1st CO_2 GEOLOGICAL STORAGE MODELLING NETWORK MEETING

Report No. 2009/05

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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

The IEA Greenhouse Gas R&D Programme supports and operates a number of international research networks and workshops. This report presents the results of a workshop held by in conjunction with BRGM, Schlumberger and CO_2GeoNet. The report was prepared by the IEA Greenhouse Gas R&D Programme as a record of the events of that workshop. The organisers acknowledge the additional financial support provided by Total and IFP for this meeting and the hospitality provided by the hosts BRGM.

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

Neil Wildgust, IEA GHG (Chair), UK
Isabelle Czernichowski BRGM & CO_2GeoNet, France
Gabriel Marquette, Schlumberger, France
Toby Aiken, IEA GHG, UK
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Tess Dance, CO2CRC, Australia
Stefan Bachu, Alberta Research Council, Canada
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The report should be cited in literature as follows:

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Summary Report of 1st IEA GHG

CO_2 Geological Storage

Modelling Network Meeting

Date: 10 – 12 February 2009
BRGM,
Orleans, France.

Organised by IEA GHG, BRGM, Schlumberger, & CO_2GeoNet
with the support of Total and IFP

Executive Summary

The concept of this workshop was previously proposed to the IEA Greenhouse Gas R&D Programme (IEA GHG) by BRGM and Schlumberger, and following the approval of the workshop in principle, discussion was initiated in June 2008 at the IEA GHG Joint Network Meeting in New York. The suggestion was that CO_2 geological modelling for Carbon Dioxide Capture and Storage (CCS) was an important topic not being adequately dealt with by the existing storage based research networks. Further discussions by these network groups concluded that this was indeed a gap, and that an initial workshop should be held to determine the viability of forming a separate network dealing solely with geological storage modelling.

As the originators of the concept, BRGM and Schlumberger offered to host the workshop in Orleans, France. A steering committee was established, partly drawing from the existing storage network membership and an agenda was formulated. The workshop was held from the 10^{th} to 12^{th} of February, 2009 and attracted over 100 delegates from 14 countries, most of whom actively participated in the discussion and breakout sessions.

The workshop included invited presentations on key aspects of modelling, as well as breakout group discussions on certain issues followed by plenary feedback. The presentations and breakout groups followed 4 main themes over the course of 3 days; assessment objectives for modelling, processes, special issues, and the aims and objectives for the potential modelling network. The workshop concentrated on storage in deep saline aquifer formations. The use of breakout groups was necessary in order to give all delegates the chance to contribute, and when the breakout groups were set tasks it was noted that although some groups took different paths in approaching problems, the outcomes and conclusions were all of a very similar nature and demonstrated a clear path forward, with a unified outlook.

The session on the assessment objectives for modelling included presentations on storage capacity, injectivity, caprock integrity, and leakage through wellbores and faults. The subsequent breakout and plenary discussions debated how well current modelling can assess reservoir and caprock behaviour during injection, and if current modelling of leakage processes is adequate. These discussions emphasised that despite the availability of various modelling packages, considerable development work remains before modelling will be able to adequately describe storage projects and inform regulators. There is a significant divergence in current approaches to modelling and a need for increased sharing of information, and some discussions highlighted the advantages that further benchmarking of models could bring, together with greater consistency of approaches and methodologies.

The session on processes included presentations on static geological models, multiphase flow modelling, geochemistry and reactive transport, geomechanics, and heat transfer. The discussion sessions then focussed on listing the key processes and parameters required to model storage, and identifying the most significant knowledge gaps. Delegates identified a variety of issues and parameters that could be considered as ‘knowledge gaps’ for many of the processes that need to be incorporated into models. Some common themes became evident in the discussions including: problems of coupling processes into models (e.g. geochemical and geomechanical factors for caprock integrity); up-scaling of properties and processes from pore to field scale; modelling representation of the heterogeneity in geological systems; and model input data – quality and availability.

The discussions also highlighted many examples of more specific technical issues where further knowledge is required to improve modelling. Frequently highlighted examples included relative permeability curves, geochemical reactions and associated kinetics, fault properties and potential reactivation, understanding and measurement of stress fields, and the deformation characteristics and compressibility of storage formations.

