5TH MONITORING WORKSHOP

Report No. 2009/11

November 2009

IEA Greenhouse Gas R&D Programme

5th Monitoring Network Meeting

Hosts : RITE, JAPEX, AIST, Kyoto University

Tokyo – 2-3 June 2009

Sponsors 5th Monitoring Network meeting

- Japan Petroleum Exploration Co., Ltd. (JAPEX)
- Japan CCS Co. Ltd. (JCCS)
- INPEX Co.
- Schlumberger Japan
- Geophysical Surveying Co., Ltd.
- JGI Inc.
- CHIYODA Co.
- SUNCOH Consultants Co.
- Kawasaki Geological Engineering Co.
- JFE Engineering Co.
- Arabia Oil Co., Ltd.
- TOYO Engineering Co
- DIA Consultants Co.
- NIPPON Steel Engineering Co. Ltd.
- OYO Co.
- SK Engineering Co.
- JGC Co.
- Japan Oil Co.
- Halliburton Overseas Limited
- Battelle Japan

IEA Greenhouse Gas R&D Programme

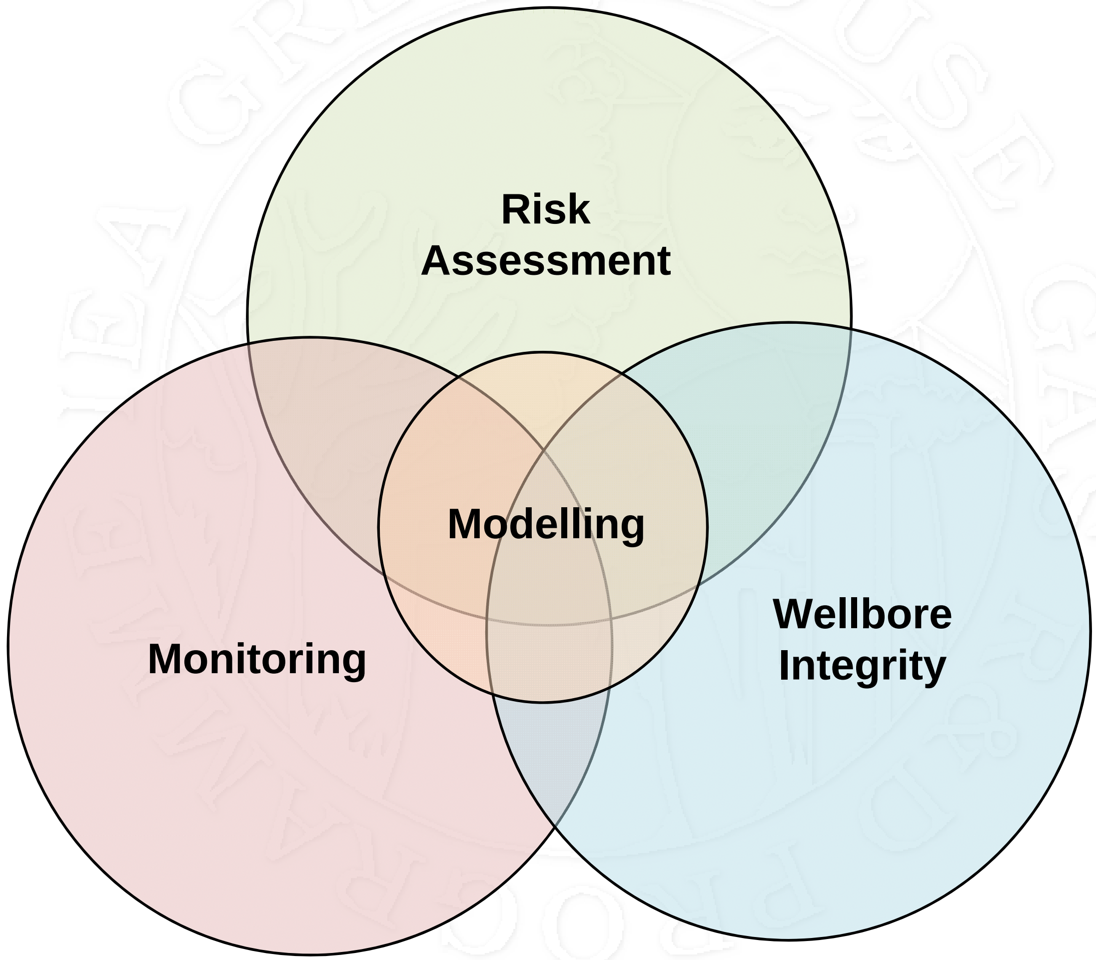
- A collaborative research programme founded in 1991
- Aim: *Provide members with definitive information on the role that technology can play in reducing greenhouse gas emissions.*
- Producing information that is:
  - Objective, trustworthy, independent
  - Policy relevant but NOT policy prescriptive
  - Reviewed by external Expert Reviewers
  - Subject to review of policy implications by Members
- Activities: Studies (>120); R&D networks :- Wells, Risk, Monitoring, Modelling, Oxy, Capture, Biofixation; Communications (GHGT9, IJGGC, etc); facilitating and focussing R&D and demonstration activities

Contracting Parties and Sponsor Organisations of IEA GHG

R&D Networks

- Bring together international key groups of experts to share knowledge and experience
- Identify and address knowledge gaps
- Act as informed bodies, eg for regulators
- CO_2 geological storage – assessing and managing risks
- Started in 2004/5
  - Risk Assessment Research Network
  - Monitoring Research Network
  - Wellbore Integrity Research Network
  - Modelling Network (2009)
- Benefit experts and wider stakeholders
- Depend on experts' time and inputs – valuable and widely appreciated

Storage Networks Overlap



- 5th Monitoring Network Meeting, Tokyo 2009

- 4th Edmonton, 2007
- 3rd Melbourne, 2006
- 2nd Rome, 2005
- 1st California, 2004

Monitoring Network -

- *Overall aim:* To facilitate the exchange of ideas and experiences between experts in the monitoring of CO2 storage, and to promote the improved design and implementation of monitoring programmes.
- *Specific aims and objectives:*
  - Assess new technologies and techniques
  - Determine the limitations, accuracy and applicability of techniques
  - Disseminate information from research and pilot storage projects
  - Develop extensive monitoring guidelines
  - Engage with relevant regulatory bodies

  - Monitoring Selection Tool

    http://www.co2captureandstorage.info/co2tool_v2.2.1/index.php

IEA Greenhouse Gas R&D Programme

5th Monitoring Meeting Agenda

1. Reports from other initiatives
2. Reports from Projects
3. Update on Japanese CCS Progress
4. What Regulators Want
5. Reality Check – What can and can't monitoring do
6. Emerging and Innovative Technologies
7. Workshop Conclusions and Key Points for other Networks

Nagaoka Site Visit

IEA Greenhouse Gas R&D Programme

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- SK Engineering Co.
- JGC Co.
- Japan Oil Co.
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- Battelle Japan

Steering Committee for 5th Monitoring Meeting

- Tim Dixon – IEA GHG
- Ziqiu Xue – Kyoto University
- Toshiyuki Tosha - AIST
- Kevin Dodds - BP
- Hubert Fabriol - BRGM
- Lee Spangler – Montana State University
- Don White - NRCan
- Charles Jenkins – CO2CRC
- Andy Chadwick - BGS
- Susan Hovorka – University of Texas
- Rick Chalaturnyk – University of Alberta
- John Kaldi – CO2CRC
- Brendan Beck – IEA GHG

IEA Greenhouse Gas R&D Programme

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4th International Monitoring Network Workshop

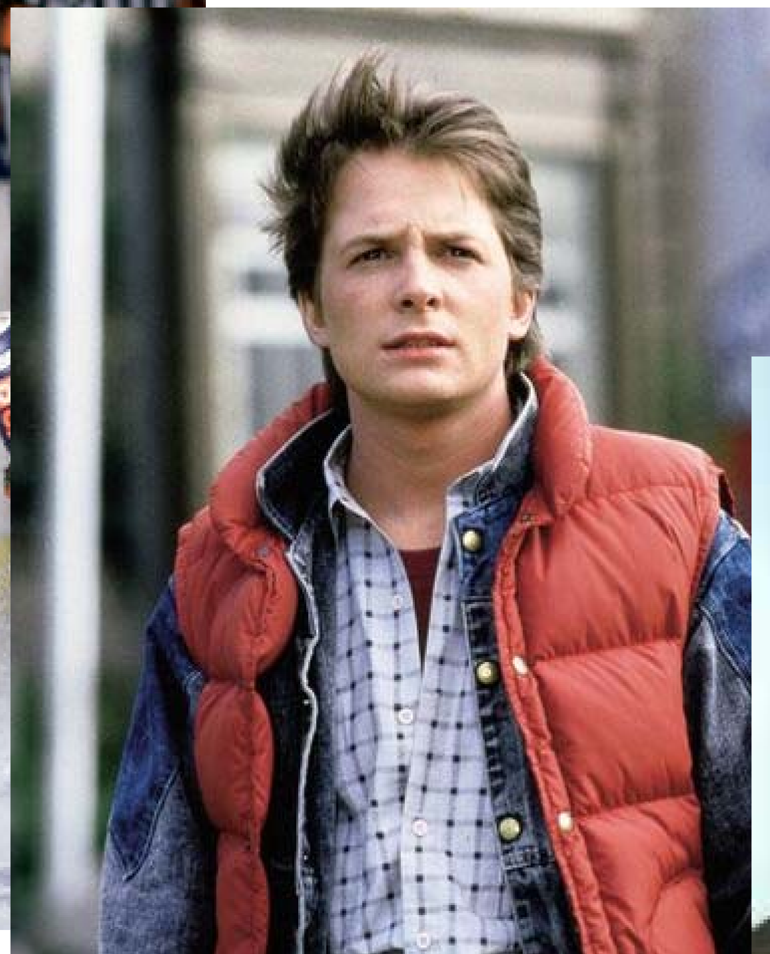
IEA Greenhouse Gas R&D Programme

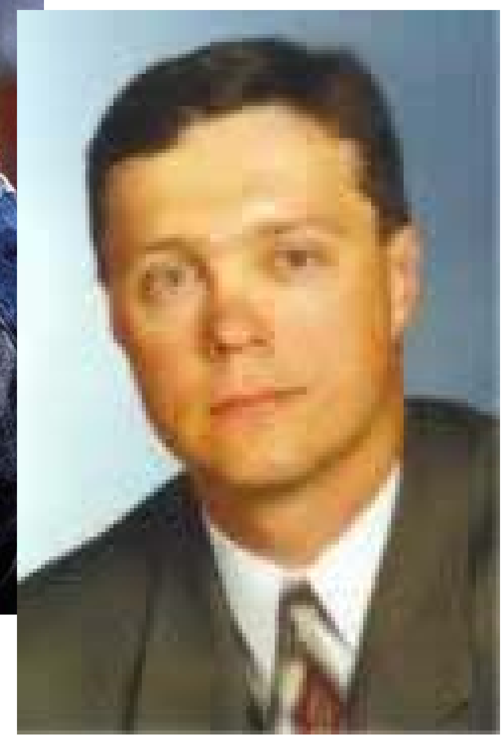
Edmonton, Canada

7th – 9th November 2007

West Edmonton Mall

Edmonton: The City of Champions





4th International Monitoring Network Workshop

- Day 1: Regulations for CCS Monitoring
- Day 2 & 3: Project Updates & Seismic Monitoring
- Day 4: Visit to Penn-West and Joffre CO2 EOR sites.

Day 1: Regulations and Monitoring

- Session 1 Opening address/Welcome
  - Introduction by Andy Ridge
  - Honorable Rob Renner, Minister of Environment, Government of Alberta

- Session 2 Regulations and Monitoring:
  - An ENGO viewpoint on CCS, Regulation and Monitoring: Mary Griffiths, Pembina Institute
  - Draft Quantification Protocol for Geological Storage Through Enhanced Oil Recovery using CO2 Injection – What Monitoring is Required?: Brent Lakeman, Alberta Research Council
  - Storage of Carbon Dioxide in Geologic Structures: A Legal and Regulatory Guide for States and Provinces - IOGCC: Rick Chalaturnyk, University of Alberta
  - MMV Components associated with G8/CSLF and Canada-Alberta Task Force Activities: Bill Reynen, Geological Survey of Canada
  - Draft Regulatory Guidelines for Geological Storage of CO2 – CO2ReMoVe: Brendan Beck, IEA GHG

Day 1: Regulations and Monitoring

- Session 3 Acid Gas Regulations for Storage Projects
  - Review of Acid Gas Regulations: Stefan Bachu, Energy and Utilities Board
  - Facilitated Discussion: Are Acid Gas Regulations a suitable analogue for the development of Geological Storage Regulations
- Session 4
  - Facilitated Discussion: Design of MMV Protocols -- How to design and establish a suite of generic MMV protocols for CO2 storage
- Session 5
  - Facilitated Discussion: Path Forward -- What are the next steps to help expedite MMV arrangements and so assist in the widescale implementation of CCS

Day 2: MMV Design and Case Histories

- Session 1 MMV Design and Reviews and Updates: CO2 Projects
  - CO2CRC's Otway Basin Pilot Project: Kevin Dodds, BP Americas
  - Nagaoka, Japan: Tsukasa Yoshimura, RITE
  - Zama Lake Acid Gas EOR Project: Steve Smith, EERC/PCOR
  - ADM Site, Illinois – Midwest Partnership: Rob Finley, GSI
  - Weyburn-Midale: Don White, GSC
  - Penn West: Gonzalo Zambrano, U Alberta
  - CO2Geonet and CO2ReMoVe: David Jones, BGS
  - Environmental Risks from Geological Carbon Dioxide Storage: Jeremy Colls, U Nottingham
  - Teapot Dome, Wyoming, USA: Ron Klusman, CSM
  - Soil CO2 Flux Measurements: Rod Madsen, LICOR Biosciences

Fort Edmonton Clerk’s Quarters

Day 3: MMV Design and Case Histories

- Session 1 MMV Design and Reviews and Updates: CO2 Projects
  - FRIO II: Sue Hovorka, Gulf Coast Carbon Centre
  - Penn West:
    - Seismic Monitoring: Don Lawton, U Calgary
    - Observation Well: Rick Chalaturnyk, U Alberta
    - Shallow Subsurface/Air Monitoring: Bill Gunter, ARC
  - CSEMP ECBM Project: John Faltinson, ARC
  - Role of Risk Assessment in Designing MMV Programs: Ken Hnottavange-Telleen, Schlumberger Carbon Services

Day 3: MMV Design and Case Histories

- Session 2 CO2 Monitoring using Seismic
  - Seismic Based MMV Programs: Tom Daley, LBNL(by phone)
  - Design of Surface Seismic Programs: Mark Egan WesternGeco
  - A New Mode of Seismic Surveillance: Leon Thomsen, BP
  - Crosswell Imaging: Mark McCallum, Z-Seis
  - Design of Surface Seismic Programs: Jeff Thompson, WesternGeco
  - Passive Seismic Monitoring: Marcia Couëslan, Schlumberger Carbon Services
  - Employing Novel MMV Technology: Eric Davies, Pinnacle

  - Discussion/QuestionsSummary Discussion Chair: Brendan Beck

Wrap Up

- Day 1: Monitoring and Regulation
  - Regulation is being developed in the US, Canada, Europe and Australia
  - Although not completely transferable lessons can be learned from other regions processes
  - There are parallels that can be drawn with acid gas injection but the scale is very different to CO2 storage
  - There are still some big regulatory issues to be solved – when and how to hand over

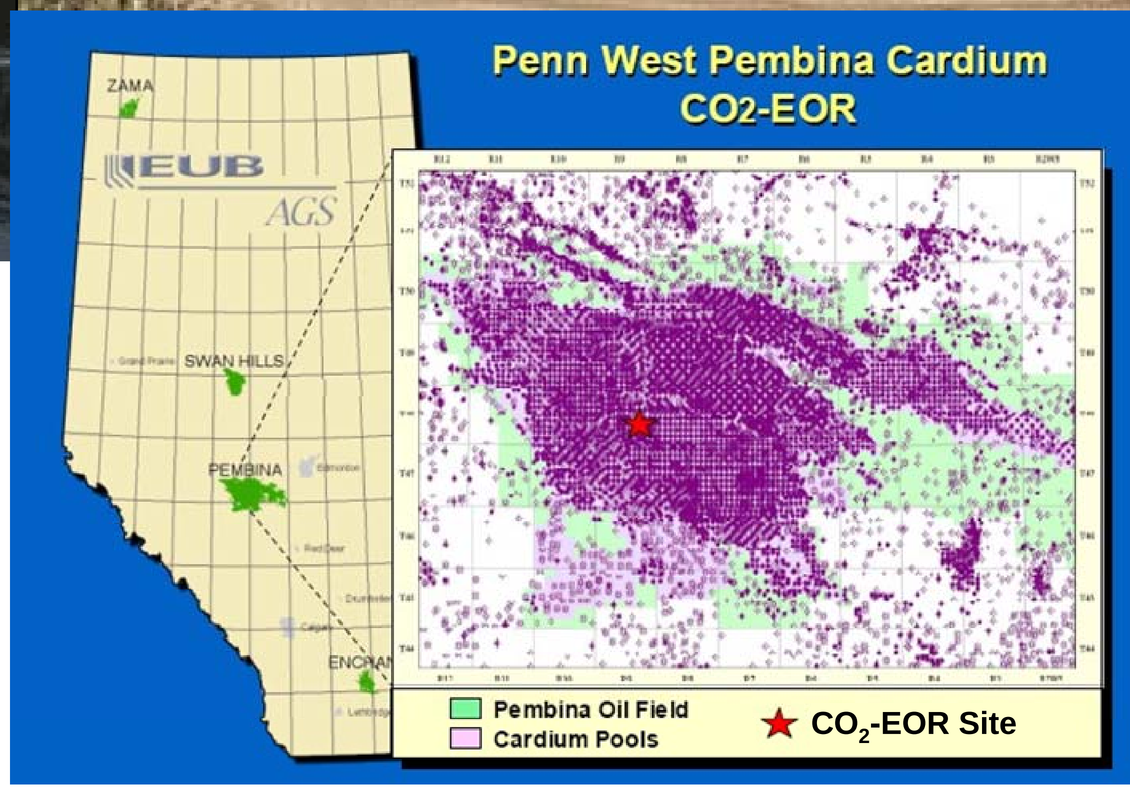
Wrap up

- Days 2 & 3: Review and Updates: CCS projects
  - Encouraging to see the number of projects existing and planned
  - Encouraging to see the wealth of monitoring techniques are being developed, tested and applied
  - As the data is collected and interpreted we will slowly start to build monitoring standards and best practices

Recurring Questions

- How do you accurately locate and quantify the CO2 in the reservoir?
- What do you do if a system parameter goes outside predicted values?
- What additional information can Seismic monitoring give us? When is it not applicable? Is it enough on its own and if not, what more do you need to complement it?
- How much monitoring is required for different stakeholders and can the current monitoring techniques provide what the need?
- How long do you monitor for? When and how does handover occur?

Canadian Rodeo Championships


Penn West Pembina Cardium
CO2-EOR
ZAMA
EUB
AGS
SWAN HILLS
PEMBINA
Pembina Oil Field
Cardium Pools
CO2-EOR Site

CO2 Plant from Joffre

4th International Monitoring Network Workshop Report

- http://www.co2captureandstorage.info/networks/monitoring4.html

Reports from IEAGHG Networks: 1st Joint Network, Modelling Workshop and 5th Wellbore Integrity Meetings

IEA Greenhouse Gas R&D Programme

4th Monitoring Network Meeting

Tokyo 2-3 June 2009

1st Joint Network Meeting

- New York
- June 2008
- Hosted by the US Environmental Protection Agency
- Bringing together representatives from risk assessment, wellbore integrity and monitoring networks
- Results:
  - Technical gaps
  - Monitoring Network Future Focus
  - Operational or Network Gaps

1st Joint Network Meeting

- Technical Gaps
  - There is a need to better identify the regulators for a CCS project
  - We need more information about leakage through the wellbore – statistics, classification, causes
  - What are the impacts of leakage into shallow marine environments and potable aquifers?
    - How do we quantify the impacts
  - What are the differences between risk assessment modelling and front end process modelling

1st Joint Network Meeting

- Technical Gaps cont.
  - We need to benchmark existing projects
  - How do you incorporate M&V into RA process (and vice versa)
  - How is public confidence linked to risk assessment
  - How do we better engage insurers, regulators and NGO’s
  - How do we perform risk screening for site selection
  - What are the risks associated with co-contaminants

1st Joint Network Meeting

- Identified topics for Monitoring Network
  - Monitoring for fault activation and pore pressure
  - Monitoring for CO_2 movement through faults
  - Monitoring for dissolved CO_2 in-situ
  - How to plan a monitoring programme
  - Innovative emerging technologies
  - Incorporating modelling into monitoring

1st Joint Network Meeting

- Network gaps:
  - Risk and monitoring networks are not sufficiently integrated
  - Need to communicate with new IEA regulator network

IEA GHG Modelling Workshop and New Network

- Formation of IEA GHG modelling network debated at JNM in June 2008
- Agreed first step to hold modelling workshop
- Aims of workshop:
  - Examine approaches to modelling
  - Discuss confidence in current approaches
  - Debate input to risk assessments and regulatory aspects
  - Identify current knowledge gaps and limitations
  - Discuss potential aims and next steps for formation of a modelling network

Workshop Details

- Workshop hosted by BRGM in Orleans, France, 10th to 12th February 2009
- Co-organised by IEA GHG, BRGM, Schlumberger and CO2GeoNet
- Sponsored by IFP and Total
- Over 100 registered delegates from 14 different countries, representing industry, consultants and academia

Social events

Civic reception

Gala dinner

Workshop Structure

- Introductory session included an overview of CO_2 storage modelling (Isabelle Czernichowski) and regulatory perspective (IEA GHG)
- Sessions on modelling objectives, processes, special issues and formation of network
- Presentations from invited speakers followed by breakout discussions and plenary feedback

Objectives of Modelling

- Discussions focussed on current models in relation to reservoirs, caprock and leakage
- Considerable work remains
- Modelling of potential leakage uncertain
- Divergence of approaches
- Sharing of information and benchmarking

Storage Processes

- Significant knowledge gaps:
- General issues include coupling of processes, up-scaling from pore to field scale, heterogeneity, input data availability
- Many specific knowledge gaps highlighted e.g. relative permeability, reaction kinetics, fault properties and reactivation, stress fields, formation compressibility

Special Issues for Modelling

- Discussions centred on how modelling relates to monitoring and risk, also confidence in current modelling capabilities
- Iterative nature of storage assessment
- Current model reliability may be hampered more by lack of input data than understanding?
- Modelling predicts distribution of free phase CO_2 – main risk source

Formation of Network

- Agreement that an international modelling network would be worthwhile and could make significant contribution
- Recognition that modelling is a distinct specialisation feeding into risk assessment
- RA network could form ‘over arching’ risk management network with inputs from modelling, wellbore and monitoring networks

Modelling Network Aims and Objectives

- Aim: provide an international forum for experts to share knowledge and promote collaboration
- Some specific objectives:
  - Online discussion forum and reference material
  - Guidance documents for practitioners
  - Guidance to non-technical specialists
  - Identification of knowledge gaps
  - Support to RA network

Modelling Network Next Steps

- Workshop report to be issued in May, following circulation of draft to steering committee
- Summary presentation of workshop outcomes to RA and monitoring networks
- Modelling network website:
  - Online discussion forum
  - Links to benchmarking studies
- First network meeting planned for February 2010 (University of Utah)

5th Wellbore Integrity Meeting

- Hosted by ARC/Theresa Watson in Calgary, May 13-14 2009
- Over 80 delegates
- Attempt to attract new speakers and delegates
- Lively debates reflecting EOR industry vs CCS
- Key message for monitoring network: how to detect leakage from wells at surface (downhole monitoring can itself compromise integrity)

Report from the 4^{th} Risk Assessment Network Meeting

IEA Greenhouse Gas R&D Programme

5^{th} Monitoring Network Meeting

Tokyo, Japan 2-3 June 2009

4^{th} Risk Assessment Network Meeting

- Hosted by CO2CRC in Melbourne, Australia, April 16 – 18, 2009
- Topics
  - Reports from other RA-related initiatives
  - Quantification of leakage impacts
  - Combining monitoring, verification and RA
  - RA and insurance
  - Risk communication
  - Update from real projects
  - Breakout groups on gaps, learnings and actions

Main conclusions

- Network's role and scope revisited. Continues to be necessary, focus on technical and subsurface.
- Commercial sensitivities will restrict information
- Learning points included: - drinking water impacts- possible benefit of re-pressurisation of aquifers, well leak sealing by precipitates; risk communication.
- Gaps, included: -
  - Use of technical risk in non-tech risk assessments
  - Evaluation of models
  - Water/brine movement and pressure front
- Monitoring specific: How to include M&V into RA? Does RA drive the monitoring in practice? No other major key learnings, gaps or actions.


CO2 CRC


BOGGY CREEK
PUB

Environmental Impacts of Leakage Workshop Summary

Report Authors:

Julie West, Jonathan Pearce, BGS

Toby Aiken, Tim Dixon, IEA

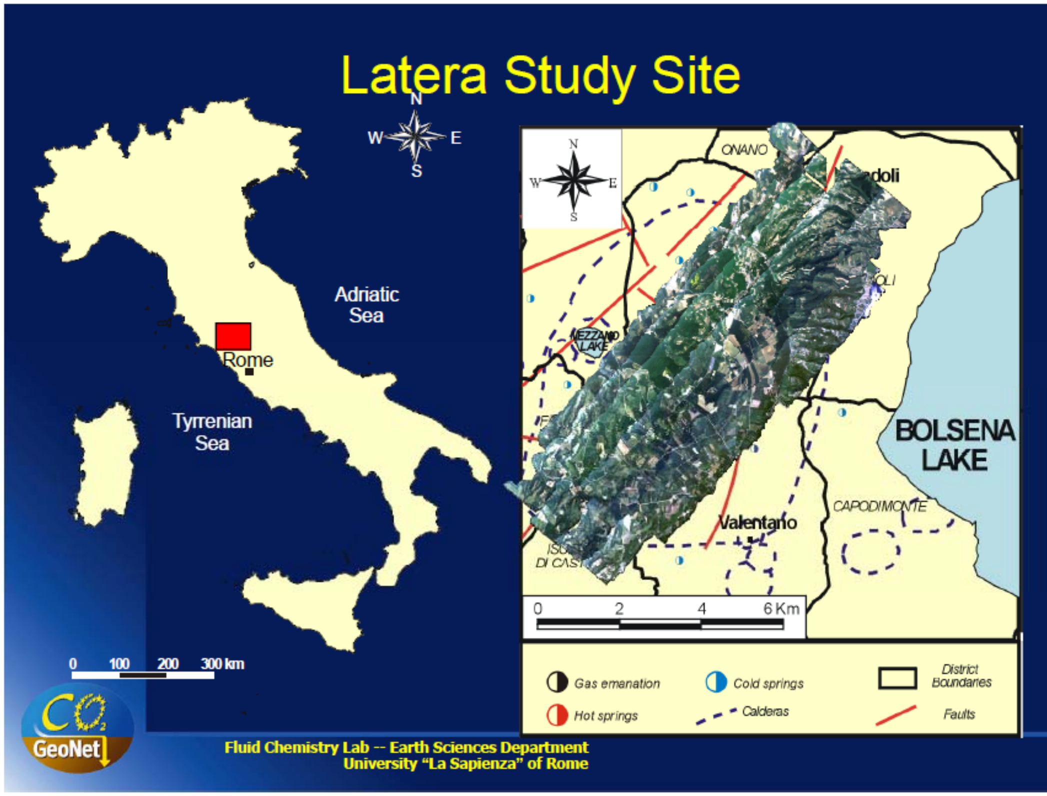
Presented by:

Lee Spangler, Montana State University

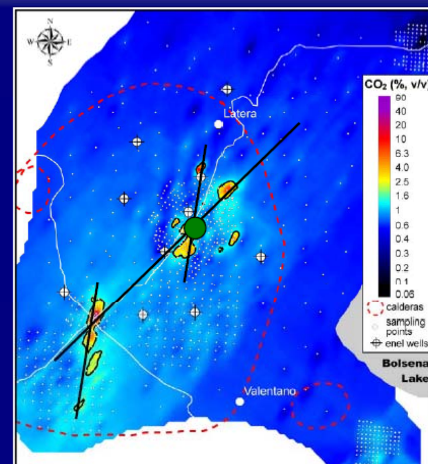
Network Meeting Feedback (GHG/08/55)

Environmental Impacts of Leakage

- IEA GHG Report by BGS, 2007
- Workshop held to help define R&D needs, 15-17 Sep 2008, BGS, UK. ~30 experts
- Reviewed research on both terrestrial and marine leaks
- Presentations on natural leaks (Latera, Laacher See, Panarea) and controlled releases (ZERT, ASGARD)
- Presentations and discussions on regulatory needs, experimental releases and monitoring research on natural analogues

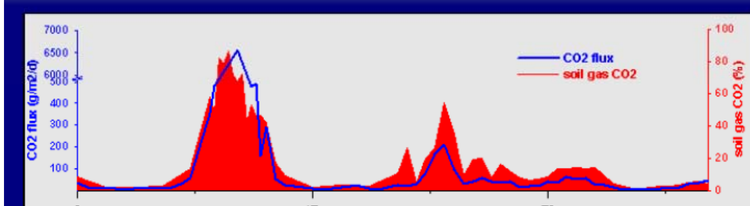


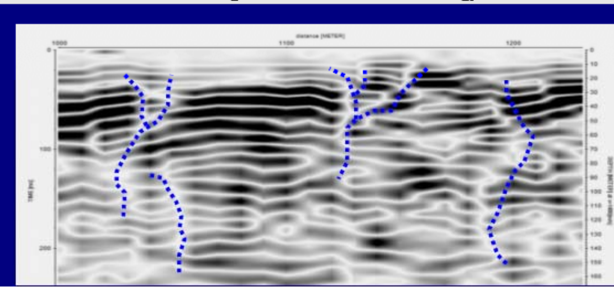
Latera – regional CO_2 leakage



- Regional soil gas CO_2 surveys of the Latera caldera
- Local N-S trends
- Regional SW-NE trend
  – Location of the study area is shown by a green circle

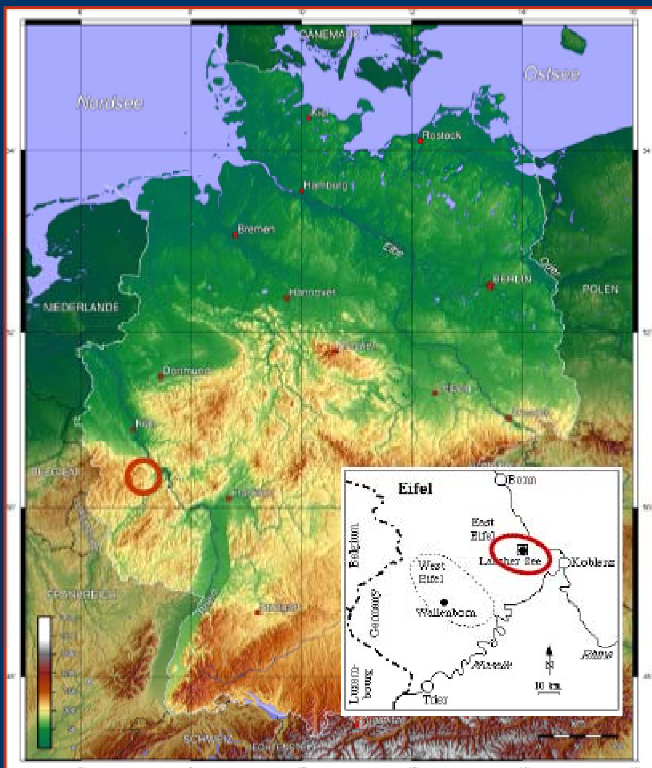
Latera –leakage pathways





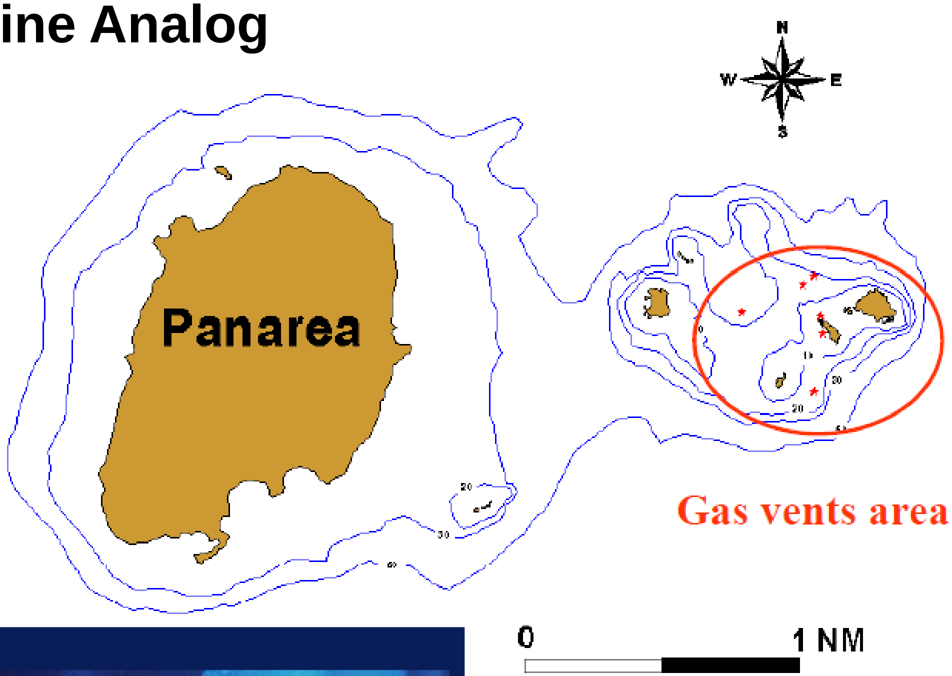
Seismic Gun profile

The Laacher See region

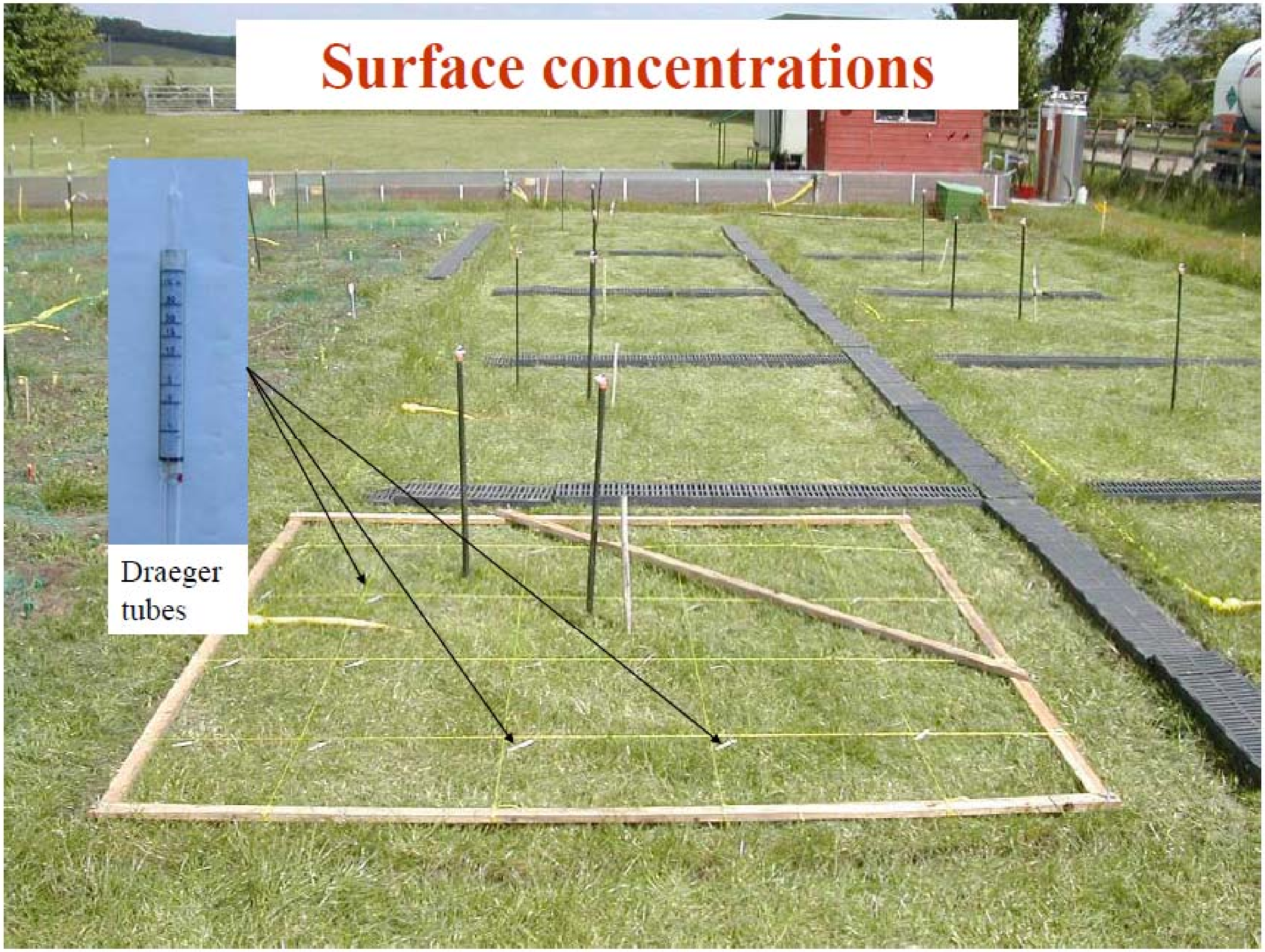


- The Laacher See region represents one of the volcanic centres of the East Eifel volcanic field
- Located at about 50°24′ N and 7°16′ E, west of the river Rhine in the uplifting Paleozoic Rhenish Massif, the Devonian basement of the Laacher See volcanic centre
- The Laacher See eruption at about 12900 yr bp is t
known large explosive
that took place in Cen
during late Quaternar

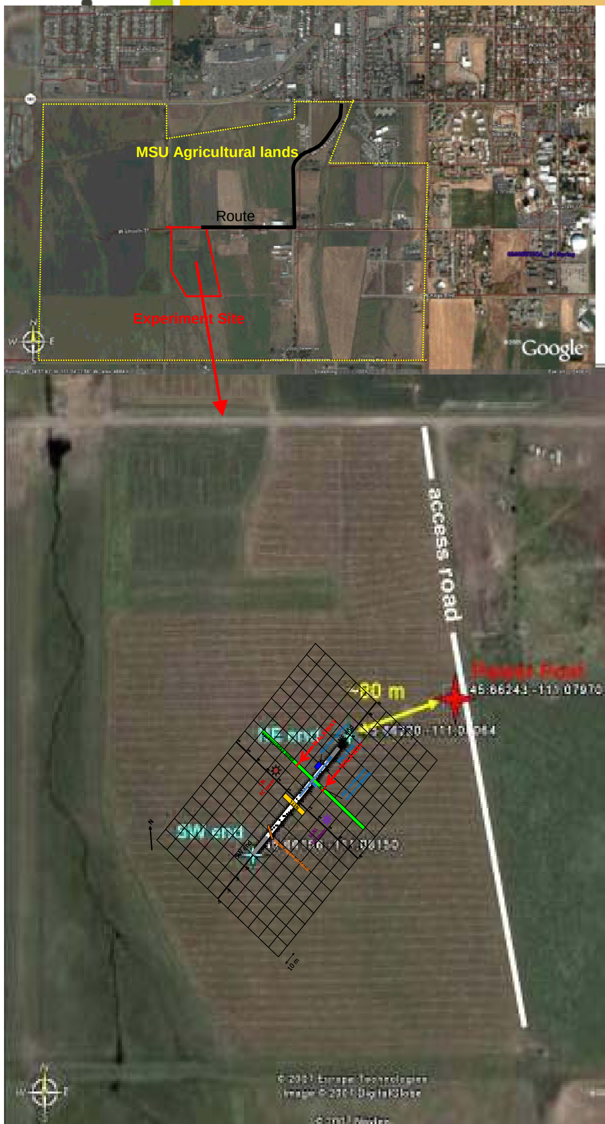
Panarea Marine Analog

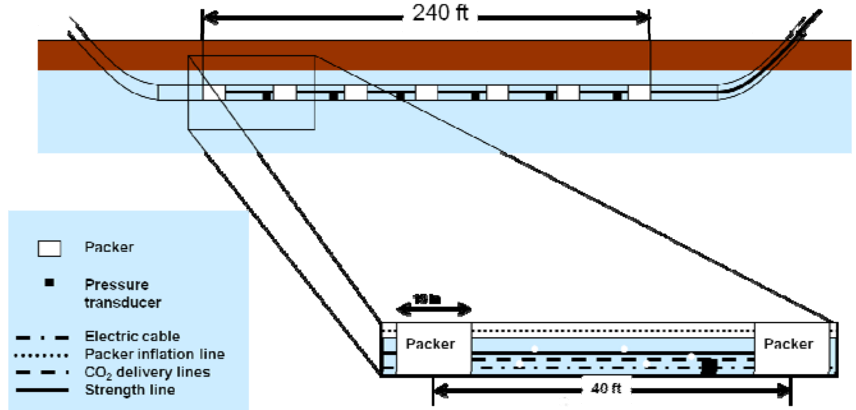


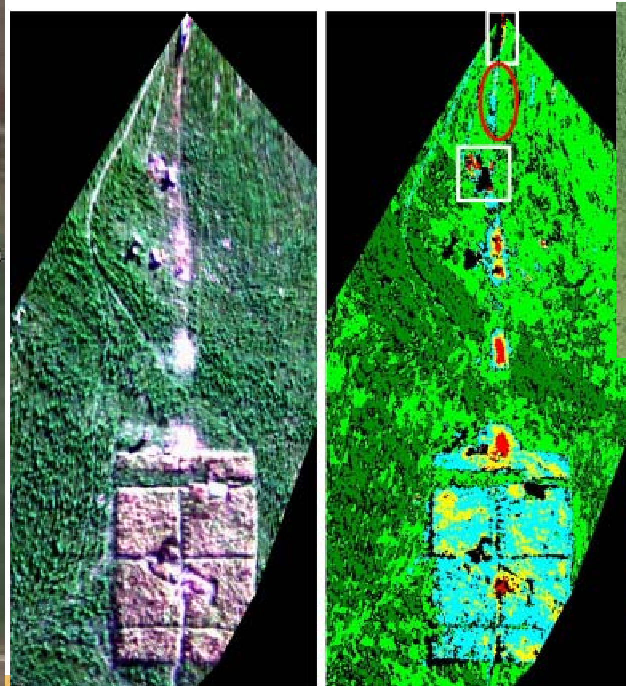
ASGARD, University of Nottingham



Near Surface Detection Site







High Stress
Moderate Stress
Low or Seasonal Stress
Healthy Vegetation (Grasses)
Healthy Vegetation (Herbaceous Legumes)
Unclassified

Environmental Impacts of Leakage

- Leakage rates need to be quantified
- A defined scope for Environmental Impact Assessments is needed
- A database of analog sites is highly desirable
- Monitoring guidelines desired:
  - Timescale for monitoring
  - Access to baseline data or required period for baseline monitoring
  - What monitoring techniques should be used

Regulator Needs

- Database of experimental sites (both leaking and non-leaking)
- Decision tools / framework for site permitting
- Identify indicator species and reference ecosystems
- Sensitivity thresholds for species / ecosystems
- Real project data needed to understand environmental risks

Public Needs

- Need to identify issues of greatest importance to public
  - May be site specific (e.g. groundwater in some areas)
- Local interest groups should be involved
- Terminology is an issue
  - For example EC Storage Directive terms “significant” and “limited”

Research Needs

- Environmental impacts at ecosystem level
- Impacts of chronic vs. acute exposure and greater understanding of physiological response
- Identification of indicator species
- Groundwater quality issues
- Database of analog sites (including brine intrusion)
- Better understanding of pathways between the reservoir and surface – coordination with modeling
- Rates of leakage and impacts
- Effects of coupled or multiple stressors
- Development of appropriate scenarios – spatial scales

High Priority Gaps

- Develop greater understanding of impacts on CO_2 and co-released or mobilized substances
- Impacts of pH changes, potential metal mobilization and brine intrusion on groundwater
- Effects of brine displacement

Additional Gaps

- Identification of indicator species
- Impact on surface fresh water
- Thresholds of exposure and “acceptable” flux rates
- Distinctions between chronic and acute effects
- Effects of coupled or multiple stressors
- Rates of processes (onset, recovery)
- Greater interaction with monitoring group, risk assessment group, modelers.
- Greater understanding of overburden and near-surface transport needed

Monitoring and EIA

- Collaboration between monitoring and risk assessment groups needed
- Monitoring should be for EIA as well as storage verification
- Monitoring should be for risk assessment as well as risk management
- EIA monitoring will be site specific
- Groundwater protection likely to be key issue

Addressing the Identified Issues

- Identification of reference species:
  - Should include commercially important species
  - Marine reference species might include corals, shellfish and nematodes
  - Terrestrial might include grasses, legumes and worms
- Experiments involving groundwater likely not to be permitted – identification of relevant natural analogs to study impacts could be important.

Summary

- Credible leakage scenarios need to be defined
  - To define scope of EIAs
  - To enable experimental studies to be properly constrained
- An analogs database is desirable
- Target species and thresholds are needed
- Understanding of ecosystem response to multiple and coupled stressors is needed
- Monitoring will need to address Environmental Impacts
- A combination of laboratory and Field experiments, analog studies and modeling studies can address the gaps

5th IEAGHG Monitoring Network Meeting Tokyo 2 - 4 June 2009

CO_2 Research into Monitoring and Verification

Andy Chadwick (British Geological Survey)

CO2 REMOVE research monitoring verification

CO2ReMoVe

EU 6th Framework Integrated Project (2006 – 2011)

Budget 15.1 MEuros

Funded by the EU and Industry

Partners: TNO (co-ordinator), BGR, BGS, BP, BRGM, CONOCOPHILLIPS, EXXONMOBIL, CMI, DNV, ECN, GEUS, GFZ, IEA-GHG, IFP, IMPERIAL COLLEGE, MEERI PAS, QUINTESSA, OGS, URS, SCHLUMBERGER, SINTEF, STATOIL, TNO, TOTAL, VATTENFALL, VECTOR, WINTERSHALL, WESTERNGECO.

Research based on datasets from real CO_2 injection sites

CO2 REMOVE
research monitoring verification

CO2ReMoVe: Five sub - projects

SP1: Provision of Site Monitoring datasets (legacy and subcontracting)

SP2: Performance Assessment

SP3: Monitoring Interpretation and tool development

SP4: Best Practice and Guidelines

SP5: Dissemination and Training

U1

SP1 Site Monitoring Datasets	SP2 Performance Assessment	SP3 Monitoring Interpretation Development	SP4 Best Practice Guidelines	SP5 Training Dissemination

Work Packages:

Interpretation, modelling and assessment of site monitoring datasets at

- In Salah
- Sleipner
- Snohvit
- Ketzin
- K-12B
- Weyburn
- Tarnow

WP Innovative monitoring tool development

WP Tool comparison and development of generic monitoring strategies

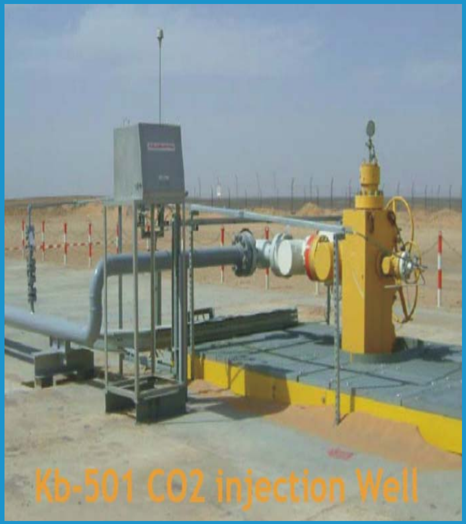
CO_2 REMOVE research monitoring verification

Slide 4

U1 I adapted the layout of the wp list

Userdef, 30/05/2007

Industrial-scale sites (~1 Mt CO_2 per year)



In Salah (Algeria): >1 Mt (1900 m depth, onshore)

Sleipner (Norway): >8 Mt (900 m depth, offshore)

Snohvit (Norway): 2900 m depth offshore

Weyburn (Canada): 1500 m depth onshore

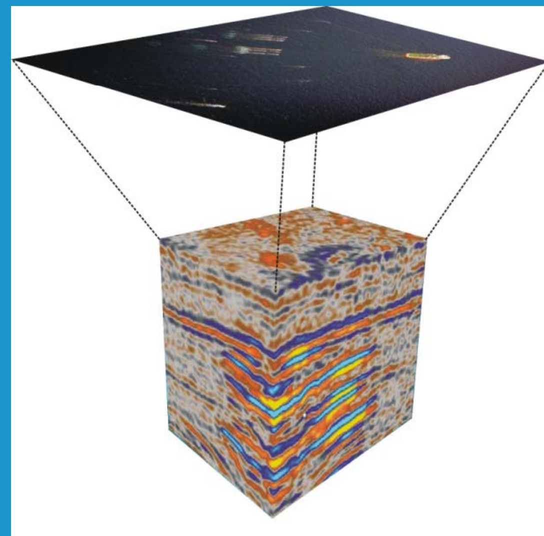
Smaller laboratory sites (< 0.1Mt CO_2 per year)

Ketzin (onshore Germany)

K12-B (offshore Netherlands)

CO2 REMOVE
research monitoring verification

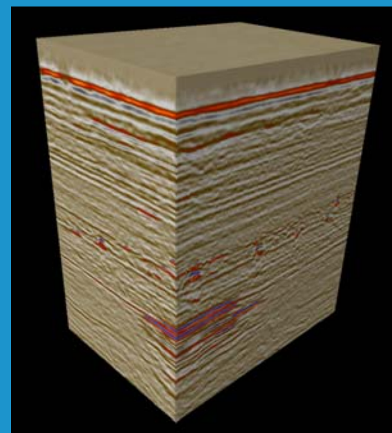
SP1/3 Monitoring datasets

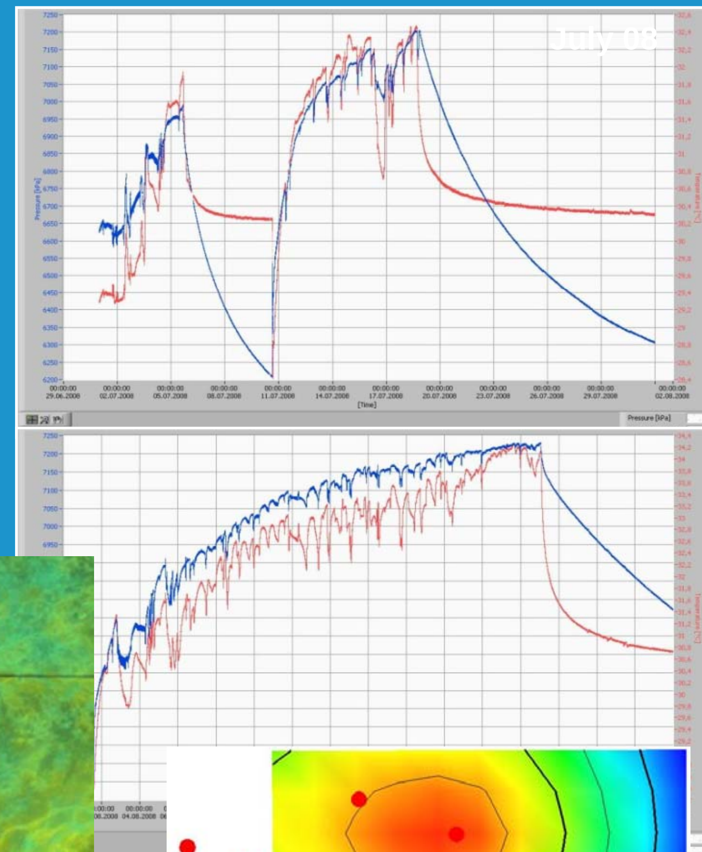


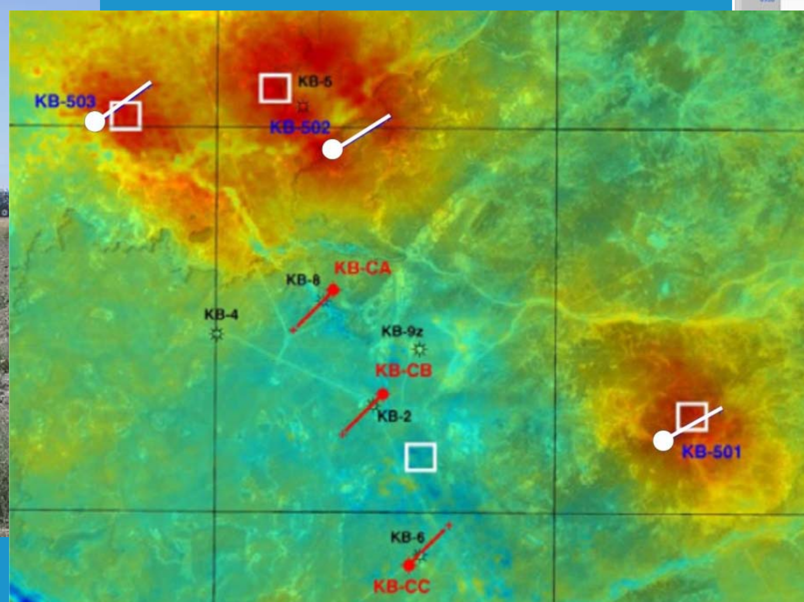
	Subsurface monitoring										Surface and near-surface monitoring				
	seismic methods				non-seismic and borehole methods										
	4D surface seismic	hi-res 2D seismic	well seismic VSP	micro-seismicity	EM / electrical	gravity	tiltmeters	P,T	Downhole logs	well fluids	seabottom imaging	soil gas	surface flux / atmospheric	ecosystems	satellite remote sensing
In Salah	■		■	■		■	■	■	■	■		■	■	■	■
Sleipner	■	■			■	■					■			■	
Snøhvit	■							■							
Ketzin			■	■	■			■							
K12-B								■	■	■					
Weyburn												■	■		

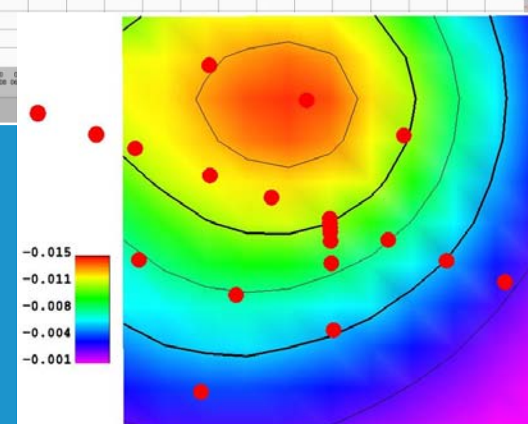
SP3: Interpret site monitoring datasets

- **Interpretation**
- **Modelling**
- **Analysis**









CO2 REMOVE
research monitoring verification

SP3: Innovative Monitoring Tool development

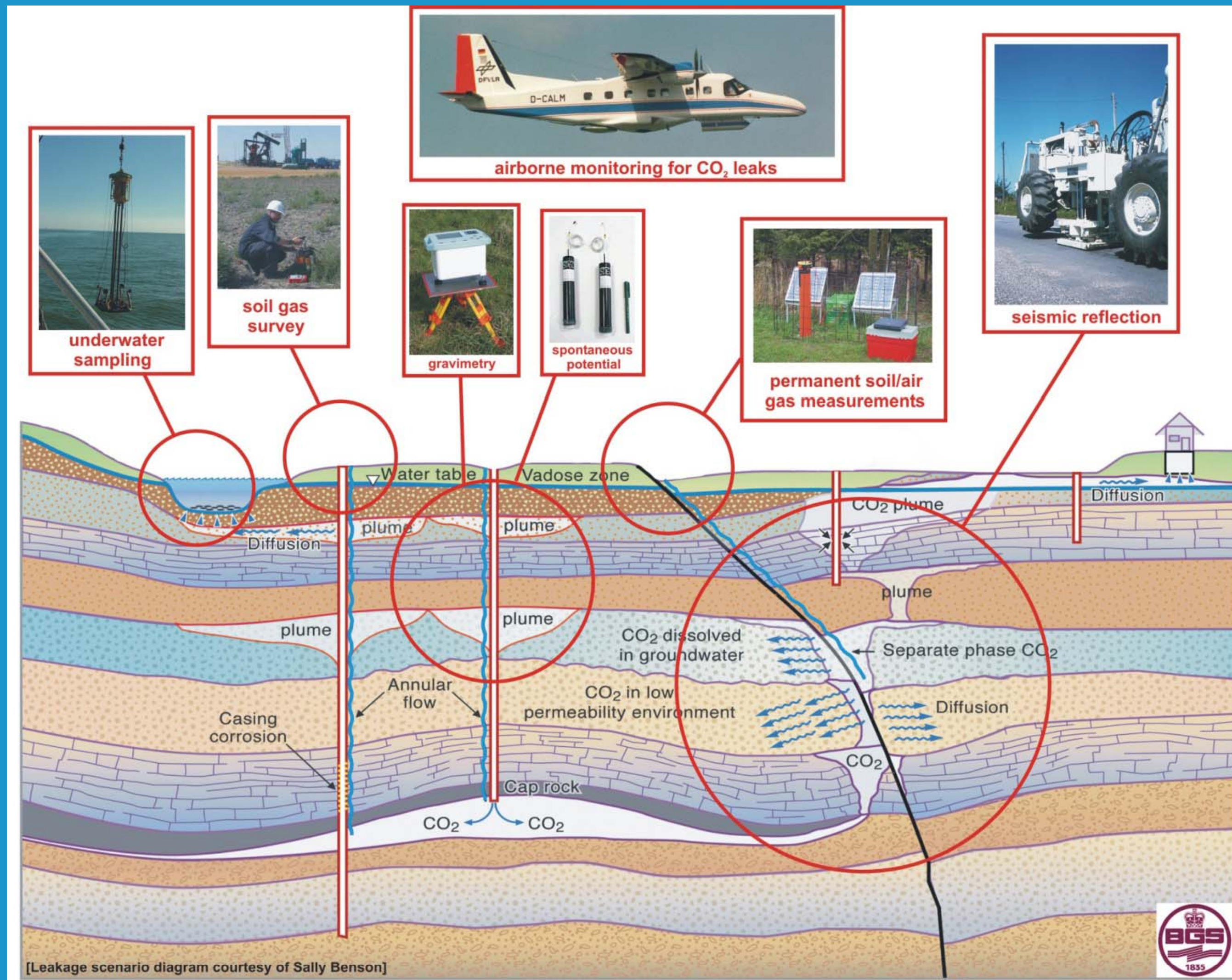
Underwater and atmospheric fluxes

Novel downhole tools

Electrical / EM

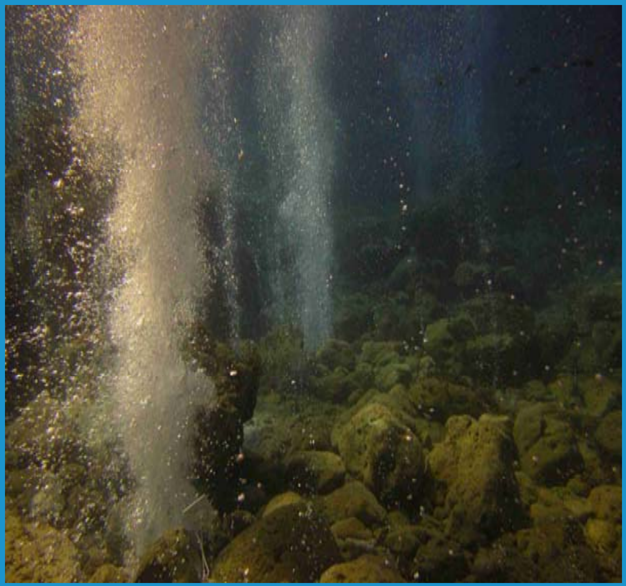
Advanced seismic

Integrated monitoring Software platform



CO2 REMOVE
research monitoring verification

Tool development: Underwater fluxes



- Wholly new prototype
- Seaflooor located and no surface infrastructure
- 12-month data storage
- Storm resistant (for use in North Sea and similar environments)

Tool development: Underwater fluxes

Option 1: Fixed funnel-based autonomous gas flow monitoring system developed. Tested in Lake Constance at 10m depth for 6 – 8 weeks. Lab testing > 9 months.

Mobile (ROV-based) tool with sonar, positioning system and sampler. Lab testing for bubble detection.

Option 2: Semi-submersed seafloor system, methane, CO_2, temperature, pressure.

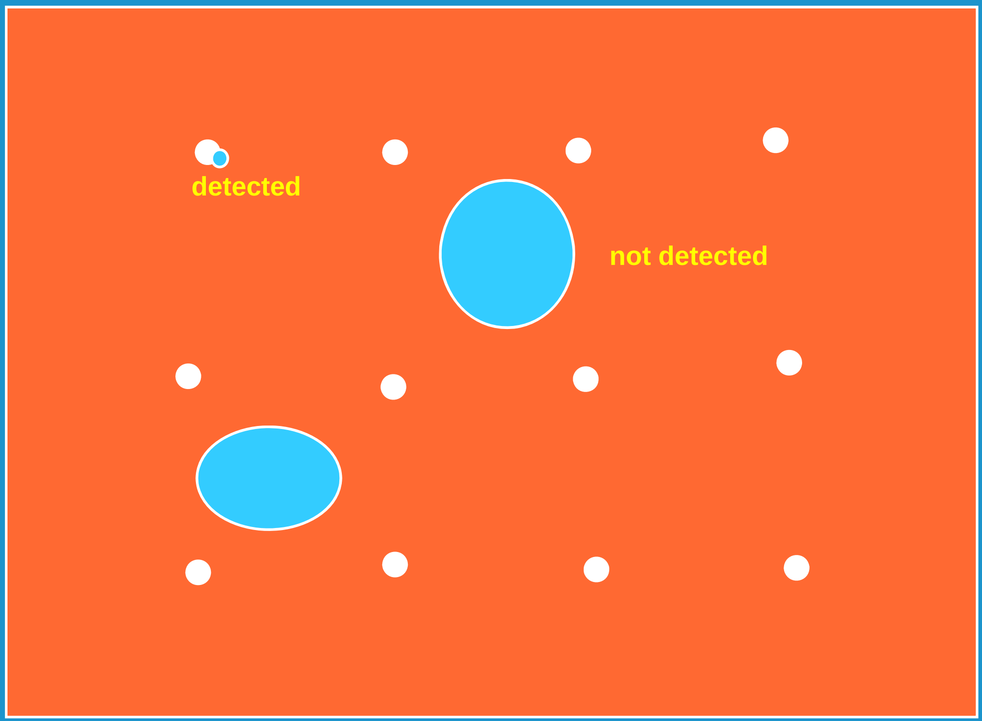
Tested at Panarea May 2008,

Modifications: non-dispersive IR sensors installed

24m in Alban Lake 3 weeks January 2009

Planned test Panarea spring 2009

Tool development: Shallow focussed monitoring coverage issues



point coverage
(non-uniform detection capability)

CO2 REMOVE
research monitoring verification

Tool development: Atmospheric fluxes

Mobile IR laser.

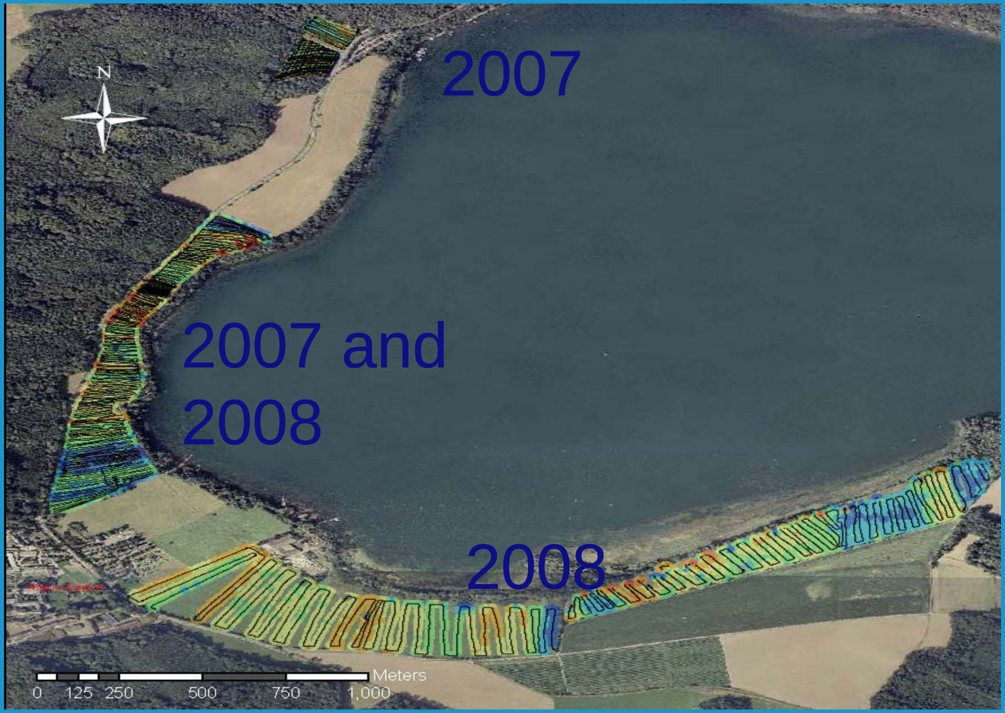
Tested at Laacher See 2007 and 2008

Tested in UK landfills (CO_2 and methane)

Deployed at In Salah

Ongoing modifications (sub-metre GPS, sensor configuration)

Integrator systems



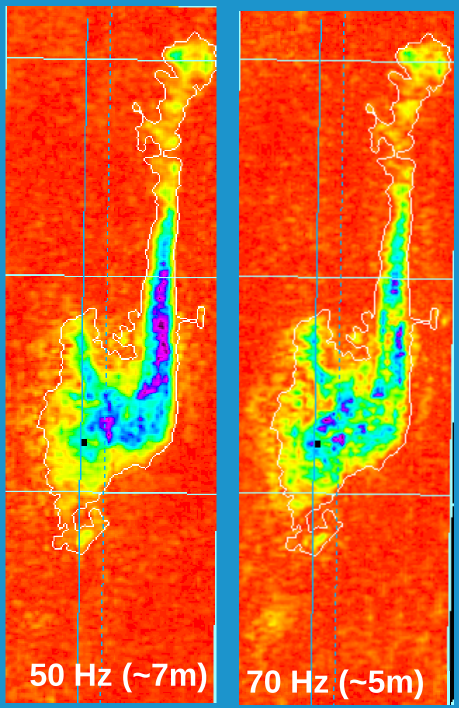
CO2 REMOVE research monitoring verification

Tool development: Advanced seismic methods

Sleipner datasets (mostly pre-stack)

– aimed at improving imaging and quantification

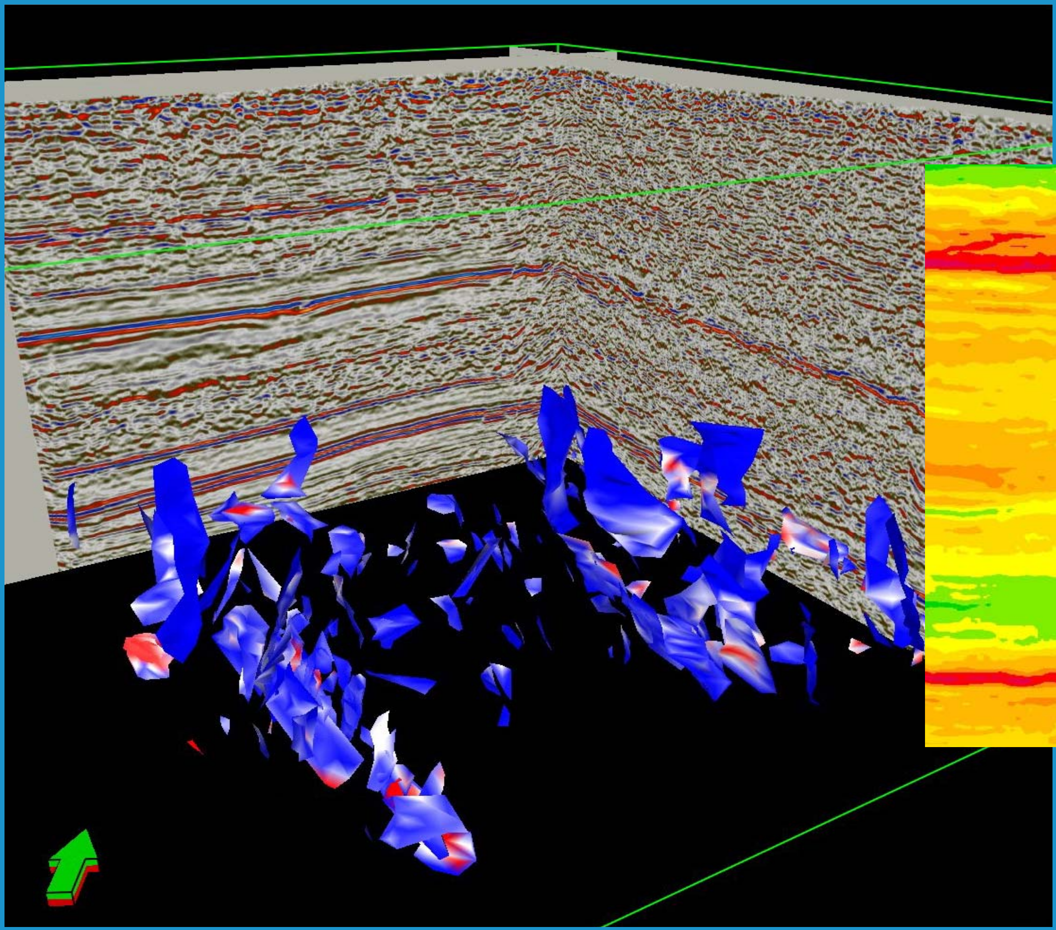
- **Spectral decomposition for thin-layer mapping**
- **Non-rigid matching and super-resolution**
- **Constrained seismic velocity/attenuation tomography**
- **Common Focus Point imaging**
- **Azimuth-dependant velocity/attenuation anisotropy**
- **Azimuth-dependant scattering**
- **AVO modelling**
- **Model based inversion**



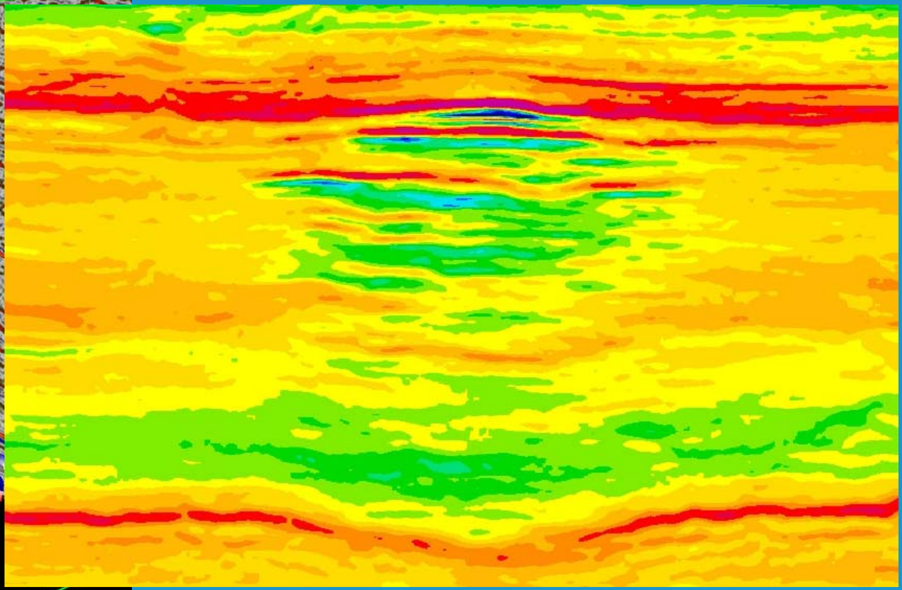
Spectral decomposition

CO2 REMOVE research monitoring verification

Tool development: Advanced seismic methods



Extrema analysis



Pre-stack inversion

CO2 REMOVE
research monitoring verification

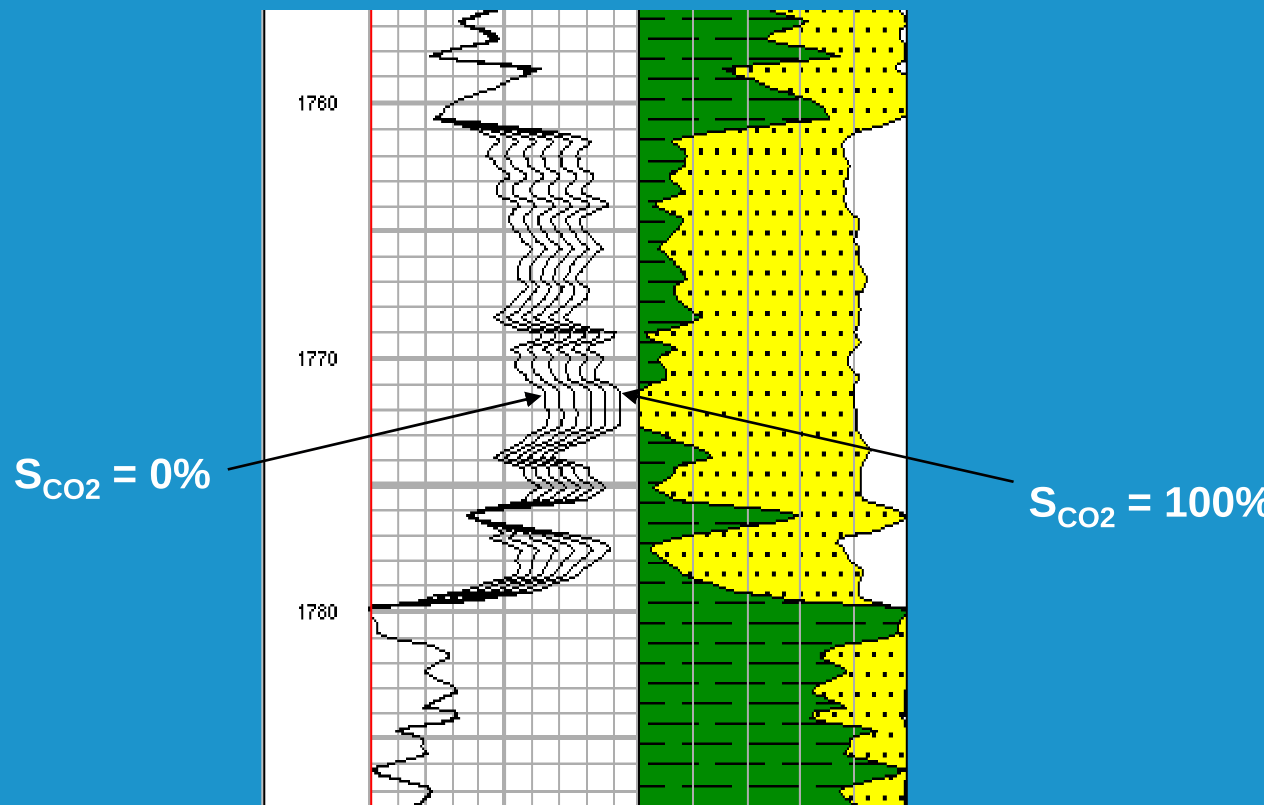
Tool development: Downhole logging

Completed adaptation of the Reservoir Saturation Tool (RST) for CO_2 logging

Tool corrections obtained through experiments in special sand/brine/CO2 tank

Sensitivity studies performed on main variables (salinity and porosity)

Synthetic responses generated for In Salah wells to show potential capability



SP3: Tool comparison and development of generic monitoring strategies

- Compare similar tools in different storage settings
- Evaluate complementary (cost-effective) tool combinations
- Generic site monitoring strategies for a range of storage scenarios
- Interface with SP2 (Performance Assessment) and SP4 (Regulatory / guidelines)

CO_2 Research into Monitoring and Verification

CO2CRC Otway Project

IEA M&V Network Meeting

Tokyo, Japan

June 2-3, 2009

Sandeep Sharma, Peter Cook and Charles Jenkins

Otway Project: Acknowledgements

- CO2CRC co… …ies …ed in the Project
- … International Collaborators: LBNL, BEG, ARC … …her advisers
- CO2CRC Participant companies

Australian Government – Geoscience Australia | CSIRO | Shell | bp | Chevron | Xstrata Coal | Rio Tinto | Woodside

The University of Adelaide, Australia | The University of Melbourne | Schlumberger | BHP Billiton | NZ Resource Consortium | Origin Energy

Monash University | UNSW | Curtin University of Technology | Solid Energy – Coals of New Zealand | Anglo American

Government of Western Australia – Department of Industry and Resources | NSW Department of Primary Industries | ACARP – Australian Coal Association Research Program | Foundation for Research Science & Technology | Mitsui & Co. (Australia) Ltd

ConocoPhillips | Stanwell Corporation Limited | State Government Victoria – Department of Primary Industries | 한국지질자원연구원 Korea Institute of Geoscience and Mineral Resources | QER

Supporting participants: Department of Resources, Energy and Tourism-AusIndustry |The Department of Environment, Water, Heritage and the Arts | CANSYD | Meiji University | The Process Group | University of Queensland | Newcastle University

Established & supported under the Australian Government's Cooperative Research Centres Programme

CRC Australia | CO2CRC

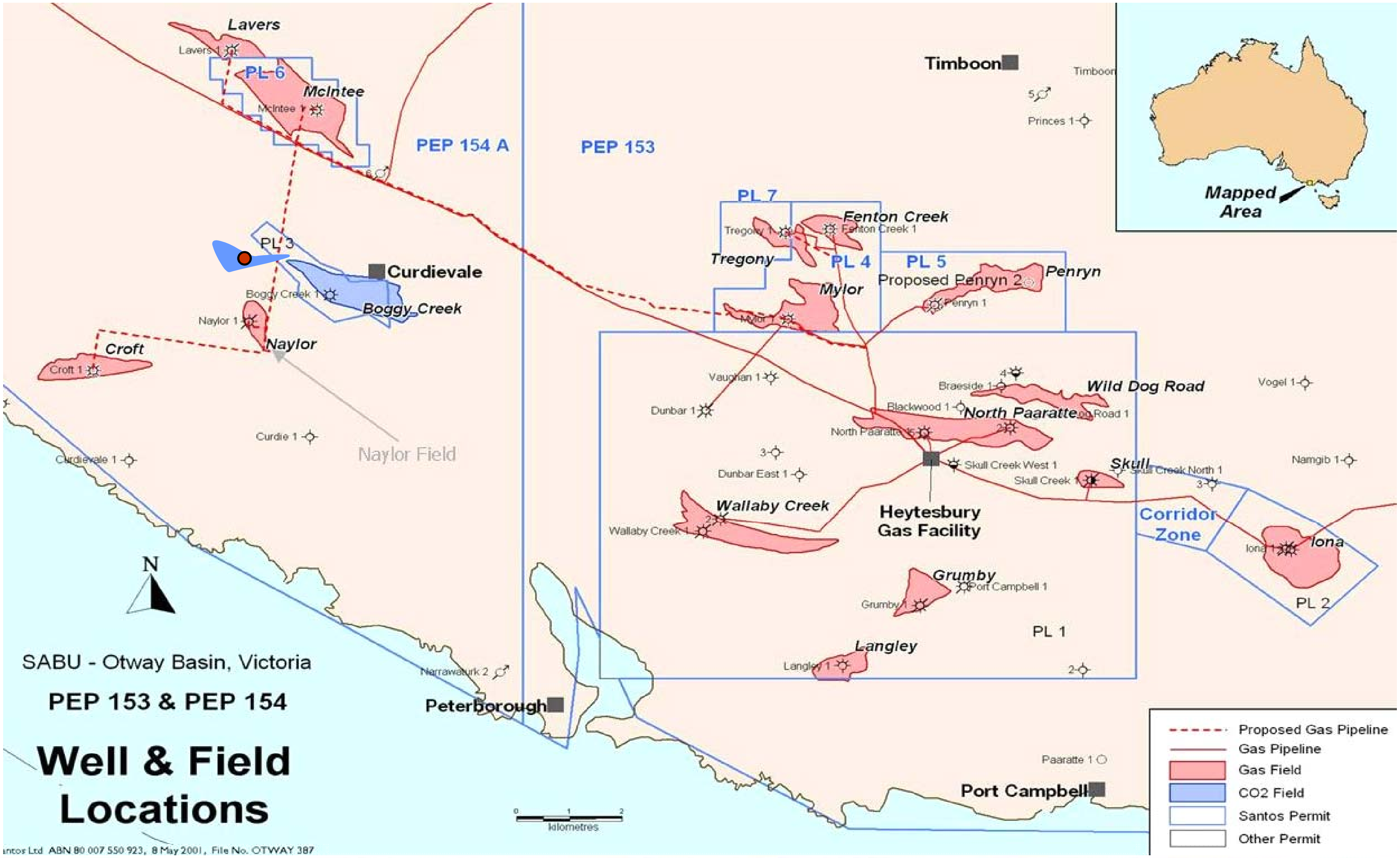
Outline

- The Otway Basin Pilot Project
- Key Challenges
- Monitoring and Verification
- Project Scorecard
- Otway Future Opportunities – Stage 2
- Residual Saturation Tests
- Way Forward

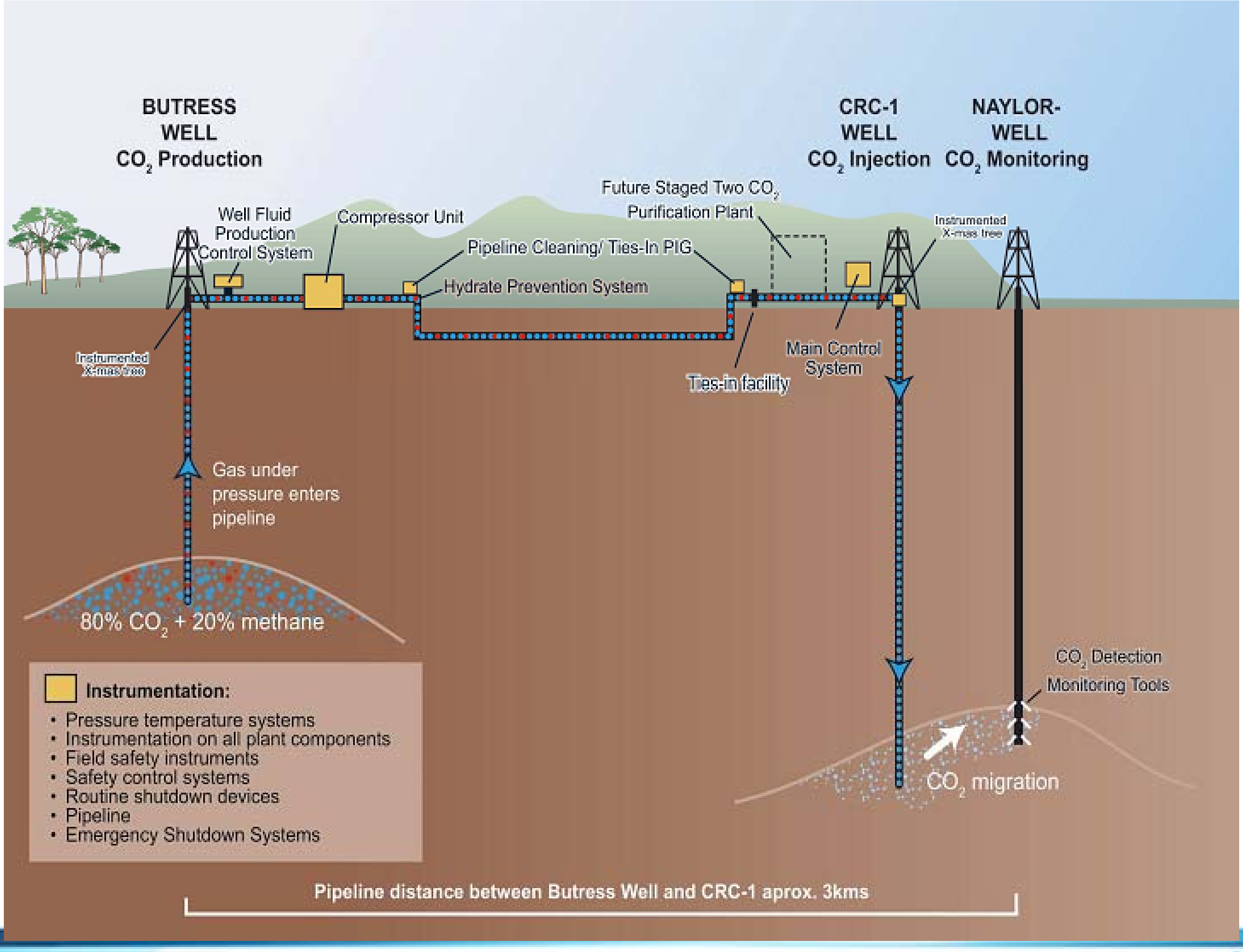
Otway Basin Pilot Project Goals

- **Contribute towards CO2CRC Vision and Mission.**
  - Demonstrate that CCS is technically feasible and environmentally safe.
  - Facilitate research into new monitoring technologies
  - Offer opportunities for trial and experimentation thereby supporting education/training in greenhouse gas technologies.
- **Specifically demonstrate to the satisfaction of stakeholders that**
  - CO_2 can be **safely produced, transported and injected** into the sub-surface
  - CO_2 can be **safely stored**
  - **Subsurface behaviour** of the injected CO_2 can be effectively **modeled and monitored**
  - Storage Volume can be verified as far as possible
  - **Build public support for CCS** as a mitigation mechanism

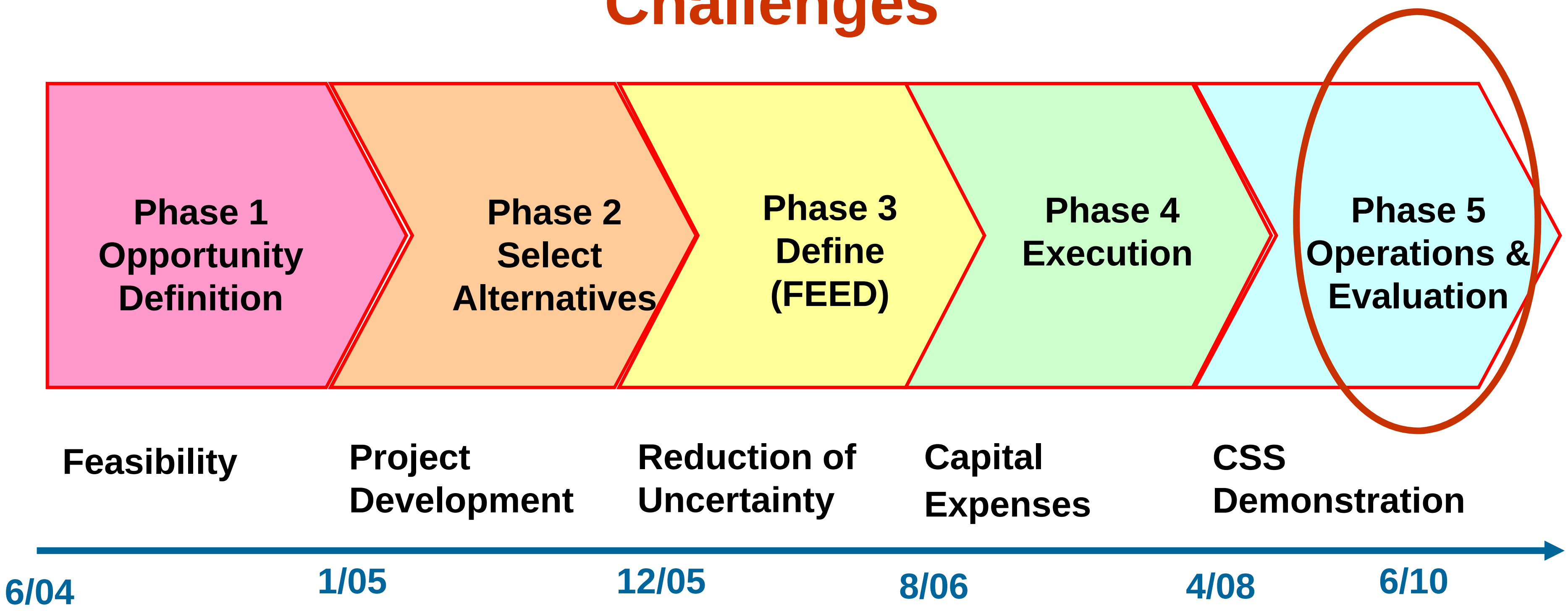
Project Assets and Site



Otway Project Concept

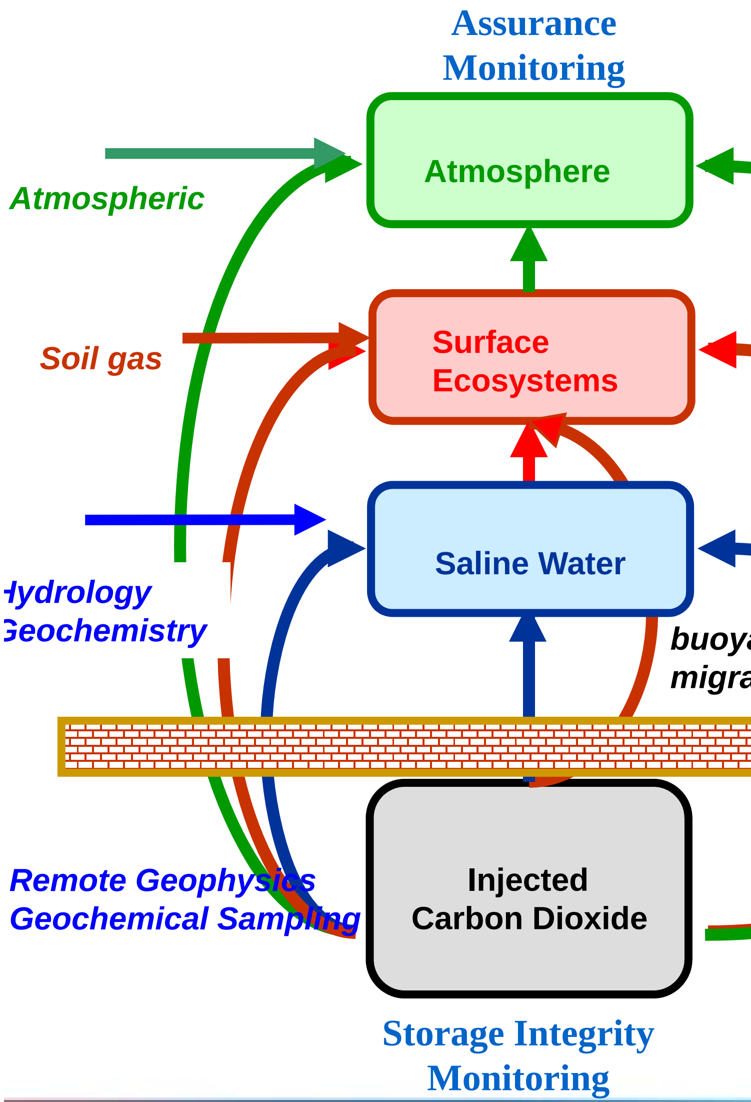


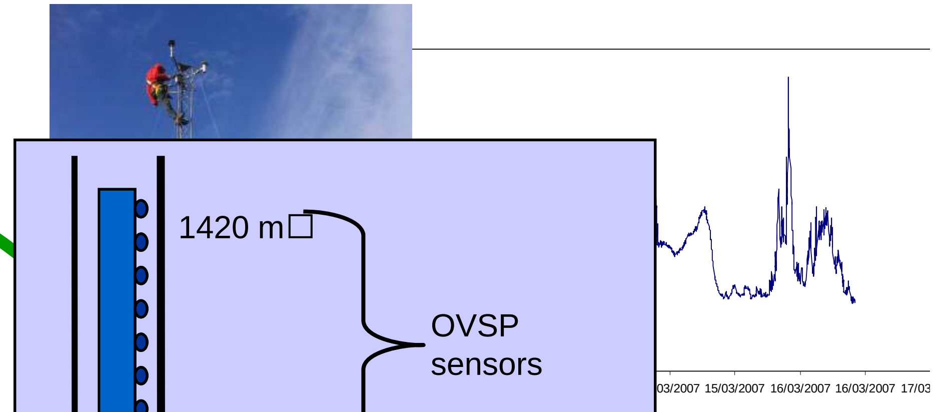
Challenges



- Regulatory
- Organisational/Operational
- Liability Management
- Site Characterisation
- Risk Assessment
- Monitoring
- Community / Public Acceptance

Monitoring and Verification: Measurements/Analysis





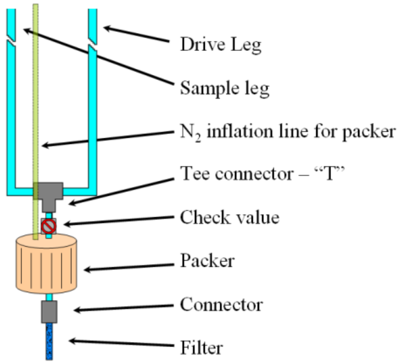
- A multitude of technologies can be used to monitor CO_2 injection in the subsurface
- There is no simple *'checklist'* for monitoring as not all technologies are applicable in all injection scenarios
- Monitoring objectives and mitigation signposts need to be clearly defined to drive technology selection
- Both business and technical criteria must be used to develop the *'fit-for-purpose'* monitoring plan
- The frequency of monitoring data acquisition should be *'performance based'*

Modified from:
http://web.princeton.edu/sites/cmi-aquifers/
Chevron : J.McKenna

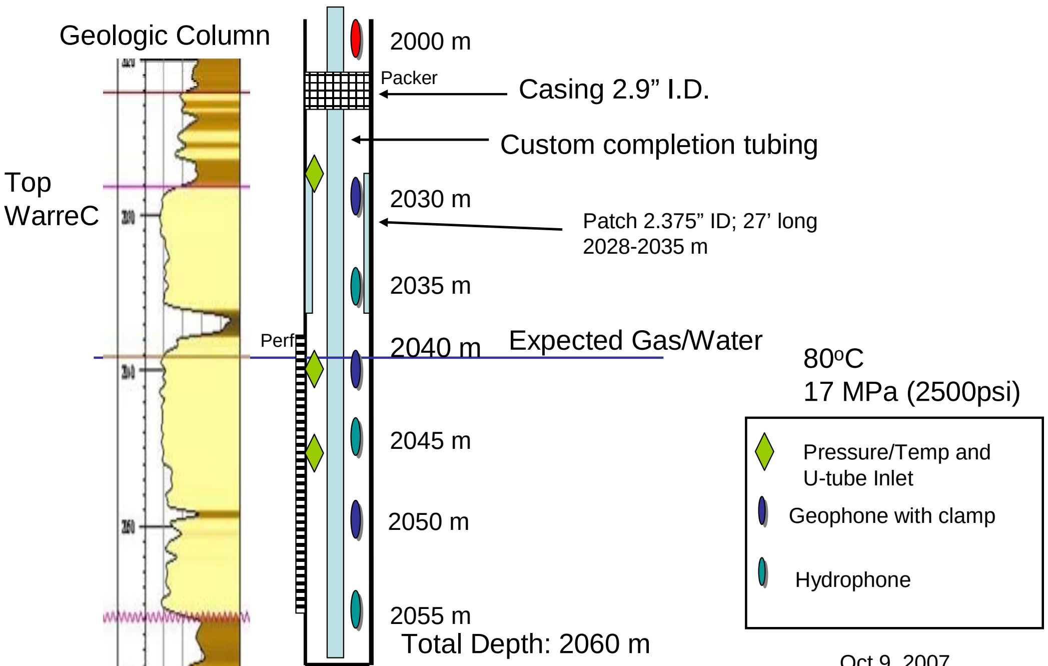
CO2CRC

Naylor 1: Integrated Monitoring

U-tube Sampler



Schematic of bottom hole completion



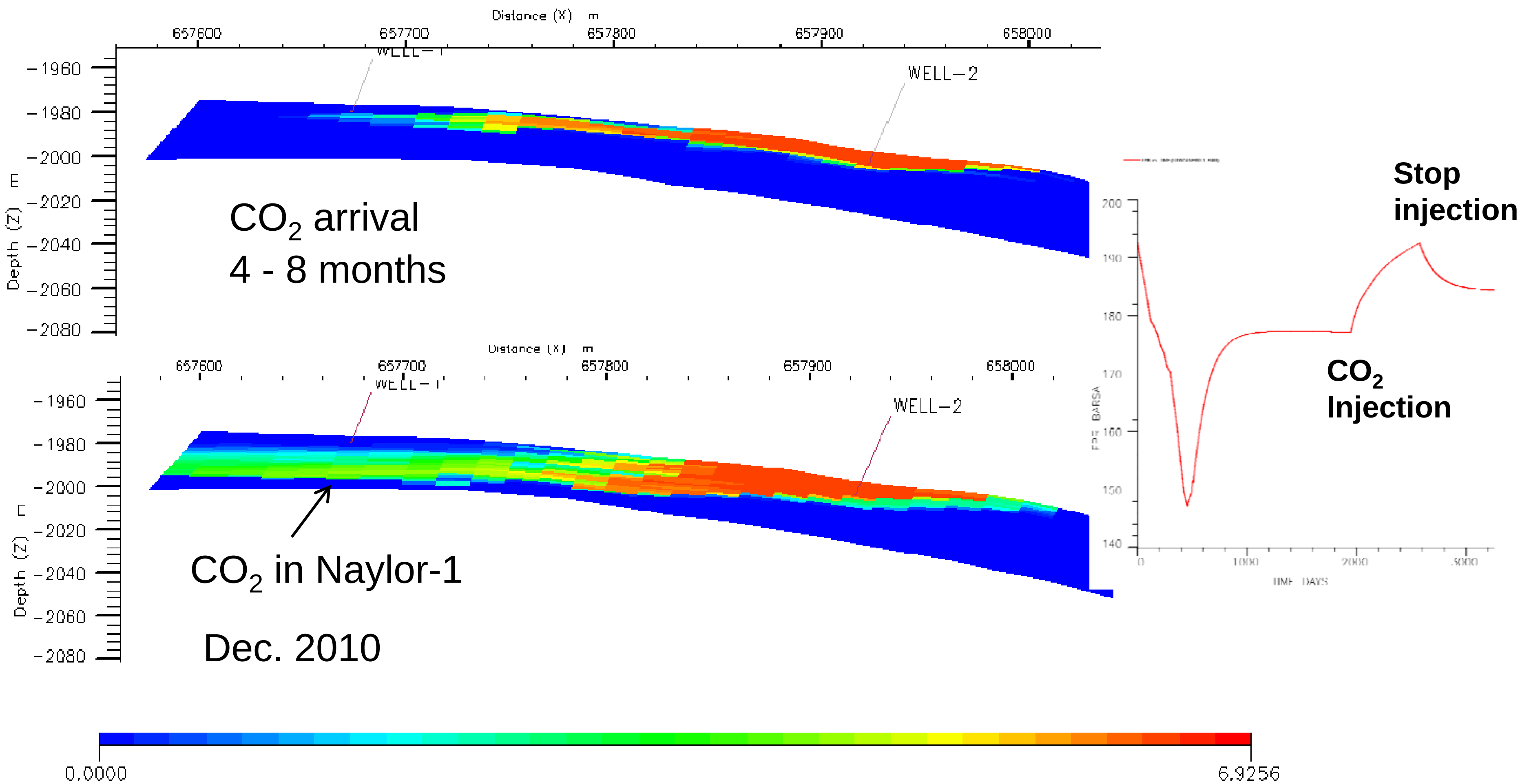
Oct 9, 2007

BERKELEY LAB

CO2CRC Otway Project Score Card

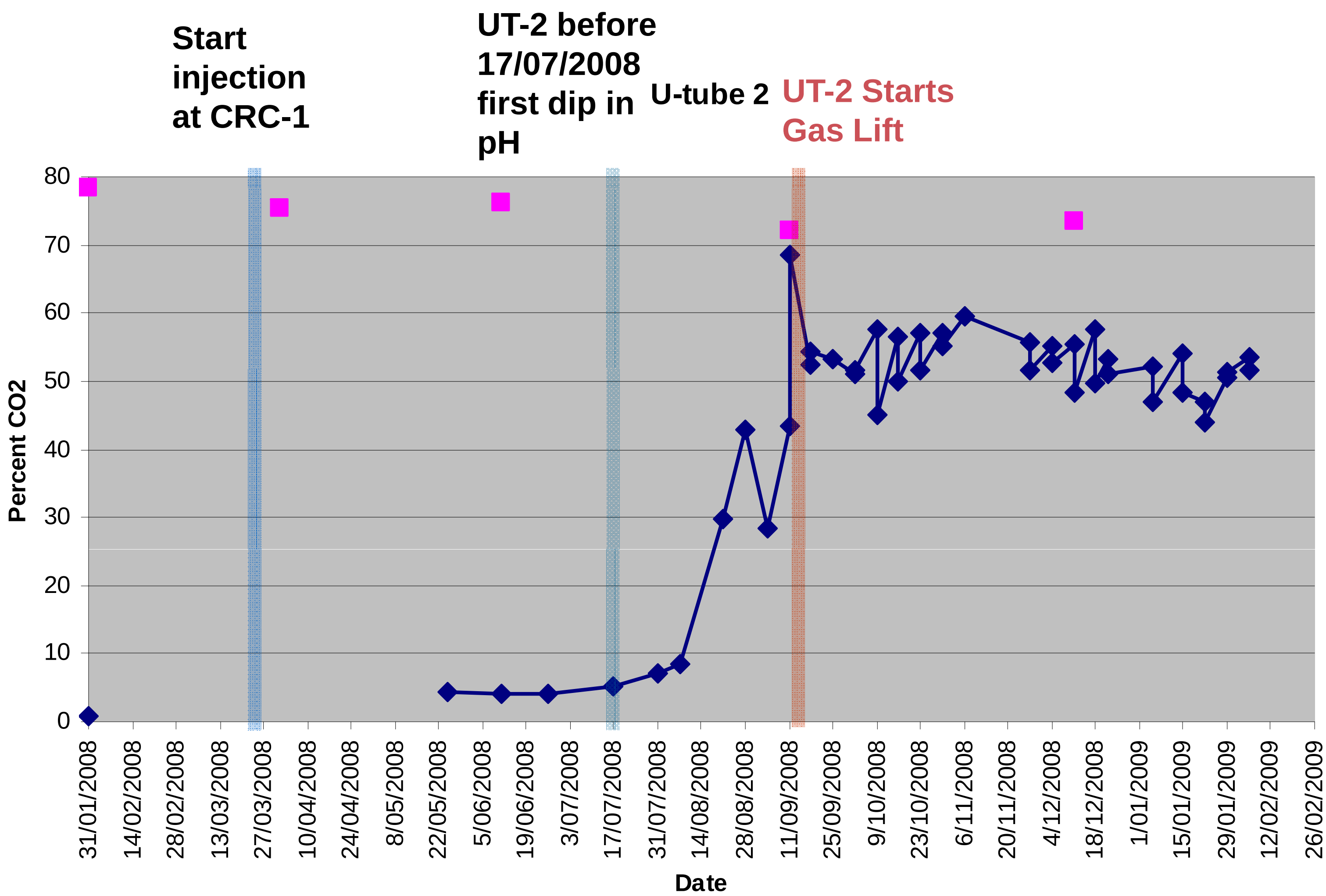
1. ✓ Safely produce CO_2 from Buttress, transport and inject in Naylor field
2. ✓ Effectively and safely store and monitor CO_2 in the sub-surface to satisfaction of stakeholders.
   - Robust Site Characterisation
   - Observations vs Modelling results
3. ✓ Test/Develop technology and methodologies for monitoring
4. ✓ Build Community Confidence
5. Safely abandon the site and facilities including necessary restoration work.

Pre-injection Simulation Results



CO2CRC

% Carbon-dioxide from all U-tube Samples

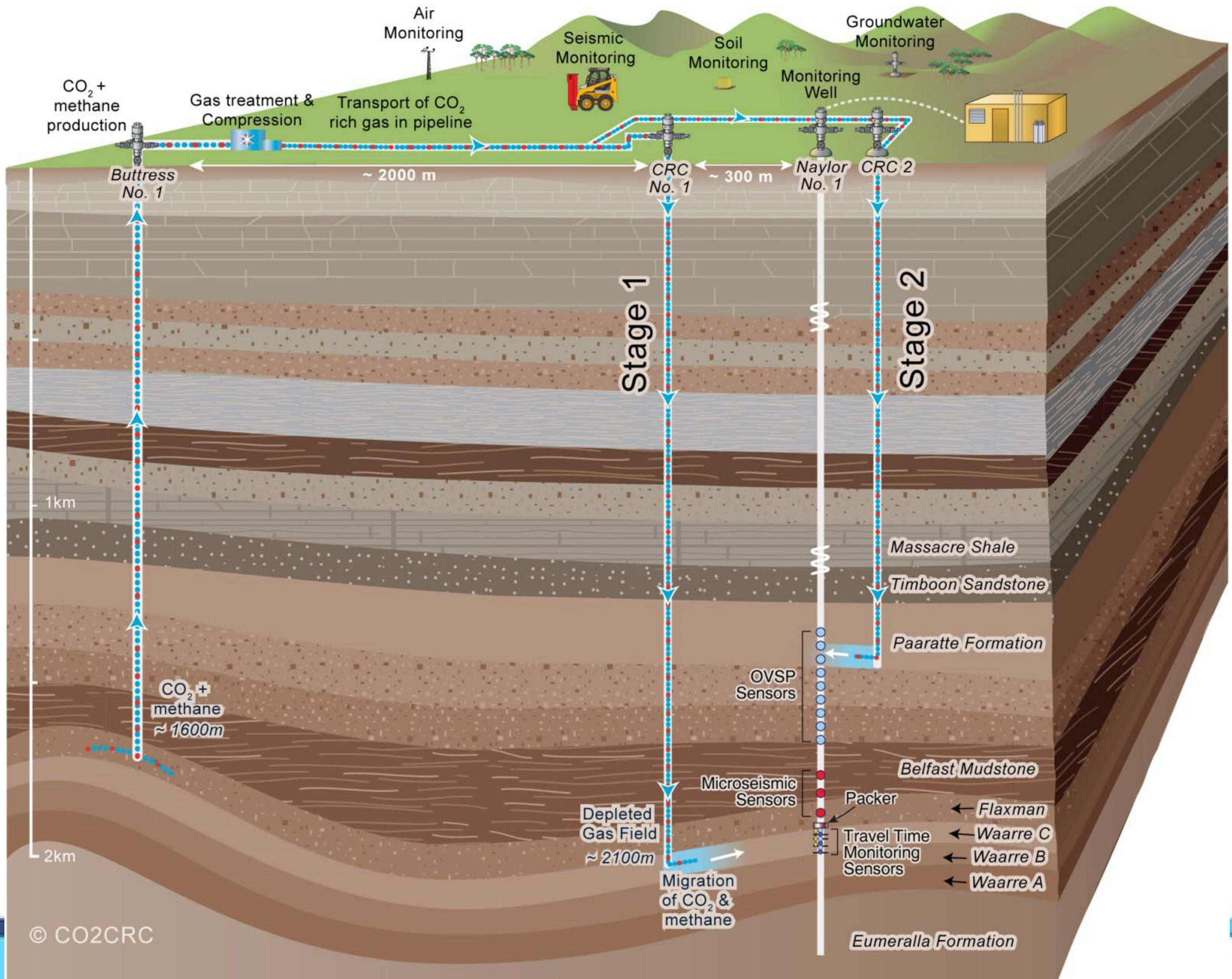


CO2CRC

Furthering CCS Research at Otway

- Opportunity
  - Injection in Parrattee formation: Heterogeneous, multilayered, unconstrained reservoir
  - Focus on non-structural trapping mechanisms
  - Leverage existing M&V equipment
    - ➢Geophysics Sensors in Naylor 1
    - ➢Baseline 3D seismic
    - ➢Near surface and atmospheric monitoring information
- Constraints
  - Injection into Paaratte via CRC-1 can't start before Stage 1 injection is complete (~Jun 09)
  - Time for monitoring (post injection Stage 2) to get results
  - Obtaining approvals in an unconstrained reservoir (CPPL, regulators)

CO2CRC Otway Project - Stage 2: Focus on Non-Structural Trapping Mechanisms

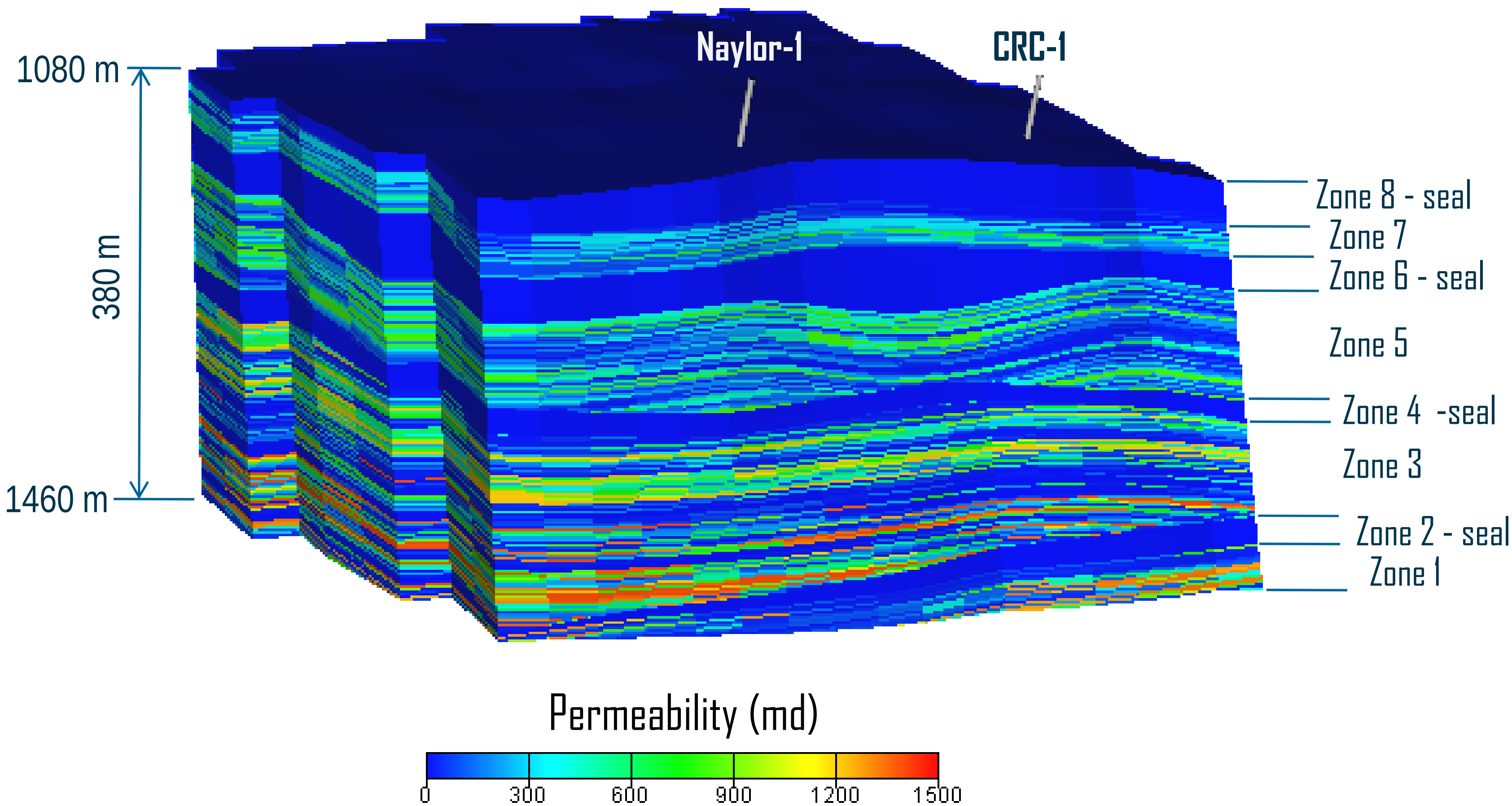


CO2CRC

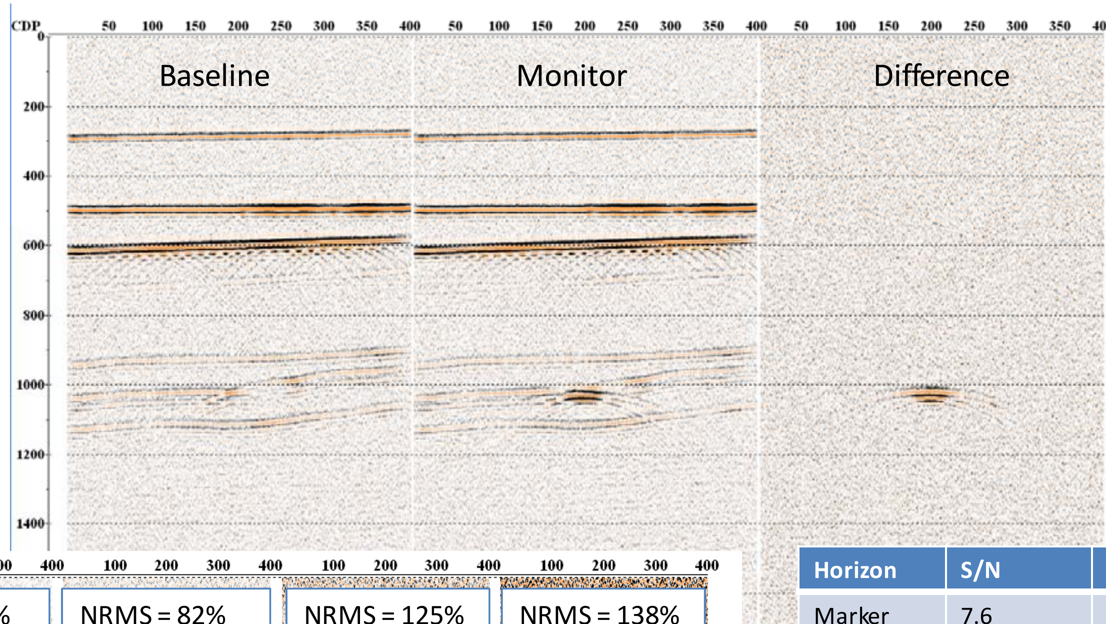
Otway Stage 2 Pathways

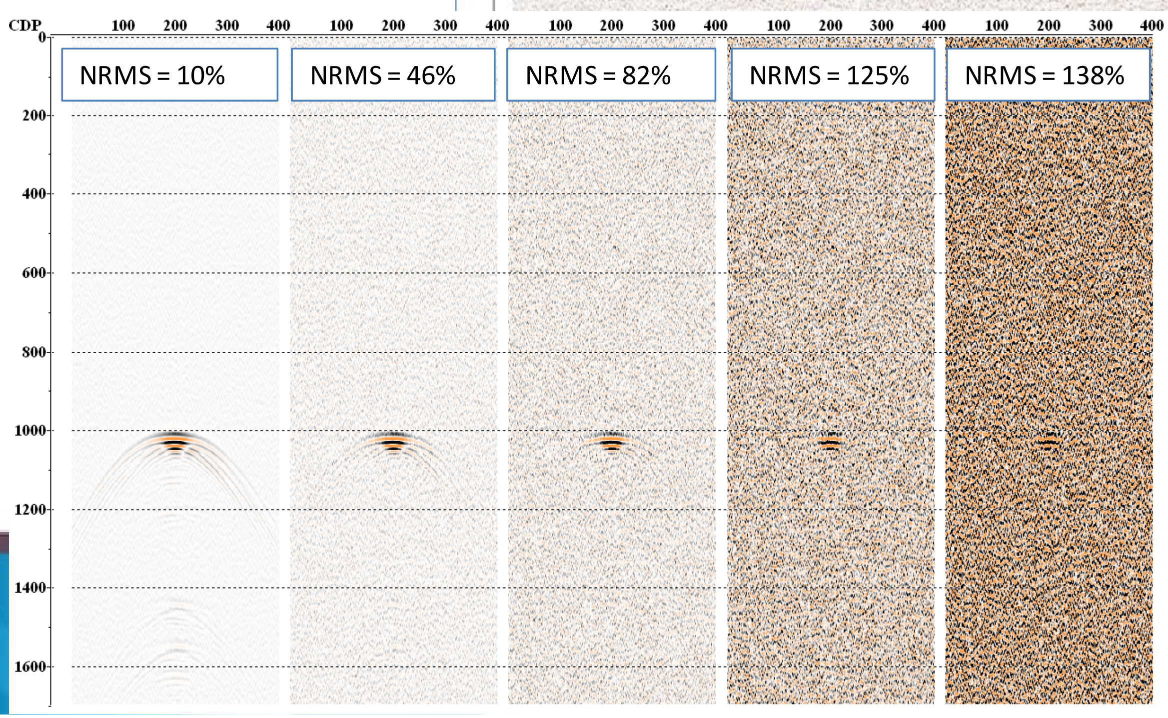
- Carrying out site characterisation of a saline aquifer using existing and newly acquired data
  - New well, cores
- Laboratory determination of relative permeability and geophysical properties from cores
- Investigate processes and kinetics governing CO2 dissolution, hydrodynamic trapping and geochemical reaction
  - Huff-n-Puff CO2 injection testing in the Paaratte Formation
- Estimating aquifer saturation from time-lapse CO2 logging
- Plume imaging in a heterogeneous reservoir using combined geophysical monitoring technologies
- Desired outcomes
  - residual gas saturations and relative permeability effects.
  - ability of the intra-formational seals to limit the vertical migration
  - the rate at which dissolution occurs into formation fluid, and;

Zones Identified in Paaratte Formation



Modelling CO2 injection into Paaratte (5)





Horizon	S/N	NRMS (%)
Marker	7.6	24.7
Paaratte	2.1	82

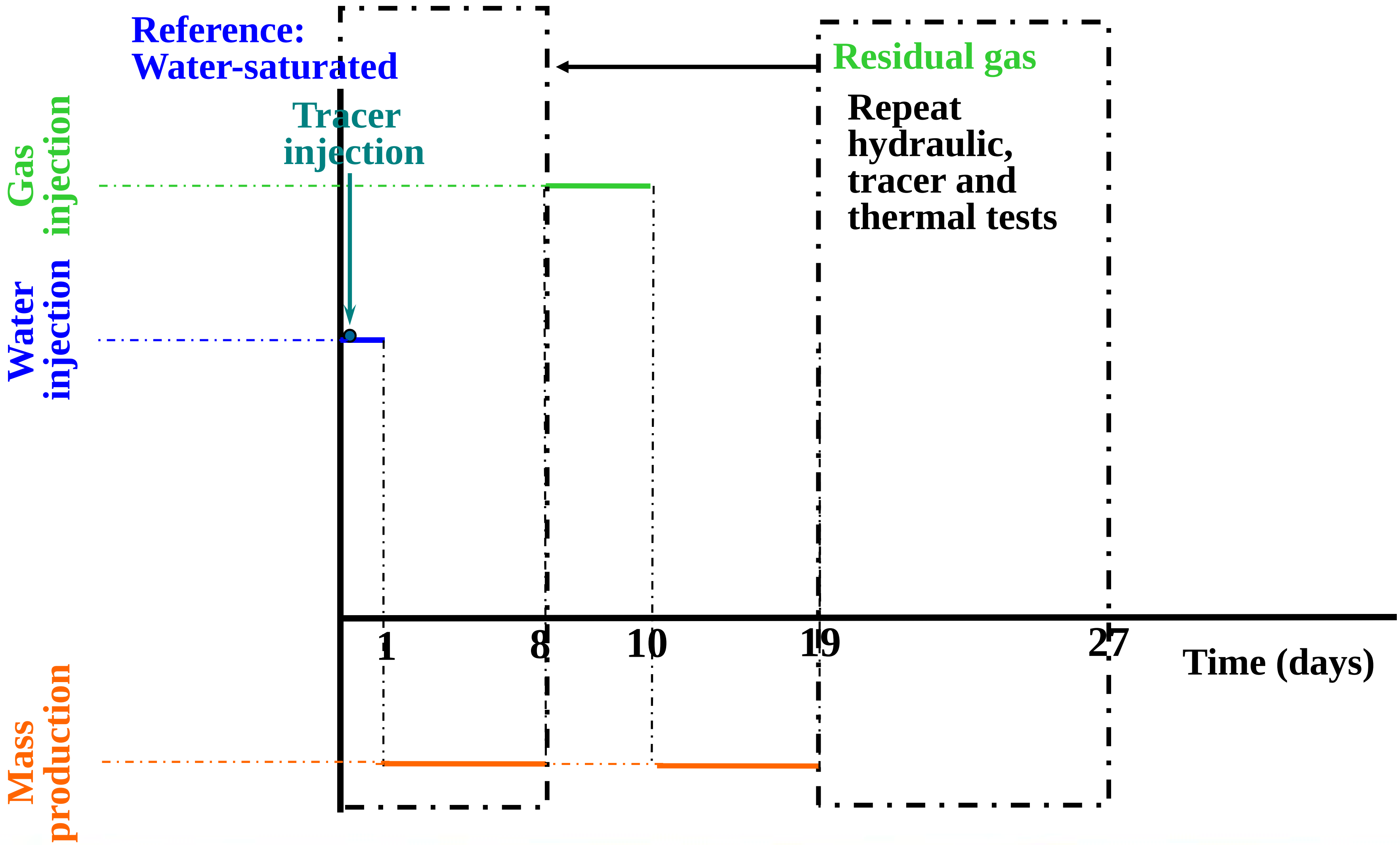
Promising results for CO2 Injection into Paaratte

CO2CRC

Adapting the Huff-n-Puff Test

- **Objective: To determine residual CO2 saturation Sgr**
  - The formation anisotropy and relative permeability control the injectivity and migration of the CO2 plume and physical trapping.
- **Three independent measurement approaches to determining residual trapping:**
  - Thermal logging
  - Tracer partitioning
  - History matching injection and production
- **Complementary Data**
  - Perform reference test under fully water-saturated conditions
  - Create system at residual gas saturation
  - Repeat reference tests
  - Analyze difference to obtain S_{gr}

Test Design



Produce gas after CO_2 injection – and *produce/remove mobile gas* and reduce gas saturation to residual

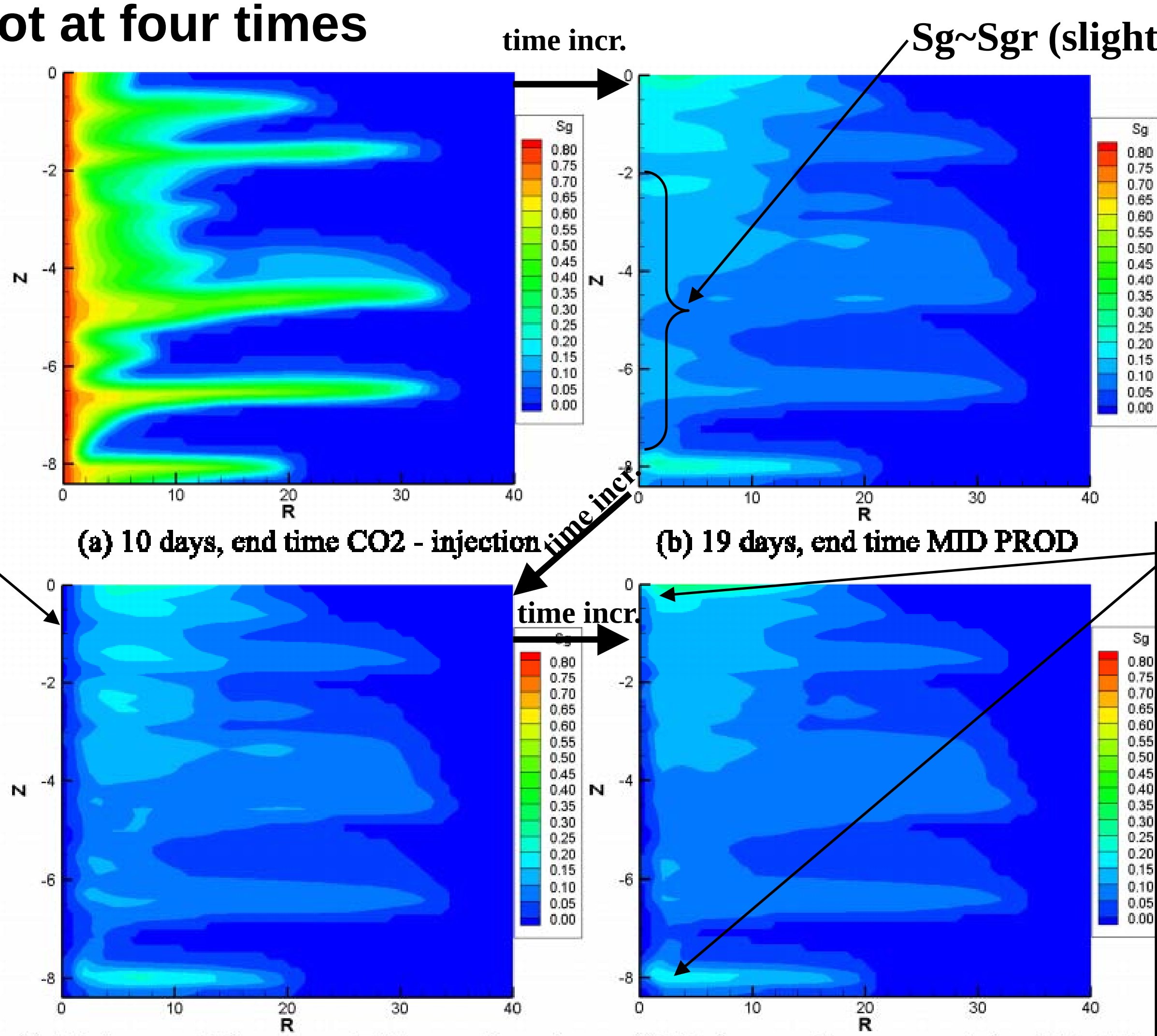
Modeling Results

- **Contour plot at four times**

Sg~Sgr (slightly above in parts)

Sg=0.1

Injected water dissolves gas partially



(a) 10 days, end time CO2 - injection

(b) 19 days, end time MID PROD

(c) 20 days, end time water INJ part of test 2

(d) 27 days, end water test 2 (end PROD)

Some low mobility gas still being produced –

which turns out to be useful with methane mass frc being distinctive between Sgr =0.05,0.1, 0.2, 0.3 cases

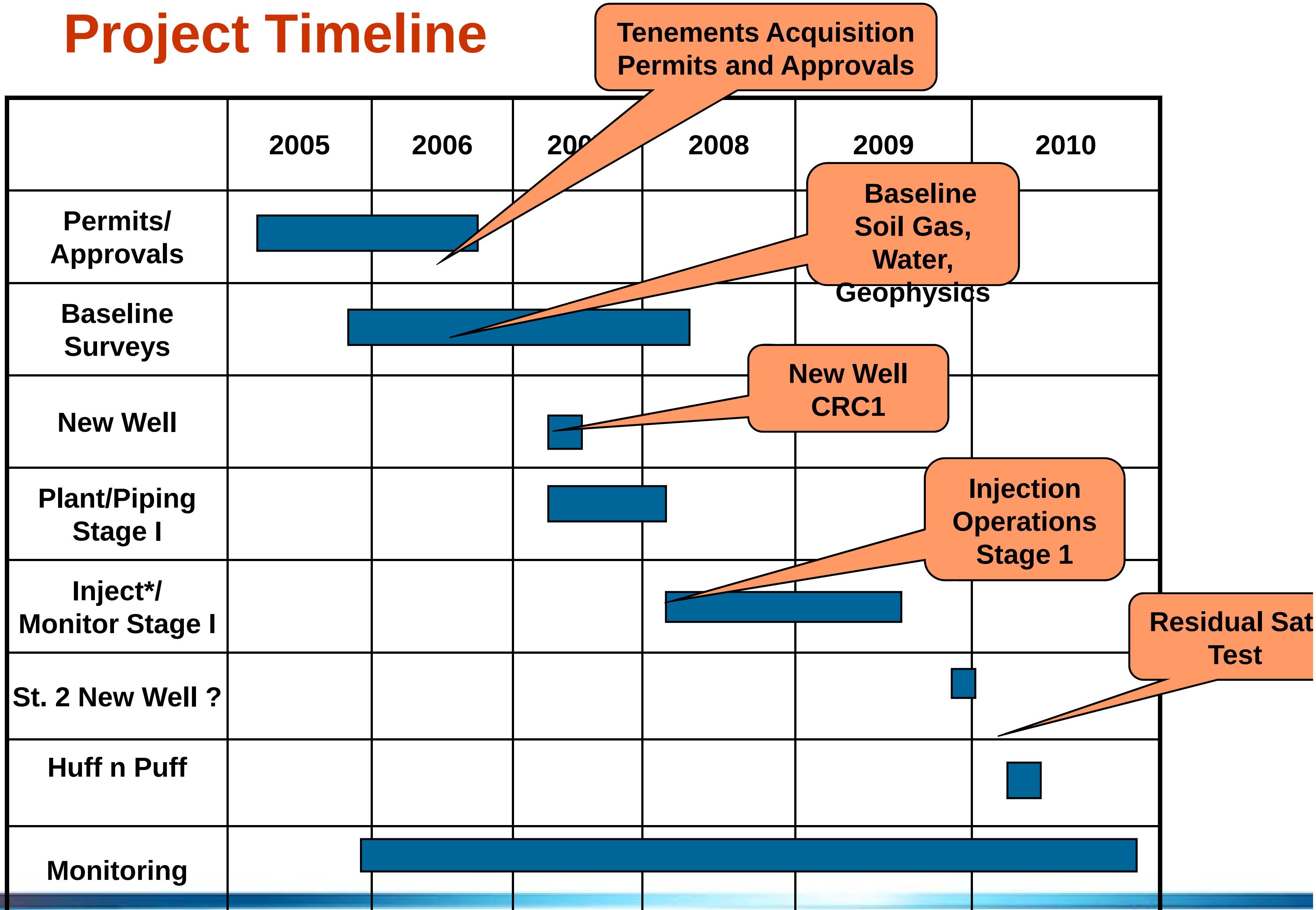
Robust Basis to Proceed

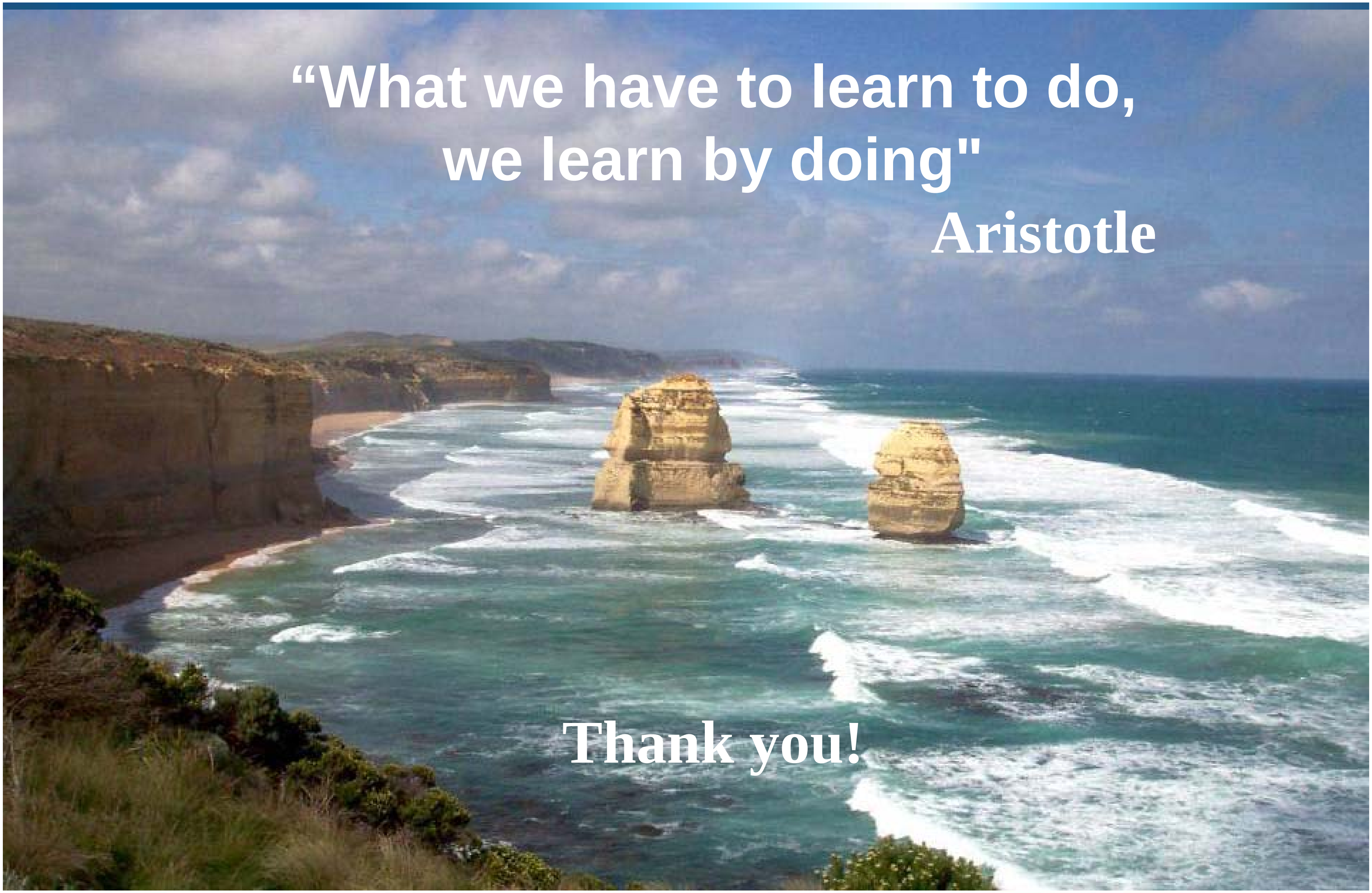
- Huff-push-pull tests can be used to study residual capillary trapping as a dominant trapping mechanism.
- Design: Produce gas after CO_2 injection – and *produce/remove mobile gas* and reduce gas saturation to residual.
- Use a water test before and after middle gas injection and displacement/removal event.
- Further testing against heterogeneity scenarios is being undertaken.
- If successful, similar small-scale tests could be used at commercial injection sites to reduce uncertainty in performance

Lessons Learnt

- In absence of legislation for CCS
  - Complex framework of overlapping jurisdictions
  - Need for communication and cooperation.
  - Clear interfaces with Govt, Public, Media
  - A single Govt focal point is of great help.
- Approvals take time and management plans need a lot of attention.
- The M&V plan should be built early – basis for discussions
- Legal consultation costs should be adequately budgeted.
- Do not under-estimate Landowner matters
- Start early on Community consultation – shire, public meetings etc.
- Long Term Liability still needs to be resolved

Project Timeline




“What we have to learn to do,
we learn by doing"
Aristotle
Thank you!

What have we learnt from large-scale CCS projects?

IEA Greenhouse Gas R&D Programme

John Gale, Tim Dixon, Brendan Beck, Neil Wildgust, Mike Haines

What have we learnt to date - projects?

