2ND CO_2 GEOLOGICAL STORAGE MODELLING NETWORK MEETING

Report: 2010/ 06

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INTERNATIONAL ENERGY AGENCY

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DISCLAIMER AND ACKNOWLEDGEMENTS

IEAGHG 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 IEAGHG as a record of the events of that workshop.

The 2nd international research network on CO_2 Geological Storage Modelling was organised by IEAGHG in co-operation with University of Utah The organisers acknowledge the financial support provided by US Department of Energy, Southwest Partnership CO_2 Sequestration, NETL, EGI, USTAR, Headwater Clean Carbon Services and the University of Utah for this meeting and the hospitality provided by the hosts at the University of Utah Officers Club.

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

Neil Wildgust, IEAGHG (Chairman)
Isabelle Czernichowski, BRGM
Gabriel Marquette, Schlumberger
Sascha van Putten, Shell
Tess Dance, CO2CRC
Stefan Bachu, Alberta Innovates - Technology Futures
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Executive Summary

The second meeting of the IEAGHG International Research Network on CO_2 Geological Storage Modelling was hosted by the University of Utah in Salt Lake City, on February 16th and 17th, 2010. The meeting comprised four technical sessions: Modelling Methodology and Recent Advances, Integrated Roles and Objectives of Modelling, Modelling of Real Storage Projects; Case Studies and International Efforts towards Best Practice and Modelling Protocols. The agenda was designed to provide ample time for discussions between participants, with breakout groups in sessions 1 and 2, and plenary discussions following sessions 3 and 4.

Discussions following Session 1 focussed on recent advances in modelling. Current theoretical and laboratory scale research has continued to advance our understanding of the processes which will control the behaviour of stored CO2 in the subsurface and govern potential leakage mechanisms. However, there was a consensus that an increased number of large-scale storage projects are required to provide data with which modelling methods can be calibrated.

Priorities for modelling R&D were discussed after the presentations in Session 2. Topics that participants felt were of pressing concern for modellers and in need of further research included:

- Storage engineering options, e.g. brine extraction;
- Wettability and relative permeability;
- Rates of CO_2 dissolution into formation brines;
- Efficiency of capillary trapping;
- Coupling of processes, and the merits of modelling processes separately to aid up-scaling (the 'divide and conquer' approach);
- Realistic boundary conditions for flow modelling.

Session 3 included presentations on modelling of real projects by representatives from Statoil, Shell Australia, the US Regional Partnerships Programme, RITE and CO2CRC. This provided scope for a lively debate, and in summing up the presenters made the following concluding remarks:

- Objectives of modelling and history matching need to be defined. Fluid models are often not critical to history matching, but heterogeneity is important.
- Models need to provide a range of possible outcomes, which can be refined with time and experience.
- Initial pilot/demonstration injection projects are vital to obtain data for predictive models.
- Current models can give good estimations, despite existing knowledge gaps – the objectives of modelling need to be defined.
- Quality of input data is vital for modelling and it is important to understand the limitations of simulations and associated outputs.

The plenary discussion following Session 4 was intended to elicit opinion from the participants on the merits of formulating best practice guidelines or protocols for modelling, and possible involvement of the network in such projects. The care required to ensure guidelines are not overly prescriptive and recognise the site-specific nature of storage projects was emphasised by several participants. Many delegates also felt that the network could be more effective in providing recommendations for best practice rather than formal guidelines. The meeting concluded that protocols emerging from the US Regional Partnerships Program and other international efforts could be placed in an international context at future network meetings.

Contents

Introduction

The second meeting of the IEAGHG International Research Network on CO_2 Geological Storage Modelling was hosted by the University of Utah in Salt Lake City, on February 16th and 17th, 2010. The meeting was attended by 58 participants from 9 countries.

Neil Wildgust of IEAGHG welcomed the delegates and the thanked the university for hosting the meeting, before introducing the agenda for the two days. Brian McPherson of the University of Utah, thanked the sponsors of the meeting; the US Department of Energy, Southwest Partnership CO_2 Sequestration, NETL, EGI, USTAR, Headwaters Clean Carbon Services and The University of Utah, before describing outcomes of the previous network meeting hosted by BRGM in Orleans, France in February 2010. Brian proceeded to list some objectives for the 2010 meeting, these included:

- Comparison of analytical to numerical approaches;
- Evaluation of current efficacy of coupling of various processes;
- Review of recent advances;
- Review of pore-scale modelling and efficacy of up-scaling;
- Review of regulators' needs;
- Review of storage capacity estimation methods;
- Review of simulation for risk assessment;
- Review of simulation for carbon credits evaluation;
- Review of international case-studies;
    - Site characterisation
    - Model calibration
- Review of Best Practices and Protocols;
    - DOE/NETL Effort
    - International Effort
    - Standards/Criteria?
- Model comparison?
- Development of a "Community" code?

Brian also reminded the audience that the meeting agenda was designed with the aim of maximising discussion time and hoped that all delegates would be actively engaged.

The following sections of this report outline the presentations given during the meeting and summarise discussions both in plenary and breakout sessions. Copies of the presentations (Appendix I) are also available on the network page at the IEAGHG website:

www.ieaghg.org/index.php?/2009112536/modelling-network-members-area.html.

Session 1: Modelling Methodology and Recent Advances

1.1 Numerical versus Analytical Approaches, Jan Nordbotten, Bergen University, Norway

Jan described the complexities and uncertainties associated with predictive modelling and the associated mathematical challenges. The CO_2 'problem' can be framed with the following questions: how fast can we inject, where does it go, and how much may leak? Answers that can be derived will be a function of many factors including the expert user, model choices, data acquisition, scaling issues, choice of numerical methods and interpretation.

Jan described model realisations ranging from 'simple' analytical approaches to full-physics, numerical simulations, and illustrated these with field examples of predicted leakage from old wells in Alberta and reservoir permeability in the Norwegian North Sea. Results of benchmarking exercises co-ordinated by the University of Stuttgart have shown that parameterisation of models is more important than choice of code.

He concluded his talk with the following points:

- Mathematical model describing geological storage can only be solved approximately;
- Analytical and numerical methods represent the end-members of a suite of approximation strategies;
- The balance and value of either approach must be judged carefully for any given application, as not only quantitative, but qualitative errors may be introduced;
- The uncertainty introduced in approximate solutions must be seen also in the context of uncertainties in the overall geological description.

Questions from the audience related to up-scaling of heterogeneity and flow, from pore scale into modelling grids. Jan confirmed this as a challenging area for researchers, and also explained that analytical models can be usefully applied to check results from more complex approaches.

1.2 Coupling of Processes, Karsten Pruess, Lawrence Berkeley National Laboratory, USA

Karsten described the significance of coupling processes and some of the challenges involved, by describing some potential interactions of processes as summarised in Table 1 below.

To illustrate potential thermal effects, Karsten described leakage through open wellbores and accumulations of CO_2 at shallow depth. Chemical effects were considered in respect of water-rock interactions affecting caprocks, whilst mechanical effects were described in terms of pressure induced slipping of faults. Karsten also described how coupling of flow and chemical effects could be used to assess rates of CO_2 dissolution into formation brines.

Table 1. Examples of Process Interactions

Coupling Aspects	Thermal Effects	Chemical Effects	Mechanical Effects
Flow	Changes in: • Fluid density • Fluid viscosity • Surface tension • Capillary pressure • Relative permeability	Changes in porosity, permeability; weakening of caprock capillary entry pressure	Changes in porosity, permeability;
Chemical	Temperatures partly control fluid-rock reactions and associated kinetics		Stress concentrations along fractures and faults could promote leakage
Mechanical	Thermally induced stress	Dissolution of minerals in fractures/faults could lead to shear failures and leakage; loss of well integrity due to cement degradation	

Karsten concluded his presentation with the following points for discussion:

- Coupling of processes is most important in connection with failure scenarios (caprock and well integrity: leakage along fractures, faults, and wells; mediated by chemical and mechanical processes, accompanied by strong thermal effects; mobilisation of contaminants);
- There is a need for mathematical process models and system parameters on appropriate scales (e.g., rates of fluid-rock reactions; *in situ* stresses and stiffness of joints; anisotropic conductivity of faults);
- Observations must be made at appropriate scales (i.e. natural analogues, field tests);
- The alternative approaches to F-T-C-M (Fluid-Thermal-Chemical-Mechanical) process modelling: full coupling vs. “divide and conquer” by tackling individual processes;
- Effective modelling of multi-scale effects, such as convectively-enhanced dissolution of CO_2, remains a difficult challenge.

In answer to various questions and comments, Karsten agreed that CO_2 could impact wetting properties and is a topic that requires better understanding, as long term trapping processes could be affected. Although coupling of processes could be regarded as less important for high quality reservoirs, an understanding of coupling processes is required for integrity aspects. Karsten also agreed that induced seismicity is an important area of research for public reassurance over storage safety.

1.3 Advances in Modelling of Experiments, Mike Krause, Stanford University, USA

Mike described core scale experimentation at Stanford University used to assess the ability of models to re-create experimental observations, and discussed the factors that affect this correlation.

Mike concluded his talk by stating that the accuracy of modelling core-flood experiments can vary from poor to very good, depending on sample permeability and heterogeneity; that accurate permeability representation is critical; and that these studies can be used to further investigate other effects such as residual trapping and the influence of factors including relative permeability, capillary pressure and gravity.

In response to various questions, Mike commented as follows:

- Creating realistic experimental conditions was challenging;
- Capillary pressure measurements were all converted to CO_2-brine values;
- Further research is focussing on gravitational effects;
- Based on history matching and a homogeneous modelling grid, relative permeability curves showed an endpoint of 0.2; this will be further assessed using a heterogeneous grid.

1.4 Pore Scale Processes, Thomas Dewers, Sandia National Laboratory, USA

Thomas gave a detailed technical presentation, looking at modelling methodologies as applied to pore scale processes, with particular emphasis on caprock pore networks.

The presentation was concluded with the following points for discussion:

1. Where(or what?) is best role/niche for pore scale modelling in CCS?
2. To what extent is pore shape, pore-lining mineralogy, and organic content as or more important than pore throat size in predicting multiphase flow behaviour in reservoir and seal lithologies?
3. How best to account for stress/pore pressure effects in stress-sensitive materials?
4. How best to upscale (include in continuum scale) so as not to lose important dynamic information?
5. To what extent does the initial structure (arrangement of permeable and impermeable strata) control the flow pattern of a reactive perturbation?
6. What other methods for pore network characterization can be brought to bear (e.g. 3D TEM, Neutron Scattering).

Thomas explained that the alternative simulations shown were examples to illustrate that a variety of approaches are available. Research is being used to assess fracture structures in caprocks at a variety of scales.

Session 2: Integrated Roles and Objectives of Modelling

2.1 Simulation for Capacity Analysis – Effects of Pressurisation, Andrew Cavanagh, Permedia Research, Canada

This presentation focussed on the topical issue of pressurisation of deep saline formations during CO_2 injection, including research currently being undertaken for a study commissioned by IEAGHG. Limitations imposed by compressibility mean that efficient use of pore space for storage capacity requires displacement of pore fluids during injection.

In this context, Andy showed how assumed boundary conditions become critical for estimation of storage capacity and predictive modelling. Examining empirical relationships between threshold pressure, permeability, porosity and depth, Andy discussed the validity of closed (impermeable) conditions for modelling. Such assumptions would be at odds with, for example, field observations of hydrocarbon accumulations in the North Sea.

The talk concluded that: closed boundaries for predictive models are only valid for extreme low-permeability caprocks (in the order of nanodarcies, or 10^{-21} m^2) ; rock matrix porosity is unlikely to be the dominant flow medium in shales and consequently, micro- or meso-scale measurements may not provide valid constraints for macroscopic flow simulations.

2.2 Simulation for Regulators, Gregory Schnaar, DB Stephens and Associates, USA

This talk focussed on how modelling can be used to support protection of potable aquifers, and posed the question as to whether regulations can ensure that modelling is performed 'correctly'.

The presentation concluded with the following challenges for future permitting:

- Reducing and characterizing model sensitivity and resulting uncertainty;
- Incorporating data from disparate scales and of varying quality;
- Demonstration of model comparison to monitoring data and calibration;
- Modelling pressure dynamics, including dissipation;
- Development of integrated platforms.

2.3 Simulation for Risk Assessment (RA), Mike Stenhouse, INTERA, USA

This presentation outlined a broad overview of risk assessment frameworks for CO_2 storage, modelling tools available and uncertainty.

Mike's talk covered the following themes:

- Frameworks for the RA process – these already exist, so no development work is needed in this area;
- RA, including treatment of uncertainties, is likely to be an important and necessary component of submission to regulators;
- Risk management is also important – this effectively means the inclusion of remediation plans to gain regulator and public confidence;
- Natural analogues *can* provide useful fields of study;

- Biosphere potential impacts are currently an active area of research'

Mike concluded his talk by posing the question – would public domain simulation codes help build confidence in storage assessment?

2.4 Performance Targets and Storage Site Closure, Marius Lunde, DNV, Norway

This talk was based on work undertaken in the CO2QUALSTORE project, with emphasis on reservoir simulations for performance targets (PT) and the assessment of uncertainty and risk for site closures.

Marius described how PT's are determined within the context of risk management frameworks, and how this process can be used to unify industry approaches, facilitate effective regulations, and accelerate CCS deployment by increased confidence in the safety of the technology. Governmental requirements from the EU and US were cited as examples of how PT's form an integral part of regulation.

Closing remarks in the presentation were as follows:

- PT's create project-specific ways to help demonstrate fulfilment of qualification goals;
- PT's enable regulators to present and assess their concerns along with the project developers, and developers to know within which frameworks they need to operate all the way from the initial stage;
- PT's that are closure-oriented assist transfer of liability by providing provable targets that are set and agreed upon by all parties;
- Use of reservoir simulations helps demonstrate control of the uncertainties in the prediction of capacity, injectivity and containment, i.e. effective control of site operations.

2.5 Breakout Groups from Sessions 1 and 2: Discussion of Recent Advances; Where Should R&D Efforts Focus to Improve Modelling Results?

Delegates were divided into 3 breakout groups for discussion sessions at the end of sessions 1 and 2 on Day 1. The groups provided feedback from their discussions on the morning of Day 2 (Appendix A). The following provides a brief account of common themes that emerged from the breakout group's feedback.

Recent Advances

Since the number and scale of operational CO_2 storage projects around the world has not increased significantly since the first network meeting of 12 months previous, some of the debates queried whether major advances have been made. There was also discussion on the value of laboratory scale research in the context of the need to implement CCS on an industrial scale, for example the IEA 2009 CCS Roadmap stipulates that 100 commercial scale storage projects need to be in operation by 2020.

Despite the problems associated with up-scaling of properties to predictive site modelling, research at the laboratory/core scale still advances scientific understanding, which is particularly relevant to caprock studies and potential leakage mechanisms.

Nevertheless, there was also recognition that large scale storage demonstration projects are urgently required to provide new learnings and insights into storage, in the context of widespread industrial development. The linked issues of pressurisation and brine displacement in deep saline formation storage are key to widespread deployment. Whilst several modelling efforts are looking at these topics and other related issues including risks to groundwater and induced seismicity, demonstration projects again are required to really demonstrate the capacity, injectivity and integrity of deep saline formations for CO_2 storage.

Future R&D Focus

The discussions on priority issues for R&D inevitably threw up some of the knowledge gaps highlighted by the discussion sessions in the first network meeting in Orleans (Appendix B), and reference should be made to the summary report of that meeting, (IEAGHG Report 2009/05)

Discussions in the breakout groups again emphasised the urgent need for large scale demonstration projects, plus research/pilot scale work for particular topics, e.g. controlled leakage, or unconventional storage media such as basalts and shales.

Topics that participants felt were of pressing concern for modellers and in need of further research included:

- Storage engineering options, e.g. brine extraction;
- Wettability and relative permeability;
- Rates of CO_2 dissolution into formation brines;
- Efficiency of capillary trapping;
- Coupling of processes, and the merits of modelling processes separately to aid up-scaling (the 'divide and conquer' approach);
- Realistic boundary conditions for flow modelling.

Session 3: Modelling of Real Storage Projects: Case Studies

Calibration with Monitoring Results

3.1 Sleipner and In-Salah, Varun Singh, Statoil, Norway

Varun described modelling work undertaken for the Sleipner and In Salah projects. He described the key insights that Statoil have gained from their experience of injection projects:

1. The Sleipner data (time-lapse seismic) implies a CO_2 plume where gravity is dominant and plume dispersion is significantly less than initially supposed;
2. The In Salah plume (well observations and InSAR data) is strongly influenced by fracture flow and geo-mechanical response.

Both projects are showing that detailed specification of reservoir simulation input data is key to any meaningful long-term forecasting.

In answer to a question, Varun stated that Statoil had used non-standard, migration modelling as dictated by monitoring data.

3.2 Otway, Jonathan Ennis-King, CO2CRC, Australia

Jonathan presented a comprehensive summary of modelling efforts for the Otway project. Key aspects presented can be summarised as follows:

- Calibrated numerical models can reproduce the key features of the monitoring data e.g. breakthrough curves, seismic amplitude difference. But there are always surprises!
- The objective should be a suite of history matches, so that model uncertainties can be estimated.
- Comparison of field sampling data and simulation requires a detailed understanding of the physics of the sampling.
- Downhole gauge data (pressure and temperature) are very valuable for calibrating the geological model.
- Heterogeneity has an important influence on breakthrough curves, and needs careful characterisation.
- Tracer simulation needs improvement. Do other couplings matter here?

In answer to a question from the audience, Jonathan confirmed that history matching was computed manually to allow the best possible fit of modelling with monitoring data.

3.3 Nagaoka, Saeko Mito-Adachi, RITE, Japan

After giving an overview of the Nagaoka pilot project, Saeko described history matching of modelling with the monitoring results of the injection and post-injection phases. The presentation concluded with the following important points:

- Anisotropy of permeability in the reservoir is a critical parameter to fit simulation results to monitoring results in the Nagaoka case;
- Feedback of monitoring results is necessary to improve long-term prediction of CO_2 behaviour by allowing calibration of predictive models with real-world data;
- The project will provide the first field data set of residual gas saturation and dissolved CO_2, although it needs to be stressed that the salinity of the formation brine is relatively low (measured as 10,000ppm at the injection point), thus increasing potential for dissolution compared to many saline formation storage prospects which may have salinity an order of magnitude higher.

Saeko confirmed that the permeability of the storage formation was relatively low, with a measured permeability of 7mD, common to many Japanese storage prospects.

Simulation for Site Characterisation

3.4 Mount Simon Sandstone, Scott Frailey, ISGS and MGSC, USA

This presentation was based on experiences gained during the Illinois Basin Decatur Project. The storage unit is present within a thick sequence of Cambrian sandstones at depths of between 5,405’ (1,647m) and 7165’ (2,184m), with measured horizontal permeability in the injection zone of 26mD.

Scott gave a detailed description of experiences and insights gained from site investigation and associated laboratory testing programmes, with the focus very much on establishing a sound geological model with realistic representations of geological heterogeneity and associated permeability anisotropy. Scott summarised the key messages from his talk as follows:

- Water injection in the well had been used to validate the geologic model of injection zone; very good agreement had been established between the results of core analysis, logging and pressure tests;
- The project had established a unique method used to transform core porosity to well log porosity;
- Vertical permeability is very important to plume distribution, and is extremely sensitive to scale (grid size issues for modelling);
- The project has produced a non-unique geologic site model for layer heterogeneity.

Scott concluded by emphasising that significant model uncertainty can be expected for reservoir characterization in thick, porous and permeable formations, due to the difficulty of upscaling data from core analysis and field testing of limited intervals.

In response to questions, Scott was unable to comment on possible fractal relationships illustrated by graphical plots, and confirmed that vertical pore scale index had not been taken into account in work to date.

3.5 Shell Australia Methodology, Aman Chauhan, Shell, Australia

This talk described the Shell workflow for site selection, evaluation and modelling, before outlining some lessons learnt from dynamic modelling to date. The basic workflow for storage assessment involves establishment of geological setting (containment), pore volume (capacity), injectivity and then dynamic modelling, the latter being sensitive to grid sizes, capillary pressures and vertical heterogeneity.

Aman firstly showed how choice of grid size in numerical models can have a dramatic impact on results. Coarse grid block sizes, often used for initial assessments can distort results, e.g. showing slower vertical migration, or leading to faster breakthrough times but with corresponding longer periods to achieving high saturation. Grid size sensitivity should always be assessed.

The talk then focussed on relative permeability curves, examining some of the experimental effects such as solubility issues, mobility ratios and fluid compressibility that can create difficulty in interpreting test results. Aman posed the questions – can pH reduction alter wettability, and what is the effect of capillary trapping?

The effects of capillary pressures for shale layers were also discussed. Aman concluded that modelling of the lateral continuity, frequency and orientation of shale layers is critical and needs to be explicitly modelled.

In wrapping up his talk, Aman posed some technical discussion points for the meeting, including the need for experimentation to capture: three phase mutual solubility; the effects of wettability alteration on hysteresis; better understanding of relative permeability; and upscaling issues for core scale capillary trapping results due to gravity override.

3.6 Panel Debate on Modelling from Real Projects

The panel debate for the 5 presenters in Session 3 took the form of a question and answer session. The panel members Aman Chauhan (AC), Varun Singh (VS), Jonathan Ennis-King (JEK), Saeko Mito-Adachi (SMA) and Scott Frailey (SF) gave the following responses to questions and comments from the audience.

Q: Could AC confirm that he does not consider critical gas saturation to be an important parameter?

AC: Critical gas saturation is not an important consideration in comparison to capillary threshold pressure.

Q: Could AC give some further comment on up-scaling issues?

AC: Up-scaling from coarse to fine grids was performed using 'pseudo' properties, but not for dynamic up-scaling.

Q: How successful was the use of tracers for the Otway project – the presentation mentioned a need for improvement.

JEK: Tracer data at Otway was considered to be good, some scattering was observed and this may be due to some sticking to seals.

Q: Can VS comment on which wells were used to inform the In-Salah model?

VS: Modelling realisations were based on 2 wells, with further borehole control available if needed.

Q: Can VS comment on the permeability of the storage formation at In-Salah, is the low permeability a problem?

VS: Seismic data used to populate the pre-injection fracture model suggested a low permeability, whilst actual injection revealed a slightly higher permeability. Actual data will always result in changes to initial models. It is definitely not the case that 200mD is too impermeable for injection projects; permeability must be considered in relation to other site-specific factors.

Q: Can SMA comment further on the earthquakes that occurred at Nagaoka?

SMA: There is no evidence that the two earthquakes that occurred in the Nagaoka region were either caused by the injection project, or resulted in damage to the storage site.

Q: Capillary pressure effects are strongest at the interface between CO_2 and brine and therefore less significant at reservoir scale?

AC: Capillary pressure effects will become more significant in reservoirs with marked heterogeneity, which can be anticipated in most real geological situations.

Q: Can AC comment if solubility be changed to reduce the effects of model grid size?

AC: The effect of grid size on modelling results can be reduced by assuming solubility equal to zero, but this is not considered to be realistic.

Q: Is the water injection testing in the Decatur project widely practised?

SF: Water injection testing as used to validate the Mount Simon Sandstone model is not 'standard' practice, but was based on practical considerations of not damaging the reservoir and this technique has been used by the oil and gas industry in the past.

Bert van der Meer, who chaired the debate, then asked the panel what lessons they had learnt from their projects. The responses were:

- Objectives of modelling and history matching need to be defined. Fluid models are often not critical to history matching, but heterogeneity is important.
- Models need to provide a range of possible outcomes, which can be refined with time and experience.
- Initial pilot/demonstration injection projects are vital to obtain data for predictive models.
- Current models can give good estimations, despite existing knowledge gaps – the objectives of modelling need to be defined.
- Quality of input data is vital for modelling and it is important to understand the limitations of simulations and associated outputs.

Bert wrapped up the debate by reminding the meeting of the importance of a conservative approach to modelling, as CCS timescales are long and potential impacts could be long lasting. Good data are also essential to meaningful modelling.

Session 4: International Efforts towards Best Practice and Modelling Protocols

4.1 SACS/CO2Store Aquifer Storage, Bert van der Meer, TNO, Netherlands

Bert presented work resulting from modelling work on the Sleipner injection scheme that formed part of the SACS/CO2Store best practice manuals (BPM). A basic description of the geological setting of the Sleipner storage site was given, and Bert emphasised that available data is essentially restricted to that derived from regional well logging and seismic surveys.

Two alternative modelling approaches had underpinned the BPM, based on differing methods employed by SINTEF (Norway) and TNO. The resulting models are however in broad agreement and provide a reasonable match to seismic monitoring of the plume development. One key difference in the model assumptions was that TNO assumed shale layers within the Utsira Sand storage formation were continuous with breakthrough governed by capillary entry pressure, whilst SINTEF assumed the presence of randomly distributed ‘holes’.

Bert stated that there were many misconceptions concerning storage in the scientific community, and finished his talk with the following questions:

- Do we have the responsibility to come up with realistic estimations?
- What (type of) data do we need?
- Are available simulators capable of predicting performance (both in the short and long term, noting CO_2 dissolution is not yet validated in the field)?

4.2 US DOE/NETL Regional Partnerships, Brian McPherson, University of Utah, USA

The US Regional Partnerships Programme aims to achieve a modelling practice comparison by evaluating model development practices of different groups within the regional partnerships. This special project initiative for US DOE/NETL, ‘Sim-Seq’, will utilise measured site characterisation data from one or more locations to provide the basis for a benchmarking exercise. A GS3 software platform will be used to facilitate common data management and modelling systems.

The ‘Sim-Seq’ initiative will encourage new approaches, improve model development and shed further light on modelling uncertainties. A key underlying aim of ‘Sim-Seq’ is to demonstrate that storage system behaviour can be demonstrated with confidence.

The results of the project will be utilised to feed into Best Practice Protocols for predictive modelling of the main storage scenarios – deep saline, enhanced oil recovery and enhanced coal bed methane. The accompanying Best Practice Manual will contain the following sections for each scenario:

1. Subject Processes (T-H-M-C-B, i.e., thermo-hydraulic-mechanical-chemical-biological processes)
2. Pre-Injection Simulation Analyses
3. During-Injection Simulation Analyses
4. Post-Injection Simulation Analyses

5. Collaboration, Technology Transfer Among Project Tasks (Site Characterization, MVA, Risk Assessment)
6. Integration with Surface Analyses
7. Code Standards and Selection
8. Modelling Practice Comparison

4.3 IEAGHG Weyburn-Midale Phase II, Ben Rostron, University of Alberta, Canada

After giving a brief overview of the CO2-EOR operations in the Weyburn and Midale fields and the associated IEAGHG Weyburn-Midale Monitoring Project (Phase II), Ben gave the following conclusions about best practices early in his presentation:

- Simulation studies are critical in integrating activities to form a coherent project;
- Geological storage needs different types of simulations;
- All simulations must honour geological and conceptual models;
- There is still a 'long way to go' in the development of simulation tools and techniques.

Ben went on to justify these statements by showing experiences and results derived from Weyburn. Key issues experienced had included: putting adequate geological representations into simulators (e.g. upscaling issues); incorporating realistic boundary conditions (e.g. initial conditions and pressure evolution; and matching numerical and conceptual models.

Phase II of the project will deliver a Best Practice Manual on utilizing CO2-EOR operations for geological storage, and guidelines for modeling will form a core part of that deliverable.

4.4 Plenary Discussion Session on Best Practice and Protocols

This plenary discussion session was designed to elicit opinion from the participants on the merits of formulating best practice guidelines or protocols for modelling, and possible involvement of the network in such projects.

The first comment from the audience warned that care needed to be taken in formulating guidelines, in not creating future problems. An example is the often quoted 1% leakage target over 1,000 years given in the IPCC Special Report on CCS – an arbitrary goal that has no scientific basis and that has been picked up by regulators. Notwithstanding this note of caution, project operators would perhaps welcome guidelines, provided that over-prescription was avoided. The site-specific aspects of predictive modelling should always be emphasised.

Some debate followed on semantics – for example, whether 'recommendations' would be more appropriate than 'guidelines', especially in relation to work that could be done under the umbrella of the network.

A suggestion was made that members of the network could come together to write a synthesis paper on a voluntary basis. However, it was pointed out that the IEAGHG wellbore integrity network had held similar ambitions, but in reality the constraints on members' time meant that the objective had never been achieved. 'Writing by committee' is a difficult task to co-ordinate.

Another suggestion was that the network could look to provide training materials, for example for professional development courses. However, a consensus view emerged that this would be straying into the territory of academia and consultancies.

There was a lively debate as to the growing tendency for industry to guard intellectual property rights, at the expense of knowledge sharing which is vital in the early deployment of CCS. A more optimistic note was struck by the example of industry and researchers working together in the Netherlands.

In summing up the discussion on best practice and protocols, Neil Wildgust thanked all the participants for engaging in this debate. IEAGHG would consider some of the comments and suggestions made, however Neil reminded the audience that the network has no formal resources and so work undertaken outside of meetings would rely on time donated by members or would require resources to be sanctioned by the IEAGHG Executive Committee (e.g. proposed studies arising from network suggestions).

Neil also pointed out that it could be a sensible strategy for the network to look at best practice guidelines and protocols emerging from the US Regional Partnerships Program and other regional efforts, before placing an international context on these projects at network meetings. There was also scope to gather specific modelling information as part of the 'What Have We Learnt' work activity, undertaken on a cyclical basis by IEAGHG on behalf of the GCCSI (Global CCS Institute).

Concluding Remarks at the Meeting

Neil Wildgust and Brian McPherson concluded the meeting by offering thanks to the hosts and sponsors for enabling the event to take place, to volunteers on the steering committee who had worked hard to set the agenda, to the excellent set of speakers and to all participants for their valued contributions in the meeting.

Neil also reminded the audience that presentations from the meeting would be posted on the network page of the IEAGHG website (www.ieaghg.org), and that a summary report of the meeting proceedings would follow. There is also an intention to launch a web-based discussion forum for the network in the near future.

Meeting Conclusions

Current theoretical and laboratory scale research has continued to advance our understanding of the processes which will control the behaviour of stored CO_2 in the subsurface and govern potential leakage mechanisms. However, there was a consensus that an increased number of large-scale storage projects are required to provide data with which modelling methods can be calibrated.

Priority topics identified for further research by the meeting included:

- Storage engineering options, e.g. brine extraction;
- Wettability and relative permeability;
- Rates of CO_2 dissolution into formation brines;
- Efficiency of capillary trapping;

- Coupling of processes, and the merits of modelling processes separately to aid up-scaling (the ‘divide and conquer’ approach);
- Realistic boundary conditions for flow modelling.

Presentation and discussion of modelling experiences from real projects in Session 3 provided the scope for debate and the following concluding remarks were made by the presenters:

- Objectives of modelling and history matching need to be defined. Fluid models are often not critical to history matching, but heterogeneity is important.
- Models need to provide a range of possible outcomes, which can be refined with time and experience.
- Initial pilot/demonstration injection projects are vital to obtain data for predictive models.
- Current models can give good estimations, despite existing knowledge gaps – the objectives of modelling need to be defined.
- Quality of input data is vital for modelling and it is important to understand the limitations of simulations and associated outputs.

Session 4 provided details on some of the current international efforts to provide best practice guidelines and protocols on modelling. A consensus view emerged that the network could best contribute to these efforts by encouraging collaboration and using future meetings to build towards recommendations for best practice, rather than formal guidelines.

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2nd CO_2 Geological Storage Modelling Network Meeting

Salt Lake City

16th—17th February 2010

University of Utah, Salt Lake City, USA

Organised by

IEAGHG and University of Utah

Hosted by

University of Utah

16th February 2010 Day 1

08.00 to 09.00 Registration

09.00 to 09.15	Welcome and Outline of agenda : Neil Wildgust; IEAGHG
09.15 to 09.30	Orleans workshop outcomes and objectives of this meeting: Brian McPherson; University of Utah

Session 1: Modelling Methodology and Recent Developments Chair: Karsten Pruess and Pascal Audigane

09.30 to 09.40	Introduction
09.40 to 10.00	Numerical Versus Analytical Aproaches: Jan Nordbotten; Bergen University
10.00 to 10.20	Coupling of Processes: Karsten Pruess; LBNL
10.20 to 10.40	Advances in Modelling of Experiments: Mike Krause; Stanford University
10.40 to 11.00	Pore Scale Processes: Grant Bromhall; NETL and Thomas Dewers; Sandia National Laboratory

11.00 to 11.30 Coffee Break Sponsored by Headwaters

13.00 to 14.00 Lunch

Session 2: Integrated Roles and Objectives of Modelling Chair: Brian McPherson and Neil Wildgust

14.00 to 14.10	Introduction
14.10 to 14.30	Simulation for Capacity Analysis: Effects of Pressurisation: Andrew Cavanagh; Permedia
14.30 to 14.50	Simulation for Regulators: Gregory Schnaar; DB Stephens & Associates
14.50 to 15.10	Simulation for Risk Assessment: Mike Stenhouse; INTERA
15.10 to 15.30	Simulation for Carbon Credits: Marius Lunde; DNV

15.30 to 16.00 Coffee Break Sponsored by Headwaters

16.00 to 17.30	Breakout discussion groups. Theme: Where Should R&D Efforts Focus to Improve Modelling Result?

17th February 2010 Day 2

08.00 to 09.30	Collated feedback from session 1 and 2

Session 3 Modelling of Real Storage Projects: Case Studies Chair: Anthony Michel and Bert van der Meer

09.30 to 09.35	Introduction
	Calibration with Monitoring Results
09.35 to 10.00	Sleipner and In Salah: Varun Singh; Statoil
10.00 to 10.25	Otway: Jonathan Ennis-King; CO2CRC
10.25 to 10.50	Nagaoka: Saeko Mito-Adachi; RITE

10.50 to 11.15 Coffee Break Sponsored by Headwaters

	Simulation for Site Characterisation
11.15 to 11.40	Mount Simon Sandstone: Scott Frailey ; ISGS and MGSC
11.40 to 12.10	Shell Australia Methodology: Aman Chauhan; Shell
12.10 to 13.00	Panel Discussion: Lessons Learnt from Modelling of Real Storage Projects

13.00 to 14.00 Lunch

Session 4 International Effort Towards Best Practice and Modelling Protocols Chair: Brian McPherson and Stefan Bachu

14.00 to 14.10	Introduction
14.10 to 14.30	SACS/CO2Store Aquifer Storage: Bert van der Meer; TNO
14.30 to 14.50	Sim-Seq: Jens Birkholzer; LBNL and Brian McPherson; University of Utah
14.50 to 15.10	Weyburn-Midale Phase 2: Ben Rostron; University of Alberta

15.10 to 15.30 Coffee Break Sponsored by Headwaters

15.30 to 16.30	Breakout discussion groups. Theme: Optimising Best Practices and Protocols to Maximise Confidence in Modelling as a CCS Tool: Potential Contribution of the Network
16.30 to 17.00	Final Discussion session and wrap up of meeting: Neil Wildgust; IEAGHG, Isabelle Czernichowski-Lauriol;

Close Day 2

18th February 2010 Day 3

Crystal Geyser Tour Sponsored by USTAR, Utah Science, Technology and Research initiative

07.00 Bus leaves from the University Guest House. Lunch will be provided

Crystal Geezer provides an excellent analogue for CO_2 geological storage and potential leakage mechanisms. Participants will need to bring suitable sturdy footwear (e.g. hiking boots) and warm outdoor clothing.

Evaluating technology options to mitigate greenhouse gas emissions

ATTENDEE LIST

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2nd CO_2 Geological Storage Modelling Network Meeting

16th—17th February University of Utah, Salt lake City, Utah, USA

Toby Aiken, IEAGHG
Pascal Audigane, BRGM
Alfredo Battistelli, Saipem SpA
Patrick Boisvert, CanmetENERGY
Andrew Cavanagh, Permedia Research
Eddy Chui, CanmetENGERY
James Damico, University of Utah
Thomas Dewers, Sandia National Laboratory
Jonathan Ennis-King, CO2CRC/CSIRO
Charles Gorecki, Energy & Environment Center
Cornelis Hofstee, TNO
Yuki Kano, Geological Survey of Japan/AIST
Michael Krause, Stanford University
Yann le Gallo, Geogreen
Marius Lunde, Det Norske Veritas
Eric May, University of Western Australia
Richard Metcalfe, Quintessa Limited
Saeko Mito-Adachi, RITE
Jean-Philppe Nicot, texas Bureau of Economic Geology
Jan Martin Nordbotten, University of Bergen
Karsten Pruess, LBNL
Ben Rostron, University of Alberta
Gregory Schnaar, Daniel B. Stephens & Associates Inc.
Varunendra Singh, Statoil
Michael Stenhouse, INTERA Inc.
Laurent Trenty, IFP
Lingli Wei, Shell
Mark White, PNNL
Yitian Xiao, ExxonMobil upstream Research Company

Chitoshi Akasaka, J Power
Stefan Bachu, Alberta Innovates – Technology Futures
Jens Birkholzer, LBNL
Grant Bromhal, USDOE/NETL
Lu Chuan, Energy and GeoScience Institute
Isabelle Chernichowski-Lauriol, BRGM
Milind Deo, University of Utah
Sevket Durucan, Imperial College London
Scott Frailey, Illinois State Geological Survey
Weon Shik Han, Energy and GeoScience Institiute
Venkata Pradeep Indrakanti, Leonardo Technologies
Anna Korre, Imperial College London
Si-Yong Lee, Energy and GeoScience Institiute
Fue-Sang Lien, University of Waterloo
John Mavor, Headwaters Clean Carbon Services (HCCS)
Brian McPherson, University of Utah
Anthony Michel, IFP
Emmanuel Mouche, CEA
Yuiji Nishi, Geological Survey of Japan/AIST
Dan Palombi, Alberta innovates - Technology Futures
Richard Rhudy, EPRI
Dave Ryan, Natural resources Canada
Darius Seyedi, BRGM
Joel Sminchak, Battelle
Robert Trautz, EPRI
Bert van der Meer, TNO
Klaus Udo Weyer, WDA Consultants Inc.
Neil Wildgust, IEAGHG
Qiang Xu, Chevron

Outcomes of Orleans and New Objectives

February 16, 2010

Brian J. McPherson

Department of Civil and Environmental Engineering
University of Utah

Lunch

(1) Walk across street; towards right, around bend.

Lunch

(2) At the bus stop, turn left and walk uphill.

Lunch

(3) Lunch in Heritage Center -- look for this building:

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Acknowledgements

Themes of Orleans

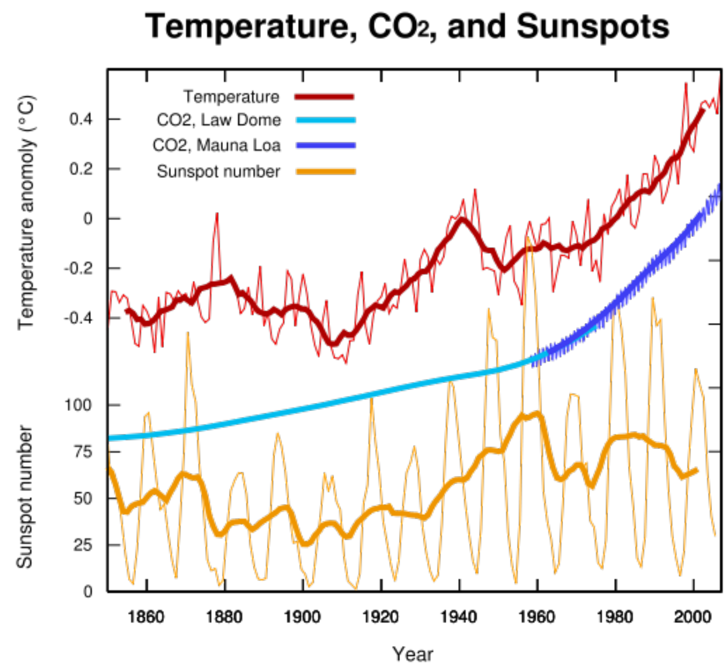
4 main themes:

1. Assessment Objectives for Modelling

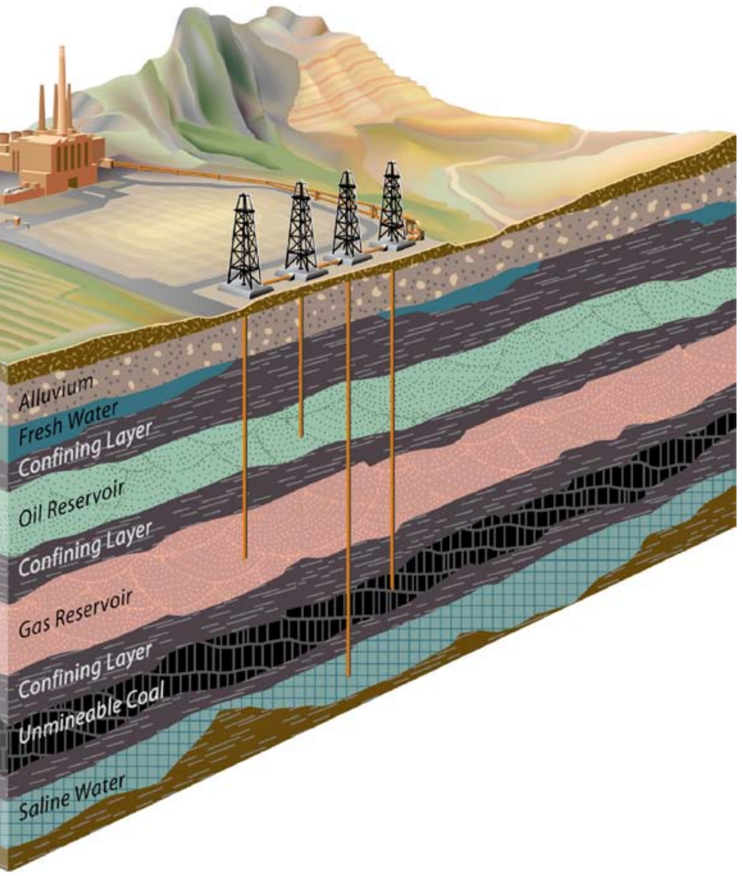
2. Physical and Chemical Processes

3. Special issues

4. Aims and Objectives for the Network



1. Assessment Objectives for Modelling



Chief Objectives:

- storage capacity evaluation
- injectivity forecasts
- caprock integrity assessment
- evaluation of potential leakage from wellbores and faults

Questions Discussed:

- How effective are current modelling methods for assessment of reservoir and caprock behaviour during injection?
- Are “current” modelling methods of leakage processes adequate?

Main Answers:

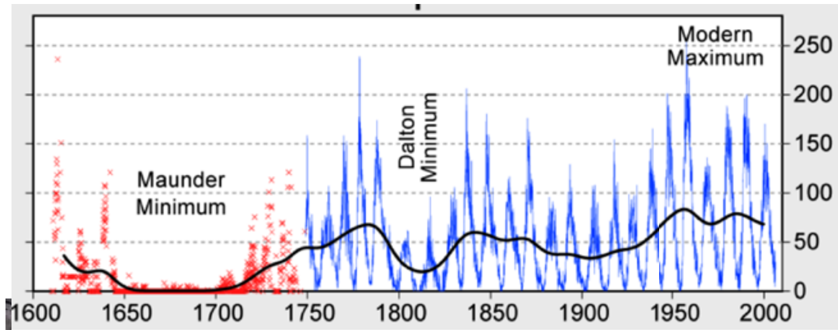
- considerable development work remains before modelling will be able to describe storage projects effectively
- more sharing of data and technology (methods) required

2. Physical and Chemical Processes

Key Processes:
- static geological models
- multiphase flow modelling
- geochemistry and reactive transport,
- geomechanics
- heat transfer.

Key Knowledge Gaps ("lacks"):
- coupling processes
- up-scaling of properties (e.g., pore to field scale)
- modelling representation of heterogeneity
- quality and availability of data

Key Parameters for Focus (uncertainty):
- relative permeability
- capillarity
- reaction kinetics
- stress fields
- fault and fracture properties
- deformation characteristics (compressibility)



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3. Special Issues

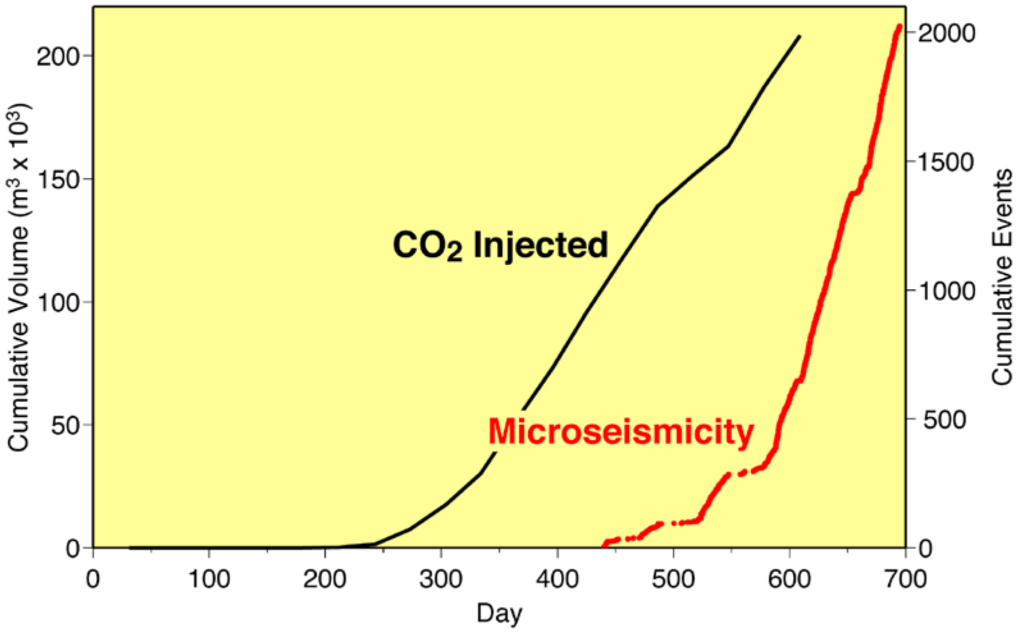
Topics of Discussion:

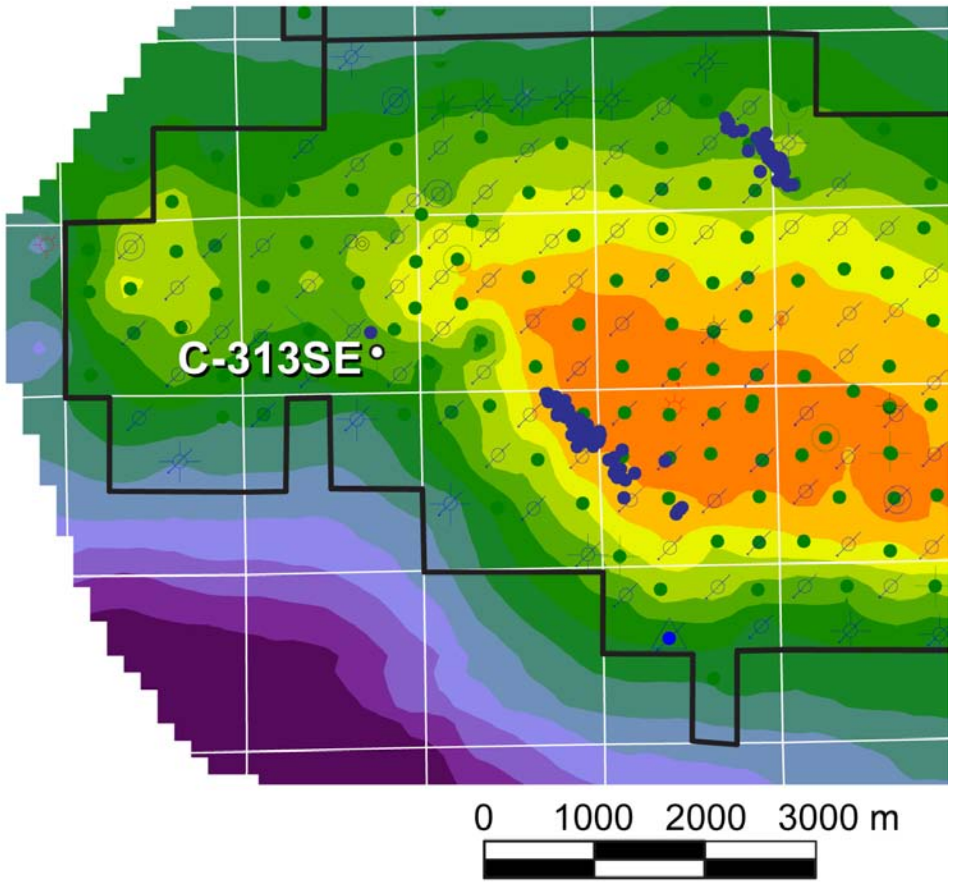
- code comparisons
- model comparisons
- numerical tool improvements
- relationship between modeling and monitoring
- relationship between modeling and risk assessment
- “degree of confidence” of current modeling practice

4. Aims of New Modeling Network

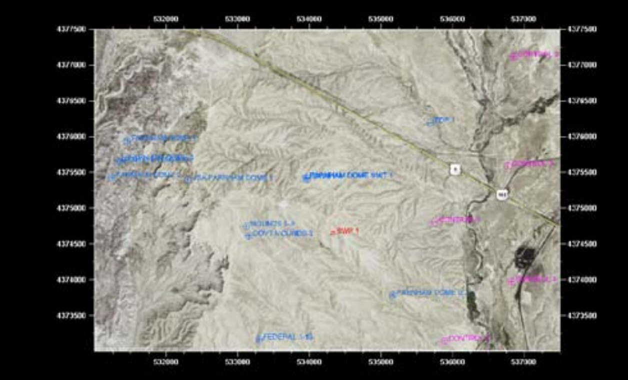
Agreement:

- form new network
- web-based discussion forum
- implement knowledge-sharing
- “modeling comparison” - NOT “code comparison” is a good goal
- development of international “Best Practices and Protocols” of geologic CCS modeling

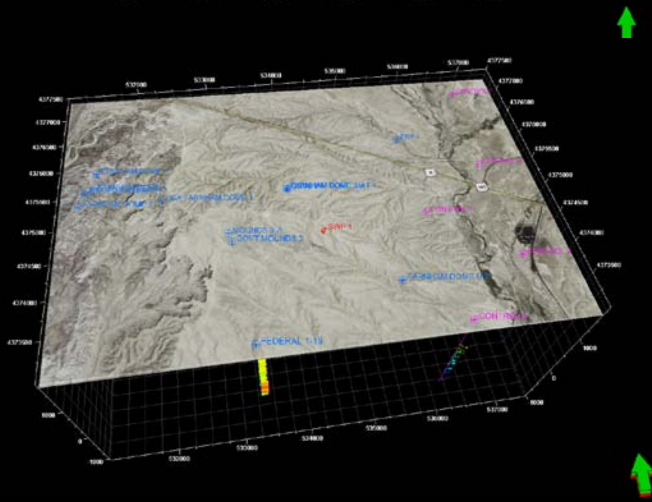


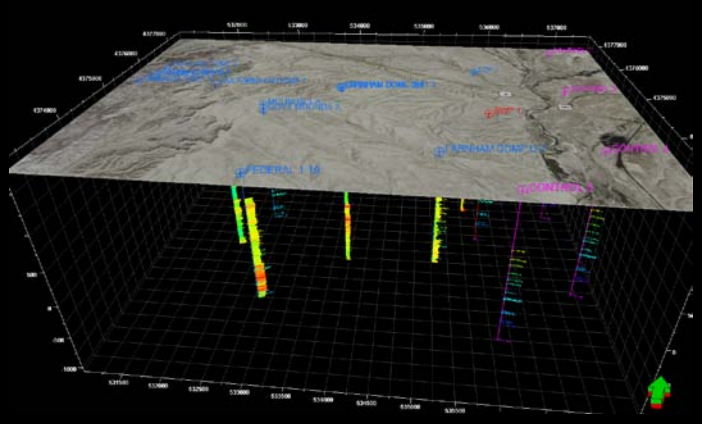


Proposed Objectives for 2nd Conference



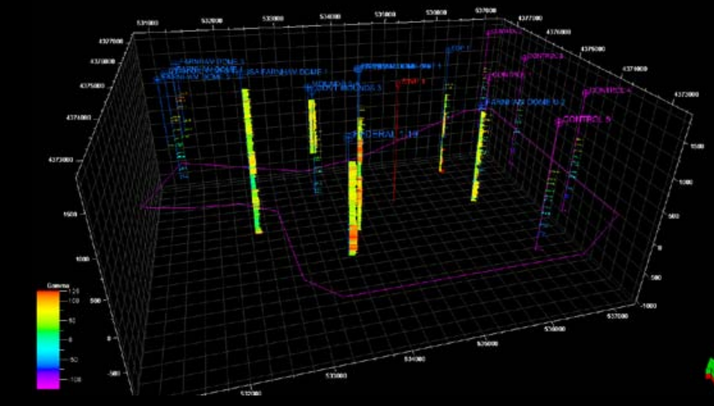
- Compare analytical to numerical
- Evaluate current efficacy of coupling
- Review recent advances
- Review pore-scale modeling and efficacy of up-scaling

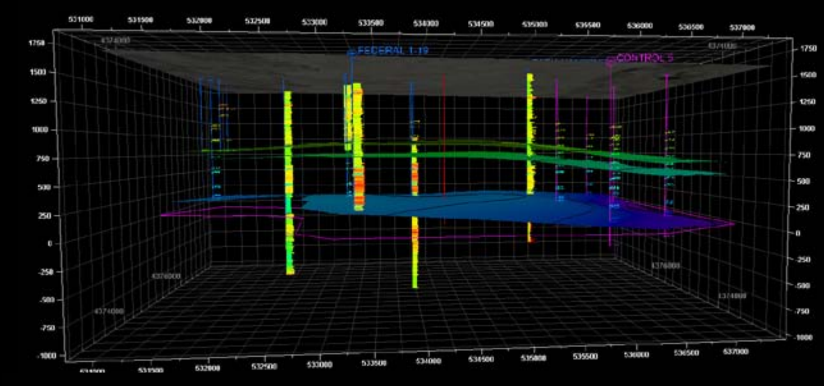


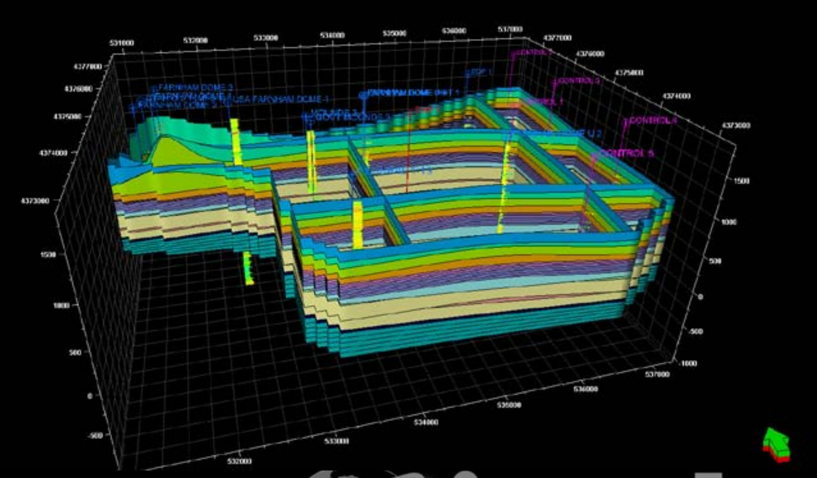


Proposed Objectives for 2nd Conference

- Review regulators’ needs
- Review capacity estimation methods
- Review simulation for risk assessment
- Review simulation for carbon credit evaluation



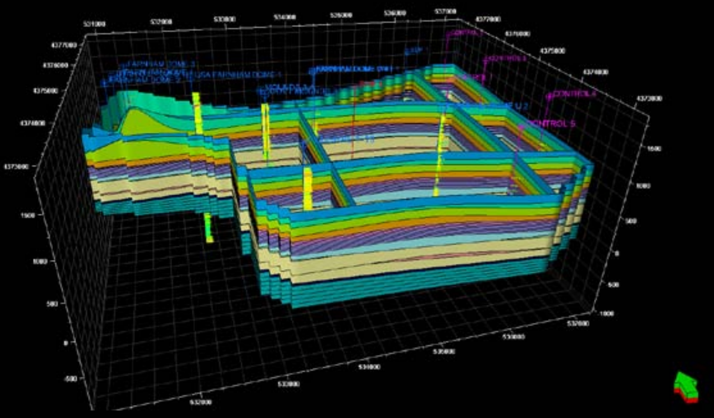


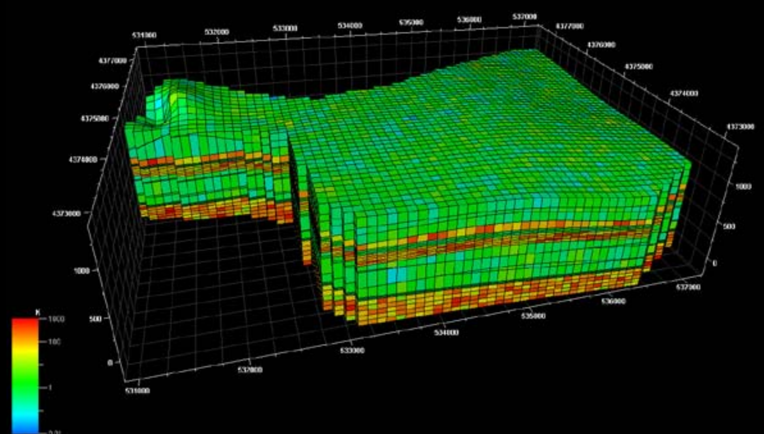


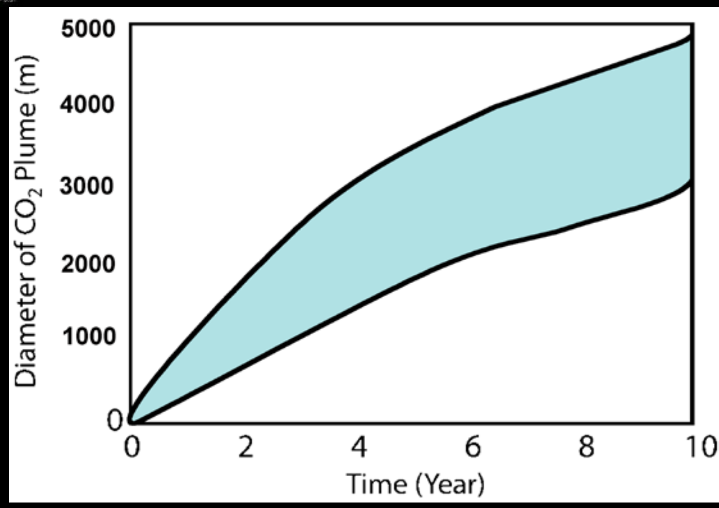
Proposed Objectives for 2nd Conference

- Review international case-studies:
  - site characterisation
  - model calibration

- Best Practices and Protocols
  - DOE/NETL Effort
  - International Effort
  - Standards/Criteria?
  - Model comparison?
  - Community code?







Proposed Objectives for 2nd Conference

MAIN EMPHASES:

- DISCUSSION
- COMMUNITY PLANS
- COMMUNITY PATH FORWARD
- INTERNATIONAL COLLABORATION

Introduction to 2nd IEAGHG Modelling Network Meeting

Neil Wildgust, IEAGHG.

University of Utah,

16 – 18 February 2010

IEAGHG


ALSTOM
B&W
power generation group
VATTENFALL
TOTAL
Statoil
BG GROUP
bp
CEZ GROUP
Chevron
Schlumberger
RWE
The energy to lead
CIAB
REPSOL YPF
ConocoPhillips
JGC
eni
GLOBAL CCS INSTITUTE
ExxonMobil
EPRI
e·on

IEAGHG Storage Networks

Modelling

Risk Assessment

- Next meeting May 17 - 19, hosted by Colorado SOM, Denver

Wellbore Integrity

- Next meeting April 28 – 29, hosted by Shell, The Hague

Monitoring

- Next meeting May 6 - 8, hosted by the Texas Bureau of Economic Geology, New Orleans

Social Research

Agenda – Day 1

Session 1: Methodology and Recent Developments

Session 2: Integrated Roles and Objectives

Evening Banquet Dinner

Agenda – Day 2

Feedback from Day 1 Breakout Groups

Session 3: Real Storage Projects: Case Studies

Session 4: Best Practice and Protocols

Field Excursion

Bus departs 7am Thursday from Guest House, for Crystal Geyser

Places still available, free of charge!

