Mitigating the risks →→→ Securing the safety

(Safety assessment = Risk assessment)

◆ **Business or investment-related risks (Fiancial & Market), Communication risks (Stakeholders), Global risks without CCS (Climate change)**

➢Safety/Risk Assessment in CO_2 Storage (2/3)

・Definition, Diversity and Uncertainty

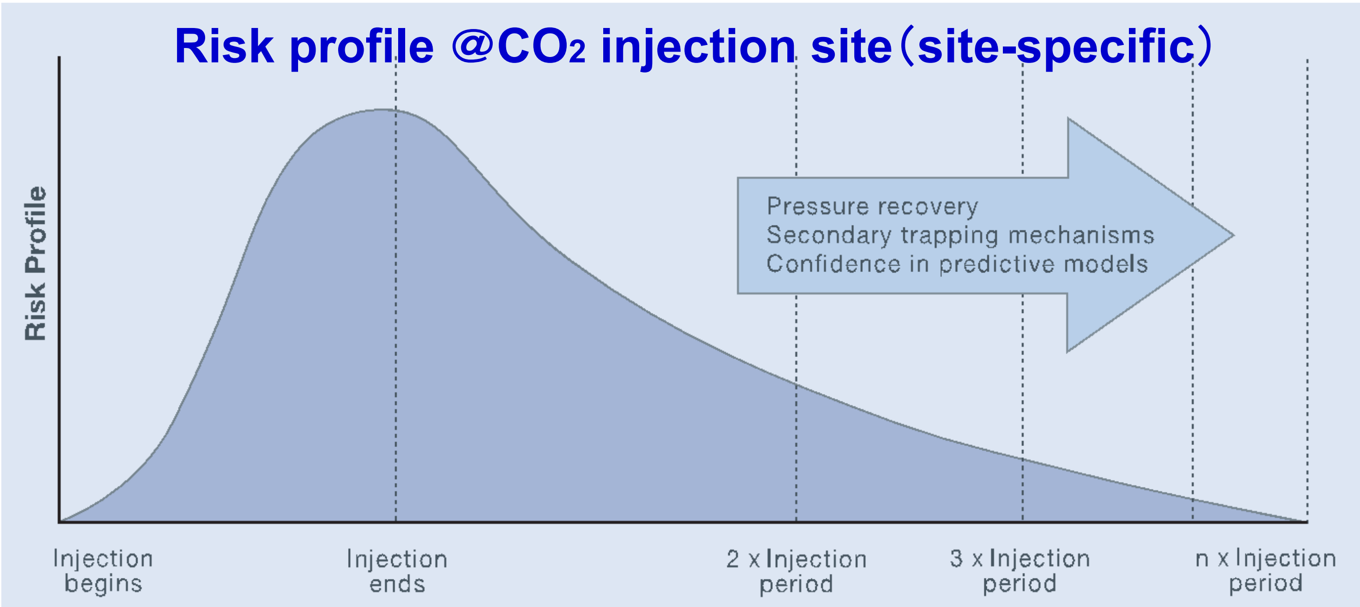
◆High Subsurface Uncertainties:

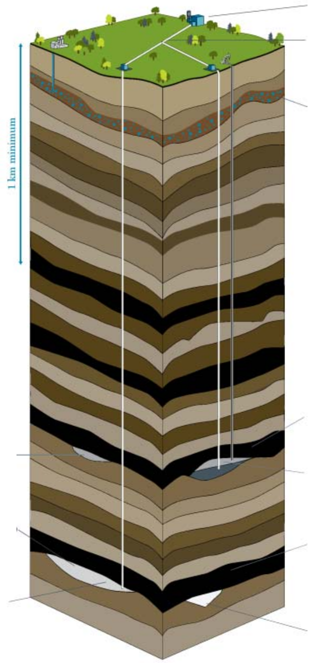
- ✓ Multiple and site-specific subsystems (injection & monitoring wells, aquifers, caprocks, aquitards, freshwater, faults….)
  - ✓ Many interacting components (rock minerals, CO_2, formation fluids….)
    - ✓ Various models (geological model, reservoir model, geochemical model, geomechanical model….)

Advantages and Limitations of Technologies used in All CO_2 Storage Activities!

➢Safety/Risk Assessment in CO_2 Storage (3/3)

・*Potential Risks*

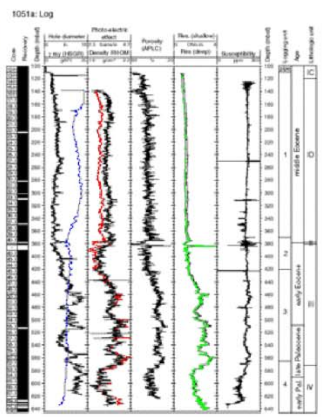


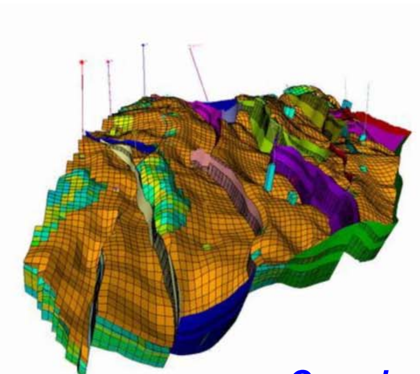


[Illustration source: Benson, 2007]

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

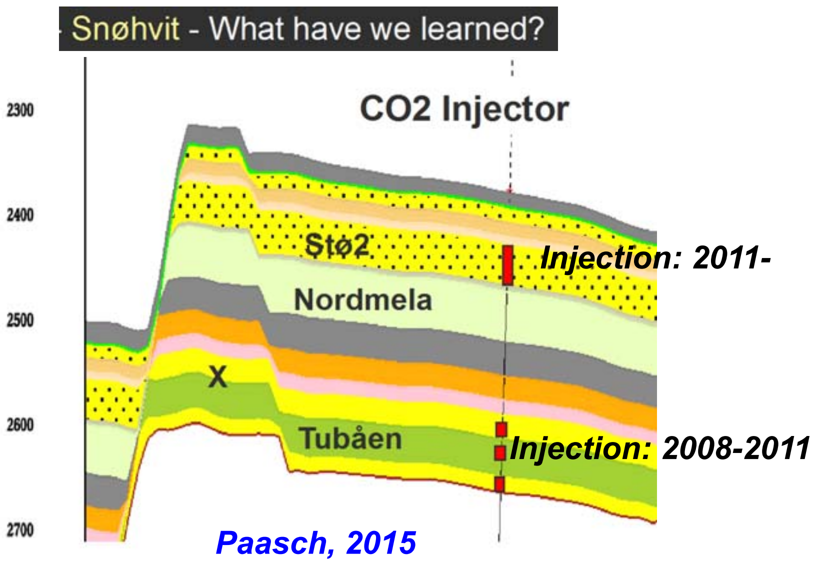
Storage Capacity & Monitoring Tech (1/3)

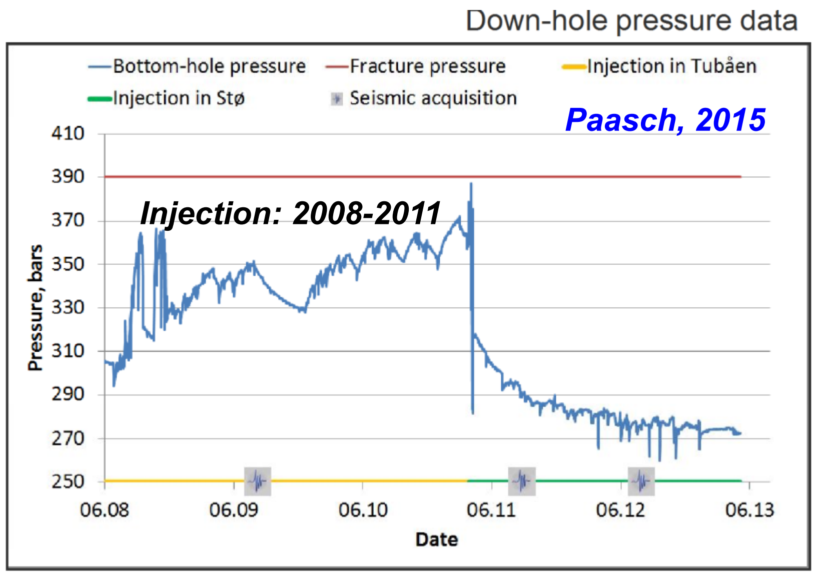




Oxand

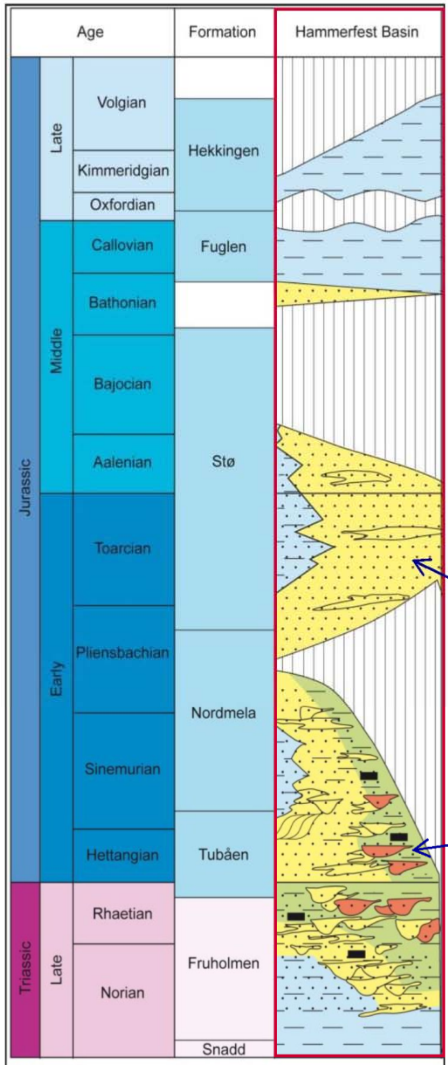
- ***Reservoir characterization: Heterogeneity and Injectivity***





Stratigraphy and Depositional Environment

@ Snohvit



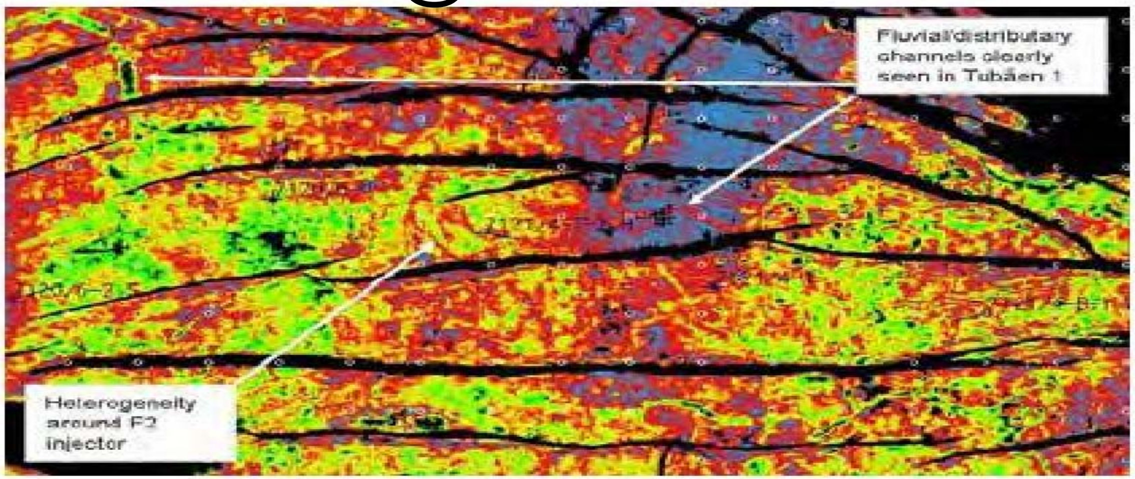


Figure 3: Amplitude map of the base Tubåen Fm reflection. Green colours are high amplitudes and blue colours low amplitudes.

Stø (main reservoir)

- Shallow-marine environment
- Good lateral and vertical communication

Tubåen

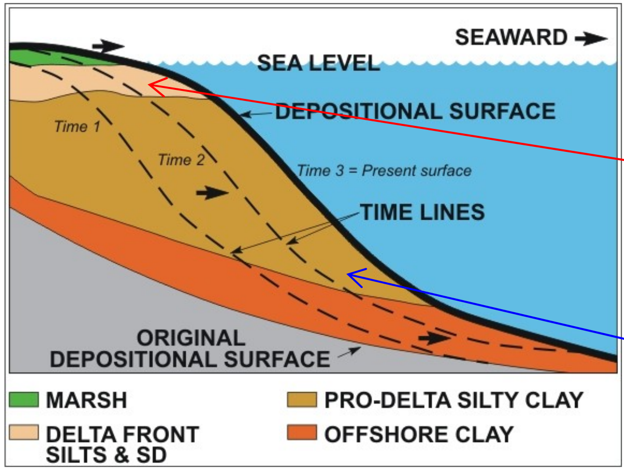
- Densely stacked fluvial channels
- Poor lateral and vertical communication

Paasch, 2015

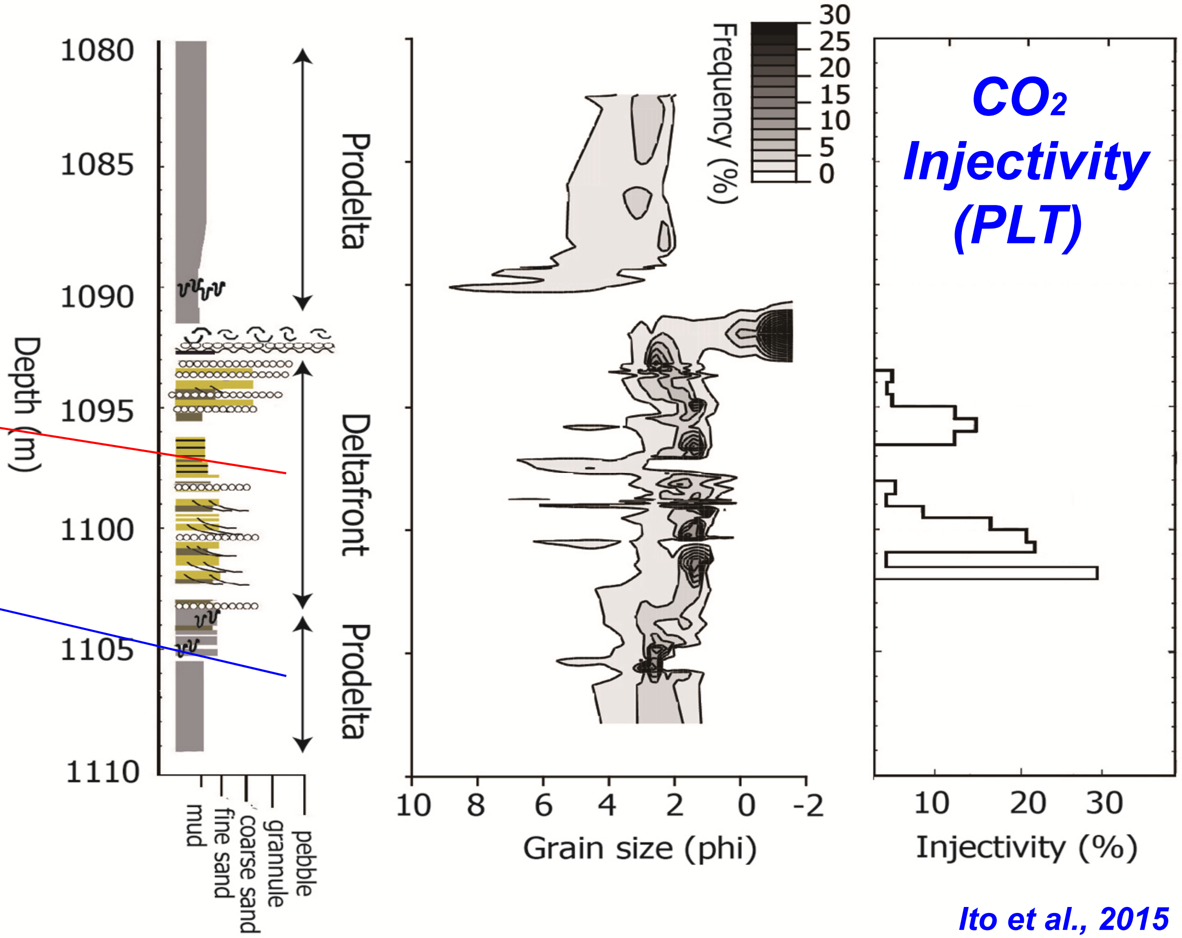
Integrating aspects from both 3D seismic and sequence stratigraphy

Application of Sequence Stratigraphy @ Nagaoka (injection well)

Clay content, γ-ray log



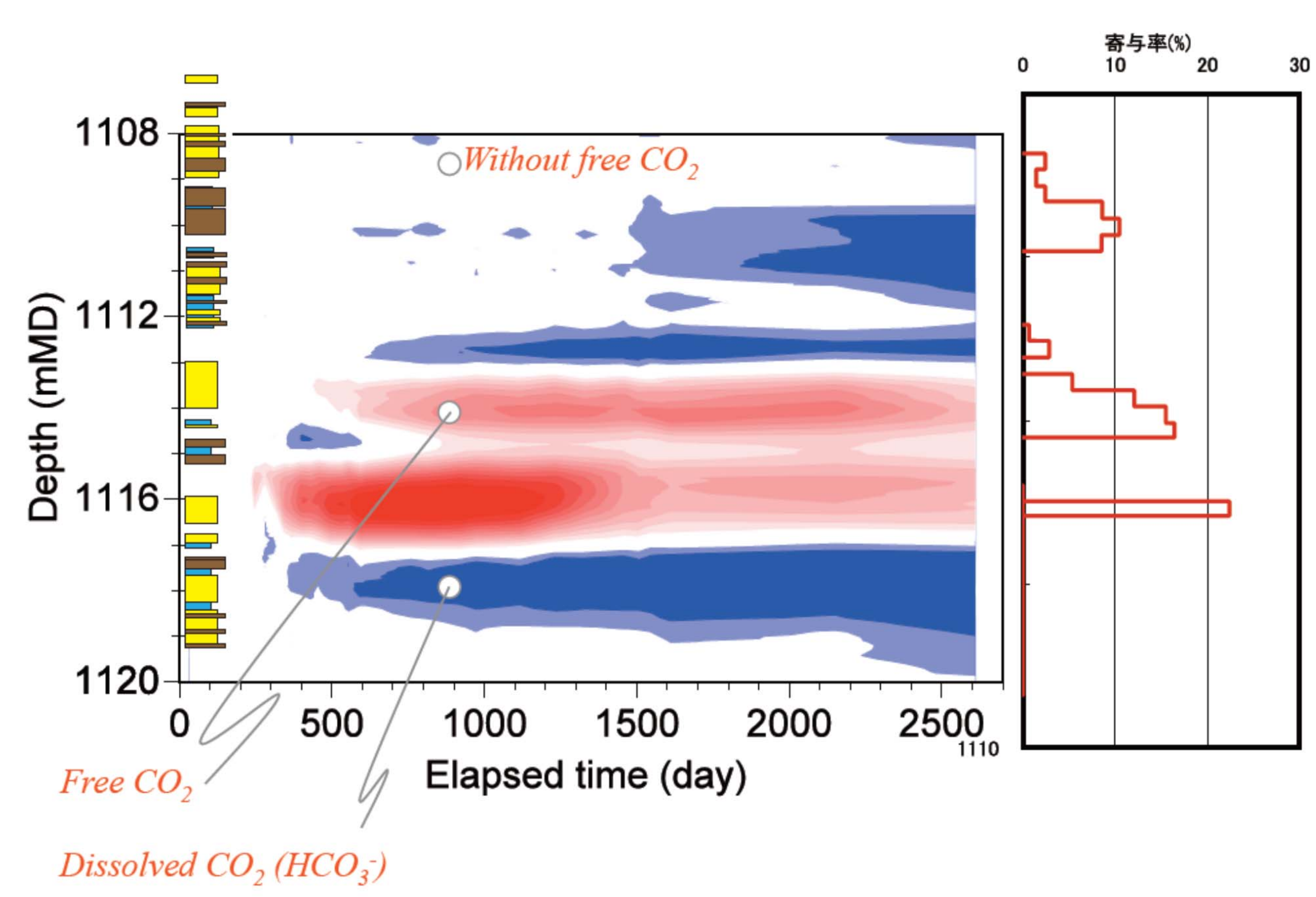
Porosity, Permeability



Ito et al., 2015

Detailed information at wells: Local to Spatial

Heterogeneity vs CO_2 distribution@Nagaoka



The New York Times | http://nyti.ms/2c9Oxfx

U.S.

Oklahoma Orders Shutdown of Wells After Record-Tying Earthquake

By NIRAJ CHOKSHI and HENRY FOUNTAIN SEPT. 3, 2016

Oklahoma officials on Saturday ordered oil and gas operators to shut down three dozen wastewater disposal wells following a 5.6-magnitude earthquake that tied a record as the strongest in state history.