- Review current operational large-scale CCS projects
  - Assess learning from projects
  - Identify gaps in the global CCS project portfolio
- Focus on projects relevant to full-commercial scale operation
  - Includes:
    - Large-scale pilot
    - Demonstration
    - Commercial
  - Excludes
    - Small and medium pilot
    - Lab scale
  - Define criteria – Identify projects – Collect information - Analyse

Criteria for large-scale operational projects

- Indicative criteria defined for 'large-scale operational projects'
- Was, or had been, operational by the end of 2008, and either:-
  - Captured over 10,000 tCO_2 per year from a flue gas
  - Injected over 10,000 tCO_2 per year with the purpose of geological storage with monitoring
  - Captured over 100,000 tCO_2 per year from any source
  - Coal-bed storage of over 10,000 tCO_2 per year
- *Commercial CO2-EOR was excluded unless there was a monitoring programme to provide learning*
- *Did not need to be fully integrated*
- Added term '*large-scale operational*' to IEA GHG Projects Database

Projects identified

Bellingham Cogeneration Facility	IFFCO CO2 Recovery Plant – Aonla
CASTOR Project	Prosint Methanol Plant
Great Plains Synfuel Plant	Rangely CO2 Project
IMC Global Soda Plant	Schwarze Pumpe
In Salah	SECARB - Cranfield II
K12-B	Shady Point Power Plant
Ketzin Project	Sleipner
MRCSP - Michigan Basin	Snohvit LNG Project
Nagaoka	SRCSP - Aneth EOR-Paradox Basin
Otway Basin Project	SRCSP - San Juan Basin
Pembina Cardium Project	Sumitomo Chemicals Plant
Petronas Fertilizer Plant	Warrior Run Power Plant
IFFCO CO2 Recovery Plant - Phulpur	Weyburn
Chemical Co. “A” CO2 Recovery Plant	Zama EOR Project

Projects identified

Bellingham Cogeneration Facility	IFFCO CO2 Recovery Plant – Aonla
CASTOR Project	Prosint Methanol Plant
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Ketzin Project	Sleipner
MRCSP - Michigan Basin	Snohvit LNG Project
Nagaoka	SRCSP - Aneth EOR-Paradox Basin
Otway Basin Project	SRCSP - San Juan Basin
Pembina Cardium Project	Sumitomo Chemicals Plant
Petronas Fertilizer Plant	Warrior Run Power Plant
IFFCO CO2 Recovery Plant - Phulpur	Weyburn
Chemical Co. “A” CO2 Recovery Plant	Zama EOR Project

- Capture over 100ktCO_2
- Injection over 10ktCO_2 for storage
- Monitored EOR over 10ktCO_2
- Capture over 10ktCO_2 from flue gas
- Coal bed storage over 10ktCO_2

Project Locations

- Capture over 100ktCO_2
- Injection over 10ktCO_2 for storage
- Monitored EOR over 10ktCO_2
- Capture over 10ktCO_2 from flue gas
- Coal bed storage over 10ktCO_2

Extent of coverage vs ZEP project matrix

Archetype 1	• Lignite/co-firing with Biomass	• Pre-combustion, variant A	• Cross-border pipeline	• Offshore depleted oil & gas field
Archetype 2	• Gas	• Post-combustion, variant A	• Pipeline	• Onshore structural deep saline aquifer
Archetype 3	• Hard Coal	• Oxy-fuel, variant A	• Ship	• Offshore open deep saline aquifer
Archetype 4	• Hard Coal	• Post-combustion, variant A	• Pipeline	• Onshore depleted oil & gas field
Archetype 5	• Lignite	• Oxy-fuel, variant B	• Pipeline	• Onshore structural deep saline aquifer
Archetype 6	• Hard Coal	• Pre-combustion, variant B	• Pipeline	• Offshore depleted oil & gas field
Archetype 7	• Hard Coal	• Post-combustion, variant B	• Pipeline	• Onshore open deep saline aquifer

Demonstrated in operational large projects

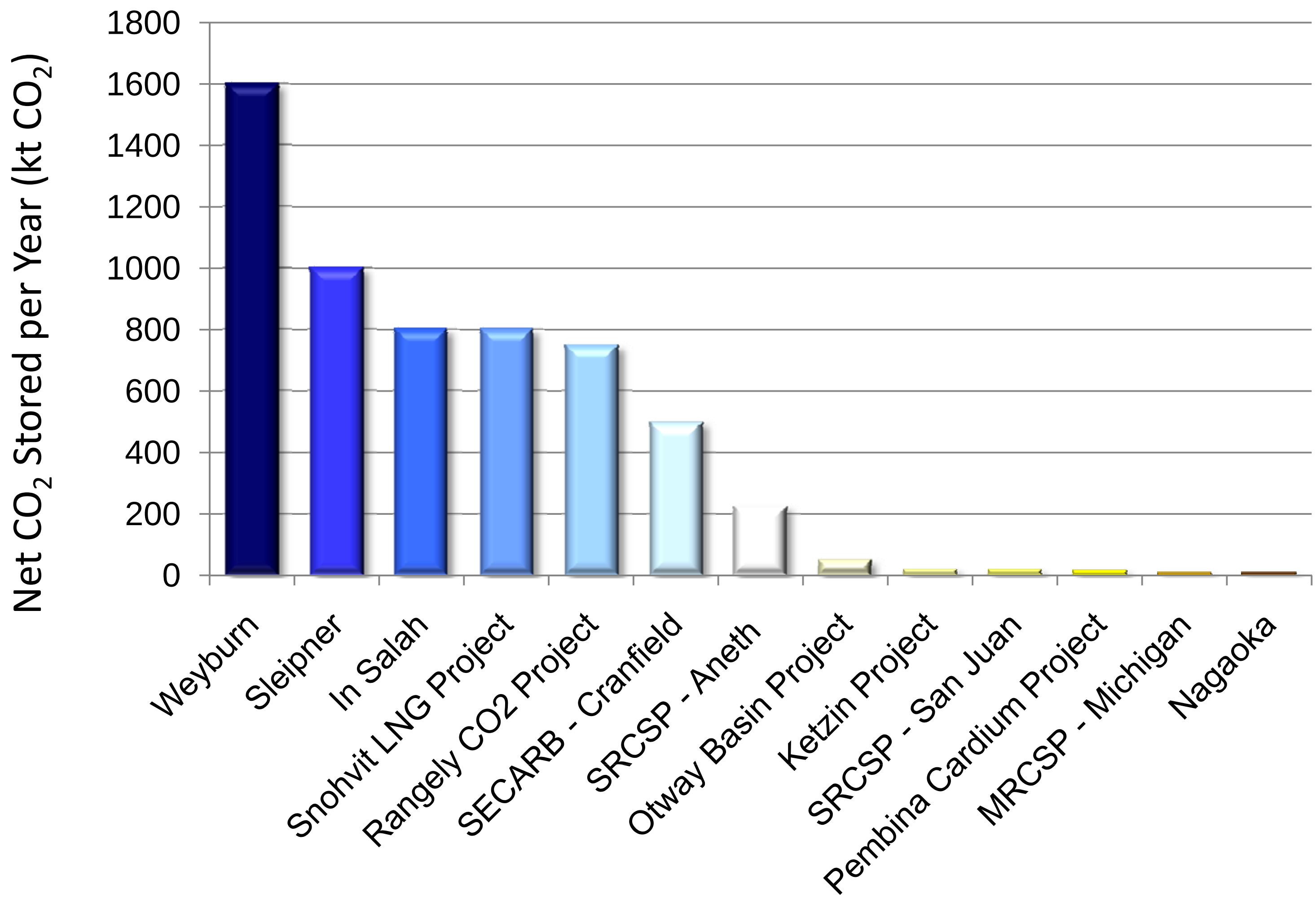
Not demonstrated in operational large projects

Project matrix courtesy of EU Technology Platform for Zero Emission Fossil Fuel Power Plants - ZEP (2008)

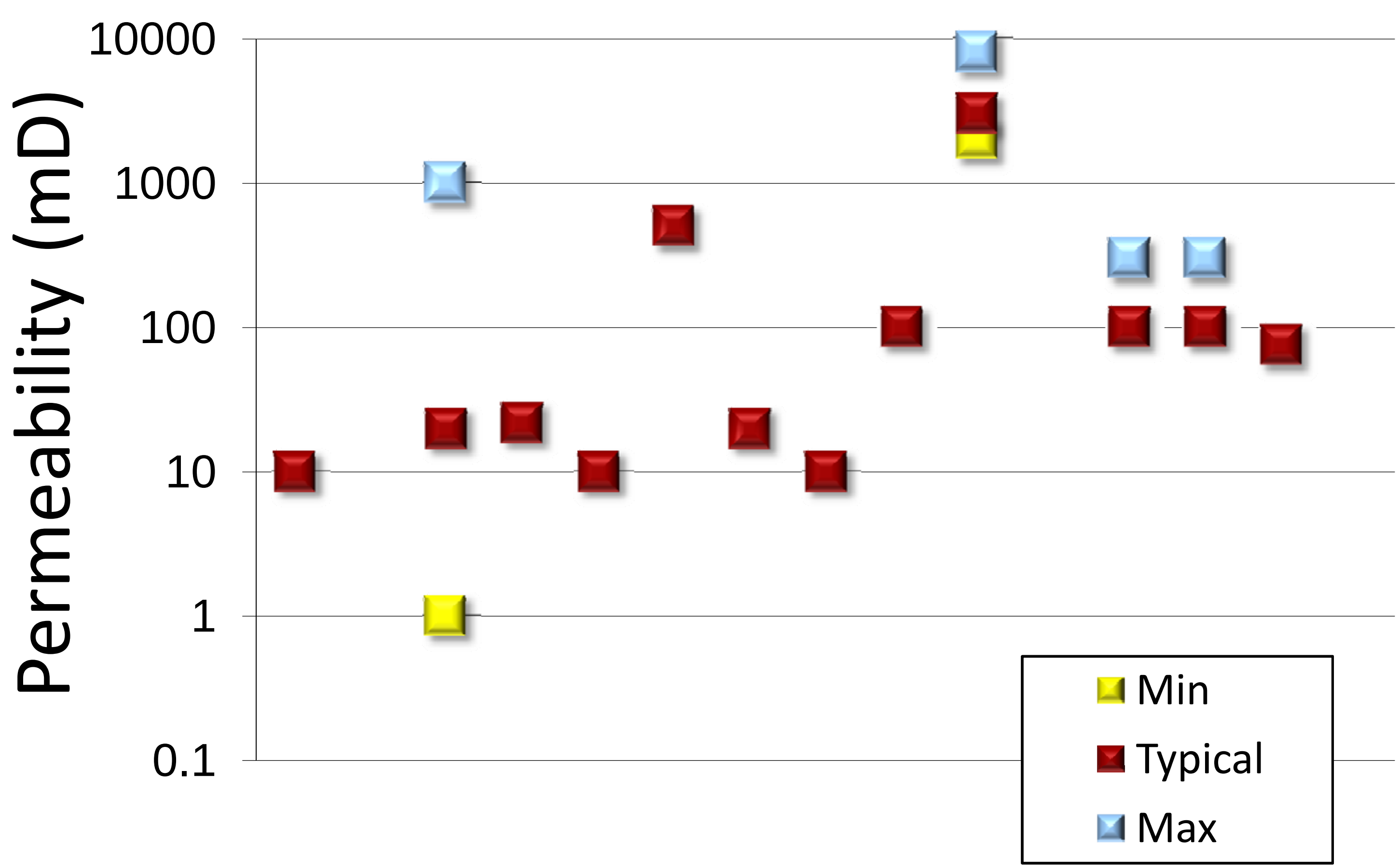
Extent of Coverage

- If integrated CCS from electricity production is a 4 link chain:
  - Electricity production
  - Capture
  - Transport
  - Storage
- 2 and 3 link chains have been demonstrated over 1Mt CO_2 per year

Net CO_2 Storage per Year



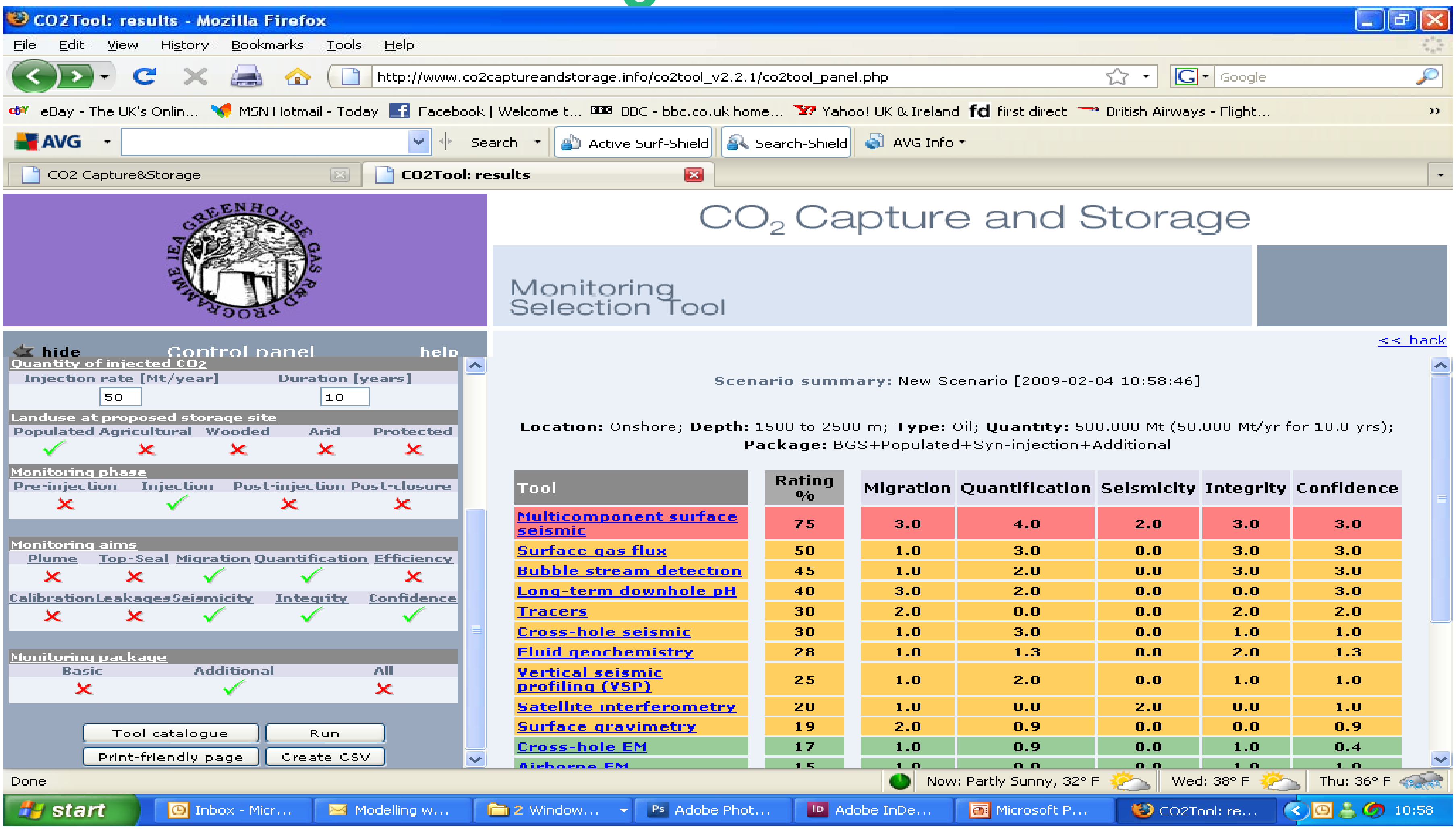
Permeability



Extent of coverage – Monitoring

- 2D seismic
- 3D seismic
- 4D seismic
- Vertical seismic profiling
- Cross-well seismic
- Electrical conductivity
- Microseismic
- Passive seismic
- Soil gas sampling
- Detector arrays
- Eddy covariance
- Observation wells
- Time lapse microgravity
- Well temperature and pressure
- Well logs
- Tracers
- Ground water geochemistry
- Interferometry
- Satellite imaging
- Tilt meters

Monitoring Selection Tool



CO2Tool: results - Mozilla Firefox

http://www.co2captureandstorage.info/co2tool_v2.2.1/co2tool_panel.php

CO_2 Capture and Storage

Monitoring Selection Tool

Control panel

Quantity of injected CO2

Injection rate [Mt/year]	Duration [years]
50	10

Landuse at proposed storage site

Populated	Agricultural	Wooded	Arid	Protected
✓	✗	✗	✗	✗

Monitoring phase

Pre-injection	Injection	Post-injection	Post-closure
✗	✓	✗	✗

Monitoring aims

Plume	Top-Seal	Migration	Quantification	Efficiency
✗	✗	✓	✓	✗

Calibration	Leakages	Seismicity	Integrity	Confidence
✗	✗	✓	✓	✓

Monitoring package

Basic	Additional	All
✗	✓	✗

Tool catalogue | Run | Print-friendly page | Create CSV

<< back

Scenario summary: New Scenario [2009-02-04 10:58:46]

Location: Onshore; **Depth:** 1500 to 2500 m; **Type:** Oil; **Quantity:** 500.000 Mt (50.000 Mt/yr for 10.0 yrs); **Package:** BGS+Populated+Syn-injection+Additional

Tool	Rating %	Migration	Quantification	Seismicity	Integrity	Confidence
Multicomponent surface seismic	75	3.0	4.0	2.0	3.0	3.0
Surface gas flux	50	1.0	3.0	0.0	3.0	3.0
Bubble stream detection	45	1.0	2.0	0.0	3.0	3.0
Long-term downhole pH	40	3.0	2.0	0.0	0.0	3.0
Tracers	30	2.0	0.0	0.0	2.0	2.0
Cross-hole seismic	30	1.0	3.0	0.0	1.0	1.0
Fluid geochemistry	28	1.0	1.3	0.0	2.0	1.3
Vertical seismic profiling (VSP)	25	1.0	2.0	0.0	1.0	1.0
Satellite interferometry	20	1.0	0.0	2.0	0.0	1.0
Surface gravimetry	19	2.0	0.9	0.0	0.0	0.9
Cross-hole EM	17	1.0	0.9	0.0	1.0	0.4

Common Monitoring Techniques

Technique	No of Sites	Positive comments	Negative comments
DH temp/pressure	8		
Soil gas	7		
Surface seismic	7	1	3
Geochemical	6		
Microseismic	6		1
VSP	4		1
Crosswell seismic	2	1	
Electrical Conductivity	2		
Satellite	2	1	
Gravity	2		1

Comments on Surface Seismic

- Seismic is unlikely to be cost-effective in the long run
- Glacial till cover made seismic difficult to use
- Imaging CO_2 under a gas cap is difficult
- A recent attempt at 3D seismic did not reveal useful information – so we do not consider effective for monitoring CO_2 floods
- The seismic survey clearly demonstrated an ability to detect anomalies in the reservoir caused by CO_2 invasion
- Detecting pressure propagation using seismic signals is sometimes easier than detecting the CO_2 itself
- Pre-injection surface seismic MIGHT have made subsequent seismic more useful

Comments on Other Techniques

- Gravity, VSP and downhole flowmeters will not deliver credible results
- Microseismic seemed more effective as a safety measure to ensure the injection did not cause any fracturing or induced seismicity
- Crosswell seismic worked quite well

Emerging Themes

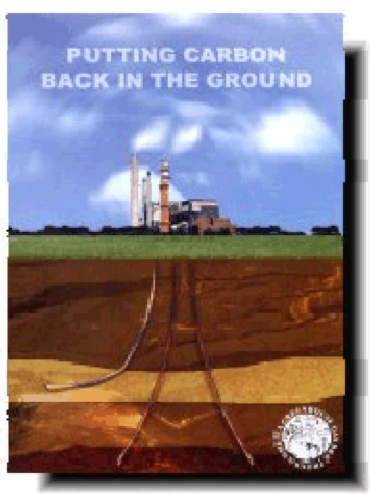
- **Injectivity** – importance, problems, solutions
- **Material corrosion** – less than anticipated
- **Seismic**
  - Effective for monitoring the CO_2 plume - where it can be used
  - Not quantitative beyond a certain resolution
  - Expensive
- **Other monitoring** – e.g. electrical conductivity viewed as promising; desire for better direct sampling at reservoir conditions; can we move from R&D to commercial suite of tools?

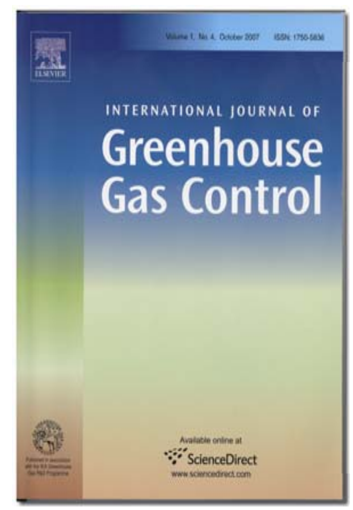
Preliminary Conclusions

- Elements of CCS are operating at large scale
- Integrated CCS is operating at large scale, just not from power plant
- **There is a lot that has been learnt from existing projects, but more can be done to share the learning**
- CCS industry can build on existing projects' experience
- Increasing IPR issues will affect sharing learning

IEA Greenhouse Gas R&D Programme

- General - www.ieagreen.org.uk
- CCS - www.co2captureandstorage.info



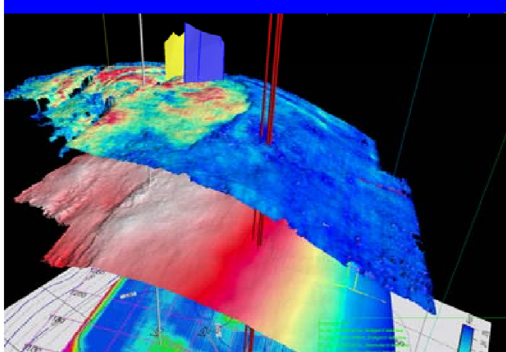


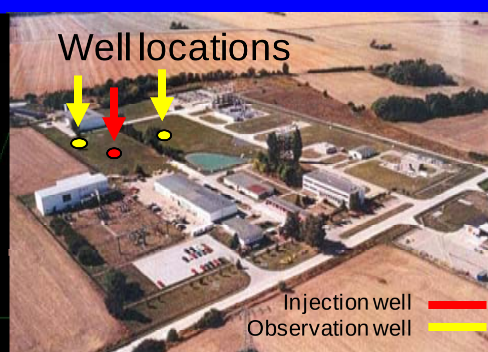
CO_2SINK - CO_2 Storage by Injection into a Natural Saline Aquifer at Ketzin (Germany)

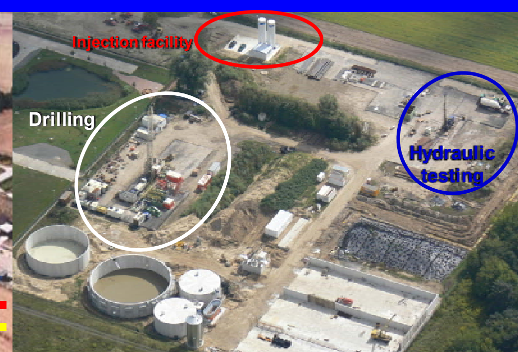
- Report from Ketzin -

German Research Centre for Geosciences - GFZ

CO_2SINK Group – presented by Conny Schmidt-Hattenberger







SIXTH FRAMEWORK PROGRAMME

Federal Ministry of Education and Research

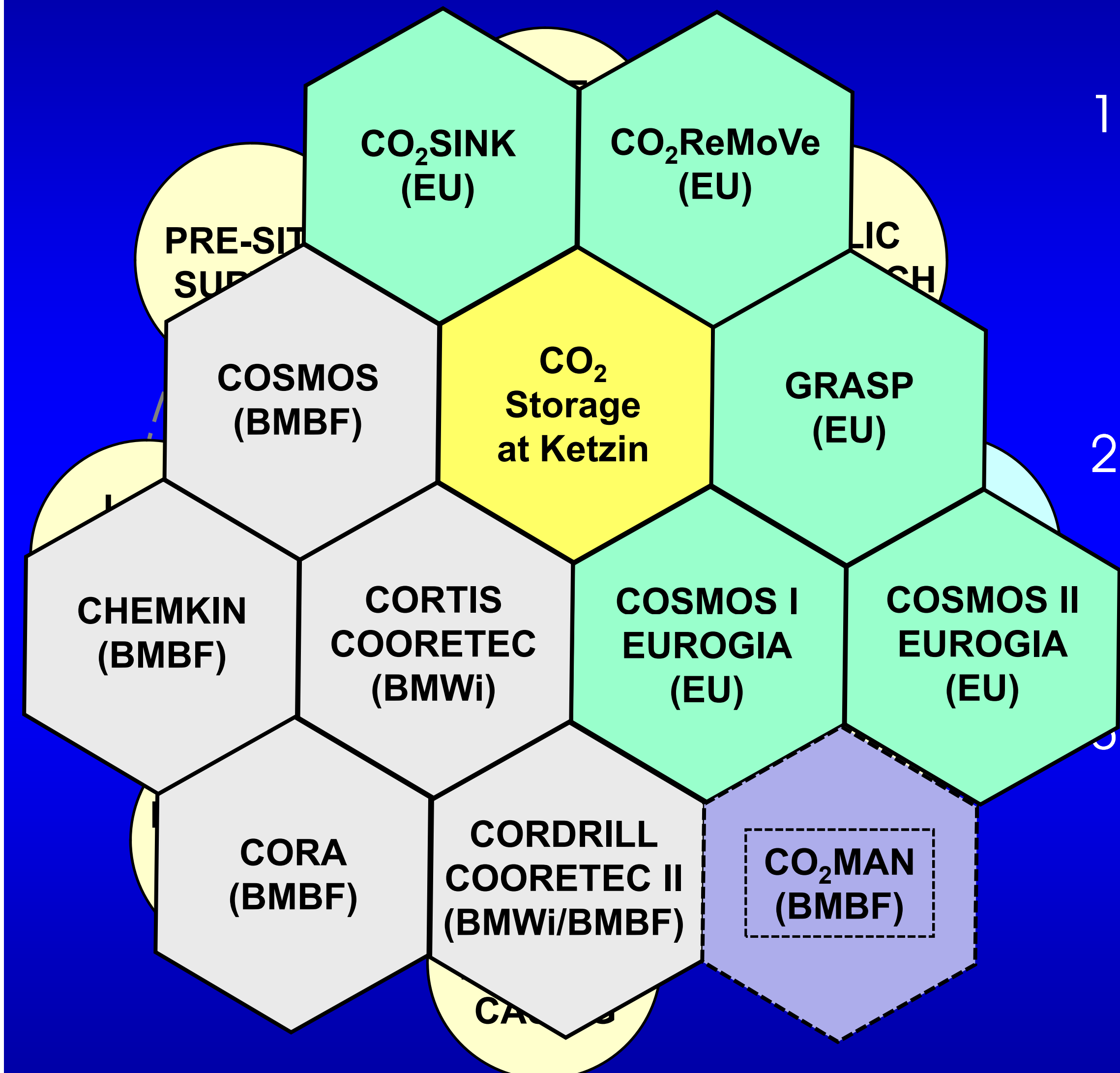
Federal Ministry of Economics and Technology

conny@gfz-potsdam.de

GeoForschungsZentrum Potsdam (D)
G.E.O.S. Freiberg Ingenieurgesellschaft (D)
Geological Survey of Denmark and Greenland (DK)
Mineral and Energy Economy Research Institute (PL)
Det Norske Veritas (N)
StatoilHydro (N)
Shell International Exploration and Production (NL)
University of Stuttgart (D)
Vibrometric Finland (SF)
University of Kent (GB)
Uppsala University (S)
RWE Power AG (D)
International Energy Agency – Greenhouse Gas Programme (GB)
Vattenfall Europe Generation (D)
Verbundnetz Gas AG (D)
Siemens AG Power Generation (D)
E.ON Energie AG (D)
Schlumberger Carbon Services (Fr)

Project Structure & Objectives

CO_2 Storage activities at Ketzin



1) Advance understanding of science and practical processes of underground CO_2 storage

2) Build confidence toward future European CO_2 geological storage

3) Provide operational field experience to aid development of regulatory frameworks and standards for CO_2 geological storage

Location and Site Specifics

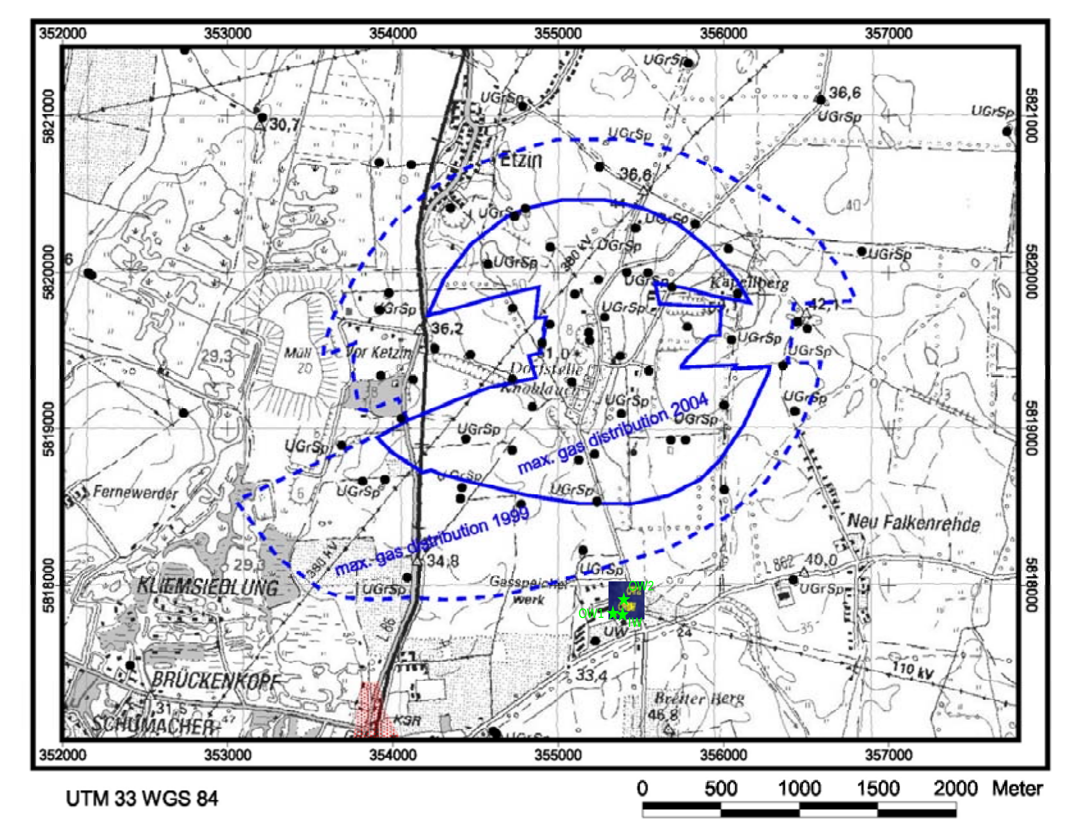
GFZ Helmholtz Centre Potsdam

Location

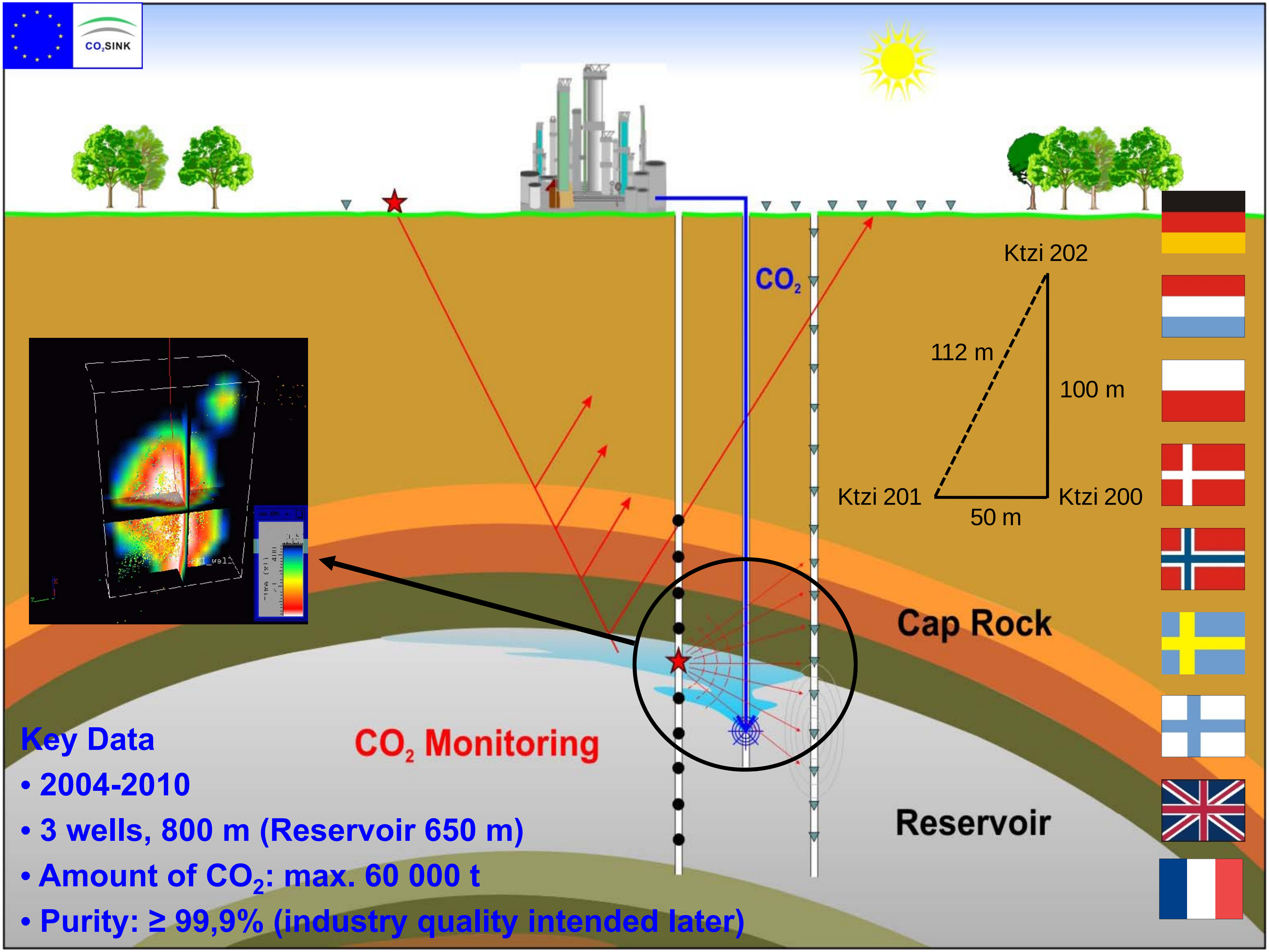
CO2SINK

Old Gas Storage Facility

- In 1960s facility for natural gas storage imported from Siberia installed
- Thoroughly modernised in 1990s
- Facility now redundant (closed 2004)
- Natural gas was stored in sandstones at shallow depth (250 – 400 metres)

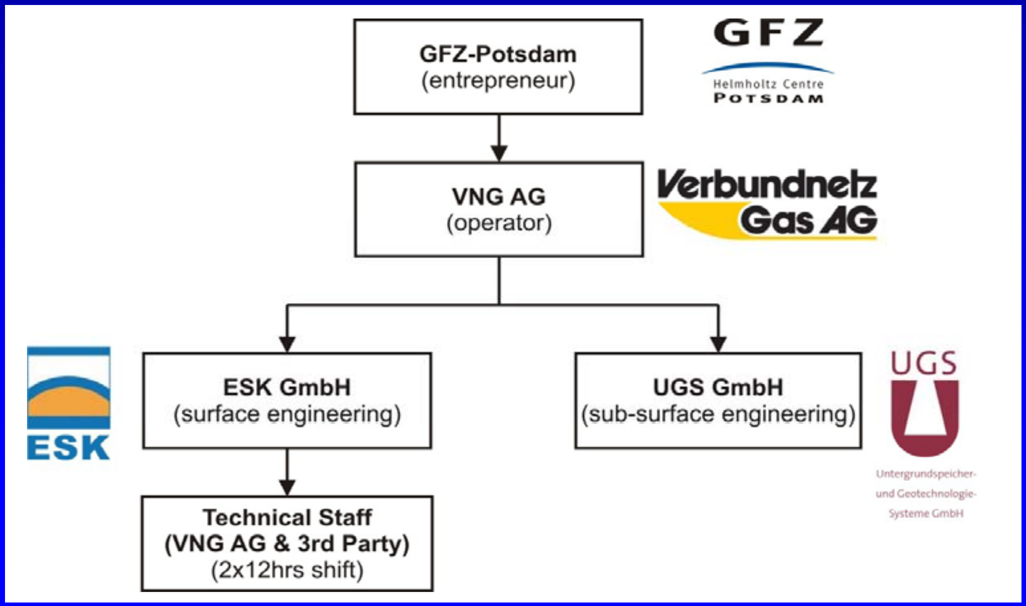


(Zinck-Jørgensen et al. 2006)


CO$_2$SINK
CO$_2$
Ktzi 202
112 m
100 m
Ktzi 201
Ktzi 200
50 m
Cap Rock
Reservoir
CO$_2$ Monitoring
Key Data
• 2004-2010
• 3 wells, 800 m (Reservoir 650 m)
• Amount of CO$_2$: max. 60 000 t
• Purity: ≥ 99,9% (industry quality intended later)

Performance & Risk Assessment

Details of the Approach



Organigram / legal organisation

(Fabian Moeller, 2009)

- "Suitability verification document" (UGS GmbH / legal requirement) → basis for the decision of the mining authority to allow for the storage operation

- "Operating Plan Injection" → covers operational safety aspects by independent experts (ESK GmbH, together with GFZ / legal requirement)

- „Long term containment study" / Safety Case (DNV / add-on) → confirms the storage at the Ketzin site to be safe, based on all available project data

- Expert's Report (detailed operating plans / add-on) prepared by GFZ-Potsdam on: 3D Seismics / Monitoring / Constructions

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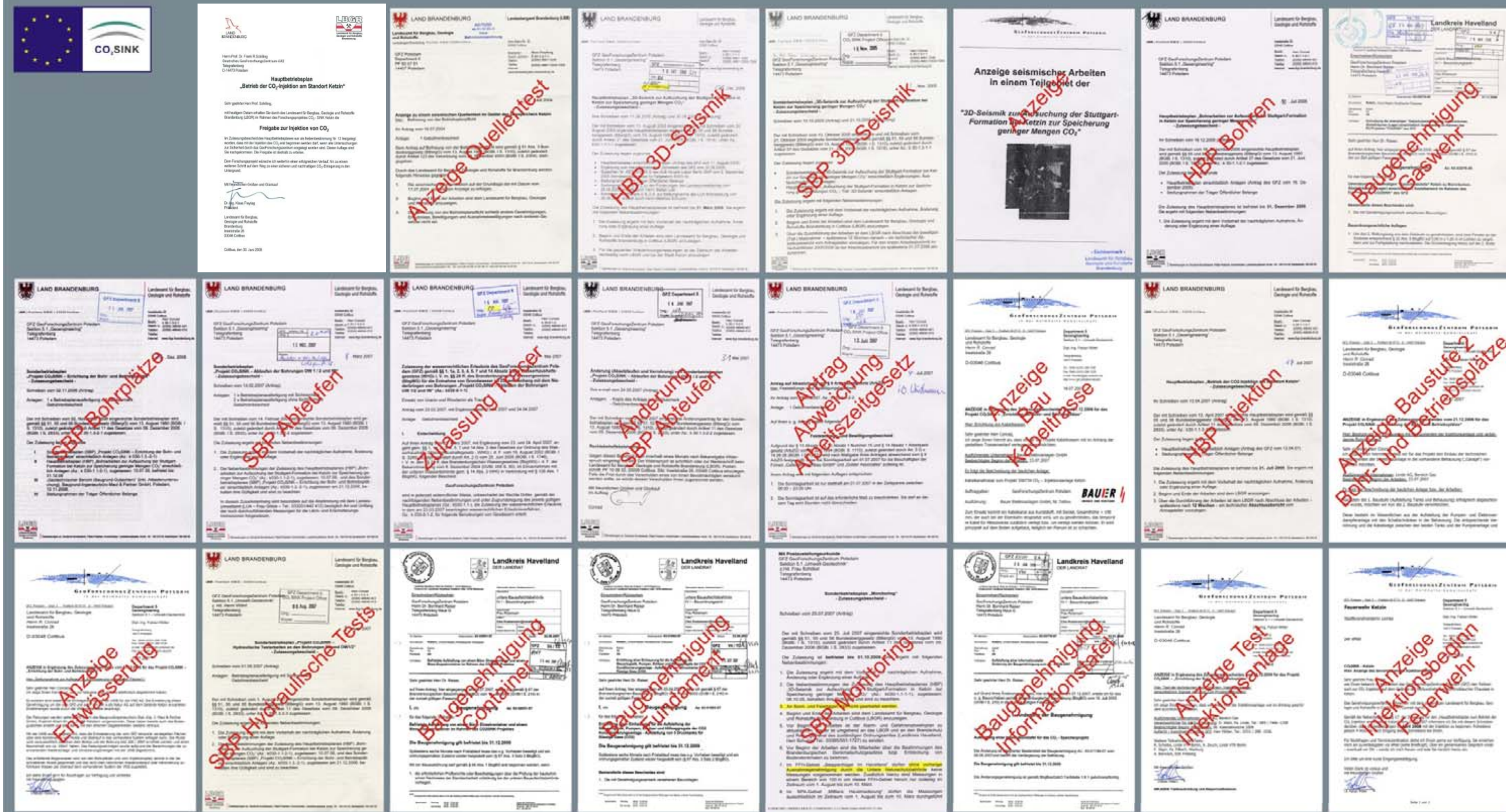
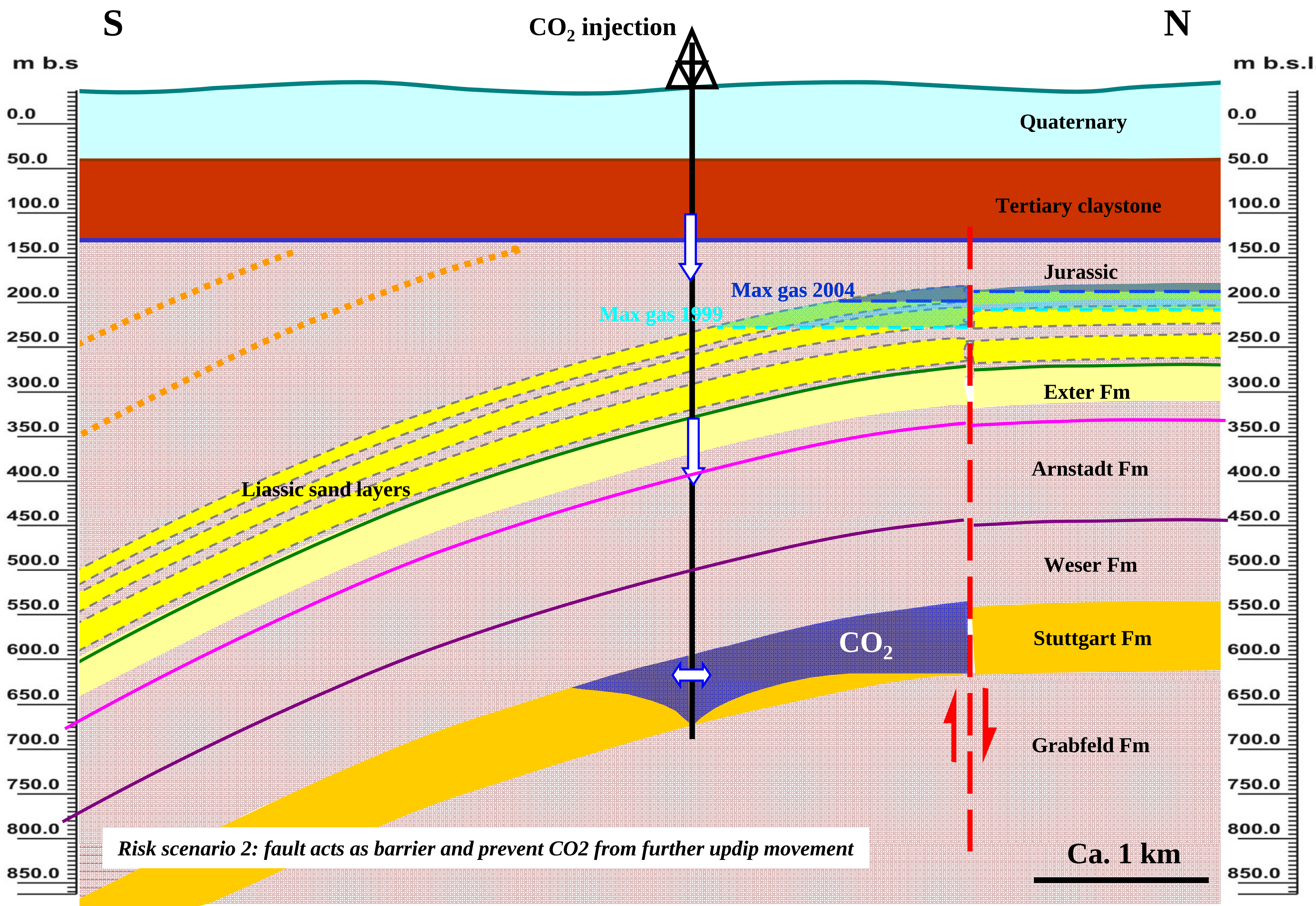
Independent Approval by Authorities (Mining Authority, Rural District Office)

CO_2SINK



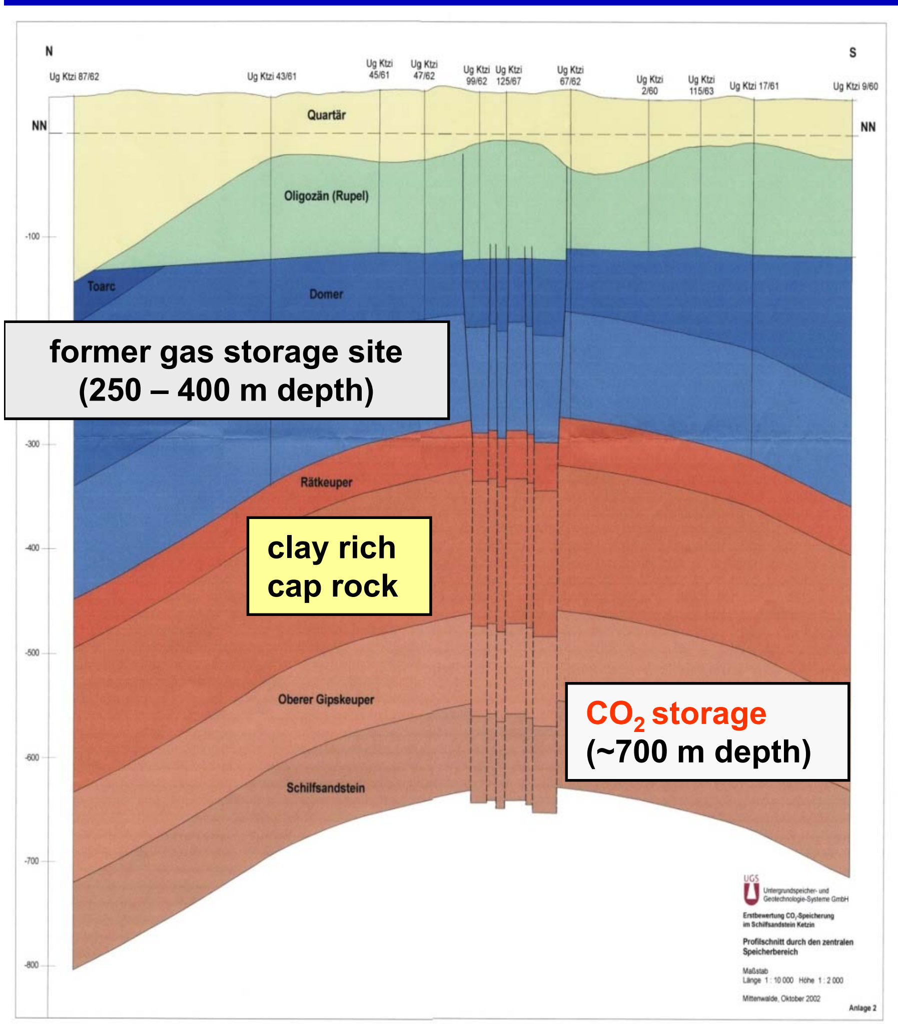
Risk Analysis Scenarios

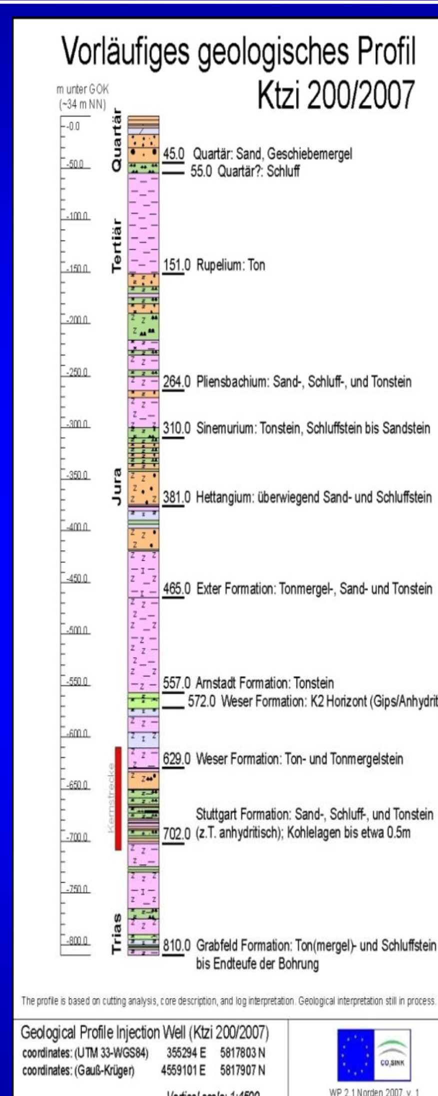


(Zinck-Jørgensen et al. 2006)

Geological Site Characterisation & Modeling

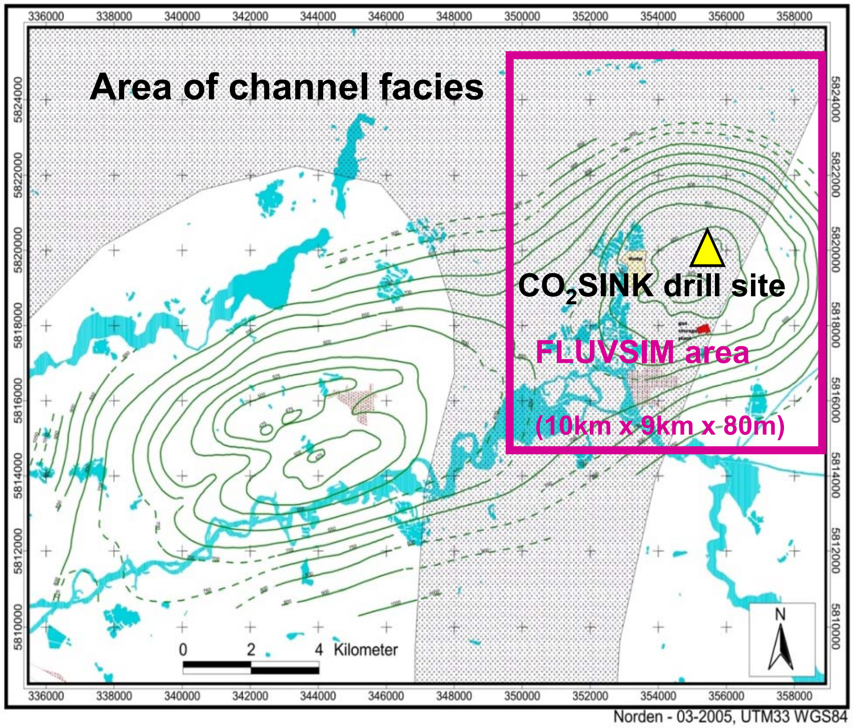
Geological Profile – Coring

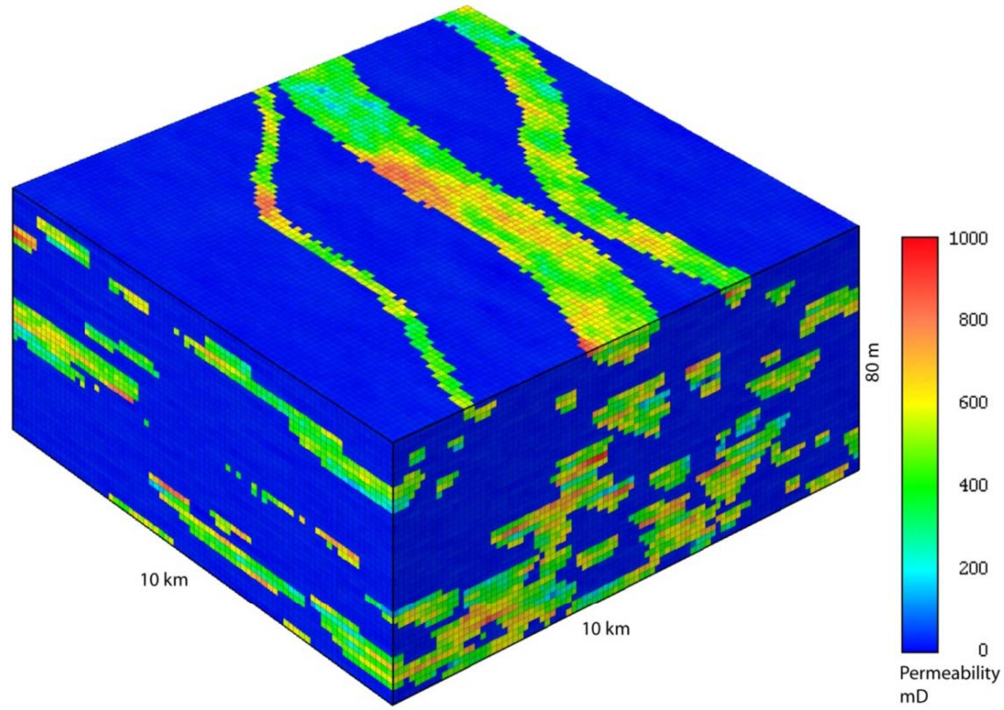




(Norden et al. 2007)

Probabilistic Reservoir Simulation





(**Foerster et al., 2006)**

(**Frykman et al., 2007)**

- Bore hole data with channel and non-channel facies
- Vertical proportion curve, account for vertical trends
- Channel parameters (orientation, number, thickness, width)
- Areal variations given as areal proportion map

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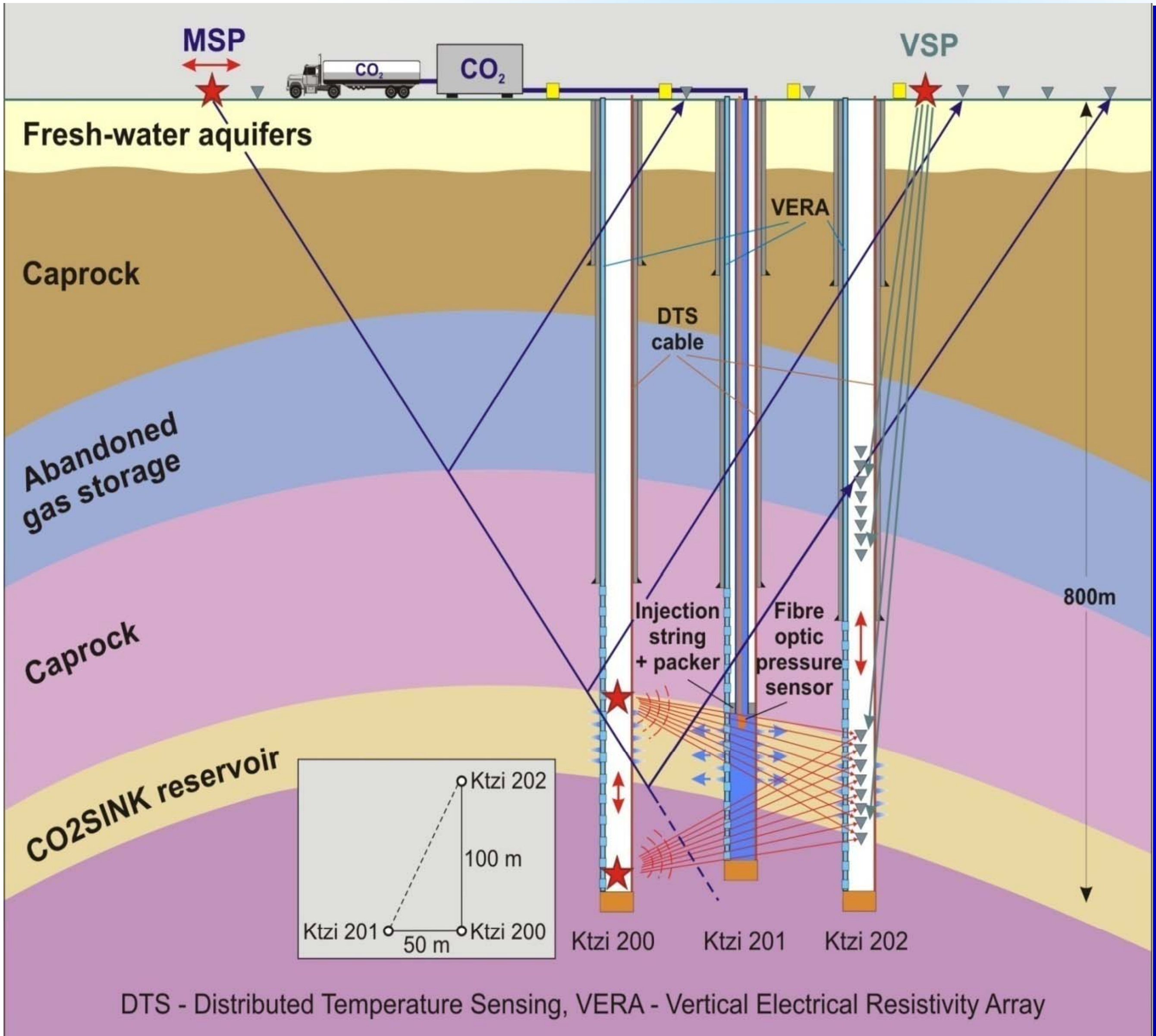
CO_2SINK

Monitoring Concept

What & why do we monitor ?



Surveys:

(I) Seismics (crosshole + VSP/MSP)

Permanent:

(I) Pressure, temperature (bottom hole) + DTS along injection string

(II) Distributed Temperature Sensing (DTS) behind casing

(III) Vertical Electrical Resistivity Array (VERA)

CO_2SINK seismic monitoring

What was done so far?

3D-Seismic and Star-survey
Baseline Sept-Dec 2005✓

MSP (Moving Source Profiling)
Baseline Nov/Dec 2007✓

VSP (Vertical Seismic Profiling)
Baseline Nov/Dec 2007✓

Cross-hole
(Between Ktzi-201 and Ktzi-202)
Baseline May 2008 ✓
1st repeat July 2008 ✓
2nd repeat August 2008 ✓

What is planned ?

Cross-hole
(Between Ktzi-201 and Ktzi-202)
3rd repeat June 2009

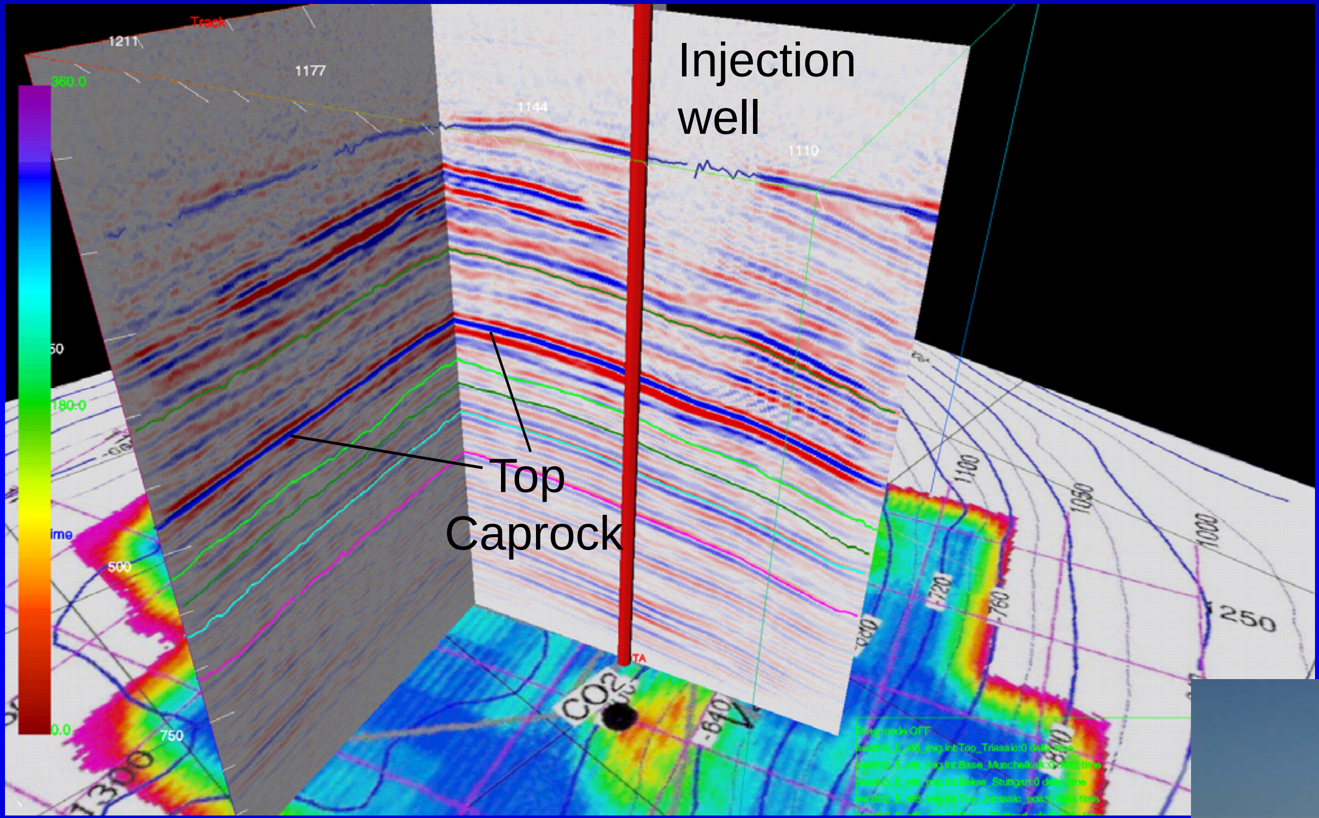
VSP/MSP
1st repeat Oct 2009

Star-survey
1st repeat Oct 2009

3D-Seismic survey
1st repeat (20 templates surrounding the CO2 injector)

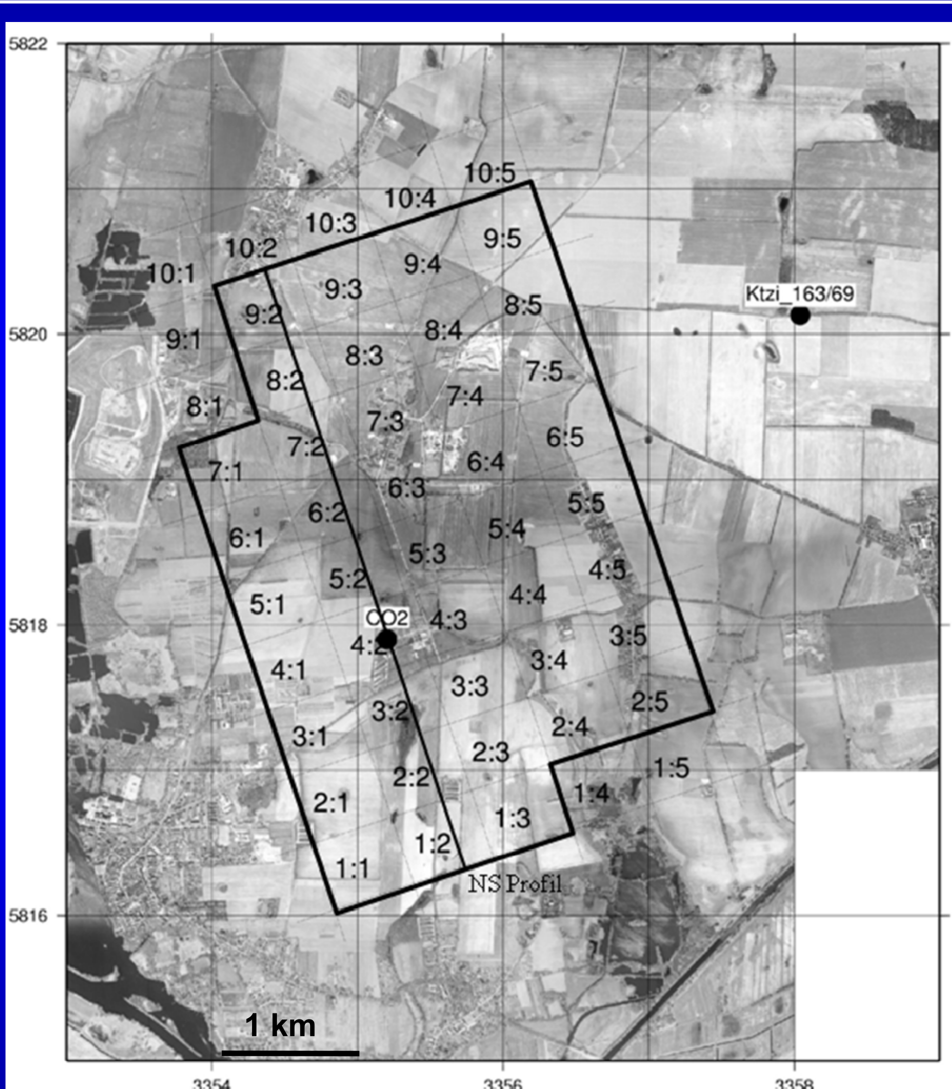
Shell/TNO seismic concept
(pre-survey test / main experiment) 2009

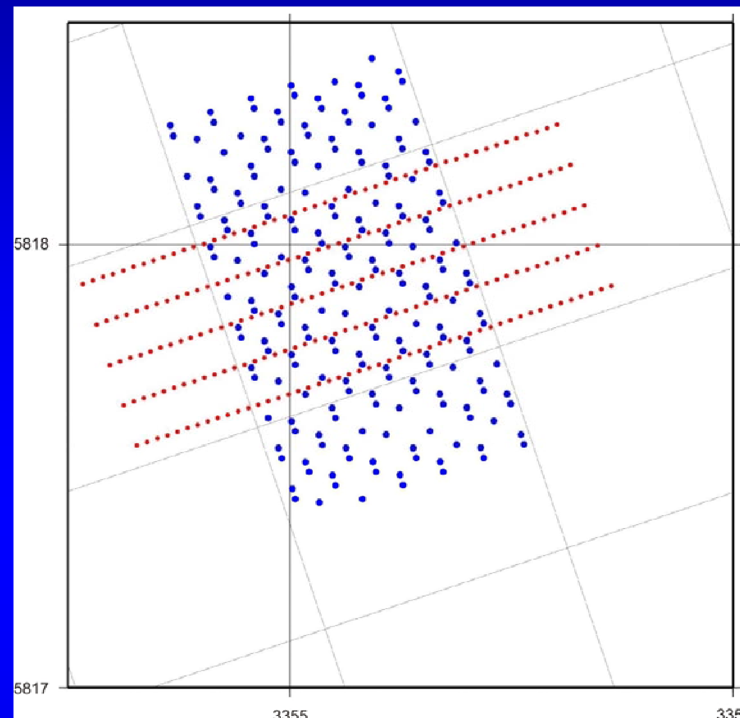
3D Seismic Baseline



(The CO_2SINK Seismic Team – 2006)

Seismic: 3D- measurement scheme

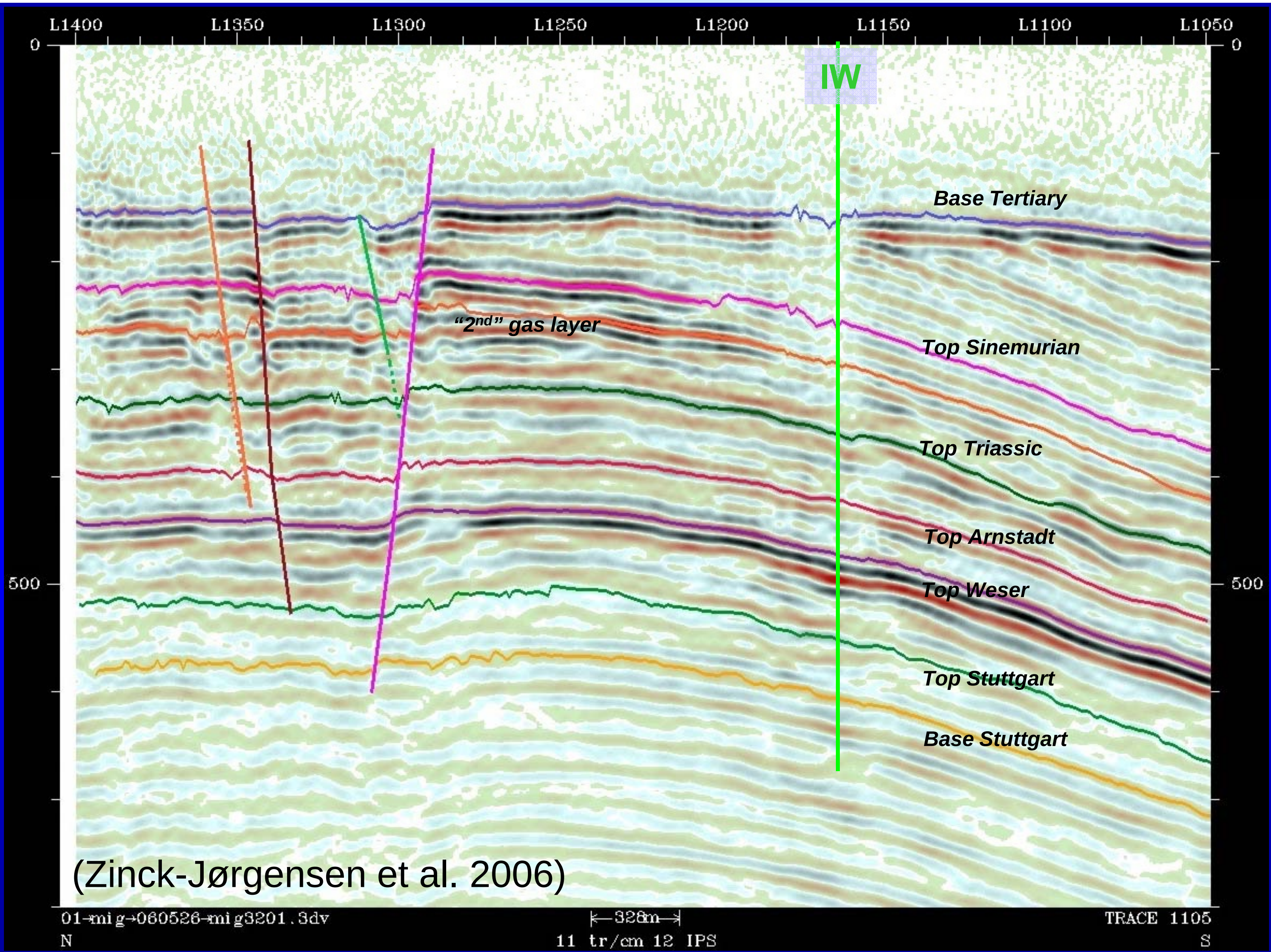




Left: Scheme of templates (41)
Right: 1 template with 200 shotpoint positions (blue) and 250 receiver positions (red)

(Juhlin et al., 2007)

Horizon and Fault Mapping



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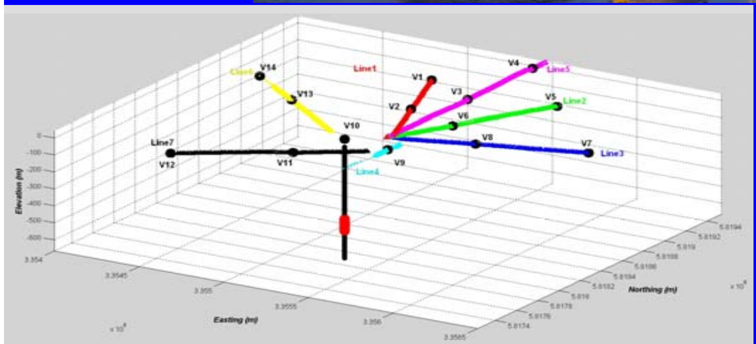
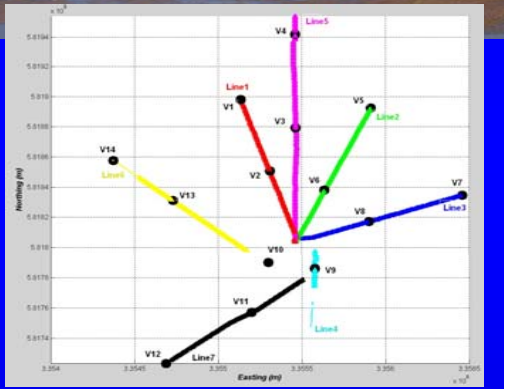
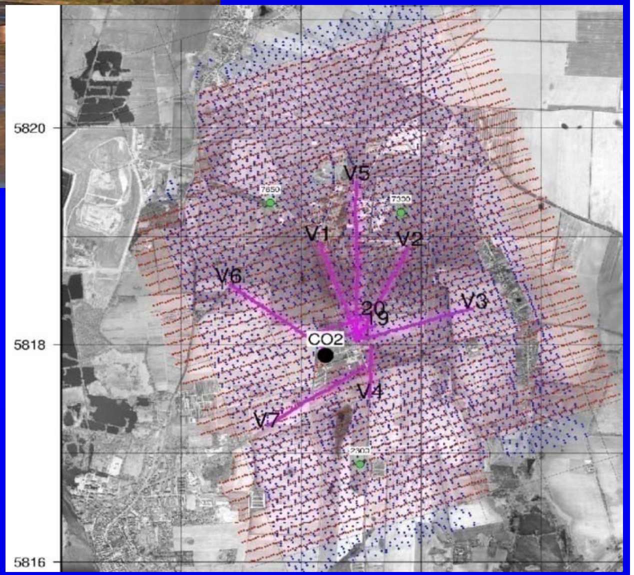
2D/VSP/MSP - measurements

CO_2SINK





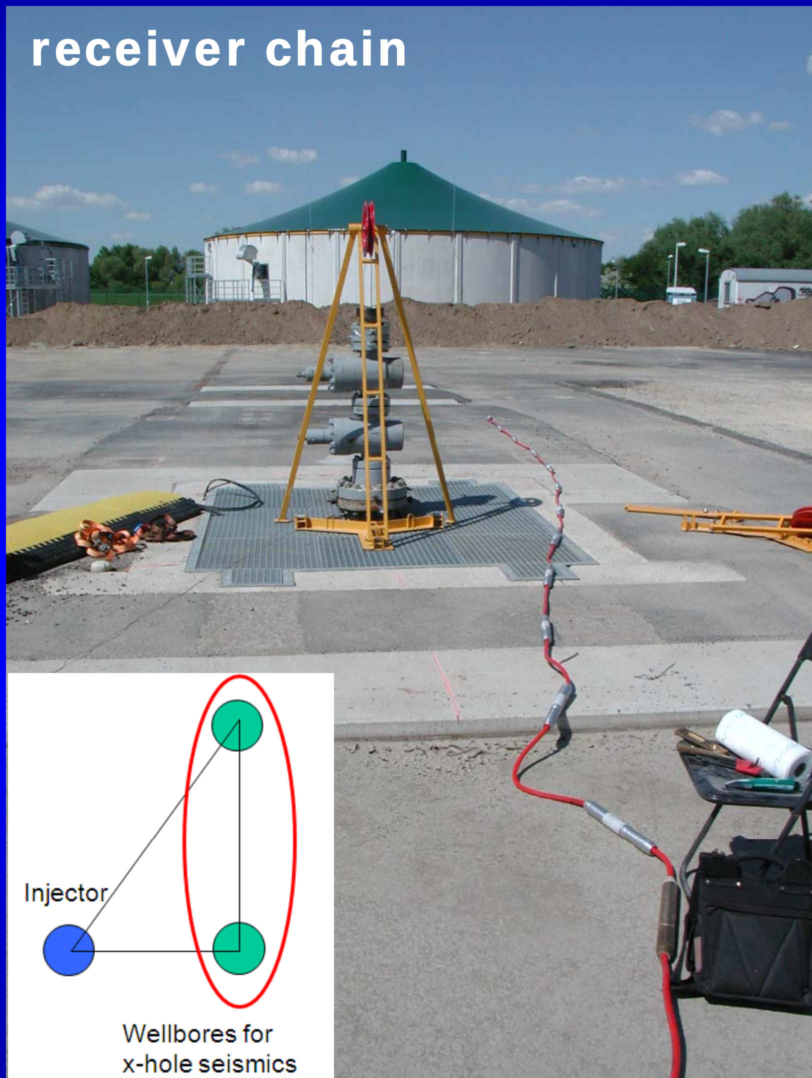


For **VSP** the source was placed at 14 locations, along the 7 lines used for the 2D time-lapse survey.

For **MSP** the source was placed along the 7 lines used for the 2D time-lapse survey (same shot points).

(C. Cosma, 2008)

Cross-hole: Performance



(C. Cosma and R. Giese, 2008)

Combined surface-measurements: Seismic and Geoelectric surveys

Setup :
16 Dipoles @ 2 concentric circles around the Ketzin test site, dipole length 150 m

Investigation area:
Outside the near-borehole area → recording of anisotropical effects

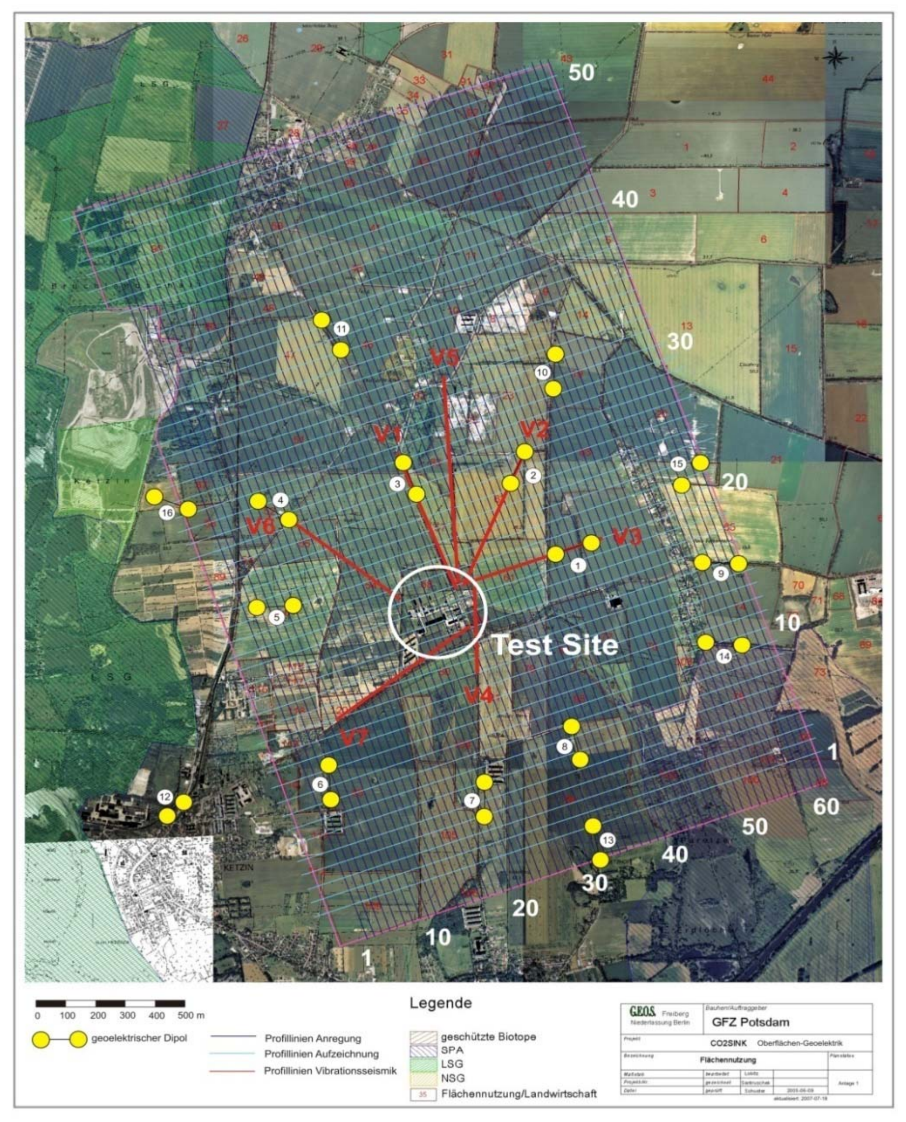
Joint field experiments with the seismic surveys:

✓ baseline in the pre-injection phase

✓ 1st repeat after CO_2 break-through (parallel to crosshole seismic)

- now: 2nd repeat in the regular operating phase, and two crossed profiles in addition

(Kiessling et al., 2008)

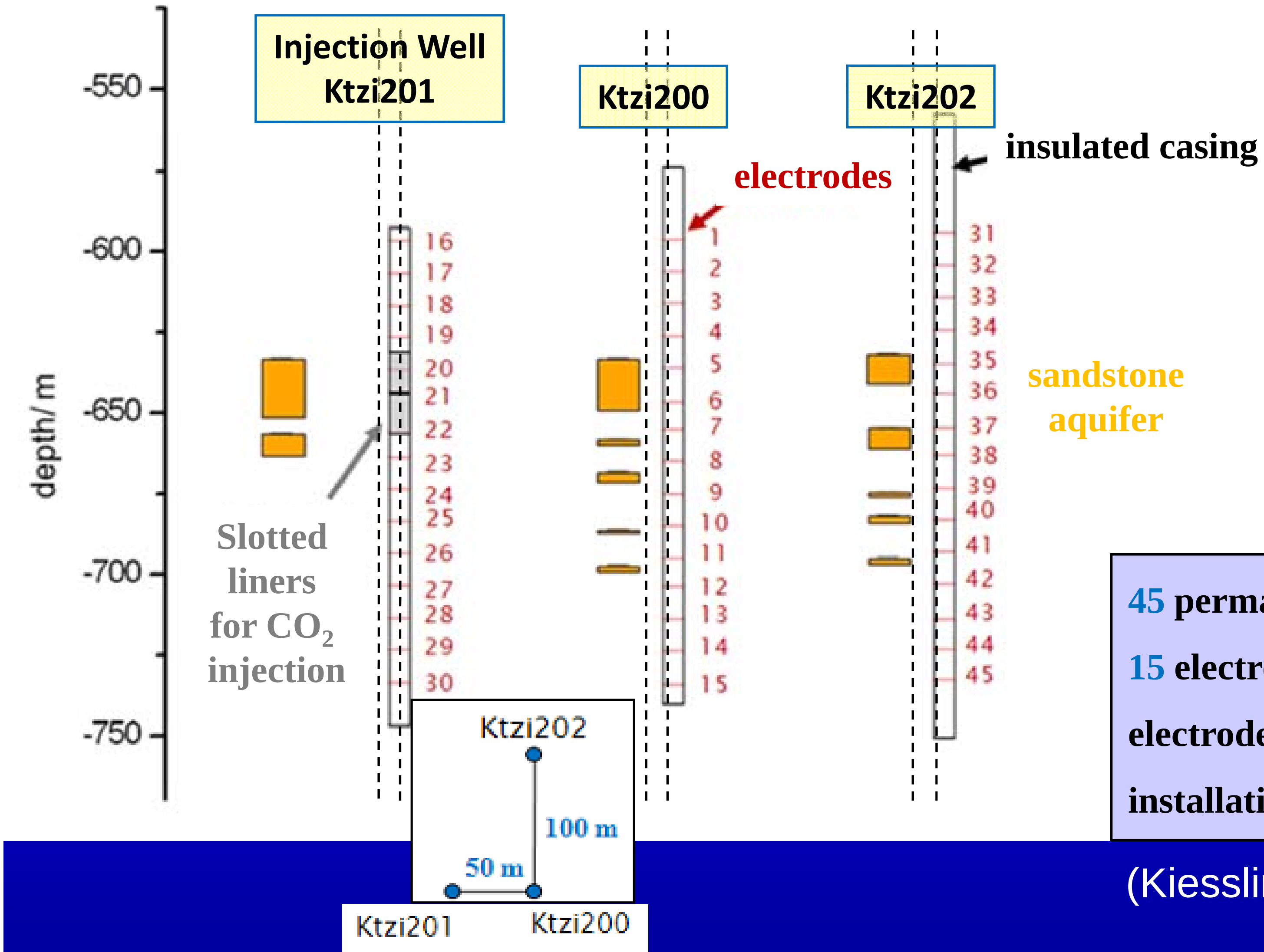


Permanent Downhole Sensors

Smart Casing Installation

- Sensors placed behind the well casing
- Fully cemented in the annular space between casing and rock formation
- Special protector systems help to avoid damaging the fiber optic cables and sensors

ERT measurements for monitoring CO_2 migration



VERA

Vertical **E**lectrical **R**esistivity **A**rray

45 permanent electrodes

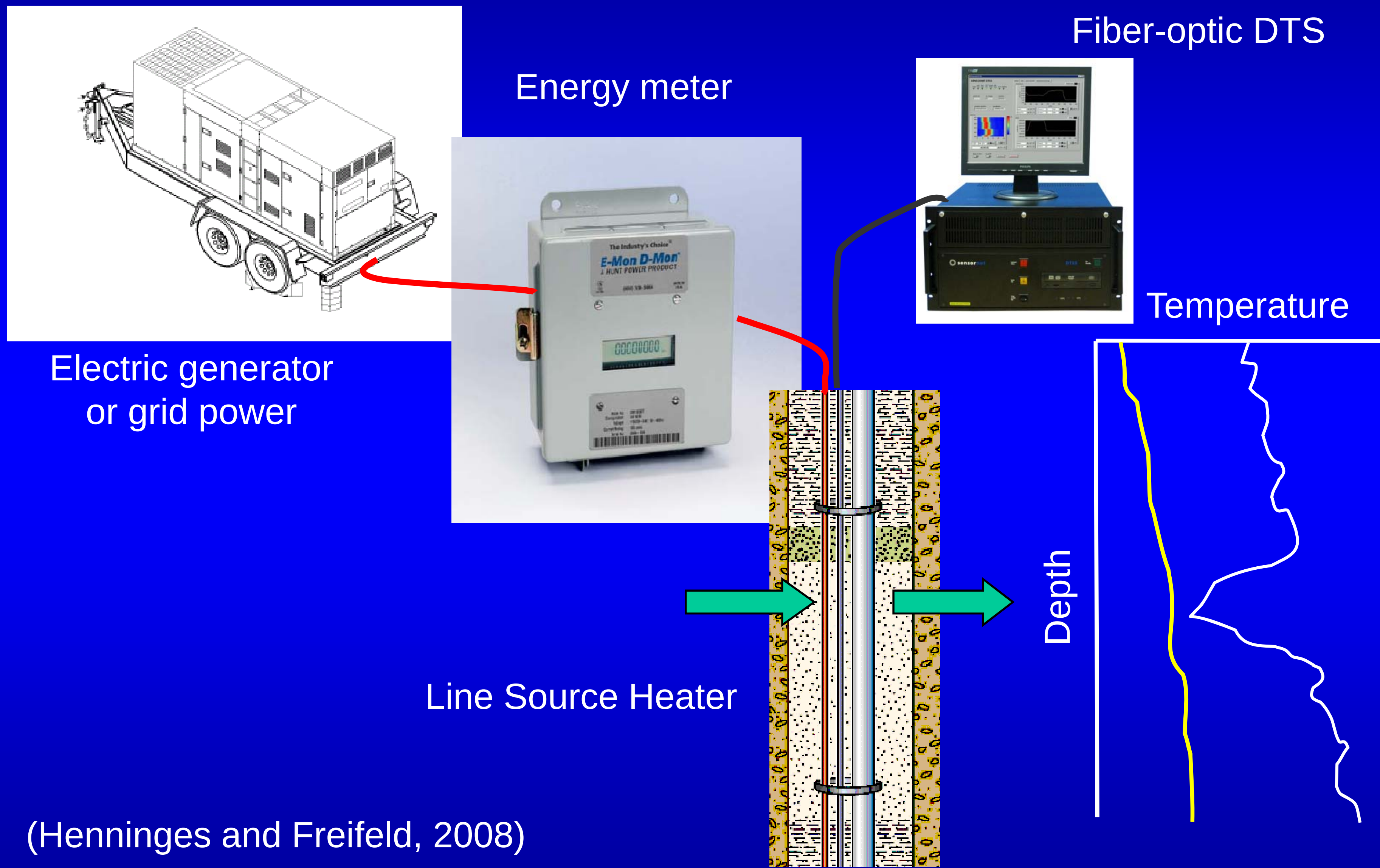
15 electrodes per well

electrode spacing ~ 10 m

installation depth ~ 590 to 735 m

(Kiessling et al., 2008)

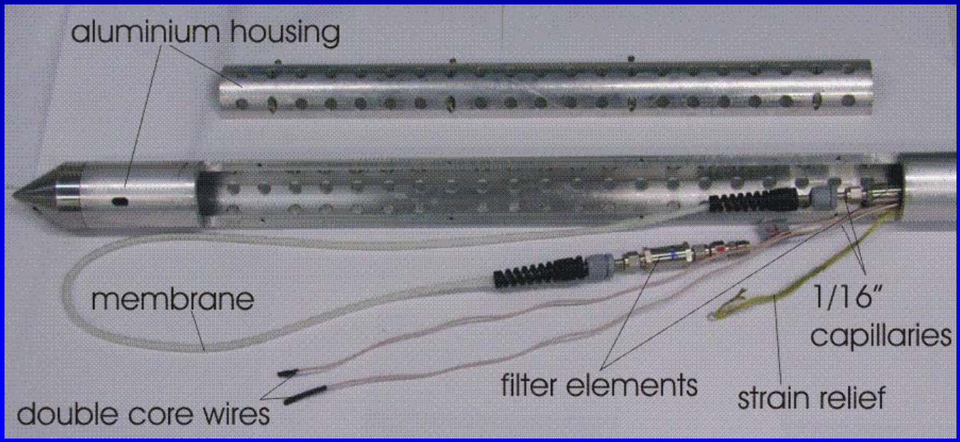
Distributed Temperature Sensing – in passive and active mode –

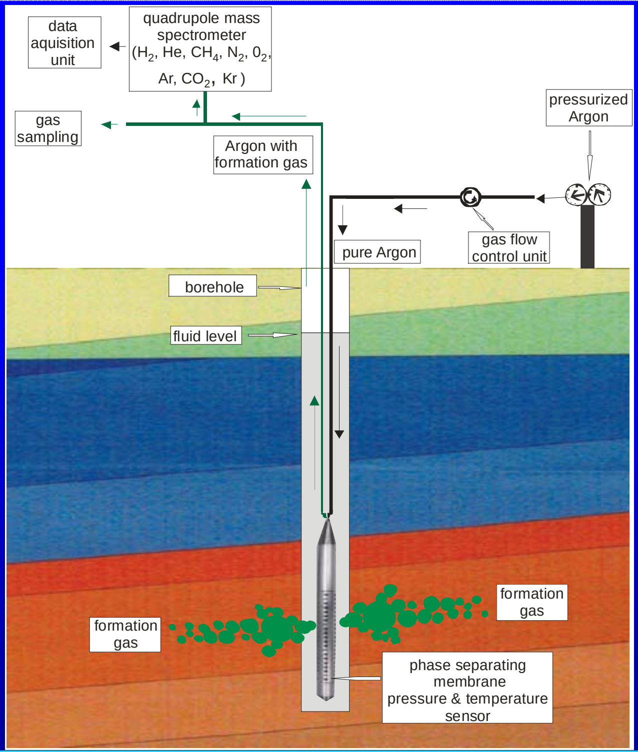


(Henninges and Freifeld, 2008)

Geochemical and Microbiological Monitoring

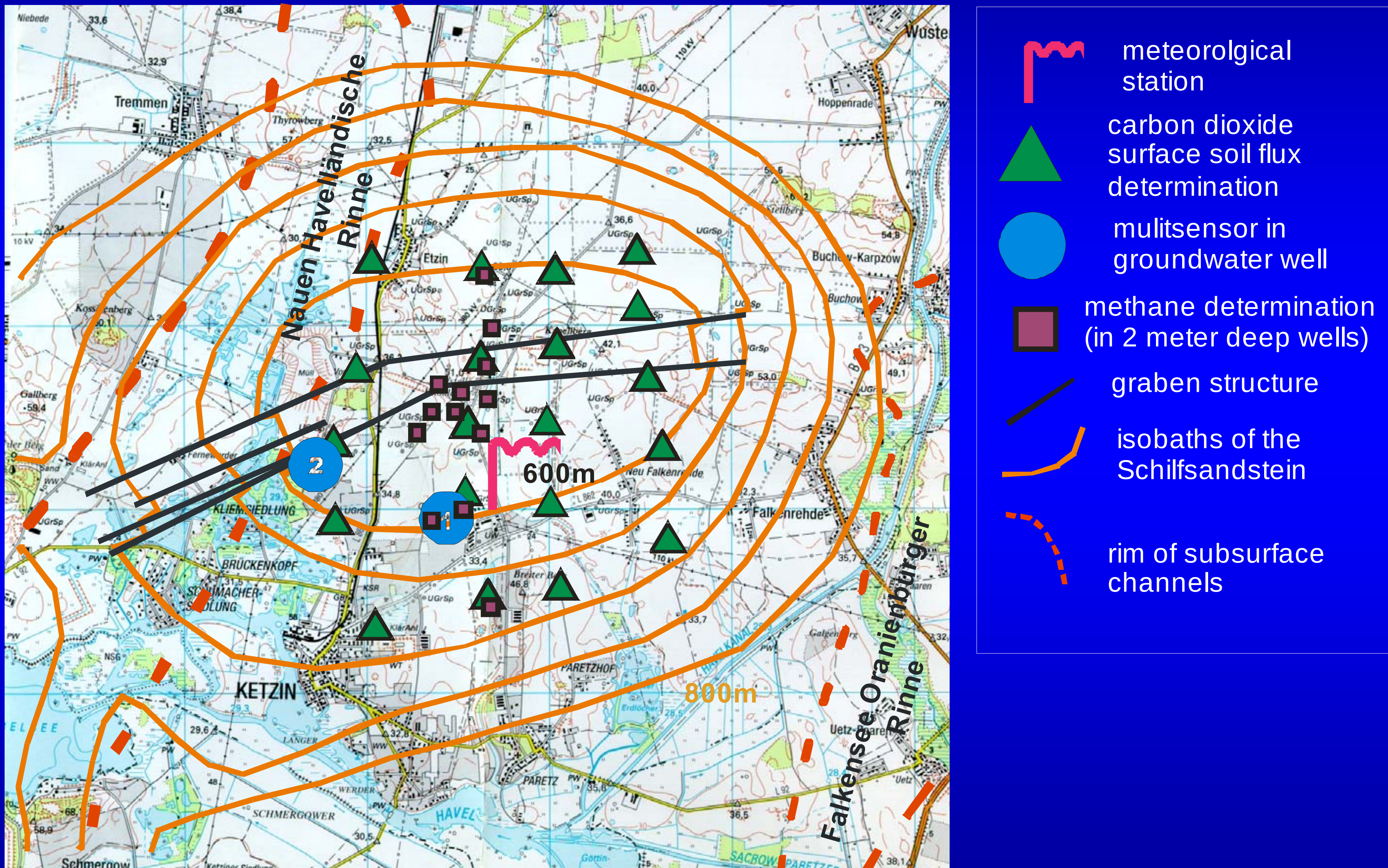
Gas Membrane Sensor





(Zimmer et al. 2008)

Geochemistry - Surface Monitoring

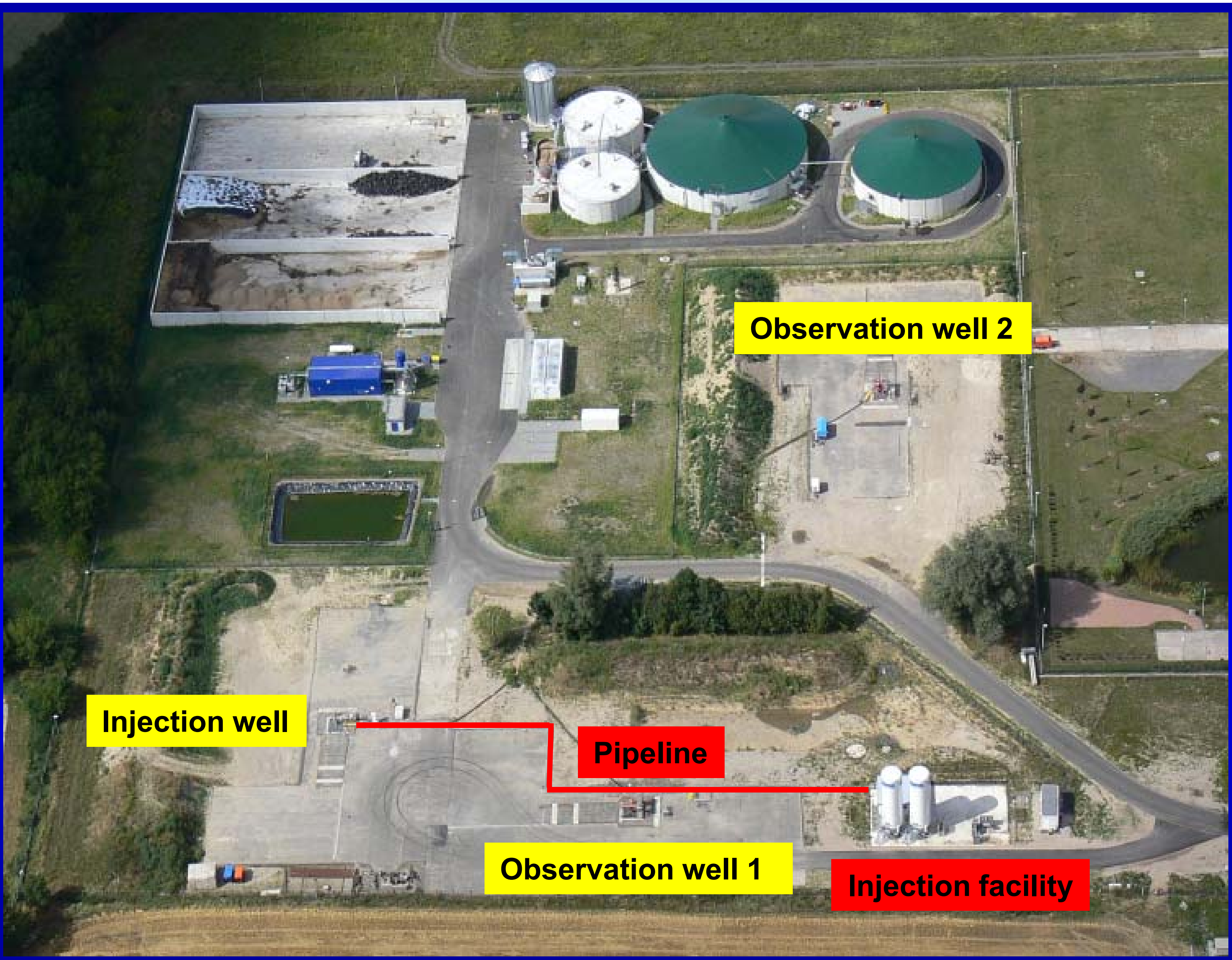


(Zimmer et al. 2007

Numbers of Microorganisms in Downhole Samples (Ktzi 201 before and after N2 lift)

Injection Operation

Aerial view

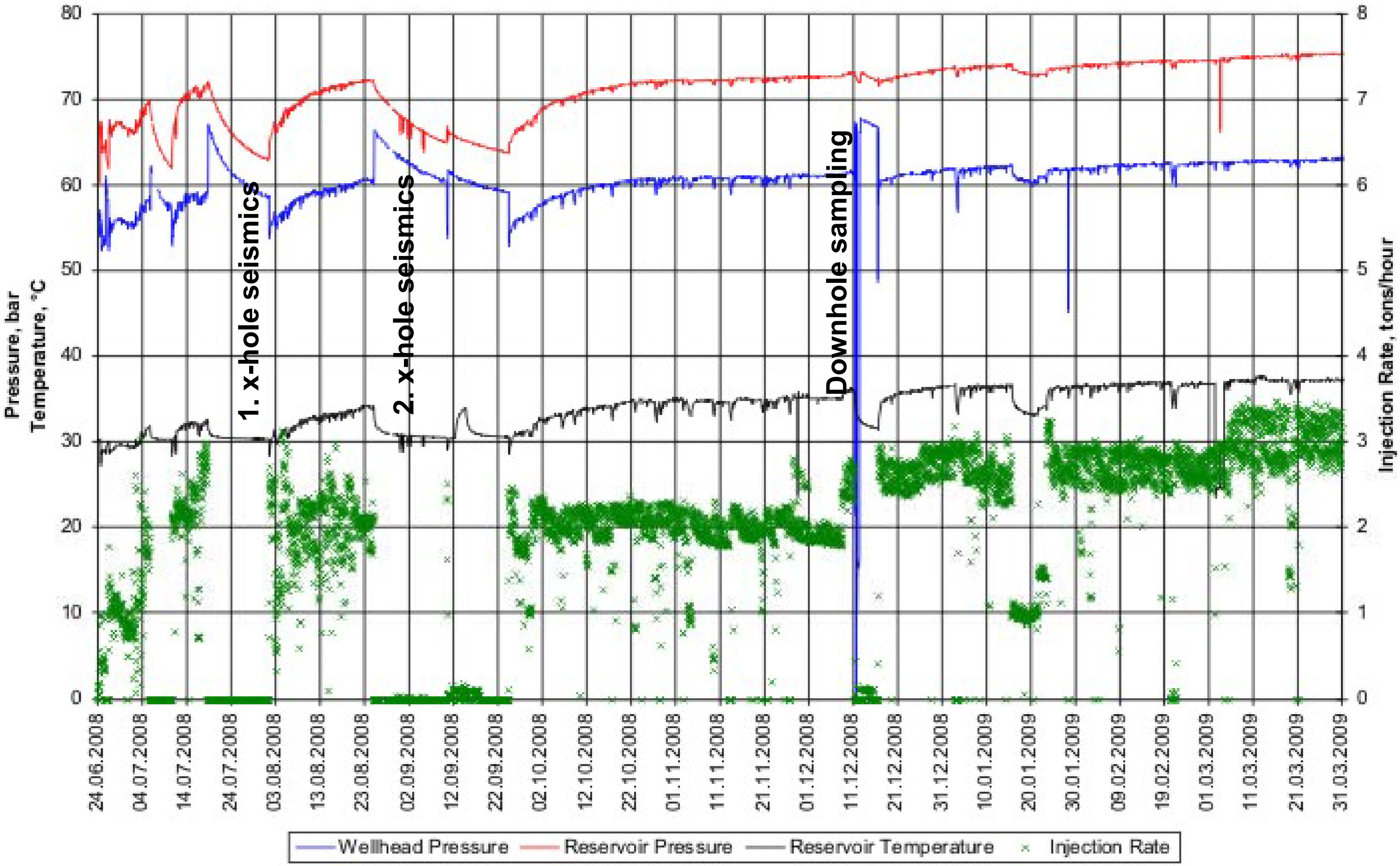


Observation well 2
Injection well
Pipeline
Observation well 1
Injection facility

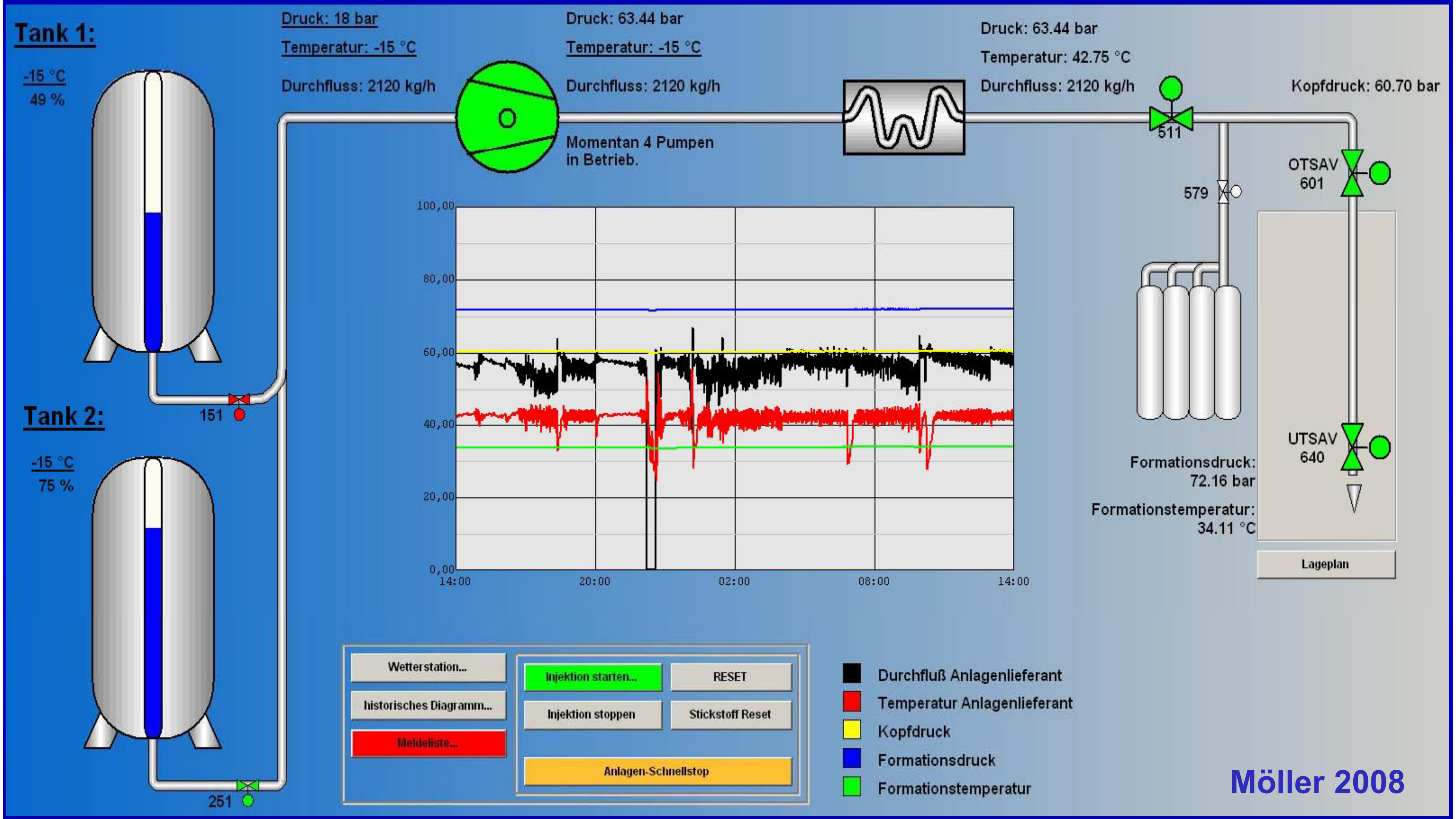
Injection Facility

- 2 storage tanks 50 to CO_2 each (liquid: -18 °C, 19 bar)
- 2 ambient air heaters for pressure keeping within the tanks
- 5 plunger pumps for rates of 0 … 1.000 kg/h liquid CO_2
- 1 plunger pump for rates of 0 … 500 kg/h liquid CO_2
- 1 electrical heater, 305 kW el., operating range 29 °C … 70 °C (gaseous injection)
- 150 m insulated piping to injection borehole Ktzi 201

Injection Rates and Amount of CO_2 injected



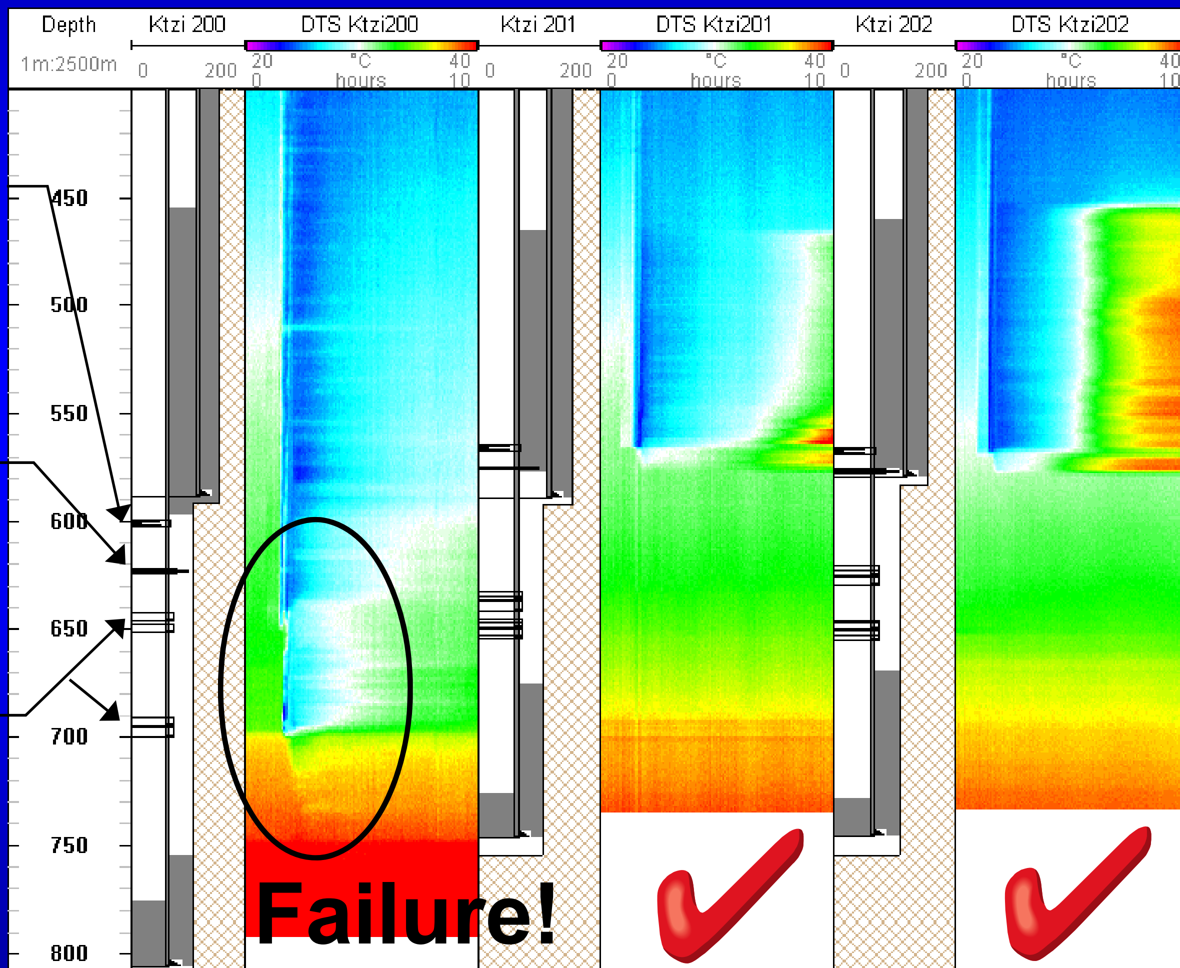
Operator Screen



Möller 2008

Main Results

DTS-Monitoring: Well cementing



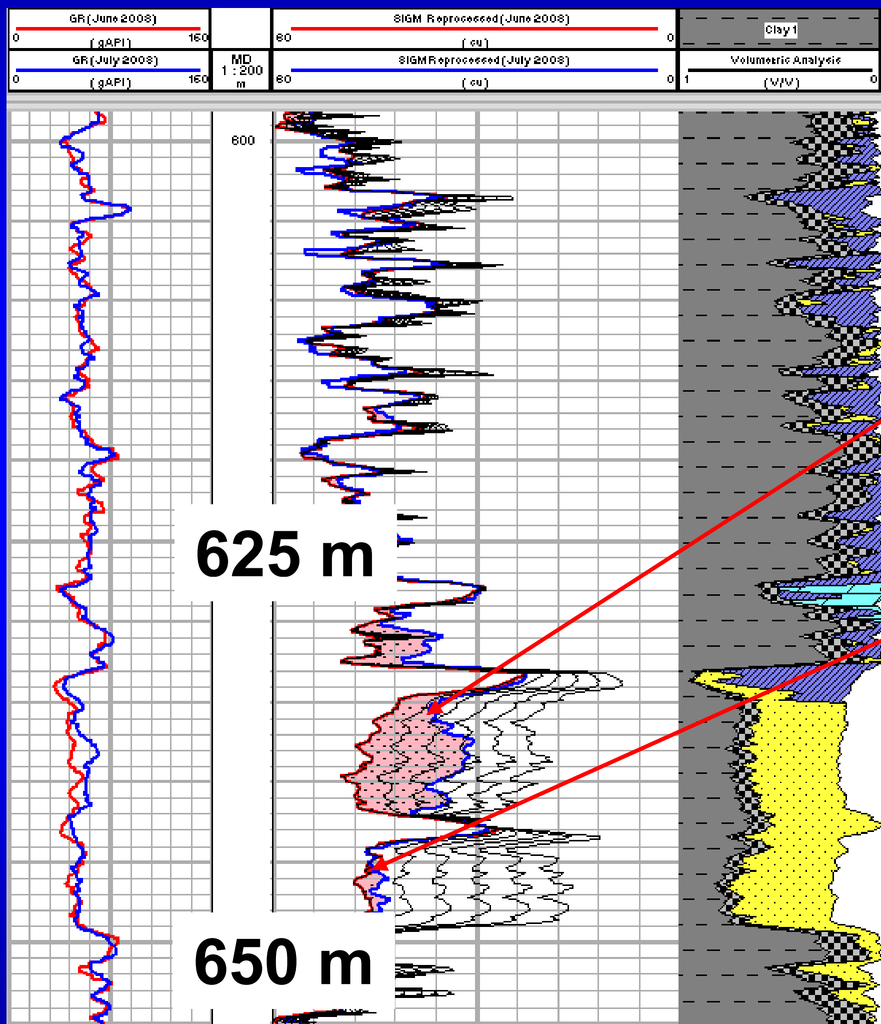
stage tool

packer

filter

Temp. increase: setting of cement (heat of hydration)

RST Measurement – Ktzi 200 (OW1)



Pink shading: ΔSaturation due to CO_2

CO_2 Saturation ~ 60% in upper sand section (yellow).

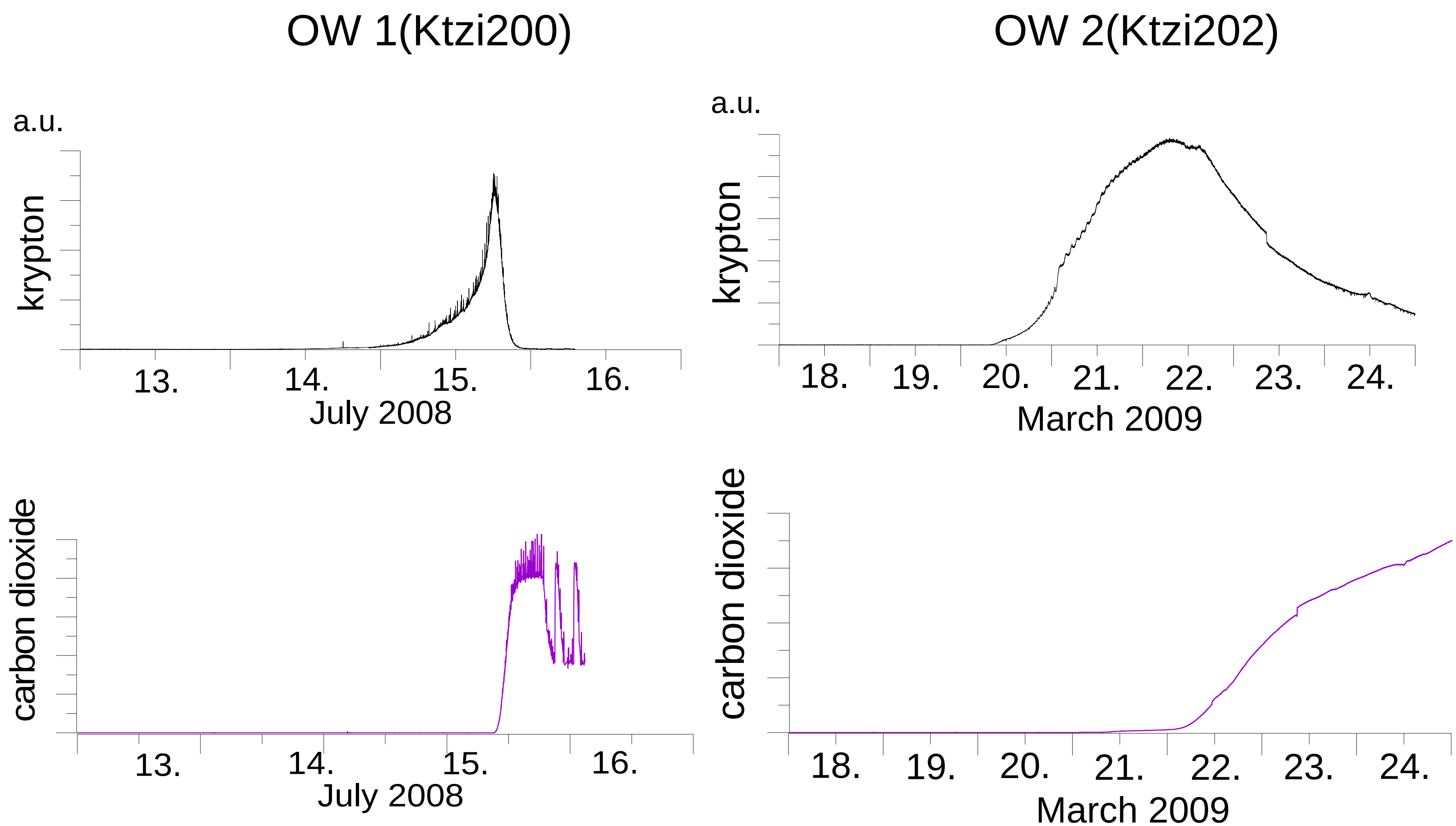
Little presence of CO_2 in lower sand

No CO_2 above 625 m

CO_2 arrival Ktzi 200 : July 15th
RST monitoring run : July 21st

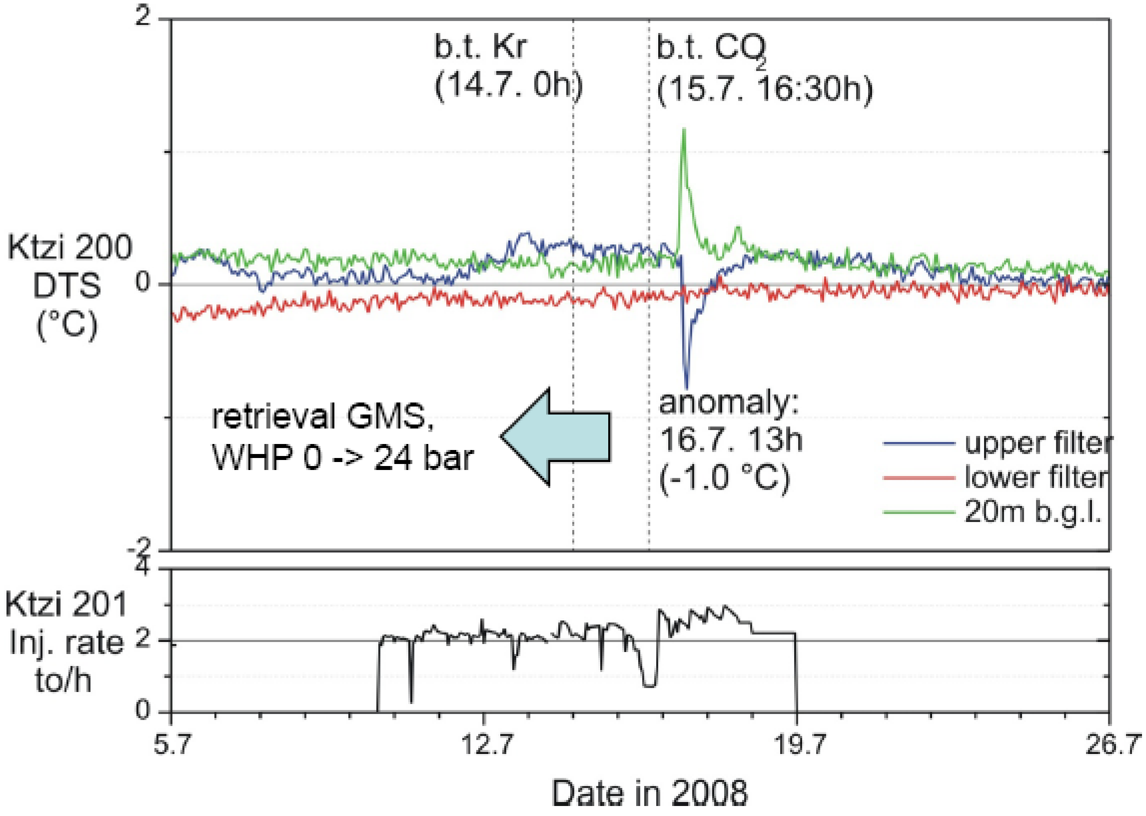
(D. Vu-Hoang, 2008)

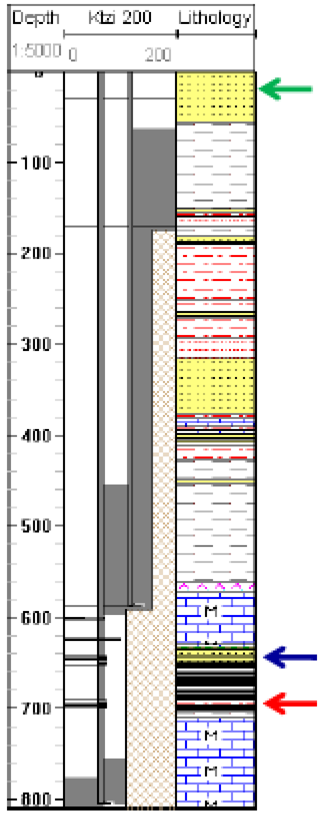
Arrival of Krypton (Tracer) and CO_2



Zimmer *et al*. 2009

Temperature changes Ktzi200 b.t. CO2





(J. Henninges, 2008)

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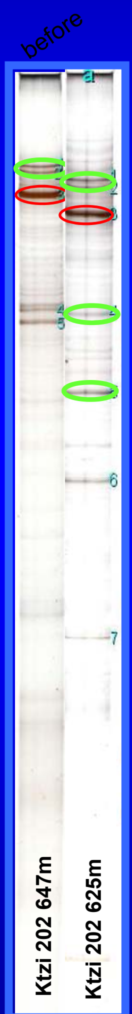
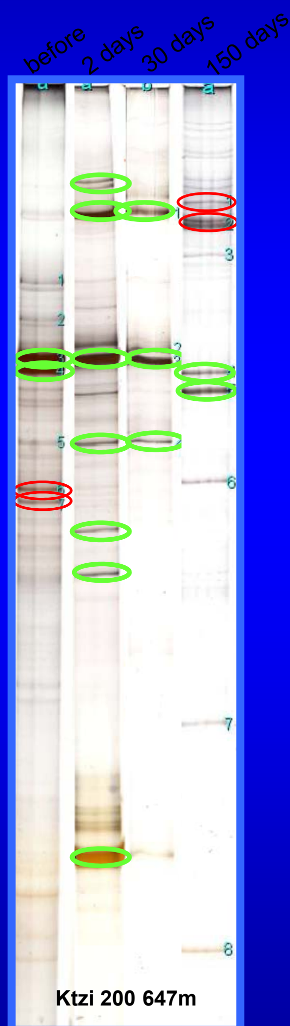
CO_2-Arrival in Ktzi 200: Fermenting + Sulphate reducing Bacteria

CO₂SINK

Downhole samples before CO_2 contact



Downhole samples before and after CO_2 contact



Identification

Ktzi 202, 647m:

***Halanaerobiaceae* bacterium** (Band 2)
Desulfohalobium utahense (Band 3)

Ktzi 202, 625m:

***Halanaerobiaceae* bacterium** (Band 2, 4, 5)
Desulfovibrionales spp. (Band 3)

Ktzi 200, 647m:

Haloanaerobium acetoethylicum (Band 3,4)
***Desulfosporosinus* sp.** (Band 6, 7)

Ktzi 200, 647m, 2 days after CO_2 arrival:

***Halanaerobiaceae* bacterium** (Band 1, 2)
Bacteroides (Band 3)
Haloanaerobium acetoethylicum (Band 4- 6, 8-9)
Halobacteroides (Band 7, 10)

Ktzi 200, 647m, 30 days after CO_2 arrival:

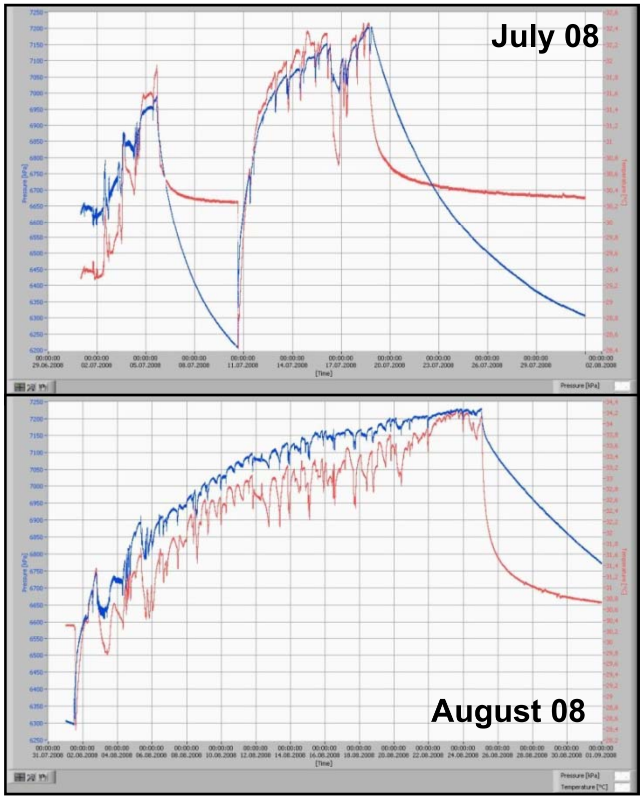
Bacteroides (Band 1)
Haloanaerobium acetoethylicum (Band 2, 3)
Halobacteroides (Band 4)

Ktzi 200, 647m, 150 days after CO2 arrival:

***Halanaerobiaceae* bacterium** (Band 4, 5)
Desulfovibrionales spp. (Band 1, 2)

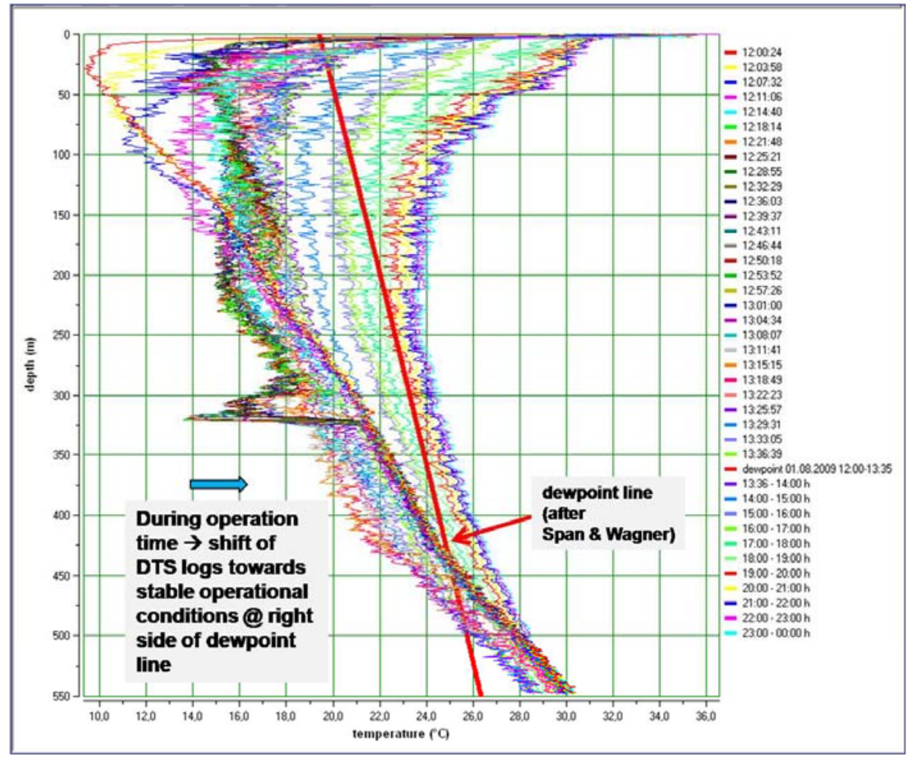
Morozova et al., 2008

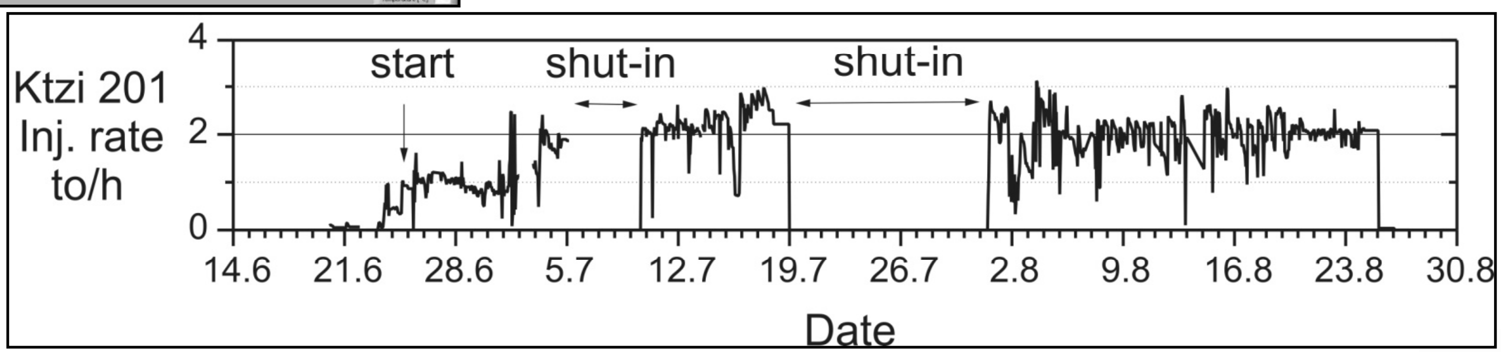
Joint interpretation of pressure/ temperature data for safety monitoring of Ktzi201 during various CO_2 injection conditions



Transient pT-response of the fiber Bragg grating point gauge sensor @ 550 m (every 5 sec)
blue: pressure (kPa)
red: temperature (°C)

DTS logs recorded During restarting the CO_2 operation





CO_2 injection rate during the first phase of operation at the Ketzin test site

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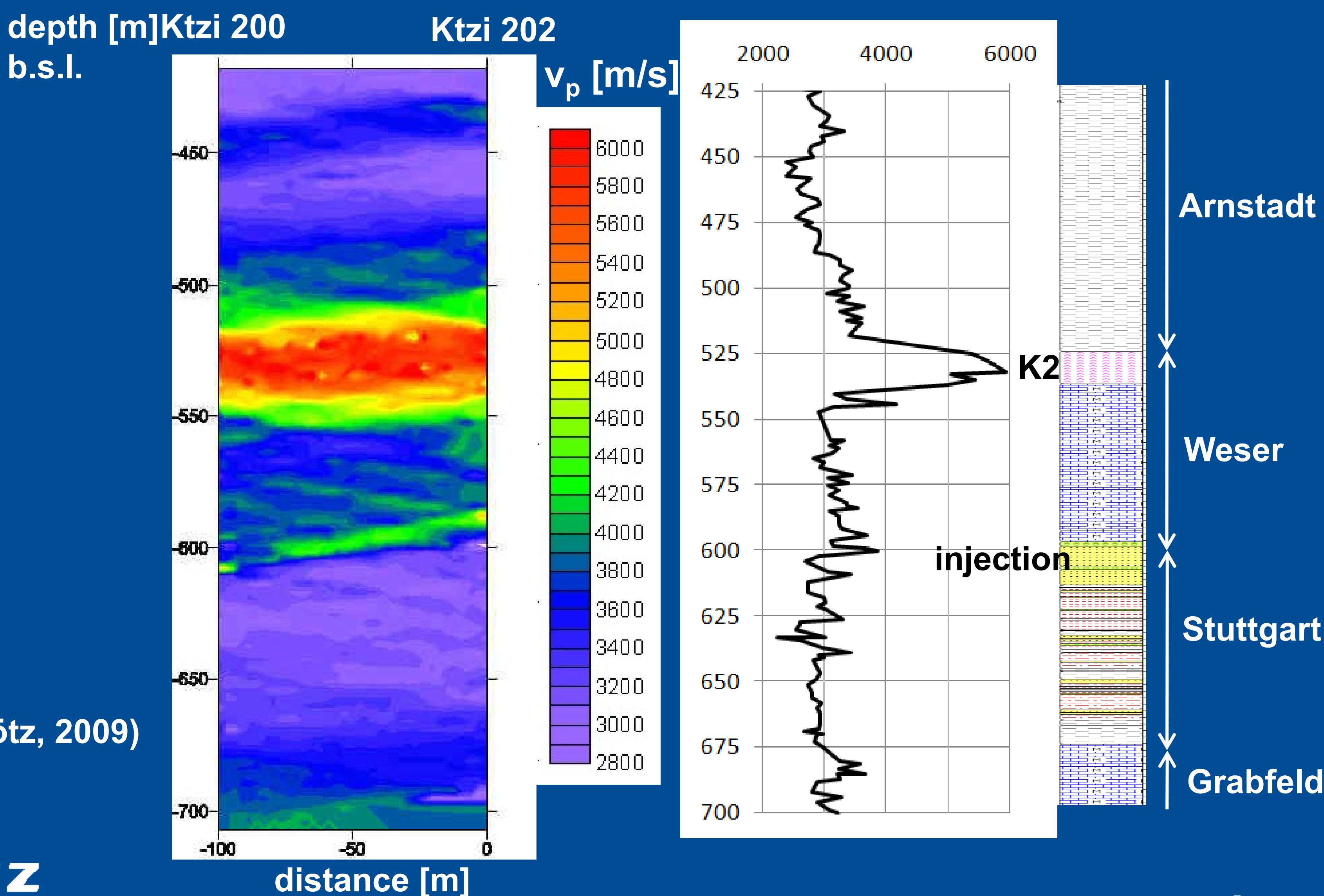
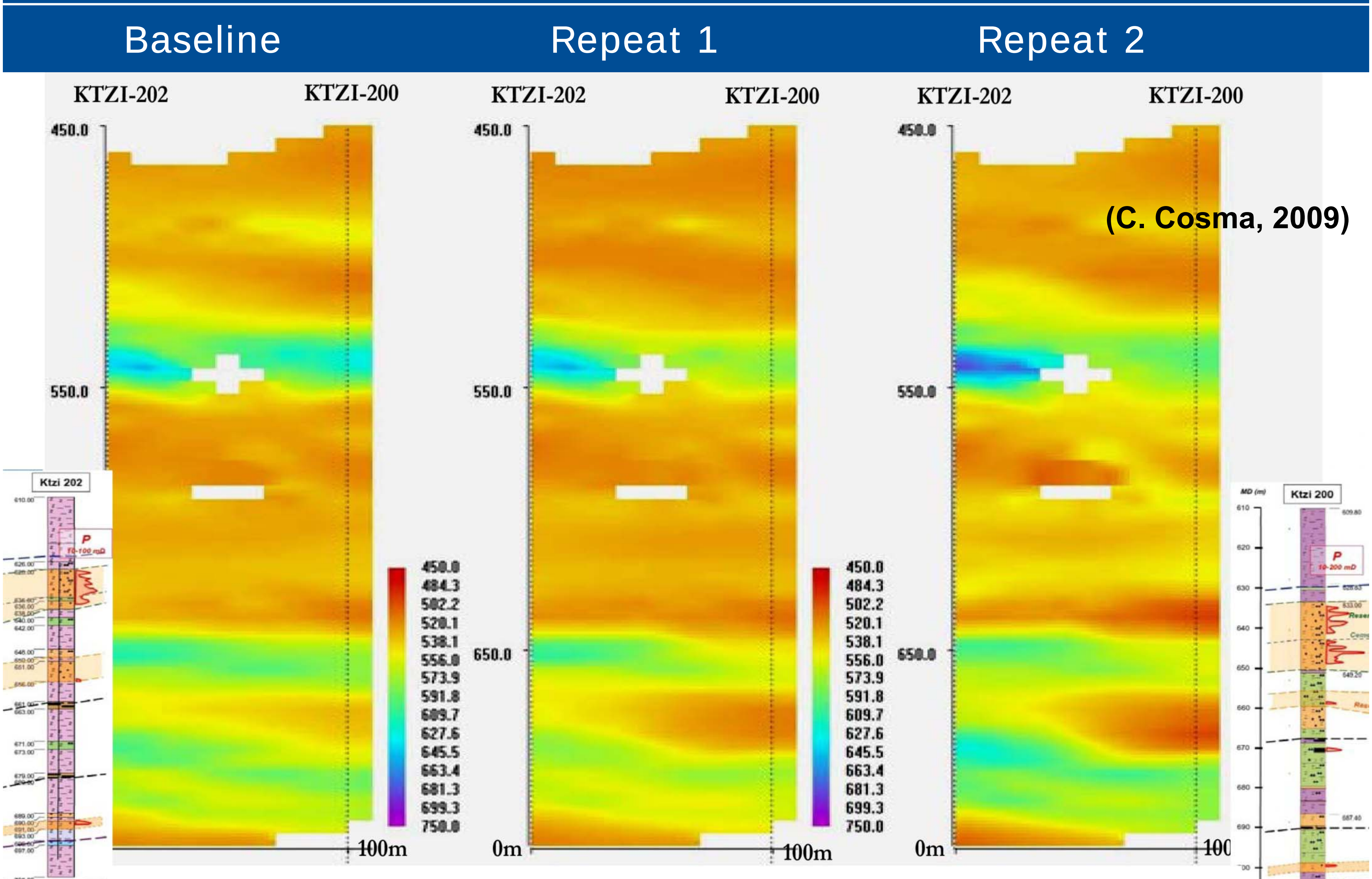
CO2 REMOVE
research monitoring verification

Cross-hole: inversion, sonic log & lithology



(J. Götz, 2009)

Cross-hole: seismic transparency tomography

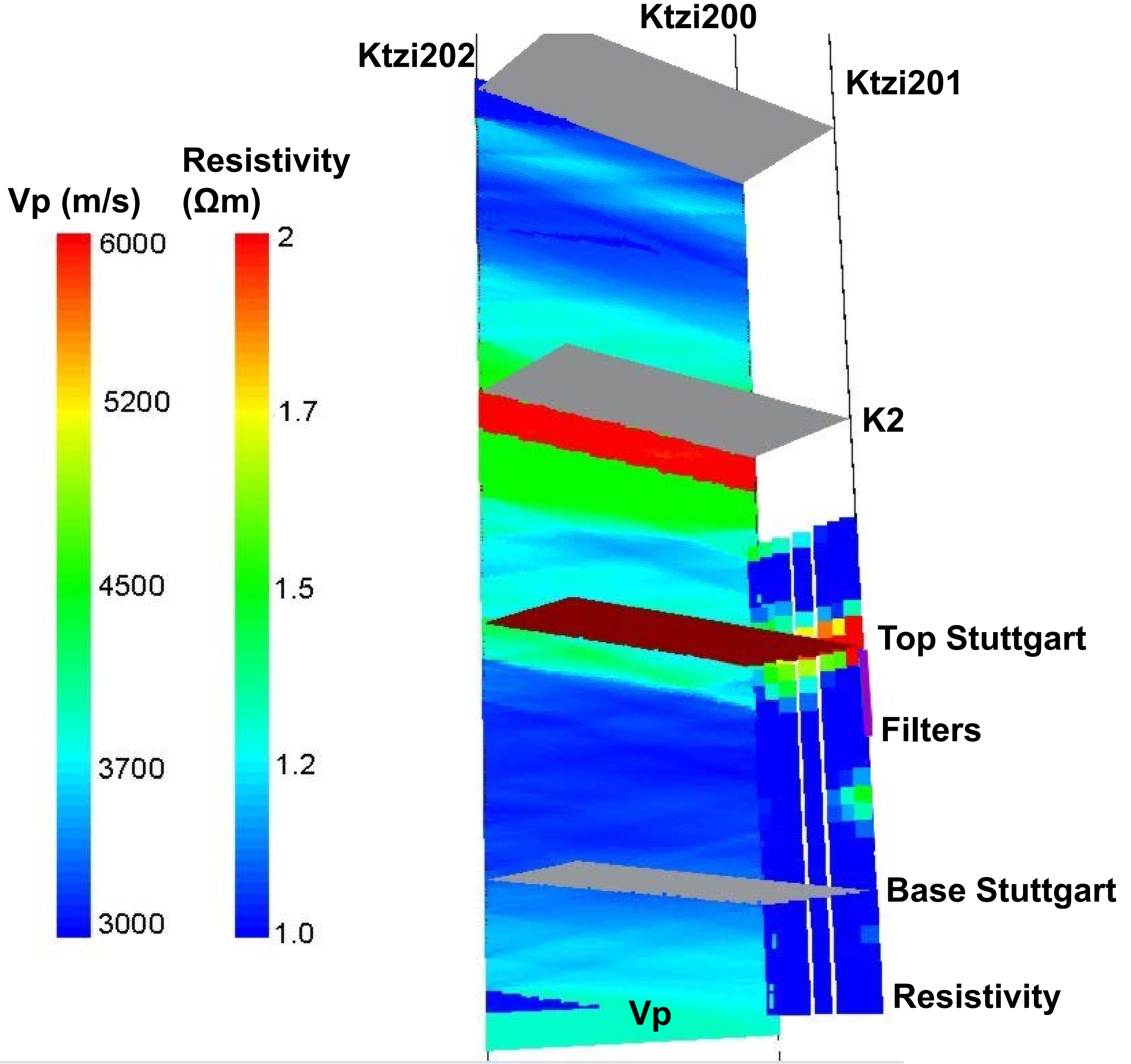


Preliminary Crosshole Tomography Results

Joint visualization

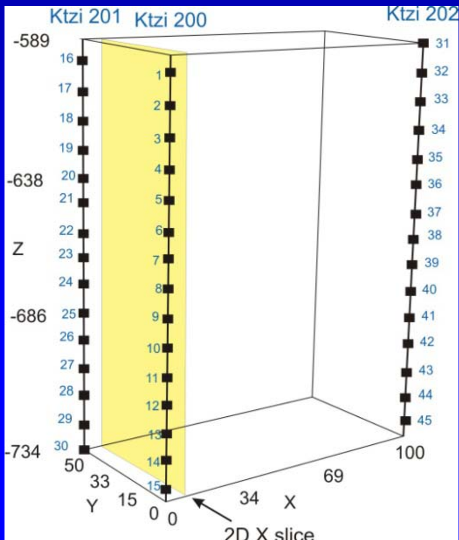
↓

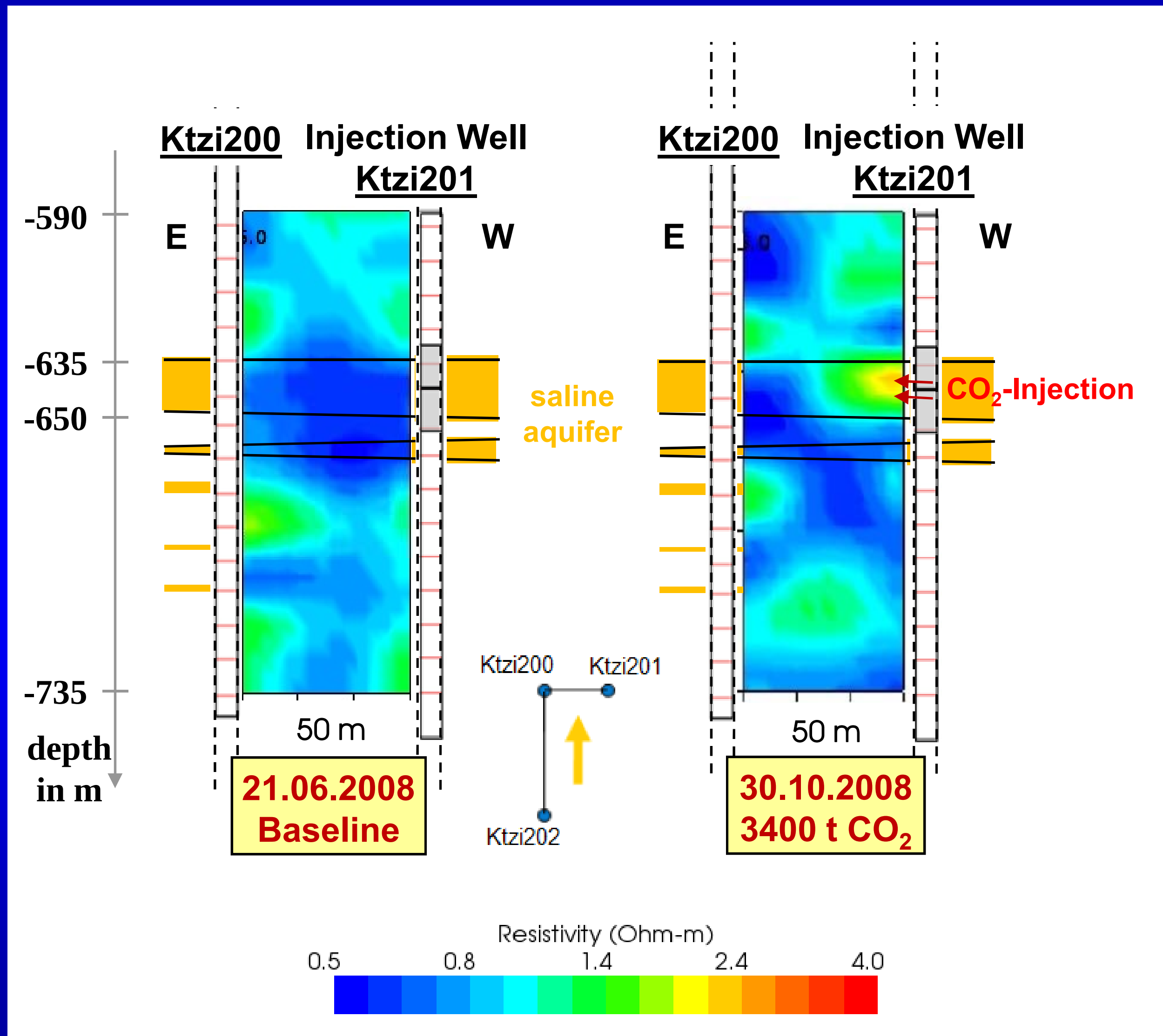
Structural joint inversion



J. Goetz, 2009

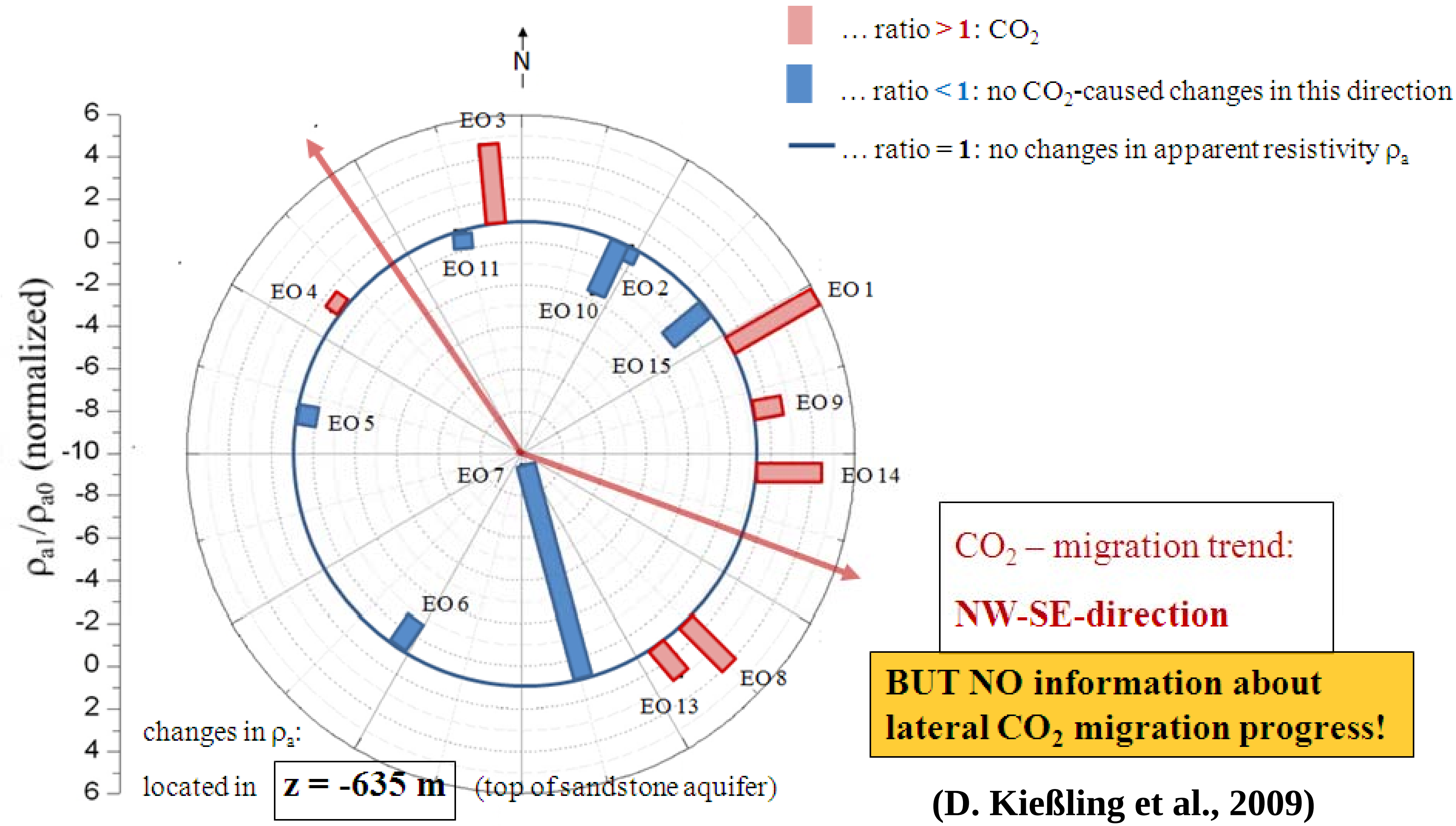
Electric Resistivity Tomography - ERT





(Kiessling et al., 2008)

Combined Surface-Downhole Concept



CO_2 – migration trend:

NW-SE-direction

BUT NO information about lateral CO_2 migration progress!