Warm clothing and sturdy footwear needed

Acknowledgements

Brian McPherson and the University of Utah

Steering Committee: ***Isabelle Czernichowski-Lauriol; Stefan Bachu; Karsten Pruess; Pascal Audigane; Sascha van Putten; Anthony Michel; Bert van der Meer; Tess Dance; Toby Aiken.***

Sponsors

1st Meeting Orleans 2009

Coupling of Processes

Karsten Pruess

Earth Sciences Division, Lawrence Berkeley National Laboratory (LBNL)

University of California, Berkeley, CA 94720

IEA Workshop on CO_2 Geologic Storage Modeling

University of Utah, Salt Lake City, Utah, February 2010

Overview

- Processes induced by CO_2 injection:
  Flow-Thermal-Chemical-Mechanical (F-T-C-M)
- Multi-scale aspects (space and time)
- Illustrative examples
- Thoughts for discussion

Thermal Effects

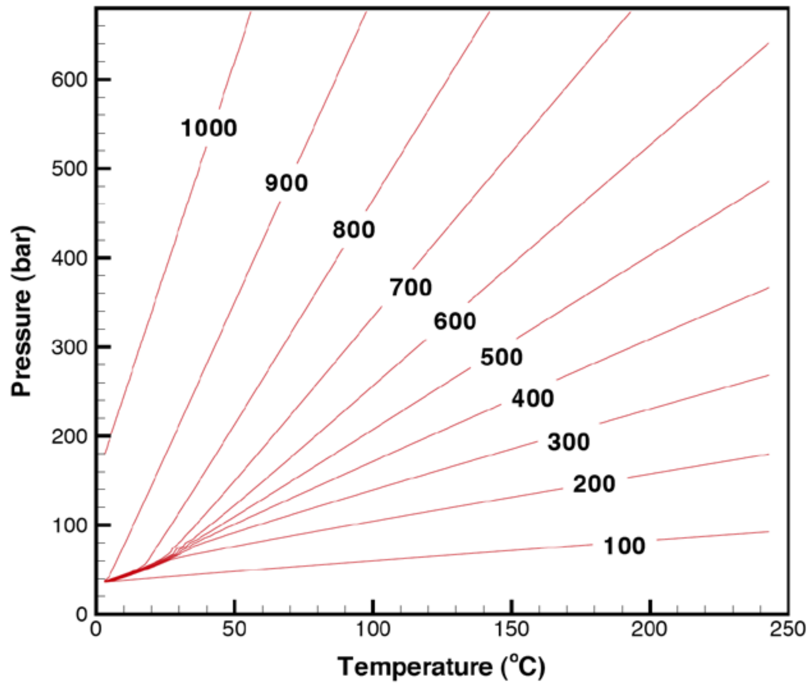
- Non-isothermal injection, such as cold CO_2 into hot formation
- Joule-Thomson cooling when CO_2 decompresses and expands
- Boiling of liquid CO_2 into gas (leakage in sub-critical T,P-regimes)
- Heat-of-dissolution effects are small

Couplings

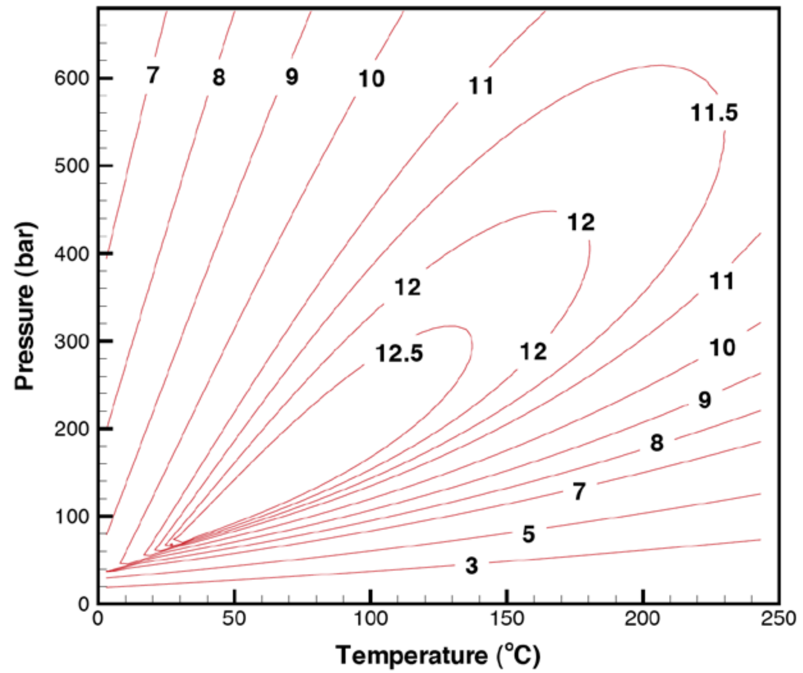
- ➢ (F) changes in fluid density and viscosity
- ➢ (F) changes in surface tension, capillary pressure, rel. perms.
- ➢ (C) fluid-rock reactions dependent on T
- ➢ (M) thermally-induced stress

CO_2 Thermophysical Properties

Density (kg/m^3)

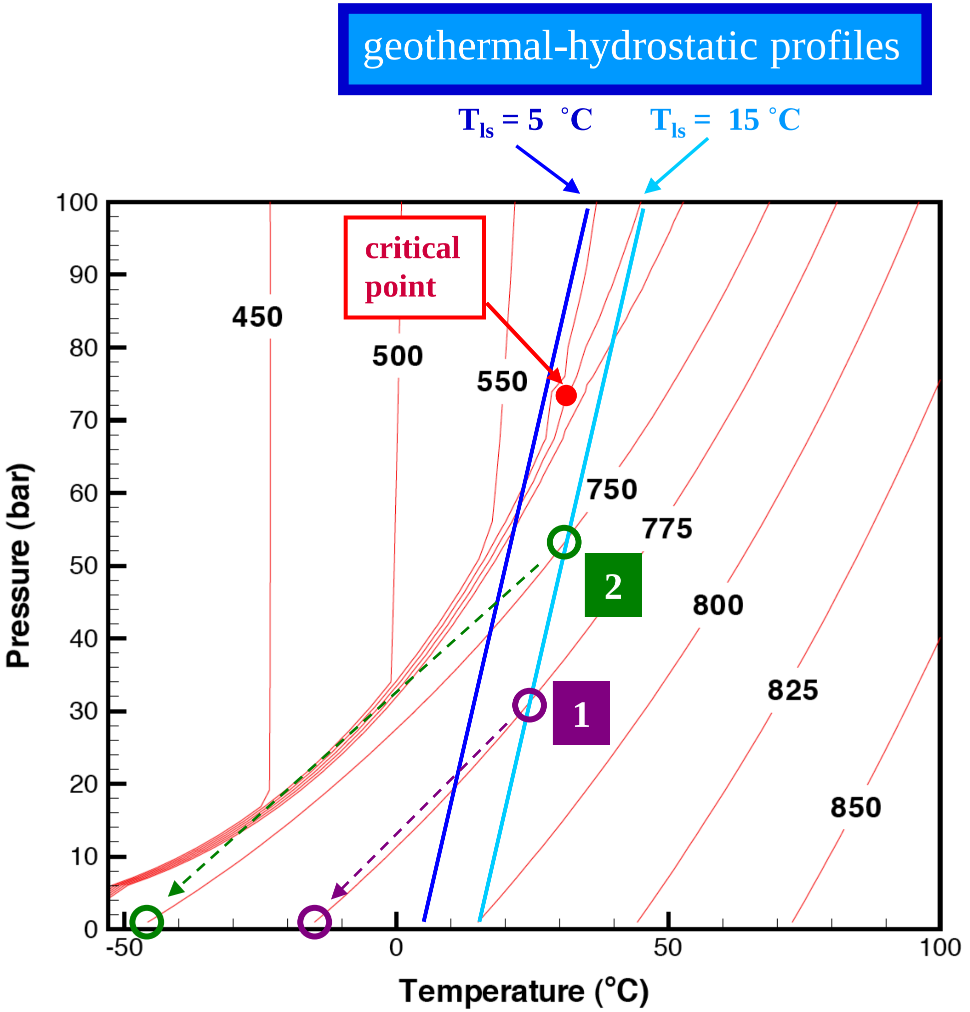


(Density/Viscosity) (10^6 s/m^{-2})



CO_2 Discharge through an Open Wellbore

(Joule-Thomson Cooling)



1

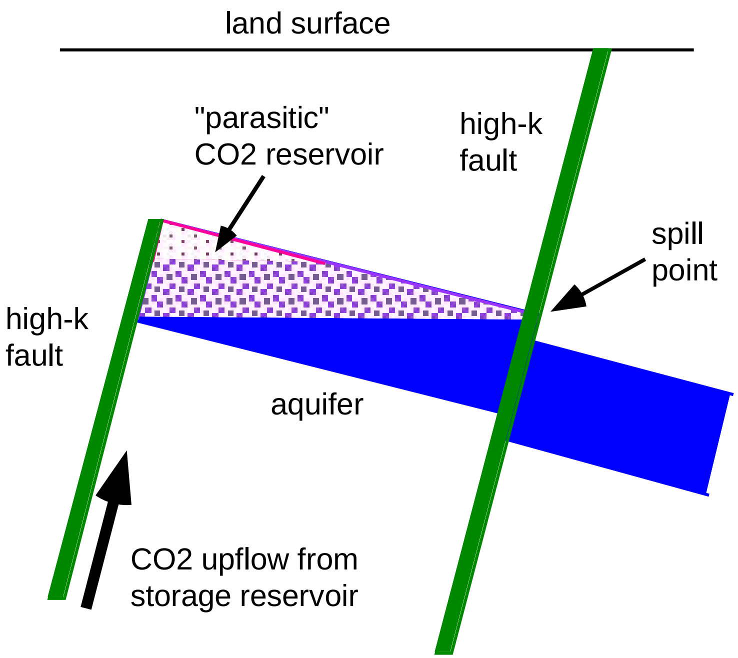
T ≈ 24 °C, P ≈ 30 bar
z ≈ 300 m

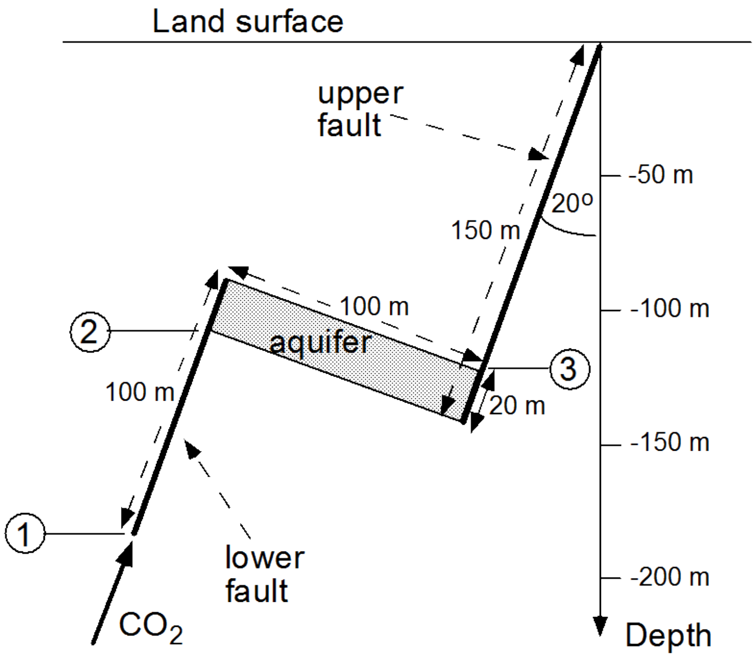
2

T ≈ 31 °C, P ≈ 54 bar
z ≈ 540 m

Expect formation of solid hydrate phases, water ice, dry ice.

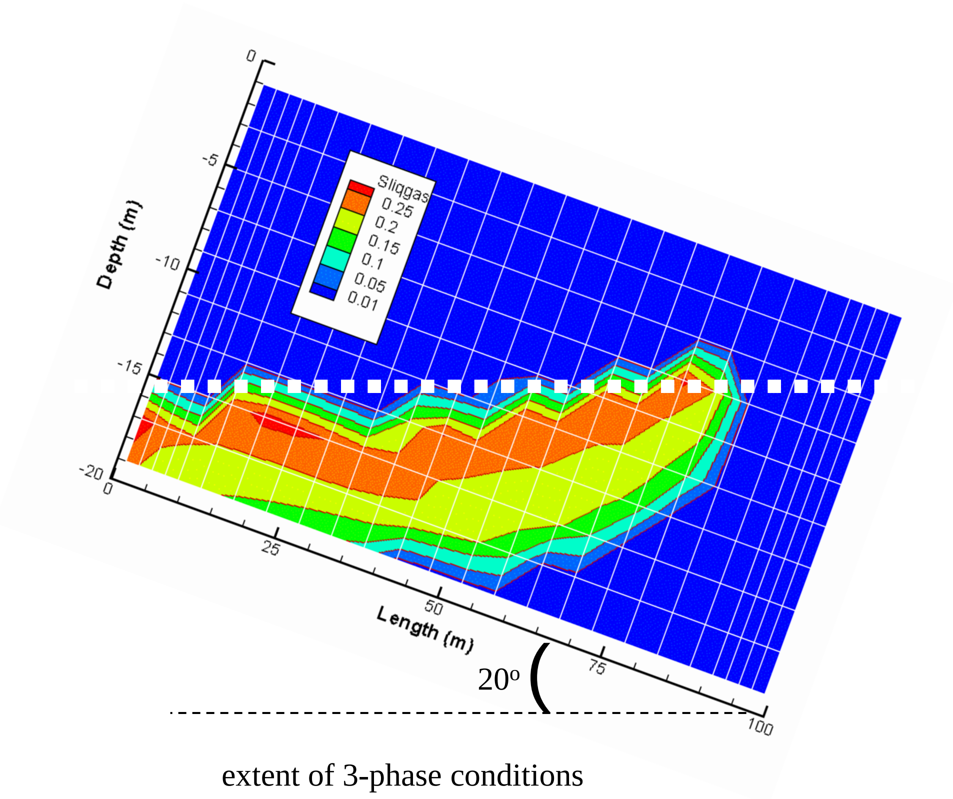
Leakage Scenario: Secondary CO_2 Accumulation at Shallow Depth



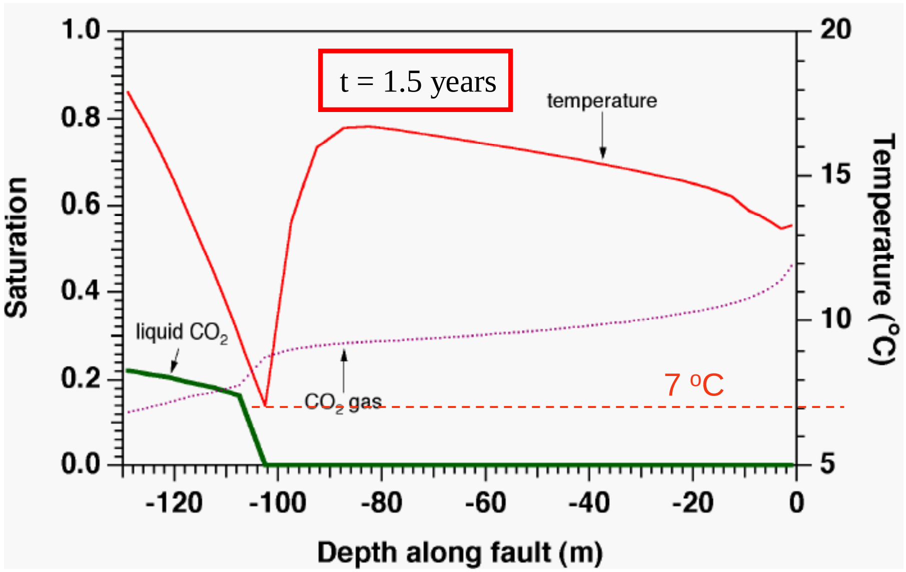


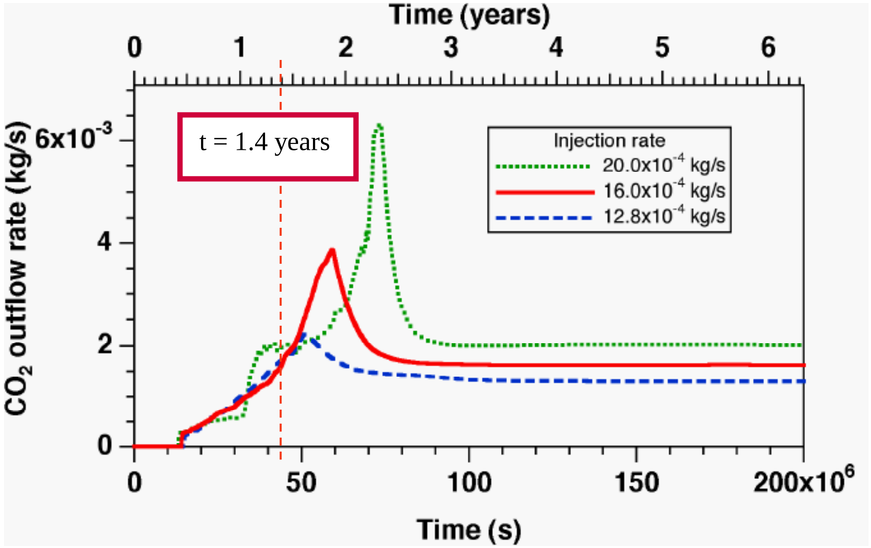
(Pruess, *IJGGC*, 2008)

Leakage Behavior



extent of 3-phase conditions
time = 1.4 years





Chemical Effects

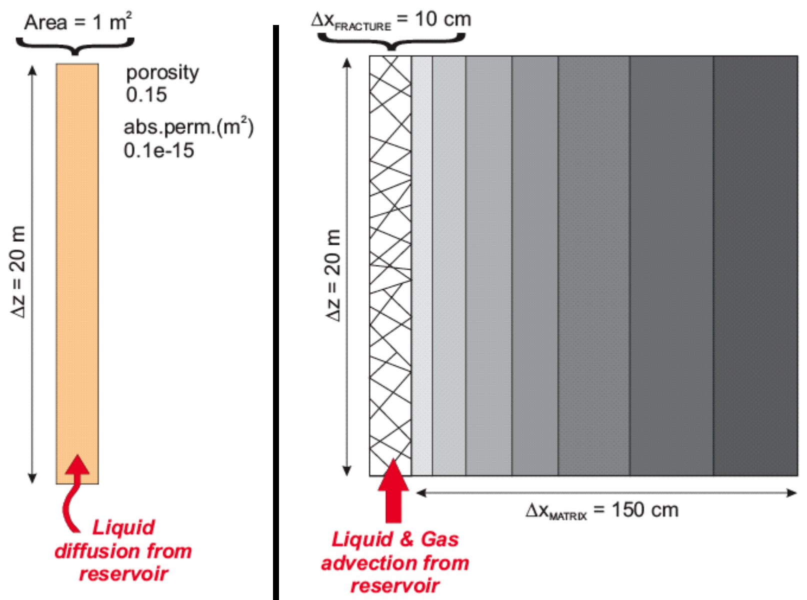
- Reactions with well construction materials (cement, casing)
- Dissolution of carbonate cements (concern in near-wellbore region and in caprock)
- Precipitation of minerals (improved sealing and long-term storage; issues for maintaining injectivity in near-wellbore region)
- Wettability alteration of mineral surfaces (concerns about containment)
- Mobilization of contaminants

Couplings

- ➢ (F) changes in porosity and permeability
- ➢ (F) loss of containment if P_{cap} weakens
- ➢ (M) loss of mechanical integrity as well and formation cements react with CO_2
- ➢ (M) dissolution in fractures and faults could facilitate shear failure and leakage

Water-Rock Interactions in a Caprock

(F. Gherardi, T. Xu and K. Pruess, *Chem. Geol.*, 2007)



unfractured caprock | fractured caprock

TOUGHREACT model: thermodynamic conditions, mineral composition, and aqueous chemistry representative of Northern Italian gas reservoirs.

Caprock Integrity - Main Findings

(Gherardi et al., 2007)

- In regions with free-phase CO_2, have net mineral dissolution with increased concentrations of aqueous species such as H^+, Ca^{2+}, HCO_3^-, CO_2(aq).
- When solutes migrate (diffuse, advect) into single-phase aqueous regions (caprock, wallrocks of fractures), pH tends to be more strongly buffered than [Ca^{2+}].
- This promotes precipitation (calcite etc.) in the region surrounding free-phase CO_2.
- Will tend to seal unfractured caprock, but will tend to increase porosity and permeability of pre-existing fractures.

Mechanical Effects

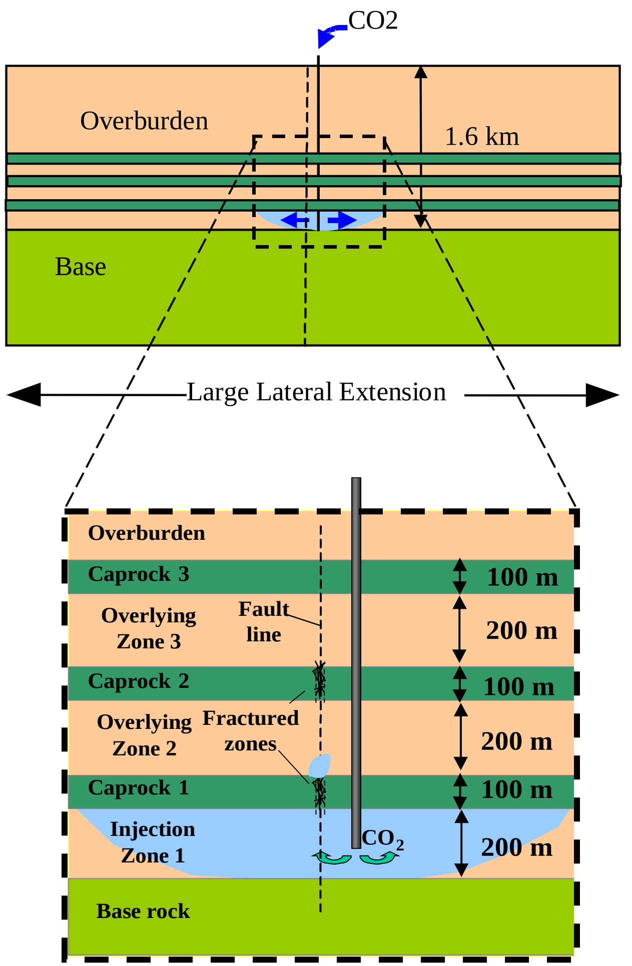
- Changes in porosity and permeability due to changes in pore pressure, effective stress
- Movement along fractures and faults
- Surface deformation (monitoring CO_2 storage as in In Salah)
- Induced seismicity

Couplings

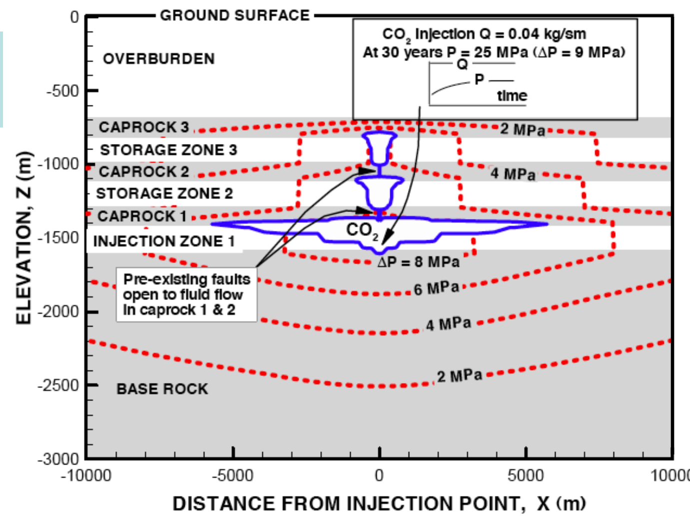
- (F) changes in porosity and permeability
- (F) movement along fractures and faults could promote leakage
- (C) stress concentrations at asperity contacts could promote dissolution

Geomechanical Coupling

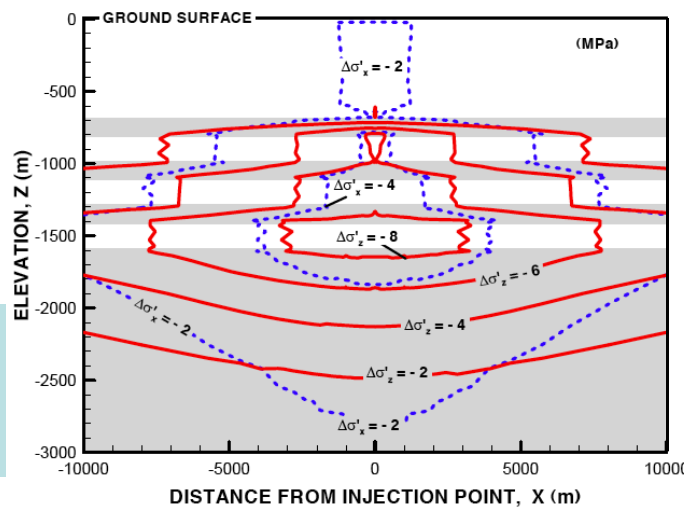
(Jonny Rutqvist, Jens Birkholzer, and Chin-Fu Tsang, *CO2SC Symposium*, Berkeley, March 2006)



CO_2 plume
pressure changes

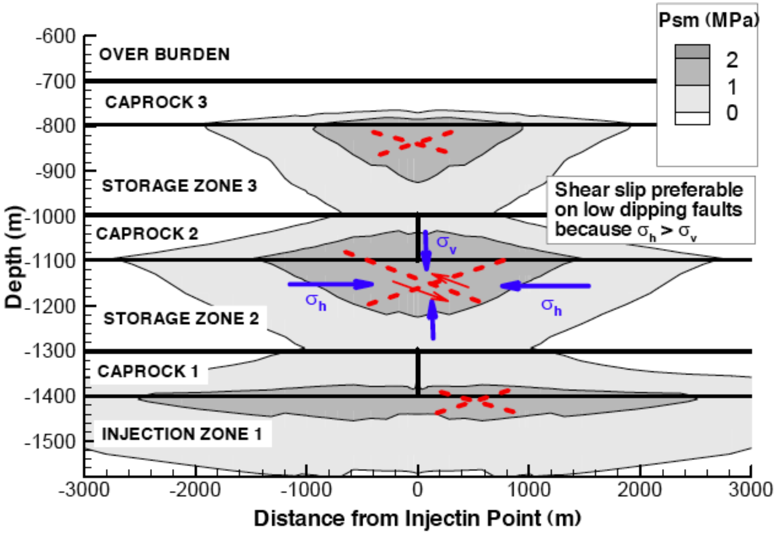


Changes in
Effective Stress
red - vertical
blue - horizontal

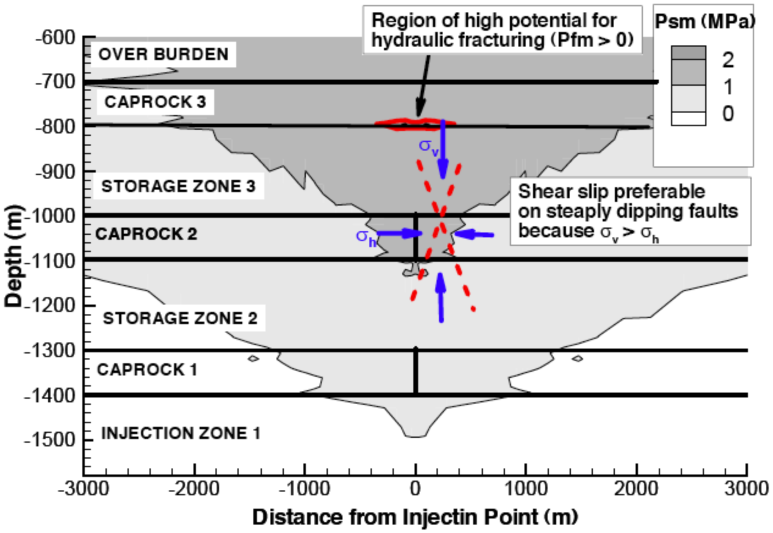


Pressure Margin for Slip of Cohesionless Faults

(Rutqvist et al., 2006, 2008)

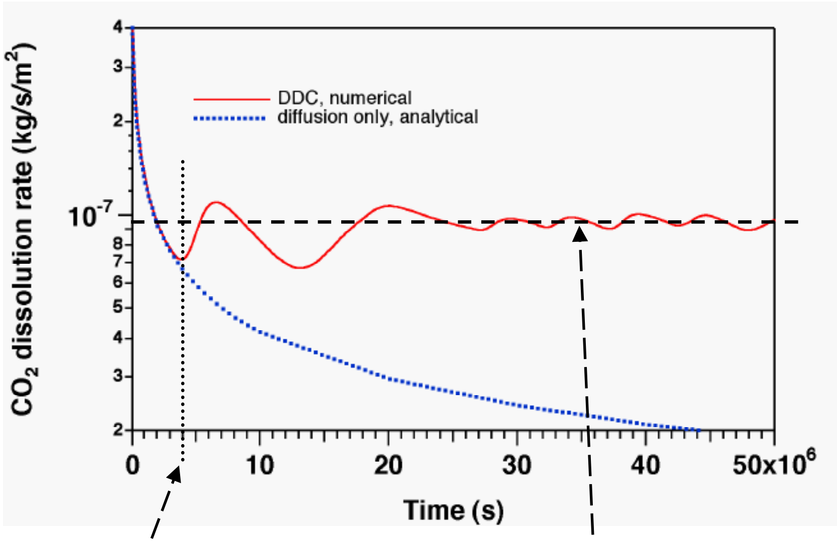


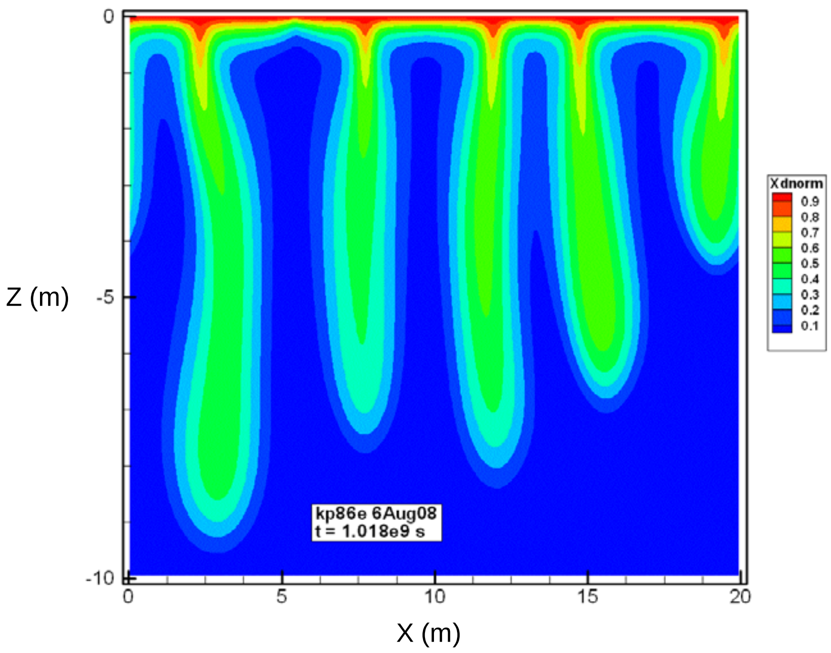
compressional stress regime with $\sigma_{hi} = 1.5\ \sigma_{vi}$



extensional stress regime with $\sigma_{hi} = 0.7\ \sigma_{vi}$

Multi-Scale Coupling: Convectively-Enhanced Dissolution of CO_2





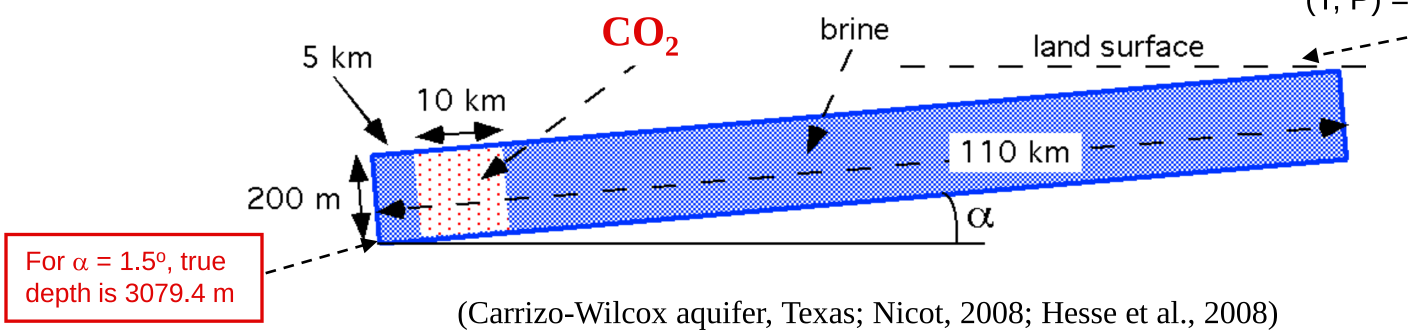
Onset of convection at $\approx 4 \times 10^6$ s (46.3 days)

Long-term stabilized CO_2 dissolution rate is approximately 10^{-7} kg/s/m^2

resolution: ΔZ = 1 mm, ΔX = 1 cm

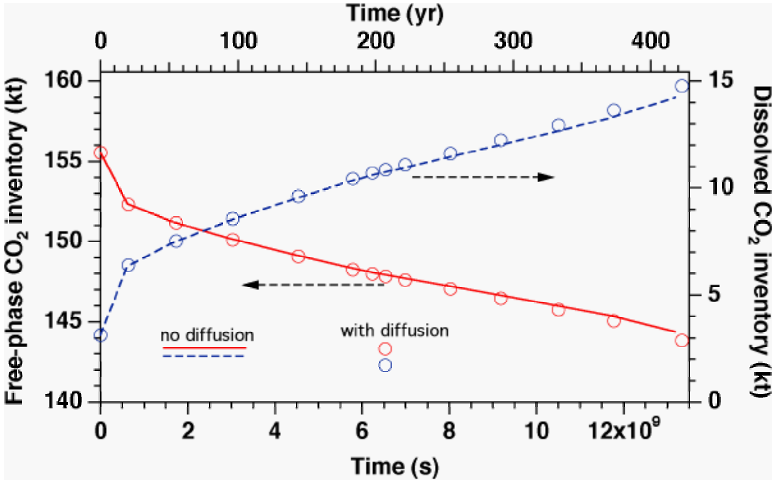
- dissolution-diffusion-convection starts on mm-cm scale
- continuously grows to reservoir scale

Coupling CO_2 Migration with Dissolution

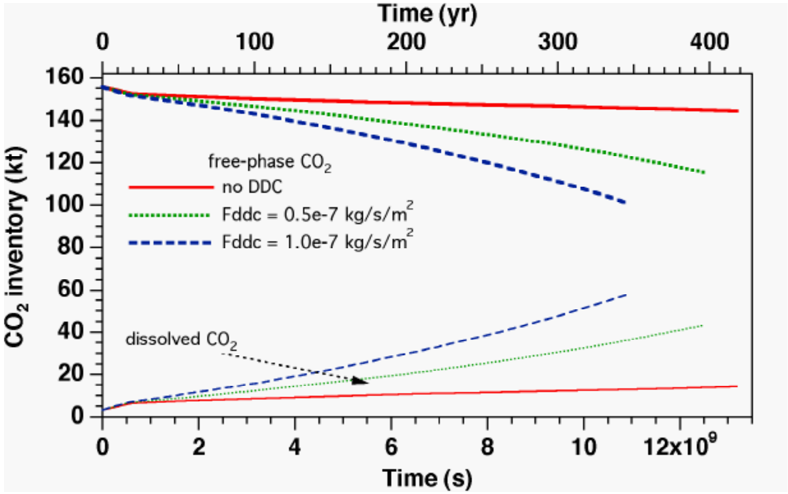


(Carrizo-Wilcox aquifer, Texas; Nicot, 2008; Hesse et al., 2008)

no sub-grid model for CO_2 dissolution



with sub-grid model for CO_2 dissolution



Some Thoughts on Coupled Modeling

- Coupling of processes is most important in connection with **failure scenarios** (caprock and well integrity: **leakage** along fractures, faults, and wells; mediated by chemical and mechanical processes, accompanied by strong thermal effects; mobilization of **contaminants**).
- Need: mathematical **process models** and system **parameters** on appropriate scales (e.g., rates of fluid-rock reactions; *in situ* stresses and stiffness of joints; anisotropic conductivity of faults).
- Need **observations** at appropriate scales (natural analogues, field tests).
- F-T-C-M process modeling: full coupling vs. "**divide and conquer**".
- Effective modeling of **multi-scale effects**, such as convectively-enhanced dissolution of CO_2, remains a difficult challenge.

Supported by the U.S. Department of Energy (DOE)

GCEP

Stanford University

Global Climate & Energy Project

IEA Greenhouse Gas R&D Programme
CO_2 Geological Storage Modelling
Tuesday February 16, 2010

Advances in Modelling of Experiments

Michael Krause, Jean-Christophe Perrin and Sally M. Benson
Department of Energy Resources Engineering
Stanford University

Science and technology for a low GHG emission world.

Acknowledgements

- Global Climate and Energy Project at Stanford University
- Jean-Christophe Perrin
- Sally M. Benson

What do we want to know?

How accurately can we model core-flooding experiments?

Specifically – Can we re-create the sub-core scale saturation distribution numerically as measured during the experiment

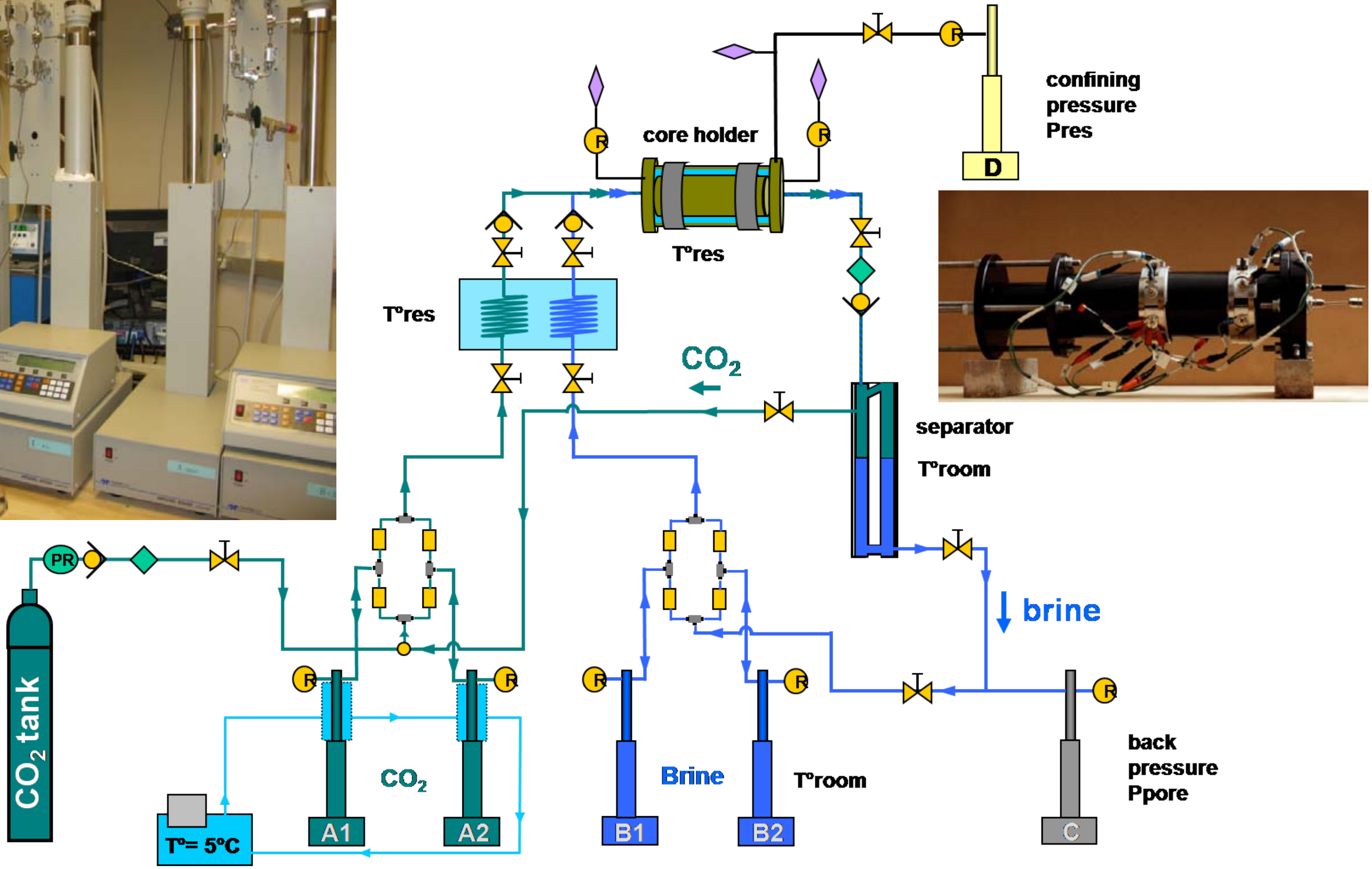
What does our ability to replicate these saturation distributions depend on?

Specifically – What property most limits our ability to match the experimental results

Outline

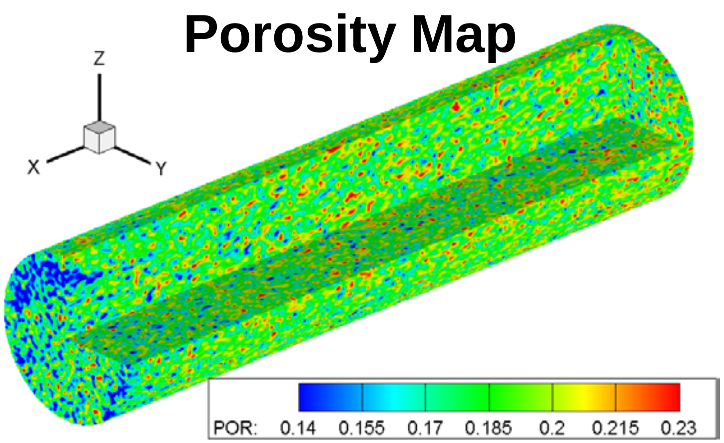
- Core flood experimental setup
- Experimental core flood results for one Berea core
- Show some different approaches taken to simulate the experiment
- Conclusions from simulation resulrs

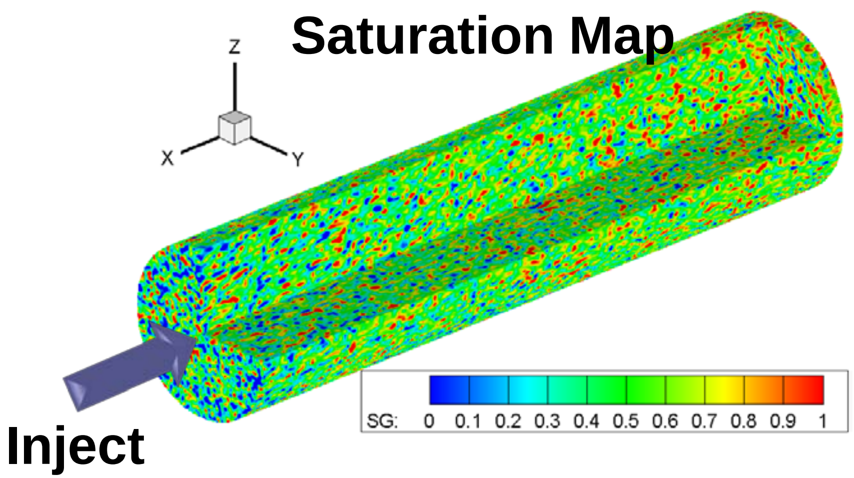
Experimental Setup (J.C. Perrin)



Experimental Measurements

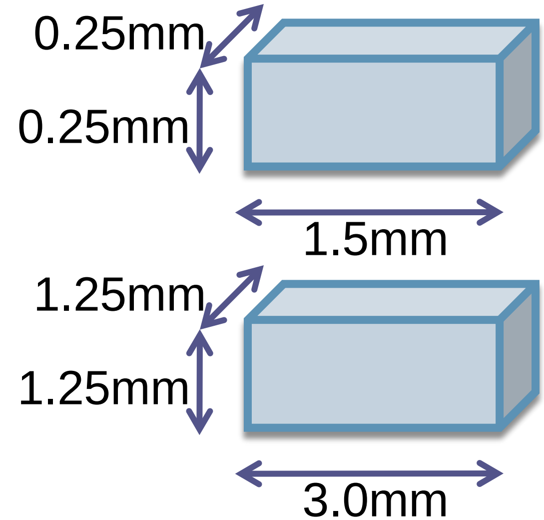
- Core average permeability and relative permeability
- Constant outlet pressure
  - 1800 psi
- Constant temperature
  - 50ºC
- Constant inlet total flow rate
  - 3 ml/min
- Medical CT-Scanner
  - Sub-core porosity
  - Sub-core saturation



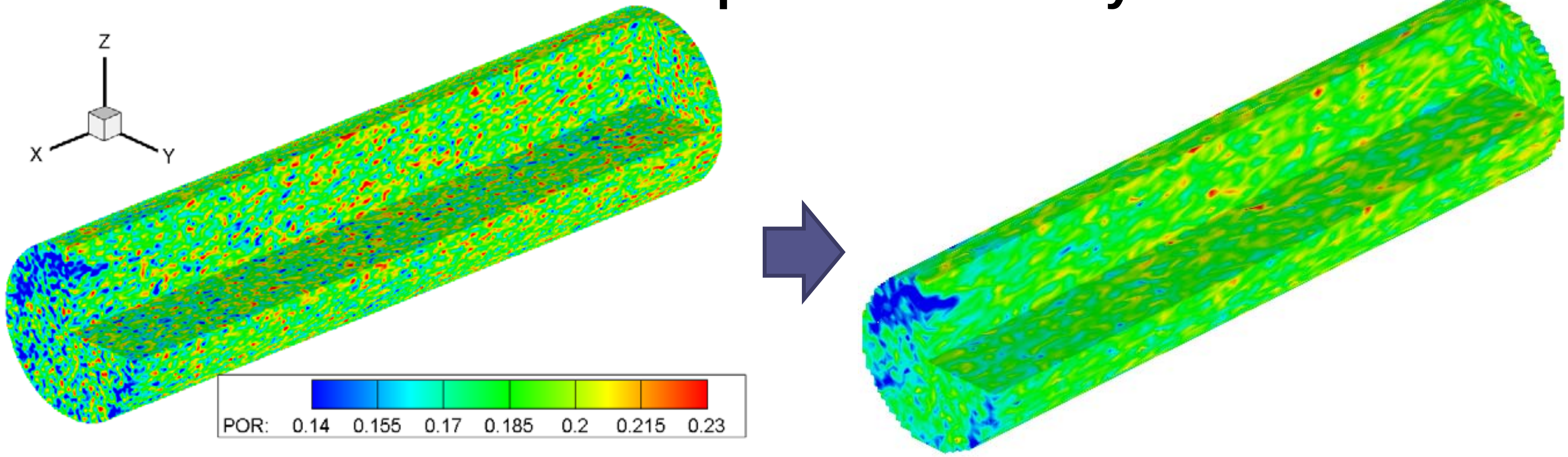


Simulations

- TOUGH2 MP ECO2N
- Need to upscale
  - 5:1 in slice plane
  - 2:1 along core



Upscaled Porosity



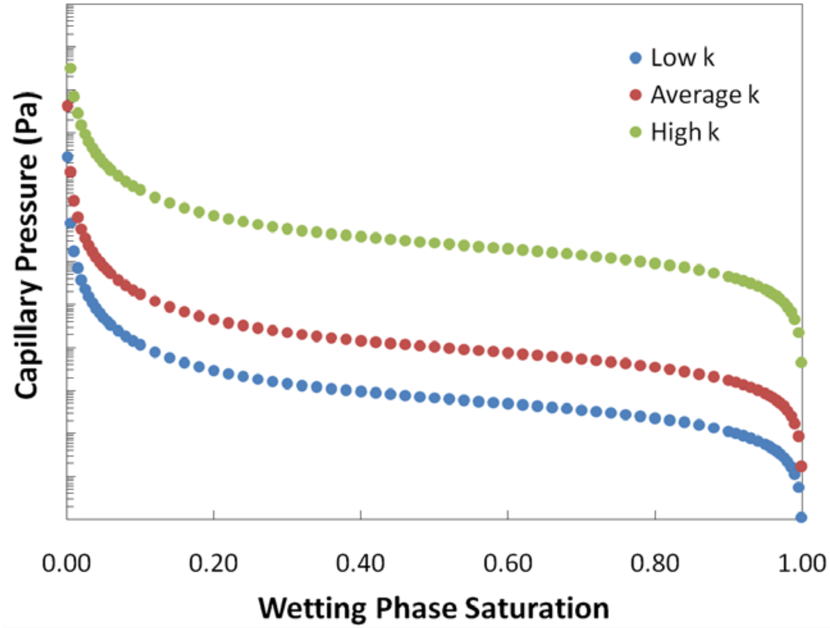
Capillary Pressure

- Accurate representation of capillary pressure is critical at such small scales
- Leverett J-Function used to scale capillary pressure from one sample to all grid elements

$$P_{c,i} = \sigma_{CO_2-brine} \cos(\theta_{CO_2-brine}) \sqrt{\frac{\phi_i}{k_i}} J(S_w)$$

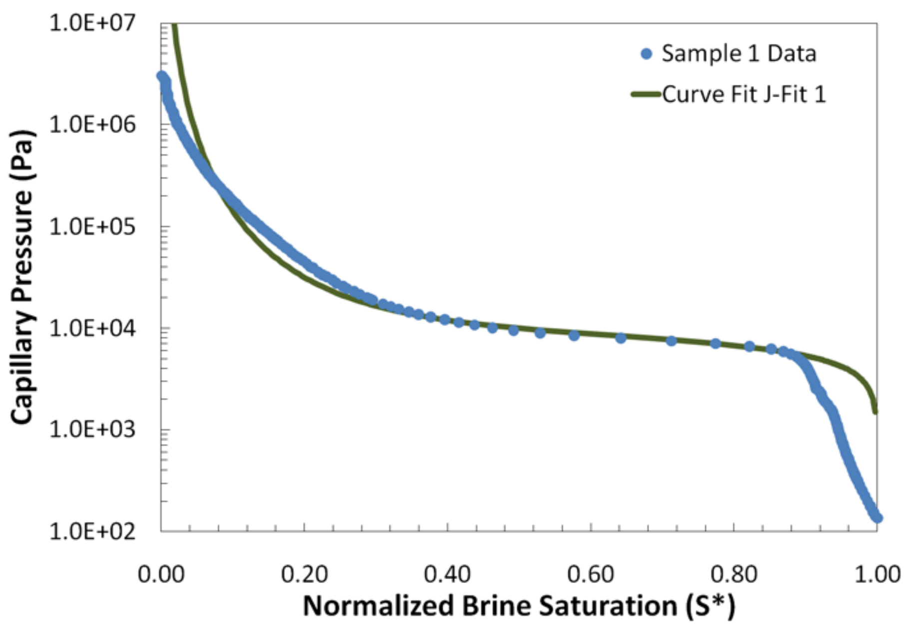
$$J(S_w) = A\left(\frac{1}{S_*^{\lambda_1}} - 1\right) + B\left(1 - S_*^{\lambda_2}\right)^{1/\lambda_2}$$

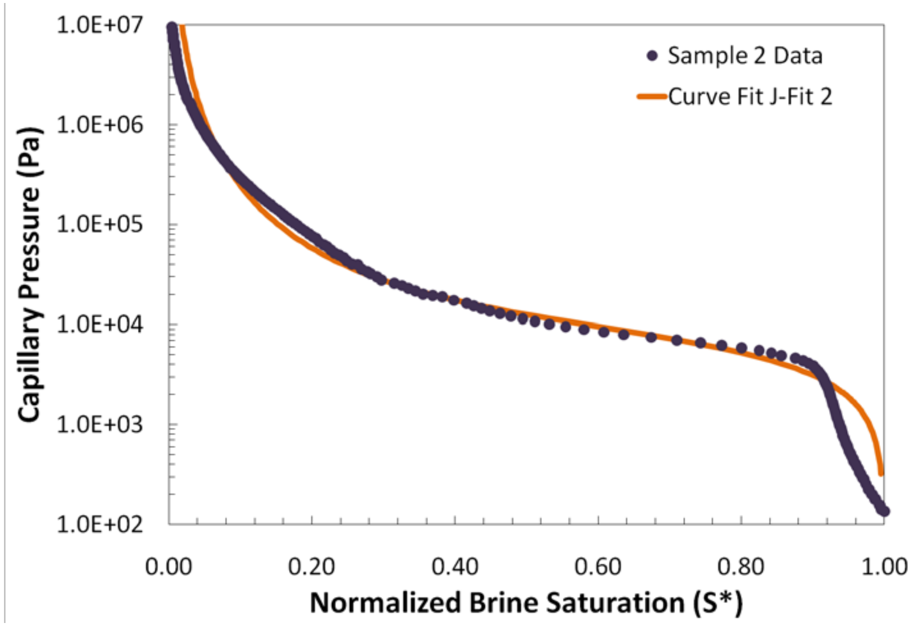
$$S_* = \frac{S_{brine} - S_{lr}}{1 - S_{lr}}$$



Capillary Pressure

Mercury injection method measurements





Fitting Parameters

A	B	λ_1	λ_2
0.01	0.20	2.5	2.8

Fitting Parameters

A	B	λ_1	λ_2
0.014	0.23	2.5	1.6

Permeability from Porosity

- Carman-Kozeny[1]

$$k_i = S\frac{\phi_i^3}{(1-\phi_i)^2}$$

- Modified Carman-Kozeny[2]

$$k_i = \frac{S}{a_v^2}\frac{\phi_i^3}{(1-\phi_i)^2}$$

$$a_V = \frac{\sum \text{Perimeter}}{\sum \text{Grain Area}}$$

$$k_i = S\frac{\phi_i^{1.42}}{(1-\phi_i)^2}$$

- Empirical Power Law Model[3]

$$k_i = S\frac{\phi_i^5}{(1-\phi_i)^2}$$

- Carman-Kozeny with Percolation Threshold[3]

$$k_i = S\frac{(\phi_i-\phi_c)^3}{(1-\phi_i+\phi_c)^2}$$

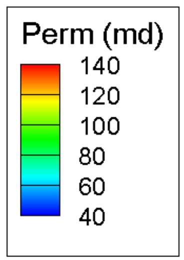
- Fractal Geometry[4]

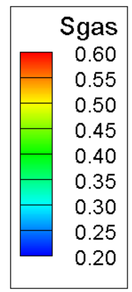
$$k_i = S\cdot\left(6.2\phi_i + 1493\phi_i^2 + 58(10\phi_i)^{10}\right)$$

1. Benson *et. al.*, 2009
2. Krause *et. al.*, 2009
3. Mavko and Nur, 1997
4. Pape *et. al.*, 2000

Simulation Results – Slice 33

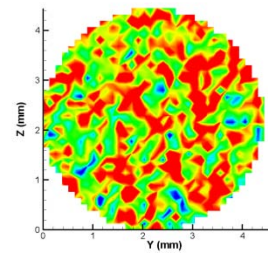
Description	Slice Permeability	Slice CO_2 Saturation	Core Saturation Histogram

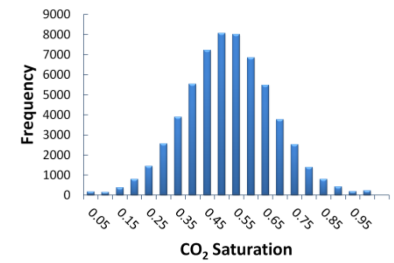




Experimentally Measured Data

CO_2 Saturation Std. Dev. 0.1572

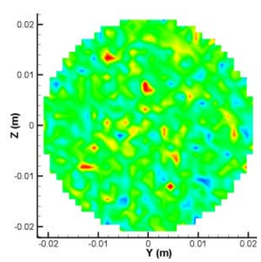


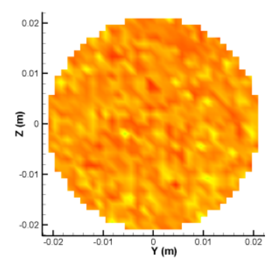


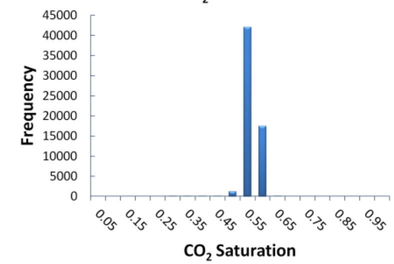
Simulation 1

CO_2 Saturation Std. Dev. 0.0171

$$k_i = S\frac{\phi_i^3}{(1-\phi_i)^2}$$



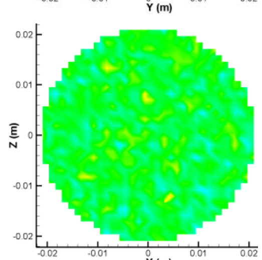


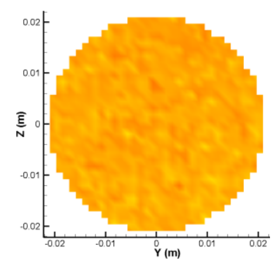


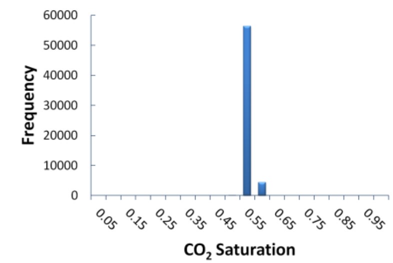
Simulation 2

CO_2 Saturation Std. Dev. 0.0103

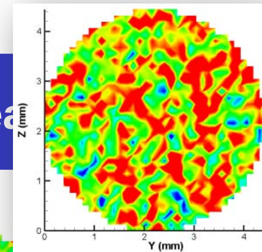
$$k_i = S\frac{\phi_i^{1.42}}{(1-\phi_i)^2}$$







Simulation Results (Continued)

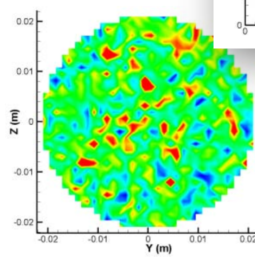


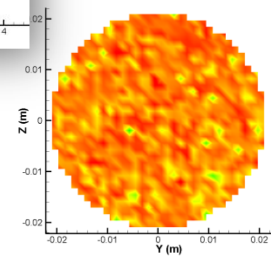
Description	Slice Permea	e CO_2 Saturation	Core Saturation Histogram

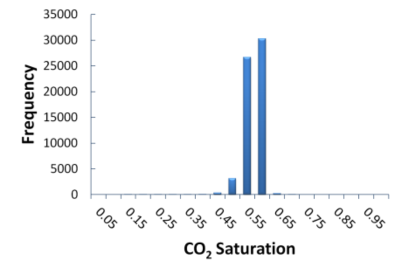
Simulation 3

CO_2 Saturation Std. Dev. 0.0288

$$k_i = S\frac{\phi_i^5}{(1-\phi_i)^2}$$



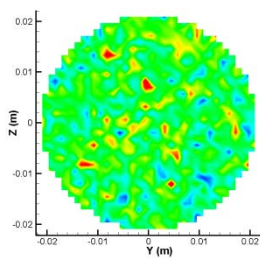


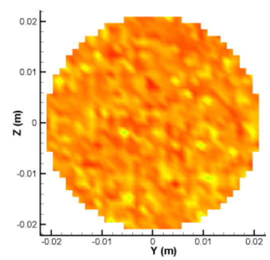


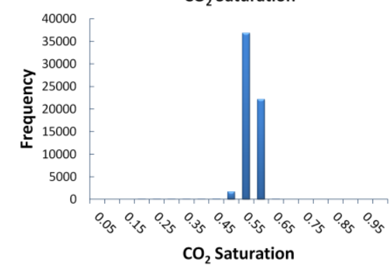
Simulation 4

CO_2 Saturation Std. Dev. 0.0198

$$k_i = S\frac{(\phi_i - \phi_c)^3}{(1-\phi_i+\phi_c)^2}$$



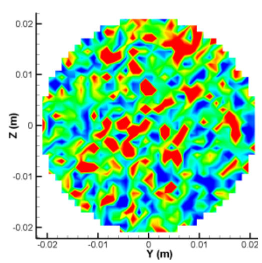


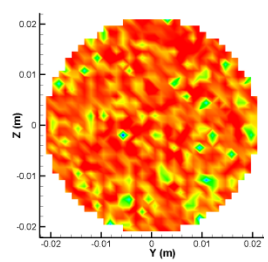


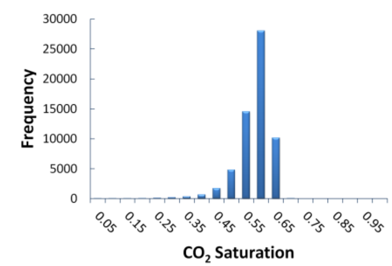
Simulation 5

CO_2 Saturation Std. Dev. 0.0594

$$k_i = S\cdot\left(6.2\phi_i + 1493\phi_i^2 + 58(10\phi_i)^{10}\right)$$

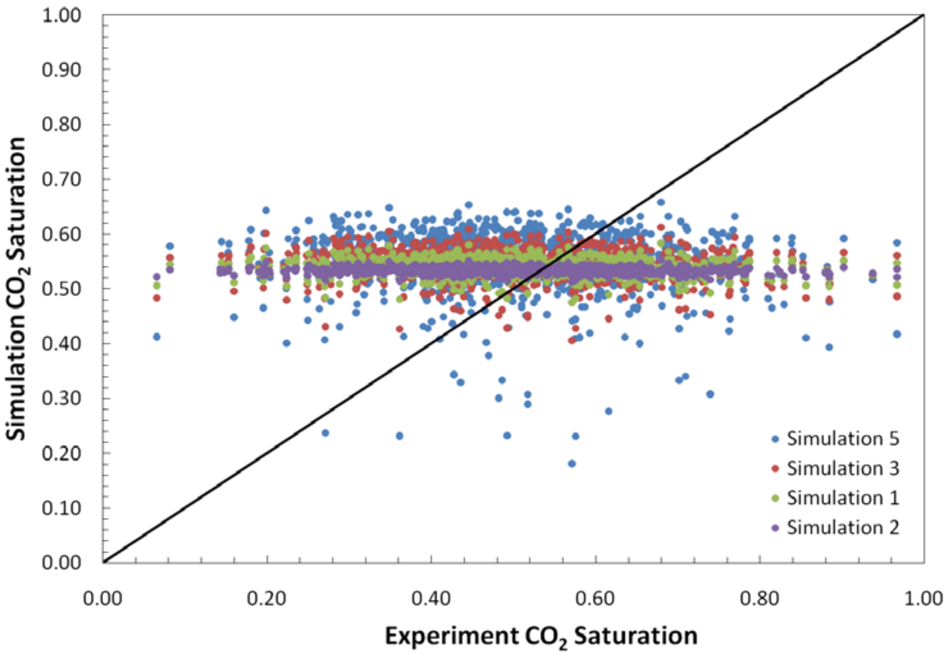






Spatial Correlation

- Plot simulation vs. experiment values
- Perfect correlation would be 1:1, diagonal line
- Plot shows no obvious correlation
- Increasing saturation contrast only spreads out the data vertically



Simulation	Slice 33 Saturation R^2	Core Saturation R^2
1	-0.0949	-0.0570
2	-0.0532	-0.0228
3	-0.1593	-0.1136
4	-0.1093	-0.0708
5	-0.3517	-0.2810

Discussion

- Porosity-based methods are inadequate
  - Low saturation contrast
  - No spatial correlation between predicted and measured values
- Take a different approach
  - Accurate permeability distributions are required to study sub-core scale phenomena
  - Can we use porosity, saturation or capillary pressure another way to derive permeability?