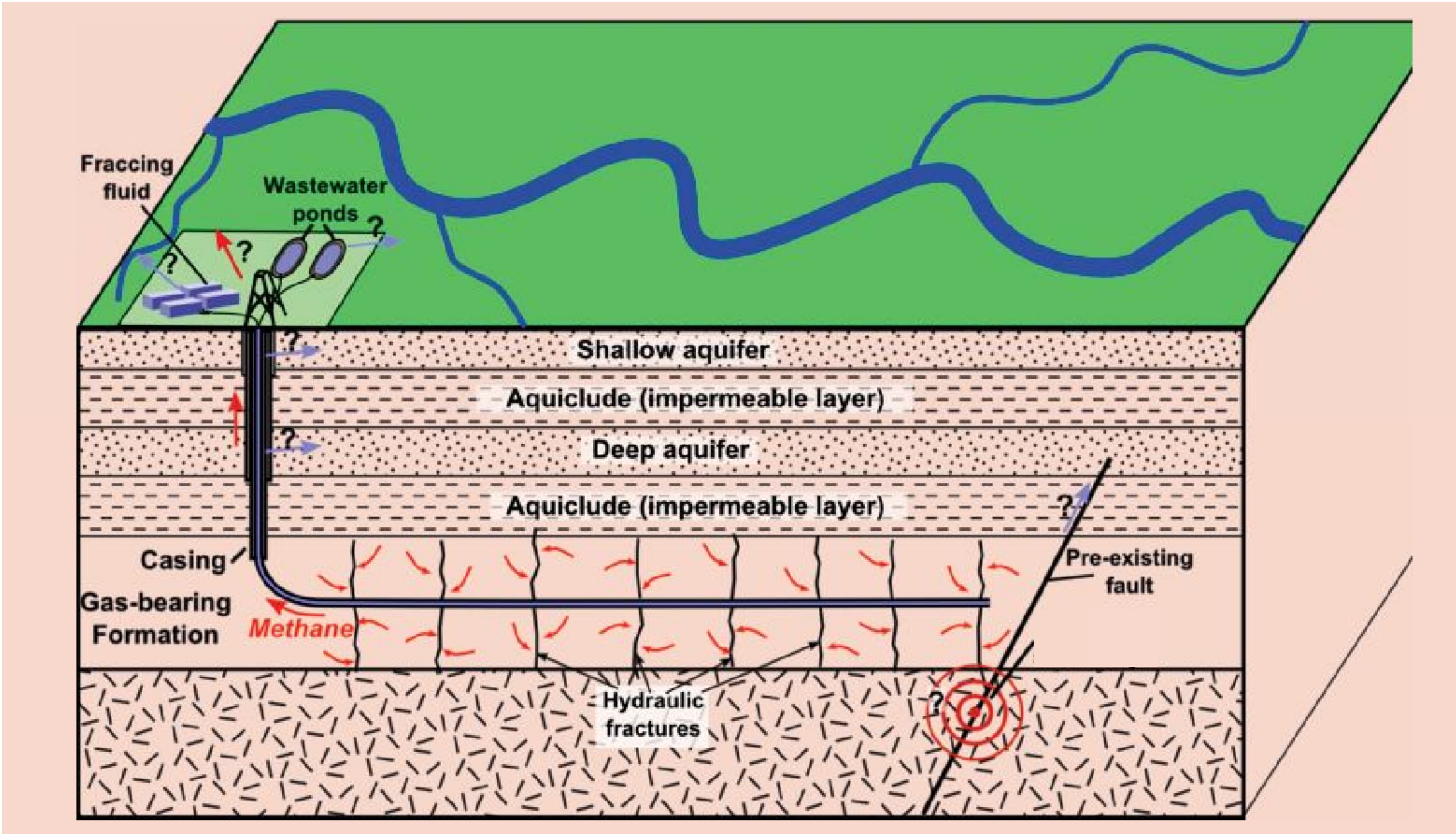
Weyburn（CO_2-EOR）Report

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

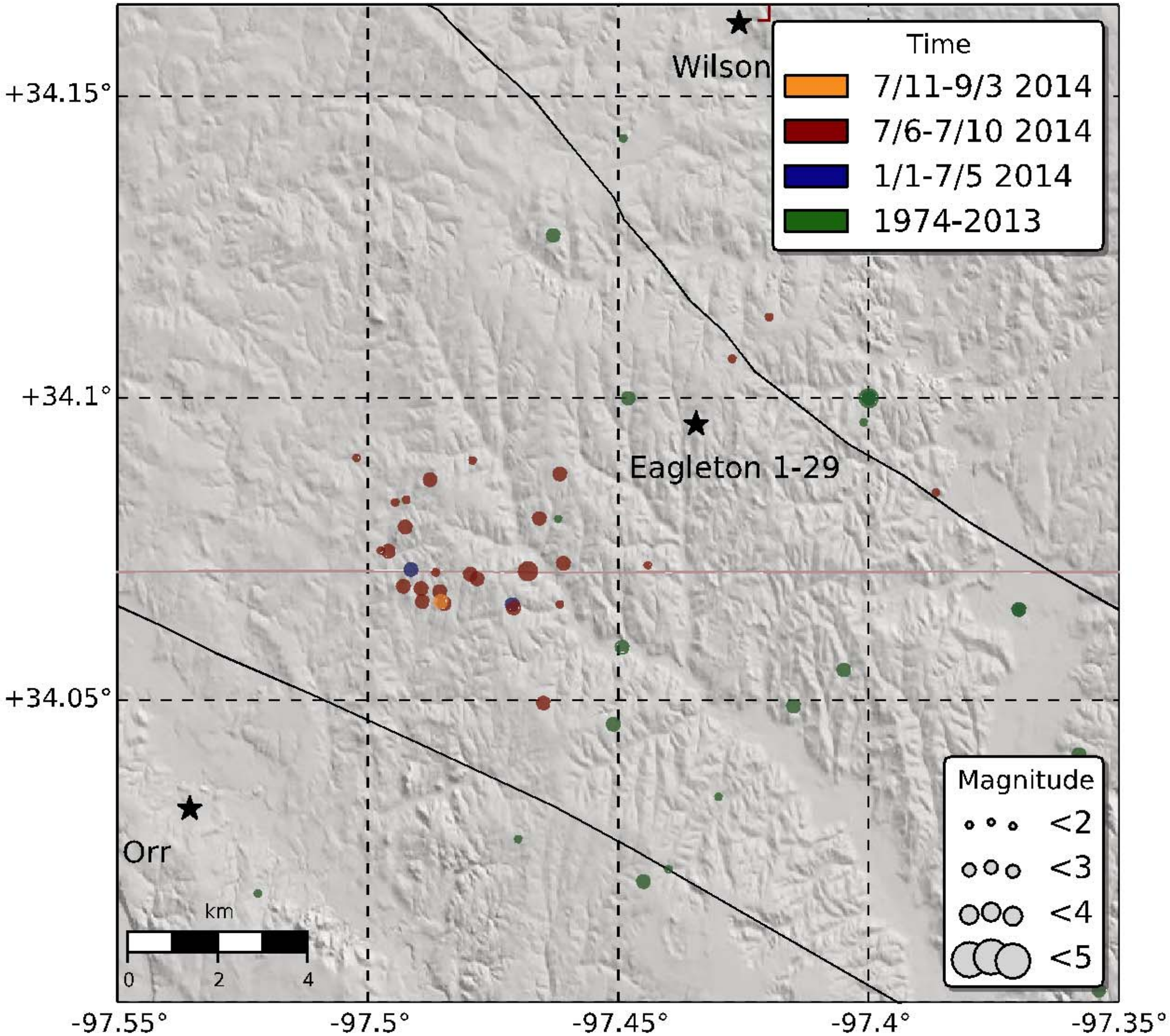
微小振動

Red = Weyburn CO_2 injection micro-earthquake sizes

Induced and Triggered Events in Fluid Injection



Microseismic Monitoring in Hydraulic Fracturing @Oklahoma



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.)

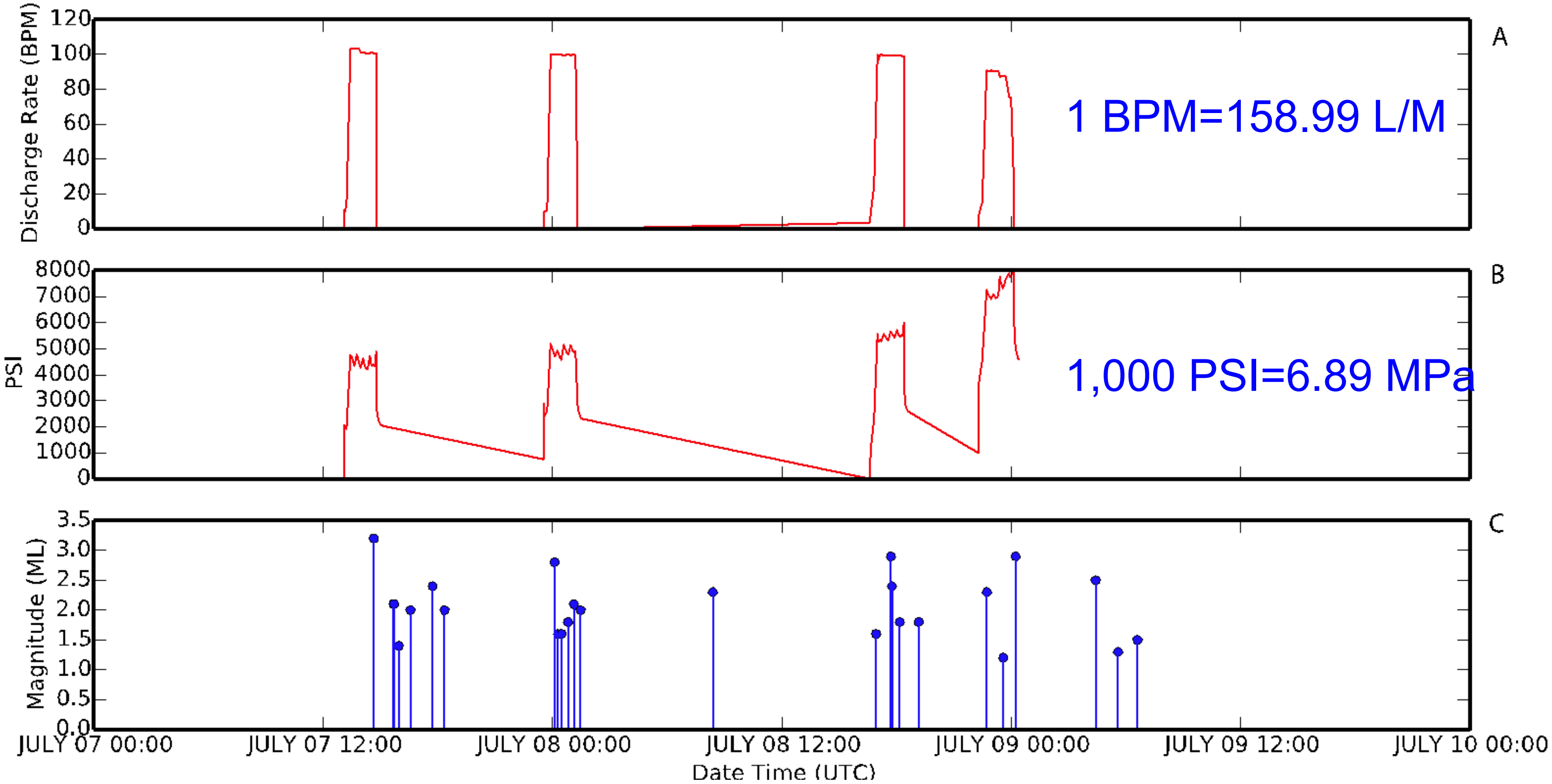
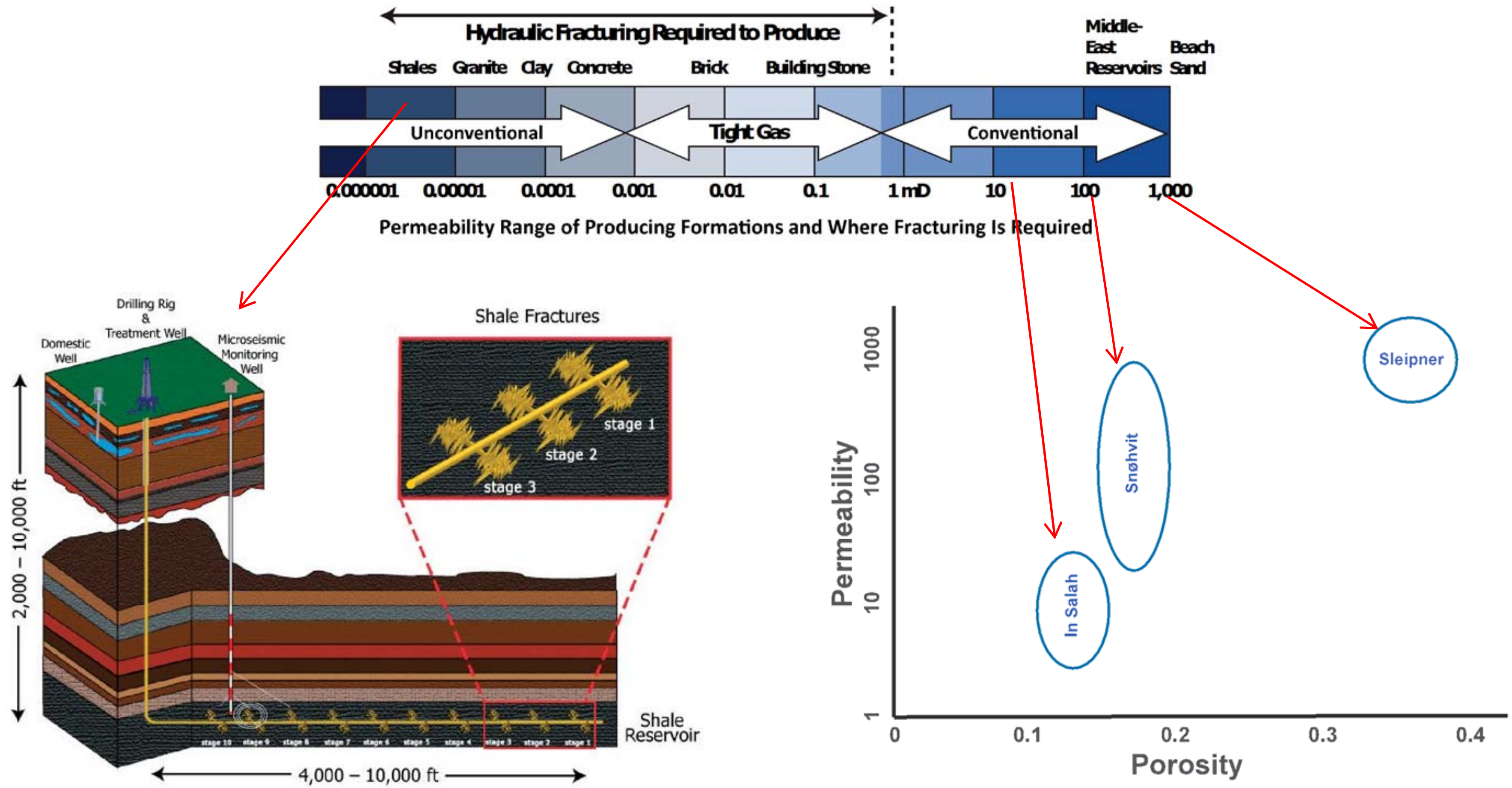


Figure 4. The plots span, in UTC time, the four fracking stages of Eagleton 1-29 well between July 7th 2014 and July 9th 2014. Plot A shows the discharge rate in BPM, or rate of injection, through time, plot B shows the pressure in PSI through time and plot C shows magnitude of earthquakes occurring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

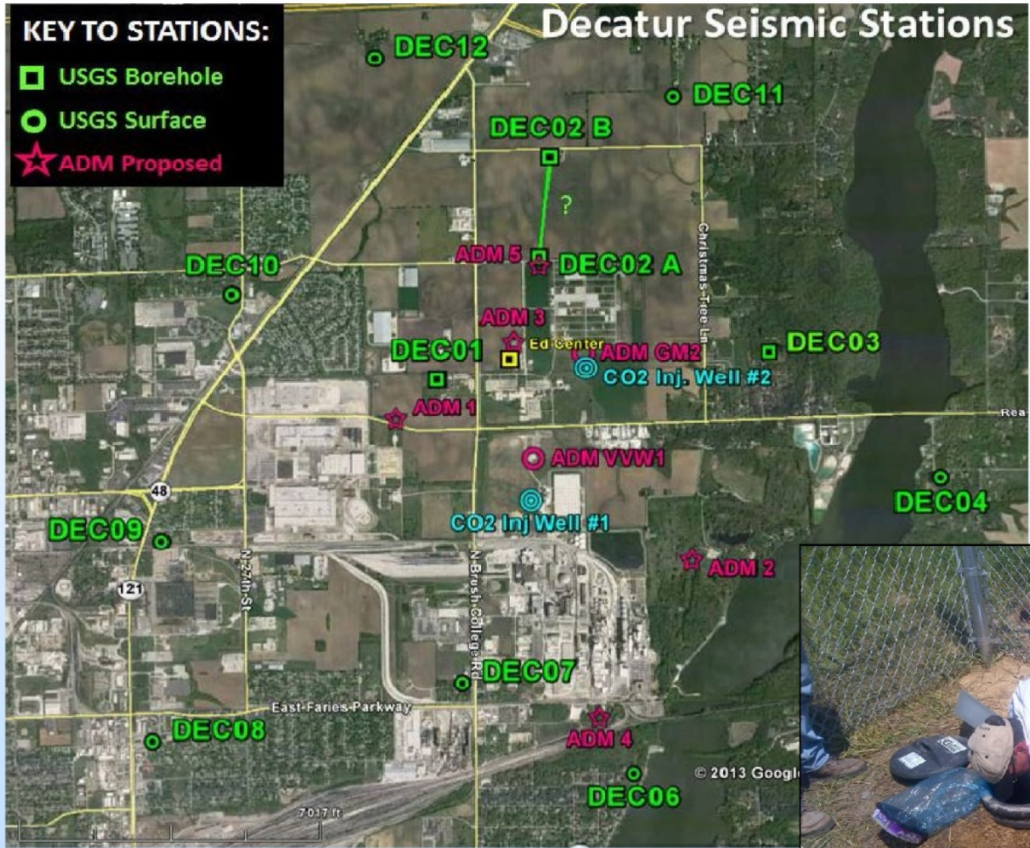
Induced Seismicity Potential in
ENERGY TECHNOLOGIES

Geothermal, Conventional and Unconventional Oil & Gas,
Waste Water Disposal, CCS



National Academy of Sciences, 2013

A Dense Microseismic Monitoring Network @ Decatur, Illinois (*onshore*)



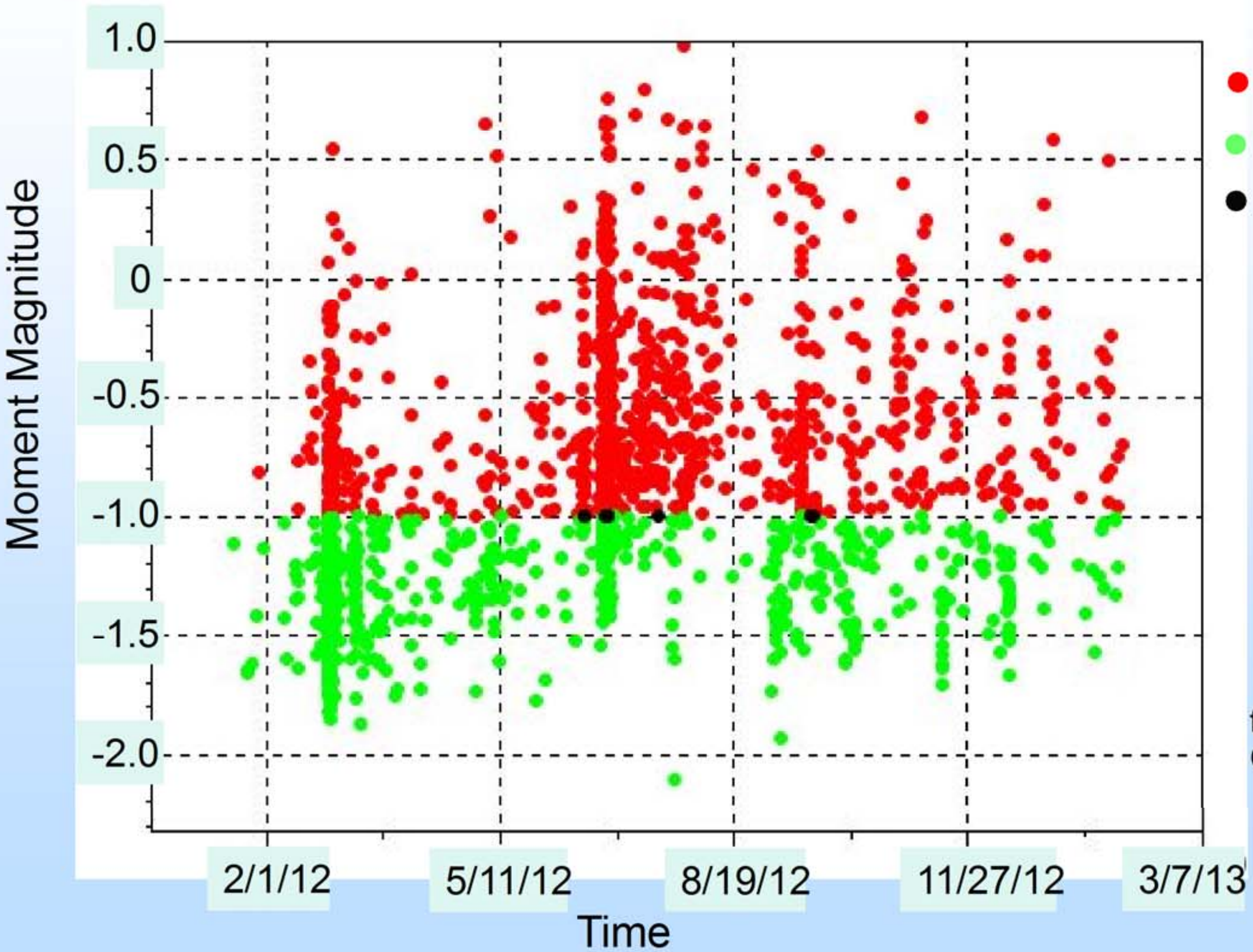
MGSC Installed Five Surface seismic Stations: ADM1-5