(D. Kießling et al., 2009)

Further European partners in active cooperations with CO2SINK:

•OGS Trieste, Italy:
Passive seismic monitoring, **CO2ReMoVe** / **concept of low-cost seismic alert system for CO2 storage sites**, **CO2GeoNet**

•BRGM Orleans, France:
Electromagnetic surveys – **LEMAM method** / ***Geochemical transport modeling***, **both** **CO2ReMoVe**

•IFP Paris, France: ***Petrophysical measurements***: **resistivity, capillary pressure and relative permeability**, **COSMOS-Eurogia**

•TNO Utrecht, NL: ***Concept of low-cost seismic alert system*** **for CO2 storage sites**, **CO2GeoNet**

•Oxand S.A. Avon, France, ***Performance and Risk study*** **for well abandonment**, **COSMOS-Eurogia**

joint field experiments / project meetings /data exchange with partners

GFZ Helmholtz Centre Potsdam

Helmholtz Association

Summary

- Injection operation is safe and reliable
- Normal reservoir response, good flow into formation, stable down hole pressure, no skin effects near the well, taken all measures (N_2, KCl-slug) to avoid halite scaling
- Down pressure below (> 10 bar) safety threshold
- Arrival of CO_2 in OW 1 detected as modelling predicted, arrival of CO_2 in OW2 detected later as modelling predicted
- Gas membrane sensor (GMS) proved reliability
- Seismic baseline and repeat measurements for structural framework.
- ERT able to image CO2 signature
- To date, seismic crosshole repeat surveys were not able to clearly image time lapse efects - amount of CO_2 below detectability threshold
- High local, national and international interest with a lot of good press response, high awareness of CCS technique

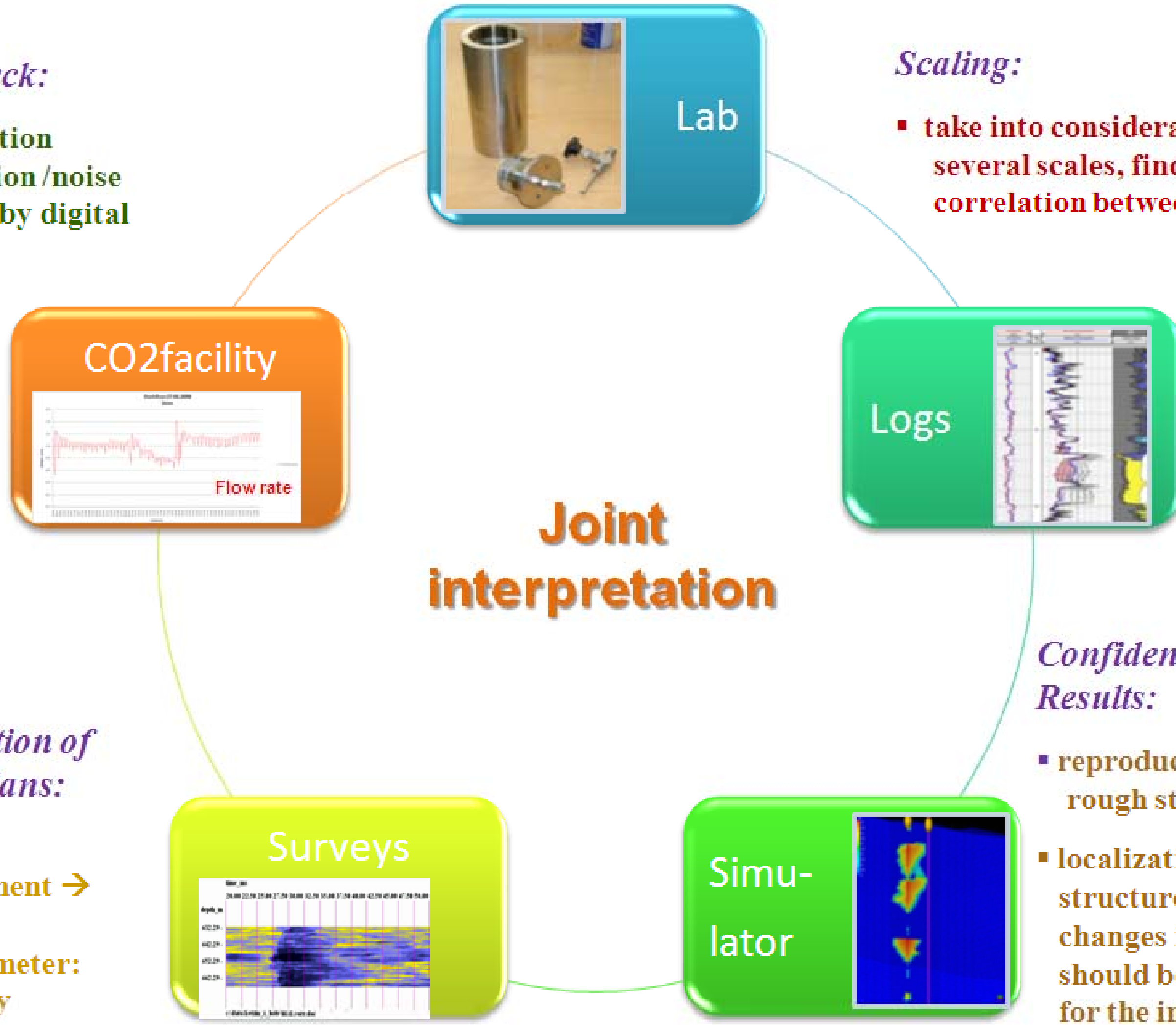
The way forward

Quality check:

- Data selection for inversion/noise reduction by digital filtering

Scaling:

- take into consideration several scales, find good correlation between them



Confidence of Results:

- reproducibility of the rough structures
- localization of structures and changes in resistivity should be consistent for the individual time-laps steps

Optimization of Survey Plans:

- Schedule improvement →

key parameter: sensitivity

US Regional Carbon Sequestration Partnerships: recent results on monitoring

Susan D. Hovorka Gulf Coast Carbon Center, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

Gulf Coast Carbon Center

The University of Texas at Austin John A. & Katherine G. JACKSON SCHOOL OF GEOSCIENCES

Bureau of Economic Geology

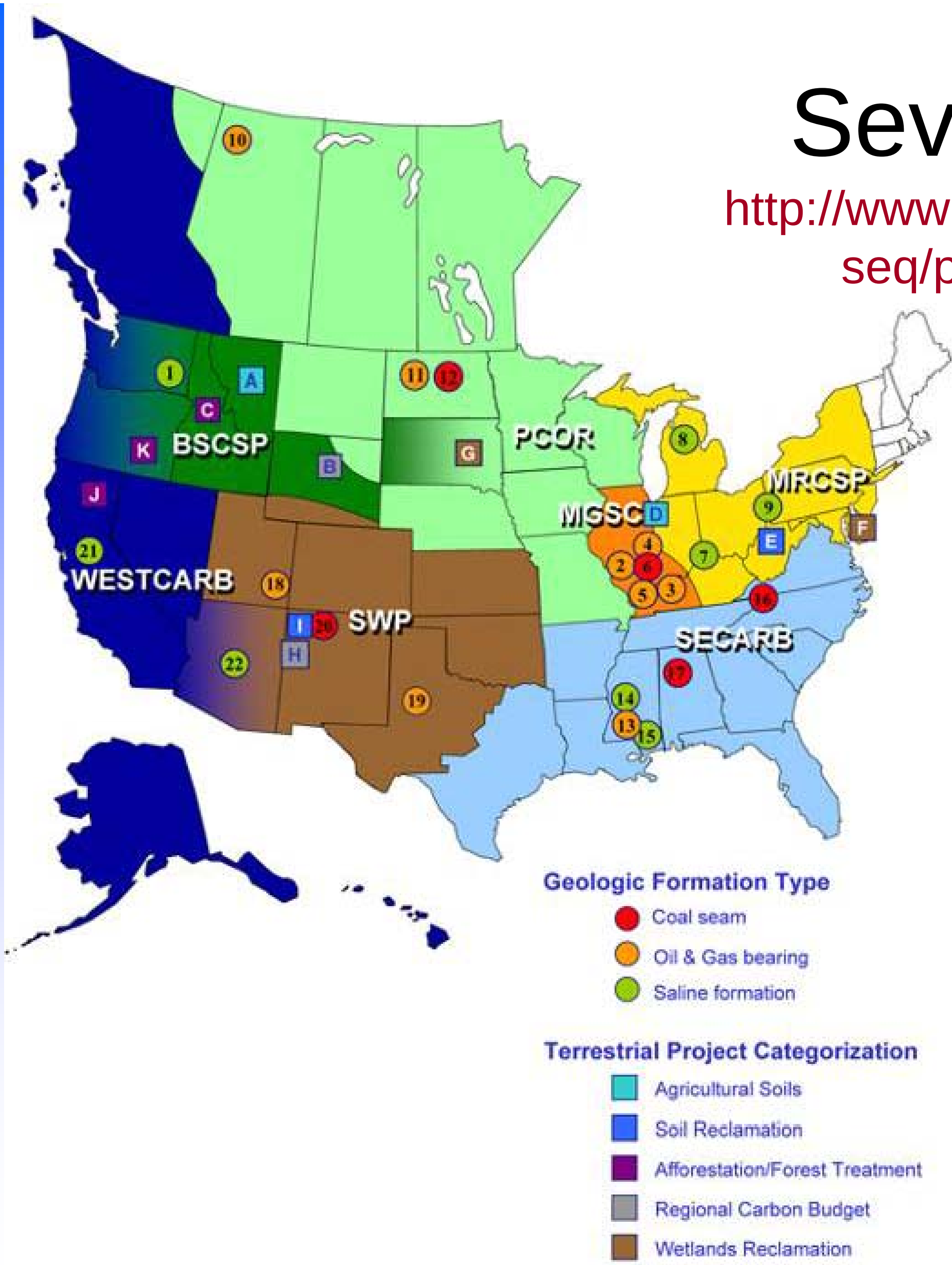
Presented to IEA GHG R&D Programme Monitoring Network Tokyo Japan June 2, 2009

Talk Outline

- Introduction to US Department of Energy Regional Carbon Sequestration Partnerships (RCSP)
- Selected case studies and highlights
  - Planning stages
  - Data collection
  - Follow-on data collection
  - Near conclusion

Seven Partnerships

http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html



244 organizations in 40 states,4 provinces, three Indian nations

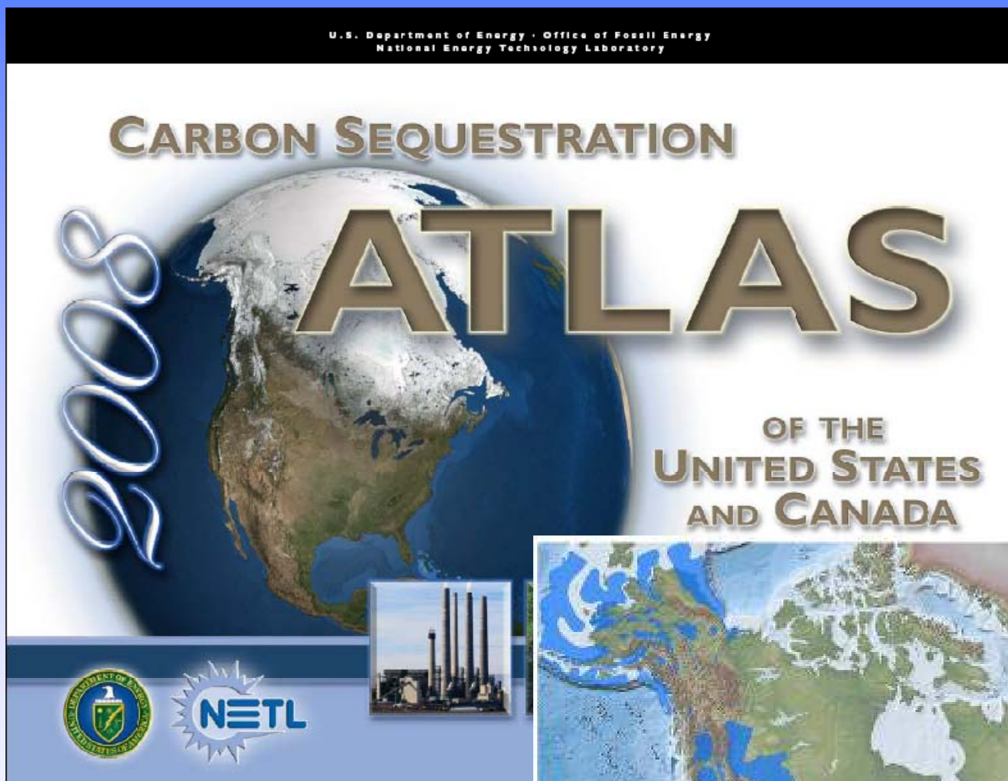
2003-2005 characterization phase

2005-2010

21 validation phase projects

2008-2017 Development phase 7+ large injections

Characterization Phase result: DOE NATCARB Atlas



Continental capacity – example saline aquifers

Storage and Incremental Recovery Through EOR[a] in Selected Fields

Basin	Cummulative Incremental Recovery, million stb	CO_2 Required,[b] Bcf	CO_2 Sequestration Potential, Bcf	CO_2 Sequestration Potential, tonnes
Williston	1023	8186	8186	455,223,186
Powder River	381	3049	3049	169,563,509
Denver–Julesberg	25	199	199	11,076,137
Alberta	NA	8888[c]	8888[c]	494,315,100[c]

[a] Enhanced oil recovery.
[b] CO_2 quantity required is the total purchase amount and does not consider recycling of CO_2 from the tertiary recovery operation.
[c] Values for the Alberta Basin were determined using a different methodology than the other basins and, therefore, may not be directly comparable to the other estimates. They are included in the table to provide insight regarding the general magnitude of CO_2 flood-related sequestration capacity and potential incremental oil production in Alberta.

44 Carbon Sequestration Atlas of the United States and Canada

Regional Studies – example PCOR oil field

http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlas/index.html

Validation Phase results - MVA* document

- Monitoring Verification Accounting
  - Downloadable report
    - www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf
- RCSP “Best Practices Manual”
  - Overview of status of knowledge
  - No new synthesis

Field Project Status

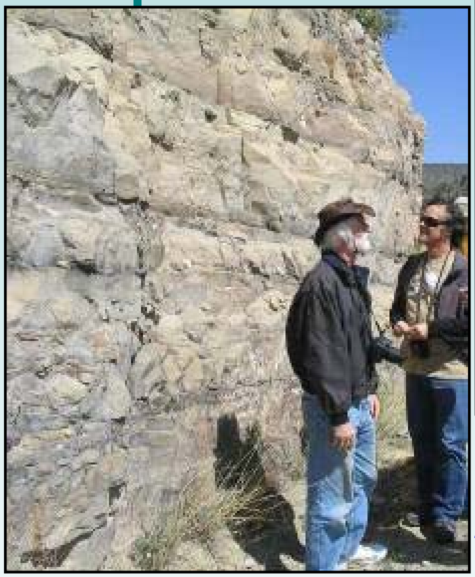
- 3 sites – uncertain site/source
- 9 planning monitoring program
- 2 data collection underway
- 11 data collected in analysis
- 3 additional follow-on work underway

WESTCARB Phase II-III

- Arizona test
  - Issues - injectivity in wildcat area -Water in a dry area
  - Planning 2000 ton injection –single well analyisis - huff and puff testing
  - Test injectivity and storage capacity of porous carbonate formations
  - Test methods for imaging CO2 plume in these formations
  - Validate multi-phase flow models
- Shell Pilot in northern California
- Kimberlina - Central Valley – experimental CO2 capture

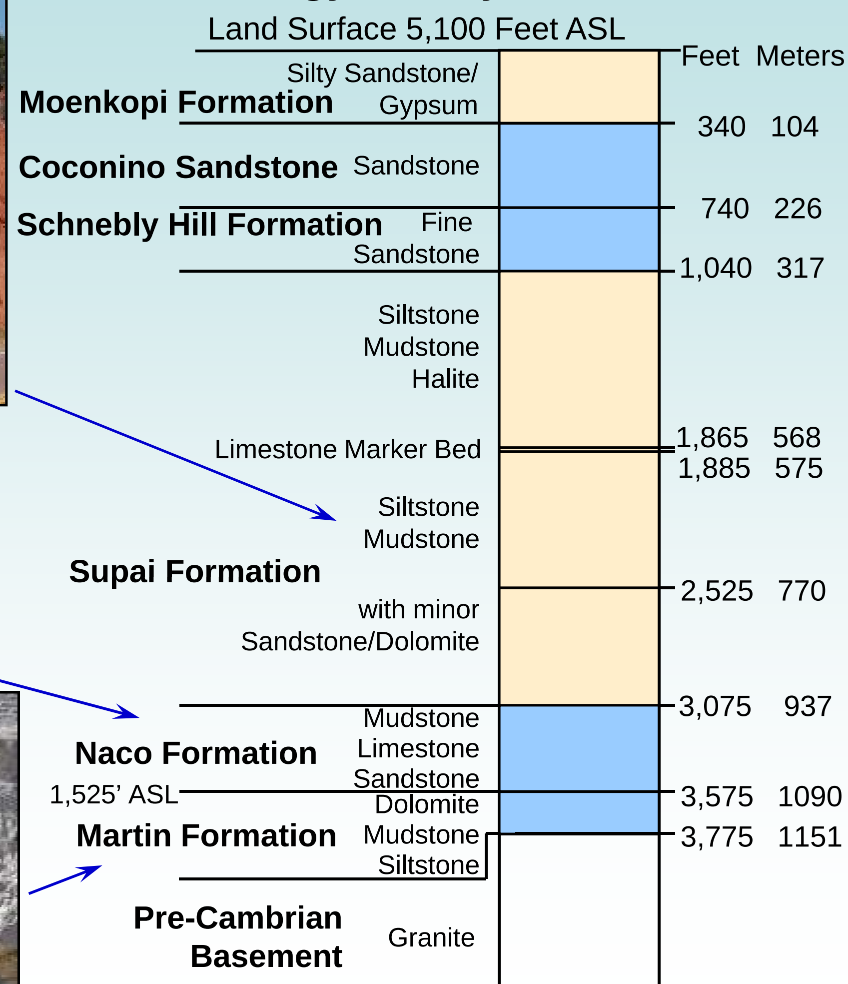
More information: John Henry Beyer
510-486-7954, jhbeyer@lbl.gov

Arizona Seal and Reservoir Formations



Salt River Canyon
~80 miles SSW of project site

Geology at Project Site

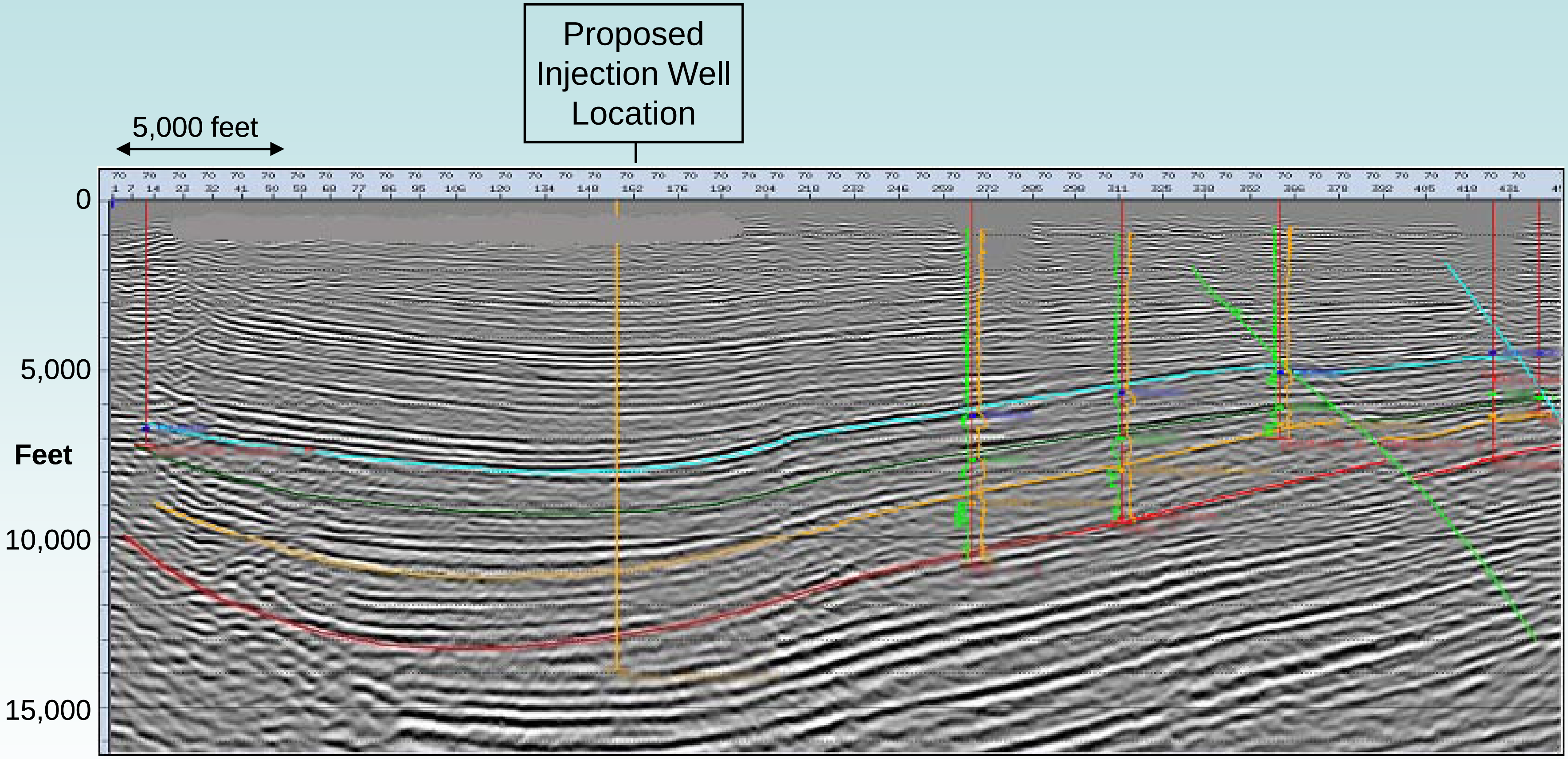


Source: Errol L. Montgomery & Associates

Arizona Drill pad near Cholla Power Plant fly ash pond

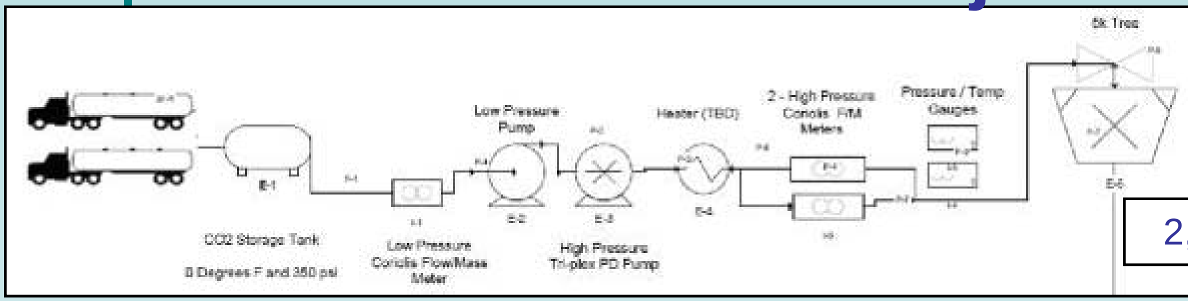
- Arizona Public Service has leveled the drill pad and installed line power to the site
- Close to major highway
- Controlled access

Seismic line through proposed project site Northern California

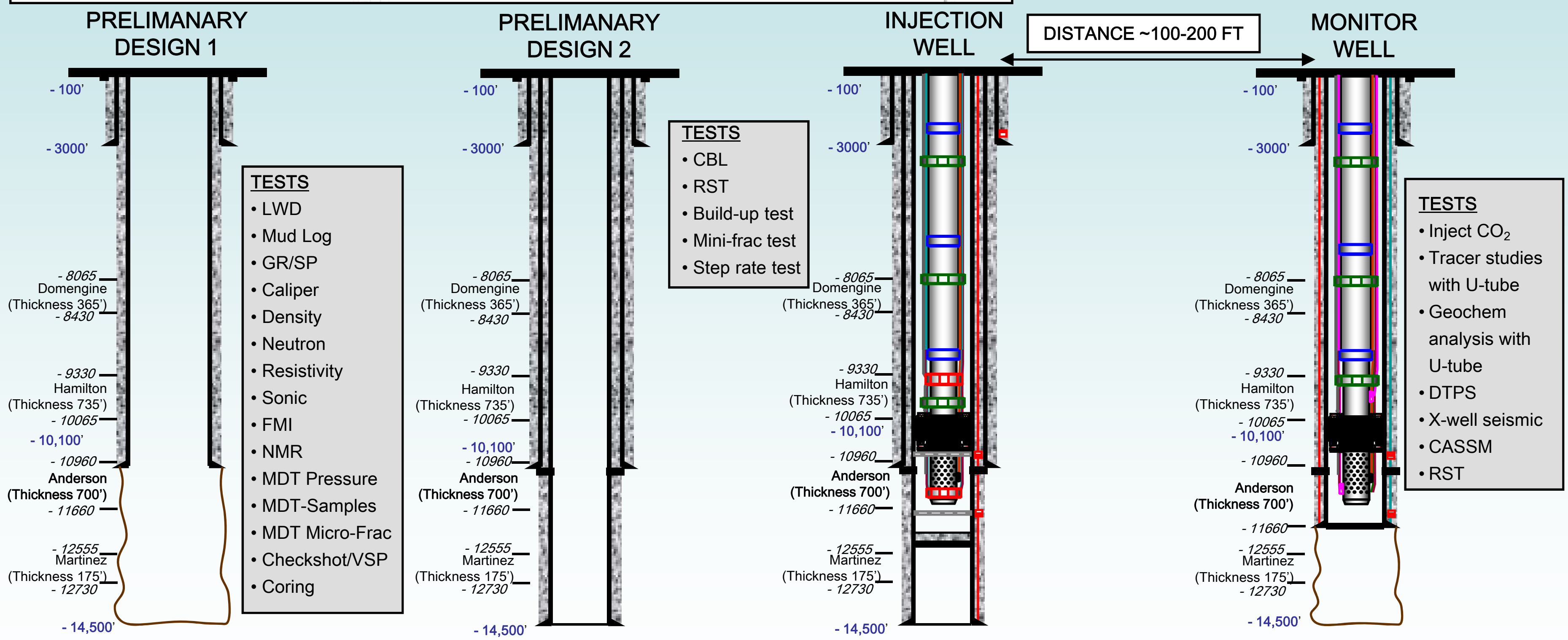


Source: Shell

Northern California Project Scope



2,000 - 6,000 Tons CO_2



Appraisal → **Run Casing** → **Pilot Injection Test**

Source: Shell

Illinois Basin Phase III

- Preparation for capture from ADM Ethanol Plant – injection into deep saline Mt Simon Formation
- baseline MVA program
  - risk assessment
  - groundwater monitoring network
  - Eddy Covariance tower
  - CIR imagery
  - CO2 soil fluxes
  - 2D seismic survey
  - shallow 2-D resistivity survey
  - preliminary characterization of CO_2 source
  - Injection well drilled May4 TD 7,230 ft, permiting in-zone verifaction well

"A lot to do and too soon to release data "

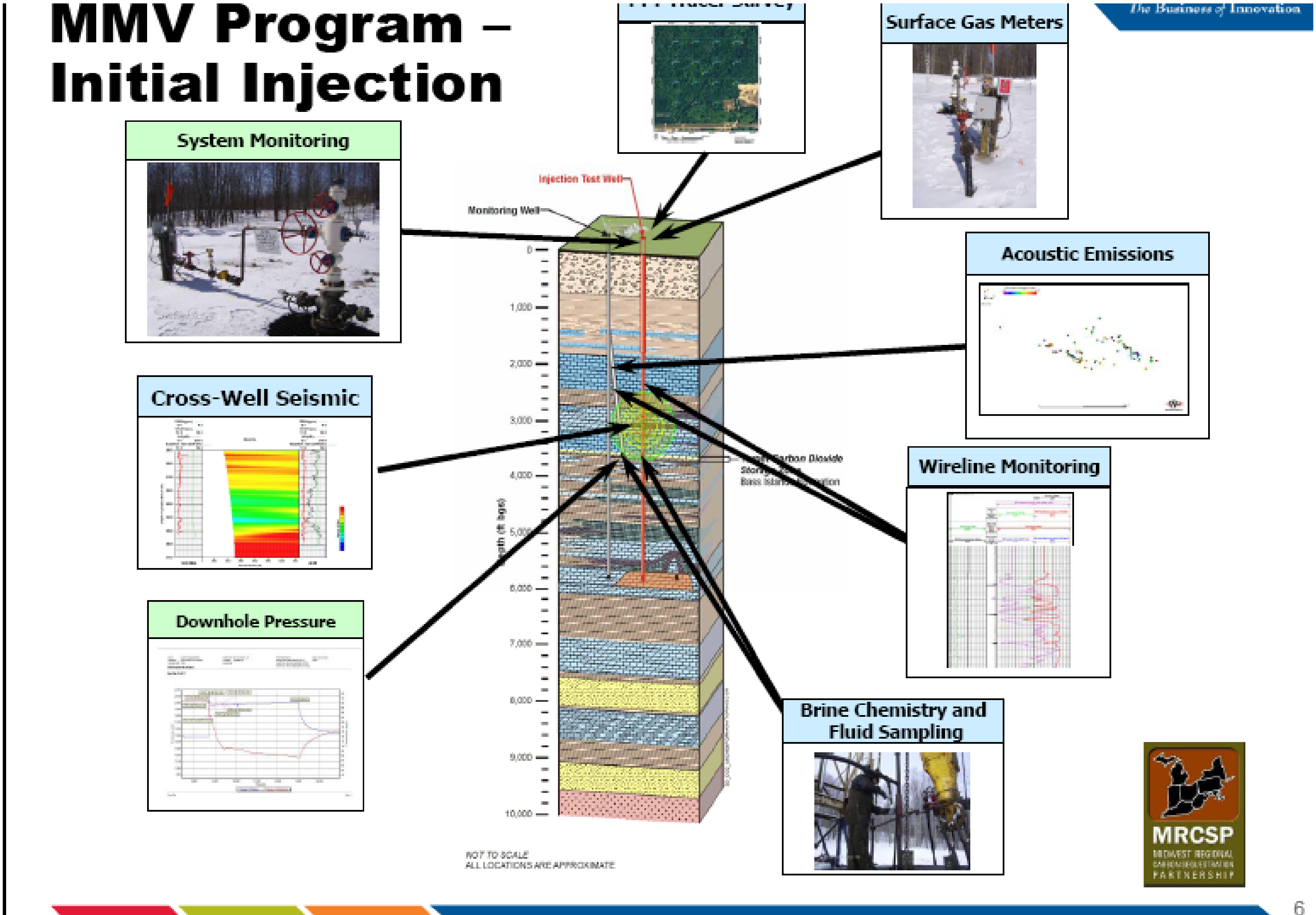
More information: **Ivan Krapac** **Krapac@isgs.uiuc.edu** **(217)-333-6442**

Sallie Greenberg **greenberg@isgs.illinois.edu 217-244-4068**

MRCSP Phase II Gaylord Michigan

- Two well-test monitoring 10,241 metric tons in brine with diverse tools completed and results assessed
  - Measured injectivity, hydrologic properties
  - Questions arose
    - Geochemical response
    - Change in gas saturation – methane or CO2
    - Micro seismic – oilfield activities
- Further testing same geometry with continued injection 600 ton/day for 50,000 ton started Feb 25, data collection underway

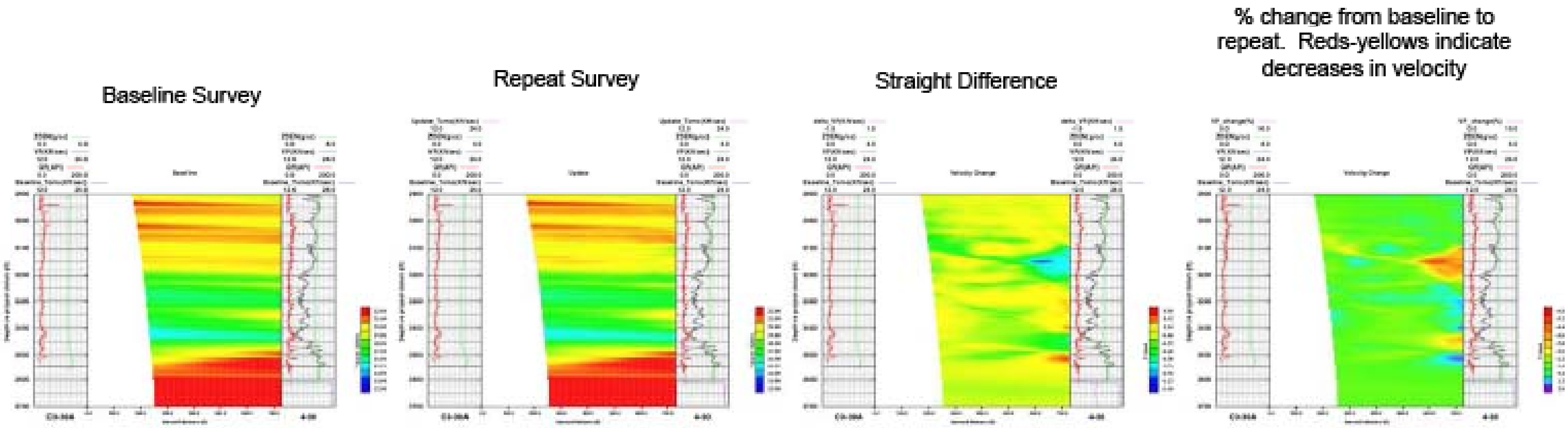
More information
Joel Sminchak: sminchak@battelle.org
Jackie Gerst: GerstJ@battelle.org



MMV Program – Initial Injection
The Business of Innovation
Surface Gas Meters
System Monitoring
Injection Test Well
Monitoring Well
Acoustic Emissions
Cross-Well Seismic
Wireline Monitoring
Downhole Pressure
Brine Chemistry and Fluid Sampling
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
NOT TO SCALE
ALL LOCATIONS ARE APPROXIMATE
MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

Cross-Well Seismic Repeat Survey

- Baseline cross-well survey run between 4-30 and C3-30A in January 2008. Repeat, post-injection survey completed on May 5, 2008
- Excellent signal to noise ratio and high energy source yield resolution of only a few meters
- The difference between the two surveys shows a velocity decrease in the Amherstburg formation, approximately 300 ft above the perforated injection interval, with no apparent connection with the velocity change area at the injection interval.

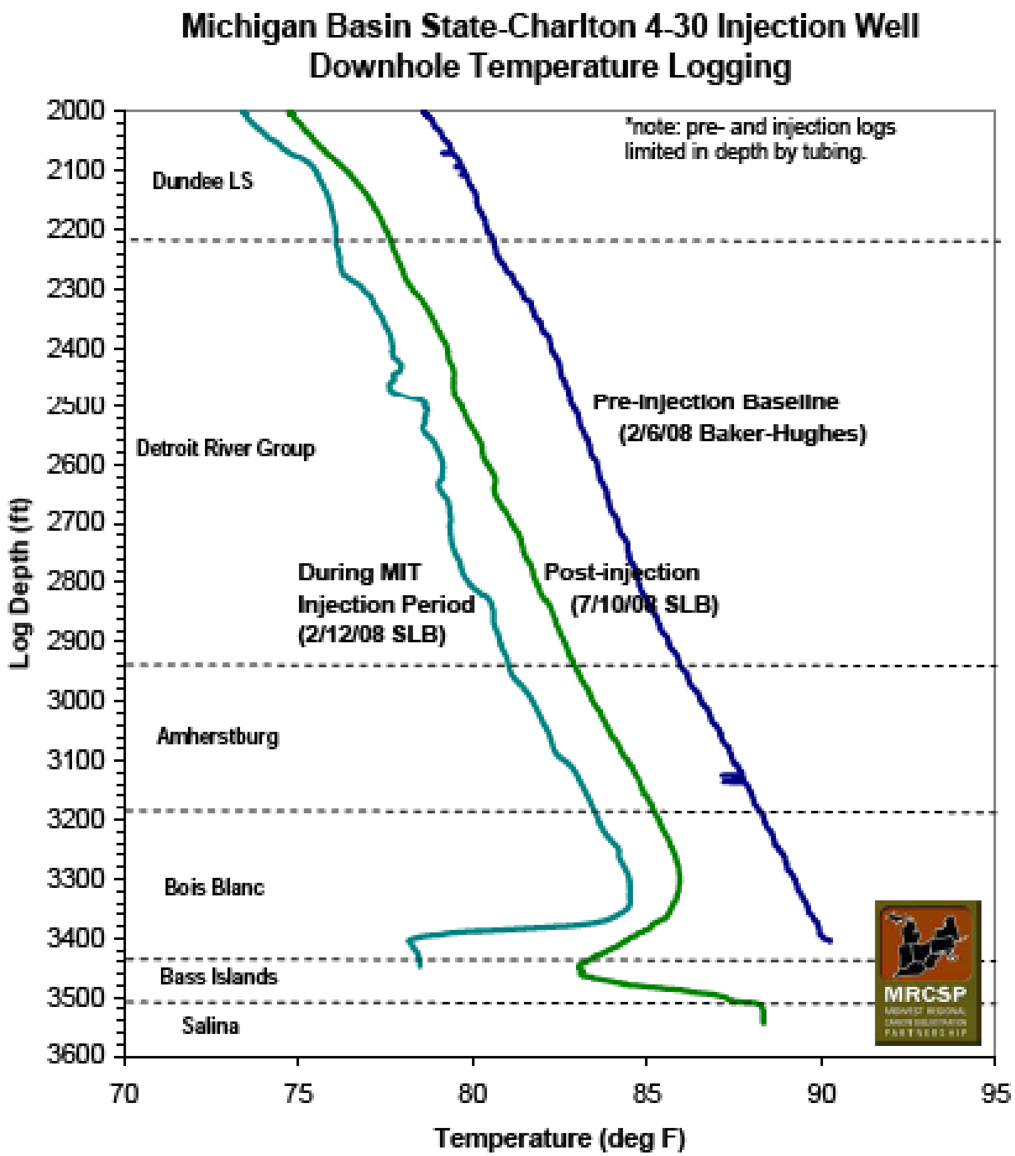


Post-Injection Thermal Response

- Sequential, downhole temperature logs provide very direct, understandable evidence of vertical CO_2 distribution.

- *No thermal evidence of CO_2 in confining layers in any temperature log*.

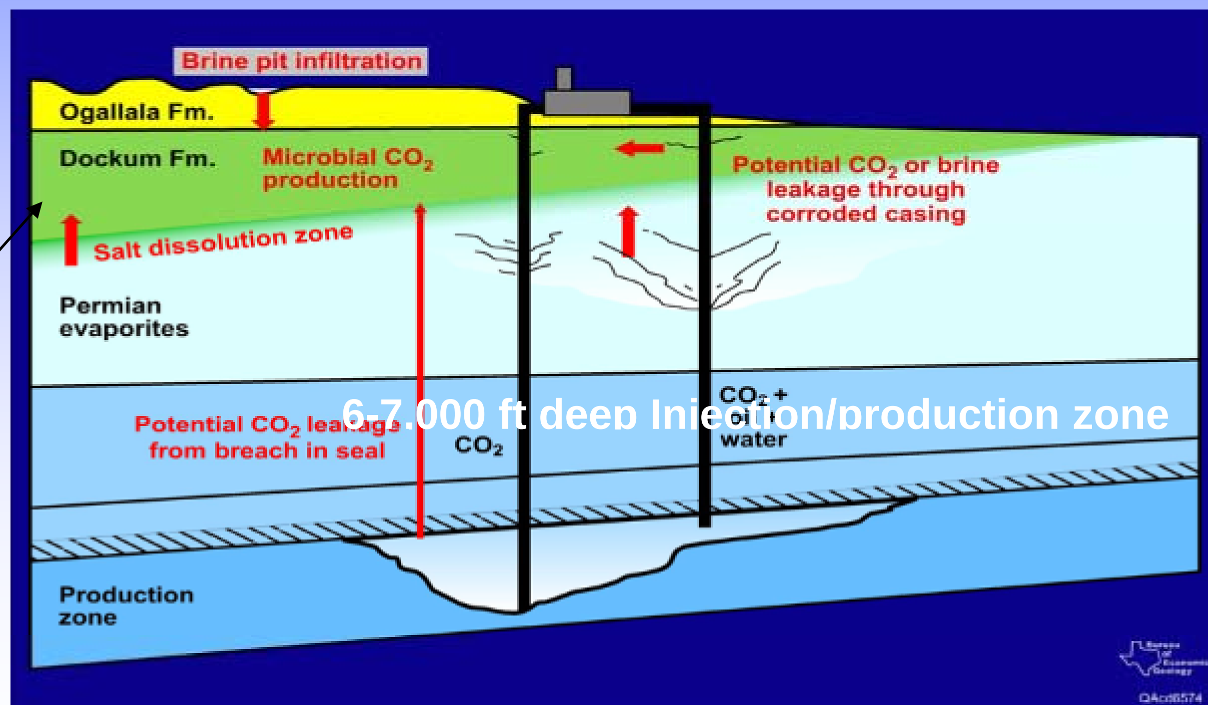
- No change in temperature change was observed in 3-30 monitoring well.



Southwest partnership–SACROC Oilfield

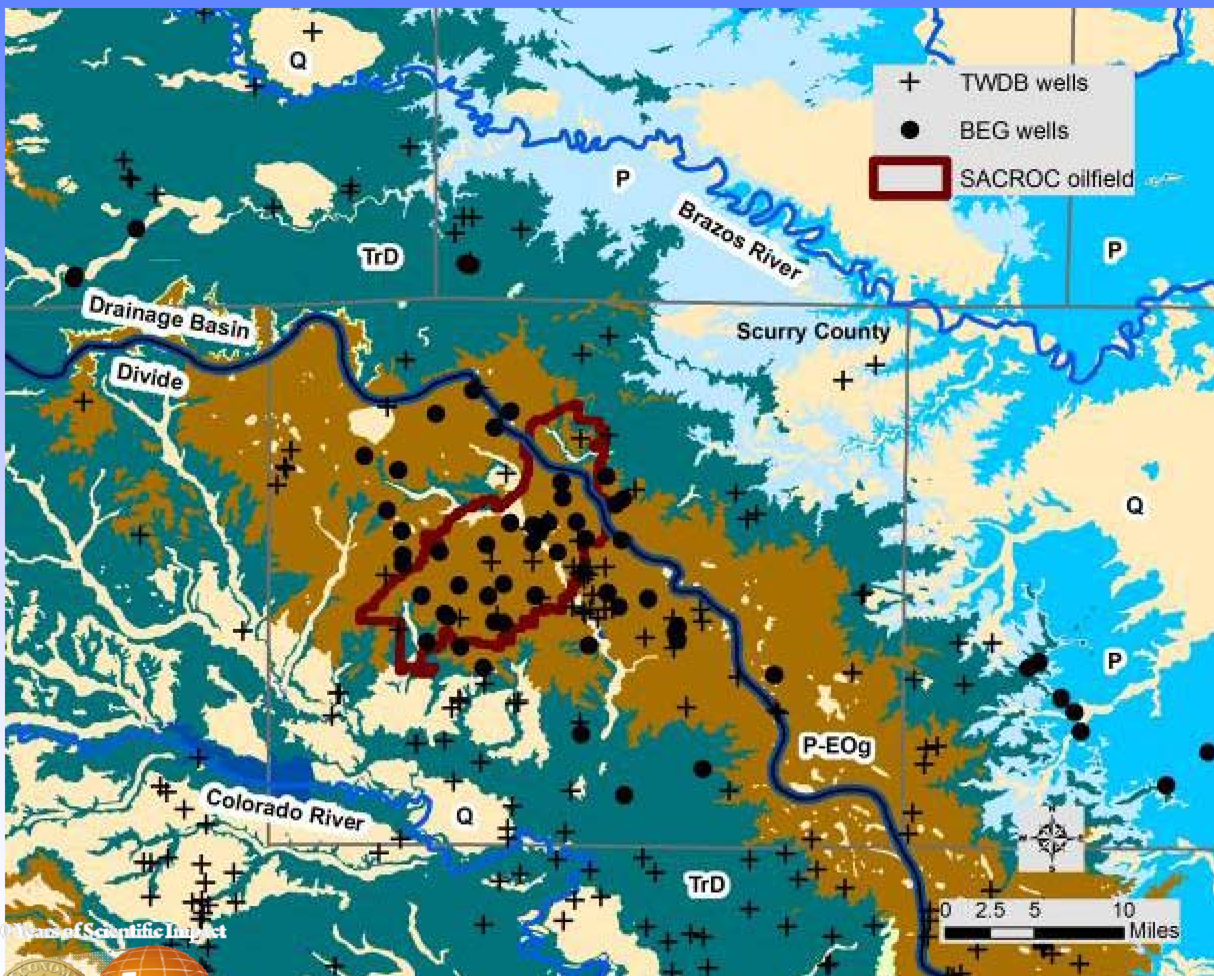
Scurry Area Canyon Reef Operators Committee (SACROC) – enhanced oil recovery using CO_2 since 1972

Any impact to overlying freshwater Dockum aquifer?



More information Rebecca.Smyth@beg.utexas.edu

SWP sampling groundwater over 37 year old sustained CO_2 flood

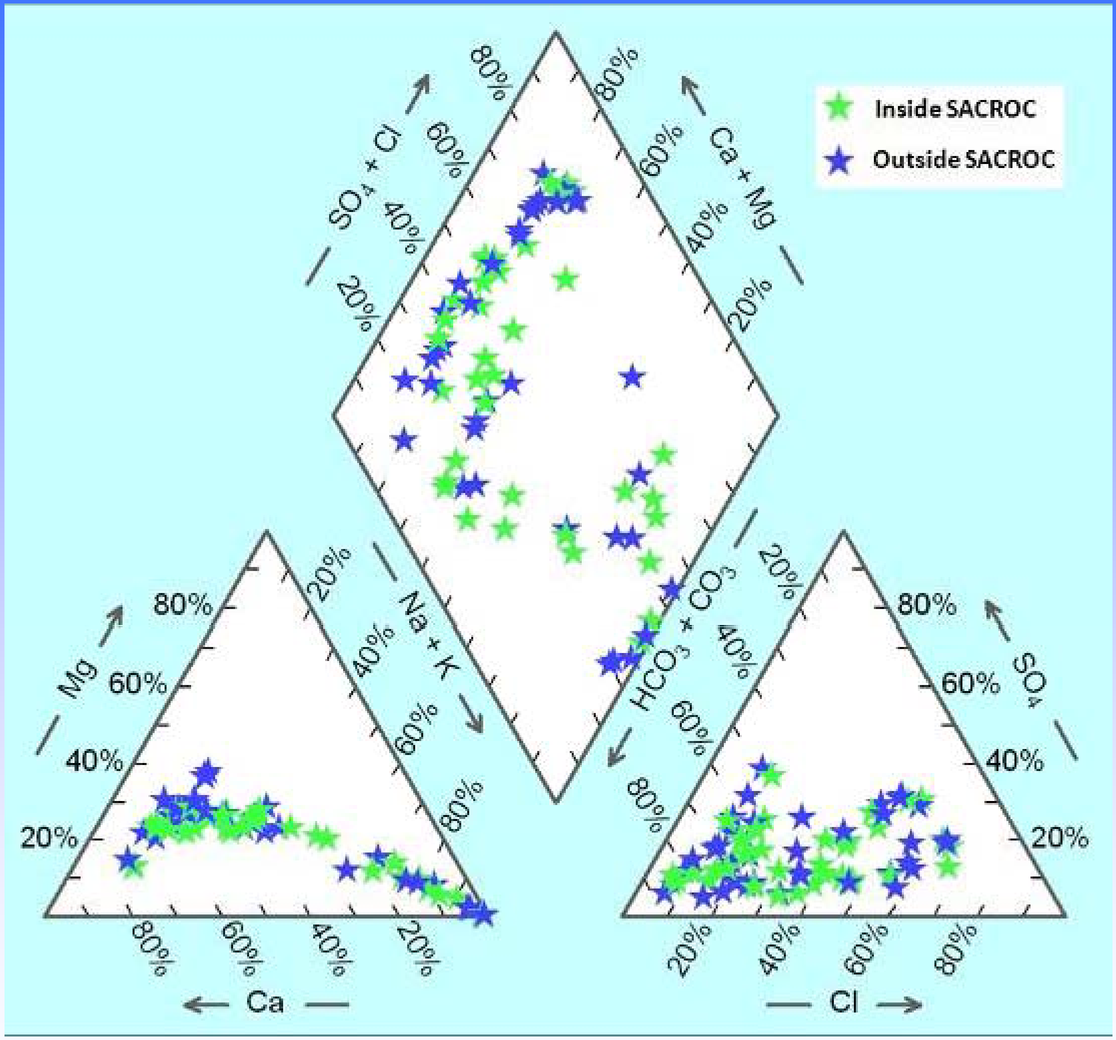


June 2006, July 2009
123 fresh water sampled 60 private water wells, 1 freshwater spring, and brine from 8 CO2 injection zone wells – total

TWDB database water quality data for analyses with charge balance error <10%, potassium analysis, and good reliability code

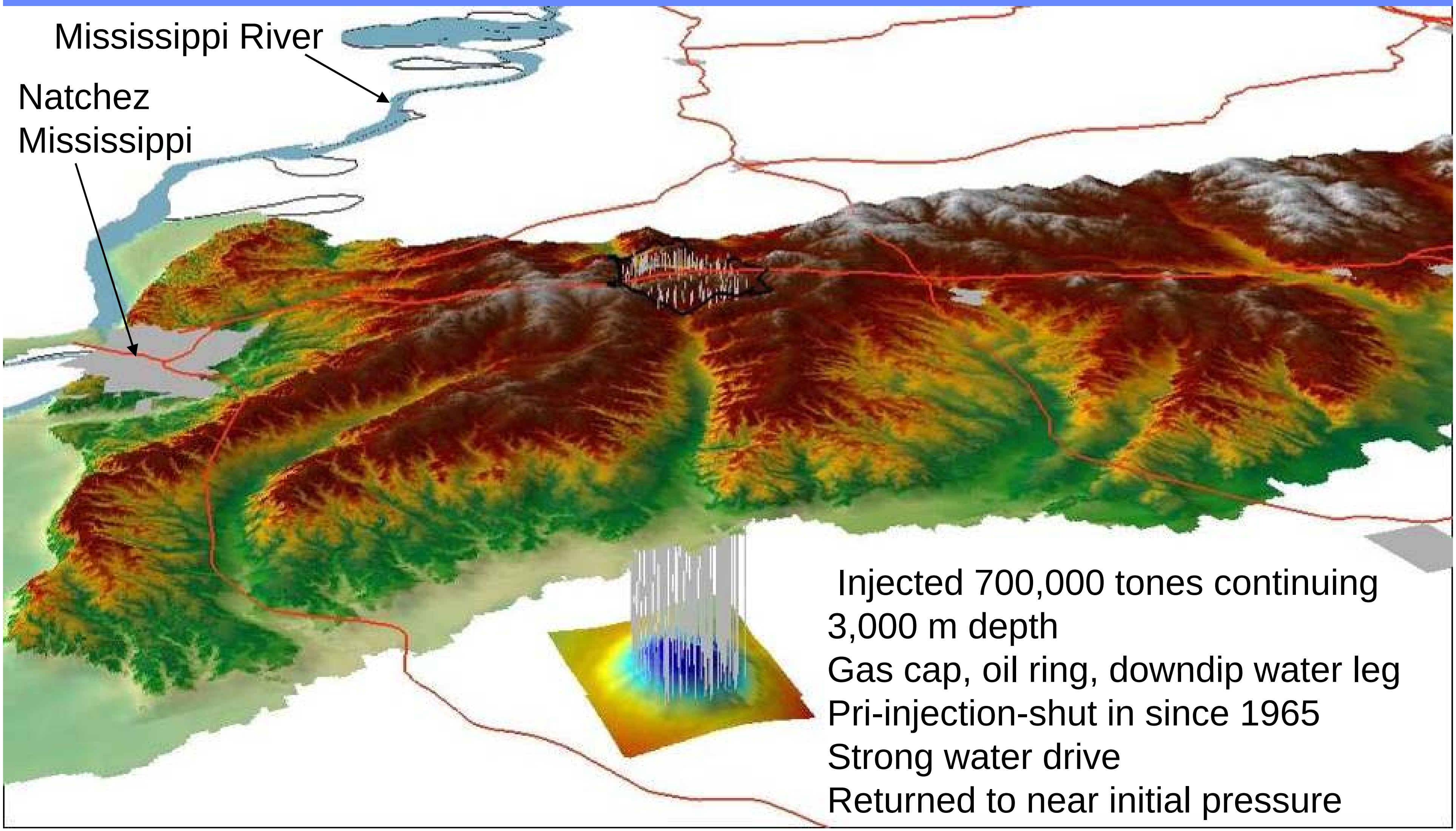
Surface geology from BEG Big Spring and Lubbock GAT sheets

SWP SACROC CONCLUSIONS



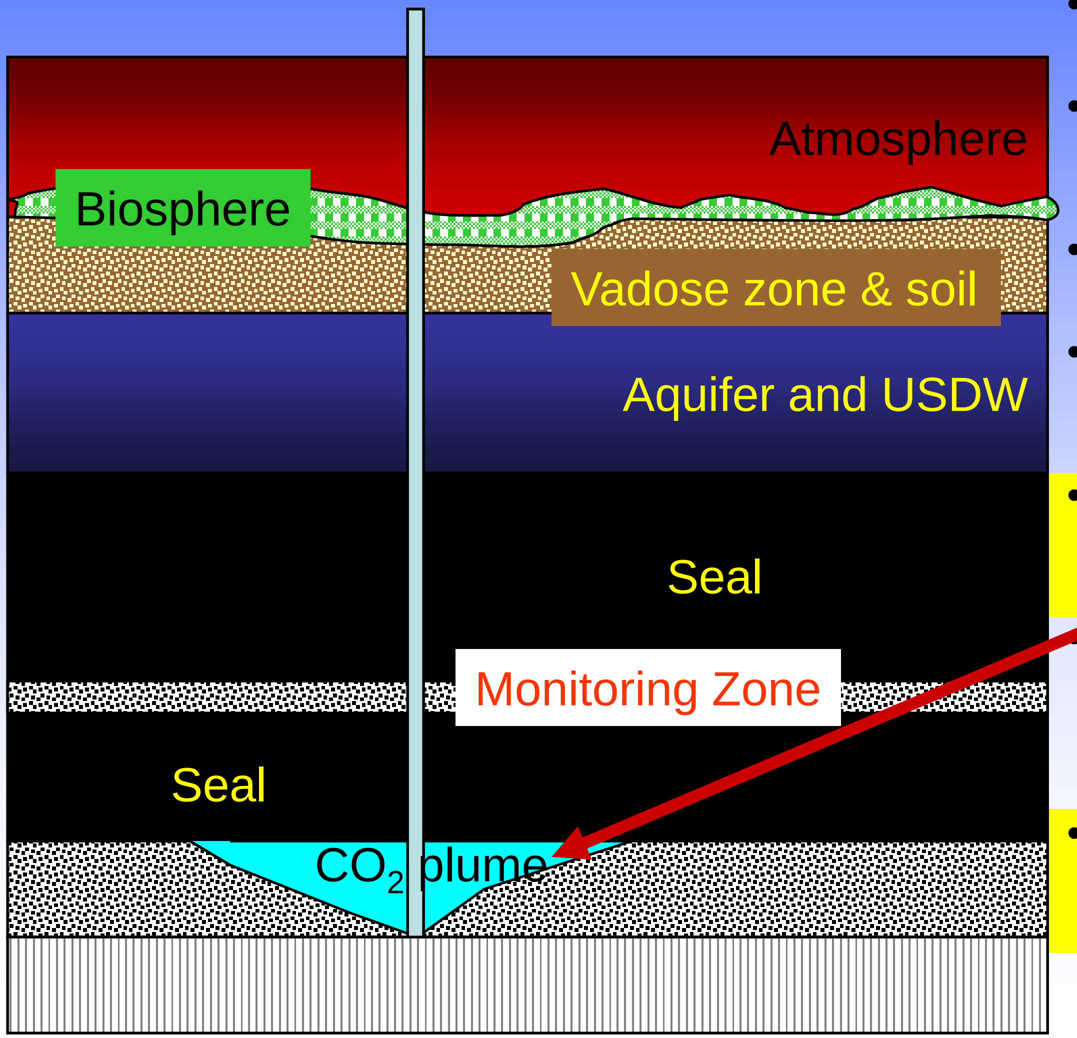
- No distinction between Dockum water quality inside and outside of SACROC
- Not clear if we can – or will be able to - see evidence of injectate CO_2 in Dockum groundwater
- Good news for GS of CO_2 from SACROC
- Good job Kinder Morgan!

SECARB Phase III – "Early" test
Cranfield unit operated by Denbury



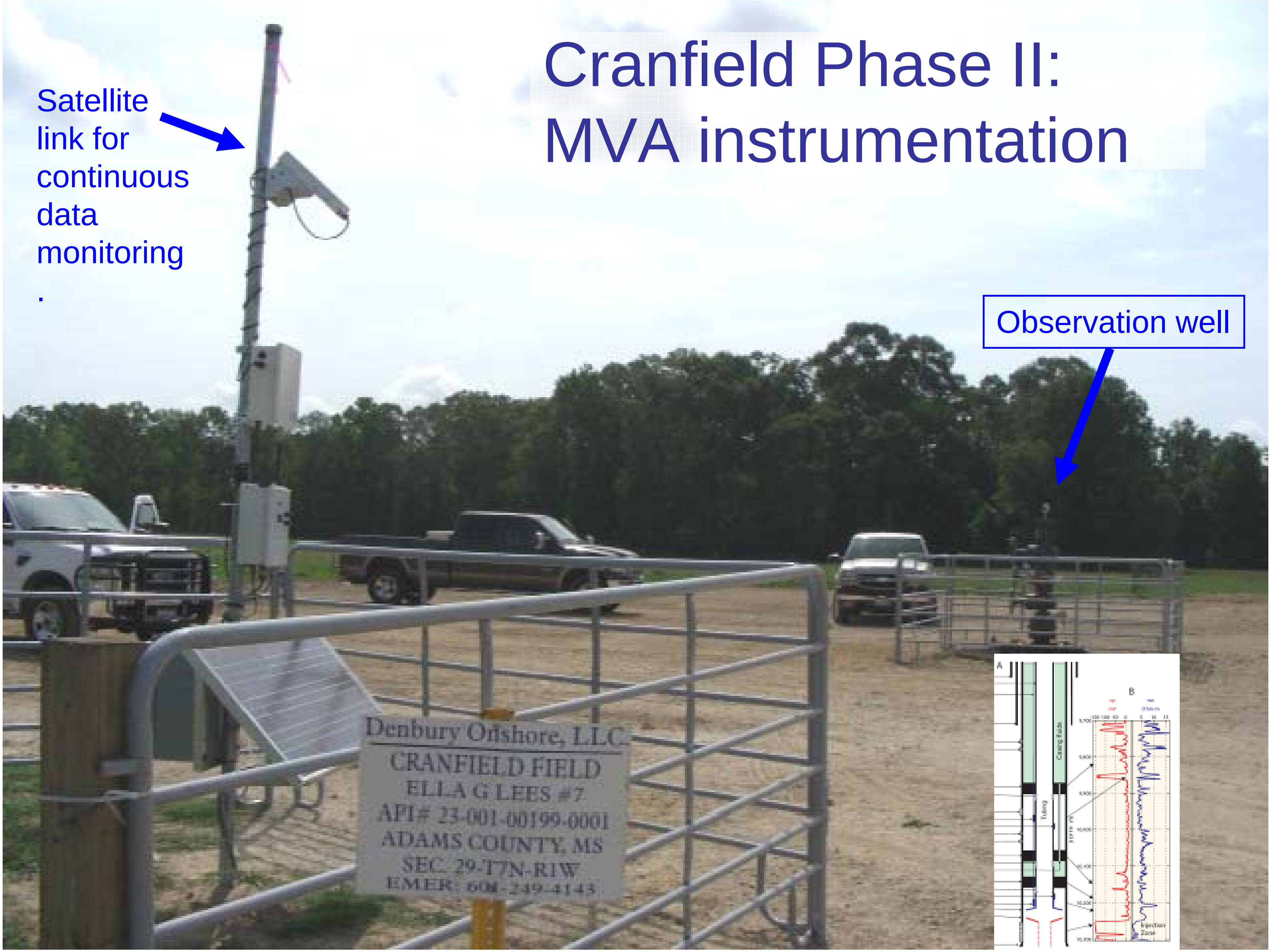
Injected 700,000 tones continuing
3,000 m depth
Gas cap, oil ring, downdip water leg
Pri-injection-shut in since 1965
Strong water drive
Returned to near initial pressure

Monitoring Hypotheses



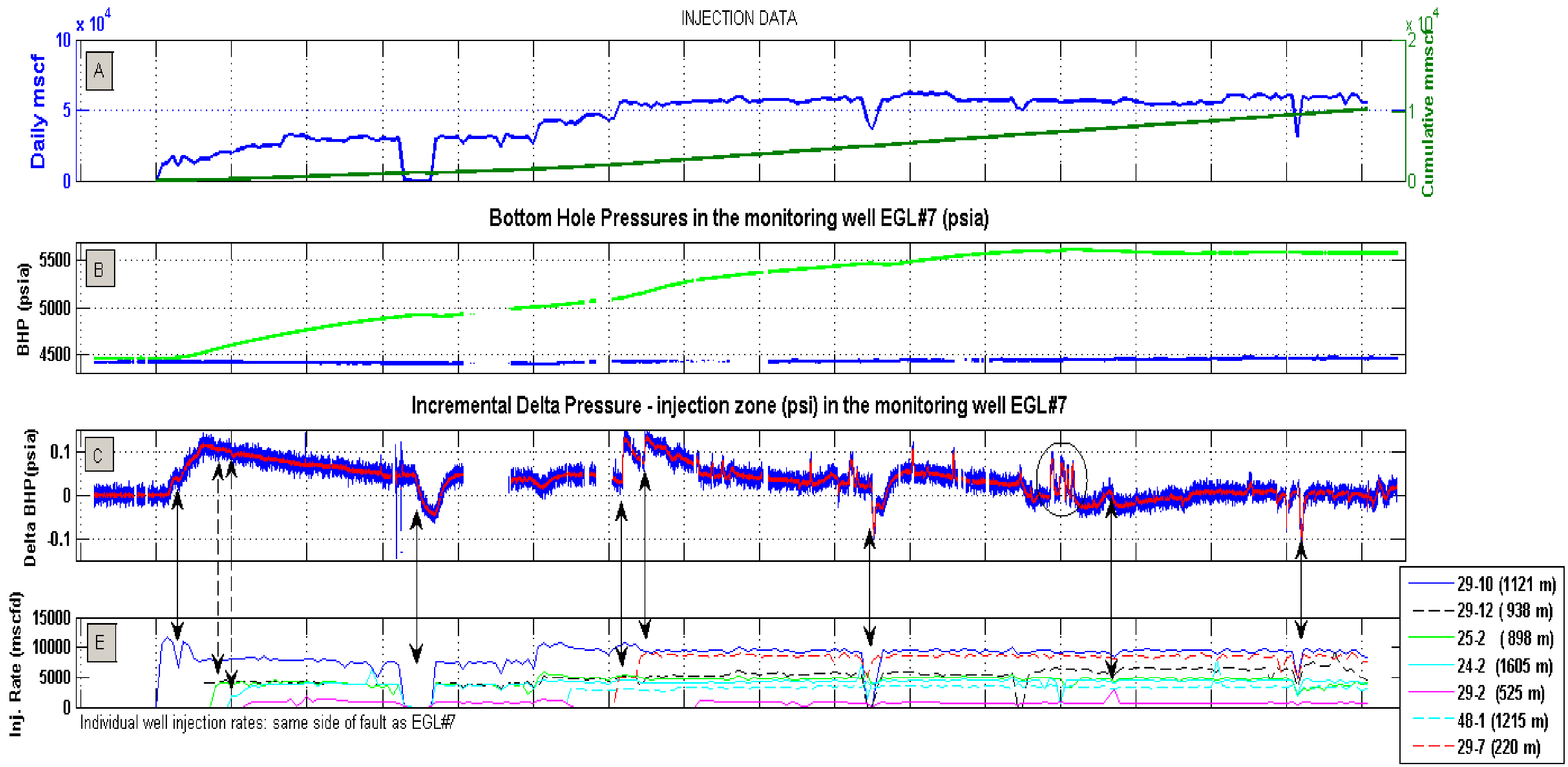
- Atmosphere
  - Ultimate receptor but dynamic
- Biosphere
  - Assurance of no damage but dynamic
- Soil and Vadose Zone
  - Integrator but dynamic
- Aquifer and USDW
  - Integrator, slightly isolated from ecological effects
- Above injection monitoring zone
  - First indicator, monitor small signals, stable.
- In injection zone - plume
  - Oil-field type technologies. Will not identify small leaks
- In injection zone - outside plume
  - Assure lateral migration of CO_2 and brine is acceptable

Cranfield Phase II: MVA instrumentation



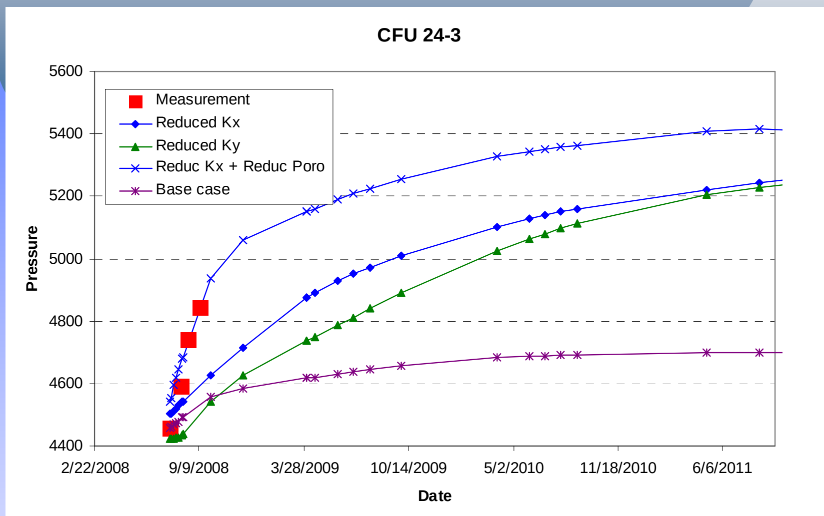
Pressure as tool for reservoir surveillance

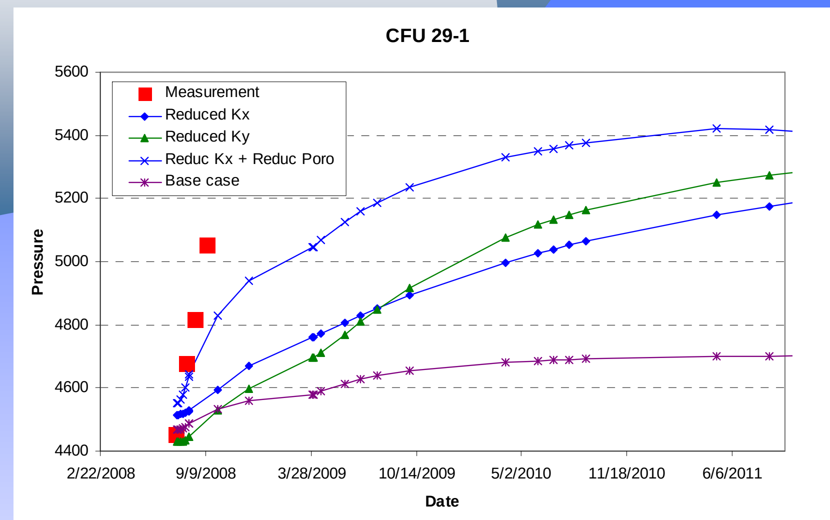
Daily fluxes of CO_2 injection rate can be correlated with observed pressure in injection interval at observation well. These sensitivities are being incorporated in monitoring design to support goal of achieving high material balance.

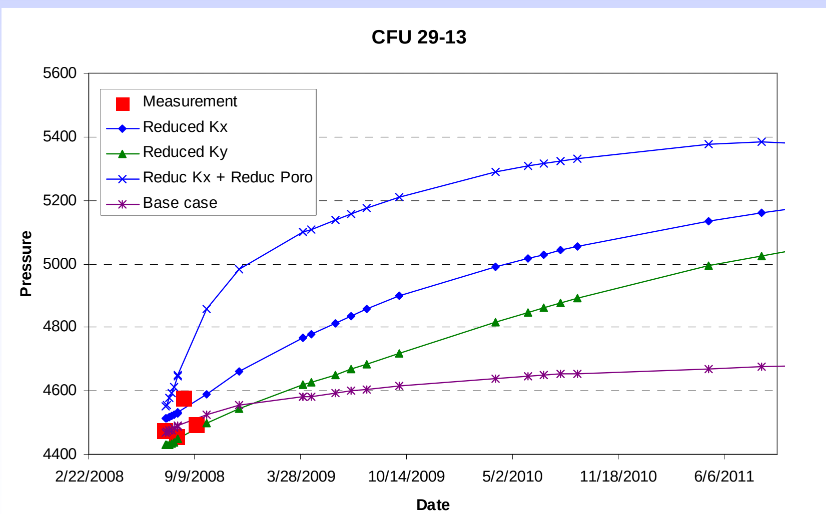


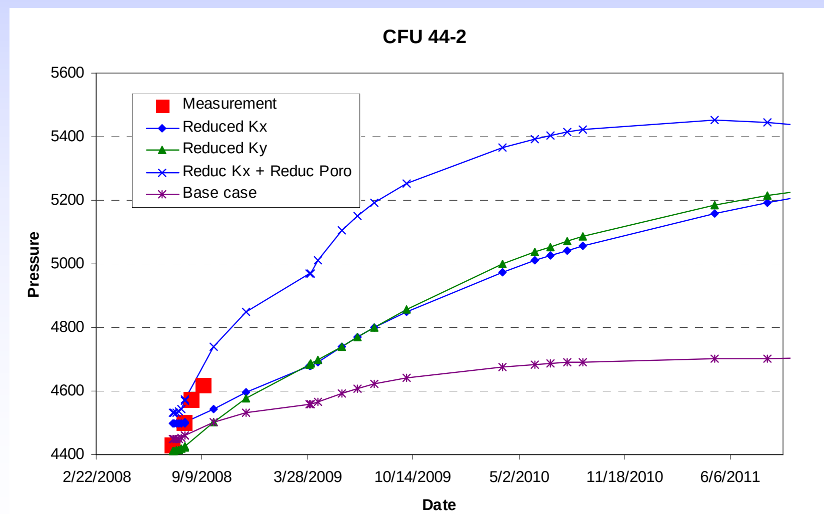
More information Tip.Meckel@beg.utexas.edu

Modeling and Observed Results From Producers



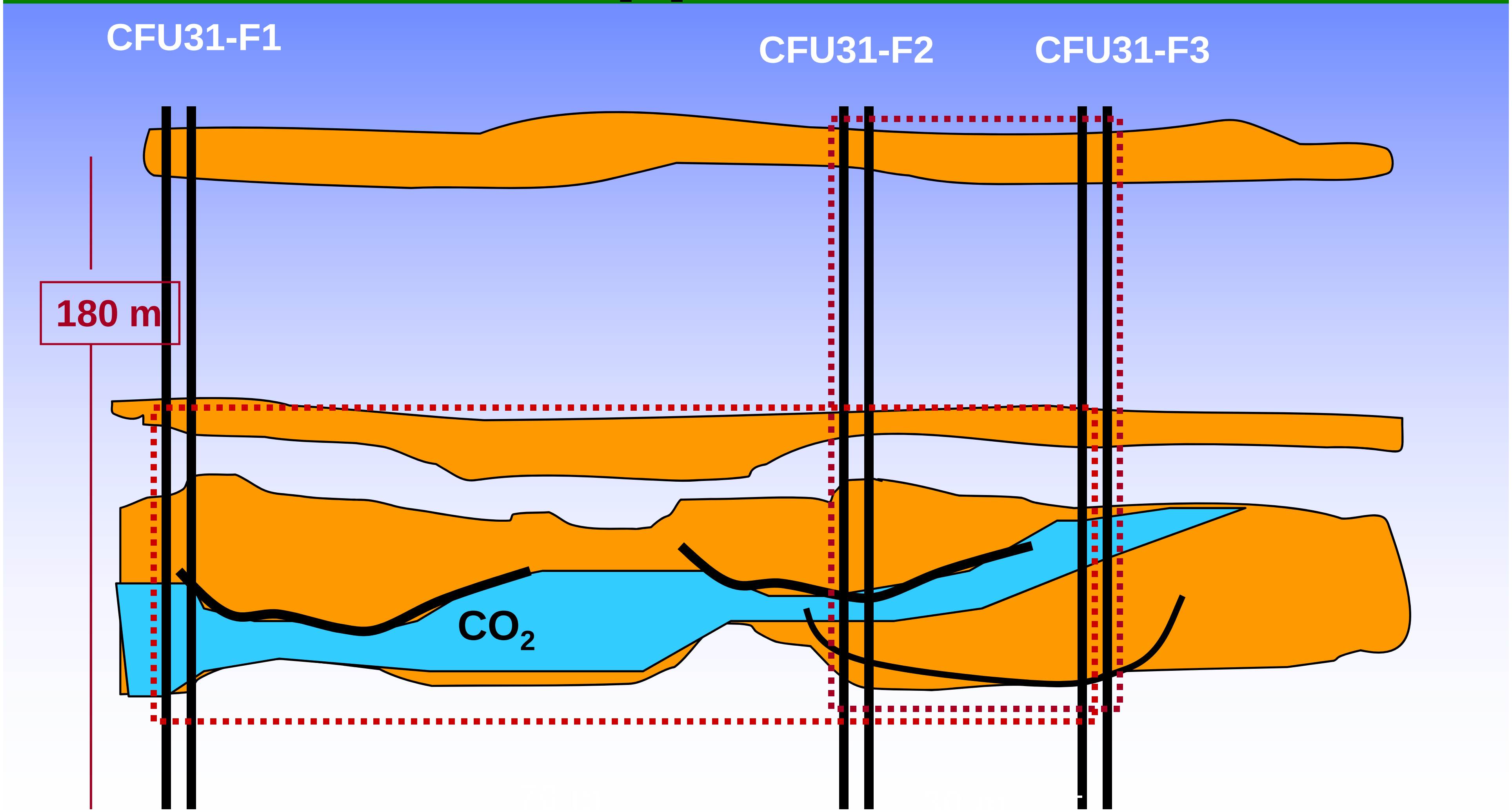




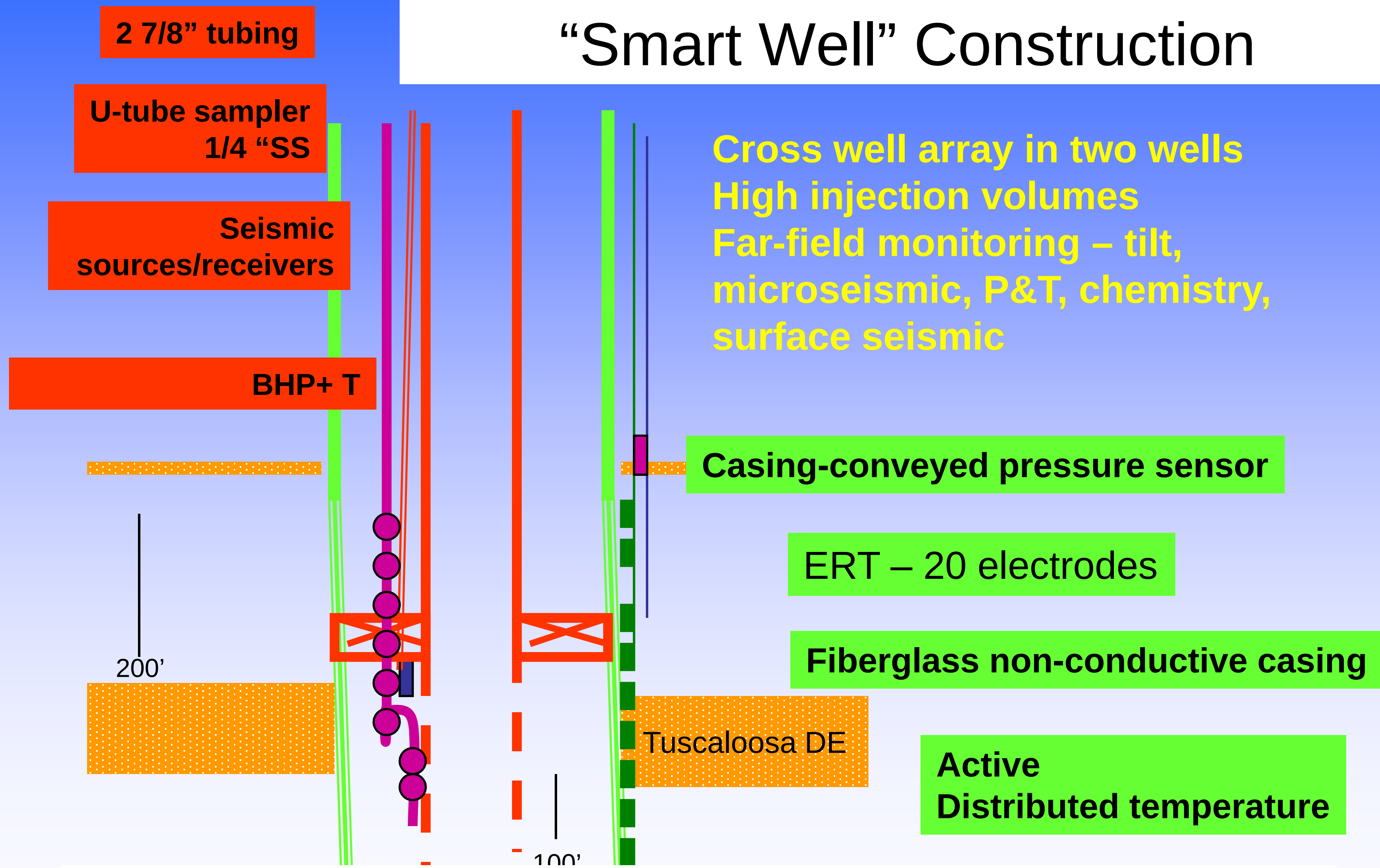


More information JP.Nicotl@beg.utexas.edu

SECARB Phase III – Follow-on Tests – "smart well" multi-physics approach



Planned Phase III Observation "Smart Well" Construction



BEG LBNL LLNL USGS ORNL Pinnacle QEA Sandia Technologies

Watch for updates www.gulfcoastcarbon.org

Thank you!

Gulf Coast Carbon Center (GCCC)

Gulf Coast Carbon Center

Mission: ***Global leadership in research and economic implementation of large scale greenhouse gas sequestration.***

GCCC Team:

Ian Duncan, **Sue Hovorka**, Tip Meckel, J. P. Nicot, Jeff Paine, Becky Smyth, + *post-docs and students*

Bureau of Economic Geology - 100 Years of Scientific Impact

- First organized research unit of The University of Texas at Austin
- State Geological Survey of Texas
- One of three units of the Jackson School of Geosciences
- Staff—140, includes 80 researchers
  - Fossil energy
  - Environment
  - Outreach
- Advising state and federal government
  - Maintaining collections for research

1909-2009

Post-Injection Monitoring to Ensure Safety of CO_2 Storage

- A case study at Nagaoka pilot site -

Saeko Mito[1,*] & Ziqiu Xue[1,2]

[1]Research institute of Innovative Technology for the Earth (RITE)

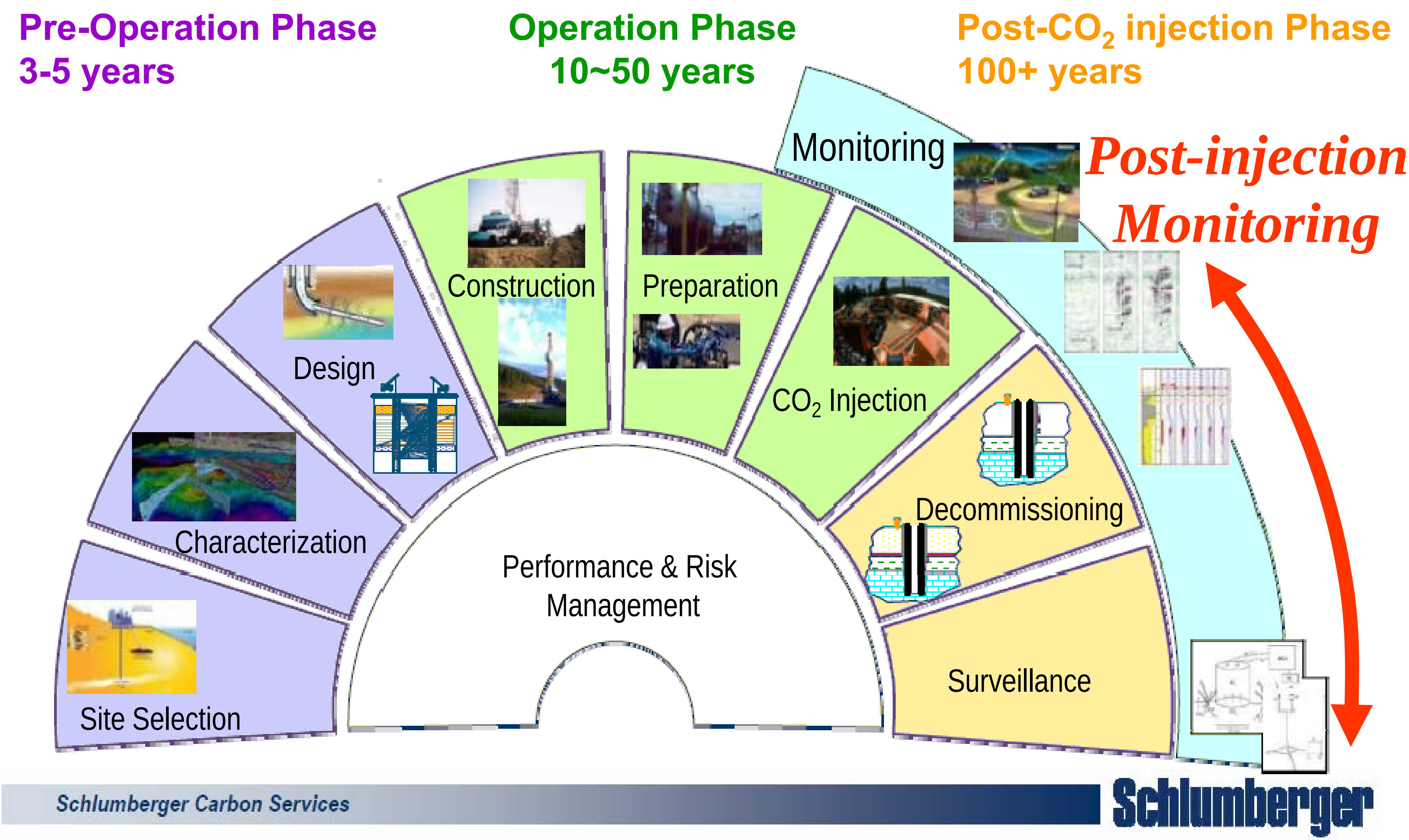
[2]Kyoto University

NAGAOKA Project

5th IEA GHG Monitoring Network Meeting, 2 June 2009

RITE Research Institute of Innovative Technology for the Earth

The CO_2 Storage Project Workflow



(After David White, IEA GHG International Summer School 2007 on CCS)

What happens after stopping CO_2 injection? (CO$_2$ behaviors at the post –injection)

Mobile CO_2
(Physical process)

Immobile CO_2
(Physical process)

Dissolved CO_2
(Geochemical process)

Mineralized CO_2
(Geochemical process)

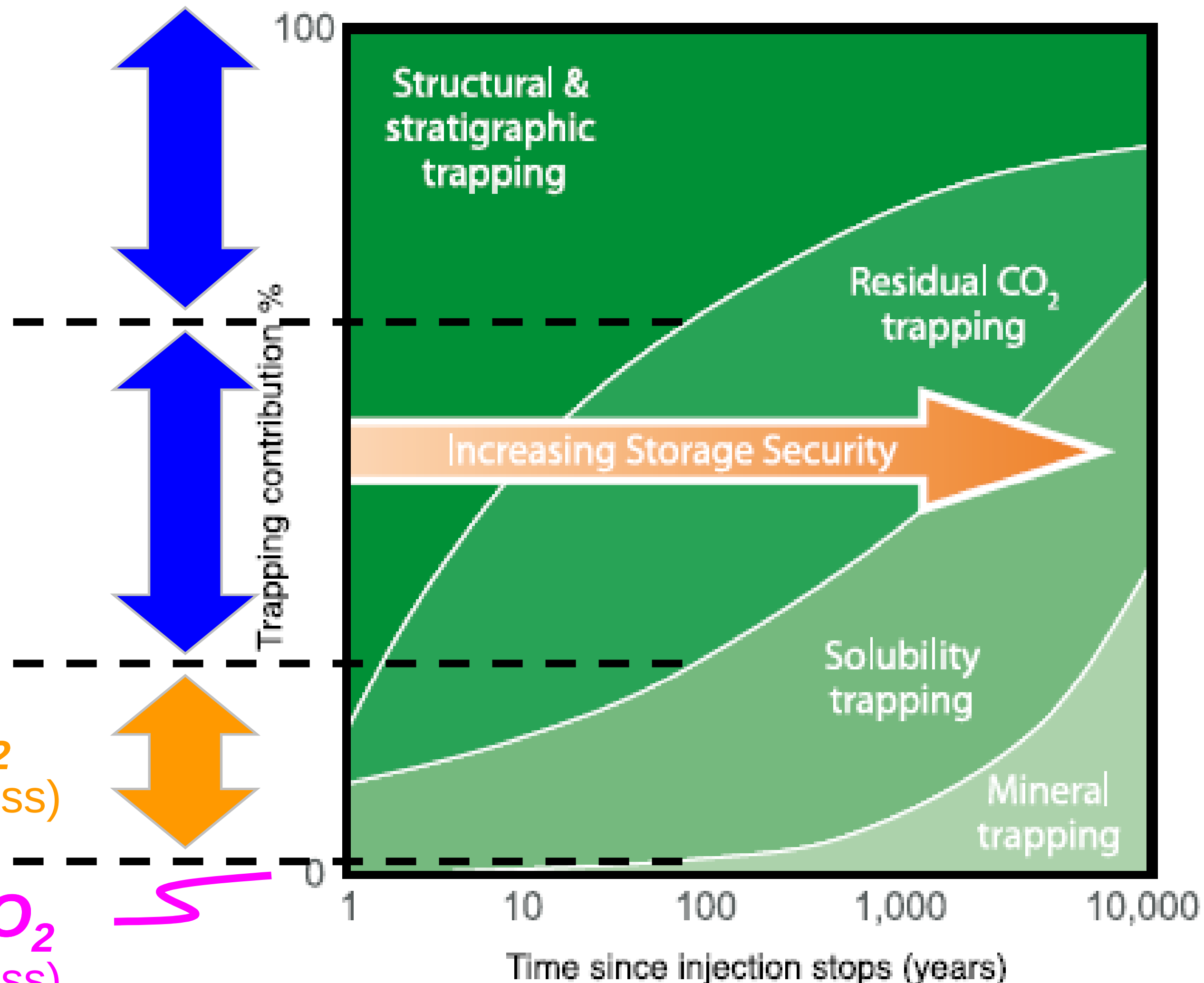
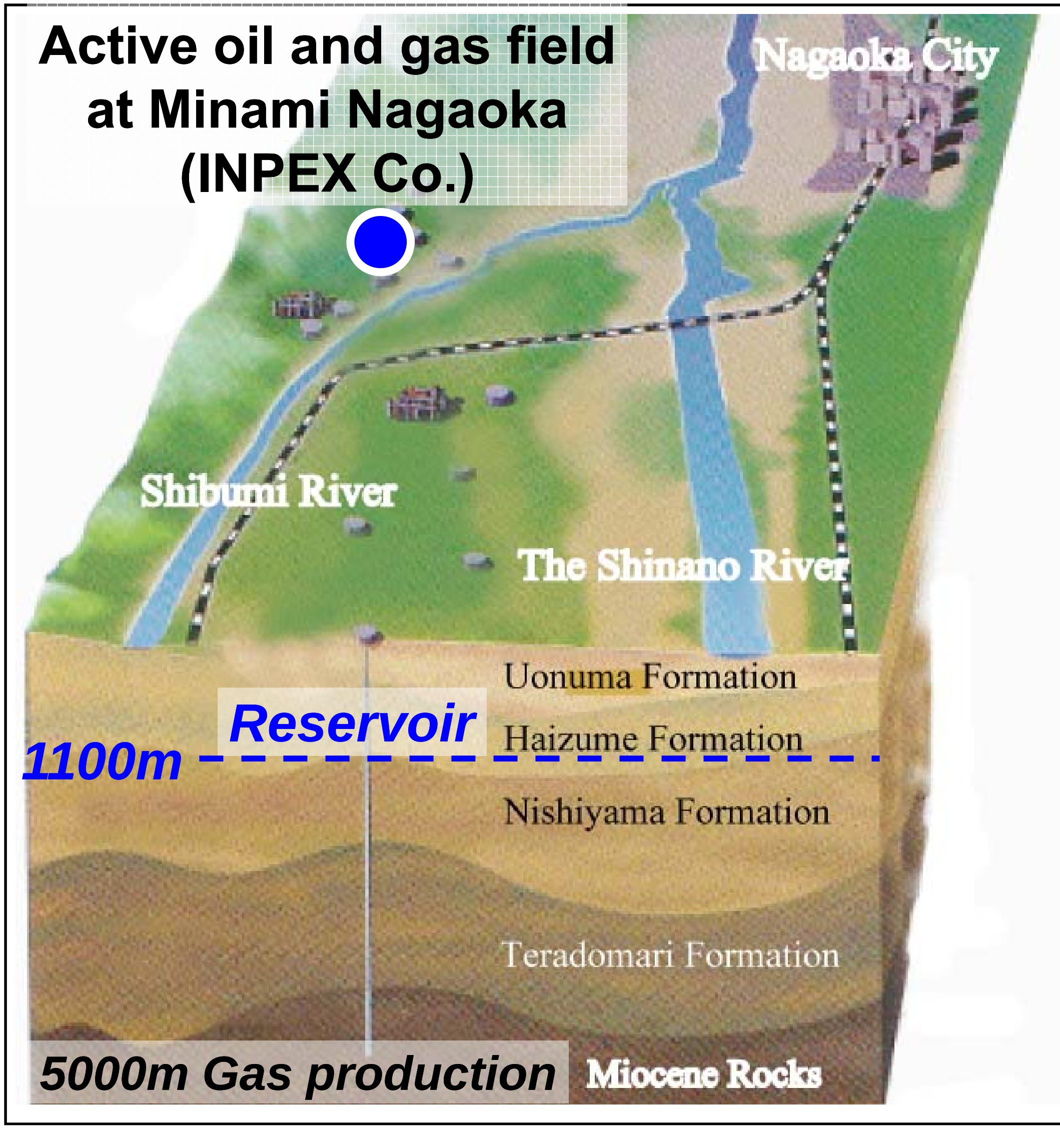


Image of trapping processes over time (IPCC 2005)

Outline

1. **Overview of the Nagaoka pilot CO_2 injection project**
2. **Results from *Geochemical monitoring* for CO_2-fluid-rock interaction (CHDT sampling)**
3. **Results from *Geophysical monitoring* for mobile & immobile CO_2 (Well loggings, seismic tomography)**
4. **Suggestions for CO_2 monitoring at post-injection**

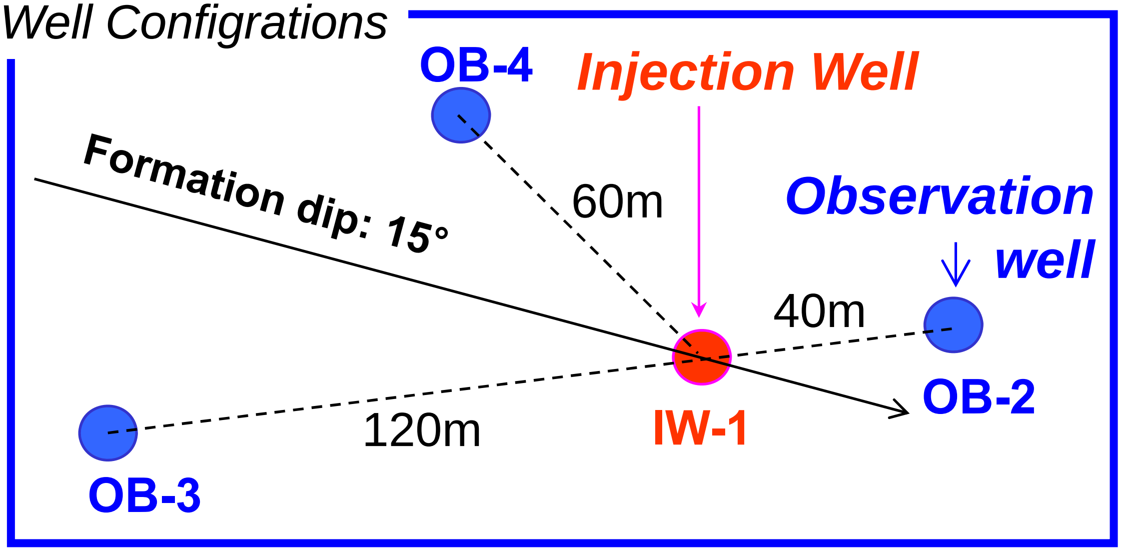
Location of the Nagaoka Pilot CO_2 Injection Site



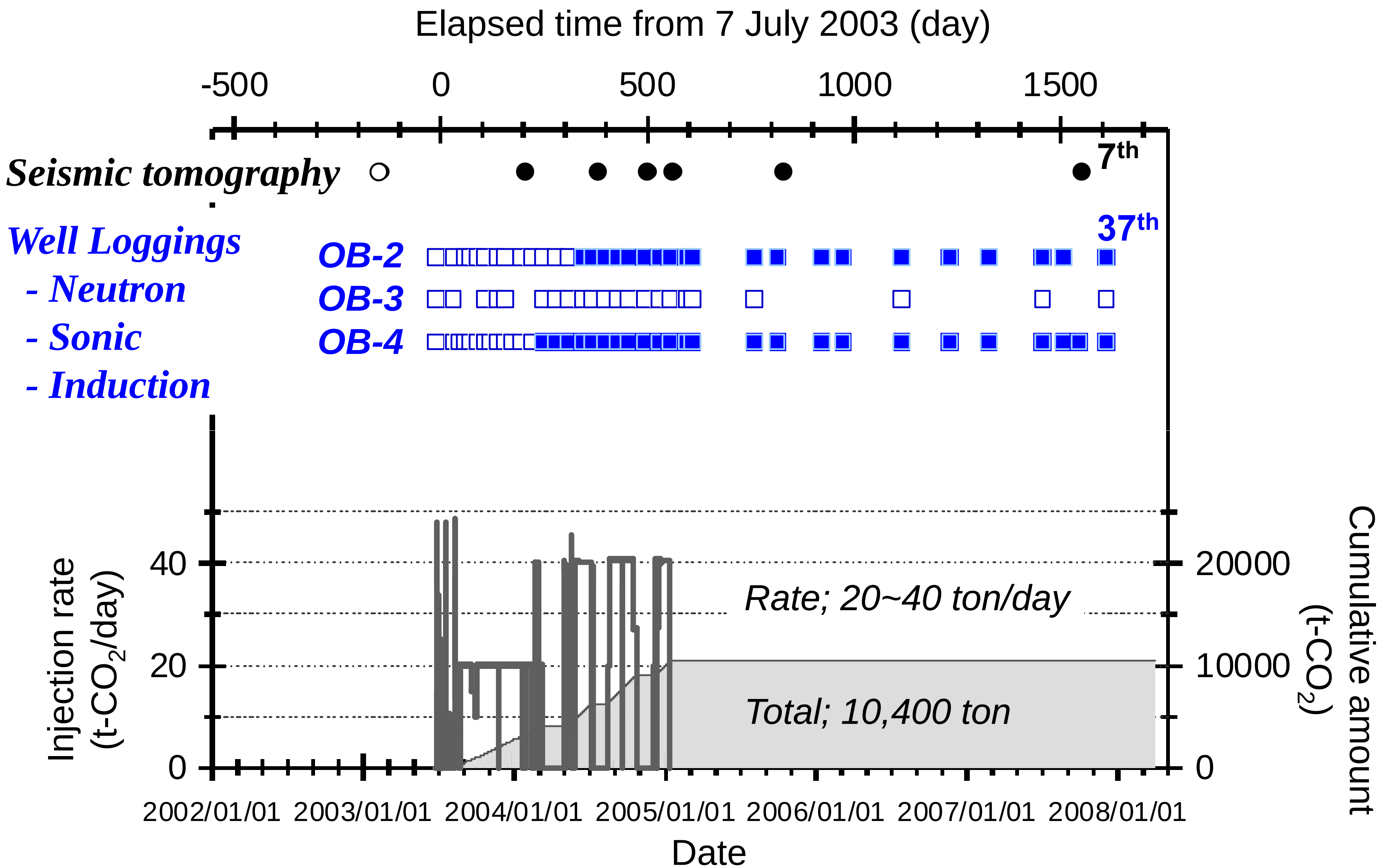
Overview of the Nagaoka Pilot Project

- Duration; FY2000-2007 funded by METI, Japan
- Total amount of the injected CO_2; **10,400 ton** (2003.7~2005.1)
- Reservoir; Pleistocene sandstone (Haizume Formation), **60m thick**
- Target injection layer; Zone 2, **12m thick**
- Conditions; **48°C**, **11MPa**
- Permeability; ave. **7mD** (pumping test)
- Porosity; **23%**

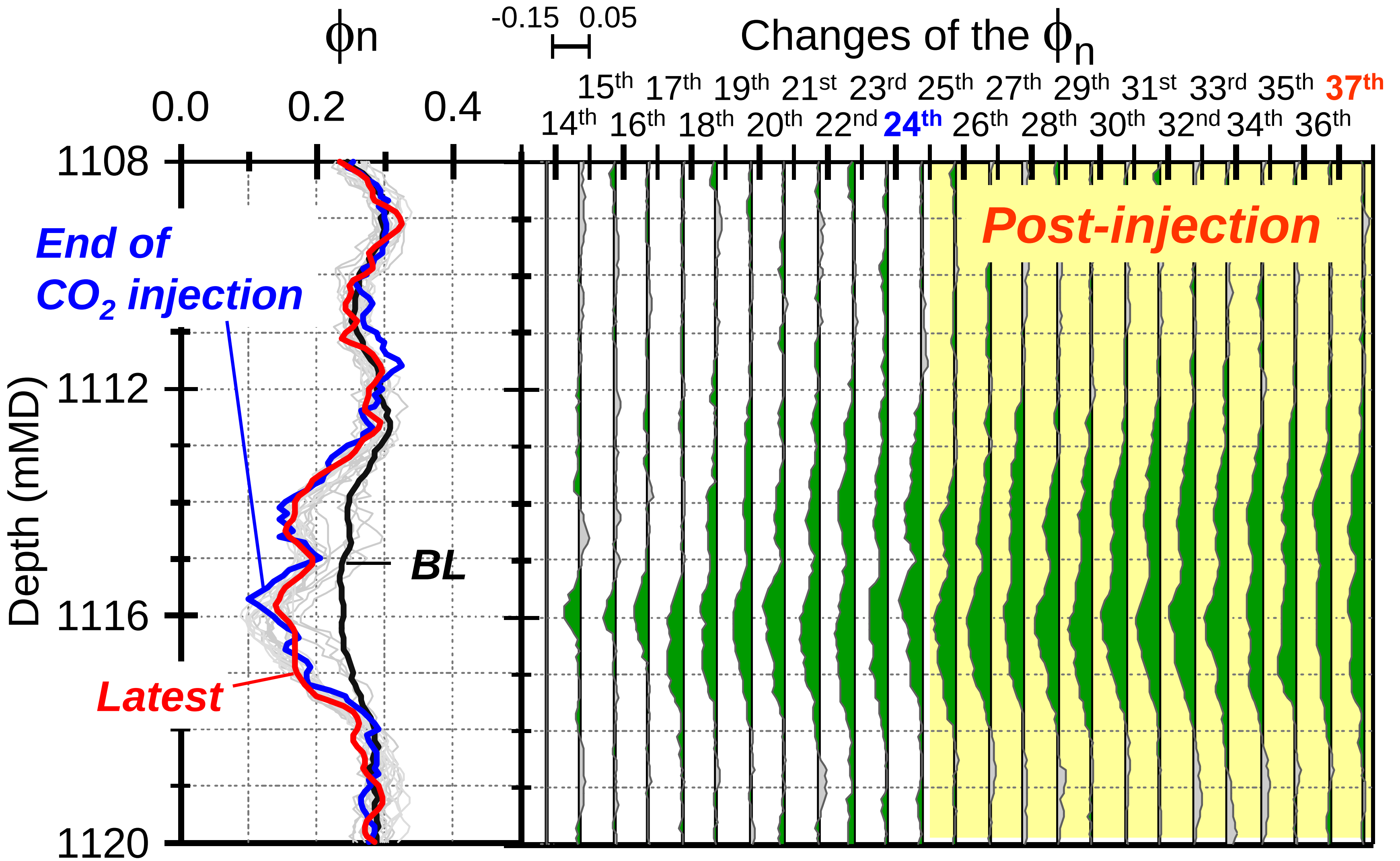
Well Configrations



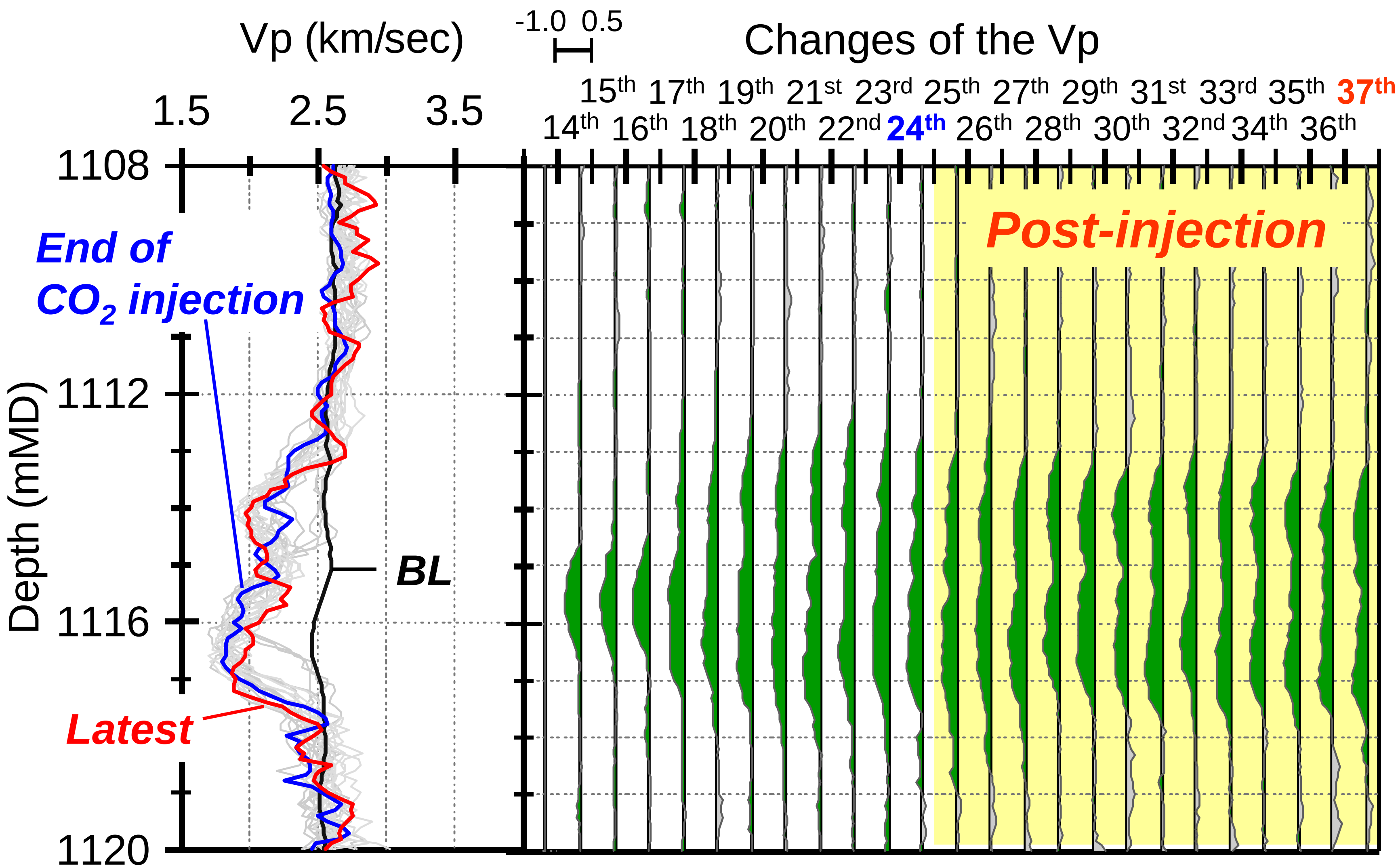
Field measurements during and post CO_2 injection (*Geophysical monitoring*)



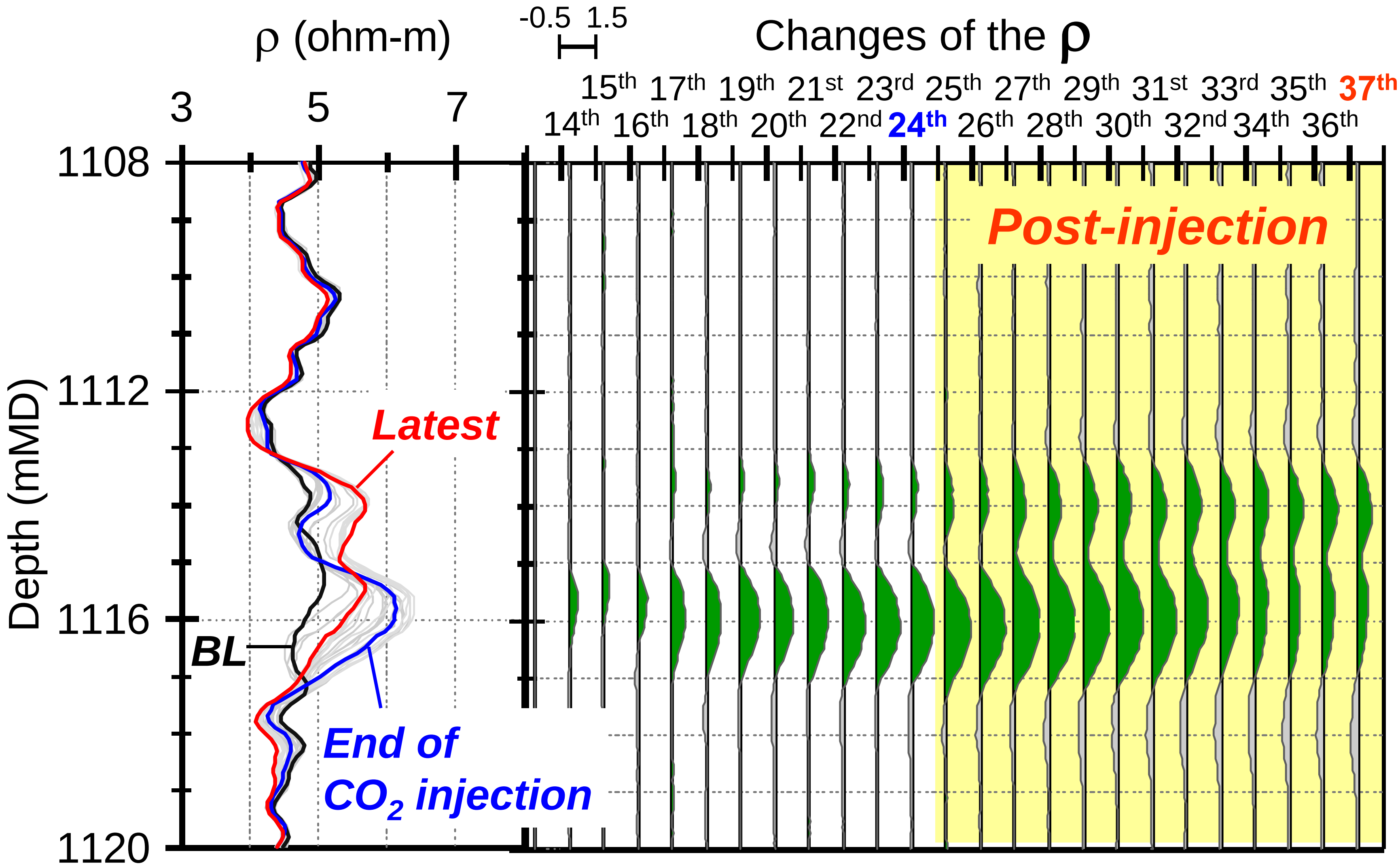
Neutron Logging (Neutron porosity; ϕ_n) @ OB-2



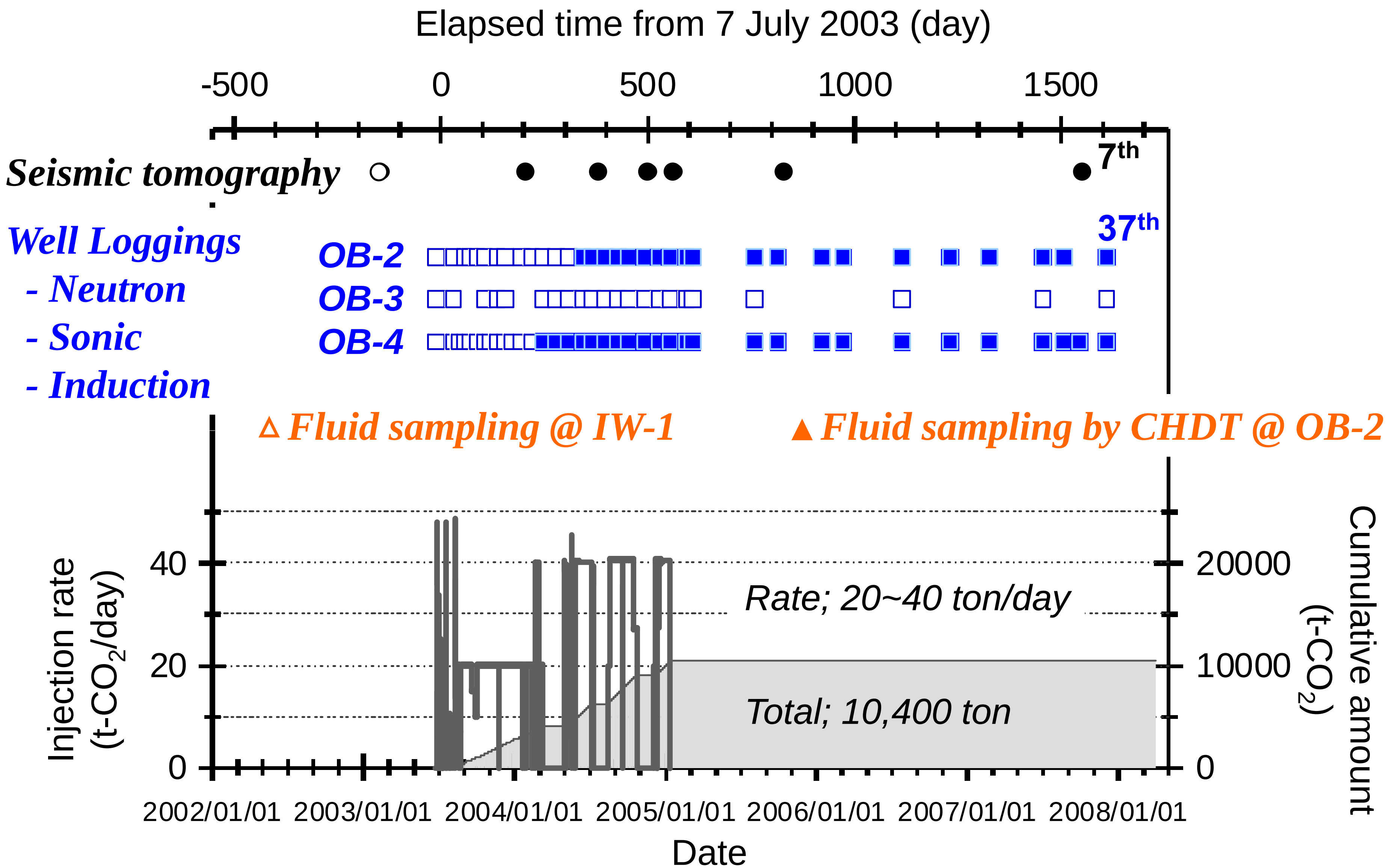
Sonic Logging (P-wave velocity; Vp) @ OB-2



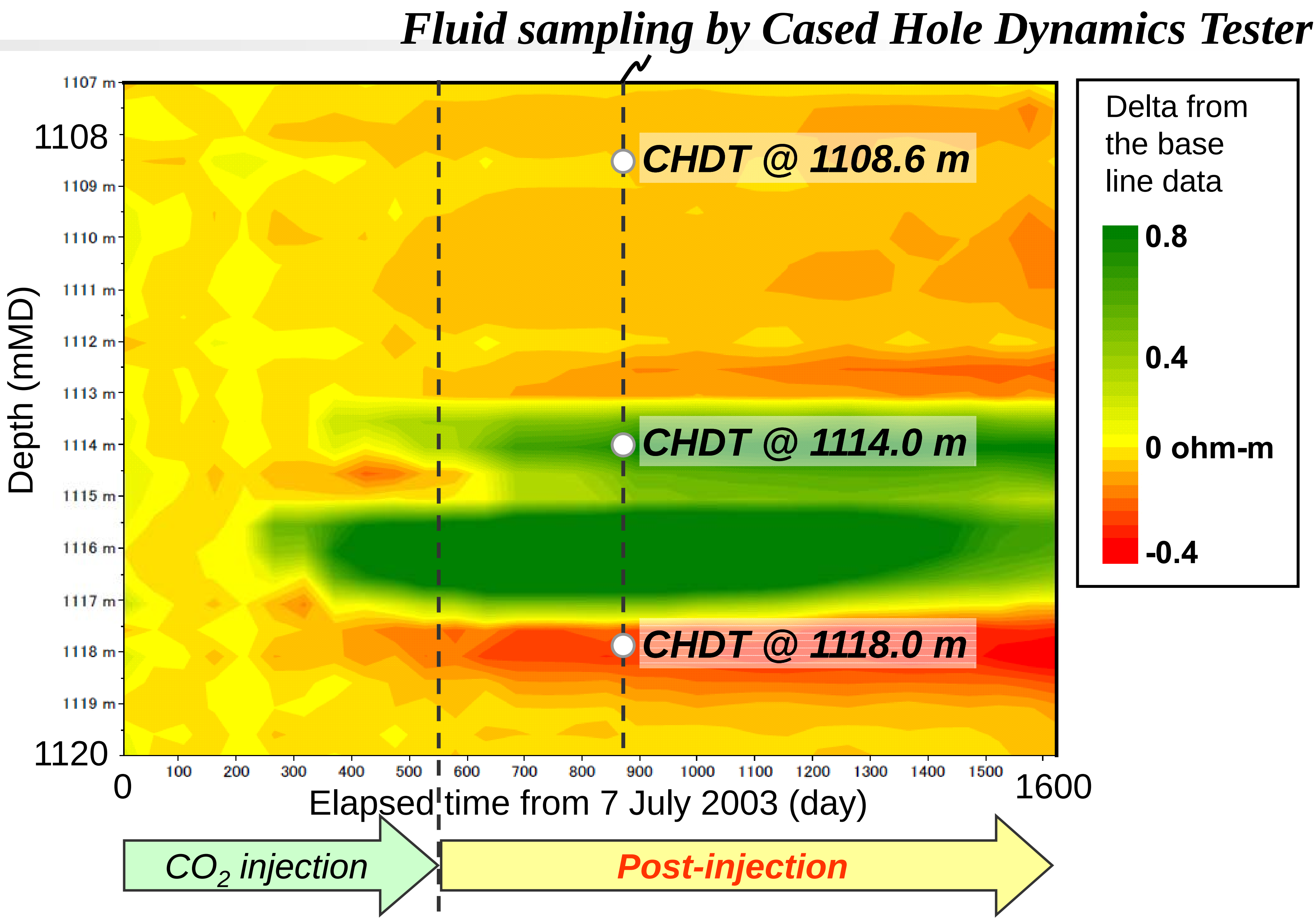
Induction Logging (Resistivity; ρ) @ OB-2



Field measurements during and post CO_2 injection (*Geochemical monitoring*)

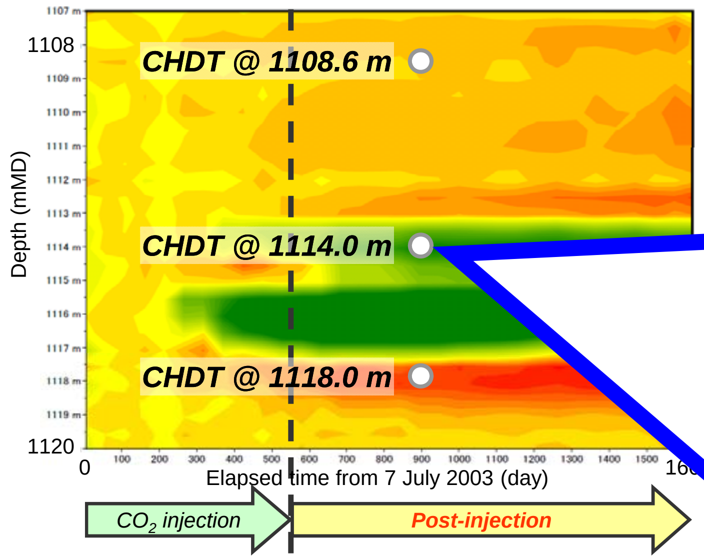


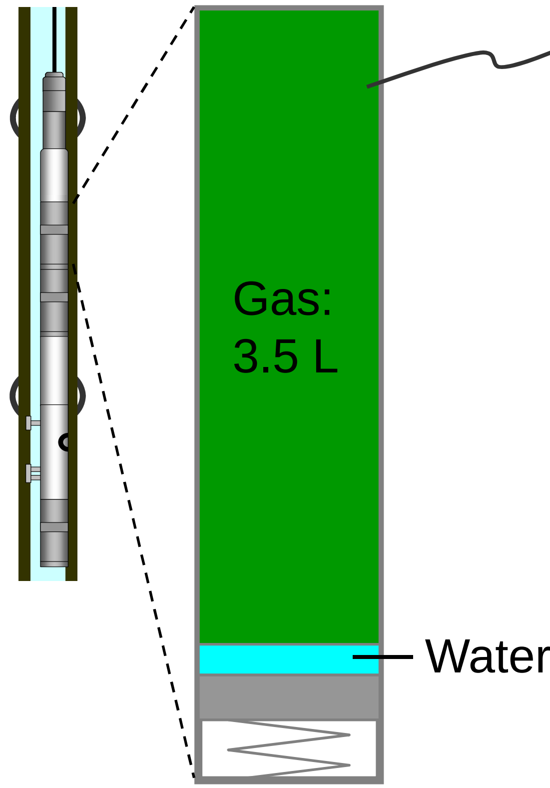
Resistivity Changes with Time @ OB-2



Sampling result-1

OB-2 @ 1114m : Mostly free CO_2





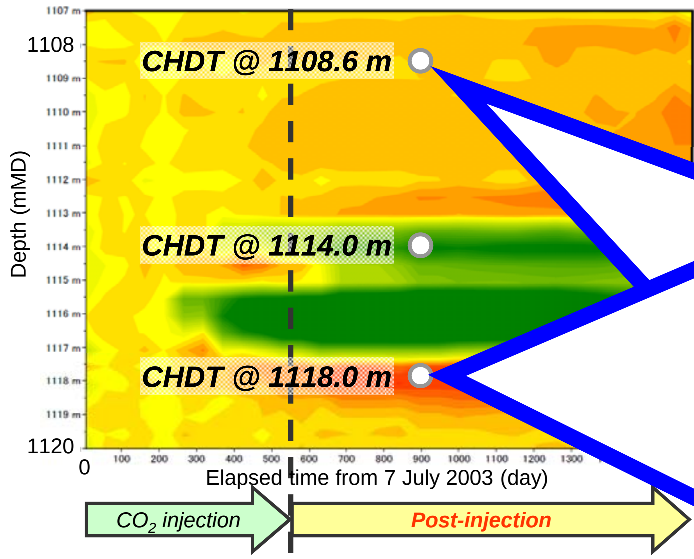
Sample Chamber (volume 3.8 L)

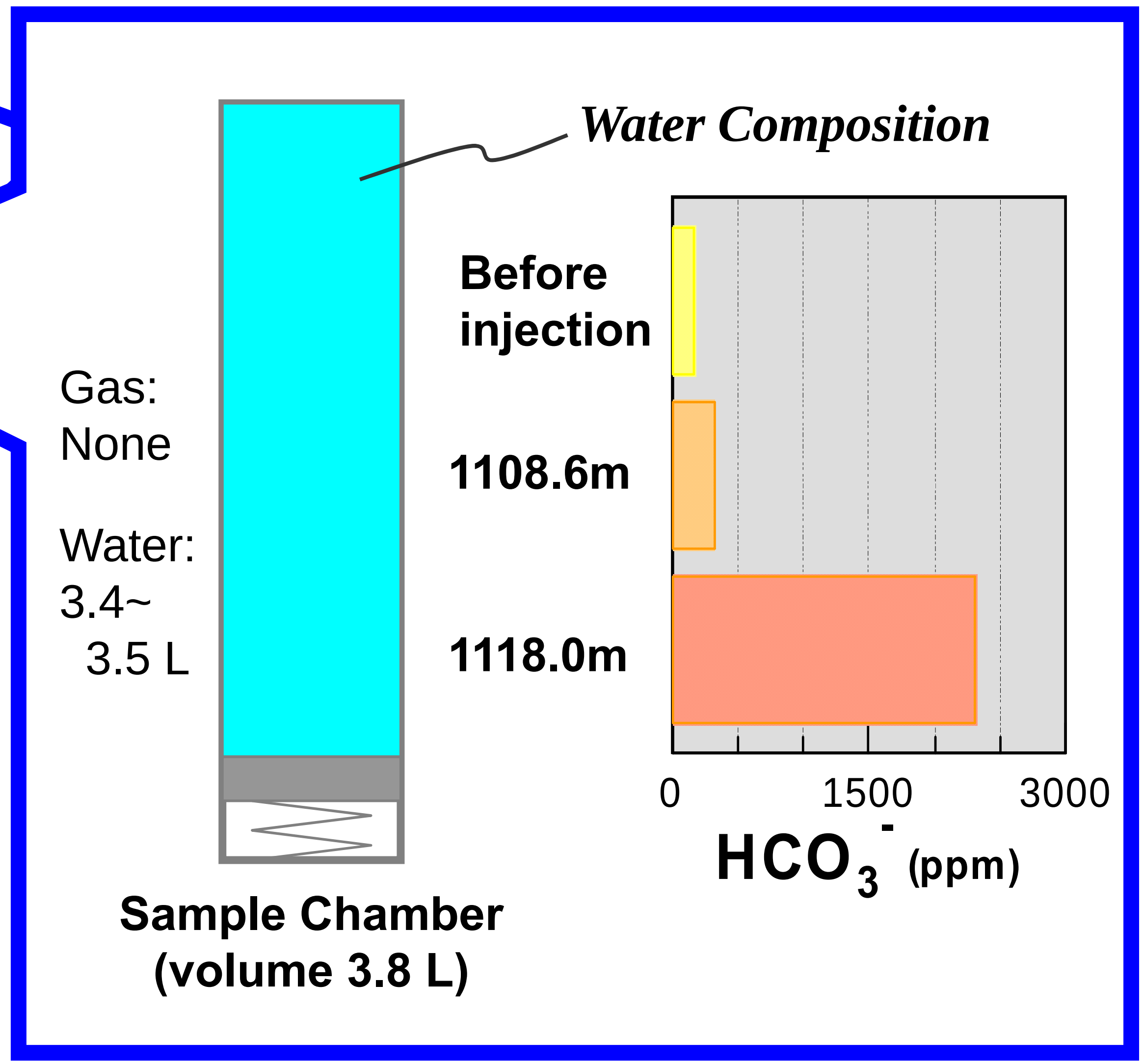
Gas composition

Comp.	mol%
H_2	0.0
O_2	0.2
N_2	0.7
CH_4	0.3
C_2H_6	0.0
CO_2	98.8

for details see
Mito et al., Int. J. Greenhouse Gas Control, Vol.2, 309-318, 2008

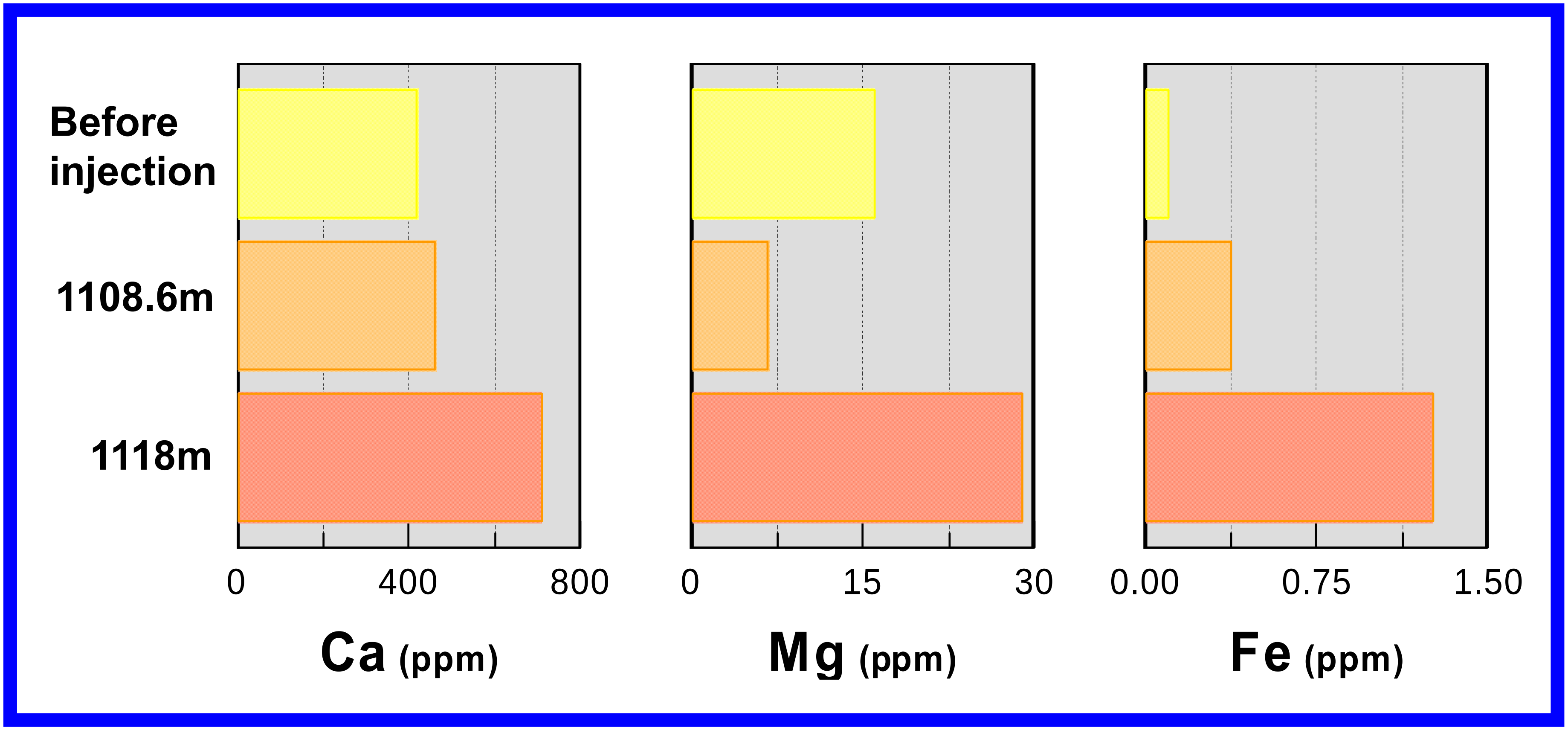
Sampling result-2
OB-2 @ 1108.6m & 1118m : Mostly Formation Water





The change in salinity by increasing of HCO_3^- (7.2%) is roughly consistent with the change in resistivity (6.5%) @ *1118m.*

Sampling result-3
OB-2 @ 1108.6m&1118m :
Cations in the formation water



At the depth of 1118m (HCO_3^- conc. increased), concentrations of Ca, Mg and Fe also increased.