Permeability from Capillary Pressure

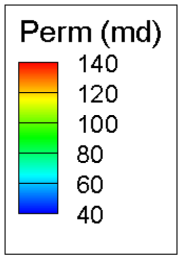
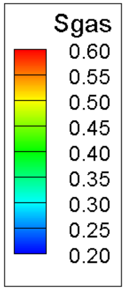
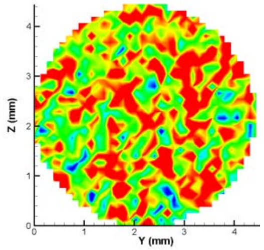
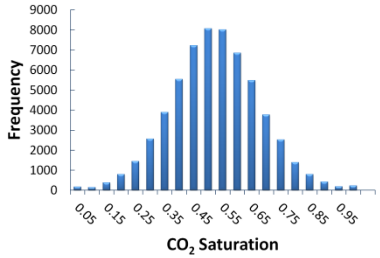
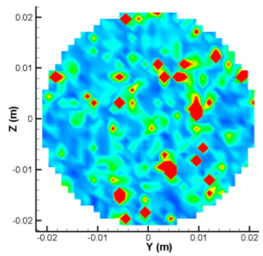
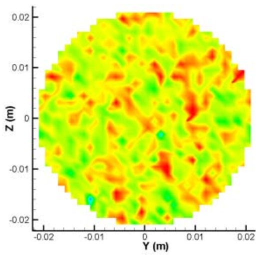
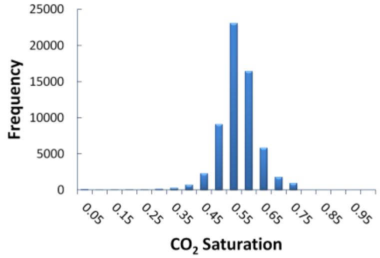
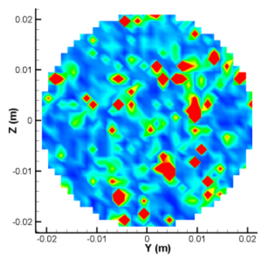
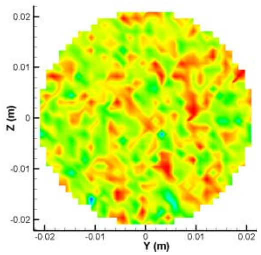
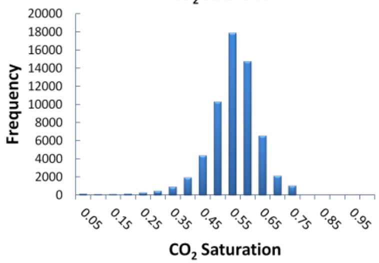
- Integrate all measured datasets through the capillary pressure relation
- $J(S_w)$ already solved, only k_i is unknown

$$P_{c,i} = \sigma_{CO_2-brine}\cos(\theta_{CO_2-brine})\sqrt{\frac{\phi_i}{k_i}}J(S_w)$$

$$J(S_w) = A\left(\frac{1}{S_*^{\lambda_1}} - 1\right) + B\left(1 - S_*^{\lambda_2}\right)^{1/\lambda_2}$$

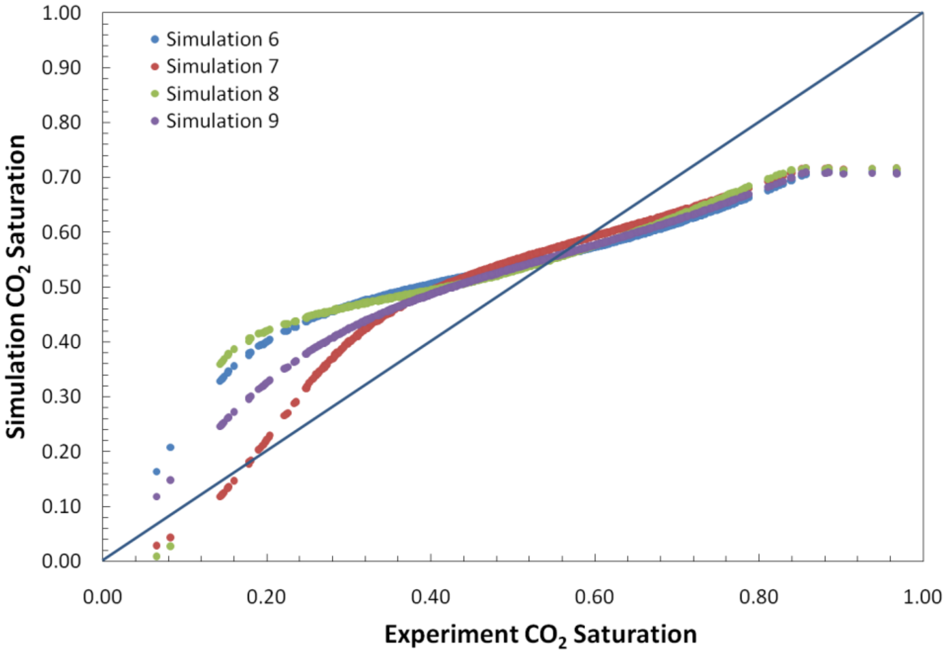
$$k_i = \frac{1}{\overline{P}_c^2}\phi_i\left[J(S_{w,i})^2\right]\cdot(\sigma\cos(\theta))^2$$

Simulation Results – Slice 33

Description	Slice Permeability	Slice CO_2 Saturation	Core Saturation Histogram
Experimentally Measured Data CO_2 Saturation Std. Dev. 0.1572	 		
Simulation 6 J-Fit 1 Std. Dev. 0.06898			
Simulation 9 J-Fit 2 Std. Dev. 0.0859			

Spatial Correlation

- Plot now shows a distinct correlation
- Correlation is not perfect, but it is unique
- P_c curve used to calculate permeability has strong effect at low saturation



Simulation	Slice 33 Saturation R^2	Core Saturation R^2
6	0.5692	0.5847
7	0.7517	0.7437
8	0.6109	0.6270
9	0.7115	0.7233

Questions & Conclusions

How accurately can we model core-flooding experiments?

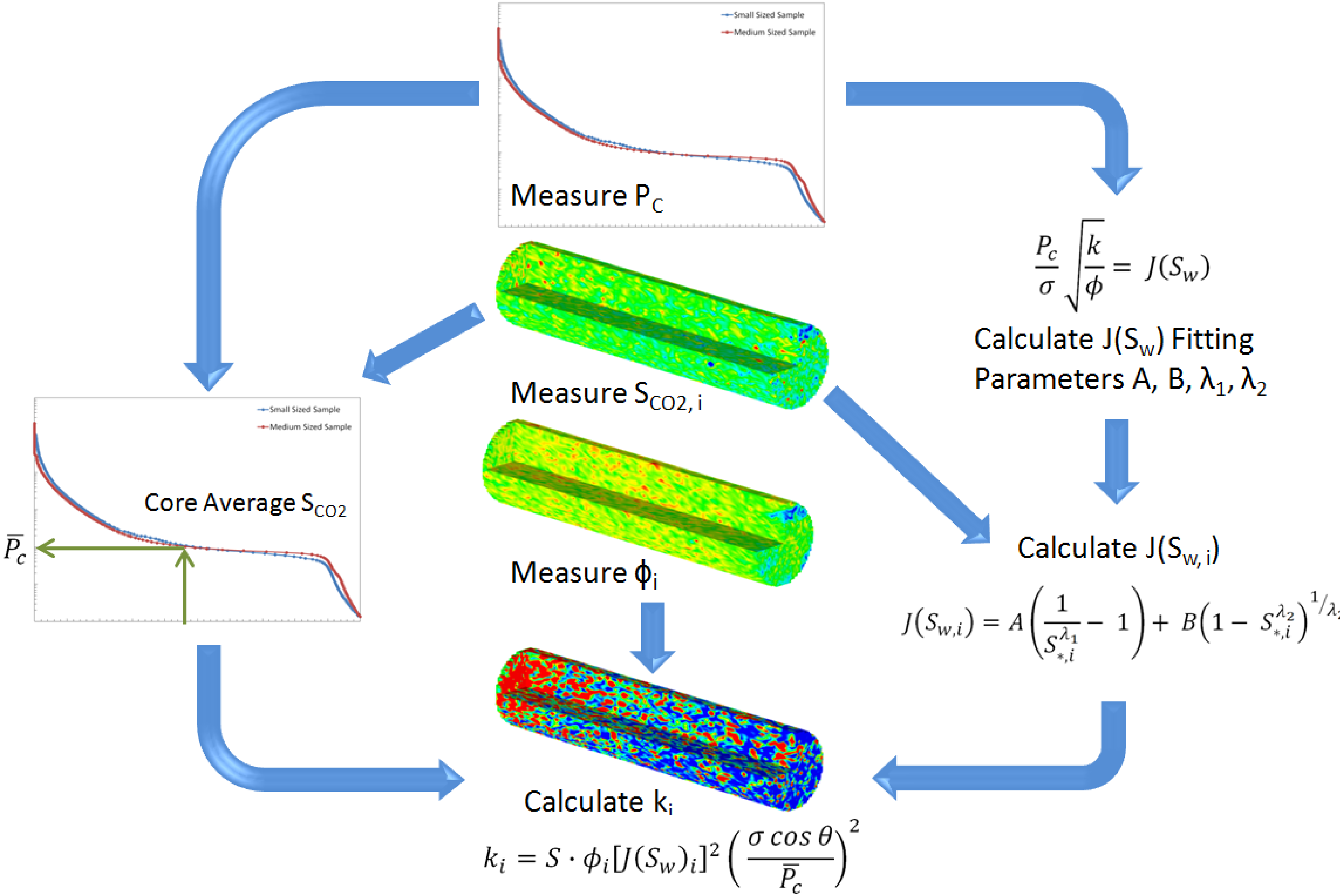
Not at all ➡ very well depending on permeability

What does our ability to accurately replicate sub-core scale saturation distributions depend on?

Accurate permeability representation is critical

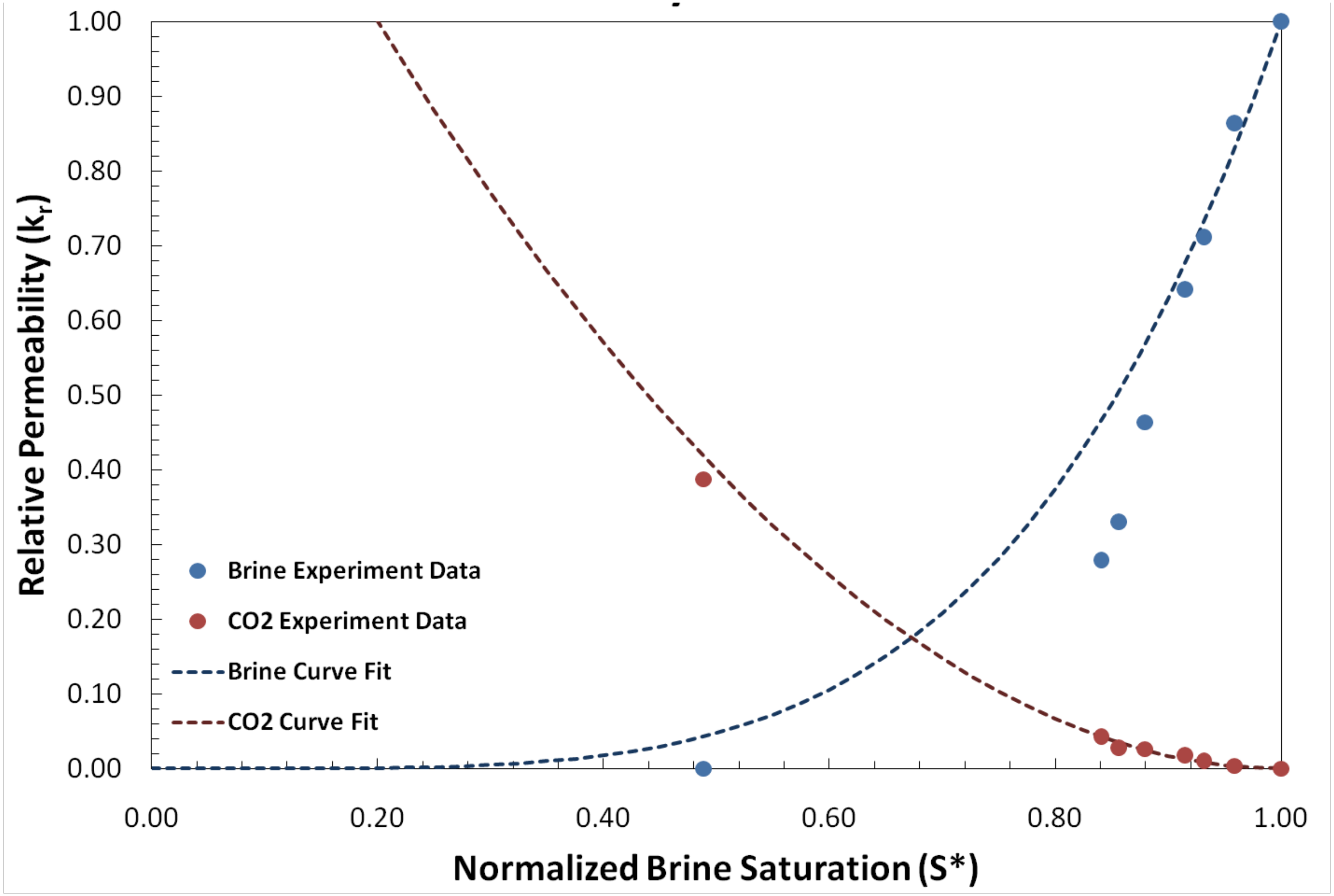
What can we do with these studies?

Use accurate permeability distributions to study other effects (capillary/residual trapping, influence of rel. perm, capillary pressure and gravity)



Small Sized Sample
Medium Sized Sample
Measure P_C
$\frac{P_c}{\sigma}\sqrt{\frac{k}{\phi}} = J(S_w)$
Calculate $J(S_w)$ Fitting Parameters A, B, λ_1, λ_2
Measure $S_{CO2,i}$
Small Sized Sample
Medium Sized Sample
Core Average S_{CO2}
$\overline{P}_c$
Measure ϕ_i
Calculate $J(S_{w,i})$
$J(S_{w,i}) = A\left(\frac{1}{S_{*,i}^{\lambda_1}} - 1\right) + B\left(1 - S_{*,i}^{\lambda_2}\right)^{1/\lambda_2}$
Calculate k_i
$k_i = S \cdot \phi_i [J(S_w)_i]^2 \left(\frac{\sigma \cos \theta}{\overline{P}_c}\right)^2$

Relative Permeability



Pore Scale modeling (cont'd)

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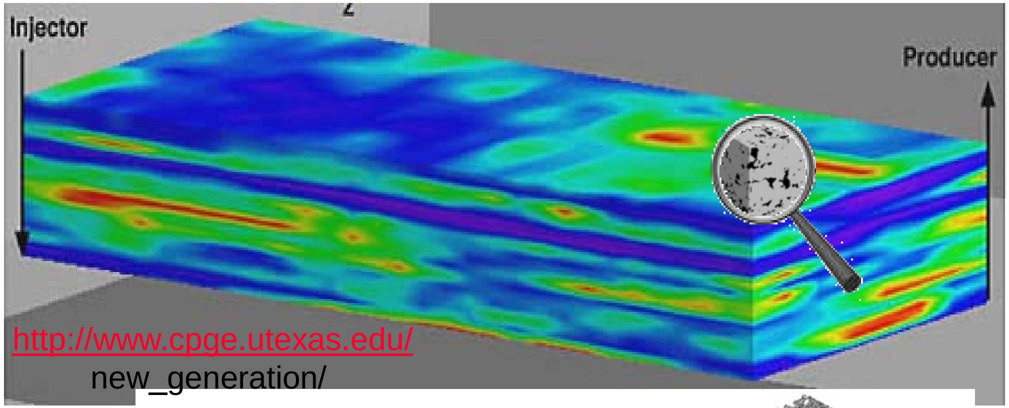
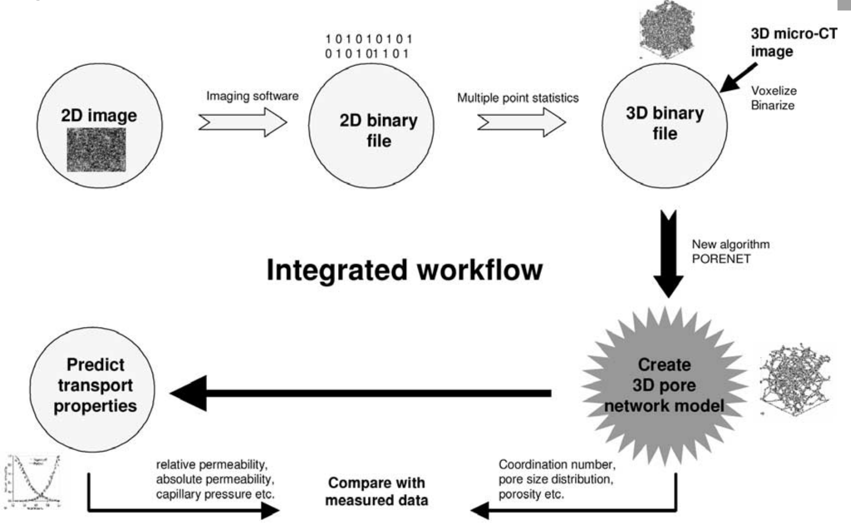


http://www.cpge.utexas.edu/new_generation/

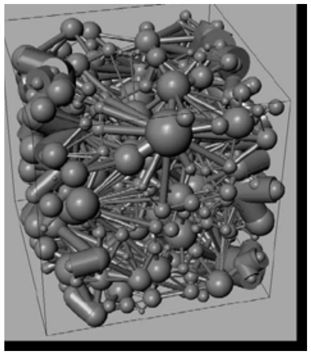
Outline

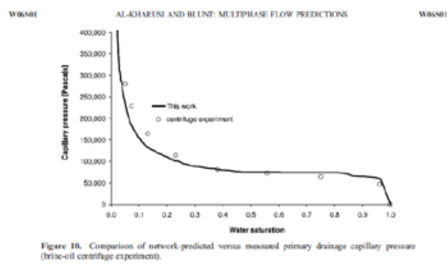
- *Examples of modeling methods*
- *Variety and structure of caprock pore networks*
- *Upscaling*
- *Questions to ponder*



Al-Kharusi and Blunt, 2008

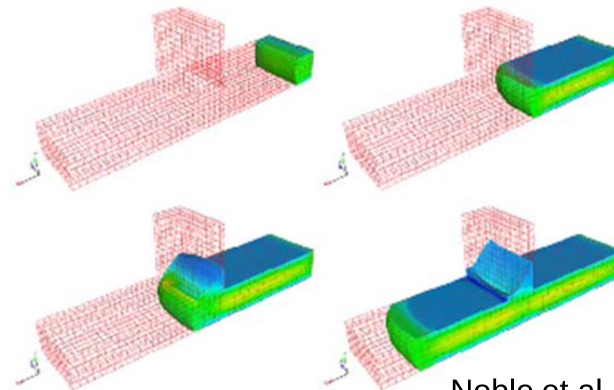
Methodologies





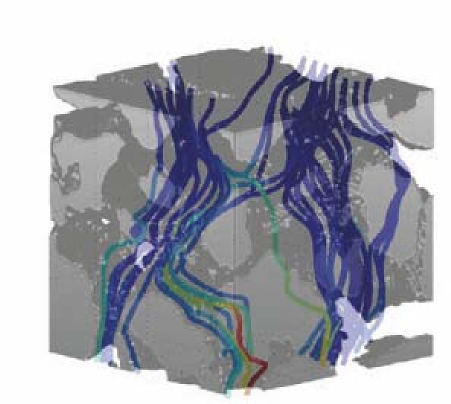
From Al-Kharusi and Blunt (2008)

Network

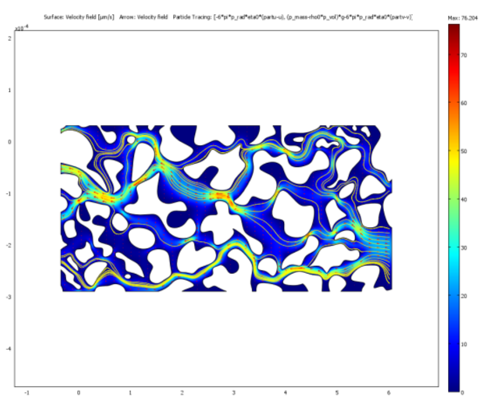


Noble et al. (2009)

Finite Element

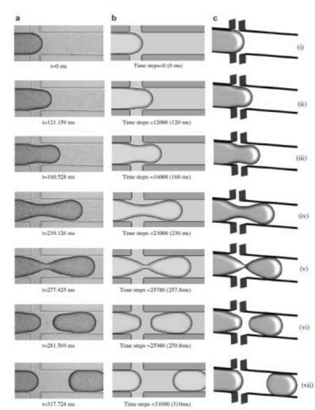


Fourie et al.(2007)

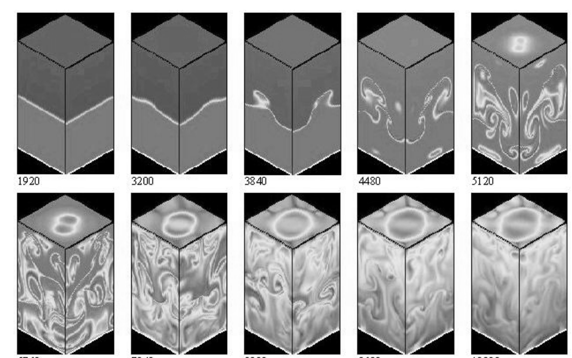


http://www.comsol.com/

CFD/Navier Stokes



Wu et al. (2008)



Stockman (1999)

Lattice-Boltzmann

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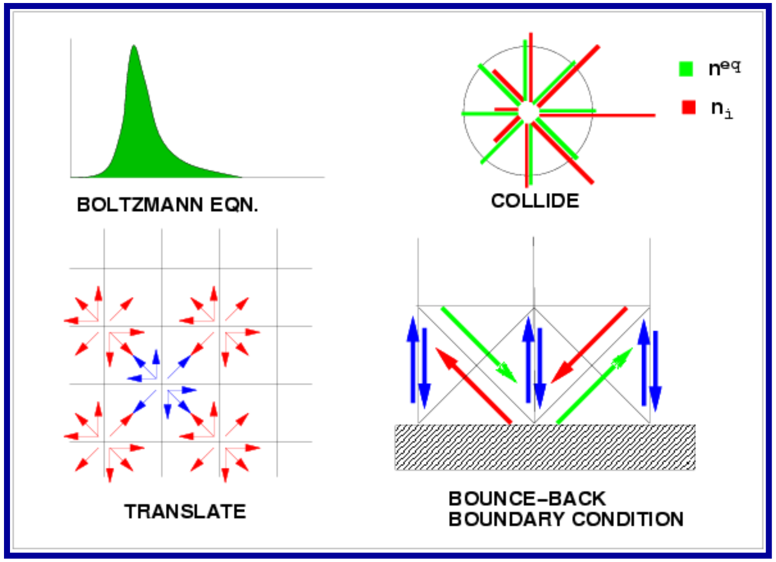
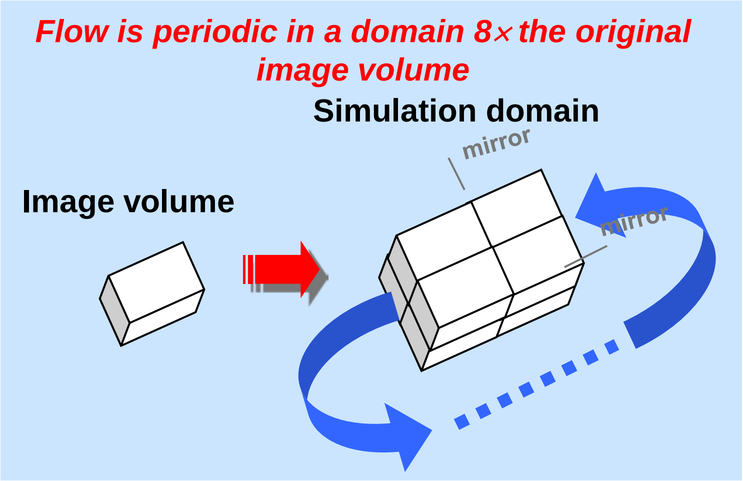
LB pore scale flow modeling

Fluid flow in time and space is formulated in terms of a discrete probability function which evolves according to the discrete Boltzmann equation. This includes "collision" and "streaming" processes.



(e.g. Fredrich et al. 1999; O'Connor & Fredrich, 1999)

- **Facilitates implementation of complex boundary conditions (solid/fluid)**
- **Numerical stability**
- **Ease of parallelization**
- **Coupled multi-physics and multi-phase flows**
- **Allows quantitative investigations at length and time scales not tractable with conventional methods**



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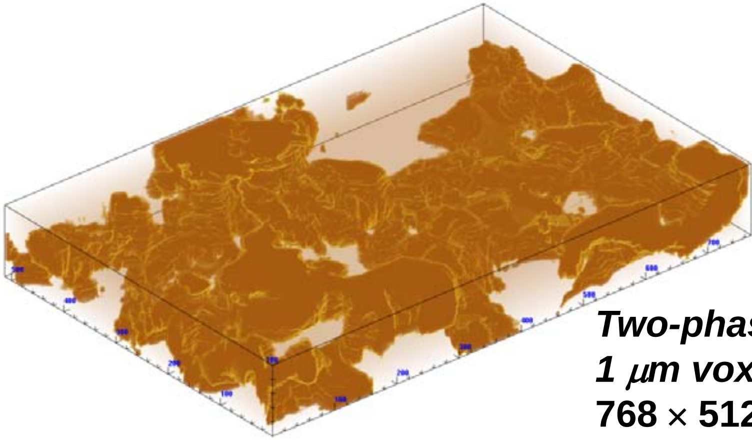
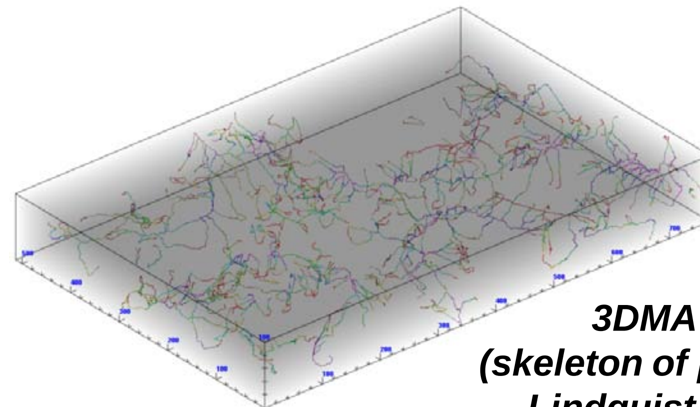
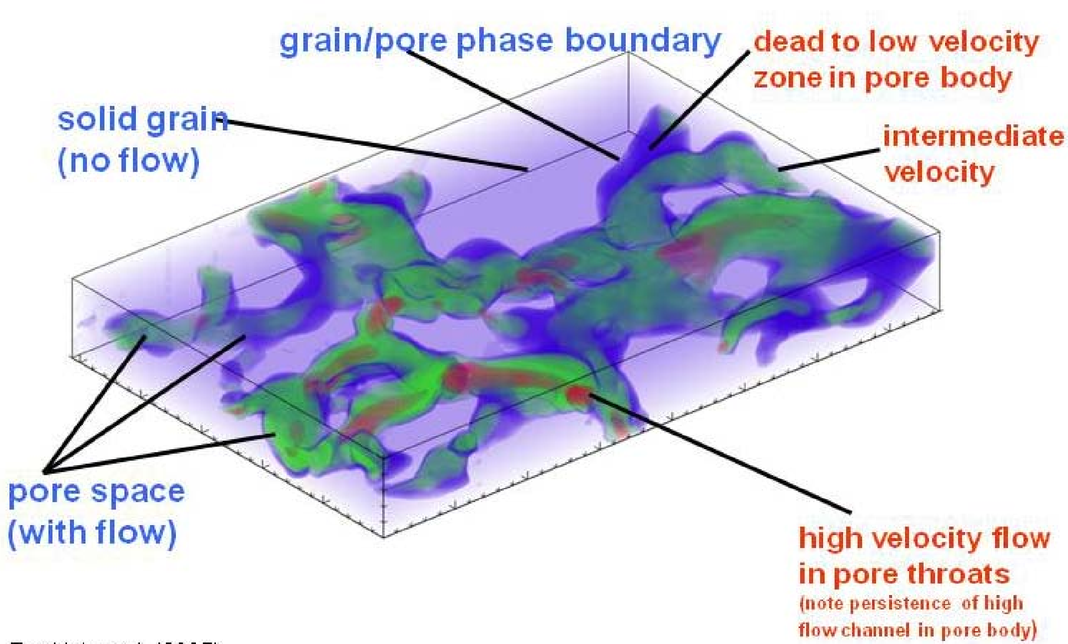
3-D Imaging, Processing, and LB Modeling

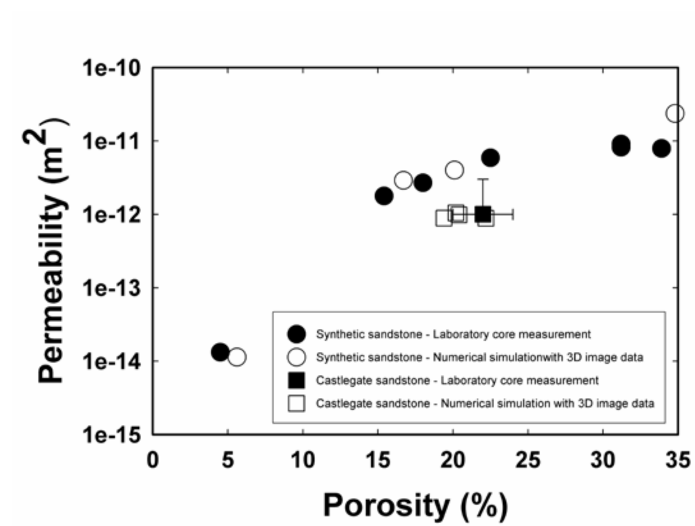


Two-phase volume
1 μm voxel size
768 × 512 × 101



3DMA Medial axis (skeleton of pore space, Lindquist et al., 1999)





Fredrich et al. (2005)

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Lattice-Boltzmann Methods (OpenLB or Palabos)

Physics: Incompressible Navier-Stokes equations, weakly compressible, non-thermal Navier-Stokes equations, flows with body-force term, thermal flows with Boussinesq approximation, single-component multi-phase fluids (Shan/Chen model), multi-component multi-phase fluids (Shan/Chen model), static Smagorinsky model for fluid turbulence.

Basic fluid models: BGK, a given MRT model, regularized BGK, a given entropic model.

Boundary conditions: Zou/He, Inamuro, Skordos, regularized BC, simple equilibrium, bounce-back, periodic. All boundary conditions work for straight walls with interior/exterior corners, and can be used to implement a Dirichlet or Neumann condition for the velocity or the pressure. The bounce-back condition is also used for curved boundaries, represented by a stair-case shape.

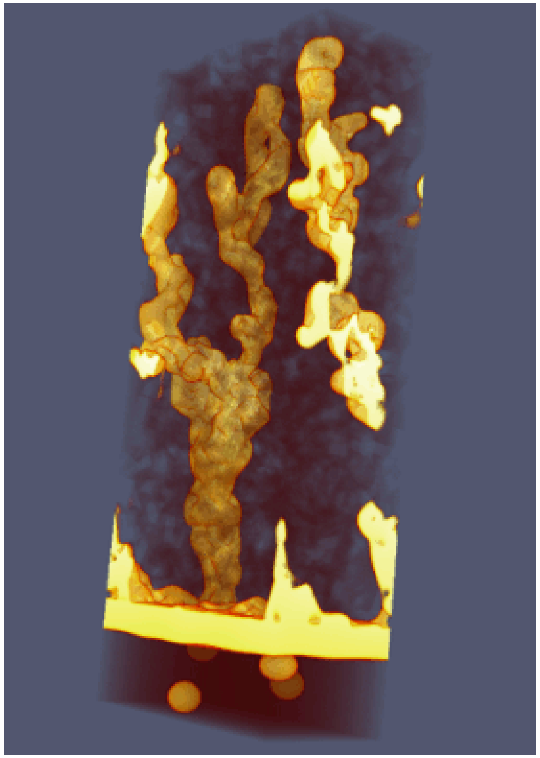
Grid: The implemented grids are D2Q9, D3Q13, D3Q15, D3Q19, and D3Q27. In all cases, the domain is either a regular matrix or a sparse domain, approximated by a multi-grid pattern.

Parallelism: All mentioned models and ingredients are parallelized with MPI for shared-memory and distributed-memory platforms.

Pre-processing: The domain of a simulation can be constructed manually, or automatically from a corresponding STL-file.

Post-processing: The code has the ability to save the data in ASCII or binary files or to directly produce GIF images. Furthermore, the data can be saved in VTK format and further post-processed with an appropriate tool.

Check-pointing: At every moment, the state of the simulation can be saved, and loaded at a later point.



Buoyant flow of hot gas in porous media

http://www.openlb.org/

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Dual FIB/SEM Caprock Pore Network Analysis

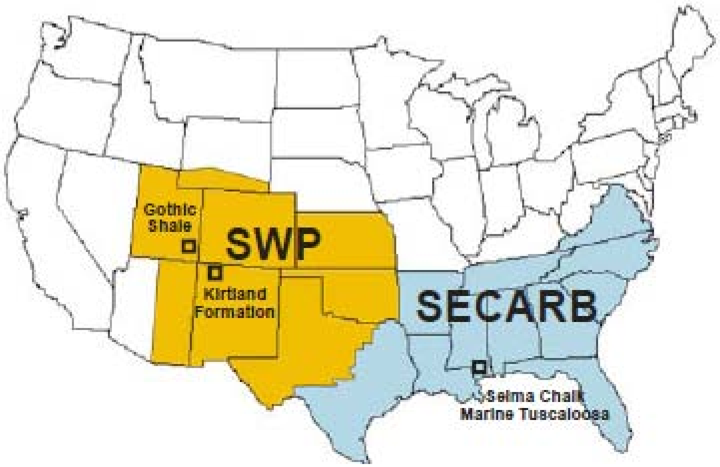
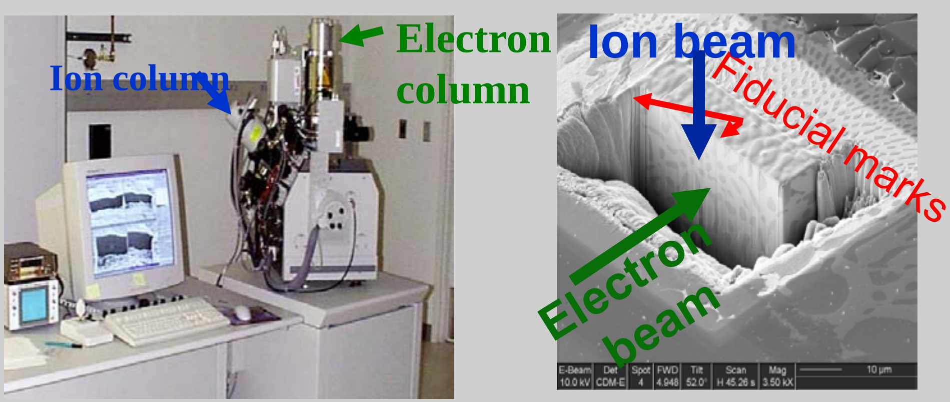


Table 1. Samples obtained for this study from SWP and SECARB. All of these samples were studied by both the FIB-SEM and MICP, except for sample 1-6SA, which was only characterized by FIB-SEM.

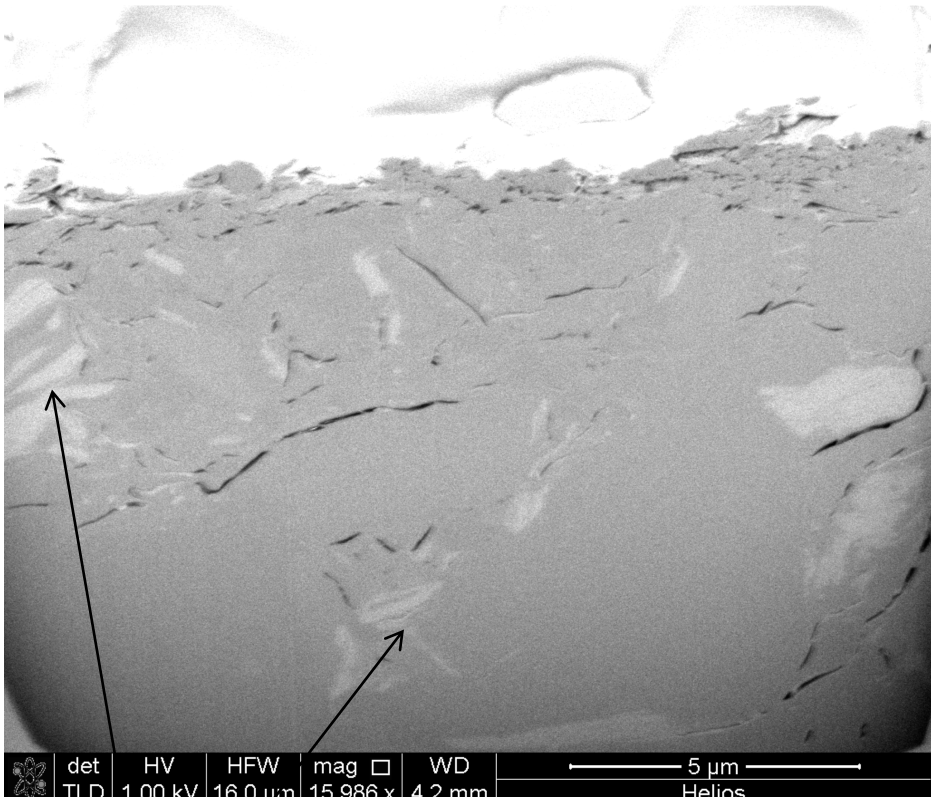
Sample ID	Formation or Geologic Unit	Depth (m)	Depth (ft)	State	Site of Interest
Gothic A @ 5390.8	Gothic Shale	1643.12	5390.80	UT	Aneth Unit - EOR
Gothic B @ 5390.8	Gothic Shale	1643.12	5390.80	UT	Aneth Unit - EOR
Upper Kirtland A @ 2692.9	Kirtland Formation - Upper Shale Member	624.749	2049.70	NM	Pump Canyon - ECBM/CO2
Upper Kirtland B @ 2692.9	Kirtland Formation - Upper Shale Member	624.749	2049.70	NM	Pump Canyon - ECBM/CO2
Lower Kirtland A @ 2692.9	Kirtland Formation - Lower Shale Member	820.796	2692.90	NM	Pump Canyon - ECBM/CO2
Lower Kirtland B @ 2692.9	Kirtland Formation - Lower Shale Member	820.796	2692.90	NM	Pump Canyon - ECBM/CO2
1-6SA	Selma Group - Selma Chalk	1890.98	6204.00	MS	Plant Daniel - CO2 injection
Marine Tuscaloosa @ 7925.5	Tuscaloosa Group - Marine Shale	2415.69	7925.50	MS	Plant Daniel - CO2 injection
Marine Tuscaloosa @ 7931.9	Tuscaloosa Group - Marine Shale	2417.64	7931.90	MS	Plant Daniel - CO2 injection
Tuscaloosa @ 8590	Tuscalossa Group - Lower Tuscaloosa	2618.23	8590.00	MS	Plant Daniel - CO2 injection
Lower Tuscaloosa @ 8590.9	Tuscalossa Group - Lower Tuscaloosa	2618.51	8590.90	MS	Plant Daniel - CO2 injection

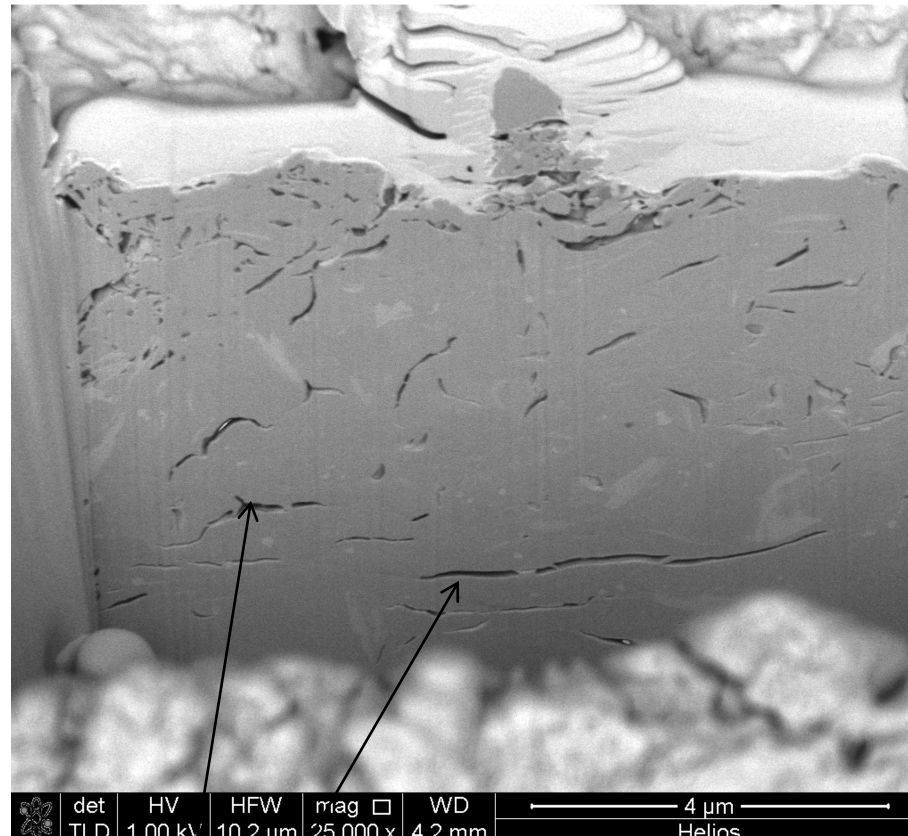


Serial Sectioning with FEI DB-235 FIB/SEM

Heath et al. (in preparation)

FIB/SEM Image of Lower Kirtland Shale (SWP)

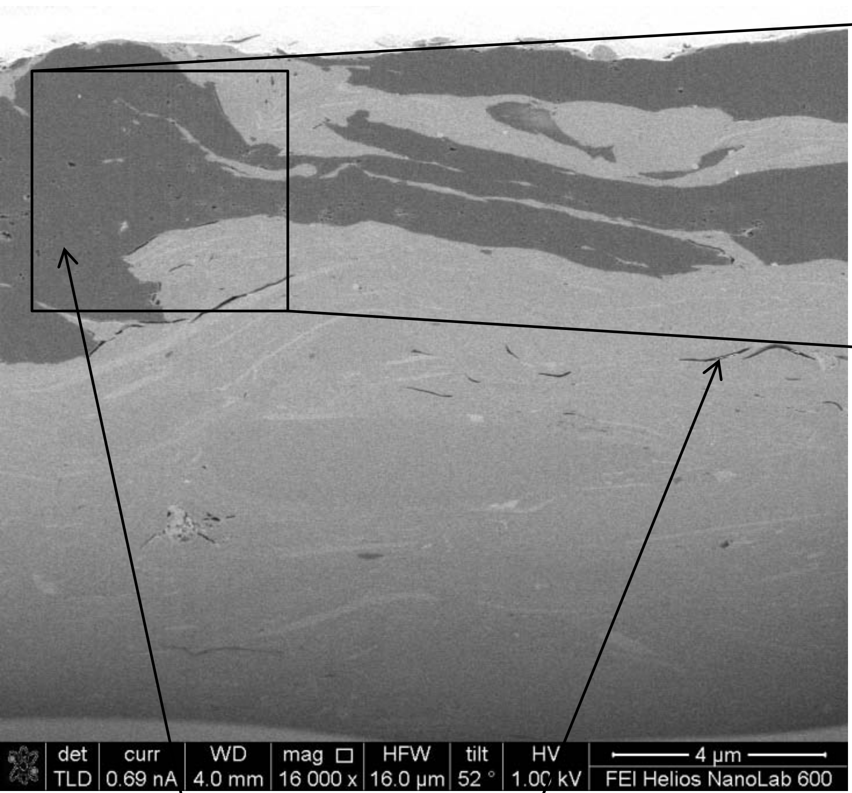


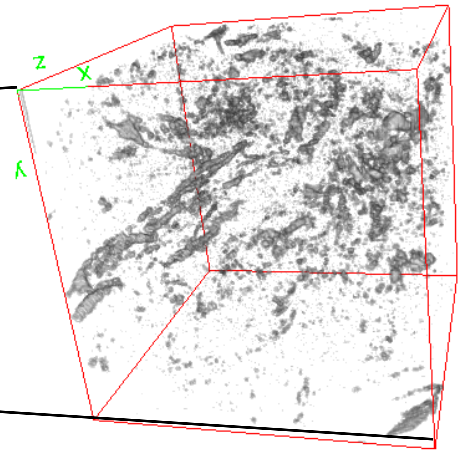


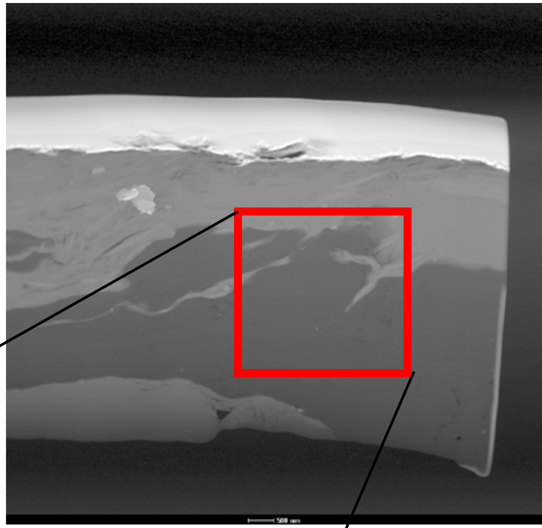
Compacted floccules of Schieber and Southard (2009)?

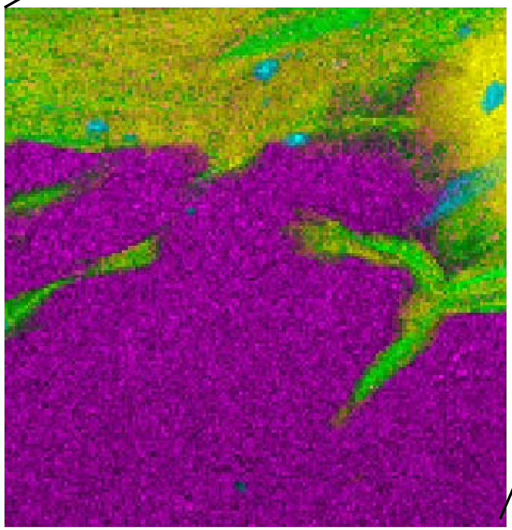
Microfracture-like slit pores (stress-sensitive?)

FIB/SEM and TEM/EDS Imaging of organic laminated Marine Tuscaloosa Shale (SEACARB)





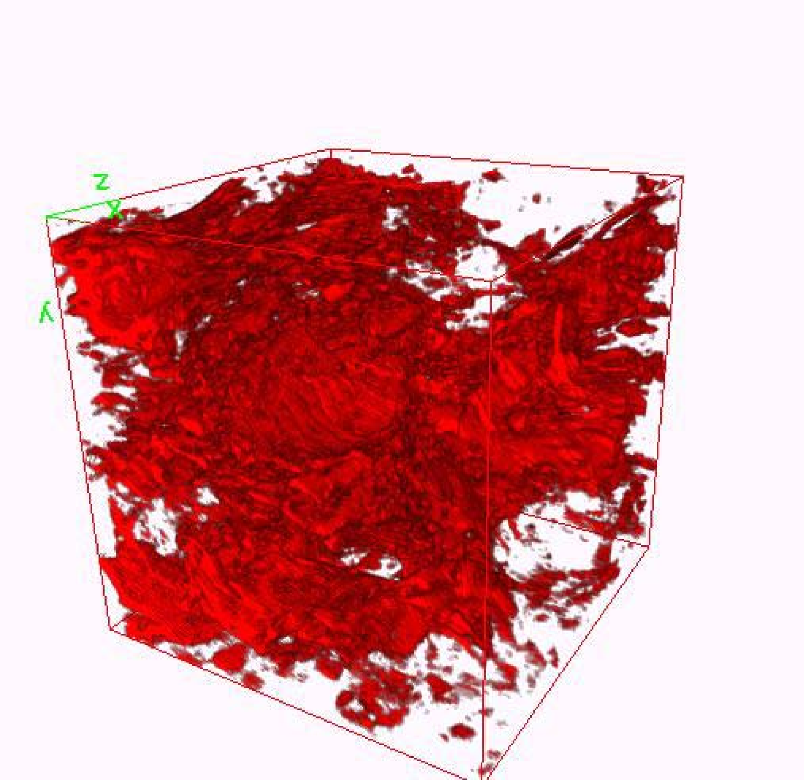




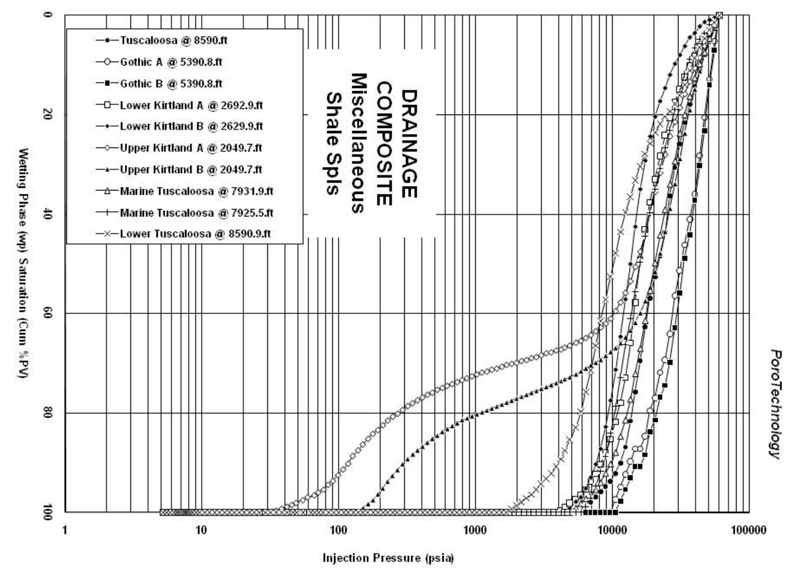
Green = Si-Al-K-Fe-O
Blue = Ca-P-O
Magenta = C-O-S-Cl
Cyan = Ti-Si-O
Yellow = Si-Al-O

Both oil-wet and water-wet pathways??

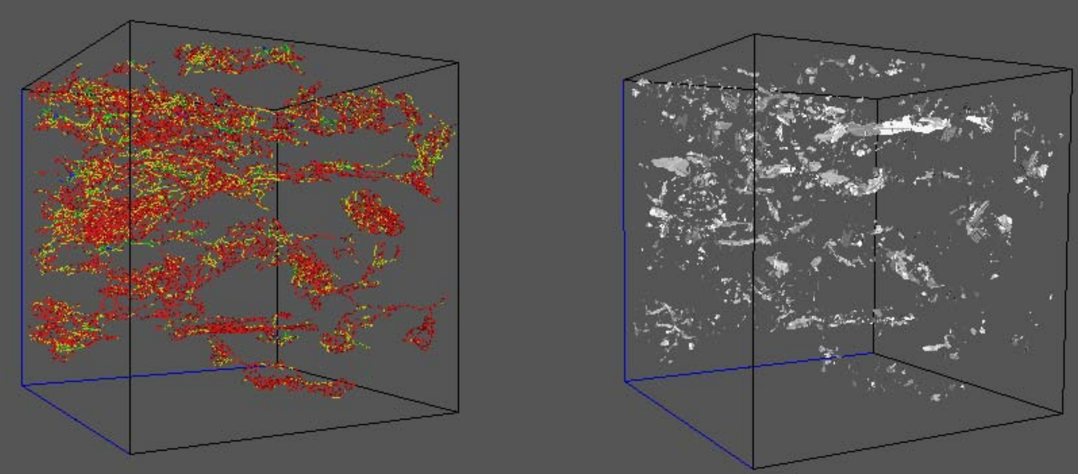
Gothic Shale Pore Topology



300x300x300; 15.6 nm voxel dimensions



MICP results from 4 proposed caprocks



Medial Axis and Pore Throat Radii of Gothic Shale Pore Network

- ~56% of resolvable pores are not connected
- MICP pore throat size is ~5 nm (10,000 psi entry pressure), about an order of magnitude larger than FIB-resolved pore throat dimension

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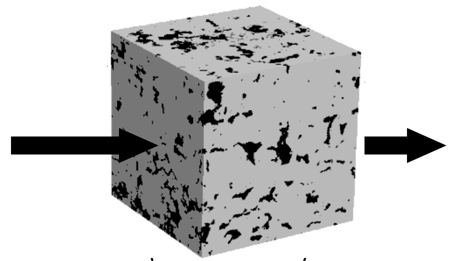
Traditional Upscaling Approach

- **Split the network into several smaller networks**
- **Solve each network**
- **Back-calculate each sub-network permeability**
- **Upscale to get K_{FD} for entire domain using a traditional finite difference upscaling**
- **$K_{FD} \neq K_{TRUE}$**



No-Flow BC

Pin = 16 Pa (left) / Pout = 0 Pa (right)

750.5	1515.7	394.1	867.5	722.9	488.9	1331.8	1110.1	535.7	387.5
24.7	17.0	13.0	103.6	9.8	35.0	17.0	127.3	21.9	453.2
14.4	2761.9	6.3	618.4	1190.9	54.1	2920.9	12.0	1984.0	16.4
4.5	16.3	13.3	33.8	34.5	1980.1	27.3	94.2	6.3	374.3
7.5	10.8	2218.1	2160.3	6.8	10.6	14.9	16.9	5.8	13.4
12.0	10.5	18.7	14.6	30.7	3225.1	24.2	1330.0	17.7	3315.3
14.0	921.7	155.6	2743.2	7.1	27.2	8.5	1825.9	9.9	82.9
22.5	15.1	18.6	9.6	305.4	7.1	11.2	7.4	11.8	11.8
10.2	32.0	14.4	1456.9	16.2	6.4	1784.4	15.4	106.3	2279.3
18.2	19.8	103.5	18.9	6.3	61.5	12.5	108.2	14.0	7.4

No-Flow BC

K
3315
2947
2580
2212
1844
1476
1108
740
372
5

See Balhoff et al. (2008)

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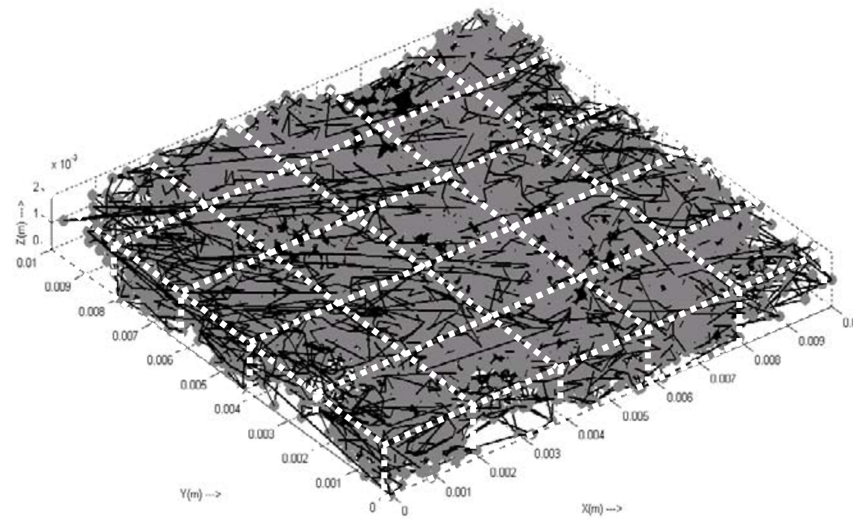
Upscaling…a Mortar Approach (Matt Balhoff, UT)

- **Split networks at natural boundaries**
- **Couple using FEM mortars**
- **Calculate Upscaled K – much better than traditional approach**



		K_{true}	K_{FD}	$K_{mortar\text{-}constant}$				$K_{mortar\text{-}linear}$			
				1x1	2x2	3x3	4x4	1x1	2x2	3x3	4x4
Network A	**Kx**	37.5	32.4	65.52	49.27	43.44	40.35	40.01	39.05	38.09	36.9
	Ky	44.7	36.2	80.23	59.94	53.34	49.2	48.62	47.29	46	44.6
Network B	**Kx**	101.0	81.1	159.58	128.46	110.73	105.89	106.52	104.08	101.04	97.4
	Ky	37.1	29.0	54.24	42.83	37.93	37.04	37.06	36.48	35.7	34.8

See Balhoff et al. (2008)

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The good and bad

- Characterize multiphysics coupling, multiphase flow at appropriate scales
- Can visualize dead-end pores and solid phase reactive surface area, together which could partially resolve the lab/field conundrum
- Can successfully predict hydrological properties
- Dangerous if imaged volumes aren't representative of geologic heterogeneity
- Some pore systems below resolution of readily accessible techniques

Pore-scale modeling

Breakout Meeting Questions

1. Where is best role/niche for pore scale modeling in CCS?
2. To what extent is pore shape, pore-lining mineralogy, and organic content as or more important than pore throat size in predicting multiphase flow behavior in reservoir and seal lithologies?
3. How best to account for stress/pore pressure effects in stress-sensitive materials?
4. How best to upscale (include in continuum scale) so as not to lose important dynamical information?
5. To what extent does the initial structure (arrangement of permeable and impermeable strata) control the flow pattern of a reactive perturbation?
6. What other methods for pore network characterization can be brought to bear (e.g. 3D TEM, Neutron Scattering)

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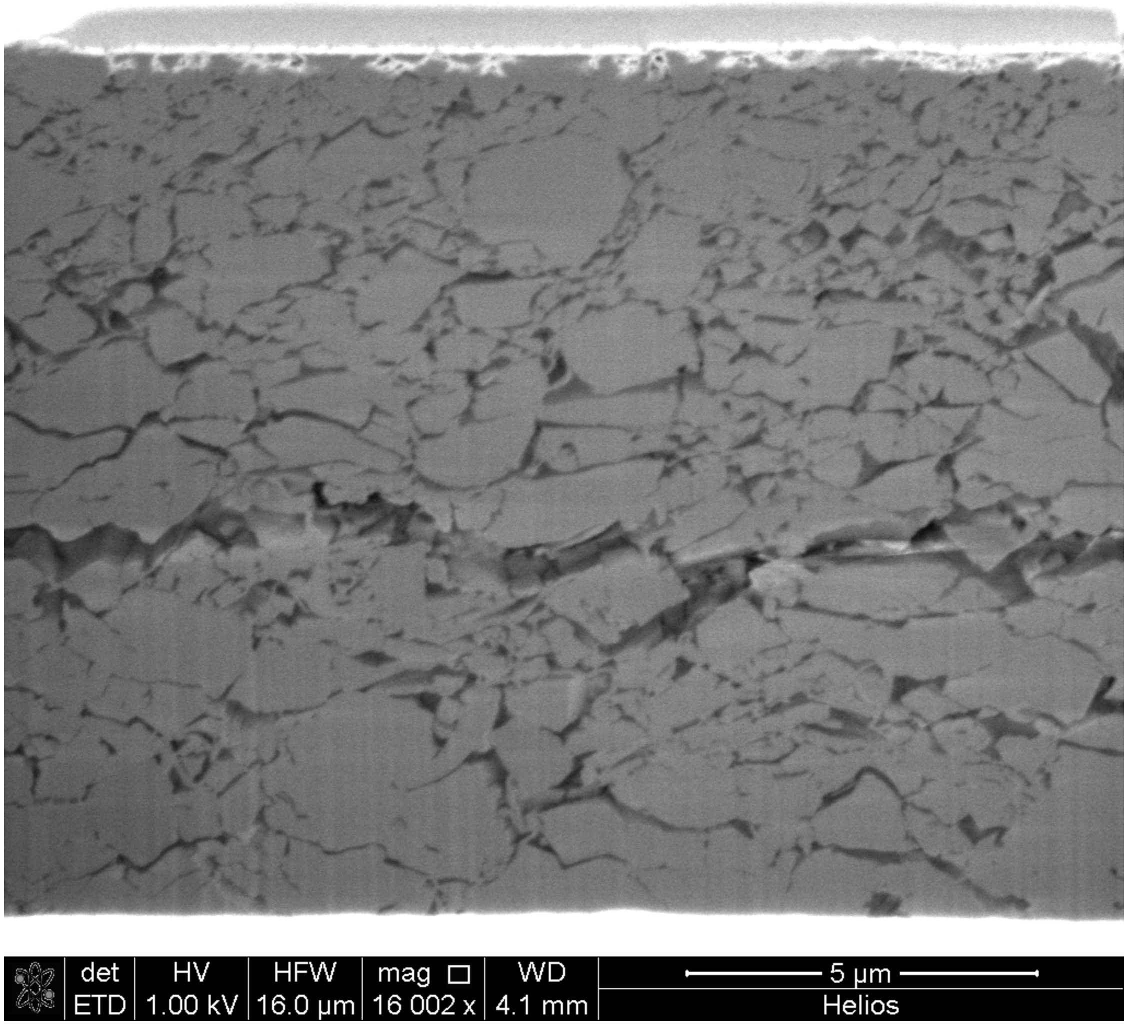
FIB/SEM Image of Selma Chalk (SEACARB)



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Performance targets and storage site closure

Applying Performance Targets to assist demonstration of compliance with storage site closure criteria – Liability transfer

Marius Bjørnli Lunde
16 February 2010

MANAGING RISK DNV

Presentation outline

- **Basis for the presentation** – CO2QUALSTORE work

- **Performance targets (PTs)**
  - Determining PTs
  - Fulfilling qualification goals and site criteria
  - Reservoir simulations and PTs

- **Examples of performance criteria for closure**
  - Addressing uncertainty
  - Addressing risk

Objectives of CO2QUALSTORE guideline

Drive towards a unified, recognized and trustworthy industry approach to selection and qualification of CO2 storage sites:

- provide developers, regulators and independent verifiers with a **common protocol** for assessing the safety and reliability of CO_2 storage sites
- provide a **structured and transparent approach** to decision making that documents the basis for granting a storage permit
- be **performance based (goal oriented)** with a sufficient level of detail to be a useful working guide for industry actors
- be **consistent with international regulations** that are emerging for governing CO_2 storage in Europe, the USA, Canada and Australia
- **guide the dialogue** between project developers and regulators, relevant stakeholders and third parties

Guideline will be made publicly available in February 2010

Motivation

Why such guidelines are needed:

- Establish a unified industry approach
- Consistent and efficient implementation of regulations across projects
- Accelerate implementation – predictable operating conditions
- Confidence in CCS as a safe and reliable option to mitigate global warming

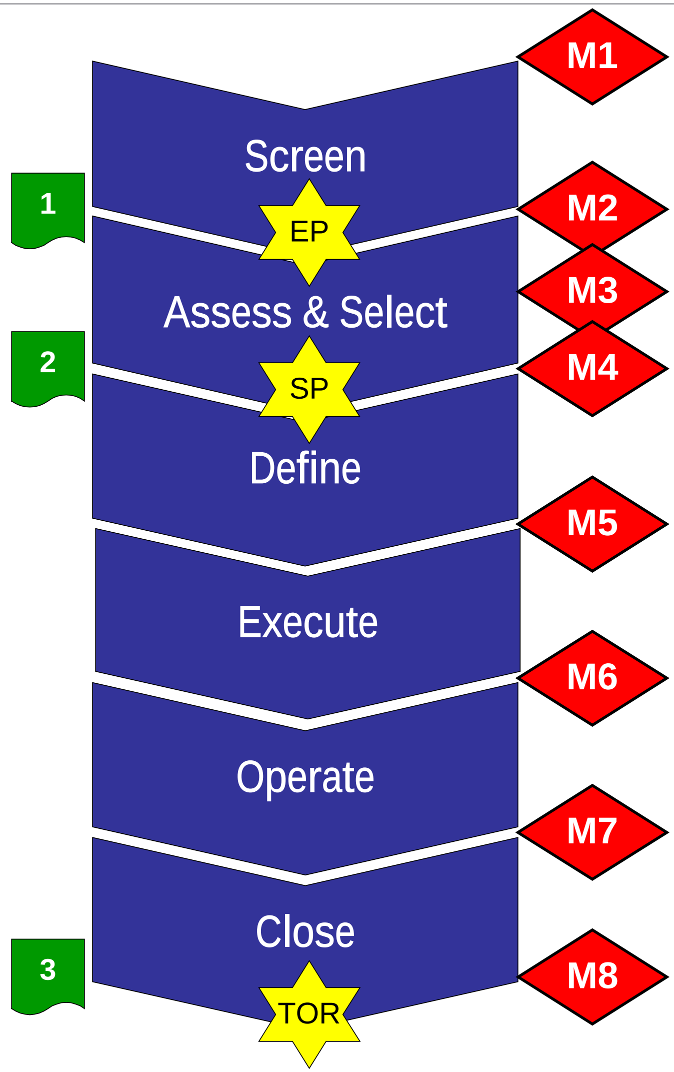
The guideline is meant to support every step of the CO2 Geological Storage-process!