Inject, Monitor, and Model

Finley., 2013

Inject, Monitor, and Model

General Trends in Activity: Moment Magnitudes vs. Time

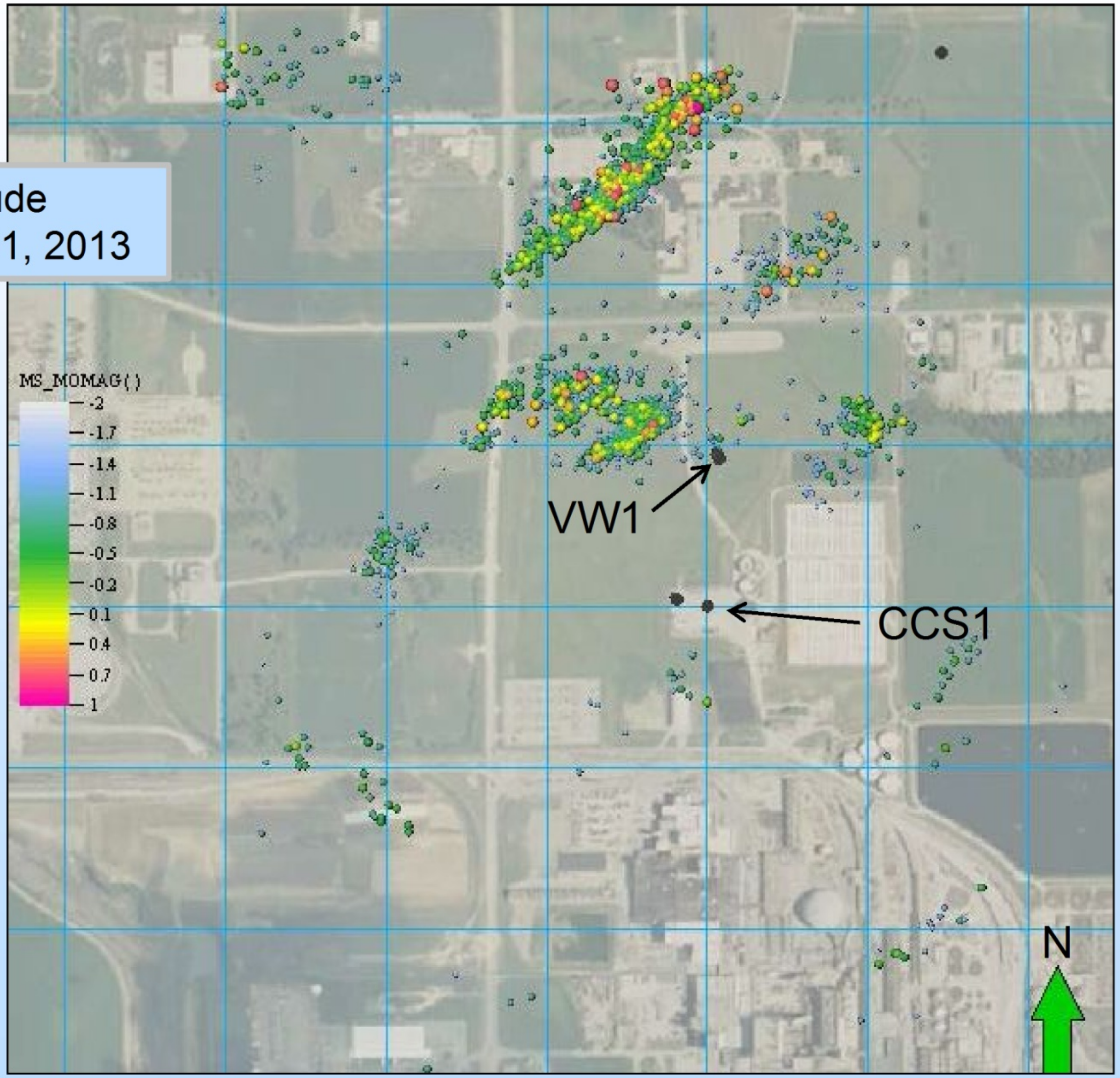


Finley., 2013

from Schlumberger Carbon Services

Microseismic Cluster Activity: Cluster Locations with Relation to Surface

Moment Magnitude
Jan 18, 2012 – July 31, 2013

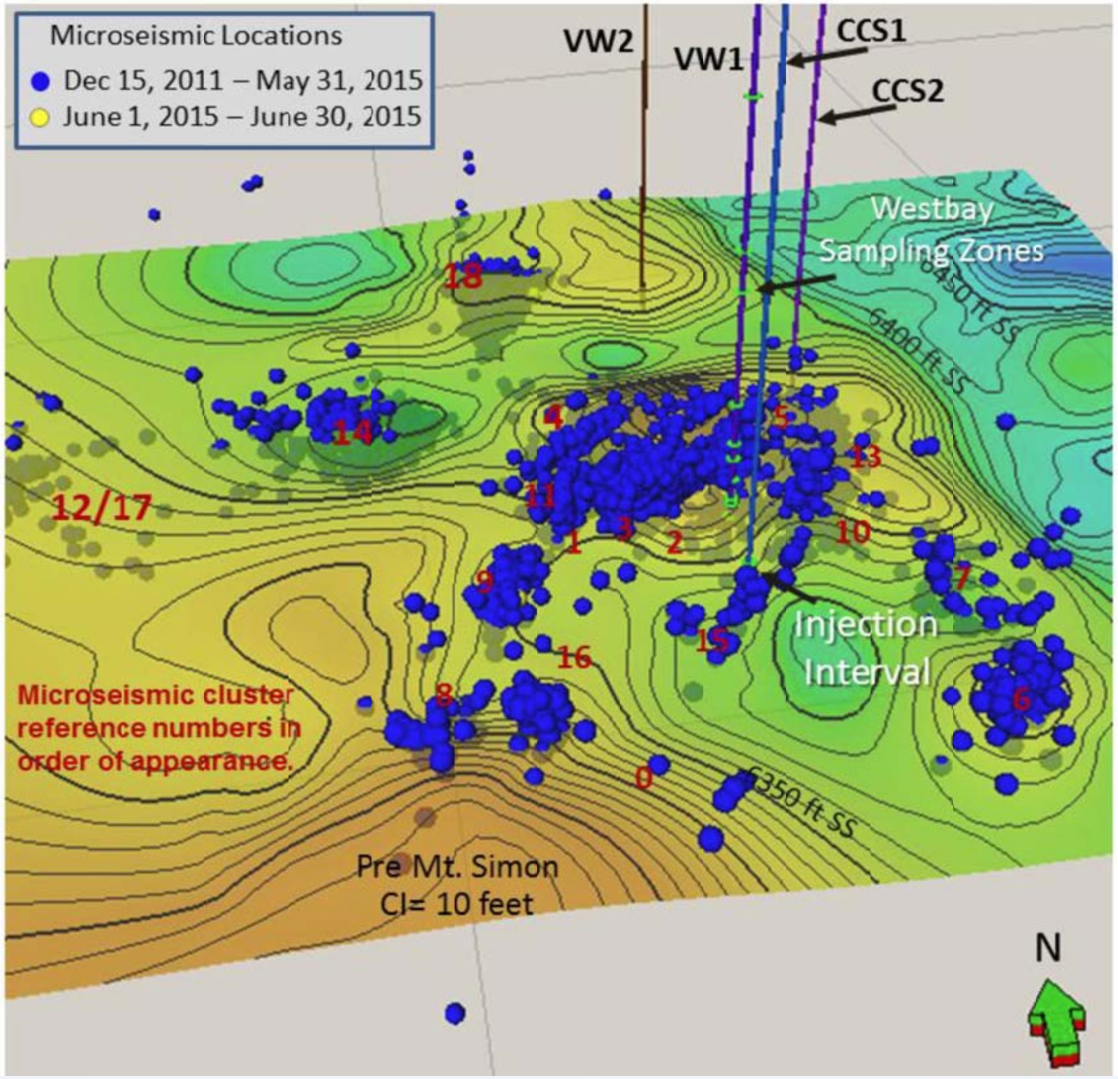


Inject, Monitor, and Model

Finley., 2013

from Schlumberger Carbon Services

Microseismic Activity and Basement @Decatur



Microseismic Cluster Activity: Relationship to Basement Structure

Greenberg, 2015

from Schlumberger
Carbon Services

Summary Information about Historical Felt Seismic Events Caused by or Likely Related to Energy Tech Develop in US

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

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

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

- French administration asked for alarms thresholds

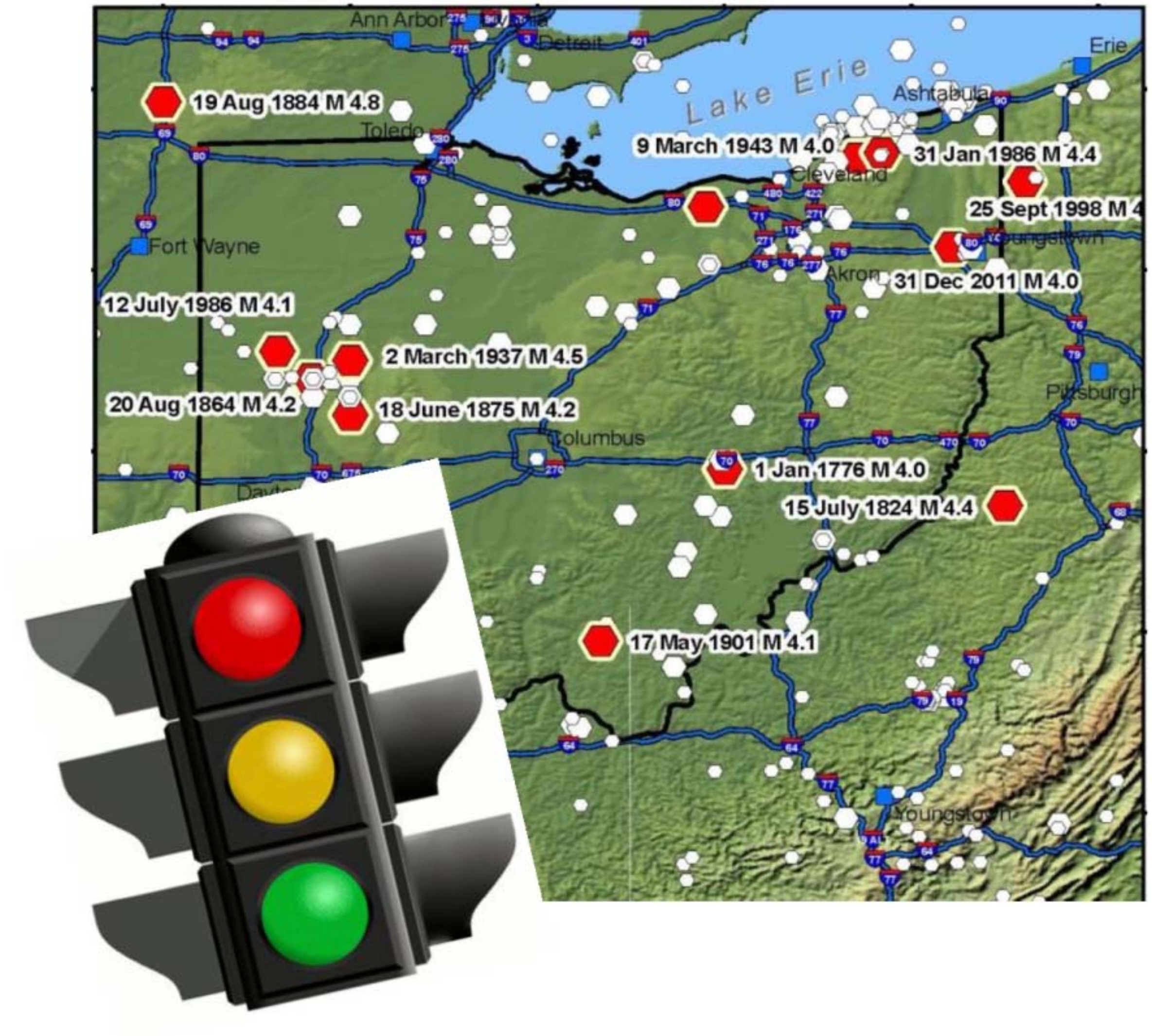
Official alarms thresholds

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

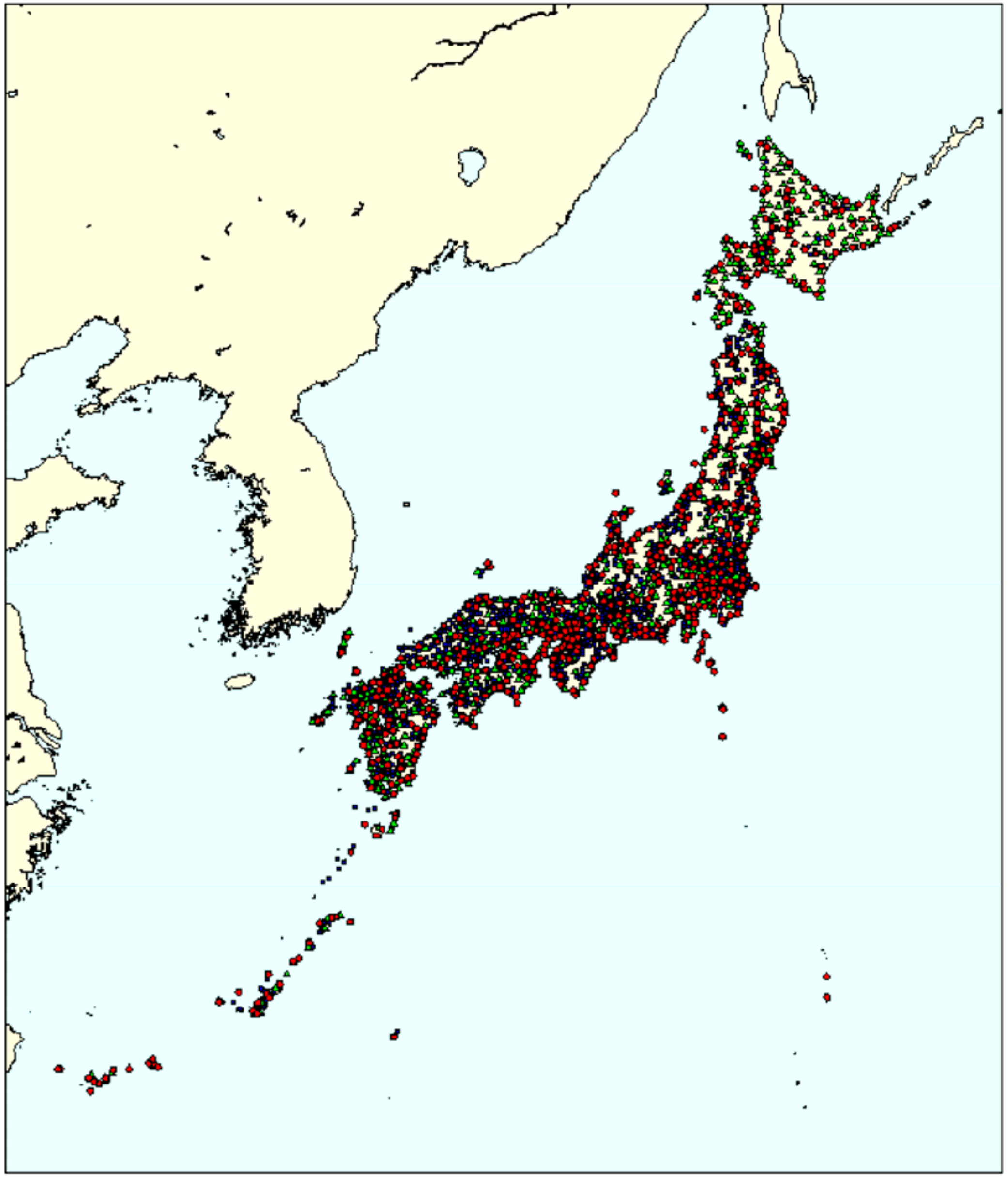
Billiot (2011)