Geochemical Reactions at Nagaoka

Verified from the field data using CHDT

- $CO_2 + H_2O \rightarrow H_2CO_3^*$ --- *Solubility trapping*
- $H_2CO_3^* \rightarrow H^+ + HCO_3^-$ --- *Ionic trapping*

Inferred from the field data and batch experiments

- **Calcite + $H^+ \rightarrow Ca^{2+} + HCO_3^-$**
- **Plagioclase + $H^+ \rightarrow Ca^{2+} + Na^+$ + aluminosilicate**
- **Smectite + $H^+ \rightarrow Mg^{2+} + Fe^{2+} + Fe^{3+} + K^+ + Na^+ + Ca^{2+}$ + aluminosilicate**

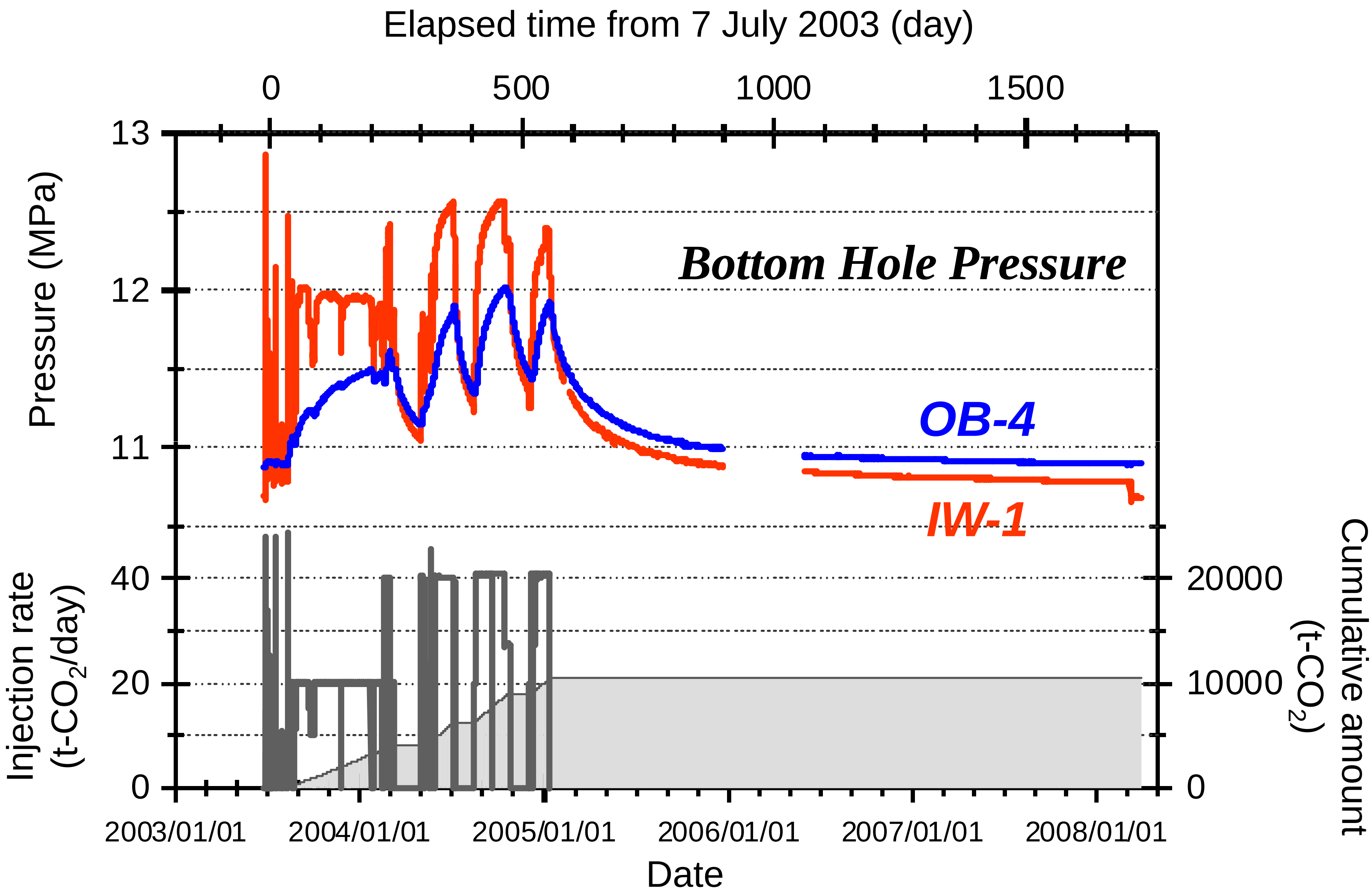
Simulated by ChemTOUGH

- $Ca^{2+} + HCO_3^- \rightarrow$ Calcite + H^+ --- *Mineral trapping*

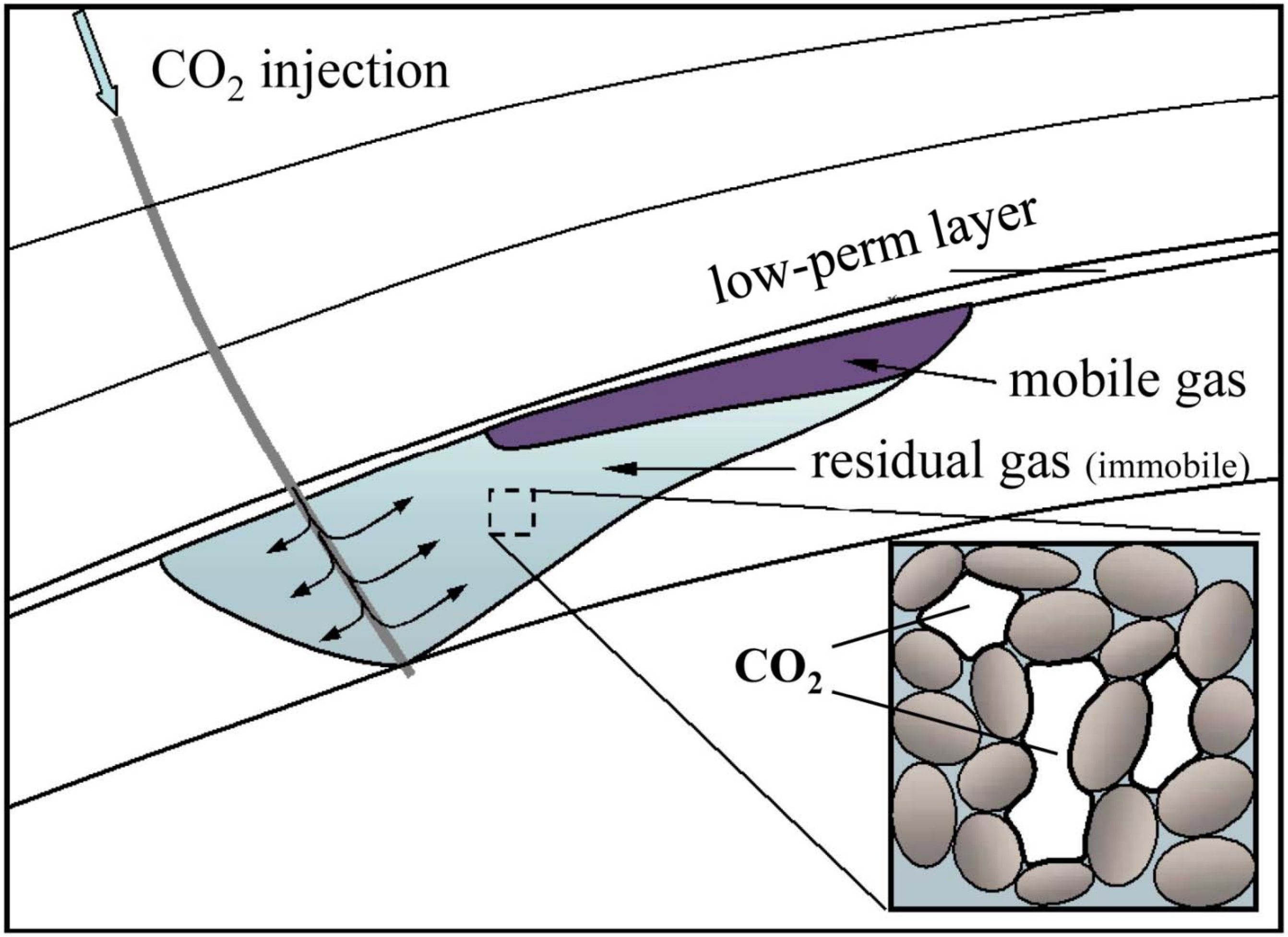
Summary of Geochemical Monitoring

- **The CHDT (Cased Hole Dynamics Tester, Schlumberger) sampling confirmed stored CO_2 as gas and dissolved phase.**
- **Because of low salinity (0.8wt%), *dissolved CO_2 was detected* by the induction logging.**
- **We are working on modification of our long-term geochemical model to integrate the well logging results now.**

Return to the Initial Formation Pressure

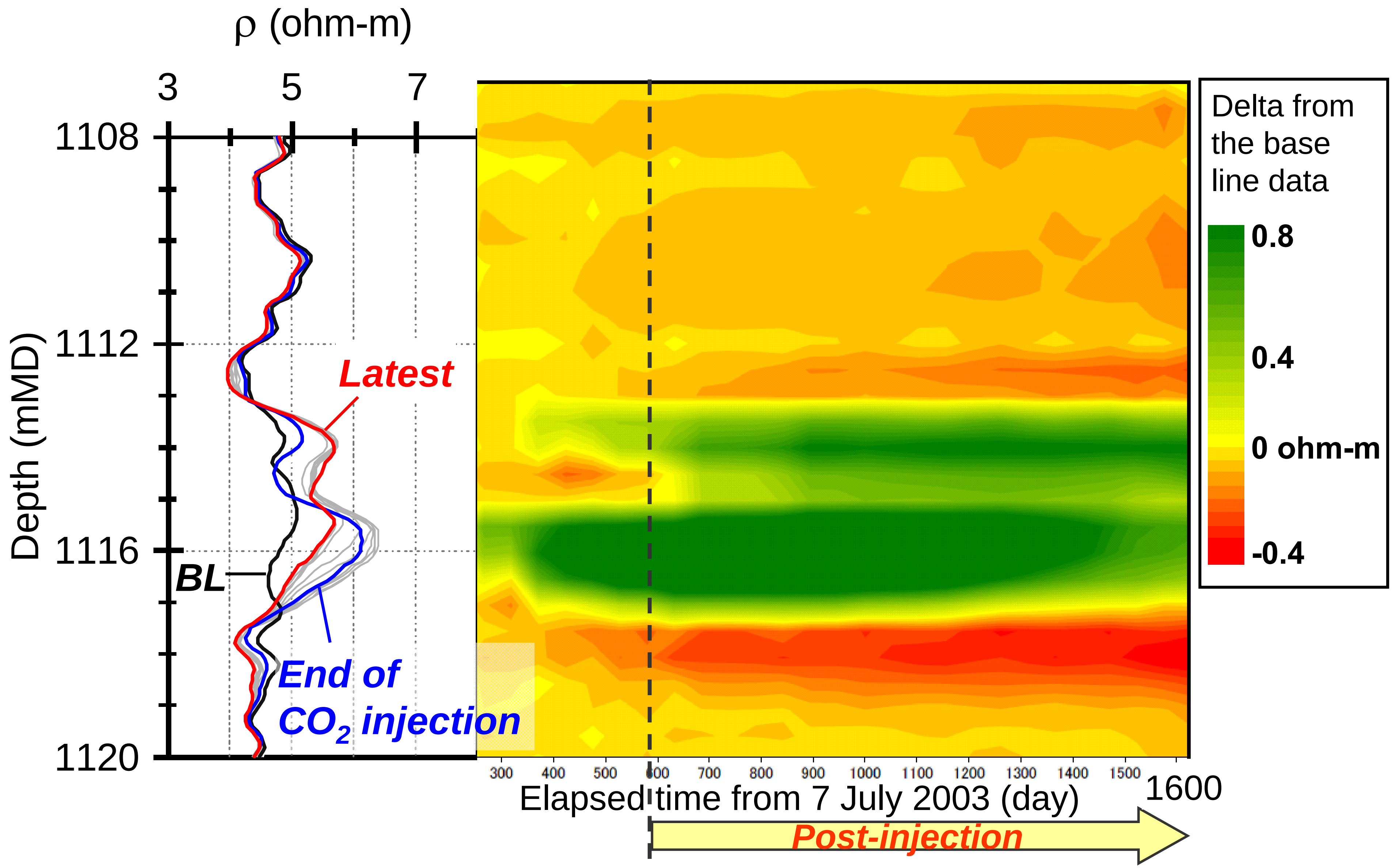


Driving Force of CO_2 ; Pressure and/or Buoyancy

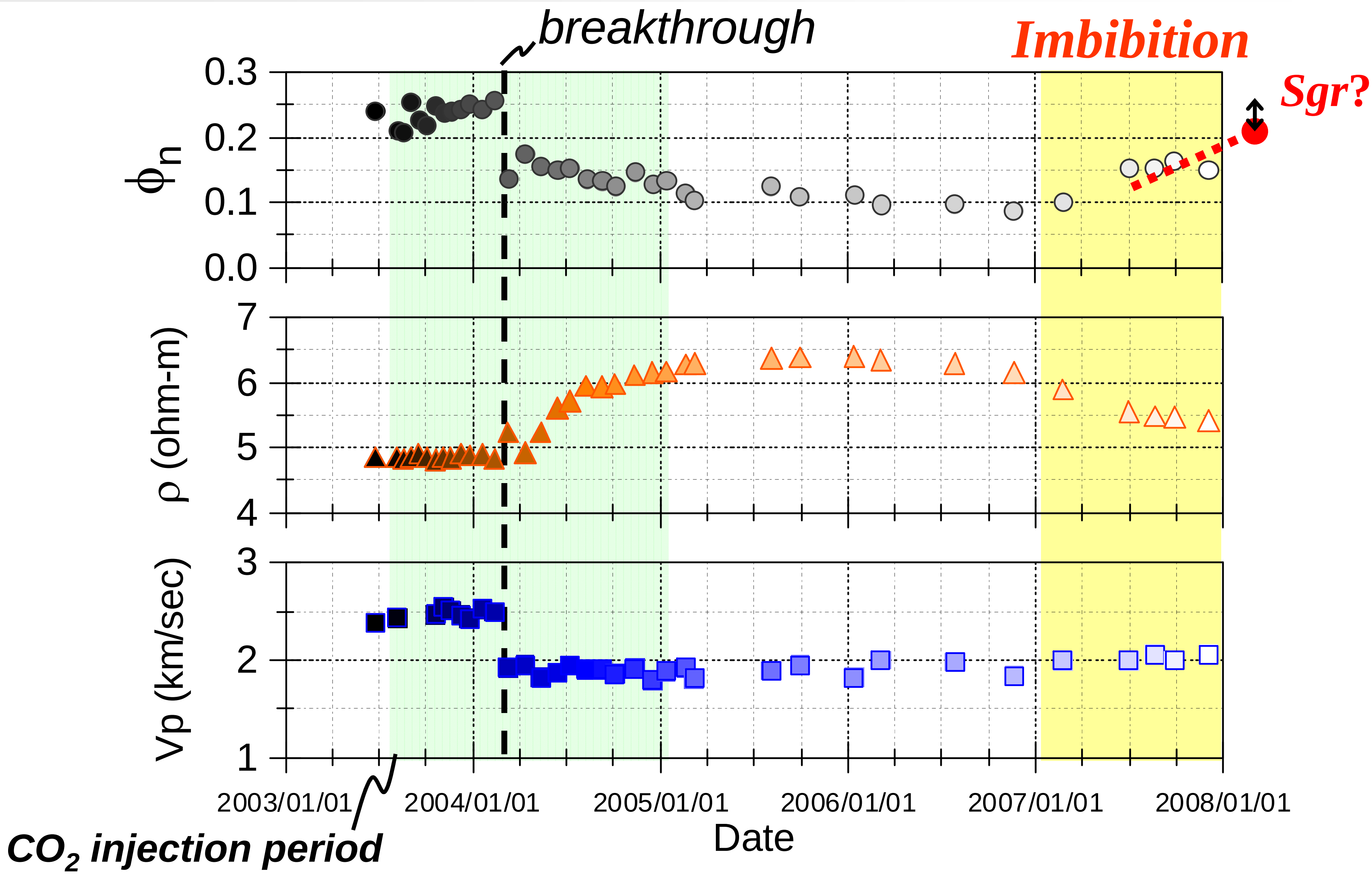


(Juanes et al., 2006)

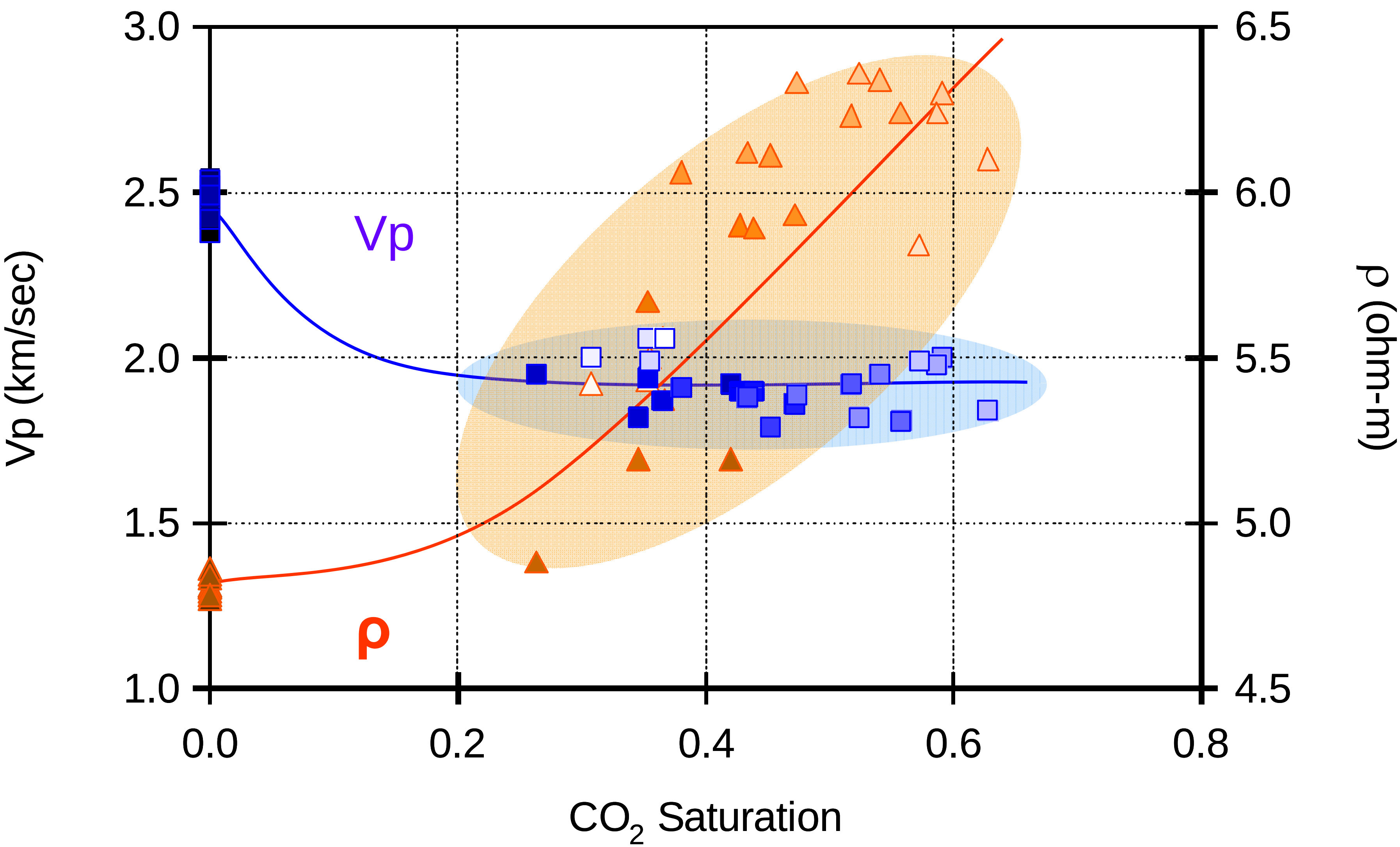
Resistivity Change during Imbibition Phase @ OB-2



Drainage and Imbibition Phase (1116.0m @ OB-2)



P-wave velocity and resistivity vs CO_2 saturation (1116.0m @ OB-2)



Summary of Geophysical Monitoring

- **CO_2 saturation has been decreasing at the lower part of the injection layer. The residual gas saturation will be determined in the actual reservoir at the Nagaoka site.**

- **Delay of P-wave velocity slowed down when CO_2 saturation exceeded 20%. But changes in resistivity with CO_2 saturation have kept increasing.**

- **Monitoring post-injection period is needed to clarify *the relationship between the P-wave velocity & the resistivity and CO_2 saturation*. We are trying to adapt a methodology for *accounting of CO_2* in the reservoir.**

Suggestions for CO_2 monitoring at post-injection

- ***Dissolved CO_2 vs Resistivity*;**

  Dissolution and mineral trapping are expected to reduce degree of rapid migration of mobile CO_2. Understanding of *geochemical reactions* helps to explain the *long-term behavior of CO_2* and the changes in geophysical logs such as resistivity.

- ***CO_2 saturation vs P-wave verosity and Resistivity*;**

  ***Joint inversion* of monitoring results of sonic wave and resistivity is key to *account CO_2 saturation*.**

- ***Geochemical & Geophysical*;**

  Feedback of geochemical and geophysical monitoring results is necessary to improve long-term prediction of CO_2 behavior.

Acknowledgements

- **This project is funded by Ministry of Economy, Trade and Industry (METI) of Japan.**

- **We thank staffs of ENAA, INPEX Co., Geophysical Surveying Co. Ltd., OYO Co., GERD and RITE involved in Nagaoka pilot CO_2 injection project.**

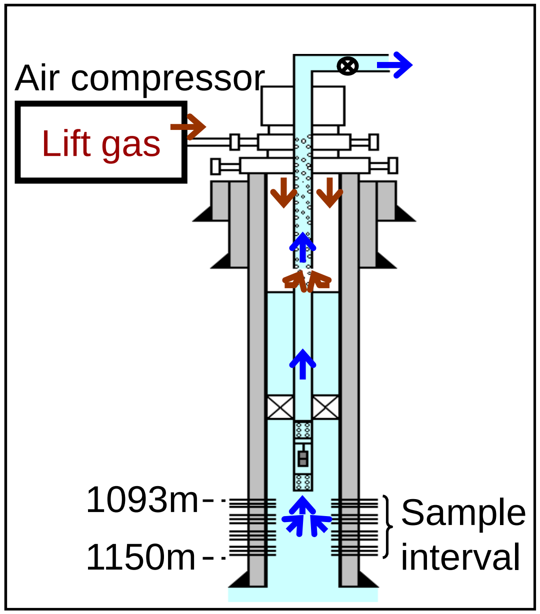
Thank you for your attention!

NAGAOKA Project

RITE Research Institute of Innovative Technology for the Earth

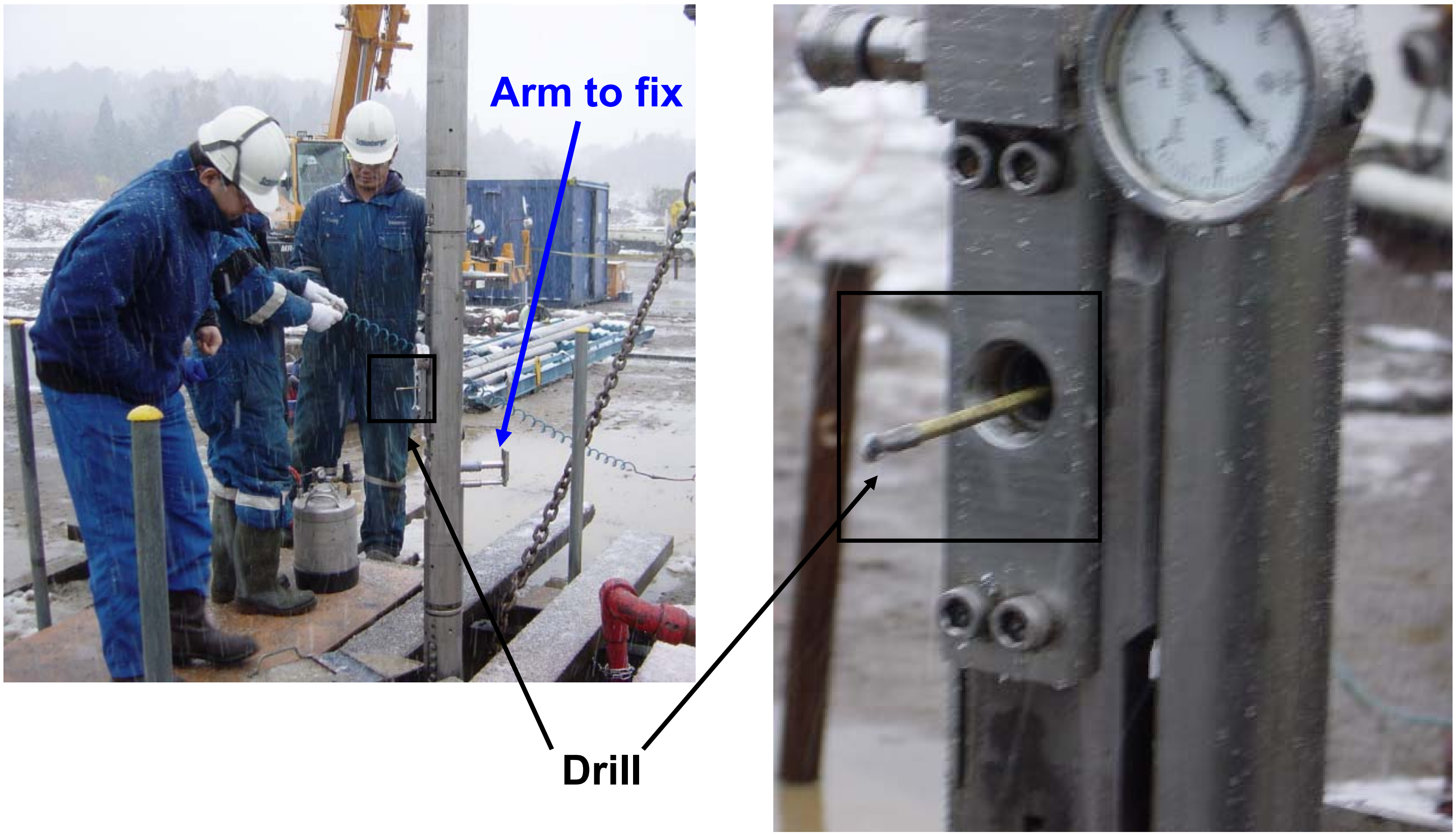
Formation Water Sampling (Prior to the CO_2 Injection)

Pump-up test



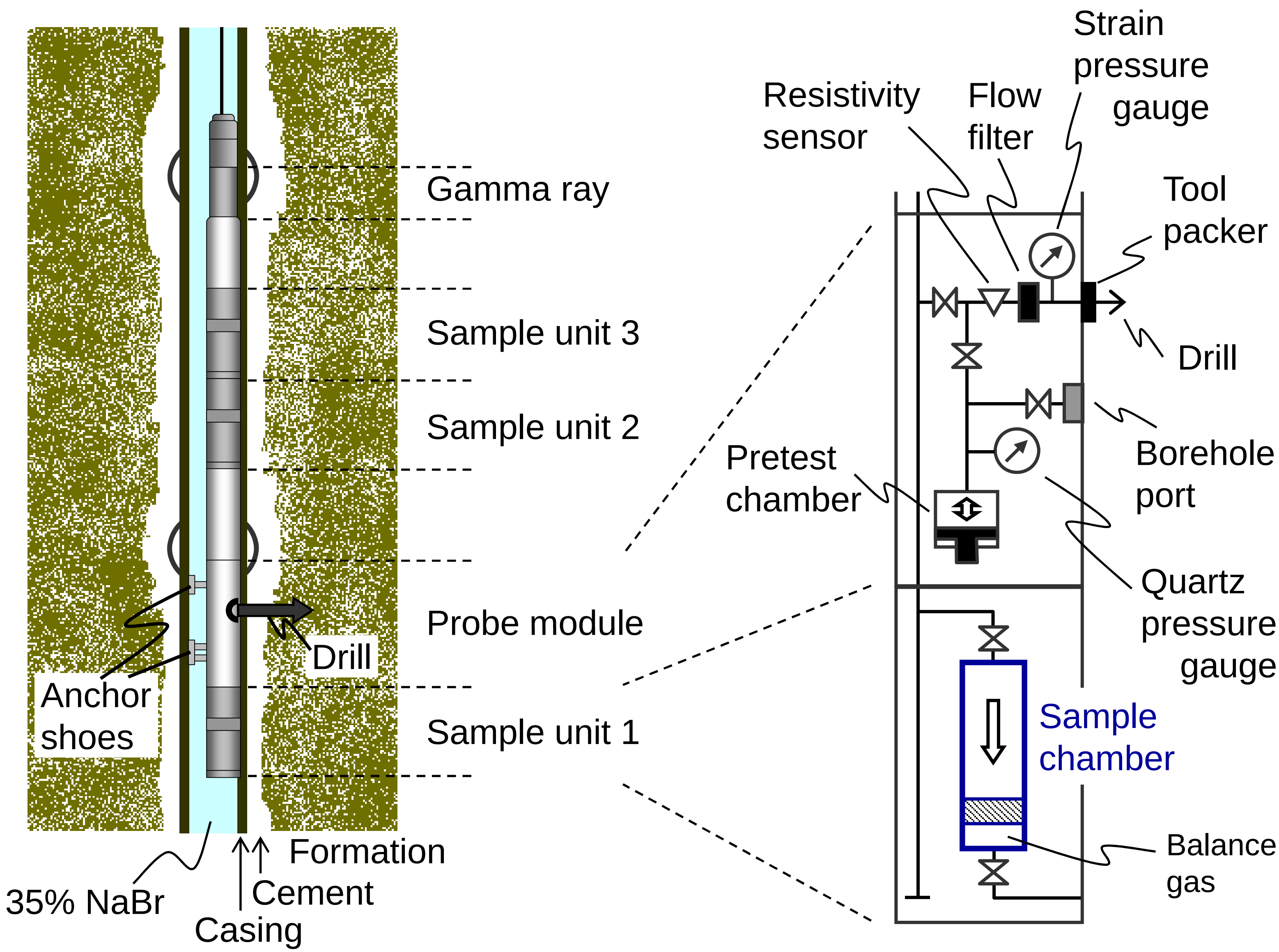
- May 2002
- From **IW-1**
- By air lift

Fluid sampling at OB-2 on Dec 2005 (Post-CO_2 injection)

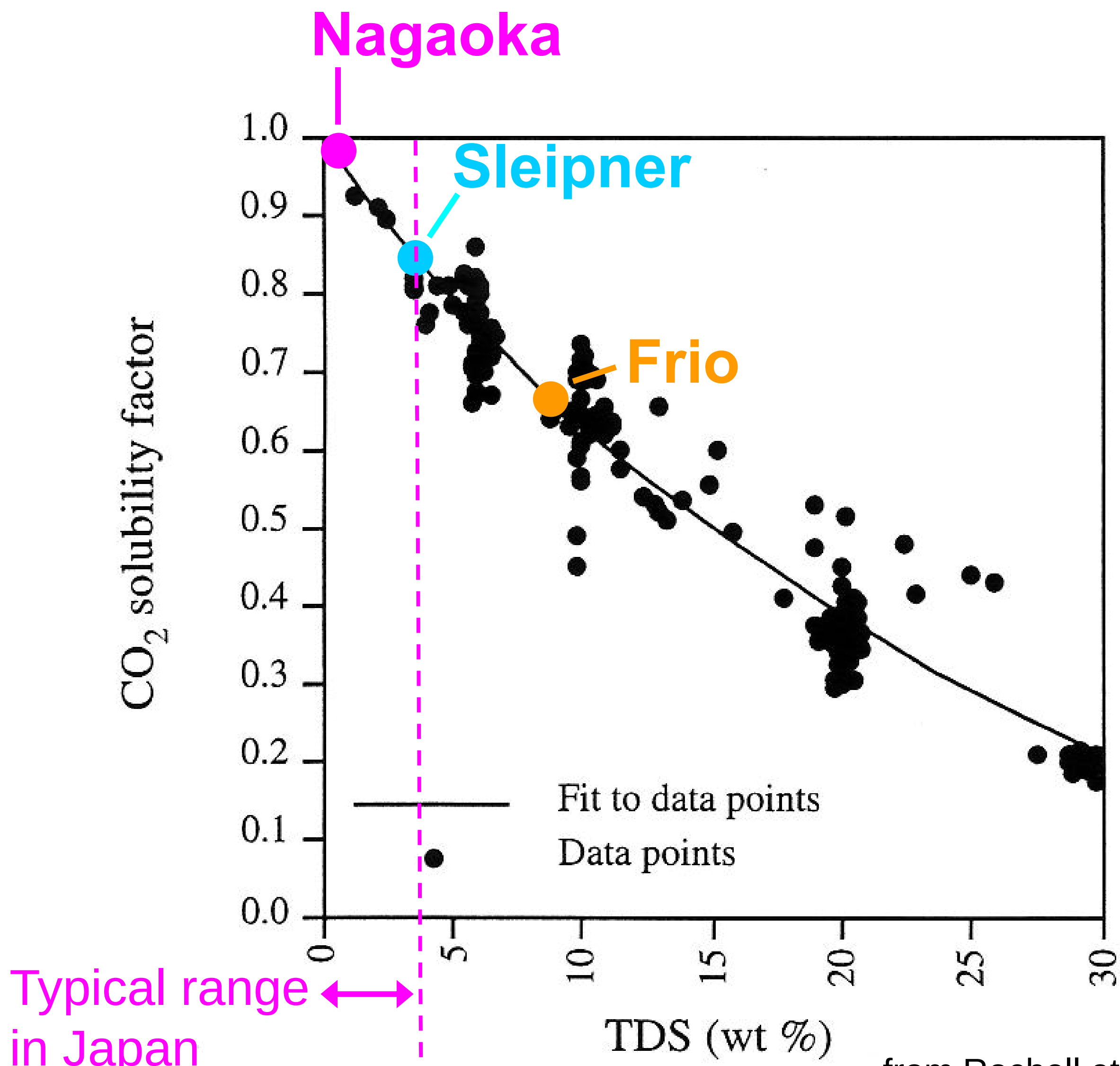


CHDT* (Cased Hole Dynamic Tester, Schlumberger)

Schematic showing CHDT and its sampling line

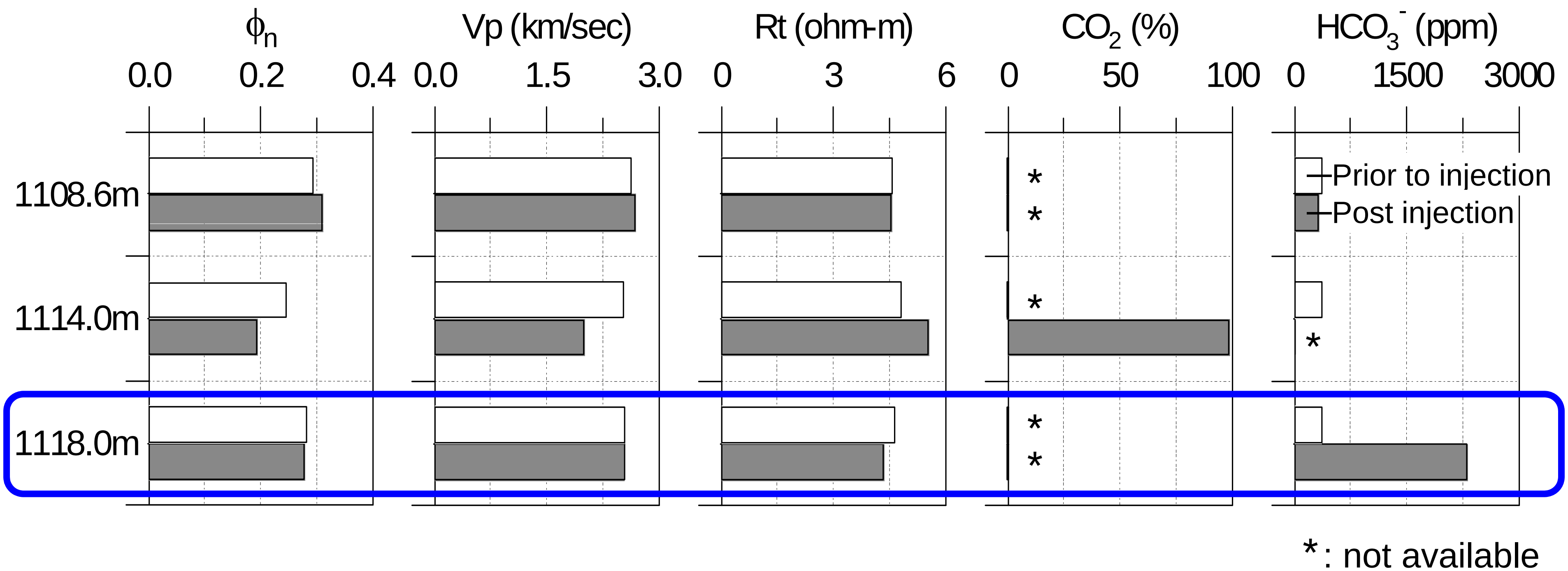


Low salinity:
High potential to dissolve CO2



from Rochell et al. (2004),
originally reported by Enick and Klara(1990)

Changes in the value for geophysical monitoring and results of CHDT sampling



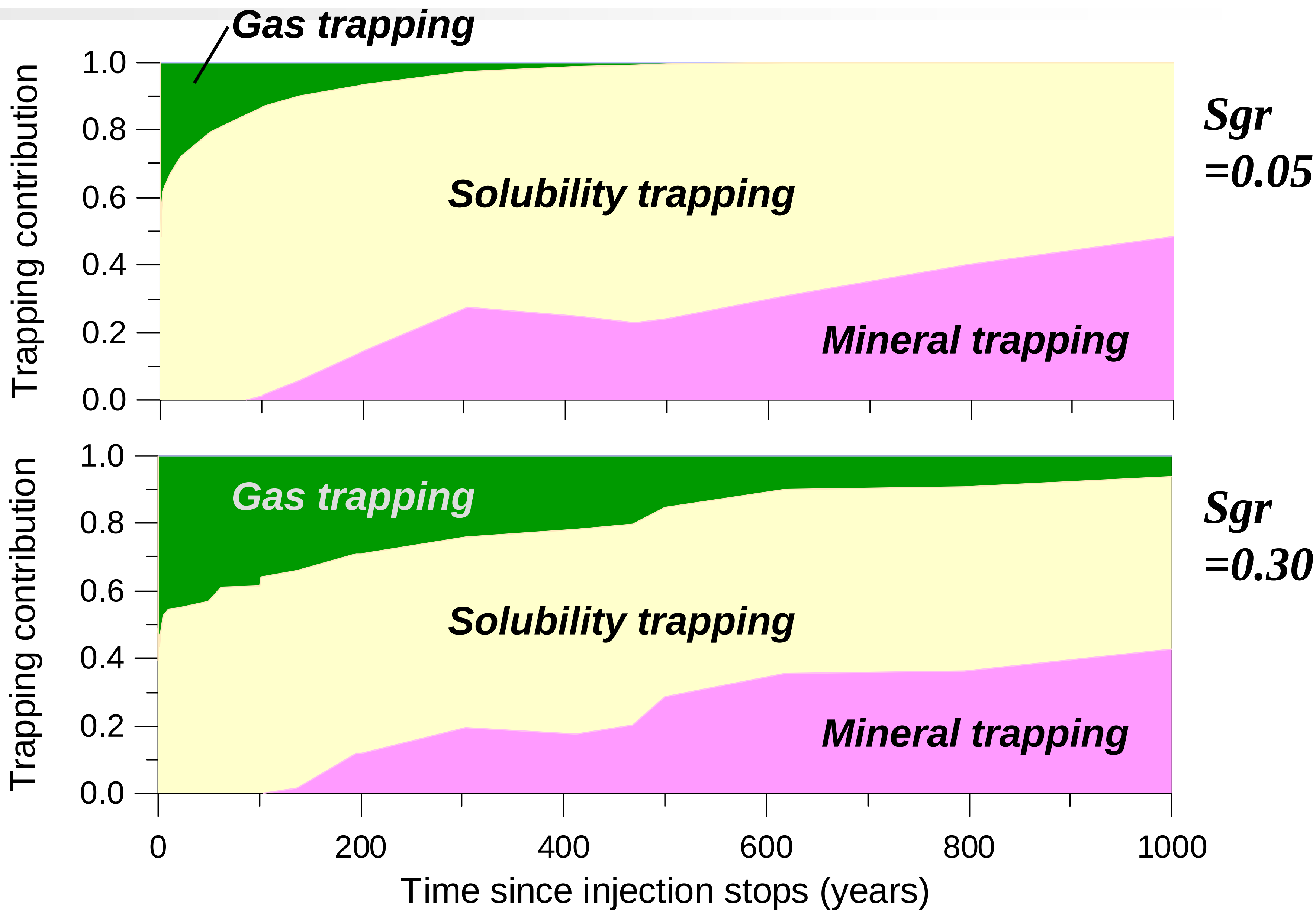
At the 1118.0m depth, arrival of dissolved CO_2 was detected as a decrease of resistivity. The change in salinity by increasing of HCO_3^- (7.2%) is roughly consistent with the change in resistivity (6.5%).

Long-Term Prediction for the Nagaoka Case (by ChemTOUGH)

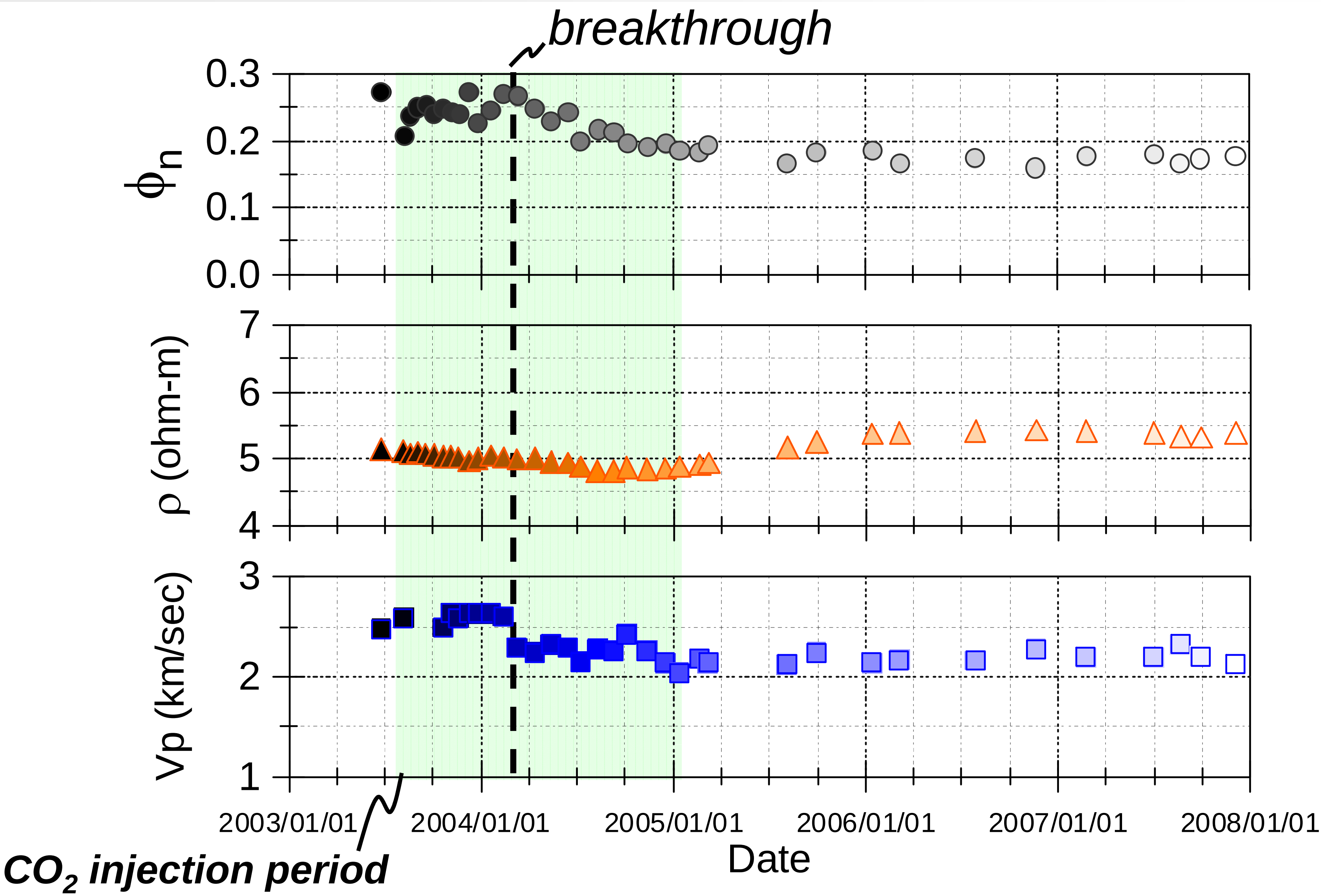
Input data

- **Mineral composition --- the actual reservoir rock**
- **Solution composition --- the actual formation water**
- **Equilibrium constants ---thermodynamics data base**
- **Rate constants --- literature**
- **Activation energy --- literature**
- **Reactive surface area --- based on sensitivity analysis of solution composition change (CO_2-water-rock reactions using Nagaoka samples)**
- **Geophysical modeling --- White et al. (2006)**

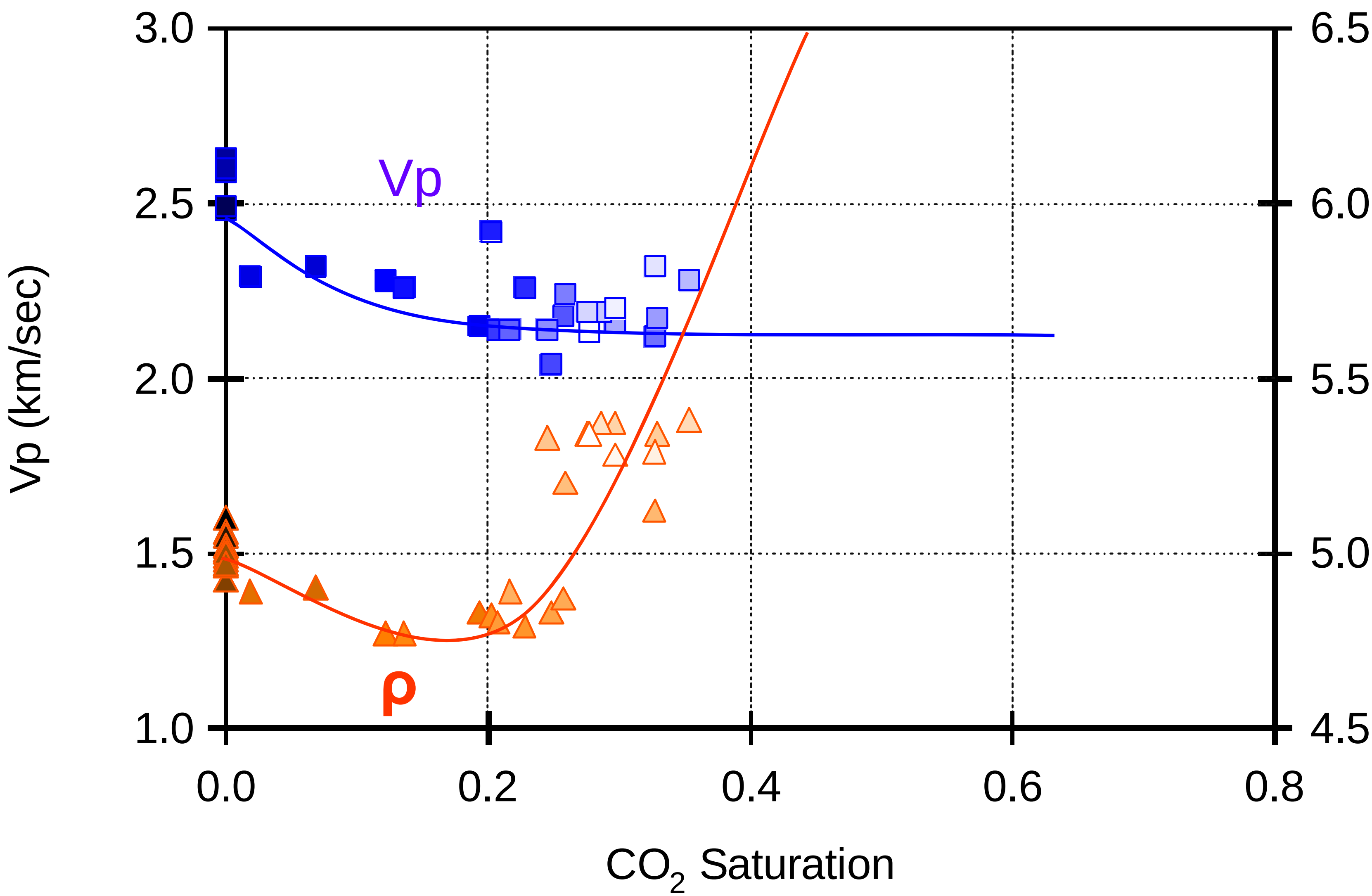
Preliminary results of long-term prediction



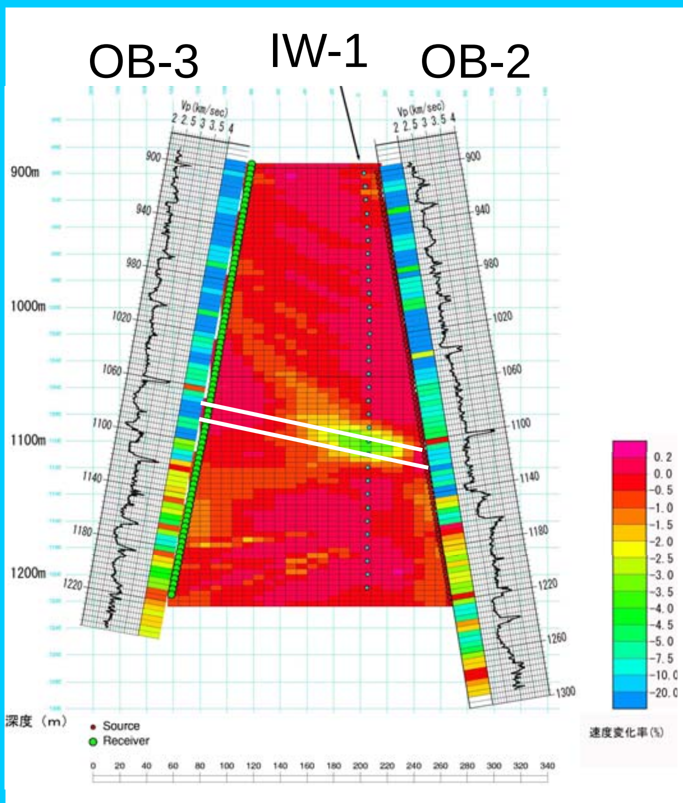
Decrease and Increase of Resistivity during Drainage Phase (1114.8m @ OB-2)



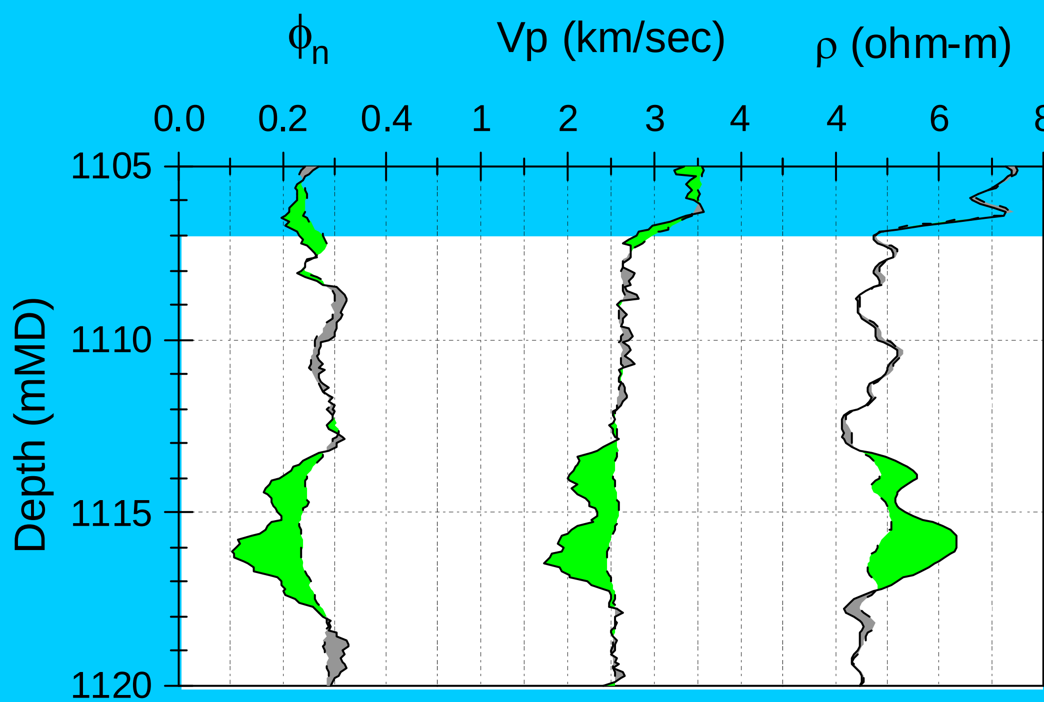
P-wave velocity and resistivity vs CO_2 saturation (1114.8m @ OB-2)



Detection and monitoring of CO_2 at the observation wells



Seismic Tomography



Well loggings

Monitoring Future Plans at CCS Demonstrations in JAPAN

5th Monitoring Network Meeting

2nd June 2009

TOKYO

Masanori Abe

Japan CCS Company Limited

Contents

- *Introduction*
- *Who is Japan CCS?*
- *Two Projects in FY 2008*
- *Two Projects in FY 2009*
- *Monitoring Future Plans*
- *Summary*

Introduction

- 1,304Mt : CO2 emissions in 2007 in Japan
- In July 2008 at the G8 Hokkaido Toyako Summit, the leaders declared, "We strongly support the launching of 20 large-scale CCS demonstration projects globally by 2010, taking into account various national circumstances, with a view to beginning broad deployment of CCS by 2020."
- In July 2008 "An Action Plan for Achieving a Low-carbon Society" was decided in the cabinet meeting in Japan. Encouragement was given to the development of major innovative technologies and the dissemination of existing advanced technologies in order to move toward a low-carbon society and achieve long-term targets.
- In December 2008, the Council for Science and Technology Policy, Cabinet Office, decided to adopt the draft evaluation of "the Demonstration Project of the CO2 Abatement Technology", which is scheduled to be implemented starting in fiscal 2009.

Who is Japan CCS Company Limited?

- Incorporated on 26th May 2008
- 32 Shareholders as of 31st May 2009
  - 11 electric power companies
  - 5 petroleum companies
  - 5 engineering companies
  - 3 petroleum resource development companies
  - 3 general trading companies
  - 2 iron and steel companies
  - 1 chemical company
  - 1 non-ferrous metal and cement company
  - 1 city gas company
- President : Shoichi Ishii, Managing Director, Japex
- Capital: \217.5m

Shareholders *as of 31st May 2009*

- 11 Electric Power
  - Chubu, Chugoku, Hokkaido, Hokuriku, J-Power, Kansai, Kyushu, Okinawa, Shikoku, Tohoku, Tokyo
- 5 Petroleum
  - Cosmo, Idemitsu, Japan Energy, Nippon, Showa Shell
- 5 Engineering
  - Chiyoda, JFE Eng., JGC, Nippon Steel Eng., Toyo Eng.
- 3 Petroleum Resource Development
  - Arabian Oil, Inpex, Japex
- 3 General Trading
  - Itochu Corp., Mitsubishi Corp., Sumitomo Corp.
- 2 Iron and Steel
  - JFE Steel, Sumitomo Metal Industries
- 1 Chemical
  - Mitsubishi Gas Chemical Comp
- 1 Non Ferrous Metal and Cement
  - Mitsubishi Materials Corp
- 1 and City Gas
  - Tokyo Gas

joined recently

What is Japan CCS Co Ltd?

A private company established with the following intentions;

1. Work on investigation and operations in demonstration projects of total system consists of CO2 capture, transportation and geological storage.
2. Plan to integrate opinions from private sectors in order to marshal applicable laws to and to establish technological standards of CCS in Japan.
3. Perform various activities on enlightenment and promotion of CCS in Japan.
4. Cooperate for promotion of CCS demonstration projects overseas.
5. Plan to gather up-to-date information on CCS inside and outside Japan and to exchange it with international research laboratories.

Two Projects in FY 2008 *August 2008 – March 2009*

- “**METI Project**”

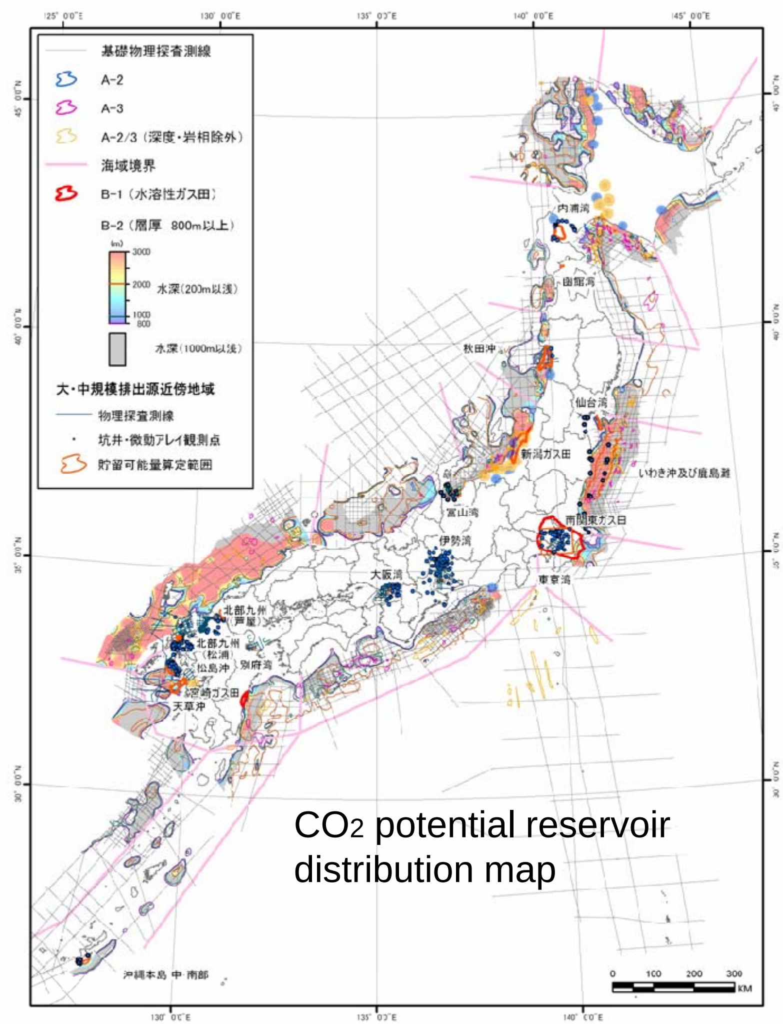
“Development of Assessment Technologies for a Deep Aquifer appropriate for Demonstration as a part of Research and Development of Underground Storage Technology for Carbon Dioxide” subsidized by Ministry of Economy, Trade and Industry (METI).

- “**NEDO Project**”

“Feasibility Study on a Total System from Electric Power Generation to CO2 Storage” as a part of the “Innovative Zero-emission Coal Gasification Power Generation Project” performed by New Energy and Industrial Technology Development Organization (NEDO).

METI Project

- Re-evaluate existing assessment of deep saline aquifers and oil & gas reservoirs appropriate for CCS demonstrations.
  - Geological Assessment
  - Fault and Marine Environment Study
  - Engineering Study
  - Economical Ripple Effects
  - Fundamental Research on leakage risk
- August 2008 - March 2009



CO_2 potential reservoir distribution map

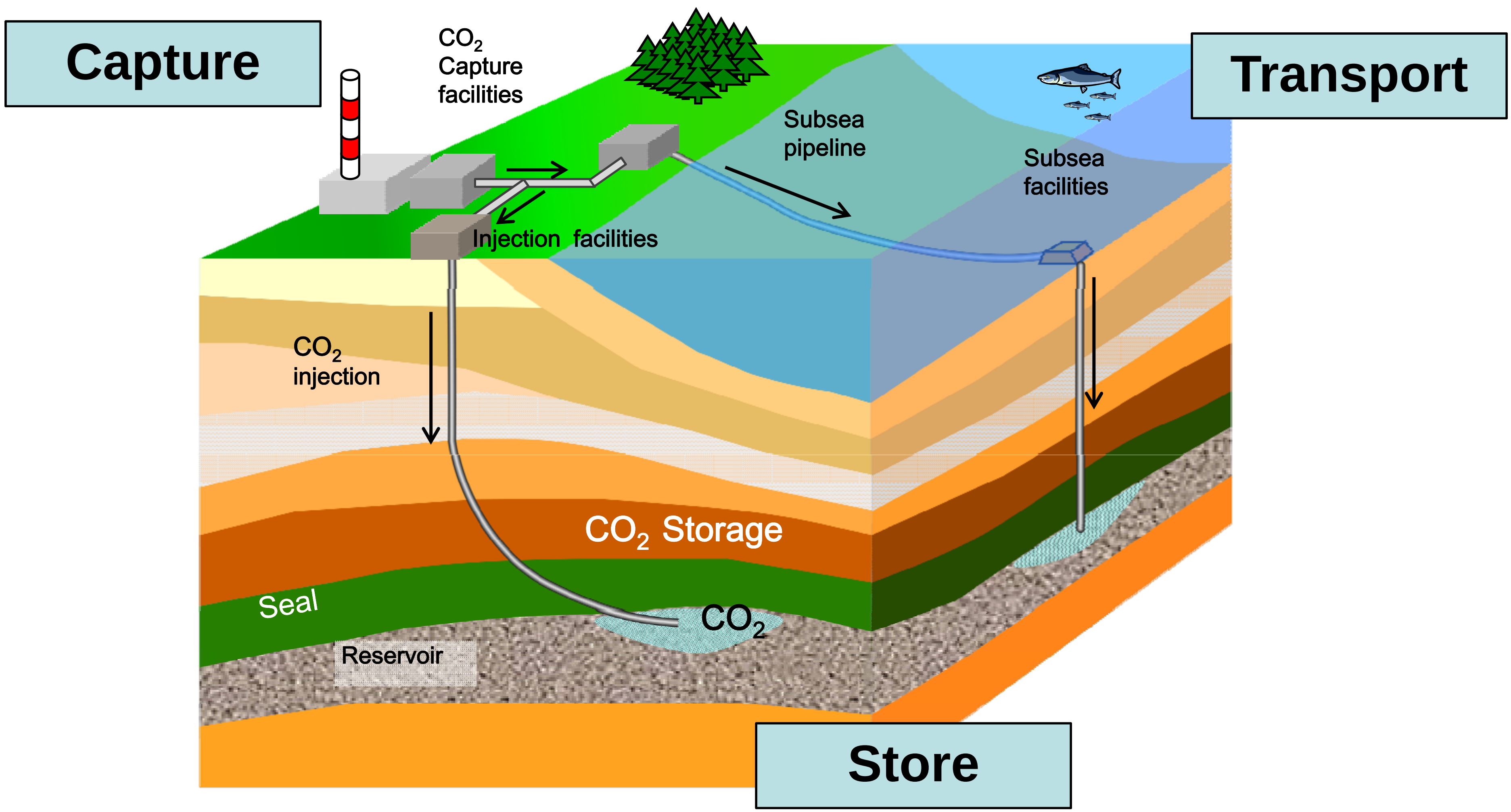
RITE Study Report (2008)

ENAA07-Enclosure-5A4_systemlink_ver.-R080307a

Note that storage potential is evaluated as about 150 Gt-CO2 around Japan.

Japan CCS

CCS in Japan



Not to scale

Demonstration Project

■ Purpose

- **Tests**

to solve remaining technical issues in **monitoring**, **reservoir simulation** and other items

- **Optimization**

in **total systems** of industrial-scale CCS

- “**Demonstration**”

to show **capabilities** of operating CCS Total System

to build a **confidence** and to be **accepted in public**

to bridge for **early massive CO2 emission reduction**

Demonstration Specs at Candidate Sites

- Source
  - Being separated at ammonia, gas processing, oil refinery plants
  - Newly build capture plant: oil refinery, IGCC
  - Scale: 50,000 – 200,000 t-CO2/year
- Transportation
  - Low pressure land pipeline
  - High pressure offshore pipeline
  - Truck
- Injection
  - Onshore compression sites
  - ERD well / Sub-sea completion
  - Sub-seabed storage points
- Reservoir Type
  - Depleted oil & gas reservoir
  - Deep saline aquifer with closure
  - Deep saline aquifer without closure (Neogene)
  - Deep saline aquifer without closure (Paleogene)

Two Projects in FY 2009 ***April 2009 – March 2010***

- **METI Project**

  "Demonstration Project of the CO_2 Abatement Technology"

  - 3D seismic survey
  - characterization wells
  - offshore pipeline route survey
  - site characterizations

- **NEDO Project** – 2nd year

  "Feasibility Study on a Total System from Electric Power Generation to CO_2 Storage"

  - Basic designing for capture, transport and storage facilities is being conducted.

Future Monitoring Plans in Japan

Law relating to the prevention of marine pollution and maritime disaster (1970)

- Only this law regulates CO2 sub-seabed geological storage within the territorial waters of Japan.
- Amendment for CO2 sub-seabed geological storage is enforced in 2007.
- Minister of the Environment permits to inject CO2 for 5 years.
- A monitoring plan is required for delineating CO2 distribution and for detecting seepage to sea water.

Future Monitoring Plans in Japan

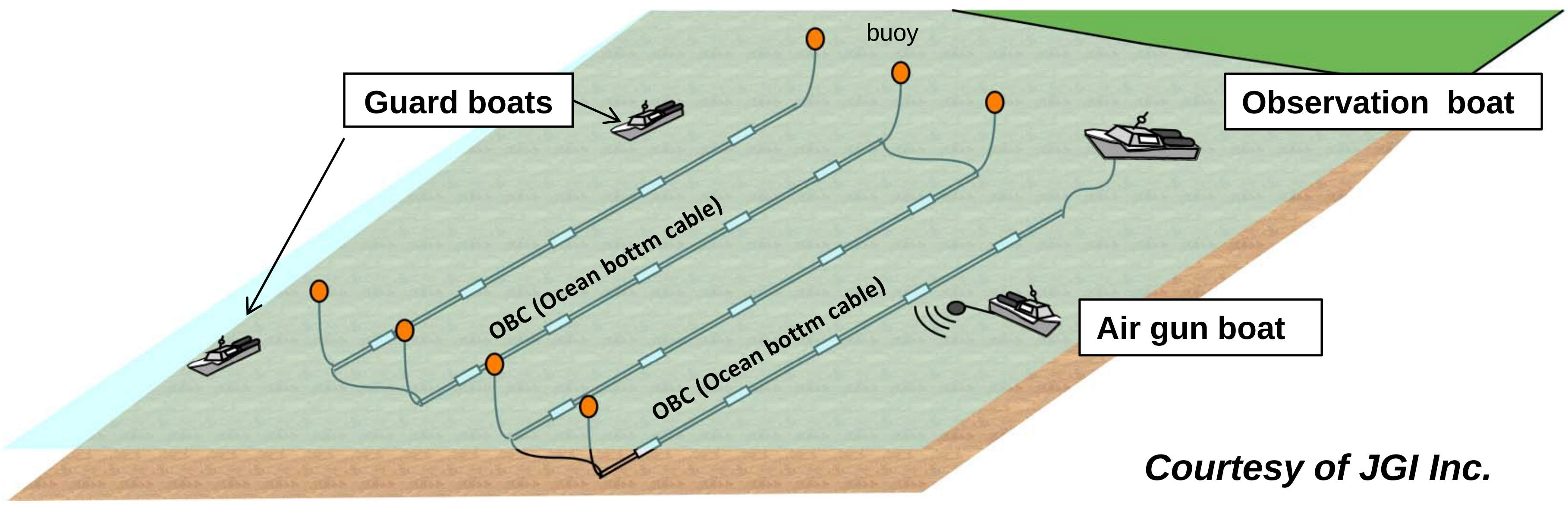
Main items only

- Regulated in the Law
  - Injected CO_2 distribution
    - ✓Volume and injection rate measurement
    - ✓PT measurement
    - ✓CO_2 distribution in the reservoir (2 times in 5 years)
      - ◆time lapse 3D seismic
      - ◆time lapse 2D seismic for interpolating 3D seismics
  - Marine survey
    - ✓physical, chemical, biological
- Seismicity
  - Required based on a question and answer in the Special Committee on Measures against Disasters in the House of Councilors*

*Private Translation

Time lapse 3D seismic

- OBC system in coastal transition zone
  - For CCS candidate sites located in shallow water
  - Too shallow for conventional seismic vessels
  - Ocean Bottom Cable (OBC) system with smaller boats
  - Care must be taken to fishing and maritime traffics.



Courtesy of JGI Inc.

Marine Survey

- Demonstration sites will be appropriately selected.
- Seepage will hardly occur at these sites.
- Questions
  - How and what do we assume seepage scenarios from the reservoir to the surface?
  - What extent?
  - How often?
  - Which item?
  - Do we really have to do these surveys?

Acoustic Doppler current profilers

Water sampler

Side scan sonner

Sea bottom sampler

Physical and Chemical Monitoring

Sea Bottom Monitoring

Monitoring of seismicity

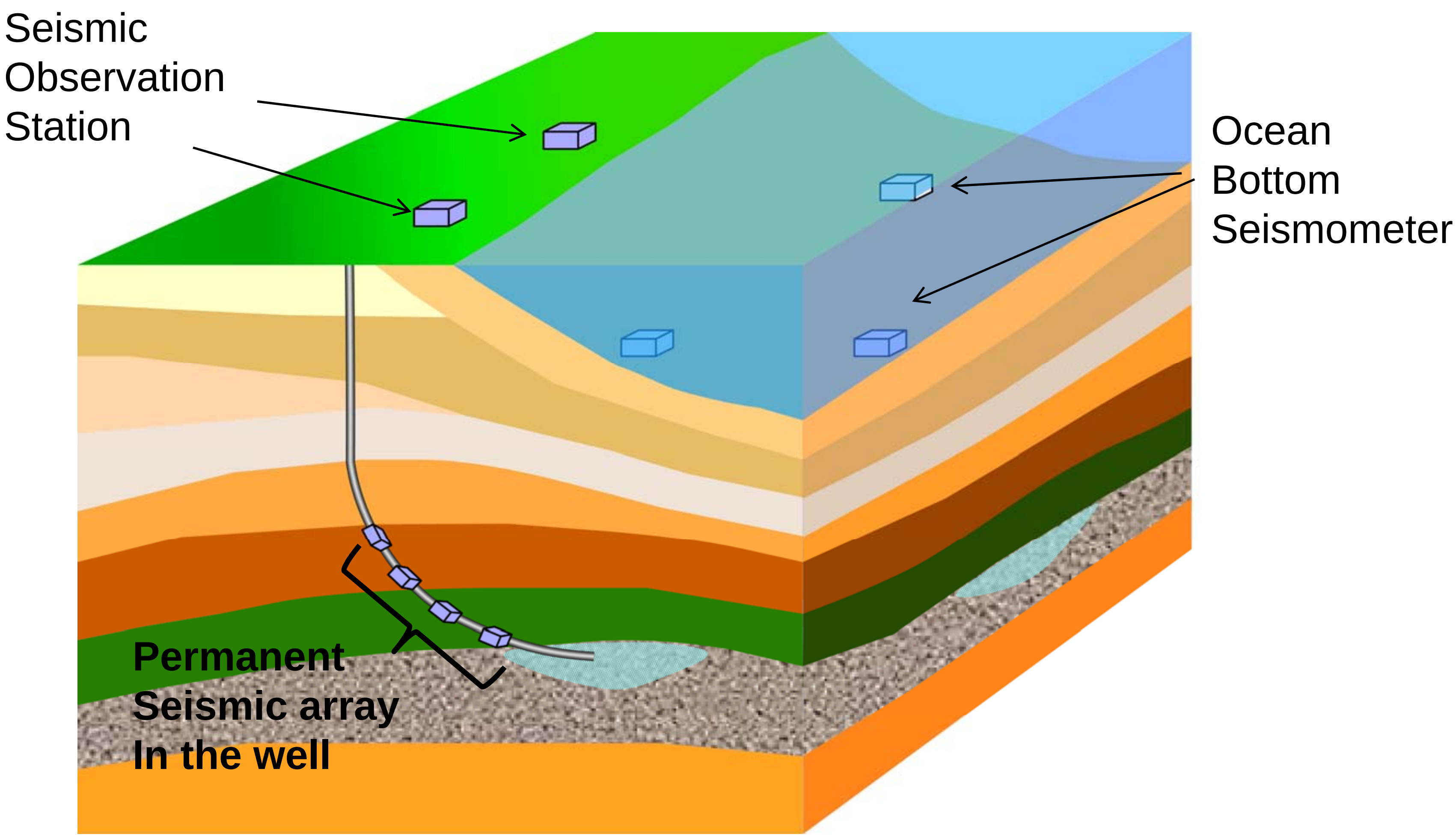
- To measure strength of seismic movement and to assess injection wells and reservoirs are intact.
- Seismometers networks covering the land (Hi-net) about every 20km. Hypocenters are accurately positioned in the case of earthquake.
- During demonstration additional seismometers are considered to be set around the injection point to accurately position the hypocenter if earthquake occurs near the injection site.
- Monitoring of acoustic emission (AE)

◆ CO_2 will be injected in 1.5 – 2.5km depth and earthquakes usually occur in 10 – 20 km depth.

◆ Do we really have to do?

Seismicity Monitoring

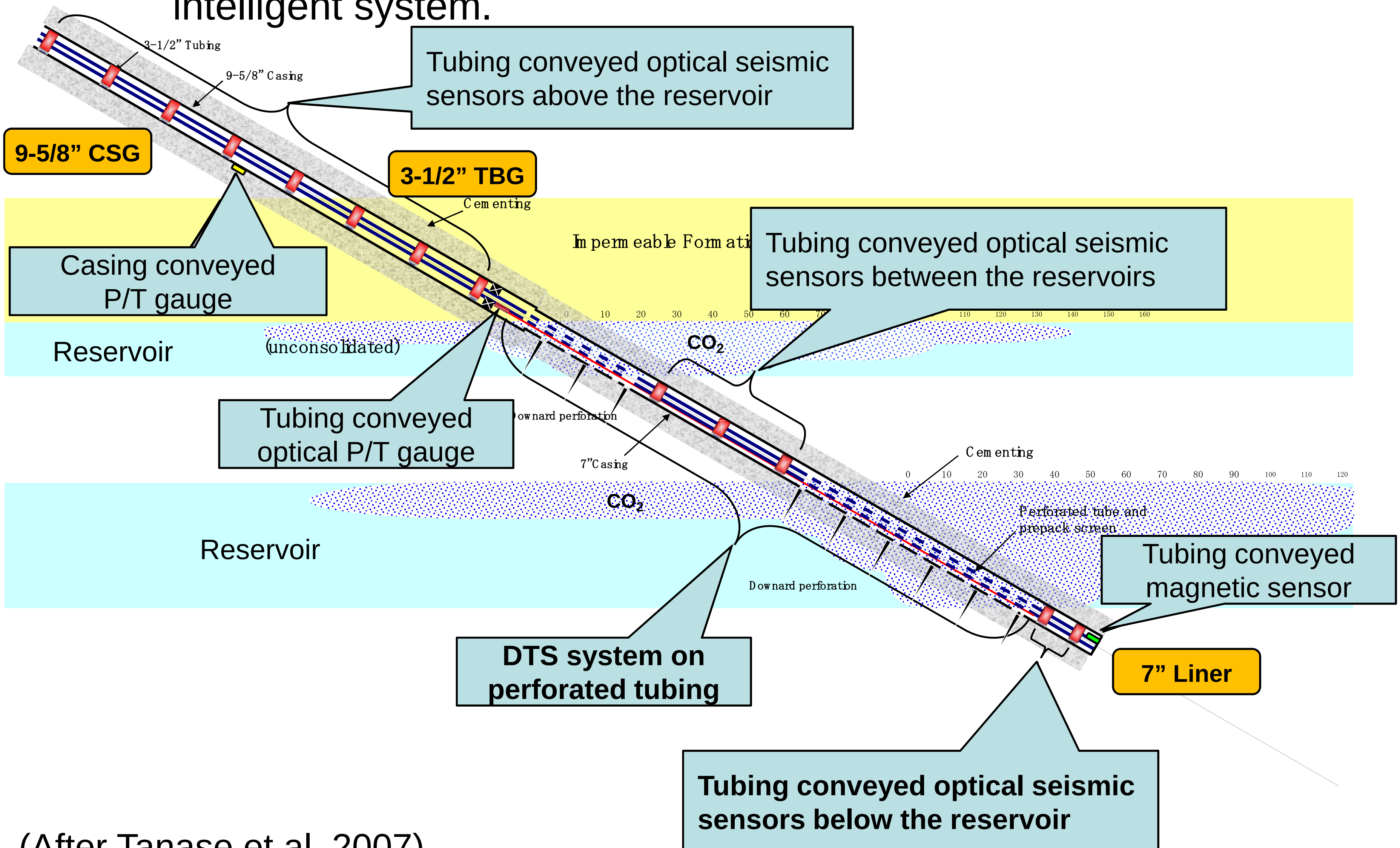
- Seismic monitoring network concept



Japan CCS

Monitoring of injected CO2 distribution

- Inclined injection well is being considered to be completed as an intelligent system.



(After Tanase et al, 2007)

Summary

- In 2009, characterization wells will be drilled, and 3D seismic survey followed by site characterizations will be conducted . Demonstration sites will be decided this year.
- 3D seismic, 2D seismic, VSP, and PT measurement are being considered for monitoring of CO2 distribution during demonstration.
- An intelligent well system will be adopted to an injection well for delineating initial CO2 distribution.
- Marine surveys and continuous seismicity monitoring will be conducted. Detail designing is being carried out this year. Several questions remain unsolved yet.

Thank you for your attention.

ほくでん

Mitsubishi Corporation

JFE
JFE エンジニアリング 株式会社

MITSUBISHI
MITSUBISHI MATERIALS

JGC

Energia

Idemitsu Kosan

JFE

TEPCO

MGC
MITSUBISHI GAS CHEMICAL COMPANY, INC.

TOKYO GAS

COSMO

SUMITOMO METALS

J-POWER

JOMO

ENEOS

NIPPON STEEL
ENGINEERING

ITOCHU

Sumitomo Corporation

INPEX

JAPEX

Recent CCS Progress in Japan

2nd June 2009

Toshihiro Mitsuhashi
Ministry of Economy Trade and Industry, Japan

The Latest Trends on CCS

Joint Statement by G8 Energy Ministers (June 8, 2008)

We strongly support the recommendation that 20 large-scale CCS demonstration projects need to be launched globally by 2010, taking into account varying national circumstances with a view to supporting technology development and cost reduction for the beginning of broad deployment of CCS by 2020.

G8 Leaders' Statement at Hokkaido Toyako Summit (July 8, 2008)

We strongly support the launching of 20 large-scale CCS demonstration projects globally by 2010, taking into account various national circumstances, with a view to beginning broad deployment of CCS by 2020.

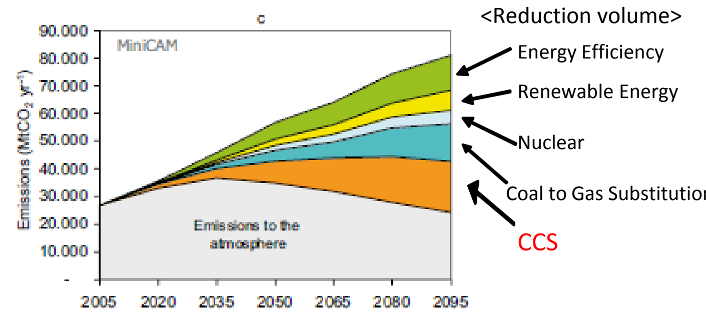
Action Plan for Achieving a Low-carbon Society (July 29, 2008)

CCS technology has the potential for massive emissions reductions in thermal power generation, which accounts for roughly 30 percent of Japan's emissions, and in the steelmaking process, which accounts for roughly 10 percent. Japan will promote the development of this technology with the target of the cost of capture and storage in the order of 2,000 yen per ton by around 2015, falling to 1,000 yen or so in the 2020s. At the same time, Japan will commence verification tests on a large scale at an early stage from 2009 onward, with the aim of implementation by 2020. Regarding application, Japan will work to resolve issues such as enhancing environmental impact assessments and monitoring, putting legislation in place, and ensuring public acceptance.

CCS policy in relation with other policy measures of Climate Change

1 . Relation with the long term target (50% reduction by 2050)

Emission reduction by technology



○CCS is a technology to be used in the transition period of getting rid of using fossil fuel.

※At the same time CCS is an indispensable technology to achieve the long term target to reduce CO_2 by 50% from the current level of emission

2 . Relation with the international negotiation

○CCS is a technology that has a potential to realize the reduction of significant amount of CO_2 in the second commitment period (2013-2020) and the commitment period comes after(2020-).

3 . CCS in the "Cool Earth innovative energy technology program"

○CCS is a technology to realize a low carbonization in an energy supply side and to have potential to be used in a cross sectoral basis (ex: steel, cement chemical industries) in a energy demand side.

4 . Roadmap for technology demonstration

○Start a large scale demonstration project as soon as possible after 2009FY

(It was agreed in the G8 Energy Ministers Meeting to initiate 20 large scale CCS demonstration project by 2020)

○Target for cost reduction (capture of CO2 2,000yen/ton by 2015 and 1,000yen/ton by 2020)

Establishment of the core technology and its demonstration

1 . Target

○To start Demonstration project (100kton of injection per year) that follows a Nagaoka project.

○Commercialization of technology in which Japan has an advantage(low cost CO_2 capture and monitoring)

2 . Concrete Action from 2008FY

(1) Establishment of implementing body

・ Establishment of JCCS

* with the investment of 29 companies including 11 utilities

(2) R&D in RITE

・ Development of membrane technology for separation of CO_2

(3) Setting a safety and environmental guideline for CCS commercialization

・ Establishment of expert group and start examination (currently under public consultation)

International cooperation

< CCS project from coal fired power generation >

1 . Japan- Australia project (Callide A)

○ Reconstruct the existing pulverized coal fired power plant to an oxygen fired type and inject the captured CO_2 in a dried up gas field 250km far from the power plant.

○ Participation of JPOWER, IHI, Mitsui corporation & JCOAL

2 . Cooperation with People's Republic of China

○Examination of the design and evaluation of the total system of CCS covering capture of CO_2 in the mid scale coal fired power plant in the northeast coal production base close to Harbin and capture of CO_2 as wells as transportation injection and EOR of CO_2 at Daqing oil field.

○ Expected participation of RITE , JGC, JCOAL, TOYOTA, JOGMEC and Japan CCS Co.Ltd.

High efficiency coal fired power generation with CCS

1 . Purpose

○Approximately 30% of the emission in the world comes from coal fired power plants

注) World Emission (2007) 27 Gton

- from the power pant 10 Gton(37%)

- from the coal fired power plant 7 Gton(27%)

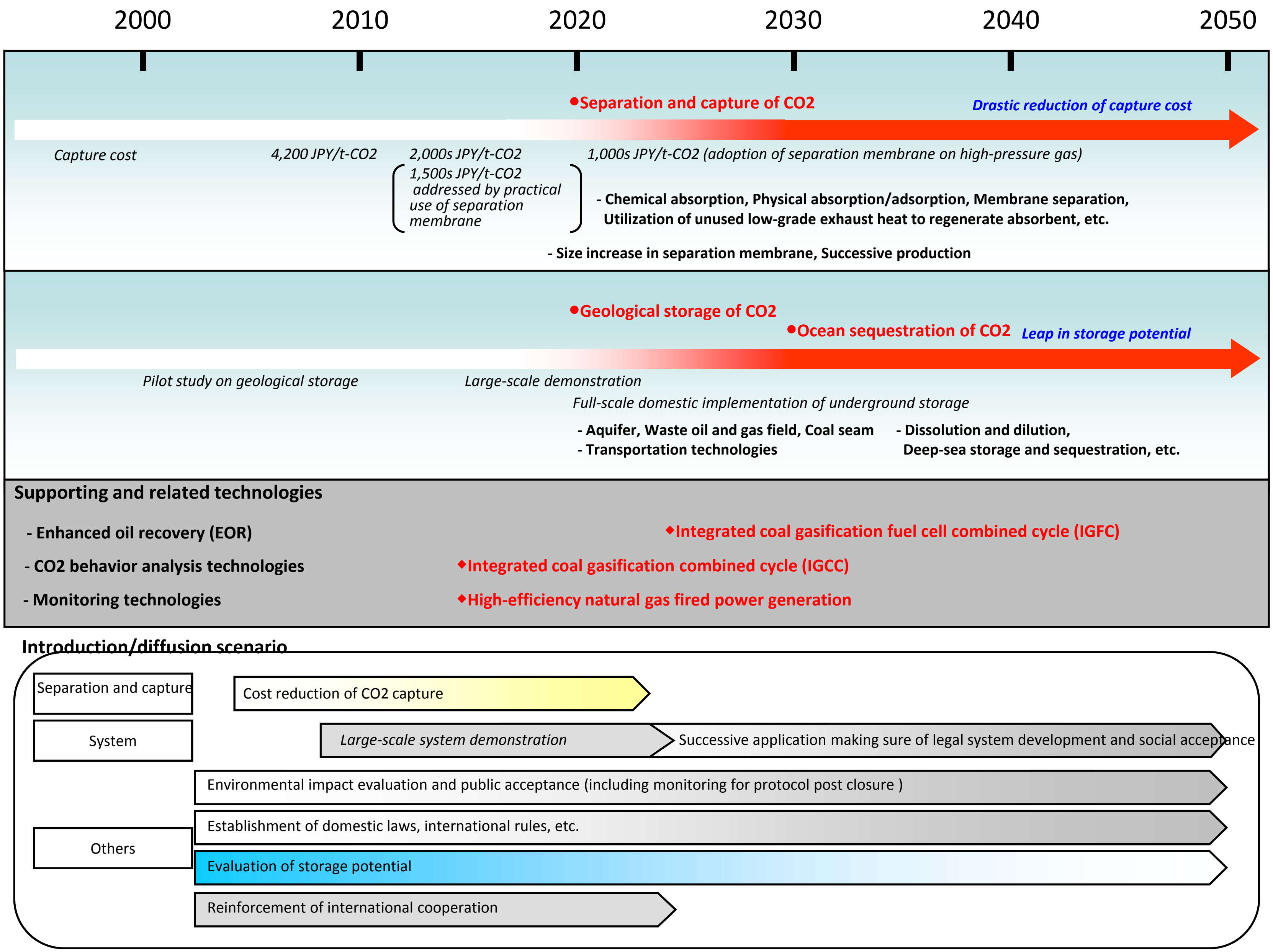
○It is necessary to realize a high efficiency coal fired power plant as well as a CCS through capture of further emitted CO_2 so to realize zero emission coal fired power plant.

2 . Concrete Measures

○Feasibility Studies bearing in mind the total system of CCS covering injection of CO_2 captured in IGCC in sub-seabed, as a expansion and extension of the R&DD of IGCC

○Future possible development of a large scale demonstration project to transport an d inject CO_2 from the coal gasification power plant.

Road Map


2000
2010
2020
2030
2040
2050
●Separation and capture of CO2
Drastic reduction of capture cost
Capture cost
4,200 JPY/t-CO2
2,000s JPY/t-CO2
1,500s JPY/t-CO2 addressed by practical use of separation membrane
1,000s JPY/t-CO2 (adoption of separation membrane on high-pressure gas)
- Chemical absorption, Physical absorption/adsorption, Membrane separation, Utilization of unused low-grade exhaust heat to regenerate absorbent, etc.
- Size increase in separation membrane, Successive production
●Geological storage of CO2
●Ocean sequestration of CO2
Leap in storage potential
Pilot study on geological storage
Large-scale demonstration
Full-scale domestic implementation of underground storage
- Aquifer, Waste oil and gas field, Coal seam
- Transportation technologies
- Dissolution and dilution, Deep-sea storage and sequestration, etc.
Supporting and related technologies
- Enhanced oil recovery (EOR)
- CO2 behavior analysis technologies
- Monitoring technologies
◆Integrated coal gasification fuel cell combined cycle (IGFC)
◆Integrated coal gasification combined cycle (IGCC)
◆High-efficiency natural gas fired power generation
Introduction/diffusion scenario
Separation and capture
Cost reduction of CO2 capture
System
Large-scale system demonstration
Successive application making sure of legal system development and social acceptance
Environmental impact evaluation and public acceptance (including monitoring for protocol post closure)
Others
Establishment of domestic laws, international rules, etc.
Evaluation of storage potential
Reinforcement of international cooperation

Guideline for the Safety and Environment for Large Scale Demonstrations

1. Status

- Public Consultation of Draft Guideline has just completed. (from May 1st to 31st)
- To be finalized in June.

2. Contents

(1) Necessary Geological Condition which Candidate Sites have to meet

(2) Condition for Transport of CO_2

(3) Safety Requirements for Construction of CCS Related Facilities

(4) Impact Assessment

(5) Safety Requirements for Drilling and Closure of the Well for injecting CO_2

(6) Safety Operation

(7) Requirement of CO_2 Density

(8) Monitoring

(9) Necessary Measures to be Taken in Case of Unusual Situation

IEA Greenhouse Gas R&D Programme

Introduction to Monitoring Requirements from Regulators

Tim Dixon
IEA Greenhouse Gas R&D Programme

Tokyo, 2-3 June 2009

- IPCC GHG Inventory Guidelines
- London and OSPAR Marine Treaties
- EU
- Australian
- US EPA draft Rule

IPCC Guidelines for GHG Inventories

- Apr 2006
- Vol 2 Energy, Chp 5 - *CO2 Transport, Injection and Geological Storage*

- Each site will have different characteristics
- **Methodology**

Site characterisation – inc leakage pathways

↓

Assessment of risk of leakage – modelling of CO_2 movement

↓ ↑

<u>Monitoring</u> – use results to validate/update modelling

↓

Reporting – inc CO2 inj and emissions from storage site

- For appropriately selected and managed sites, supports **zero leakage** assumption unless monitoring indicates otherwise

IPCC Guidelines for GHG – cont.

Monitoring Plan

- Measurement of background fluxes of CO_2
- Continuous measurement of CO_2 injected
- Monitoring of injection emissions
- Periodic monitoring of CO_2 distribution
- Monitoring of CO_2 fluxes to surface

- Post-injection monitoring – as above, linked to modelling, **may be reduced or discontinued once CO2 stabilises at its predicted long-term distribution**
- Incorporate improvements in technologies and techniques over time
- Non-prescriptive on monitoring technologies – each site is different

Monitoring technologies – Annex 1

- Deep subsurface technologies
- Shallow subsurface technologies
- Surface / water technologies

London Convention and Protocol

- Marine Treaty - Global agreement regulating disposal of wastes and other matter at sea
- Convention 1972 (85 countries), Protocol 1996 – ratified March 2006 (35 countries)
- Uncertainty over whether it prohibited some CCS project configurations

CCS work

- Assessed by LC Scientific Group
- 2006 - Risk Assessment Framework for CO2

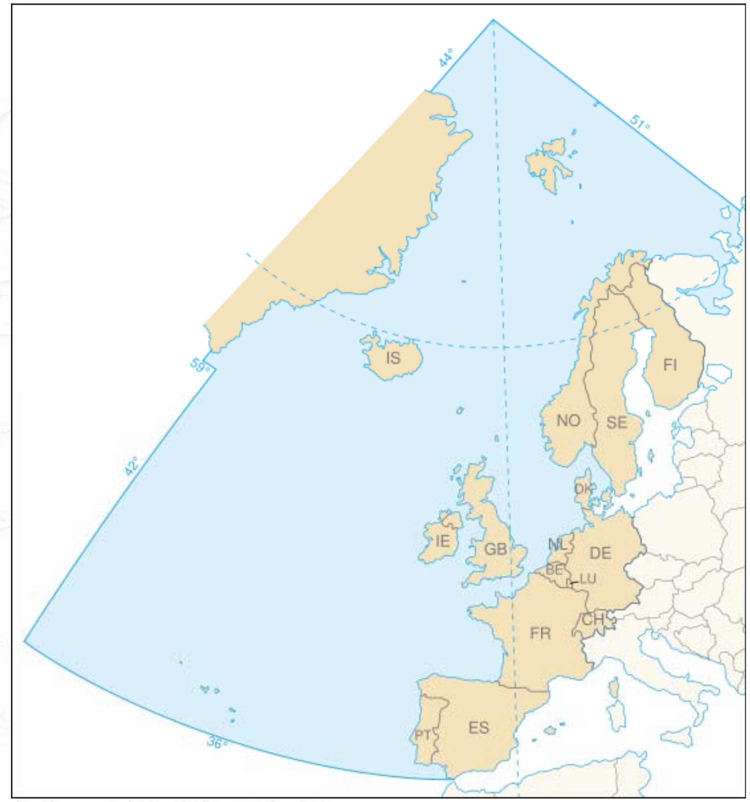
- To allow prohibited CCS Configurations - **amendment adopted** at 28th Consultative Meeting, 2 Nov 2006 - came into force 10 Feb 2007 **to allow disposal in geological formations**

- With 'CO2 Specific Guidelines' to be used by regulators for guidance

OSPAR

- Marine Treaty for NE Atlantic
- 15 nations and EC
- Prohibited some CCS configurations
- Considered CCS and CO2 impacts on seas

- To allow prohibited CCS configurations - **OSPAR amendments** (to Annexes II and III) for CO2 storage **adopted June 2007** - but need ratification by 7 Parties



- **OSPAR Decision** – requirement to use Guidelines when permitting.
- **OSPAR Guidelines** for Risk Assessment and Management of Storage of CO2 in Geological Formations – includes the Framework for Risk Assessment and Management (FRAM)
- Decision - Storage in water column prohibited

London and OSPAR Guidelines for Risk Assessment and Management

- **Scope** – scenarios, boundaries
- **Site selection and characterisation** – physical, geological, chemical, biological – using geological modelling
- **Exposure assessment** – characterisation CO2 stream, leakage pathways - characterisation and movement of the CO_2 stream within formations
- **Effects assessment** – sensitivity of species, communities, habitats, other users
- **Risk characterisation** – integrates exposure and effects - environmental impact, likelihood
- **Risk management** and permitting requirements – incl. **monitoring,** mitigation plans

LP Guidelines

- Monitoring of CO_2 migration has four elements:
- .1 performance monitoring;
- .2 monitoring the geological layers above the reservoir for CO2 and substances mobilized;
- .3 monitoring the seafloor and overlaying water to detect and measure leakage of CO2 and substances mobilized
- .4 monitoring benthic communities to detect and measure effects (of CO2, impurities, and mobilized substances)
-
- Until migration of CO_2 above the reservoir is detected and seen to possibly extend to the seafloor, monitoring the seafloor and overlaying water for leaking CO_2 may not be necessary. Similarly, until CO_2 is known to be leaking into the marine environment, biological monitoring may not be necessary.
- Methods chosen for monitoring should not compromise the integrity of a sealed formation. As confidence grows that CO_2 is not migrating from the reservoir, the frequency of measurement can be decreased.

OSPAR

- **Guidelines**
- a requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options; monitoring shall continue until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.

- Monitoring in the OSPAR Guidelines as in LP guidelines

EU CCS Directive

Enabling regulatory framework to ensure environmentally sound CCS (proposed Jan 2008, agreed Dec 2008))

- Follows IPCC GHG Guidelines and OSPAR
- Objective is permanent storage
- Storage permit only if “no significant risk of leakage”
- Emphasis on site selection and characterisation (details in Annex 1), risk assessment, monitoring plans (details in Annex 2)
- Doesn’t specify monitoring technologies
- Monitoring to:
  - Compare between actual and modelled behaviour
  - Detect significant irregularities, migration, leakage, environmental impacts

EU CCS Directive

- Permit application to include monitoring plan, including ETS monitoring,
- *(also reservoir pressure, pressure in connected hydraulic units to not cause any site to breach Directive).* Updated every 5 years.

- Post-closure plan to include monitoring

- Operator responsible until transfer to authority (min 20 years) – "all available evidence indicates that the stored CO_2 will be completely and permanently contained" ..."demonstrate, at least:

  (a) the conformity of the actual behaviour of the injected CO2 with the modelled behaviour,

  (b) the absence of any detectable leakage;

  (c) that the storage site is evolving towards a situation of long-term stability."

- Then authority responsible for monitoring – reduced to level to identify leakages or significant irregularities. Operator to contribute financially to cover 30 years such monitoring.

EU CCS Directive

- " 'significant irregularity' - any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health"

- " 'significant risk': means a combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without putting into question the purpose of this Directive for the storage site concerned"

EU CCS Directive – Annex 2 Monitoring Plan

To include rationale for monitoring technology, locations and timing.

To measure:
Fugitive emissions from injection
Volumetric flow at injection
Pressure and temp at injection
Chemical analysis
Reservoir temp and pressure

Non-prescriptive on technologies
To detect migration paths and plume behaviour

EU ETS Directive

Proposed 23 Jan 2008 - to strengthen, expand and improve the ETS from 2013. Now agreed.

CCS

- CCS fully included from 2013
- "the operator may subtract from the calculated level of emissions of the installation any CO_2 which is not emitted from the installation, but transferred out of the installation: to another installation holding a greenhouse gas emissions permit,"
    - Site and operation will need to comply with CCS Directive
    - Needs monitoring and reporting guidelines – underway
- No free allocation to CCS (same as electricity)
- Separate permitting of capture, transport and storage
- If any leakage – surrendering of allowances
- If leakage from storage suspected from monitoring under CCS Directive, then trigger ETS monitoring to quantify

EU ETS Revised MRG for Phase II

Measurement based. Boundaries specified.

- MRG for Capture
  - Measure CO2 transferred to transport, subtract from installation's calculated emissions
- MRG for Transport
  - Measure CO2 in and out (mass balance) – difference is leakage emission
  - Or, emission factors for each component
- MRG for Injection and Storage
  - Injection - Measure CO2 received and injected to storage (mass balance) – difference is leakage emission
  - Storage – leakage emissions to be measured.......

EU ETS Revised MRG - 2

Leakage emissions from storage

- Measurement based – based on monitoring
- Stepwise procedure based on IPCC GHG Guidelines = site characterisation and modelling + risk/peformance assessment + monitoring plan + modify in light of operational results
- Monitoring to detect leakage (CCS Directive)
- If detected, calculate amount :
  - Identify and characterise leakage source and pathway
  - Apply range of measurement techniques to estimate flux
  - Flux duration – backdated to a reference point
  - ➢ Total leakage amount tCO2 per day

Australian Legislation

- **Offshore Petroleum and Greenhouse Gas Storage Act 2006 (Nov 2008)**
- Access and property rights for waters under Commonwealth juristiction
- Site Plan – site characterisation, predictions, operations, monitoring, risk assessment and management, remediation
  - Monitoring – to detect "serious situation"
- Requires operators to bear the Commonwealth's costs of post-closing monitoring and verification
- 20-year limit following project closure on common law liability (5 +15). After this time, the Federal Government assumes long-term liability
- "No significant risk of significant adverse impact" (petroleum and ghg)
- Regulations and Guidelines under development.

Australian Legislation

- **Victoria Greenhouse Gas Geological Sequestration Act 2008**
- **Queensland Greenhouse Gas Storage Act 2009**
- Onshore
- State owns rights to storage reservoir
- GHG Substance = “overwhelmingly GHG included related substances”
- Exploration, Injection and <u>Monitoring</u> permits
- Injection and <u>Monitoring</u> Plan, Leakage pathways, impacts, probability
- <u>Monitoring</u> – to detect “serious situation”
- Costs of <u>monitoring</u> after licence surrender – licensee to pay (Vic)
- Surrender of License – State owns CO2, only if no risk to env and risk man plan OK (Vic).

US EPA proposed draft rule for CO_2 injection wells for geological sequestration

- III.A.6 Proposed Plume and Pressure Front Monitoring Requirements
  - for verification of model predictions
  - for changes in ground water quality
  - surface air/soil as last line of monitoring
  - site specific
  - monitor well materials for corrosion
  - pressure monitoring – including fall–off tests every five years
  - monitoring wells
  - geochemical monitoring -in and above confining system – including to detect mobilised substances ie heavy metals and organic contaminants
  - tracers optional
  - geophysical methods - describes

- Status - public consultation ended on 24 Dec 2008, EPA aiming to have a final rule published in late 2010 / early 2011.

Conclusions

- Monitoring of CO2 behaviour is central to the regulation of geological storage and to the ability for regulators to make assessments and decisions on granting, renewing and withdrawal of permits.

Regulatory lessons learnt

Regulatory principles for CCS to ensure environmental integrity:

- Site-by-site assessment
- Risk assessment
- Site characterisation and simulation, supported by **monitoring – non-prescriptive on technologies and techniques**
- CO_2 stream impurities determined by impacts on integrity
- = Flexibility in regulatory framework

Development of regulation:

- Use the technical and scientific evidence base
- Learn from existing regulatory developments
- Benefit of having real projects to drive and test regulations

IEA Greenhouse Gas R&D Programme

- General - www.ieagreen.org.uk
- CCS - www.co2captureandstorage.info

M&V –

A regulators view

John Frame

EPA Victoria

EPA VICTORIA

Victoria The Place To Be

The Otway Basin Pilot Project

- Regulation started with a blank sheet
- Agreed to milestones (KPIs) developed by the project and used in approval
- EPA, DPI and CO2CRC noted regulatory framework not clear but agreed framework necessary.
- Worked with other Govt agencies to provide a regulatory framework

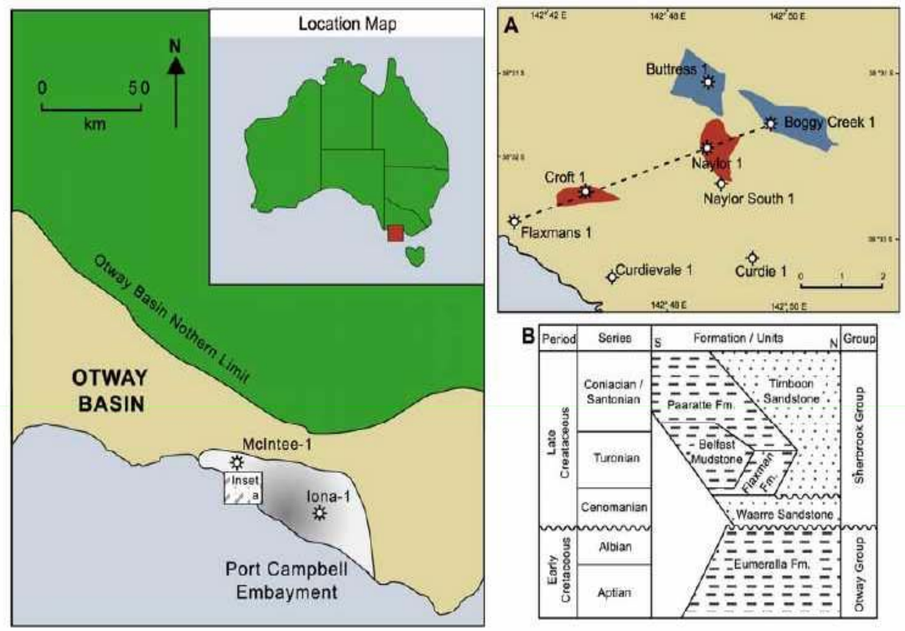


Figure 15. Location, fields (red is methane, blue is carbon dioxide) and simplified vertical section.

Victorian Legislation

- Onshore CCS subject to *Greenhouse Gas Geological Sequestration Act 2008* which comes into force 1 Jan 2010
- Undertakes two tasks resource allocation and M&V
- Environment protection remains under *Environment Protection Act.*
- Offshore being developed by Commonwealth Govt.
- Key aspect is requirement for development of "monitoring and verification plans" for different phases of CCS.
- All M&V plans subject of review by the environmental regulator (EPA Victoria).

What will the Act require?

EPA VICTORIA

- This is uncertain at the moment as the regulations required by the Act are being prepared.
- However, experience with Otway trial leads me to want to know answers to

  - ❖ What will you need to know from a M&V program?
  - ❖ What will you require as M&V outcomes?

What will you need to know from an M&V program?

- Location of CO_2 (Monitoring)
- Evidence that the CO_2 is not having or going to impact on other aquifers or the surface (Monitoring)
- Evidence the CO_2 is behaving as expected (Verification)

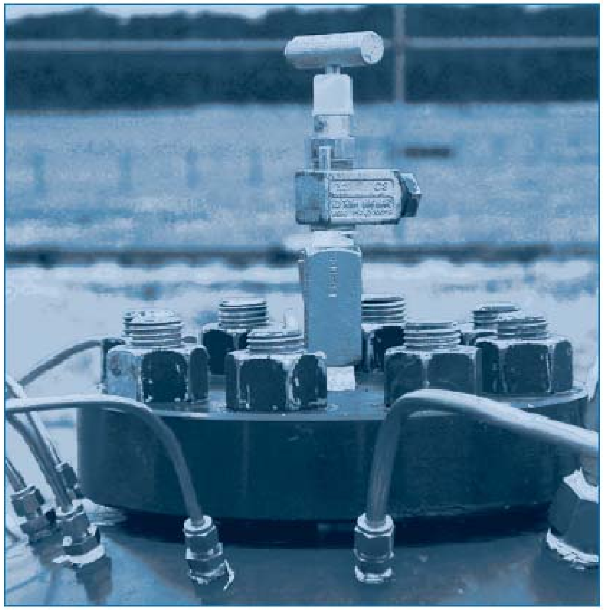

Table 25. M&V Trigger Points.

Phase	M&V Tasks	Trigger Points	Expected Outcomes	KPI's
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

What will you require as M&V outcomes?

EPA VICTORIA

- Ability to detect and quantify leaks
- Ability to detect any behaviour having an adverse impact.
- A suite of techniques that enable matching the risk to the environment to the cost of the monitoring and the phase of the project
- Ability to verify the milestones in the project
- Suitable methods for communicating the results to the community
- Assurance that if CO_2 behavior continues will not have adverse environmental impact



The Naylor well is equipped with monitoring sensors. Reservoir fluids are retrieved through the tubes shown for laboratory analysis.

CCS Monitoring under the Marine Pollution Prevention Law

HIROTAKA　HAMANAKA
Ministry of Environment, JAPAN

June 3, 2009
5th Meeting of the IEA-GHG Monitoring Network

Outline

1. Amendment to the London Protocol 1996 and the Marine Pollution Prevention Law
2. Monitoring Requirements under the Marine Pollution Prevention Law
3. Research Project – Development of CO_2 Seepage Monitoring Methodology

Amendment to the Marine Pollution Prevention Law

- October 2006
  Amendment to *the London Protocol 1996*
  ⇨ Enables offshore CCS under the framework of the international convention
- May 2007
  Amendment to *the Marine Pollution Prevention Law*
- September 2007
  Amendment or new establishment of the related regulations (Cabinet Order, Ordinance, Notification)
- November 2007
  Japan ratified *the London Protocol 1996*

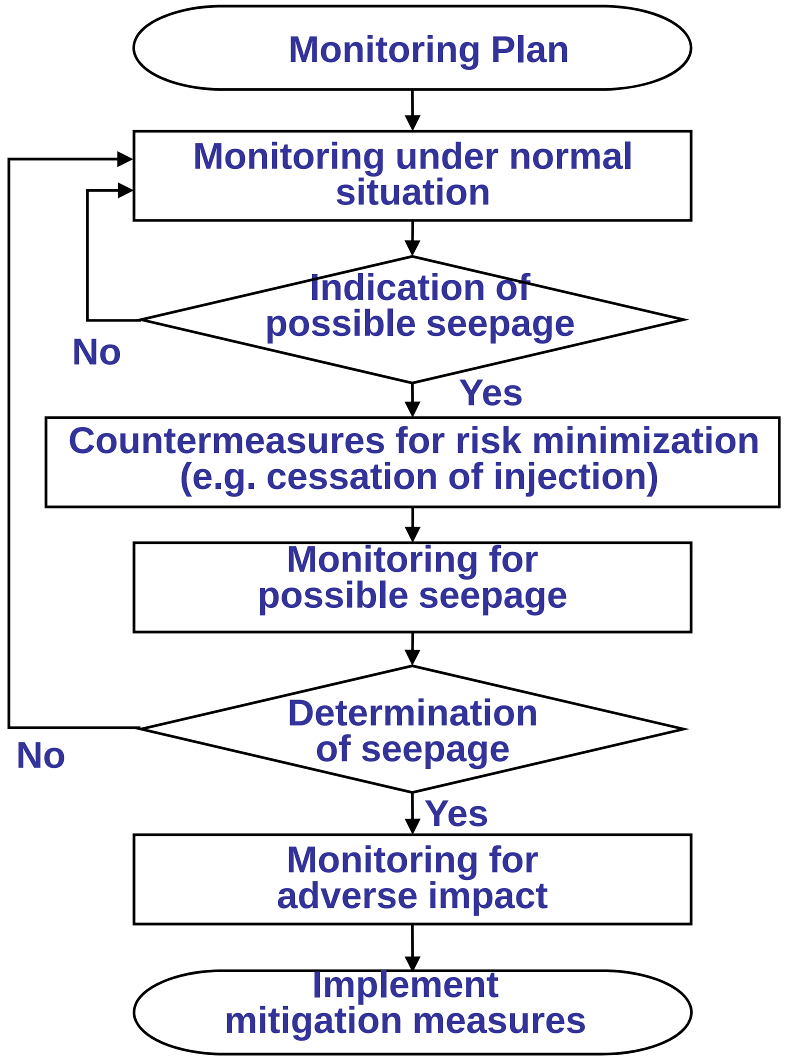
Regulating Offshore CCS under the Marine Pollution Prevention Law

- Principle purpose of the Law:
  Marine Environment Protection
- Regulate only offshore CCS
- Permit from Minister of the Environment is required （every 5 years）
- Applicants are required to provide:
  - Environmental Impact Assessment Report
  - Monitoring Plan
  - Mitigation Plan, and others

Monitoring Requirements (1)

- Marine Pollution Prevention Law (Article 18.8-2.3)

  "Monitoring Plan for Pollution"
- Ordinance for offshore CCS permission (Article 1-3)
- Notification of offshore CCS permission (Article 2-3)



Monitoring Requirements (2)

- Monitoring under normal situation (Notification 2-3(3))
  - Characteristics of CO_2 stream (once a year or more, during injection)
    - Volume, purity (percentage of CO_2 and other substances)
    - Continuous monitoring of injection pressure, injection rate, temperature
  - Condition of the site
    - Condition of geological formation, such as formation pressure and temperature (once a year or more)
    - Front and extent of CO_2 plume (approx. twice in permit period)
    - Chemical characteristics of seawater (once a year)
    - Condition of marine organisms and status of sea usage (once in permit period or more)

Monitoring Requirements (3)

- Monitoring for possible CO_2 seepage (Notification 2-3(1))

  When there are possibilities of adverse effect on marine environment from CO_2 seepage, specific monitoring should be conducted to determine the impact or evaluate the risk.

  ⇒ Quick, wide-area, and accurate monitoring is required

- Monitoring for adverse impact in case of CO_2 seepage (Notification 2-3(2))

  When seepage adversely impacts the marine environment or the risk is high, specific monitoring should be conducted.

  ⇒ Identifying the seepage location, understanding the severity of the impact, planning specific mitigation measures

Monitoring Requirements (4)

- Post injection requirement
  - Monitoring should be conducted for a reasonable period.
  - Duration? Frequency?

⇨ To continue to be discussed as a future issue, while reviewing the results from our ongoing research projects as well as new knowledge and findings from CCS activities worldwide.

Challenges

- To what extent can monitoring assure the safety of CCS?
- What technology can be applied to CCS monitoring? – What can monitoring do and not do?
- What should regulators expect from operators in terms of monitoring?

Research Project

Investigating the Environmental Management System for Offshore CCS

As the responsible authority, the MOE has started to obtain the necessary knowledge and resources to adequately examine the permit applications (e.g. monitoring plan)
…the guideline for permit review to be established in the near future

Two 3-year project in progress:

- Development of EIA Methodology
- Development of Marine Monitoring Methodology

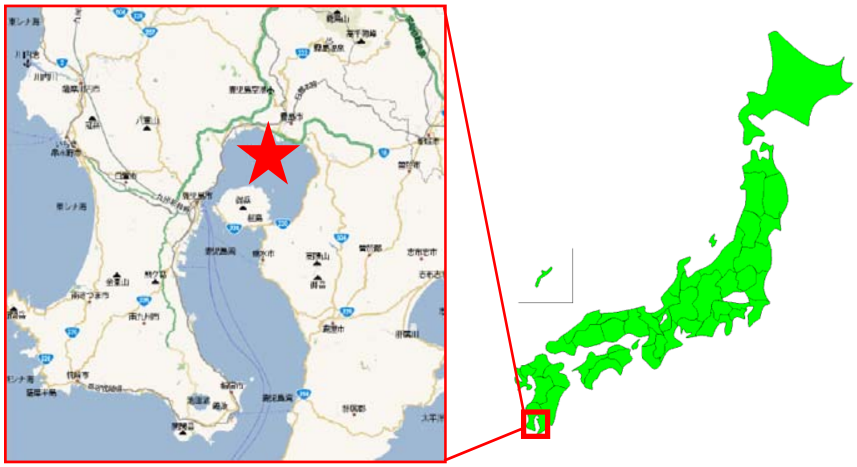
Purposes of the Project

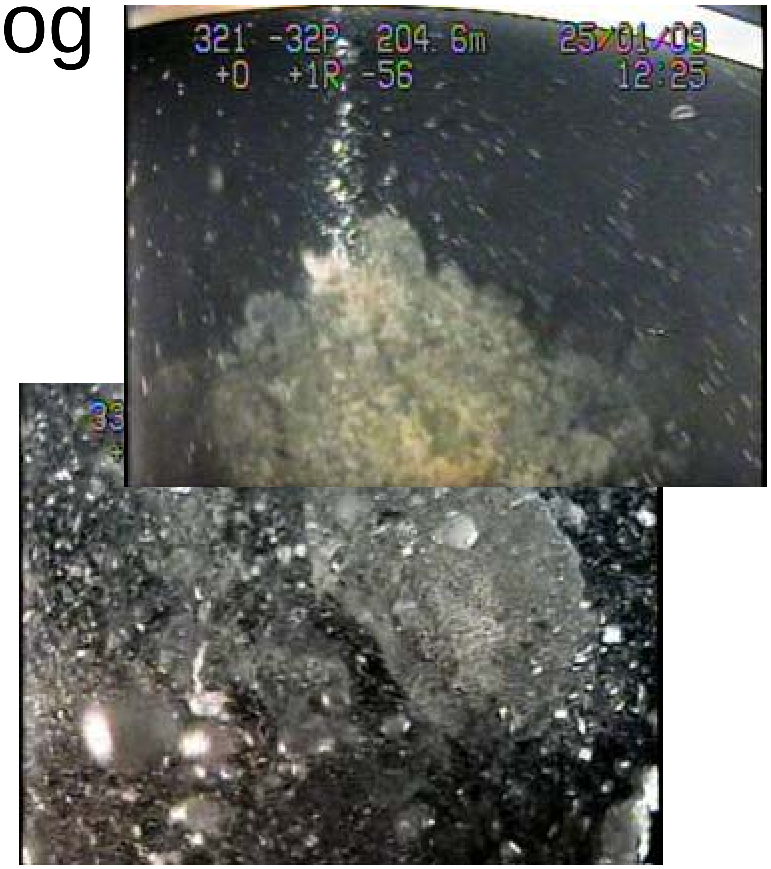
- Development of EIA Methodology
  - Development of seepage scenarios
  - Development of ocean model to simulate seepage and its impact
  - Establishment of ocean EIA methodology for CCS
  - Aggregate the scientific data of CO_2 impact on marine organisms
- Development of CO_2 Seepage Monitoring
  - Indicators of CO_2 seepage: chemical property of seawater and sediments
  - Monitoring methodology of CO_2 seepage into the ocean

Development of CO_2 Seepage Monitoring Methodology (1)

Phase I (2008 fall – 2009 summer)

Utilization of natural analog





CO_2-rich volcanic gas from
Wakamiko Submarine Caldera

Development of CO_2 Seepage Monitoring Methodology (2)

Phase I (2008 fall – 2009 summer)

- Chemical analysis of seawater and sediments (pH, total CO_2, alkalinity etc.)
- pH sensor on seabed
- Sidescan sonar and fish finder – gas bubble detection

Expecting results and issues

- Annual CO_2 flux: seasonal thermocline to be considered
- Detection limit for CO_2 seepage
- Monitoring methodologies in shallow waters and open seas

Development of CO_2 Seepage Monitoring Methodology (3)

Phase II (2009)

- Assessment of Phase I results and issues and further investigation

  (Examples)

  – Chemical analysis improvement: spatial coverage of monitoring, monitoring in shallow waters etc.

  – Development of CO_2 detection by physical property monitoring: density change etc.

- Examine reasonable monitoring methodology for the possible CCS sites
  – Parameters
  – Methods
  – Sampling intervals, and others

Development of CO_2 Seepage Monitoring Methodology (4)

Phase III (planned)

- To be adjusted flexibly for CCS progress and situation in Japan

  (examples)

  – Coordination with the large scale demonstration project

  – Baseline measurements in the areas with high storage potential

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チーム・マイナス6%

Thank you.

Western State Region Regulatory Approaches to CCS

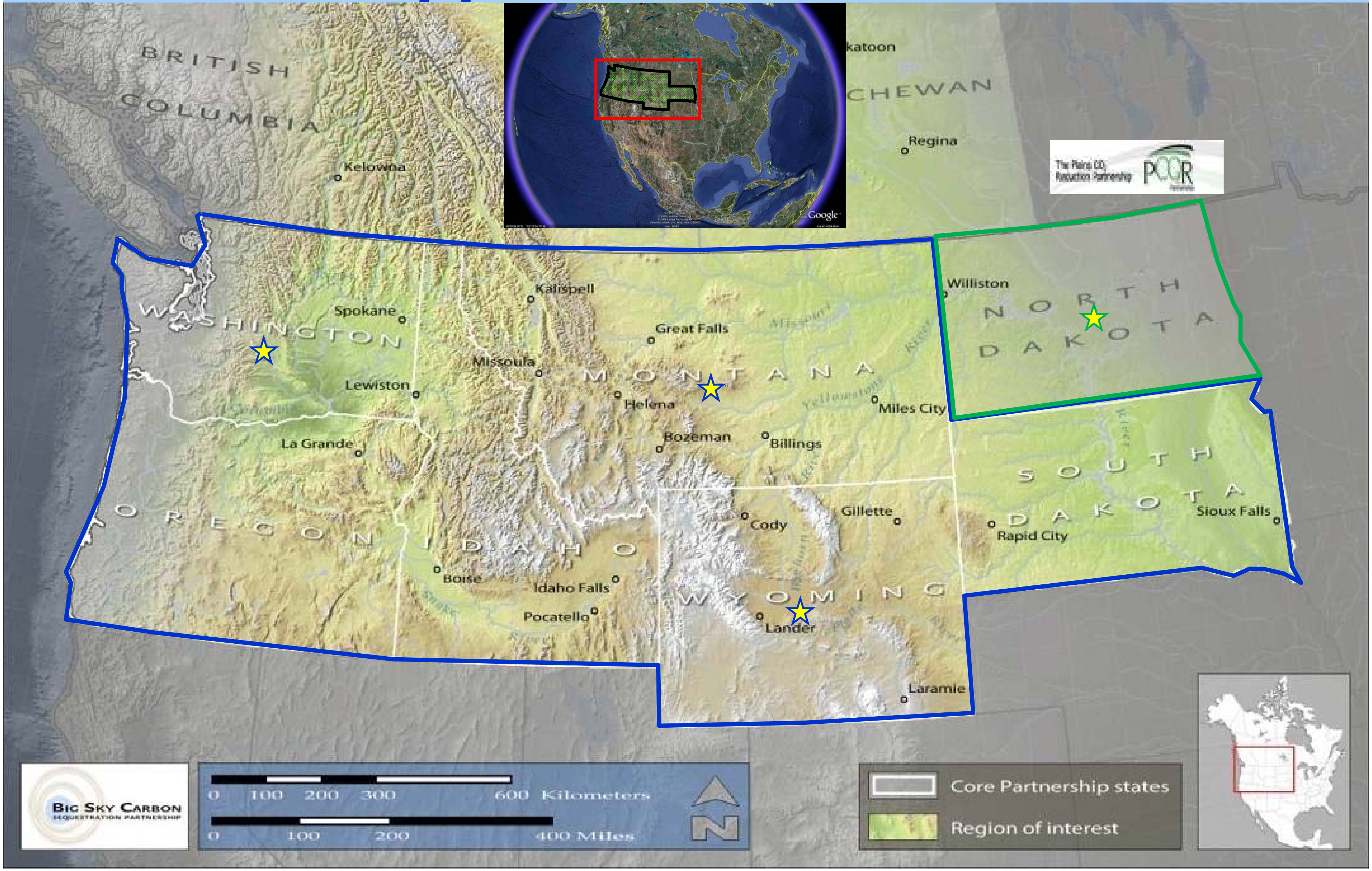
Lee Spangler and John Talbott
Big Sky Carbon Sequestration Partnership
Montana State University

- **To date, Wyoming, Montana, Washington, (Big Sky Partnership Region) and North Dakota (PCOR Region) have developed specific statutory requirements to regulate geologic sequestration of CO2**
- **Oregon, South Dakota and Washington also have terrestrial sequestration statutes to establish registries and to promote carbon markets for agricultural and forestry practices**

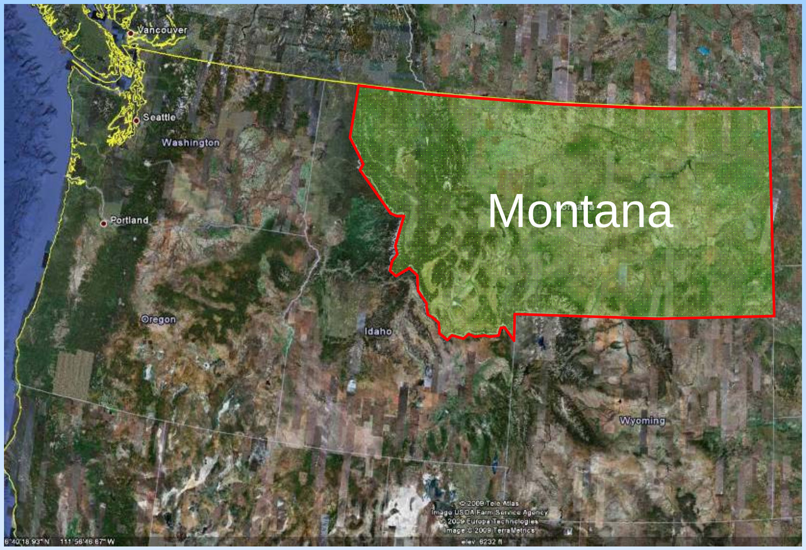
Big Sky Carbon Sequestration Partnership

Montana State University

Western State Region Regulatory Approaches to CCS



A Brief Comparison of Japan and Montana



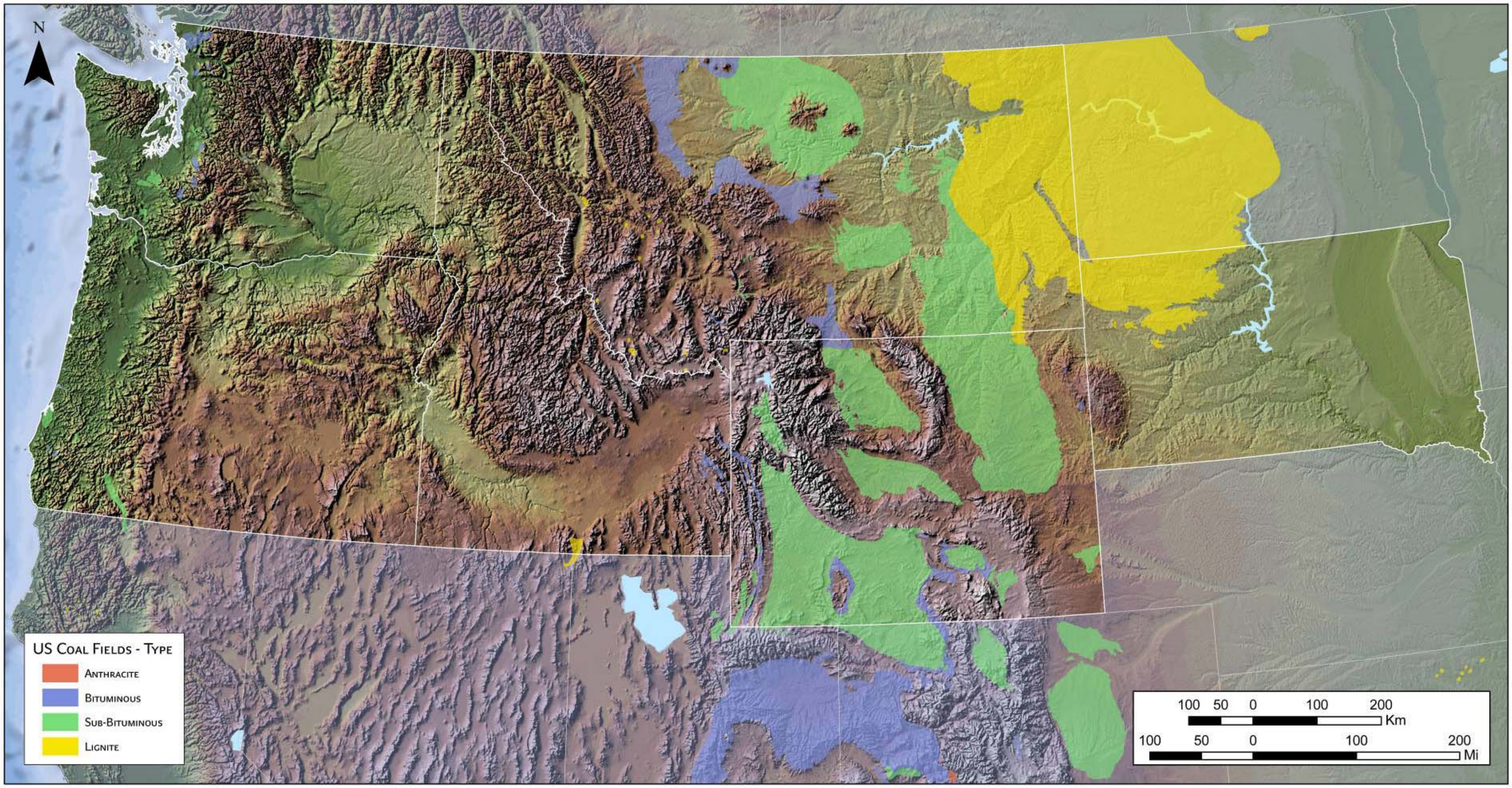
Area: 380,837 km²
6% of world's coal reserves
Large sedimentary Basins
Agriculture (snowpack dependent)
Population: 967,440

Area: 377,930 km²
Population: 127,078,680

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

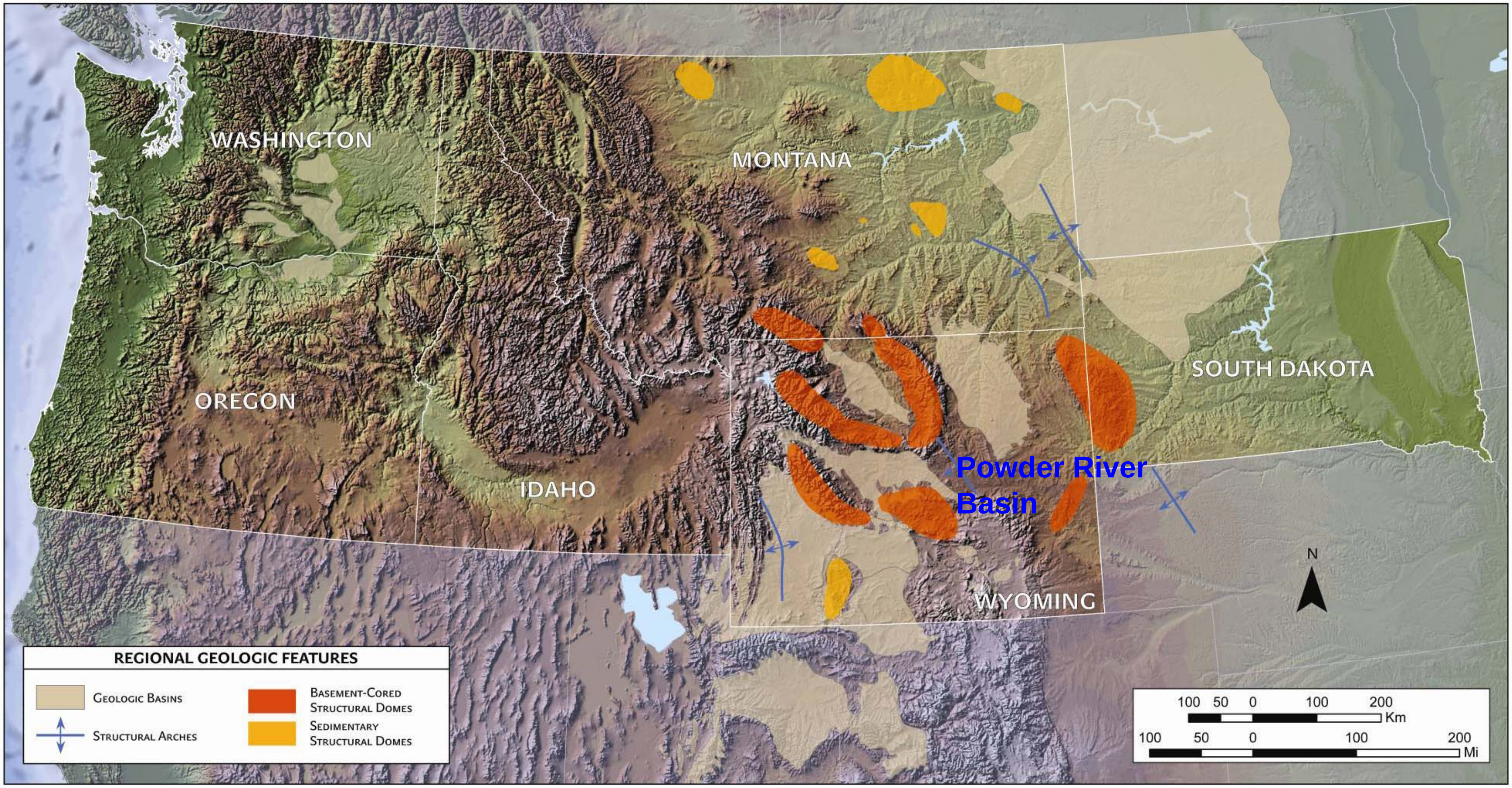
Regional Coal in the Big Sky Region



Big Sky Carbon Sequestration Partnership

Montana State University

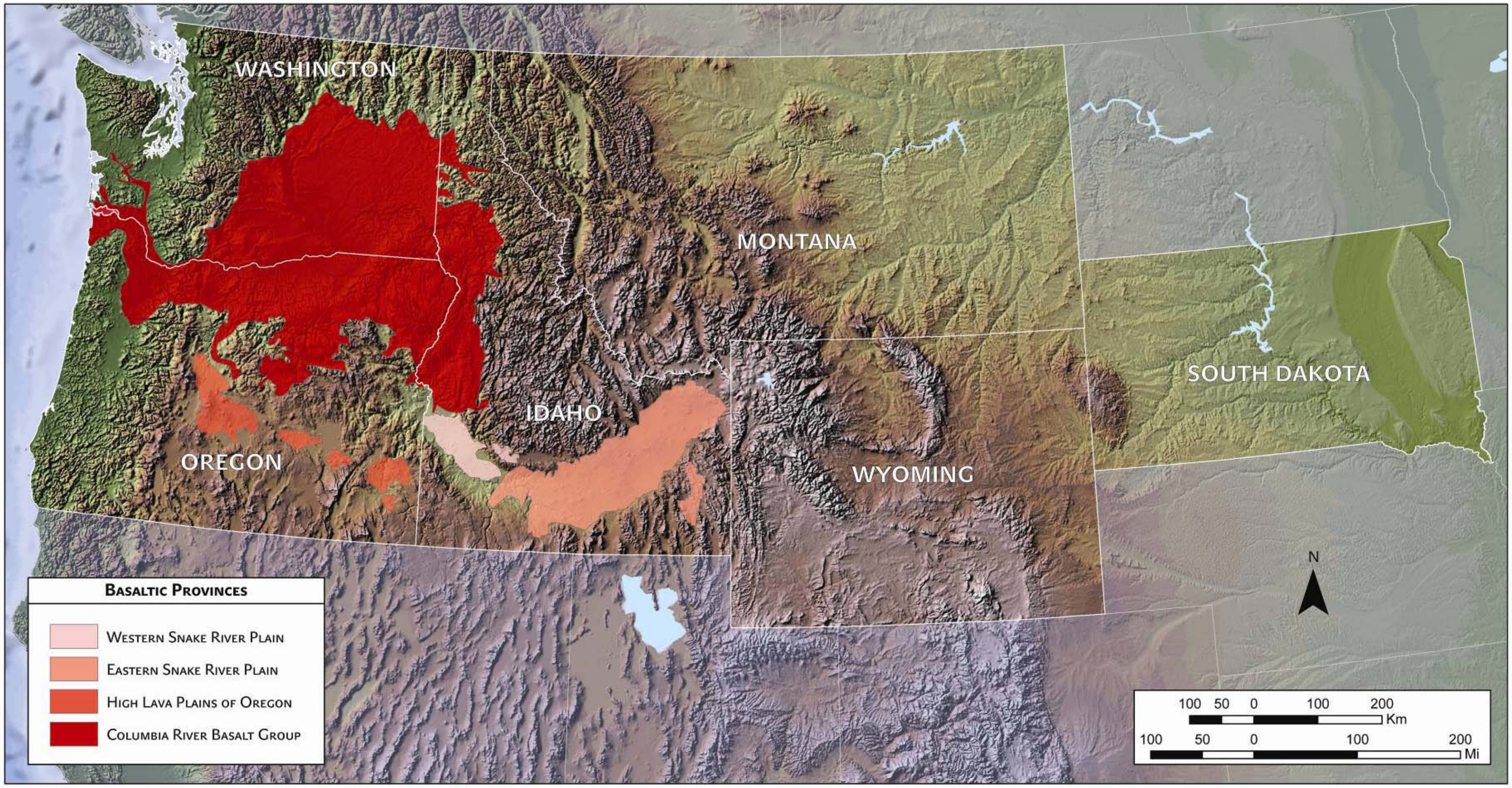
Regional Basins



Big Sky Carbon Sequestration Partnership

Montana State University

BASALTIC PROVINCES OF THE BIG SKY REGION



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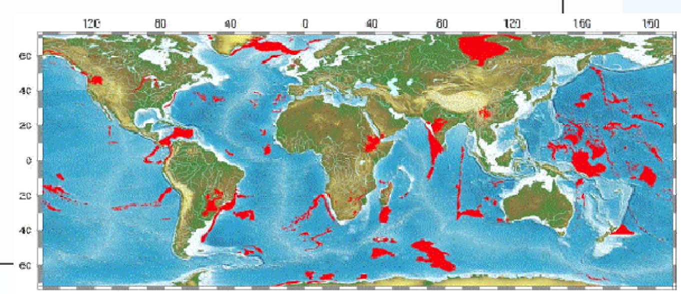
BIG SKY CARBON SEQUESTRATION PARTNERSHIP



BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Geologic Sequestration

Requirements	Wyoming	Montana	North Dakota	Washington
UIC Primacy	Yes	No	Yes	Yes
Pore Space Owner	Surface Owner	Surface Owner	Surface Owner	State
Split Estate w/ Minerals	Mineral Estate Dominant – no injection in structures with HC	Equal Standing	Equal Standing	Equal Standing
Regulating Agency	DEQ/WOGCC	MBOG/DEQ/ DNRC	Industrial Commission/Health Department	WDOE
Unitization Requirement	75%	60%	60%	Not Defined
Fee Structure	Application Fee	per/T charge TBD	per/T charge TBD	Application Fee
Financial Responsibility	Surety Bond TBD	Surety Bond TBD	Surety Bond TBD	Financial Assurance Mechanism
Release of Liability to third party	UIC Requirement – No State Ownership	15	10	Determined post-closure and does not terminate with permit termination
Other constituents allowed in injection stream	Yes	Yes	Yes	No
Area of Review beyond predicted plume size	1 Mile	½ Mile	¼ Mile	10 Miles
Separate Process for Research Wells	Yes	No	Yes	Yes

State Primacy for the UIC Program

Requirements	Wyoming	Montana	North Dakota	Washington
UIC Primacy	Yes	No	Yes	Yes

- States can elect to accept primacy for the Underground Injection Control (UIC) Program of the Safe Drinking Water Act (SDWA).
- Montana's adoption of new CCS statutory authority is predicated on assumption of primacy from EPA and the statute is not valid until EPA grants primacy.
- WY, ND, and WA currently have primacy over the UIC program.