Project organisation

Consulted Parties
COM
NSBTF
National authorities

Sub-contractors
Quintessa
SINTEF
IPAC

QUALIFICATION STAGES



Milestones

1) Begin site screening
2) Shortlist storage sites
3) Select site & engineering concept
4) Storage permit application
5) Initiate construction
6) Initiate CO_2 injection
7) Qualify for site closure
8) Initiate decommisioning

Qualification Statements

1) Statement of storage feasibility
2) Certificate of fitness for storage
3) Certificate of fitness for closure

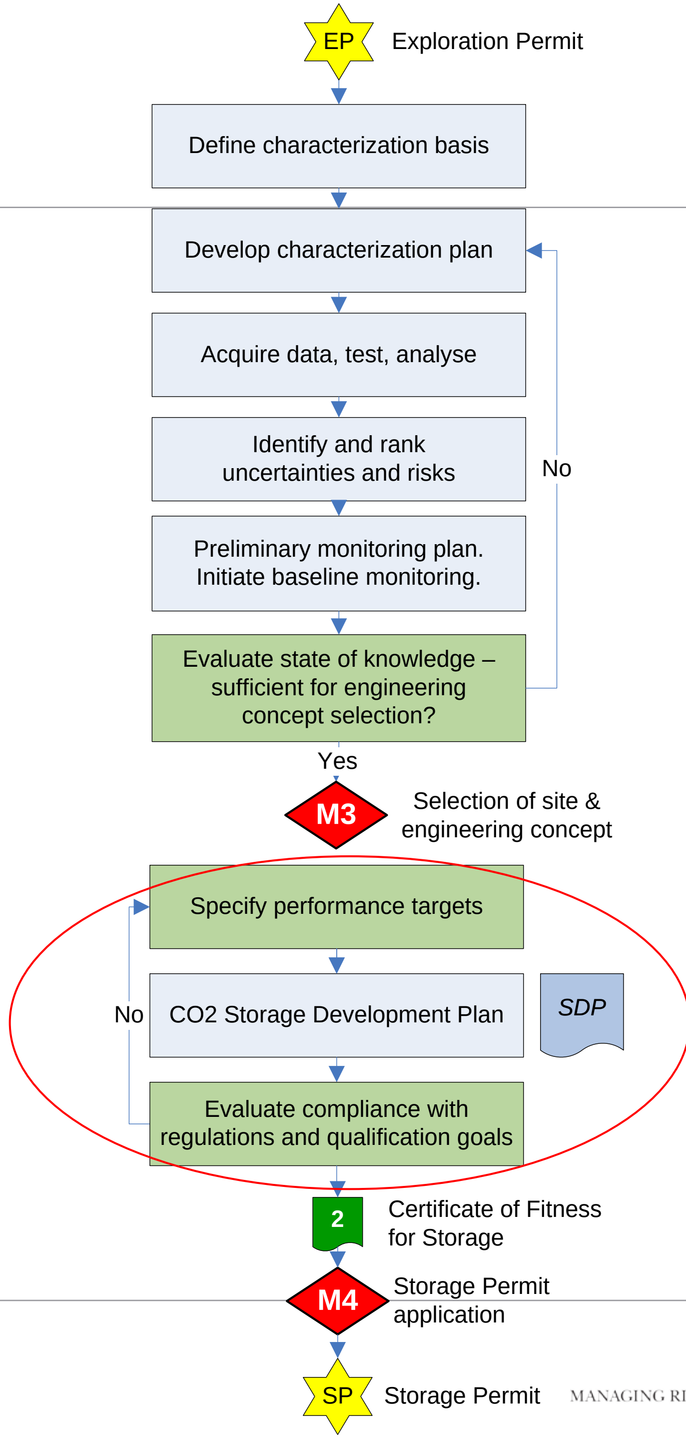
Permits issued by Regulator

EP – Exploration Permit
SP – CO_2 Storage Permit
TOR – Transfer of Responsibility

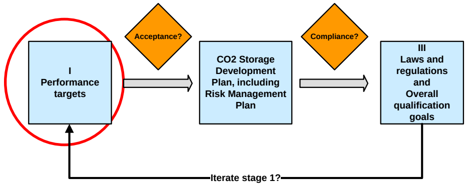
Assess and Select

- Collect and assess data – define criteria for demonstrating “fitness for storage”.
- Identify and assess risks and uncertainties.
- State of knowledge - present alternatives prior to final site & concept selection
  - M3: Select site and engineering concept
- **Specify performance targets – agree with regulator on acceptable level of risk. *Propose Performance Targets for closure***
- Define site development plan
- Evaluate if site meets criteria for storage
  - M4: Submit storage permit application

Guideline recommends involvement of regulator or competent independent body assisting regulator



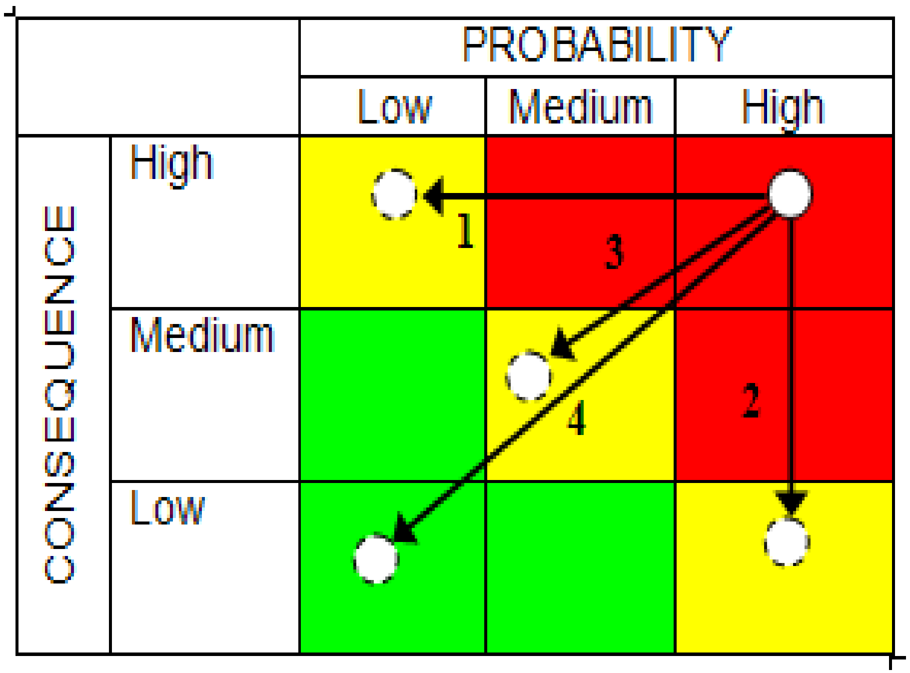
Performance targets



“A targeted level of risk/uncertainty reduction achieved through implementation of a defined risk/uncertainty reducing measure, or range of such measures,

i.e. = required terminal risk level + measures to prevent significant irregularities”

Regulator and operator beneficial

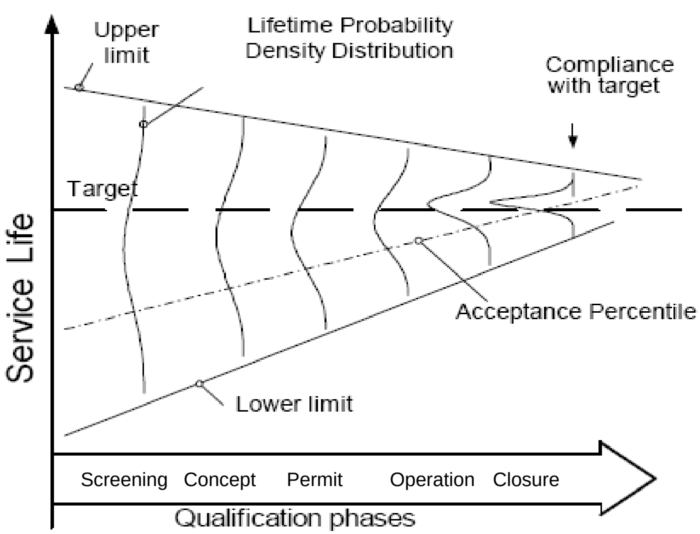


- Operational Performance targets
- Performance Targets for closure

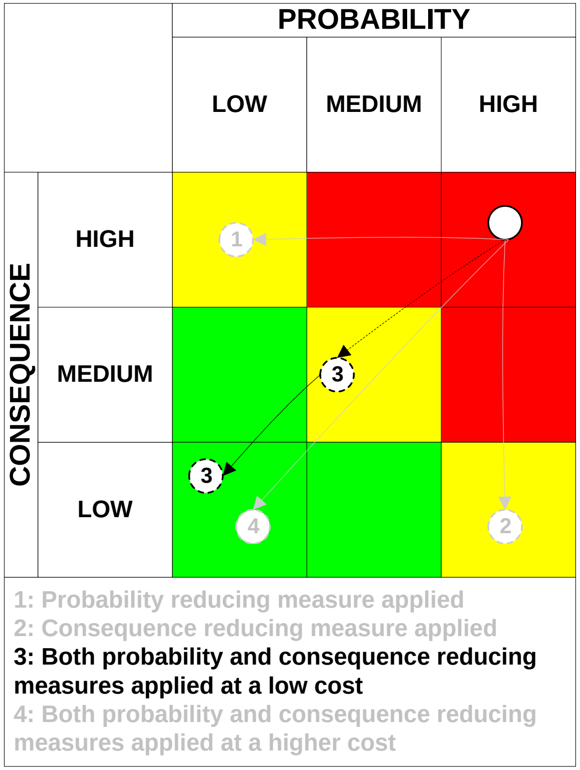
Performance targets for closure – Uncertainty focused

- Uncertainties systematically reduced throughout life-cycle
- Criterion for transfer of liability: level of knowledge supports performance targets.

Conservative risk ranking implies that proper management of uncertainty will effectively reduce assessed risk.



Acceptance percentile: There should be a higher level of confidence in the future performance of a CO_2 storage site at the time of closure than at start of injection



Examples of governmental requirements

EU criteria:

- all available evidence indicates that the stored CO_2 is completely and permanently contained
- need to demonstrate the absence of any detectable leakage
- demonstrate the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour
- the storage site is evolving towards a situation of long-term stability

US criteria are similar in nature

- E.g. CO_2 plume and pressure front should have stabilized

Proposed Qualification Goals (for site closure)

- **QG1:** *The total system relevant to CO2 storage is understood in a sufficiently detailed way that its future evolution can be adequately assessed;*
- **QG2:** *Negative impacts on human health or the environment are negligible provided future activities that may compromise the integrity of the storage site are avoided.*

- Performance targets for site closure are project specific criteria that if met will help demonstrate compliance with qualification goals and any supplementary conditions for transfer of responsibility imposed by regulations

Uncertainty assessment using reservoir simulations

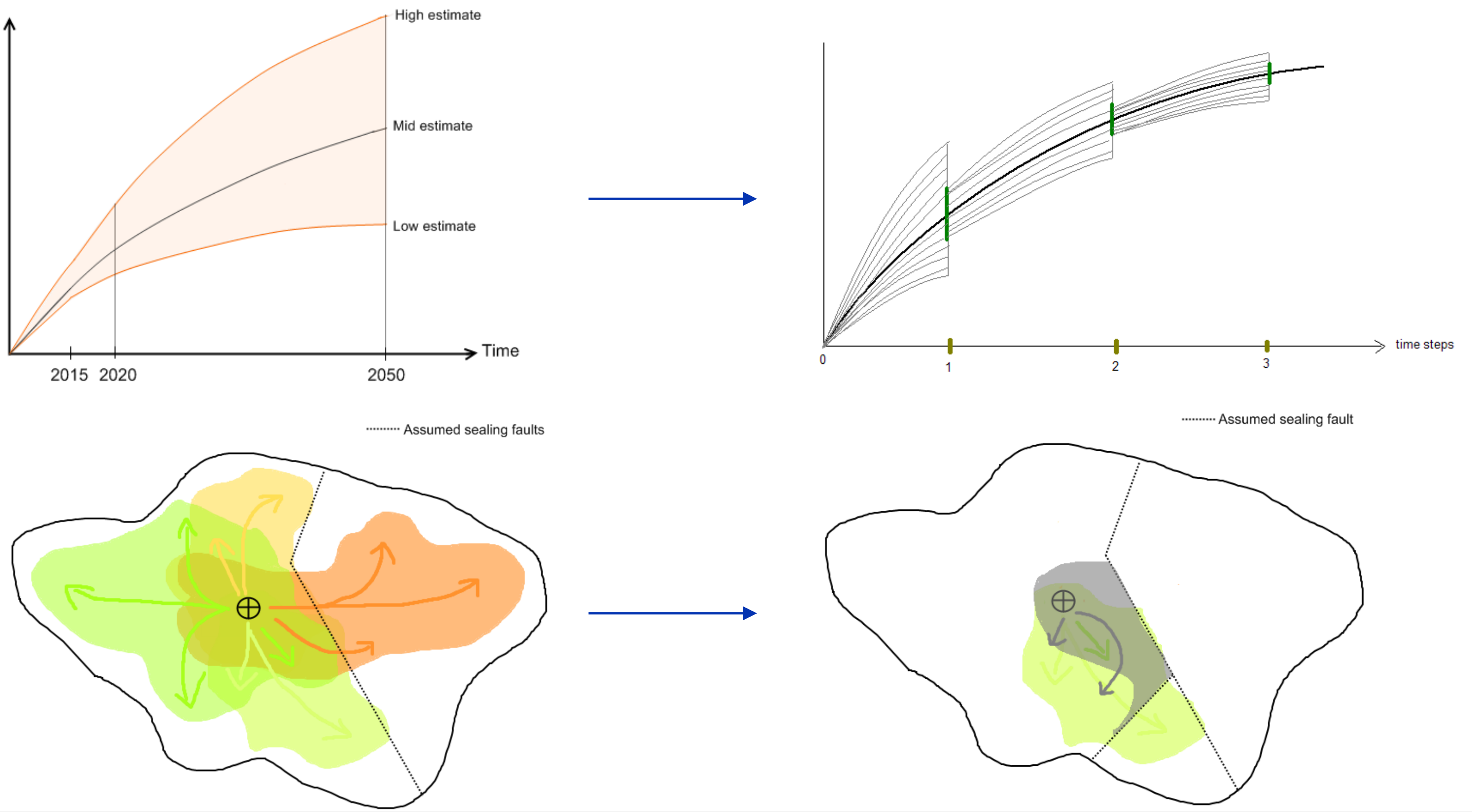
Demonstrating control of operation, facilitating for final liability transfer

- A vital tool for uncertainty analysis and screening studies (predictive)
  - Results from representative static models
  - Quantify risk by stochastic modelling of possible scenarios, to capture the uncertainty spread between “best” and “worst”

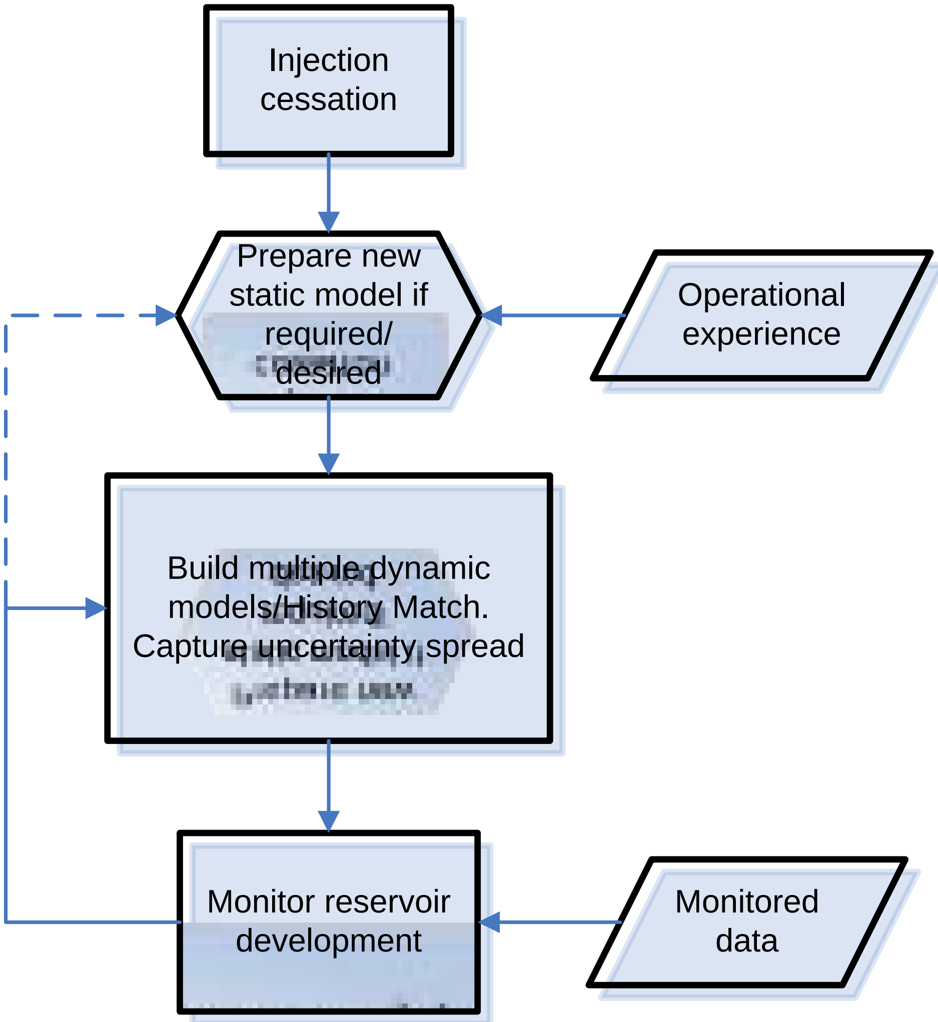
- Creates understanding and acceptance of the subsurface (corrective):
  - Update simulation model, track changes
  - Does acquired understanding change the operations planning?

Uncertainty assessment (cont)

Examples on how simulations are used to fulfil QGs:



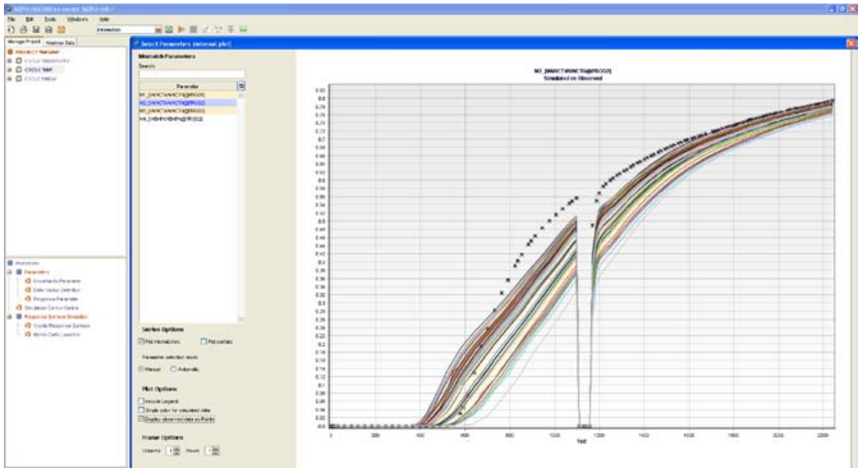
Workflow for model calibration after cessation of injection



Post-injection phase, could last up to 20 or 50 years

A loop consisting of

- *Updating of geomodel*
- *Monitoring*
- *Multiple dynamic models*
- *History matching*



Performance targets fulfilling QG1 –uncertainty handling

These are **examples** of performance targets for closure

1. It is not necessary to continue to update the static model as a basis for predicting future behaviour of the storage site.

2. Model calibrations made by history matching dynamic models no longer alter the basic understanding of the storage site characteristics in a way that may significantly influence the reliability of predictions.

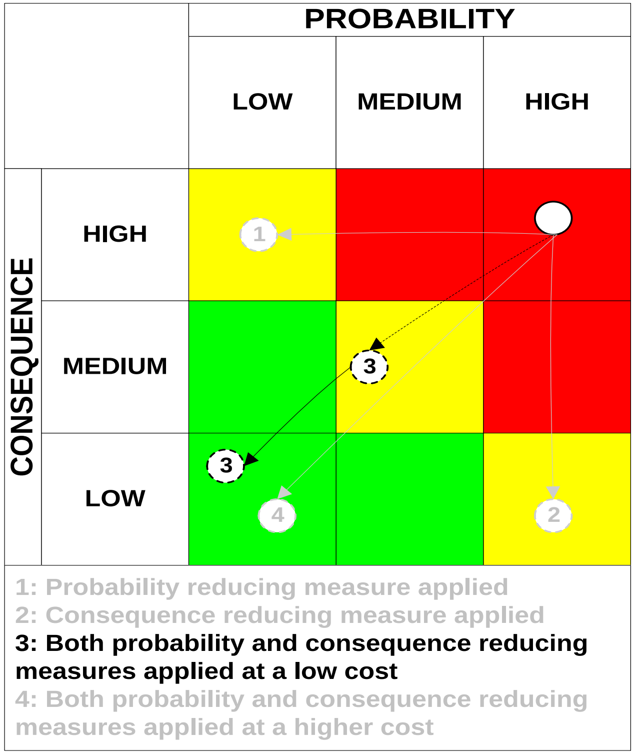
3. The modelling studies performed post injection demonstrates that the uncertainty band on the observed CO_2 migration and pressure development is within acceptable limits
   - **Plume development**
   - **Pressure development**

Performance targets fulfilling QG2 – focused on risk

Handled as in the operational stage. However, the reduced uncertainty should implicitly have reduced the risks further

Examples

- Impact of CO_2 plume intercepting an abandoned well, risk of leakage should be reduced to a certain level
- Lateral spread should be less extensive than the assumed spill points
- Pressure build-up due to long-time post injection migration up-dip into a trap should not be beyond a certain limit



To summarize

- Performance targets creates project specific ways to help demonstrate fulfilment of the qualification goals, and are the *acceptable levels of risks/uncertainties plus the means to get them there*
- Enables the regulators to present and assess their concerns along with the project developers, and developers to know within which frames they need to operate. All the way from the initial stage
- Performance targets that are closure-oriented assists transfer of liability by providing provable targets that are set and agreed upon by all parties
- Usage of reservoir simulations helps demonstrate control of the uncertainties
- ***Guideline finalized as we speak!***

Thank you!

Questions?

Marius Bjørnli Lunde
16 February 2010

Safeguarding life, property and the environment

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MANAGING RISK

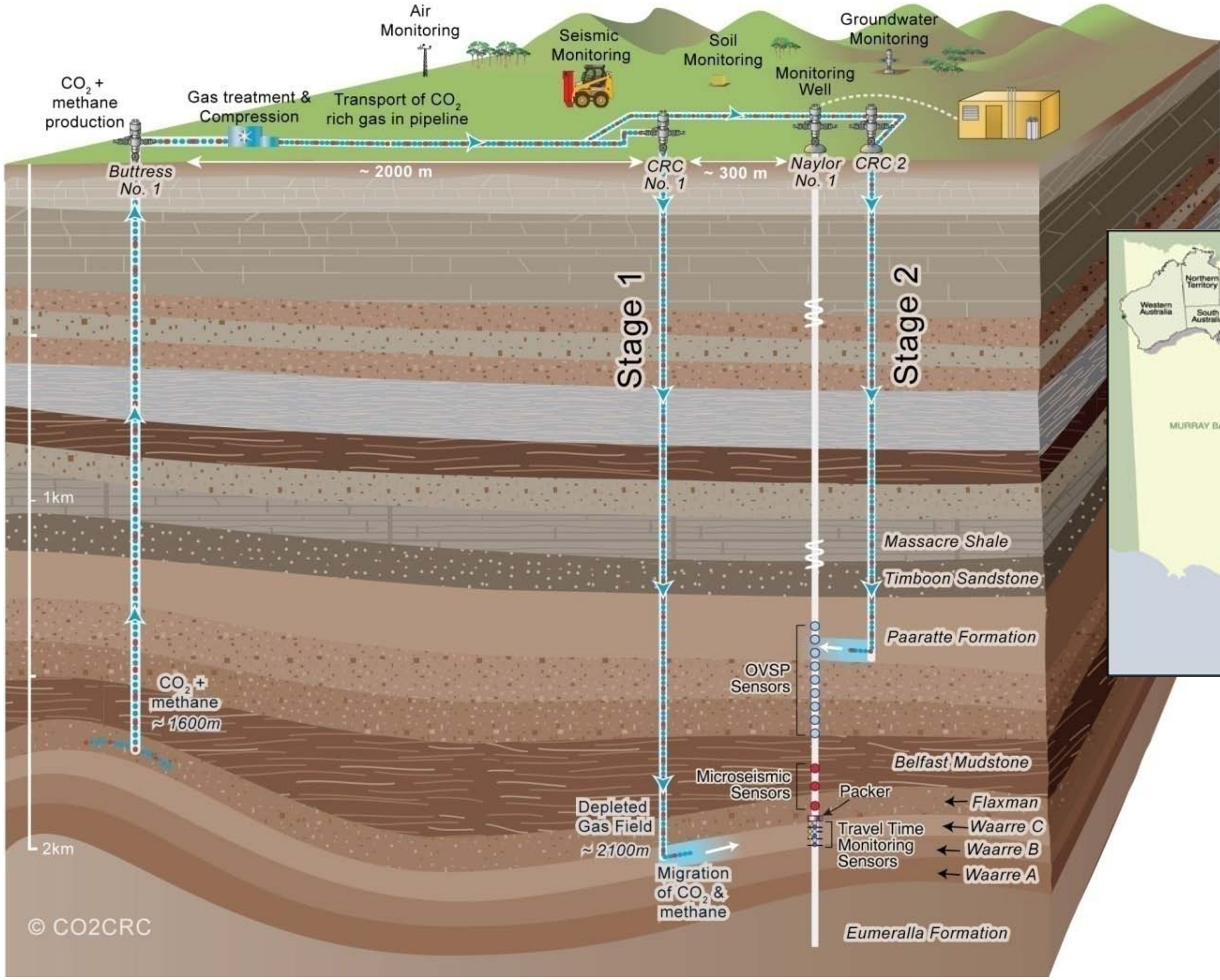
Calibration of simulation models to monitoring data for the CO2CRC Otway project.

Jonathan Ennis-King[1], T. Dance[1], J. Xu[2], C. Boreham[3], B. Freifeld[6], J. Gunning[1], B. Gurevich[4], C.Jenkins[1], L. Paterson[1], R. Pevzner[4], S. Sharma[5], L. Stalker[1], J. Underschultz[1], M. Urosevic[4]

CO2CRC, [1]CSIRO Earth Sciences and Resource Engineering, [2] Chevron [3]Geoscience Australia [4]Curtin University [5]Schlumberger [6]Lawrence Berkeley National Laboratory

CO2CRC

Project location & concept



Naylor field history

- **June 2002 – November 2003: Gas produced from Waarre C unit in the Naylor field through the Naylor-1 well (84.4 mole % CH_4, 1.0 % CO_2). Data includes monthly production rates and tubing head pressure (THP). Post-production GWC (May 2006).**
- **March 18th 2008 - August 28th 2009 : Injection at CRC-1. Data includes daily injection rates, surface conditions and downhole pressure and temperature gauges, brought up every six months.**
- **Two batches of tracers injected (April 4th 2008, Jan 15th 2009) – first one includes SF_6, CD_4, Kr**
- **Injection stops after 65400 tonnes of gas injected - 76.7 mole % CO_2, 20.0 % CH_4 - (58400 tonnes of CO_2).**
- **Weekly sampling of Naylor-1 well via U-tube assembly.**

CO2CRC

Geological model

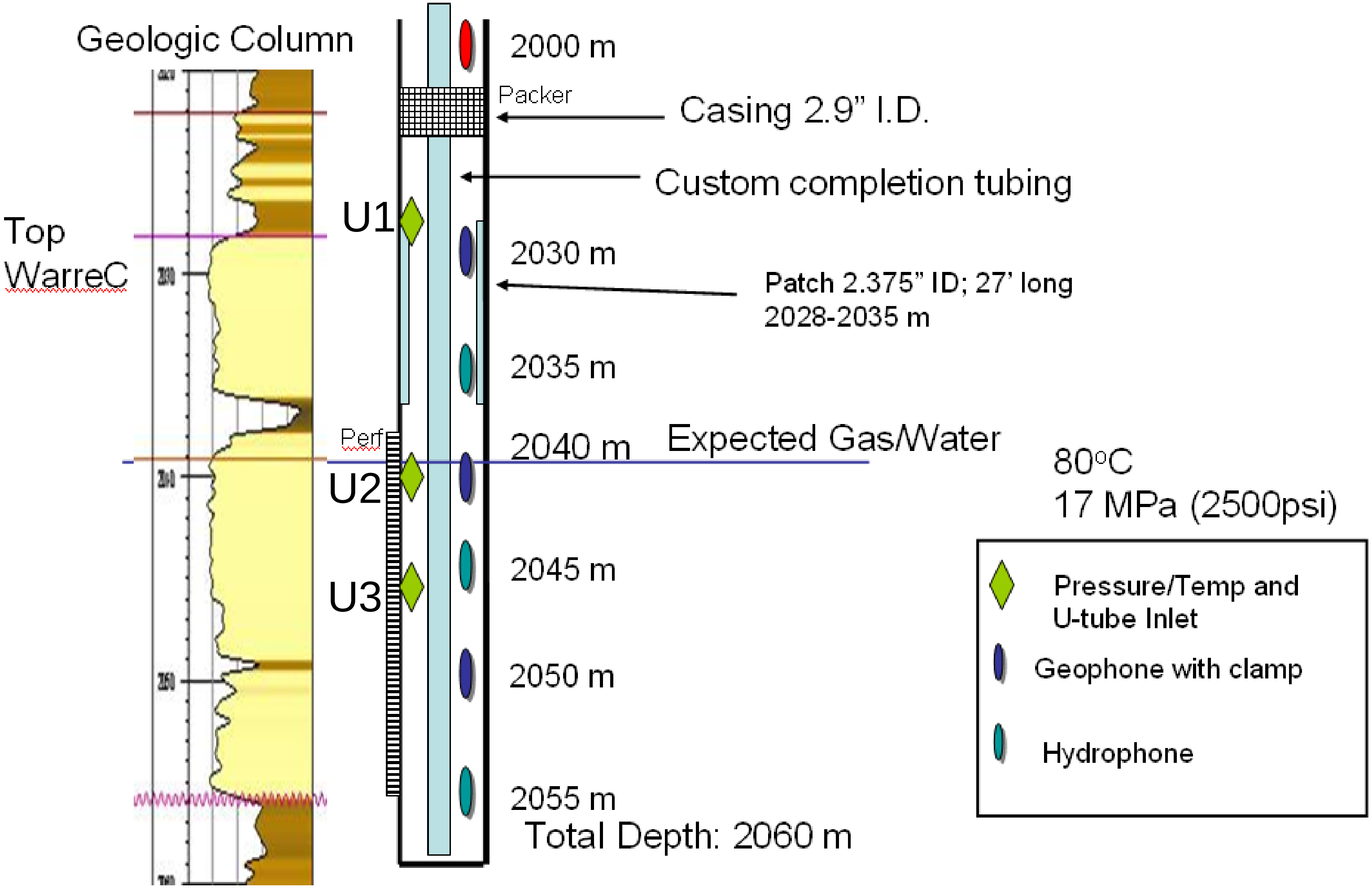
- Waarre C reservoir unit is fault-bound on three sides
- Overlying low permeability Flaxmans formation
- Belfast Mudstone seal is 300m thick
- Excellent quality reservoir; 25-30% average porosity, permeability around 1 Darcy.
- Well logs show heterogeneity: stacked sandstone bodies and thin shale baffles.
- Depositional environment suggested as tidally influenced channels in a near marine setting.
- Geostatistical models used to generate multiple realisations of rock properties for the static model

Simulation model

- TOUGH2 with EOS7C module – CH_4, CO_2, brine and tracer– and relative permeability hysteresis.
- Actual gas composition represented only by CO_2 and CH_4 components, so density is only approximate.
- Tracer partitioning is represented by a Henry's law coefficient
- Relative permeability and capillary pressure curves are taken from lab measurements where available (but still sparse).
- Aquifer properties (vital for pressure history) are represented by large volume boundary blocks.
- Grid: Resolution ~ 20m lateral, ~ 1m vertical, 45,000 blocks
- Model converted from cornerpoint grid to PEBI grid.

CO2CRC

Bottomhole assembly in Naylor-1



The sampling process matters

- U-tube sampling is (slow) production.
- Before self-lift, the U-tube sample compositions are of exsolved gas (preferentially concentrates CO_2 compared to CH_4). After self-lift, the U-tube samples are gas phase compositions.
- Therefore the timing of self-lift, as analysed from the simulation data, is crucial to the predictions of U-tube results.

Unfortunately, the U-tube locations are not packed off from each other, so there is potential communication between levels.

Further field testing and theoretical analysis suggests:

- The sampling rate is so low that U1 is almost independent of U2.
- After U3 self-lift, there may be communication between U2 and U3, but they are still distinct.

Objectives of simulation

2004

- **Acquisition: is the concept workable? Very simple models of migration and leakage, with accumulation below the gas cap.**

2005-7

- **Permitting and planning: Where should the new well be located? What is the uncertainty in the forward predictions?**

2008-9

- **Operational: Is the reservoir behaving as expected? When should tracer injection be done? When should injection stop?**

2010

- **Validation: How can we calibrate the models to make sense of the observations? How much model uncertainty remains? Where is the CO_2? Long-term behaviour (post closure)?**

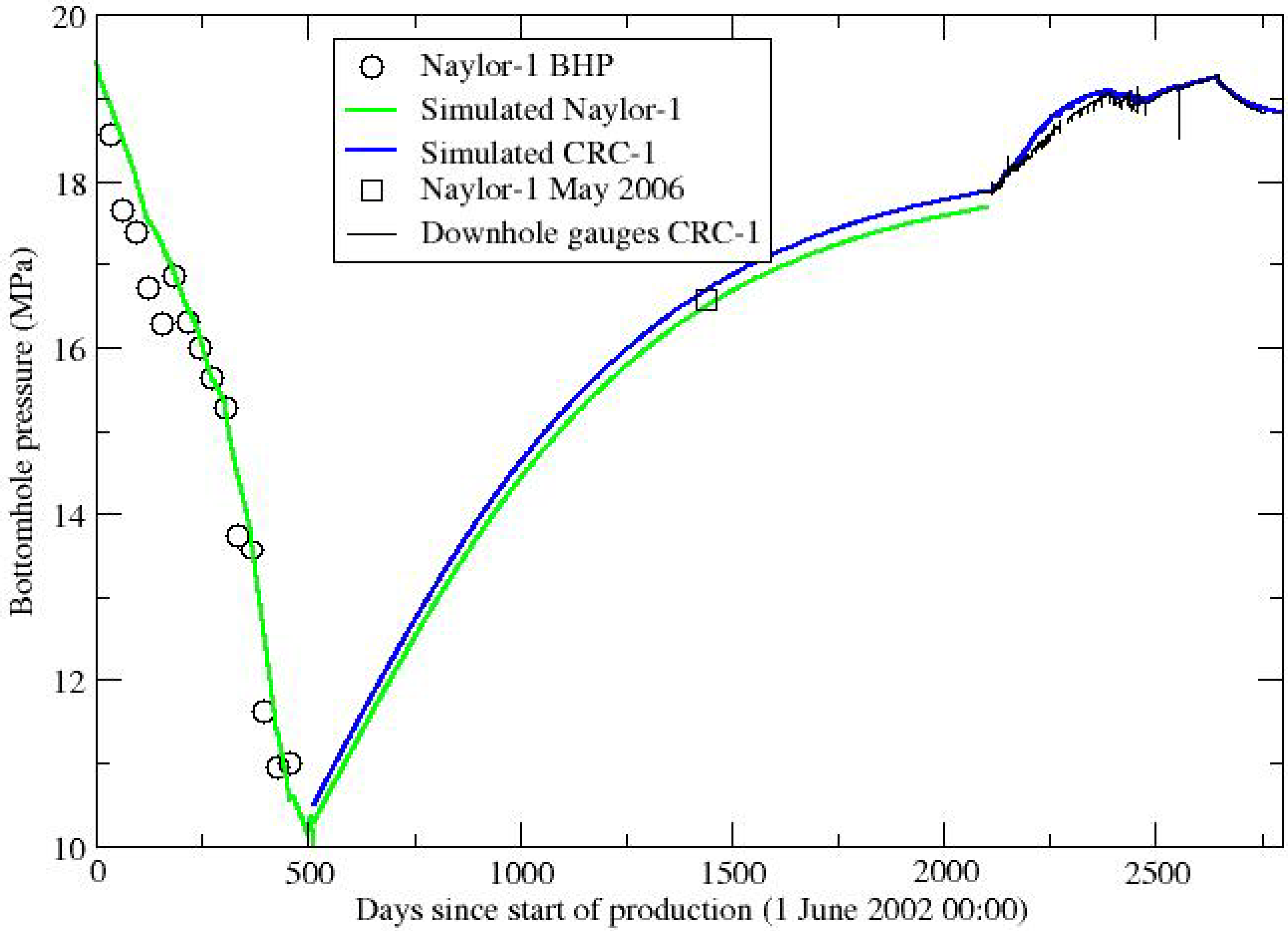
History matching process

- Four realisations of the geological model were simulated, and matched to the following data:
  - Location of GWC before and after production
  - Wellhead pressure during production
  - Downhole pressure gauge data at CRC-1 during injection
- The major adjustments were made to
  - Aquifer properties to match pressure recovery
  - Bulk permeability to match downhole pressure
- The next stage of the history match will involve adjustments to the relative permeability curves to improve the matching of arrival times at U2 and U3.

Geostatistical realisations

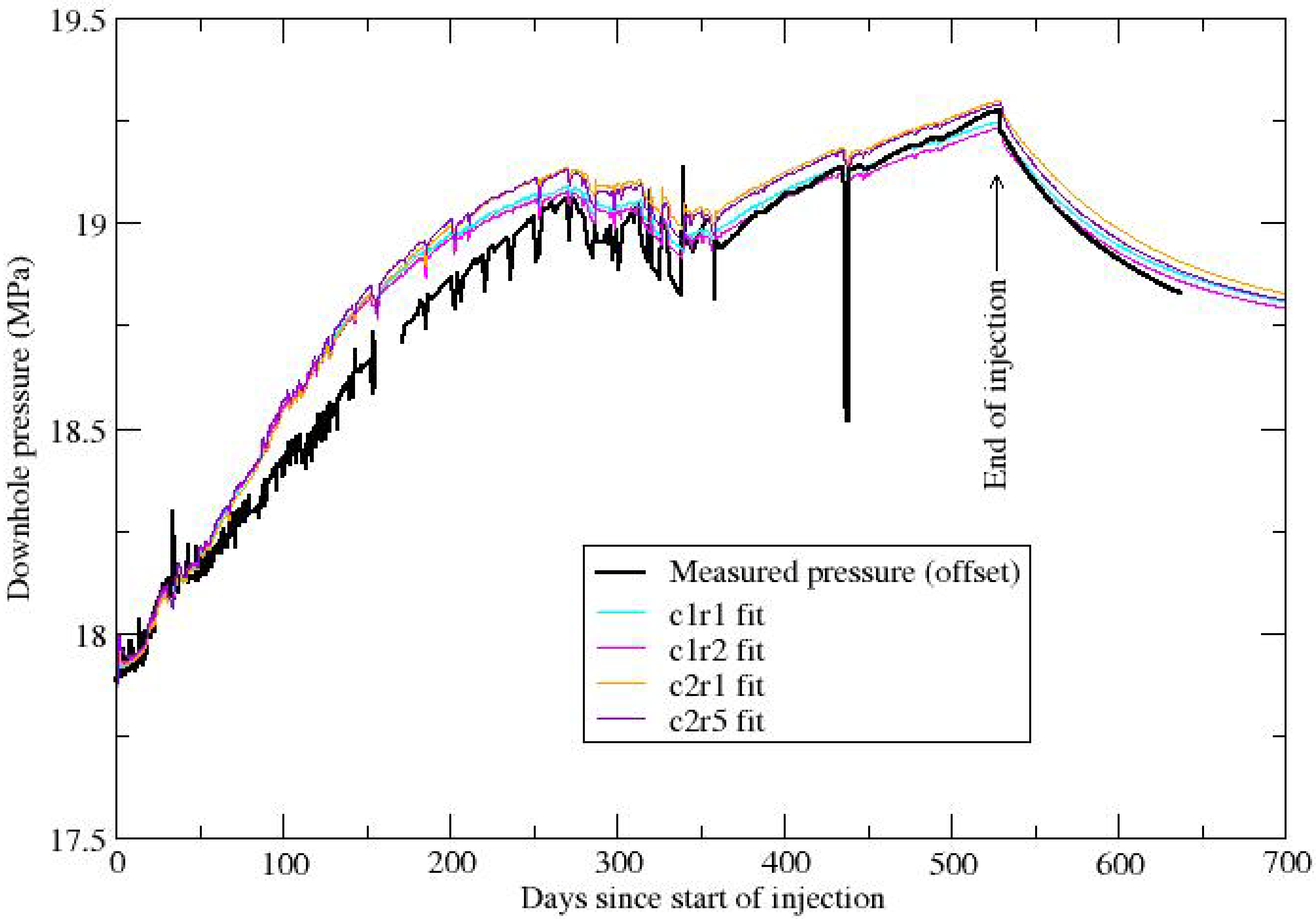
- The geological models for case 1 use a shorter range of correlation for the heterogeneity. Two realisations of this were simulated and matched (denoted c1r1 and c1r2).
- The geological models for case 2 use a long range of correlation for heterogeneity. Two realisations of this were also simulated and matched (denoted c2r1 and c2r5).
- After matching to downhole pressure, the average permeability varies by 60% over the four realisations.
- Six more realisations are currently being fitted to observations.