Advanced Traffic Light System for CO_2 Storage

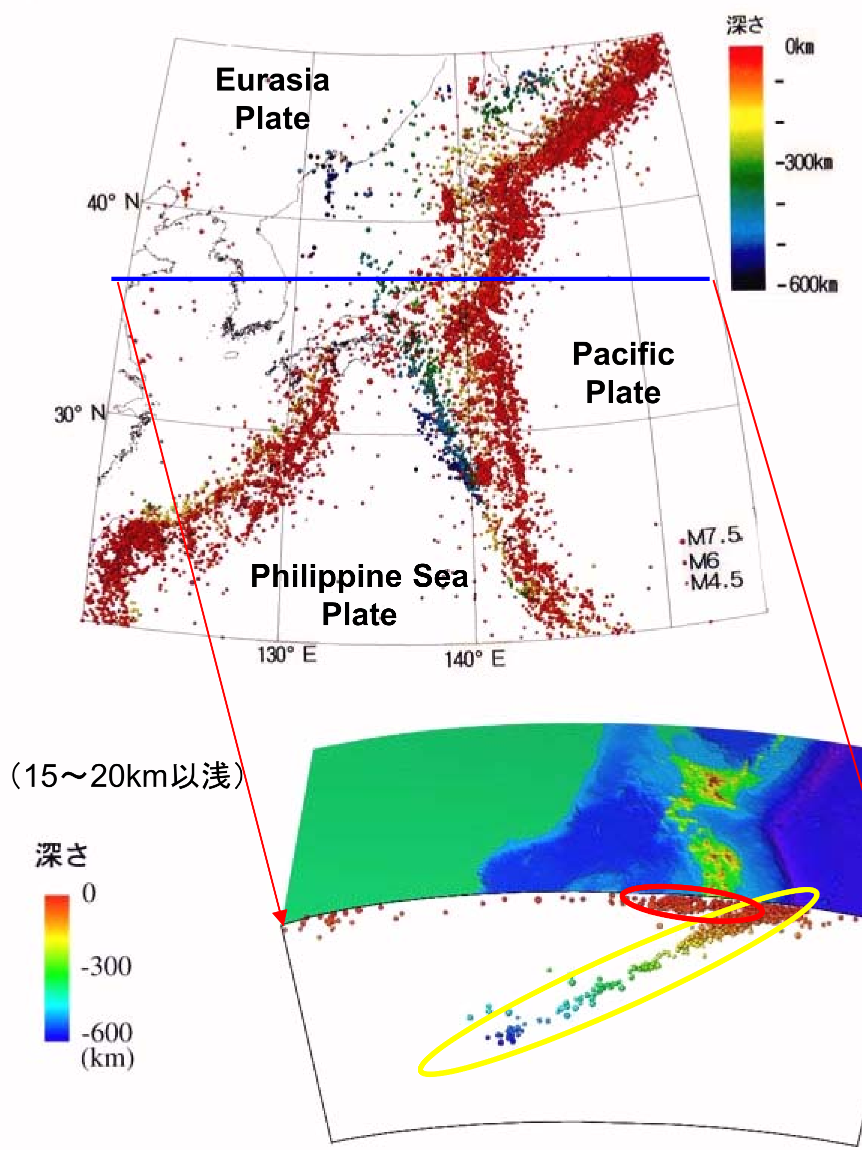


震度観測点（全国）

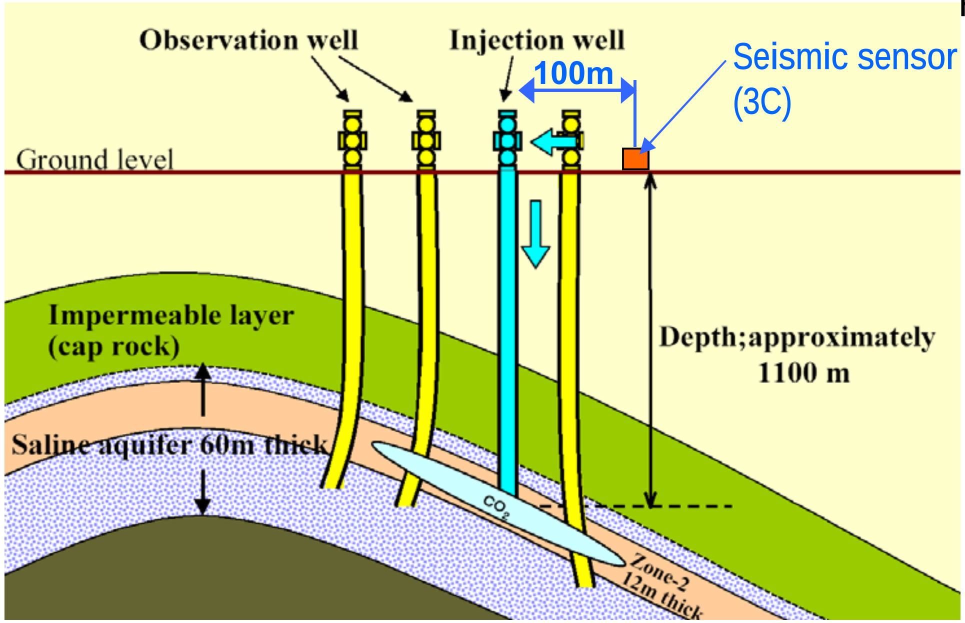
●気象庁：■地方公共団体：▲独立行政法人防災科学技術研究所

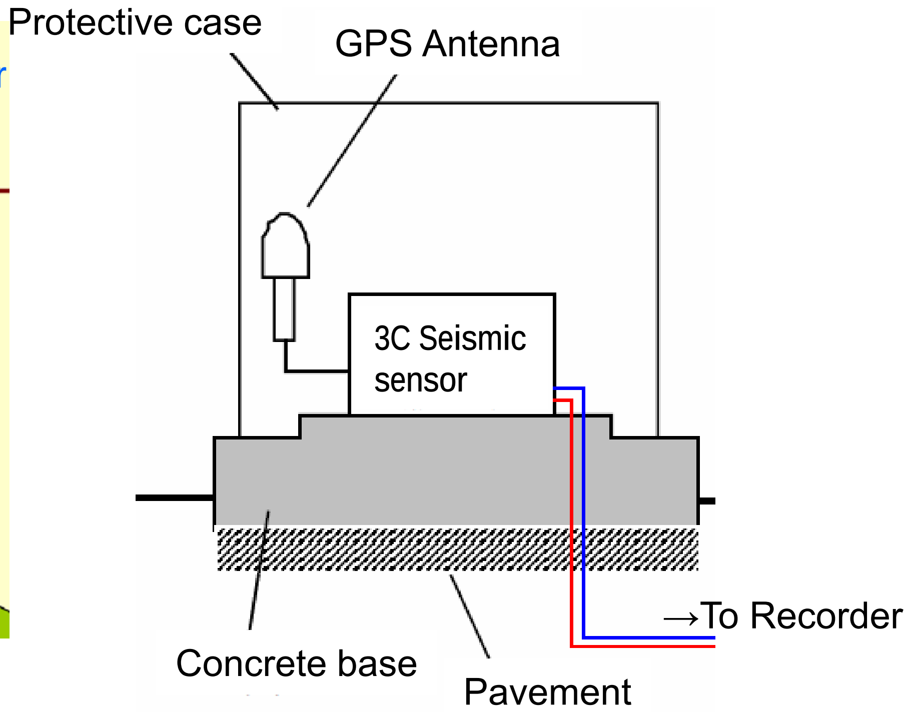


Natural Earthquake in Japan



Microseismic Monitoring at Nagaoka Site

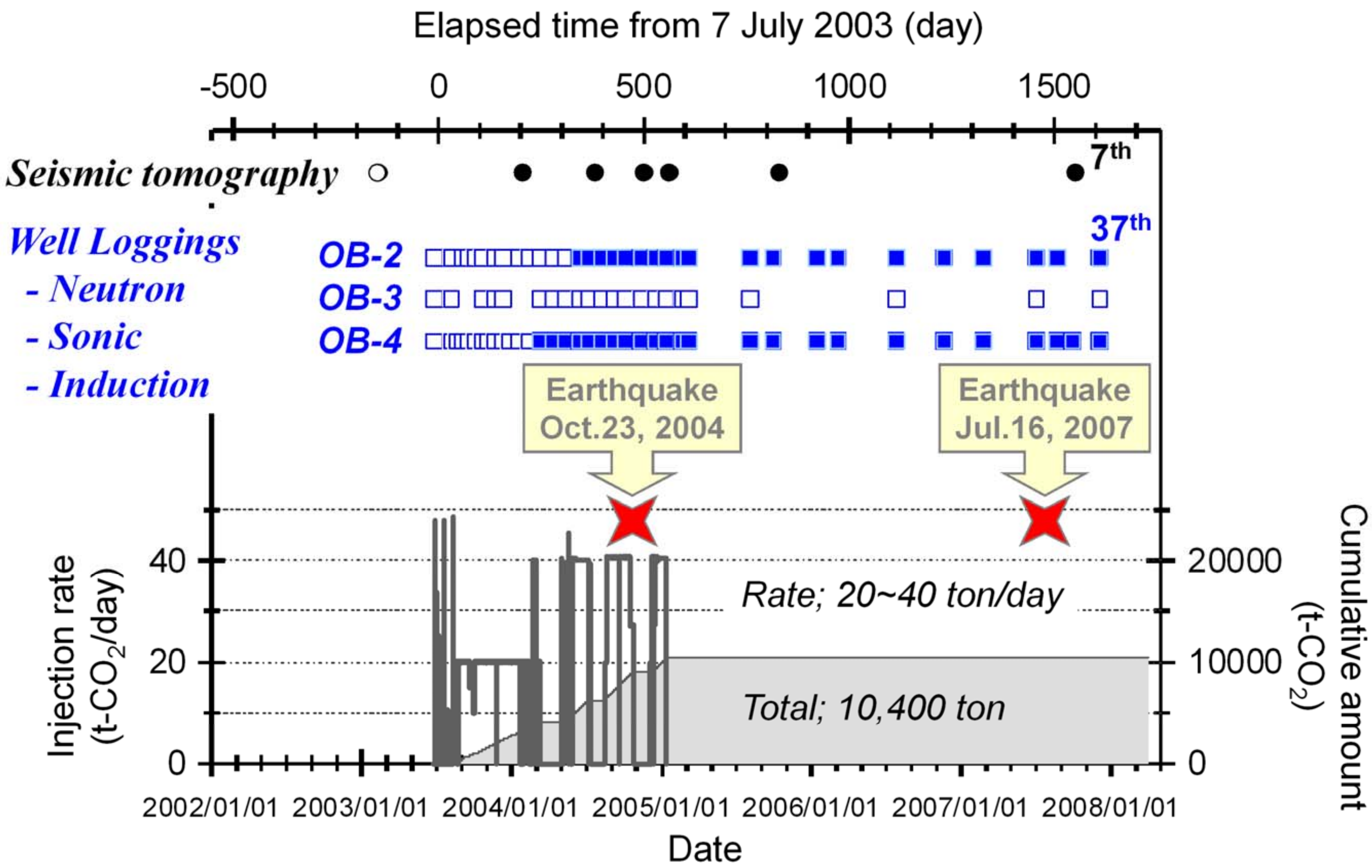




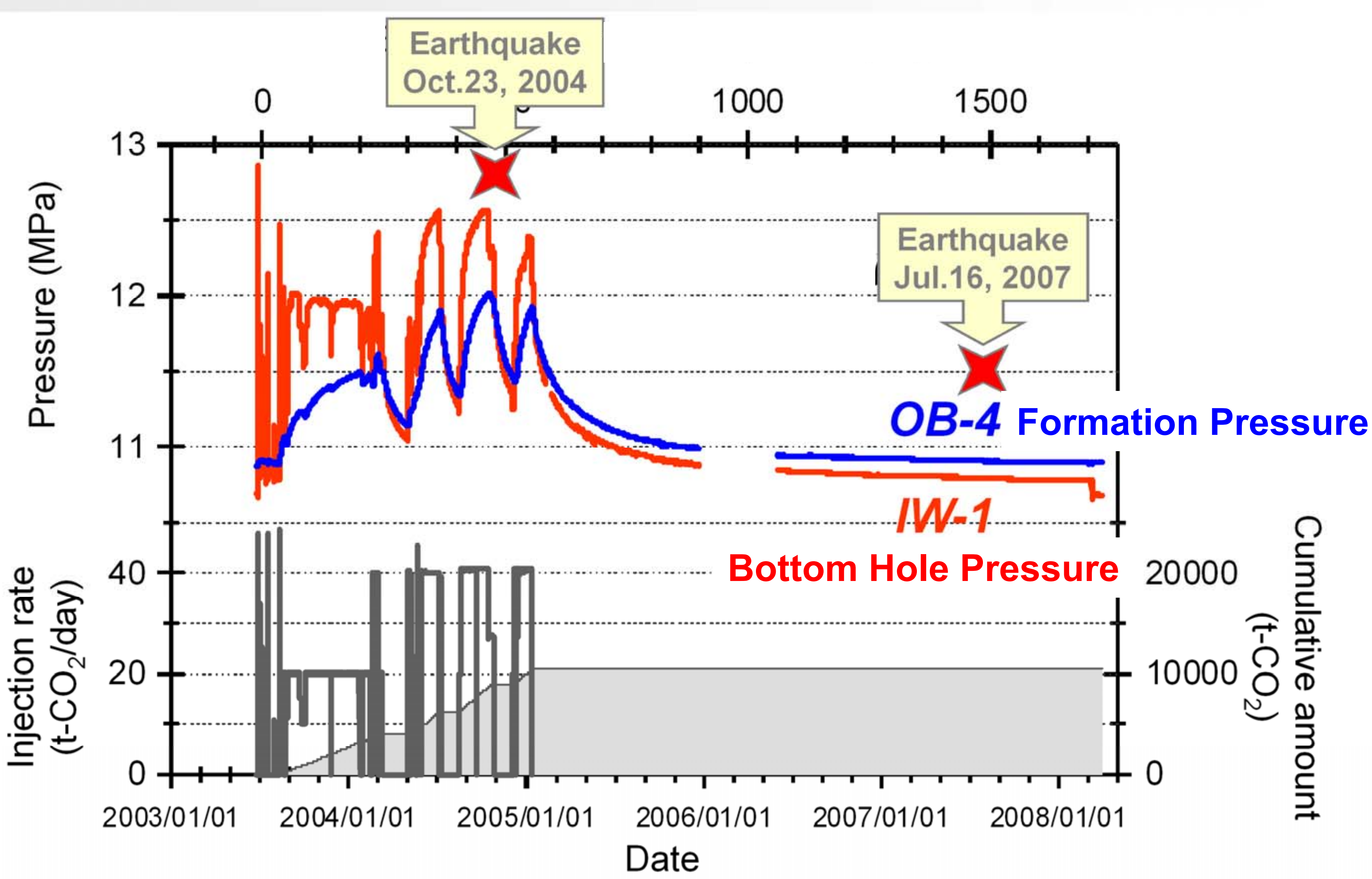
Seisimic sensor specifications

Item	specification
Seismic Sensor (ALTUS Enta; Kinemetrics)	Sensor type: triaxial EpiSensor force balance accelerometer Full scale: ±2G Frequency range: DC～100Hz Dynamic range: 135dB
Seismic Recorder (ALTUS –K2; Kinemetrics)	Number of channels: 6ch Sampling time: 20, 40, 50, 100, 200, 250Hz Frequency range: DC～40Hz（in 100Hz sampling case） Dynamic range: 114dB（19Bit） Power supply: Internal battery 12V, 12Ah

Geophysical Monitoring (incl. earthquake safety surveys)



Pressure Changes at Injection and Observation Wells



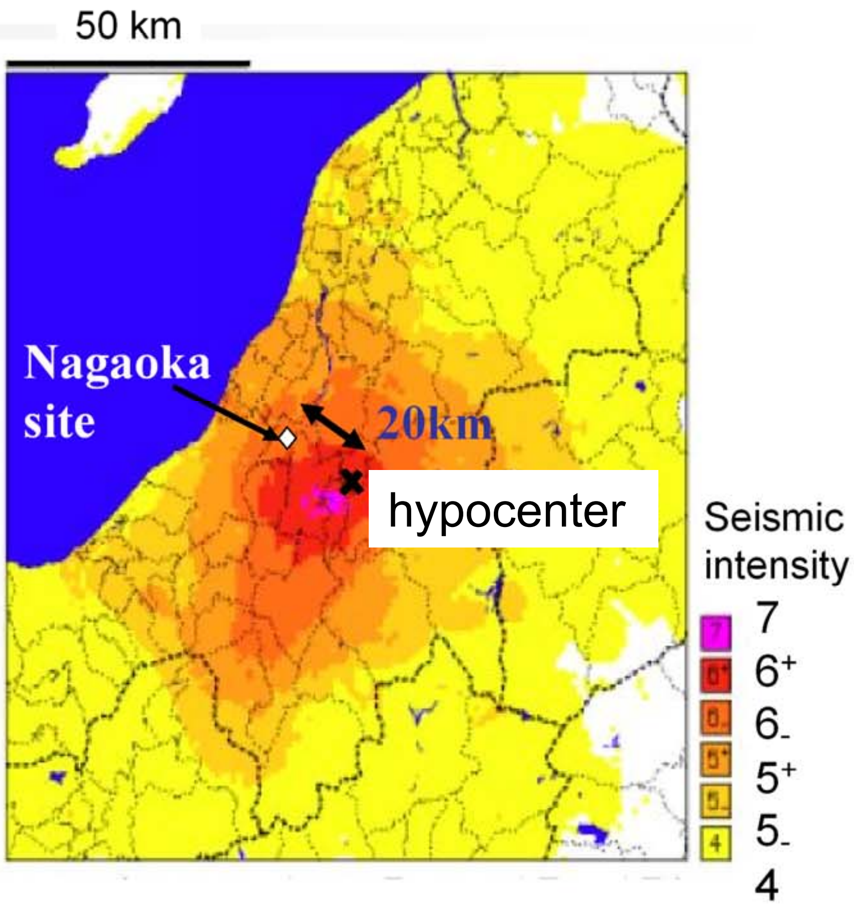
The Mid Niigata Prefecture Earthquake in 2004

Main shock: 23 Oct 2004
M6.8 at 10km depth
Seismic intensity: 7
→Injection was automatically stopped at the main shock.

Access road was damaged.

CO_2 detector (No leak)

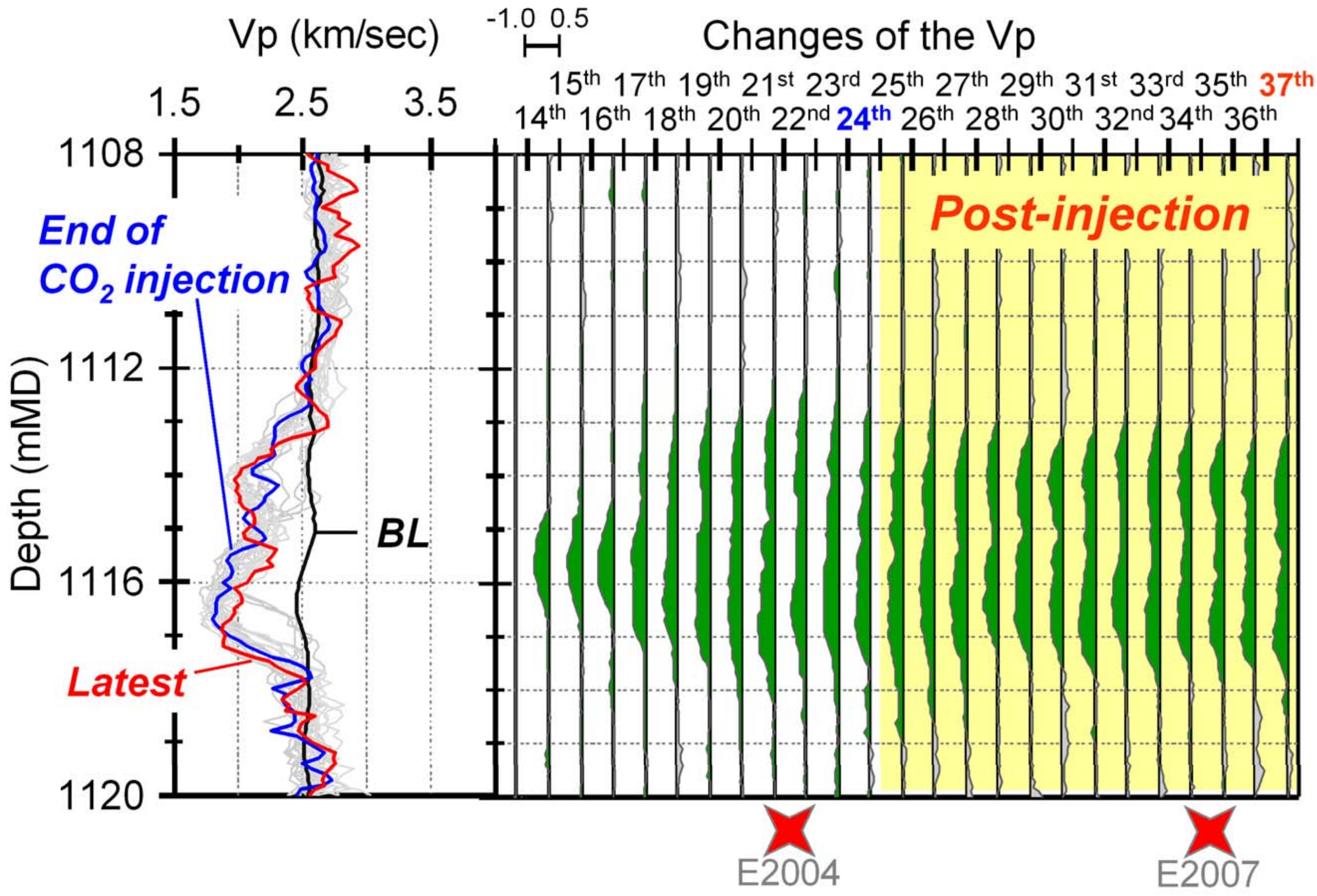
Injection was carefully resumed after confirming safety (6 Dec 2004)
injection rate: 40t-CO_2/day



(GSJ, 2004 http://www.gsj.jp/jishin/chuetsu_1023/)

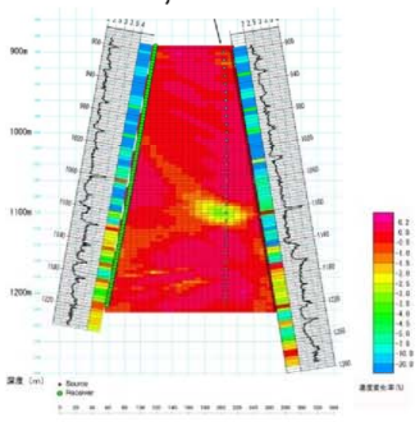
For detail: Xue et al. (2006)
3rd Monitoring Network Meeting (Melbourne)