Big Sky Carbon Sequestration Partnership

Montana State University

Pore Space Ownership

Requirements	Wyoming	Montana	North Dakota	Washington
Pore Space Owner	Surface Owner	Surface Owner	Surface Owner	State

- Many states that harbor significant subsurface mineral and/or oil and gas deposits create a "split estate" that separates the surface estate from the mineral estate.
- Within the subsurface there are pore spaces or voids that are not occupied by minerals or oil and gas and these spaces are statutorily assigned to the surface owner in WY, MT and ND independent of the mineral estate.
- WA does not define nor establish ownership of the pore space.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Dominance of Subsurface Ownership

Requirements	Wyoming	Montana	North Dakota	Washington
Split Estate w/ Minerals	Mineral Estate Dominant – no injection in structures with HC	Equal Standing	Equal Standing	Equal Standing

- Wyoming established dominance of the mineral estate over the pore space ownership. Geologic storage in the pore space is prohibited without the consent of the mineral estate owner. Geologic storage is prohibited in formations that contain commercial quantities of hydrocarbons. This does not apply to EOR operations.

- The other states all give equal standing to the mineral estate and the pore space owner and require that neither approach can interfere with the other.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Regulatory Agency

Requirements	Wyoming	Montana	North Dakota	Washington
Regulating Agency	DEQ/WOGCC	MBOG/DEQ/ DNRC	Industrial Commission/Health Department	WDOE

- For Wyoming and Montana, primary responsibility for geologic sequestration rests with the state environmental agency and the oil and gas agency. However, the environmental agency has a consultative role in MT and the oil and gas agency a consultative role in WY. ND has an arrangement similar to MT.

- The Washington Department of Ecology has sole responsibility for CCS activities in that state.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Unitization of Pore Space

Requirements	Wyoming	Montana	North Dakota	Washington
Unitization Requirement	75%	60%	60%	Not Defined

- During geologic sequestration, the plume may extend across several surface owners. To facilitate cooperation among surface owners, the storage reservoir can be "unitized" to establish volumes occupied for each surface owner for pricing purposes and to require some surface owners to cooperate with the injection even though they may object to the project. As noted in the table, each state (except WA) has determined that a majority (60-75%) of affected surface owners agreeing to the occupancy of the pore space will require adjoining affected landowners to cooperate as well. This approach is similar to eminent domain.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Fee Structure

Requirements	Wyoming	Montana	North Dakota	Washington
Fee Structure	Application Fee	per/ton charge TBD	per/ton charge TBD	Application Fee

- To protect the public from an operator that does not properly operate the site or abandons the site prior to closure, states have imposed a fee structure that places funds in a dedicated account to reimburse the state should the government have to assume responsibility for the site. This is done through application fees and annual operating fees, and through a per ton charge levied on each ton of CO2 placed in the reservoir (MT and ND). The fees can also be used to administer the program and to monitor operations.

Financial Responsibility

Requirements	Wyoming	Montana	North Dakota	Washington
Financial Responsibility	Surety Bond TBD	Surety Bond TBD	Surety Bond TBD	Financial Assurance Mechanism

- Operators of geologic sequestration sites are required to maintain financial responsibility for the site, including any mitigation of leaks, contamination of ground water, etc, for the life of the injection and for a varying period of time post-closure of the site. All states accept a surety bond in an amount determined by the regulatory agency and Washington allows for other financial assurance instruments including letters of credit, cash, and liability insurance policies.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Release of Liability

Requirements	Wyoming	Montana	North Dakota	Washington
Release of Liability to third party	UIC Requirement – No State Ownership	15	10	Determined post-closure and does not terminate with permit termination

- Once injection ceases, each state requires a post injection monitoring period to ensure that the CO2 stabilizes and that no problems arise concerning containment of the gas.
- Wyoming follows UIC guidance for Class V wells and for proposed Class VI wells that would maintain responsibility for 50 years.
- Montana and ND assume responsibility for the site after 15 years and 10 years respectively.
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BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

CO2 Purity

Requirements	Wyoming	Montana	North Dakota	Washington
Other constituents allowed in injection stream	Yes	Yes	Yes	No

- MT and ND require the injection stream to be of sufficient purity that it does not compromise the ability of the reservoir to store the injected CO2.
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BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Research Wells

Requirements	Wyoming	Montana	North Dakota	Washington
Separate Process for Research Wells	Yes	No	Yes	Yes

- To properly characterize a geologic sequestration site, it is often necessary to drill research wells involving the injection of small volumes of CO2 to determine injectivity and capacity of the storage reservoir.

- WY, ND, and Washington have established regulatory provisions that allow much easier permitting processes for research wells. MT statutes currently have no such provision.

Geologic Sequestration

Requirements	Wyoming	Montana	North Dakota	Washington
UIC Primacy	Yes	No	Yes	Yes
Pore Space Owner	Surface Owner	Surface Owner	Surface Owner	State
Split Estate w/ Minerals	Mineral Estate Dominant – no injection in structures with HC	Equal Standing	Equal Standing	Equal Standing
Regulating Agency	DEQ/WOGCC	MBOG/DEQ/ DNRC	Industrial Commission/Health Department	WDOE
Unitization Requirement	75%	60%	60%	Not Defined
Fee Structure	Application Fee	per/T charge TBD	per/T charge TBD	Application Fee
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Other constituents allowed in injection stream	Yes	Yes	Yes	No
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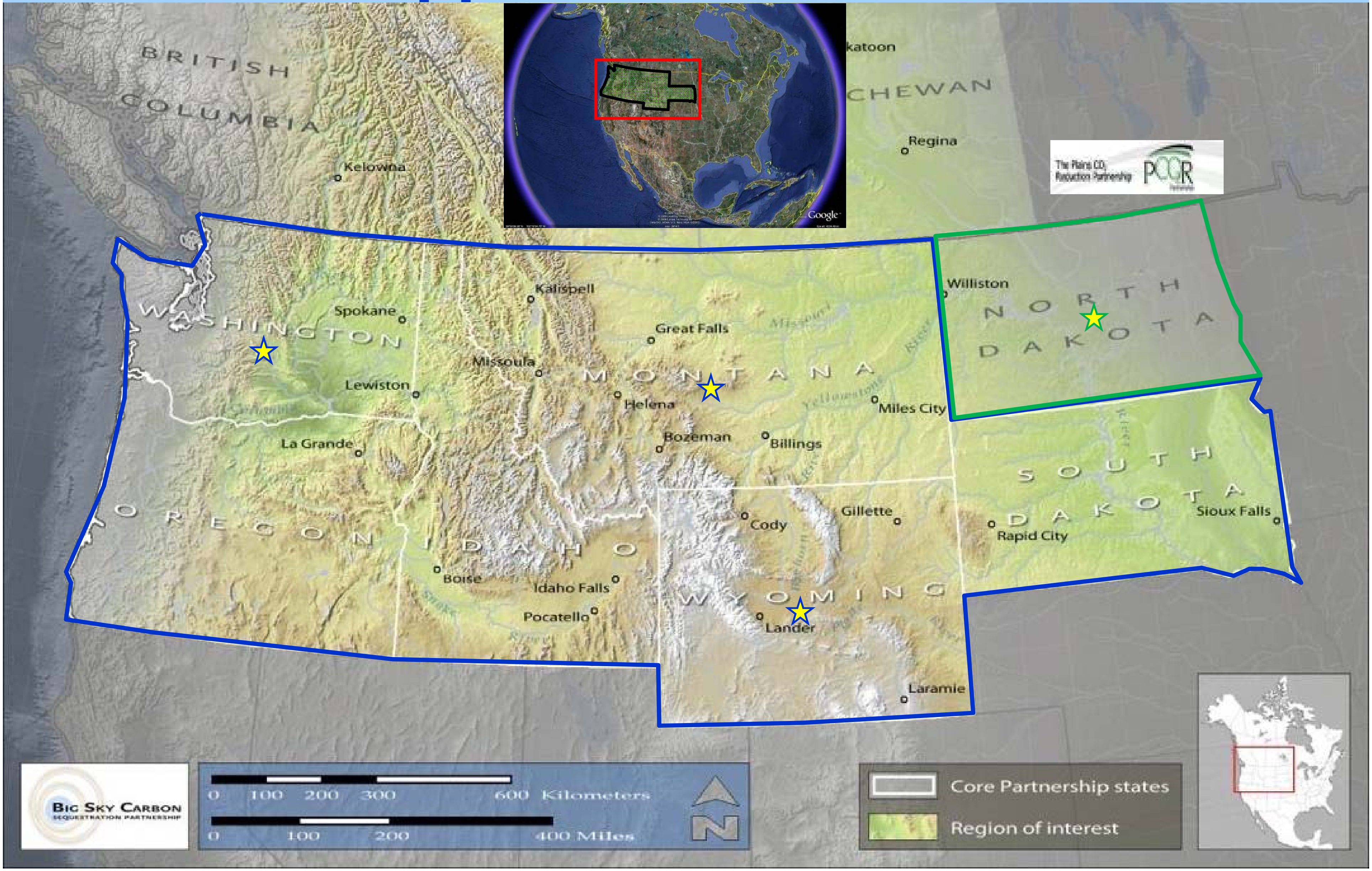
Separate Process for Research Wells	Yes	No	Yes	Yes

Western State Region Regulatory Approaches to CCS

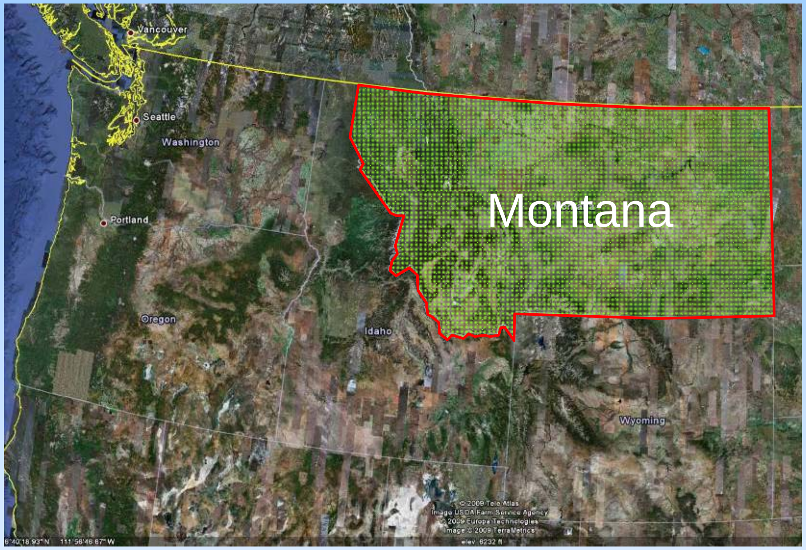
Lee Spangler and John Talbott
Big Sky Carbon Sequestration Partnership
Montana State University

- **To date, Wyoming, Montana, Washington, (Big Sky Partnership Region) and North Dakota (PCOR Region) have developed specific statutory requirements to regulate geologic sequestration of CO2**
- **Oregon, South Dakota and Washington also have terrestrial sequestration statutes to establish registries and to promote carbon markets for agricultural and forestry practices**

Western State Region Regulatory Approaches to CCS



A Brief Comparison of Japan and Montana



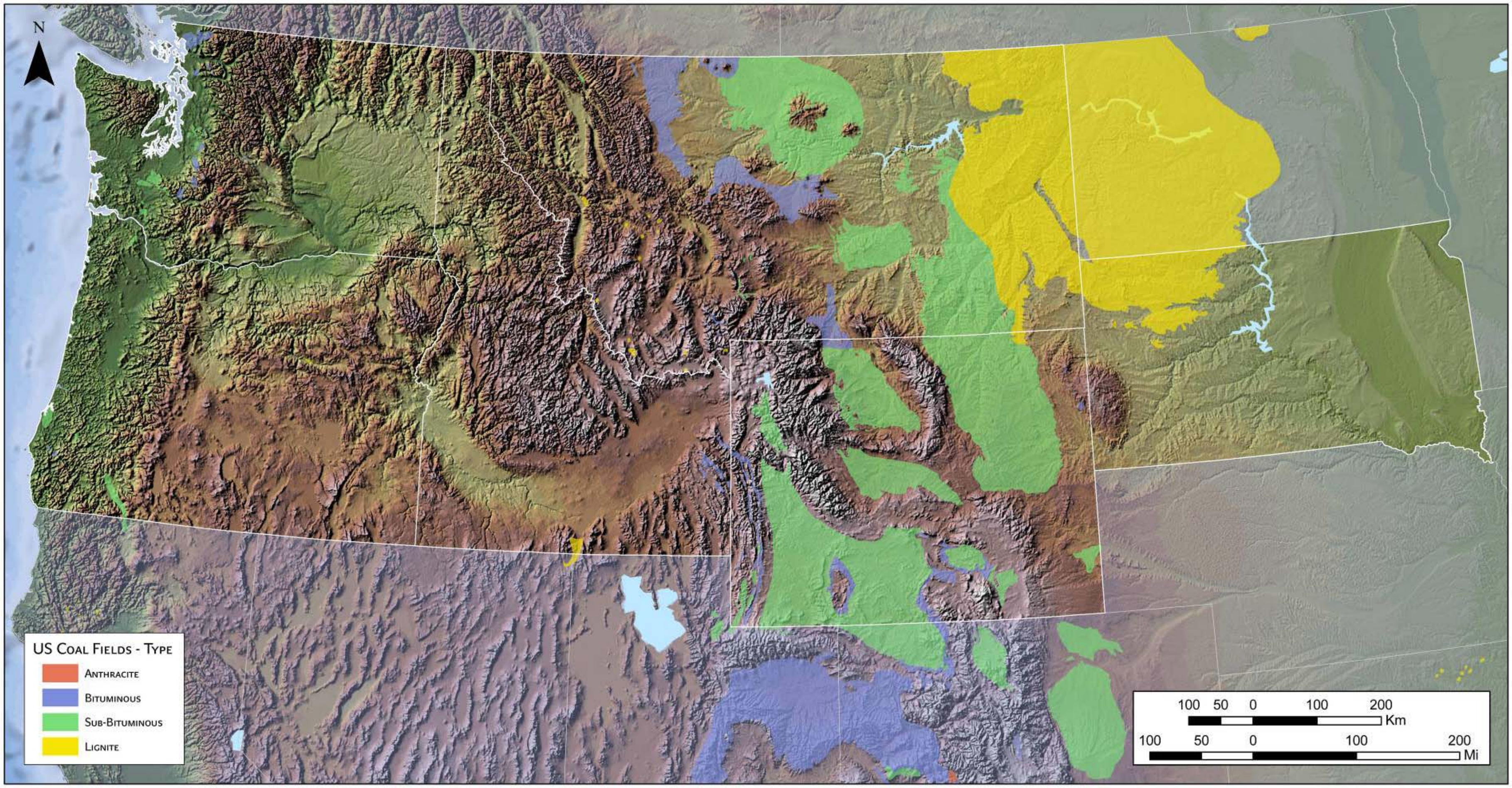
Area: 380,837 km²
6% of world's coal reserves
Large sedimentary Basins
Agriculture (snowpack dependent)
Population: 967,440

Area: 377,930 km²
Population: 127,078,680

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Regional Coal in the Big Sky Region



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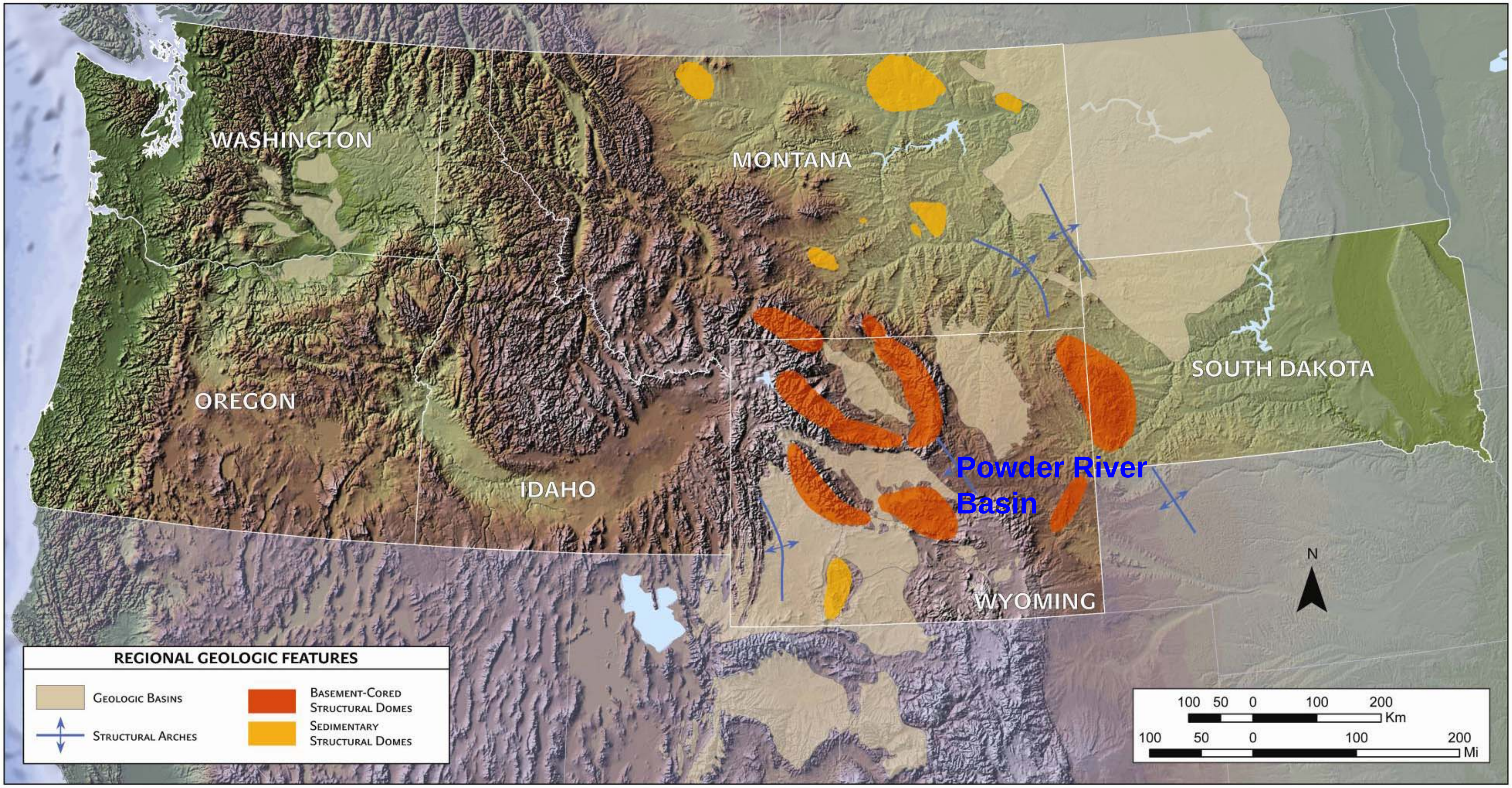
Montana State University

Regional Basins



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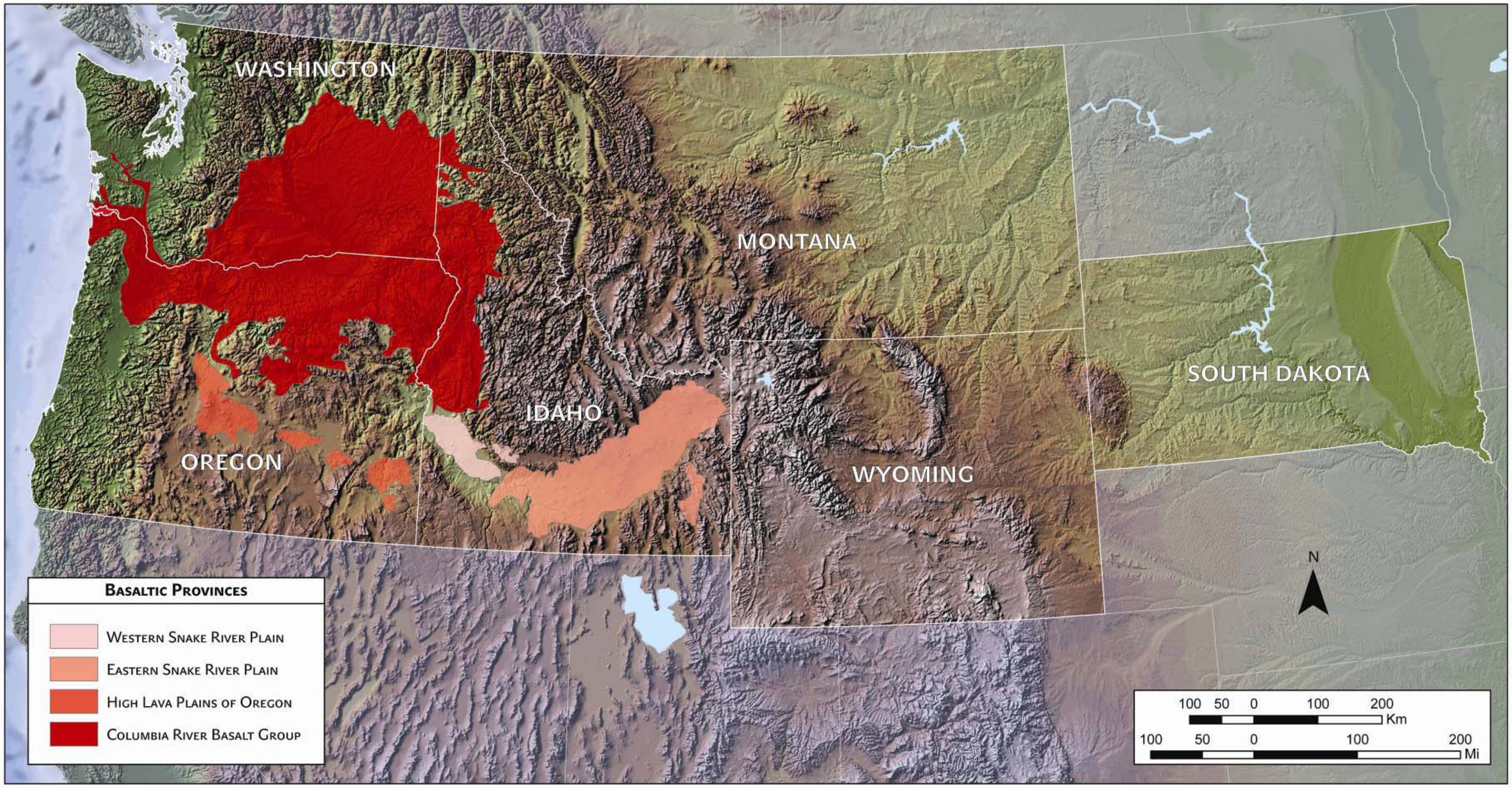
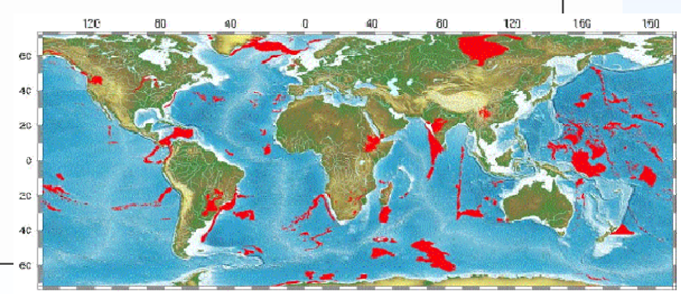
Montana State University

BASALTIC PROVINCES OF THE BIG SKY REGION



MONTANA STATE UNIVERSITY

BIG SKY CARBON SEQUESTRATION PARTNERSHIP



BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

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Area of Review beyond predicted plume size	1 Mile	½ Mile	¼ Mile	10 Miles
Separate Process for Research Wells	Yes	No	Yes	Yes

State Primacy for the UIC Program

Requirements	Wyoming	Montana	North Dakota	Washington
UIC Primacy	Yes	No	Yes	Yes

- States can elect to accept primacy for the Underground Injection Control (UIC) Program of the Safe Drinking Water Act (SDWA).
- Montana's adoption of new CCS statutory authority is predicated on assumption of primacy from EPA and the statute is not valid until EPA grants primacy.
- WY, ND, and WA currently have primacy over the UIC program.

Big Sky Carbon Sequestration Partnership

Montana State University

Pore Space Ownership

Requirements	Wyoming	Montana	North Dakota	Washington
Pore Space Owner	Surface Owner	Surface Owner	Surface Owner	State

- Many states that harbor significant subsurface mineral and/or oil and gas deposits create a "split estate" that separates the surface estate from the mineral estate.

- Within the subsurface there are pore spaces or voids that are not occupied by minerals or oil and gas and these spaces are statutorily assigned to the surface owner in WY, MT and ND independent of the mineral estate.

- WA does not define nor establish ownership of the pore space.

Dominance of Subsurface Ownership

Requirements	Wyoming	Montana	North Dakota	Washington
Split Estate w/ Minerals	Mineral Estate Dominant – no injection in structures with HC	Equal Standing	Equal Standing	Equal Standing

- Wyoming established dominance of the mineral estate over the pore space ownership. Geologic storage in the pore space is prohibited without the consent of the mineral estate owner. Geologic storage is prohibited in formations that contain commercial quantities of hydrocarbons. This does not apply to EOR operations.

- The other states all give equal standing to the mineral estate and the pore space owner and require that neither approach can interfere with the other.

Big Sky Carbon Sequestration Partnership

Montana State University

Regulatory Agency

Requirements	Wyoming	Montana	North Dakota	Washington
Regulating Agency	DEQ/WOGCC	MBOG/DEQ/ DNRC	Industrial Commission/Health Department	WDOE

- For Wyoming and Montana, primary responsibility for geologic sequestration rests with the state environmental agency and the oil and gas agency. However, the environmental agency has a consultative role in MT and the oil and gas agency a consultative role in WY. ND has an arrangement similar to MT.

- The Washington Department of Ecology has sole responsibility for CCS activities in that state.

Unitization of Pore Space

Requirements	Wyoming	Montana	North Dakota	Washington
Unitization Requirement	75%	60%	60%	Not Defined

- During geologic sequestration, the plume may extend across several surface owners. To facilitate cooperation among surface owners, the storage reservoir can be "unitized" to establish volumes occupied for each surface owner for pricing purposes and to require some surface owners to cooperate with the injection even though they may object to the project. As noted in the table, each state (except WA) has determined that a majority (60-75%) of affected surface owners agreeing to the occupancy of the pore space will require adjoining affected landowners to cooperate as well. This approach is similar to eminent domain.

Fee Structure

Requirements	Wyoming	Montana	North Dakota	Washington
Fee Structure	Application Fee	per/ton charge TBD	per/ton charge TBD	Application Fee

- To protect the public from an operator that does not properly operate the site or abandons the site prior to closure, states have imposed a fee structure that places funds in a dedicated account to reimburse the state should the government have to assume responsibility for the site. This is done through application fees and annual operating fees, and through a per ton charge levied on each ton of CO2 placed in the reservoir (MT and ND). The fees can also be used to administer the program and to monitor operations.

Financial Responsibility

Requirements	Wyoming	Montana	North Dakota	Washington
Financial Responsibility	Surety Bond TBD	Surety Bond TBD	Surety Bond TBD	Financial Assurance Mechanism

- Operators of geologic sequestration sites are required to maintain financial responsibility for the site, including any mitigation of leaks, contamination of ground water, etc, for the life of the injection and for a varying period of time post-closure of the site. All states accept a surety bond in an amount determined by the regulatory agency and Washington allows for other financial assurance instruments including letters of credit, cash, and liability insurance policies.

Big Sky Carbon Sequestration Partnership

Montana State University

Release of Liability

Requirements	Wyoming	Montana	North Dakota	Washington
Release of Liability to third party	UIC Requirement – No State Ownership	15	10	Determined post-closure and does not terminate with permit termination

- Once injection ceases, each state requires a post injection monitoring period to ensure that the CO2 stabilizes and that no problems arise concerning containment of the gas.
- Wyoming follows UIC guidance for Class V wells and for proposed Class VI wells that would maintain responsibility for 50 years.
- Montana and ND assume responsibility for the site after 15 years and 10 years respectively.
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BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

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BIG SKY CARBON SEQUESTRATION PARTNERSHIP

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Big Sky Carbon Sequestration Partnership

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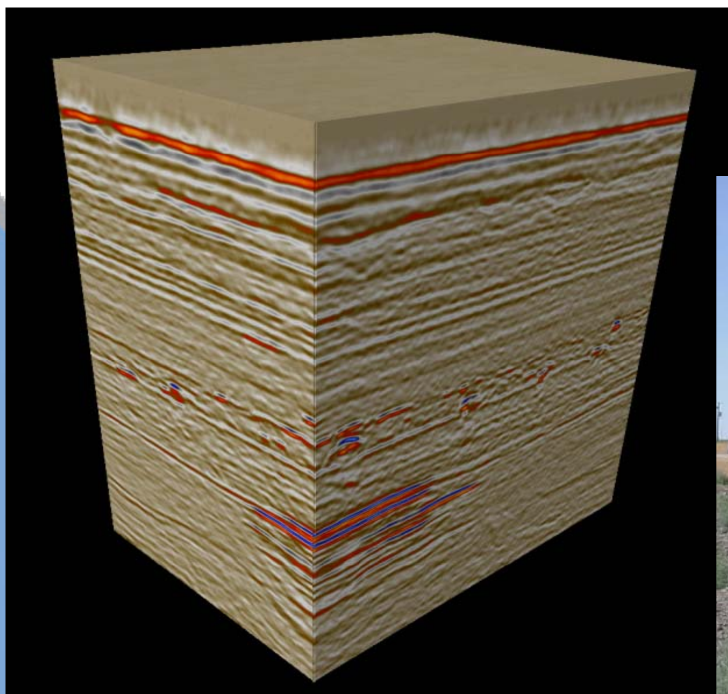
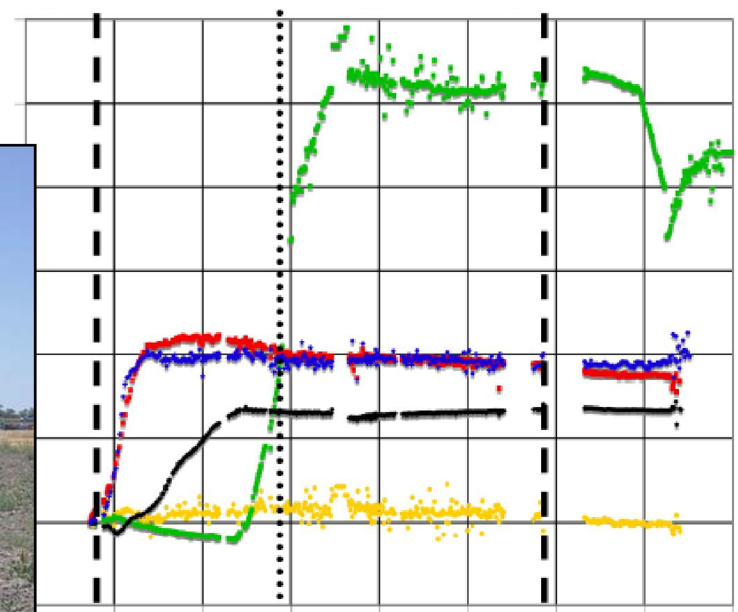
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

5th IEAGHG Monitoring Network Meeting Tokyo 2 - 4 June 2009

What monitoring can and can't do: Quantification

Andy Chadwick





Monitoring Aims

SITE PERFORMANCE: CURRENT AND FUTURE (EC Storage Directive)

- **Image / measure CO_2 in the reservoir**
- **Monitor containment risks**
- **Show site is currently performing as expected**
- **Constrain predictions of long-term site behaviour**
  - **Enable site closure**

EMISSIONS ACCOUNTING (EU ETS / National Inventories)

- ***Monitor outer envelope of the storage complex***

HEALTH AND SAFETY (National legislations)

- ***Detect potentially hazardous leakages / accumulations at or near - surface***

Sleipner Monitoring

CO_2 injection commenced 1996

~ 1 Mt CO_2 injected per annum, ~11 Mt currently *in situ*

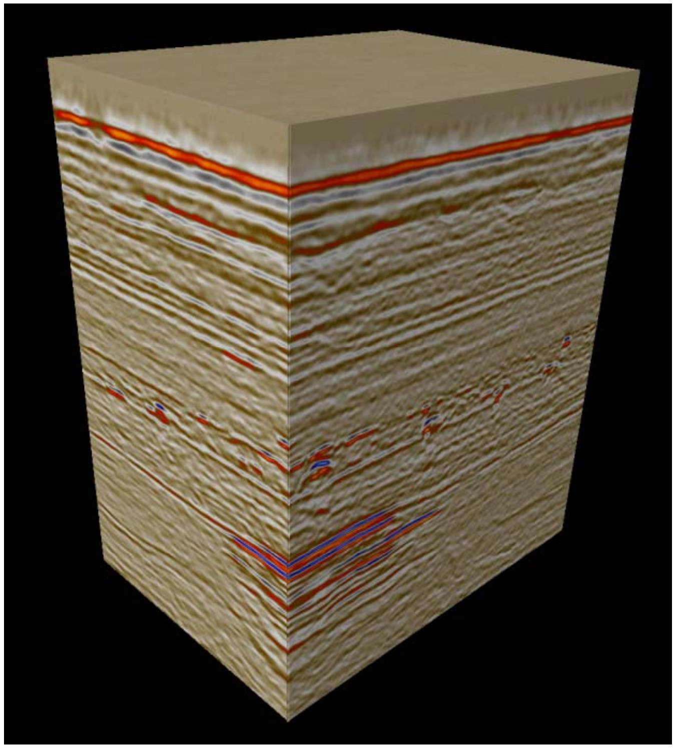
4D surface seismic

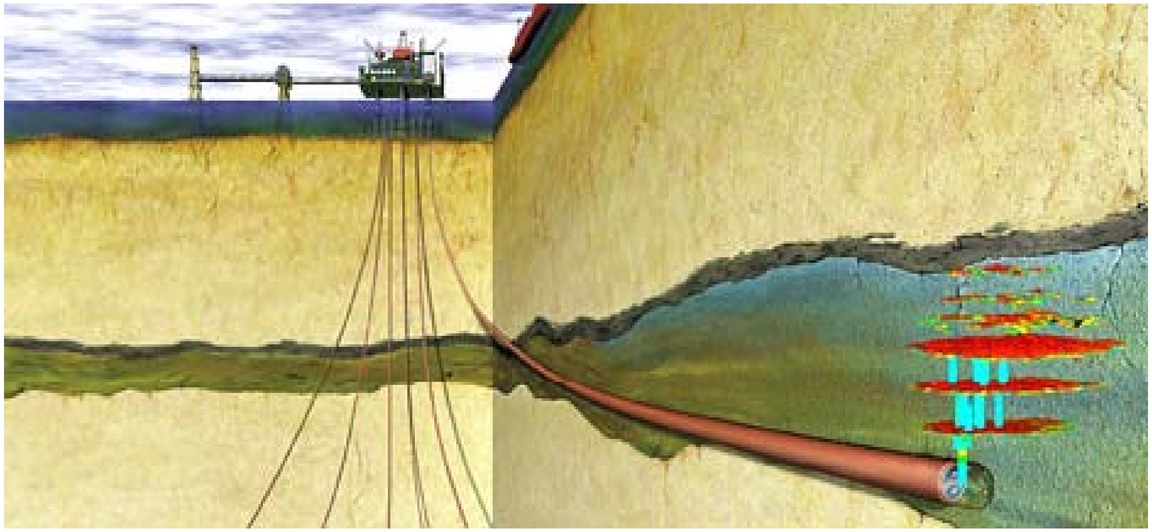
2D hi-res seismic

Seabed gravity

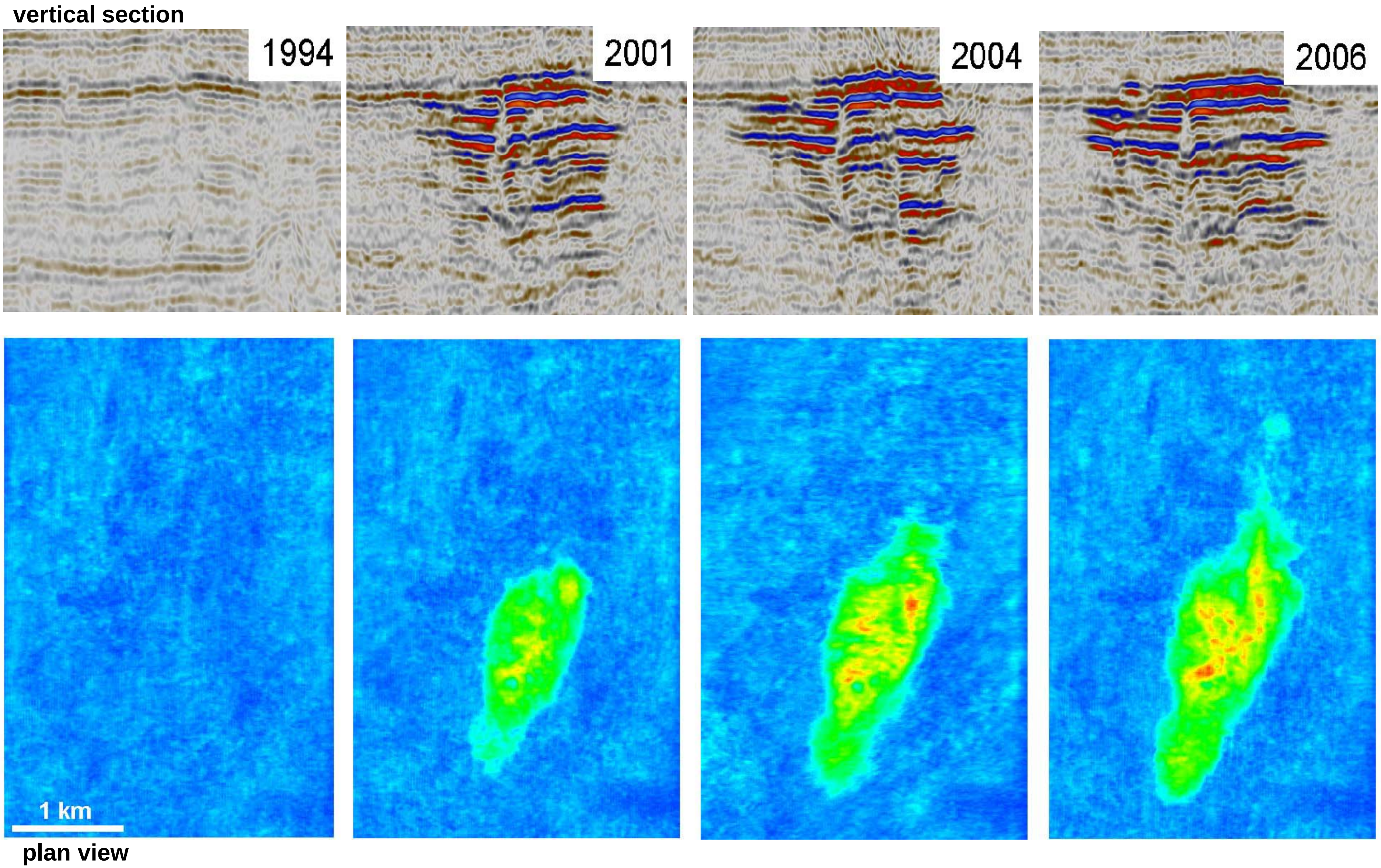
CSEM

Seabed imaging

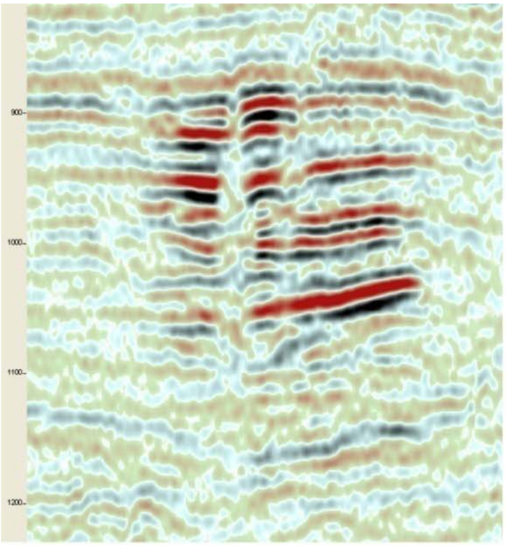




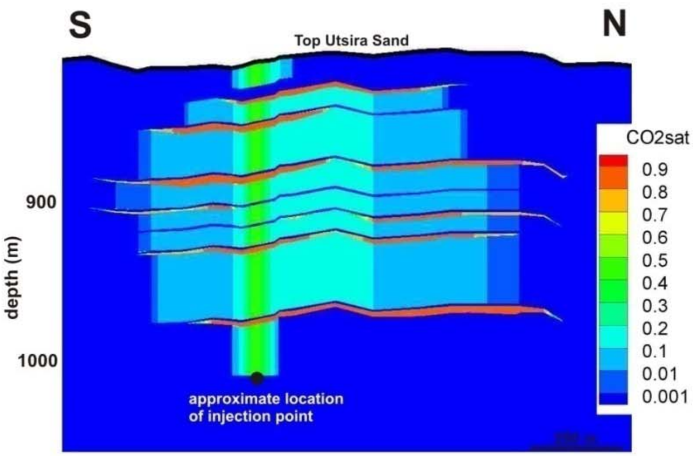
Imaging CO_2 in the reservoir



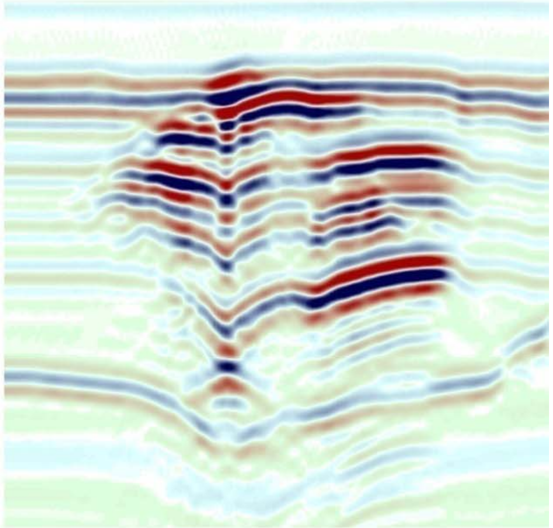
Quantification 'mass verification' at Sleipner



Observed seismic



(3D) saturation model)
(~known amount)



Synthetic seismic

Uncertain temperature – fluid mixing (uniform / patchy) uncertainty
Accurate temperature – uniform mixing likely

NOT REGULATORY REQUIREMENT

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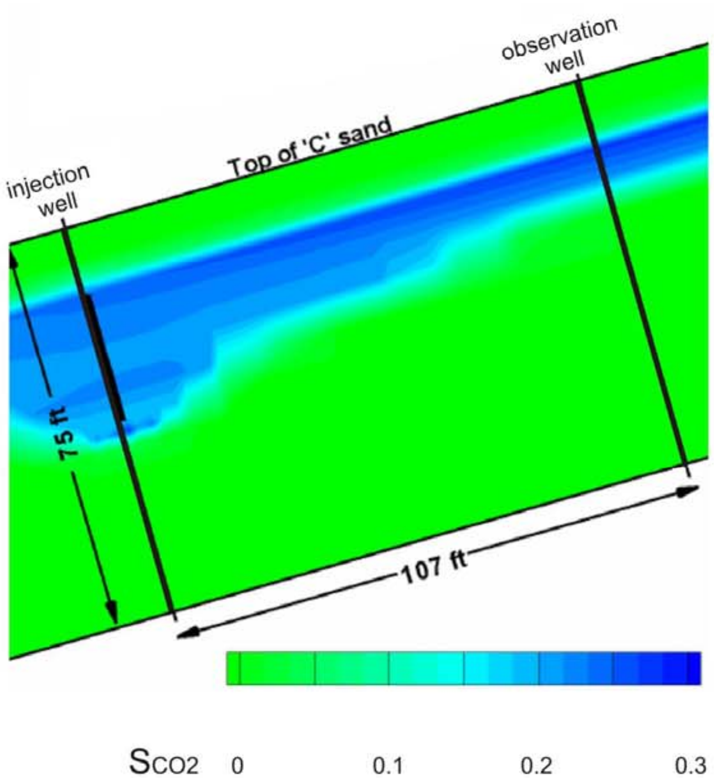
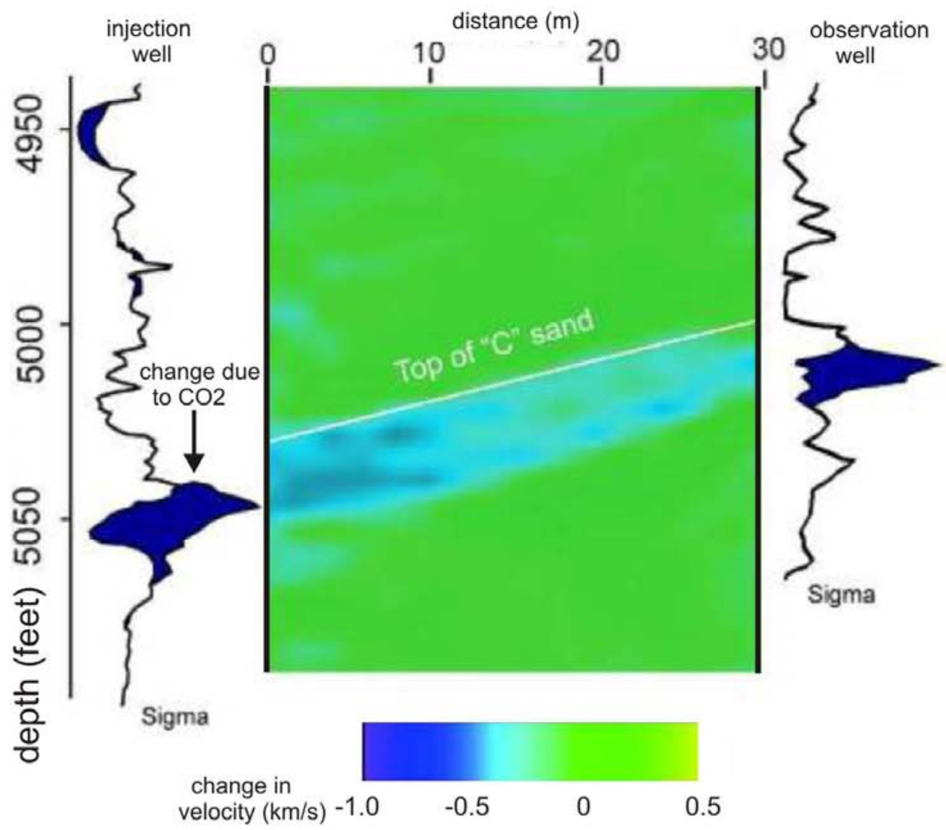
Performance monitoring: saturation / distribution

Downhole seismic and saturation logging at Frio



predictive flow simulation

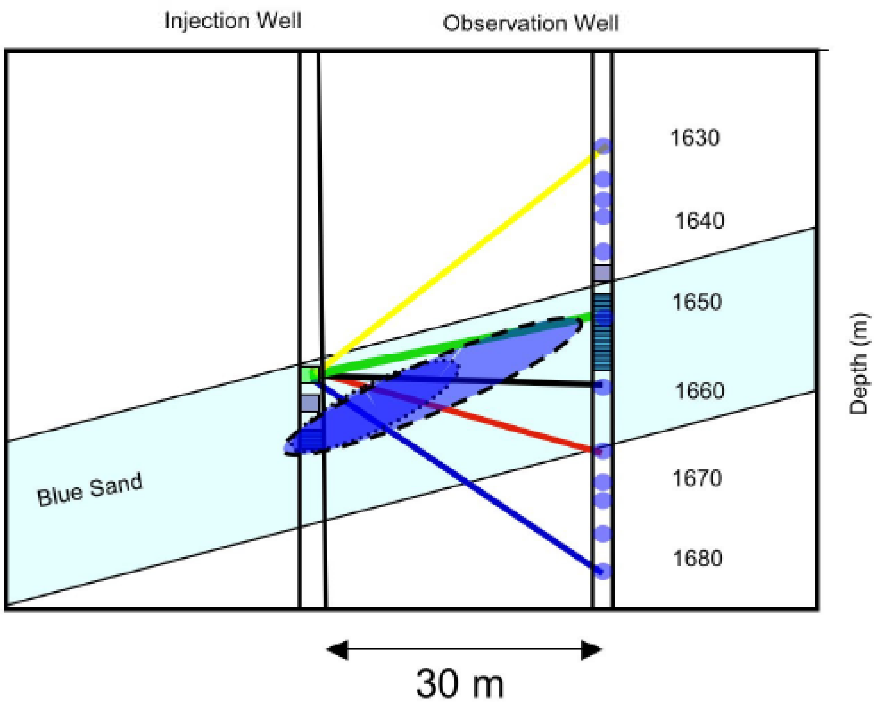


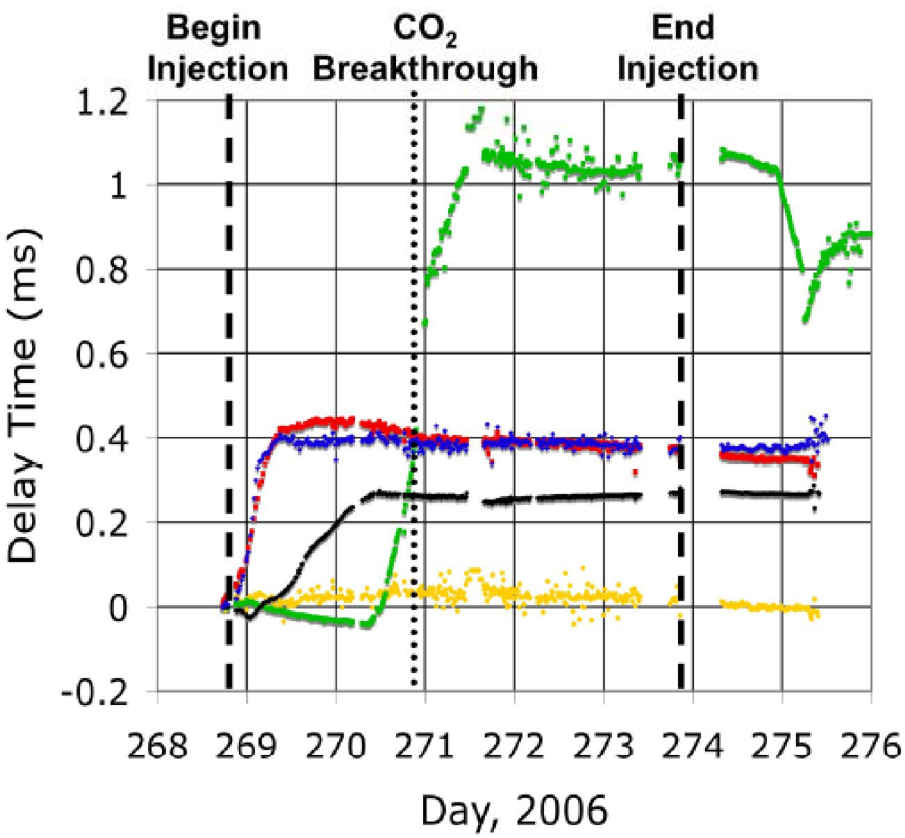
monitoring observations
(RST logs and crosshole seismic)

[courtesy of Tom Daley (LBNL), Christine Doughty (LBNL) and Susan Hovorka (University of Texas)]

Performance monitoring: flow velocity

Downhole seismic at Frio





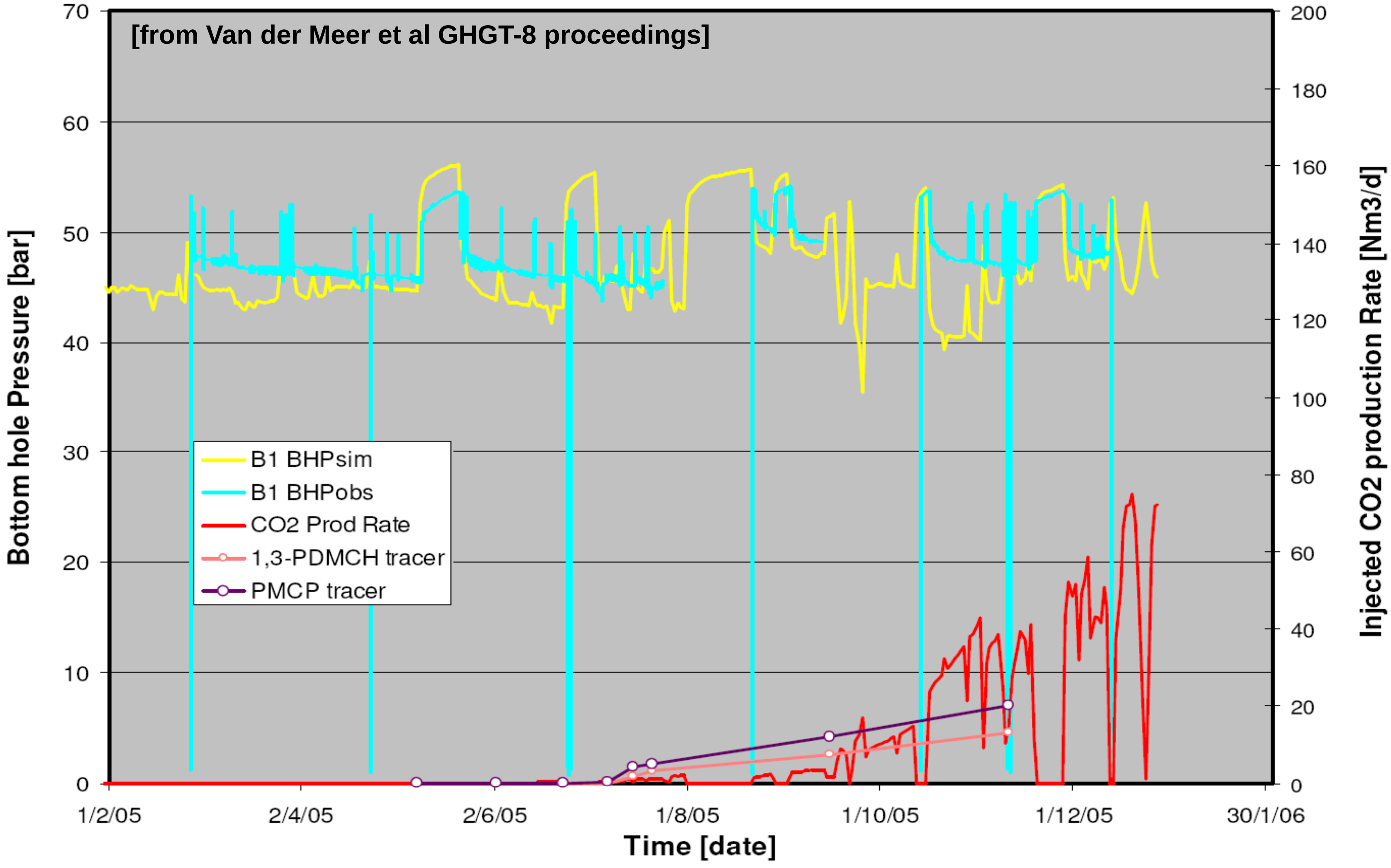
15 minute temporal sampling

Continuous active source seismic monitoring

[from Freifeld et al. 2009]

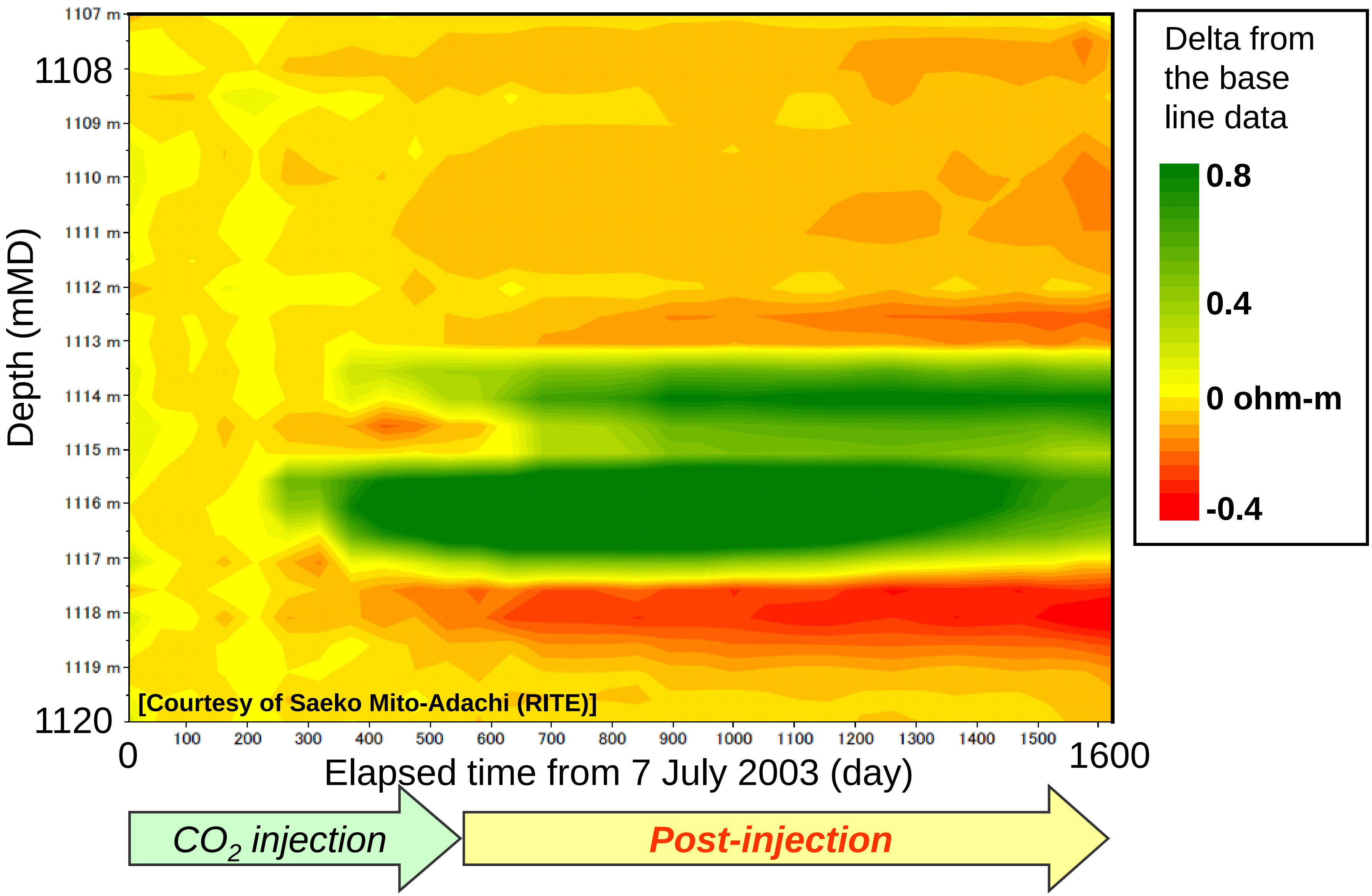
Performance monitoring: pressure and flow velocity

Downhole methods at K12- B



Performance logging: dissolved CO_2

Post-injection downhole methods at Nagaoka



Studies from pilot-scale injection are providing detailed evidence that we understand injection processes and can make credible and robust predictions.

(Industrial-scale sites may not provide this)

Evidence base:

Detailed history - matching
Reservoir heterogeneity
Saturation distributions
Pressure matching
Dissolution

Monitoring for closure

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EU Storage Directive: Minimum conditions for closure….

Actual behaviour of the injected CO_2 conforms with the modelled behaviour

No detectable leakage

Storage site is evolving towards a situation of long-term stability

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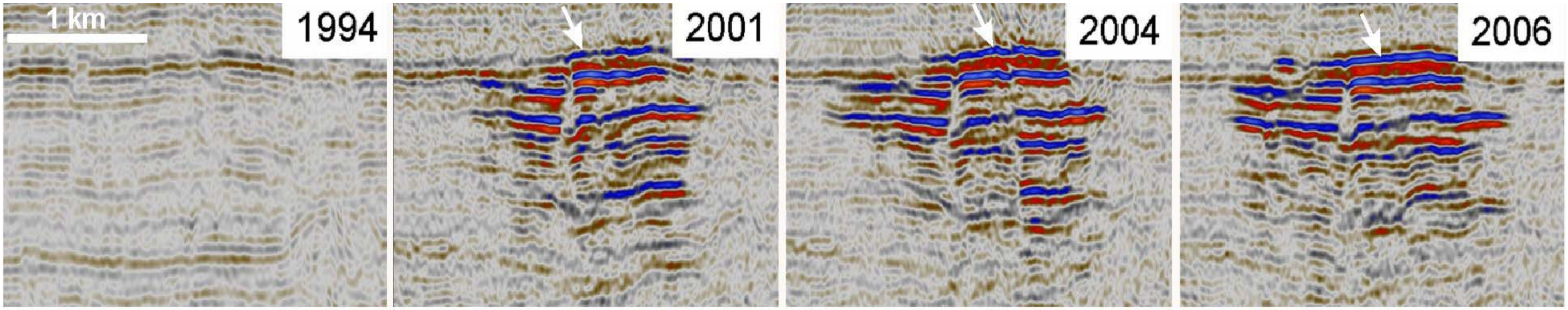
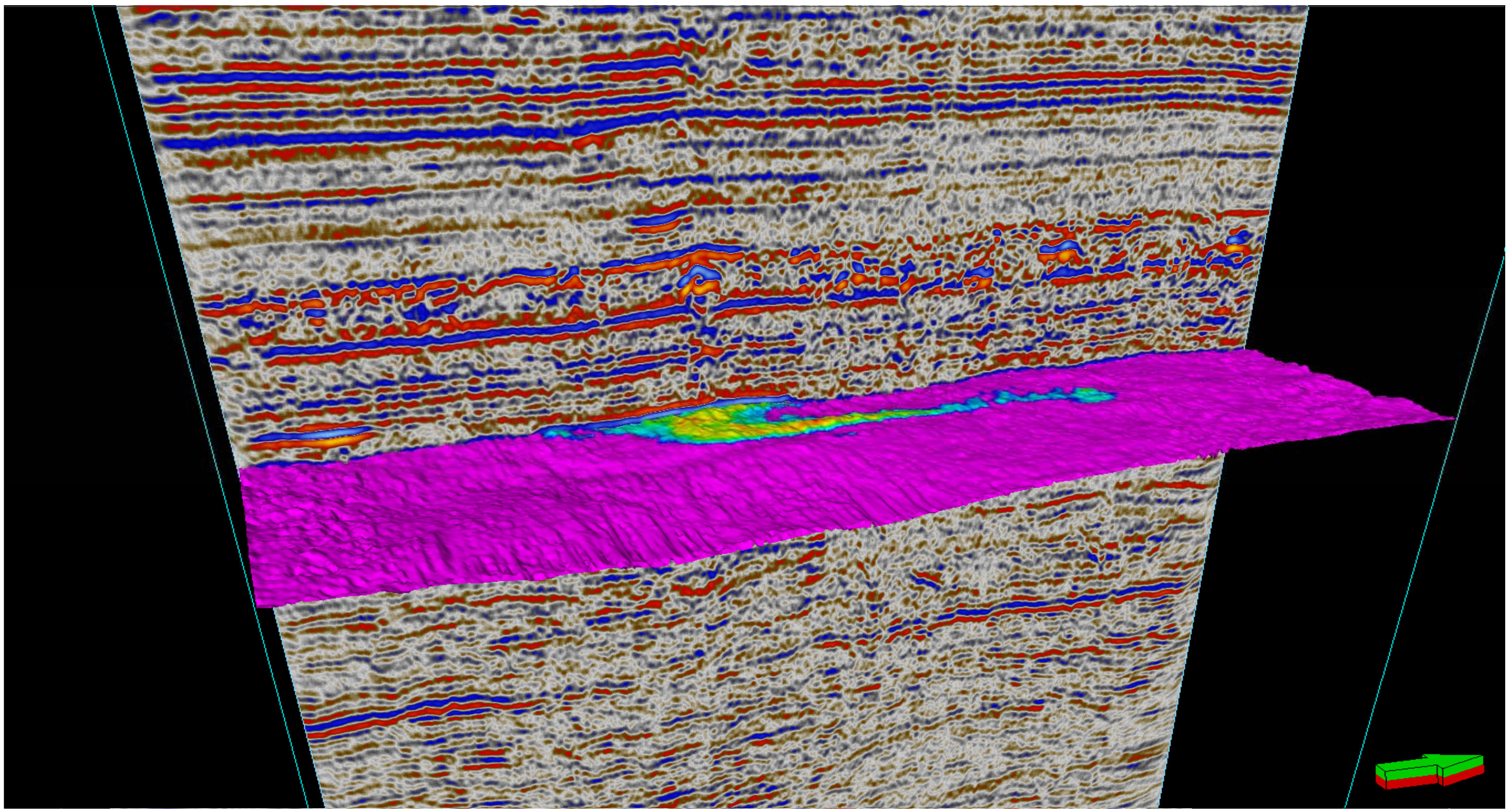
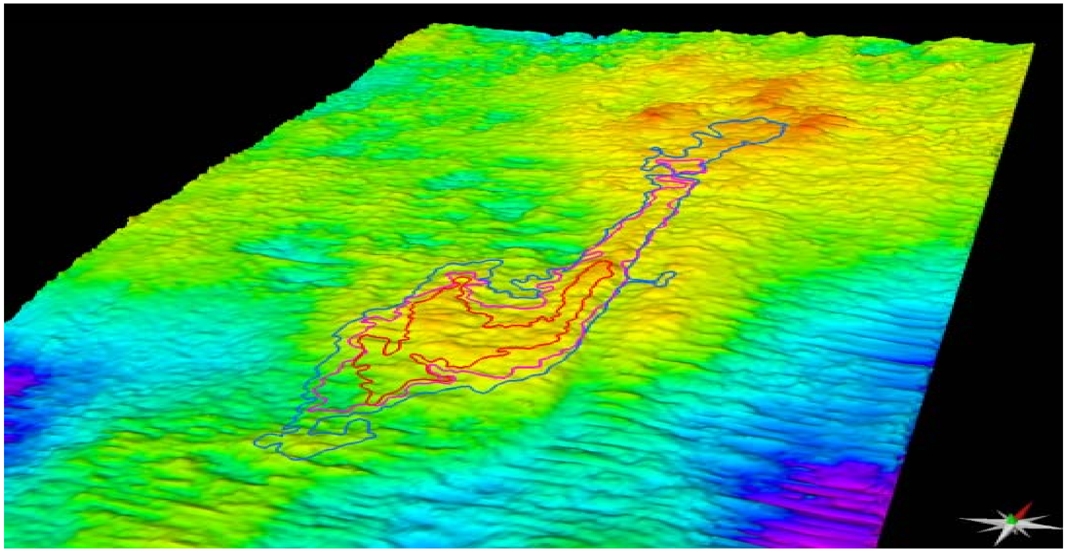
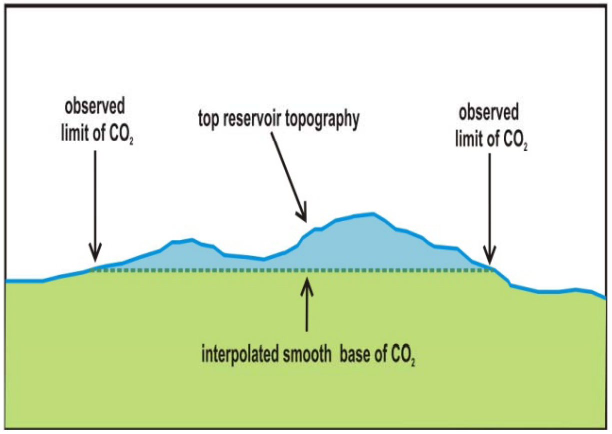
Actual behaviour

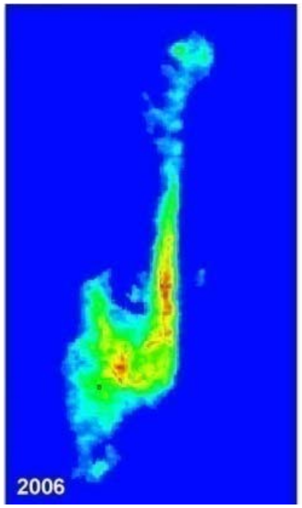


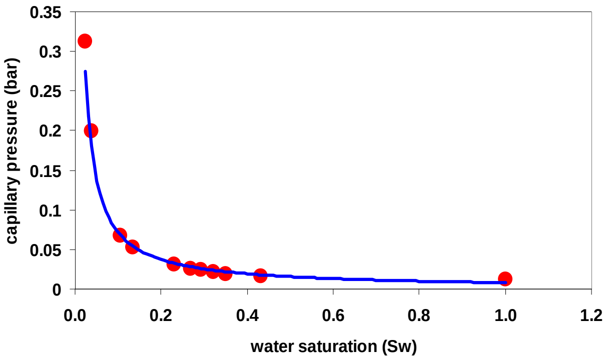


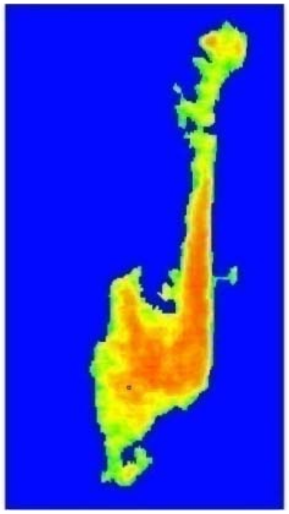
Quantification





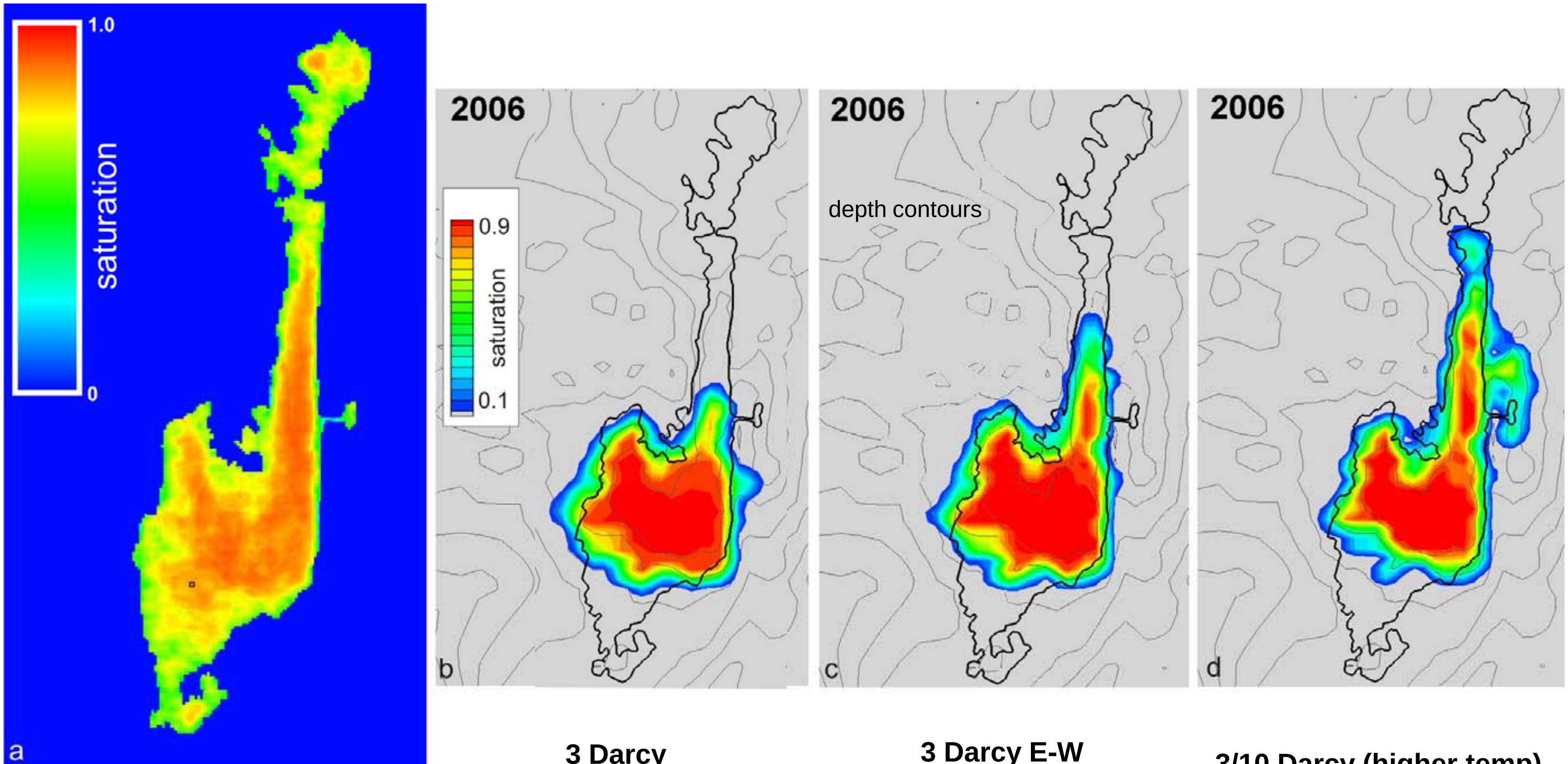






thickness **core** **capillary pressures** **saturation** **VOLUMES**

3D flow simulation of topmost layer growth by 2006



3 Darcy

3 Darcy E-W
10 Darcy N-S

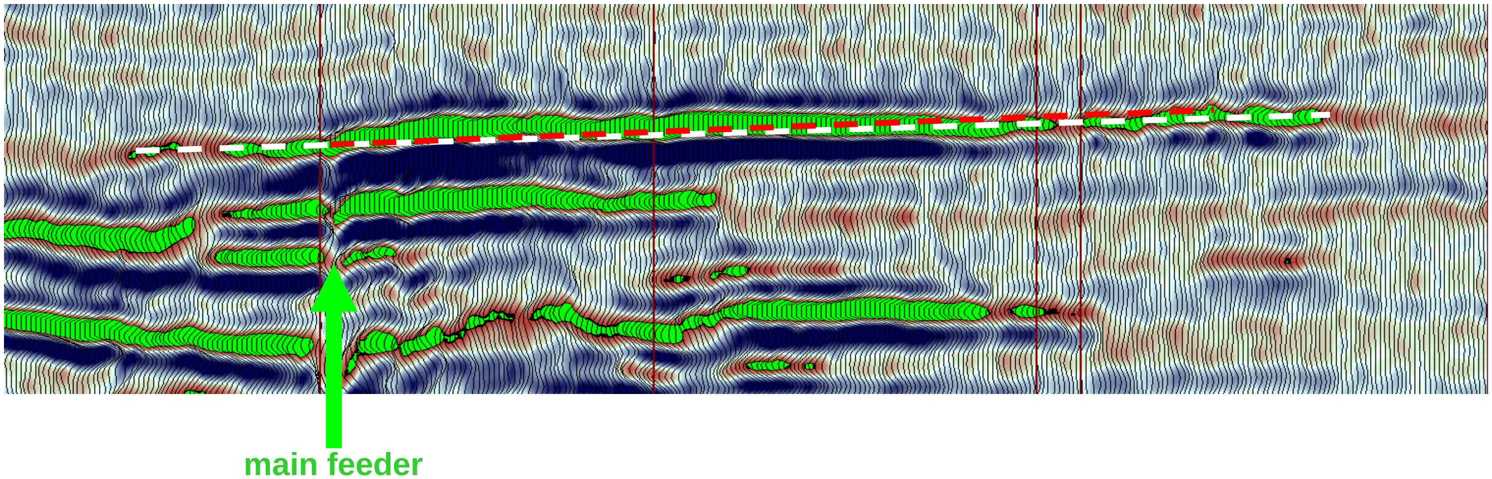
3/10 Darcy (higher temp)

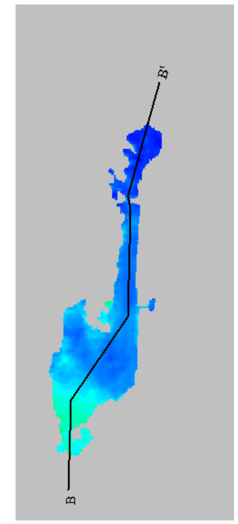
Core testing 2 - 3 Darcy
Well testing 1 - 8 Darcy

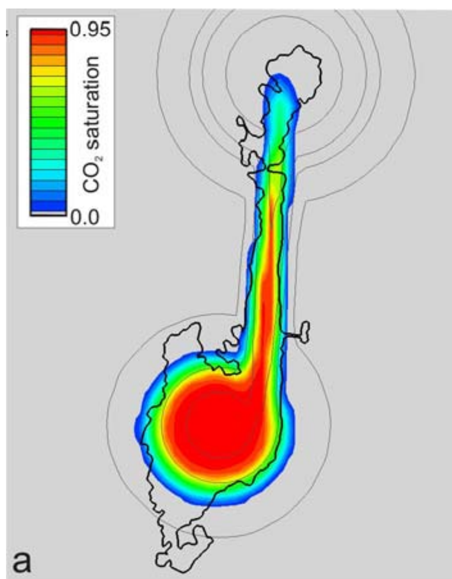
Model 3 Darcy

3D simulation of topmost layer growth by 2006

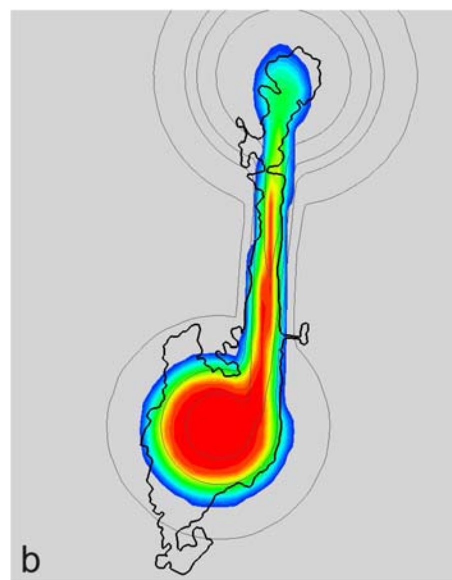
- adjusted depth model compatible with observed velocity variation







Mean gradient (0.0058)



Enhanced gradient (0.0082)

EU Storage Directive: Minimum conditions for closure….

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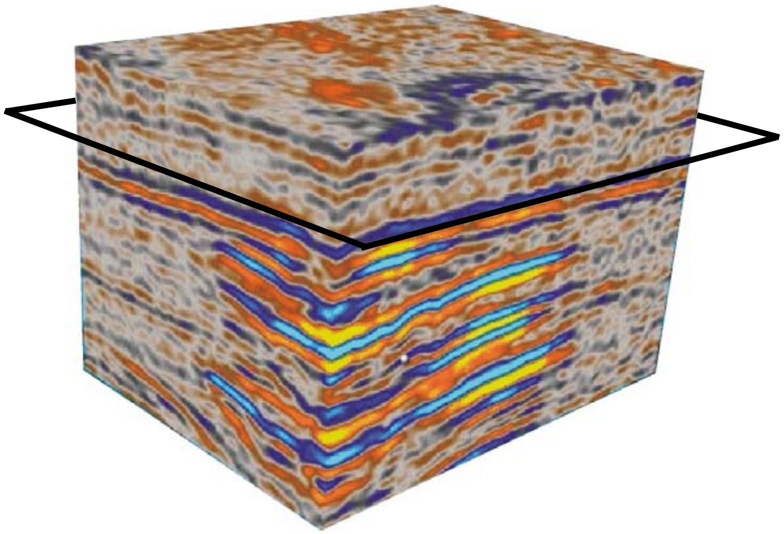
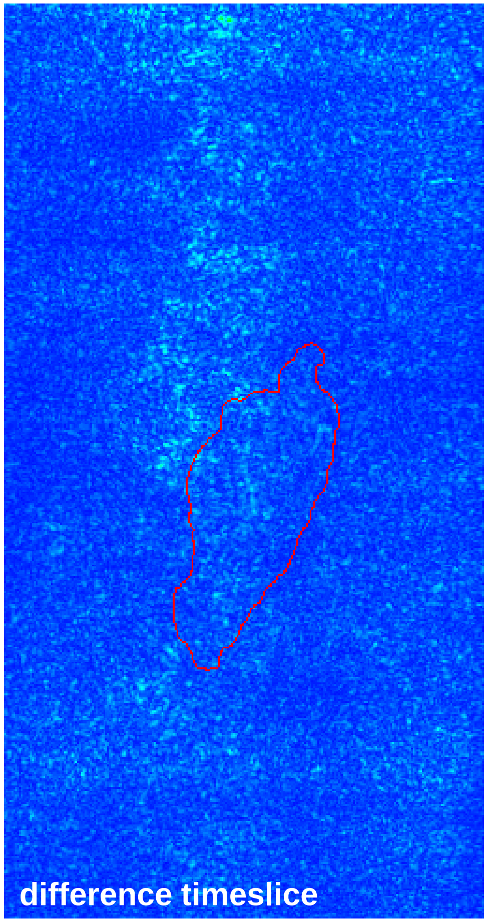
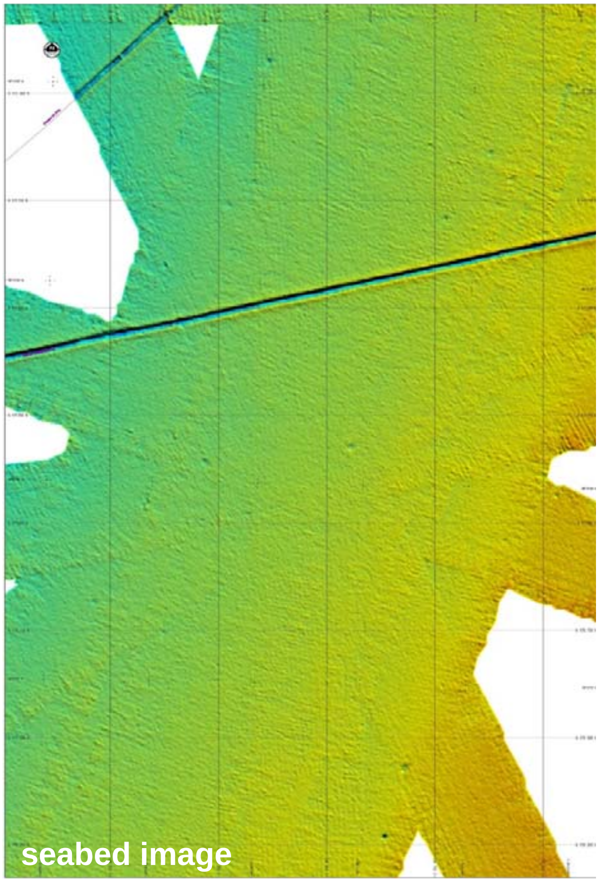
No detectable leakage

Storage site is evolving towards a situation of long-term stability

No current detected leakage







Detection limit for Sleipner data:

~ 4000 m^3

~ 2500 tonnes at top reservoir (~0.01% of projected total)

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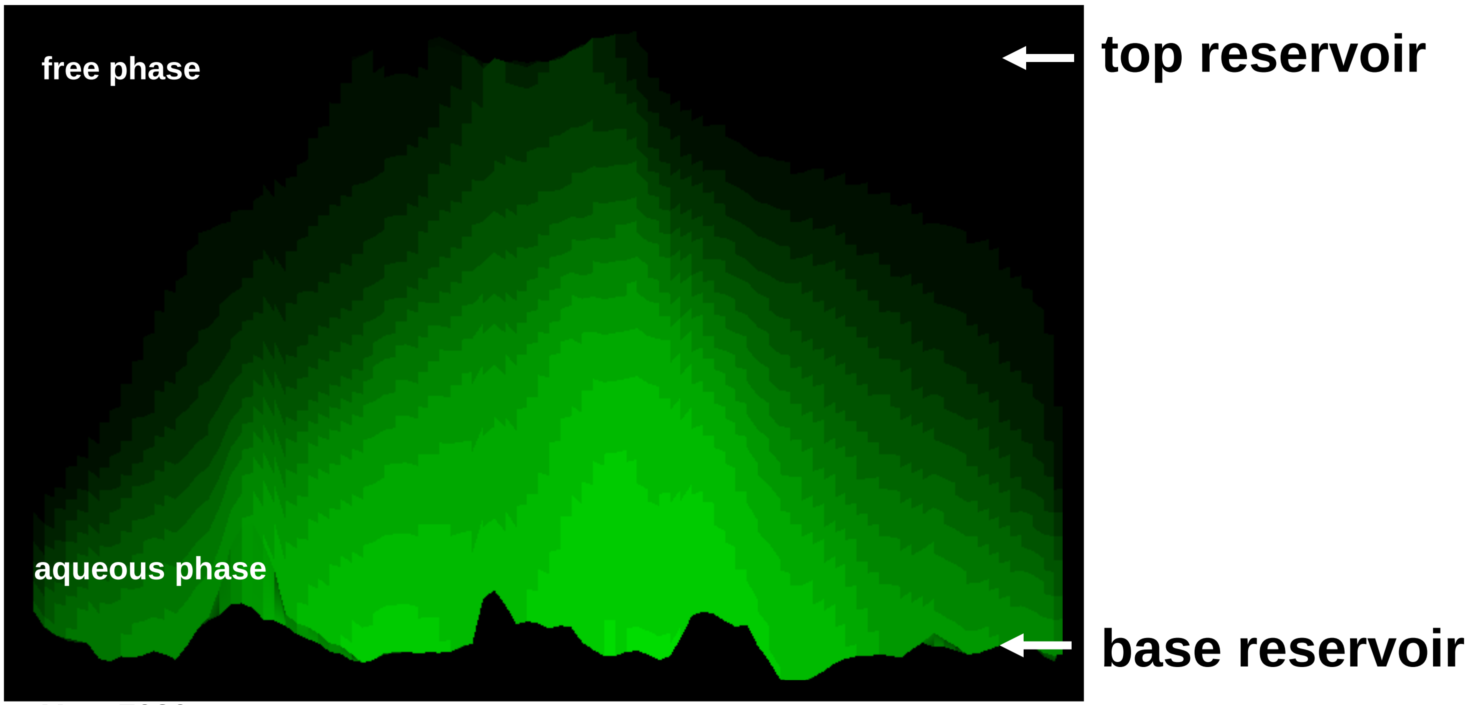
Actual behaviour of the injected CO_2 conforms with the modelled behaviour

No detectable leakage

Storage site is evolving towards a situation of long-term stability

7000 year flow simulation



Year 7020

0 to 160 years: free CO_2 spreads laterally at top reservoir

> 160 years: CO_2 in aqueous phase sinks in reservoir

[simulation courtesy of Erik Lindeberg SINTEF)

EU Storage Directive: Minimum conditions for closure….

Actual behaviour of the injected CO_2 conforms with the modelled behaviour	Observations and simulations are essentially coherent
No detectable leakage	OK subject to detectability limits
Storage site is evolving towards a situation of long-term stability	Simulation suggests this is the case. No well data, but observations from e.g. Nagaoka support.

+ FURTHER EVIDENCE FROM POST - INJECTION MONITORING

CAN THE SITE BE CLOSED ?

Acknowledgements

European Commission and industry funded projects (1998 – present)

SACS / SACS2 / CO2STORE / CASTOR / CO2GeoNet / CO2ReMoVe

Atmospheric monitoring of the CO2CRC Otway Project

D. Etheridge, A. Luhar, R. Leuning, P. Steele, D. Spencer, C. Allison, S. Zegelin, Z. Loh, P. Krummel, M. Meyer *(CSIRO Marine and Atmospheric Research, CSIRO Energy Transformed Flagship, CO2CRC)*
S. Sharma (*CO2CRC and Schlumberger*)

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CSIRO

CO2CRC

Otway Project
Soil & Water Monitoring

Charles Jenkins

CO2CRC

Strengths and Weaknesses of Subsurface Monitoring in the Context of Monitoring Requirements and Risk

a perspective

Mark Raistrick

5th Monitoring Network Meeting
Tokyo
3rd June 2009

Carbon Capture & Storage Association

Classification: Internal Status: Draft

In Salah CO2 JIP: Status and Overview

5th IEA Monitoring Meeting, Tokyo, Japan June 2-3 2009

Kevin Dodds

on behalf of

Alan Mathieson, Rob Bissell	BP
Phil Ringrose	StatoilHydro
Don Vasco, Ernie Majer	LBNL
Joe Morris	LLNL
Eric Davis, Glenn McColpin	Pinnacle Technologies
Clare Bond	MVE
Peter Armitage	Univ of Liverpool

Detection of Surface Deformation related with CO_2 Injection by DInSAR at In Salah, Algeria - Updated Results -

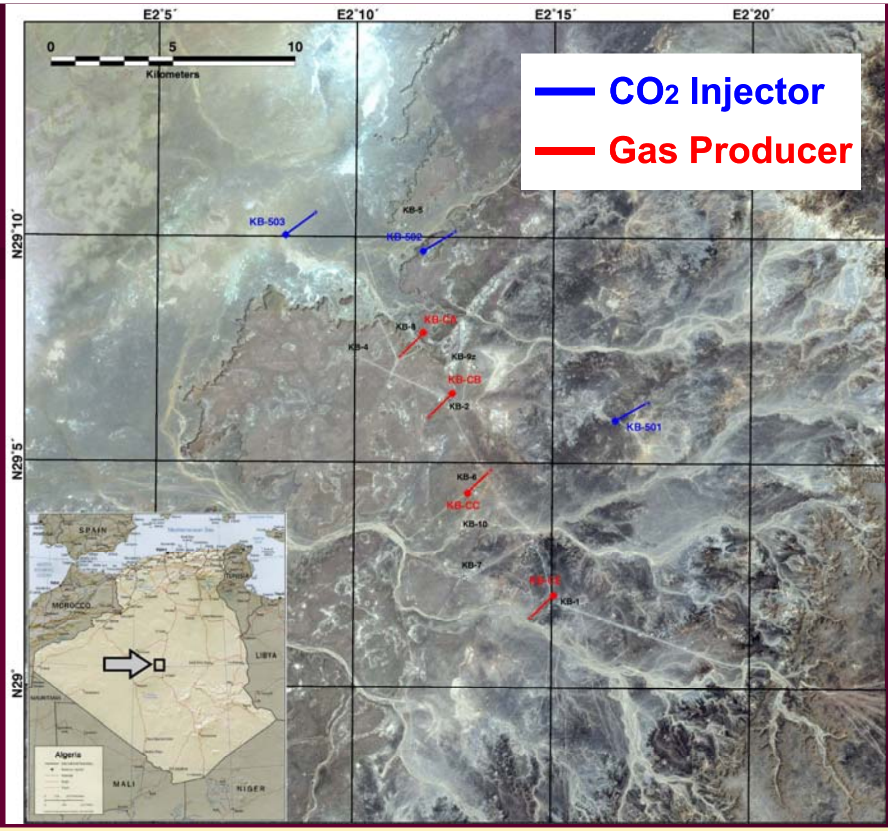
Takumi Onuma

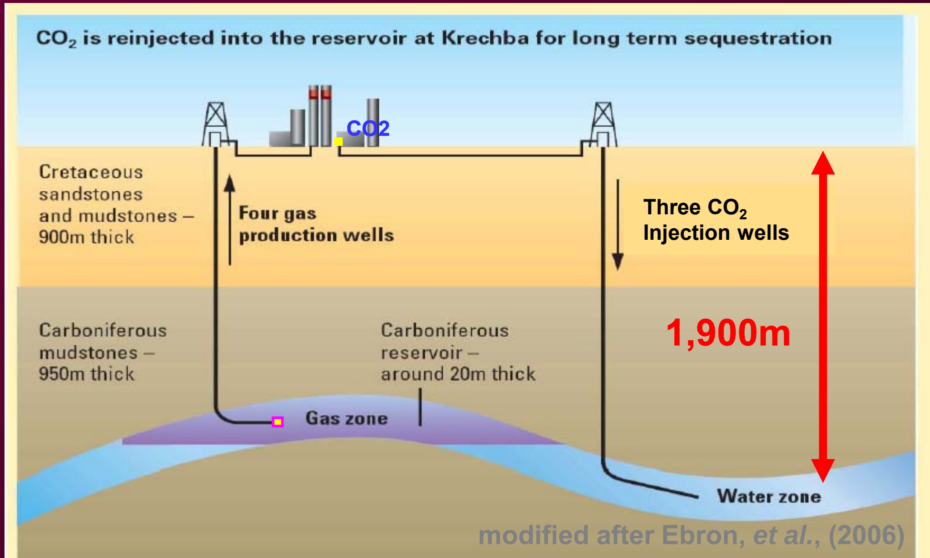
JGI, Inc., Tokyo, Japan

Presented at IEA GHG 5th Monitoring Network Meeting, Tokyo, June 3, 2009

Outline

- ***Data & Processing***
  - ***Pros and Cons, Stacking***
- ***Previous results***
  - ***DInSAR / PSInSAR***
- ***Updated results***
- ***Updated History***
- ***Summary***

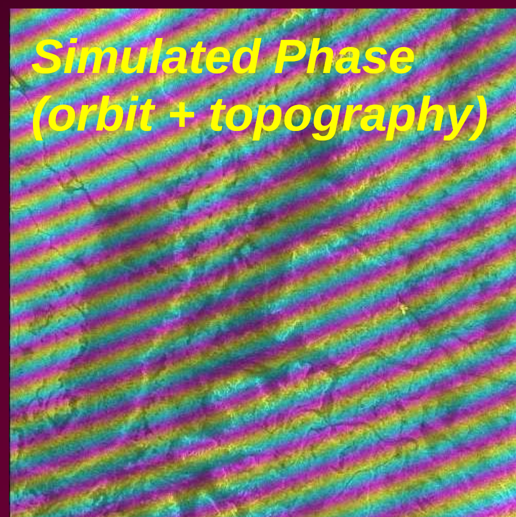




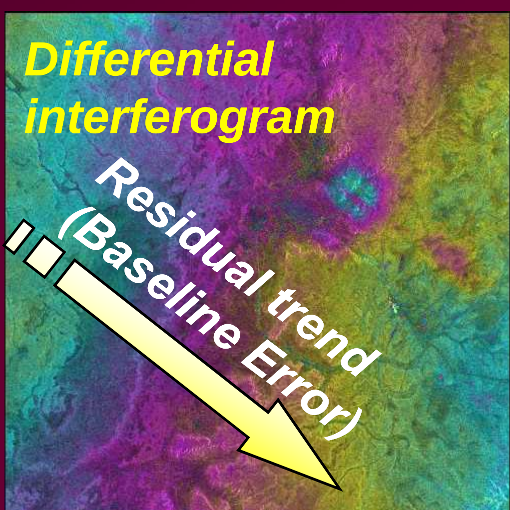
modified after Ebron, *et al.*, (2006)

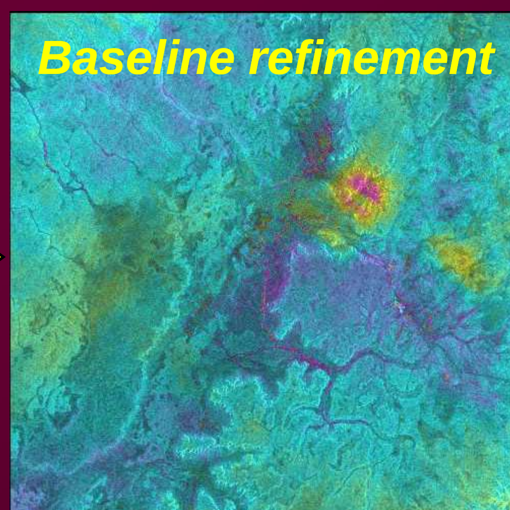
Data & Processing

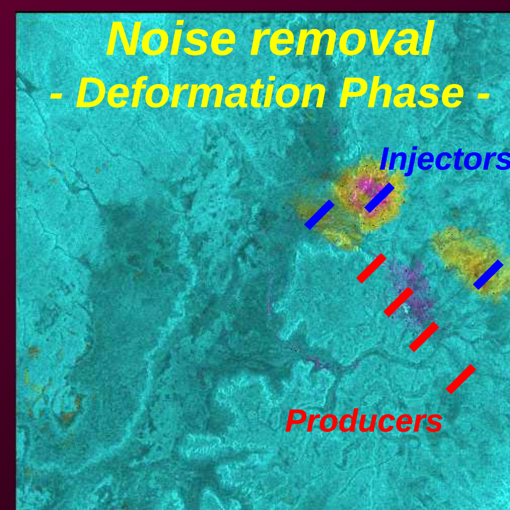
- ENVISAT ASAR
  - 36 scenes spanning 2003/7 – 2009/3
- 162 Pairs
- Stacking;
  - reduce noise, derive phase rate
- Time series
  - Reconstruction of deformation history



“subtract”



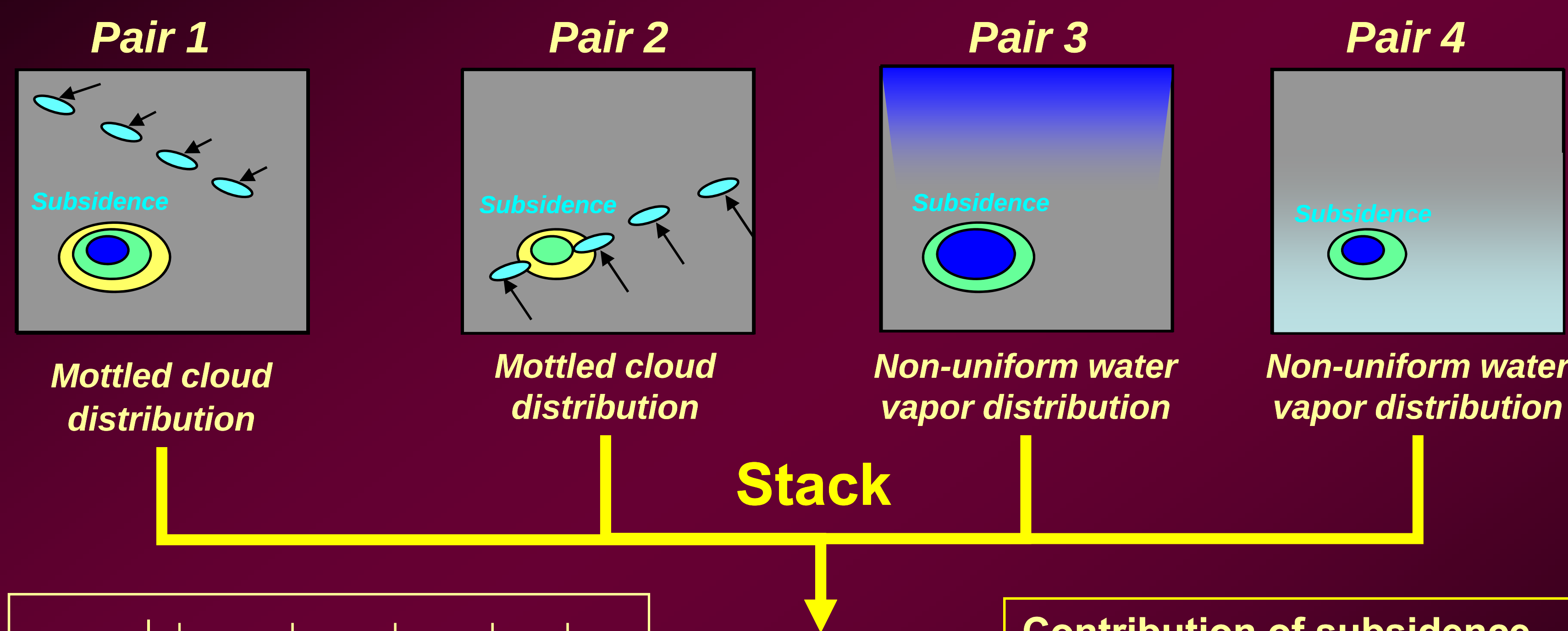


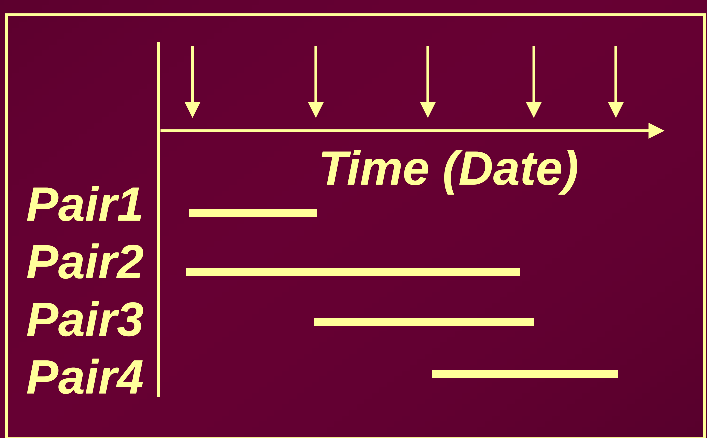


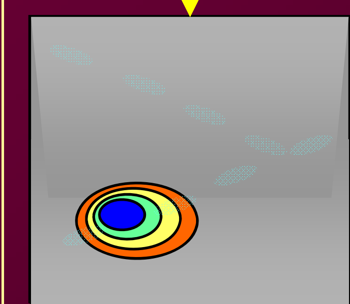
Pros and Cons

- *All weather, day & night observation capability*
- *Inexpensive data (~€400/scene)*
- *Broad coverage (~100km*100km/scene)*
- *Frequent observation (35 days interval)*
- *cm ~ mm order accuracy*
- *Not always interfere*
- *Atmospheric delay and phase noise (~1λ)*
- *Onshore, only surface (not underground)*
- *Not known if data is usable until processed*
  (must be purchased…)

Concept of Stacking





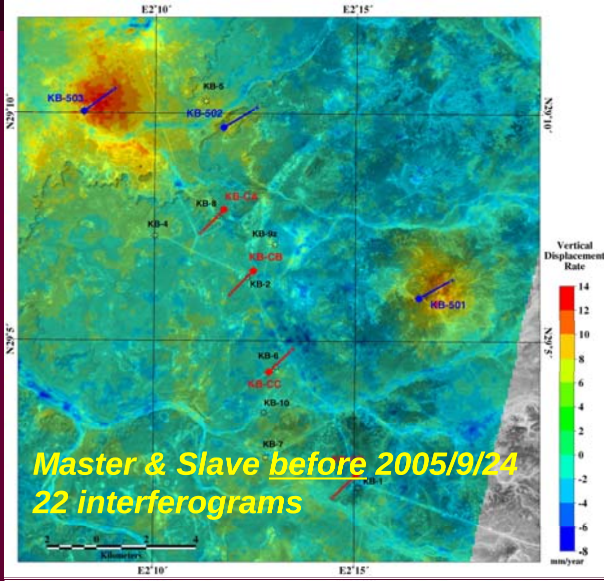


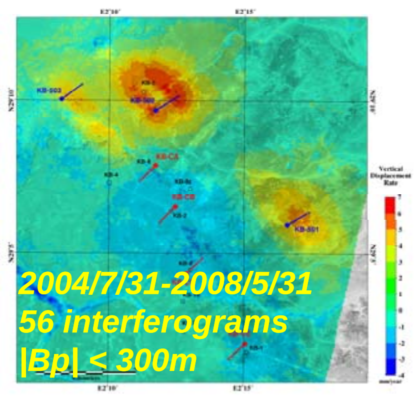
Contribution of subsidence
→ Amplified.

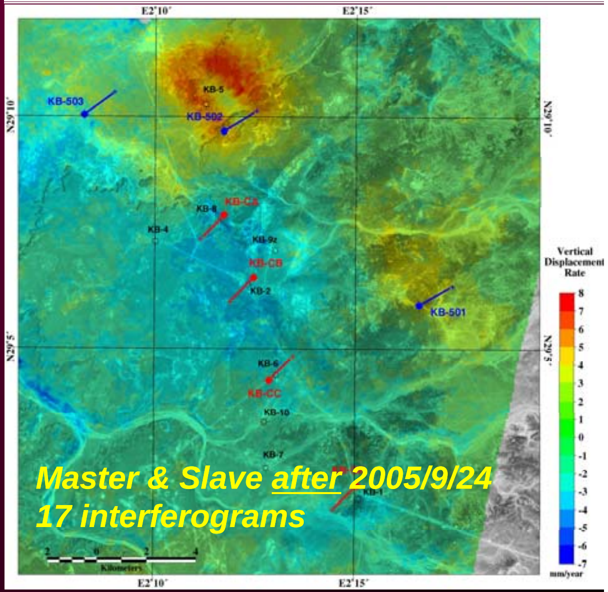
Contribution of temporal feature
→ Diminished

Previous Results (DInSAR)

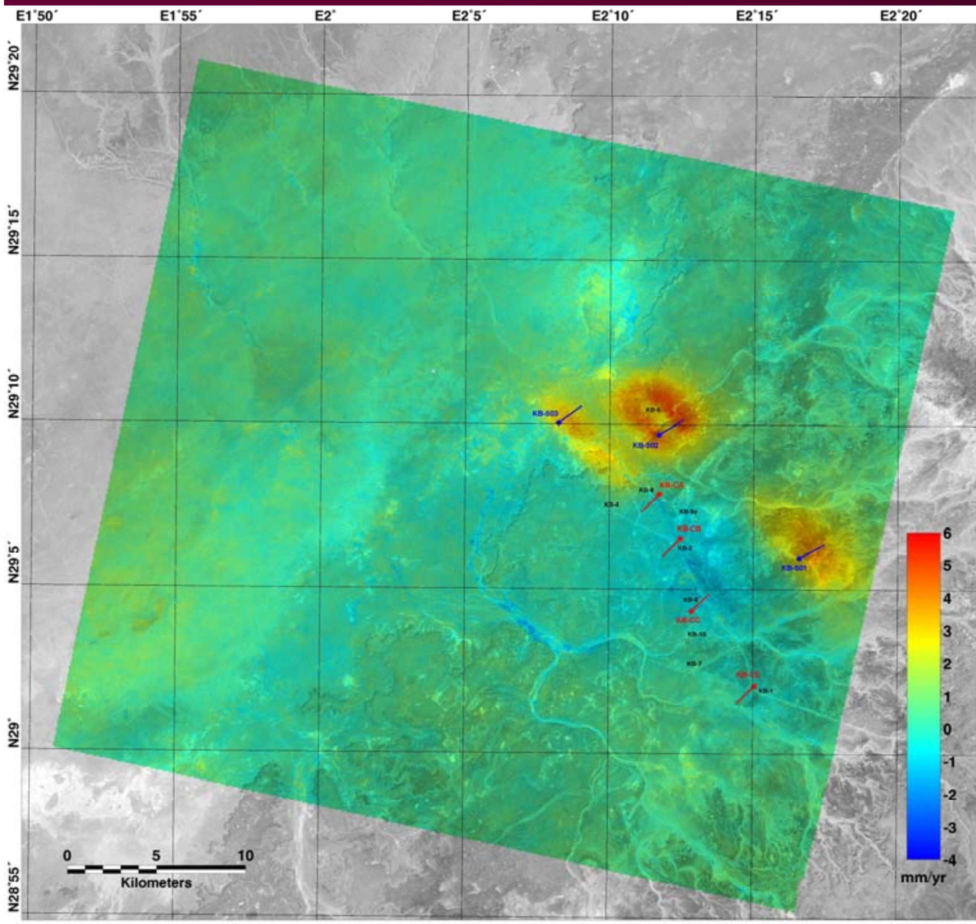
- *Upheaval for all of 3 injectors, as well as subsidence for producers.*
- *But not simultaneous.*
- *Around KB-502; quiet until fall(?) in 2005. (Injection at KB501 & 503 commenced 2004/8)*
- *Different deformation history for each injection well.*

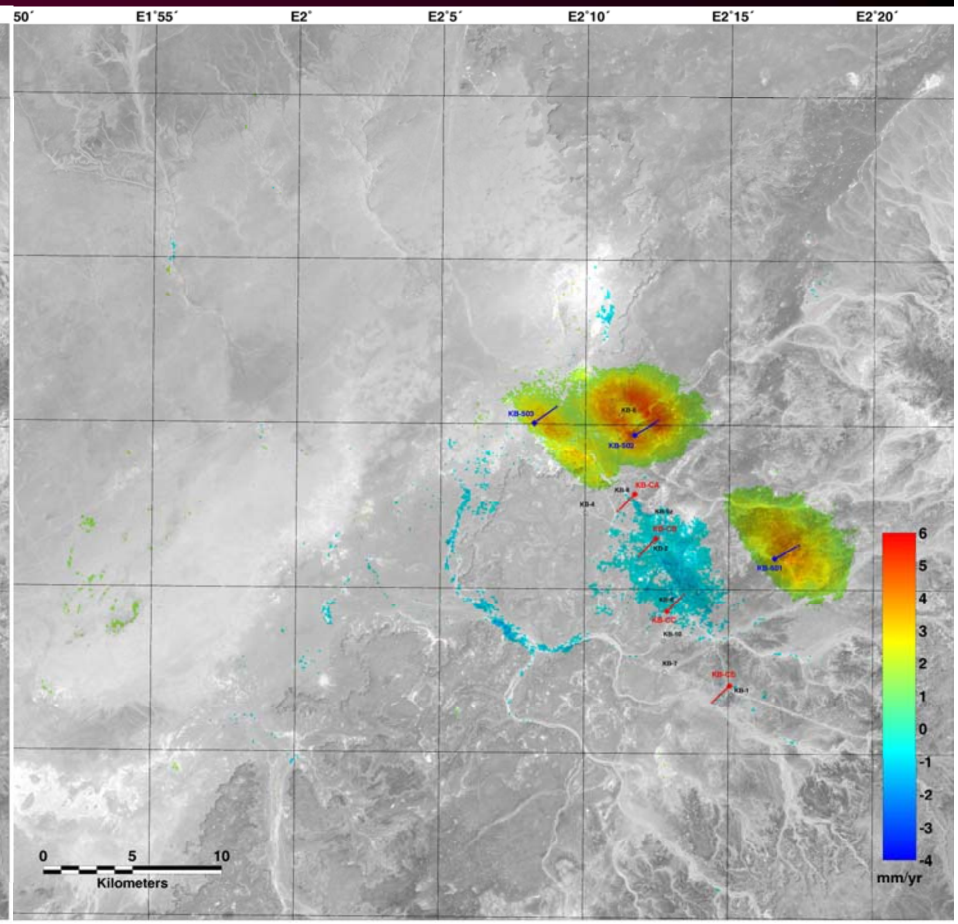






Updated Stacking Result

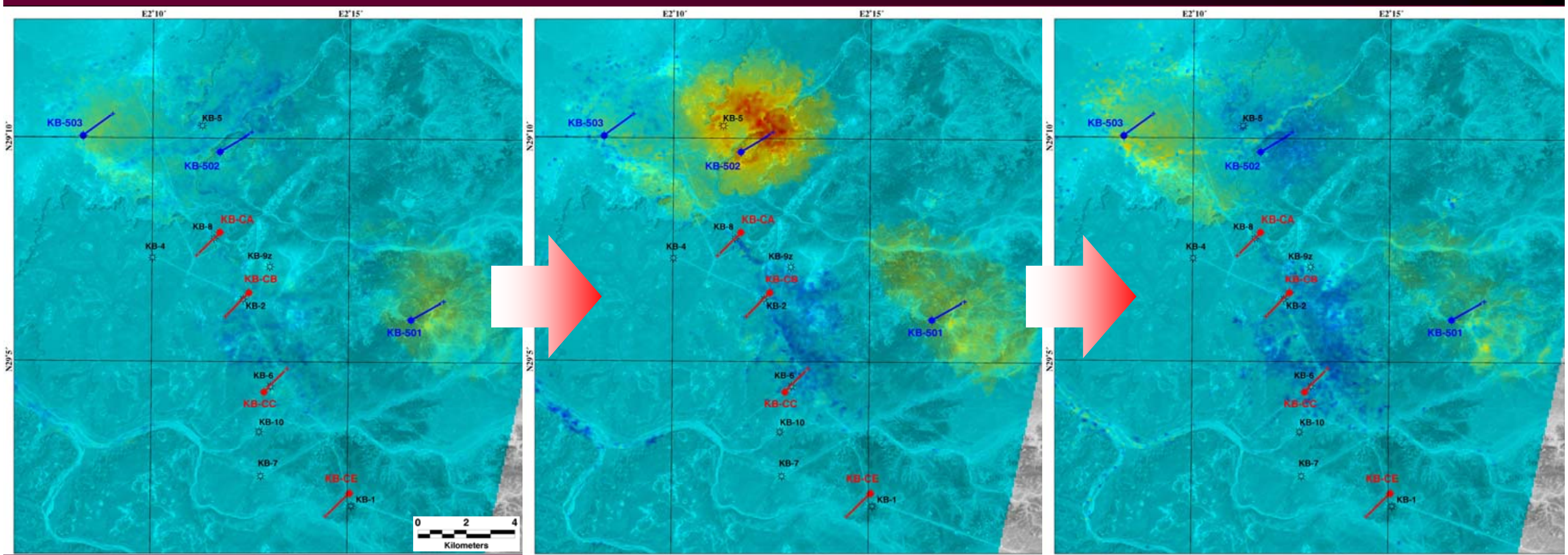




~ 2009/3/7, 55 pairs, |Bp|<150m **|rate| > 1 mm/yr ➡ deformed area**

Retrieve atmospheric phase delay and phase noise from non-deformed areas.

Non-linear Deformation!



2004/7/31-2005/2/26 *2005/2/26-2007/3/3* *2007/3/3-2009/3/7*

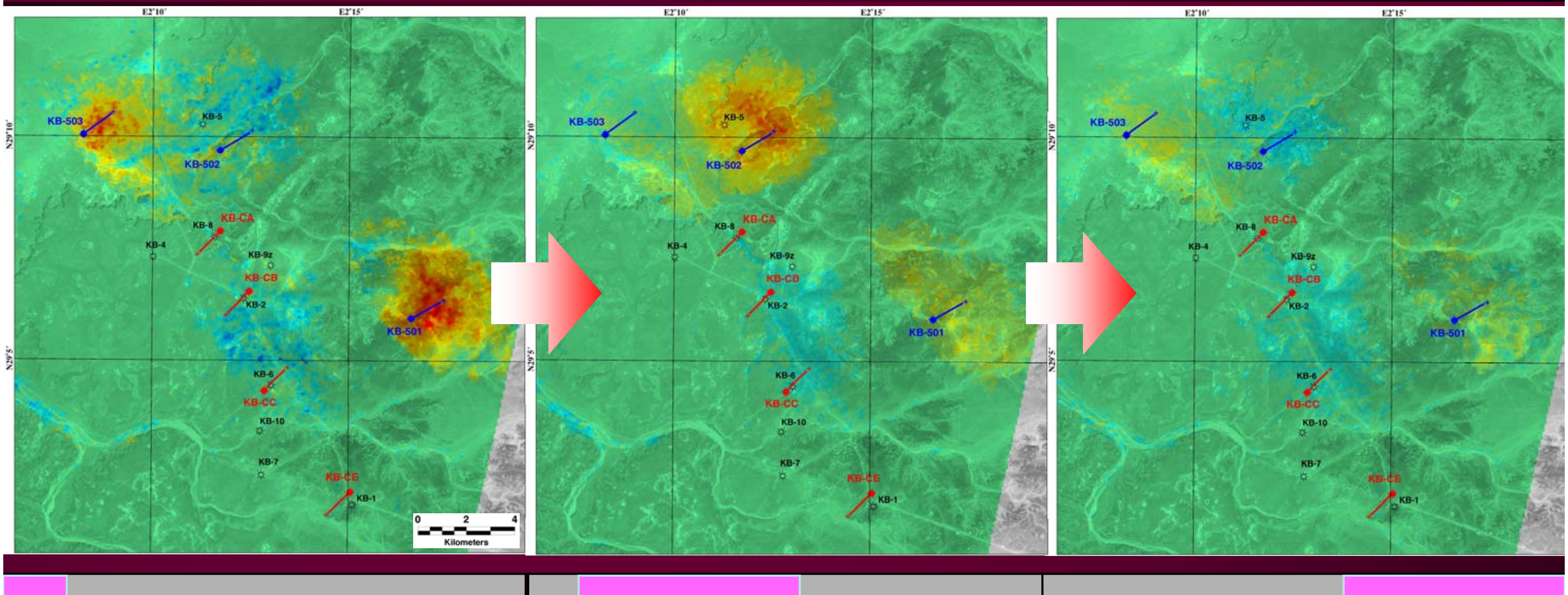
mm

-12 -8 -4 0 4 8 12 16 20 24 26

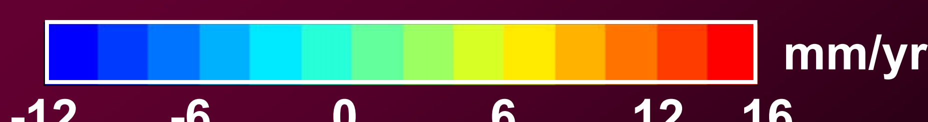
2005/4; Injection@KB-502 started.

2007/7 ?; KB-502 was shut-down

Updated Phase Rates



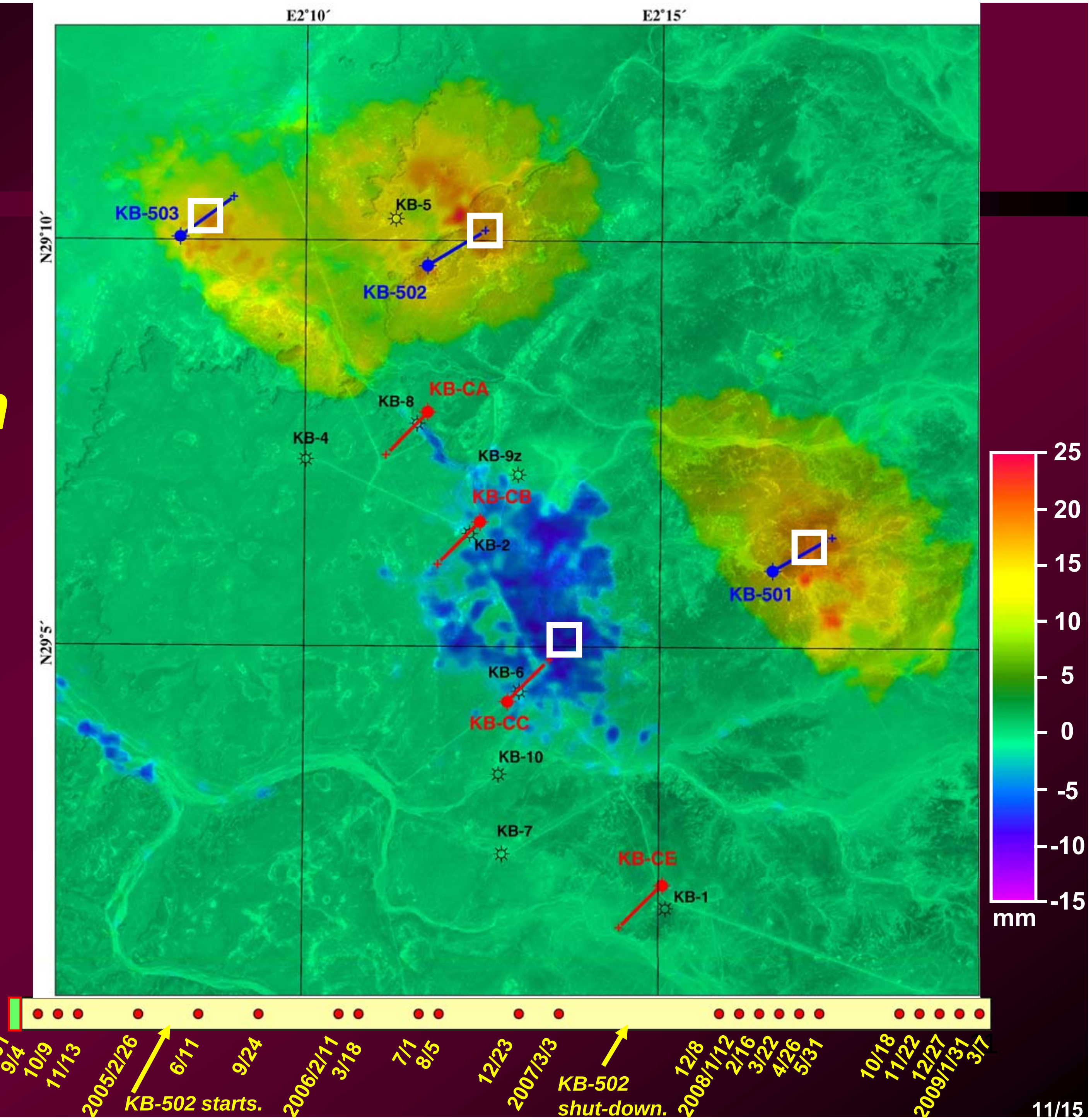
2004/7/31-2005/2/26	***2005/2/26-2007/3/3***	***2007/3/3-2009/3/7***
-9 mm/yr ~ 16 mm/yr	**-5 mm/yr ~ 13 mm/yr**	**-5 mm/yr ~ 6 mm/yr**
Stacking 31 pairs	**Stacking 23 pairs**	**Stacking 51 pairs**



In Salah

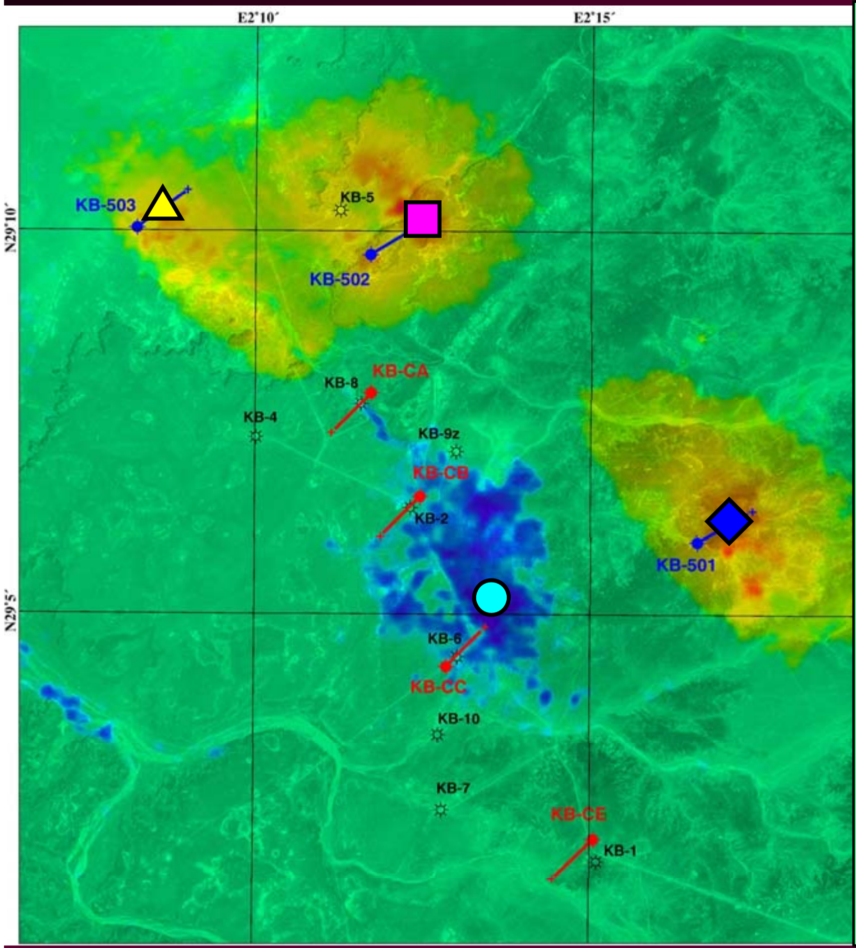
Surface Deformation Time Series

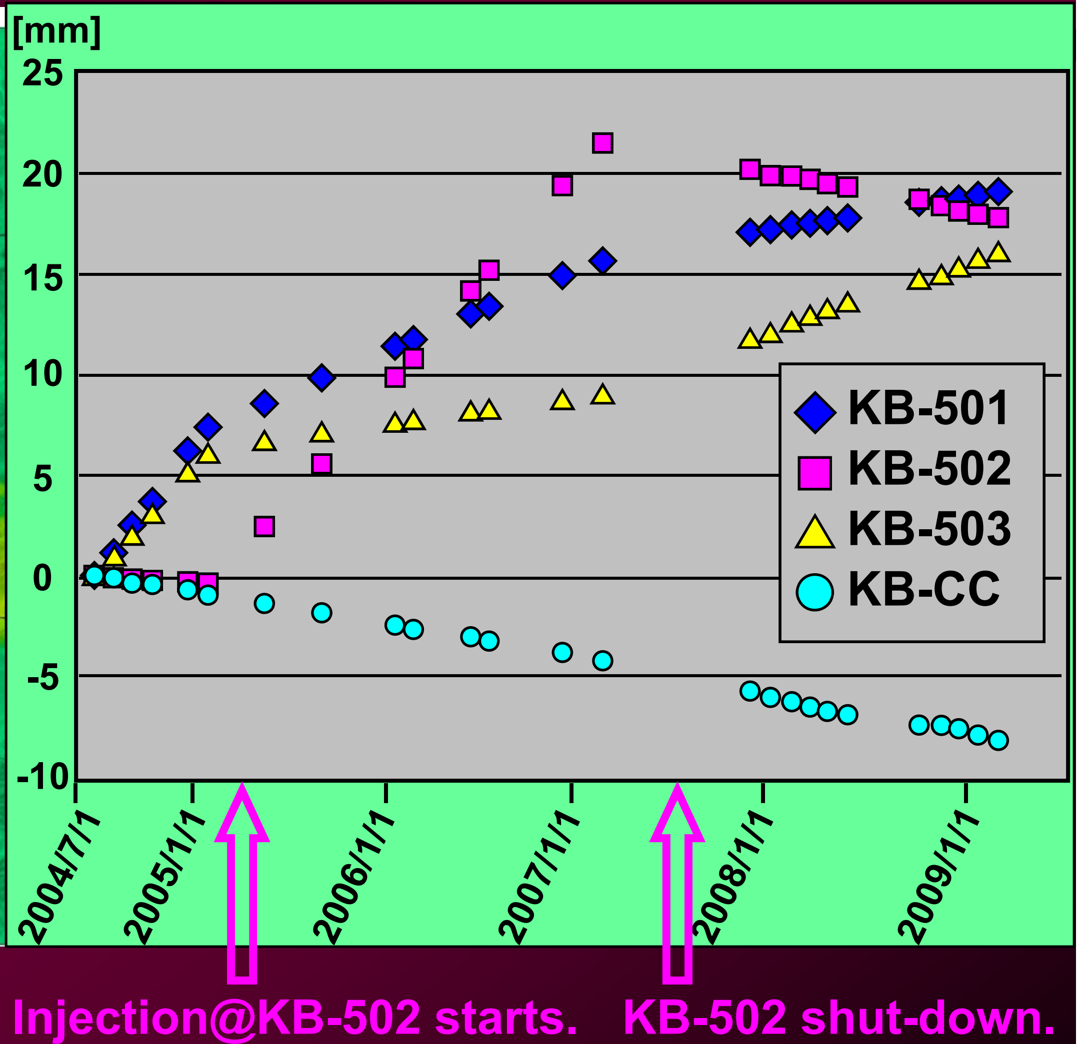
2004/7/31 to 2009/3/7



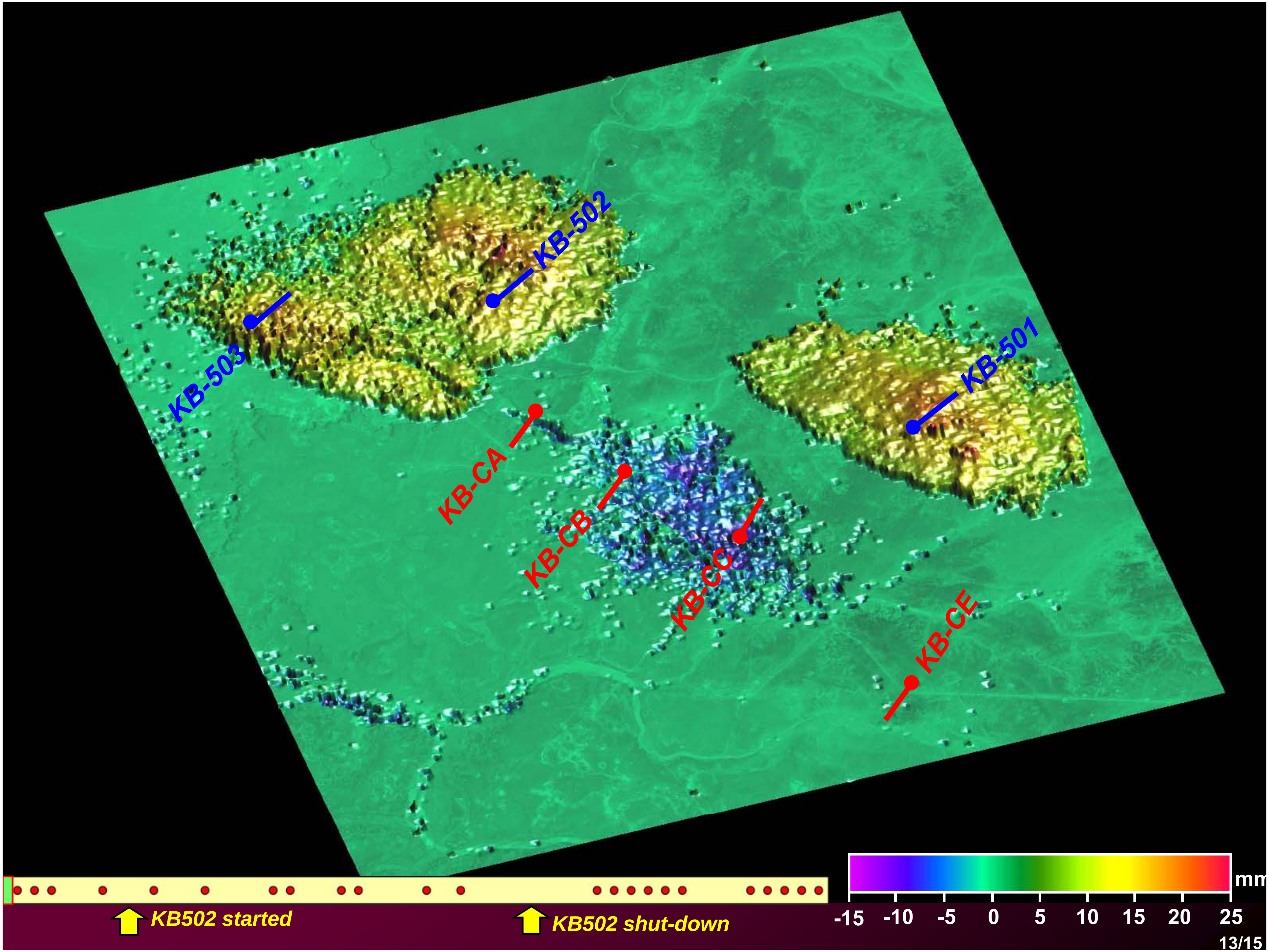
0 2 4
Kilometers

Updated Deformation History





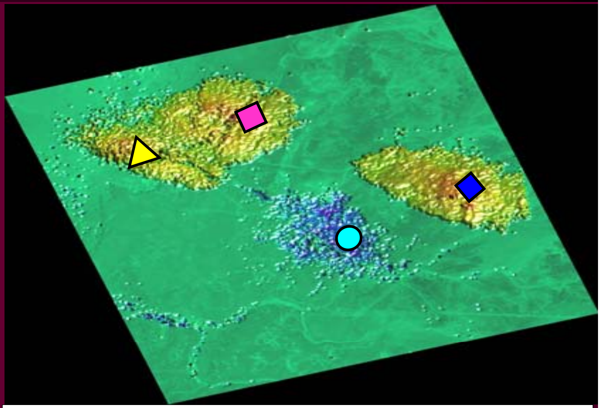
➢*KB-502 is slightly subsiding….*

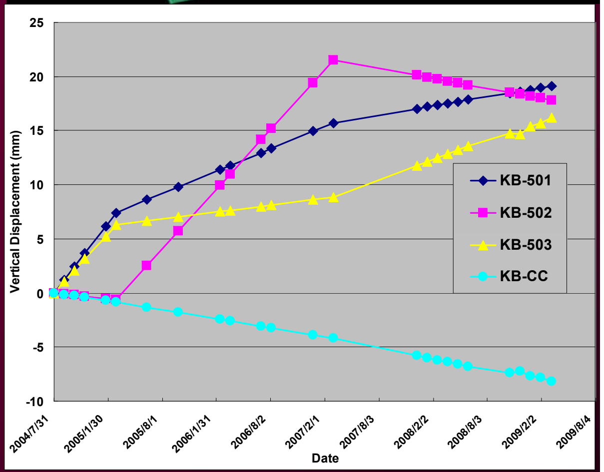


KB-502
KB-503
KB-501
KB-CA
KB-CB
KB-CC
KB-CE
KB502 started
KB502 shut-down
-15
-10
-5
0
5
10
15
20
25
mm

Summary

- ***The DInSAR analyses using ENVISAT ASAR has successfully revealed the surface deformation related with CO_2 injection.***
- ***Stacking of interferograms; the simplest and robust method for detecting phase rate, with reducing phase noise.***
- ***New finding: the area around the well KB-502 is slightly subsiding after shut-down.***
- ***The DInSAR can provide us with a powerful and a cost-effective tool for monitoring of behaviors of the injected CO_2 .***





Budget size; at an order of 10^{-2} ~ 10^{-3} (or smaller) of 4-D seismic
FYI; ENVISAT ASAR €400 / scene, volume discount available.
If ALOS PALSAR, €120 /scene.