c1r1 fit to the entire pressure history



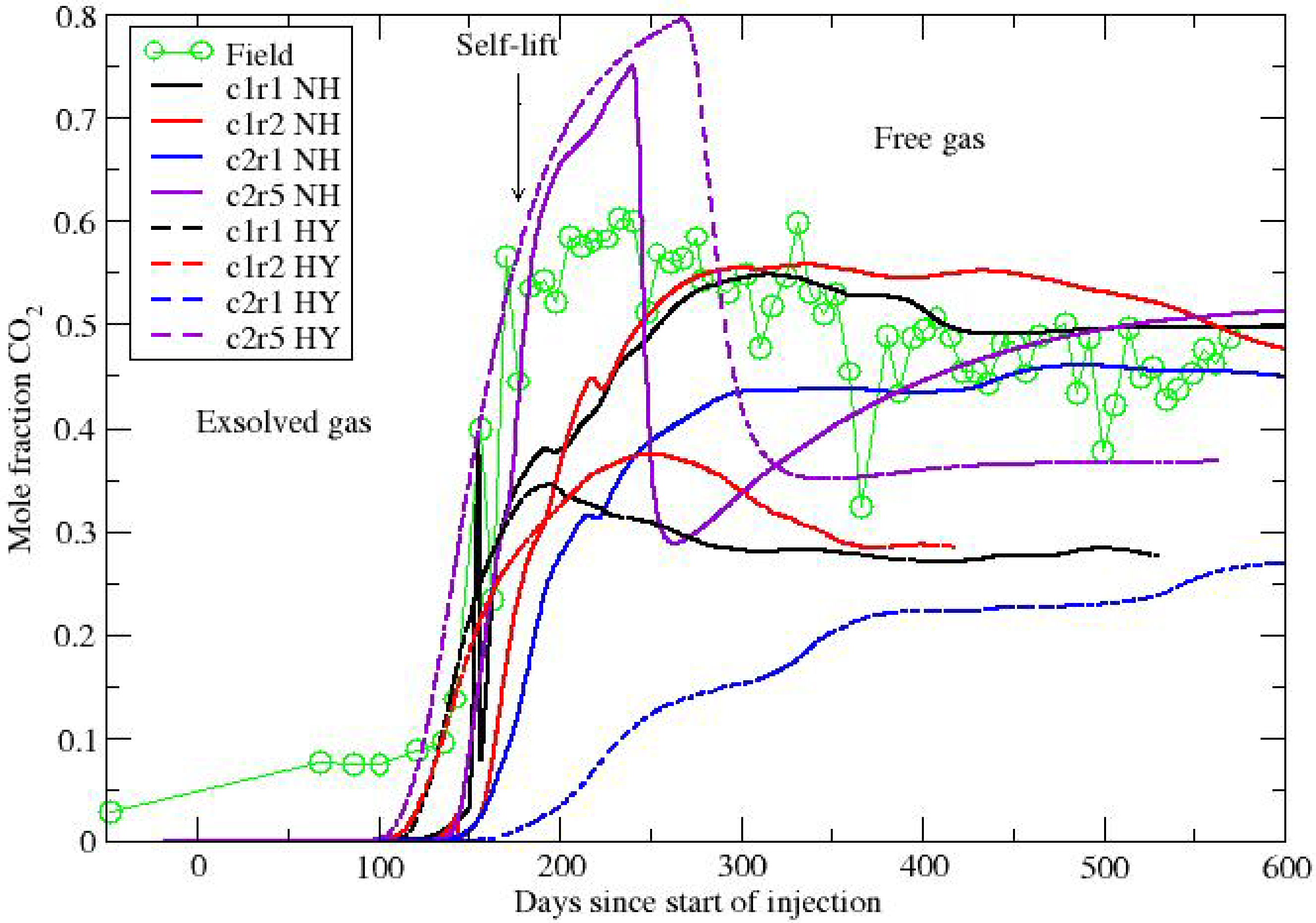
CO2CRC

Comparison of observed and simulated pressures at CRC-1

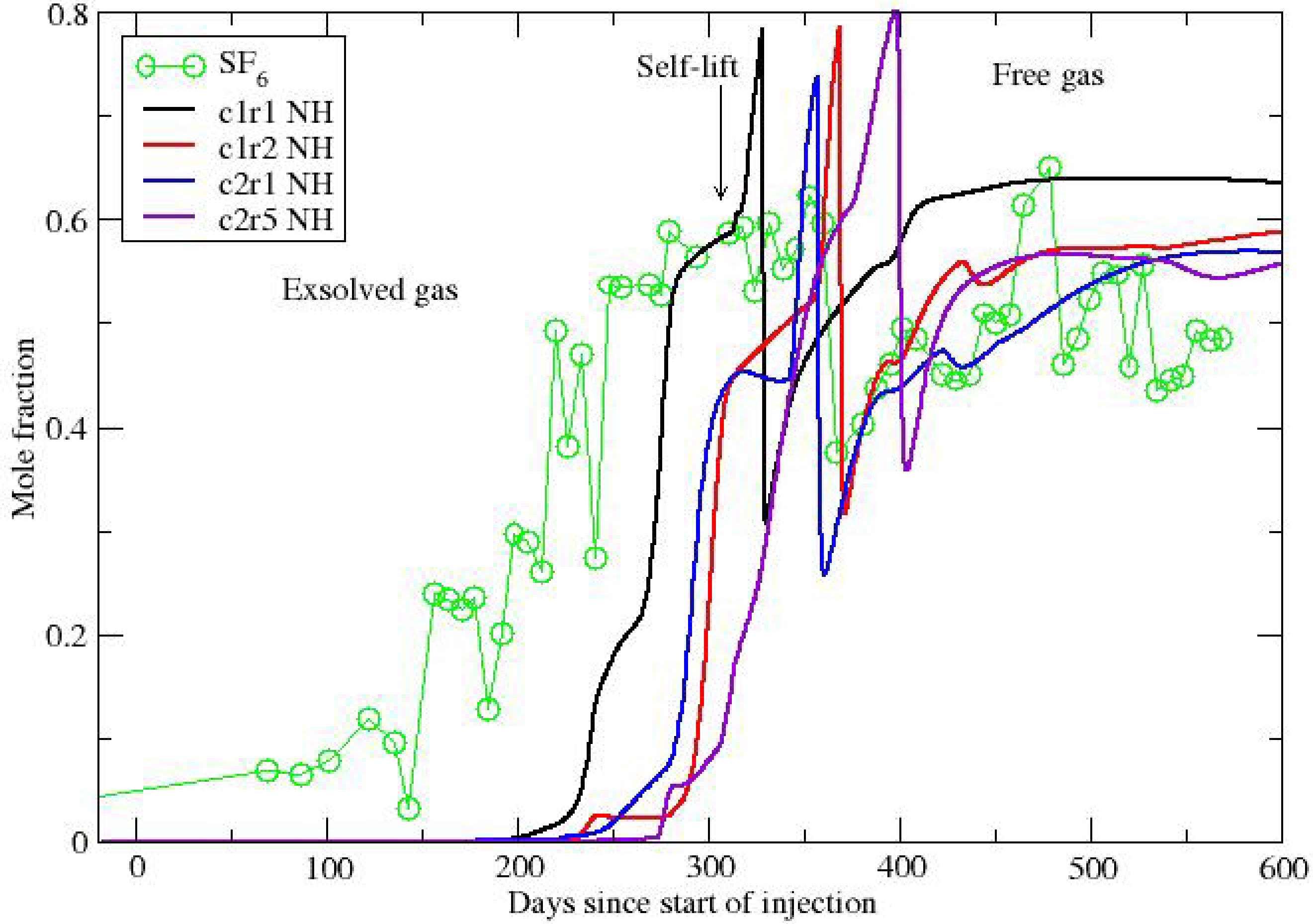


CO2CRC

U2 gas composition data vs simulations

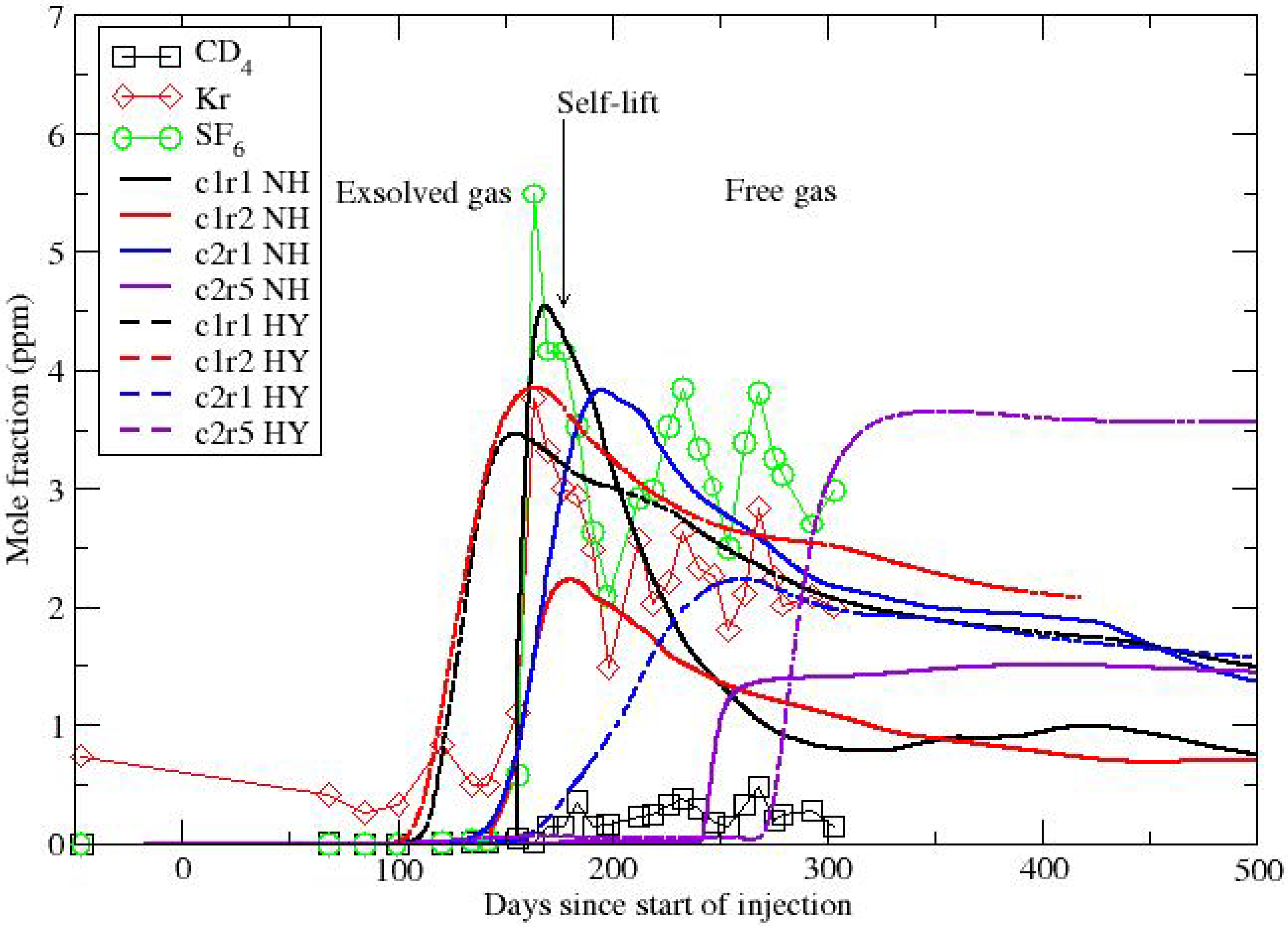


U3 gas composition data vs simulations



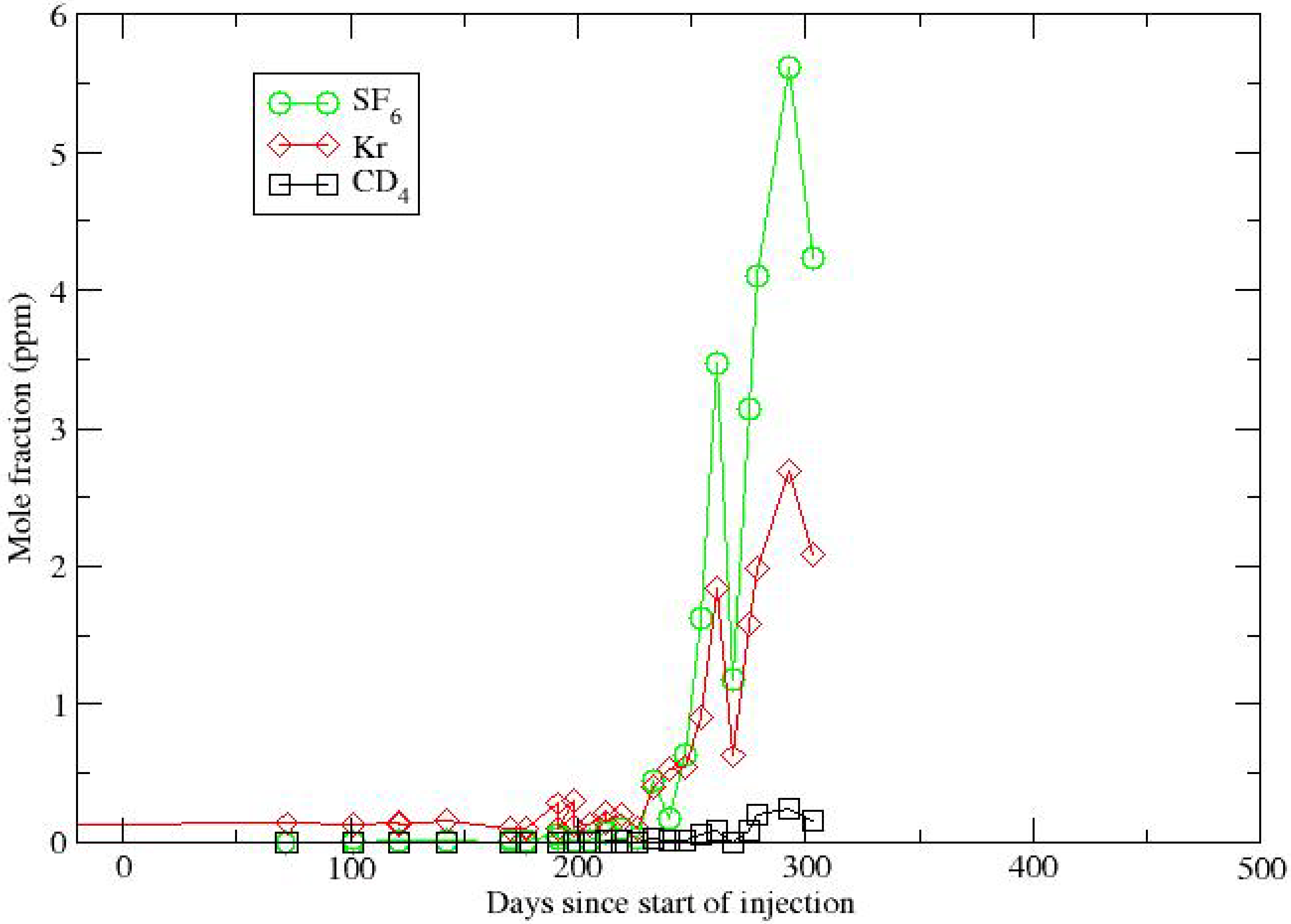
CO2CRC

U2 SF_6 tracer data vs simulations

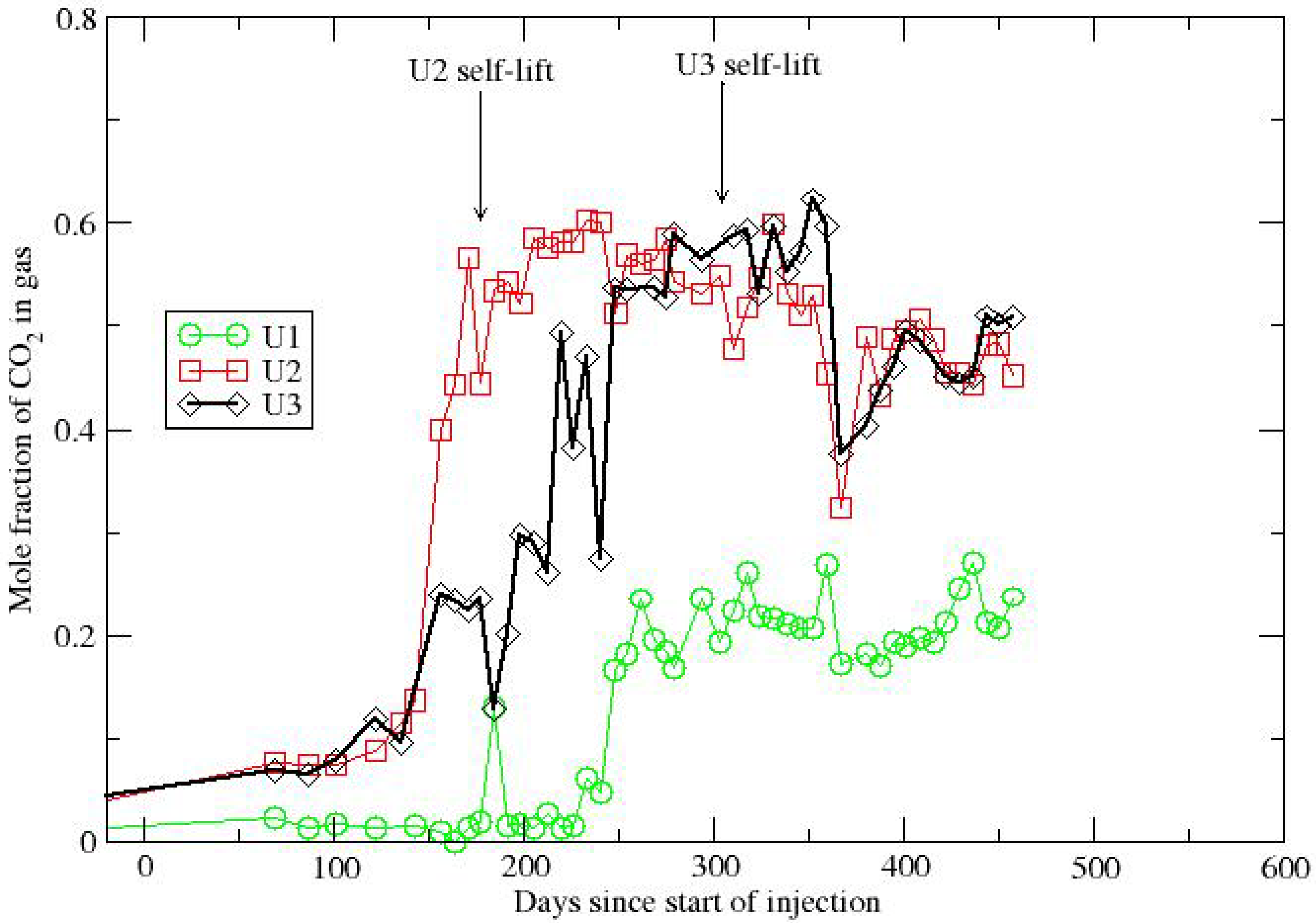


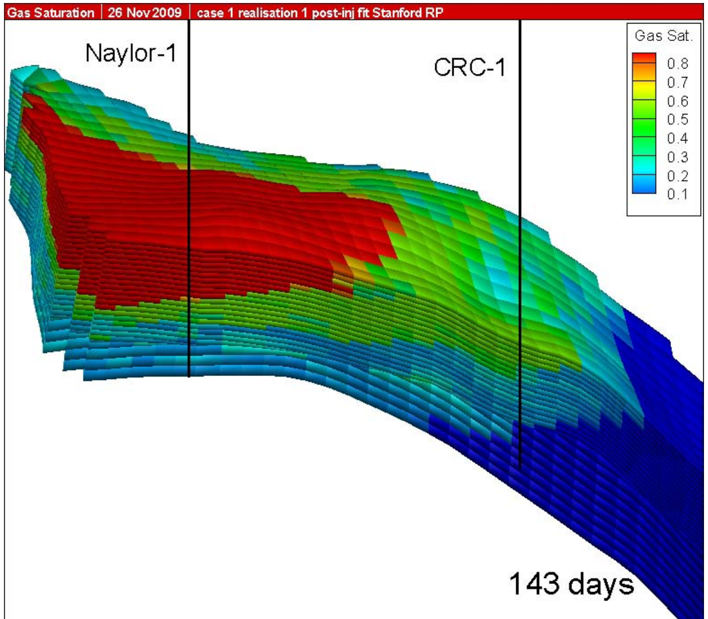
CO2CRC

U1 tracer data

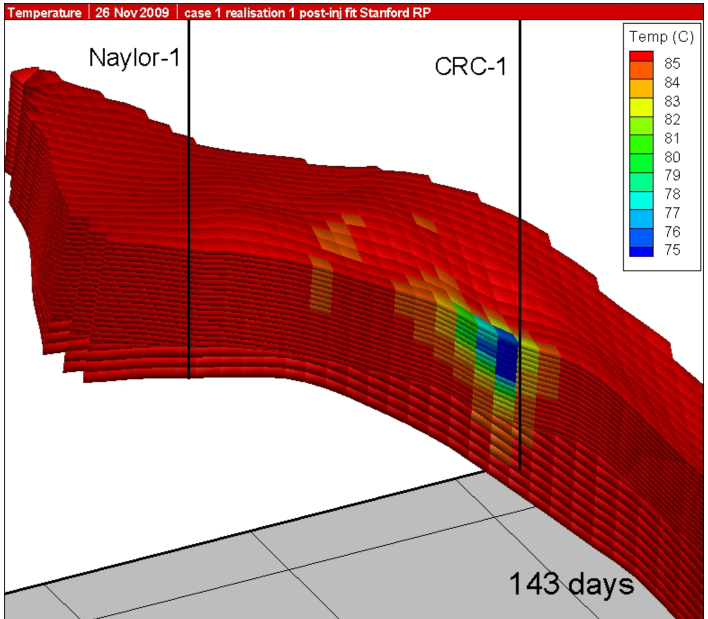


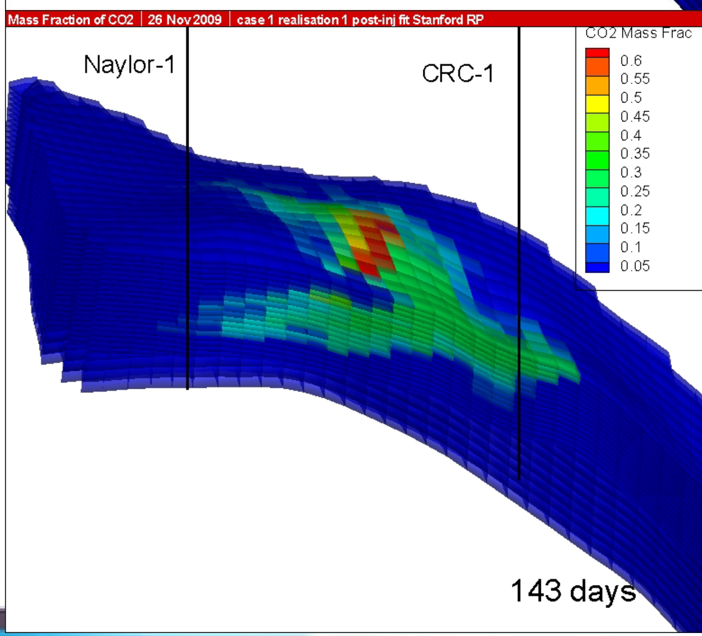
U1, U2 and U3 gas composition data

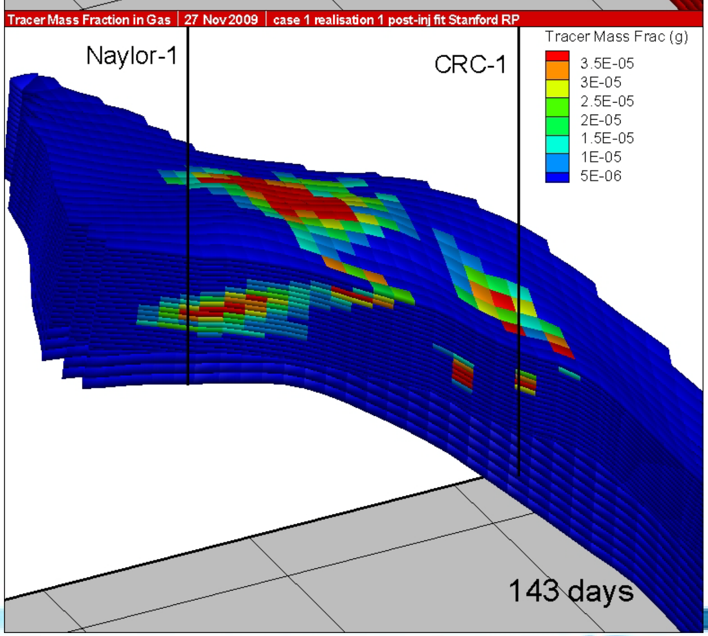


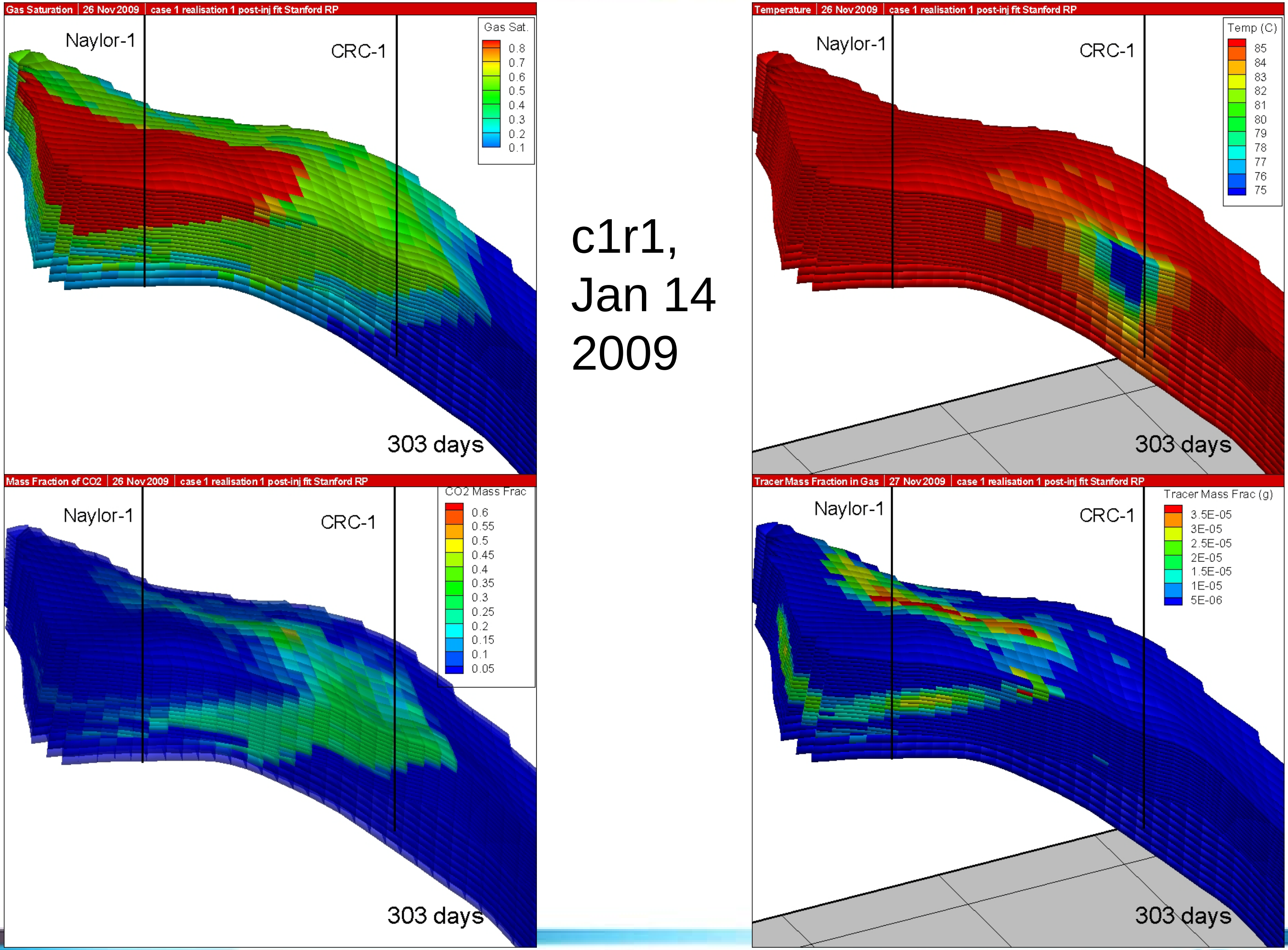


c1r1, Aug 7, 2008





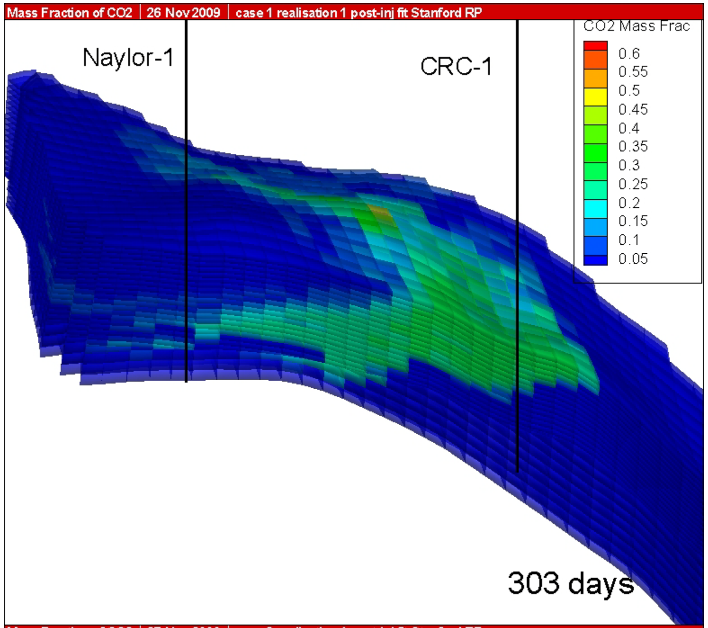




c1r1, Jan 14 2009

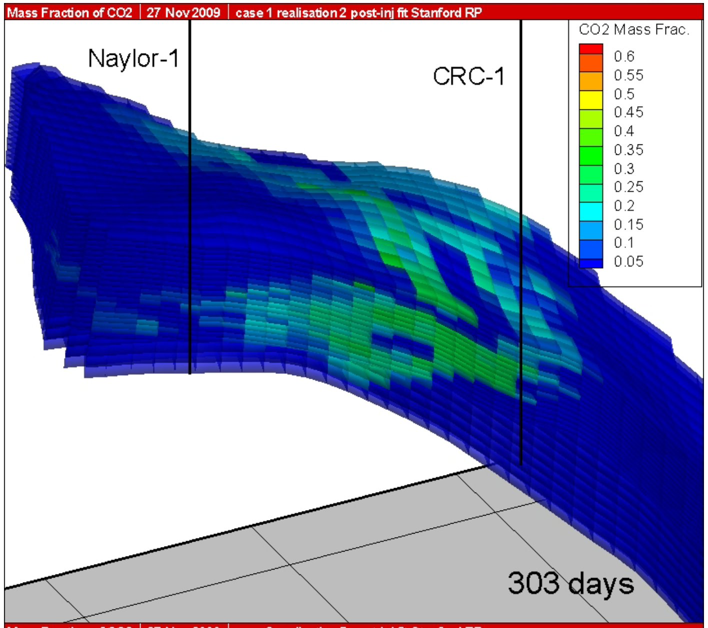
CO2CRC

c1
r1



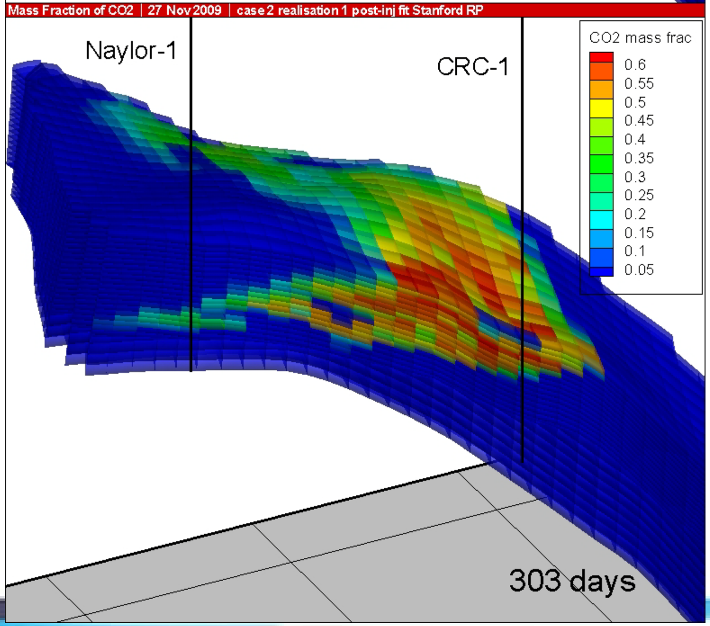
CO_2
Mass
Frac.

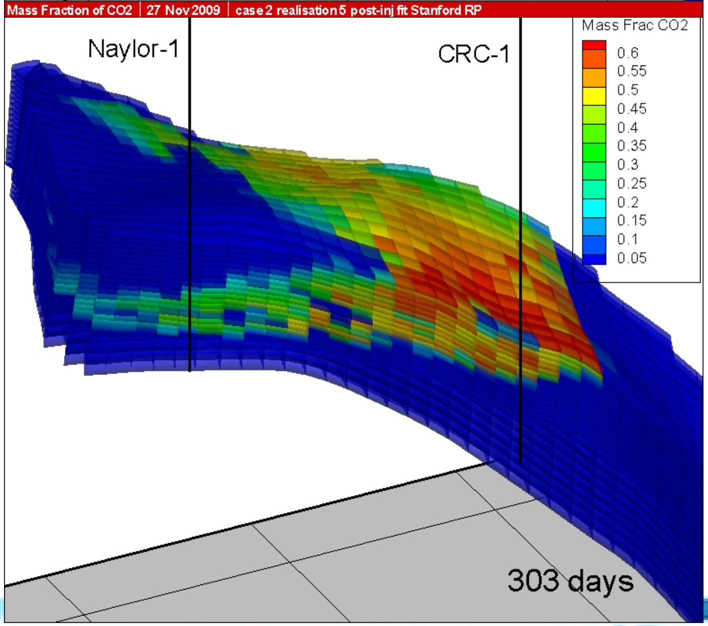
Jan14
2009



c1
r2

c2
r1





c2
r5

Matching of Naylor-1 observations

- Timing of U2 and U3 breakthroughs in CO_2 and tracer from realisations fitted to pressure is OK, but still late in some cases.
- U1 results are so far not reproduced at all
  - Not due to wellbore mixing
  - Most likely due to heterogeneity e.g. shale arrangement
- Match could be improved by adjusting rel perm curves
  - Spread of predictions indicates inherent uncertainty due to geology and model. The ‘null space’ has many dimensions!
- Filling from U2 to U3 (storage capacity of the depleted gas field) depends on relative permeability curves (hysteresis).

Seismic forward model

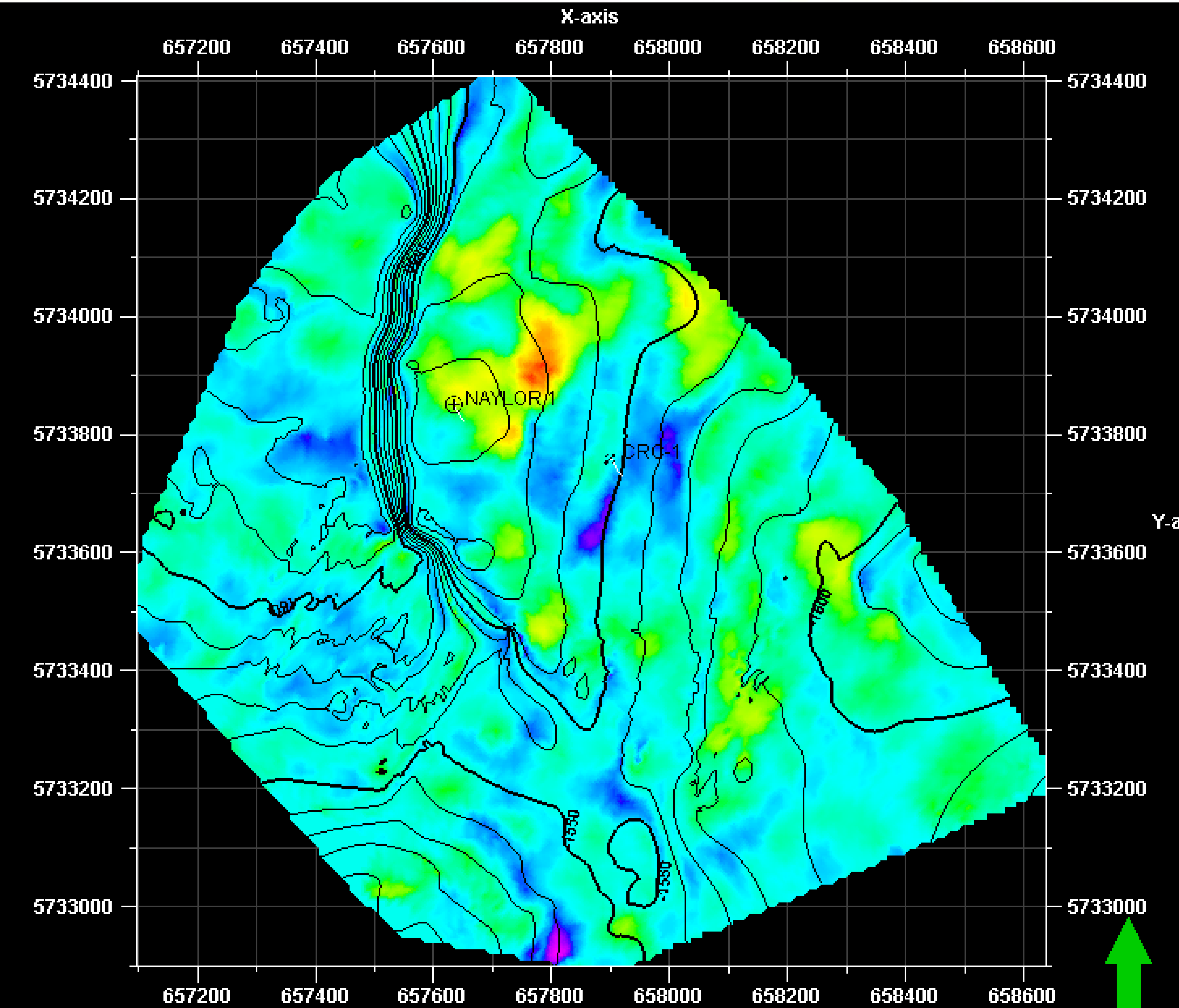
Objective:

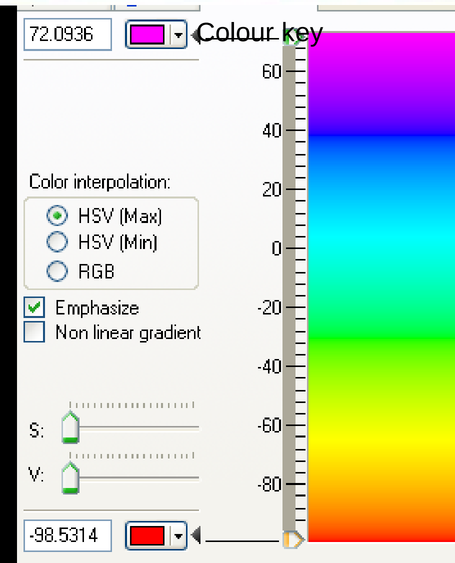
take simulated realisations and compute the difference in the seismic amplitude between January 2008 and January 2009.

Ingredients:

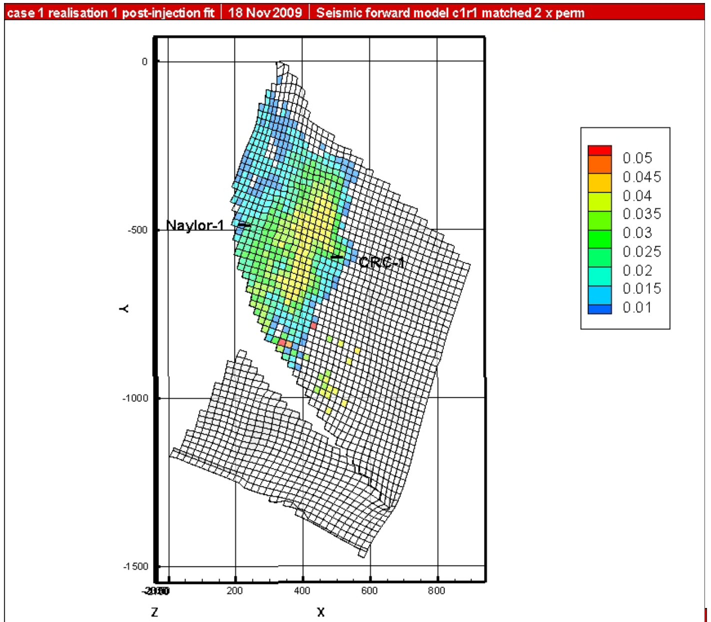
- **Delivery software (open source) for seismic inversion (J. Gunning)**
- **Rock physics model for Naylor (B. Gurevich, P. Wiseman)**
- **Representation of bulk modulus of gas mixtures (GERG EOS)**
- **‘Glue’ code to get data from TOUGH2 -> Delivery -> Tecplot.**

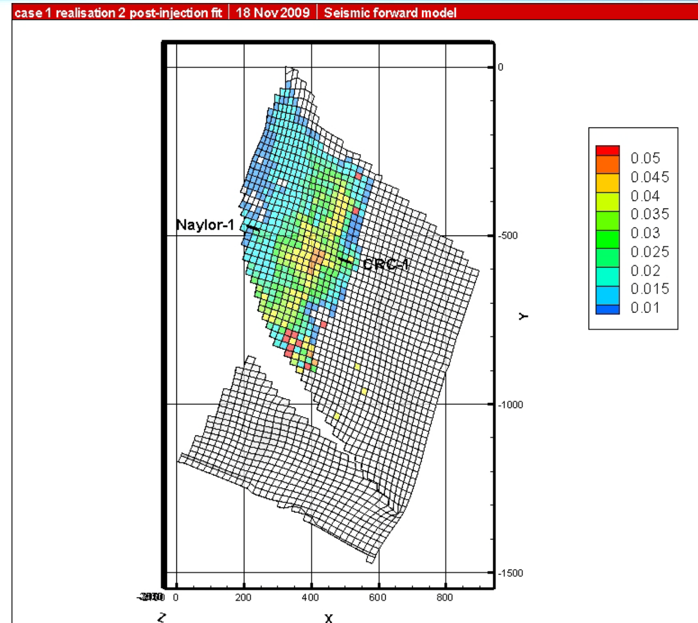
Compare to processed seismic amplitude difference between the two surveys. So far, no fitting to this response.





Amplitude Difference 2009-2008


case 1 realisation 1 post-injection fit | 18 Nov 2009 | Seismic forward model c1r1 matched 2 x perm
Naylor-1
CRC-1
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0
-500
-1000
-1500
200
400
600
800
Y
X
Z


case 1 realisation 2 post-injection fit | 18 Nov 2009 | Seismic forward model
Naylor-1
CRC-1
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0
-500
-1000
-1500
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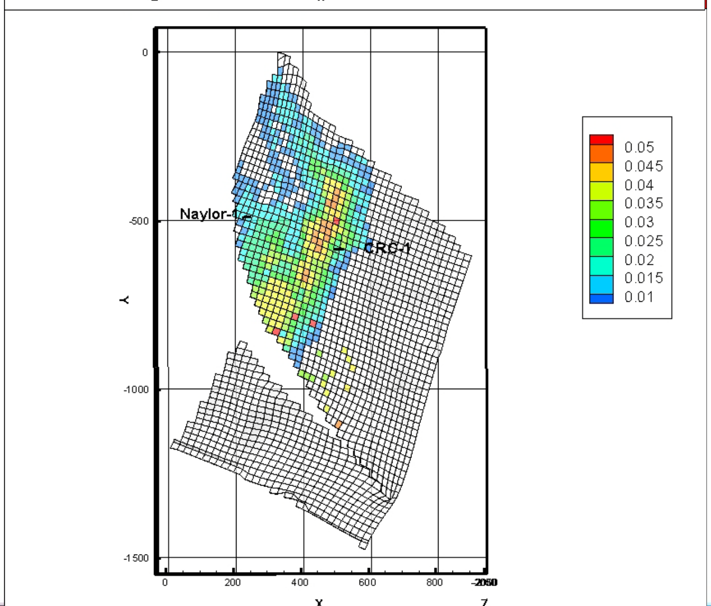
600
800
Y
X
Z


Naylor-1
CRC-1
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
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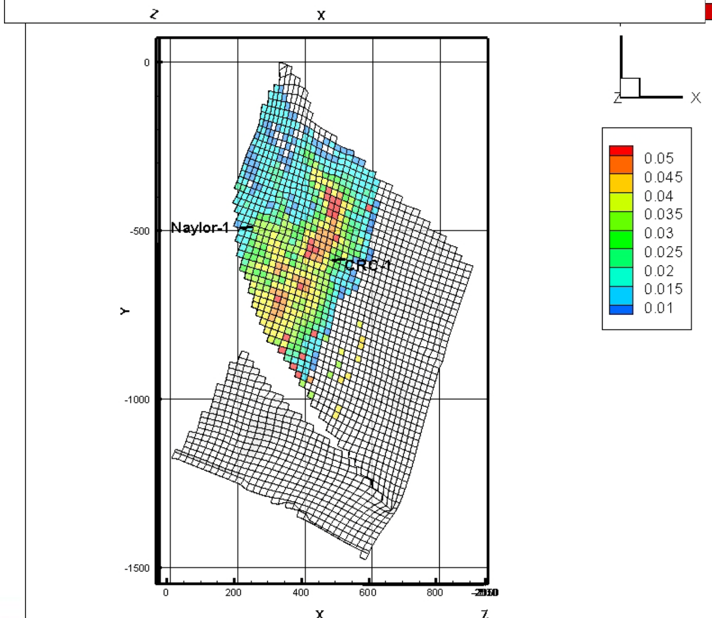
600
800
Y
X
Z


Naylor-1
CRC-1
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0
-500
-1000
-1500
200
400
600
800
Y
X
Z

CO2CRC

Forward model vs field data

- Qualitative agreement on the location of the maximum change in amplitude from Jan 2008 to Jan 2009 i.e. between the wells.
- Disagreement of the magnitude of the effect: simulation ~ 5%, field ~ 15 %.
- Rock physics model needs improvement
- Repeat seismic survey in January 2010 will need to be processed to confirm the observed features
- Only coarsest features will be reliable due to depth (2km), location (on land), thinness of reservoir (25 m) and subtle change in bulk modulus (due to gas composition changes)

Conclusions

- **Calibrated numerical models can reproduce the key features of the monitoring data e.g. breakthrough curves, seismic amplitude difference. But there are surprises!**
- **The objective should be a suite of history matches, so that model uncertainties can be estimated.**
- **Comparison of field sampling data and simulation requires a detailed understanding of the physics of the sampling.**
- **Downhole gauge data (pressure and temperature) are very valuable for calibrating the geological model.**
- **Heterogeneity has an important influence on breakthrough curves, and needs careful characterisation.**
- **Tracer simulation needs improvement. Do other couplings matter here?**

CO2CRC participants

Supporting participants: **Department of Resources, Energy and Tourism | CANSYD | Meiji University | Process Group | University of Queensland | Newcastle University | U.S. Department of Energy | URS**

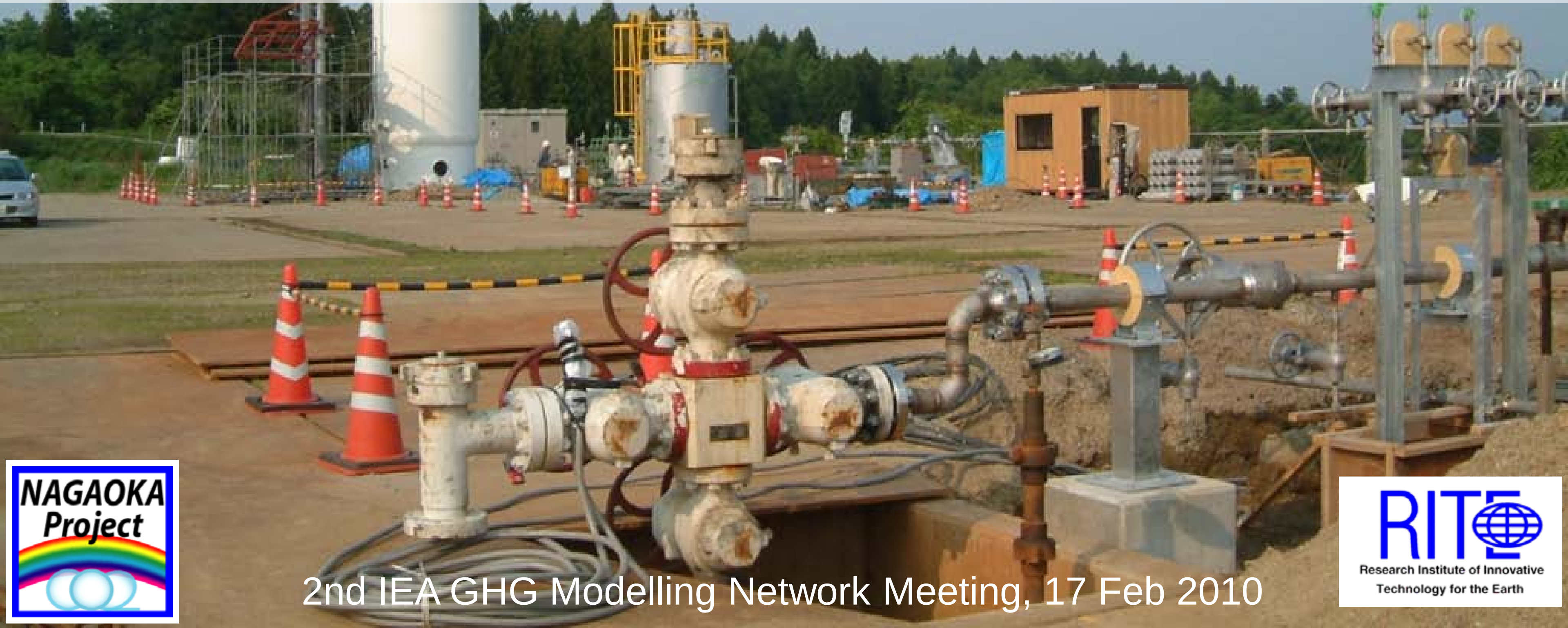
Established & supported under the Australian Government's Cooperative Research Centres Program

Calibration and Modeling of CO_2 migration with Field Data at the 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

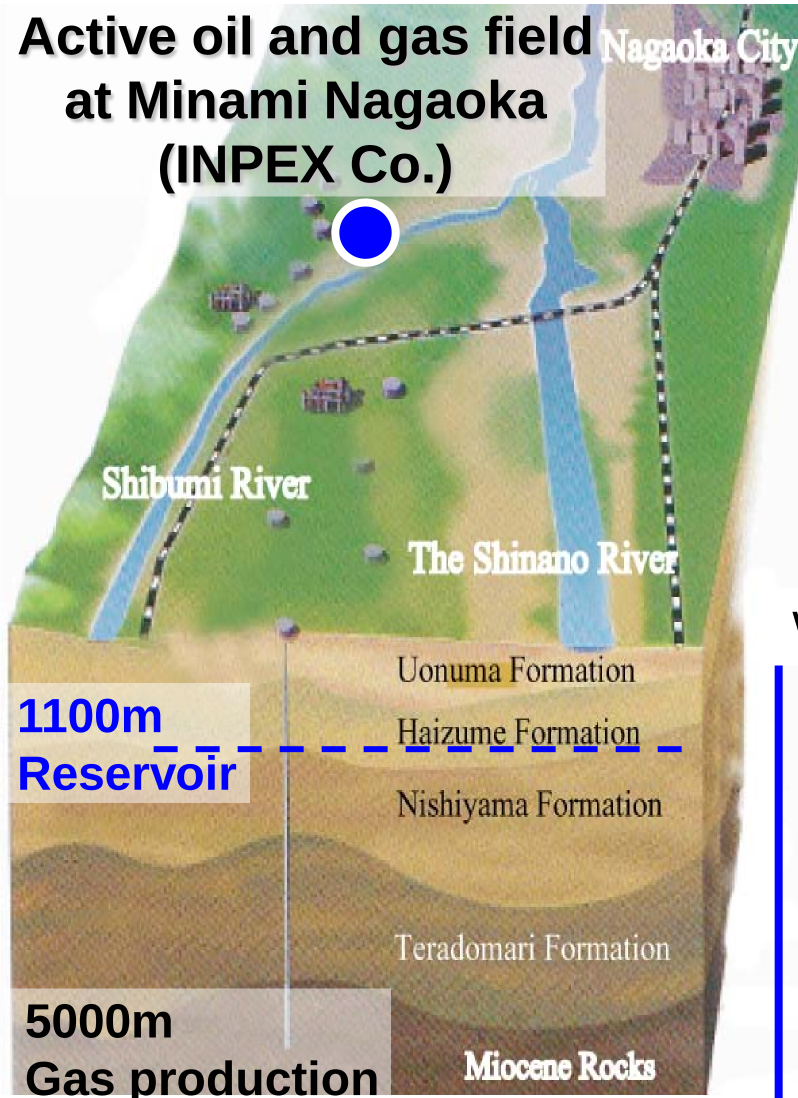
2nd IEA GHG Modelling Network Meeting, 17 Feb 2010

RITE
Research Institute of Innovative Technology for the Earth

Outline

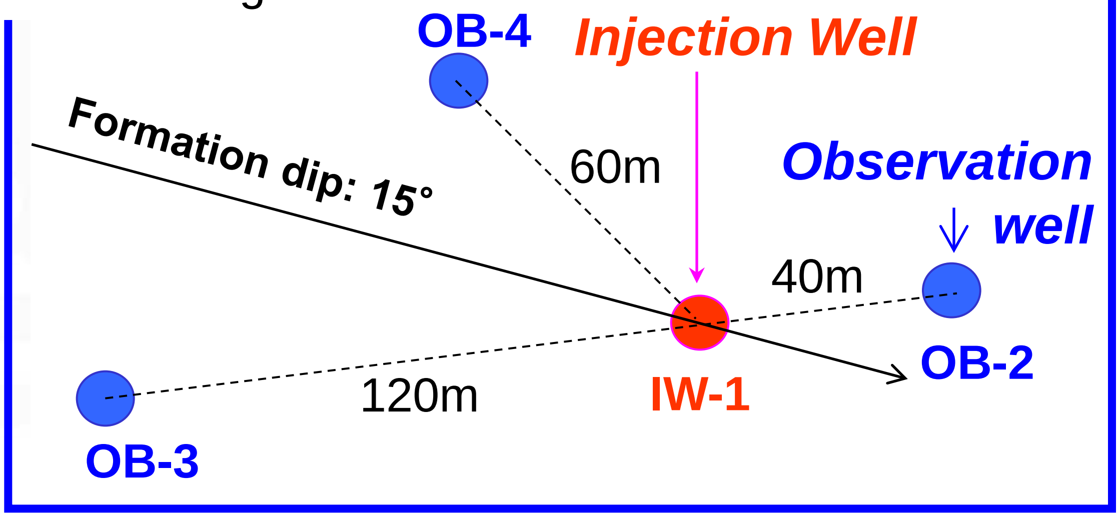
1. Overview of the Nagaoka pilot CO_2 injection project
2. History matching to CO_2 monitoring results with TOUGH2 during the injection phase
3. Post-injection monitoring of CO_2 stored in the reservoir
4. Summary

Overview of the Nagaoka Pilot CO_2 Injection Test

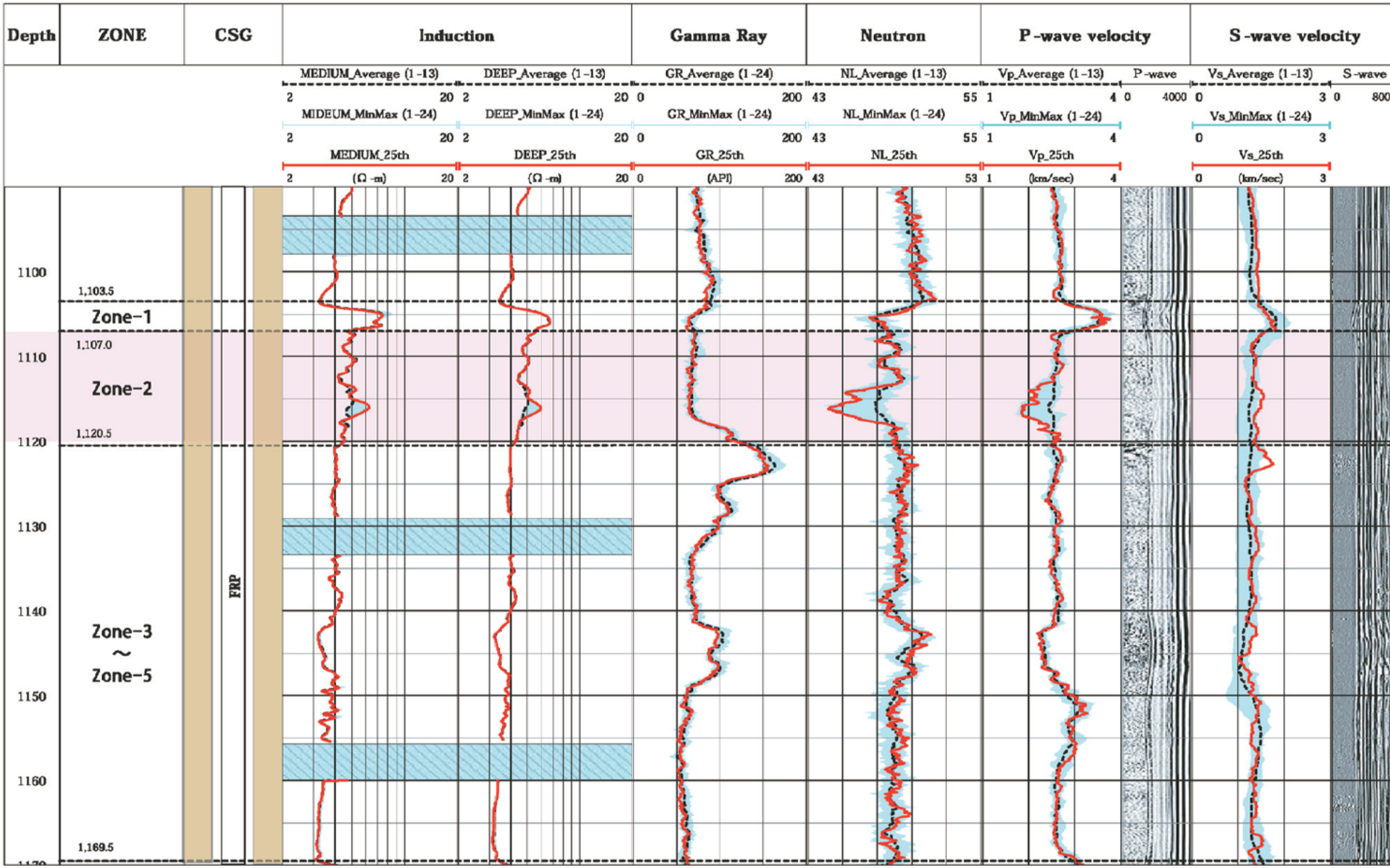


- *Duration; FY2000-2007 funded by METI, Japan*
- *Total amount of the injected CO_2;* ***10,400 ton***
- *Reservoir; Pleistocene sandstone*
  Haizume Formation, ***60m thick***
- *Target injection layer; Zone 2,* ***12m thick***
- *Porosity;* ***23%***
- *Permeability; ave.* ***7mD*** *(pumping test)*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

Well Configurations

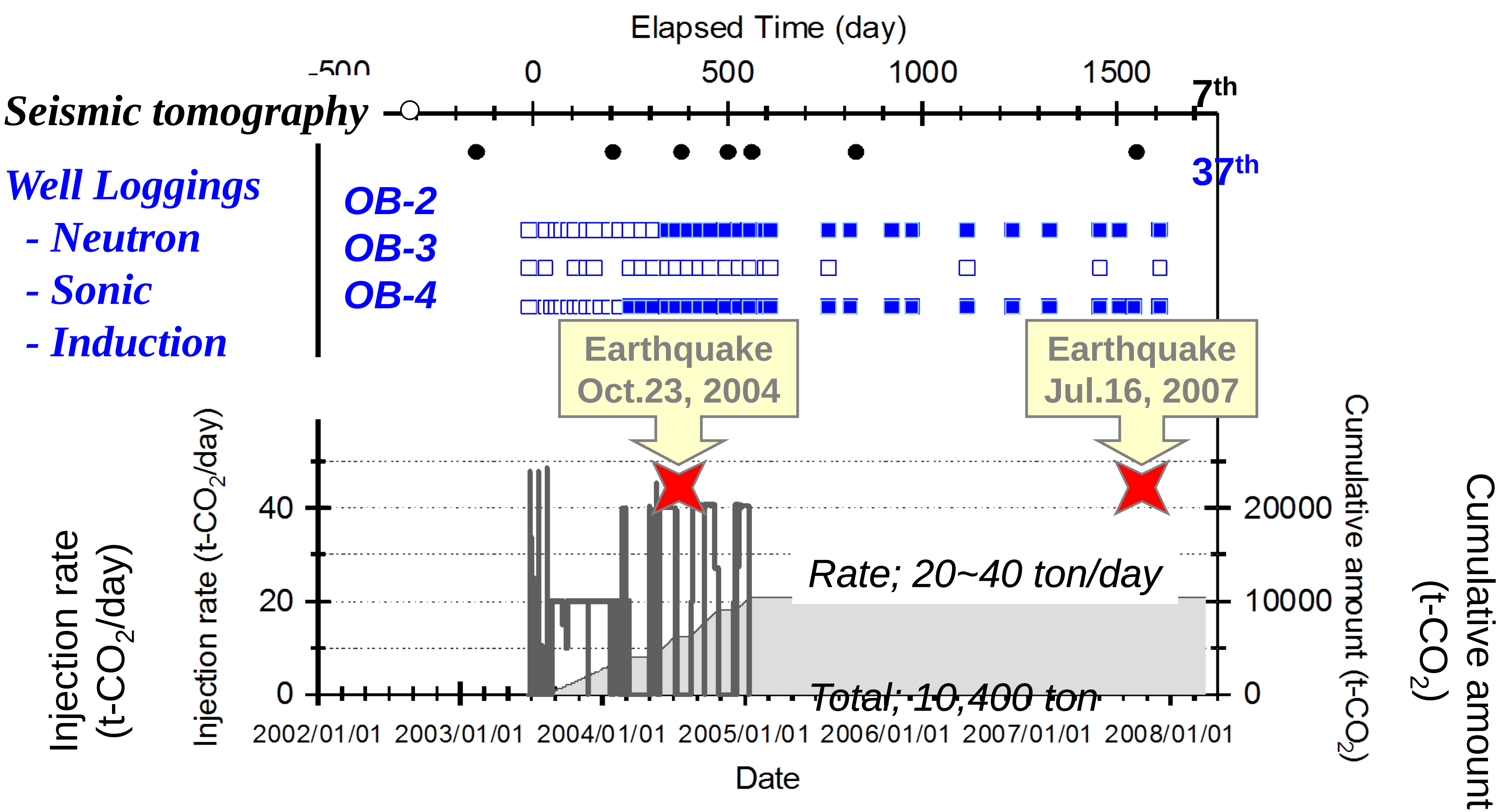


Reservoir Formation & Properties



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

Elapsed time from 7 July 2003 (day)



Date

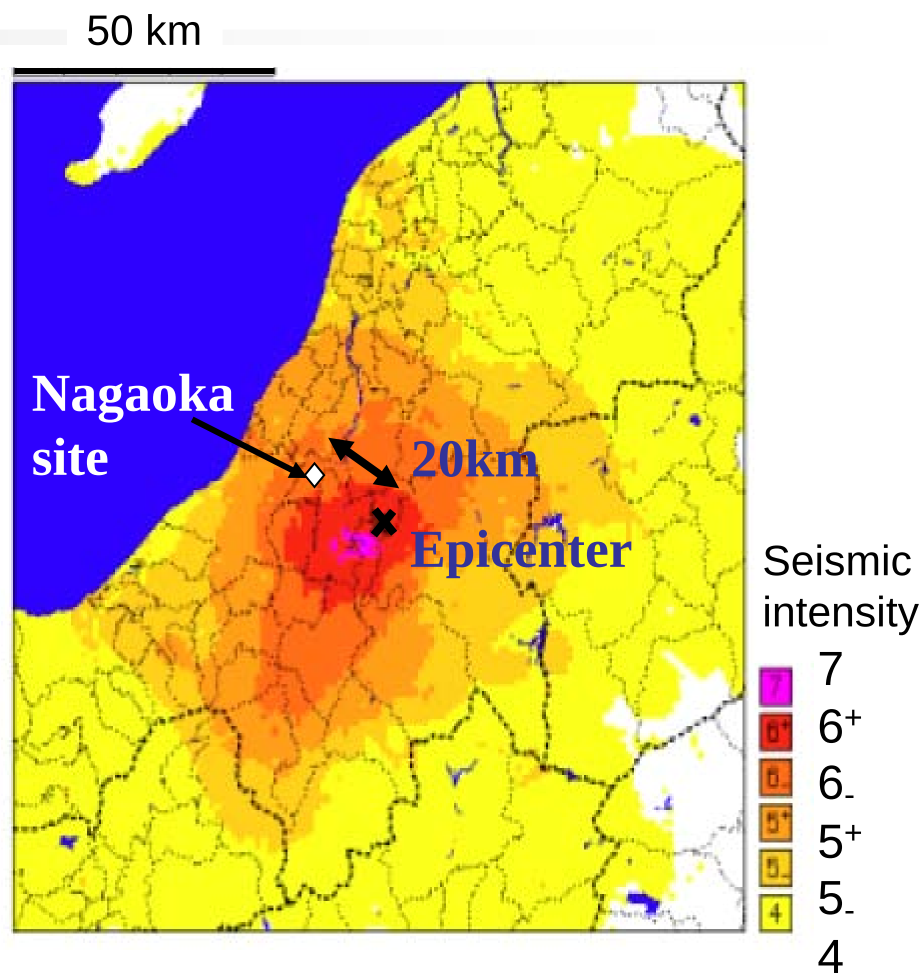
The Mid Niigata Prefecture Earthquake in 2004

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

Access road was damaged.

CO_2 detector (No leak)

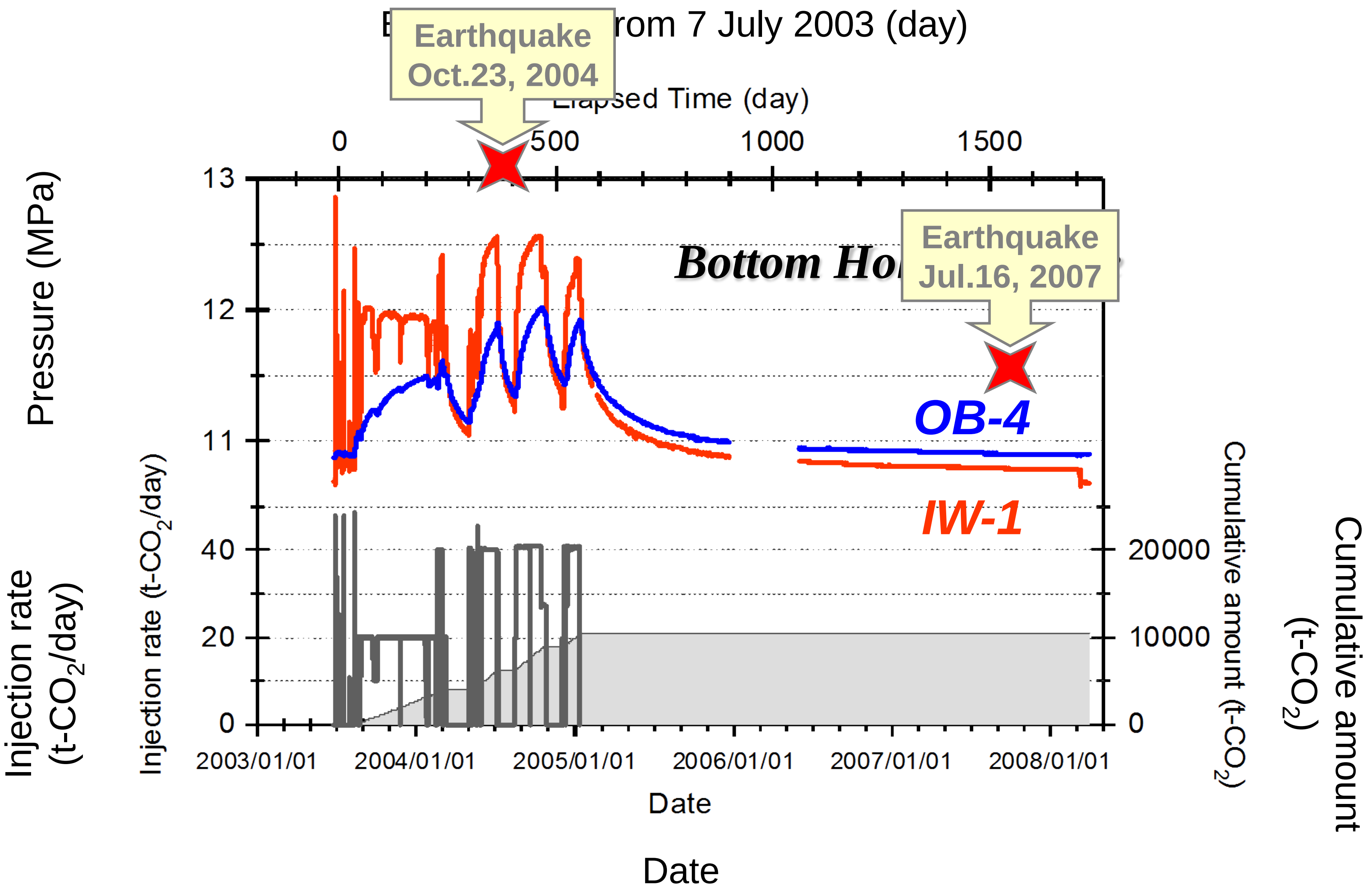
Injection was carefully resumed after confirming safety (6 Dec 2004)
injection rate: 40t-CO_2/day



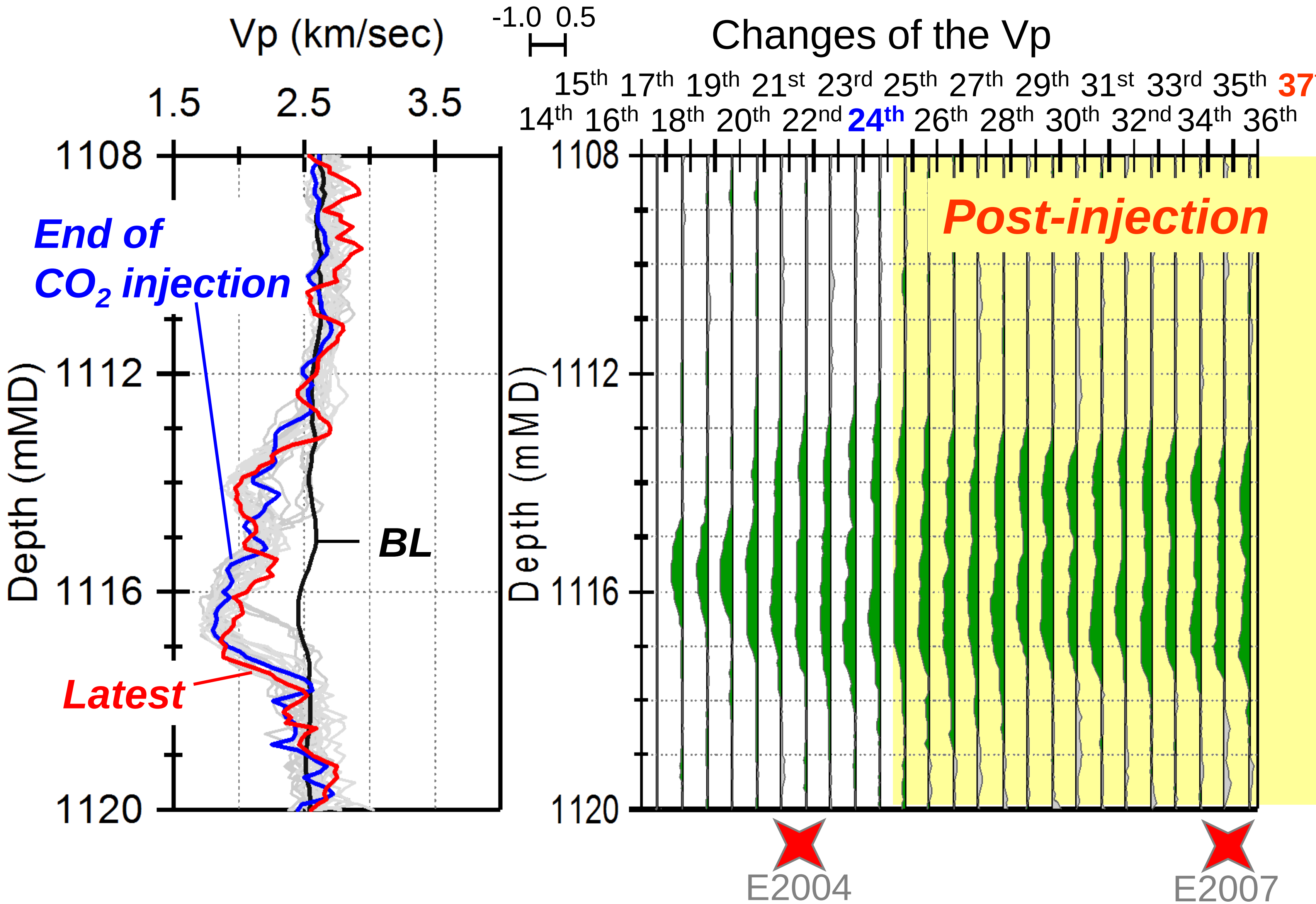
(GSJ, 2004 http://www.gsj.jp/jishin/chuetsu_1023/)

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

Changes in Bottom Hole Pressure

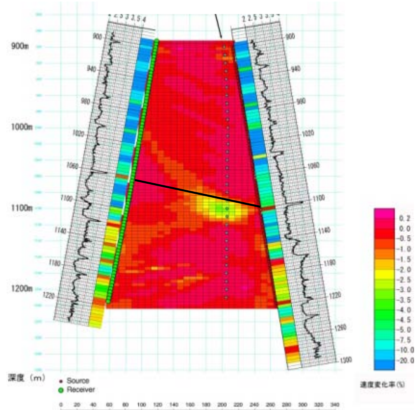


Sonic Logging (Vp) @ OB-2

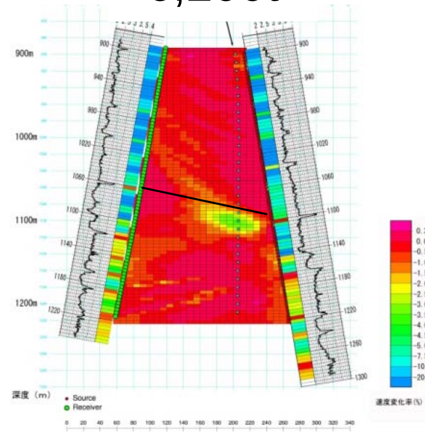


Results of Crosswell Seismic Tomography (OB-2:OB-3)

MS1/BL
3,200t

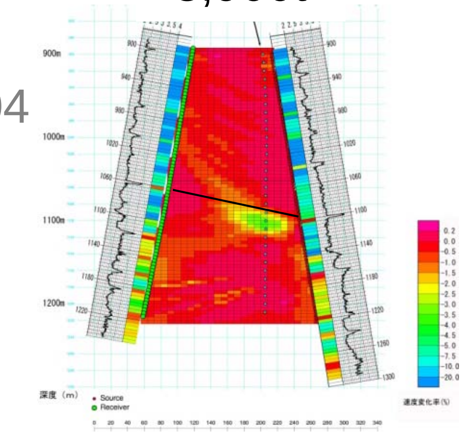


MS2/BL
6,200t

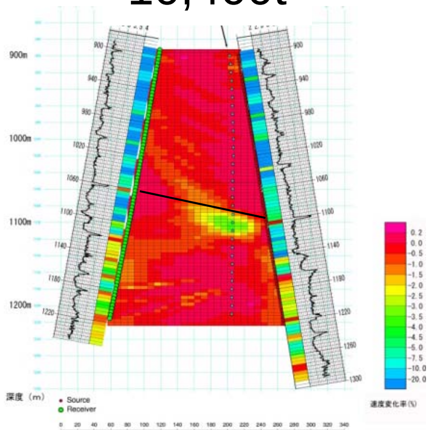


E2004

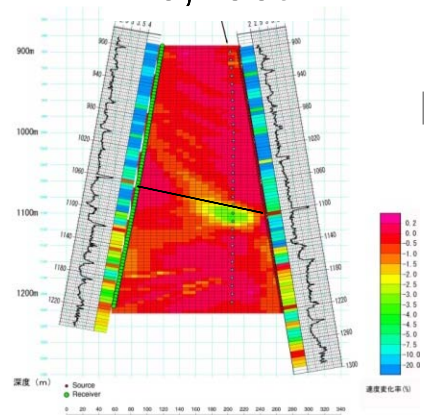
MS3/BL
8,900t



MS4/BL
10,400t

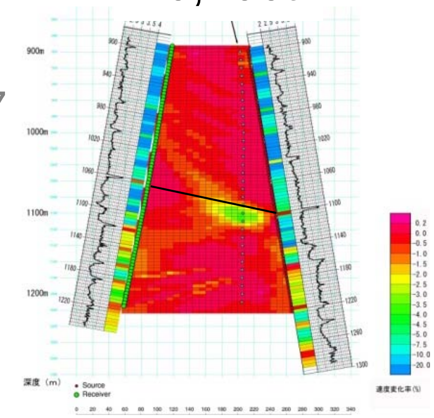


MS5/BL
10,400t



E2007

MS6/BL
10,400t



Summary of the Field Surveys

- **No differences between drawdown curves of usual shut downs and the emergency shut down**

  → ***Integrity of the reservoir***

- **No anomalies in well logging results**

  → ***Integrity of CO_2 containment***

- **No anomalies in crosswell seismic tomography results**

  → ***Integrity of the aquifer & CO_2 containment***

Objectives of CO_2 Simulation with TOUGH2

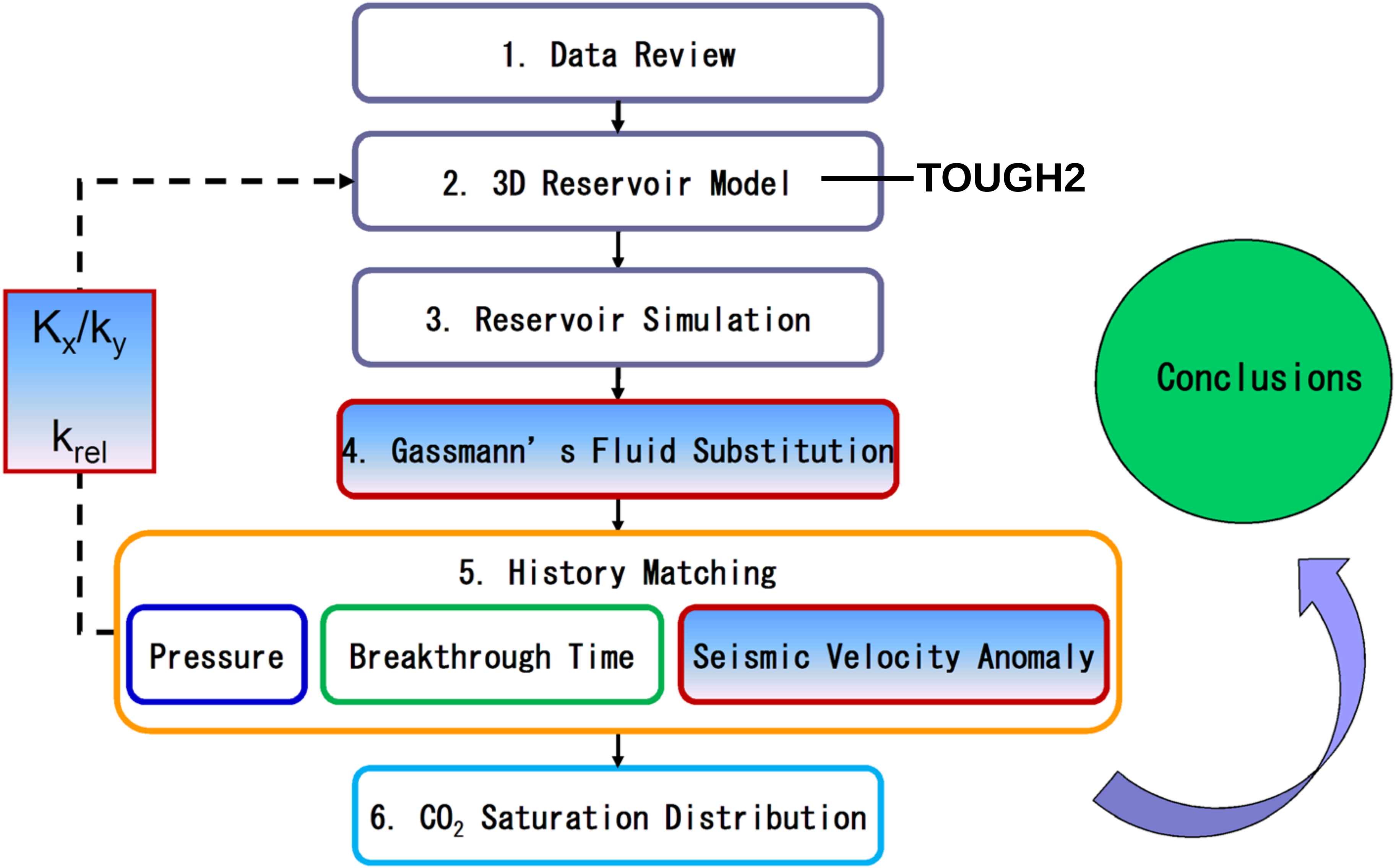
- Build a 3D Reservoir Model for CO_2 flow simulation

- Calibrate the geological model by history matching the ***bottom-hole pressure*** , ***CO_2 breakthrough time*** , ***p-wave velocity anomalies*** ***(****Crosswell Seismic Tomography****)***

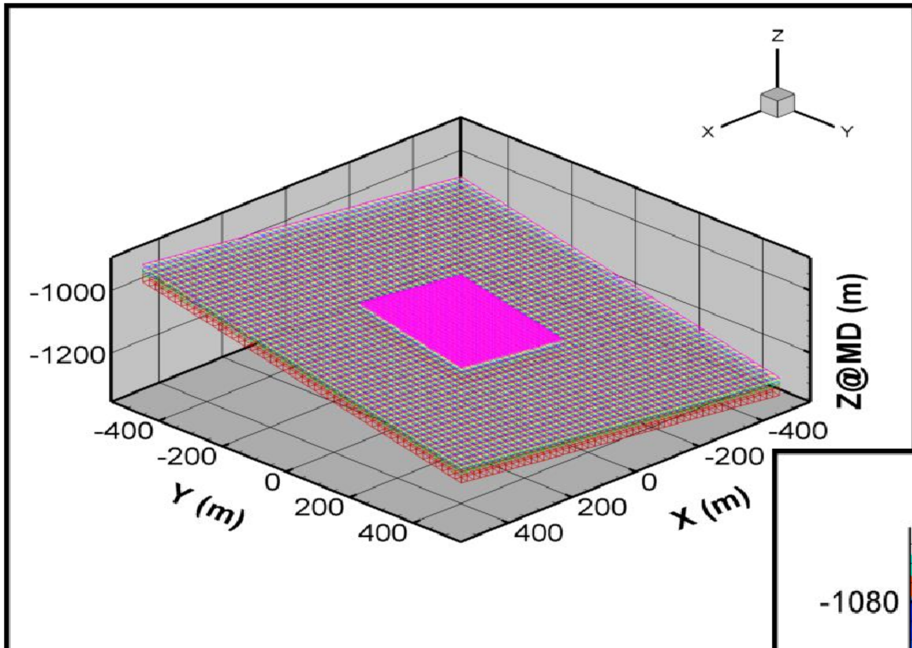
- Improve understandings of the CO_2 plume in the reservoir

Predicting *long-term behavior of CO_2* in reservoir!