Sonic Logging (Vp) @ OB-2

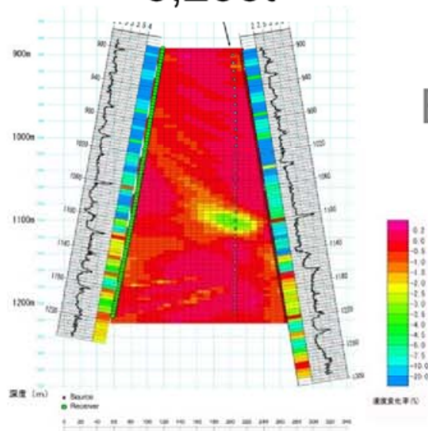


Results of Crosswell Seismic Tomography

MS1/BL
3,200t

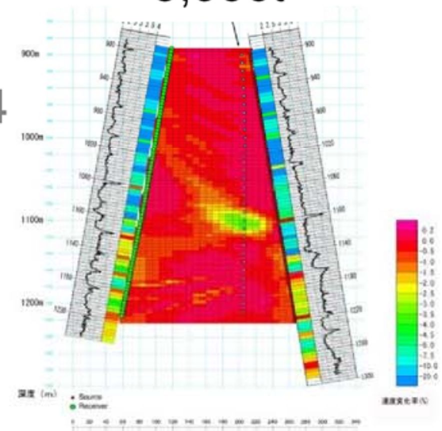


MS2/BL
6,200t

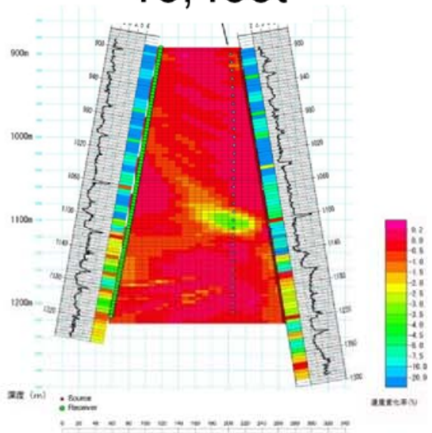


E2004

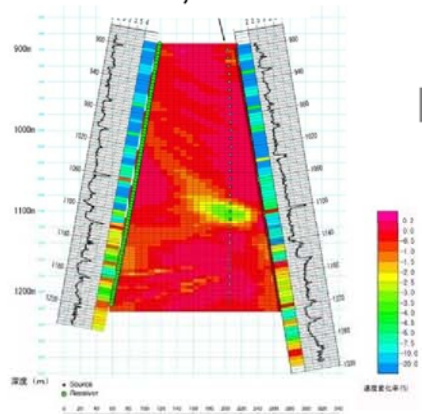
MS3/BL
8,900t



MS4/BL
10,400t

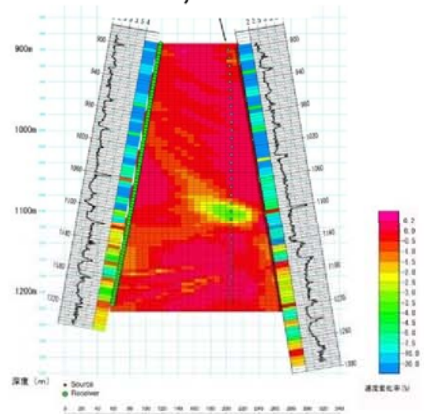


MS5/BL
10,400t

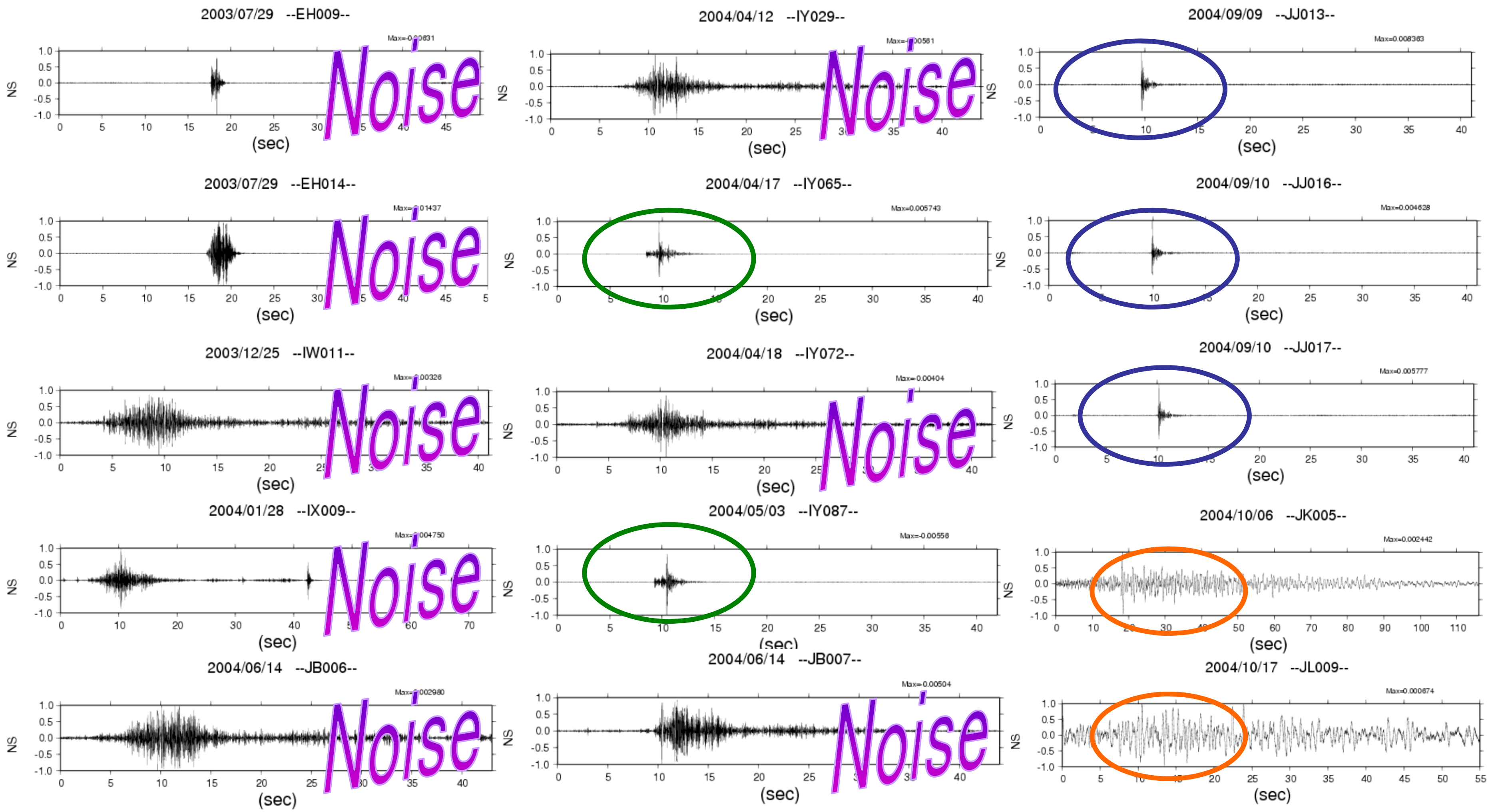


E2007

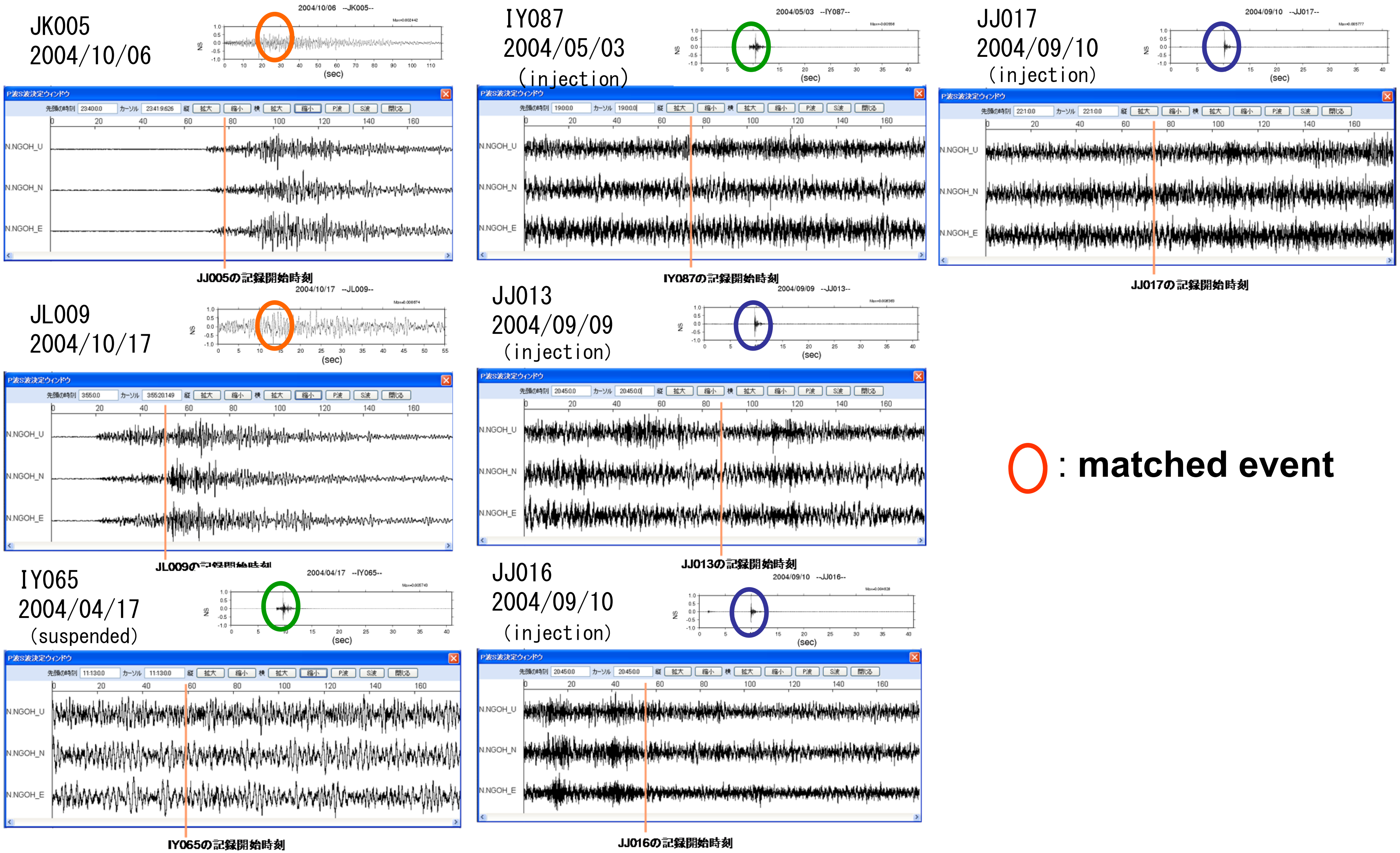
MS6/BL
10,400t



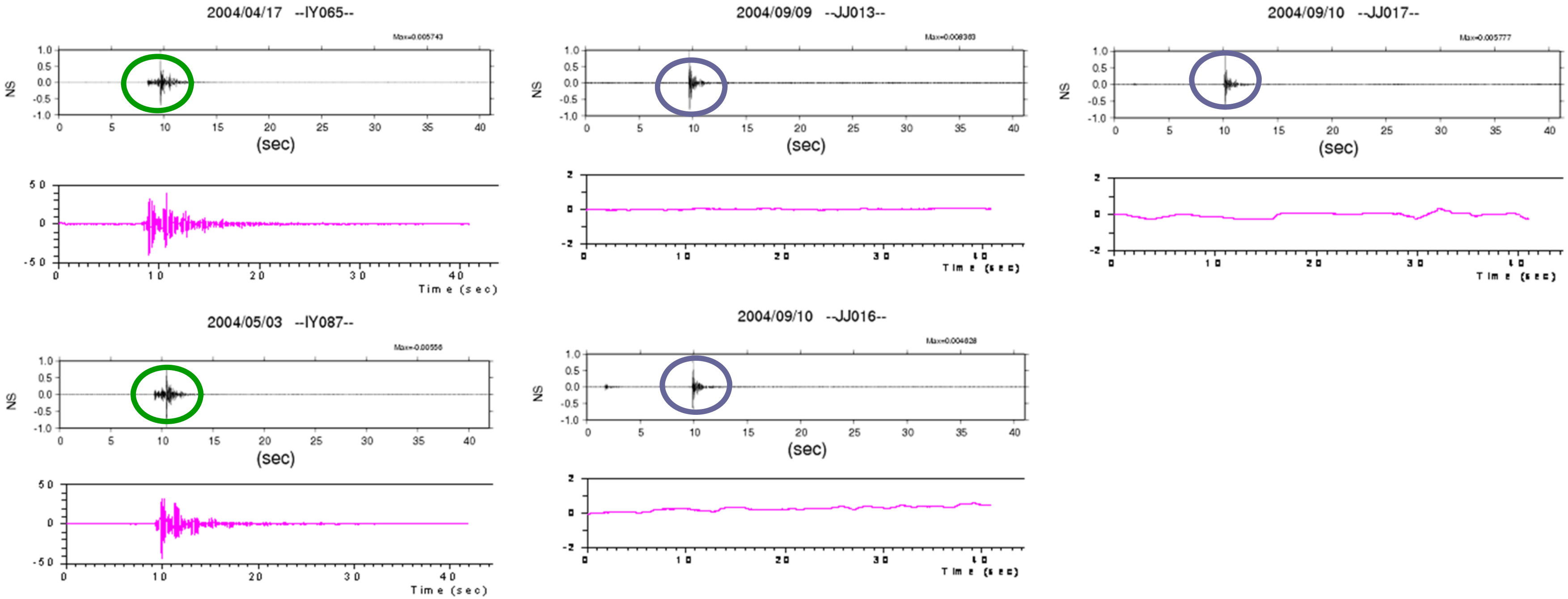
Likely Events Observed from starting injection to Mid-Niigata Earthquake



Comparison with Hi-net data



Comparison with Hydrophone data



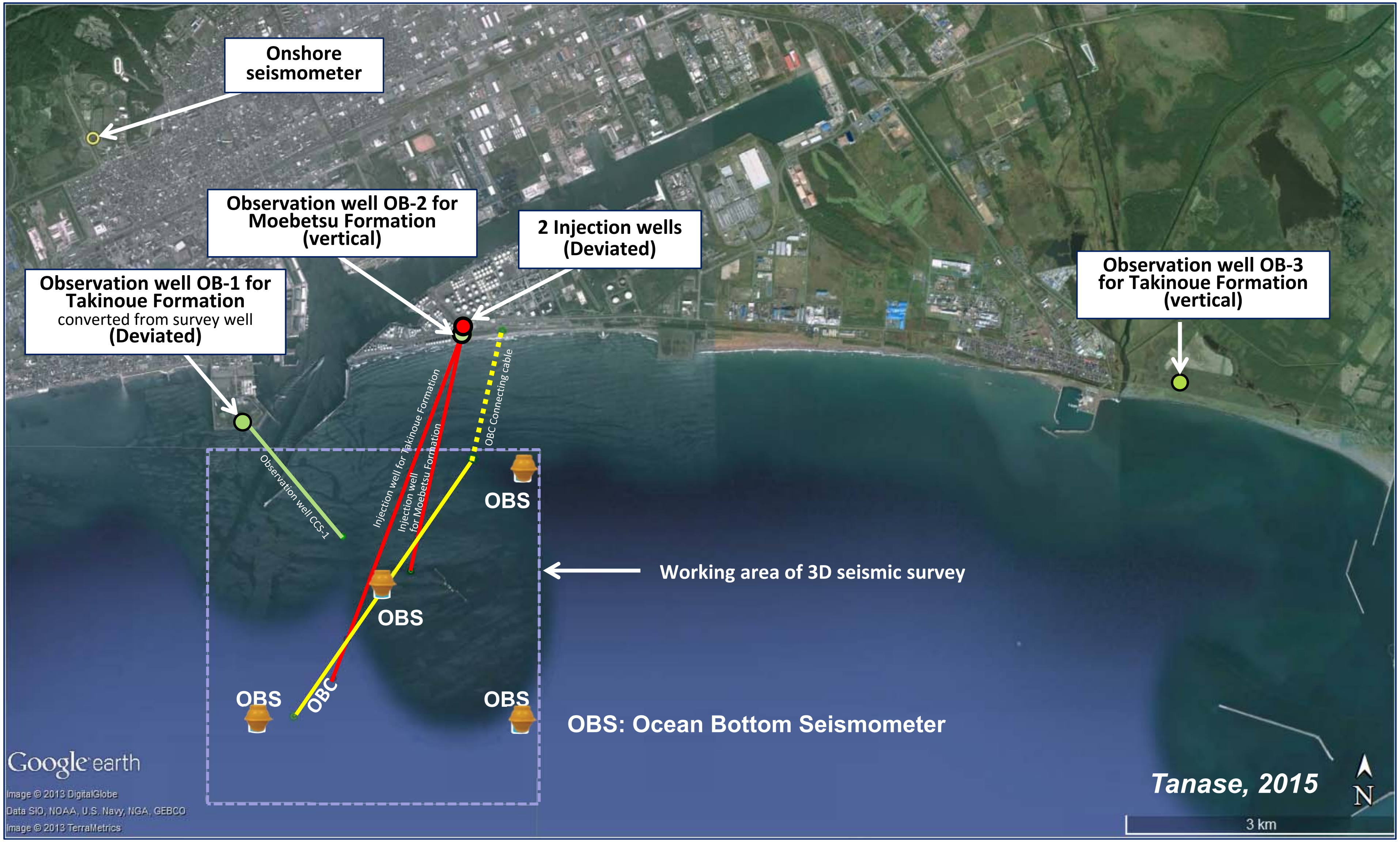
: matched with Hydrophone record, phase lag in P, S-waves

→ ***possibly seismic event***

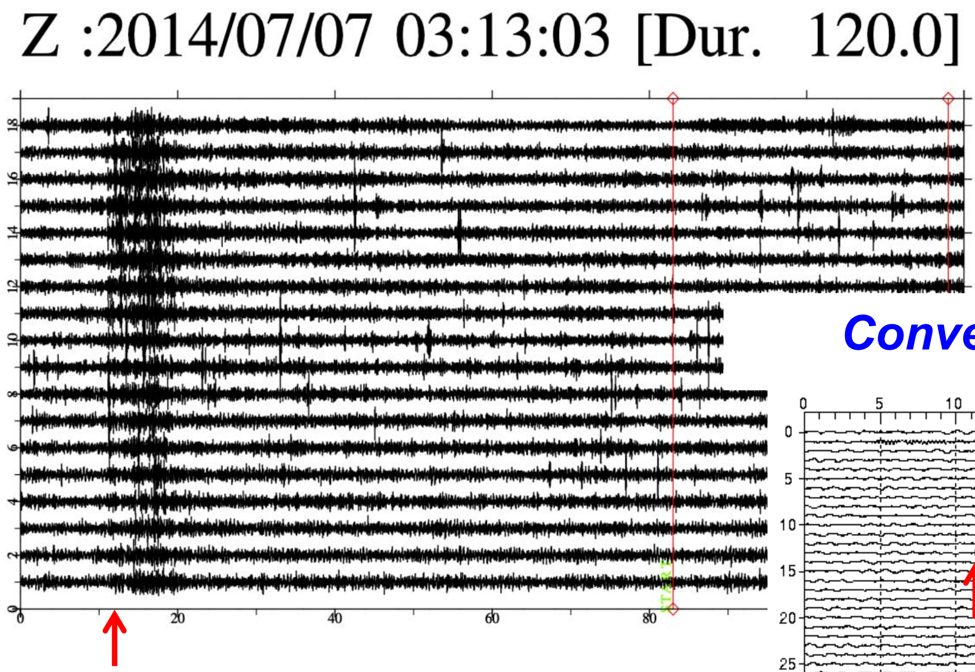
: no record in Hydrophone data, no phase lag in P, S-waves

→ ***Noise***

A Dense Microseismic Monitoring Network @Tomakomai (*offshore*)

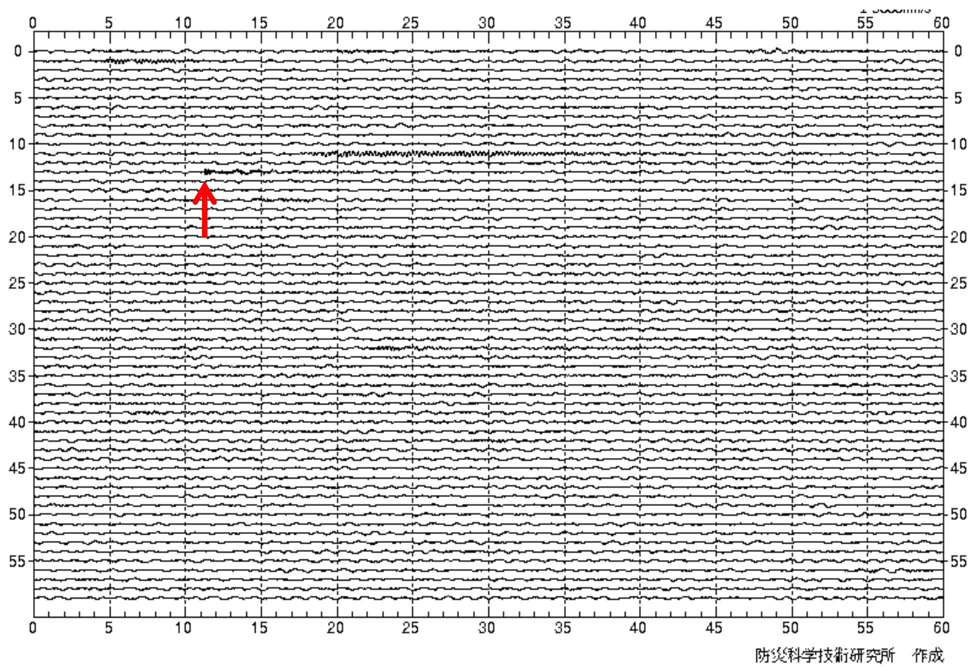


Microseismicity (M<1) detected by OBC and Conventional seismometer @ Tomakomai



OBC Record

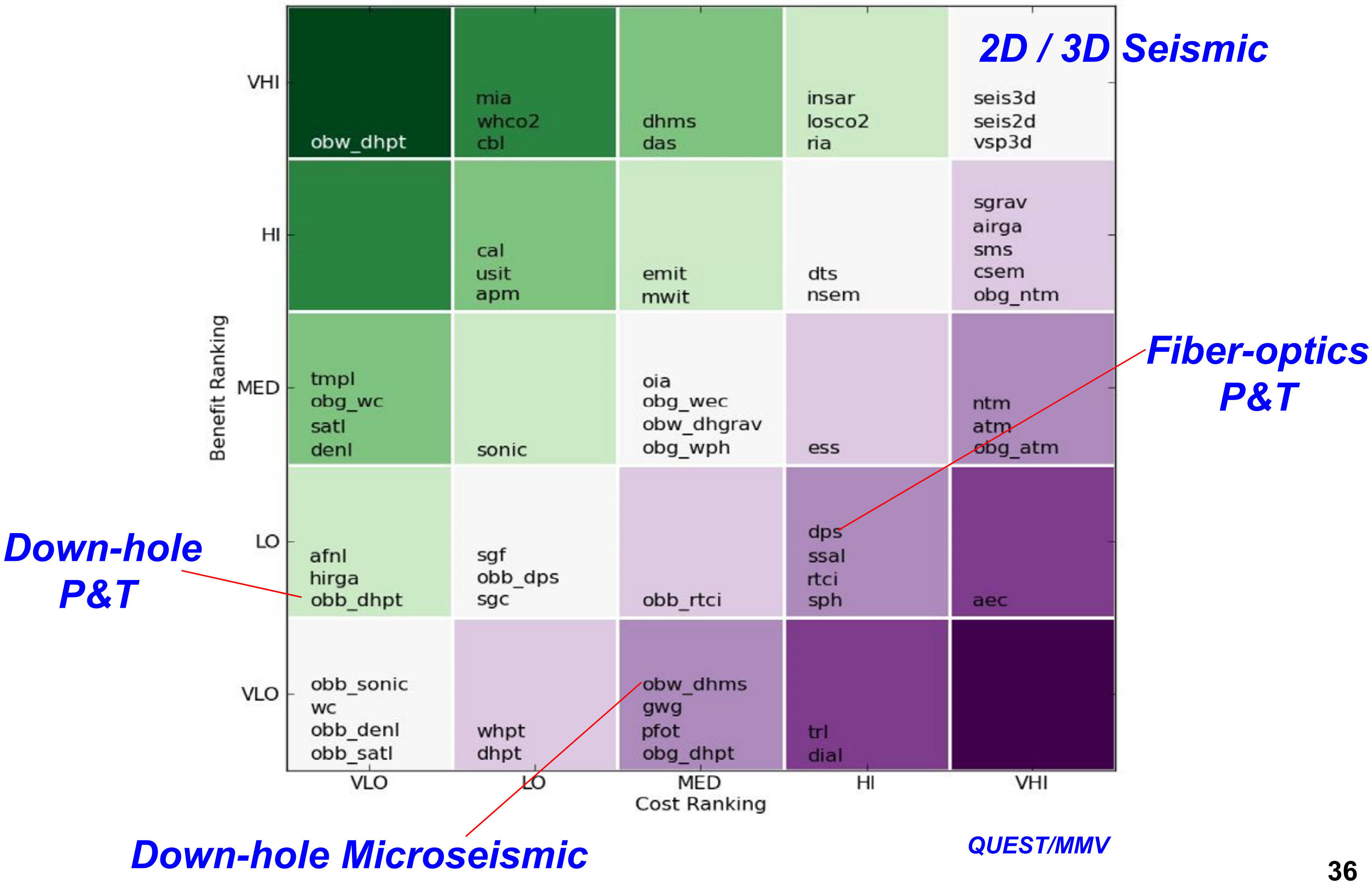
Conventional Seismometer Record



The proverb says:

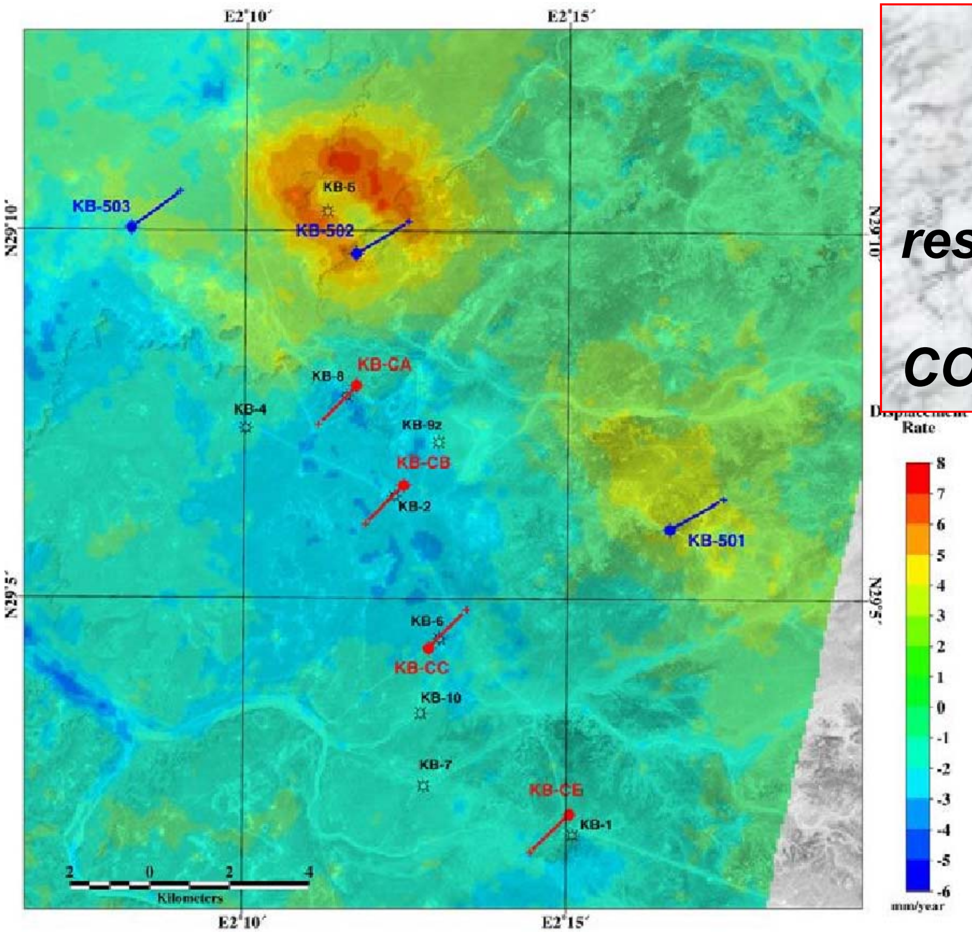
"Kill two birds (2D/3D Seismic, Microseismic) with one stone (OBC)"

Monitoring Techs & Cost-Benefit Ranking



QUEST/MMV

Uplift Caused by Pressure Buildup at In Salah During CO_2 Injection



Pressure buildup depending on

reservoir porosity & permeability,

CO_2 injection rate & volume.