Accuracy; 1/10~1/20 of wavelength. ~3 mm in case of ENVISAT ASAR.

Acknowledgement

The research was sponsored by

JAPEX

Thank you for your attention.

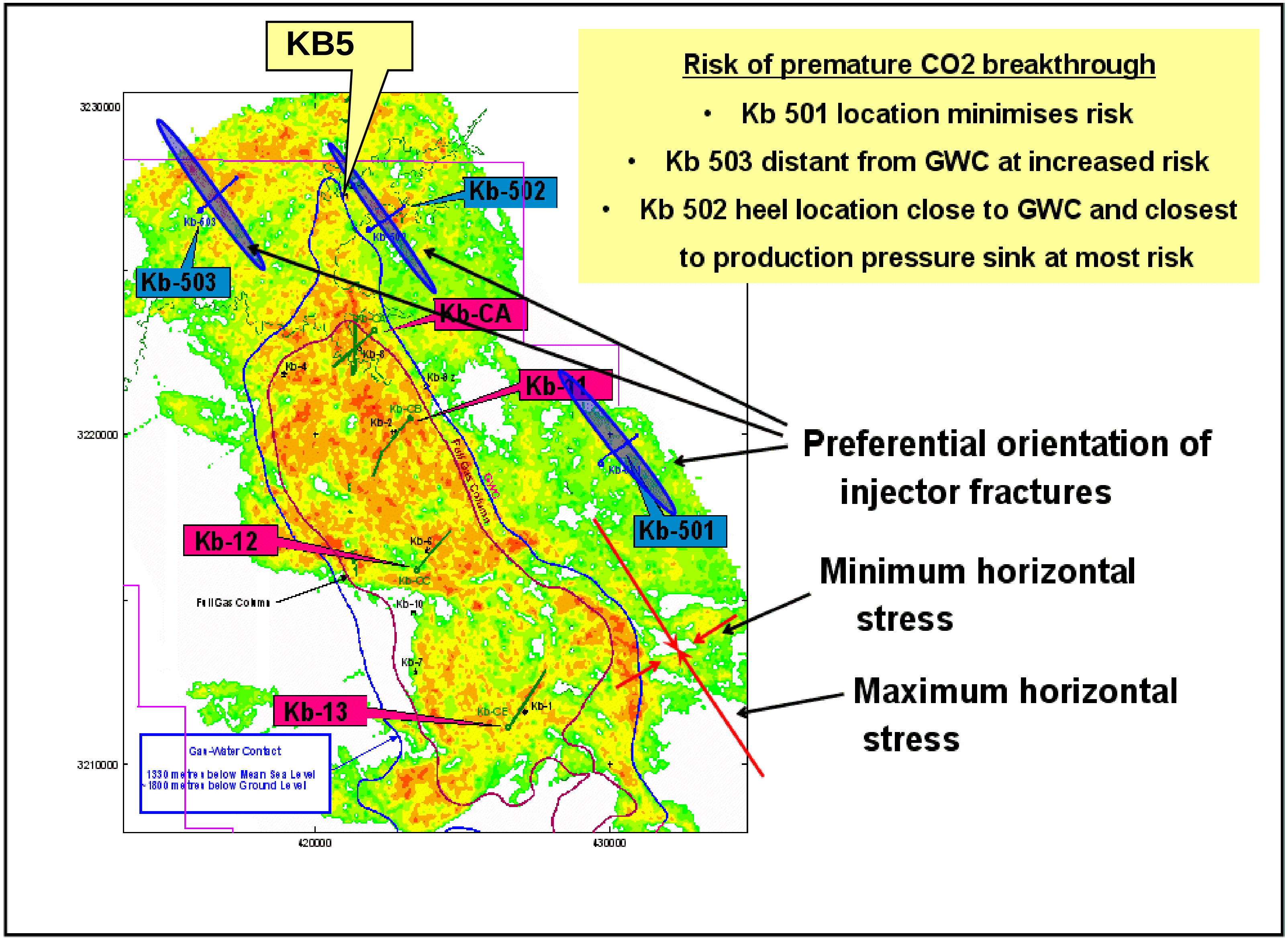
Question?

Outline

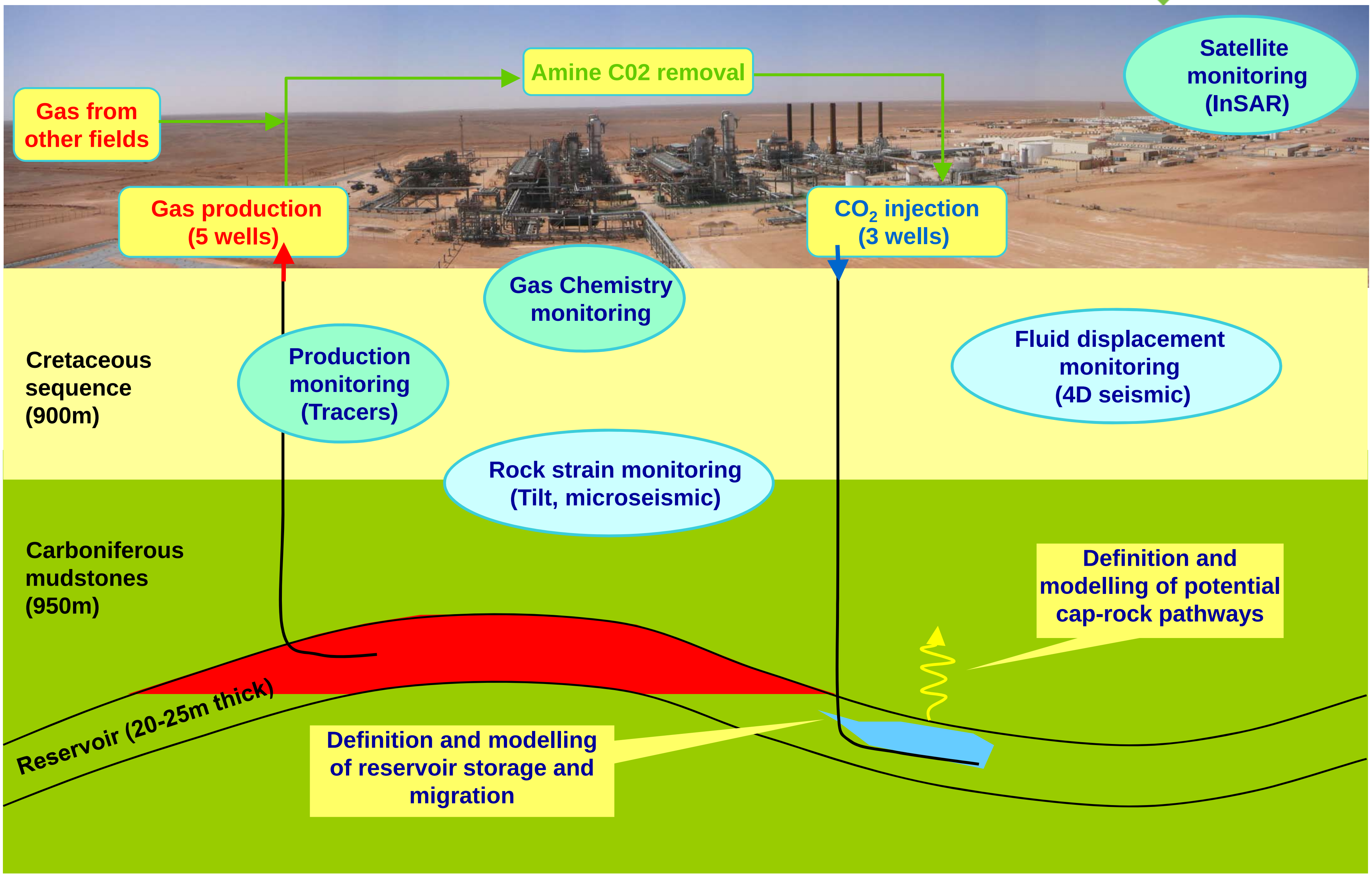
- Geological and Structural Context
- Plume development modelling - Permedia
- Key Risks Risk Evaluation URS Risque et al
- INSAR Deformation and Inversion Pinnacle Tech, LBNL
- Geomechanical / Geochemical Modelling and Experimental Summary LLNL,Univ of Liverpool,
- Monitoring Update

Krechba Key Risk Locations

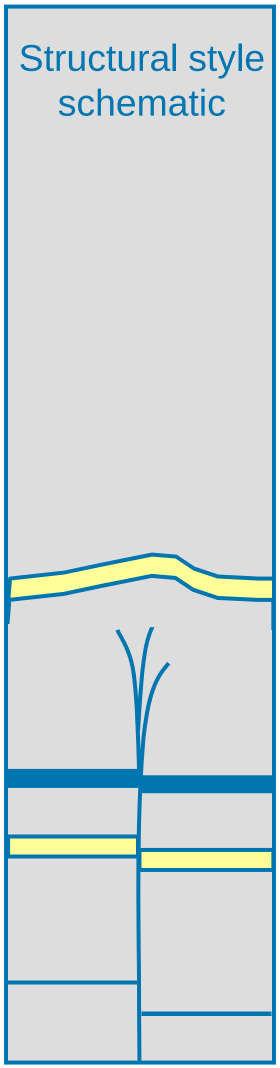
In Salah Gas
Stockage de CO_2



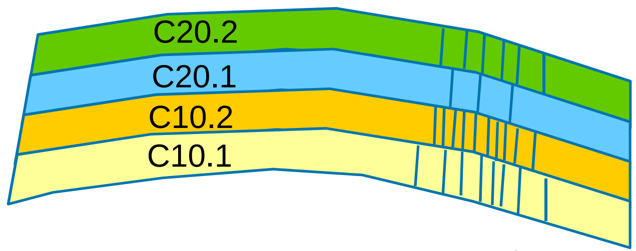
The In Salah CO2 storage site at Krechba



Conceptual Structural Geological Model for Krechba



Schematic of strata-bound fractures



Carboniferous reservoir (C10)

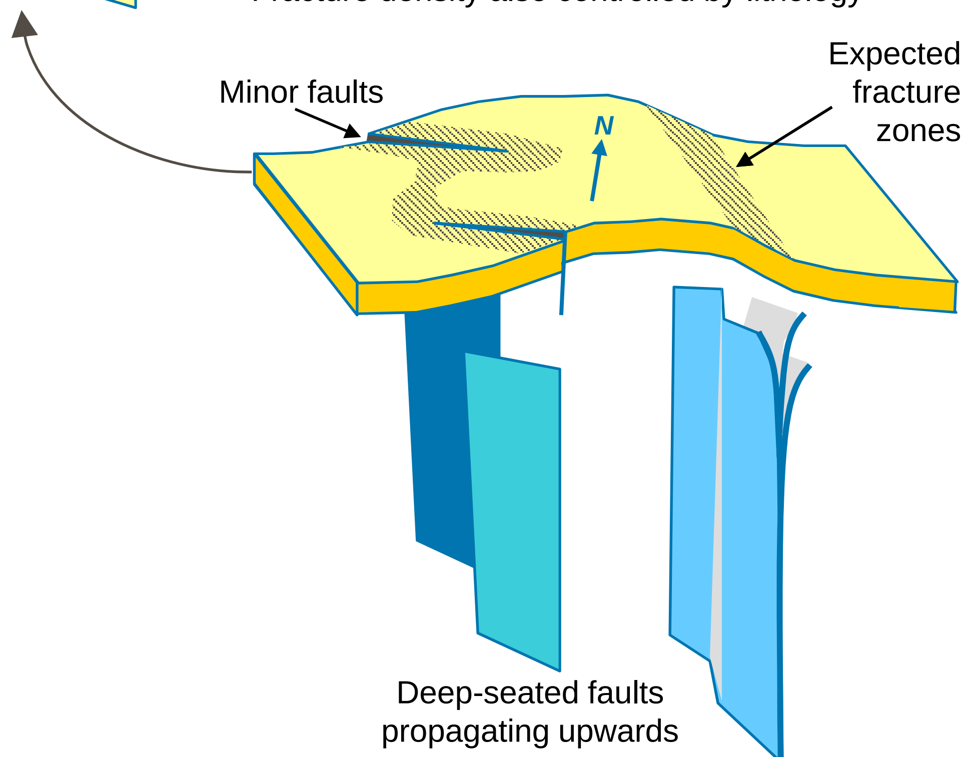
- Broad folds influenced by underlying strike-slip faults

Devonian sequence:

- Deep seated faults reactivating earlier extensional faults in dominantly strike-slip mode with some reverse faulting

Conceptual model for Krechba reservoir:

- West limb of reservoir east-west faults probably associated with fracturing
- East limb has some subtle faults and a steeper dip segment related to underlying fault activity
- Fracture density controlled by folding and faults
- Open fracture direction controlled by stress field
- Fracture density also controlled by lithology

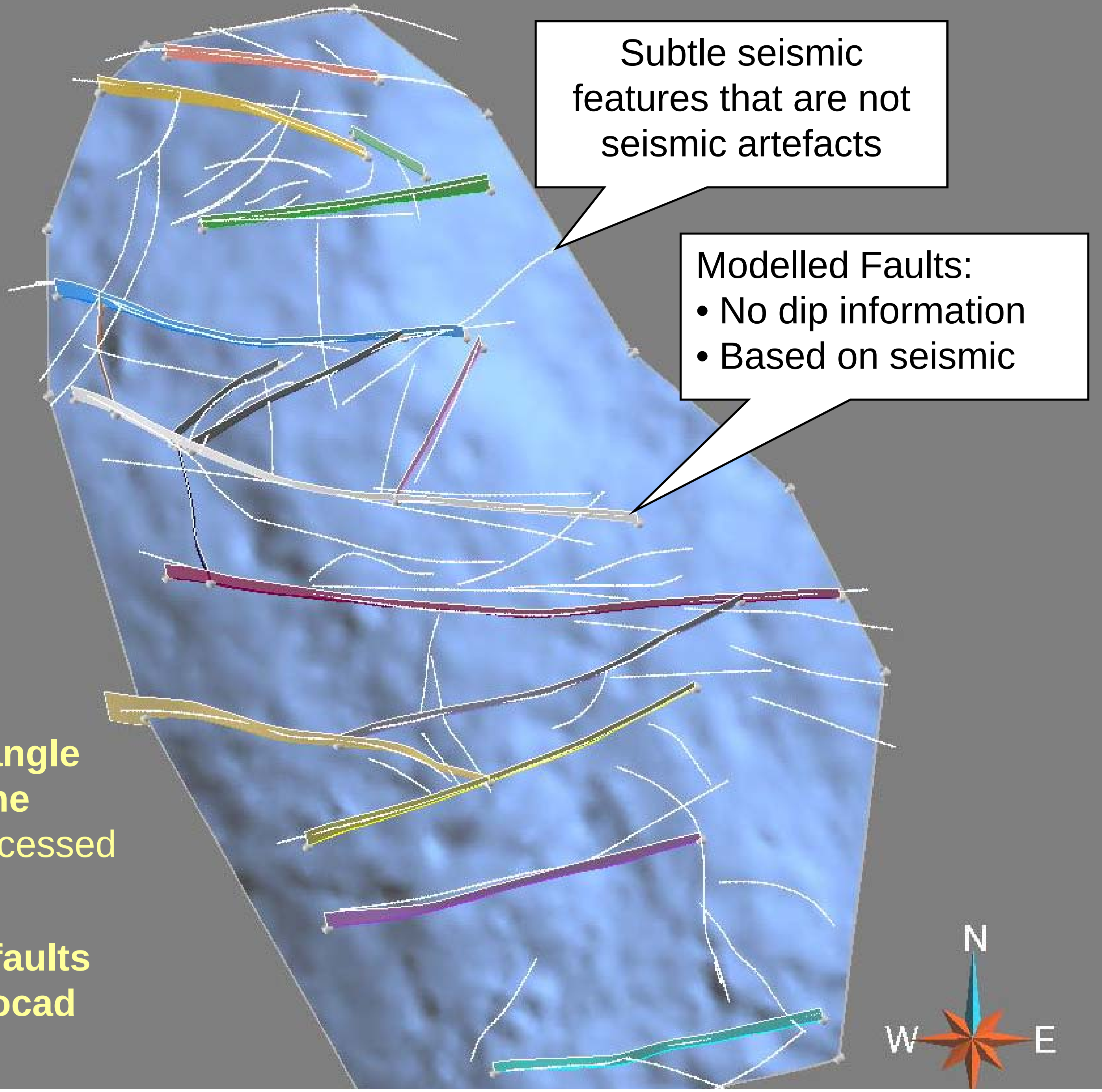


Clare Bond **MVE**

Technical questions for Research

- How does subsurface CO_2 injection affect rock properties
  - (a) at the reservoir level
  - (b) in the overburden
  - (c) surface deformation?
- How much is CO_2 injection controlled by faults or fractures (or both)?
- Have we induced fractures in the reservoir
  - (a) mechanically
  - (b) thermally?
- What flow parameters control dispersion and channelling of the CO_2 plume:
  - (a) rock property heterogeneity
  - (b) fracture distribution
  - (c) rock mechanical response
  - (d) fluid properties & PVT?
- How can the current monitoring dataset/package be best used to calibrate our models and ultimately long-term storage verification?
- What additional data should/could we be measuring?

Faulting

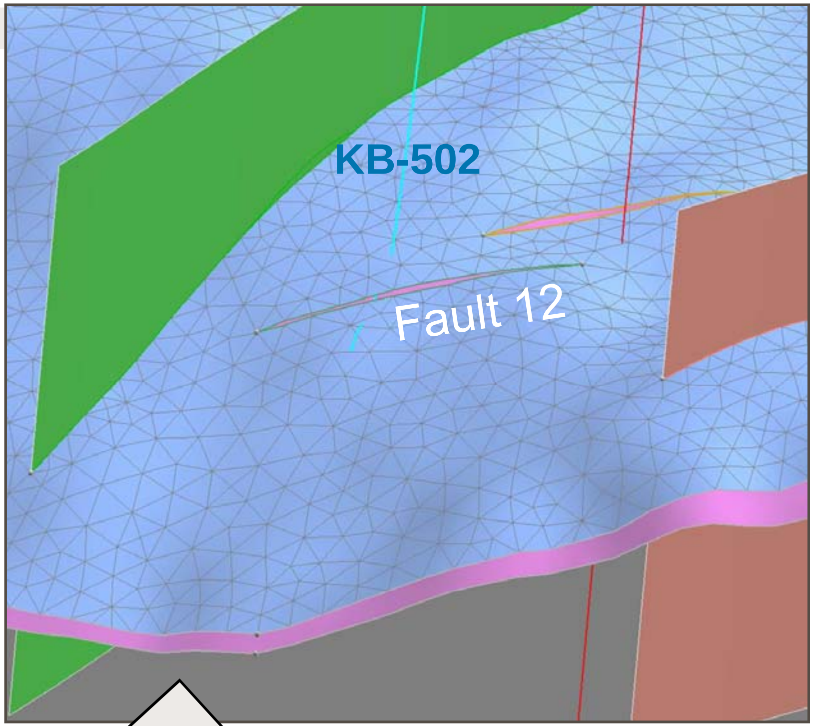


- **Subtle faults best detected on low-angle illumination of time surface** (pre-reprocessed dataset)
- **Reservoir model faults digitized using Gocad**

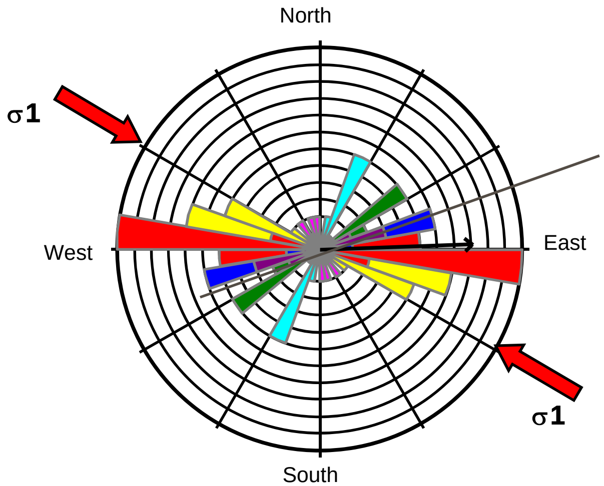
Faults and Fractures

Analysis shows that:

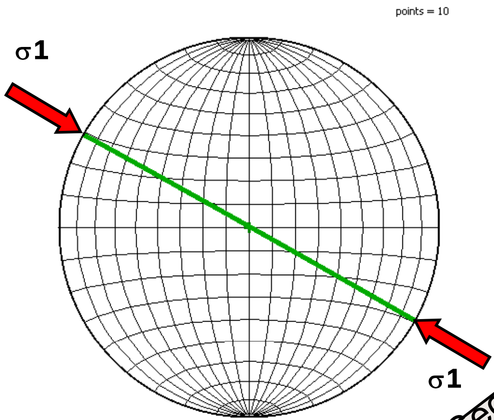
- Fault 12 could be open under the current-day stress field.
- Main fracture set is also closely aligned with current-day field
- Other fault and fracture sets more likely closed/cemented/old



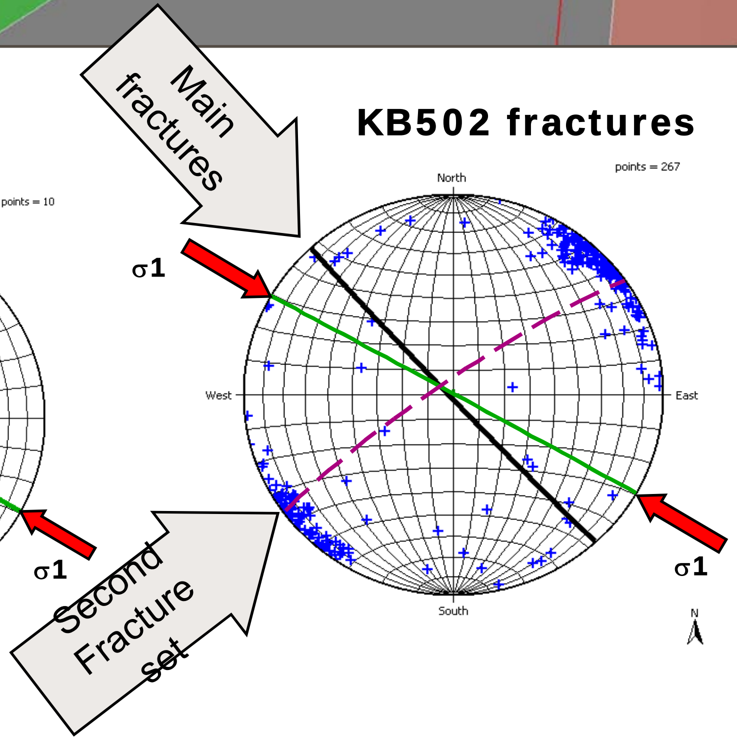
All digitised fault data



Fault 12



KB502 fractures

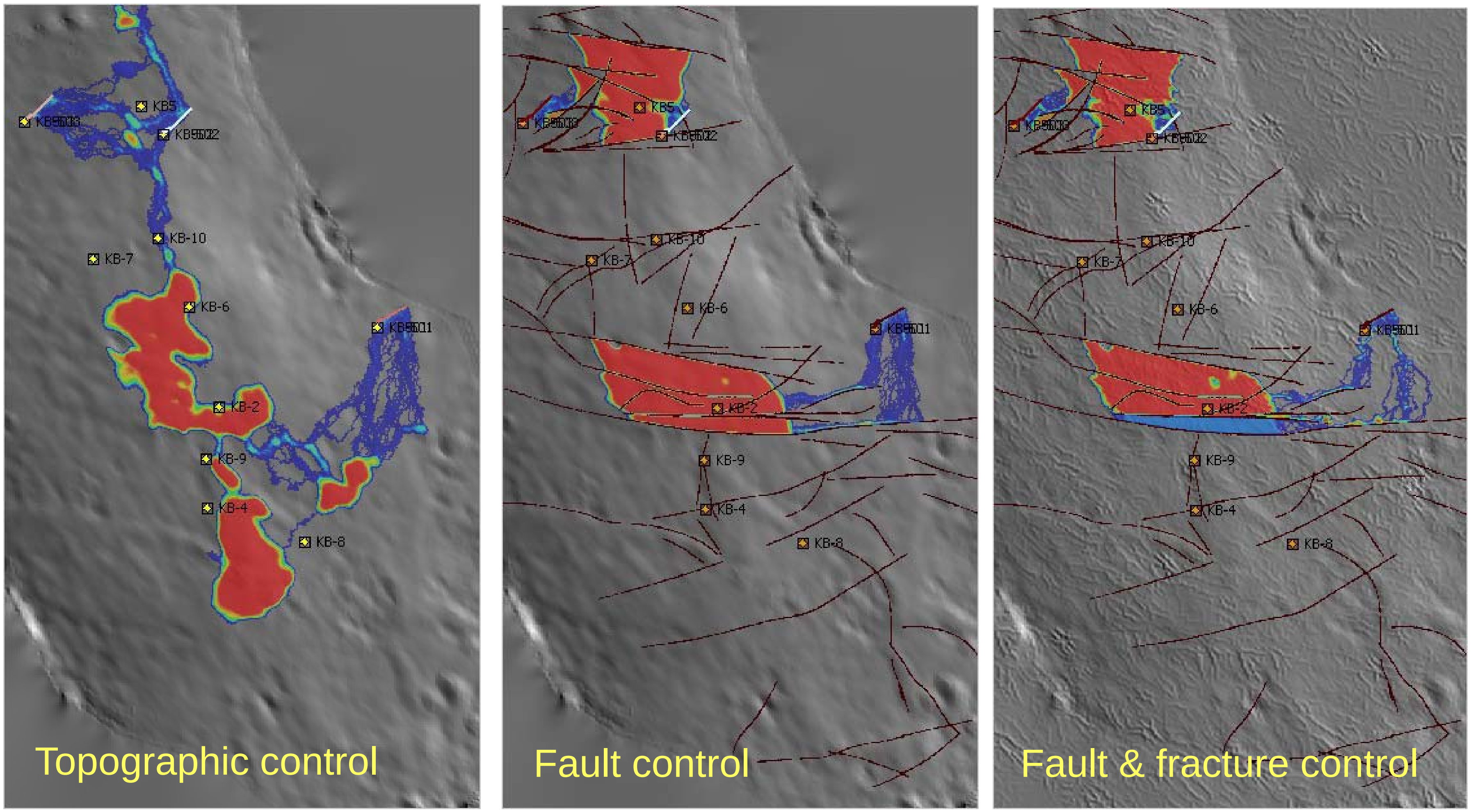


Clare Bond MVE

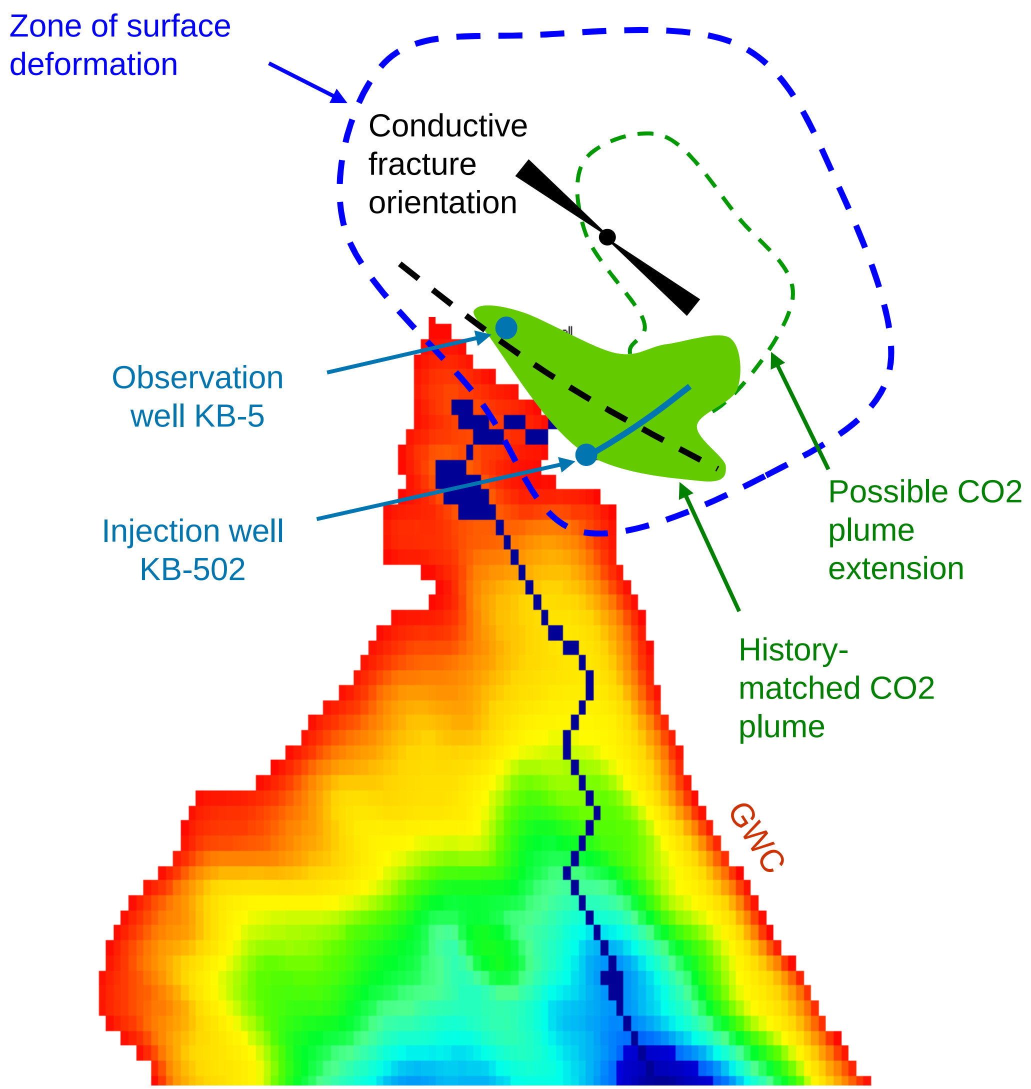
Permedia Study- mPath

Andrew Cavanagh CO2 Toolkit In Salah Gas Stockage de CO_2

- Invasion percolation approach (capillary limit)
- Preliminary result from high resolution mesh (400M cells)
- Next stage will compare black-oil simulation with IP approach
- Rapid realisations, that can explore different scenarios



The KB-502 Story
(First Break, 27, January 2009)



Well observations:

- CO_2 from injector KB-502 detected at appraisal well KB-5 after 2 years injection (Distance 1.3km)

Reservoir history match (Eclipse):

- 4D permeability corridor (suspected fault?)
- Fracture flow also important

Satellite Data:

- Deformation ellipse detected around injector
- Larger area than the breakthrough zone

Risk assessment aims

- General aims to assess:
  - the risk of leakage (containment risk) from the intended reservoir
  - the capacity of the site to store the intended mass of CO2 at the planned rates (effectiveness risk)
- Specific aims to provide outputs that help BP to:
  - understand and communicate containment risk
    - understand and communicate effectiveness risk
    - identify knowledge gaps
    - develop strategies to reduce risk

Risk assessment aims

- URS Risque process used,
  - Externally acceptable, benchmarked on a number of projects
    - Gorgon, Otway, Weyburn, Zerogen
  - Independent review process using external managed process
    - URS and CO2CRC representatives
  - Rigorously defined base case, and probabilistic scales
  - Based on expert judgements
- Further plans
  - Risk workshop highlighting different processes as communication to European regulatory people, DNV, Shell, Risque.
  - In Salah planning to benchmark risk processes
    - RISQUE Process
    - CCP Certification Process UT and LBNL
    - CO2 PENS LANL
    - DNV

Risk Assessment Process

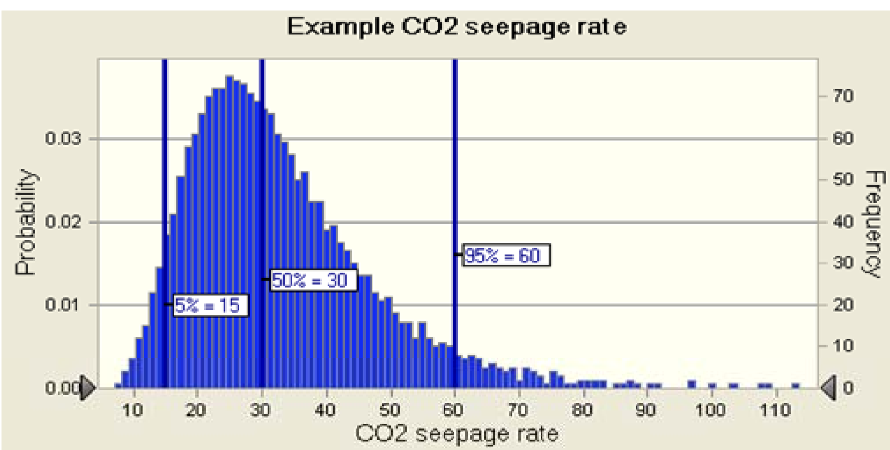
- In light of updated monitoring data, review characterisation and re evaluate risks

- Risk = Likelihood x consequences

(rate volume)

Estimated rate of CO2 seepage (t/an)
Log normal distribution

High estimate:	CL 95%	60
Best estimate:	CL 50%	30



Establish the context

Identify risks

Analyse risks

Likelihood

Consequences

Estimate level of risk

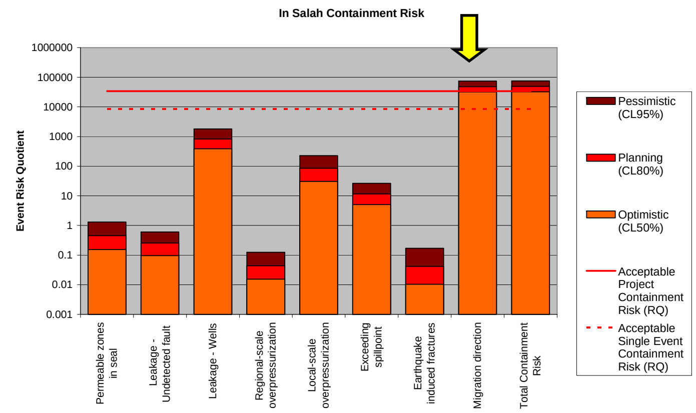
Evaluate risks against targets

Strategy to treat risks

Potential actions

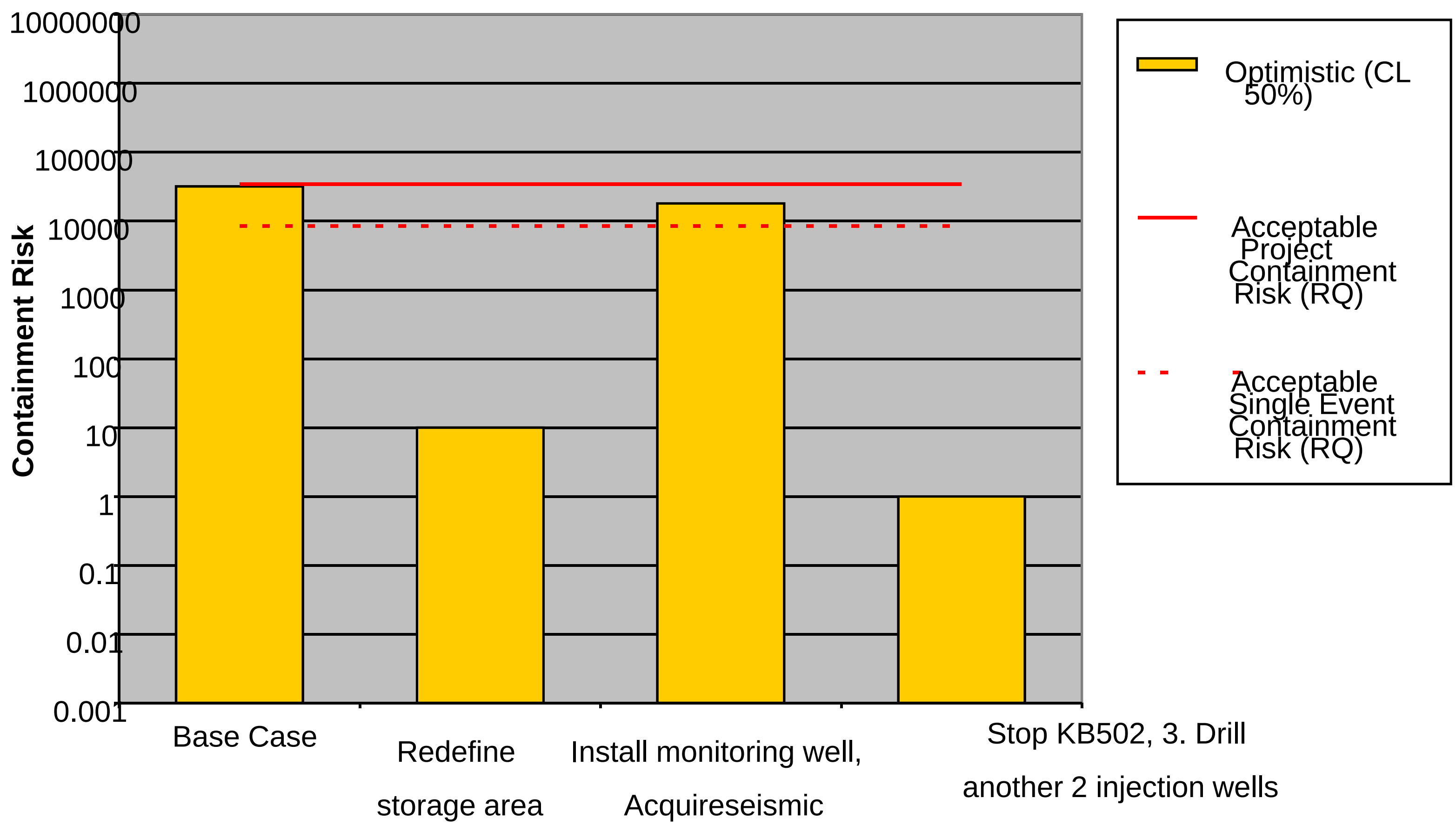
	Containment risks addressed			Effectiveness risks addressed	
Potential action	**Migration direction**	**Wells leakage**	**Local scale over-pressurisation**	**Lack of capacity**	**Resource contam-ination**
Re-define storage area	**X**			**X**	**X**
Stop KB502, 503. Drill another 2 to 3 injection wells	**X**			**X**	**X**
Install monitoring well, seismic	**X**				
Well survey, remediation		**X**			
Proper cement job		**X**			
Drill 2-3 more injection wells			**X**		

Potential risk reductions



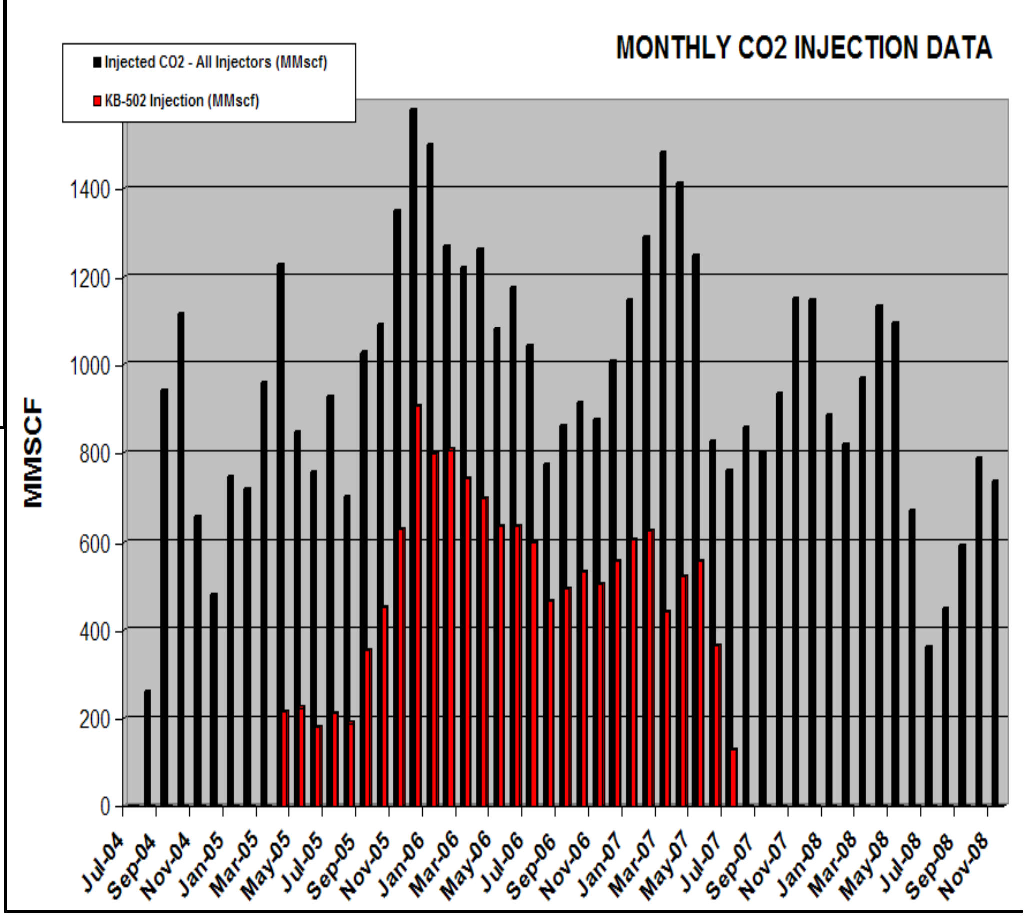
- **Containment - Migration direction**

Potential impact of actions on containment risk - Migration direction



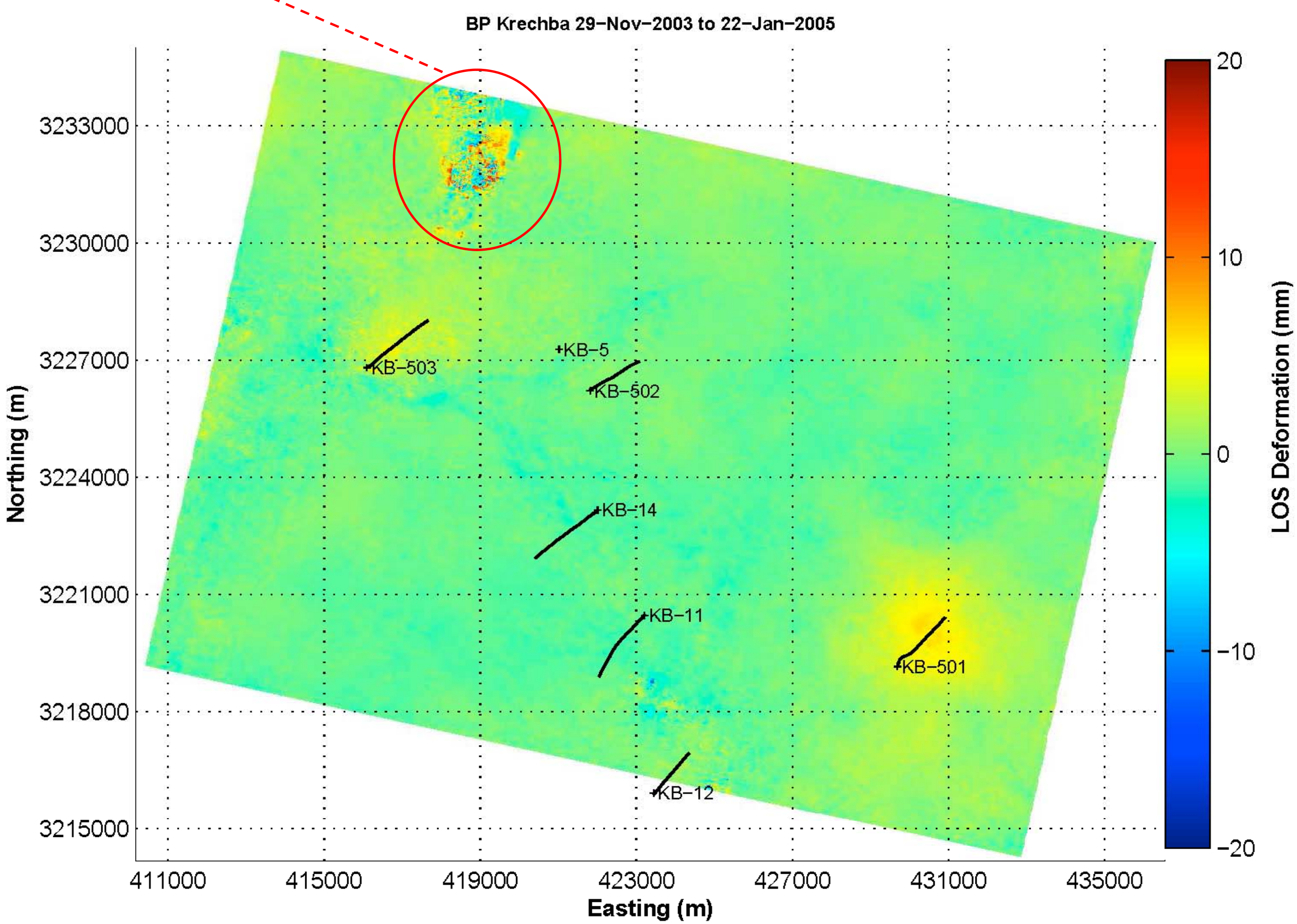
KB-502 Injection Overview

- **CO_2 injections began in April 2005**
  - *Slow start-up of ~200 MMscf per month through Aug 2007*
- **CO2 Injections ramp up to a maximum of 907 MMscf in December 2007**
  - *Steady decline in injection volume through August 2006 (468 MMscf)*
- **Two additional periods of injection ramp-up and decline after September 2007**
  - *Steep decline in injection volume after May 2007*
- **CO_2 identified in adjacent well KB-5 in early August 2007**
- **CO_2 injections were shut-in August 2007**



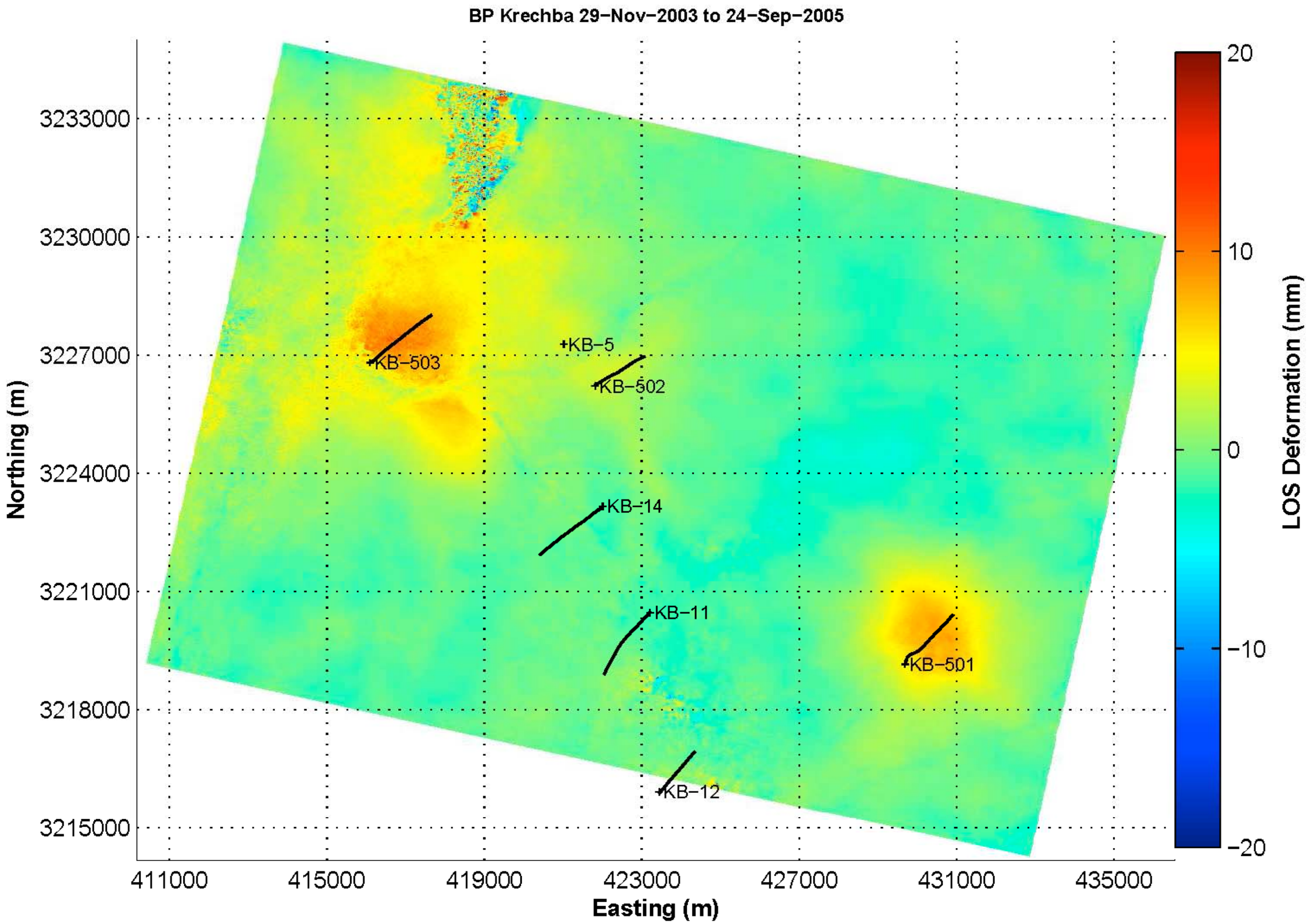
Track 65: 11-29-2003 to 01-22-2005

Note the temporal decorrelation due to sand movement. This feature is not filtered out within these SVD optimized interferograms to preserve near-well deformation magnitudes.

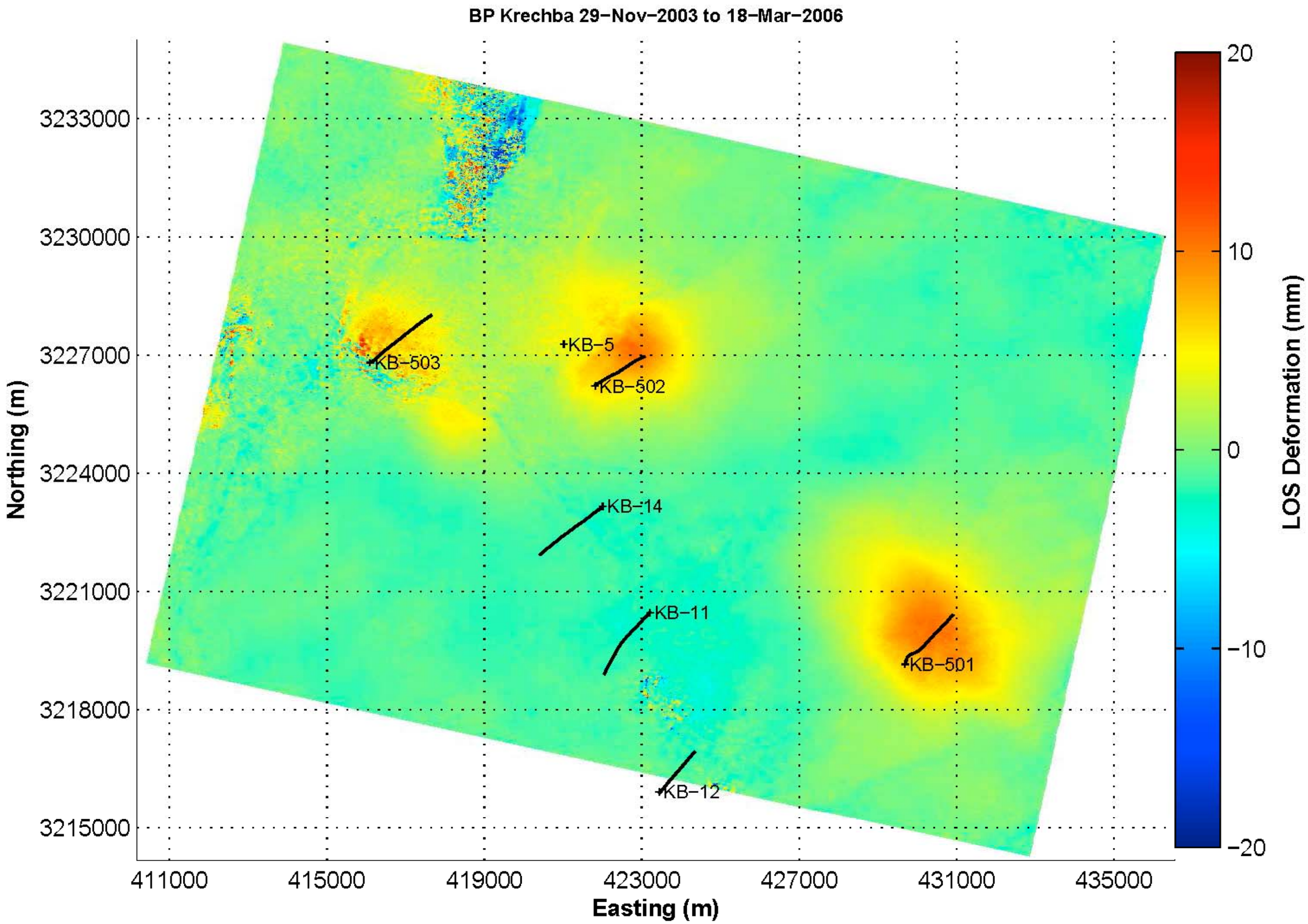


Pinnacle Technologies MDA March 26,2009

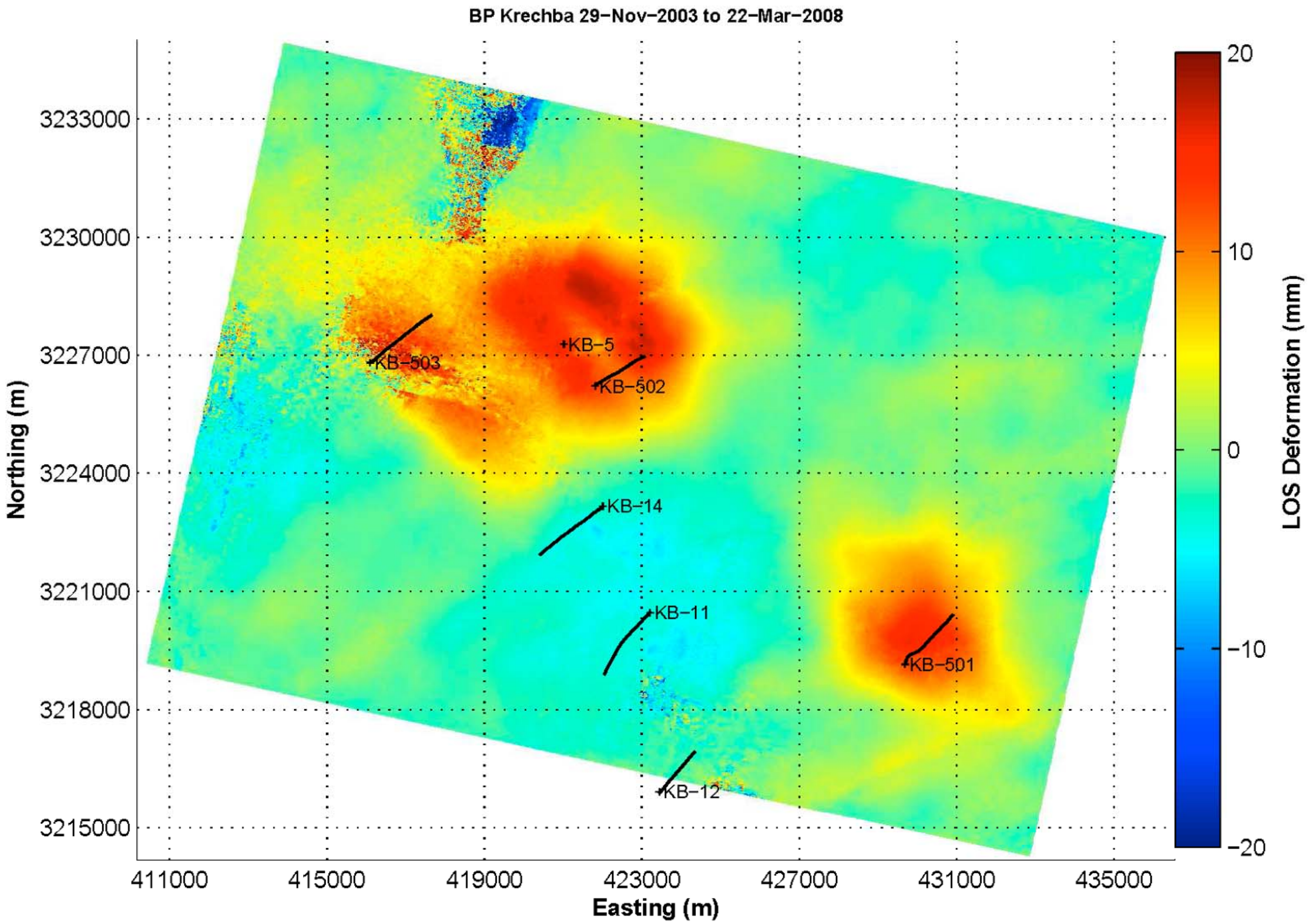
Track 65: 11-29-2003 to 09-24-2005



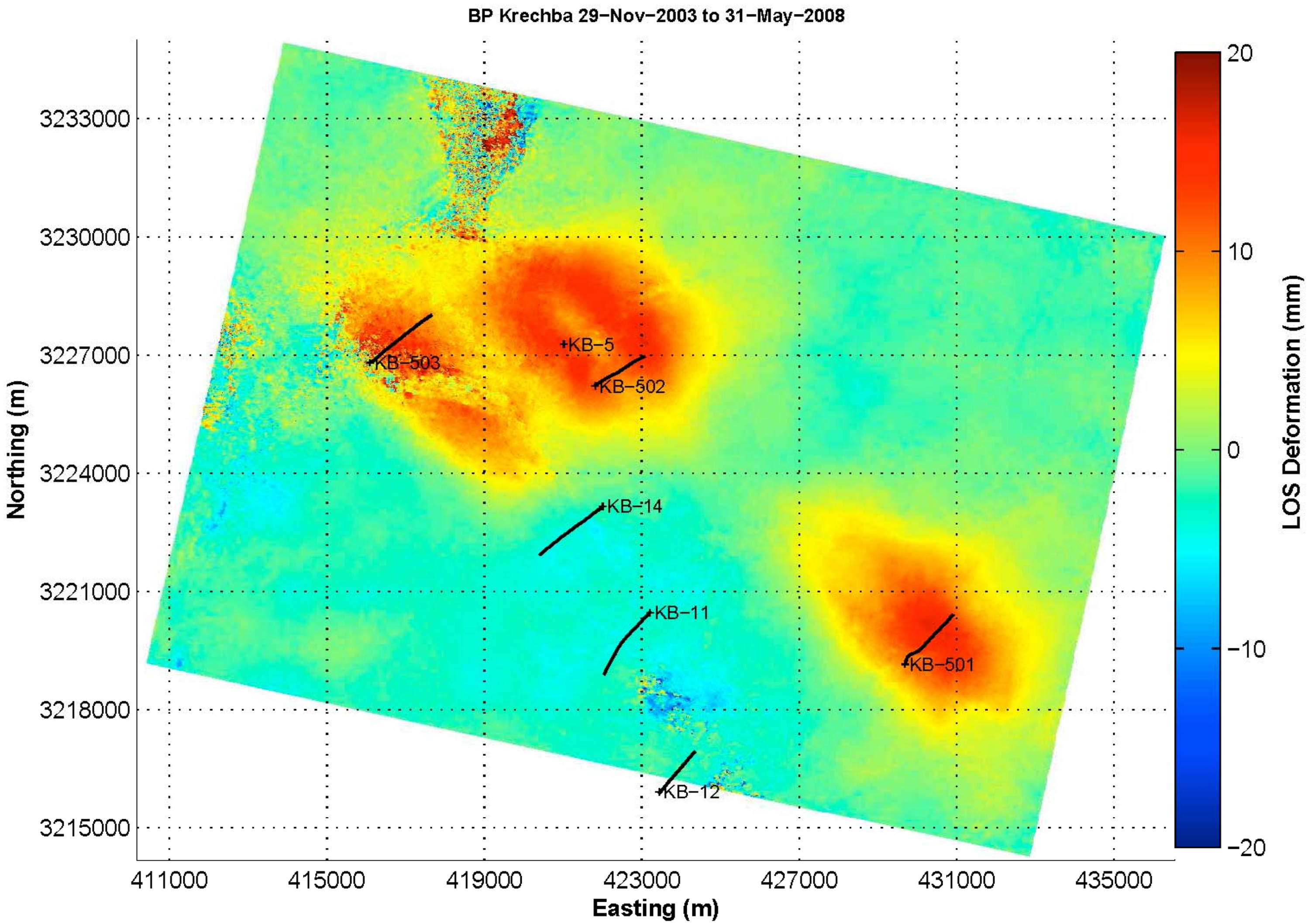
Track 65: 11-29-2003 to 03-18-2006



Track 65: 11-29-2003 to 03-22-2008



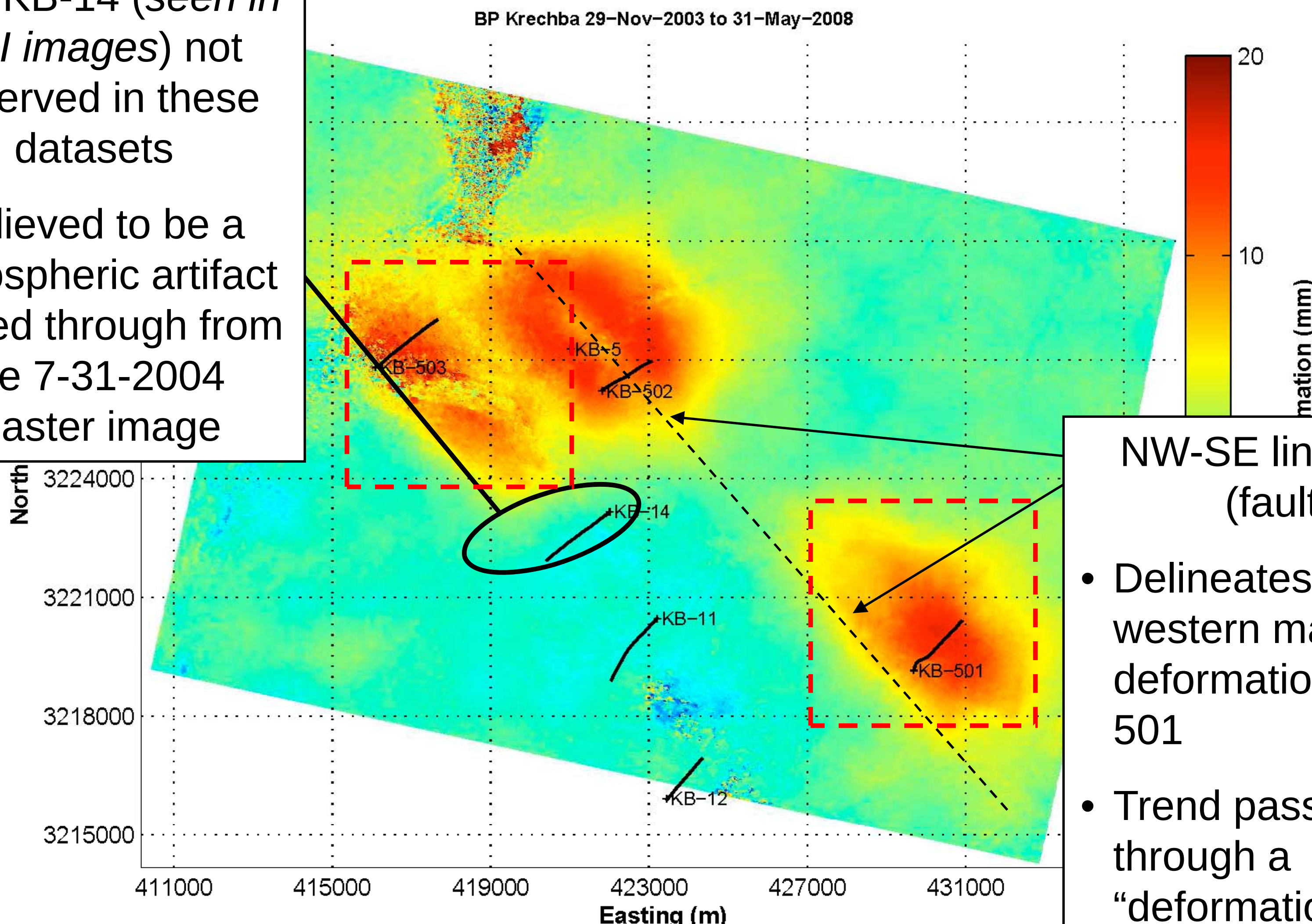
Track 65: 11-29-2003 to 05-31-2008



Track 65: 11-29-2003 to 05-31-2008

NE-SW lineation near KB-14 (*seen in JGI images*) not observed in these datasets

Believed to be a atmospheric artifact carried through from the 7-31-2004 master image



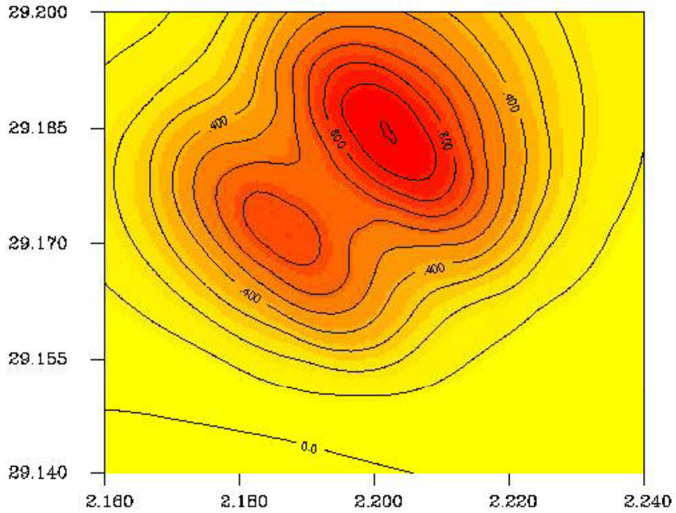
NW-SE lineation (fault?)

- Delineates western margin of deformation at KB-501
- Trend passes through a “deformation trough” at KB-502

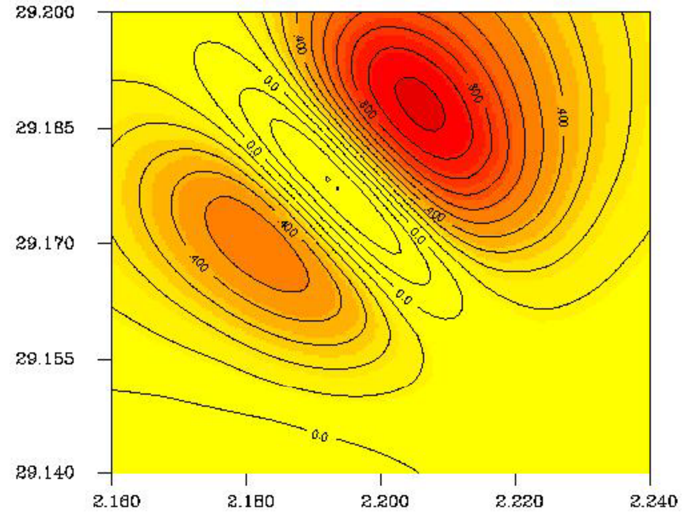
Zoom in on KB-501 and KB-503

In the Krechba elastic model Surface deformation changes signficantly with source depth:

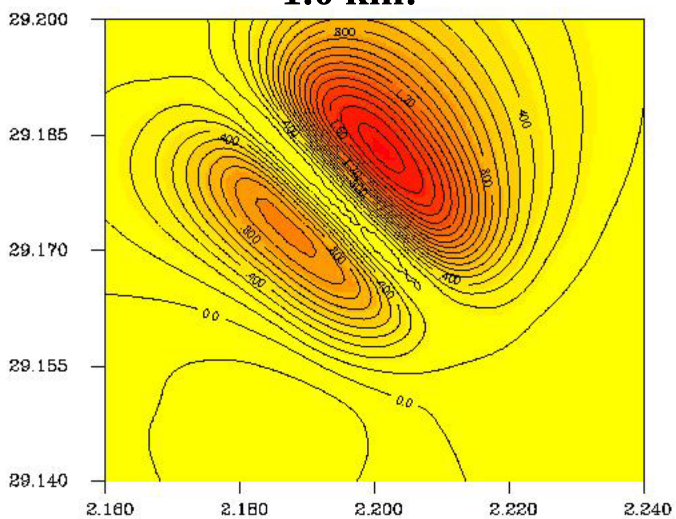
1.8 km:



1.6 km:



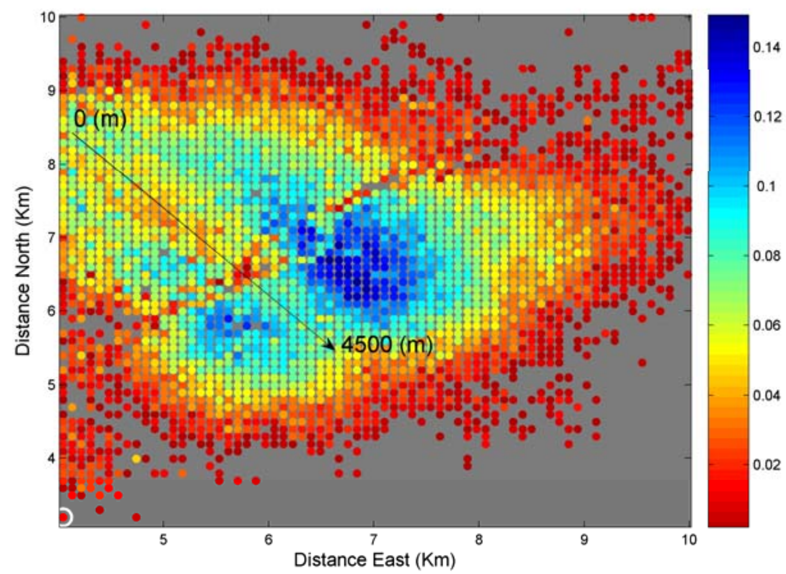
1.0 km:



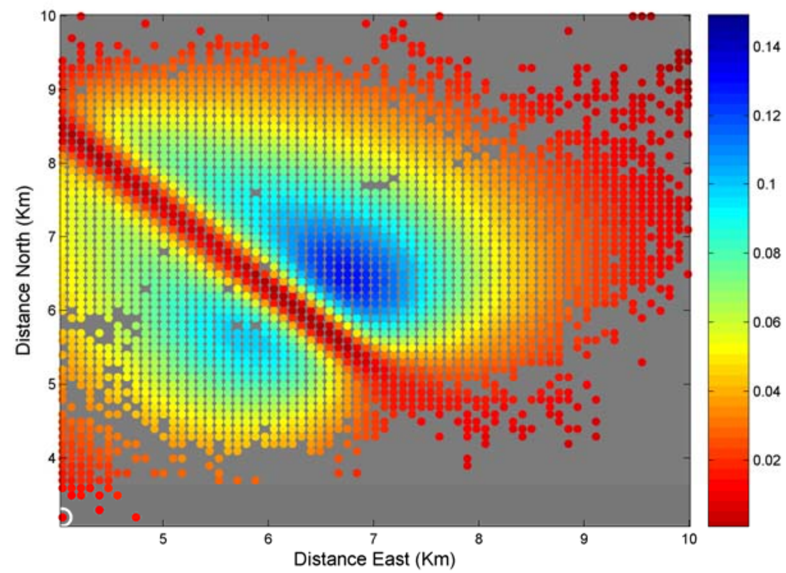
D. W. Vasco, Berkeley Laboratory A. Ferretti, F. Novali, A. Rucci TRE

Can match range change data-

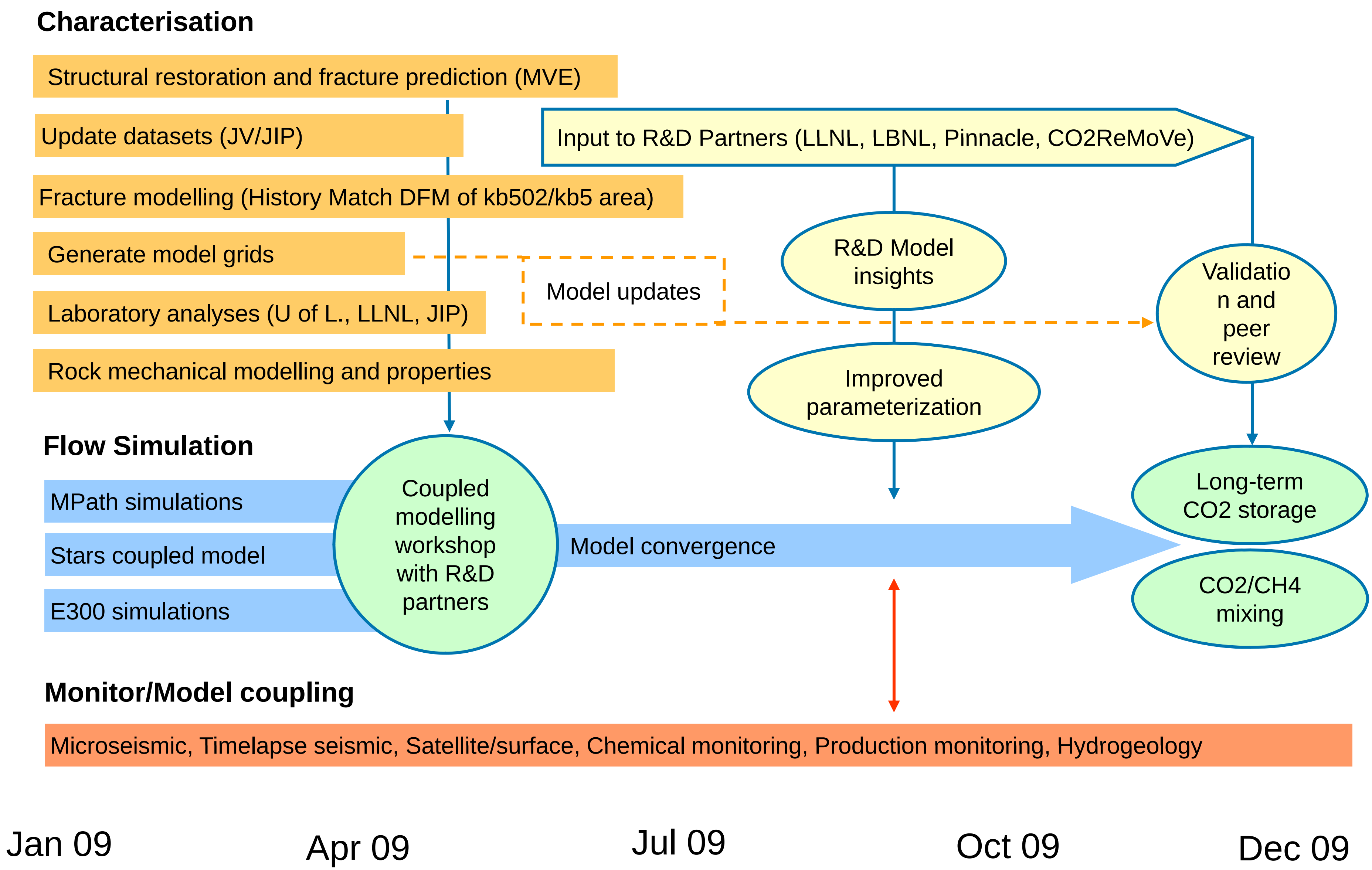
Observed range change:



Predicted range change:



Modelling Tasks for 2009



Monitoring Overview

Year 2009 involves a major effort in monitoring activities at Krechba ($12M)

- 3D/4D Seismic – Northern field area (improved imaging and time-lapse)
- Microseismic test well – KB601 drilled to 500m with geophone string)
- Tiltmeters/DGPS – in the KB501 area; 64 tiltmeter and 3 DGPS stations
- Satellite Imagery – whole field; monthly acquisition programme
- Observation wells to monitor potable aquifer – two to be drilled in 2009
- Surface gas flux, Lineament Analysis, microbiology – being done by CO2ReMoVe (BGS, BRGM, Uiv. Rome)
- Wellhead Annulus Monitoring – continual (from 2006) gas composition and tracer analysis (IFP and IFE)
- Data acquisition from development/water wells – KB-15, KB-16 and KB-17
  - Cuttings analysis, headspace gas
  - Electric logs, behind casing sonic (MSIP)

Summary of Progress, April 2009

- **Shared Earth Model updates:**
  - Seismic depth cube updated (using new velocity model from JV)
  - New faulted reservoir mesh (17 faults) built using GoCad triangular mesh
  - Discrete Fracture Network (DFN) models refined to cover realistic ranges
- **Permedia CO2Toolkit** (MPath & Fast Black-Oil Simulator):
  - In Salah dataset is being used as a Case Study in the Permedia CO2Toolkit Consortium. Case study results will be shared with JIP.
  - Most recent model uses 400M cell discretization.
- **Midland Valley (MVE) Fracture Study:**
  - Aim is to predict fractures based on structural geological reconstruction
  - Phase 1 is mainly on structural interpretation and restoration
  - Phase 2 will generate geo-cellular/fracture models of Krechba Carboniferous

Summary of Progress, cont.

Core Analysis Programme:

- Obtained sample shipment from Algeria
- CT scans made of all samples to help decide analysis plan
- Discussions with U. Liverpool to decide core analysis programme

Input to Monitoring programme:

- Prepared and submitted groundwater wells plan
- Support microseismic well plan (KB-601)
- Gocad used as Shared Earth Model and planner
- Geoprobe used for seismic co-visualisation

Flow modelling:

– Fracture modelling	LLNL
– Geomechanical/geochemical modelling	LLNL
– Experimantal elastic rock properties	Univ of Liverpool
– Surface deformation Inversion and geomechanical modelling	LBNL

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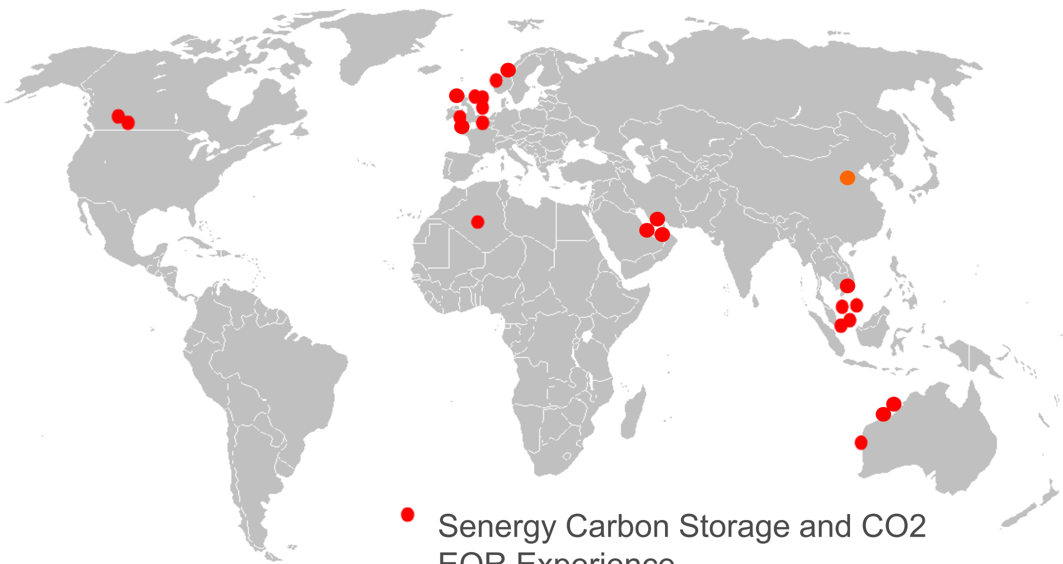

- **$100M Turnover, 500 Specialists in Oil and Gas and Alternative Energy Sectors**
- **Offices in UK (London and Aberdeen), Australia, Abu Dhabi, Malaysia, Norway, New Zealand, Russia**
- Over 45 major carbon storage projects undertaken in the past five years
- **BSI Certified ISO9001 Quality System, ISO 14001 Environmental Management, ISO Health and Safety System**

INVESTOR IN PEOPLE

1ST POINT FPAL.COM

BSI REGISTERED

UKAS QUALITY MANAGEMENT 003

Talk Structure

- What are we trying to monitor?
  - reminder of relevant subsurface CO2 trapping processes
- What are we expected to monitor?
  - A view of emerging regulations
- What can we monitor?
  - proven subsurface technologies
- How should we be doing this?
  - risk based?
  - pressure measurements?

What are we trying to monitor?

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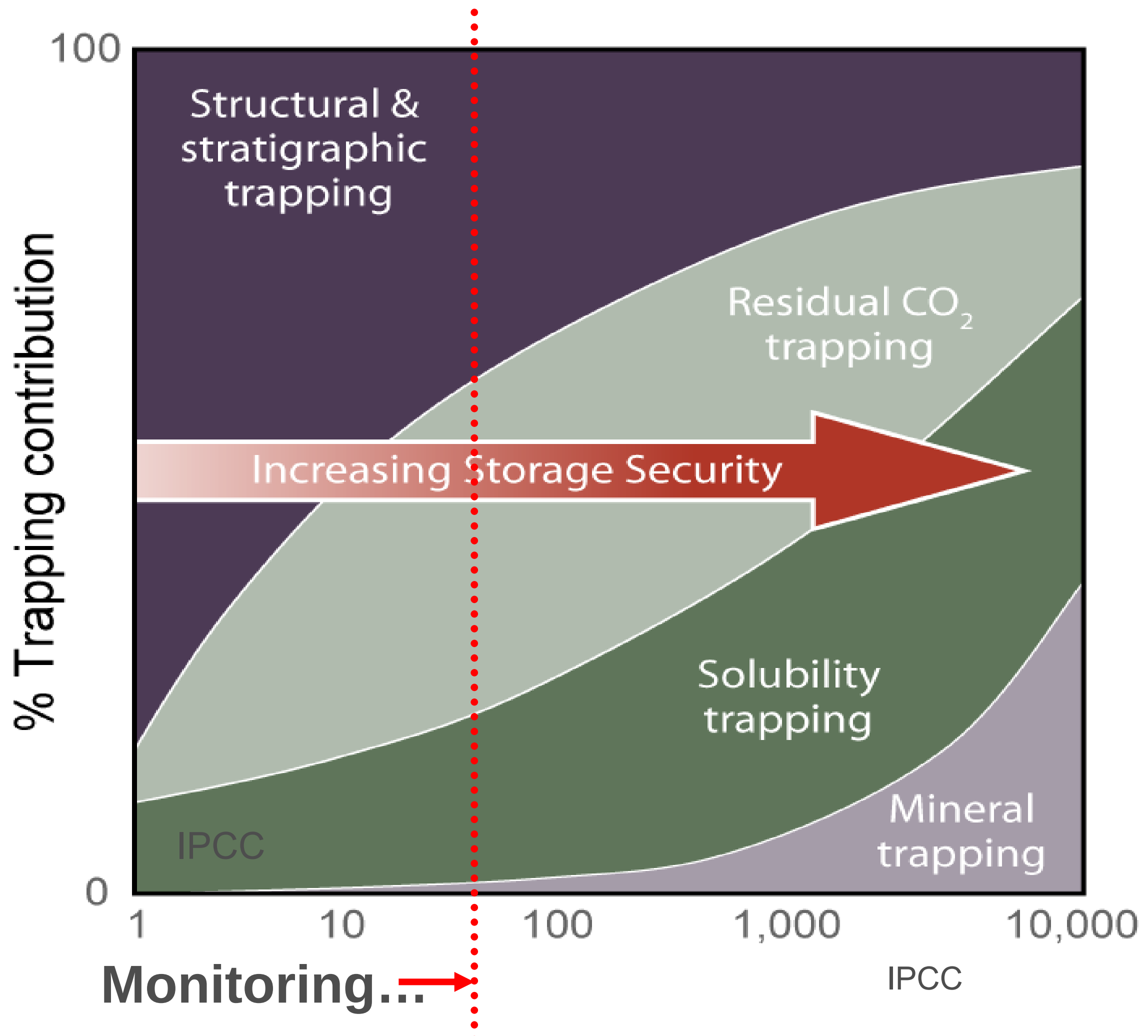

What are we expected to monitor? EU draft directive

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- To simulate, track and predict injected CO_2 throughout the subsurface
- Detect previously unidentified migration pathways in the storage complex and beyond
- Evaluate the different storage processes and the evolution of the storage reservoir inc. pressure complex
- Show that CO_2 is permanently contained within the storage complex for the indefinite future
- Ensure well integrity


EUROPEAN UNION

THE EUROPEAN PARLIAMENT — THE COUNCIL

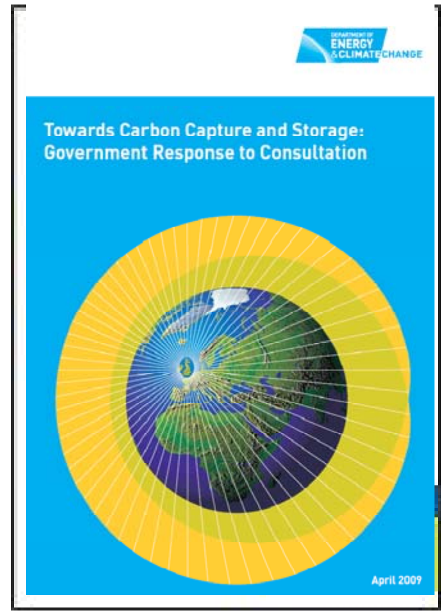
Brussels, 26 March 2009
(OR. en)

2008/0015 (COD) — PE-CONS 3739/08

ENV 1044
ENER 482
IND 240
CODEC 1908

LEGISLATIVE ACTS AND OTHER INSTRUMENTS

Subject: DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006



Can we meet monitoring regulations? EU directive Update 2009

- To simulate, track and predict injected CO2 throughout the subsurface
- CO2 plume behaves as expected (**where possible 'CO2 plume'**)
- Detect previously unidentified migration pathways in the storage complex and beyond (**detect migration**)
- Evaluate the different storage processes and the evolution of the storage reservoir
  - **site is evolving towards a situation of long-term stability**
  - **detect irregularities and leakage**
- Liability transfer show that CO2 is permanently contained within the storage complex for the indefinite future – **revised liability transfer definition in EU directive**
- Ensure well integrity

Canadian, US, Australia, Japan

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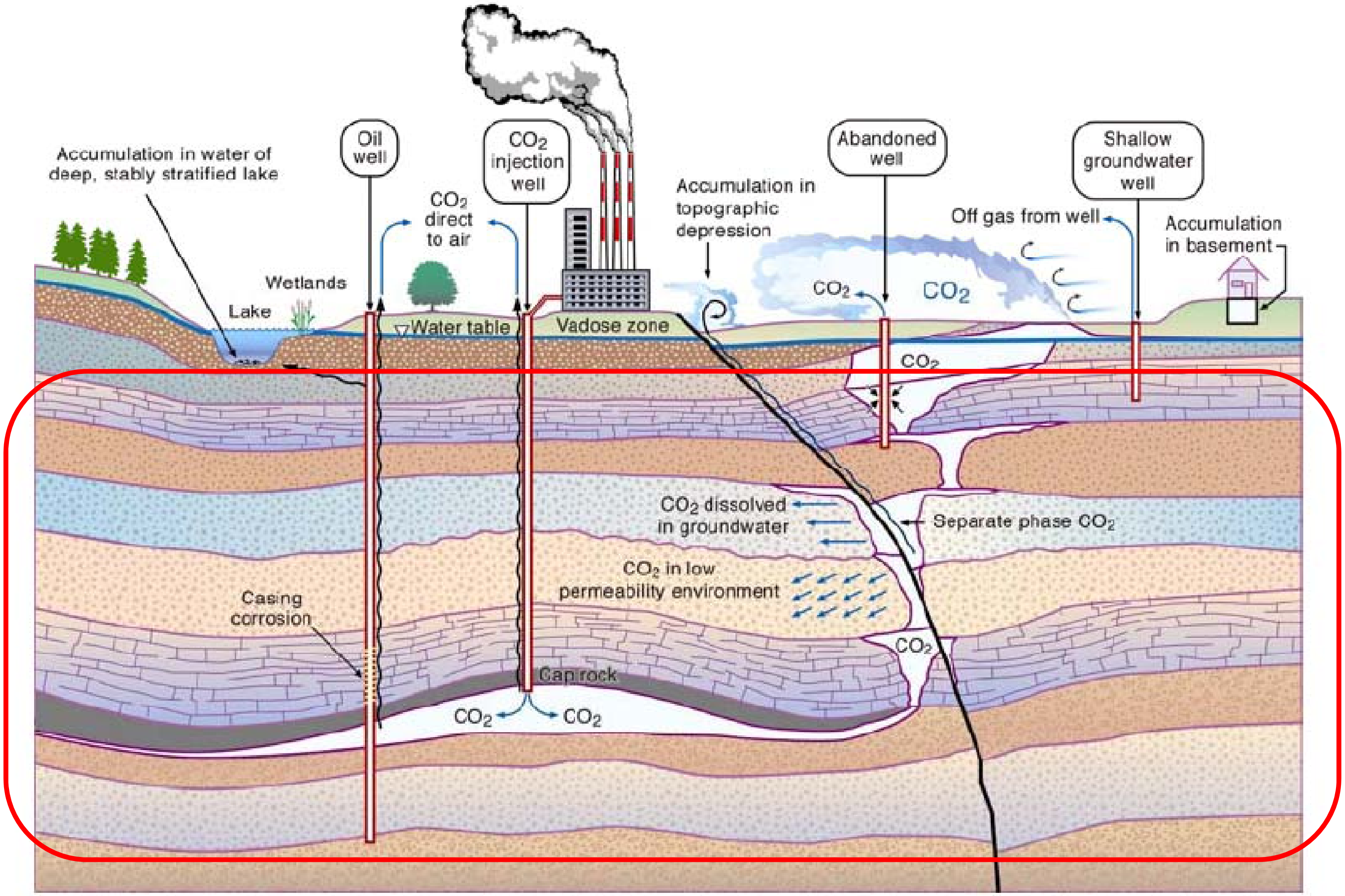
- Canada (Alberta)
  - ‘Monitoring the fate of the injected CO2’
  - Long term security of storage reservoir
  - CO2 plume behaves as expected
  - Percent of CO2 dissolved in the formation
  - Pressure levels match predictions
- US EPA
  - Plume imaging and pressure front/footprint?
- Australia
  - Location of CO2, behaves as expected, i.d. and quantify leaks
- Japan
  - Front and extent of CO2 plume

What can we monitor ? – proven technologies

- Subsurface monitoring
  - Selected tools that have been shown to work
  - Limitations of these monitoring techniques

Subsurface monitoring – not just the store



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Subsurface monitoring - what is measured?

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- Remote measurements of the CO2 ‘plume’
  - Seismic image of separate phase CO2
- Direct measurement via wells,
  - CO2 migration and CO2-water-rock interactions
  - Discriminate between different CO2 sources (injected versus natural)
- Selected examples follow

Subsurface monitoring example - 4D seismic

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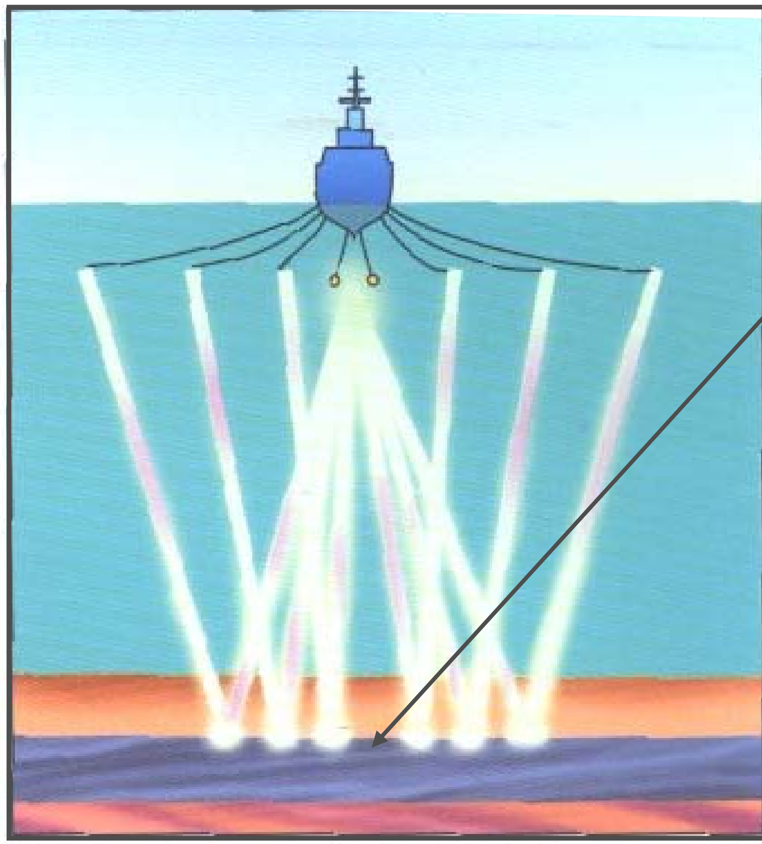
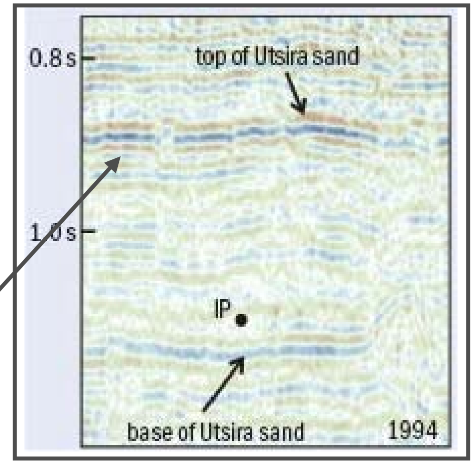
- Track migration of CO_2 in subsurface using seismic measurements of storage reservoir
- Seismic wave velocity reduced with substitution of highly compressible CO_2 for less compressible water
- Multiple surveys; before and during CO_2 injection, analyse differences in seismic data and map CO_2 distribution

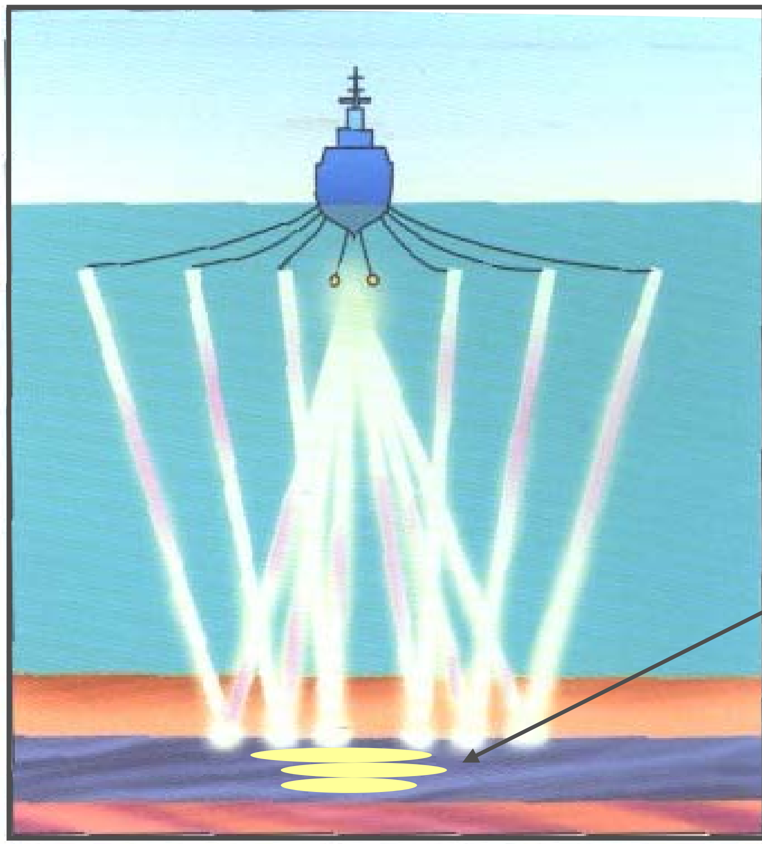
How 4D surface seismic works – Sleipner baseline survey

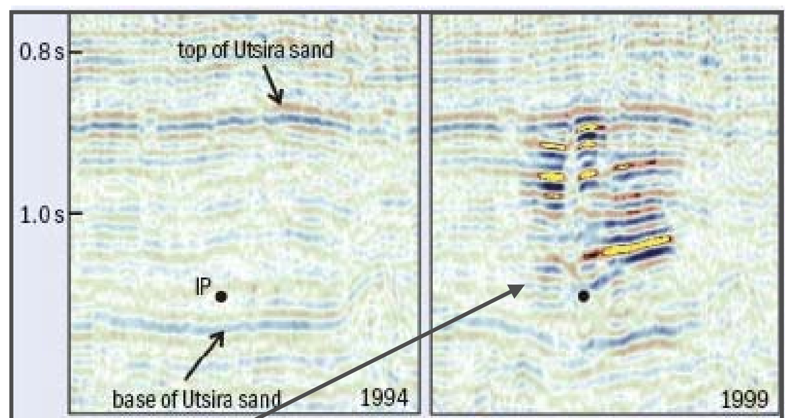




BGS

How 4D seismic monitoring works -Sleipner post injection repeat survey; anomaly is image of CO2 'plume'





BGS

4D seismic monitoring limitations

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- No detection of CO_2 dissolved in water – no information on solubility trapping (could be 20% of CO_2)
- Resolving 'plume of CO_2' challenged if there are other compressible fluids or gases in storage reservoir
  - Therefore may not work with depleted hydrocarbon reservoir storage if gas or gas rich oil in situ
- Resolution also limited, by reservoir geometry and depth/overburden
- Not able to accurately derive volumes, sensitivity limited above ~20-30% CO_2 saturation

Subsurface monitoring – wells

Image PTRC

Overview of well monitoring

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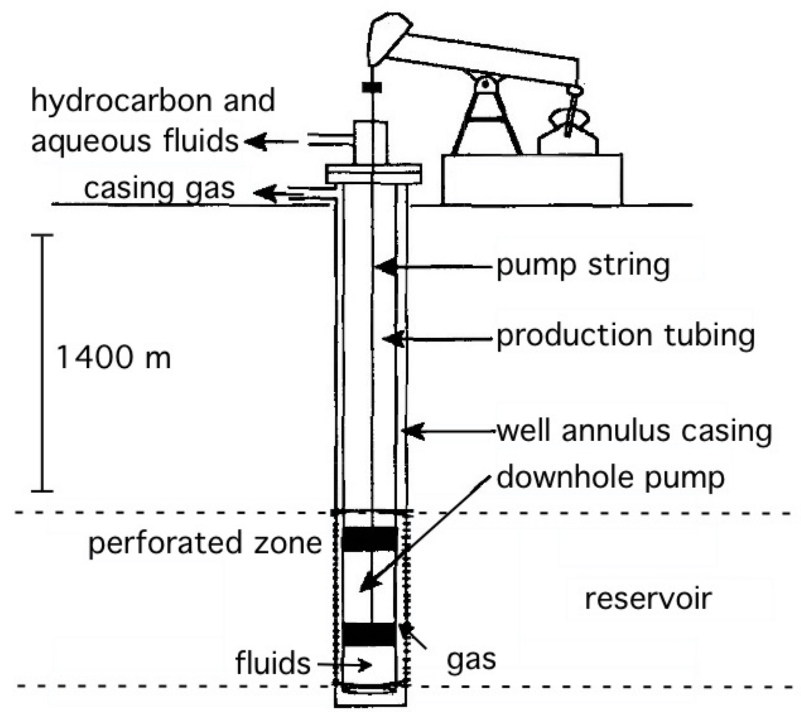
- Collect samples of produced fluids and gases from wellhead or downhole for chemical analysis
  - Monitor progress of solubility trapping and mineral reactions
  - Discriminate between different CO2 sources
- Also a range of physical measurements: borehole seismic technologies, P,T. wireline measurements and well integrity techniques

Surface v downhole fluid and gas sampling

- CO2-water rock reactions
- Surface sampling - large uncertainties due to chemical changes that take place in response to changing well physical conditions
- Isotope measurements and dissolved metals robust
- U-tube downhole measurements and sampling for reservoir conditions – close to, but still not pristine
- Flowing versus static samples



Well monitoring example surface – progress of solubility trapping

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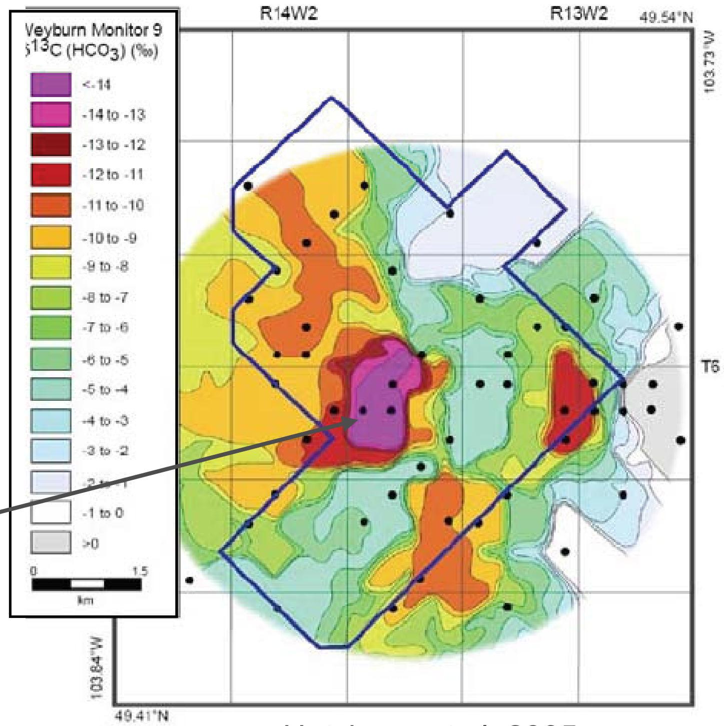
- Weyburn - 4 million tonnes injected 2000-2004
- Contour map shows amount of dissolved injected CO2 (HCO3-) in reservoir water samples from monitoring wells
- High concentration of dissolved injected CO2 = effective solubility trapping of CO2

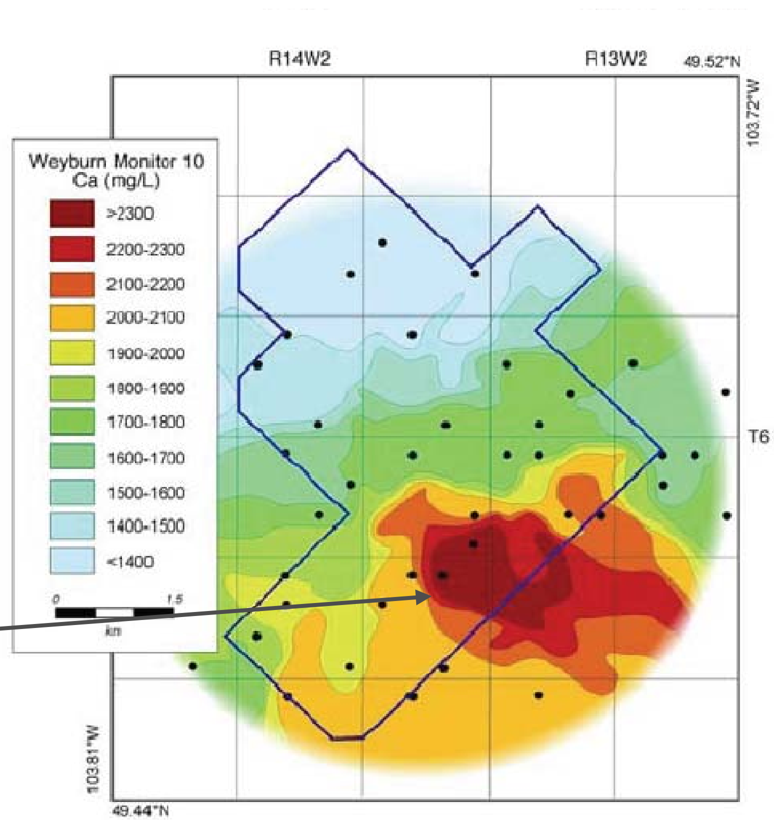


Hutcheon et al. 2005

$$CO_2 + H_2O = CO_{2(aq)} + H_2CO_3 = H^+ + \mathbf{HCO_3^-}$$

Well monitoring example – mineral reactions

- Weyburn - 4 million tonnes injected 2000-2004
- Contour map shows amount of dissolved calcium in reservoir water samples from monitoring wells
- High calcium concentration = carbonic acid dissolving calcium minerals (calcite)



Hutcheon et al. 2005

$$H_2CO_3 + CaCO_3 = \mathbf{Ca^{2+}} + 2HCO_3^-$$

Well monitoring - discriminating between different CO2 sources

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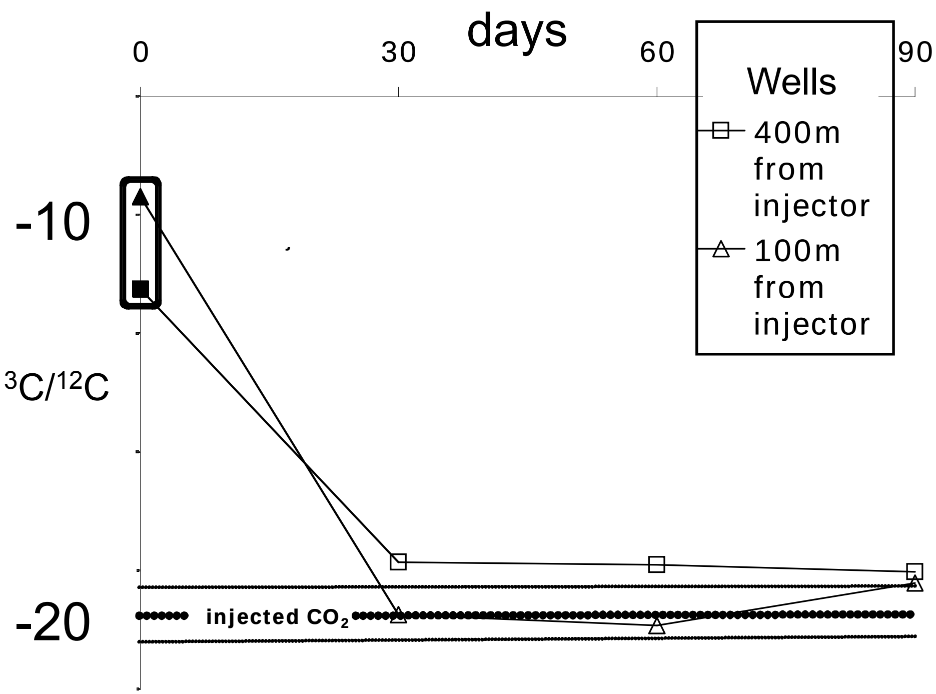
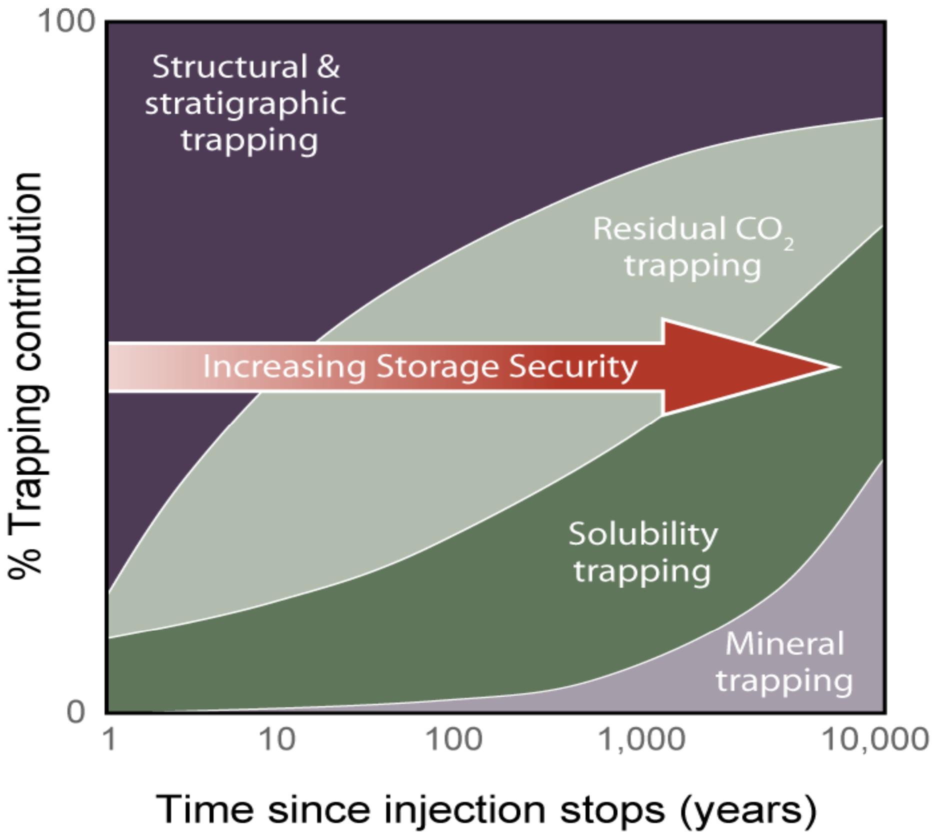
- Reservoir with an injection rate of <1000 tonnes CO2 per month
- Wellhead CO2 samples
- Natural CO2 in reservoir isotope 'fingerprint' ($^{13}C/^{12}C$): -10
- Injected anthropogenic CO2 $^{13}C/^{12}C$: -20
- Using $^{13}C/^{12}C$ changes injected CO2 detected in the reservoir after one month of injection
- **This worked at Otway, Pembina and Weyburn**



Subsurface monitoring – well measurement summary

- In favourable conditions well monitoring can track CO2 and quantify solubility trapping
- Information on CO2 – reservoir reactions
- Isotopes and artificial tracers higher signal/noise than aqueous chemistry
- **Limited volume accessed**



Can we fulfil potential requirements?

- Plume imagining, location of CO_2
- Detect migration pathways in the storage complex and beyond
- Evaluate the and the evolution of the storage reservoir
  - site is evolving towards a situation of long-term stability
  - detect irregularities and leakage
  - different storage processes, CO_2 dissolved in formation
- Show that CO_2 is permanently contained within the storage complex for the indefinite future
  - ***'all available evidence indicates that the stored CO_2 will be completely contained for the indefinite future'***
- Ensure well integrity

How should we approach Monitoring?

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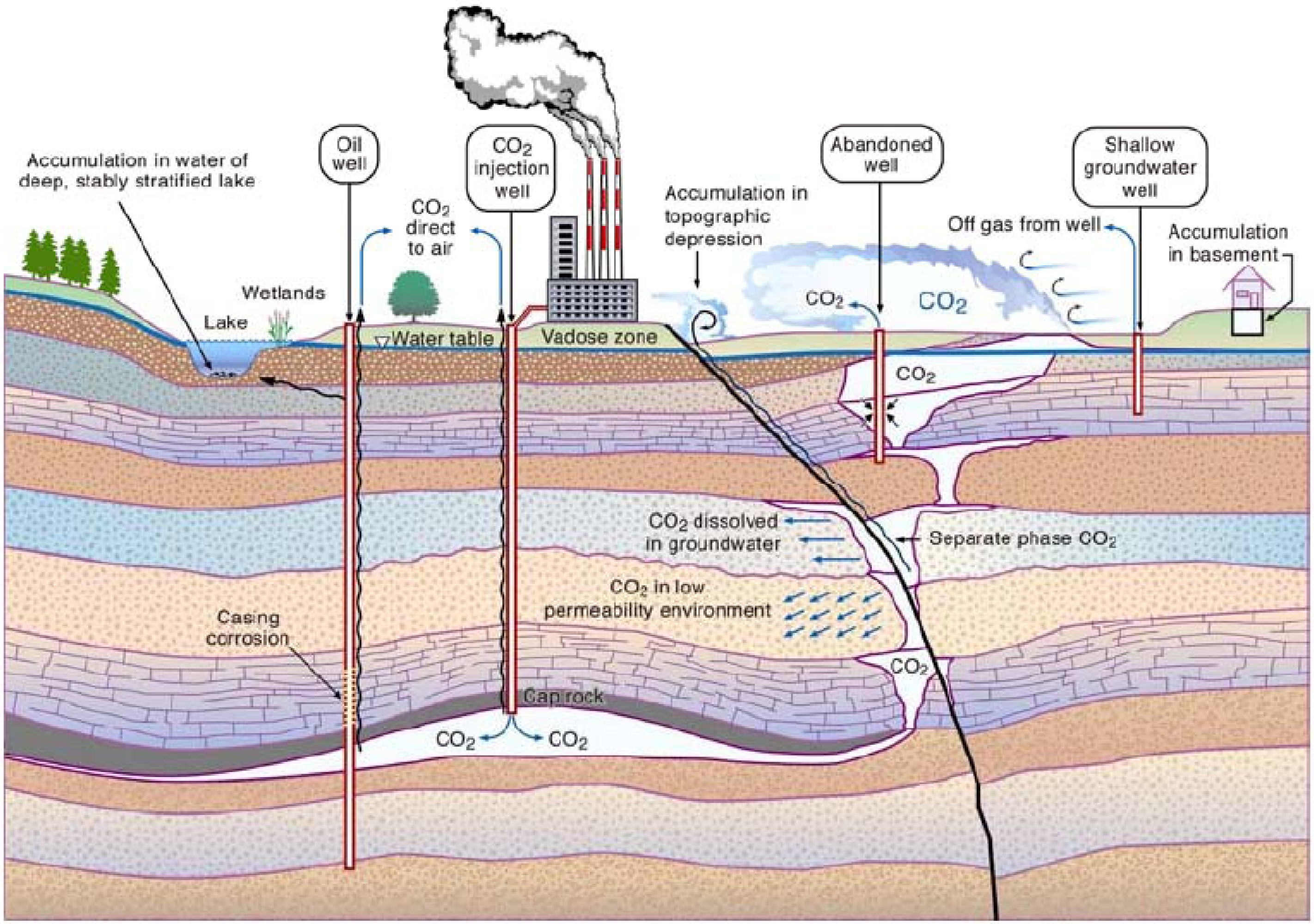

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How should we approach Monitoring?

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- Risk based
  - Prioritise by likelihood x severity
- Agreement and communication of tolerable risk and uncertainty
  - CCS risks v no CCS
- Cost effective and pragmatic application of techniques
  - Should we reject low risk sites if plume cant be imaged by 4D seismic?

A few thoughts on pressure

- Could subsurface multi interval pressure monitoring be sufficient to calibrate models, i.d. plume and demonstrate integrity?
  - Relies on comprehensive understanding and prediction of dynamic response of site and pressure complex
    - challenging with greenfield aquifer sites
  - Pressure/hydraulic communication ≠ CO_2 migration pathway
    - Risk of false positive

Thank You

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Spares

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UK EU update – more pragmatic, less prescriptive?

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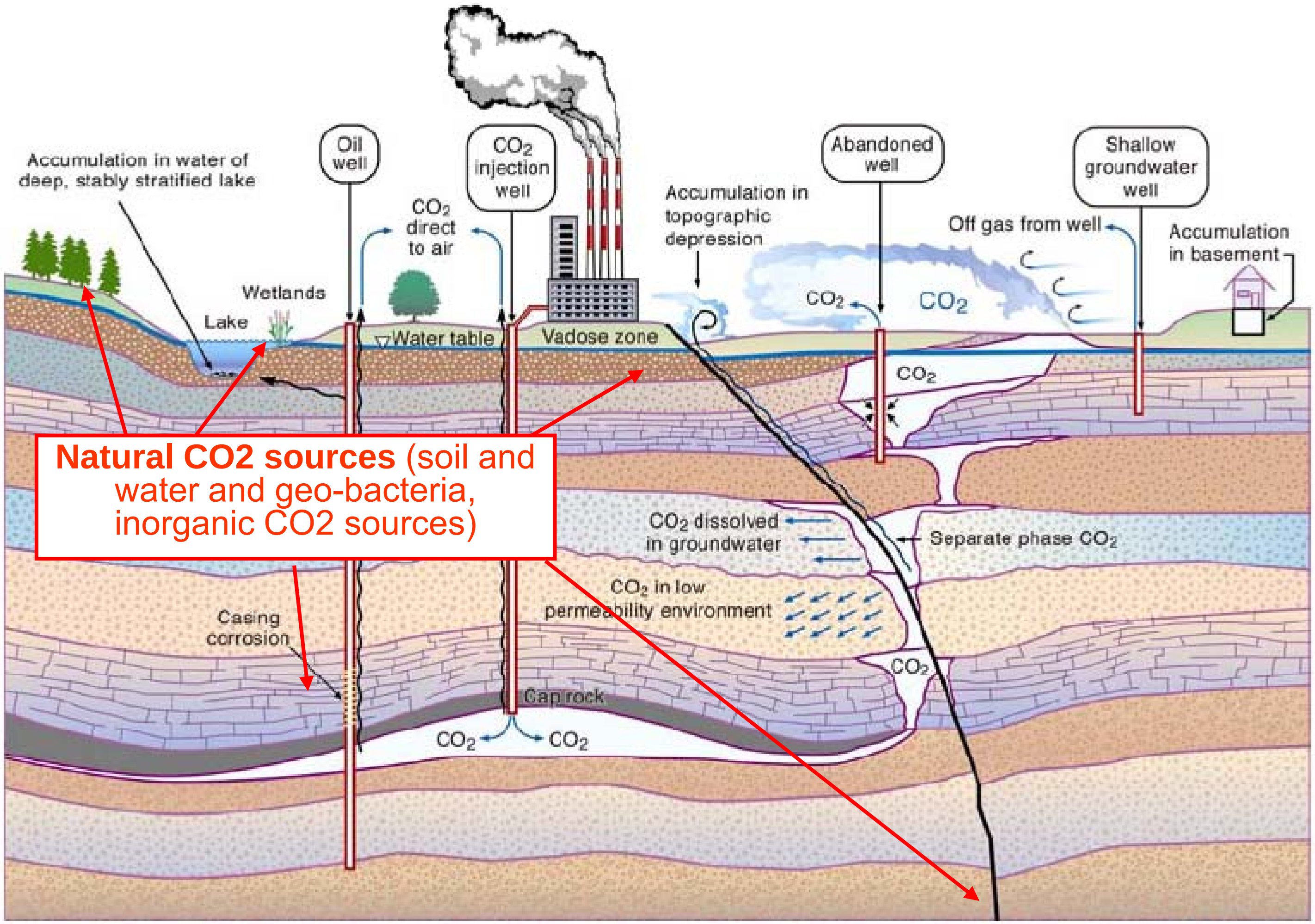
Show CO_2 is permanently contained (now in agreed EU directive);

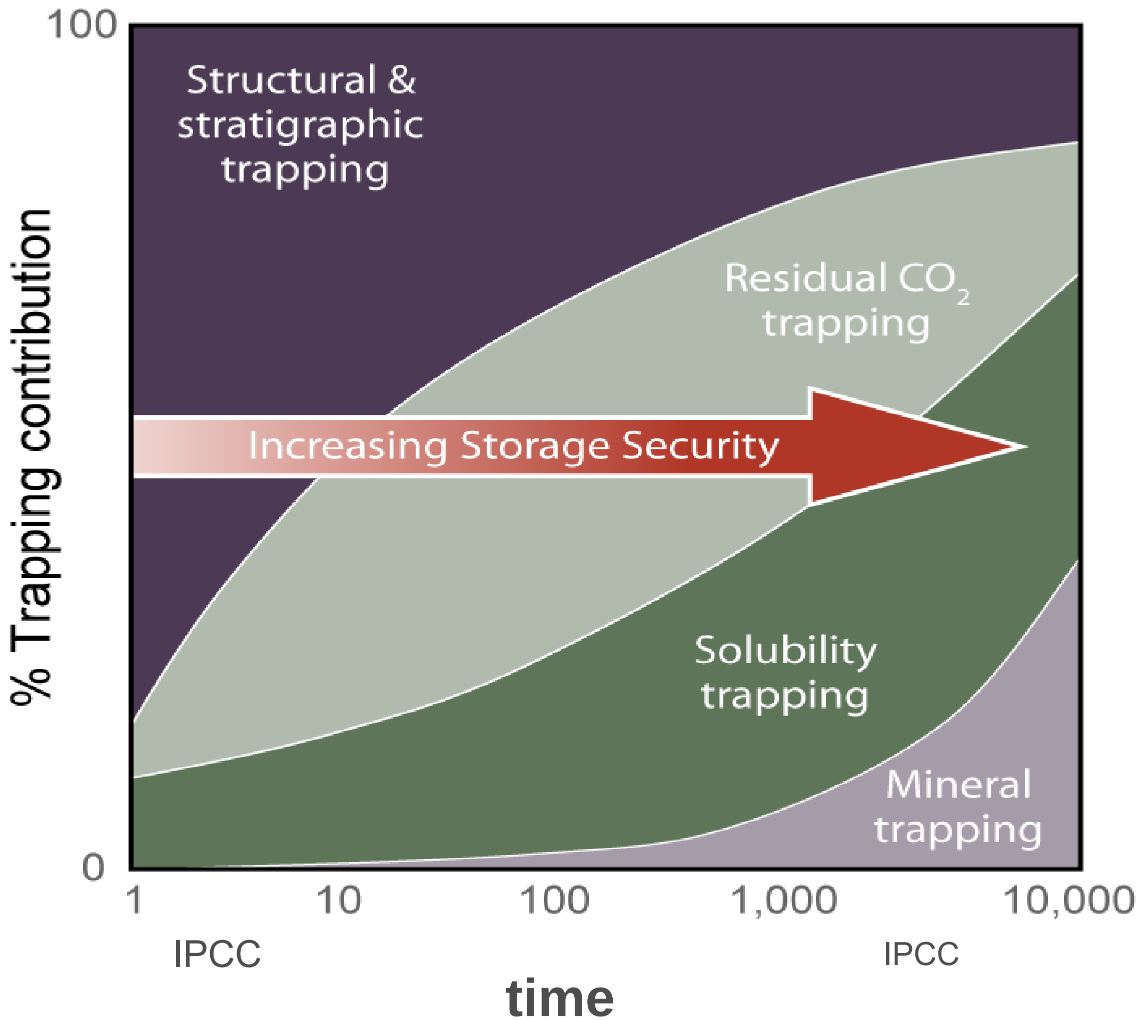
- the actual behavior of the injected CO_2 conforms with the modelled behavior;
- there is no detectable leakage; and
- the storage site is evolving towards a situation of long-term stability
- **Monitoring program will provide evidence to support these assessments**
  - ‘*all available evidence indicates that the stored CO_2 will be completely contained for the indefinite future*’

Why baseline is essential – there is ‘natural’ CO2 everywhere!



Zhang Oldenburg and Benson

What are we trying to monitor?



Structural and stratigraphic trapping

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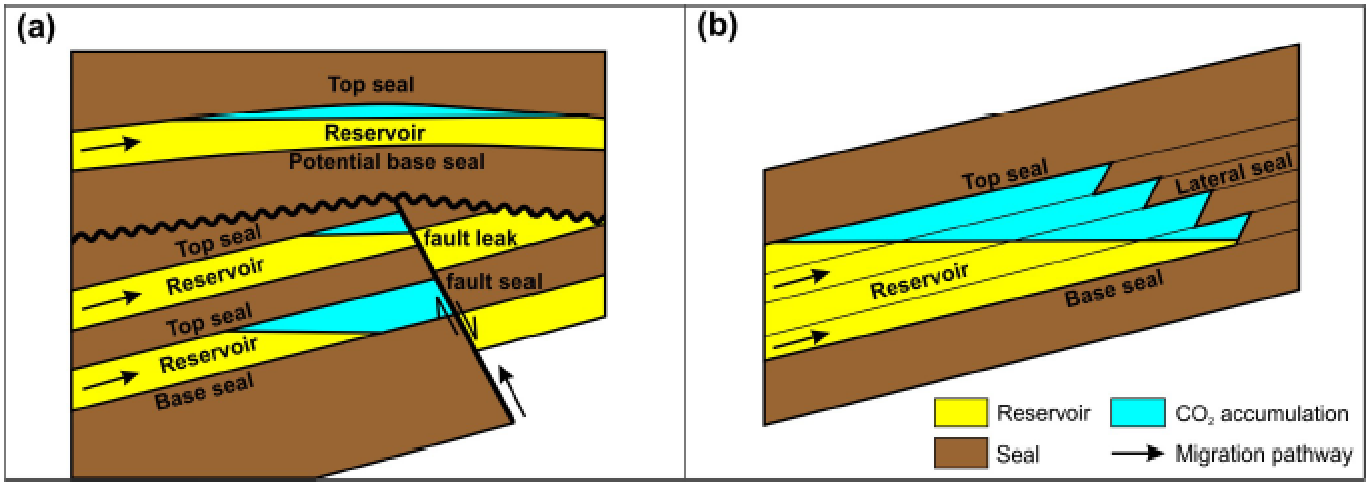
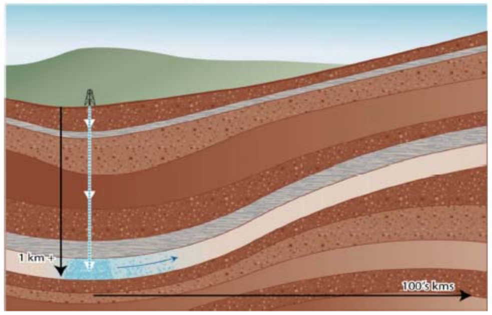


Examples of (a) structural and (b) stratigraphic physical traps for CO_2 (modified from Biddle & Wielchowsky, 1994).

CO2CCRC

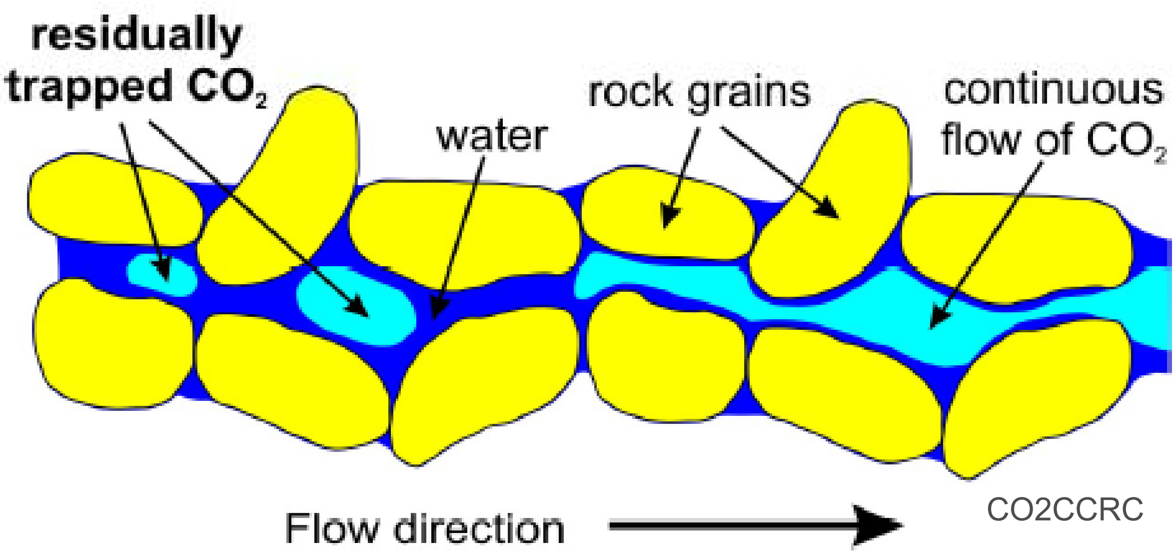
- Closely analogous to hydrocarbon trapping
  - Many hydrocarbon prospects fail because trap is not as envisaged (challenge of proving a negative where there are no hydrocarbons)
  - Hydrocarbon pools prove presence and effectiveness of the trap

Residual trapping



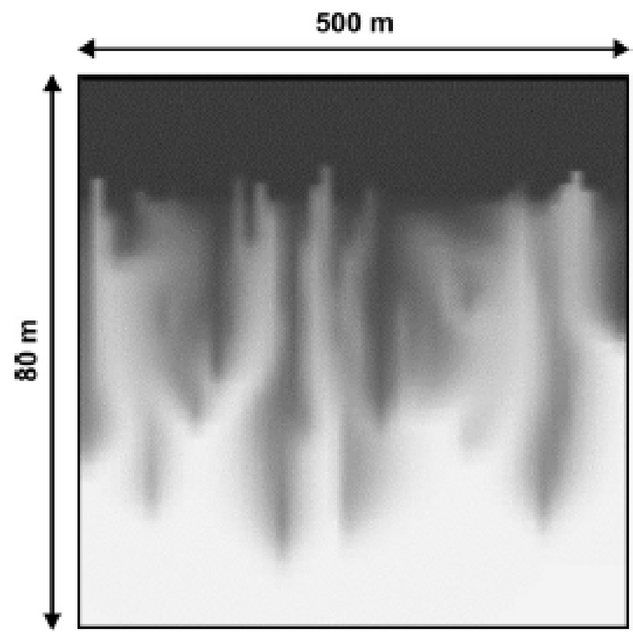
Hydrodynamic trapping of CO_2, where the CO_2 migration pathway is 10s to 100s km long allowing for a long residence time.

- Key criterion is that there is an effective top seal to force the CO2 to migrate sideways rather than vertically



Residual trapping of CO_2.

Solubility trapping - dissolution of CO_2 in water



Convective mixing of CO_2: example of a numerical simulation showing the high-density plumes of CO_2-saturated brine (grey colours) sinking into the brine column below (white colour) (kv/kh = 0.01, after 14400 years) (Ennis-King & Paterson, 2005a).