Methodology



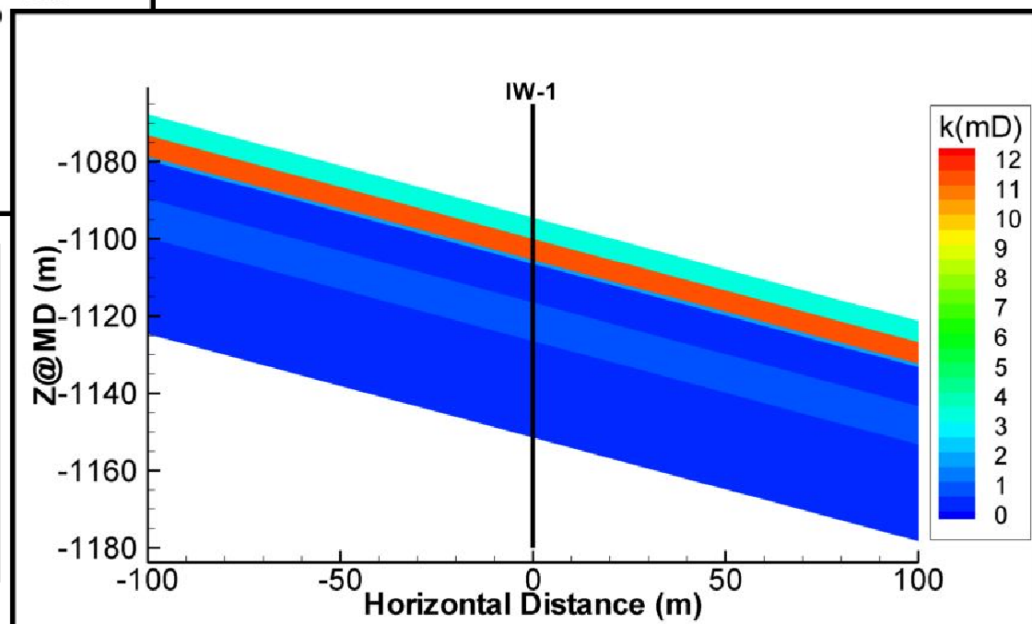
3D Reservoir Model



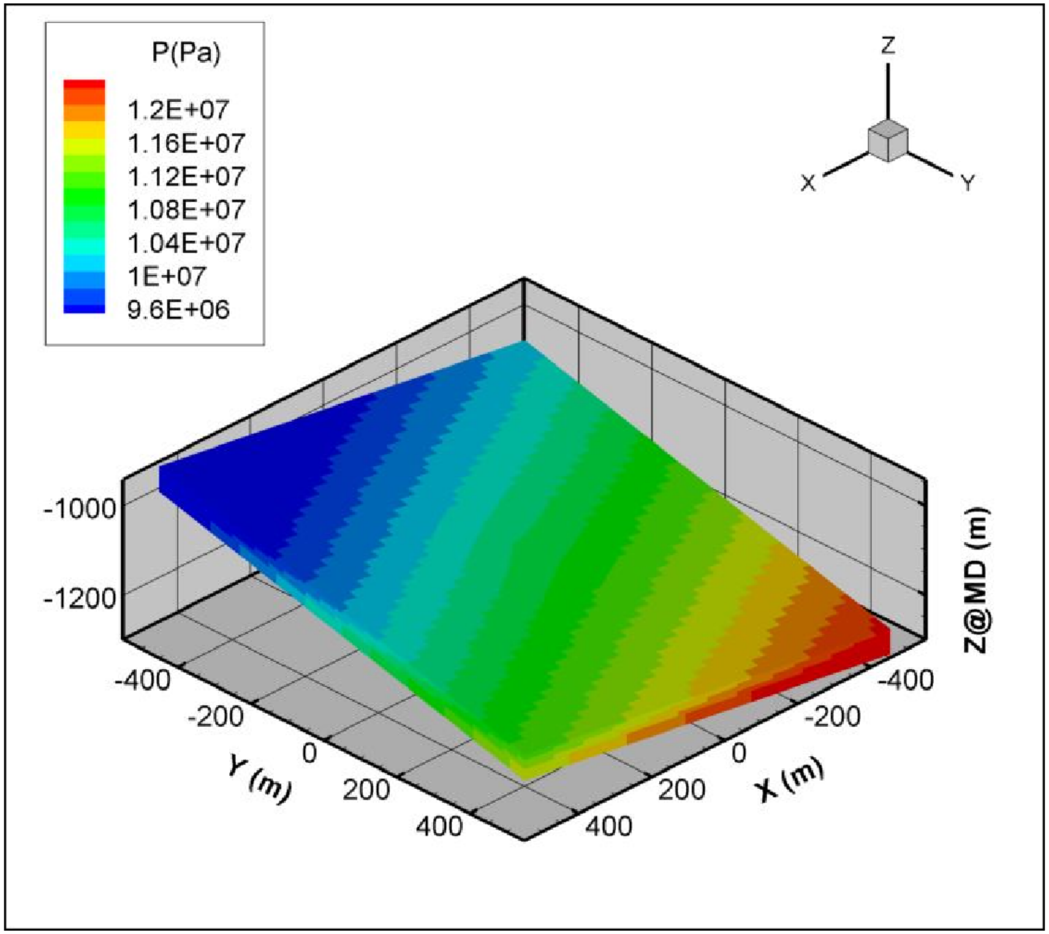
Area Name	Area Size (m^2)	Gridblock Size (m^2)
Outer Area	1000x1000	20x20
Inner Area	320x320	5x5

Layer	ϕ	Thick. (m)	Kh (mD)	kv/kh	β (1/Mpa)
Zone 2 U.	0.225	5.5	3.19	0.25	2.9×10^{-3}
Zone 2 M.	0.225	5.5	11.15	0.25	2.9×10^{-3}
Zone 2 L.	0.225	1.0	1.59	0.25	2.9×10^{-3}
Zone 3 U.	0.204	10.0	0.330	0.25	2.9×10^{-3}
Zone 3 L.	0.204	10.0	0.660	0.25	2.9×10^{-3}
Zone 4&5	0.234	25.0	0.460	0.25	2.9×10^{-3}

Ohkuma, H. (2008)



Initial Conditions

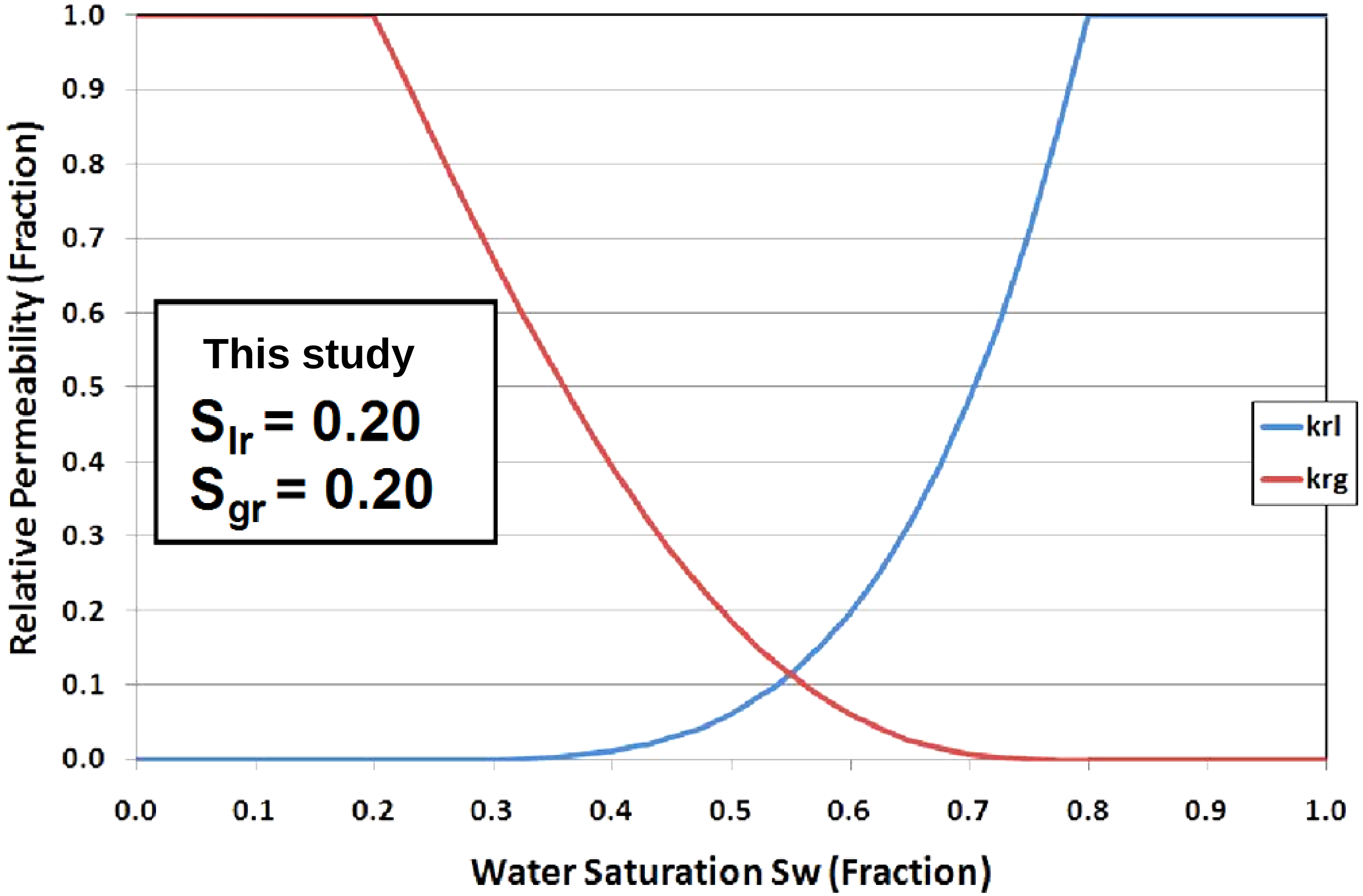


- **Initial Conditions at the injection point:**
  P_o: 10.8 MPa
  T: 48 °C
  Salinity: 1 %
  Sw = 1
- **Hydrostatic Gradient:**
  ~ 9.4 MPa/km
- **Boundary Conditions:**
  -Closed boundaries
  -Constant P boundaries
  -Injection Rate

Conditions for History Matching

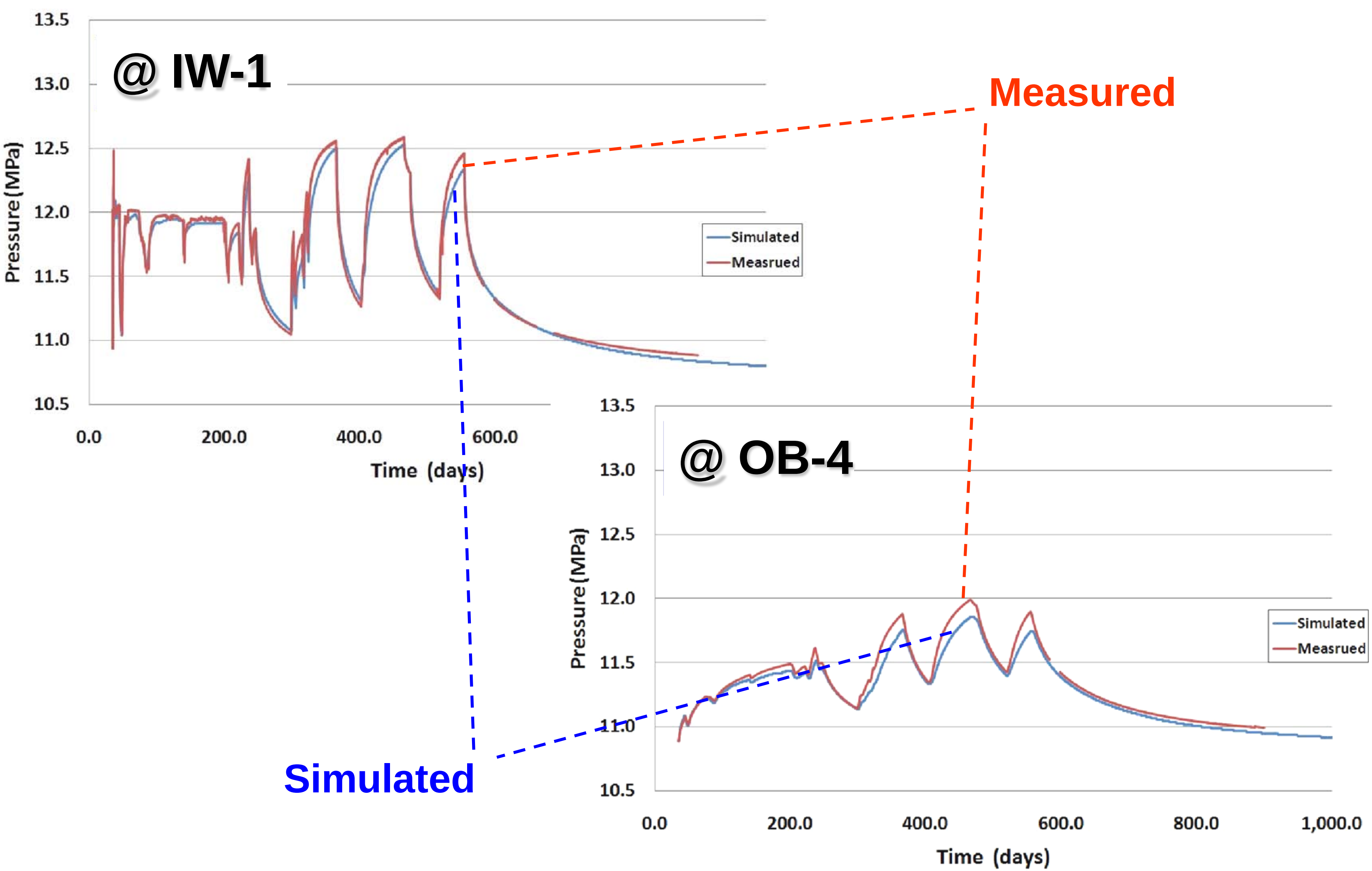
- Parameters fixed during first attempts
  - Geometry
  - Absolute Permeability
  - Porosity
  - Compressibility
- Parameters calibrated:
  - Geometrical Components of kh: $kh = (kx \cdot ky)^{-0.5}$
  - Relative Permeability
- Response to be Matched:
  - Bottom-hole Pressure
  - CO_2 Breakthrough time
  - Seismic (P-Wave) Velocity Anomaly

Setting of Relative Permeability

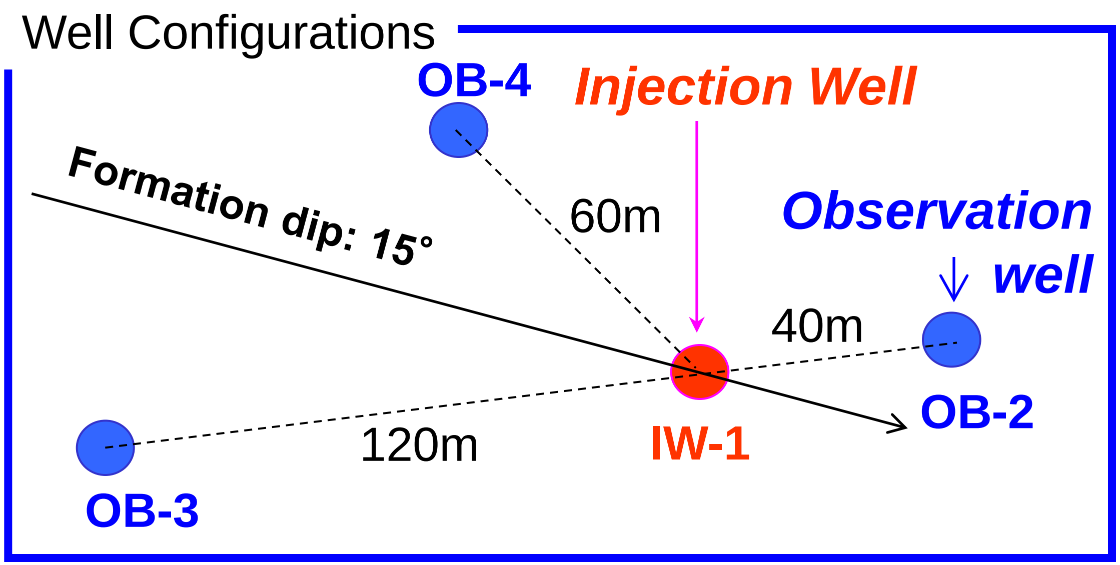


Corey's Curves (1945)

Bottom-hole Pressure Matching (ky/kx=1.2)



Breakthrough Time Matching



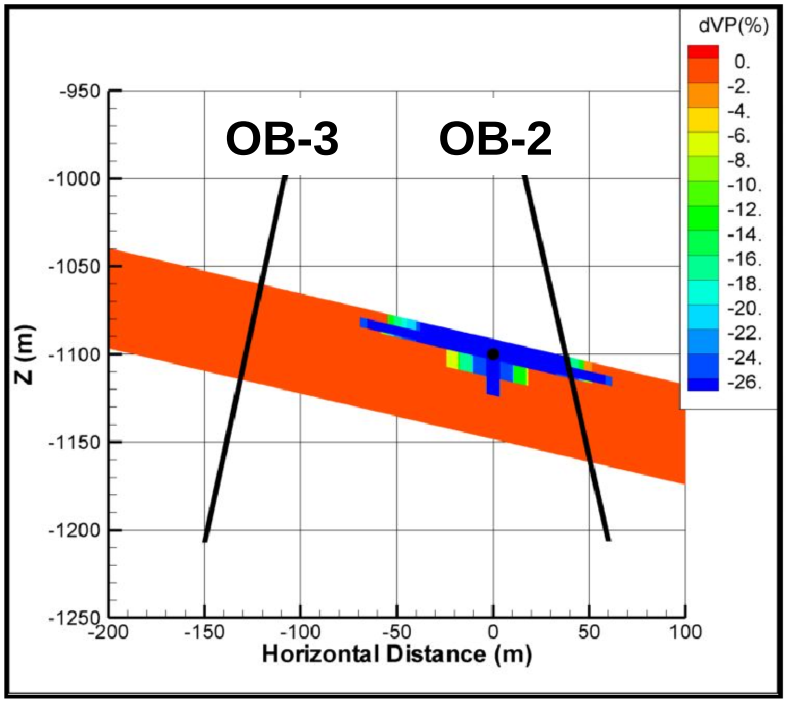
Breakthrough time	Logging Data (Days)	Case1 (Days)	Case2 (Days)	This study (Days)
OB-2	232-259	154	200	234
OB-3	No detected	No detected	No detected	No detected
OB-4	325-359	201	259	342

Good Match!

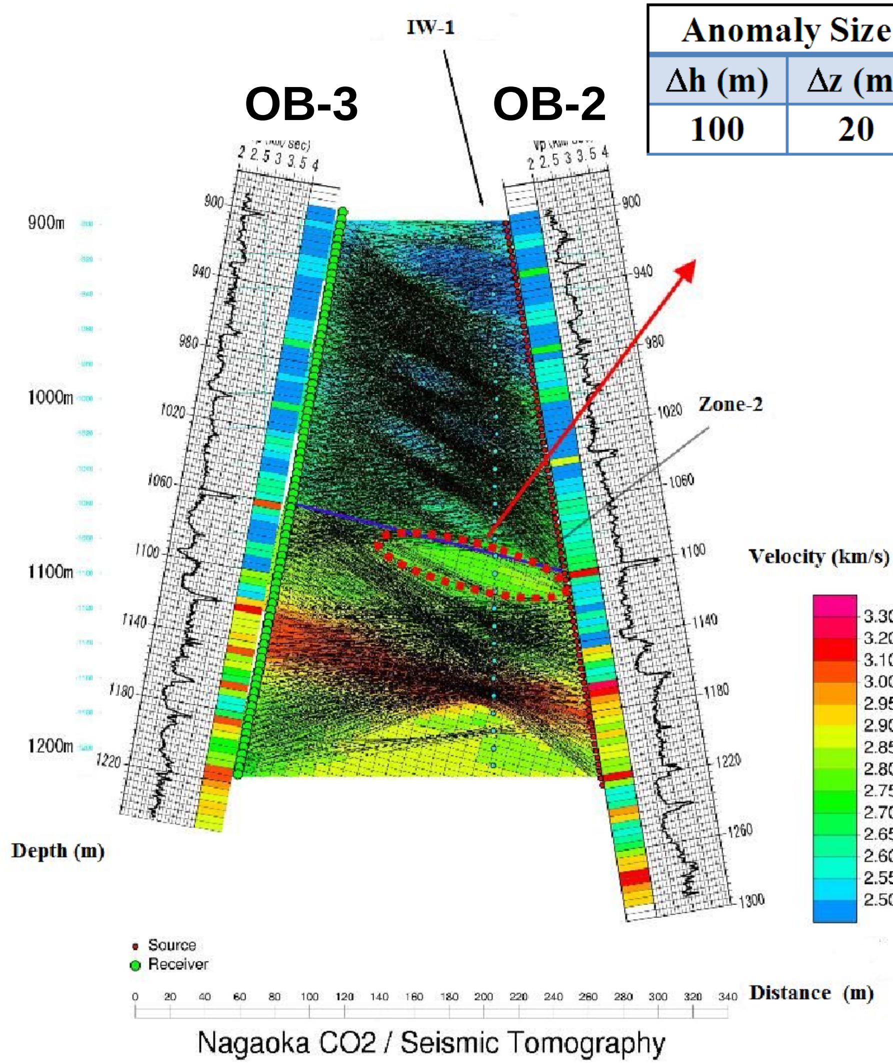
P-Wave Velocity Anomaly Matching

This study

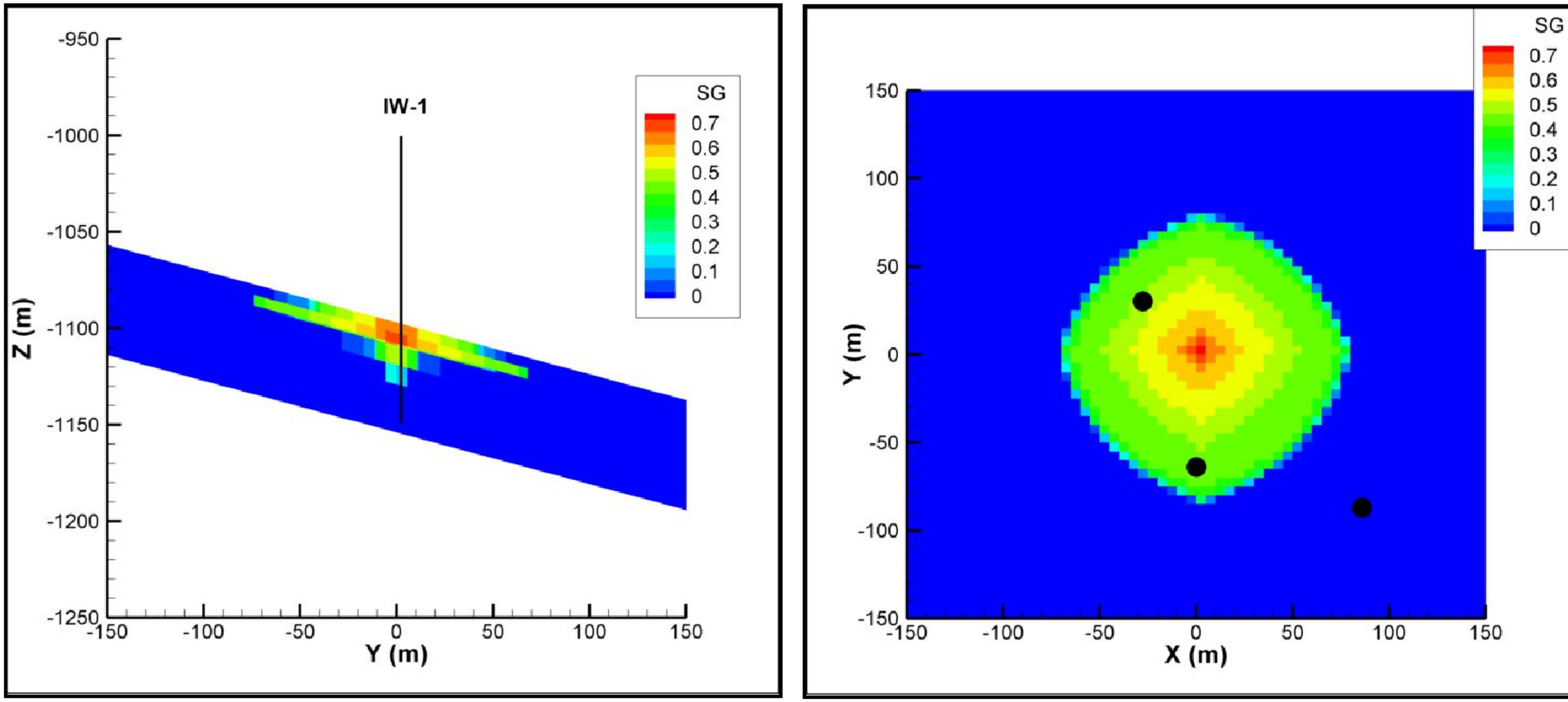
Anomaly Size	
Δh (m)	Δz (m)
105	22



Anomaly Size	
Δh (m)	Δz (m)
100	20



3D Distribution of the CO_2 Saturation

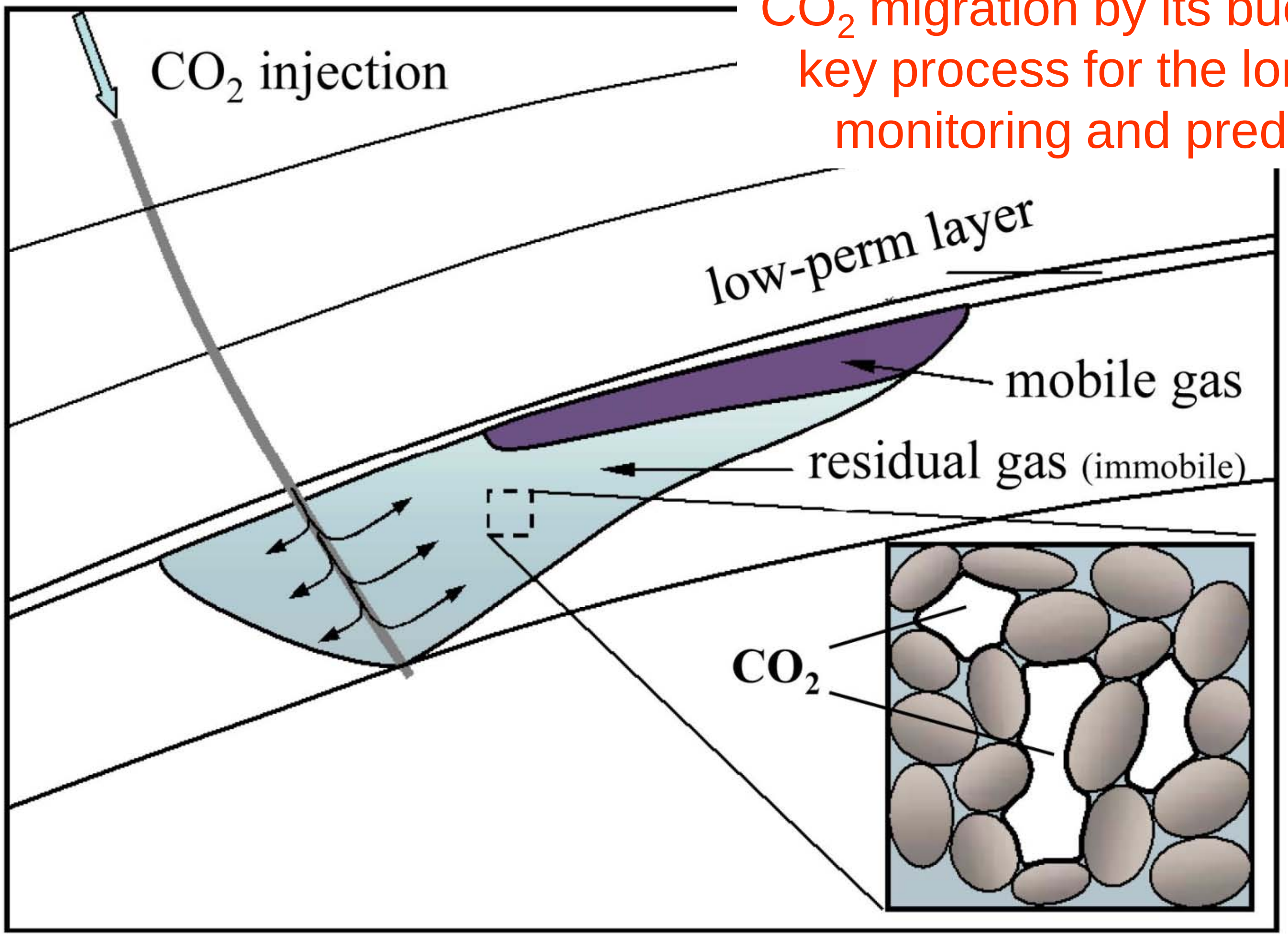


Relative permeability: Slr=Sgr=0.2, ky/kx= 1.2

Pictures: t = 1.5 years (End of Injection)

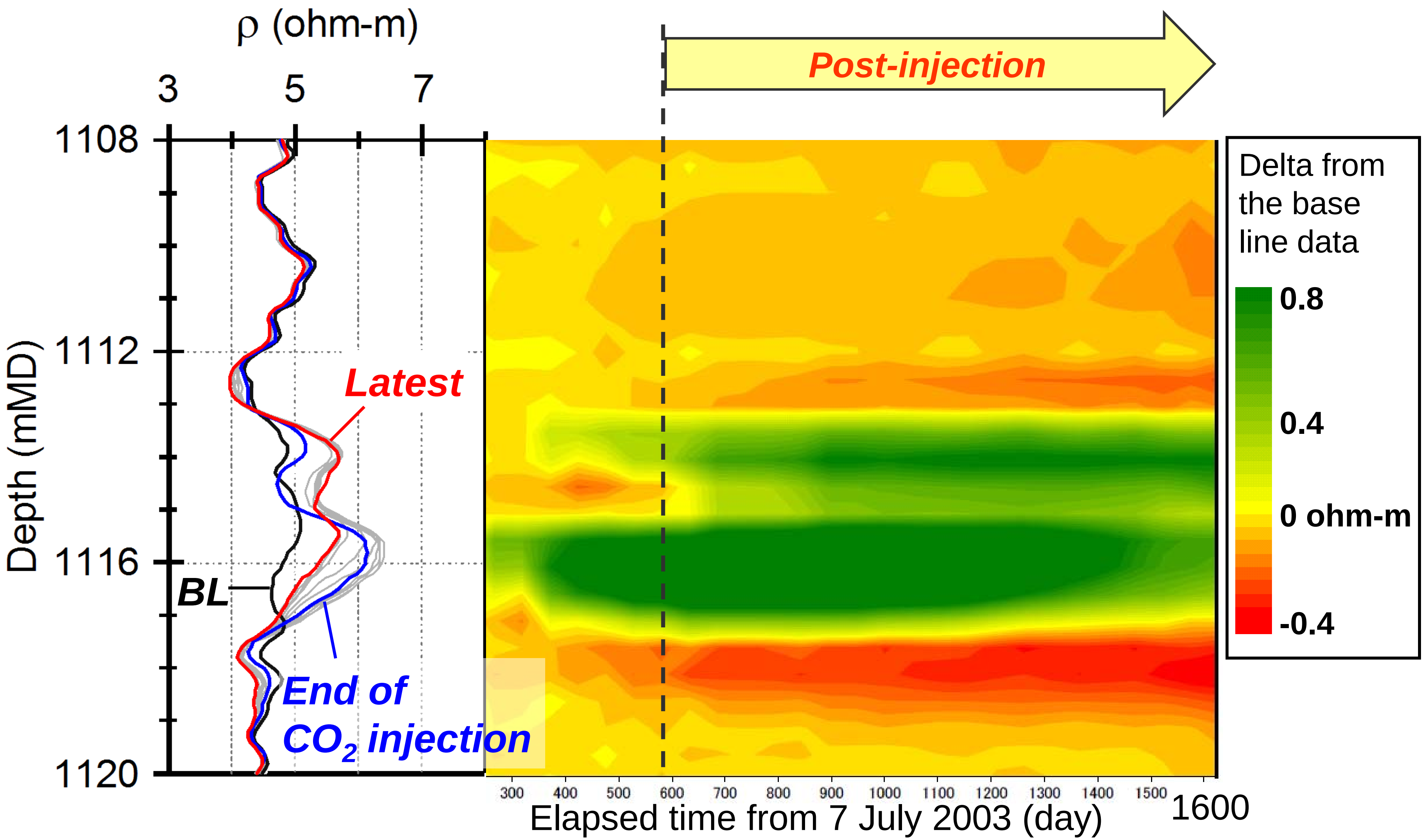
Driving Force of CO_2 ; Pressure and/or Buoyancy

CO_2 migration by its buoyancy is key process for the long-term monitoring and prediction.

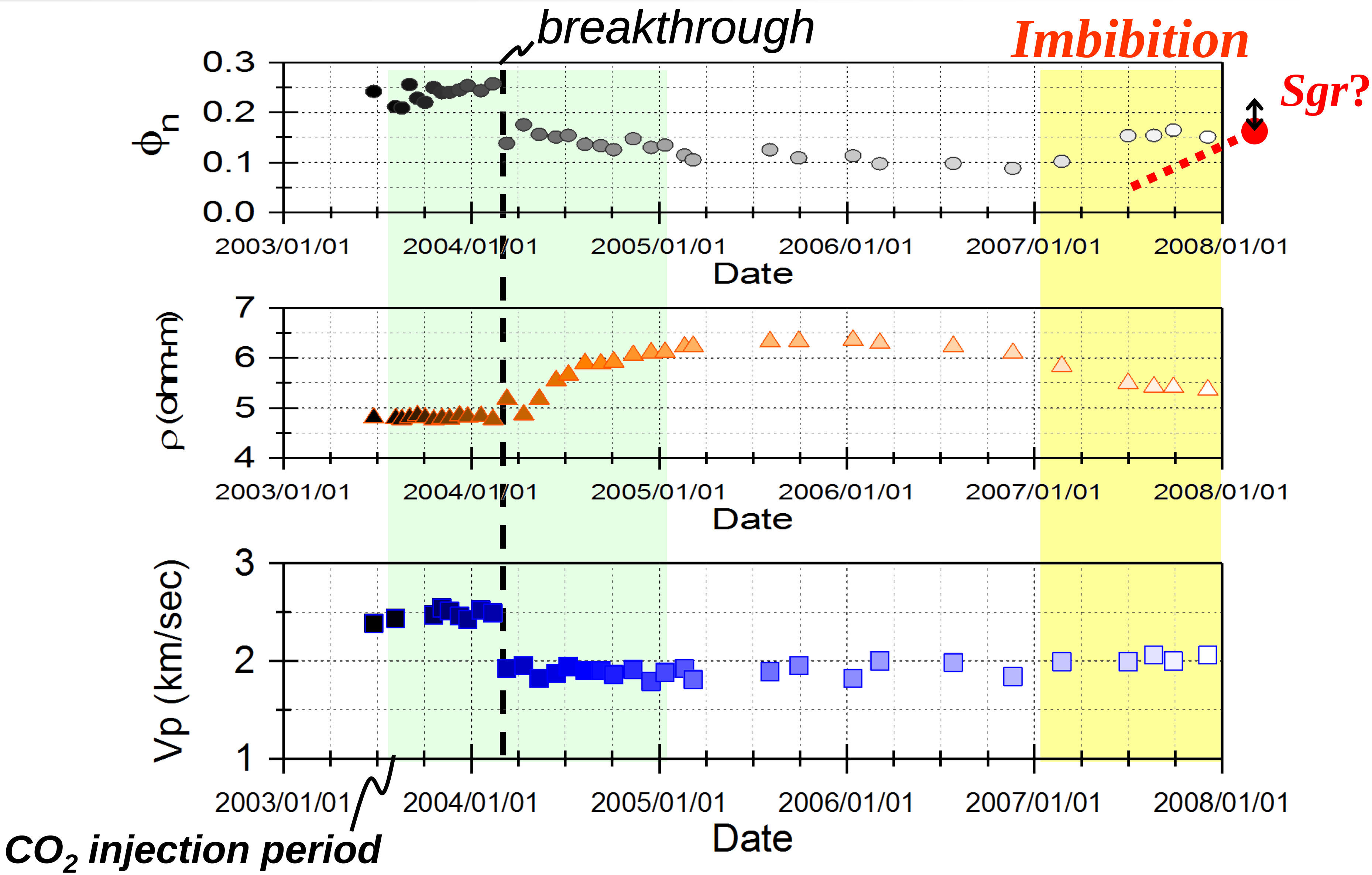


(Juanes et al., 2006)

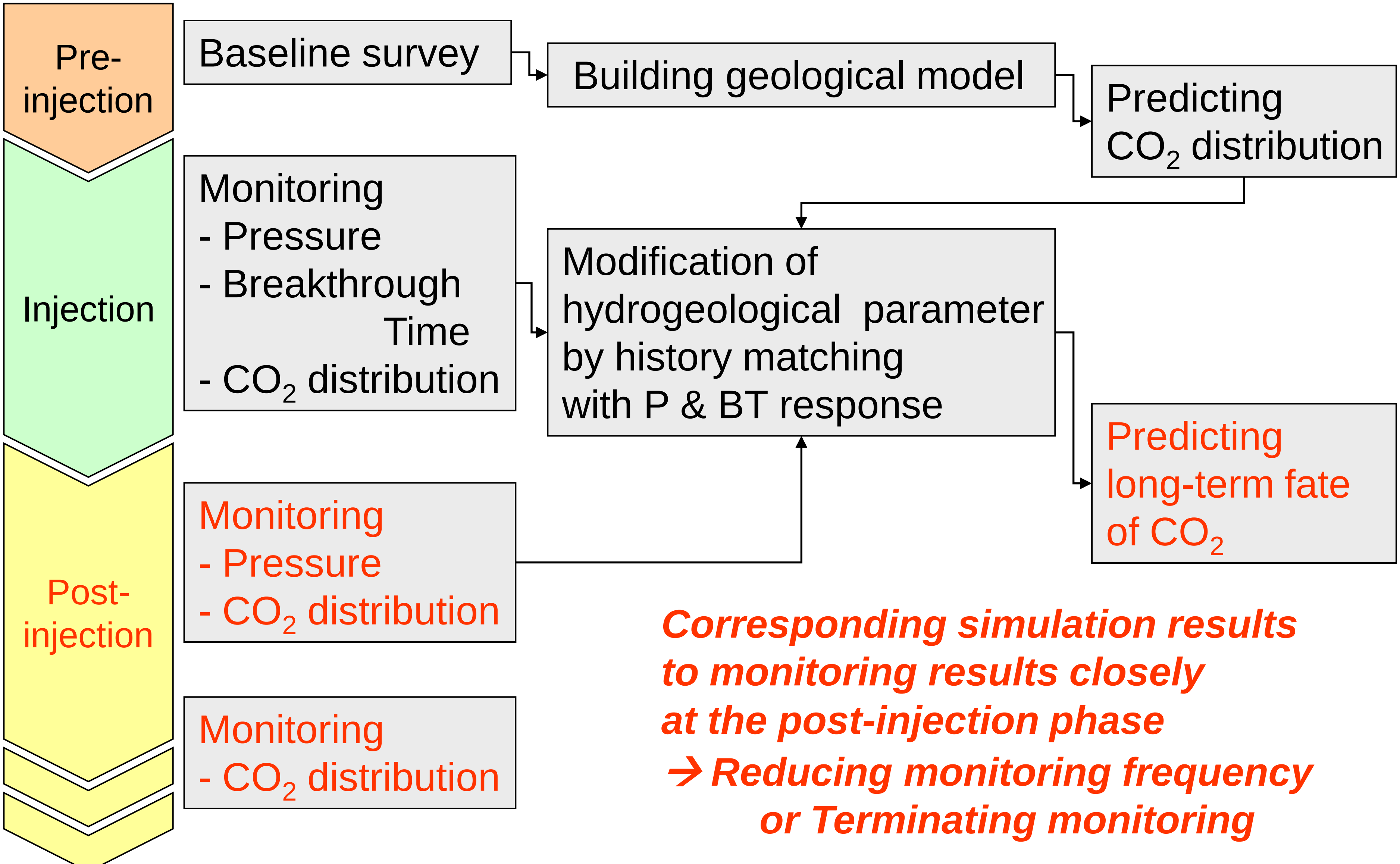
Resistivity Change during Imbibition Phase @ OB-2



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



How long should we monitor the site?



Corresponding simulation results to monitoring results closely at the post-injection phase
→ Reducing monitoring frequency or Terminating monitoring

Summary

- Anisotropy of relative permeability in the reservoir is a critical parameter to fit simulation results to monitoring results in the Nagaoka case.
- Feedback of monitoring results is necessary to improve long-term prediction of CO_2 behavior.
- We will provide the first field data set of residual gas saturation and dissolved CO_2.

Acknowledgements

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

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

- Part of simulation study was conducted by Henry Garcia (BP) as his Master's degree thesis at Kyoto University.

NAGAOKA Project

Thank you for your attention!

RITE Research Institute of Innovative Technology for the Earth

Simulation for Site Characterization: Mt. Simon Sandstone

Scott M. Frailey
James Damico
Hannes E. Leetaru

February 16-17, 2010

Midwest Geological Sequestration Consortium
www.sequestration.org

Acknowledgements

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- The Midwest Geological Sequestration Consortium (MGSC) is a collaboration led by the geological surveys of Illinois, Indiana, and Kentucky
- Landmark Graphics Software donation via University Program and Schlumberger Carbon Service for technical support and consultation

Illinois Basin Decatur Project: Objectives

- Assess feasibility of CO_2 sequestration in the Mt. Simon sandstone and effectiveness of the Eau Claire shale
  - Injectivity
  - Storage efficiency
  - Pressure thresholds
- MVA: implement and test several techniques to monitor plume and pressure distribution
- Validate Phase I CO_2 storage estimates
- Identify barriers to commercialization
- Develop sequestration process model

Project Description: Pilot Specifics

- Single well injection perforated low in the stratigraphic unit
  - Permanent pressure gauge
- Single injection zone monitoring well
  - Multiple injection interval completion
    - Pressure and fluid sampling
- Single geophysical monitoring well above primary seal

Illinois Basin-Decatur Test Site

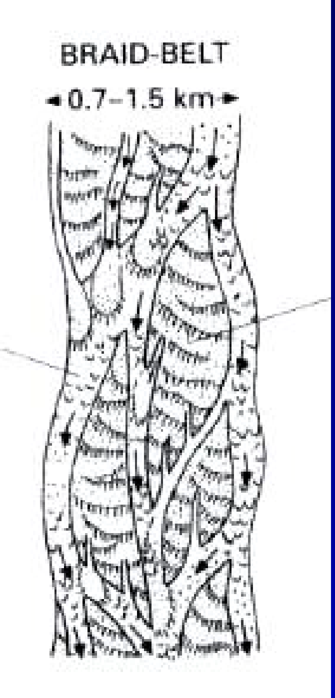
- A Dehydration/ compression facility location
- B Pipeline route
- C Injection well site
- D Representative verification well sites

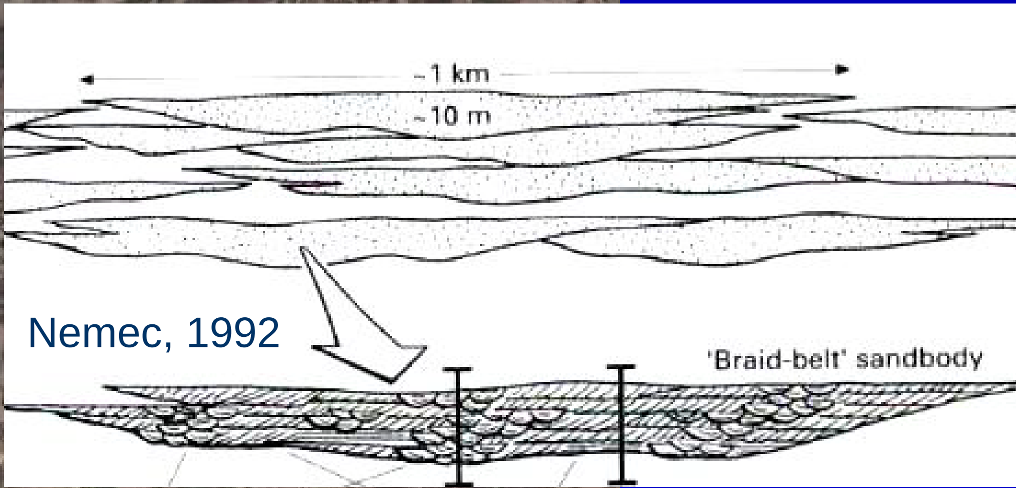
Quickbird Satellite Image: 9/16/ 2008

Geology

- Age: Cambrian
- Depositional System: braided river system
- Depth: 5405 – 7165 ft
- Gross Thickness: 1620 ft
- Average Total Porosity: 13.4%
- Average Absolute Perm (transformed):
  - k_h 26.4 md; k_{varth} 22.4 md; k_{vharm} 0.0482 md
- Pressure: 3206 psig @ 7045 ft (0.455 psi/ft)

Project Description: Geology
Brahmaputra River System





Nemec, 1992

Modeling Tools

- Geographix: mapping software
  - 2d regional structure and thickness maps
- Isatis: Geostatistical software
  - 3d porosity and absolute permeability models
- VIP reservoir simulation program
  - Fluid flow models

Data Available

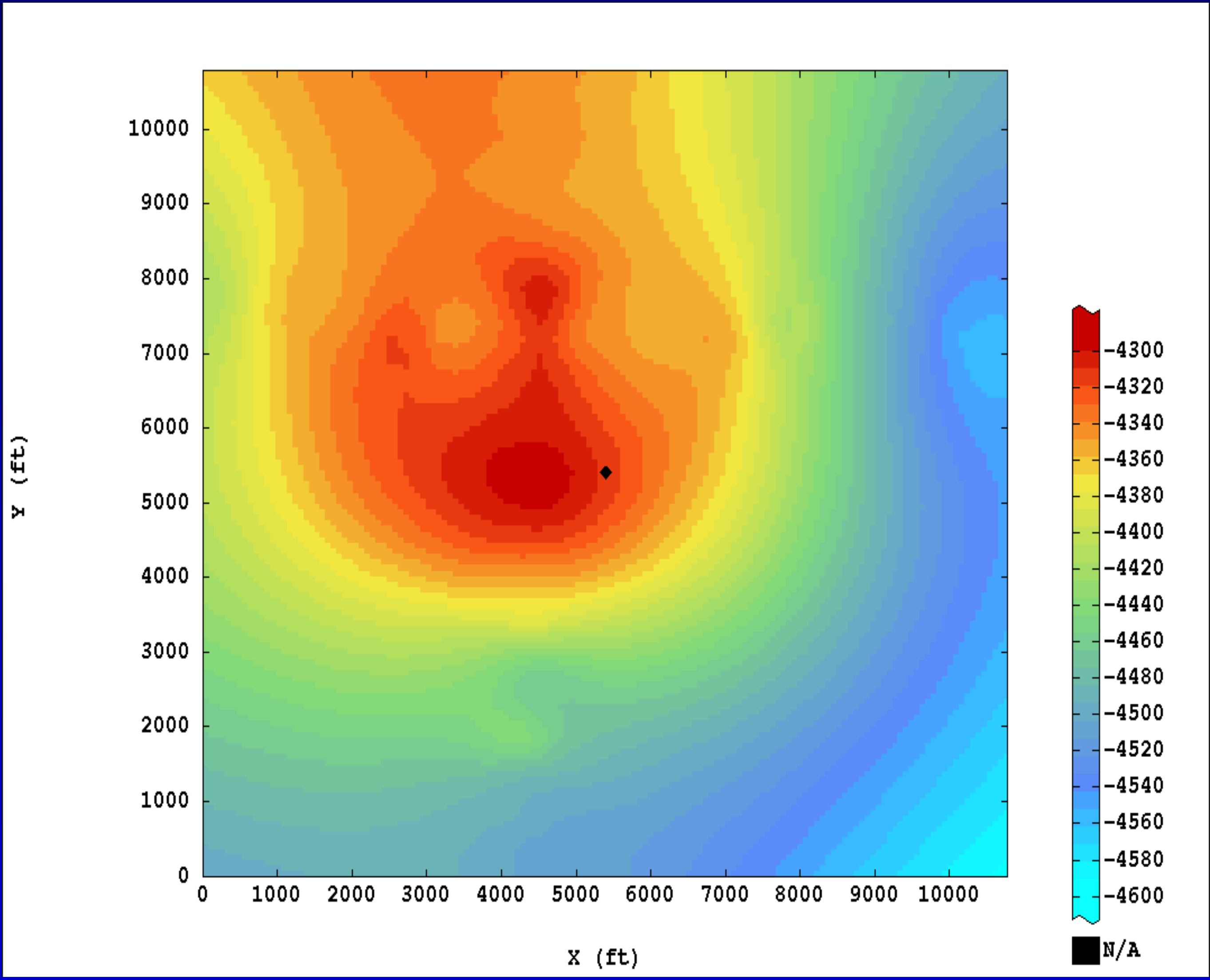
- Logs: Laterolog, lithodensity, neutron, spectral gamma ray, fullwave sonic, magnetic resonance, FMI
- Core: Sidewall Rotary and Whole Core
  - Routine porosity and perm: Vertical and horizontal
  - Mechanical Strength
  - Electrical resistivity
  - Capillary pressure
  - Effective perm to gas
  - T2
- Petrography: thin sections, SEM/XRD
- Seismic: 3d-Surface and 3d-VSP

Geologic Model

- Structure
- Porosity: Total and effective
- Thickness: gross and net
- Absolute permeability: horizontal & vertical
- Lateral heterogeneity: continuity

Geologic Model: Structure
Top of Mt. Simon

- Depth 5545 ft MD
- Nearest Mt. Simon well 18 miles southeast
- Two orthogonal, 2-D seismic lines



FMI shows the same orientation for structural dip

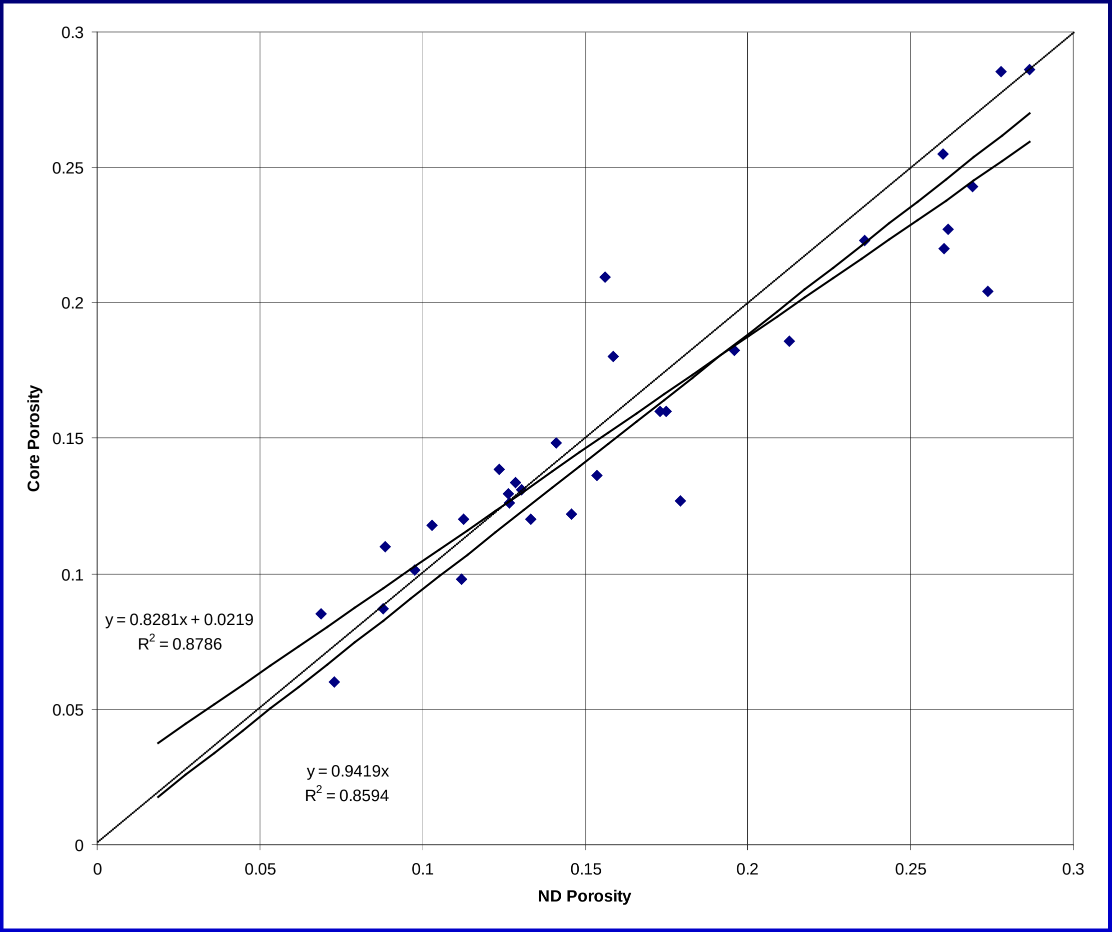
Geologic Model: Porosity and Permeability

- Importance of Petrography
- Thin Section indicated micro-fractures
  - Investigating: in situ vs. post coring development of micro-fractures