Uplift at ground surface

How to interpret?

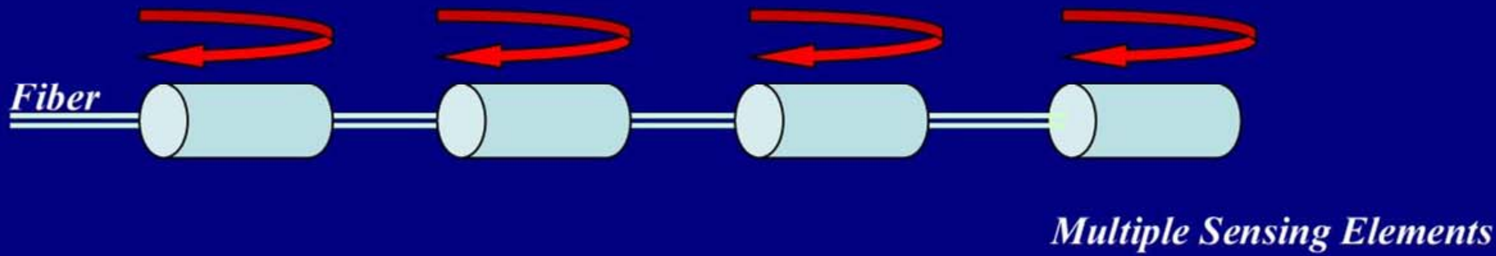
Pressure buildup at subsurface

Need continual strain data along depth?

Single → Multi → Distributed

- Single Point Sensor

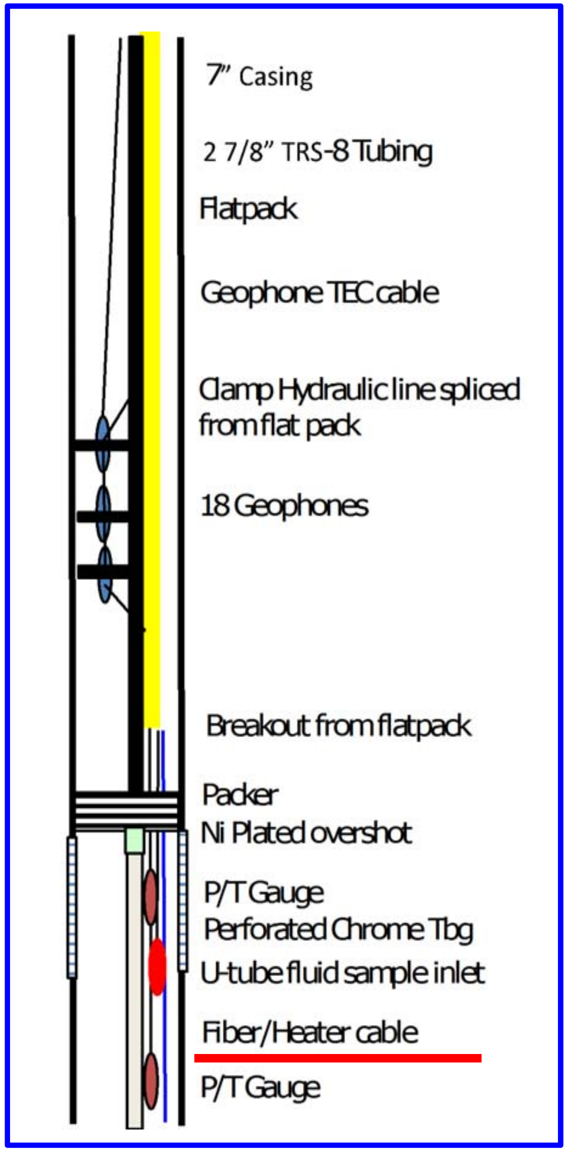
- Multi-point (quasi-distributed) Sensor



- Distributed Sensor

(Dria, SPE/DL 2012)

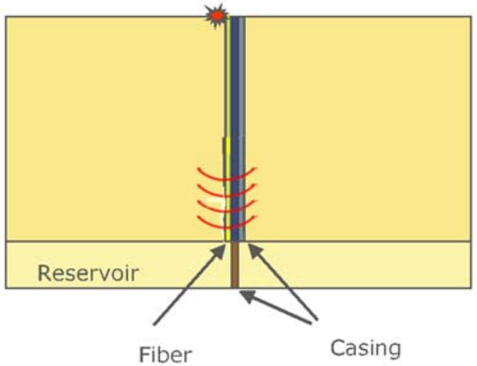
Application of Fiber Optics@QUEST



QUEST Project

Zero-Offset Source for CO2 Leak Detection

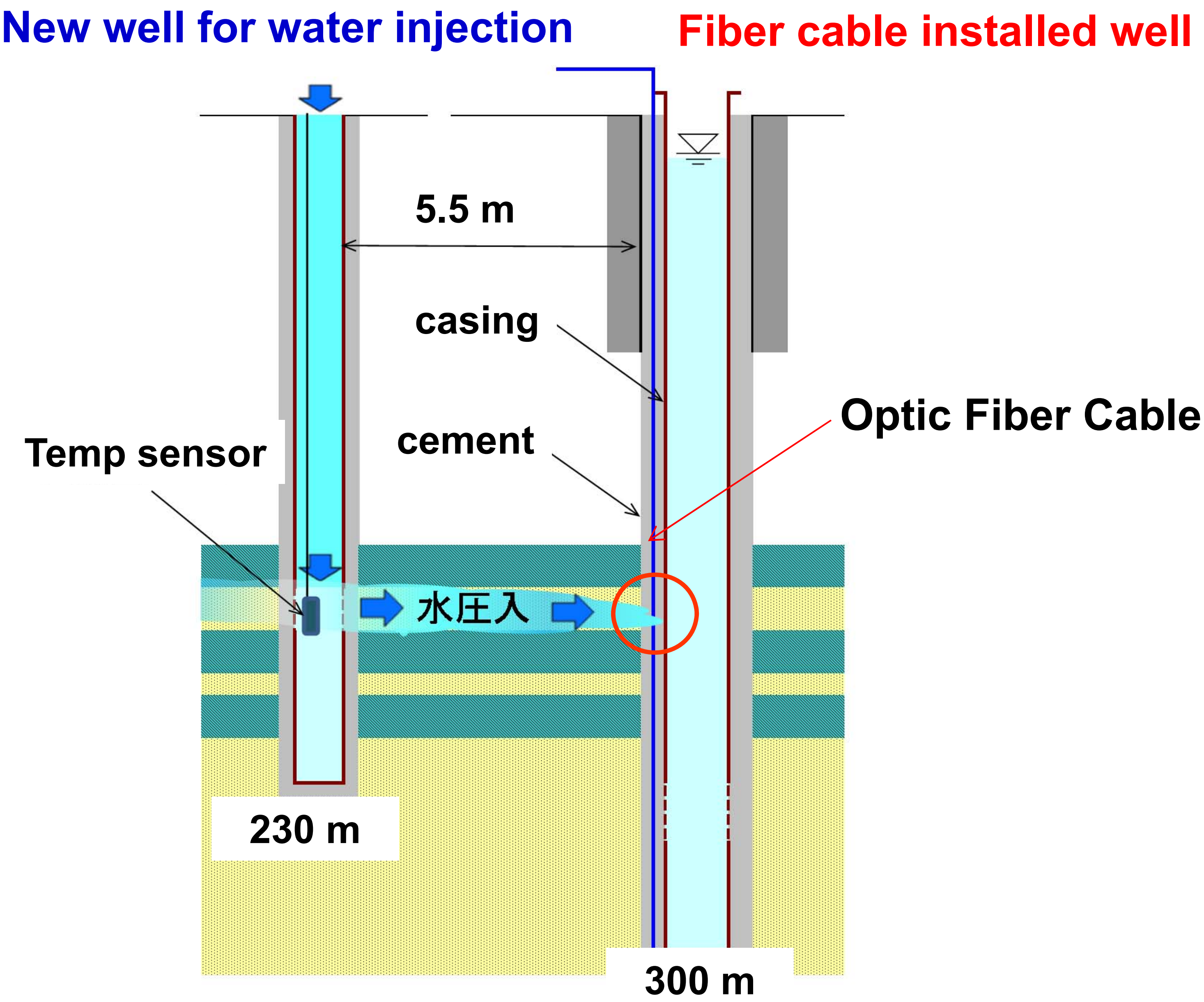
Velocity change in overlying formations



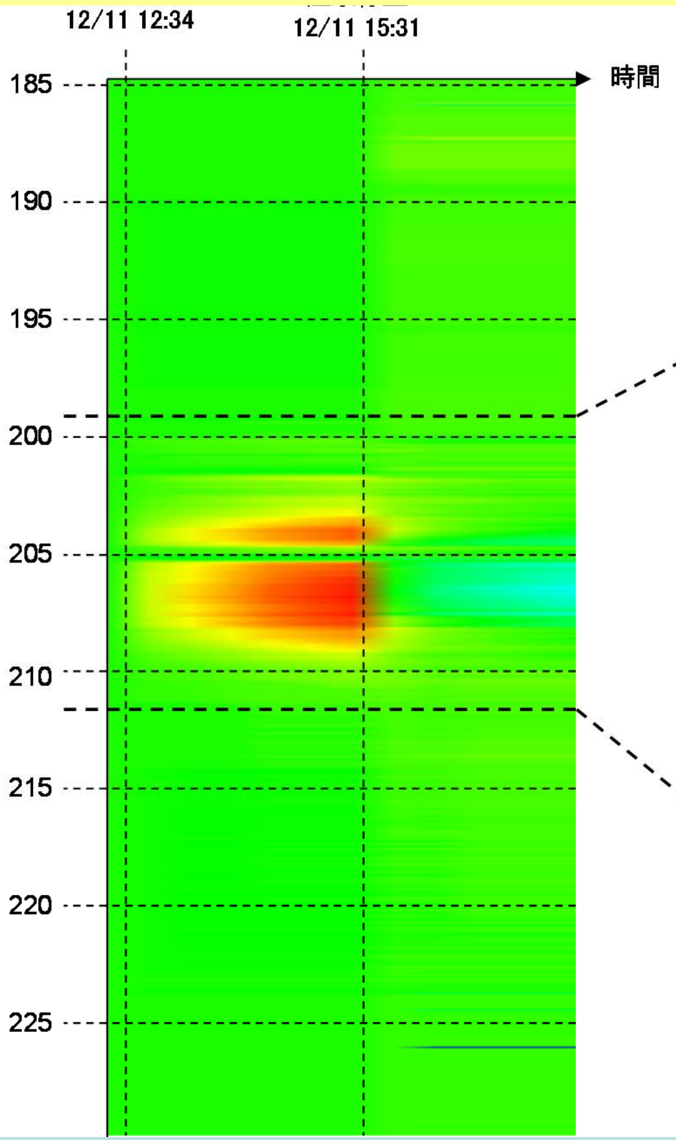
DTS - Distributed Temperature System

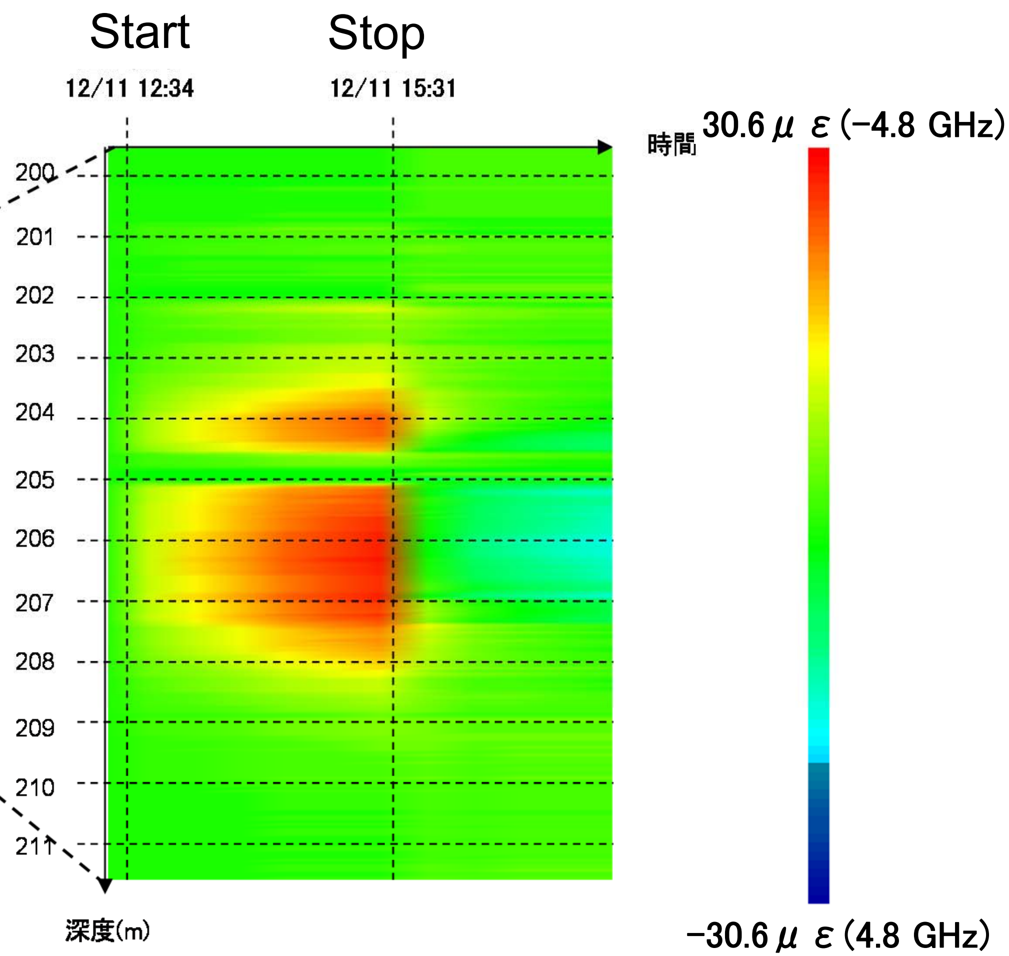
DAS - Distributed Acoustic System

Fiber Optics: Water Injection Test

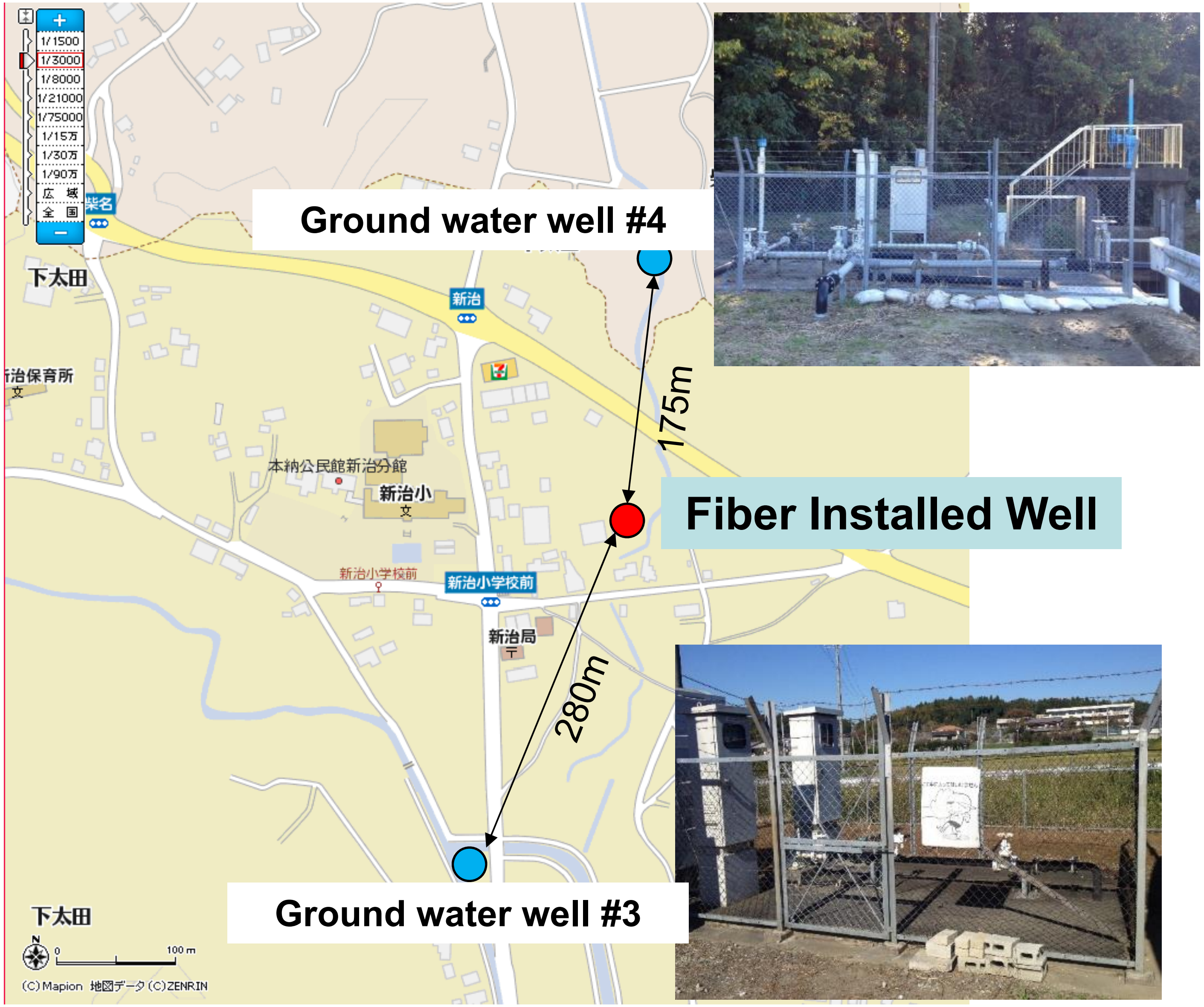


Strains estimated during water injection

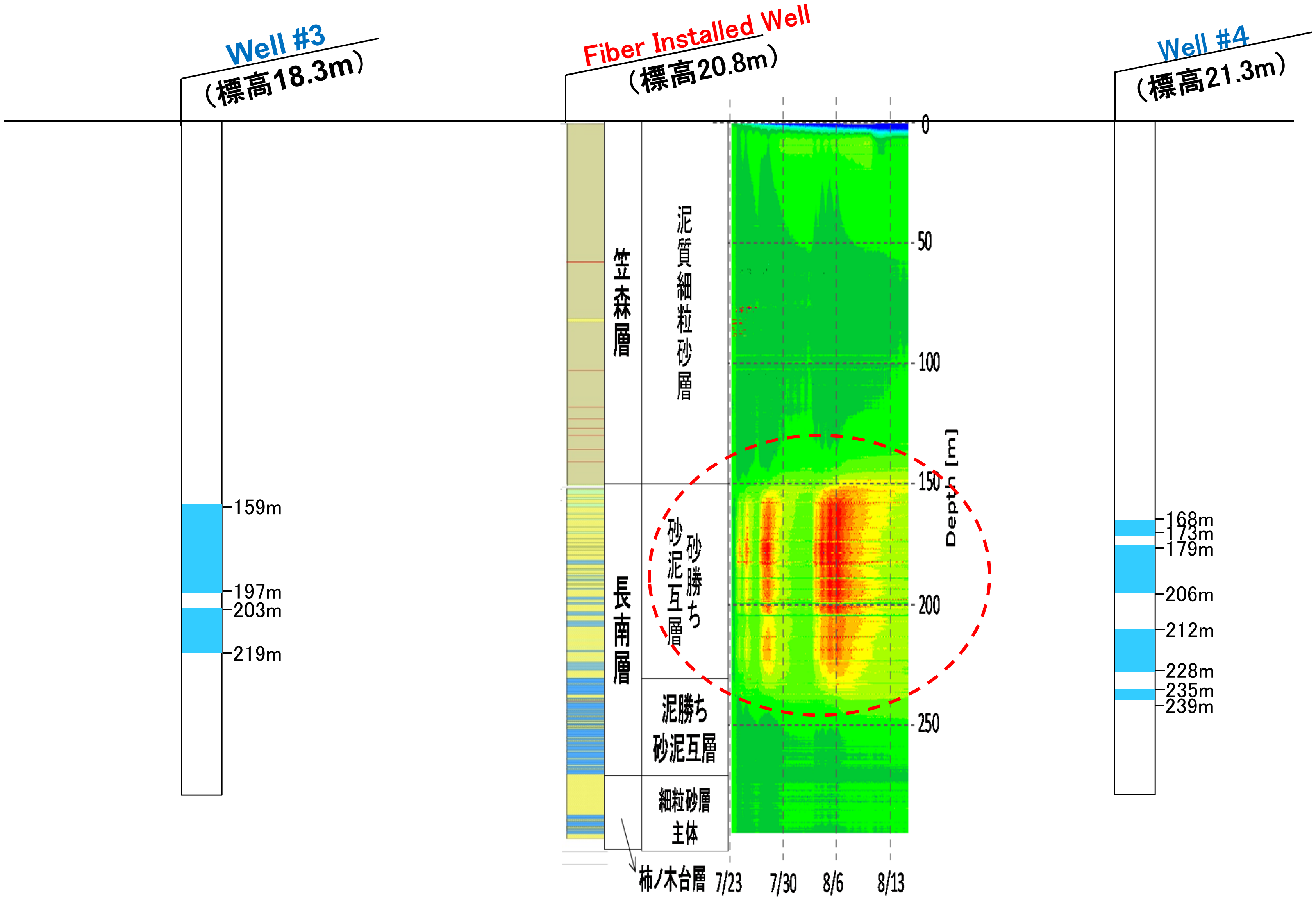




Response to Water Extraction (1/2)