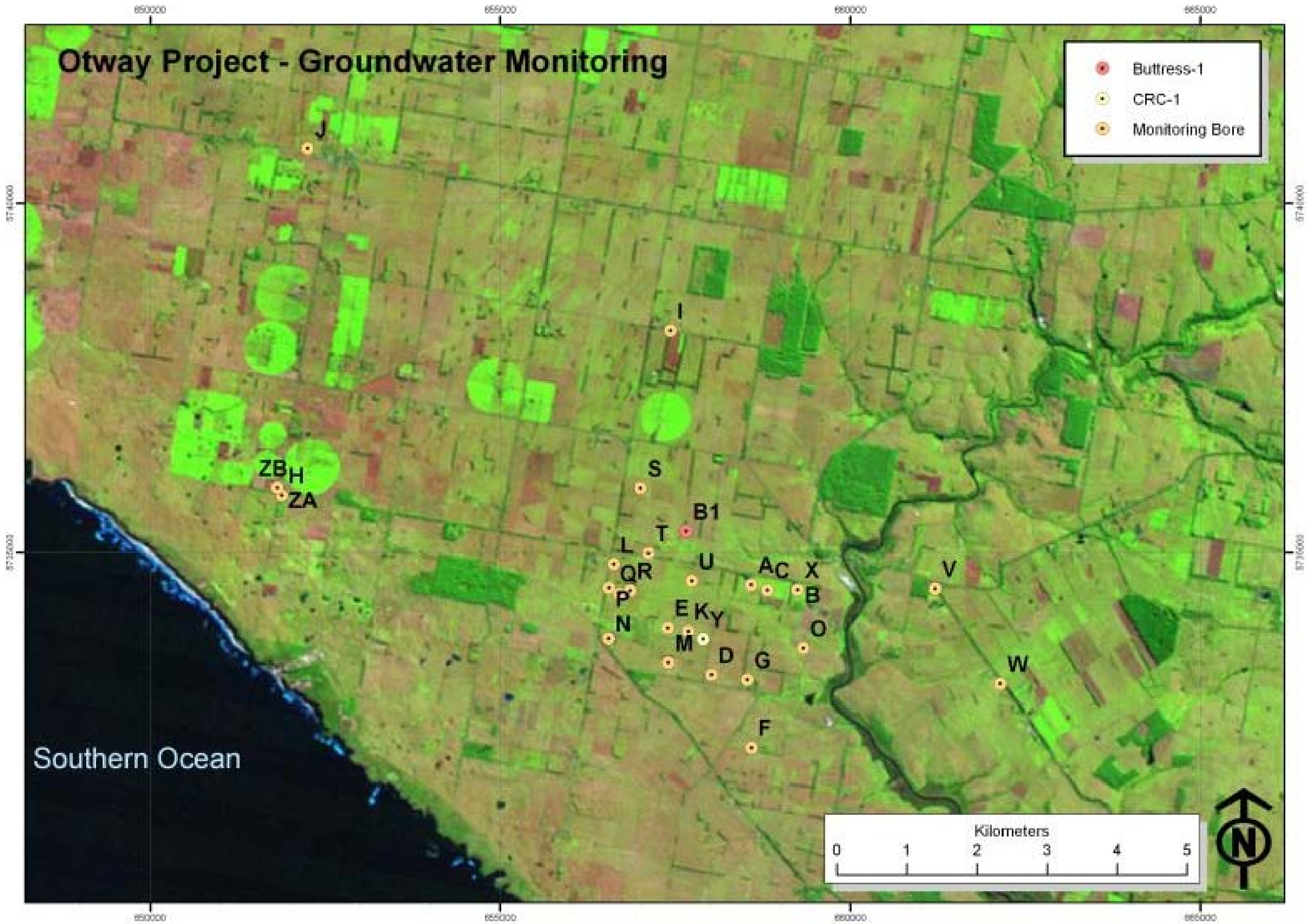
Note timescale: though dissolution is fast, large scale mixing is likely to be a very slow process and geology may intervene

Mineral trapping

- Mineral storage reactions are slow and therefore are unlikely to be important over operational timescales:
- Consequently mineral reactions should be regarded as a very effective long term storage mechanism, but not one that provides storage space

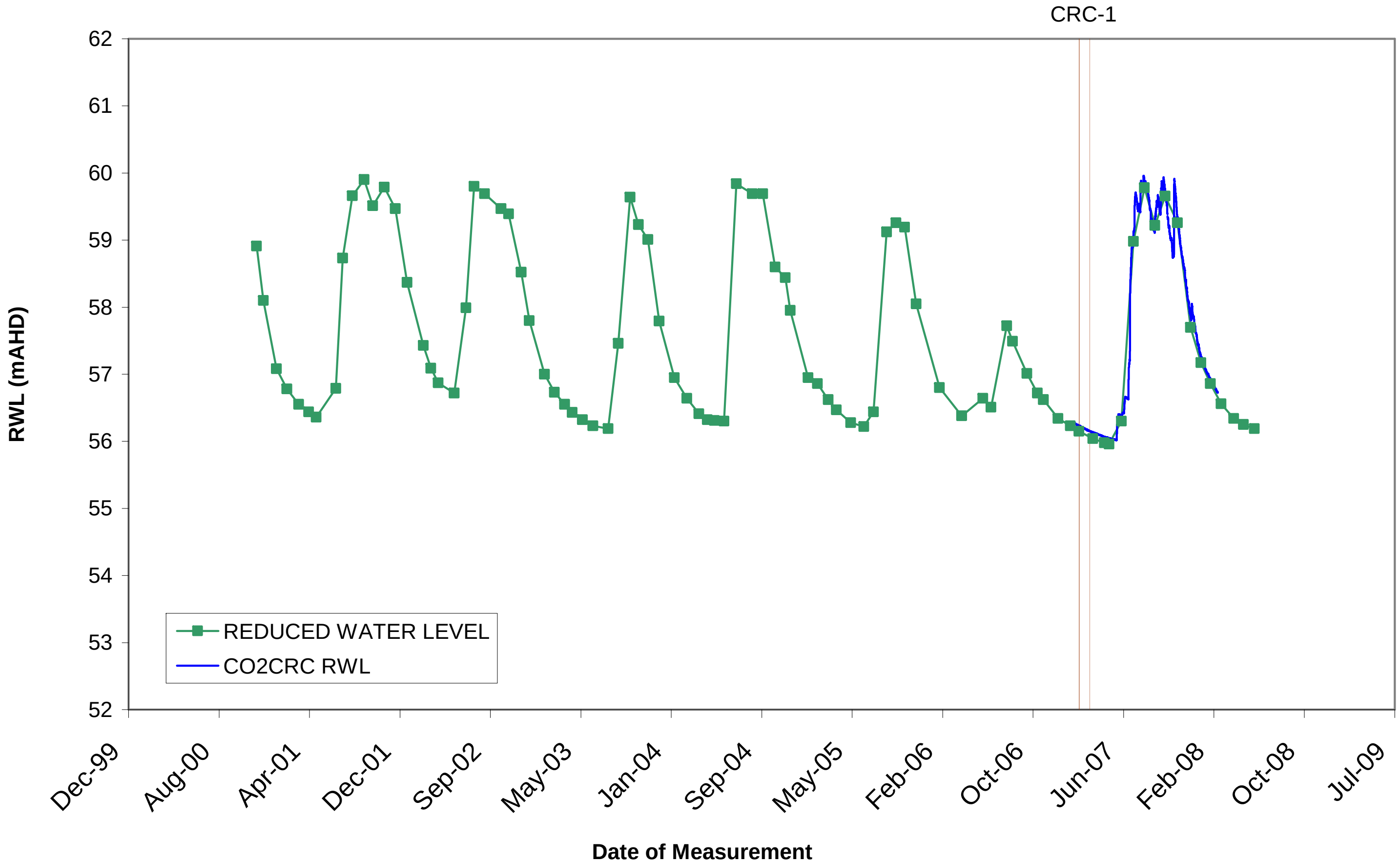
- However, some mineral reactions may be important over operational timescales: they influence the progress of solubility and mineral reactions (pH) and can be critical in storage integrity and performance (formation damage, cap rock, fault seal)

Groundwater monitoring

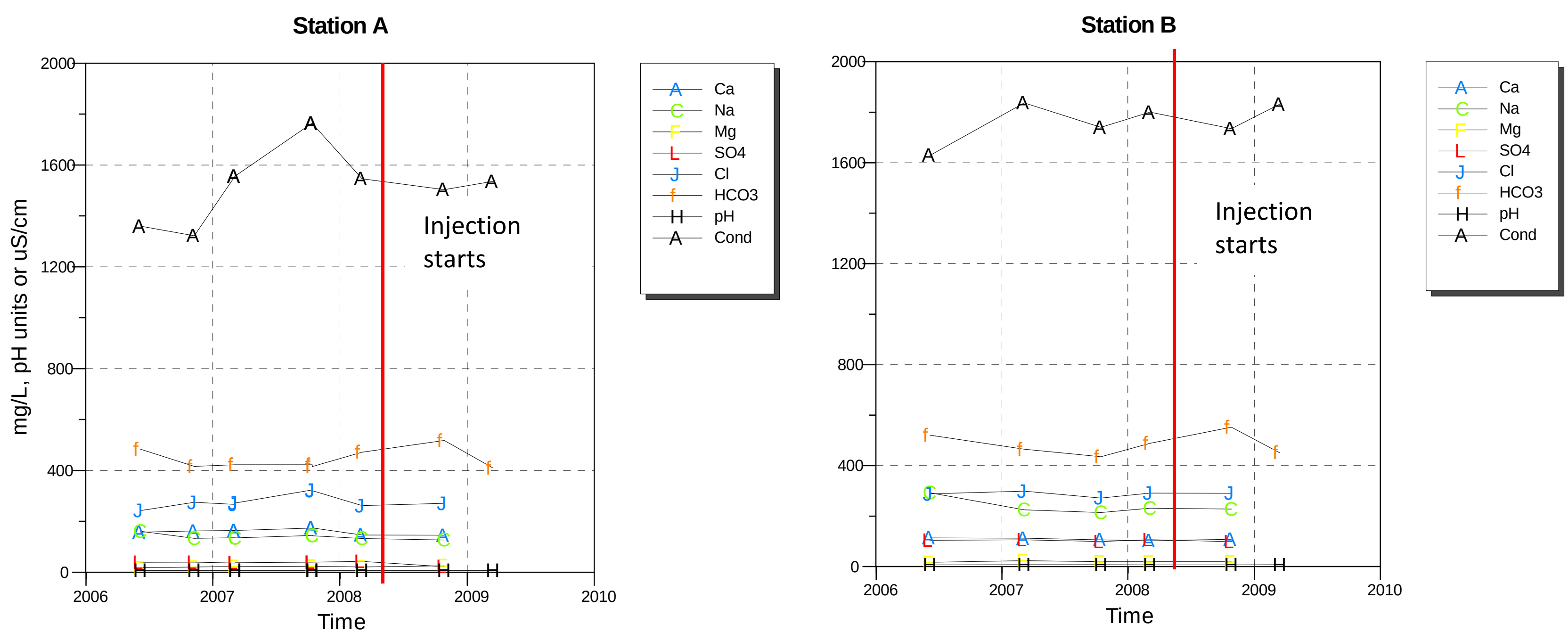


CO2CRC

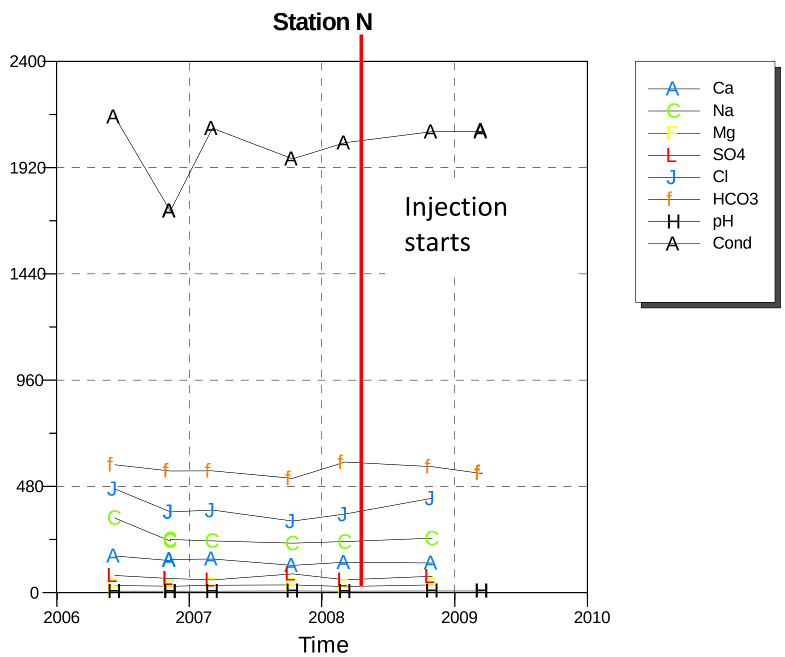
Port Campbell limestone

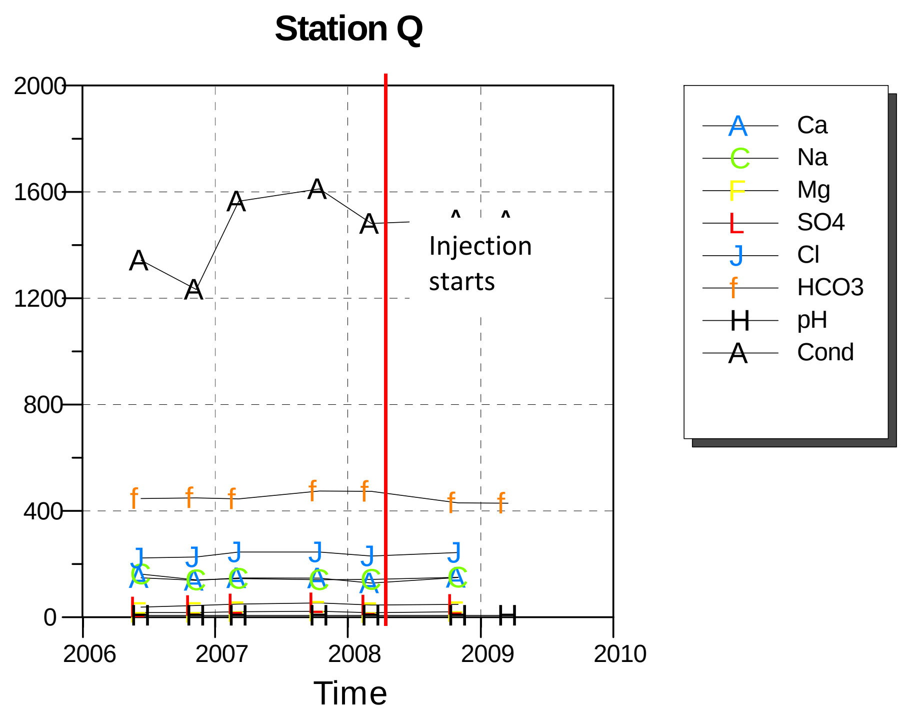


Groundwater chemistry



Groundwater chemistry

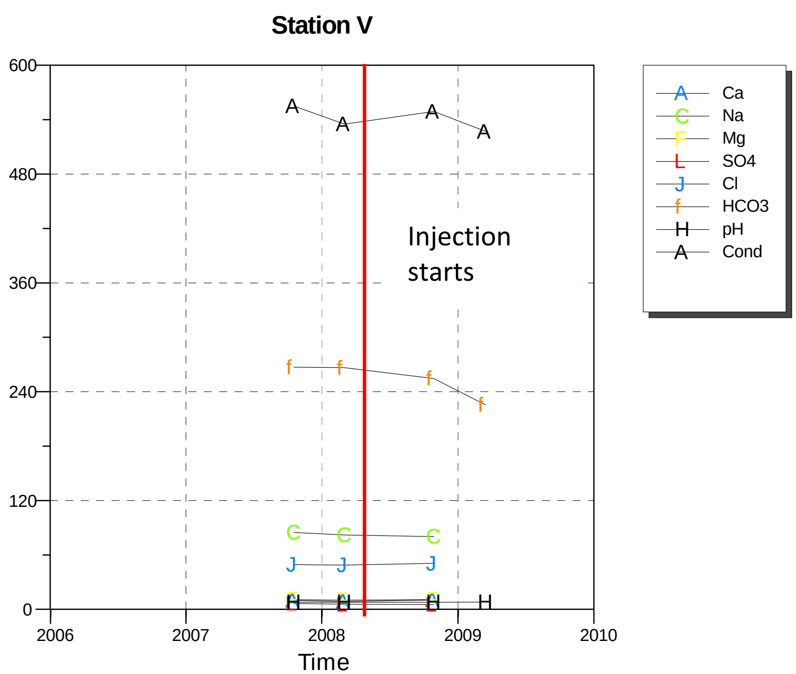


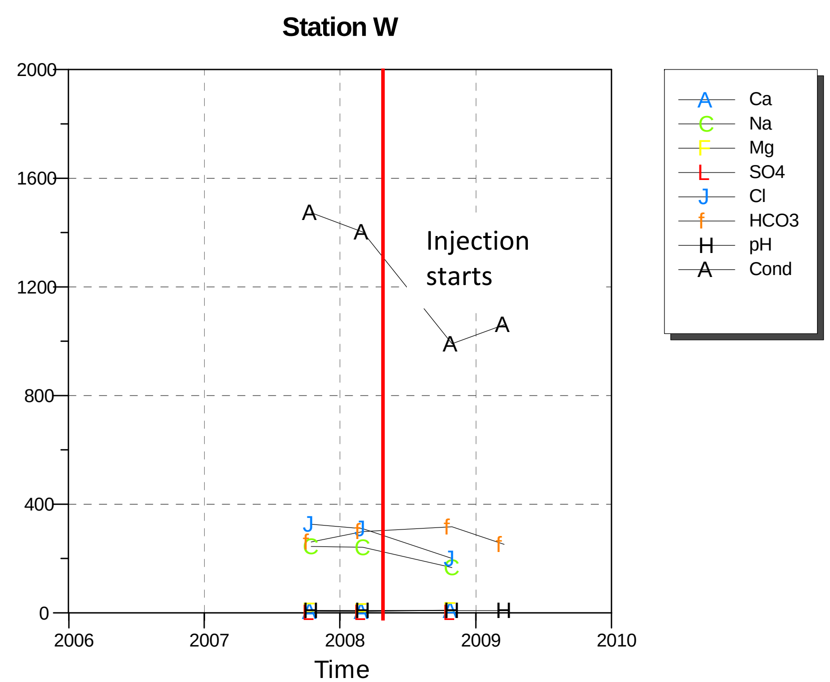


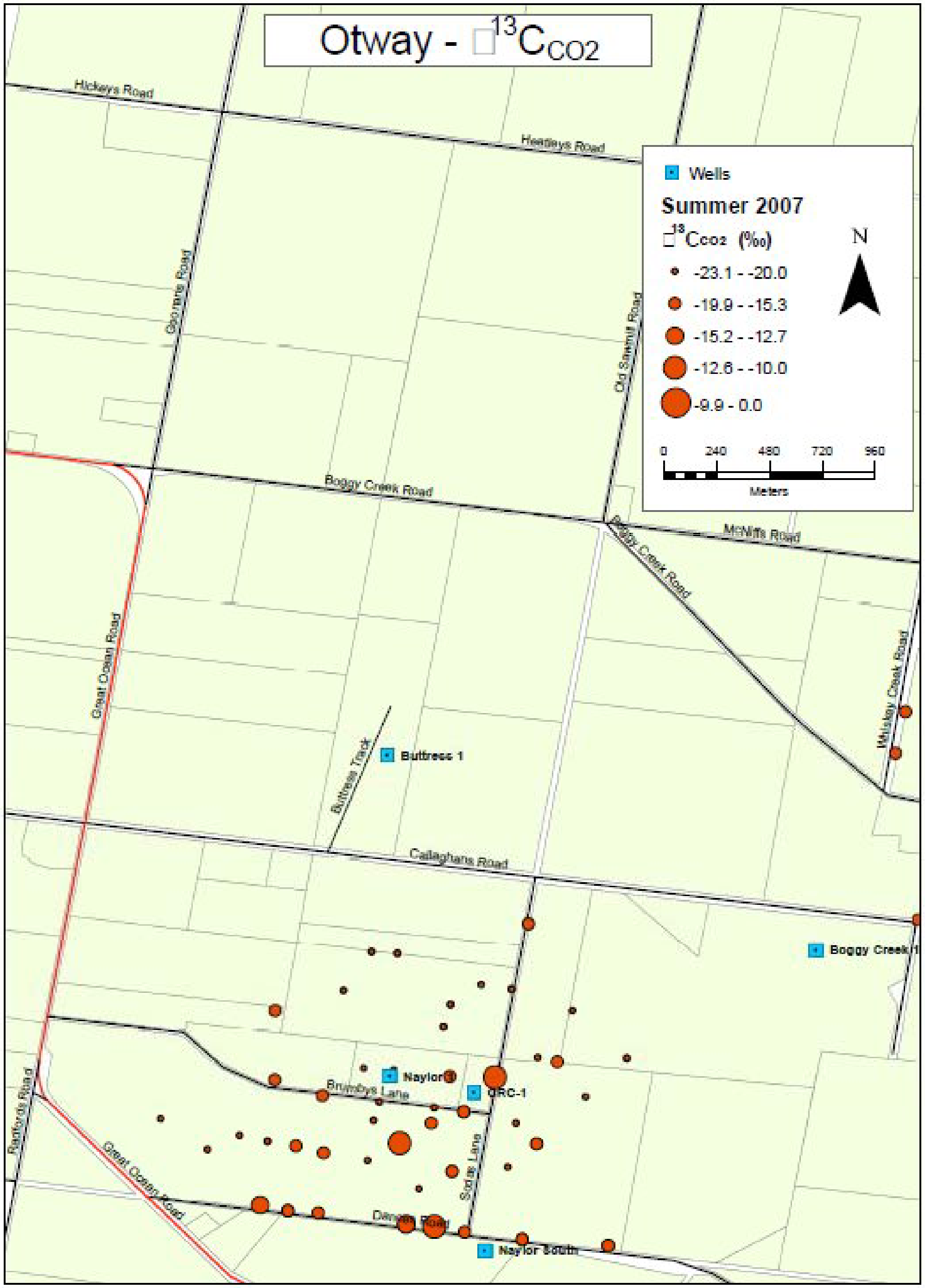
MSO FoF
21May 09

CO2CRC

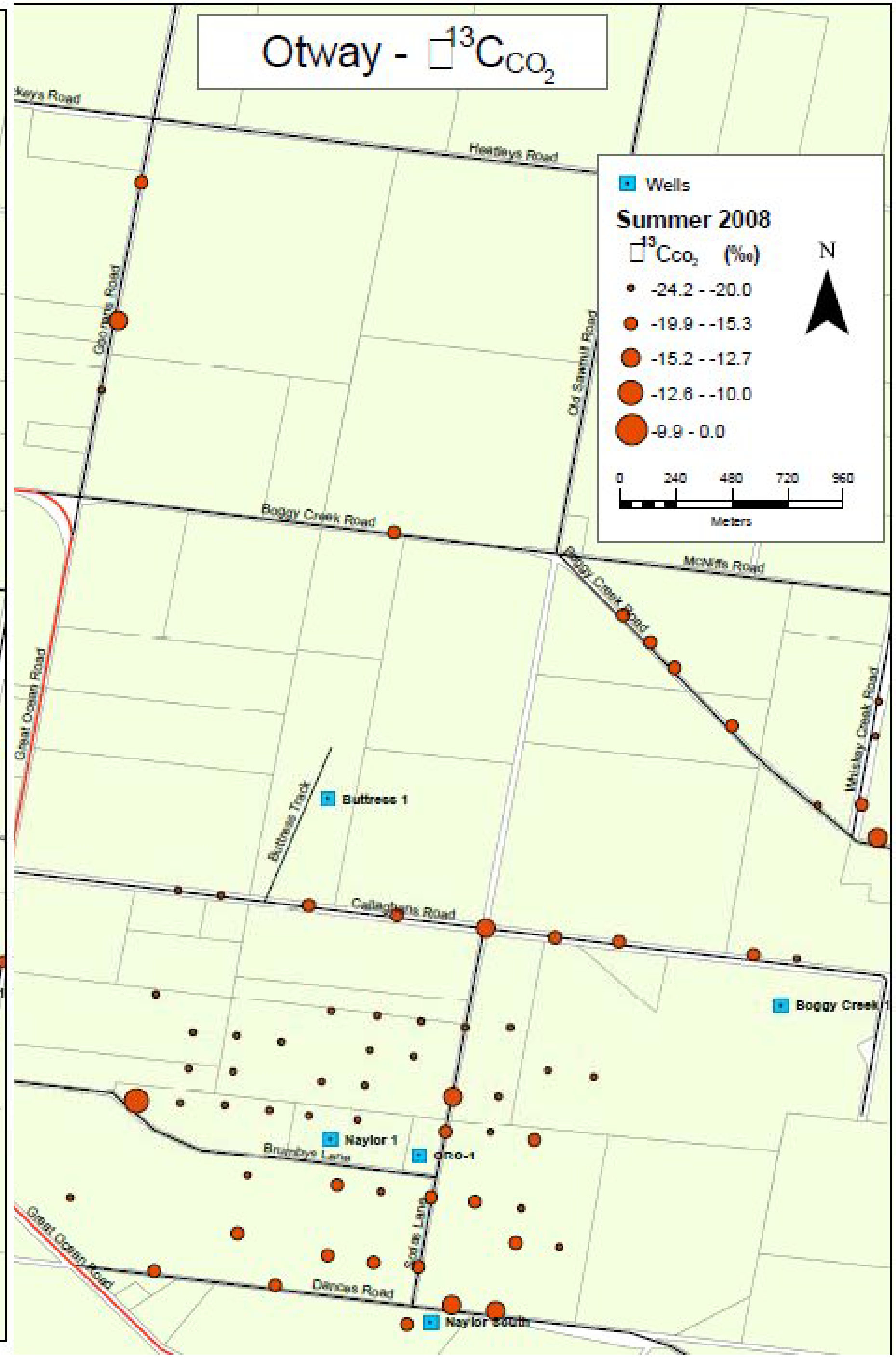
Groundwater chemistry







Otway - $\delta^{13}C_{CO2}$
Wells
Summer 2007
$\delta^{13}C_{CO2}$ (‰)
-23.1 - -20.0
-19.9 - -15.3
-15.2 - -12.7
-12.6 - -10.0
-9.9 - 0.0
N
0 240 480 720 960
Meters
Hickeys Road
Headleys Road
Georges Road
Old Sawmill Road
Boggy Creek Road
McNiffs Road
Boggy Creek Road
Great Ocean Road
Whiskey Creek Road
Buttress Track
Buttress 1
Callaghans Road
Boggy Creek 1
Naylor 1
CRC-1
Brumbys Lane
Radfords Road
Great Ocean Road
Sodas Lane
Dances Road
Naylor South



Otway - $\delta^{13}C_{CO_2}$
Wells
Summer 2008
$\delta^{13}C_{CO_2}$ (‰)
-24.2 - -20.0
-19.9 - -15.3
-15.2 - -12.7
-12.6 - -10.0
-9.9 - 0.0
N
0 240 480 720 960
Meters
Headleys Road
Boggy Creek Road
McNiffs Road
Boggy Creek Road
Old Sawmill Road
Great Ocean Road
Whiskey Creek Road
Buttress Track
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Callaghans Road
Boggy Creek 1
Naylor 1
CRC-1
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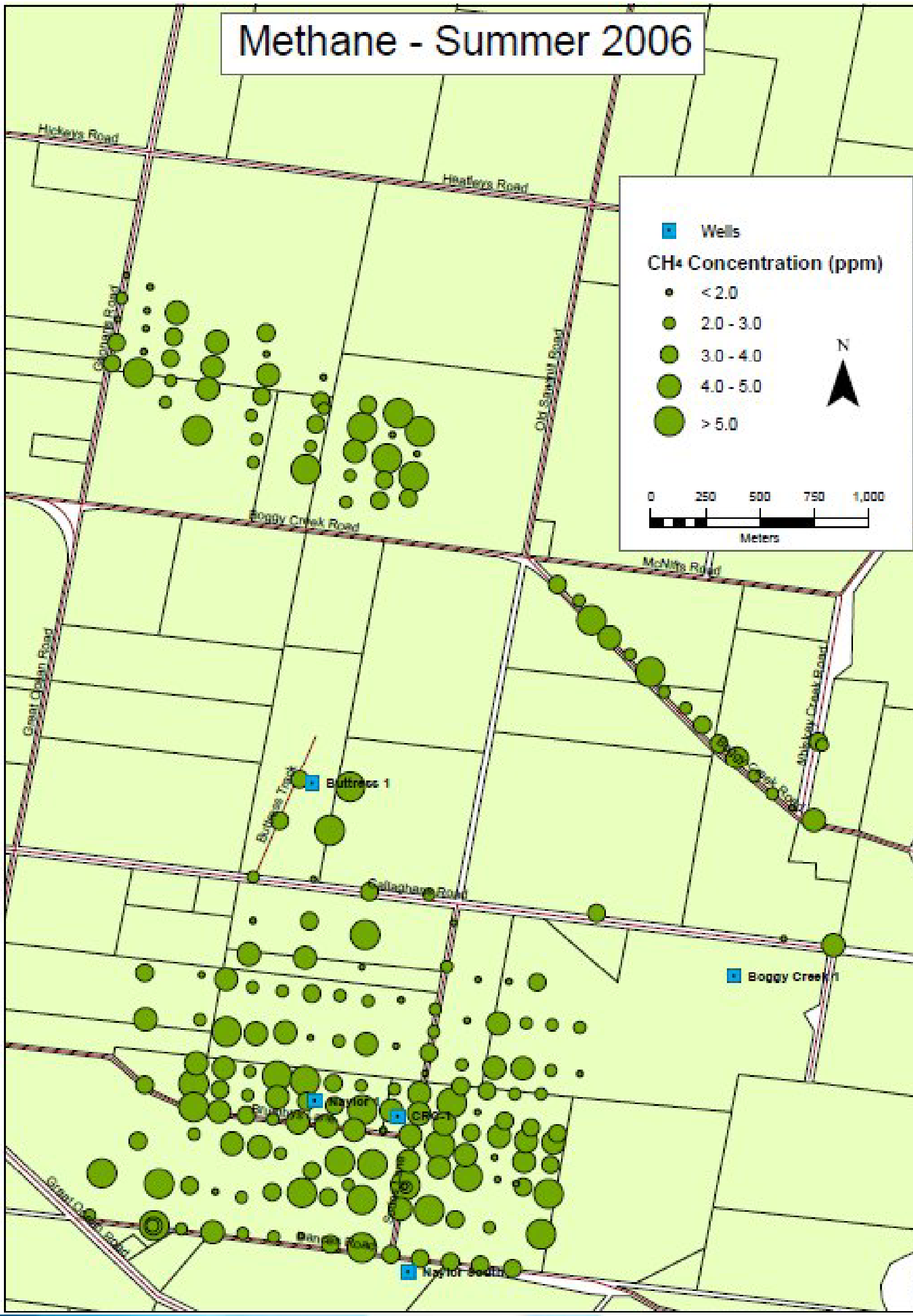
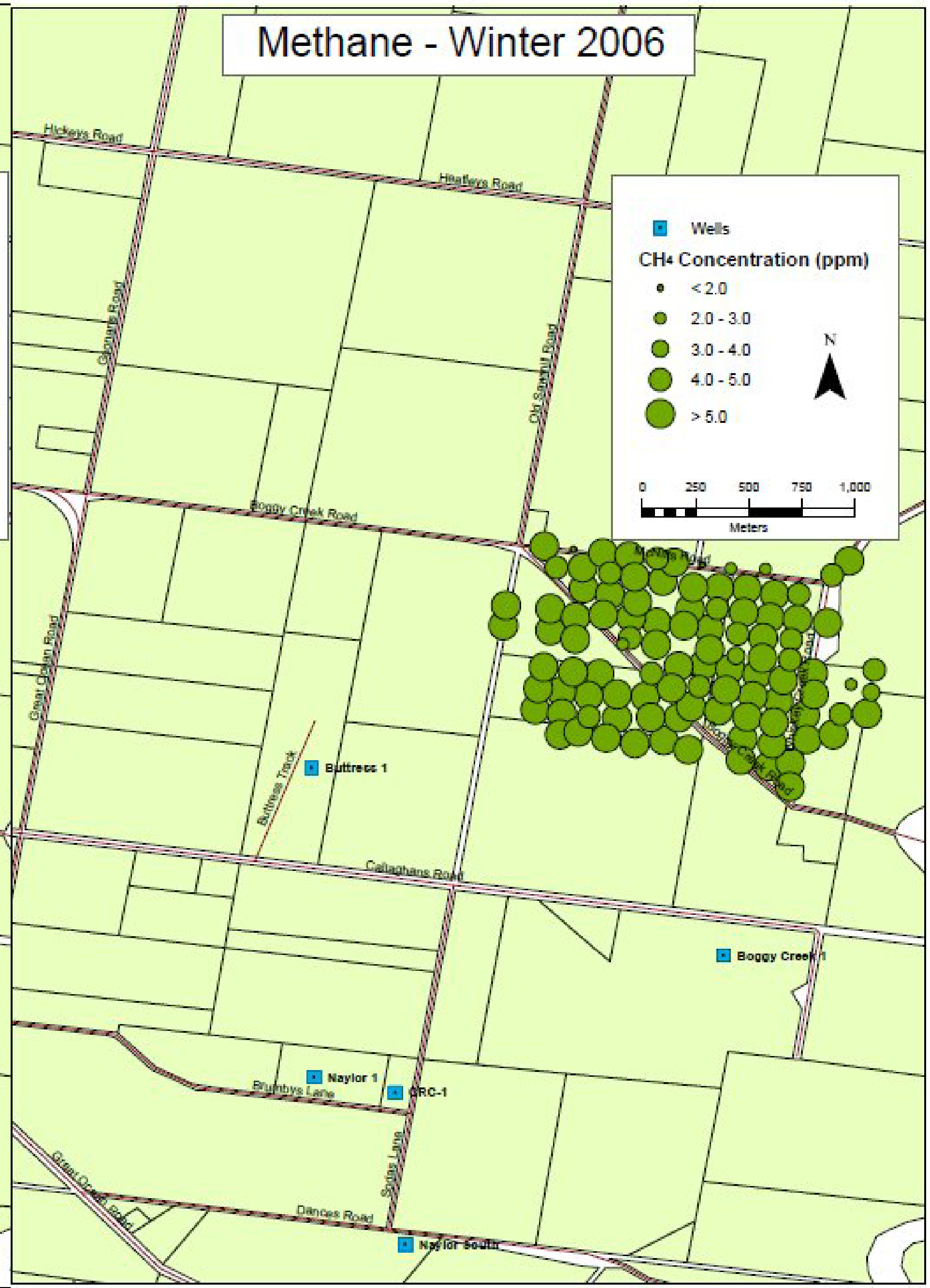
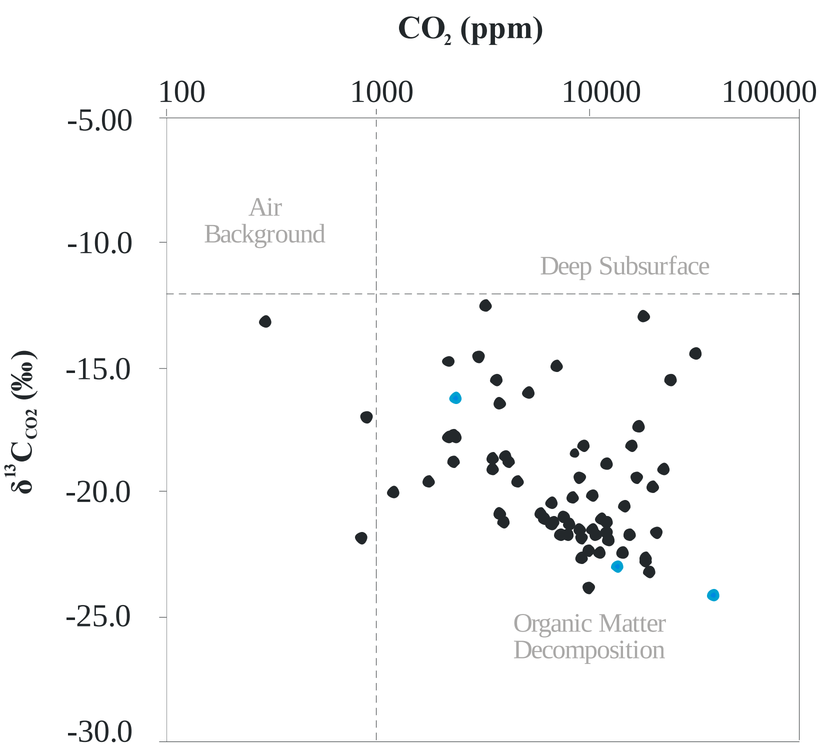
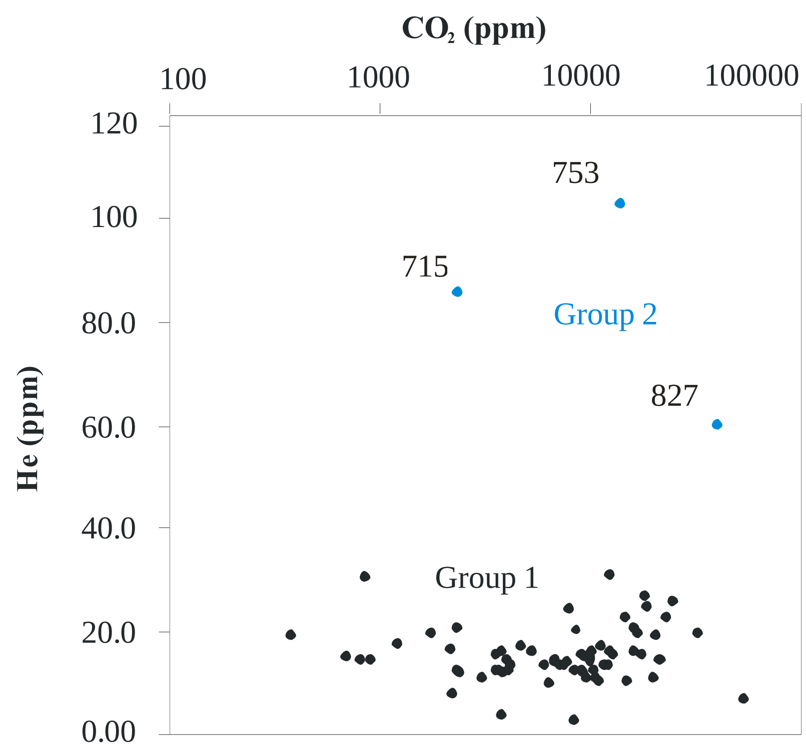
Dances Road
Naylor South


Methane - Summer 2006
Wells
CH4 Concentration (ppm)
< 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
> 5.0
N
0 250 500 750 1,000
Meters
Hickeys Road
Heatleys Road
Boggy Creek Road
McNitts Road
Old Sawmill Road
Callaghans Road
Buttress 1
Boggy Creek 1
Naylor 1
CRC-1
Naylor South
Dances Road
Great Ocean Road


Methane - Winter 2006
Wells
CH4 Concentration (ppm)
< 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 5.0
> 5.0
N
0 250 500 750 1,000
Meters
Hickeys Road
Heatleys Road
Boggy Creek Road
McNitts Road
Old Sawmill Road
Callaghans Road
Buttress 1
Buttress Track
Boggy Creek 1
Naylor 1
CRC-1
Brumbys Lane
Dances Road
Naylor South
Great Ocean Road

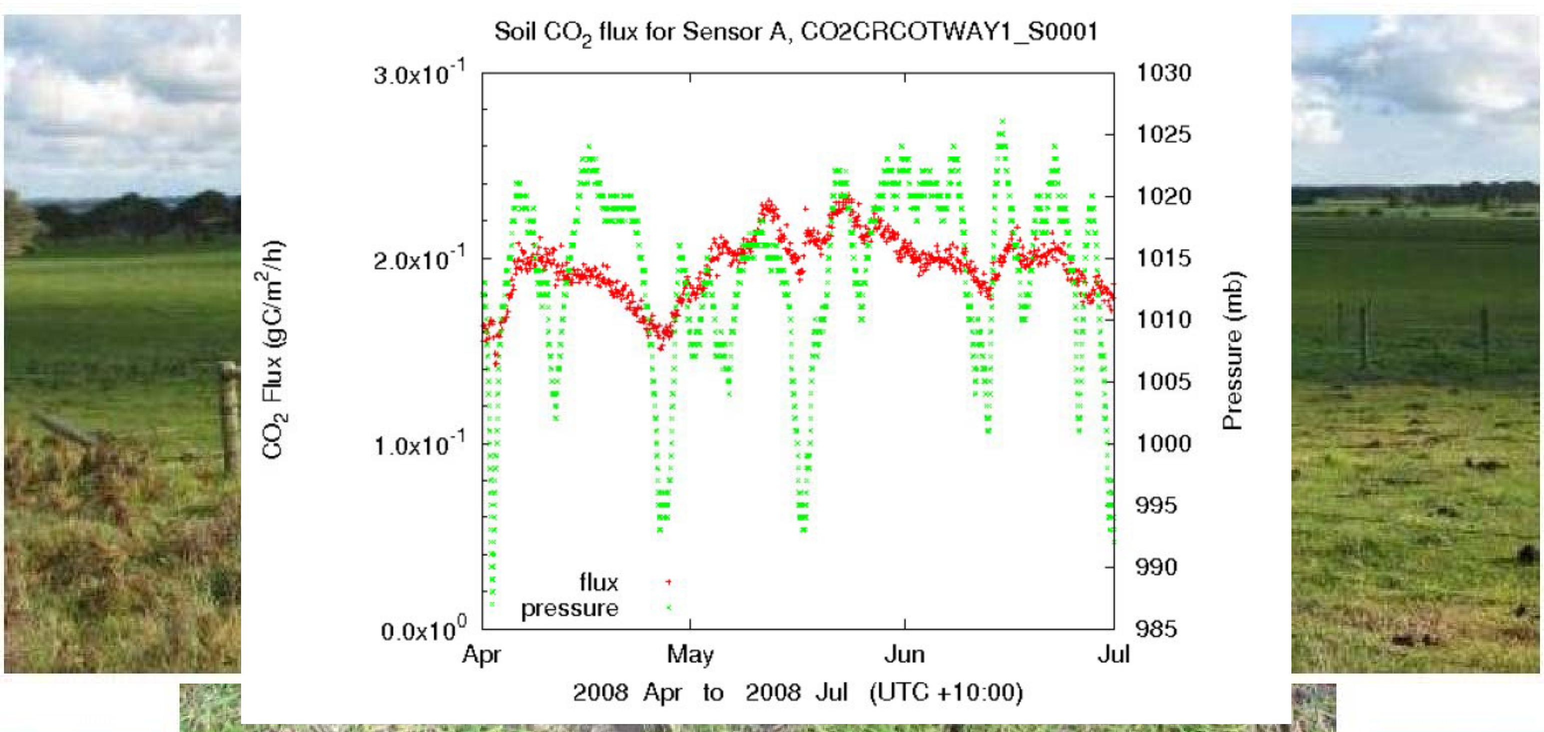
Analysis of 2008 data





Other relevant monitoring

- Headspace gas monitoring in selected water bores - CSIRO
- Soil flux monitoring (campaign basis) – CSIRO
- Continuous soil flux monitoring – R&D - CANSYD



CO2CRC

Interpretation…

- These data give assurance of the integrity of important near-surface assets, both to the local community and to regulators.
- They form part of the picture of safe containment, to satisfy KPIs.
- Direct interpretation as evidence for containment, while possible in principle, is probably not their main use.
- Usefulness as a sentinel system is likewise complicated by difficulty in assessing their sensitivity to hypothetical leakage events.
- Development of the monitoring techniques creates valuable expertise and "operationalizes" the activity.

Integrated real time monitoring workflows

Guillemette Picard, Laurent Jammes, Schlumberger Carbon Services
Christophe Champagnon, Grenoble Technical Product Center,
IEA- 5th monitoring network– 4th June 2009

Schlumberger

GFZ Helmholtz Centre POTSDAM

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Geoelectric Crosshole and Surface-Downhole Monitoring:

First Results

Dana Kiessling[1], Hartmut Schuett[1, 2], Cornelia Schmidt-Hattenberger[1], Frank Schilling[1, 3], Erik Danckwardt[4], Kay Krueger[1], Birgit Schoebel[1], and CO_2SINK Group

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(2) now at StatoilHydro ASA, Stavanger, Norway
(3) now at: Institute for Applied Geosciences, Universität Karlsruhe, Germany
(4) Institute of Geophysics and Geology, University of Leipzig, Germany

CO_2SINK

IEA GHG - 5th Monitoring Network Meeting, June 2-4, 2009 / Tokyo

GFZ Helmholtz Centre POTSDAM

Outline

I. Introduction

II. Combined Downhole and Surface-Downhole Concept

III. Preliminary Results

IV. Conclusions

V. Outlook

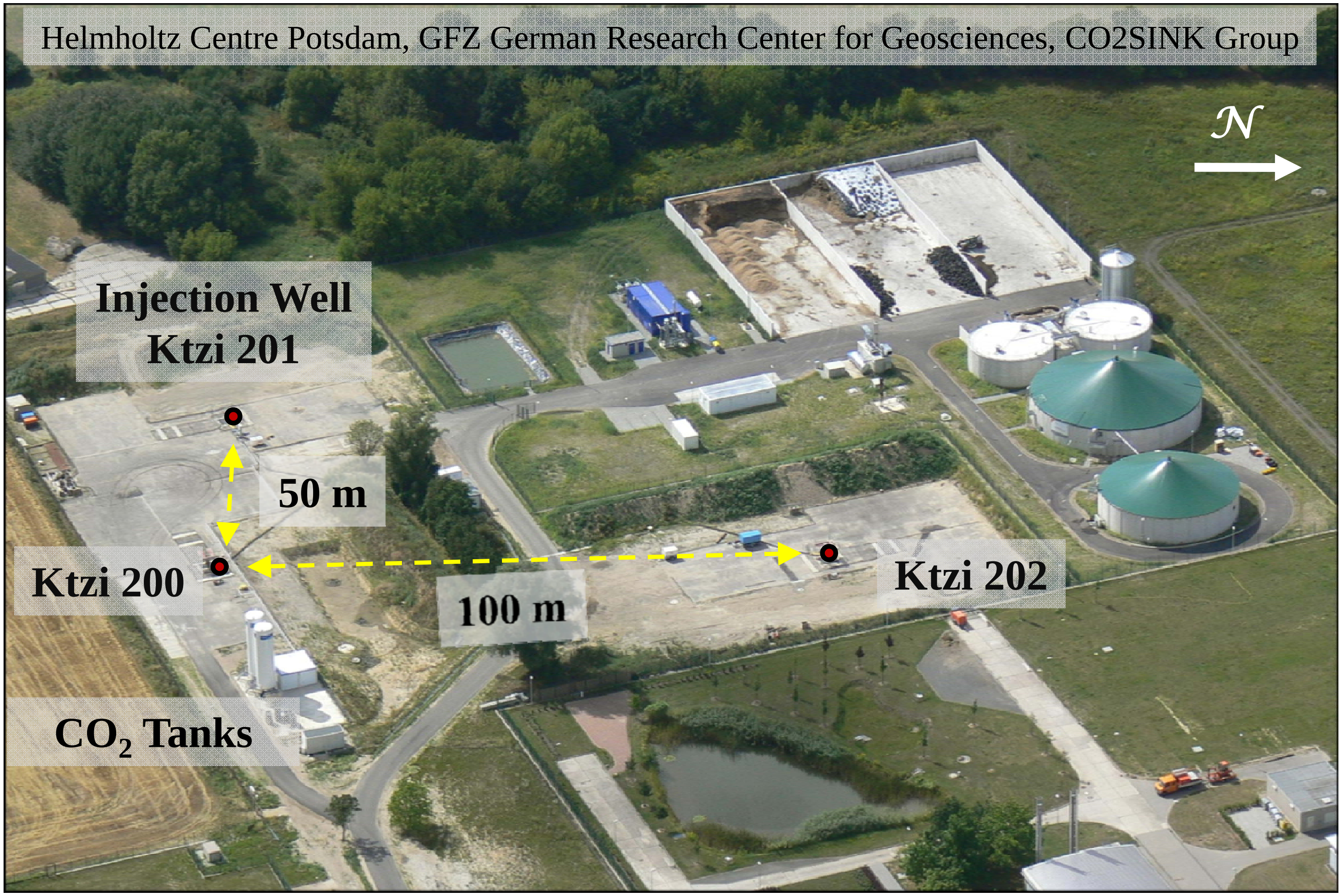
CO_2SINK …

CO_2 Storage by **I**njection into a **N**atural Saline Aquifer at **K**etzin

Universität Leipzig

GFZ Helmholtz Centre Potsdam

I. Introduction



September 2008

first European onshore CO_2 storage at Ketzin

I. Applications for Geoelectrics

- hydrological questions:
  prospecting of groundwater
  boundary of saline and freshwater…

- investigation of structures and processes (contrasts in resistivity!)

→ CO_2 plume monitoring

{References:

Ramirez, A. L., Newmark, R. L., Daily, W. D.,2003. Monitoring Carbon Dioxide Floods Using Electrical Resistance Tomography (ERT): Sensitivity Studies. Journal of Environmental and Engineering Geophysics, Volume 8, Issue 3, pp.187–208.

Christensen, N. B., Sherlock, D., Dodds, K., 2006. Monitoring CO_2 injection with cross-hole electrical resistivity tomography. Exploration Geophysics 37, pp.44-49. }

II. Geoelectrical Monitoring Concept

	Date	injected CO_2
Last facility tests and preparation	20/06/2008	
Start of CO_2 Injection	30/06/2008	0 t
Arrival of CO_2 at 1st observation well	15/07/2008	531 t
Arrival of CO_2 at 2nd observation well	20/03/2009	about 11000 t
today	**26/05/2009**	**about 15500 t**

Drilling of the wells
2007

Start of CO_2 Injection
2008

Ktzi 200 201 202 Ktzi 201

May July August **June 30**

time

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II. Geoelectrical Monitoring Concept

taper pin

electrical cable

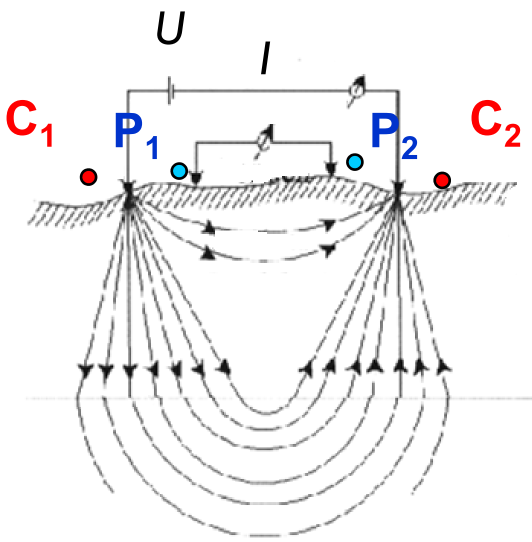
ring-shaped steel electrode

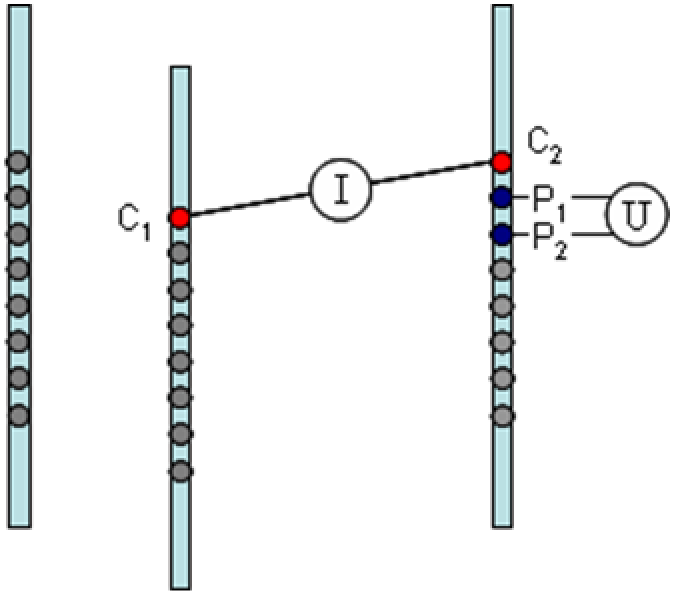
insolated casing

(two-component material consisting of an epoxy matrix and a Polyphenylene Sulfide (PPS) membrane)

II. Geoelectrical Monitoring Concept

four-point-method → Crosshole Measurements





- **current** injected between 2 electrodes **C_1, C_2**
- **potential** measured between 2 electrodes **P_1, P_2**
- apparent resistivity $\rho_a = k \cdot R = k \cdot \frac{U}{I}$
- increasing of resistivity with CO_2 injection

ρ_a … apparent resistivity
k … geometric factor
R … resistance
U … voltage
I … current

II. Geoelectrical Monitoring Concept

- **geophysical monitoring** of the migration of the injected CO_2 by using seismic and geoelectric measurements

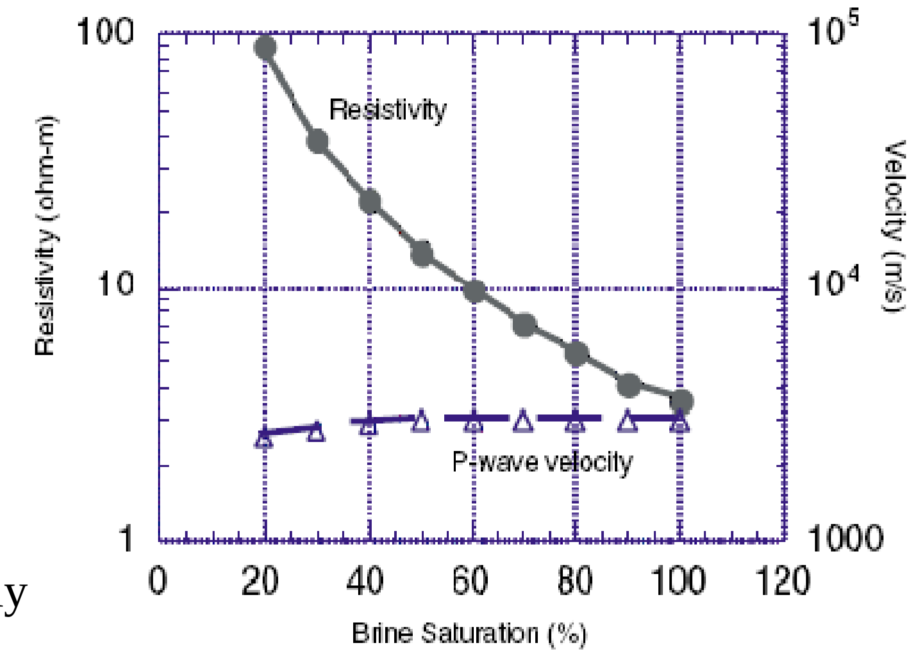
- different methods = more information & risk reduction

- geoelectrical methods are more sensitive at intermediate and high gas saturation (above 20 %) than seismic methods

- geoelectrical measurements are relatively easy to deploy permanently and operationally simpler than seismic methods

➢ higher repetition rate and more cost-efficient

➢ but: lower resolution



Wilt & Alumbaugh, 2006

❖ investigation of the feasibility of the geoelectrical monitoring of the CO_2 migration into the saline aquifer in Ketzin

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Where we are: Overview (status CO2SINK 12th proj. m. Feb. 2009 / Phase of data matching

Method	Physical quantity considered	Criterion	Depth range [m]	Lateral extent around Ktzi201 [m]	Maximum S_{CO2}	Remarks
reservoir modeling	**CO_2 saturation**	$S_{CO2} \geq x$	**(a) 635 – 645** **(b) 645 – 655** (c) 665 – 675	40 40 40	**50%**	No absolute depth scale in figure; depth estimated. Q: Does the model reflect the reservoir 1:1 or just statistically?
RST	**CO_2 saturation**	$S_{CO2} \geq x$	(a) 625 – 627 (b) 630 – 633 **(c) 634 – 642** **(d) 645 – 648**	n/a	**60%**	Very short penetration range.
DTS	**temperature**	deviation from linear trends	**625 – 675**	n/a	n/a	Very short penetration range. $\Delta T \approx +5.0$ °C
crosshole seismic	**signal correlation**	correlation or anticorrelation $\geq x$	**(a) 644 – 652** (b) 657 – >662 (c) 640 – 672	n/a n/a 80 (between Ktzi200 and 202)	?	Sources and receivers in Ktzi200 and Ktzi202!
ERT	**resistivity**	resistivity increase $\geq x$	(a) 600 – 615 **(b) 630 – 655** (c) 700 – 715	15 25 20 (in the middle betw. 200 and 201)	**50%** (Archie estimate)	(a) artefact? (c) very likely artefact

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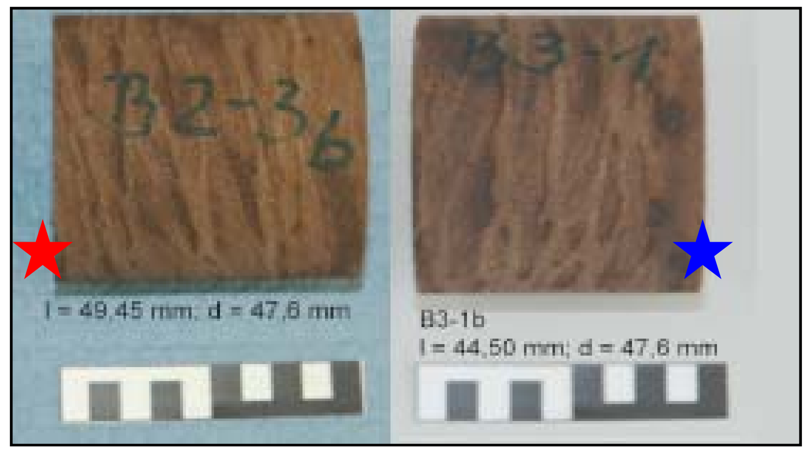
II. Geoelectrical Monitoring Concept

Laboratory results:

	Lab data before CO_2	Lab data after CO_2	difference	CO_2 saturation from model
★ Ktzi202_B2-3b				
ρ [Ωm]	**0.52**	**1.75**	+240%	50% Archie
★ Ktzi202_B3-1b				
ρ [Ωm]	**0.47**	**1.40**	+200%	46% Archie

Kummerow et al., 2008

- available data (lab, logs, Archie, reservoir modeling) suggest a bulk CO2 saturation of 50% which corresponds to a resistivity increase of 200% to 300%



Archie formula: $\rho = \rho_w \, a \, \phi^{-m} \, S_w^{-n}$

without any additional data:
a = 1, m = 2, n = 2 (standard for sandstone)
brine resistivity: ρ_w = **0.037 Ωm**

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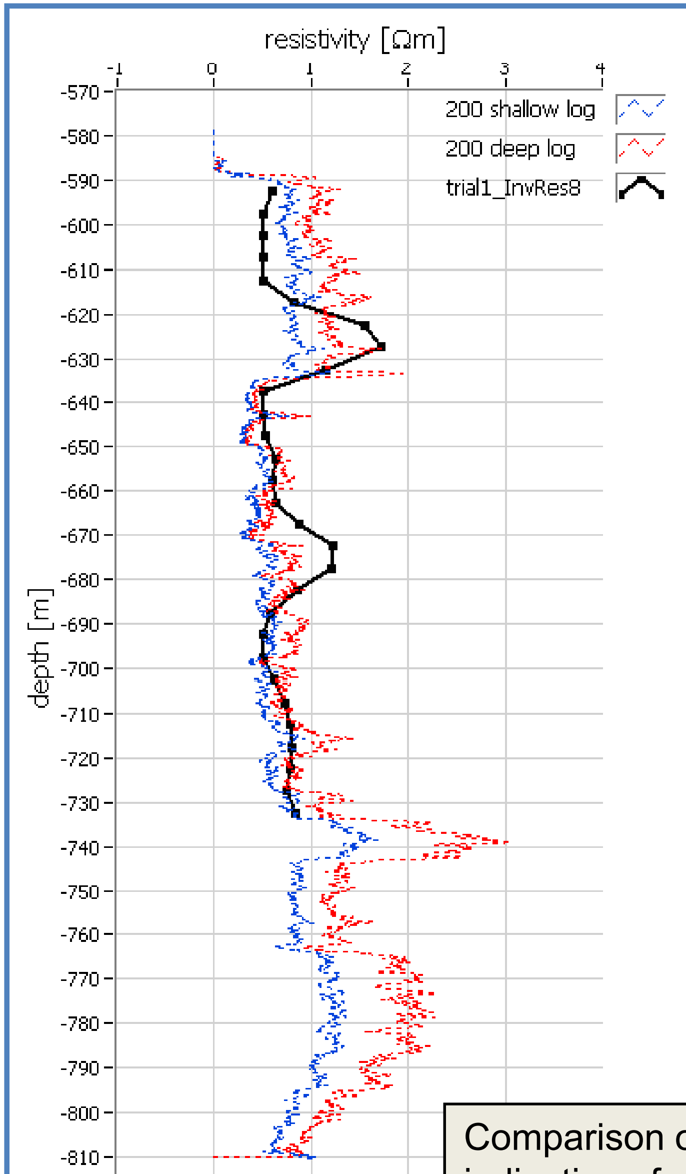
Resistivity logs and ERT crosshole data (baseline)

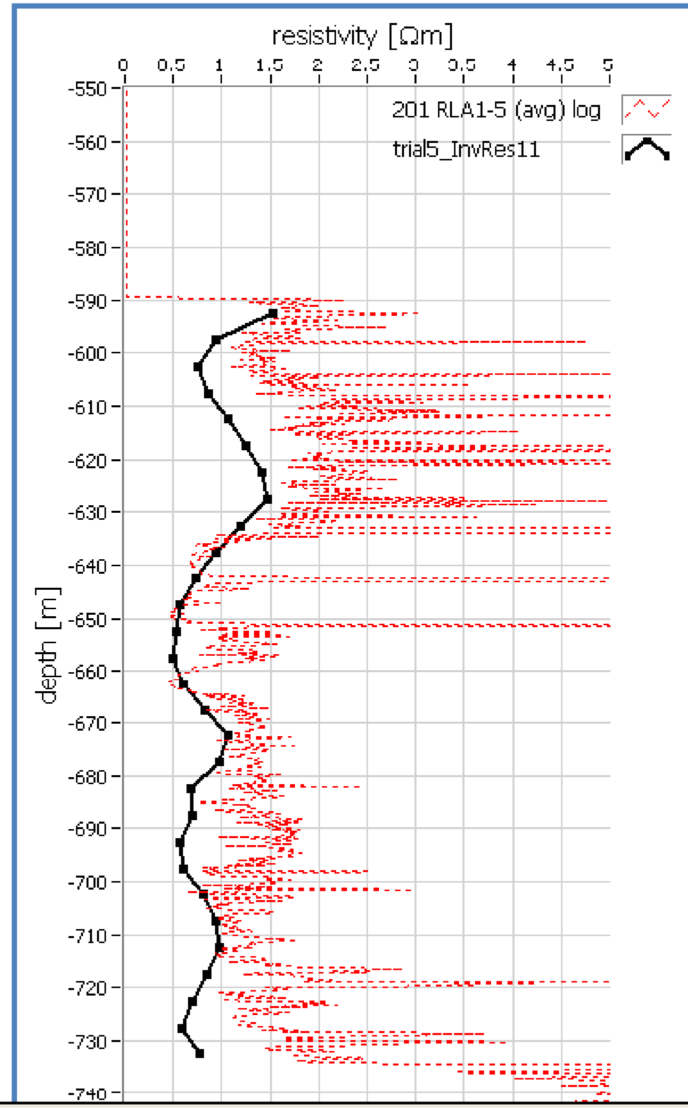
Ktzi200

BLM



Ktzi201

HRLA/SLB



Comparison of inverted data with the trend of logs → give indications for parameter settings

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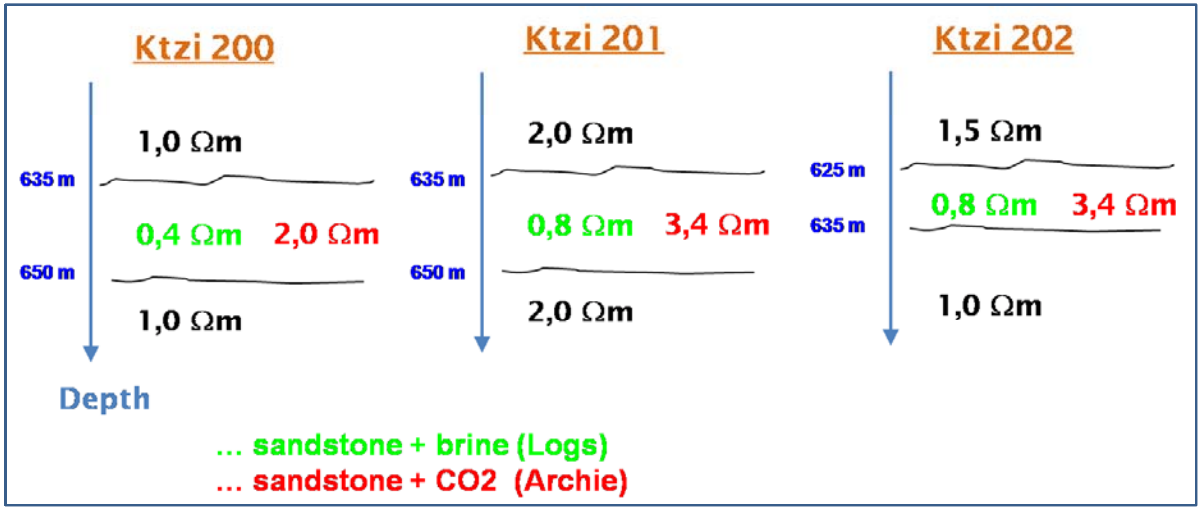
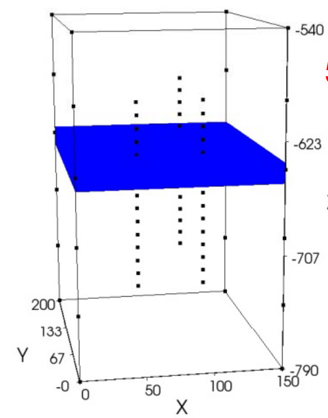
II. Geoelectrical Monitoring Concept

Ketzin resistivity model – feasibility study :



synthetic resistivity model



50% CO_2

~ 4.0 Ωm layer
635-650 m depth

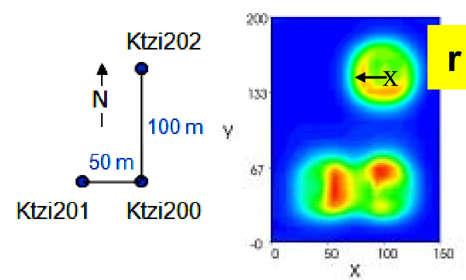
+ 300 %

changes in resistivity are expected

what we expect:

- 3 layers, middle layer is saline sandstone aquifer
- CO_2 effect from **Archie** for $\mathbf{S_{CO_2} = 50\ \%}$
- resistivity range for inversion: 0.5 Ωm (ρ_{min}) to 4 Ωm (ρ_{max})
- **Low resistivity environment and low resistivity contrast !**

z slices of resistivity changes



r ≈ 30 m

- no sensitivity in the middle and in the top left corner (no electrodes)
- ”investigation range” around the wells: about **30 m**

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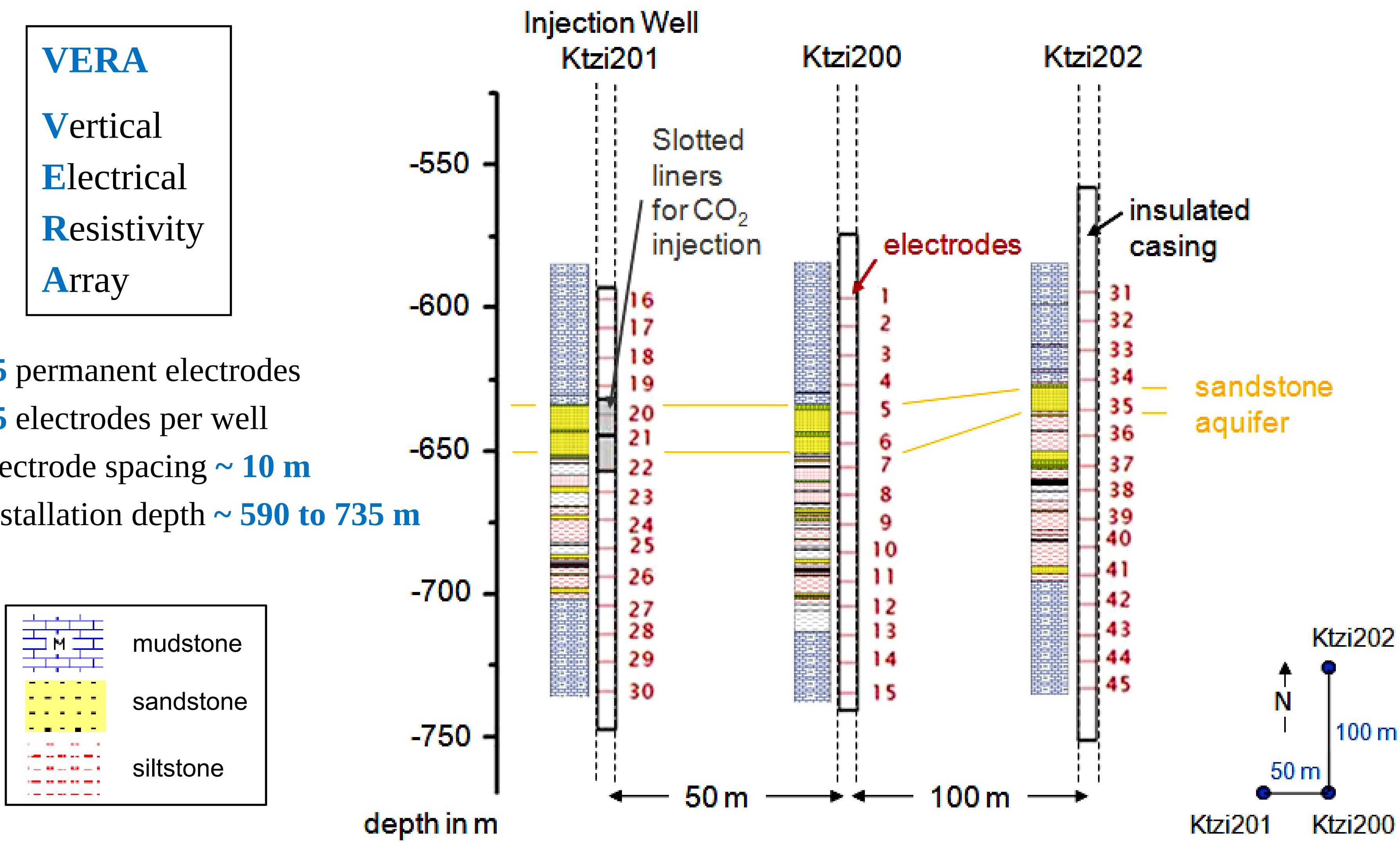
II a. Crosshole Measurements

VERA

Vertical
Electrical
Resistivity
Array

45 permanent electrodes
15 electrodes per well
electrode spacing **~ 10 m**
installation depth **~ 590 to 735 m**



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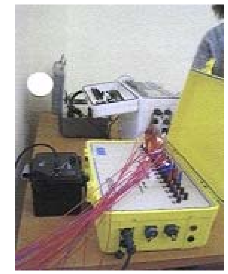
II a. Crosshole Measurements





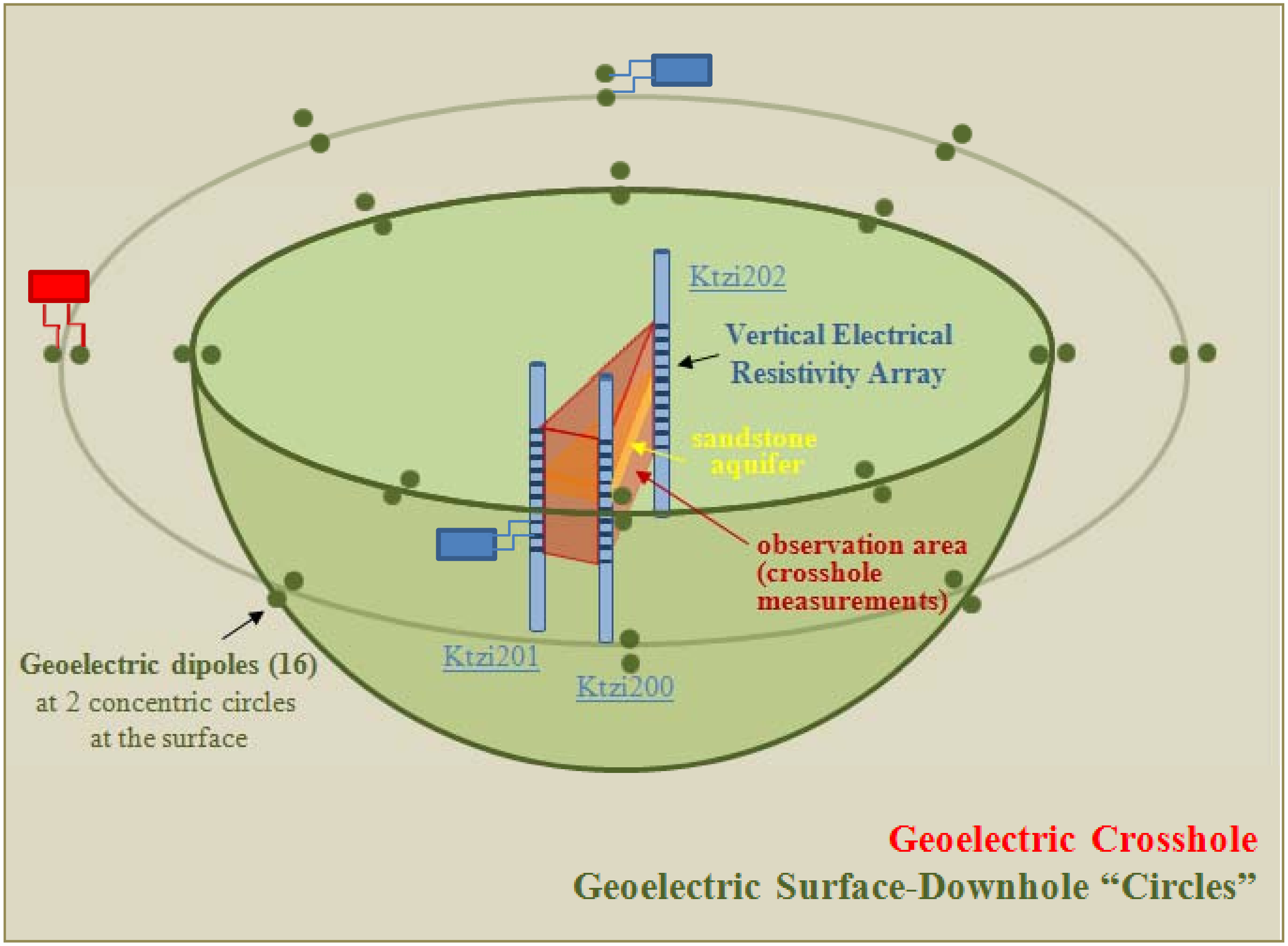
- monitoring of CO_2 migration between injection well Ktzi201 and the two observation wells Ktzi200 and Ktzi202
- using **dipole-dipole** configurations, **bipole-bipole** configurations including **cross-hole** configurations and user defined configurations having one current and one potential electrode in each well
- equipment: **GDP-32^{II}, ZT-30, MX-30** (Zonge, USA)
  - used current: **2.5 A** max.
  - used channels: **15** (for potential registration)
  - measured potential: **50 µV** to **100 mV**
- continuous measurements since start of injection

II b. Surface-Downhole Concept

electric power source TSQ-4 (Scintrex Limited, Canada)

I = 4 – 18 A
U = 500 – 1300 V

Texan-125 (Refraction Technology Inc., USA)



16 dipoles at the surface for current injection **(C_1C_2)**
dipole length: 150 m, r_1 = 800 m, r_2 = 1500 m

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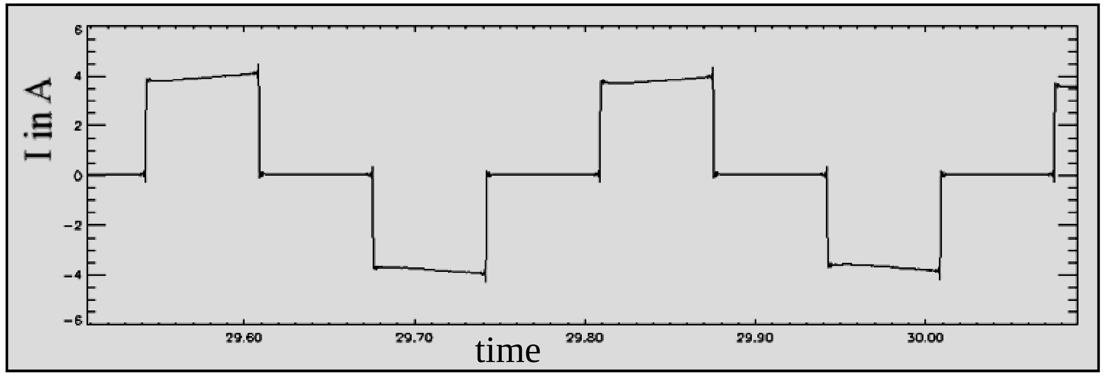
II b. Surface-Downhole Concept

electric power source TSQ-4
(Scintrex Limited, Canada)

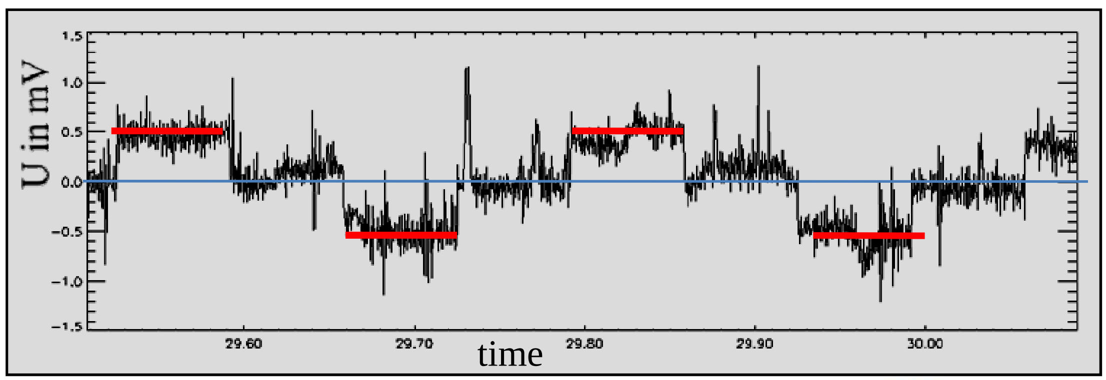
I = 4 – 10 A
U = 900 – 1300 V

current injection at surface



potential registration Downhole

Texan-125 (Refraction Technology Inc., USA)



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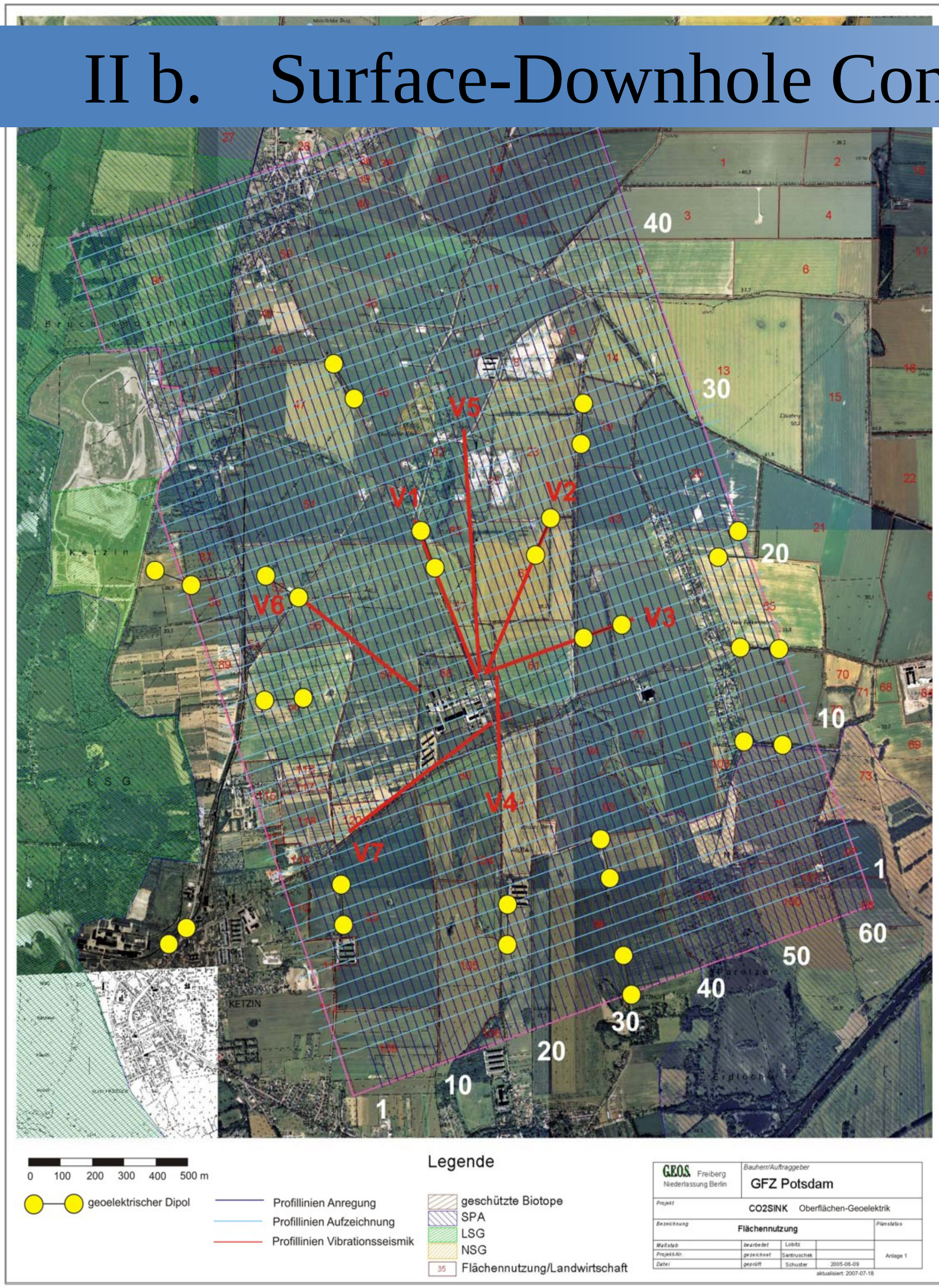
II b. Surface-Downhole Concept



geoelectrical (yellow dots)
and
seismic (red lines and
light blue grid)
survey <u>at the surface</u>

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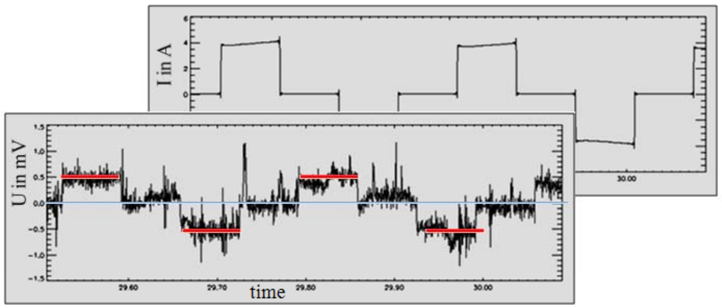
(3) Study of pre-inversion data

Real field data



Engineers' Toolbox

$$R = \frac{U}{I}$$

R … resistance

geometry

$$k = 4\pi \left[\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2} \right]^{-1}$$

$$\rho_a = k \cdot R = k \cdot \frac{U}{I}$$

ρ_a … apparent resistivity

inversion

$$\rho$$

ρ … resistivity

- Automized evaluation of field data sets by digital filtering according relevant criteria

- Skip of defective data / enlarge the set of applicable data

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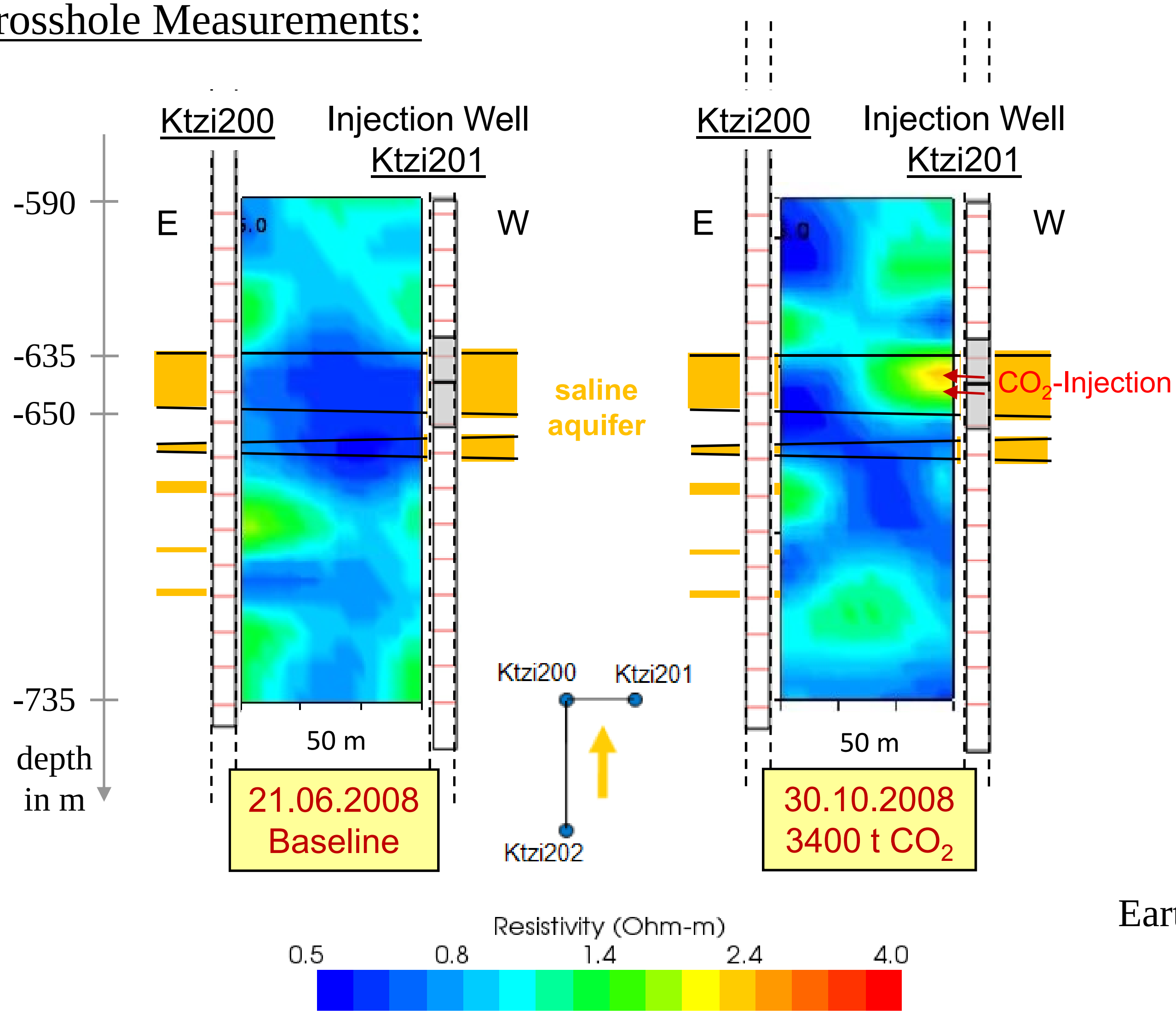
Quality check of data

Skip !

o.k.

III. Preliminary Results

Geoelectric Crosshole Measurements:



EarthImager, AGI

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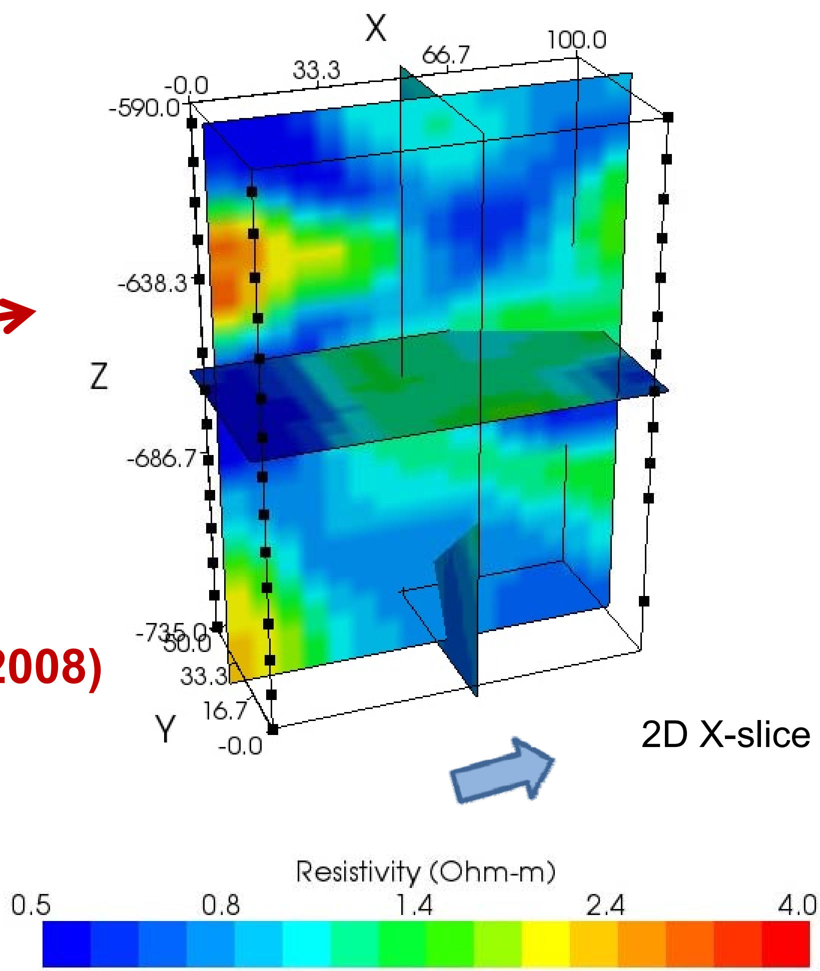
Preliminary inversion results of crosshole measurements

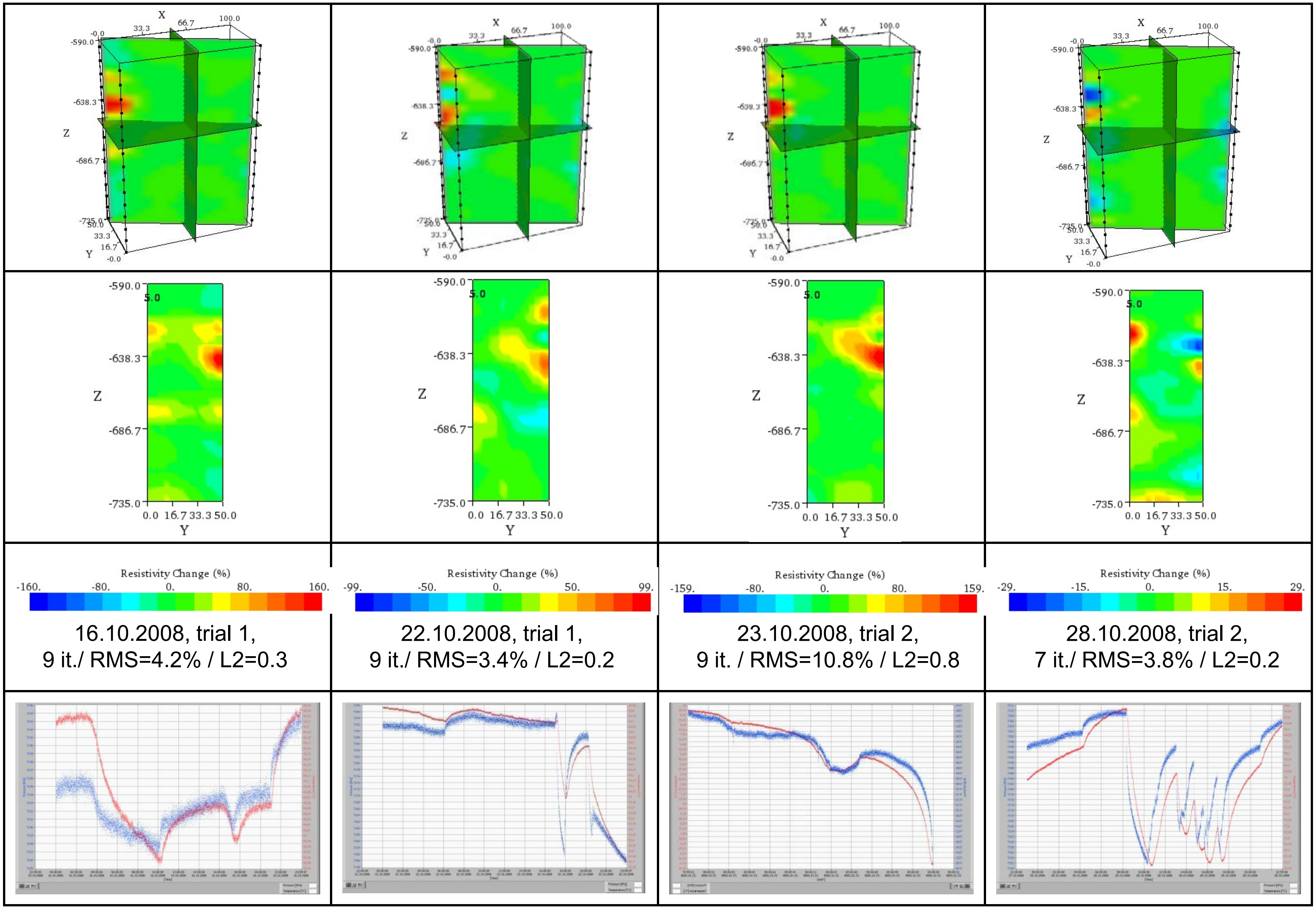
CO_2 injection point

5300 t
(Dec 11, 2008)



- time lapse difference method
- base line June 21, 2008
  (EarthImager, AGI)

2D X-slice / area near boreholes under consideration

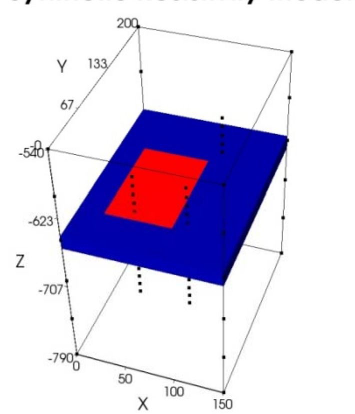


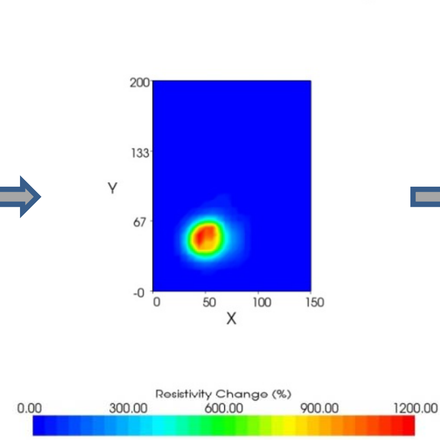
BHP BHT

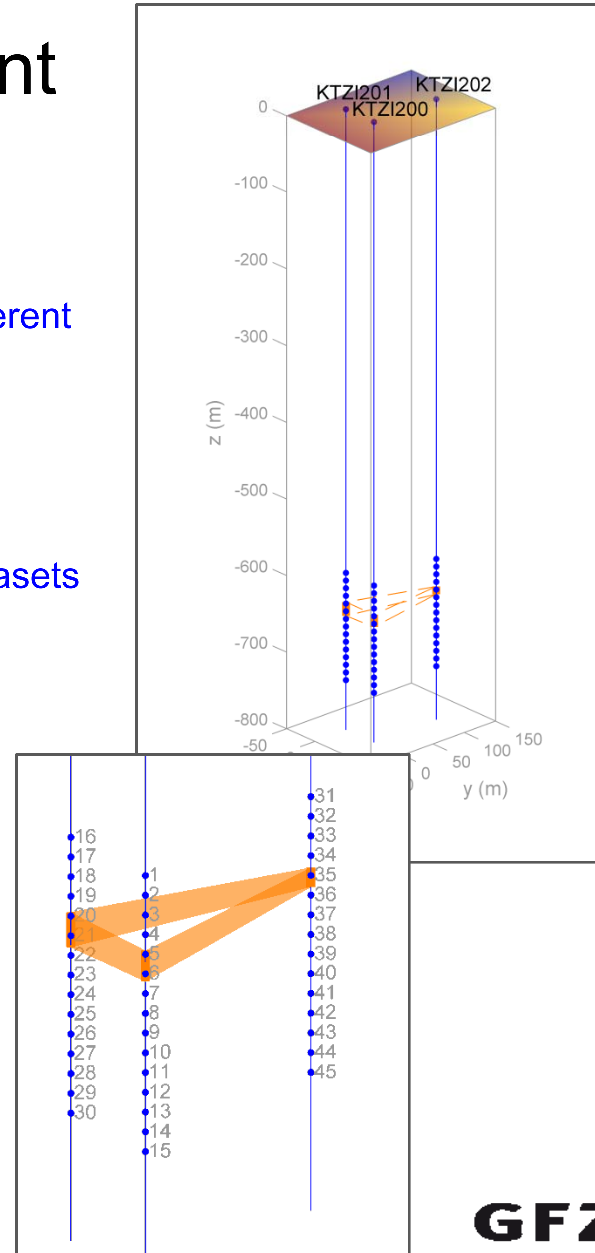
Cross-hole data from regular storage operation

Sensitivity analysis of measurement configurations

- **Electrode configuration evaluation**
  - Forward modelling (e.g. finite elements, finite differences) with different electrode configurations (dipole-dipole, bipole-bipole etc.)
  - Modelling on homogenous resistivity distribution
  - Modelling on homogenous distribution with local perturbation
  - Comparison of synthetic model response
  - Evaluation of possible resolution within synthetic pre-inversion datasets







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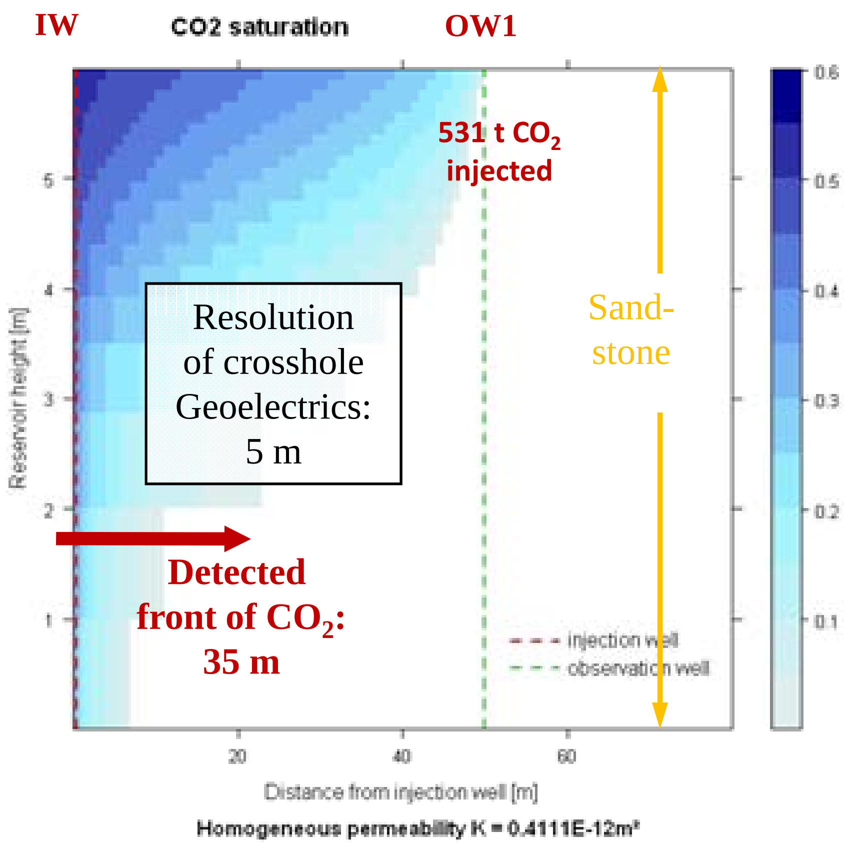
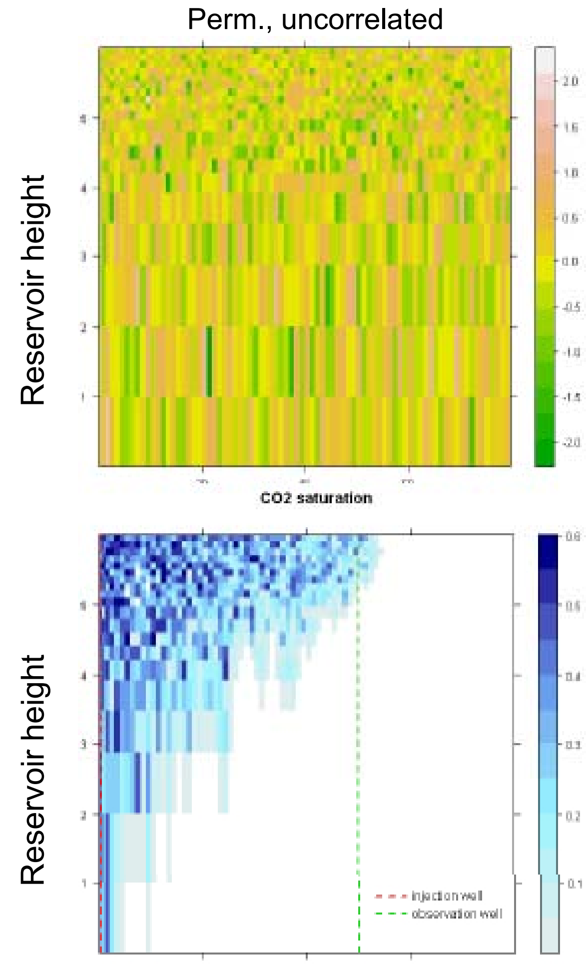
Joint interpretation with other modeling work

- THOUGH2, V2: homogeneous aquifer, homogeneous permeability, circular migration

CO2 distribution dependent on the heterogeneity of permeability





model data

(U. Lengler, 2009)

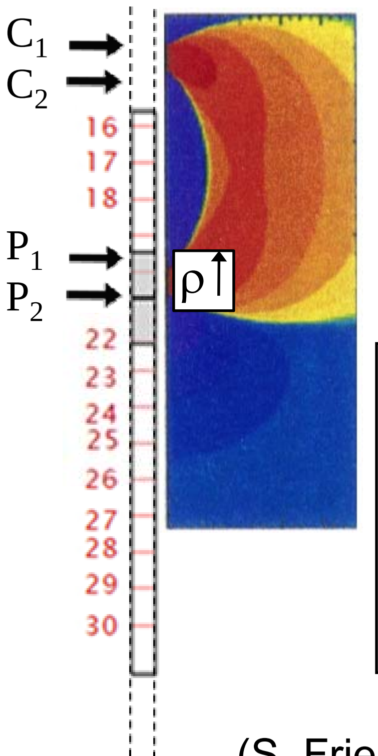
1 realization

III. Preliminary Results

<u>Combined Surface-Downhole Concept :</u> Fundamentals

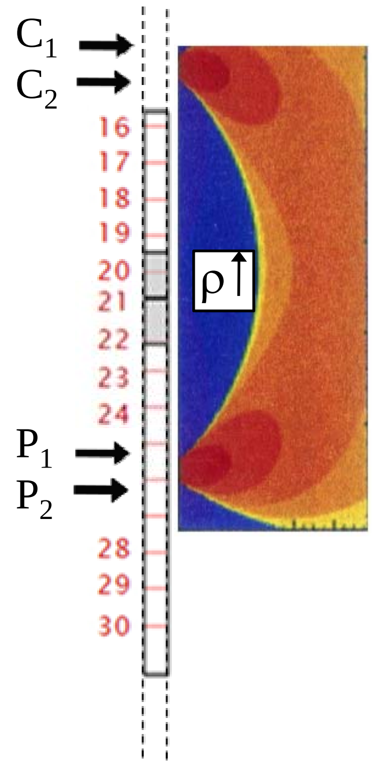
$$S = \frac{d\rho_a}{d\rho}$$

- <u>schematical:</u> 2D dipole-dipole-configuration (CCPP)



S⁺: $\rho\uparrow = \rho_a\uparrow$

positive sensitivity:
<u>increasing</u> in **resistivity**
lead to
an <u>increasing</u> in
apparent resistivity
(measured)



S⁻: $\rho\uparrow = \rho_a\downarrow$

negative sensitivity:
<u>increasing</u> in **resistivity**
lead to
an <u>decreasing</u> in
apparent resistivity
(measured)

(S. Friedel, 2000)

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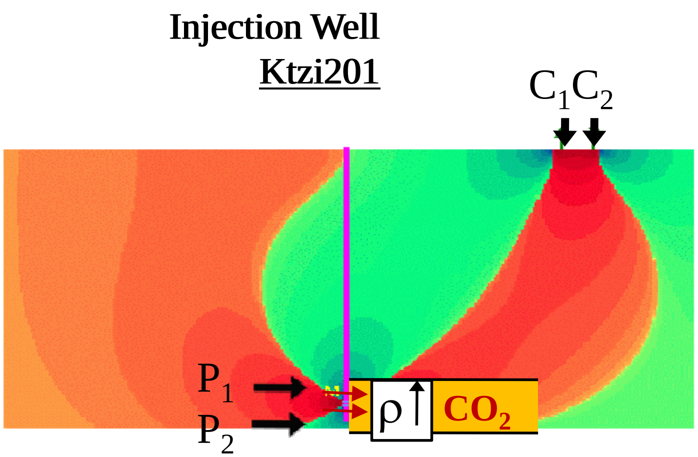
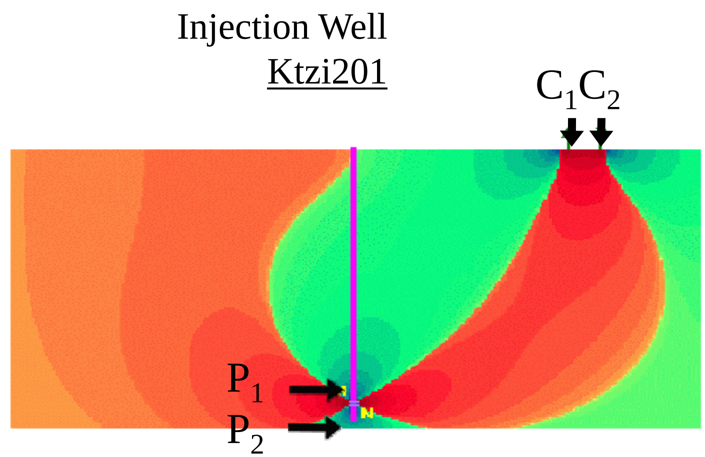
III. Preliminary Results

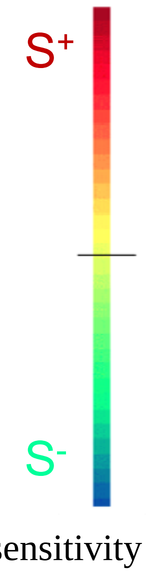
<u>Combined Surface-Downhole Concept :</u> Fundamentals

$$S = \frac{d\rho_a}{d\rho}$$

- equally valid for Surface-Downhole Principle (CCPP)







S^+: $\rho\uparrow = \rho_a\uparrow$

S^-: $\rho\uparrow = \rho_a\downarrow$

an <u>increasing</u> in **apparent resistivity** (measured) **is caused by CO_2**

a <u>decreasing</u> in **apparent resistivity** (measured) is caused by an <u>increasing</u> in **resistivity** in another direction (in range of **negative sensitivity**)

(E. Danckwardt, 2001)

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III. Preliminary Results

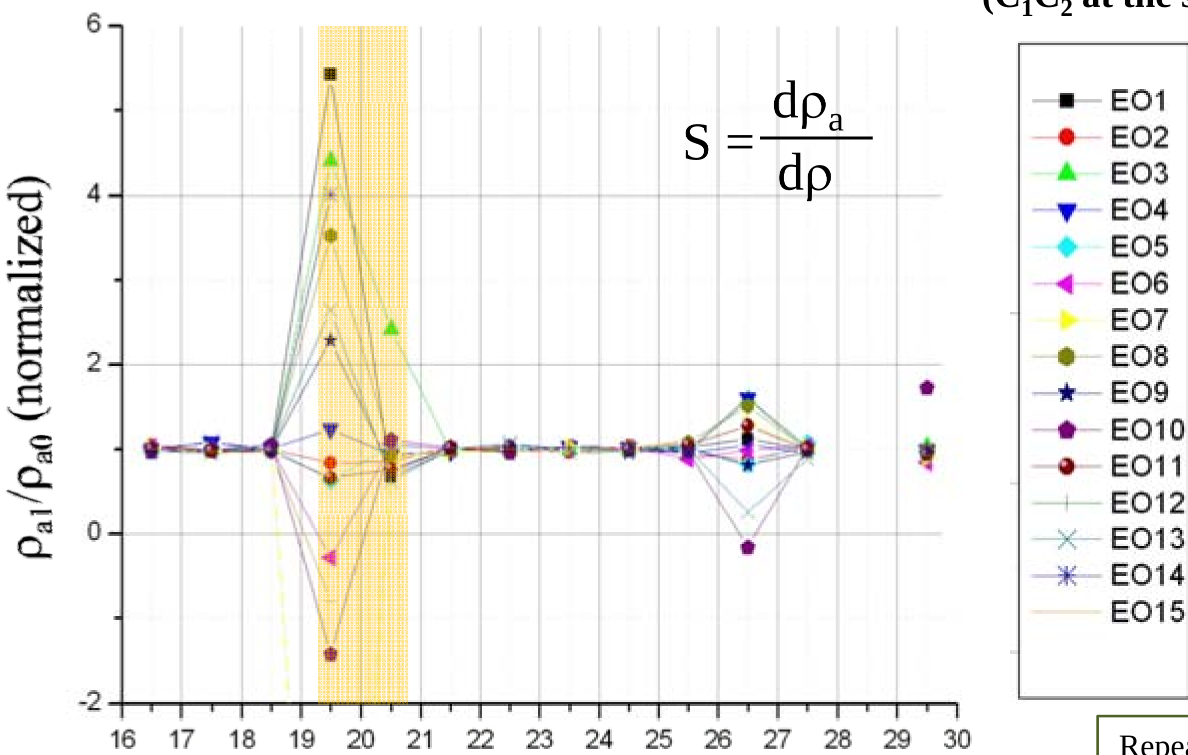
Combined Surface-Downhole Concept:

ratio **= 1**: no changes in apparent resistivity ρ_a

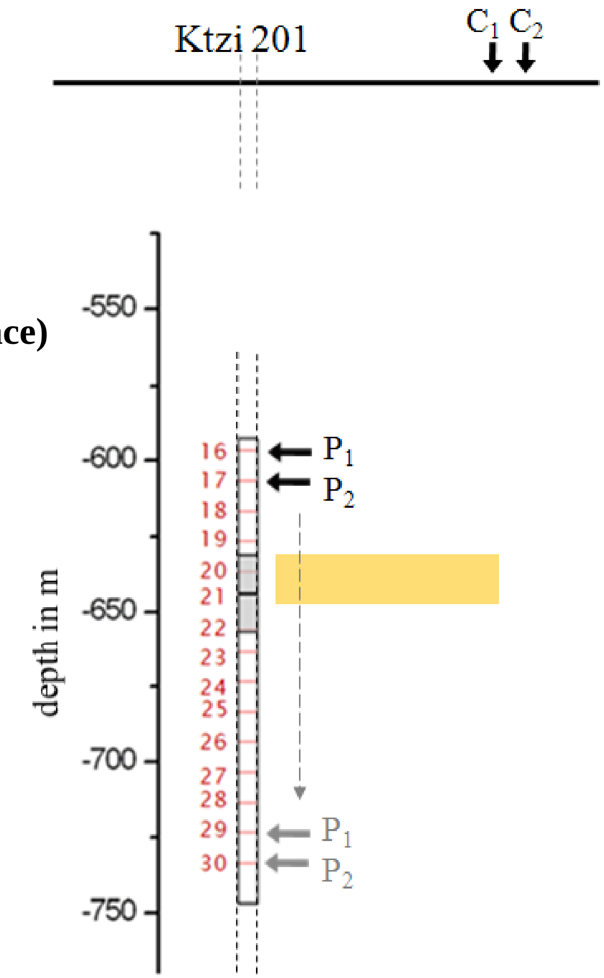
ratio > **1**: increasing in apparent resistivity = CO_2

ratio < **1**: no CO_2-caused changes in this direction

(C_1C_2 at the surface)



Electrodes 16-30 in Ktzi201 **(P_1P_2 in the borehole)**



Repeat November 2008: 4500 t CO_2
Baseline April 2008: 0 t CO_2

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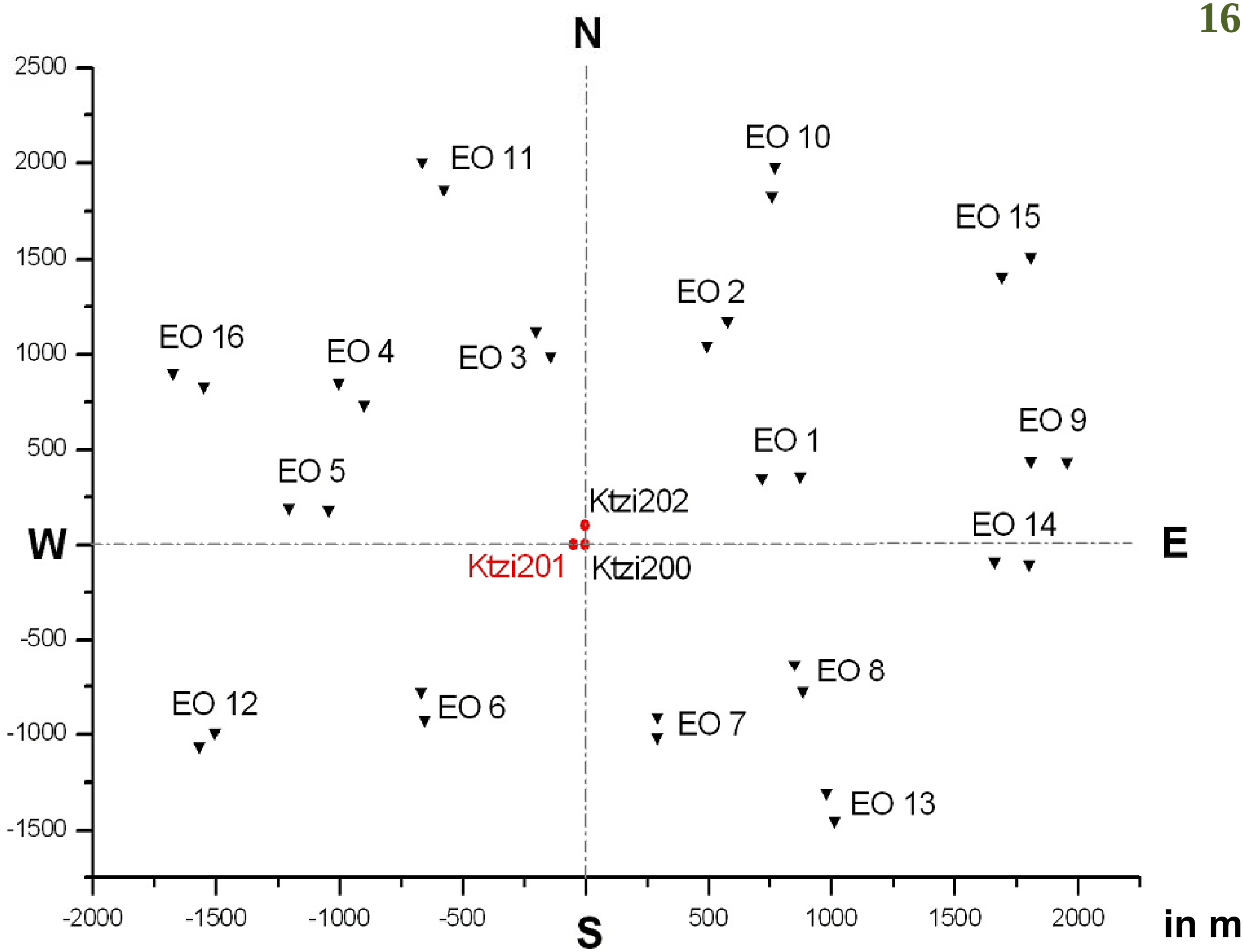
III. Preliminary Results

Combined Surface-Downhole Concept:



16 dipoles at the surface

(dipole length: 150 m)

r_1 = 800 m

r_2 = 1500 m

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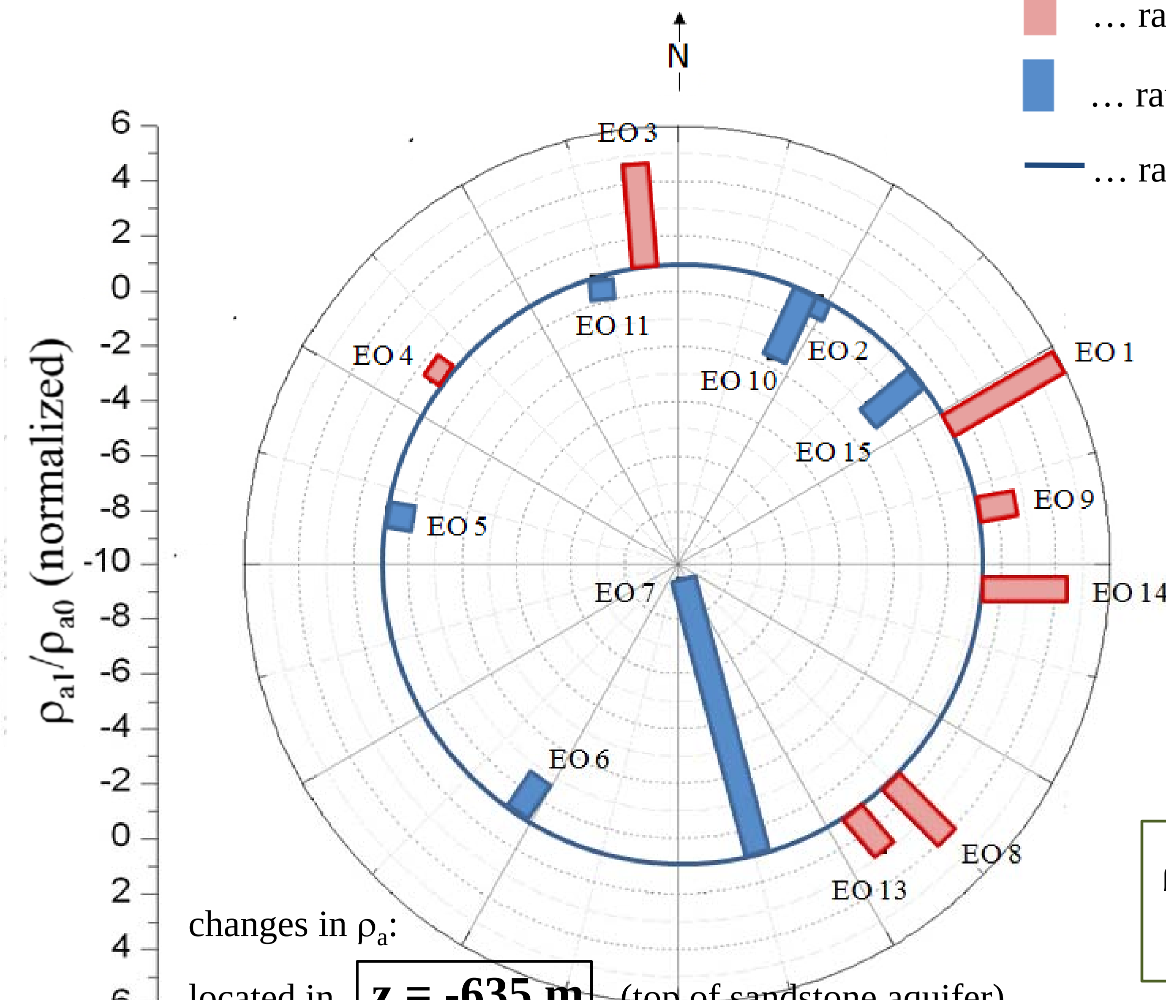
III. Preliminary Results

<u>Combined Surface-Downhole Concept:</u>

... ratio > **1**: CO_2

... ratio < **1**: no CO_2-caused changes in this direction

... ratio = **1**: no changes in apparent resistivity ρ_a



changes in ρ_a:

located in **z = -635 m** (top of sandstone aquifer)

- **current electrodes (C_1, C_2):**
  16 dipoles at the surface
- **potential electrodes (P_1, P_2):**
  Ktzi201 (at sandstone aquifer/ depth of injection)

ρ_{a1} from Repeat November 2008: **4500 t CO_2**

ρ_{a0} from Baseline April 2008: **0 t CO_2**

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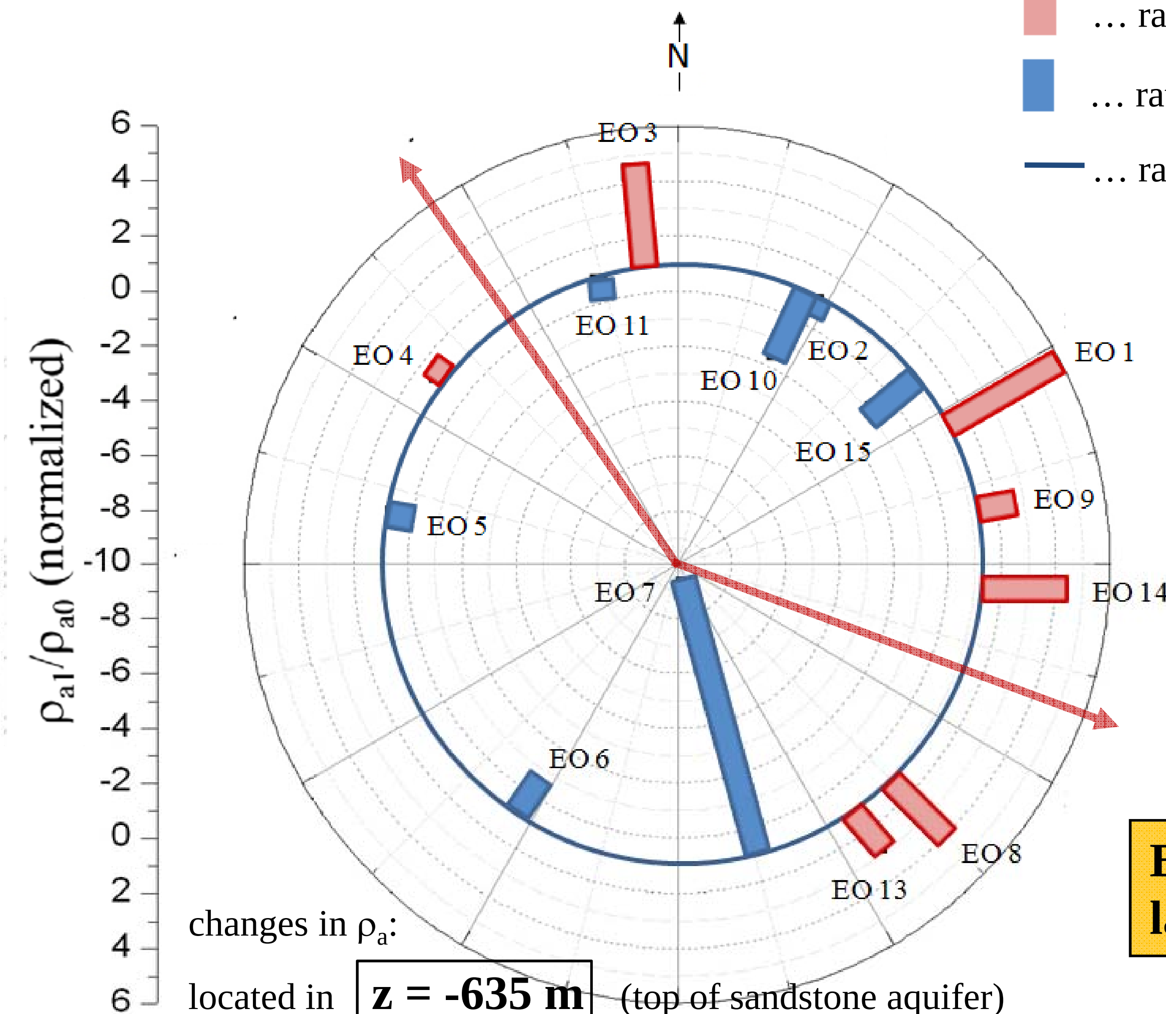
IV. Conclusion

Combined Surface-Downhole Concept:



... ratio > **1**: CO_2

... ratio < **1**: no CO_2-caused changes in this direction

... ratio = **1**: no changes in apparent resistivity ρ_a

CO_2 – migration trend:

NW-SE-direction

BUT NO information about lateral CO_2 migration progress!

changes in ρ_a:

located in **z = -635 m** (top of sandstone aquifer)

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IV. Summary and Conclusion

Geoelectrical monitoring at Ketzin:

- deepest permanent downhole electrode array (from 590 to 735 m)
- using "smart-casing" technology
- part of a monitoring concept which integrates Geophysics, Geochemistry, Microbiology

- Crosshole Geoelectrics can **resolve an increase of the electrical resistivity** caused by the CO_2 injection, however, **small-scale fingering effects** in CO_2 migration **could not be delineated** by the VERA system

- **geoelectrical Crosshole and Surface-Downhole Measurements for monitoring CO2: it works in general, it has to be further developed**

  but some problems were underestimated at the beginning of project
  → data quality depends strongly on the noise of the injection process
  → we missed doing sufficient preliminary studies (by lack of manpower, e.g.)

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V. Outlook – more results in process…

Geoelectric Downhole Measurements:

- ongoing measurements
- signal processing and inversion
- sensitivity studies concerning measurement configurations

Combined Surface-Downhole Measurements

- **3rd Repeat** finished in end of April (for **verification** of CO_2-migration trend)
- **additional profiles at the surface** for lateral separation of migration progress were measured in May and are under evaluation now
- **signal processing is ongoing**
- **3D inversion is planned**

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Thanks to all involved persons!

GEOTECHNOLOGIEN

COSMOS

CO_2SINK

Federal Ministry of Education and Research

Federal Ministry of Economics and Technology

We thank the Federal Ministry of Education and Research, and its R&D program "Geotechnologien" for funding our work.

…and for your attention!

University of Leipzig

GFZ Helmholtz Centre Potsdam

Agenda

- Why Monitoring in Real-Time? – the Example of Underground Gas Storage
- Real-Time Monitoring Workflows for CO_2 Storage
- System Architecture
- Conclusion

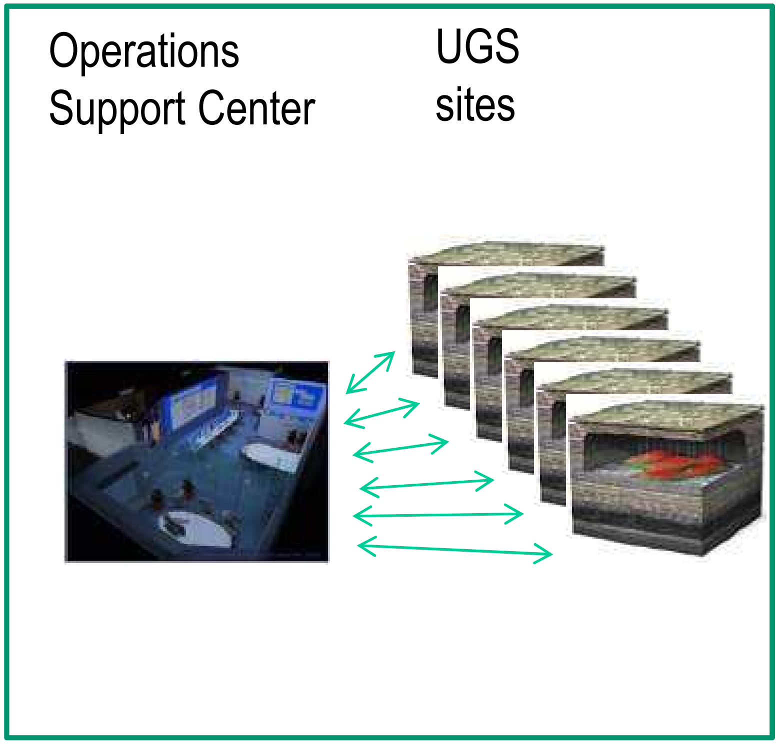
Mature technology for Underground Gas Storage

Wells and reservoir are submitted to repeated injection and withdrawal of natural gas, that are seasonal (France) or adjusted to the faster varying demand (California)

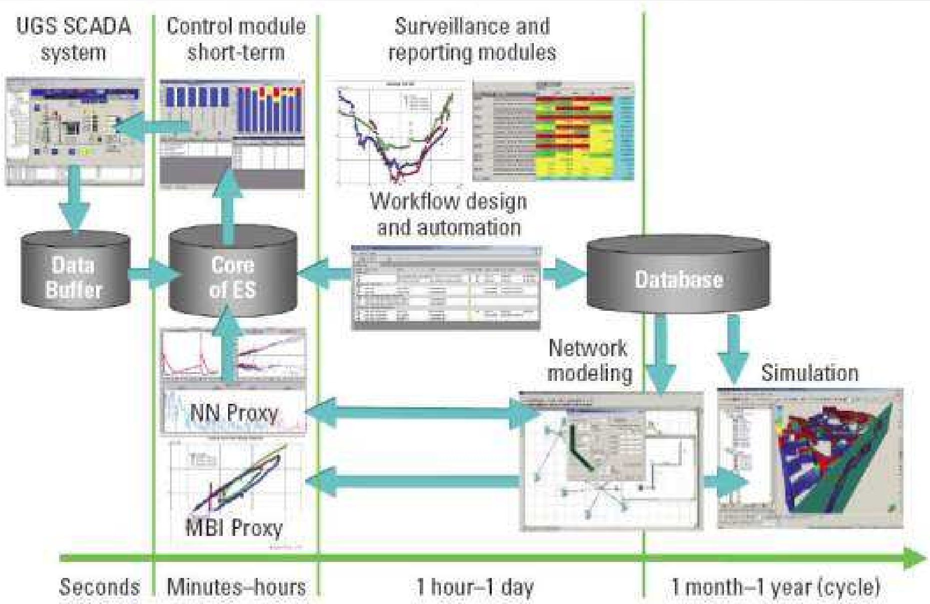
- Risk management and performance optimization are crucial, in terms of safety and value of the storage.

- Automated integration of data at different time scale, with reactive measures for short term workflows

- This enables having several UGS sites connected with an Operation Support Center, where experts are based.