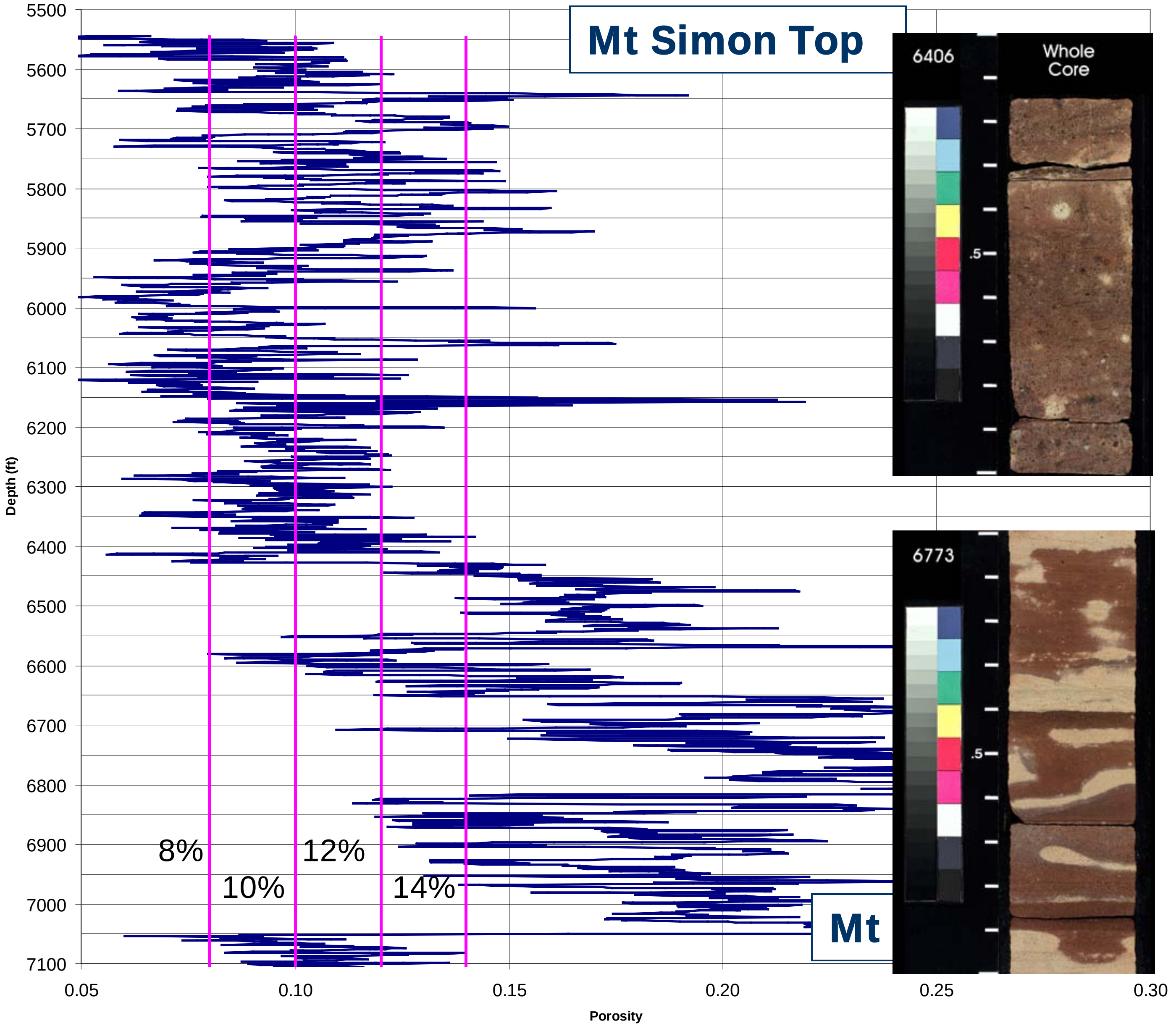
Depth, ft MD	6763	7045
ϕ, %	28.5	28.6
k, md	43.2	1440

Geologic Model: Effective and Total Porosity

- Core Porosity: Effective
- Neutron-Density Porosity: Total
- $\phi < 20\ \%$: $\phi_e = \phi_t$
- $\phi > 20\ \%$; $\phi_e < \phi_t$



Geologic Model: Thickness



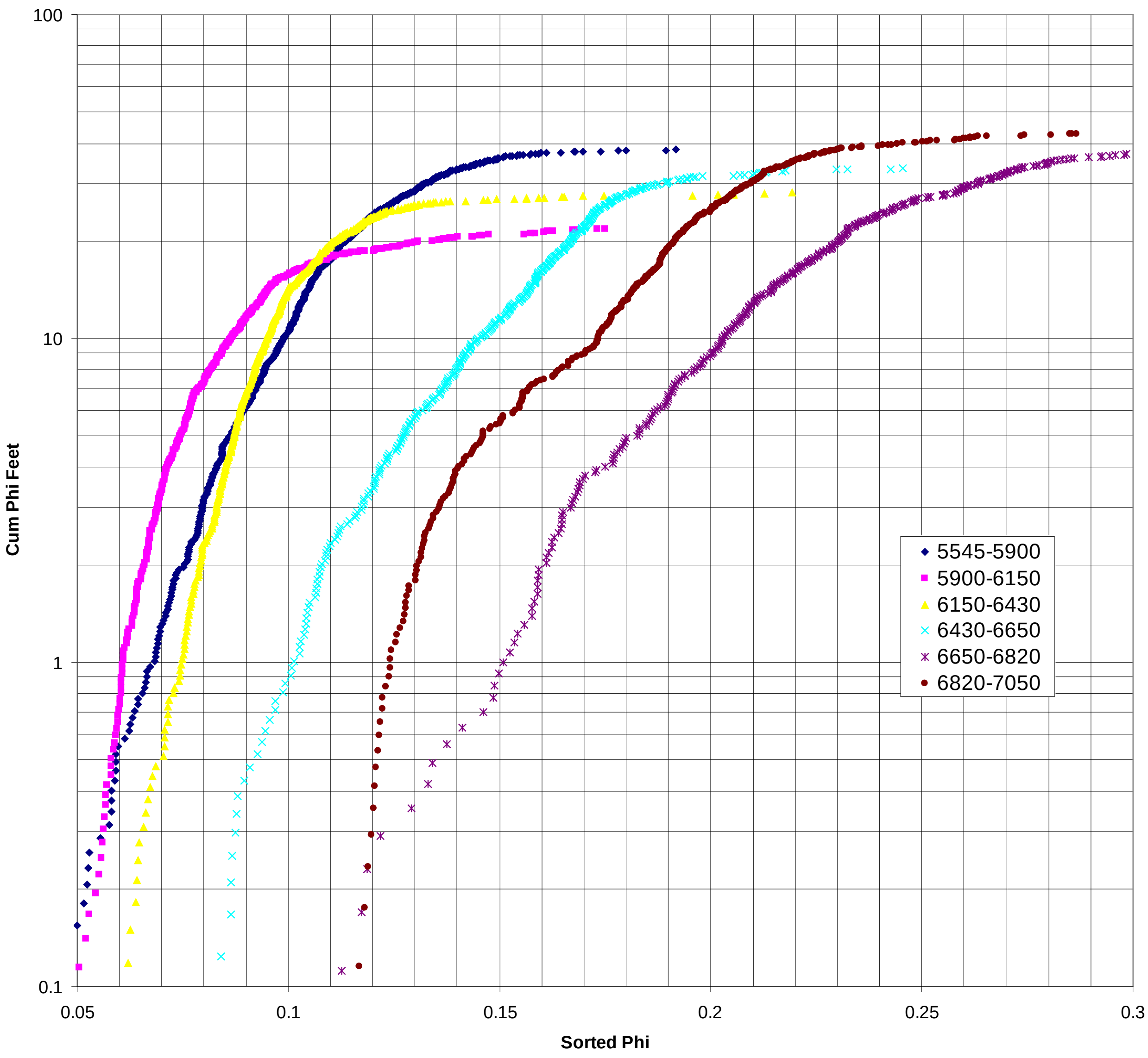
Gross and Net Thickness: Porosity Cutoffs

Neutron-Density Porosity

Geologic Model: Gross and Net Thickness

	Porosity Cutoff, %			
Depth	**8**	**10**	**12**	**14**
5545-7050	*1322*	*1009*	*744*	*569*
h_{net}/h_{tot}	0.878	0.670	0.494	0.378
5545-5900	310	229	105	34
5900-6150	145	51	23	9
6150-6430	249	120	33	10
6430-6650	220	211	188	152
6650-6820	170	170	168	166
6820-7050	230	230	228	200

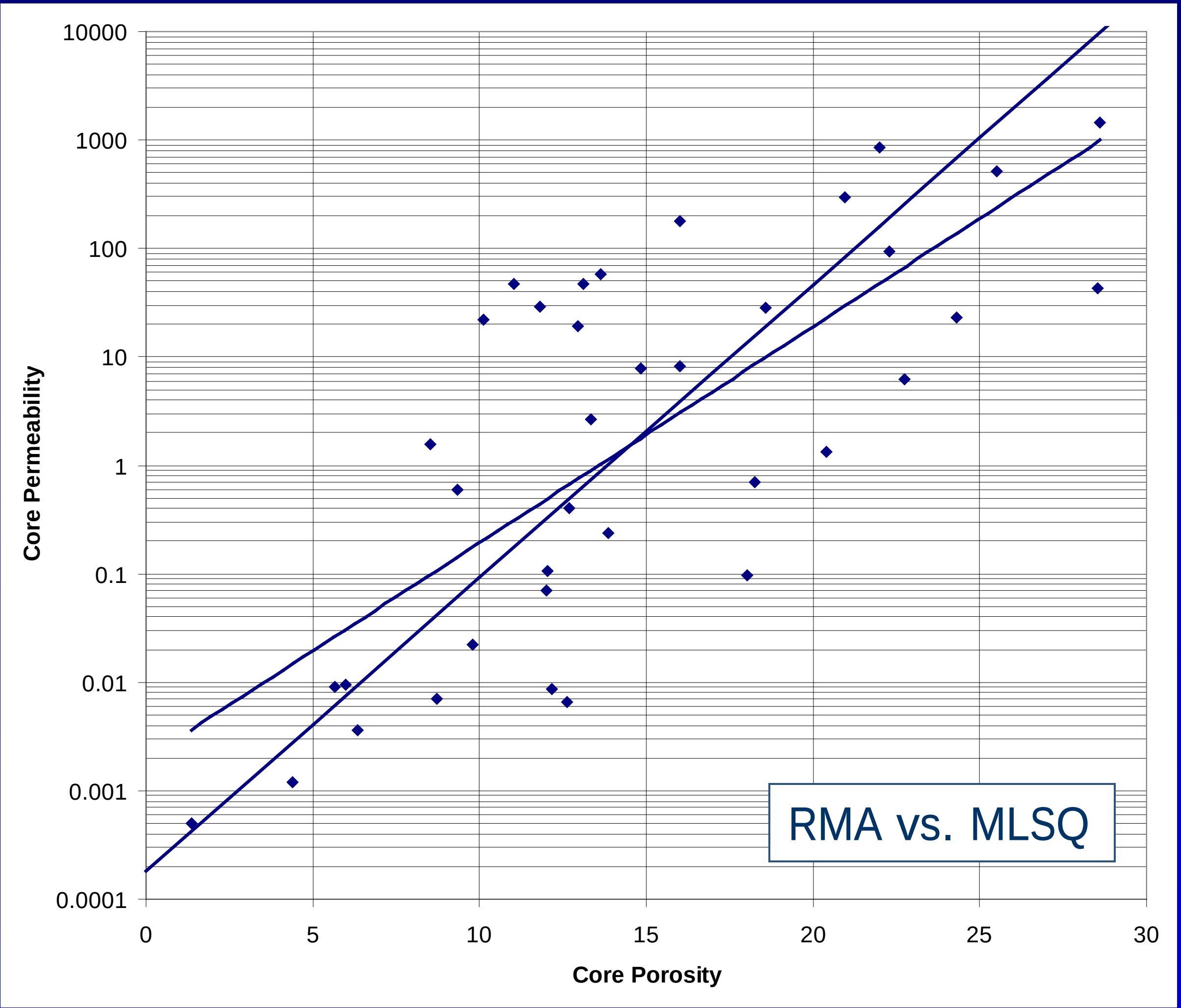
Geologic Model: Example of Determining Porosity Cutoff



Looking for break in the trend of the high porosity data.

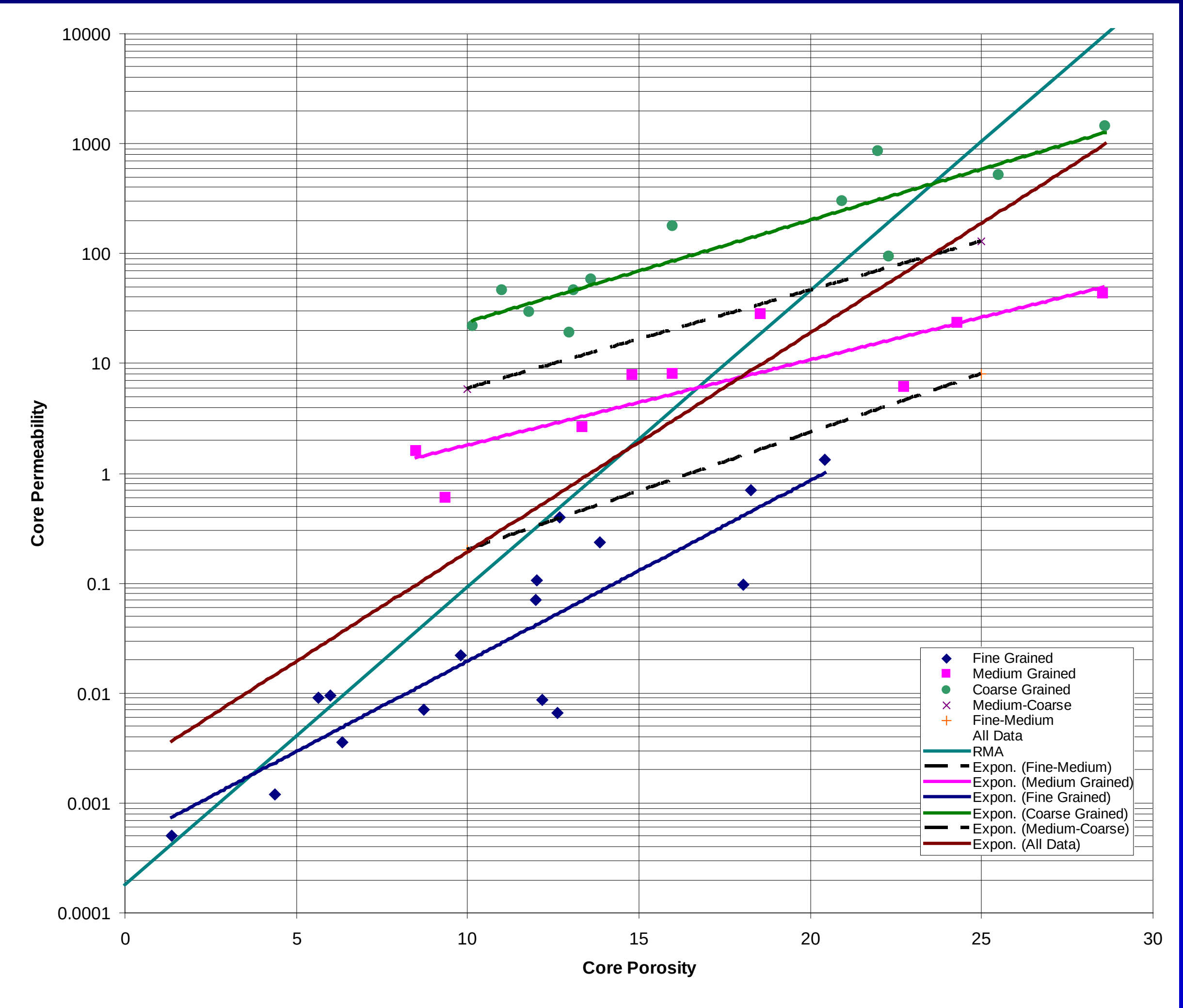
G.B. Asquith, personal communication 2009

Geologic Model: Absolute Permeability-Core Data



- Depth Shift: core to log
- Transform core porosity to core permeability
- Conventional semilog plot not good predictor of perm

Absolute Permeability- ϕ-k Transform Based on Grain Size



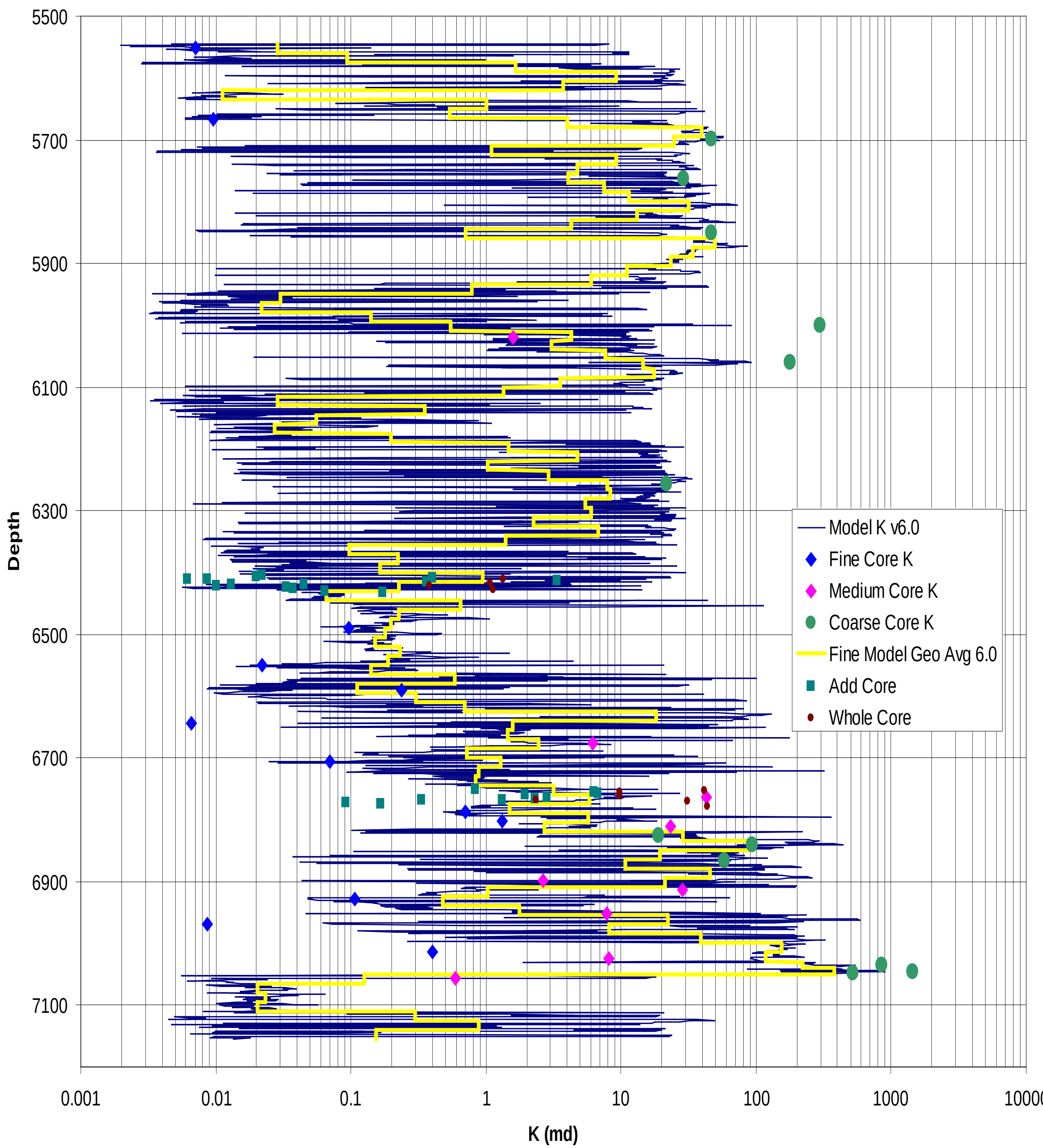
- Sub-divide data by grain size
- Better representation of the core data
- How to pick transform based on log response?

Absolute Permeability-Correlating to a Well Log Signature

- Calculated log attributes:
  - Gamma Ray: Volume of Shale
  - Magnetic Resonance: pore size
  - Resistivity: Cementation exponent, m
- Archie's cementation exponent gave best results
  - Reflects ratio of pore throat/pore body area

Geologic Model: Absolute Permeability

15 ft model



Geologic Model: Core Data
Vertical Permeability and Scale

Core*	k_h	K_{varth} 1.5”	K_{vhar} 30’	K_v/k_h 1.5”	K_v/k_h 30’
6404 - 6433	0.33	0.031	0.011	1.0	0.033
6751 - 6779	2.3	0.94	0.30	0.55	0.013
All	1.2	0.43	0.019	0.76	0.016

*Does not include 10 ft of whole used for whole core analyses

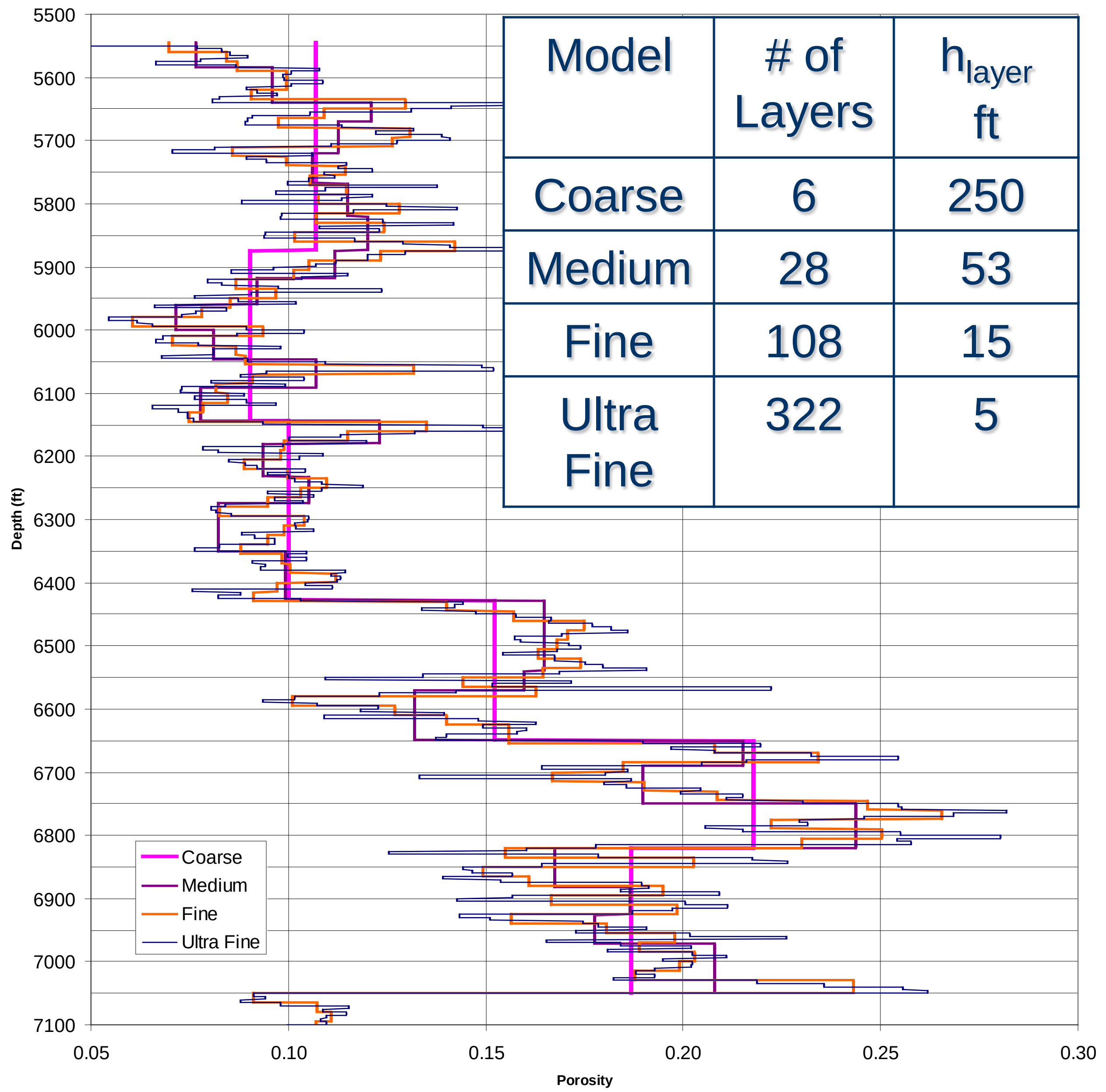
Geologic Model: Lateral Heterogeneity

- Lateral continuity uncertain
  - Width: 1000 ft to 1-2 miles
  - Length: 2000 ft to 2-3 miles
  - Thickness: 10 ft to 50 ft
- Seismic and long term pressure transient tests expected to reduce uncertainty
- Whole Core Scale Permeability Anisotropy
  - Upper Core: 1:1.07 / Lower Core: 1:1.13

Reservoir Model

- Gridding
- Relative permeability
- Pressure transient testing
- CO_2 Forecasts
  - Plume management
  - Pressure management

Reservoir Model: Gridding



Model	# of Layers	h_{layer} ft
Coarse	6	250
Medium	28	53
Fine	108	15
Ultra Fine	322	5

- Averaging Flow Properties:
  - Honor geologic features
  - Understand flow mechanisms and choose grid to model these effects
- Grids chosen for computational reasons are considered for general guidance only

Reservoir Model: Relative Permeability

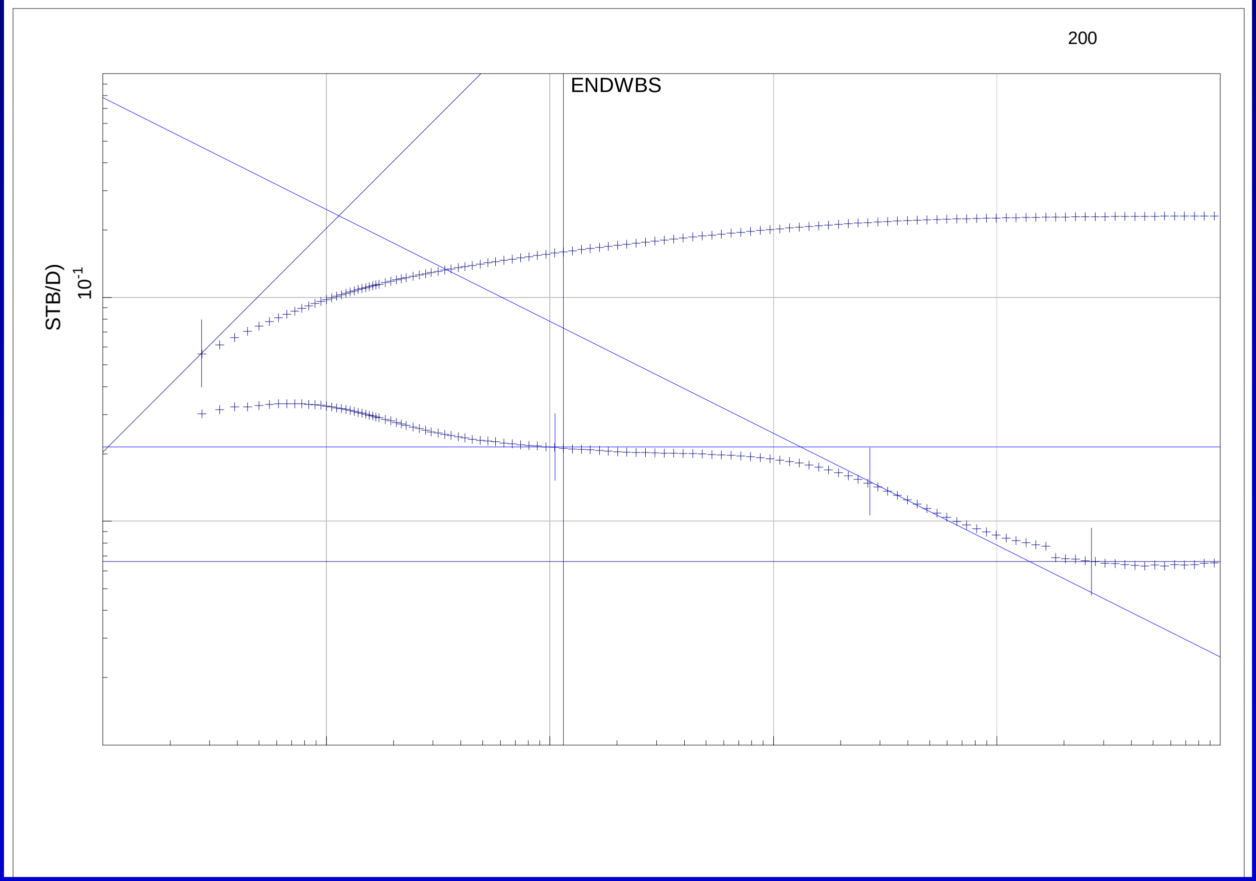
- Tests designs in progress
- Issue: Include or exclude mass transfer between CO_2, brine and core?
  - Use two fluids with similar viscosity ratio that have no reaction and low dissolution?
  - Saturate brine with CO_2?
  - Saturate CO_2 with water?

Reservoir Model:
Geologic Model Injection Zone Validation

- Single Well Water Injection Pressure Transient Test
  - 25 ft perforated interval (Injection/falloff, step-rate test)
  - 25 ft + 30 ft perforated (injection/falloff)
    - Injection spinner logs infers no water injection into upper perfs

Reservoir Model: Water Pressure Transient Test

Partial Penetration/Completion Model



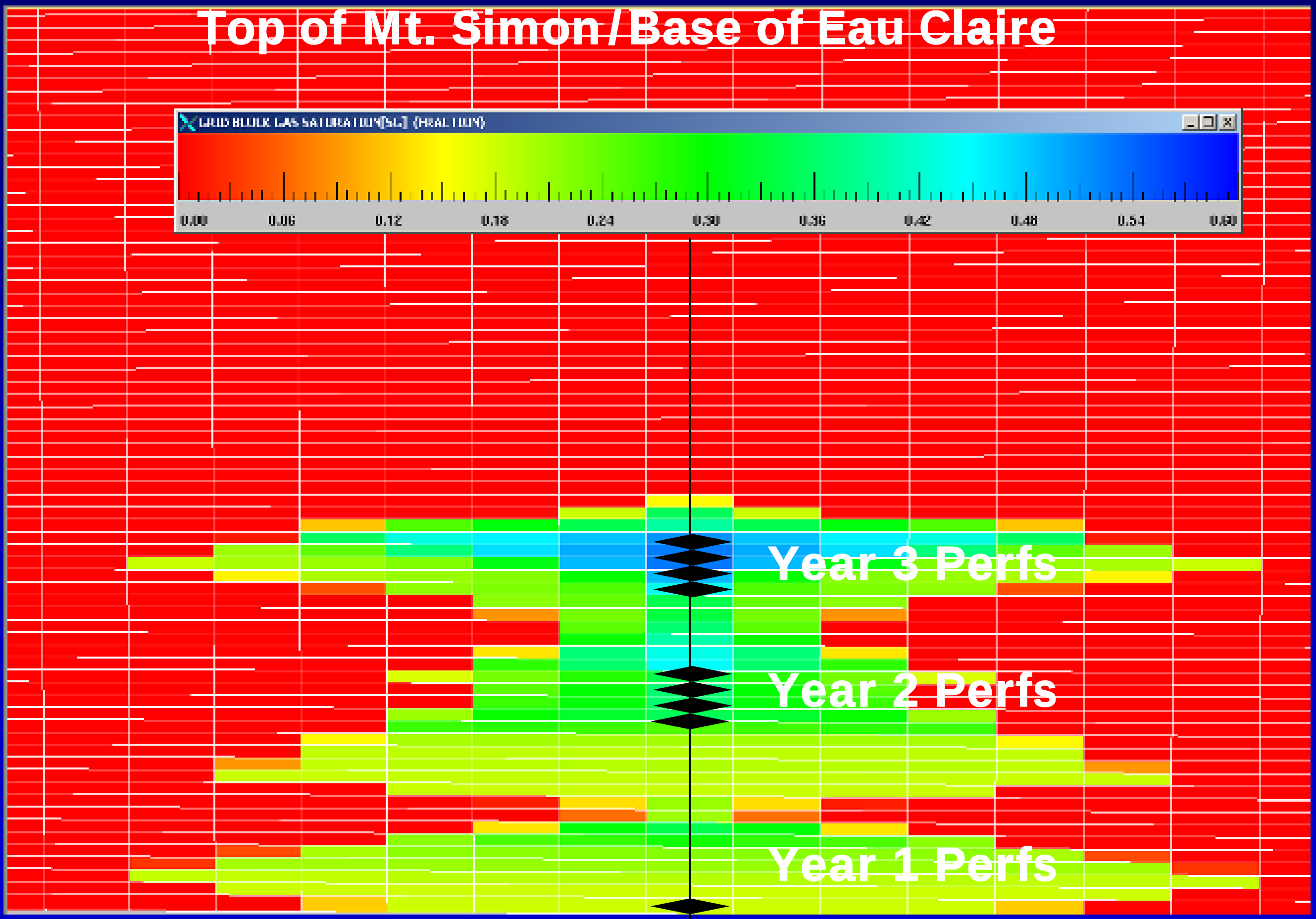
- k_h 185 md
- k_v 2.45 md
- k_v/k_h 0.0133 (over 75 ft interval)

Comparison of Water PTA and Transformed Permeability

- k_h calculated every 0.5 ft
- k_v/k_h of 0.85 used every 0.5 ft for k_v
- Harmonic average (series flow) used to calculate k_v over 75 ft interval.

	Log/ Core	PTA
k_h, md	182	185
k_v, md	2.43	2.45
h, ft	78	75

Reservoir Model: Forecasts
Plume Management



Perforation Strategy:

Perforate bottom to top in annual increments

Cell size: 220 x 220 x 15 ft

Reservoir Model: Forecasts Pressure Management

- Bottomhole injection pressure compared to fracture pressure
- CO_2 pressure below caprock and intermediate seals compared to capillary entry pressure
- Far-field pressure and “regulated” area of review and pressure thresholds.

Reservoir Model: Characterization

- Multiwell Water Injection Test (Planned)
  - Interwell permeability
  - Vertical permeability
- Single Well Water Injection Test (Planned)
  - Vertical permeability

Reservoir Model: CO_2 Injection History Matching

- Baseline: well-defined geological model developed with core, well logs, seismic, and pressure transient analyses
- Calibration (planned)
  - Seismic reflection of CO_2
  - CO_2 PTA Tests and fluid sampling
  - Cased hole logs
- Variables
  - CO_2/brine relative perm and capillary pressure
  - Geologic model

Conclusions

- Water injection used to validate geologic model of injection zone
  - Very good agreement between core, logs and PTA
- Unique method used to transform core permeability to well log porosity
- Vertical perm
  - Very important to plume distribution in thick zone
  - Extremely sensitive to scale (grid size)

Conclusions, contd.

- Non-unique geologic model for layer heterogeneity
- Greater uncertainty in reservoir characterization in thick, porous and permeable formations:
  - 60 ft of core
  - 75 ft injection/falloff test

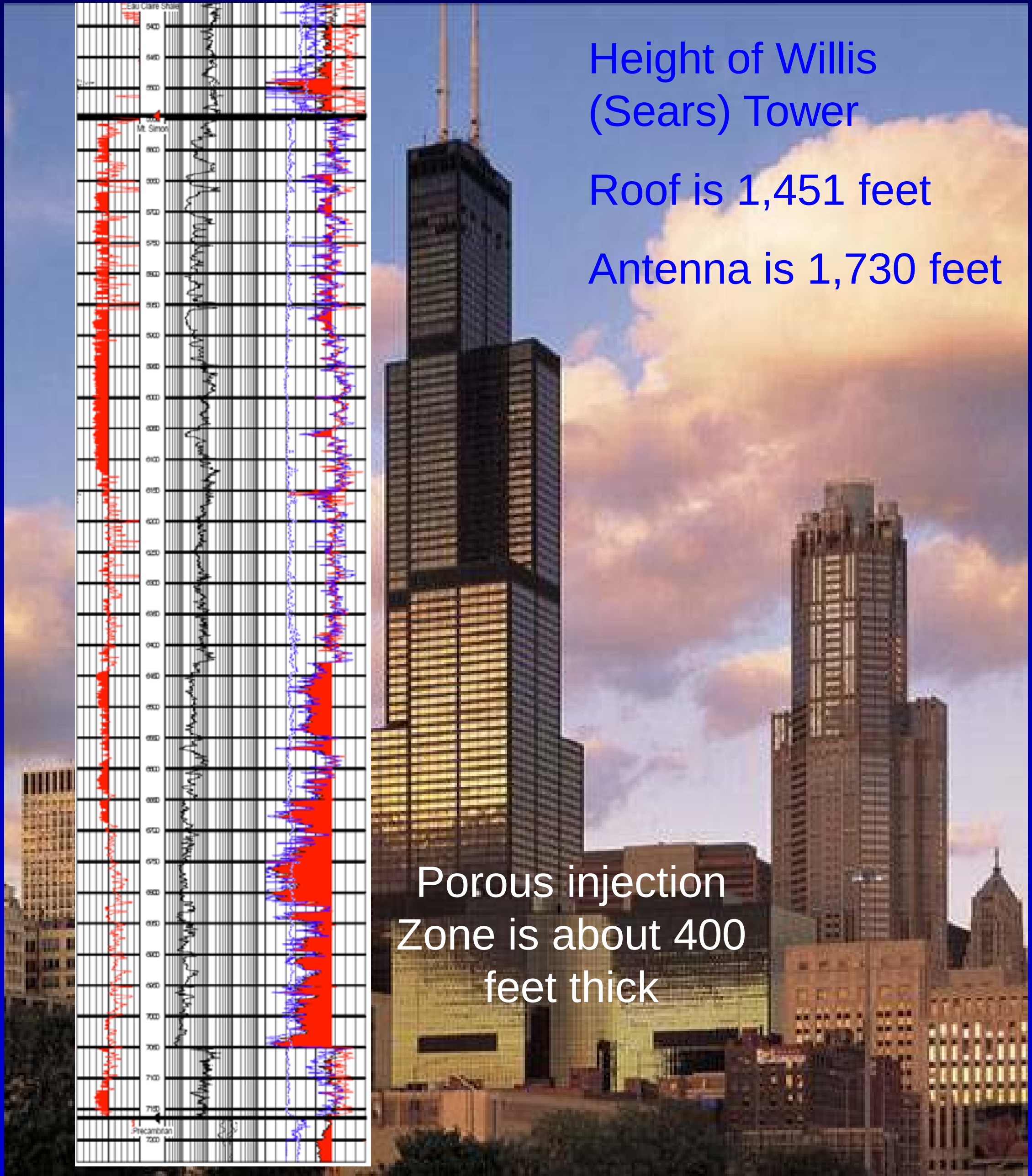
PERSPECTIVE…

Gross Thickness Mt. Simon 1,640 feet

Washington Monument

555 feet

Core and flag pole about 30 feet



Simulation for Site Characterization: Mt. Simon Sandstone

Scott M. Frailey
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February 16-17, 2010

Midwest Geological Sequestration Consortium
www.sequestration.org

Best Practice Manual
Sleipner CO_2 Storage Project

Salt Lake City, 17-18 February 2010

TNO | Knowledge for business

Bert van der Meer, Senior Reservoir Engineer

Outline

- Introduction
- Sleipner CO_2 storage
- Misperception 1 - Rumors
- Sleipner modelling
- Misperception 2 - Overestimations
- Questions

Introduction

- Best Practice Manuel, SACS – Sam Holloway
- Best Practice for Aquifers, SACS, CO2STORE – Andy Chadwick

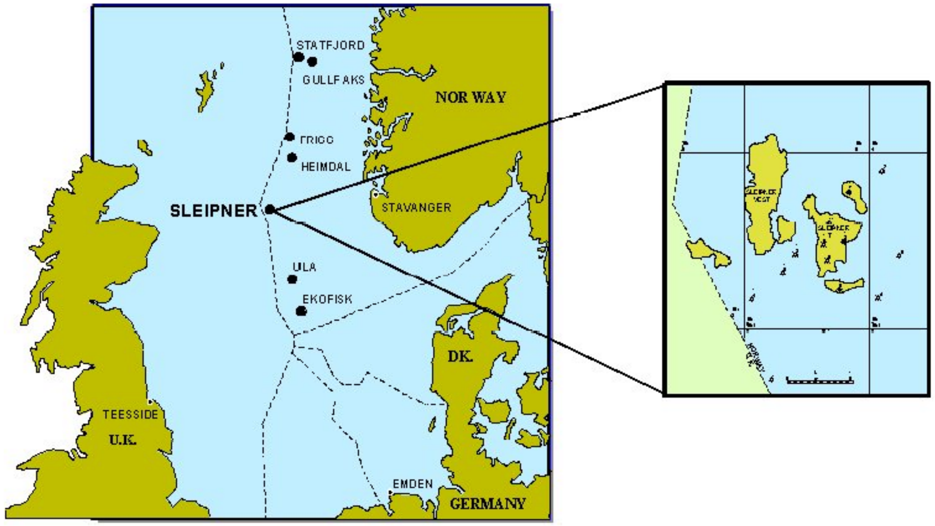
- Sleipner first CO_2 sequestration project
- Environmental purposes
- Knowledge sharing and building on experiences
- Aim of manual:
    - describe what is done
    - why it is done
    - what is learnt
    - what went well
    - gaps in knowledge and/or data

Introduction

- Earth’s subsurface is an extremely variable natural system
- Some issues and highlighted could be site specific
- Not a set of standard procedures
- 44 Profesionals involved
- 9 organizations

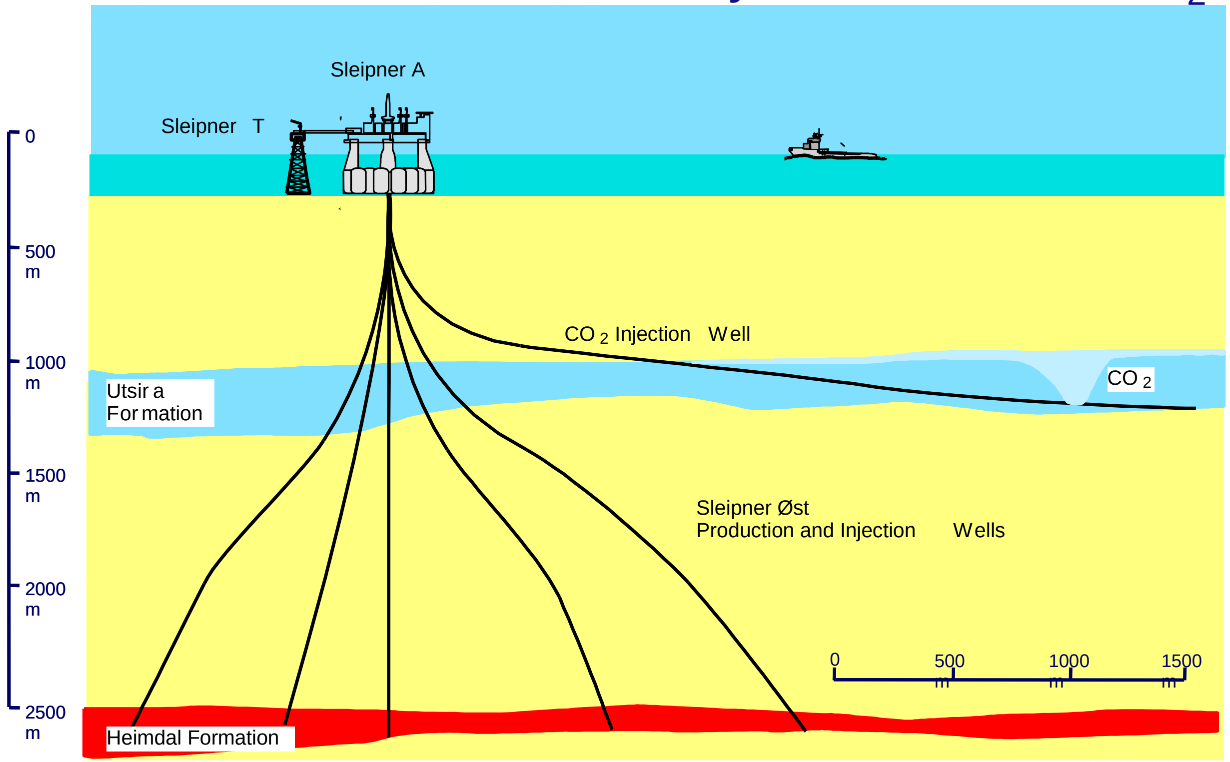
Sleipner CO_2 Storage

- Sleipner fields 250 km from the west coast of Norway
- Statoil is operator
- Licence partners are: ExxonMobil, TotalFinaElf, Statoil
- 202 GSm^3 rich gas
- CO_2 content varies 4 to 9.5 %
- Reduction below 2.5 % (pipe line quality), ~ 1Mt/y CO_2

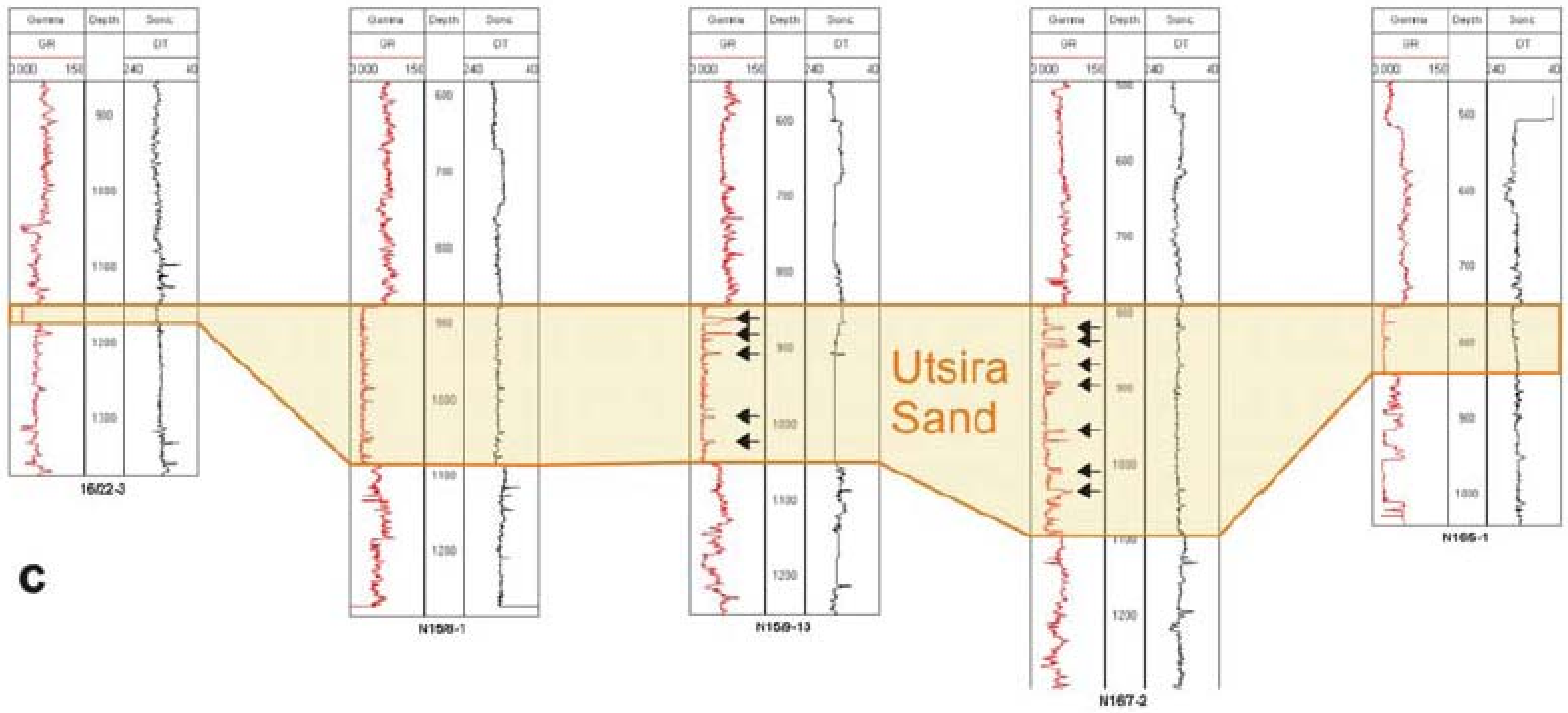


Sleipner CO_2 Storage

- Storage in Utsira formation
- Very large – 26.000 km^2
- Aquifer - top 800 mSS ~ 250 thick
- One 7” injector near horizontal
- Injection from end 1996 until today some 12Mt of CO_2



Utsira Formation



Misperception 1- Rumors

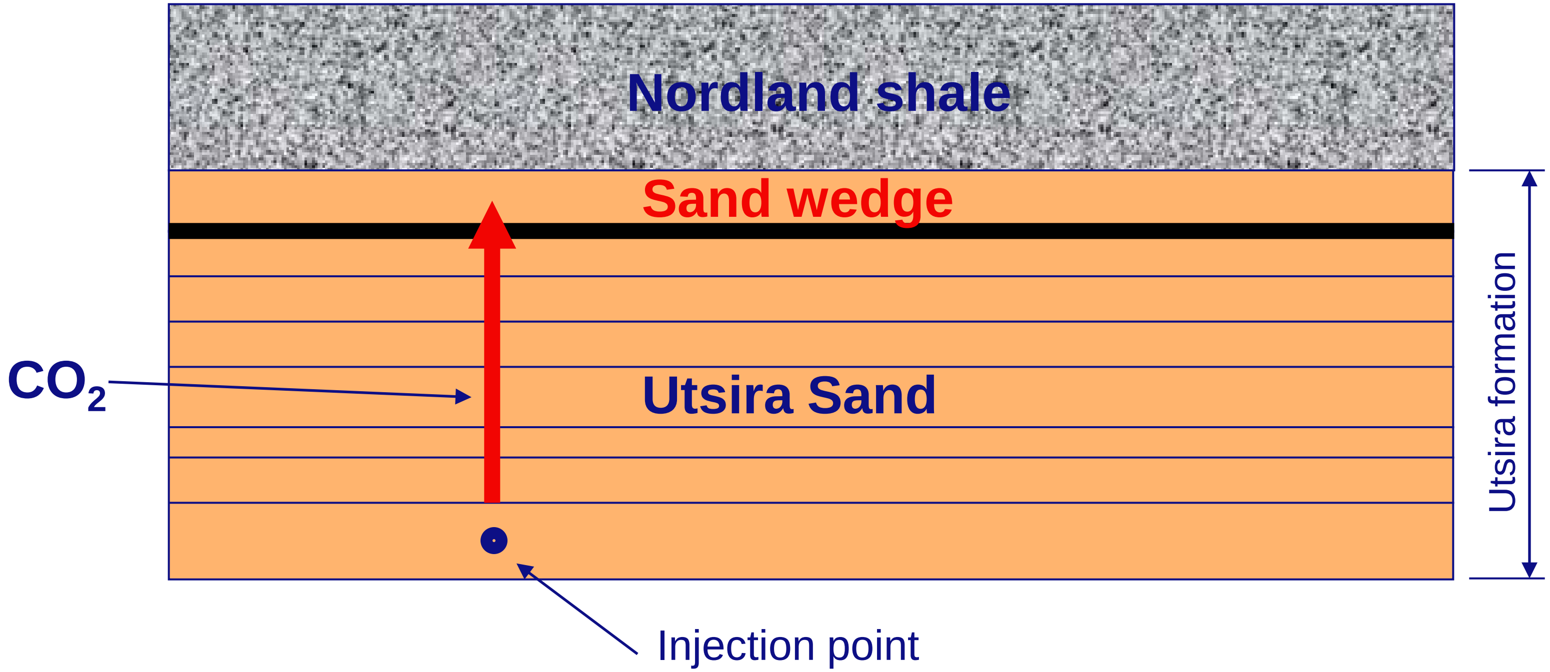
- The Sleipner project shows that much less CO_2 is stored radially than what seismic reflection data show (Bickle et al., 2007). They have seen significant leakage to overlying layers.

  Michel J. Economides, Journal of Petroleum Science and Engineering 70 (20110) 123-130.

Can we spread rumors?

Sleipner modelling

- High permeable sand body (~250 m thick) with intersand shale layers (1 m thick, only from log's)
- On top 10 m thick shale (good marker)
- Sand wedge
- Nordland Group (very thick)
- Utsira formation only logs



Sleipner Modelling Procedure

1 Location and processes (Process)

size, fluids, interaction, PVT, reservoir conditions

2 Type Simulator (Tool)

type, assumptions, approximations, limitations

3 Data

description, measured, accuracy, reliability

4 Question

Sleipner Modelling

- Process
  - Gas/water, infinite aquifer, high permeable, CO_2 sensitive to P, T., CO_2 solubility
- Simulator
  - Multiphase flow simulators
    - Black\oil approach
    - Compositional
- Data
    - Utsira basin scale, limited water, temp., no reservoir pressures, wellhead daily P, T, Q, 4D seismics => 1999 CO_2 at top
- Question
    - CO_2 bubble development?

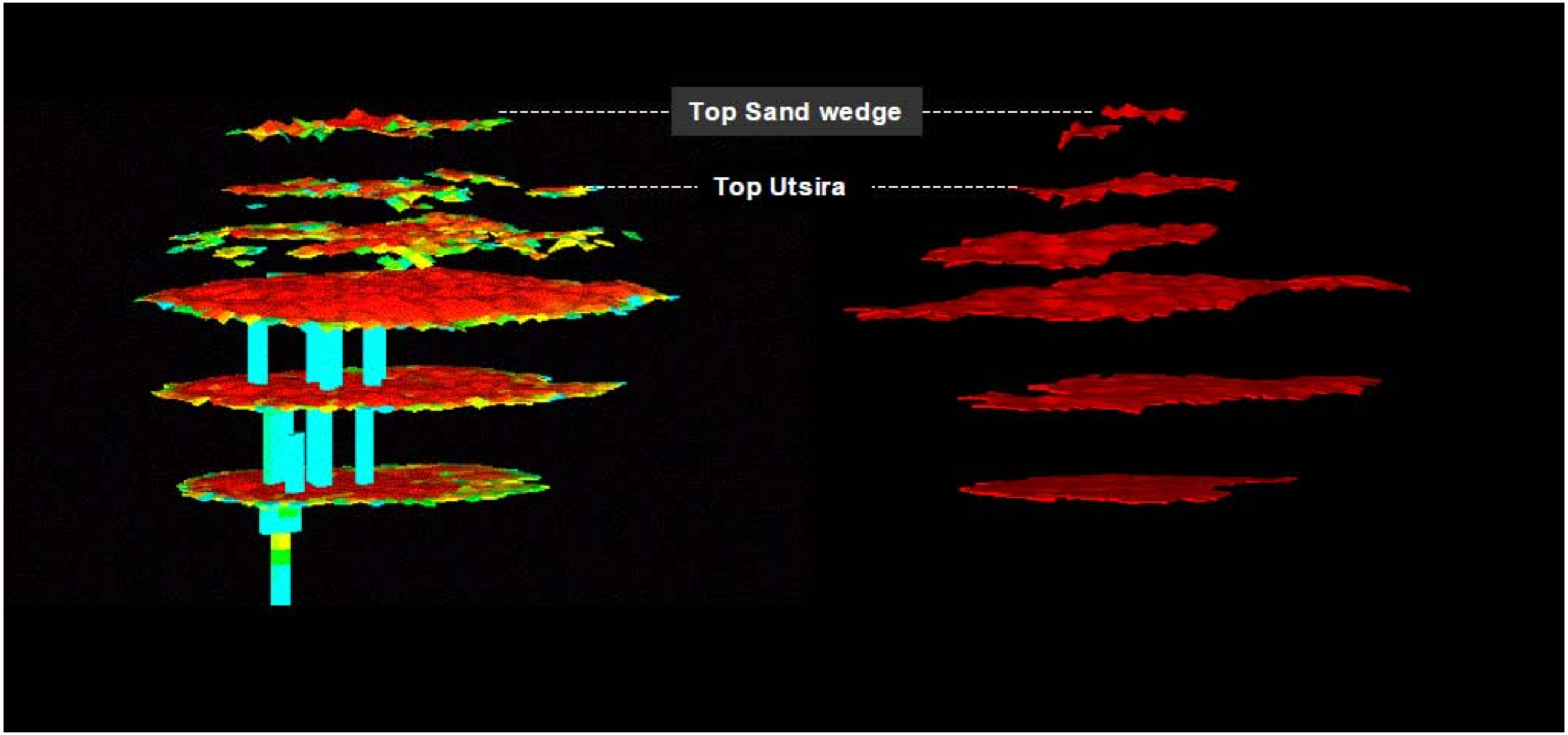
Sleipner Modelling

- SINTEF
  - Intersand layers, randomly holes, black oil approach oil=water, CO_2 = gas, solubility=Rs (ECLIPSE)
- TNO
  - Continues intersand shale layers = transmissibility, Gas\water, CO_2 PREOS, T gradient (SIMED)

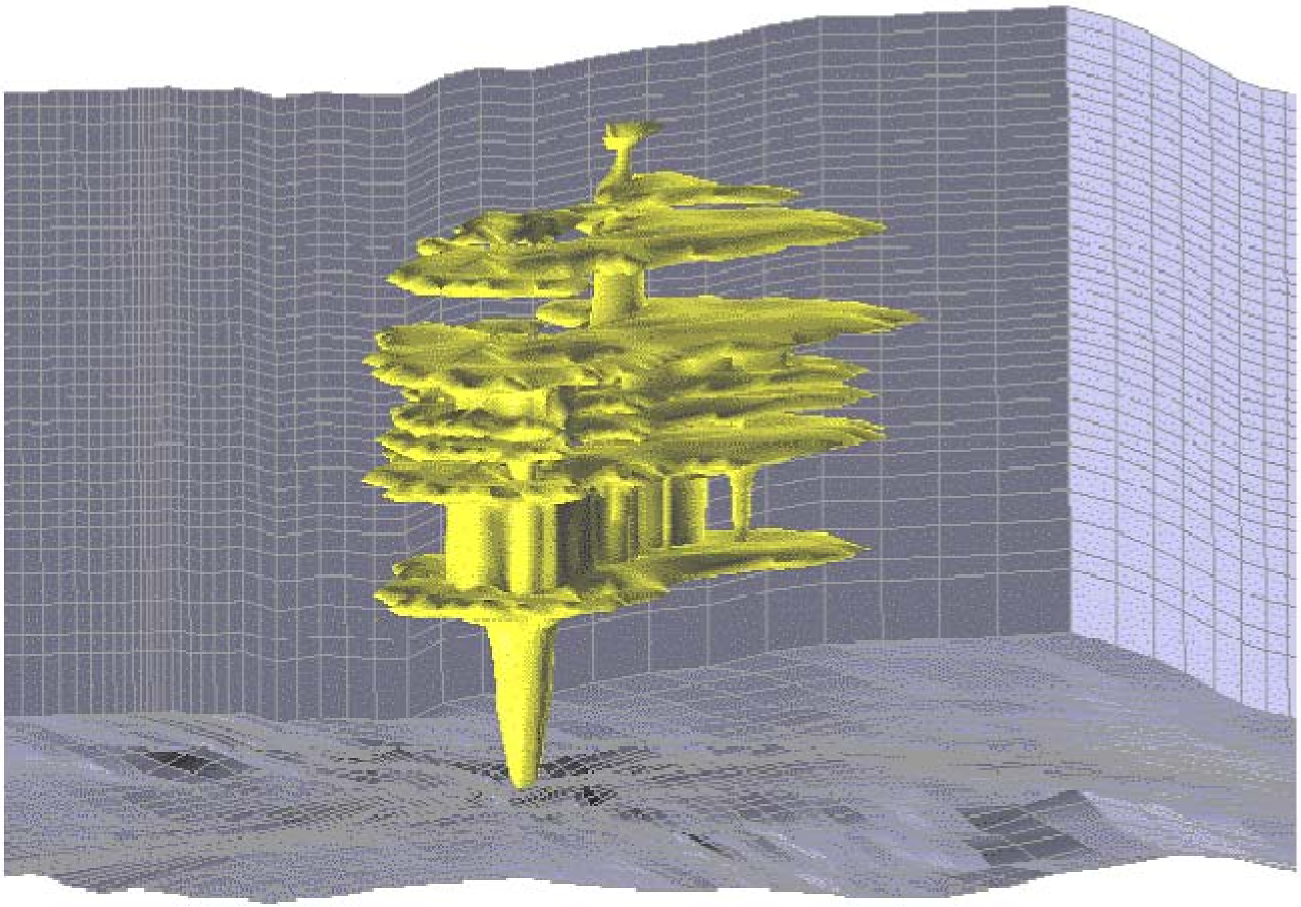
- Many others

- Conclusion:
  - Simulators are suitable? (adequate, solubility not validated)