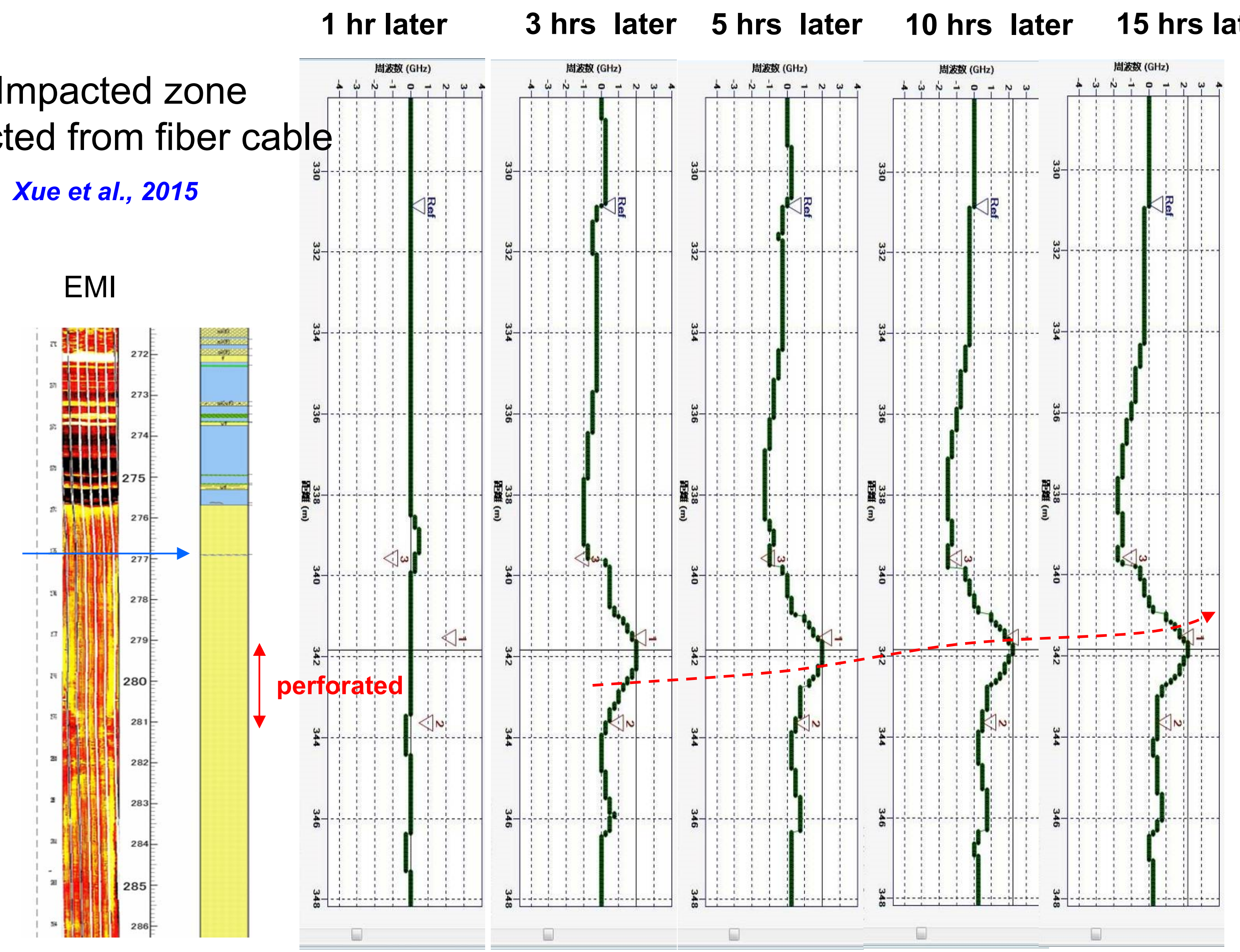
Response to Water Extraction (2/2)



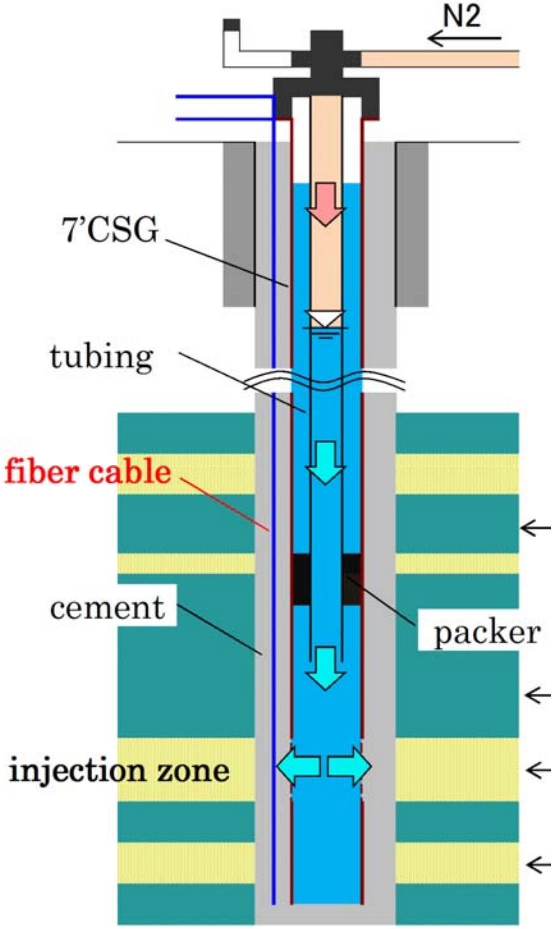
Impacted Zone Detected during CO_2 Injection

Impacted zone
detected from fiber cable

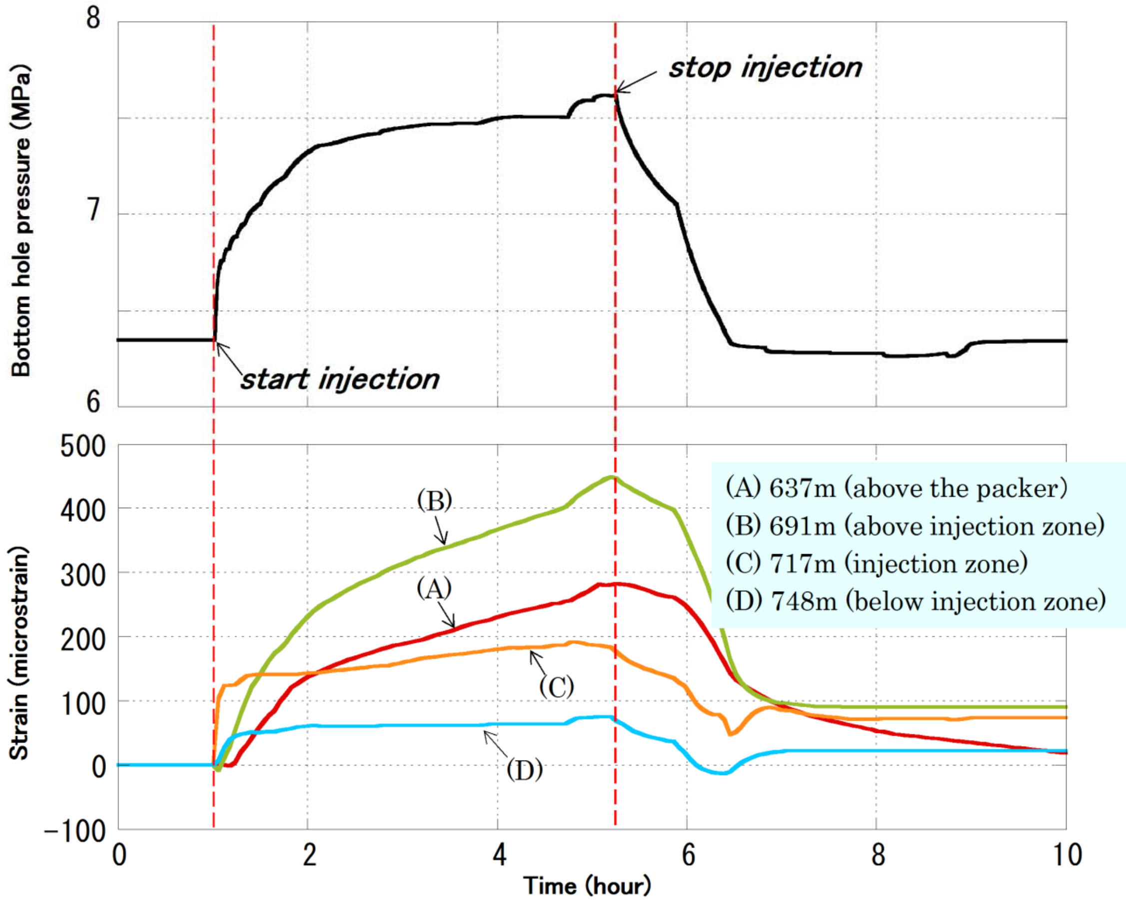
Xue et al., 2015



Impacted Zone Detected at the Deep Well

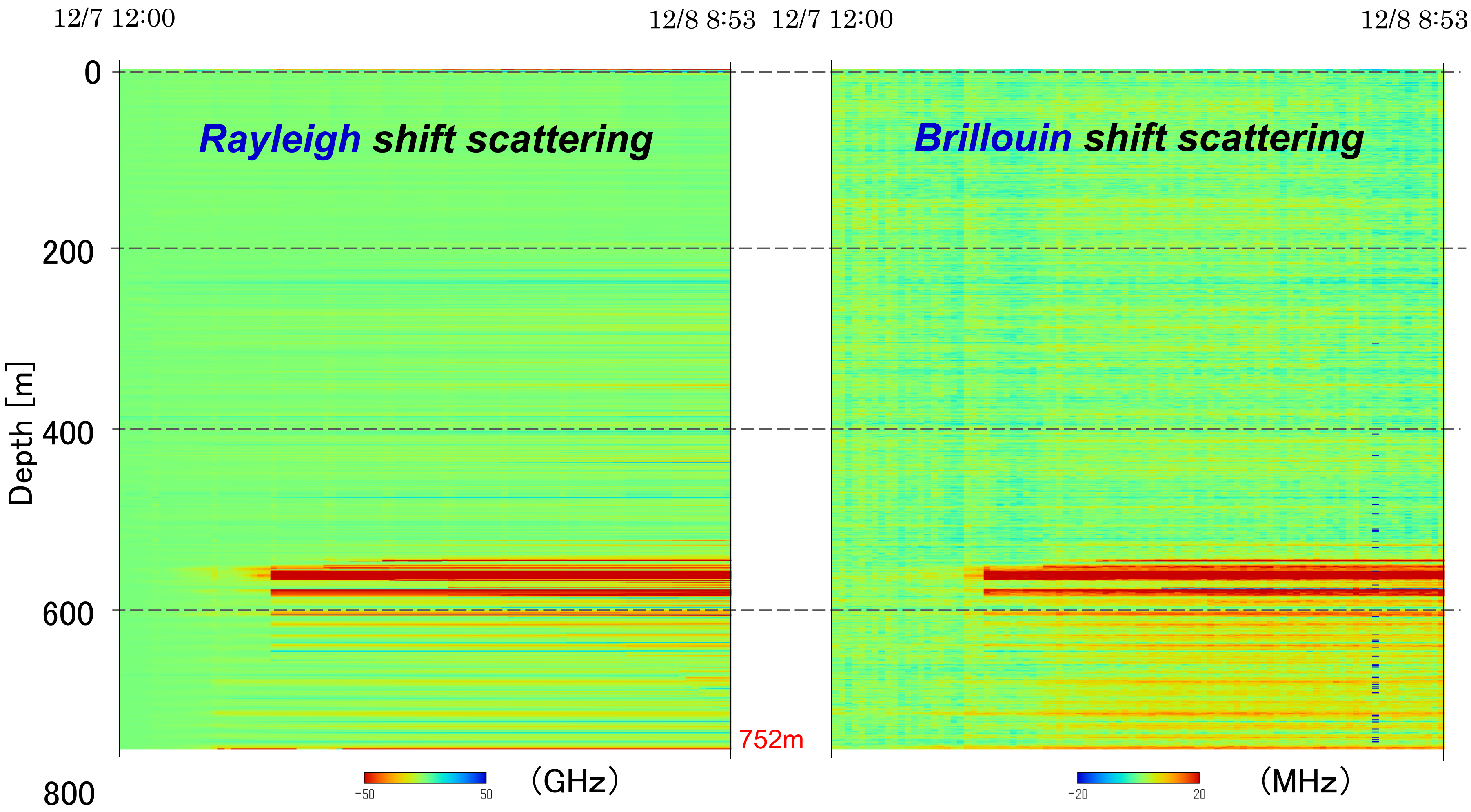


Well depth: 880m

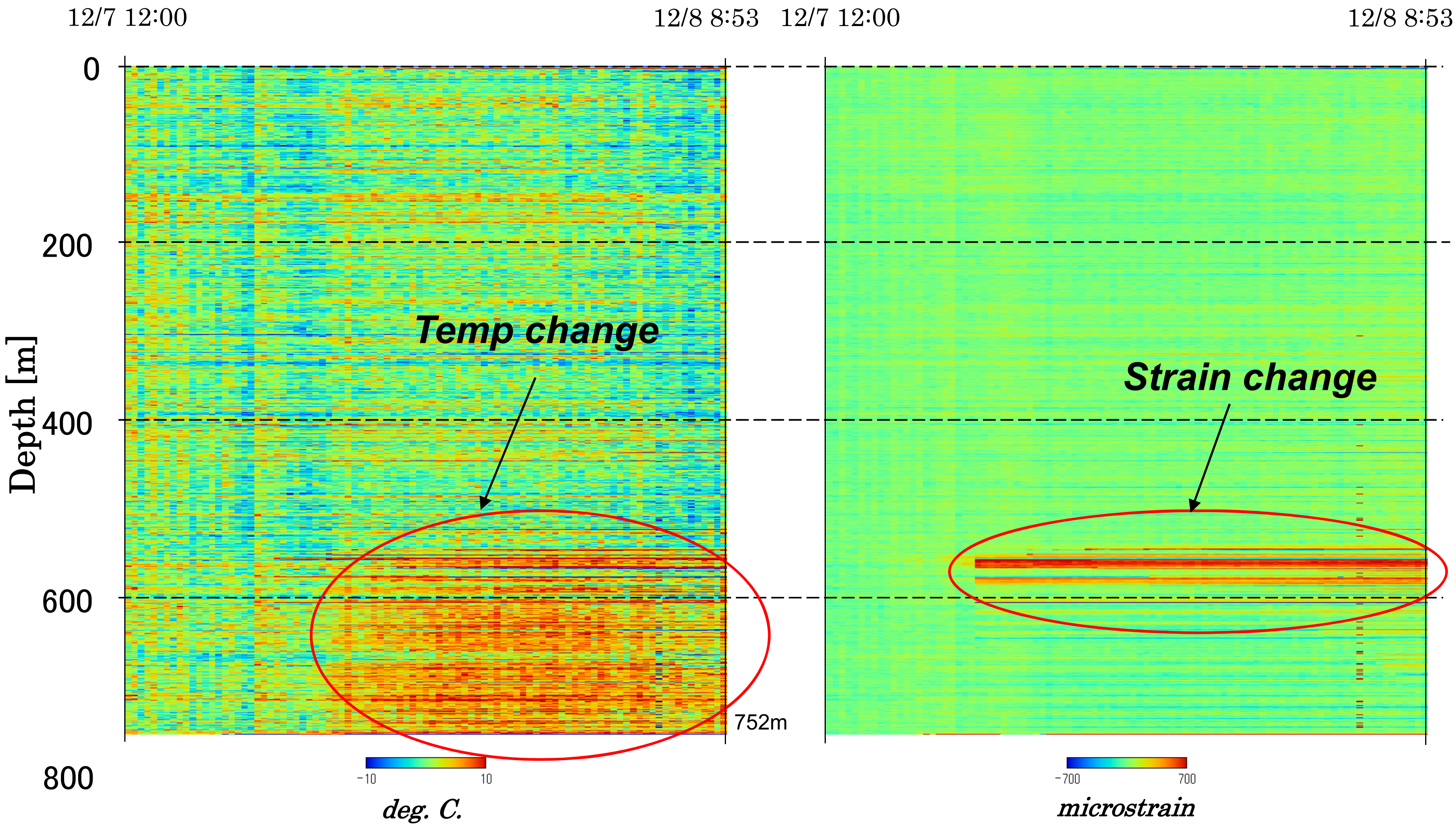


Strains estimated at different depths in N_2 injection

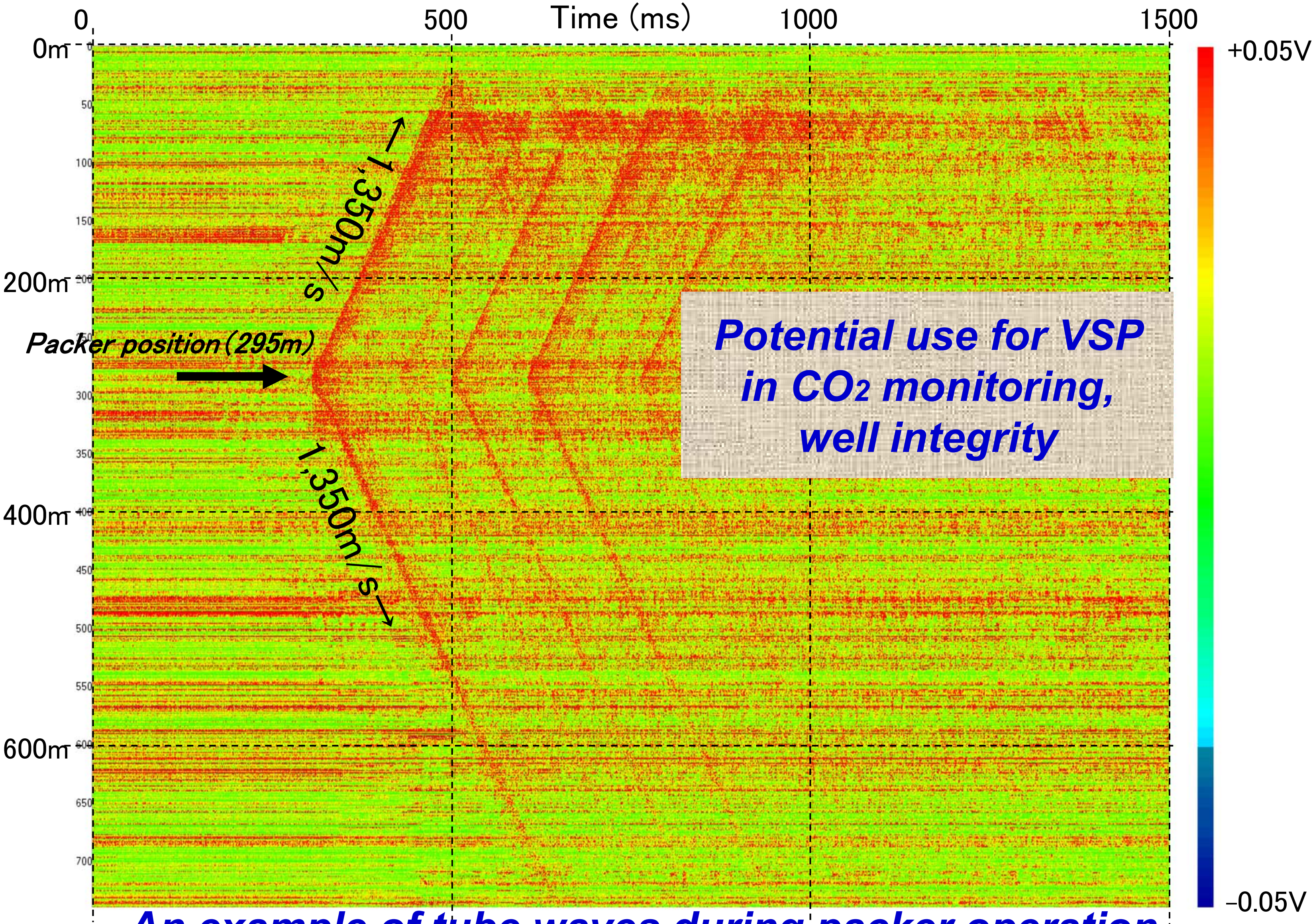
Combined effects of temperature and strain in recorded frequency shifts



Temperature and Strain Separation from the Observed Frequency Shifts in Rayleigh & Brillouin Scattering