Examples of monitoring workflows



From Oilfield Review, Spring 2008

Short term workflows reactive

- Compressors and transport to the wellhead: (*seconds)*
- Well performance : Continuous calculation of the mechanical skin factor, and non darcy flow coefficient *(day)*

Long term workflows

- Optimization of the volume of the cushion gas *(months, years)*

Application to CO_2 storage

- Motivations:
  - Control of injection operations (surveillance and diagnostics)
    - Related to site performance: capacity, injectivity, integrity
    - For accounting and reporting
  - Ensure maximum safety of operations with fast-loop controls

- First steps in the data integration process

  Integrated workflows with a turn around time between several minutes to one day

- No experience, therefore:

  Caution on systematic integration, no excessive automation, care on “alarms”

CO_2 Storage Monitoring by objectives

Operational Monitoring

Injection operation control

- Wellhead pressure
- Bottomhole pressure, Temperature
- Injection rate & transport sensors
- Microseismicity

Quantification of injected CO_2

- Mass flow
- Gas stream composition and phase

Verification Monitoring

Well Integrity

- Annulus pressure
- Corrosion
- Cement
- Soil gas measurements

Cap Rock / Fault Integrity

- Microseismicity
- Pressure interference

CO_2 displacement & fate

- Geophysics techniques
- Pressure, Temperature
- Well logs (CO2 Saturation)
- Sampling
- Geodetic methods

Assurance Monitoring

Impact: HSE monitoring

- Potable water quality
- Soils acidity/ Seawater purity
- Atmospheric concentration
- Ecosystems monitoring

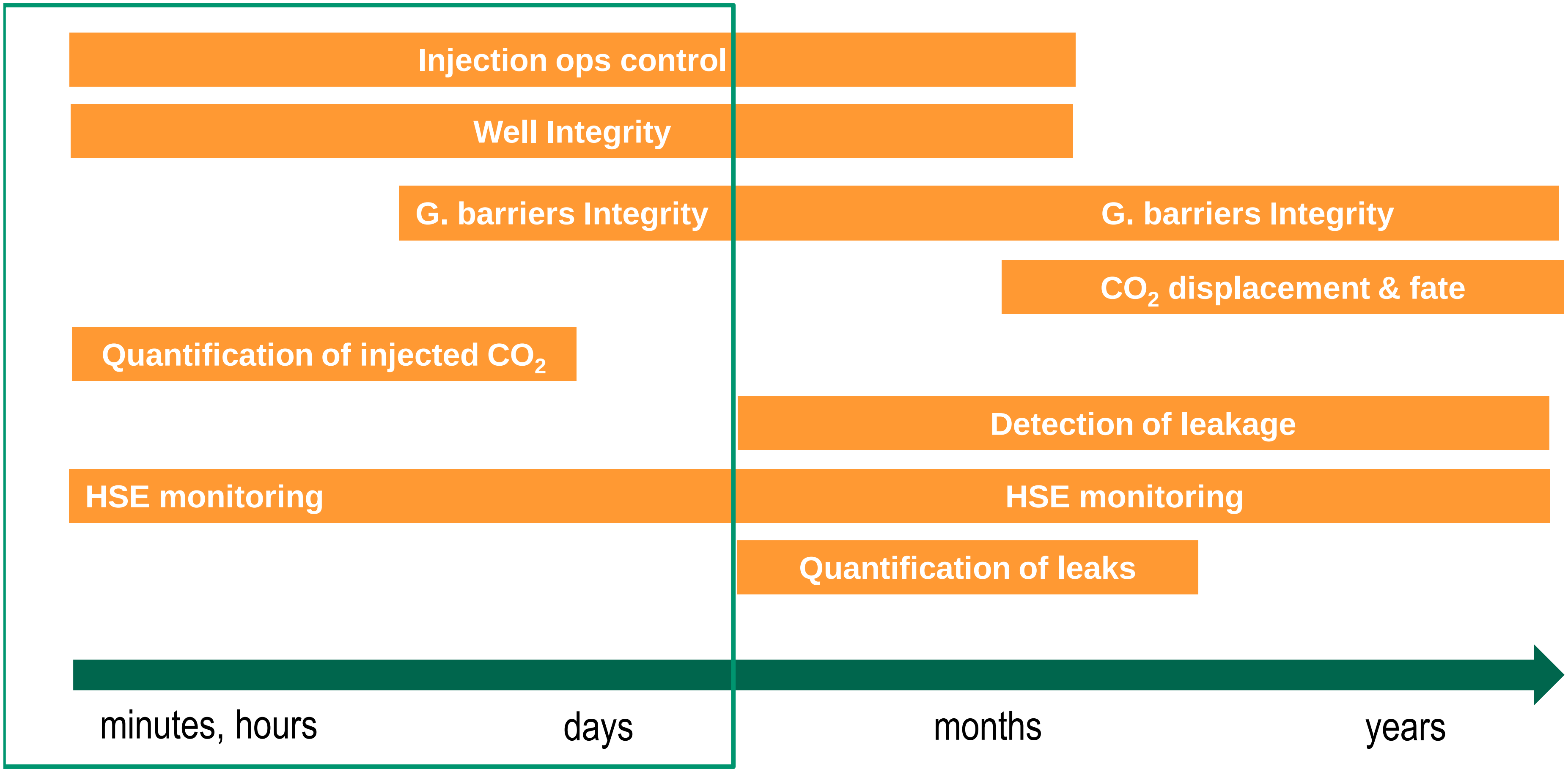
Detection of leakage

- Sampling & chemical analysis
- Geophysics techniques
- Pressure interference
- Soil gas measurements
- Vegetation stress
- Eddy correlation tower

Quantification of leaks

- Soil gas measurements
- Surface gas measurements
- …

Integrating the data at different time scales



Workflows for real time monitoring

- Optimization of the injection operations
- Integrity of the injection well & Integrity of the reservoir
- Counting the CO_2 injected
- Health, Safety and environment monitoring

Combination of sensors (site specific):

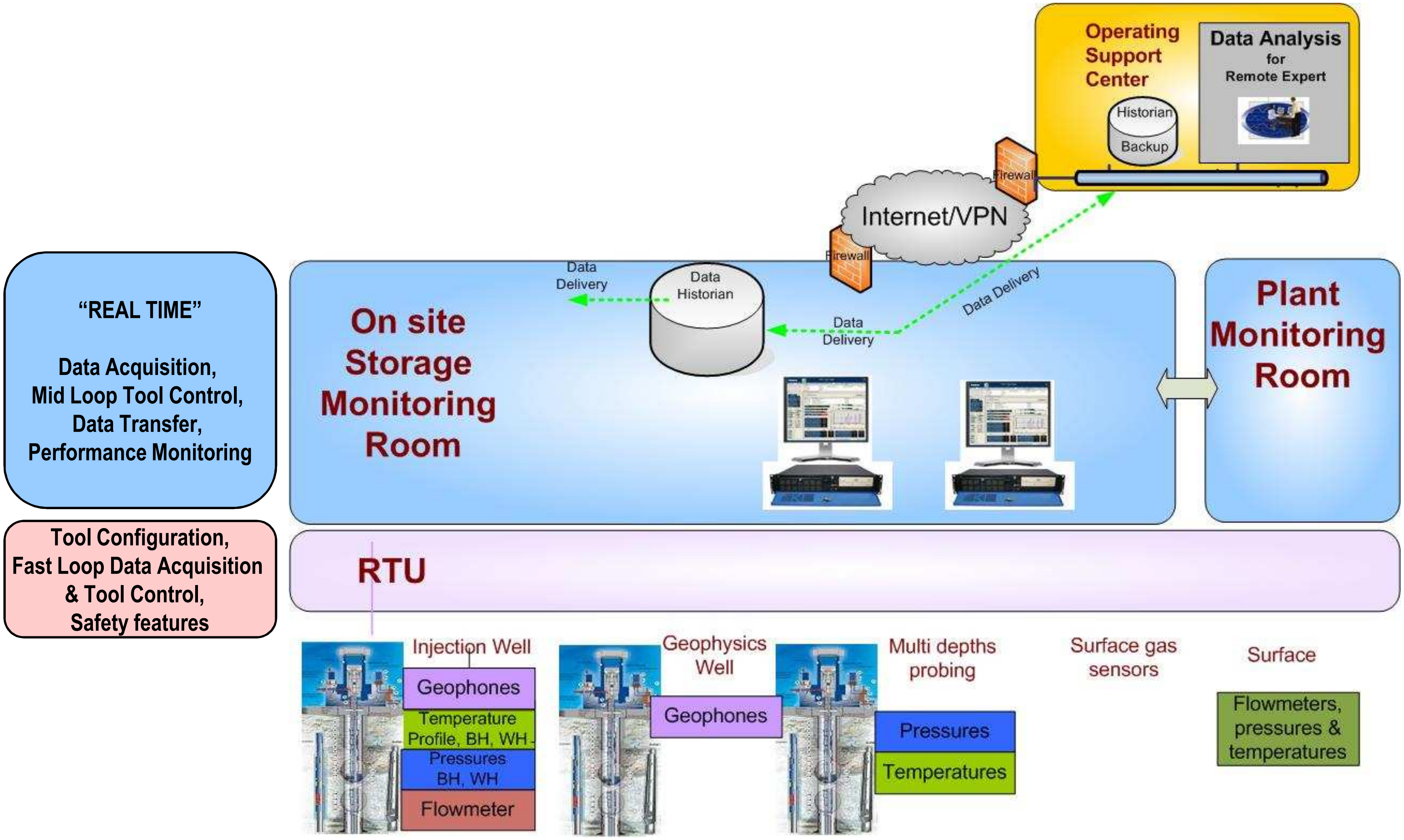
- Wellhead and bottomhole sensors pressure, temperature, chemicals microseismicity, …
- Surface sensors for the subsurface network of electric, microseismics, …
- Near surface and atmospheric gas sensors

Output from other workflows

Manual Reactions
(not systematized at this stage)

- Modification of the injection rate (increase, decrease or stop)
- Trigger ancillary modeling or simulating
- Intensify monitoring: frequency of exisiting measurements, deployment of other sensors

Example: System Architecture



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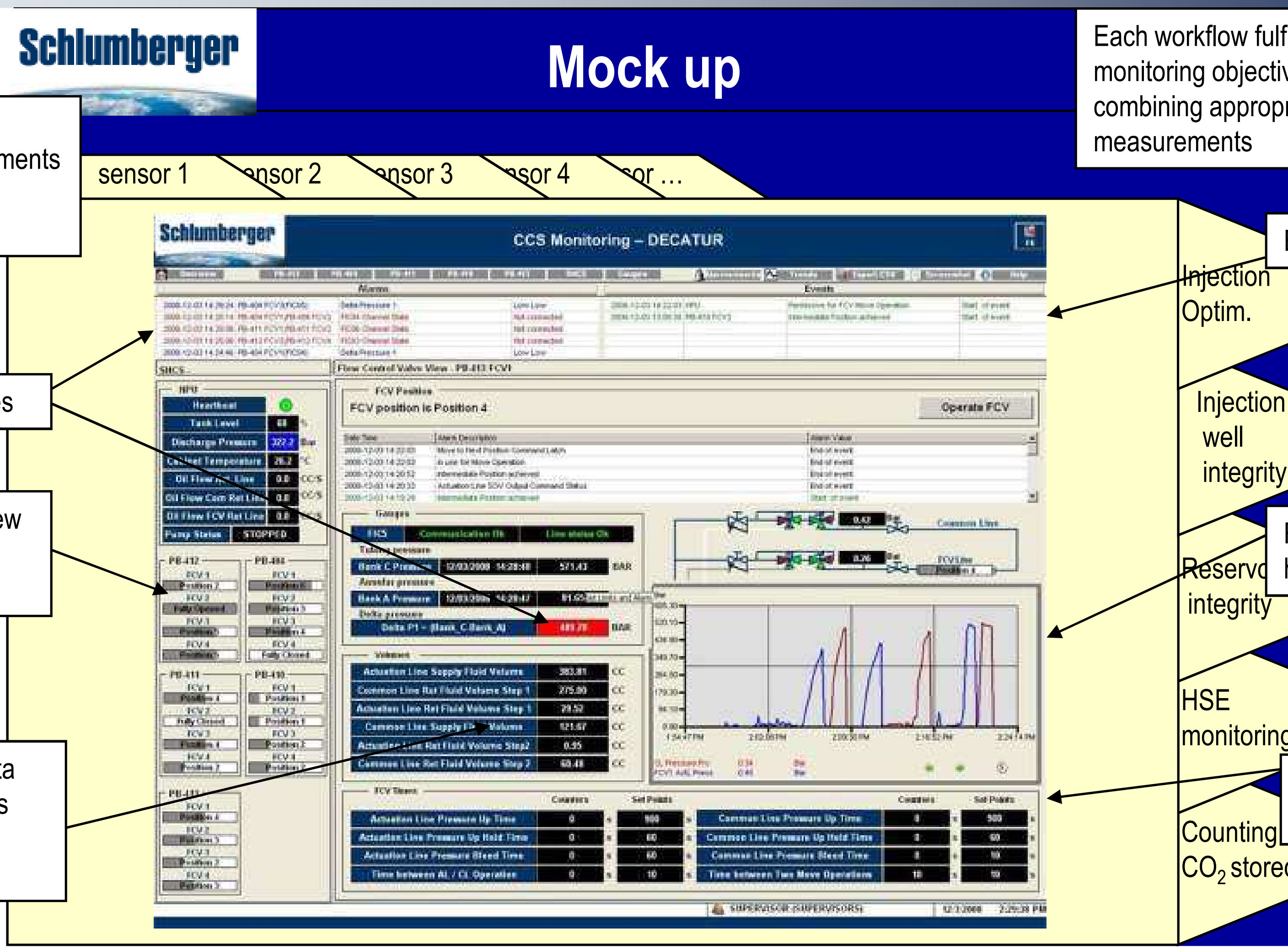
“Sensor screen”

For each sensor:
-Display measurements
-Set alerts,…
- …

Each workflow fulfills a monitoring objective by combining appropriate measurements



Alarm Messages

System Overview Real Time Parameters

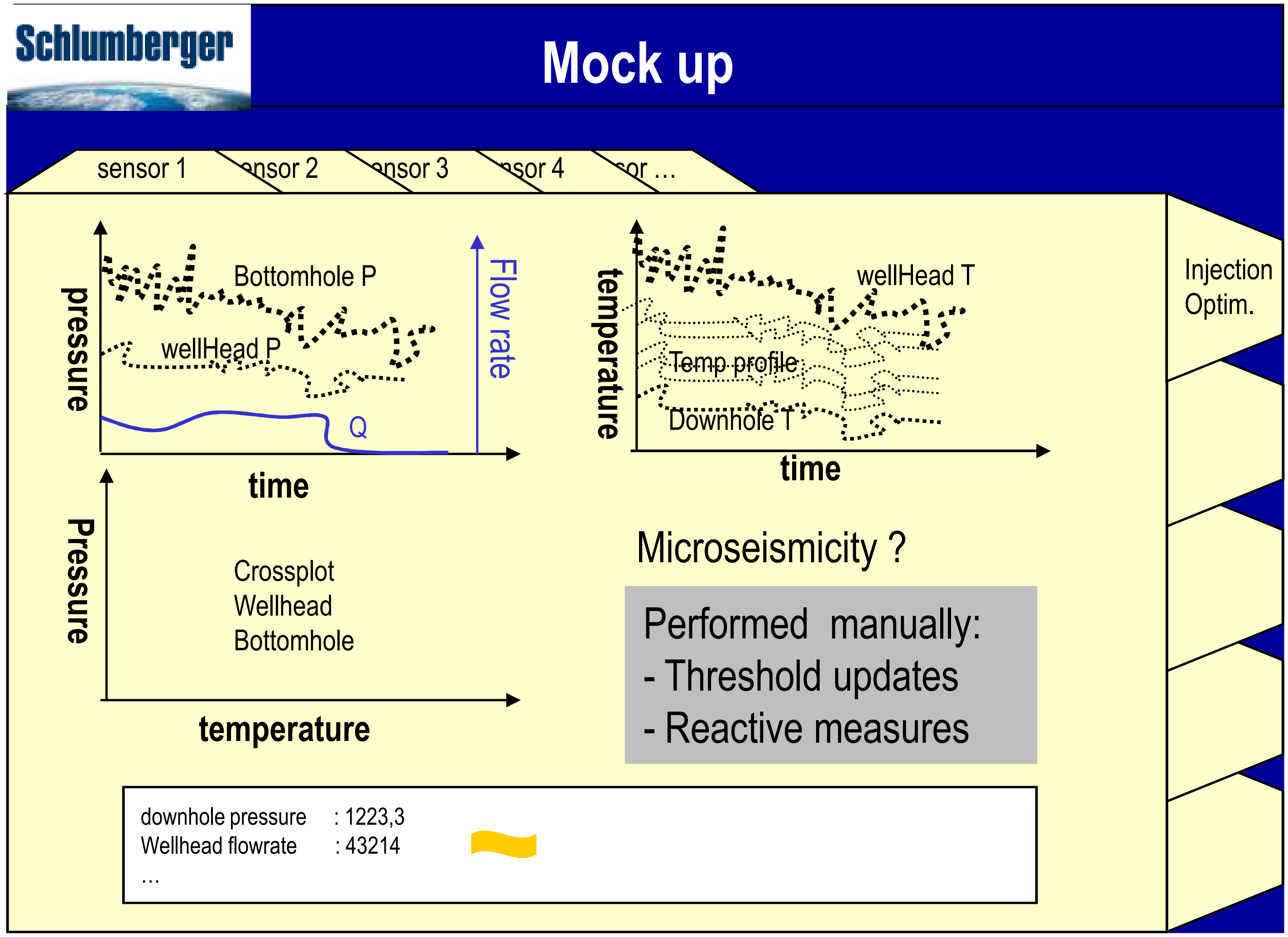
Real Time Data Measurements assembled by topics

Event Messages

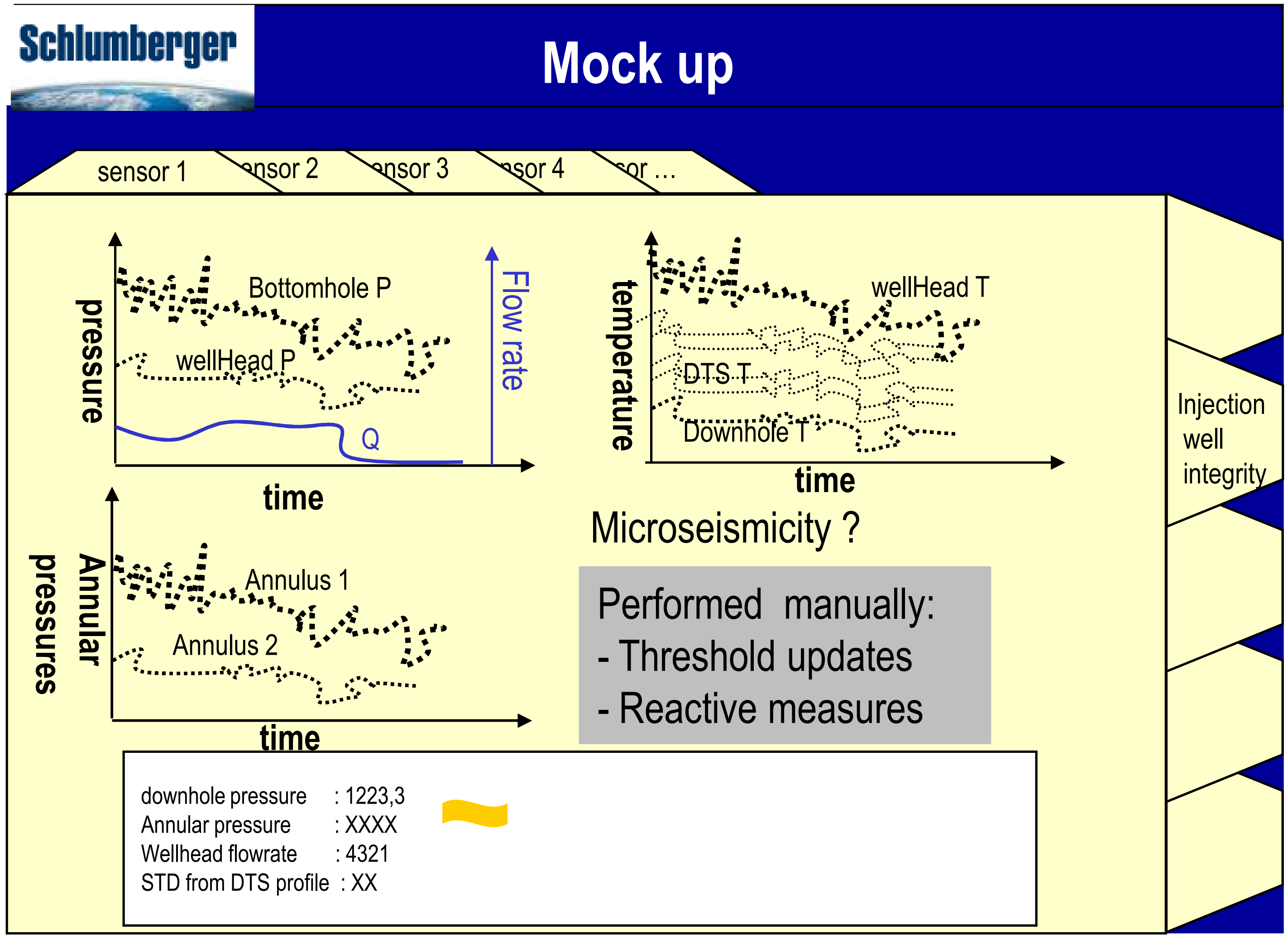
Real time and historical trending

Computed Real Time KPIs

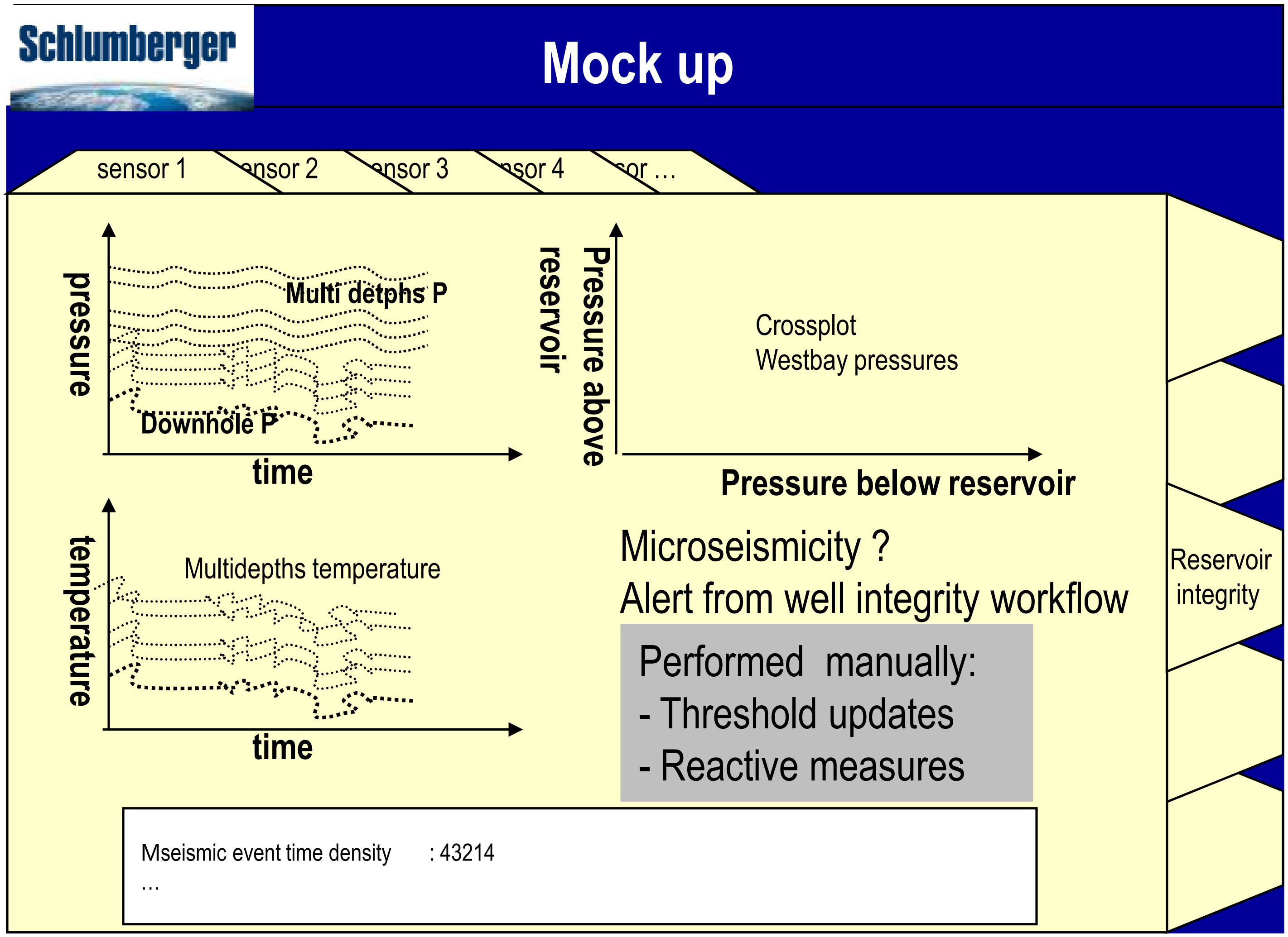
Injection operations optimization



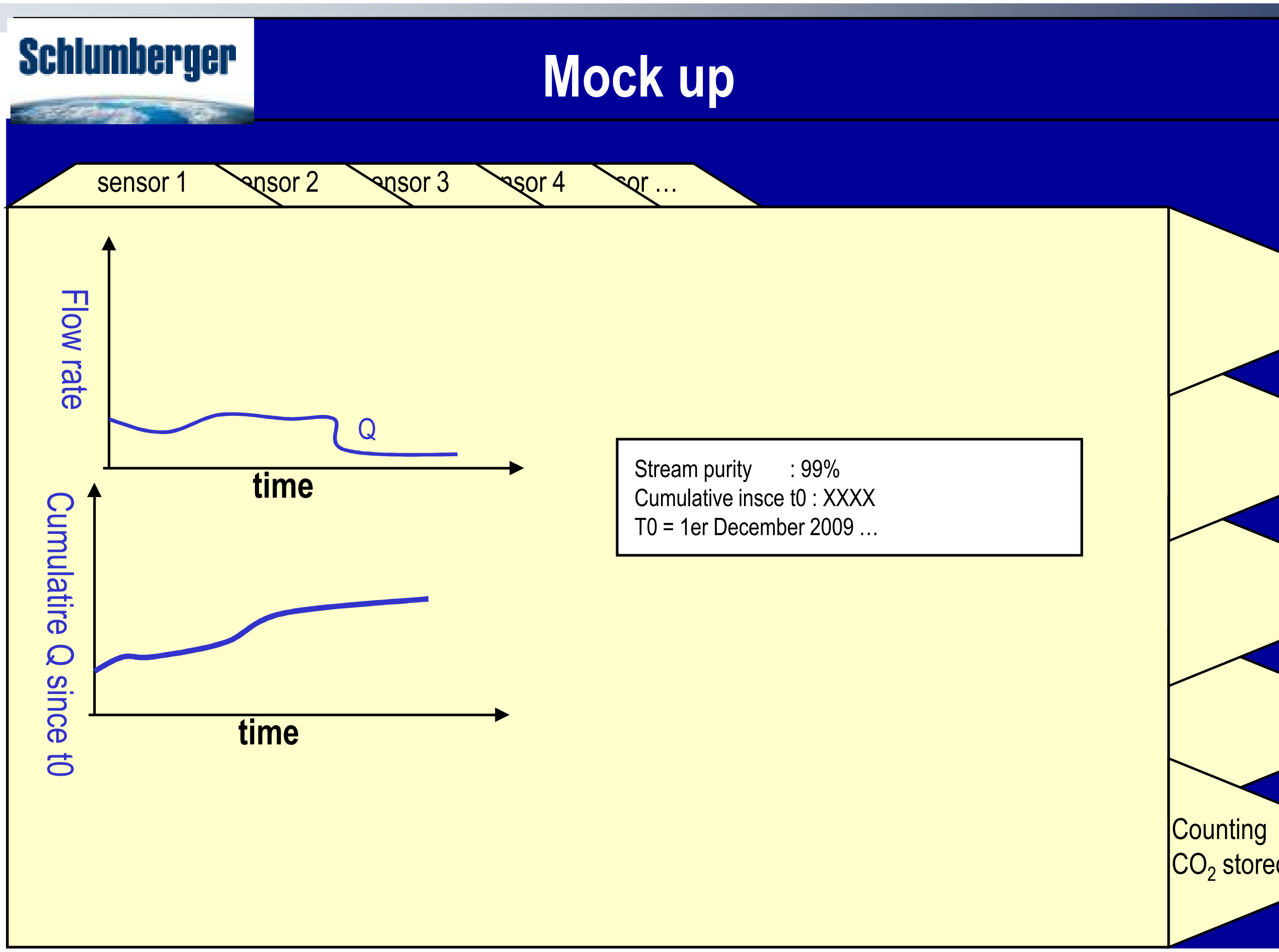
Injection well integrity



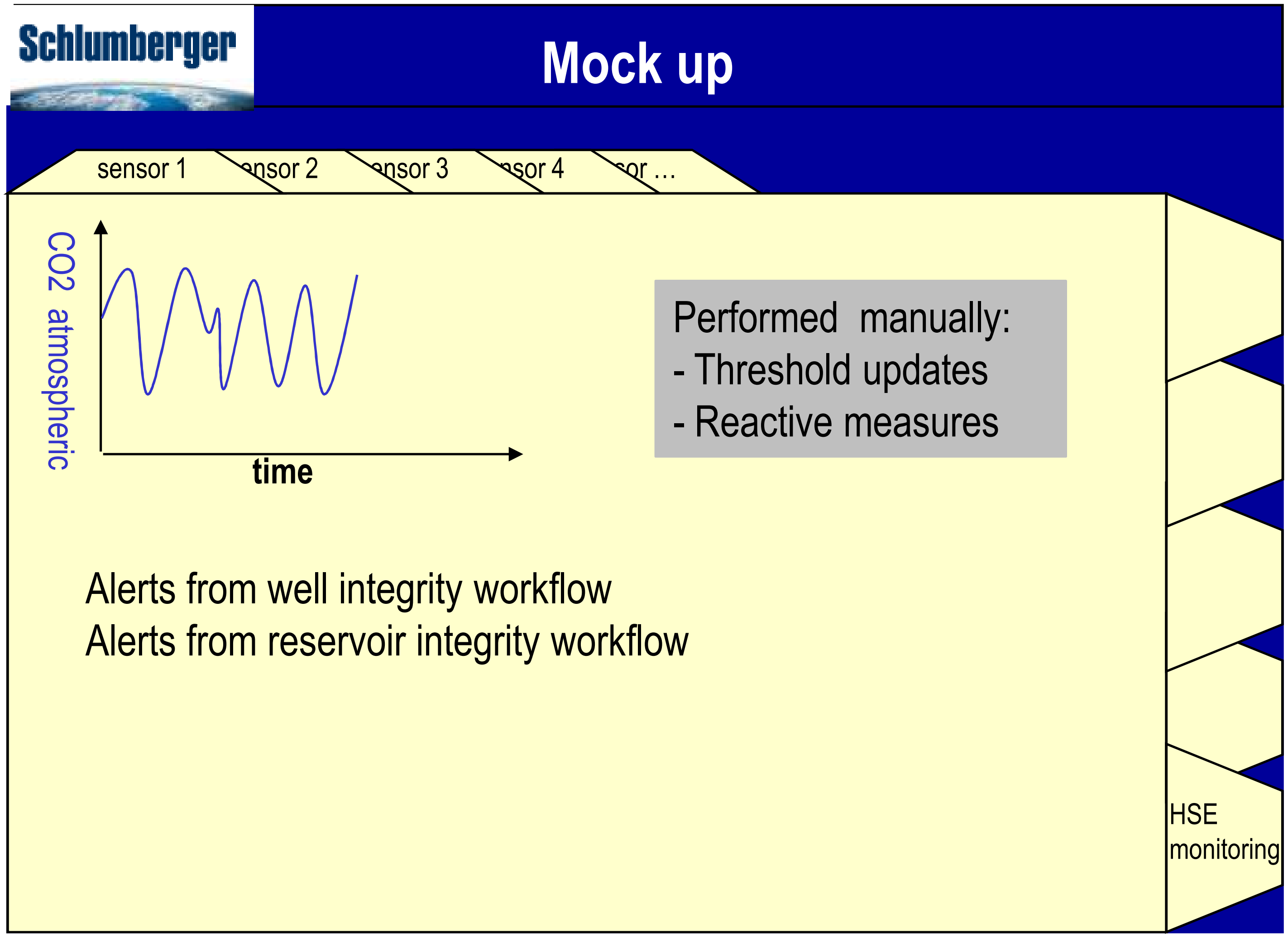
Reservoir Integrity



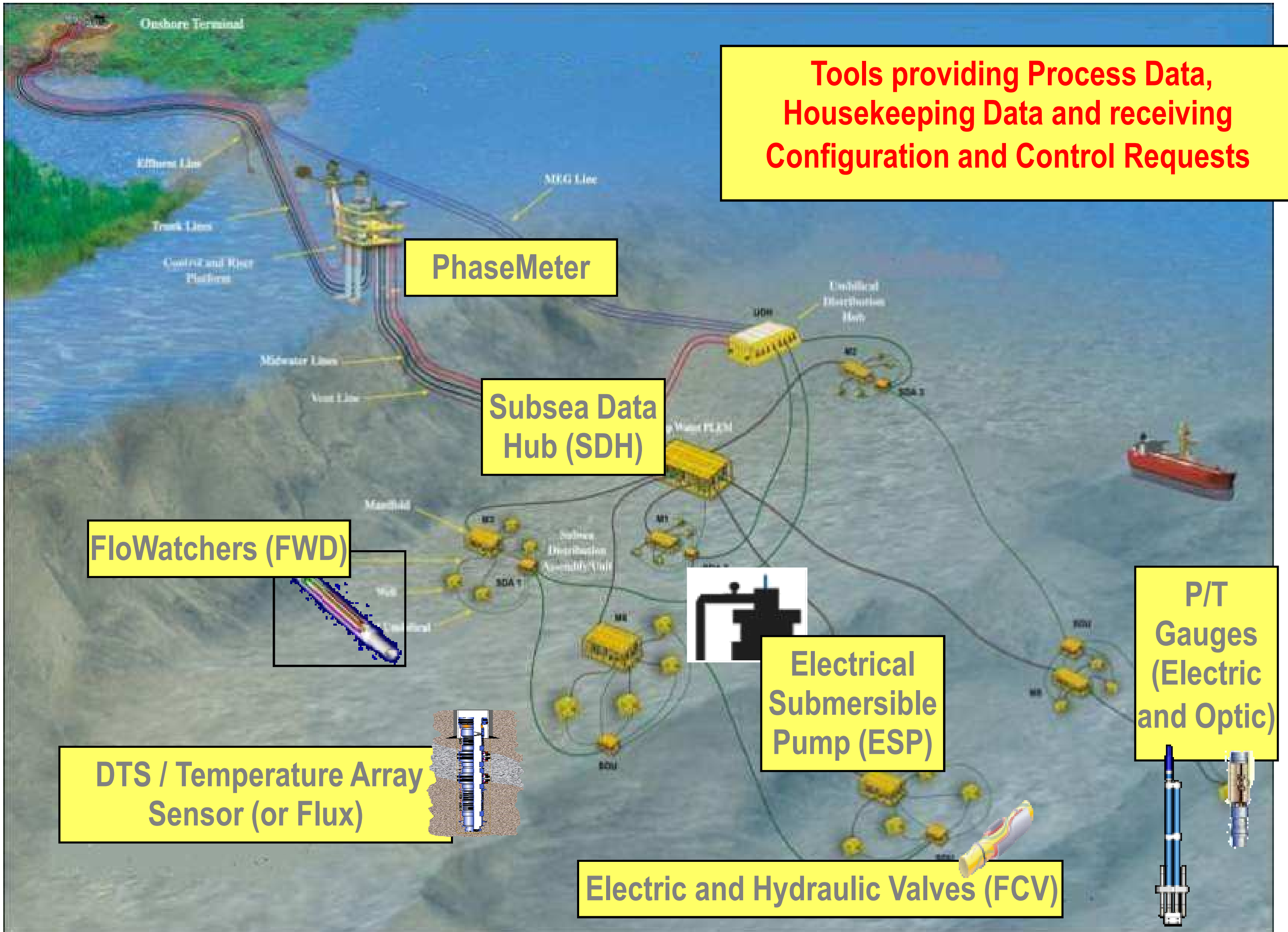
Counting CO_2



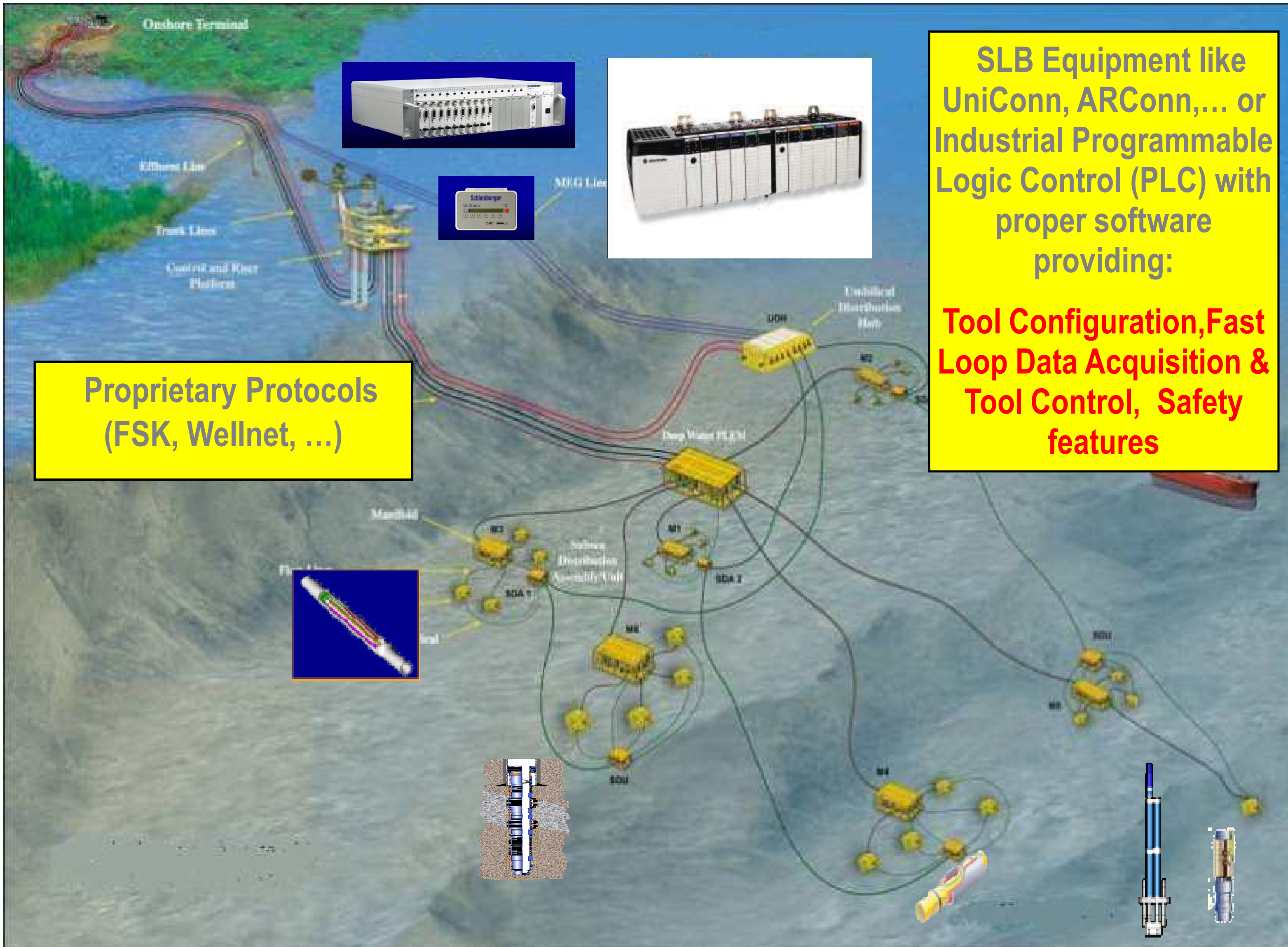
Health, Safety and Environment monitoring



From Tools and Sensors…



… to Remote Terminal Units (RTU)…

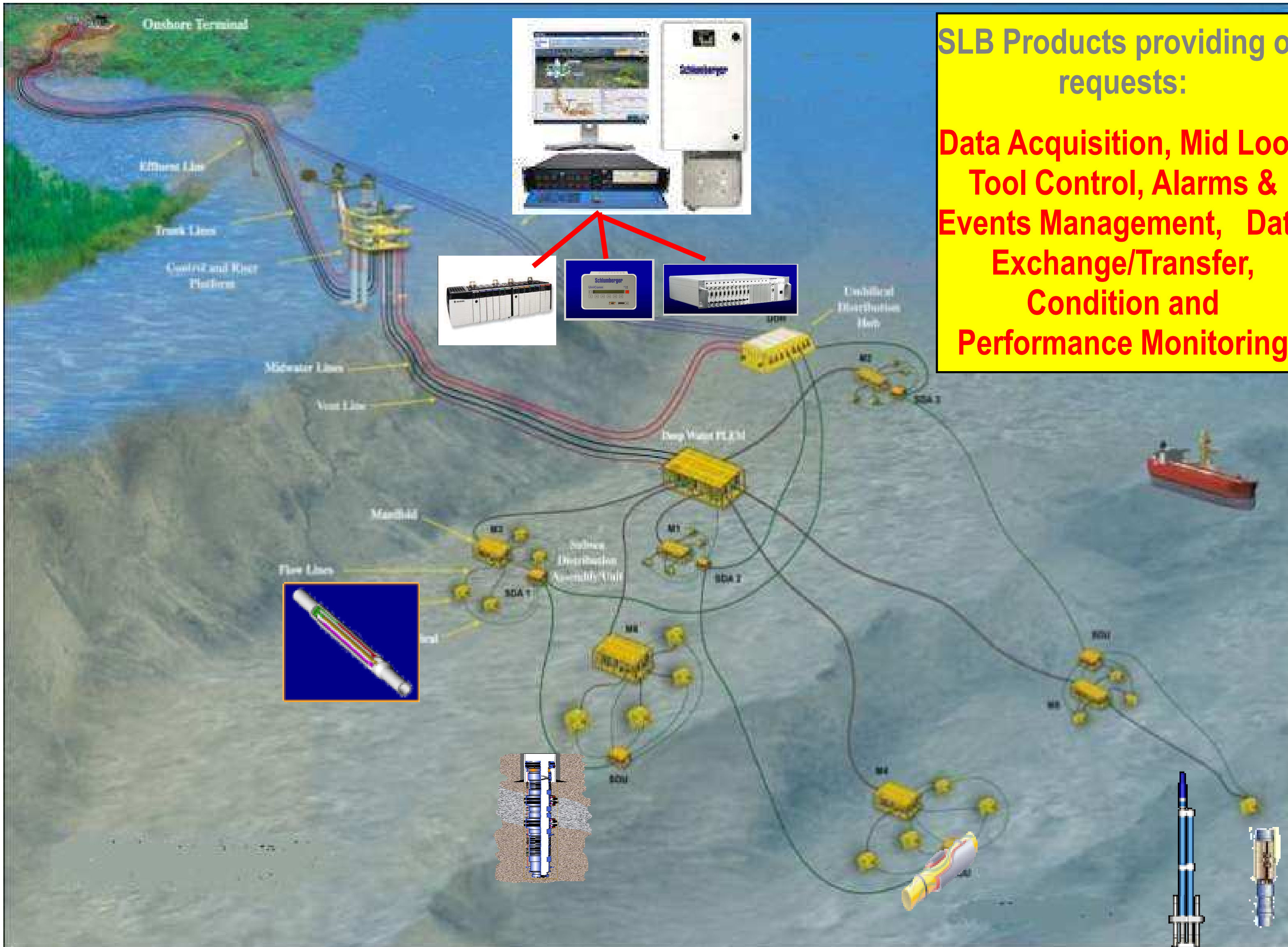


SLB Equipment like UniConn, ARConn,… or Industrial Programmable Logic Control (PLC) with proper software providing:

Tool Configuration,Fast Loop Data Acquisition & Tool Control, Safety features

Proprietary Protocols (FSK, Wellnet, …)

… to Supervisory Control and Data Acquisition Systems…



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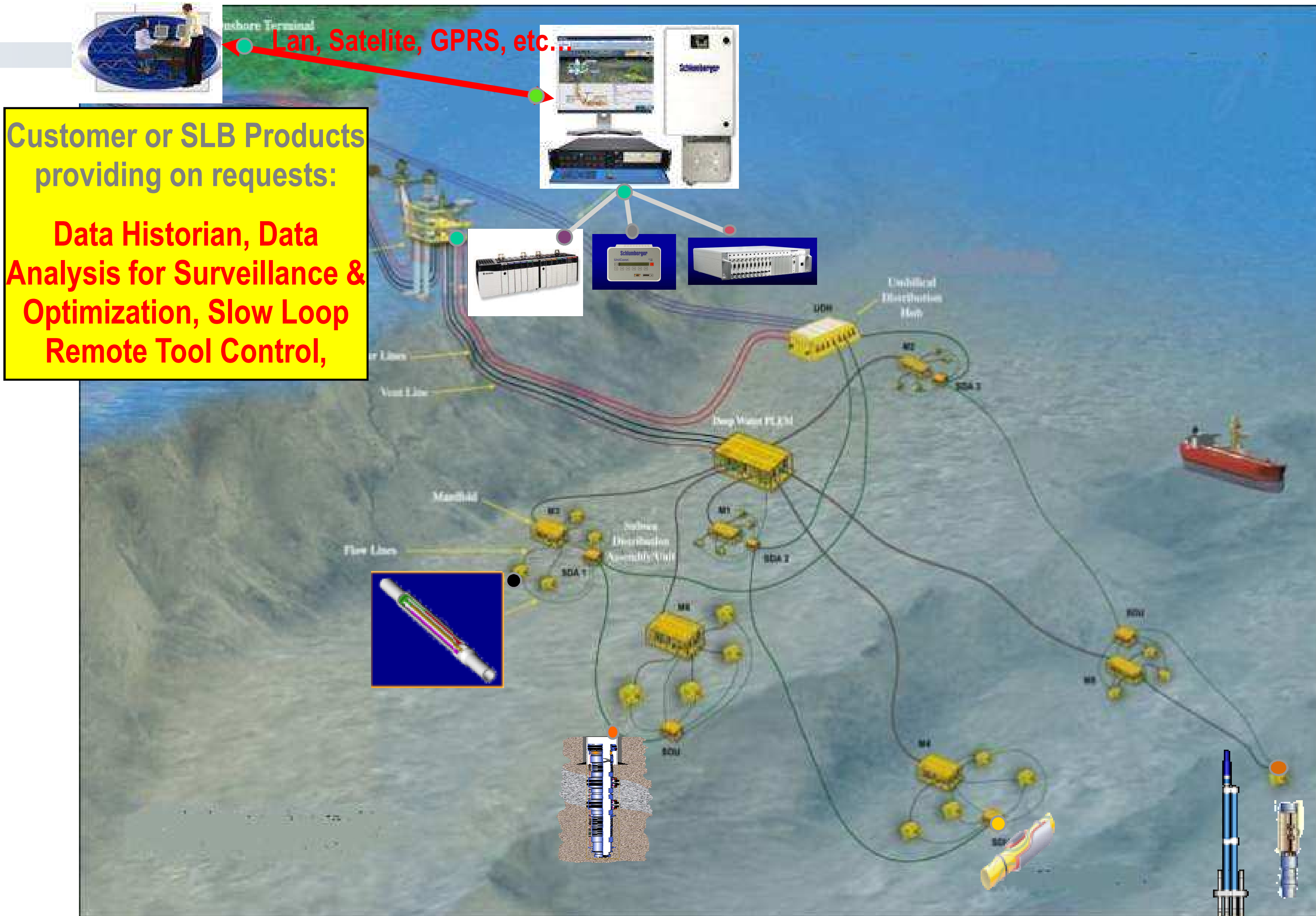
… to Remote Operation Support Centers (OSC)



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Conclusion

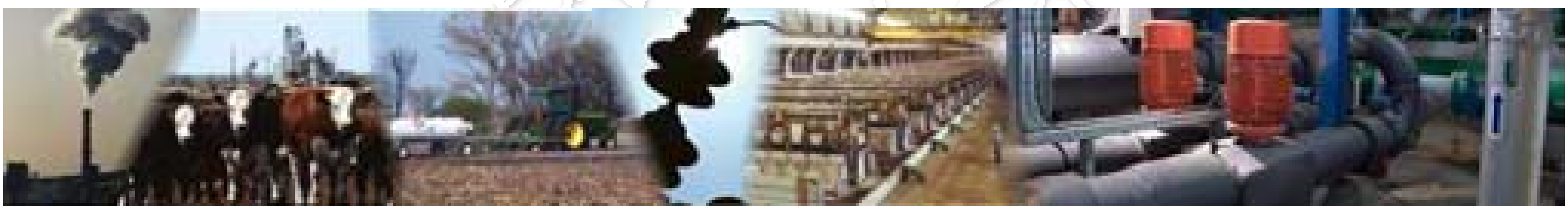
- Real time monitoring allows improving risk management and performance optimization – it is the first step in data integration workflows
- Benefits have already been demonstrated in other industrial processes, including Underground Gas Storage and Oil & Gas production
- The detailed architecture of the overall system and the combination of sensors will be site specific. However, there is common basis on the workflows.
- Real time monitoring implies to identify
  - Fast turn-around time workflows with clear objectives
  - The combination of parameters / measurements to allow a quick diagnostic of "irregularities"
  - Real-time display and appropriate data storage
- Further steps: systematization of some "slow workflow" and interactions between fast and slow loops

IEA Greenhouse Gas R&D Programme

IEA Greenhouse Gas R&D Programme

Conclusions from 5th Monitoring Network Meeting

Tokyo – 2-3 June 2009



Key Learnings

Reports from other initiatives

Reports from Projects

Update on Japanese CCS Progress

What Regulators Want

Reality Check – What can and can't monitoring do

Emerging and Innovative Technologies

Recurring key learnings and other points

Workshop Conclusions and Key Points for other Networks

Learnings from Reports from Other Initiatives

- Using benchmarks
- Understanding fault activation (from EI workshop) leading to leaks
- Understanding leakage through overburden processes – hydroligists and reservoir engineers collaborate
- Natural CO2 analogues not same as leaks from reservoirs (eg leaching)
- Risk and Monitoring Networks together
- Comprehensive coverage of workshops' areas and summaries
- Modelling – coupling effects, basin scale

Learnings from Reports from Projects

- Ketzin
- CO2CRC Otway
- US RCSP

- Get support of stakeholders
- Regulation approval takes longer
- Learning from faults in projects is recommended, proving not leaking, studying fault behaviour in seismic activity
- Natural faults not same as faults associated with reservoirs
- Use literature for man-made release (brine, not CO2)
- Usefulness of these workshops in sharing learnings between regions/countries

Learnings from Japanese CCS

- Integrated multiscale study provides calibration of fluid processes over time
- Gives insight to post injection processes and monitoring – imaging of dissolved CO2 — welcome and encourage to take further, sensitivities, error-bars – appropriate site for this work
- first study providing evidence of stabilisation – providing lots of learning
- Instrumenting injection wells

Learnings from What Do Regulators Want?

- Better understanding now of regulatory requirements
- Qualitative performance targets, not quantitative
- Evidence required at liability transfer?
- Accuracy required of leakage measurement (ETS)
- Pressure front monitoring and hydraulic connectivity at distance – how to monitor?
- Uncertainty over defining acceptable match of predictions and reality
- First regulated projects will set precedence, and larger scale will need more data
- Emphasis on good site characterisation and prediction in advance
- First time hearing on Japanese Marine Pollution Prevention Law

Learnings from….What Can and Can't Monitoring Do

- Example of closing Sleipner to EU CCS Directive – does it satisfy criteria?
- Results from research-intensive pilot-scale projects should inform regulators – commercial scale projects won't monitor to the same level
- Monitoring can be good enough to get on with projects in a regulatory- and caveated- sense
- What do we need to quantity? Eg not plume in situ
- Measurement of dissolved CO2
- Reliance on expert opinions – who? – well recorded and transparent judgements
- Atmospheric monitoring can provide assurance – challenges to prove/determine sensitivities of different techniques
- Soil/water – fit for purpose measurements only
- Coupling surface behaviour with subsurface behaviour

Learnings from Emerging Technologies

- Satellite monitoring success
- Satellite data - anyone can buy data and use or mis-use (also for other monitoring data) – develop standards for interpretation
- Coupling surface behaviour with subsurface behaviour
- Real-time and integrated monitoring has value (cost efficient, safety)
- Gravity measurements may have a role for gaseous and dissolved CO2

Recurring Learnings and Points

- "Innocent until proven guilty" (zero leakage assumption until monitoring indicates otherwise) (EU, not necessarily)
- Study faults (more)
- Close to inj wells, monitoring geochemistry processes in-situ
- Use pilot-scale projects to focus and learn on post-injection behaviour
- Multi-scale integration of multiple datasets, eg combining seismic and electrical resistivity
- Regulator requirements may differ for small-scale from large-scale

Conclusions (draft)

- Recommendation to use pilot-scale projects to focus and learn on post-injection CO2 behaviour, as at Nagaoka
- Benefits of multi-scale integration of multiple datasets, eg combining seismic and electrical resistivity
- Regulations are based more on qualitative performance than quantitative, and need expert opinion to make decisions
- More work needed to understand faults and overburden leakage pathways.
- Uncertainty over defining acceptable match of predictions and reality of CO2 behaviour, first regulated projects will set precedence.
- Pressure front monitoring will be required.
- Atmospheric monitoring can provide assurance for public
- Monitoring can be good enough to get on with projects

IEA Greenhouse Gas R&D Programme

5th Monitoring Network Meeting

Hosts : RITE, JAPEX, AIST, Kyoto University

Tokyo – 2-3 June 2009

- Presentations will go onto Network's web page
- Report will be produced
- Next Monitoring Network meeting

Sponsors

Japan Petroleum Exploration Co., Ltd. (JAPEX)

Japan CCS Co. Ltd. (JCCS)

INPEX Co.

Schlumberger Japan

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- Ziqui Xue, Kyoto Univ.

- Shin'ich Terada, RITE
- Eiji Hayashi, RITE
- Kimiko Nakanishi, RITE
- Hironobu Komaki, RITE
- Shigeo Murai, RITE
-

- Fumio Hara, ENAA
- Akihisa Takahashi, JAPEX
- Shiro Okawa, JCCS
- Masanori Abe, JCCS
- Tadashi Horie, INPEX

- Osamu Nishizawa, AIST
- Toshiyuki Tosha, AIST

International Steering Committee for 5th Monitoring Meeting

- Tim Dixon – IEA GHG
- Ziqiu Xue – Kyoto University
- Toshiyuki Tosha - AIST
- Kevin Dodds - BP
- Hubert Fabriol - BRGM
- Lee Spangler – Montana State University
- Don White - NRCan
- Charles Jenkins – CO2CRC
- Andy Chadwick - BGS
- Susan Hovorka – University of Texas
- Rick Chalaturnyk – University of Alberta
- John Kaldi – CO2CRC
- Brendan Beck – IEA GHG

Sarah Hannis - BGS

IEA Greenhouse Gas R&D Programme

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5th Monitoring Network Meeting

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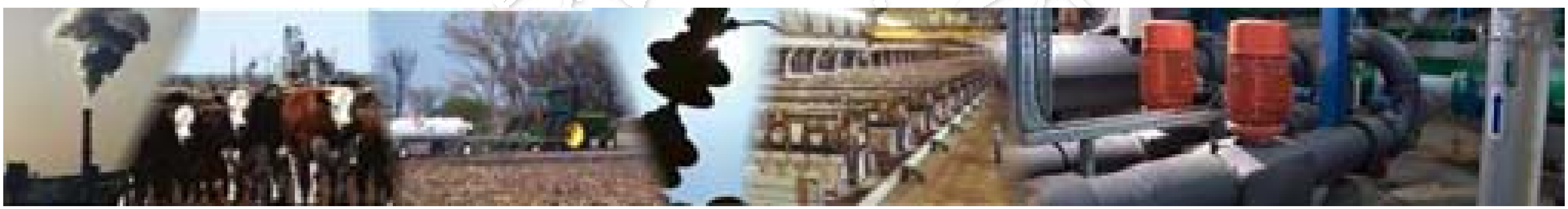

INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

The IEA Greenhouse Gas R&D Programme supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by the IEA Greenhouse Gas R&D Programme as a record of the events of that workshop.

The fifth international research network on monitoring was organised by IEA Greenhouse Gas R&D Programme in co-operation with JAPEX, AIST, RITE and University of Kyoto. The organisers acknowledge the financial support provided by Japan Petroleum Exploration Co., Ltd. (JAPEX), Japan CCS Co. Ltd. (JCCS), INPEX Co., Schlumberger Japan, Geophysical Surveying Co., Ltd., JGI Inc., CHIYODA Co., SUNCOH Consultants Co., Kawasaki Geological Engineering Co., Arabia Oil Co., Ltd., TOYO Engineering Co., DIA Consultants Co., NIPPON Steel Engineering Co. Ltd., OYO Co., SK Engineering Co., JGC Co., Halliburton Overseas Limited, Battelle Japan, and JFE Engineering Co. for this meeting. The organisers would also like to thank Sarah Hannis of the British Geological Survey for the preparation of the report.

A steering committee has been formed to guide the direction of this network. The steering committee members for this network are:

Kevin Dodds, BP
Rick Chalaturnyk, University of Alberta
Hubert Fabriol, BRGM
Lee Spangler, Montana University
Don White, NRCan
Susan Hovorka, University of Texas
John Kaldi, CO2CRC
Andy Chadwick, British Geological Survey
Ziqiu Xue, University of Kyoto
Charles Jenkins, CO2CRC
Toshi Tosha, AIST
Neil Wildgust, IEA Greenhouse Gas R&D Programme
Tim Dixon, IEA Greenhouse Gas R&D Programme

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "5th Meeting of the Monitoring Network, 2009/11, August 2009".

Further information on the network activities or copies of the report can be obtained by contacting the IEA GHG Programme at:

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E-mail: mail@ieaghg.org
www.ieagreen.org.uk

Summary Report of 5th Monitoring Network Meeting

Date: 2 – 4 June 2009
JAPEX HQ, 12F Sapia Tower, Tokyo, Japan

Organised by IEA GHG, University of Kyoto, JAPEX, RITE and AIST

With the sponsorship of:
Japan Petroleum Exploration Co., Ltd. (JAPEX), Japan CCS Co. Ltd. (JCCS), INPEX Co., Schlumberger Japan, Geophysical Surveying Co., Ltd., JGI Inc., CHIYODA Co., SUNCOH Consultants Co., Kawasaki Geological Engineering Co., Arabia Oil Co., Ltd., TOYO Engineering Co., DIA Consultants Co., NIPPON Steel Engineering Co. Ltd., OYO Co., SK Engineering Co., JGC Co., Halliburton Overseas Limited, Battelle Japan, JFE Engineering Co.

FIFTH WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON MONITORING

Executive Summary

This was the 5th meeting of the IEA Greenhouse Gas R&D Programme (IEA GHG) Monitoring Network. Since the inception of the Monitoring Network a significant amount of work has been done in this field. There are now a great number of very elaborate Carbon Capture and Storage (CCS) demonstration projects occurring worldwide with each one developing and testing new monitoring techniques. While this is happening there is also a great drive from many Governments to put in place the regulations needed to properly licence and supervise CCS activities. This meeting hoped to review where we are with both aspects of CCS and identify what questions still need to be answered.

The main outcomes of the meeting were:

1 A review of various CCS demonstration projects around the world, with a focus on Japanese projects and plans. Some of the monitoring techniques reported on demonstrated new examples of how plume observations are matching predictions and also an example of the first imaging of CO_2 dissolving in the reservoir. These examples add to our knowledge and evidence base of successful monitoring. Together with assurance monitoring and continued public communication, these will help gain, improve and maintain public and regulator confidence in CCS. This is important for all projects at all scales. It was agreed that the continued sharing of knowledge and technology transfer between current projects, operators and countries is very useful and should be encouraged.

2 An analysis of CCS monitoring and the requirements from regulations in different countries. Regulations are developing, driven by the Directive on CO_2 Storage and Emissions Trading Scheme (ETS) requirements in Europe, and mainly evolving in parallel with pilot projects elsewhere. Regulations require different levels of requirements and are all generally non-prescriptive regarding monitoring. This allows projects the flexibility to develop and 'learn by doing'. The ability of current monitoring techniques to perform the tasks required by regulation was also addressed. It was concluded that in general, available methods can be fit for purpose for projects to proceed. Many of the recurring questions regarding closure of sites were thought likely to be determined by the approach of the first few projects to go through the process and that these will set the precedent.

3 New and emerging technologies were discussed including INSAR surface deformation data from In Salah and also the behind-casing installation for crosshole electrical resistivity tomography (ERT) measurements at Ketzin. The role and relative merits of integrated technologies for real time monitoring and controlling multiple storage injection sites was also discussed. This type of system may be useful for integrating multiple datasets at multiple scales.

The increasing reliance on expert opinions for both the permitting process and most likely at the hand over stage also was emphasised. Finding independent experts may be an issue and because of the time scale of CCS projects, it was noted that any decisions made need to be transparent and documented for future generations.

As well as continuing to work on some of the unresolved issues from previous meetings, a number of questions and possible research gaps were identified throughout the course of the meeting that will need to be addressed in the future. These include:

- The transmissivity of faults to CO_2 in different phases
- Coupling the subsurface to the surface: transport of CO_2 through overburden
- The importance of expressing uncertainty
- Basin scale models and linking them to the smaller scale site specific models
- What are the likely requirements for transfer of liability and closure?
- Models will never exactly match observations, so how good is good enough?
- How can we define the edge of the plume in terms of pressure and hydraulically linked units and what happens if neighbouring sites interact?
- How do we quantify CO_2 in the various parts of the system, including the deeper subsurface?

Contents

i. Introduction

This is the report from the 5th IEA Greenhouse Gas R&D Programme (IEA GHG) Monitoring Network Meeting held in the Tokyo, Japan on the 2nd – 4th June 2009.

The monitoring of CO_2 injected into geological formations is a topic of great interest and importance. As CO_2 capture and storage (CCS) becomes more widely implemented regulatory bodies will require that detailed monitoring programmes are put in place to ensure that the health and safety of both operating staff and the general public are assured. In addition, if organisations wish to gain credits for the CO_2 that is injected, monitoring of the injected CO_2 will be necessary to ensure that emission reduction credits can be validated and any leakage accounted for both in the credit awards and in national inventories.

A significant amount of work has been done in this field since the inception of the Monitoring Network. There are now a great number of very elaborate CCS demonstration projects occurring worldwide with each one developing and testing new monitoring techniques. There is also a great drive from many Governments to put in place the regulations needed to properly licence and supervise CCS activities. This 5th Monitoring Network meeting reviewed both the current status of CCS monitoring techniques and updates in regulation occurring worldwide. This report provides a summary of this meeting which was held in the JAPEX headquarters, organised jointly by the IEA Greenhouse Gas R&D Programme, University of Kyoto, AIST and JAPEX.

Aims and Objectives

The overall aims of the network are to facilitate the exchange of ideas and experiences between experts in the monitoring of CO_2 storage projects, and to promote the improved design and implementation of monitoring programmes that will support CCS projects. Specific aims and objectives of the network have evolved during successive meetings, but can be summarised as follows:

- To assess new technologies and techniques as they become available;
- Determine the limitations, accuracy and applicability of monitoring techniques;
- Disseminate information from research and pilot storage projects around the world;
- Develop extensive monitoring guidelines for the different sub-categories of geological storage; oil and gas fields, unminable coal seams, and saline aquifers, covering the differing conditions and reservoir properties encountered globally;
- Engage with relevant regulatory bodies.

ii. Delegates

The meeting was attended by over 90 delegates. The delegates represented geological researchers, international industrial operators and regulators from Japan, Europe, North America and Australia.

iii. Programme structure

The meeting was divided into a series of sessions which focussed on specific topics within the area of monitoring and verification. Presentations were given, followed by questions, with opportunities for discussion at the end of each session.

Welcome and Introduction
Session 1 Reports from other initiatives.
Session 2 Reports from projects.
Session 3 Update on Japan CCS progress.
Session 4 What regulators want.
Session 5 Reality Check: What monitoring can and can't do...
Session 6 Emerging and innovative monitoring technologies.
Conclusions and key learnings.

Following the meeting, a field visit was organised for the 4th June 2009 to the CO_2 capture plant of INPEX and the Nagaoka CO_2 injection site.

iv. Introductory session

Introduction to the meeting

Delegates were welcomed to the meeting by Toshi Matsuoka; Kyoto University and Prof. Yoichi Kaya; RITE and Tim Dixon; IEA GHG. Special thanks were given to the sponsors, JAPEX in particular for providing the venue. Tim Dixon introduced the IEA GHG and the Monitoring Network. He explained the purpose of this meeting and outlined the two-day agenda.

Questions and comments:

How are the networks set up and how are they financed? There is no formal membership, anyone can attend, even from non-member countries. Usually delegates have either a professional or technical background. There is no specific budget. IEA GHG run them to get international experts together to share their knowledge. The networks are needs driven, so please send any ideas for new networks to Tim Dixon or Neil Wildgust. If there is not sufficient interest for a full network, a one-off workshop could be arranged, such as the Environmental Impacts Workshop, held in September 2008.

Report from the 4th Monitoring Network Meeting: Don White; NRCan

A review of the previous Monitoring Network meeting held in Edmonton Canada. This meeting focussed on the progress of monitoring and regulation (day 1), the review and updates of several CCS projects (day 2 and day 3) with a field visit to Penn West and Joffre CO_2 EOR sites (day 4). Some of the recurring questions from this meeting were highlighted during the presentation. A draft version of the report is available for download from:
www.co2captureandstorage.info/networks/monitoring4.html

Questions and comments:
Have we moved further in the monitoring and regulatory framework since the last meeting? Yes, monitoring is progressing gradually and the regulation is starting to mature. Studies are underway in the monitoring area to assess capability techniques for quantification of leakage. These are driven by the impacts of the Emissions Trading Scheme (ETS) in Europe. Questions from previous meetings are still valid and developing. Gaps identified by this 5th meeting can be used to justify seeking funding.

The presentation mentions acid gas. Are there any common technical issues relating to acid gas injection, what are the specifics and how do they relate to CO_2 monitoring? In Canada, toxic gases produced (e.g. H_2S) were previously flared or stripped, however recently they are being re-injected into the subsurface. Current regulations allow this under certain conditions and not much monitoring is required by the regulators.

Report from the 1st Joint Network Meeting and 1st Modelling workshop: Neil Wildgust; IEA GHG

The first Joint Network meeting was held in June 2008, at the US Environmental Protection Agency in New York, USA. This involved the Risk Assessment, Wellbore Integrity and Monitoring Networks. The aim was to identify technical, operational or network gaps and identify which network might be the most appropriate to follow up and focus on those issues in the future.

The first Modelling Network Workshop was held in February 2009, at BRGM in Orleans, France. Discussions focused around current status of modelling, sharing information and identifying knowledge gaps. As a result of this meeting it was decided to initiate a Modelling Network which would feed into the 'over-arching' Risk Assessment Network. The first meeting will be in 2010 in Utah, USA.
The 5th Wellbore Integrity Meeting, was held in May, hosted by ARC and Theresa Watson in Calgary, Canada. The EOR industry brought a new perspective on CCS.

Questions and comments:
The interaction between networks is encouraging. Documentation on the website (online discussion forum) sounds like a good way of moving things forward. In terms

of particular aspects or techniques, what is different about CO_2 compared to the other modelling applications?
Specialised models generally arrive at similar conclusions. The models are generally good (many years of research have gone into the theories and concepts) but input data is uncertain. Good quality input data from real sites where CO_2 storage is occurring is now required in order to calibrate the models. For example, modellers are struggling with realistic values for relative permeability.

Differences between hydrocarbon models compared to CCS models include a) the spatial scale (e.g. a CO_2 plume is likely to be on a kilometre scale and the pressure footprint may be tens of kilometres) and also b) the temporal scale. CCS is modelling very long time scales (hundreds to thousands of years). There is a need to develop simulators that can accurately predict how CO_2 reacts with water over these time periods. (Ideally CO_2 reacts in water, dissolves and loses its buoyancy).

Note that a large proportion of potential CO_2 storage capacity is in deep saline aquifers, which is very different from EOR sites.

There is a need for basin scale models. Currently models are on a site-scale basis. But as sites increase in size and number, it is likely that adjacent sites may have an overlap or interaction between either the plume or the pressure footprint. This overlap in the pressure footprint has resulted in an 80% estimated storage capacity reduction in the Netherlands. How should we deal with pressurisation in saline aquifers? An IEA study is being commissioned as a basin-scale assessment on the implication of several large storage sites.

Two scales or types of models are needed: the process-models which couple all effects (geomechanical, chemical and thermal processes etc) into one model, and the basin-scale, CO_2 movement or pressure footprint models. There was much discussion surrounding the distinction between these at the Modelling Workshop (Feb 2009).

What do the regulators have to say about the pressure front moving ahead of the plume? For example, what happens if the pressure goes outside the licensed area? This is recognised as a significant issue, but no conclusions were reached at the meeting, despite regulators being present. Perhaps the Risk Assessment network, which is more over arching would be more appropriate to instigate contact with the regulators on this point.

What is envisaged for the benchmark studies mentioned? 1) work by the University of Stuttgart into software codes. IEA GHG may set up a link to their website. 2) Lawrence Berkeley National Laboratory is working on a model comparison exercise with the aim of using data from real sites from the US Regional Carbon Storage Partnerships (US RCSP) (Anyone wishing to get involved should contact them). 3) The IEA GHG modelling network may set up a benchmarking study (if recommended by the network following their next meeting and commissioned by IEA GHG).

Would geophysics and seismic output fall under the Monitoring or Modelling Networks? Seismic belongs in the monitoring area, because it is used to assess capability techniques. It may be appropriate to have a back to back meeting between the two networks, so an overlap day can be planned.

1. Reports from Other Initiatives, Chair: Charles Jenkins; CO2CRC

1.1. Report from the Environmental Impacts Workshop: Lee Spangler; Montana State University

A summary of the content and results from the Environmental Impacts Workshop held in September 2008 at BGS, Nottingham, UK. Research was reviewed on terrestrial and marine leakage sites at natural analogue sites (Latera and Panarea, Italy and Laacher See, Germany) and controlled release sites (ASGARD, UK and ZERT, USA). Outcomes on regulatory, public and research needs were also outlined.

Questions and comments:
What perturbations did you expect when modelling the ecosystems at ZERT? There are so many effects, did this help or confuse issues? At ZERT what was modelled was: a) Transport mechanisms and b) flux or concentration differences along the scaled 'fault'. For example, both at controlled release and natural analogue sites microbial communities have a rapid response to concentration changes.

Japan plan to inject CO_2 under the sea. In the photo showing the bubbles of natural CO_2 released from the sea floor how much CO_2 was leaking? The full presentation and report from the meeting will be imminently available. The advantage of subsea natural analogues is that the bubbles make the leakage sites much easier to detect compared to diffuse terrestrial releases. The next study and series of workshops by the IEA are likely to focus on quantification of leakage of CO_2. It is likely that one will focus specifically on natural analogue sites (and controlled release sites).

1.2. Report from the Risk Assessment Network: Tim Dixon; IEA GHG

The 4th Risk Assessment Network meeting was held in April 2009, hosted by CO2CRC, in Melbourne, Australia. The report is still being drafted. The network decided to continue to focus specifically on technical subsurface risks, rather than expand to include economic and political risks.
CO_2 storage groundwater impacts were usefully put in perspective in the context of other human activities such as hydrocarbon and drinking water extraction (and the associated brine / non-brine interactions). For example, in the Great Artesian Basin, Queensland, Australia, man-made water extraction has decreased the water table by around 100 m. There is a possibility of re-pressurising the formation by injecting CO_2 beneath it.

No questions.

1.3. Report from CO2REMOVE: Andy Chadwick; BGS

Results from ongoing research based on real CO_2 injection sites were presented, with the focus on the 'Interpretation and monitoring tools' part of the project (SP 3). A range of sites, both terrestrial and marine, ranging from 900 m to 2900 m in depth, with injection amounts from 0.1 Mt/yr (pilot scale) to 1 Mt/yr (industrial scale) projects were examined. A variety of monitoring programmes are being used. Some of the problems with existing tools were highlighted (for example, the point-based sampling nature of some techniques may allow anomalies between point to potentially go unnoticed) in addition to new developing techniques including sea floor stations etc.

Questions and comments:
What are the ecosystem monitoring techniques for sea bed bio-indicators? In the North Sea, on the sea bed above Sleipner, Bergen University and Statoil sampled representative communities. These were taken to a laboratory and tested for sensitivity to CO_2 fluxes and concentrations with the aim of using results to identify indicators of potential CO_2 leakage on sea bed ecosystems.

What techniques are used for distinguishing a small scale signal arising from geologically stored CO_2 from the vast amounts of atmospheric and surface ecosystems sourced CO_2? Carbon isotopes are generally used. Different sources of CO_2 have different isotopic signatures which allow them to be distinguished from one another. Other gases are also monitored for, for example, the presence of radon or helium may also give an indication of deep conduits.

What sampling strategy is used for atmospheric monitoring for leaking CO_2? (Is it grab samples, analysed in a laboratory, or is it monitored in situ?) The general strategy is aerial sampling for elevated CO_2 flux. This will identify any elevated areas. The samples are subsequently characterised in a laboratory.

Are the instruments sufficiently sensitive to be able to give an 'early warning' system, or is a high flow required for detection? A challenging problem, to which the answer is probably: yes. *A follow on question is: how much flow do we need to be able to detect? Any flow at all, or enough flow to create an effect?*

1.4. Report from Otway, Sandeep Sharma: CO2CRC

A review of the Otway Basin pilot CCS project south west of Melbourne, Australia. To date 53 kt of CO_2 have been injected into a depleted gas field, sourced from a nearby natural CO_2 field. The regulatory regime was defined at the project initiation stage and has been adapted and developed along with the project. The project is currently at the stage where if anything is not proceeding as predicted, the regulators must be informed. Assurance monitoring is being carried out at surface, with storage integrity monitoring of the subsurface. A future opportunity has arisen to inject CO_2 into the saline aquifer above the current reservoir. The huff and puff method has also been applied.

Questions and comments:
Did you detect the EGR effect at the Naylor 1 well by injecting? Changes in the gas-water contact (GWC) were detected in the monitoring well. It was modelled that the CO_2 plume would move through the reservoir and occupy the space previously occupied by the methane (CH_4). However the exact amount of CH_4 released is not known. Integrated models predicted the plume arrival in the 4 – 8 months range. This model could be improved with an increased understanding of the heterogeneities.

How successful was the vertical seismic profile (VSP)? 24 sensors were placed in the well, with several below the reservoir, 3 multi-component geophones above the reservoir and shallow sensors for the offset VSP. The technique was hampered because the injected CO_2 only created a 3 – 4 % change in acoustic impedance. The microseismics and deep sensors were insufficiently sensitive. The offset VSP data is still being analysed.

Has the huff and puff method been written up? The approach, model assumptions and results have been documented for the project. Lincoln Patterson can forward the information.

What were the details of the 3D seismic programme? A 3D seismic survey was carried out pre-injection in December 2007. The next survey was conducted in January 2009 after 32 kt of CO_2 had been injected. The 4D analysis is in progress. At the end of the project it is anticipated that a further survey will be conducted, either as a full 3D dataset, or as 2D lines combined with a surface VSP survey.

The residual saturation tool (RST) was run at the Nagoaka site, but there were some difficulties. How and how often did you monitor the residual saturation? There is a limited capacity to log in the Naylor 1 as it is filled with completion gear. It is possible to log in the CRC well, however it would require filling the well with water which could contaminate the results. The RST tool was run in open hole and cased hole and estimated residual saturations were based on that.

Were any high resolution travel times measurements made during the huff and puff test? This would be a great opportunity to measure seismic velocity changes and get first insights into whether CO_2 was mixing patchily or uniformly at the reservoir scale. Discussed during break.

1.5. Discussion Session 1, Chair: Charles Jenkins

What amounts of CO_2 leakage are detectable at the surface? At the US controlled release site (ZERT, Montana) the release rate is 0.3 t/day of CO_2 (equivalent to 4 cars idling). The CO_2 is released from a 70 m pipe, scaled down from a 1 km long fault leaking 2 % of the stored CO_2 over 1000 years from a storage scenario where 4 Mt was emplaced over 50 years. Plant stress was monitored using hyperspectral imaging and this level of flux was easily detectable. A lower (0.1 t/day, i.e. below the IPCC figure) or more distributed flux was also detectable, but depended on looking in the right place.

There is an important distinction between tolerable standards (impact on assets) and leakage detection.

Surface detection has two purposes, 1) health and environmental impact monitoring for public assurance and 2) for storage verification. (The ZERT site is mainly contributing to the former).

If we know where the leak is, we can detect and quantify it with high precision. The problem is in locating potential leaks, especially with point source type monitoring. Many storage sites cover large areas and are often remote. Access frequency could be a practical limitation. It is likely that larger scale monitoring can help us target likely areas.

There is a lack of clarity between the research setting (solving the basic sensitivity, capability, process issues of monitoring tools) and commercial settings (how these tools can be realistically be deployed). We need to be clear what our aims are and distinguish between what is *necessary* and what is *possible* to achieve.

Given the urgency of climate change we need to view CCS as “innocent until proven guilty”.

Injecting CO_2 into the ground is constrained by the regulatory environment. It needs to be confined, but if it leaks, it needs to be below a certain limit. The problem is that if leaks are allowable, it means people may expect some coming out of the ground. What does a surface leak of 0.3 t represent in terms of rate of discharge from deeper levels? The 0.3 t represents the rate coming out rather than the actual amount. We need to understand leakage mechanisms through the overburden to the surface (e.g. by modelling). So far is patchily coming out at surface. Hyperspectral and other airborne studies cover large areas.

We also need to be aware of looking too hard for problems. There are significant emissions from natural sites, which are not a significant health risk. We are doing research into the sensitivity of the system. It depends on whether the problem relates to HSE impacts or to whether storage performance as it relates to climate change mitigation. Leakage into ecosystems has to be relatively high to be observable. *If leakage is that high, is it negating mitigation in terms of greenhouse gas emissions?*

Once we are detecting CO_2 at surface, is that too late to do anything? There will be a time delay from injection to CO_2 arriving at the surface. If we are able to catch leakage deeper, as close to injection time and location as possible, it may be possible to change the injection strategy accordingly.

We should be wary of using natural analogues for monitoring groundwater effects as it is likely any metals mobilised would have already been leached out some time ago. Not all analogues are completely natural. At crystal geyser, a well was drilled through a CO_2 bearing formation, so that site has existed for decades rather than millennia.

How can we find out more about the transport mechanisms at this (and other) natural analogues? (What monitoring tools can we use?)

The rate of leakage is at natural analogues is relevant, but we don't have any baseline data.

We need to know more about CO_2 transport and what phase it is moving in (dissolved, or two phase, etc) from the storage site up to surface.

Studying the transport mechanisms at Otway were a challenge. This would require looking at and characterising the overburden which is order of magnitude greater in terms of cubic kilometres of rock compared to the reservoir itself. The required time and effort required to do this is simply not economic.

At the Risk Workshop insurance industry representatives claim they have sufficient information to be able to price storage insurance, but they were unwilling to share how exactly this will be calculated, because of commercial sensitivity.

Early ground water pollution test sites were conducted on military establishments (although a lot of these were already polluted). At the natural analogues sites there is the opportunity to monitor discharge sites in detail. However, to date there has not been many studies on brine intrusion. Are there any studies of any natural analogues for brine intrusion? There are man-made analogues in the North Sea oilfield where produced water (brine) is often disposed of in seawater or injected into shallower, lower salinity formations. A recent problem occurred 300 km north west of Sleipner, where produced water was injected into a shallow clay formation which fractured, resulting in the release of brine at the sea bed and caused an oily slick on the sea surface and 40 m pock mark on the sea bed.

There should be much literature on this type of man-made, introduced salinisation in oilfields causing environmental damage if we know where to look. (e.g. Texas Railroad Commission records). We may be able to use these as useful analogues.

Otway is in a fault bounded block. Have you addressed any issues regarding CO_2 transport along faults? This is viewed as a scientific research opportunity by some, but as a potential problem by others.

If a fault was present where CO_2 was being injected, what would you monitor? How could the transmissivity of the fault be tested?

If wells are present you could monitor fluid communication between/up faults.

Were any simulations of CO_2 leakage through faults conducted at Otway? Was this explained to the community for acceptance, or was it purely an academic study?

This was required by the regulators in order to show the project would not impact other beneficial users e.g. of the aquifer. The two pressure bounding faults were modelled for potential impacts of two transmitting scenarios. 1) The fault opening up for a short time causing a large CO_2 release and then closing partially, 2) The fault transmitting a smaller amount for a longer period. A public statement was issued that the scenarios had been considered which showed that the users of the aquifer were not impacted.

Part of the Otway success was in public education and communication. As a result, local farmers knew sufficient geology to pose questions about the faults.

From the viewpoint of a lawyer, how can we test that our assumptions about flow along faults are correct? We need to know how to handle verification of flow along a fault. This is an extremely difficult area and requires experimental rather than commercial settings to expand our knowledge and to help 'prove' our assumptions. At Otway there is an opportunity theoretically to build on the current model. Action could also be taken at crystal geyser.

At Otway we would have liked to have a water observation well penetrating the aquifer, however this was not possible, so we used the seismic survey for monitoring. There was no leakage of hydrocarbons above the fault block and we are confident this will provide the necessary public assurance that there is no leakage up the fault, because there are no seismic anomalies above it. The seismic survey conducted after ¼ of the full injection shows the CO_2 staying in place.

However, there needs to be a sufficient volume of CO_2 to be able to create a seismic anomaly. Also if leakage is occurring along a fault it may not be visible on the seismic. For example, at crystal geyser CO_2 is flowing from the reservoir to the surface, but it is not detectable on seismic.

Note that faults at natural CO_2 leakage areas are not the same as faults in sedimentary basins. In general, faults in sedimentary basins are likely to be more predictable. For example in a basin with argillaceous sediments, it is likely that under a normal burial trend you could expect the faults to be closed with an argillaceous seal. Many of the natural analogue sites are in different geological settings such as in exhumed, volcanic basement, which behaves very differently and the faults are more likely to be open.

Note also that a fault which seals to methane or hydrocarbons may not necessarily seal to CO_2 if it is dissolved in water or water saturated. CO_2 is a reactive molecule, and creates carbonic acid which could react with the fault seal.

2. Reports from Projects, Chair: Ziqiu Xue; Kyoto University

2.1. Report from IEA GHG on What We Have Learnt from Projects – Monitoring: Neil Wildgust; IEA GHG

A review of current large scale operational projects relating to capture and storage of CO_2 is being carried out by IEA GHG (including projects capturing greater than 100 kt/yr from any source or over 10 kt/yr from flue gas, or projects injecting over 10 kt/yr into monitored geological storage or coal-bed storage over 10 kt/yr). 28 such projects have been identified and so far 18 have responded. The review looked at how these demonstration projects relate to the CCS chain (electricity production to capture to transport to storage). The projects cover a wide range of the EU Zero Emissions Platform (ZEP) archetypal projects and have a range of permeabilities and net storage amounts. Many different monitoring techniques are being used across these sites and comments have been collected from the operators about their relative successes. Some techniques are obviously more applicable and successful at some sites than others.

Questions and comments:
Are large projects necessarily more relevant to commercial projects? Large projects may still be in a 'research mode' and dealing with issues, whereas smaller projects might in fact be more similar to commercial projects. The large project focus was requested and approved by IEA GHG members. (the budget also limits staff time and resources). However, IEA GHG is aware of the value of looking at different scales of projects and is by no means ignoring small scale projects.

Does the slide showing the 'injection tonnage per year', show CO_2 injected or the net figure? Specifically, for the Weyburn EOR project, does the figure include recycled CO_2 and also that stored in Midale? (and is it a well performing EOR project if that much is staying in ground?). About 30 % of the CO_2 is being recycled. They could recycle more, but they are balancing the injection rate to the oil production rate.

It would be helpful if we know precisely how much is input, how much is stored, how much is mobilised and how much is recycled. i.e. Some that is injected won't come out but some could come out.

2.2. Report from Ketzin: Conny Schmidt-Hattenberger; German Research Centre for Geosciences

The Ketzin site is the in-situ R & D laboratory for injection and storage of CO_2 for the CO2SINK integrated project. It is located in the North East German basin, about 30 km west of the centre of Berlin in a populated area. The site is a former gas storage facility, which was abandoned in 2004 where the gas was stored in a sandstone at 250 – 400 m depth. The CO_2 reservoir is below that, at 630 - 650 m depth. Up to now 20 kt of the final 60 kt food industry grade CO_2 has been injected. There are three 750 m wells (one injector, and two observation wells) and many monitoring techniques are being employed. A permanent sensor for pressure has been installed in the injector well, and permanent sensors for temperature electrical resistivity tomography (ERT) have been cemented into the annular space behind the casing of all three wells. The ERT has been successful at tracking the CO_2 plume between injector (Ktzi201) and first observation well (Ktzi200) and so far all monitoring techniques show the CO_2 staying in the reservoir.

Questions and comments:

Do you have any additional information on the gas membrane tool? It is a special tool developed by GFZ. It is 1 m long and has a semi-permeable membrane. It uses an argon gas stream to transport the gas sampled from the reservoir up-hole through 2 stainless steel capillaries (one for argon gas down and one for argon gas plus borehole gas up), where it is analysed by a mass spectrometer. Pressure and temperature measurements are also sent up-hole. There was a problem with the cable reliability, causing the tool to fail which required the cable being cut shorter. When breakthrough was detected, the tool was at 150 m depth. GFZ intends to run and improve the tool.

The reservoir is at 650 m depth and so far only 20 kt of the total 60 kt injection has occurred, so there may be a limit to what you can see so far. However, presumably the CO_2 is not supercritical at that depth. How different is this in terms of migration? The initial reservoir conditions are ~ 32 °C/64 bar, due to the injection P and T increased and the actual conditions are ~ 36 °C/76 bar. The data clearly show that the CO_2 is at supercritical T-conditions in the reservoir. Subcritical conditions accompanied by condensation and evaporation processes only occur within the two observation wells and within the injection well during shut-in phases. These changes in phase states could well be detected by the P-T measurements (logging, DTS). Although at supercritical T-conditions, the density of the injected CO_2 (~ 0.3 g/cm^3 in the reservoir) is well below that present in deeper seated storage sites. The effect of this lower density on migration behaviour cannot yet be resolved with the data at hand.

In term of the biological studies, what are the major findings and implications in terms of environmental impact of CO_2? These studies were valuable particularly accompanied by geochemical studies because of the degrees of injectivity. Hydraulic testing and deep fluid samples indicated that biological activity was responsible for reducing injectivity. Organic molecules from drill fluids had blocked the filters. It has been eliminated by nitrogen lift before CO_2 injection was started.

The basics of this study were well described. Was the CO_2 breakthrough later than the model predicted? We are trying to match the observations with the model and we have a good fit for the breakthrough in the first observation well. Breakthrough at the second observation occurred notably later than predicted by the models. The reason for this later breakthrough is still under evaluation and we are discussing different potential scenarios.

2.3. Report from US RCSP: Susan Hovorka; University of Texas

Several of the US Department of Energy Regional Carbon Sequestration Partnerships projects (RCSP) were described. 2003 – 2005 was the characterization phase and 2005 – 2010 is validation phase which included 21 projects. An output of the validation phase is the Monitoring Validation Accounting draft 'best practice document' which is available from:
www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf

The RCSP is now moving into the development phase from 2008-2017, for which there are 7+ large injections planned. The status of the field projects were outlined, focusing on particular case studies including (among others): A wildcat area in Arizona (WESTCARB) where a 2 kt injection is planned involving huff and puff testing and the Cranfield II site in Mississippi (SECARB) for which "smart well" monitoring well construction is planned incorporating permanent downhole sensors. More details and updates on the Cranfield II site can be found on the www.Gulfcoastcarbon.org website.

Questions and comments:
After how long did the pressure flatten out? It depends on the production, although it is not totally dominated by this. We don't know how unique the modelling solution is. (there may be multiple solutions). Pressure should flatten out with increasing size of the plume. But because production started we can't say whether there is a relative permeability issue or whether water is moving out through overburden. (Although it can be balanced in the model from before production started). There is a lot of data, so it may be possible to get a more unique solution when the analysis is complete.

A comment: the GHGT-9 North American CCS publication and other projects including those by the National Laboratory are very beneficial for scientists. We (in Japan) found this a very well organised and helpful publication.

What are the major results of projects such as Frio? There is a long list of lessons learned. Expect complexity. When results do not match predictions, more money is usually required to understand why. This means for commercial jobs, money should be put aside to deal with if the reality does not match your prediction. If the tools are not showing what is expected, you need to find out if it's a misunderstanding or a serious problem and the operation needs to stop.

2.4. Discussion Session 2, Chair: Ziqiu Xue

How should we go about site selection with respect to faults systems?
Faults are taken into account in the safety risk assessment. The faults need assessing and describing. It can't be generalised, but at Ketzin the injection is around 2km from a fault series and this was established as not critical for the operation.

When results don't match predictions a 'conform or stop' approach would be unlikely for CO_2 storage when so much money has been invested in capture systems. In the same way that oil and gas production would never go ahead if they took this approach.

Other industries have studied faults. One example is the lignite industry: they expected faults in the overburden to be sealed but they were not. We can’t assume that even in a clayey overburden the faults will be sealed. By surface mapping we can see fault lines even in unconsolidated formations. We don’t need to drill through faults to be able to see them.

At Ketzin it took a long time to get permissions for operating the test site. *For the risk assessment did you use Features, Events and Processes (FEPs) or other methods? Did you use a simulation in proving the faults?* A simulation was done along with two independent risk assessments. One was by DNV (Det Norske Veritas) and one by another company. They were done by modelling and building on the experts’ knowledge from the former gas storage site. The gas storage was safe and we concluded that CO_2 storage was also safe, as we have a multi-barrier system as overburden of our target storage reservoir.

There is a problem when using probabilistic models in that you always get leakage, it is never zero. Draft statutes say that CO_2 brines must stay in the formation that they were injected into. EU is also discussing zero leakage. The solution is to not use probabilistic models. Assume zero leakage from storage and then monitor it.

In terms of getting a permit, regulators may think differently to scientists. Regulators don’t usually ask for probabilistic models. So you could make one, but use it within the project only.

Depending on the jurisdiction there is likely to be different regulators for environmental regulations to petroleum safety regulations. In Victoria, Australia, environmental regulation focuses on impact on other segments of the environment and is mostly consequence analysis. (i.e. if this happens, what are the consequences?) For monitoring this means: *can we measure or detect it before it is significant?*

The problem with consequence analysis is that measuring things costs money. Probability is important to consider too.

Educating or training the public can be challenging especially when explaining issues like sensitivity and iteration to reduce the size of errors or uncertainty. Farmers suggested repeating the experiments until there is no error.

3. Update on Japan CCS Progress, Chair: Toshi Matsuoka; Kyoto University

3.1. Post-injection Monitoring to Ensure Safety of CO_2 Storage: Saeko Mito-Adachi; RITE

The Nagaoka pilot CO_2 injection site is 200 km north of Tokyo. This project is now in the post injection phase. From 2003 – 2005, 10.4 kt of food industry grade CO_2 was injected into a 60 m Pleistocene sandstone reservoir at 1100 m. The injection well is surrounded by 3 monitoring wells and geophysical and geochemical monitoring results were presented, with a focus on post injection monitoring. Geophysical logging has indicated that the site has now reached imbibition phase. Geochemical sampling using a CHDT tool verified that CO_2 is entering the dissolved phase at the base of the reservoir. This has created a sufficient resistivity contrast (because of the low salinity of the formation water) for this dissolution of CO_2 to be imaged. This is the first time this dissolution process has been imaged and infers that (in accordance with the IPCC figure) the storage safety is increasing as the CO_2 moves from structural to dissolved trapping.

Questions and comments:
A very nice set of data, especially the resistivity. Could this be repeated at other sites? Salinity of the formation water was 0.8 wt % (very low) so CO_2 injection gave a clear resistivity change. Other sites might not see this, for example at Frio, USA, the salinity is 10% which may be too high to see a contrast.

Can you see the decrease in saturation on the neutron porosity as well as on the resistivity logs? It also changed but not so much as the resistivity.

Is there any statistical analysis of the change? How well did the other logs show this? No statistical analysis has been done yet. Velocity and resistivity decreased together in the lab and in the field. The sonic log showed CO_2 saturation changes up to 20%, so it is less sensitive to CO_2 saturation than the resistivity tool. Neutron porosity only partly showed this, so we hope that the CO_2 is the residual gas.

Can you see similar results in different scaled data? For example, is there another way of acquiring resistivity data on lower scale but covering a larger area? Cross well seismic data has this capability, but electrical resistivity tomography (ERT) has a resolution of about 4 m, which is not enough to detect small migrations.

It is very encouraging to see the dissolved CO_2 increasing beneath the gas in the reservoir. Can you estimate what percentage is dissolving? Beneath the reservoir samples showed 0.004 % in the formation water equivalent to a 0.5 wt % of CO_2 (a small amount).

What about the actual mass of CO_2 dissolving in reservoir over time? We don't know the mass, but it is likely that the dissolved CO_2 will increase and free CO_2 decreases. We will need to use a CO_2 flow simulation to answer this.

From analysis of the formation water in the lab, it is possible to calculate how much has dissolved, although there is scale difference. It would be better to map the CO_2 in solution using the flow model. There are 3 observation wells, so it is hard to calculate the mass dissolved at the points between the wells.

Is it possible to compare porosity before and after injection from all logs? An early prediction was that porosity would increase with the injection of CO_2? The model does not take into account any porosity change.

The model predicts that by the end of injection, 35 % of the total injected CO_2 will be dissolved and that 1000 years later, 60 – 65 % will have dissolved. Post injection monitoring is very important; will logging continue given that imbibition has just started? We agree it is very important, but money is the problem!

3.2. Monitoring Future Plans: Masanori Abe; Japan CCS Company

The Japan CCS company is the first private company set up specifically for CCS. They aim to promote and demonstrate the total CCS system (from capture → transport → storage) both in Japan and elsewhere by cooperating in projects overseas, and establishing technological standards. They have a number of candidate demonstration sites at different scales, which include a wide variety of CO_2 sources, transport processes and types of reservoirs.

In 2007 Japan emitted 1304 Mt CO_2. Storage potential offshore Japan has been estimated at 150 Gt (RITE 2008). Japan CCS company currently has two 2 demonstration projects: "METI" to develop assessment technologies for deep aquifers and the "NEDO" project looking at the feasibility of a total CCS system (from electricity generation through to storage). Injection and monitoring is being considered from a single well, completed as an intelligent system fit for both purposes.

Questions and comments:
It was mentioned that the depth of earthquakes (10 - 20 km) versus the depth of CO_2 injection and possible associated seismicity. (1.5 - 2.5 km) would allow events to be easily separated. Remember that the pressure perturbation associated with CO_2 injection is much greater than the plume itself and could potentially extend to several kilometres below injection possibly. We are not planning on injecting that much CO_2, but yes, we have to be careful.

The 2D seismic profile to interpolate between 3D surveys will be carried out more often than twice in 5 years. Why? The law does not state you must do 3D seismics twice in 5 years, but we are planning 2D seismic in between because it is much cheaper.

In the offshore injection project, will you have a dedicated intelligent monitoring well? (the slide showed only 1 injection well). It would be difficult to get a monitoring well close enough to monitor the distribution of CO_2. We hope the injection well is useful to monitor the first phase of injection. We will try and collect as much data as possible from this one well in order to be able to explain what happens to the CO_2 as it disseminates and moves to other places.

If you are injecting CO_2 and also monitoring in the same well, will the noise from injection affect the seismic? Yes, we need to consider that.

The concept of having a single well for injection and monitoring is very interesting. Have any of the design details been released? No, not yet.

Regarding using 2D seismic in lieu of 3D, it is important to get enough data to recognise the behaviour and movement of CO_2. Do you thing that this is achievable?
At the beginning stage of injection, we hope to gather enough data to anticipate the long term movement. We appreciate that this is an optimistic challenge for this well. We also have permanent sensors installed in the well. If it functions well, then it will be very helpful to this and other studies.

The difficulty is in not affecting fish or marine traffic.

How long will it take to inject 50 – 100 kt/yr? There is a 100 % government subsidy for the project, so probably 3 – 5 years for the government grant.

What is the distance between the two reservoirs? 30 m.

3.3. Recent CCS Progress in Japan: Toshihiro Mitsuhashi; METI

Japan hosted the G8 summit in 2008. Outcomes included the recommendation for 20 large-scale CCS demonstration projects to be launched globally by 2010 and in Japan, an action plan for a low carbon society was developed. It was established that CCS is an interim solution during the transition away from fossil fuels and necessary if the 50 % emission reduction by 2050 is to be achieved. This target requires a 100 Mt reduction per year. Renewable energy is very important but is not sufficient alone. A list of the draft guidelines for the safety and environment for large scale demonstrations projects was displayed.

Questions and comments:
The requirement in Japan is that the purity of the injection stream is 99% CO_2. Is this likely to be a problem? Yes, for example the ammonia production facility produces a 96% CO_2 stream. This requirement is controlled by the Ministry of the Environment. We propose to ask them to make an improvement to this and any changes will need a decision from ministers.

The presentation showed capture costs reducing from 4200 JPY in 2010 to 1000 JPY by 2020. That is a 75% reduction in 10 years, is that aspirational, or based on current *trend?* RITE are doing some R&D activities using a membrane to capture CO_2. We believe this can be done by 2020 and achieve the 1000 JPY capture costs.

The final slide shows some surface and some subsurface guidelines. Where do risk assessment and modelling fit? One part of monitoring is modelling to see if the site conforms to predictions. So modelling is included in monitoring. This requires you to set up an abstract model and numerical detailed simulation model to prove that CO_2 can be locked in.

With respect to time scales, is this for the long term or just the initial requirement? We must improve the history matching in point 1 and 8 of the last slide.

4. What Regulators Want, Chair: Susan Hovorka; University of Texas

4.1. Introduction to Monitoring Requirements from Regulators: Tim Dixon; IEA GHG

A summary of the UK, EU, Australian and USA legislation, focussing on the IPCC Guidelines and marine treaties applicable to European countries or worldwide. The specific definitions and guidelines for monitoring of storage sites according to the recently published EU CCS and ETS directives were also examined. Current regulatory frameworks show flexibility and monitoring is important but not prescriptive.

Five short (5 – 10 minute) presentations were then given, followed by a structured panel discussion.

4.2. Regulation and Otway: Charles Jenkins; CO2CRC

The regulations developed in parallel with the Otway Basin pilot project in Australia resulted in a high level set of requirements which were qualitative rather than quantitative. A list of non-prescriptive Key Performance Indicators were established for the project, allowing flexibility appropriate for a small scale research orientated project.

4.3. Australian Regulator: John Frame; EPA Victoria

At the initiation of the Otway Basin pilot project there were no Victorian or federal laws covering CCS. These regulations have developed and evolved in conjunction with this research pilot project, culminating in the Greenhouse Gas Geological Sequestration Act 2008 which will become effective from Jan 2010.

4.4. CCS Monitoring under Marine Pollution Prevention Law: Hirotaka Hamanaka; Ministry of Environment. Govt. Of Japan

Offshore CCS in Japan requires a CCS permit from the Ministry of Environment renewed every 5 years. The Marine Pollution Prevention Law is currently the only Japanese Law covering CCS. Japan was the first nation to take account of the amended London Protocol document.

4.5. Regulation on an EU Project: Hubert Fabriol; BRGM

In 2008 TOTAL requested authorisation for the Lacq-Rousse project, to inject 120 kt of CO_2 over 2 years into the depleted Lacq gas field at 4500 m depth. At the time the only law covering CCS in France was the Mining Code and Environmental Code (the EU CCS directive will apply from May 2009). It was a 2 year process to establish the administration and the final authorisation was given in May 2009.

4.6. Comparison of US State Regulation: Lee Spangler; Montana State University

As yet there is no federal guidance on CCS. This means that the four states in the Big Sky Carbon Sequestration Partnership have different approaches to many aspects of CCS such as ownership of pore space, transfer of liability timescales and financial responsibility etc. This is largely because historically in the USA 'land rights' have been divided into surface and mineral rights at the state level.

4.7. Structured Discussion: If we can't see it does it matter? Chair: Susan Hovorka

Panel: Charles Jenkins, John Frame, Hirotaka Hamanaka, Hubert Fabriol, Lee Spangler, Tim Dixon

A strong relationship is needed between monitoring and regulation. Two areas we need to be sure about are:

- If we say it won't leak and it does – people will lose confidence in CCS.
- If we set the standards too high – industry won't use it.

The theme is that the regulations are not prescriptive, but industry likes certainty so they know what is expected and how much it costs. What do the panel think about this? Remember that the cost of monitoring is a very small percentage compared to the cost of the whole chain of capture, transport and storage.

It may not cost relatively much to monitor, but the consequences of inappropriate monitoring could cause an operation to stop. Therefore we would be wary of prescriptive regulations.

There may be uncertainty in the environmental outcome, but numbers in environmental regulations have to be adhered to. So the non-prescriptive regulation is a good thing as it gives flexibly to convince the regulator that the site meets those numbers.

In the US the RCS Partnership interest is at the state and federal level. They have communicated that the regulations at least initially, will be performance based. They want to learn by doing, but if the regulations are too prescriptive you don't get that option. It's possible that the regulations may become more prescriptive with time.

Yes, industry do want certainty, but you don't get that when you're learning by doing. The first projects will set the trend for the level of evidence required for the transfer of the site to the regulators (probably over the next 20 years or so).

There has been no mention of quantification and carbon credits as yet. How will this work if the regulations are qualitative? For the ETS in Europe, we quantify what we put into storage, then monitor for irregularities and leakage. If leakage is detected, then you have to quantify the leak. The USA do not have an ETS yet. In Australia the

ETS has been postponed, but through the national inventory system leakage will have to be quantified.

With respect to the plume following modelled predictions, which prediction should it be following, as the models are constantly updated? This a key point, reflecting the requirement for iteration. Predictions are revised based on monitoring results. So when the transfer of liability occurs, it will be necessary for CO_2 to be following the *latest* version of predicted behaviour not the initial model from the start of the project.

We can't just reveal the models and predictions that work. To use randomised drug trials as an analogue, these must be registered, otherwise they could just not report if they did not get the expected result.

Do we have a definition of 'leakage'? For example, would it include if CO_2 migrated into an oil and gas field? It would depend on the regulatory context. In the oil and gas example it is the pore space allocation which is being impacted. Environmental regulators are only likely to be interested if an environmental resource is being impacted. The ETS will drive monitoring to a level of detail an order of magnitude higher than environmental regulations will require.

The definition of leakage is very important. In the EU, leakage is environmental protection driven and does not consider other economic resources (unlike Australian legislation). This may be an issue for member states rather than the EU. The EU directive defines leakage as "movement outside of the storage complex" i.e. it could include migration into secondary trapping mechanisms. The IPCC defines leaks as into the atmosphere and water column. The ETS monitoring in the EU is triggered by leakage as defined under EU directive i.e. into the water column or atmosphere. It would be interesting to compare different leakage definitions across the world.

It is different in the USA. There are mineral rights and surface rights at the state level. As yet there are no federal level CCS regulations. These will probably come from the EPA air requirements or ground injection control. Or may be kept separate...

The US Energy committee has passed a bill to reconciliate the two, but that still has to go to the senate.

If we detect a leak, can we quantify it (as stated in the ETS)? Or is that not technically feasible yet? Under ETS you would lose credits according to the sensitivity of the monitoring system. Less expensive techniques may be less sensitive, so credits would be up to the detectability of that system. So there is an incentive to use more sensitive equipment to ensure credits are kept as low as possible.

So operators will have to pay every year for the uncertainty on their leakage measurements? If you can't achieve a 7.5% uncertainty, then a supplement will be added on. So a conservative estimate for emissions will be to overestimate for less sensitive monitoring (or operators may get 'rewarded' for leaks). Note that point source, offshore bubble stream leaks should be fairly straightforward to quantify compared to diffuse leakage over land, which is more challenging.

If a storage site is discovered to be leaking, what would be the required mitigation plan? For example, ideally block the leaking well, or change the injection plan, but could a company just pay for it i.e. buy that amount of credits? Then when the licence is eventually transferred to the regulators, would they then pay the credits?

Remember that the cost of monitoring is tiny compared to the cost of the rest of the chain. The problem is that the cost of monitoring and upfront cost of capture are completely separated in time and space. A possible solution could be to tax the early part of the chain more and save the money for monitoring later on.

What would be the attitude if leakage is suspected to have been occurring some time before discovery? In the ETS, emissions get backdated from when you could last prove that it was not leaking, back to the start of injection if necessary.

The onus will be on the operator to prove his contentions. (And monitor regularly to catch leakage as early as possible).

So you measure what you put in and measure what leaks out into the subsurface or the atmosphere? ETS is concerned with leakage into the water column or the atmosphere, not into the subsurface.

What will regulators want us to measure as the edge of the plume? (Which edge?)

We don't have an answer for that yet. In the USA they measure the pressure front. The EU directive talks about hydraulically connected units.

How do you monitor if CO_2 has moved outside the storage complex?

What might be the process for dealing with these questions? These are technical issues with major uncertainties, which we are not good at addressing. Will they be settled in courts?

It depends on how jurisdictions deal with these sorts of issues. Defining the edge of the plume is likely to be dependent on regulators agreeing with the operator initially and looking at modification over time as monitoring techniques change. There are other historical examples where regulations have evolved with advances in science and the increased sensitivity of monitoring techniques e.g. toxins in air. CCS is long term so it needs flexible objectives/limits as environmental laws change.

If these issues end up in courts, the decisions will be based on expert opinions. The government and regulators will use their experts and information provided by the operator's experts. It will probably be dealt with on a case-by-case basis. Hopefully common sense will prevail. The EU commission is setting up a panel of independent experts to deal with permitting.

From the measurement aspect, it gets triggered when there is evidence of leakage. So the situation is much simpler pre-leakage. We have a zero-leakage assumption, if all predictions are modelled in advance. So we assume zero, unless monitoring indicates otherwise.

That is the innocent until proven guilty philosophy.

We should remember that migration pathways can be horizontally far. For long distance migration, the operator has an incentive to monitor often enough to ensure that this is not happening or to catch it early, otherwise emission credits will be charged back to the start date of injection.

Would operators be penalised for expelling saline brine at the surface? Expelling saline water would impact other users of the environment. In Australia, this would come under the definition on pollution, for which there are criminal penalties under the environmental protection legislation.

This assumes that you can detect it's your CO_2 or brine which is leaking, not that from a neighbouring storage site. In Australia, the regulator would have to prove their case. They have a strict liability regime.

It is important not to confuse different sorts of regulatory regimes. Expelling brine would be part of an EIA prior to getting permit.

What do we need to do in terms of closure and post closure care for transfer of liability to the government? If transfer occurs after say 20 years and there is a leak detected after 19, does the liability clock reset itself? Could a company get away with minimal mitigation to make it to year 20? In the EU the number of years of post-closure monitoring required is individual to each site. The decision is the result of negotiation and has not yet been fixed in. It is up to regulator if they reset the clock.

In the USA, there is a defined number of years but performance based requirements have to be met. These are very broad and not prescriptive. So the clock doesn't get reset until the regulators are satisfied.

It's about performance over time. If there is a leak after 19 years, it means the site hasn't been performing for the previous 19. So those predictions were not appropriate.

How are, or will the projects discussed so far be closed?

In Japan, this is not fixed, the regulation development is still under discussion.

The Otway project has research demonstration approval for a fixed 9 year period. (Usually R & D projects are normally 6 - 9 months trials). Otway finishes when the permit expires and has been demonstrated that it complies with the permit. Assurance was given that the state will then accept long term responsibility for the site.

There is a leap of faith required. It is currently uncertain how surrender processes will evolve until we get there for the early large-scale projects. The first projects will set the precedent. Note that the Lacq project (France) will be large enough to come into

CCS directive if injection exceeds 100 kt. Below that threshold counts as a research pilot.

Lacq is a 5 year project, 2 years of injection followed by 3 years of monitoring. The site should be given back to the administrators after 5 years. They may well inject under 100 kt.

Waiting 10 – 20 years to decide how closure works should be avoided. Why not practice closure (steps, language etc) on smaller projects that will stop soon anyway?

There has been considerable emphasis on predictive modelling. Pressure and hydraulic head can be modelled well, however the transport modelling of the plume itself is often quite poor. These models tend to deviate rapidly from reality within a few years. Do you have confidence in models as a way of closing the site? –Getting hold of the dataset to characterise heterogeneity is a challenge.

Do we have a choice?

Divergence from predictive models needs to be considered in the context of risk. Models are not the only part of the process. At Otway, performance indicators expected at different stages were agreed upfront. There may be some deviation, but milestones should still be met. Big companies will not be taking a leap of faith. They accept the risks and manage the process towards closure and liability handover.

5. Reality Check: What can and can't monitoring do, Chair: Kevin Dodds; BP

5.1. Quantification: Andy Chadwick; BGS

A focus on the monitoring requirements of the EC storage directives, using real examples. The requirement to image or measure the CO_2 in the reservoir was demonstrated using the Sleipner 4D seismic data although mass verification itself is not a requirement. Results of various monitoring techniques from Frio, KS12-B and Nagaoka were used to show that those sites were currently performing as expected. In terms of predicting long-term site behaviour to enable site closure, hypothetical minimum conditions for closure were given and how certain examples might fulfil those criteria. By demonstrating how sites fulfil these conditions, an evidence base is developing which can help build confidence with the public and regulators.

Questions and comments:
A lot rests on what is 'no detectable leakage'. Who is going to define that and evaluate the sensitivity?
This will be set out in the monitoring plan required to get the permit. If that monitoring plan is accepted as fit for purpose initially when the permit is granted, then by definition, it should also be acceptable at the end of the project. For example, if a permit was granted for sub-salt storage in the North Sea, and only pressure monitoring of the reservoir was proposed because seismic cannot image sub-salt. If the pressure is acting according to predictions into the post injection phase, then the assumption is that the site is not leaking. Unless something untoward happens, for example, bright spots on seismic in the overburden, then closure would have to be re-evaluated accordingly.

What would the sensitivity in the bright spots be? This is irrelevant, because you can see something.

So would you only advocate storage sites that can get good 3D seismics, where the model can be tweaked to give a better match (like at Sleipner)? No, like in the sub-salt scenario, you may never see the plume.

So how do you know it's behaving as predicted?
It depends on the site characterisation. For example, when skyscrapers are built, you assume it's not going to fall over because you know and understand the rock properties.

So is pressure monitoring enough for the EU?
It is, if it is sufficient for the site. That is up to an expert panel to decide. For example, they may recommend collecting a seismic dataset for the overburden to show that there are no bright spots.

So the monitoring protocol is accepted when the permit is granted. At that time would you submit the sensitivity of the monitoring techniques?
It is likely that objectives will be set, but the actual sensitivity is irrelevant. E.g. at Sleipner, the best tool to use is 3D seismic. This has built in sensitivity but what it is doesn't matter because we don't have anything better. All monitoring techniques employed suggest no leak. Remember the 'Innocent until proven guilty' philosophy. What is there to gain from getting something twice as sensitive?

What level of leakage would have to occur before you detect it?
This would depend on the sensitivity of the monitoring techniques used in each instance.

5.2. Otway Atmospheric Monitoring: David Etheridge; CO2CRC

At Otway, 2.5 years of atmospheric monitoring has demonstrated the capacity to detect surface leakage and also developed techniques which could be applicable to other projects. Different sources of CO_2 were identified using CO_2 isotopic signatures and other tracers (CH_4, CO, SF_6, halocarbons, $^{13}CO_2$). Sampling results were used in atmospheric dispersion models and also integrated with shallow subsurface monitoring results. Baseline monitoring showed that over the monitoring period, concentration of background CO_2 had increased by the equivalent of 1 million Otways. Large and varying ecosystem CO_2 flux dominated the CO_2 detected and characterised. Different possible rates of leakage compared to natural ecosystem fluxes were examined and also the amounts of leakage that would be climatically acceptable.

Questions and comments:

The $\delta^{13}C$ signature of the injected CO_2 is likely to be different to any background sources. But it should be kept in mind that the CO_2 injected might have a different signature to any that leaks to surface because of mineral interaction. Hydrology may make $\delta^{13}C$ tend to zero.

Does this describe a typical set up of a sampling system? At Otway, the set up was one sampling point at 10 m. Ideally you would have a network of inter-calibrated sampling points, both upwind and downwind at a level which allows you to pick up any surface release.

Would you expect similar atmospheric monitoring results in hilly terrain, forested, or urban areas compared to open areas, Or would you expect complication due to the different sources of CO_2? Any ecosystem fluxes are largely CO_2. At Otway, although it is pasture, the site is very productive and has a similar CO_2 flux to some forests. (10 µ mol CO_2 m^{-2} s^{-1}). If you had to measure in a forest, you could target measurements to coincide with ‘quiet’ low productivity periods, e.g. late summer when it’s dry. Ecologists can predict ecosystem CO_2 changes because they have an understanding of the system.

But any signal from CO_2 from a potential leak is likely to be a much smaller signal than other CO_2 sources. If you can’t use CO_2 isotope signatures to eliminate other sources of CO_2, then other tracers can be used, ($\delta^{13}C$ etc) to explain CO_2 sources.

5.3. Otway Water and Soil Monitoring: Charles Jenkins; CO2CRC

Ground water and soil flux were monitored at Otway to give public and regulator assurance that there was no leak and that the aquifer was not being impacted. Geochemical results from ground water monitoring via water wells in the shallow surface limestone aquifer were in accordance with the regulations, although assessing their likely response to a hypothetical leak was challenging. Soil gas flux was measured using accumulation chambers and continuous versions of these were being developed through the Otway project.

Questions and comments:
An interesting implication showing a larger view. The research team were monitoring to protect ground water and grass which is the livelihood of the residents, but residents didn't want you to access the monitoring stations when the ground was wet to avoid damage by trucks. It is the immediacy of the problem.

What about the bicarbonate anomaly? This anomaly was not in all wells and was not repeatable.

How did you established criteria for ground water monitoring in terms of possible leakage of brine? How would you detect if brine was increasing the concentration of heavy metals? We have state requirements for water quality (what chemicals are allowed and at what levels) and we must demonstrate that it meets those requirements. Any further work requires a detailed model of the aquifer and those below it, which was not possible with the budget/staff resources of the project.

There seems to be evidence that we do need this kind of detailed work if we don't understand the system, even if it does meet the regulations. This project is a R & D trial with limited duration, scale and budget. That level of detail is not appropriate for a pilot project. If it was a large scale commercial project, then you might expect the construction of a proper ground water model.

This is not the attitude of regulators in the USA.

It is important that the monitoring programme is fit for purpose. The regulator has to decide if it's appropriate for these small scale pilots.

We need to remember that best practice can't be best practice if no one can afford to do it.

Soil gas and ground water monitoring seem to be areas of contention. It appears that many operators may do soil gas monitoring as a matter of course to show 'due diligence' and because it is very cheap to do.

At the end of the Otway project, could the team reveal any difficulties and realities? Is there any way we could we do it better next time for other projects?

The CO_2 is being stored 2 km beneath where we are measuring soil gas. Lots of effort has gone into characterising the 1/10 km^2 of reservoir, but while characterising the 10 km^2 of overburden above is possible, it is not feasible within the budget of the project.

5.4. Strengths and Weaknesses of Monitoring in the Context of Monitoring Requirements and Risk Assessment: Mark Raistrick; Senergy

A view of how well monitoring capabilities match up to regulator expectations, such as the draft EU directive and other regulatory regimes from around the world. The performance and merits of various techniques were examined against these goals and also their current limitations. For example, 4D seismic is limited by acoustic impedance contrast, so difficulties arise in imaging the CO_2 plume in situations where the reservoir already contains gas (e.g. depleted hydrocarbon fields), or monitoring dissolved CO_2. The cost effectiveness of techniques and the communication of acceptable levels of risk was also discussed.

Questions and comments:

On the last slide, what is meant by the statement "hydraulic pressure communication ≠ CO_2 migration pathway"? It means that the CO_2 injected may be contained in the reservoir but it may be in hydraulic communication with the overburden through the caprock; i.e. it is a connected volume of rock.

Doesn't the pressure fall off once injection has been turned off? Yes, but CO_2 still migrates under density gradients. We have to be wary of just using pressure. Pressure dissipation might be good news (in an aquifer) or bad news (in a depleted gas field).

Would a site get rejected if 4D seismic is not suitable? In sites below salt, 4D seismic won't work, but also at a very deep gas storage site in Germany, 4D seismic was also not available, so expert judgement is required to say that the site will act as containment for CO_2.

5.5. Discussion Session 5, Chair: Kevin Dodds

Can seismic imaging quantify the amount of CO_2 in tonnes. What would be the uncertainty on that figure? With accurate temperature control, you could get 20-30% uncertainty, but that is not important. At Sleipner, the later surveys show the lower layers become less reflective. This could be that it's emptying upwards, or more likely that the seismic attenuation is increasing, so the uncertainty also increases. But regulations don't require you to measure the tonnage in the reservoir, or state the uncertainty of the measurements.

What about if it leaks? Then we still don't need to quantify what is in the reservoir. We only then need to characterise the leak.

Error bars have an impact on carbon credits. Uncertainty becomes relevant if you have to give back credits. So then you need to measure the amount of leakage and will be able to see from the previous monitoring event how long it has been leaking for.

For example, in a sub-salt scenario where there is no seismic data. We can't monitor the amount in reservoir, although we know the amount injected in. It is only any leakage that needs quantifying. If you still have 20 – 30 % uncertainty, that is relating to a much smaller amount.

When using repeat seismics to detect leakage, what if there are ‘statistical errors’. These may look like leaks to regulators, how can we tell what is a leak and what is a static error? (For example, at Little Michigan, there was a strong anomaly in the seal on seismic.) Any technique sometimes gets errors. That anomaly or suspicious data needs explaining. You would have to go back and check. That way the data is consistent, repeatable and evolving and it is possible to develop confidence in results over time.

From the geological characterisation (assuming its thorough) we know about the seal and believe it to be good and the regulator accepts that. The aim of monitoring would be to make sure that the storage concept is adhered to: for example, monitoring at reservoir outcrop, to confirm storage capacity has not been exceeded, rather than installing monitoring wells directly above perfectly sealed sites which would reduce the safety of the seal.

This puts lots of faith in the geological characterisation. At Sleipner the plume migrated in a way that was not expected or modelled due to ‘high permeability pathways’. How can you predict that sort of thing in advance?

If the geological characterisation flags up the seal as questionable then yes, the regulator might insist on additional monitoring directly above the site.

When monitoring a plume with seismic, does the regulation require reference to the risk plan? Does it state you must identify the risk and place monitoring accordingly? Yes, There is a framework for risk assessment and management. The regulations state you must have a risk register and a plan on how to contain those risks. So you don’t monitor safe bits, you only monitor the risky bits.

Who is this expert panel who chooses what’s necessary and what technique is used where? The weight on expert decisions seems to be increasing. There is a large burden of responsibility on expert panels of regulators.

6. Emerging and Innovative Monitoring Technologies, Chair: Don White; NRCan

6.1. In Salah Satellite Imaging: Kevin Dodds; BP

At In Salah in Algeria, gas is extracted from 5 wells, CO_2 is separated from the stream at surface and re-injected through 3 wells into the reservoir below the hydrocarbons. The reservoir is 20 – 25 m thick, at around 1800 m depth with a thin anhydrite seal overlain by a thick sequence of low permeability carboniferous mudstones. Various monitoring techniques are being employed including tracers, gas chemistry, tilt, microseismic, 4D seismic, geophysical logging and satellite imagery etc. The geological characterisation model included a zone of fractures and faults. These and the plume were further modelled using geochemical and geomechanical modelling. The URS Risque process was used to assess the leakage or containment risk and also the effectiveness of the site to store the CO_2. Future plans include the benchmarking of this risk process.

Questions and comments:
What are the depths of the observation wells? They are just starting to be drilled. The microseismic well will be the deepest, at 500 m.

But the water bearing layers are at a depth of 900 m, why not go that deep? Don't know.

6.2. In Salah Satellite Data: Takumi Onuma; JGI

The InSAR technique provides a wide aerial coverage of remotely sensed data, which is updated every 35 days, not weather dependent and relatively cheap. Through independent work funded by JAPEX, surface deformation of the In Salah injection site in Algeria was analysed. INSAR image processing techniques were described (noise removal, filtering, stacking etc). The processed, interpreted data showed the surface deformation relating to CO_2 injection over the In Salah site. A rise of around 20 mm was detected following injection and then the ground subsided slightly after injection had ceased.

Questions and comments:
A very detailed, interesting study. As the plume grows, there is slight subsidence, which mirrors what is expected of the pressure: that as CO_2 spreads out, the pressure decreases. We did not examine other datasets such as pressure, so we are unable to comment on that aspect.

The elevation of the injection site looks like it is of a much higher magnitude than the subsidence at the extraction site, is this the case? For this study we did not look at the subsidence volume where gas was extracted.

The different deformations could be explained because the permeability around the edges of the injection site is less. Integrating the surface deformation across a 6km by 6 km block shows that 80 % of the injection volume is expressed in the deformation. Also note that the total production of gas is greater than the volume of injected CO_2.

This application of INSAR at In Salah is a unique example of how well the technique can work, (similar to the success of 4D seismic at Sleipner). It may not work so well at other sites. For example at the seasonal gas storage site in France, INSAR doesn't work well because of dense vegetation cover. There is a new technique which is better at seeing through vegetation. L band data instead of C band is now being used in Canada, where the technique had previously been unsuccessful.

6.3. Real Time Integrated Monitoring: Guillemette Picard; Schlumberger

Real time integrated monitoring has been used successfully for some time for underground gas storage. Gas is repeatedly injected and withdrawn either seasonally or based on demand. For CO_2 storage, potentially multiple storage sites could be linked, monitored and controlled from a single operation room in a similar way. This can result in a better understanding of processes as they occur and the ability to remotely shut down or divert flow at sites if, for example, a leak is detected. This can improve risk management and performance optimization. Data on different time scales can be more easily integrated to help make informed decisions. At present there is insufficient experience in applying this system to CCS to be able to have automated thresholds for shut down etc, but with time, these may be able to be added in.

Questions and comments:
These all seem to describe reactive measurements by definition. But only the reaction to unexpected events. It would be indicated whether you would then require to either a) use a new measurement technique, or deploy more sensors, b) do more modelling, c) change the injection rate.

Have you thought about using a derivative level? Yes, but we should exercise caution. We don't have enough experience yet to set alerts or values on absolute numbers or derivative levels.

If the national system is making CO_2, where does that CO_2 go? Where can we store it in the interim? If there was too high a flow rate, or a problem, the system could be shut down. The worst case scenario would be to vent it.

In the oil and gas industry, sometimes the pipes can be used as storage for a few days. For CO_2 there would not be enough capacity, it is being produced too fast. This type of integrated system could be linked to multiple well storage. It is a matter of planning that they are not all working to capacity, so that if there is a problem with one site, flow can be diverted to others.

What about the risks associated with power cuts or internet supply problems for real time monitoring? This risk is taken account of in offshore systems and there are back-up options. If only one well is connected to the system there are not so many options.

6.4. Electrical Results from Ketzin: Conny Schmidt-Hattenberger; German Research Centre for Geosciences

Geo-electric crosshole measurements and surface to downhole measurements were taken at the Ketzin CO_2 injection test site in Germany. These techniques can be used for CO_2 plume monitoring. The ERT electrodes were permanently installed behind casing on the three Ketzin wells (one injector and two observation wells). Time lapse difference images from crosshole resistivity measurements were used to track the migration of the plume (because of the increase in resistivity of the CO_2). However the resolution of this technique means that small perturbations may not be visible.

Questions and comments:
How does the data quality correlate with pump rate? For example, interactions with temperature when pumping or not pumping? This is in progress. Temperature has not yet been considered, but it should be. There is a need to distinguish what is related to injection and what is related to strange electrode behaviour. There has been a decrease in the data quality over the lifetime of the electrodes.

There is a very low resistivity contrast less than one ohm metre. Is that caused by mineralisation or salinity? It is due to the high residual water saturation and also the clay mineral content. The detailed analysis of the impact of both effects will be done at the IFP in Paris hopefully.

Were the surface electrodes permanent or temporary? What were the logistics of installing them? They were not permanent. It takes one week to do the measurement. There had to be a good link with the regulators and the rural population, because of the use of the dipole source and because the equipment was sited in several farmers fields.

At Nagaoka, ERT measurements were planned, but did not go ahead due to problems. Can you see the dissolved CO_2 at Ketzin? Only free CO_2 can be detected by ERT measurements. The effects of dissolved CO_2 on resistivity are too small to be detected by ERT measurements due to the very low solubility of CO_2 in brine at the Ketzin P-T conditions. Other measurement methods have to be used where this electrical method doesn't work.

6.5. Thermal Monitoring at Ketzin: Barry Freifeld; LBNL

Barry Freifield was unable to attend. His presentation will be available on the website.

6.6. Discussion Session 6, Chair: Don White

How do vegetation and steepness of terrain affect the INSAR technique?
The C band wavelength of 6 cm is very sensitive to scattering by leaves. Longer wavelength are more successful at penetrating vegetation. Using a wavelength of 24 cm there is still some scattering, but results are much better. There is a 1 – 2 cm

sensitivity, which is no problem for seeing through grass and shrubs, but trees still create some difficulties.

The steepness of terrain doesn't matter unless it is in the Radar shadow. The Radar look-angle is 40° off vertical depending on the satellite position in the sky. Topography can be simulated e.g. from a Digital Terrain Elevation Model (DTEM), so sometimes there can be a decorrelation problem if the DTEM is out of date (for example, if there has been terrain modification which can quite often be the case in the oilfield).

In the EGS weekly paper there was an article about how INSAR had been successfully used for fault identification in the California coastal range, which is both hilly and wooded.

To use INSAR as a monitoring tool for CCS you need to apply inversion. The CO_2 is at depths of several kilometres. Modelling can give a reasonable value to predict the amount of deformation expected from injecting CO_2 into the subsurface, but this is very project dependent. At In Salah, there is more deformation than expected according to the subsurface terrain model.

Looking at the deformation measurements at surface and of the storage itself through inversion, what geomechanical parameters can be extracted? Build an underground strain model, with grid blocks and alter the model until results match the surface measurements. There is 10 – 15 % of depth error or sensitivity because of the spatial gradient (how quickly the peak rises at the surface).
Where the strain source is very deep and it diffuses as it rises to the surface, the surface expression will be very diffuse. If injection was at a shallower depth, you might expect a more 'pointy' response.

How well did you characterise overburden for that model? So far it has been modelled as homogenous. A layer model is now being looked at. So refining the model is ongoing.

With that amount of surface deformation, was associated microseismics expected?
It would depend on the type of rock. At In Salah, the microseismic monitoring well is at 500 m depth, whereas the injection is at 1500 m. So it might be expecting a lot for the instruments to pick up microseismic events through 1 km of overburden.

There was a trade off with the location of the monitoring wells at 500 m. If any microseismic events are detected during injection, it may be possible to move them closer.

Regarding the issue of inversion. More complex models take longer and require heterogeneity, although they might get closer to the real situation. The INSAR data is relatively cheap and available. This means that anyone can get hold of it and do some analysis for any site. 1) Can we use this to replace other monitoring? 2) Do we need to do it?

This technique can fill in gaps between 4D seismic surveys, which may be limited to 1 or 2 surveys throughout injection, whereas INSAR can be much more frequent at up to 35 day intervals.

The presentation on groundwater investigation was good, but it can't be confined to the reservoir only. We should get information about water drive etc to our monitoring.

The INSAR measures deformation, but so does a tilt meter. Was a tiltmeter also used at In Salah to detect deformation?

Would tiltmeters measure the earth tide? If so how could it be removed? How can we use tiltmeters to get good data for CCS? Earth tides are normally at the wrong frequency to interfere with CCS monitoring. They would only become relevant if the monitoring process was 12 - 24 hours long. If this was the case, the earth tide could be modelled and then removed.

Good surface deformation information requires tilt, GPS and INSAR data. GPS is critical to validate and improve INSAR and tilt results. Note that tilt uncertainty increases with time, whereas GPS uncertainty doesn't. So these data can be combined to get more accurate results.

Anyone can get hold of INSAR data for your site, e.g. NGOs, environmental groups etc. There is a possibility they could misprocess this data, or make it look misleading. Should we develop a best practice or least caution on worst practices for INSAR processing? This could happen. Independent contractors may not do it right. We could write some pre-emptive papers about how we feel the data should be treated.

It is also the interpretation of that data, not just the processing.

The Earth tides paper from Nagaoka looked at pressure variations in extracting out saturation data. The bottom hole pressure (BHP) was measured and subtracted. There was a nice correlation between the observations and CO_2 arrival time.

A general question: are there any emerging technologies that we haven't yet considered here, or given a fair evaluation of? Gravity monitoring is one that we should mention.

Sea bed time lapse gravimetry surveys were carried out in 2002, 2005 and 2009 at Sleipner. A change in CO_2 mass (2.5 Mt between 2002 and 2005 surveys) is just about detectable. This technique would have been more robust if a baseline survey had been carried out prior to injection. The offshore data (ROV) is more accurate than on land. Sleipner is particularly suitable for this technique because the site is shallow and stacked vertically. If the reservoir was thin horizon and covered a larger area it would create a much smaller effect that may not be detectable.

The repeatability is 5 µgals. The difference between the 2002 and 2005 signals are about 5 µgal. At In Salah, the difference is only 3 – 4 microgals. So the current sensitivity of tools could not detect this. Borehole tools are available, which could be used as a complementary method in an observation well.

A good example to look up is the gravity evaluation following water injection at Prudhoe Bay (Conoco Phillips / BP).

How much did the trawlers or ROVs deployed at Sleipner cost? (How many seismics surveys would that be equivalent to?)

The cost to perform CSEM and gravity measurements was the order of another seismic survey offshore. Onshore it would be cheaper. It may not work at Otway because the CO_2 is stored too deep. Gravity in a borehole could be around £50k.

How do we predict dissolution of CO_2 into water if it can't be detected by seismic? Can seismic detect shrinkage of the accumulation and could this be an indication of leakage? At Sleipner, the deeper areas have become less bright, rather than shrinking. Dissolution is tricky to detect, because CO_2 becomes invisible to seismic because the density contrast is reduced. So gravity could be a useful technique for ensuring the dissolving plume is still in place, but if CO_2 did get through the caprock, the density might still look the same from the surface.

The sensitivity of the gravity technique depends on depth. In the scenario of leakage, microgravity could perhaps be used to detect leakage.

The size of the anomaly is inversely proportional to the square of the depth. So if CO_2 were to migrate to half the depth, it would become 4 times more visible. So the gravity causes more effect when CO_2 is shallower. But it might still require a large leak (mass of CO_2) to be detectable using this technique. There are some contradictions in the literature, as to whether the Sleipner CO_2 injection is detectable or not.

7. Conclusions & Key Learnings, Tim Dixon; IEA GHG, Toshi Matsuoka; University of Kyoto, and Kevin Dodds; BP

The key learning points and conclusions agreed by the workshop attendees are provided in Appendix 3

Day one highlighted key findings from the previous monitoring and other network meetings. It also provided a review of various CCS demonstration projects around the world, with a focus on Japanese projects and plans. There were many recurring questions and issues from previous meetings which were still valid, despite noted progress in both the development of monitoring techniques and of regulations, (e.g. the EC directive, amongst others). It was encouraging to note that delays in permitting approval to date were generally not due to technical, monitoring-related barriers. Some of the monitoring techniques reported on demonstrated new examples of how plume observations are matching predictions. These examples add to our knowledge and evidence base of successful monitoring. Together with assurance monitoring and continued public communication (successful at Otway and Ketzin), these will help gain, improve and maintain public and regulator confidence in CCS. This is important for all projects at all scales. It was agreed that the continued sharing of knowledge and technology transfer between current projects, operators and countries is very useful and should be encouraged. The post injection monitoring results from the Nagaoka site were particularly interesting, as they showed the first imaging of CO_2 dissolving in the reservoir and moving towards long term stability. (An important step to be able to demonstrate to enable transfer of liability and site closure).

Day two dealt with the requirements for monitoring from regulations in different countries. Regulations are being developed, driven by the ETS in Europe, and mainly evolving in parallel with pilot projects elsewhere. Regulations require different levels of requirements (although mostly high level) and are all generally non-prescriptive regarding monitoring. This was seen as a good thing for now, as it allows projects the flexibility to develop and 'learn by doing'. The ability of current monitoring techniques to perform the tasks required by regulation was also addressed. It was concluded that in general, available methods can be fit for purpose. Many of the recurring questions regarding closure of sites were thought likely to be determined by the approach of the first few projects to go through the process and that these will set the precedent. The smaller projects that are nearing completion were encouraged to 'practice' closure. New and emerging technologies were discussed including INSAR surface deformation data from In Salah and also the behind-casing installation for crosshole ERT measurements at Ketzin. Additionally, gravity measurements may have a role in detecting gaseous or dissolved CO_2 in the reservoir. The role and relative merits of integrated technologies for real time monitoring and controlling multiple storage injection sites was also discussed. This type of system may be useful for integrating multiple datasets at multiple scales. The increasing reliance on expert opinions for both the permitting process and most likely at the hand over stage also was emphasised. However, finding independent experts may be an issue and because of the time scale of CCS projects, it was noted that any decisions made need to be transparent and documented for future generations.

Recurring Llearnings, themes, gaps and points identified:

- Use pilot-scale projects to focus on and learn on post-injection behaviour.
- Leakage should be approached as 'Innocent until proven guilty'. There should be an assumption of zero leakage until monitoring indicates otherwise.
- How can we define the edge of the plume in terms of pressure and hydraulically linked units and what happens if neighbouring sites interact?
- Study faults more including their transmissivity to CO_2 in different phases.
- Monitor geochemistry processes in-situ close to injection wells.
- Multi-scale integration of multiple datasets, e.g. combining seismic and electrical resistivity.

Conclusions agreed by the workshop:

- Strong recommendation to use pilot-scale projects to focus and learn on post-injection CO_2 behaviour, as at Nagaoka.
- Benefits of multi-scale integration of multiple datasets, e.g. combining seismic and electrical resistivity.
- Regulations are based on qualitative rather than quantitative performance and require expert opinion to make decisions. This may become difficult due to a limited number of such independent experts in the CCS field at this early developmental stage.
- Atmospheric and surface monitoring can provide assurance to the public.
- The transmissivity of faults to CO_2 may be different to other molecules such as methane due to the ability of CO_2 to react with some materials in the presence of water. Additionally, more work is required to understand fault and overburden leakage pathways, i.e. Uncertainty over defining what is an acceptable match of predictions and the reality of CO_2 behaviour for the closure and liability transfer of storage sites. The first projects will set the precedent.
- Pressure front monitoring will be required.
- Monitoring capabilities are good enough to get on with projects.

All the presentations are available on the web site:
http://www.co2captureandstorage.info/networks/monitoring.htm

Tokyo at dusk

5th Monitoring Network Meeting

2nd - 4th June 2009

JAPEX HQ, 12F Sapia Tower, Tokyo, Japan

Organised by

IEA Greenhouse Gas R&D Programme,
Kyoto University
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AIST

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OYO Co.
SK Engineering Co.
JGC Co.
Japan Oil Engineering Co.
Halliburton Overseas Limited
Battelle Japan
JFE Engineering Co.

2nd June 2009 Day 1

08.15 to 08.45 Registration

08.45 to 09.00 Welcome Tim Dixon; IEA GHG, Toshi Matsuoka; University of Kyoto and Prof. Yoichi Kaya; RITE

09.00 to 09.30 Report from the 4th Monitoring Network Meeting: Don White; NRCan

09.30 to 10.00 Report from the 1st Joint Network Meeting and 1st Modelling workshop: Neil Wildgust; IEA GHG

10.00to 10.30 Break

Session 1 Reports from Other Initiatives Chair: Charles Jenkins; CO2CRC

10.30 to 10.40 Report from the Risk Assessment Network : Tim Dixon; IEA GHG

10.40 to 11.00 Report from the Environmental Impacts Workshop: Lee Spangler; Montana State University

11.00 to 11.20 Report from CO2Remove: Andy Chadwick; BGS

11.20 to 11.40 Report from Otway: Sandeep Sharma: CO2CRC

11.40 to 12.30 **Discussion**

12.30 to 13.30 Lunch

Session 2 Reports from Projects Chair: Ziqiu Xue; University of Kyoto

13.30 to 13.50 Report from IEA GHG on What We Have Learnt from Projects– Monitoring: Neil Wildgust; IEA GHG

13.50 to 14.10 Report from Ketzin: Conny Schmidt-Hattenberger; German Research Centre for Geosciences

14.10 to 14.30 Report from US RCSP: Susan Hovorka; University of Texas

14.30 to 15.30 **Discussion**

15.30 to 16.00 Break

Session 3 Update on Japan CCS Progress Chair: Toshi Matsuoka; University of Kyoto

16.00 to 16.20 Post-injection Monitoring to Ensure Safety of CO_2 Storage: Saeko Mito-Adachi; RITE

16.20 to 16.40 Monitoring Future Plans: Masanori Abe; Japan CCS Company

16.40 to 17.00 Recent CCS Progress in Japan: Toshihiro Mitsuhashi; METI

17.00 to 17.30 **Discussion**

Close Day 1

18.00 to 20.00 Dinner—4F Sapia Tower

3rd June 2009 Day 2

Session 4 What Regulators Want…. Chair: Susan Hovorka; University of Texas

08.30 to 08.45 Introduction to Monitoring Requirements from Regulators: Tim Dixon; IEA GHG

08.45 to 09.30 **Panel Discussion**
Regulation and Otway: Charles Jenkins; CO2CRC
Australian Regulator: John Frame; EPA Victoria
CCS Monitoring under Marine Pollution Prevention Law: Hirotaka Hamanaka; Ministry of Env. Govt. Of Japan
Regulation on an EU Project: Hubert Fabriol; BRGM
Comparison of US State Regulation: Lee Spangler; Montana State University

09.30 to 10.00 Structured Discussion: If we can't see it does it matter? Site Closure monitoring. Onshore vs offshore

10.00 to 10.30 Break

Session 5 Reality Check: What Can and Can't Monitoring Do…. Chair: Kevin Dodds; BP

10.30 to 10.50 Quantification: Andy Chadwick; BGS

10.50 to 11.10 Otway Atmospheric Monitoring: David Etheridge; CO2CRC

11.10 to 11.30 Otway Water and Soil Monitoring: Charles Jenkins; CO2CRC

11.30 to 11.50 Strengths and Weaknesses of Monitoring in the Context of Monitoring Requirements and Risk Assessment: Mark Raistrick; Senergy

11.50 to 12.30 **Discussion**

12.30 to 13.30Lunch

Session 6 Emerging and Innovative Monitoring Technologies Chair: Don White; NRCan

13.30 to 13.50 In Salah Satellite Imaging: Kevin Dodds; BP

13.50 to 14.10 In Salah Satellite Data: Takumi Onuma; JGI

14.10 to 14.30 Real Time Integrated Monitoring: Guillemette Picard; Schlumberger

14.30 to 15.00 Electrical Results from Ketzin: Conny Schmidt-Hattenberger; German Research Centre for Geosciences

15.00 to 15.30 Thermal Monitoring at Ketzin: Barry Freifeld; LBNL

15.30 to 16.00 **Discussion**

16.00 to 16.20 Break

16.20 to 17.30 **Conclusions:** Key learning for other networks and summing—up including topics for next meeting: Tim Dixon; IEA GHG, Toshi Matsuoka; University of Kyoto and Kevin Dodds; BP

Close Day 2

4th June 2009 Nagaoka Site Trip

08.00	Meet in lobby of Sapia Tower 1F
08.24	Shinkansen Max/Toki 309 for Nagaoka
10.14	Arrive at Nagaoka Station
10.30	Bus to CO_2 Capture Plant of INPEX
12.00	Bus to Nagaoka CO_2 Injection Site
12.40	Bus to New Hotel Otani
13.10 to 14.00	Lunch at New Hotel Otani

Option 1

14.31	Shinkansen from Nagaoka to Tokyo arrive 16.20
Or	
15.10	Shinkansen from Nagaoka to Tokyo arrive 17.00

Option 2

14.30	Bus to Japanese rice wine factory
15.00	Tasting Sake (rice wine)
16.00	Bus to Nagaoka Station
17.39	Shinkansen Max/Toki 340 for Tokyo
19.20	Arrive Tokyo station

5th IEA GHG Monitoring Network Meeting

2nd-3rd June 2009, Tokyo, Japan

Attendee List

Masanori Abe	Japan CCS Company Limited
Chitoshi Akasaka	J-POWER
Andrew Chadwick	British Geological Survey
Zhenjie Chai	The University of Tokyo
Eric Davis	Pinnacle
Tim Dixon	IEA GHG
Kevin Dodds	BP Alternative Energy
David Etheridge	CSIRO Marine and Atmospheric Research
Hubert Fabriol	BRGM
Barry Freifeld	Lawrence Berkeley National Laboratory
Henry Alberto Garcia Pinto	Kyoto University
Sarah Hannis	British Geological Survey
Susan Hovorka	Bureau of Economic Geology
Charles Jenkins	CO2CRC
John Frame	EPA Victoria
Yoichi Kaya	RITE
David Larssen	Schlumberger Water Services
Toshifumi Matsuoka	Kyoto University
Richard Metcalfe	Quintessa Limited
Meguru Miki	Japan NUS Co. Ltd.
Saeko Mito-Adachi	RITE
Toshihiro Mitsuihashi	Ministry of Economy, Trade and Industry of Japan
Yuji Miyake	JOGMEC
Dai Nobuoka	OYO Corporation
Shigetaka Nakanishi	Electric Power Development Co. (J-Power)
Shinsuke Nakao	AIST
Yuji Nishi	AIST
Komei Okatsu	Japan Oil Gas and Metals National Corporation
Takumi Onuma	JGI, Inc.
Nobukazu Soma	AIST
Kano Koji	ENAA SEC
Toyokazu Ogawa	Nippon Steel
Guillemette Picard	Schlumberger Carbon Services
Sohei Shimada	The University of Tokyo
Takeshi Sasakura	Kajima Corporation
Cornelia Schmidt-Hattenberger	German Research Centre for Geosciences - GFZ
Sandeep Sharma	CO2CRC and Schlumberger
Chiaki Shinohara	Japan NUS Co., Ltd.
Steven Smith	Energy & Environmental Research Center
Masao Sorai	AIST
James Sorensen	Energy & Environmental Research Center
Lee Spangler	Montana State University
Ann Troelsgaard Sørensen	Vattenfall R&D
Masaru Toida	Kajima Technical Research Institute
Fumio Takahashi	The General Environmental Technos Co., Ltd.
Takashi Takehara	AIST
Atsuko Tanaka	AIST
Daiji Tanase	J-power
Mark Thrupp	Chevron Australia Pty Ltd
Toshiyuki Tosha	AIST
Robert Trautz	Electric Power Research Institute
Claudia Vivalda	Services Petroliers Schlumberger
Klaus Udo Weyer	WDA Consultants Inc.
Donald White	Geological Survey of Canada
Neil Wildgust	IEA GHG
Ziqiu Xue	Kyoto University
Hajime Yamamoto	Taisei Corporation
Tsukasa Yoshimura	ENAA SEC
Mark Raistrick	Senergy Alternative Energy
Mark Thrupp	Chevron Australia Pty Ltd
Komei Okatsu	Japan Oil Gas and Metals National Corporation
Osamu Nishizawa	AIST
Ikuo Okamoto	RITE