Sleipner Modelling SINTEF

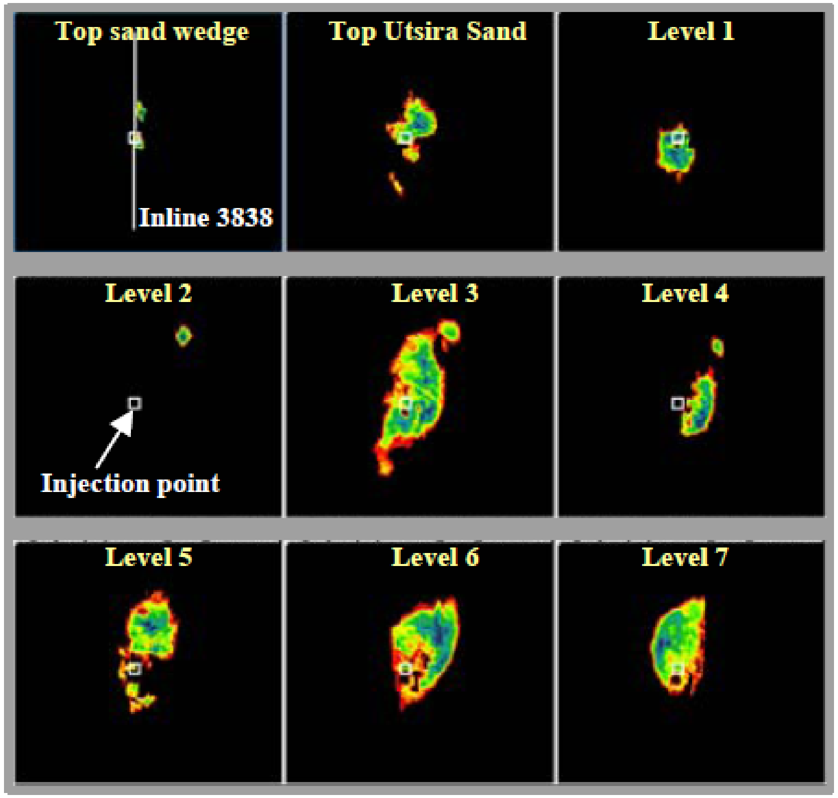


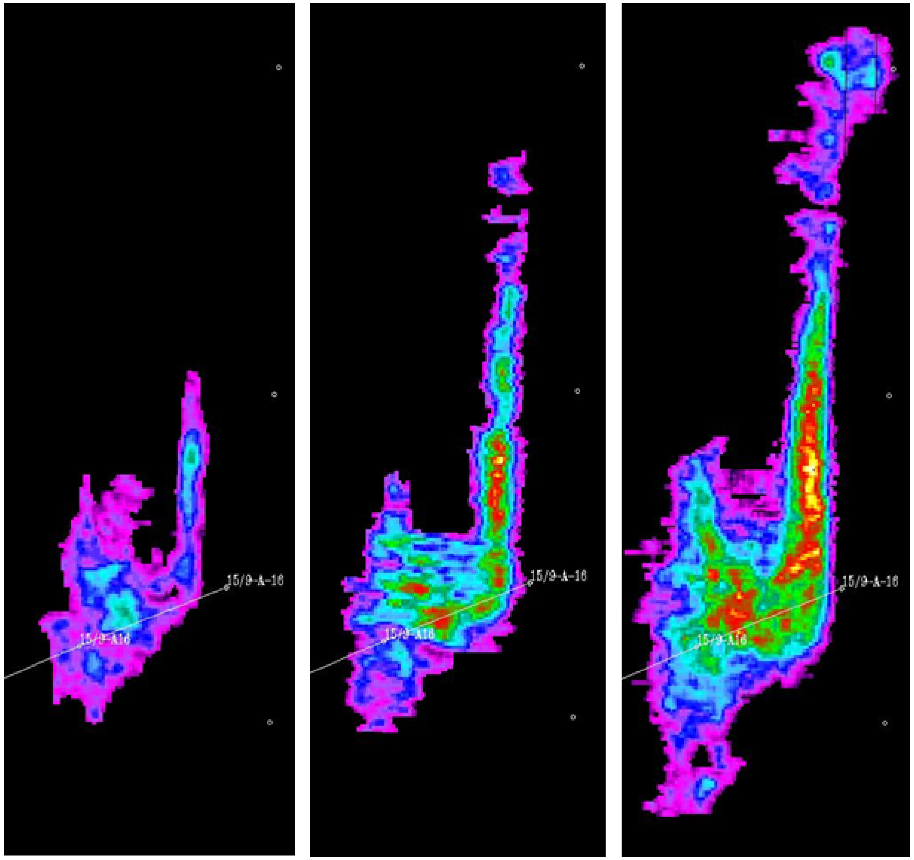
Sleipner Modelling TNO



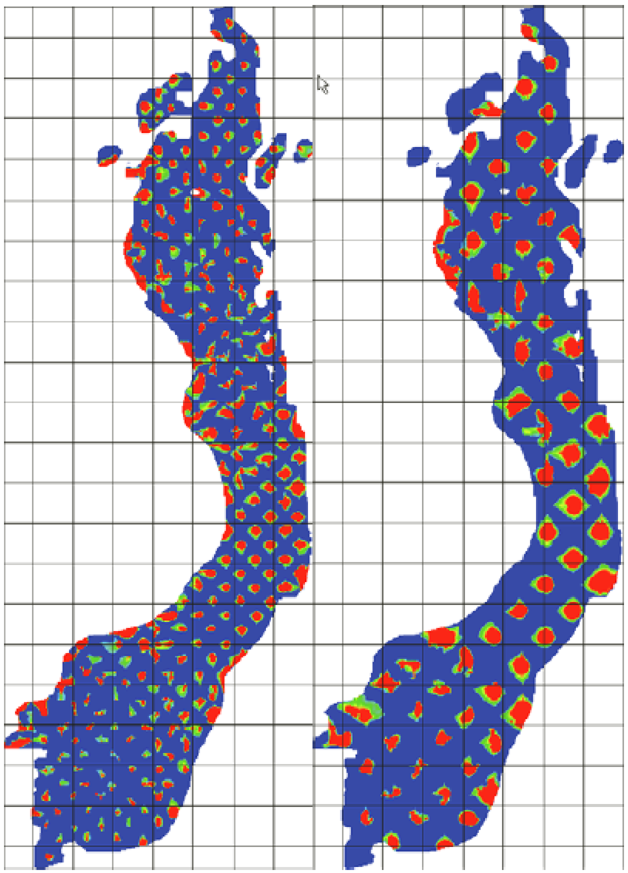
Sleipner Modelling Parameter to Match

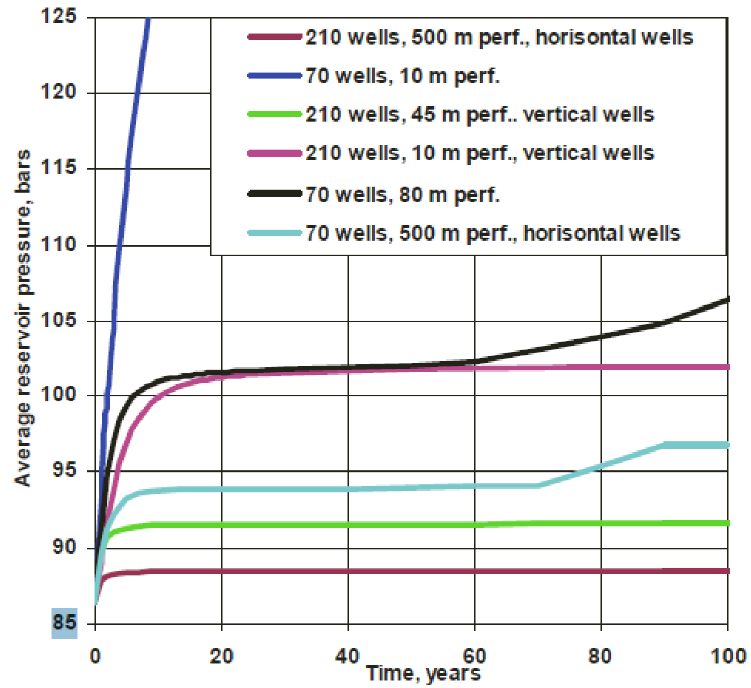
CO_2 distribution in October 1999





Misperception 2, Overestimation

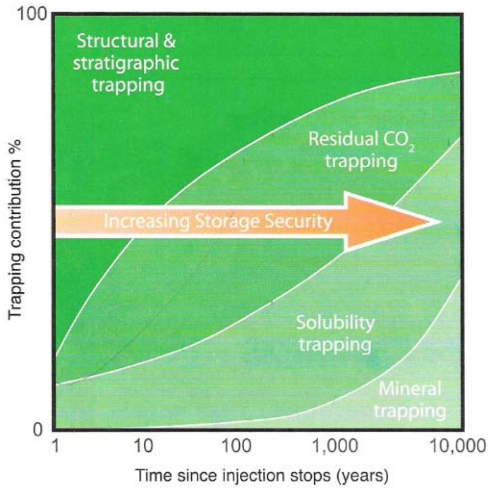




- Is this realistic? – (20 to 60 Gt)

Question to modellers

- Do we have the responsibility to come up with realistic estimations.
- What (type) data do we need?
- Are available simulators capable of predicting performance? (short and long term, not validated solubility)



Thanks for your attention

- Please QUESTIONS

Best Practices and Protocols:

U.S. DOE / NETL Regional Partnerships' Effort

February 17, 2010

Brian J. McPherson
Jens Birkholzer
Mark White
J.P. Nicot

Best Practices Protocols for Geologic CCS Simulation Analysis

Proposed Topics for the Best Practices Protocols:

Section I. Deep Saline Sequestration Simulation

1. Subject Processes (THMCB)
   - Conceptual Models
   - Numerical Models

2. Pre-Injection Simulation Analyses
3. During-Injection Simulation Analyses
4. Post-Injection Simulation Analyses
5. Collaboration, Technology Transfer Among Project Tasks (Site Characterization, MVA, Risk Assessment)
6. Integration with Surface Analyses
7. Code Standards and Selection
8. Modeling Practice Comparison

Best Practices Protocols for Geologic CCS Simulation Analysis

Proposed Topics for the Best Practices Protocols:

Section II. EOR With Sequestration Simulation

1. Subject Processes (THMCB)
   - Conceptual Models
   - Numerical Models

2. Pre-Injection Simulation Analyses
3. During-Injection Simulation Analyses
4. Post-Injection Simulation Analyses
5. Collaboration, Technology Transfer Among Project Tasks (Site Characterization, MVA, Risk Assessment)
6. Integration with Surface Analyses
7. Code Standards and Selection
8. Modeling Practice Comparison

Best Practices Protocols for Geologic CCS Simulation Analysis

Proposed Topics for the Best Practices Protocols:

Section III. ECBM With Sequestration Simulation

1. Subject Processes (THMCB)
   - Conceptual Models
   - Numerical Models

2. Pre-Injection Simulation Analyses
3. During-Injection Simulation Analyses
4. Post-Injection Simulation Analyses
5. Collaboration, Technology Transfer Among Project Tasks (Site Characterization, MVA, Risk Assessment)
6. Integration with Surface Analyses
7. Code Standards and Selection
8. Modeling Practice Comparison

Best Practices Protocols for Geologic CCS Simulation Analysis

Example: Timeline (Progression) of CCS Simulation Analysis:

1. Pre-Injection: Baseline Conceptual Model
2. Pre-Injection: Baseline Numerical Model
3. Pre-Injection: Injectivity Forecast Simulations
4. Pre-Injection: Capacity Forecast Simulations
5. Pre-Injection: Monitoring Design Simulations
6. Pre-Injection: Risk Assessment Baseline Simulations
7. During-Injection: Updated Injectivity Simulations
8. During-Injection: Updated Capacity Simulations
9. During-Injection: Updated Monitoring Design Sim’s
10. During-Injection: Risk Assessment Update
11. Post-Injection: Updated Monitoring Design Sim’s
12. Post-Injection: Final Capacity Evaluation
13. Post-Injection: Updated Risk Assessment

Best Practices Protocols for Geologic CCS Simulation Analysis

Proposed Topics for the Best Practices Protocols:

Main Sections: Deep Saline, EOR, ECBM

1. Subject Processes (THMCB)
   - Conceptual Models
   - Numerical Models

2. Pre-Injection Simulation Analyses
3. During-Injection Simulation Analyses
4. Post-Injection Simulation Analyses
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8. **Modeling Practice Comparison**

Best Practices Protocols for Geologic CCS Simulation Analysis

The Regional Partnerships will achieve a Modeling Practice Comparison by evaluating model development practices of different groups (Partnerships) with a single site case study.

(1) We've proposed "Sim-Seq" - a special project initiative - to NETL, to instigate and coordinate the single-site case study.

(2) We will use GS3 as a software platform for facilitating the comparison study.

Sim-SEQ

A Planned DOE Initiative on Model Comparison for CO_2 Geologic Storage

Objectively evaluate models against data, using defined and agreed-upon performance metrics

Demonstrate in an objective manner that the system behavior of GCS sites can be predicted with confidence

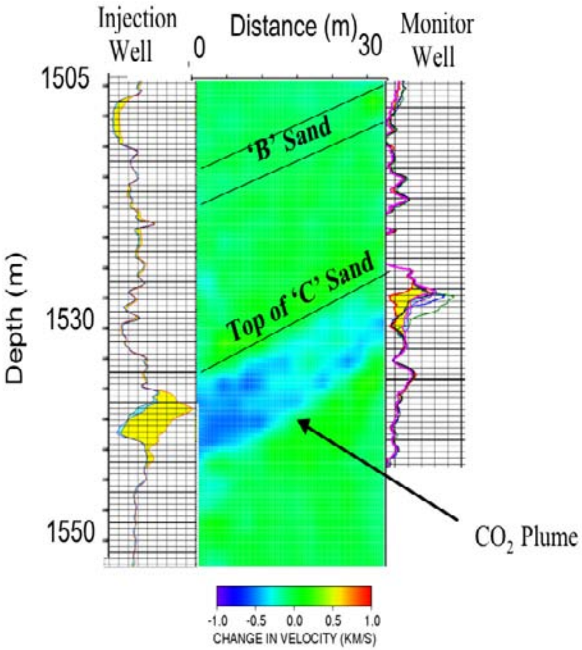
Provide a forum for discussion, interaction, cooperation, and learning among modeling groups

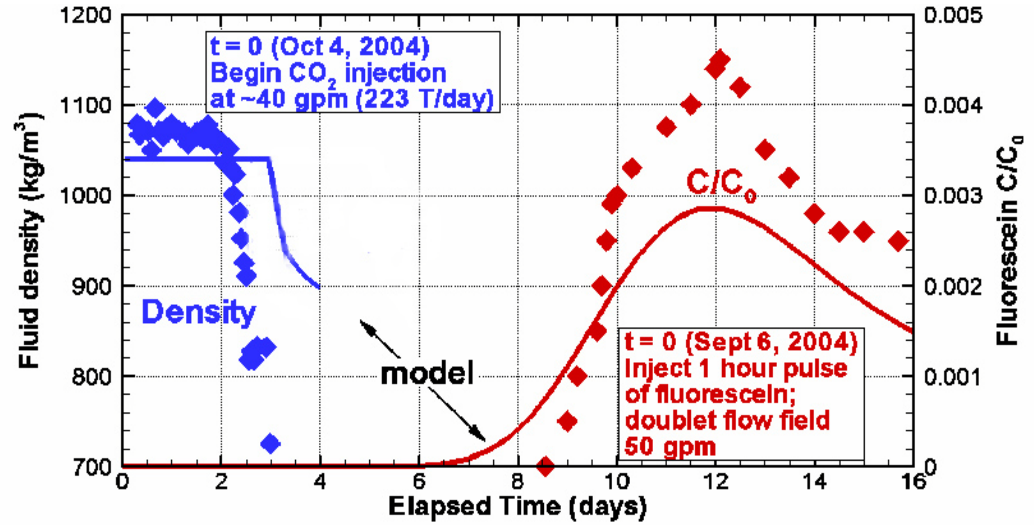
Encourage development of new approaches and model improvement

Evaluate model uncertainties and assess their impacts

Sim-SEQ Is About ….

- Model Evaluation and Comparison Against Measured Data





Examples from Frio test (tomography from Daley, et al, Env. Geol. 2007)

- NOT Just Code Comparison and Verification Against Benchmark Tests

Sim-SEQ Model Evaluation

Approach

- Participating modeling groups will perform simulation analysis of selected soon-to-start large field tests
- Using the same set of site characterization data, modeling groups will use different conceptual approaches and numerical simulators
- Results will be compared with monitoring data and among different modeling groups, and discrepancies will be evaluated

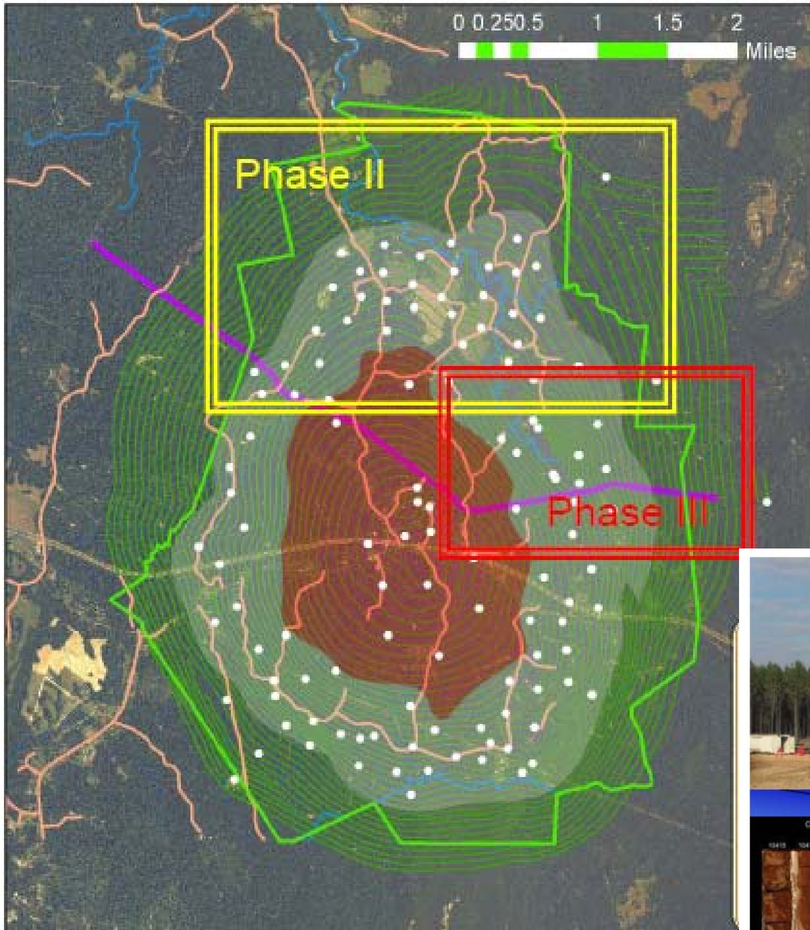
Organization

- Initiative will be facilitated by LBNL (Jens Birkholzer) and embedded in DOE's simulation and risk assessment working group (Brian McPherson)
- Participants will convene regularly via videoconferences and workshops

Status

- Awaiting funding decision, hopefully starting soon

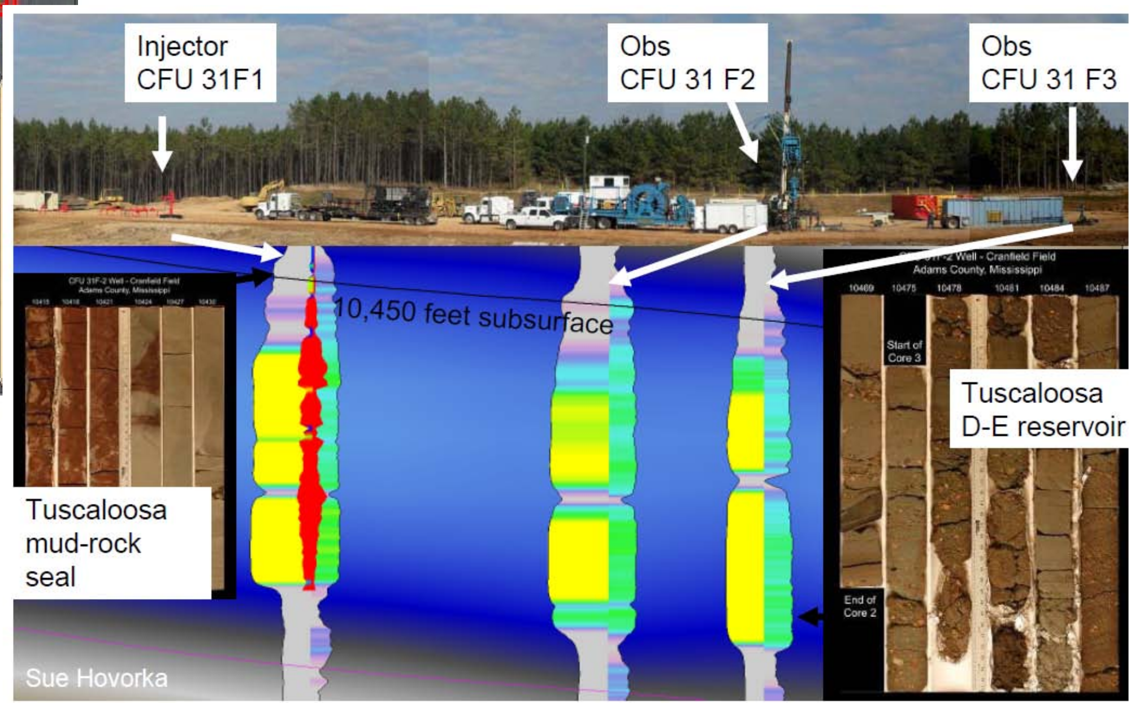
Potential Sim-SEQ Study Site



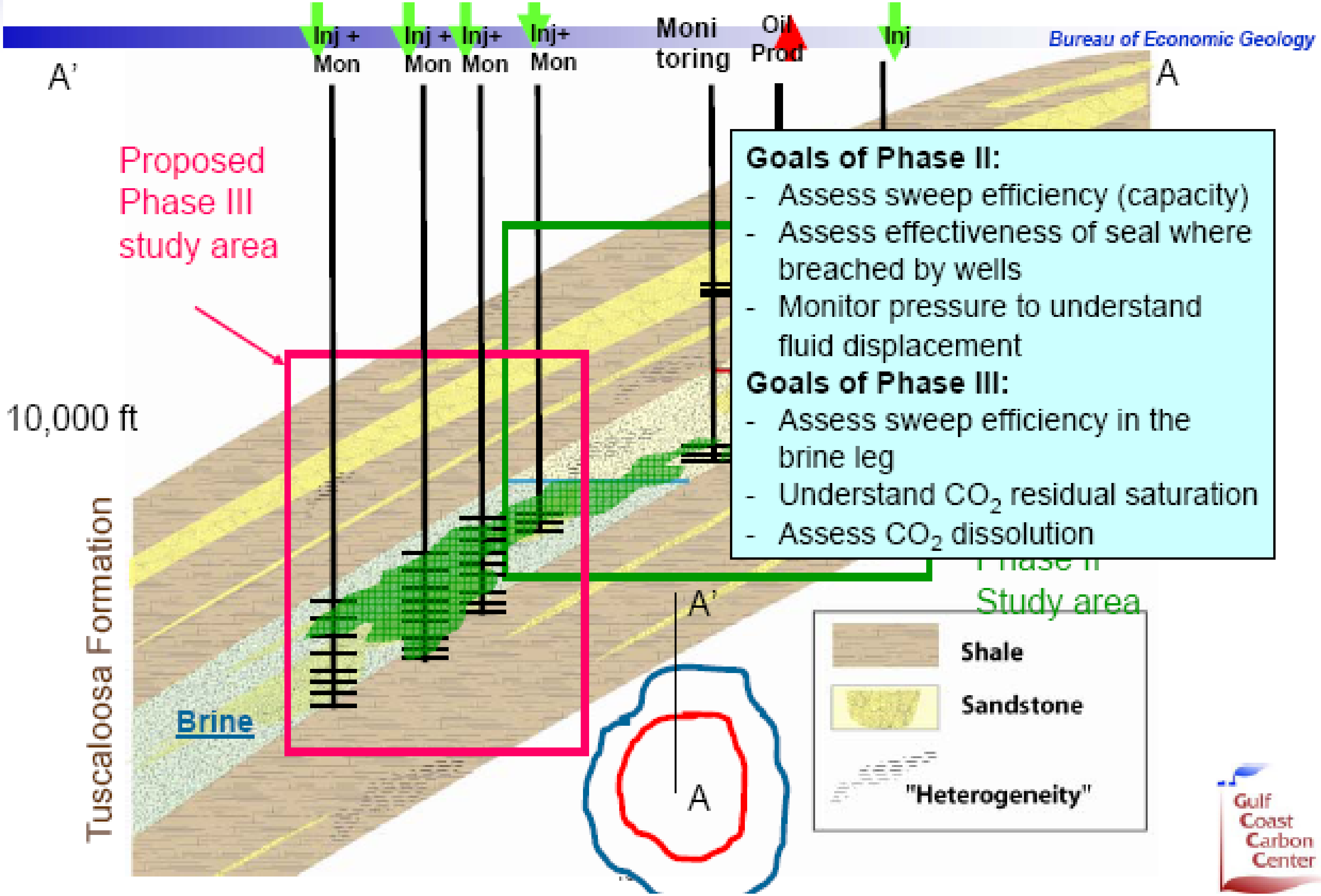
From JP Nicot, BEG, UT Austin

Cranfield, MS

- Massive Sandstone Lower Tuscaloosa
- Injection into down dip water leg of EOR field
- 1.5 million tonnes per year for ~1.5 years, started in November 2009
- Site characterization data reasonably good compared to deep saline formations
- Extensive monitoring



Cranfield Schematic Overview



Goals of Phase II:

- Assess sweep efficiency (capacity)
- Assess effectiveness of seal where breached by wells
- Monitor pressure to understand fluid displacement

Goals of Phase III:

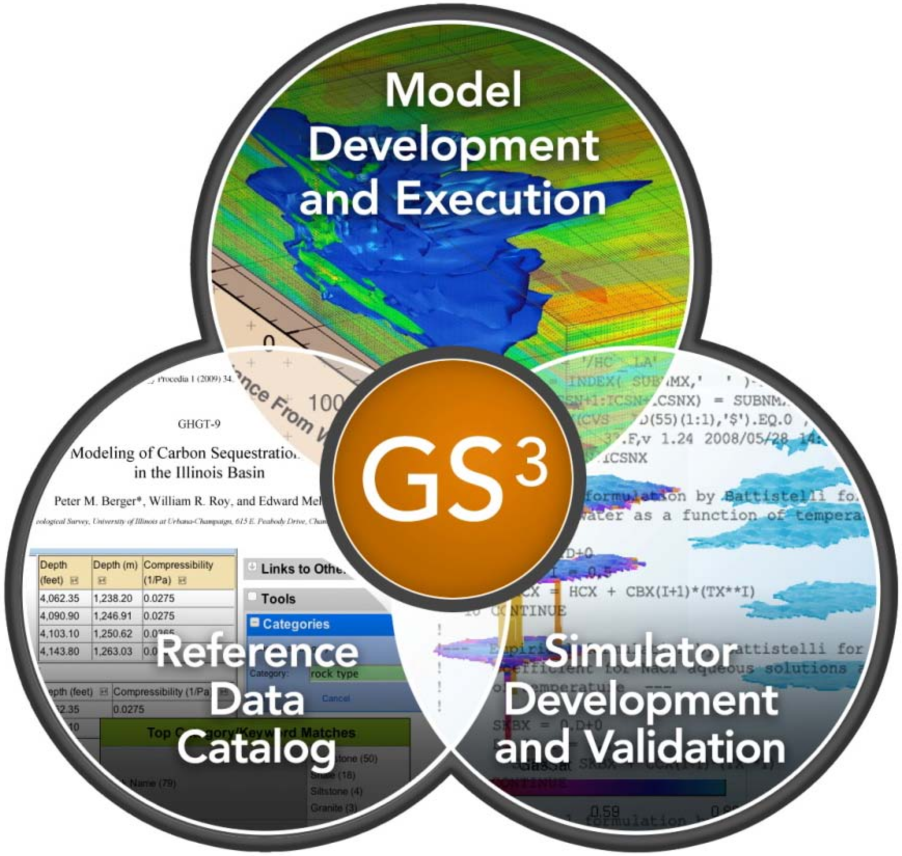
- Assess sweep efficiency in the brine leg
- Understand CO_2 residual saturation
- Assess CO_2 dissolution

8. Modeling Practice Comparison

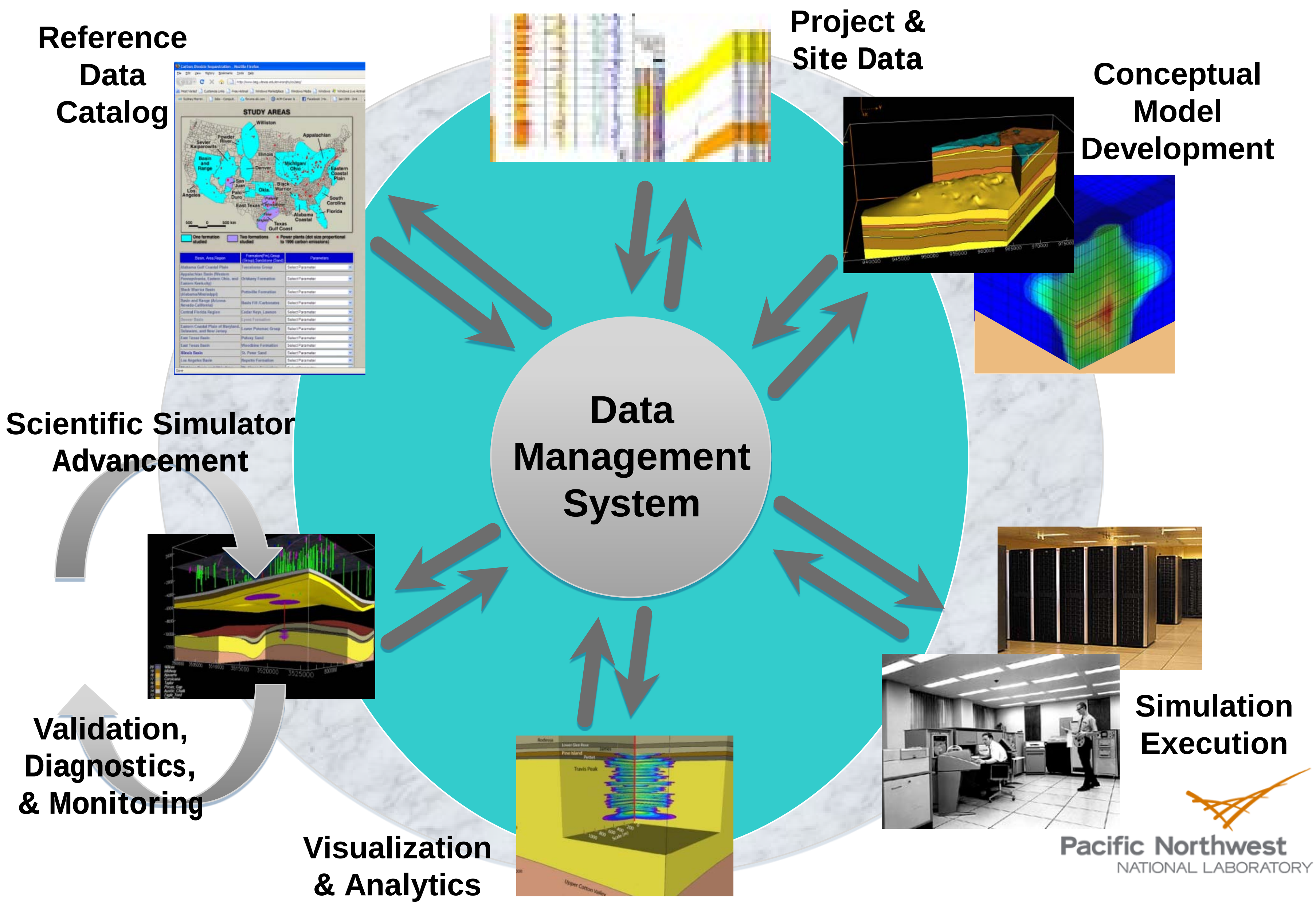
- Sim-Seq
- GS3

Prospect for geologic sequestration modeling

- Interdisciplinary Teams
- protocols for modeling best practices
- Knowledge Management
- data provenance
- data transparency & protection
- historical archive
- Flexibility
- commercial tools
- integrated tools
- tool registry
- innovative data assimilation
- Scientific Simulators
- infusing new science
- accelerating scientific advances
- code diagnositics and validation
- scalable computing
- Analytics and Visualization
- Optimization & Stochastic Realizations



Flexible Structure for modeling process and data management



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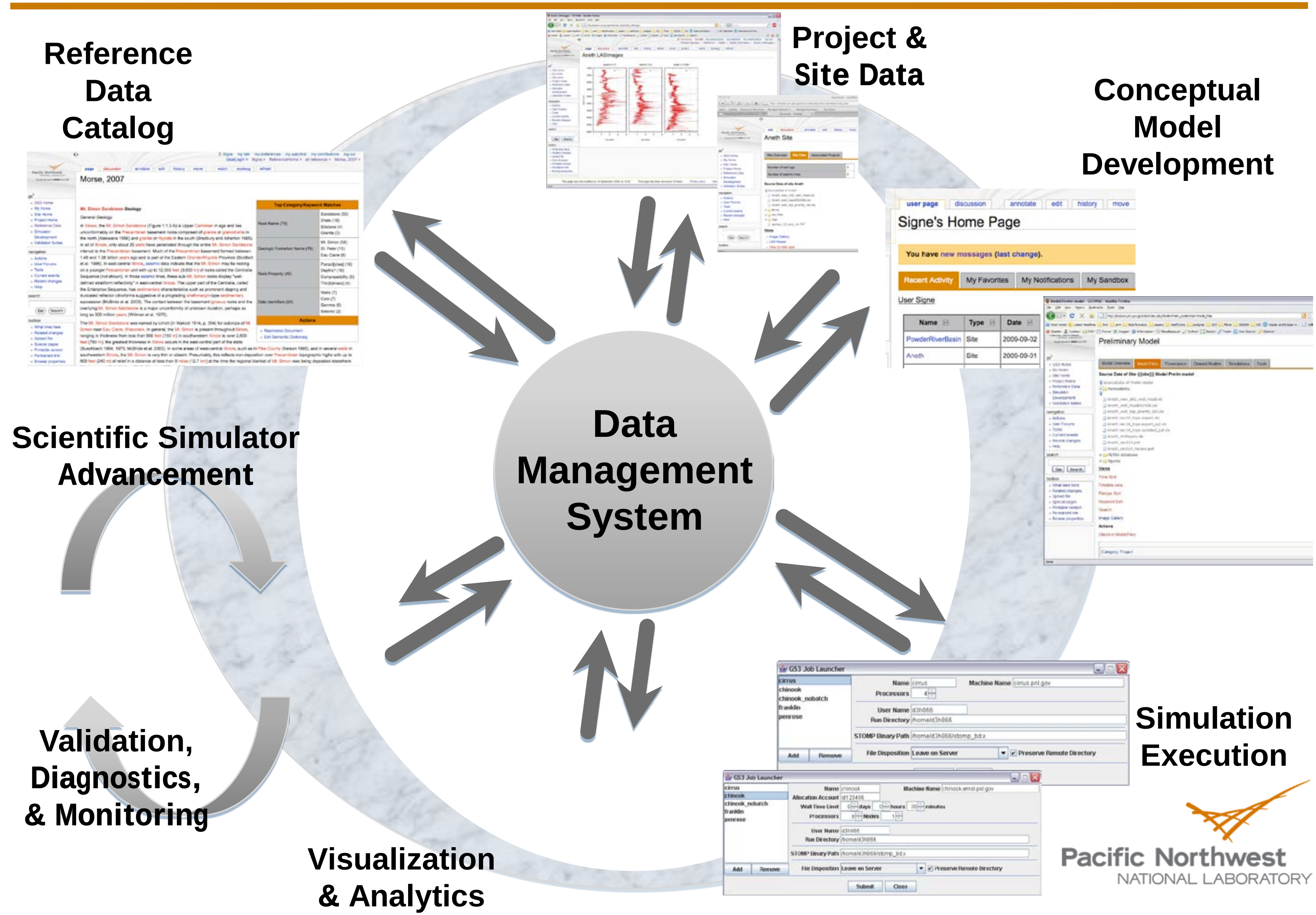

Requirements for the function of GS^3

- Collaboration & Secure Data Management
- sequestration projects & sites
- project team roles
- Dynamic Content and Tools
- project data & annotation
- reference data (with semantic markup)
- tool registry, including user scripts
- Integration of Model Development Tools
- site characterization to geologic models
- geologic to conceptual models and input files
- visualization and analytics
- Data Provenance
- data sources, workflow, & conceptual models
- simulation inputs, outputs, & analytics
- Simulator Support
- job launching on workstations, clusters, and supercomputers
- validation, diagnostics, & benchmarking

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Guiding Principles for the development of GS^3

- Support and enhance current work practices of scientists rather than dictating a rigid research methodology
- Provide scalable framework/platform for tool integration - not monolithic software package
- Develop tools in areas that are currently bottlenecks or gaps in the model development process
- Create a user extensible environment – shared development of modeling tools will increase productivity for all
- Facilitate data management, data sharing, data tracking (versioning and provenance), and documentation of the modeling process
- Exploit off-the-shelf software and infrastructure

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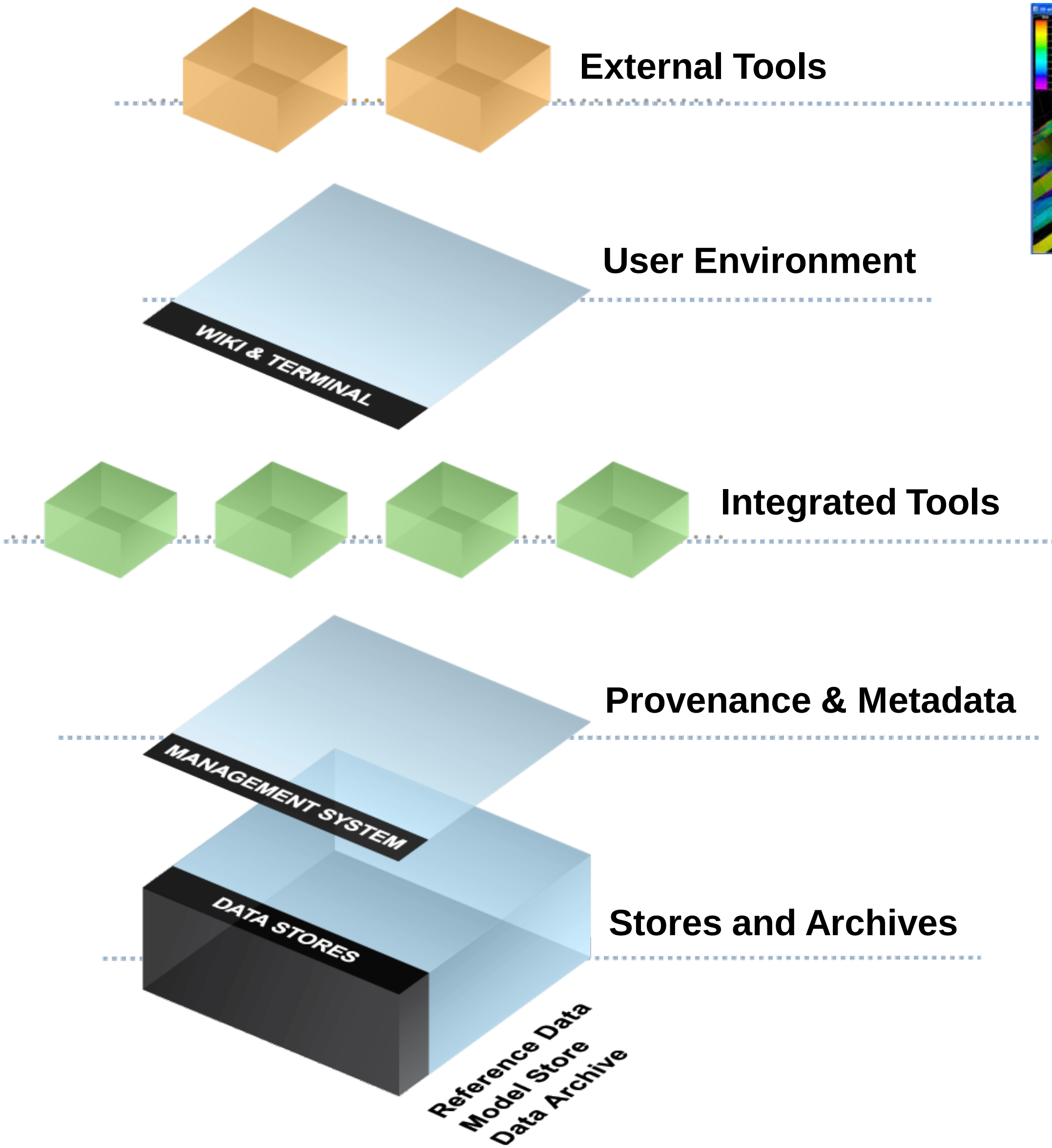
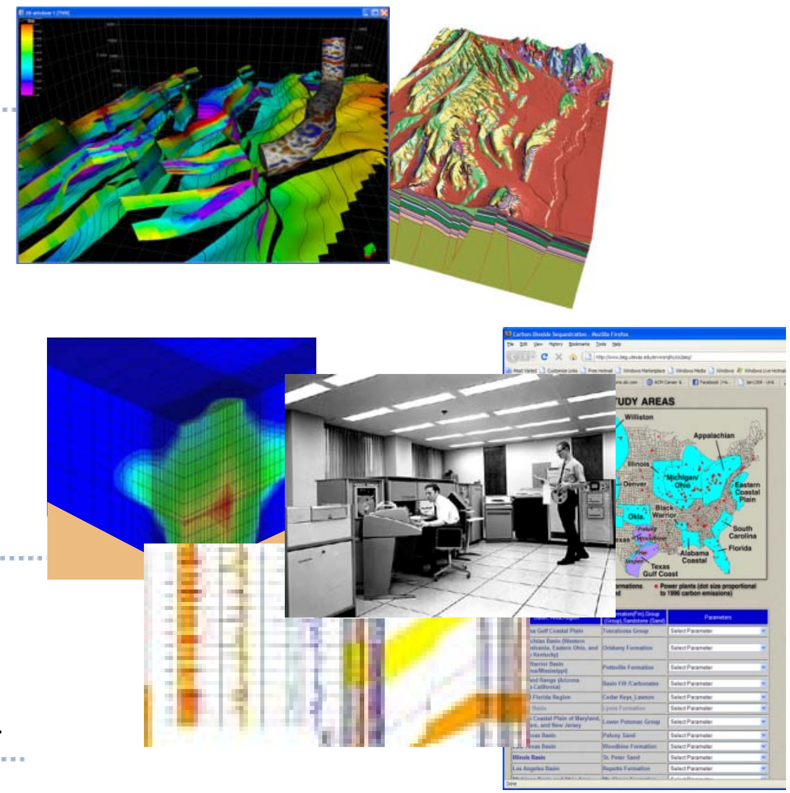
Platform Architecture from a component perspective





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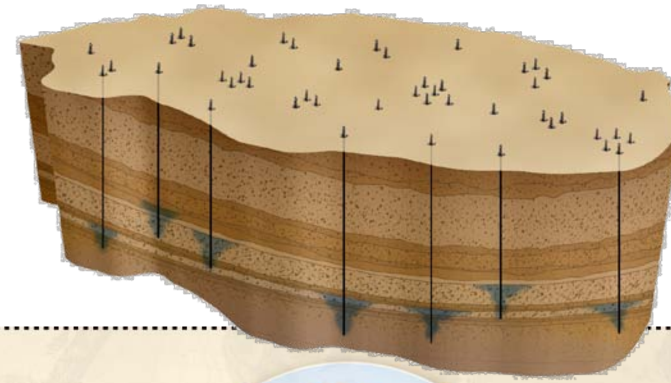
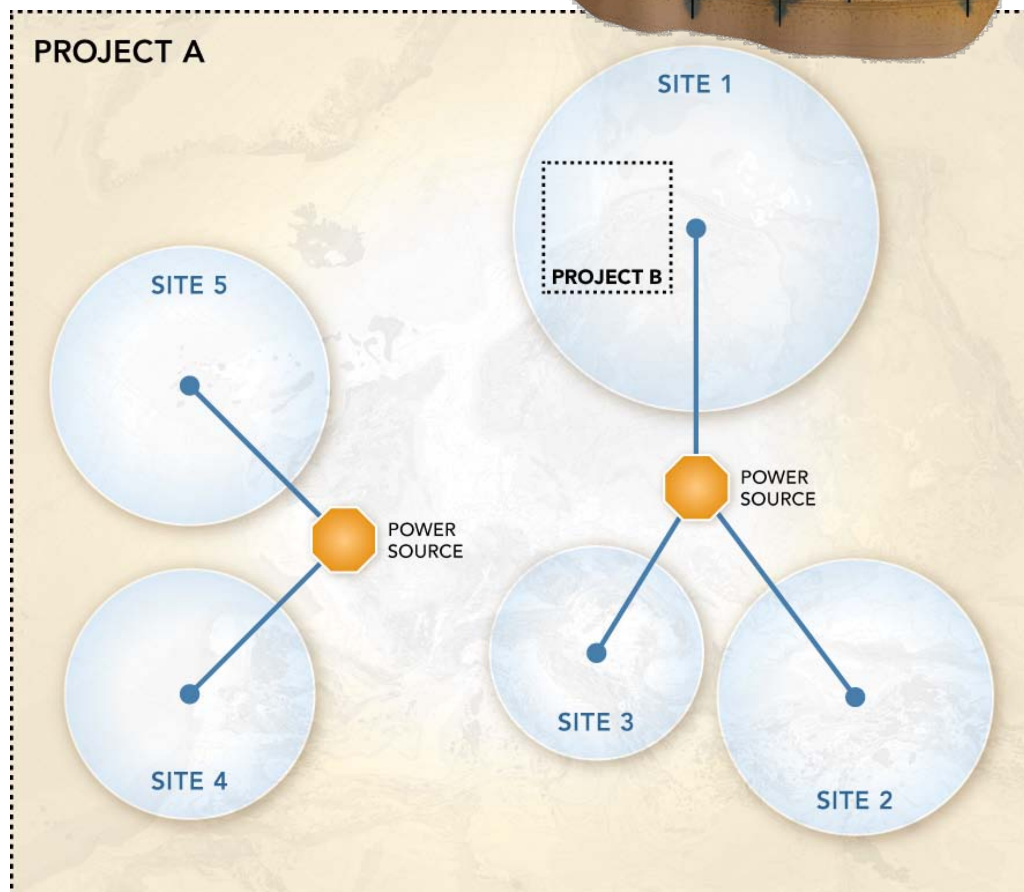
Project & Site Data key features

but only Projects can have Models and Simulations

- Data Gathering
  - browsing data – geolocation, creation time, etc.
  - search on metadata – well depths, well location
  - **extract data subsets**
    - **range of parameter values**
    - **well logs from an area**
    - **specific geologic unit**
- User Control
  - project organization & managment
  - **dynamic collection views**
  - **custom display of data files**
- Tools
  - user extensible registry
  - data format translation
  - unit conversion & checking

black = current focus
grey = future scope





Conceptual Model Development data assimilation tools

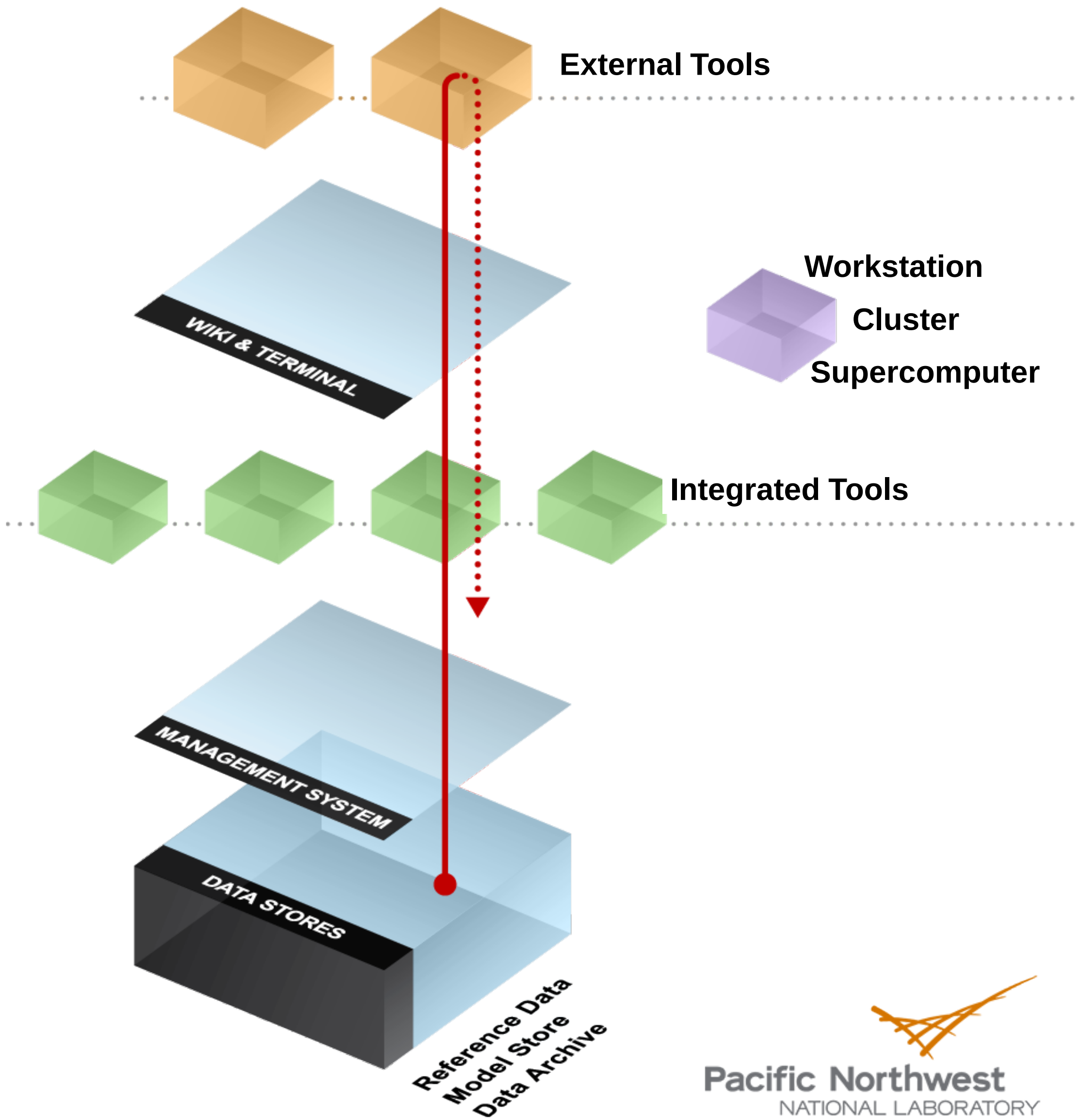
Solid Earth Modeling
- EarthVision
- Petrel

Seismic Interpretation
- Landmark
- Geoframe

Petrophysical Analysis
- TerraStationII
- Interactive Petrophysics
- PfEFFER Pro & Kipling

Geostatistics
- GSLIB
- S-GeM

Facies Modeling
- Roxar
- LithANN



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Conceptual Model Development data assimilation tools

Core and Well Log Analysis

- dominant lithology and mineralogy definition -- compositional analysis
- facies identification -- principle component analysis and cluster analysis
- continuous and categorical data prediction -- neural network modeling
- 3-d multi-well cross plots
- well log data correction -- environmental conditions

Spatial Statistics

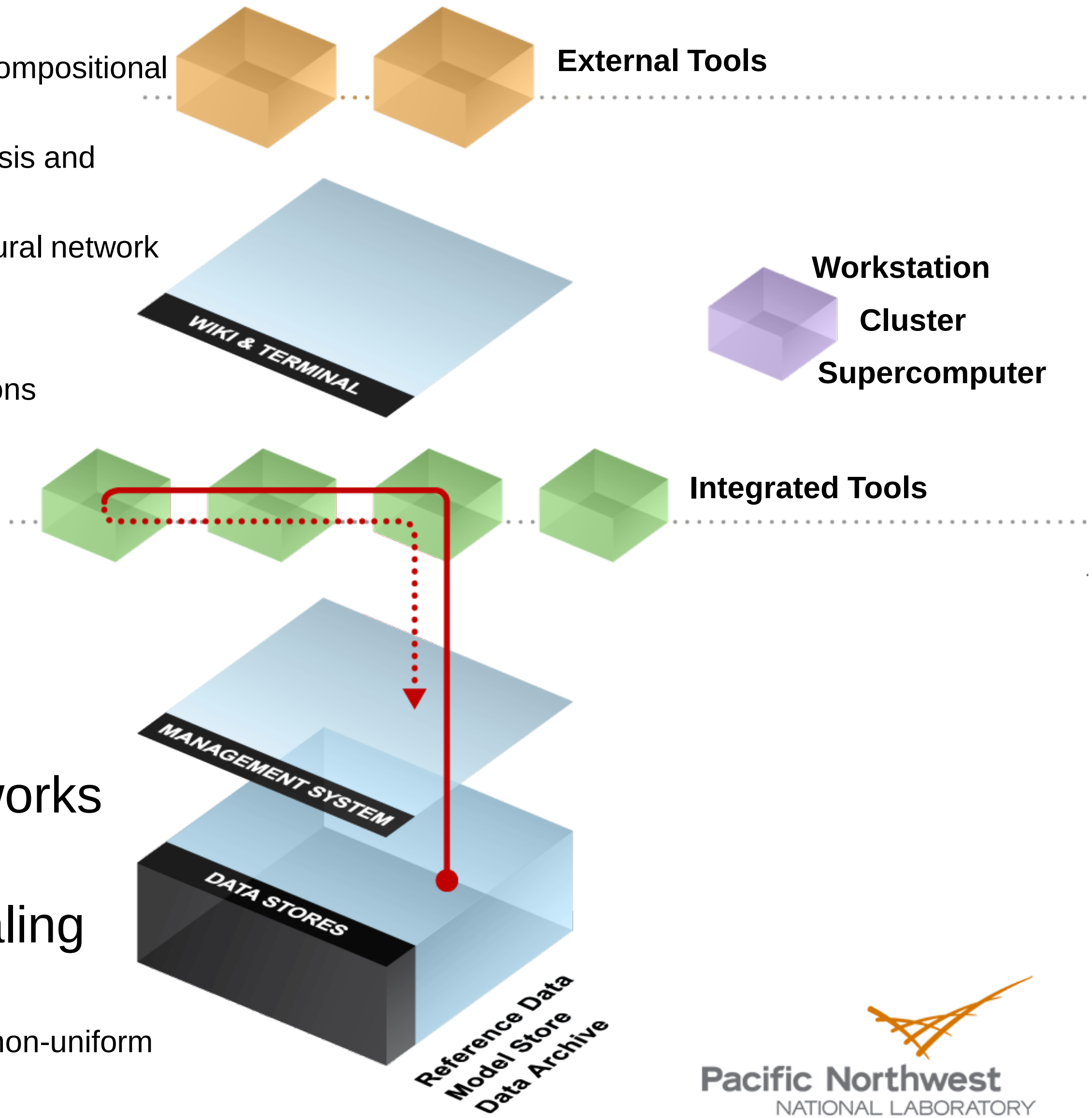
- variography
- sequential Gaussian and indicator simulation
- multipoint geostatistics
- transition probability geostatistics
- 3-d visualization

Geochemical Reaction Networks

- geochemical reaction network generation

Parameterization and Upscaling

- reaction rate upscaling
- 3-d property distribution upscaling -- uniform to non-uniform grids



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Conceptual Model Development numerical model tools

Multi-scale Numerical Models

• common solid-earth conceptual models

• injectivity simulations & reservoir performance assessments

• coarse & fine spatial discretizations – boundary conditions, sources, geochemistry, geomechanics

Multi-simulator Numerical Models

• national laboratory developed simulators – FEHM, PFLOTRAN, TOUGH, STOMP

• simulator independent & specific components

• data requirements – alerts, tracking

Flexibility

• revise numerical model specification during the development process – grid modifications

• regenerate numerical models in response to revisions in conceptual model – new or changed data

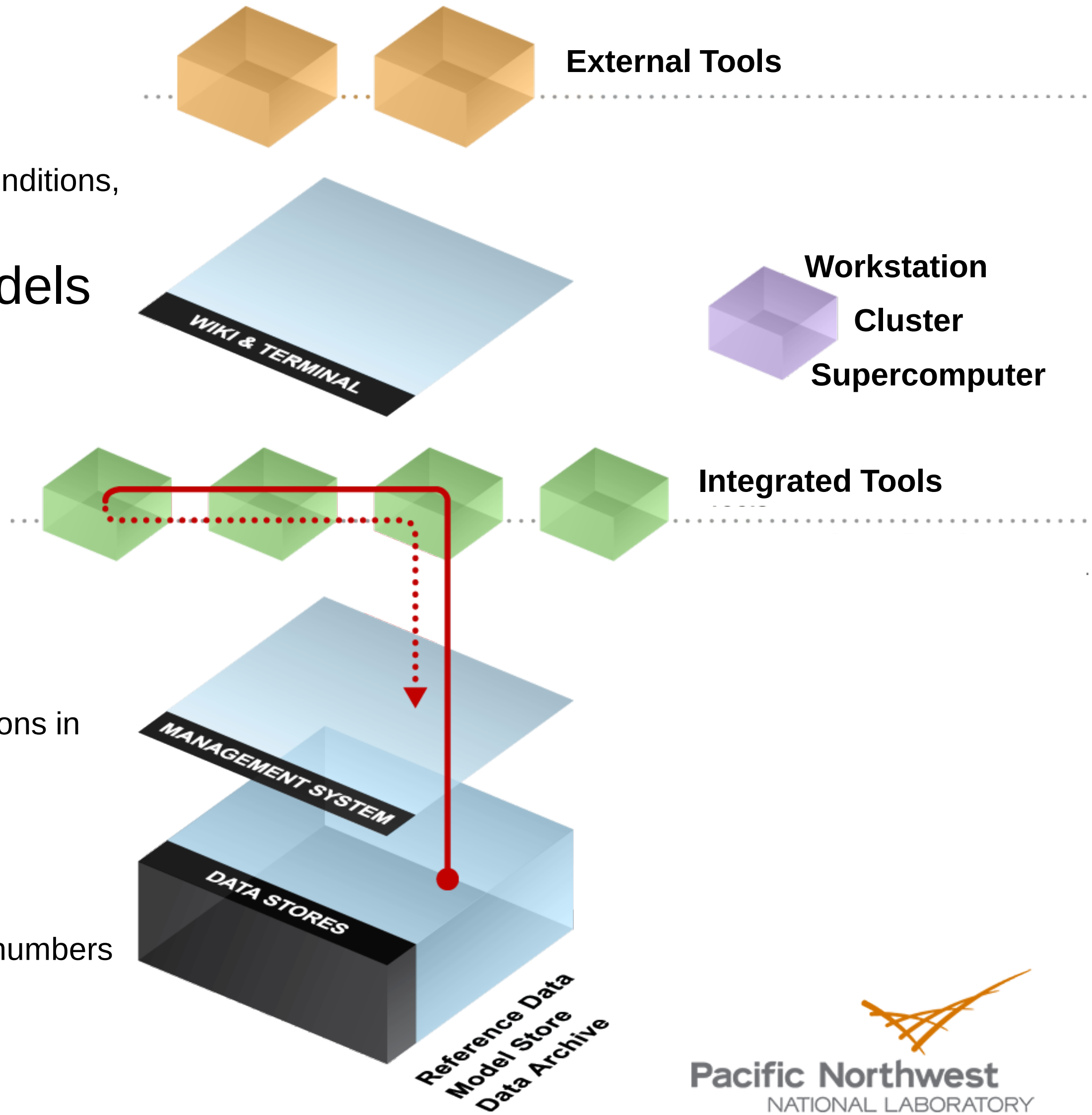
• Approach

• object driven – points, lines, polygons, geobodies

• minimize or eliminate storage of node or element numbers

• tools for objects – data types

• translation to grid -- nodes, surfaces, elements



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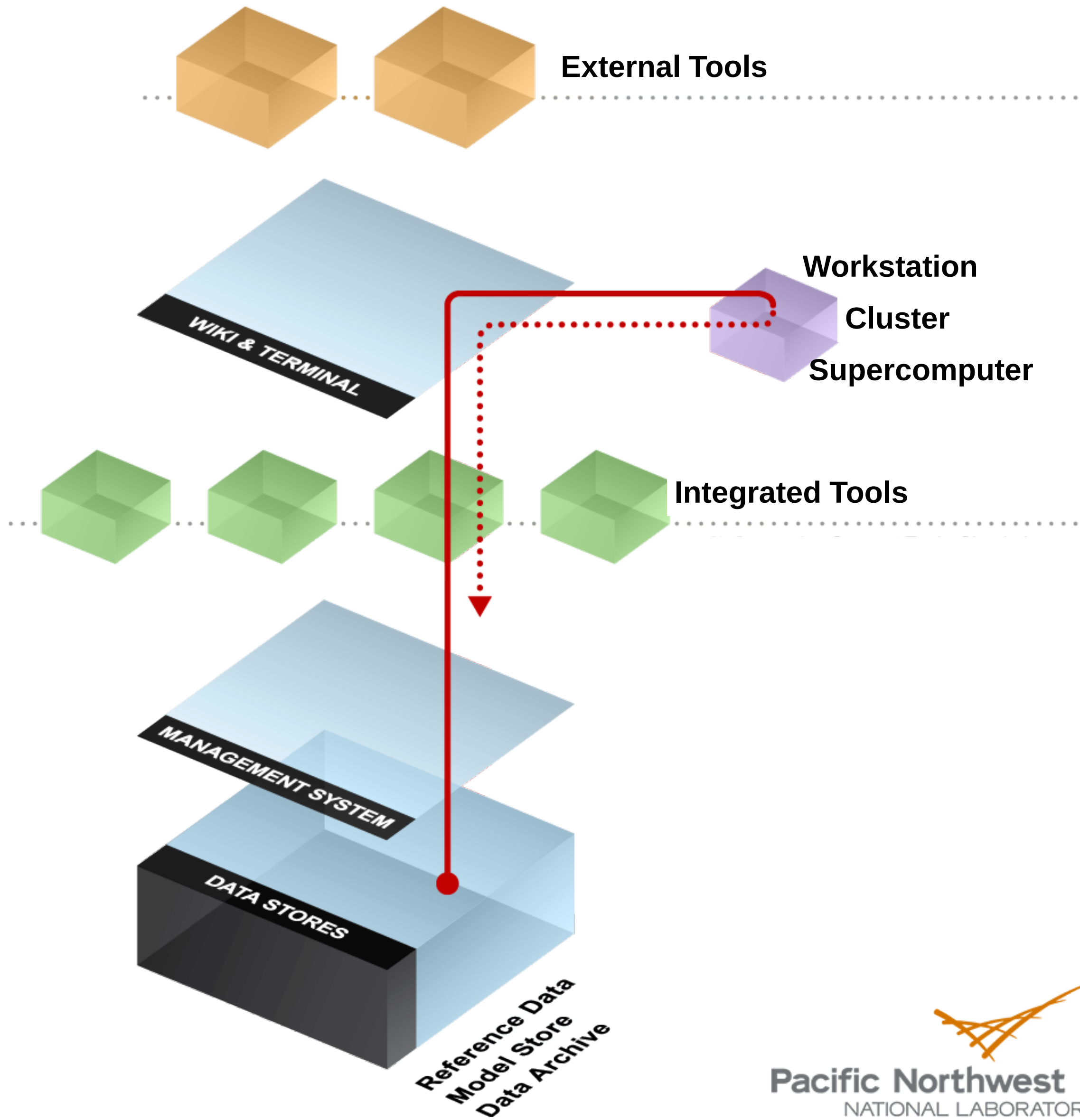
Simulation Execution job launching and monitoring

Registry of Computers

- simulator build – executable & libraries
- submission protocols
- job monitoring – crashes & fault recognition



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