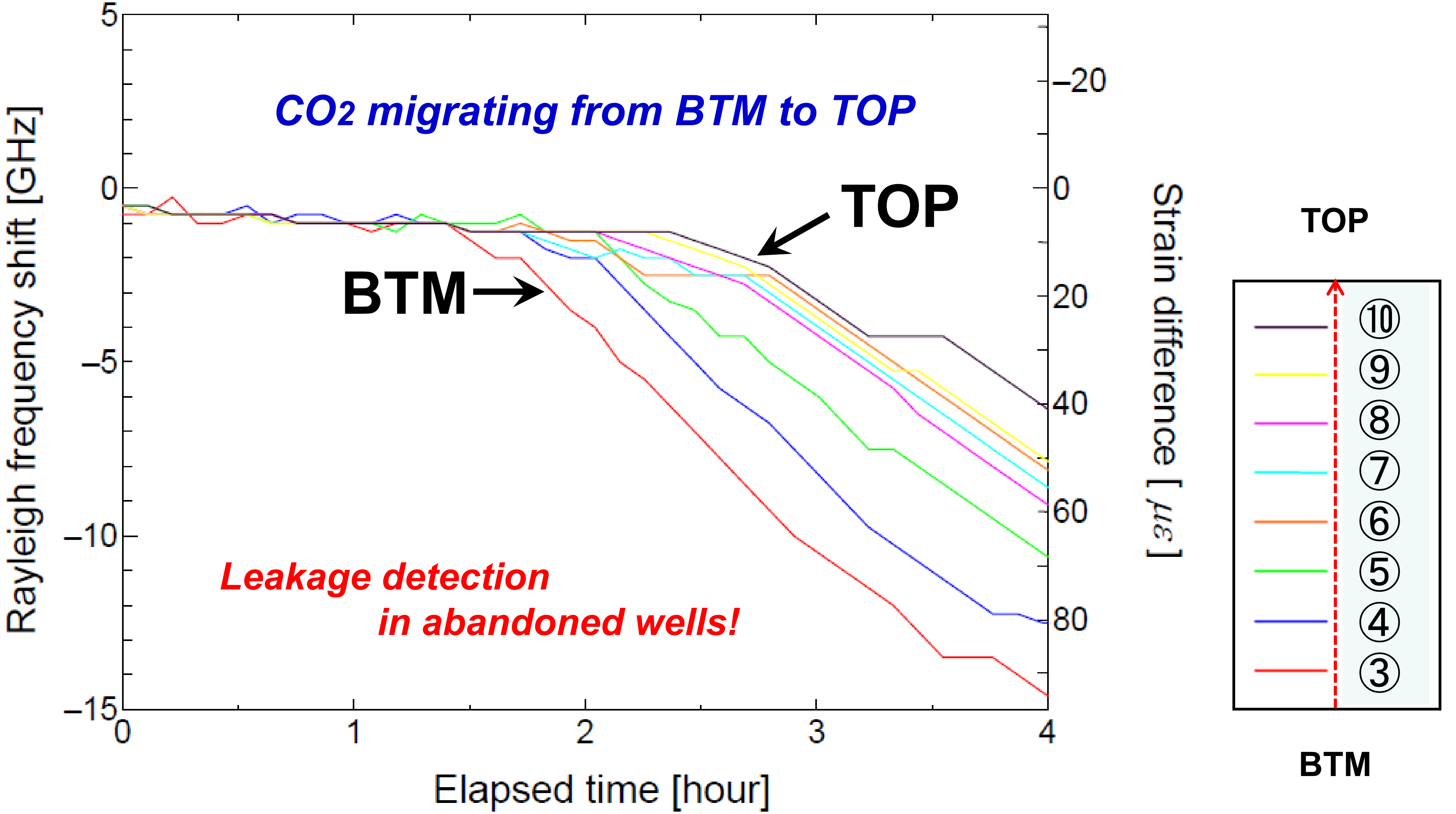


Distributed Acoustic System（DAS）



An example of tube waves during packer operation

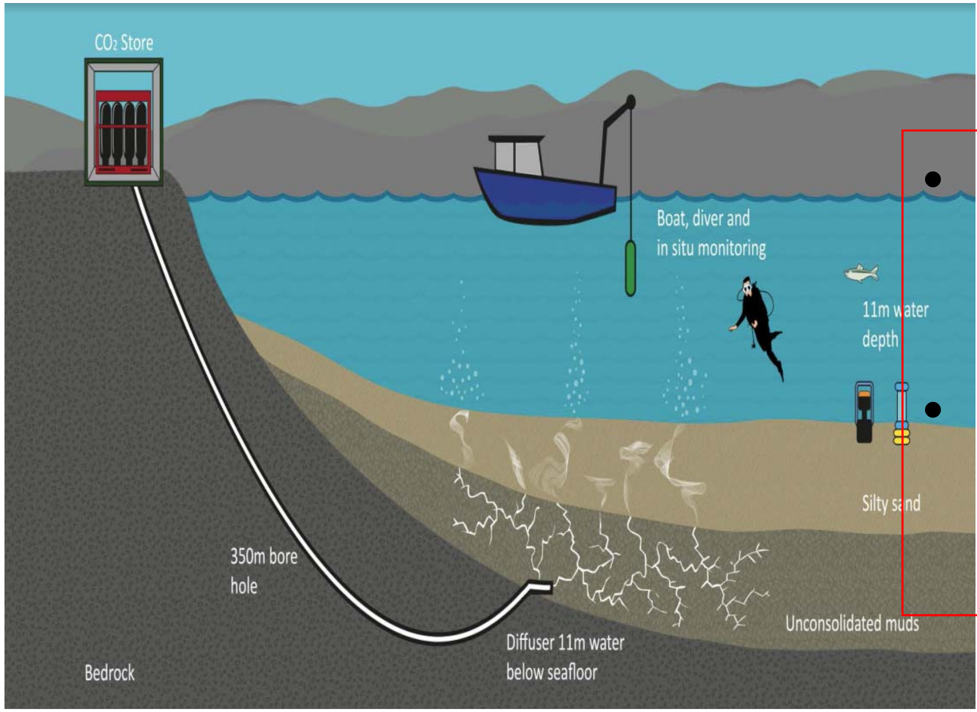
Lab test: CO_2 front migration detection



A field test planned this year !

Controlled CO_2 Release Experiment in the Ocean
QICS: UK – Japan Collaboration

Quantifying and Monitoring Potential Ecosystem Impacts



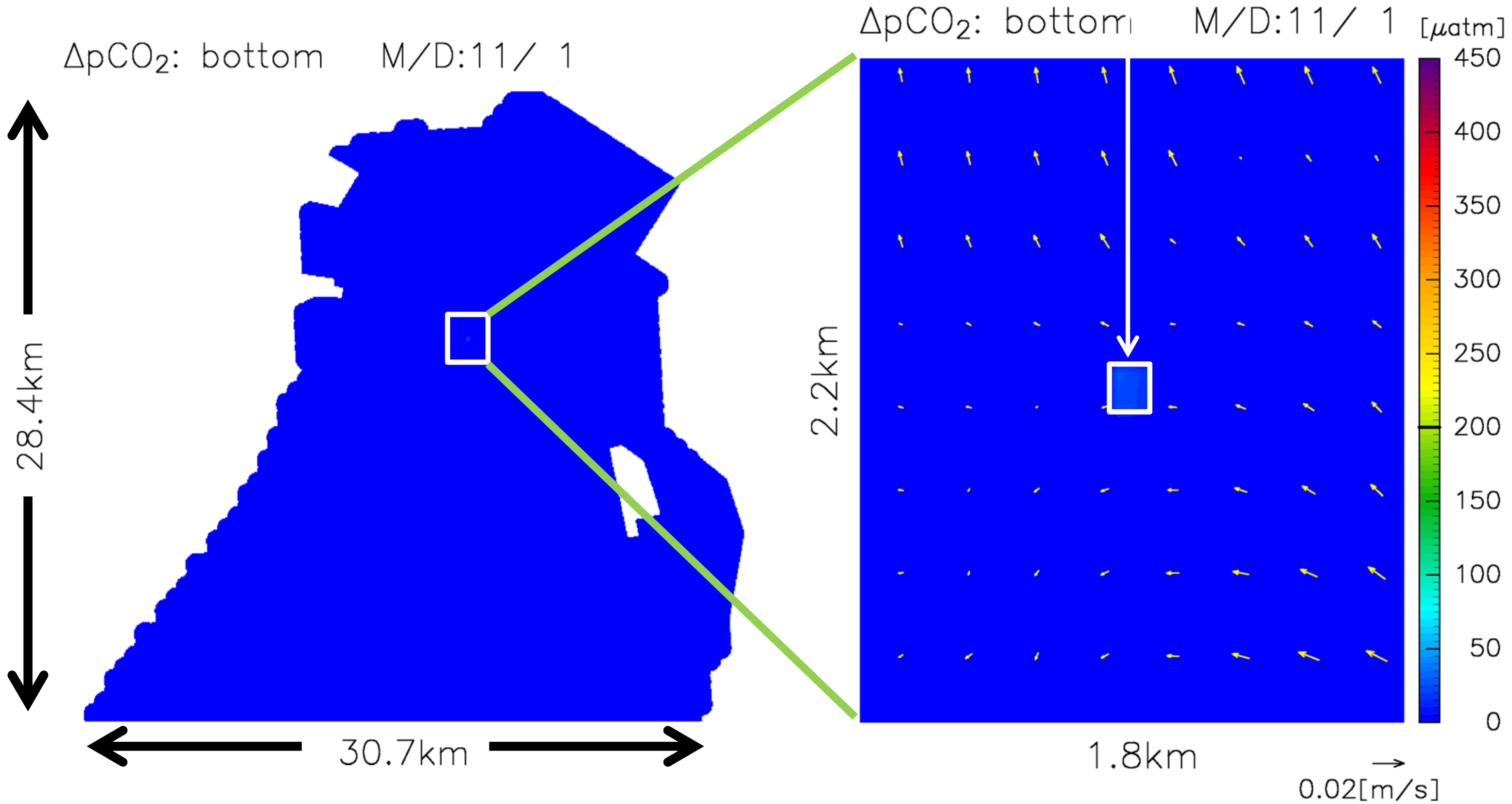
- CO_2 Leakage detection using the geophysical, acoustic, geochemical methods
- Evaluation of ecological impacts by gene-analysis, photo-graphics observation etc.

QICS special issue: CCS and the Marine Environment
21 research papers, Int. J. Green Gas Control: Vol.38, 2015

Simulating Leaked CO_2 in the Ocean

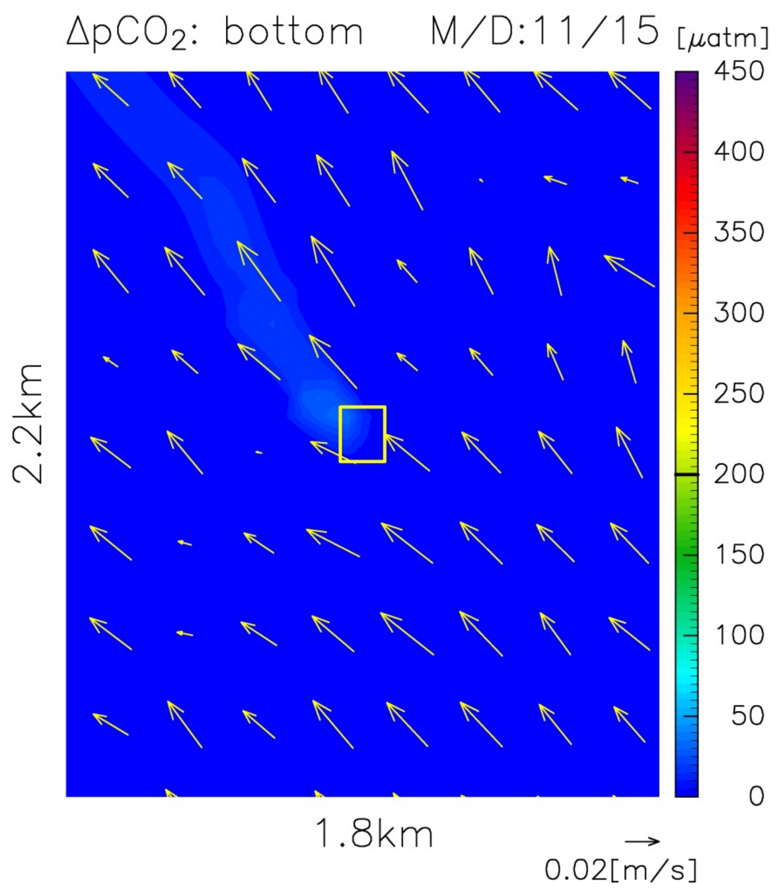
Modeling area driven by temporally variable heat flux and wind stress at sea surface ⇒ Able to represent seasonal variation

- *CO2 leakage: 250 tonnes/year within 150m×150m*

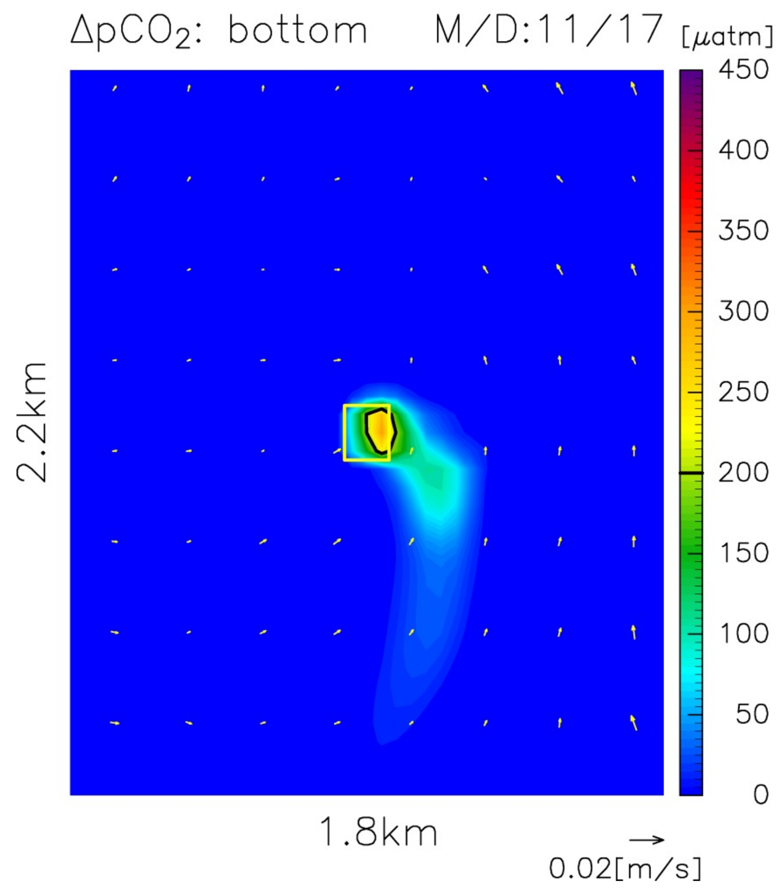


ΔpCO₂ predicted in two flow fields at same leakage rate

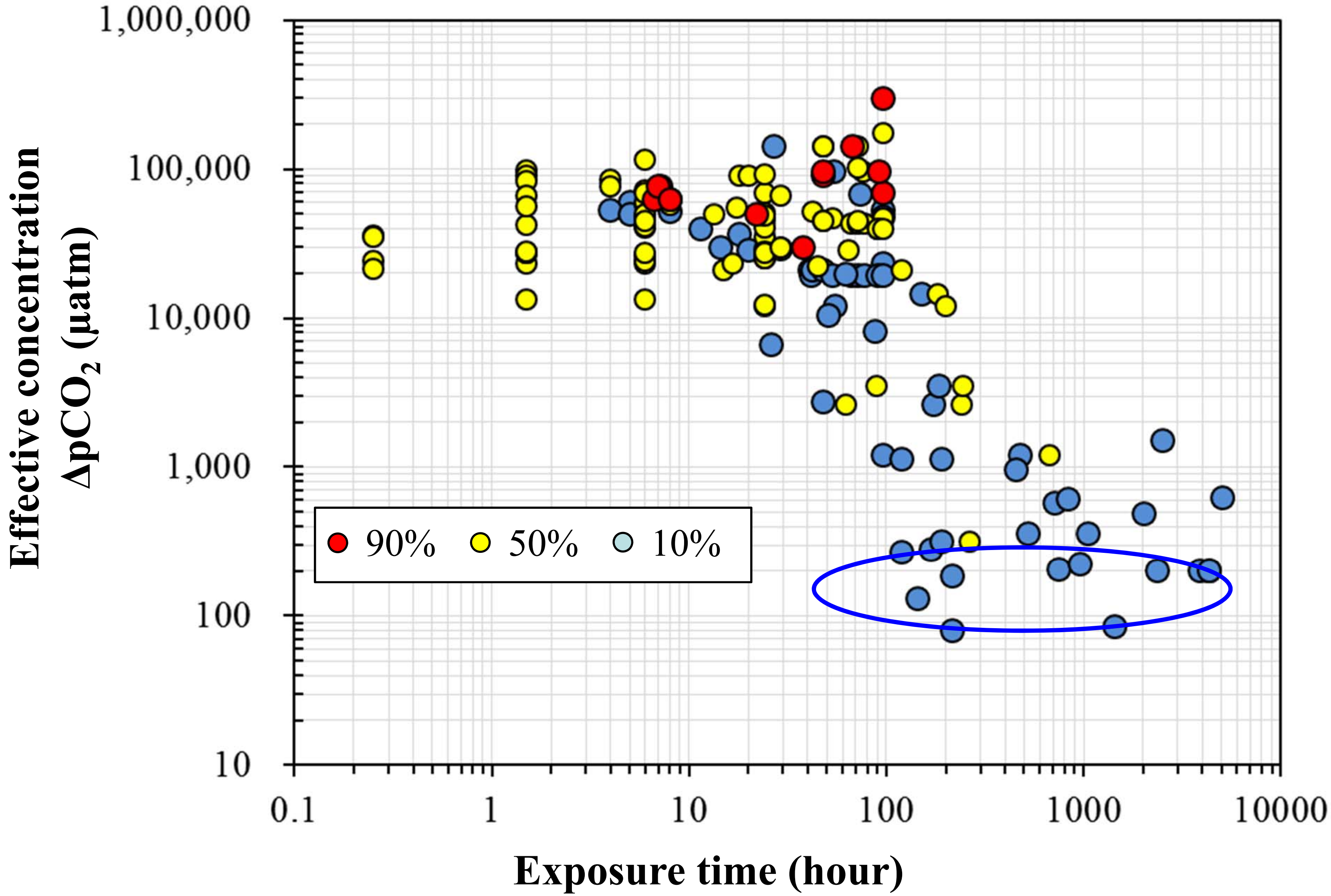
Strong flow field



Weak flow field



Threshold for Ecological CO_2 Impacts Estimated from a Biological Impact Database



EIA at the Tomakomai offshore project

Act for the Prevention of Marine Pollution and Maritime Disasters

- **May 2007**: The act was amended for permit procedure on dumping CO_2 stream into sub-seabed formation.

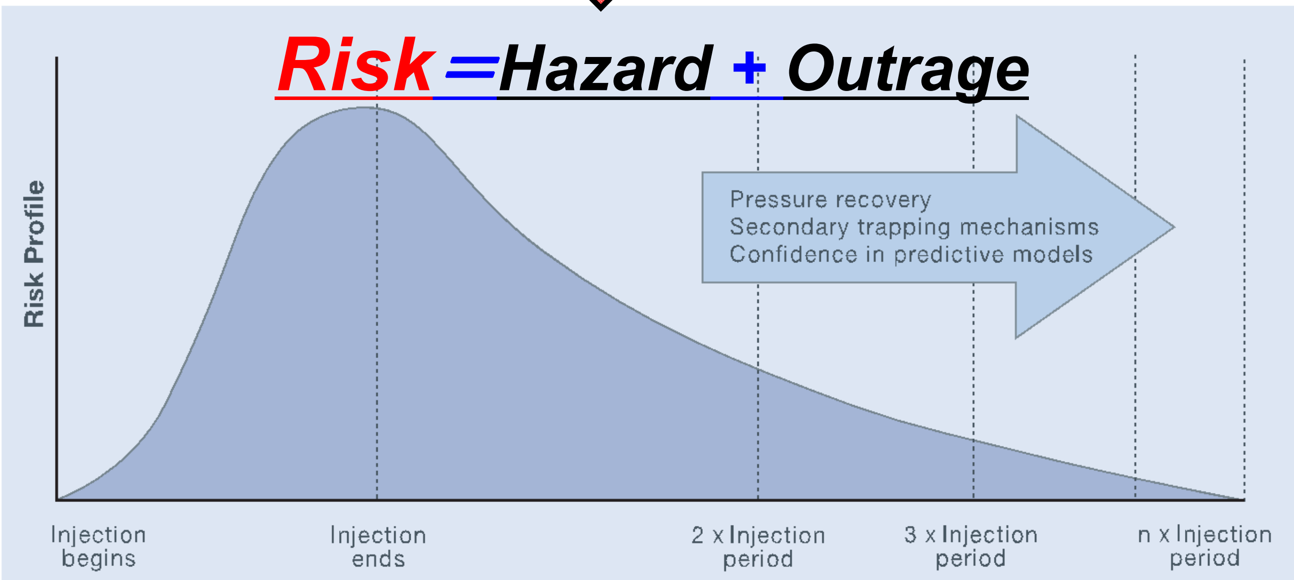
- ***Preliminary Assessment Document***
  *"Estimation of CO_2 dispersion and its impact assessment **on the assumption that stored CO_2 leaks out to the sea**"*

Learning from Demonstration Projects
Understanding Uncertainty and Managing Risks

Risk = Consequence Severity x Probability

Scientific Knowledge & Evidence-based Risk Communication

Risk = Hazard + Outrage



[Illustration source: Benson, 2007]

Reducing Uncertainty／Mitigating Risks
to the Manageable Levels！