The session on special issues considered code and model comparisons, numerical tool improvements, and the relationships between modelling and monitoring/risk assessment. The discussion sessions asked how modelling can inform monitoring programmes, feed into the wider risk assessment process, and also debated the degree of confidence that could be placed in current modelling predictions. Discussions highlighted the iterative nature of the assessment process, whereby modelling is used to design monitoring programmes but subsequent monitoring results can be used to calibrate and improve models. An important aspect of the relationship between modelling and monitoring identified is the potential duration of post-injection monitoring requirements and the principle that agreement of monitoring results with predicted, stabilised CO_2 distribution from modelling could be the justification for monitoring to decrease or end.

One view strongly expressed on the question of confidence in current modelling, was that current modelling efforts are often hampered more by limitations in available input data/parameters than understanding of the relevant processes. This situation should improve over the coming few years as more large scale demonstration and possibly commercial storage schemes come into operation, providing field data for calibration of processes and models. Discussions also highlighted the role of modelling – to provide storage performance assessment – as an essential element in the risk assessment process. Also noted was the point that free phase CO_2 provides much greater potential for leakage and associated risks, than dissolved phase. Assessment of the probability and magnitude of potential leakage is a key developing area where modelling can feed into the risk assessment process.

The outcome of the workshop was agreement on the need to form a full research network, and this workshop was therefore classed as the first meeting of this network, with expressions of interest in hosting the second meeting in 2010 being received from the University of Utah in the USA. The workshop identified development of a web-based discussion forum, where problems can be shared, discussed, debated and solved between peer users, as an important 'next step' for the network. Another key element recognised was the implementation of knowledge sharing across networks, and although this has been actioned by the initiation of the joint network meetings, it was felt that feedback to networks on activities and meeting outcomes was necessary at more frequent intervals.

It was also noted that the network should not focus too heavily on code comparison exercises, nor should it become a promotion platform for particular software solutions for modelling.

Contents

Session 1: Introduction

1.1 Welcome and Introduction, Christian Fouillac, BRGM & CO_2GeoNet.

The workshop was opened by Christian Fouillac, the Research Director for BRGM and Chairman of CO_2GeoNet's General Assembly. He extended thanks to the delegates, sponsors and organisers of the workshop for sharing their knowledge of the modelling work currently undertaken around the world.

He explained that modelling has an important role to play in the widespread deployment of carbon dioxide capture and storage (CCS) technologies, and CCS is likely to be a necessary tool in order to control atmospheric levels of CO_2. Being able to model the behaviour of CO_2 in the subsurface will likely prove to be vital in providing confidence in the whole chain of storage, from capture, through transportation, to the injection process. It will also play a key role in both allowing formulation of risk strategies, and minimising the risks involved with the storage process.

The CCS and modelling communities must improve the interactions between the various groups working on the subject around the world, and this is the base purpose of this workshop. BRGM has been involved in many projects around the world, including various roles in CCS research projects in many countries.

1.2 Welcome and Outline Agenda, Neil Wildgust, IEA GHG.

Neil Wildgust also welcomed the delegates on behalf of IEA GHG, and hoped that the workshop would be beneficial, and include meaningful discussions. He expressed thanks to the organising committee, and the level of work and commitment willingly provided. Special thanks were given to Karsten Pruess, who was heavily involved in the run up to the workshop, but unable to attend due to illness.

Neil followed with an introduction to the IEA Greenhouse Gas R&D Programme (IEA GHG), explaining the background of the programme, its activities and involvement in the CCS field and explained the funding structure of the programme.

The background and origination of the workshop was explained, touching briefly on the three existing storage based networks, covering wellbore integrity, monitoring and risk assessment. In 2008 IEA GHG brought together the three networks to hold a joint network meeting, looking to address any gaps that exist between the networks' activities, and identify opportunities for the networks to contribute to each other. BRGM and Schlumberger presented a proposal for the formation of a network covering geological storage modelling, and this was instrumental in the organisation of this first workshop.

The agenda was presented, and the topics to be covered over the three day workshop were listed as:

- Assessment objectives,
- Processes,
- Special issues,
- Objectives for a modelling network.

A copy of the agenda can be found in Appendix 2.

The format of the workshop included short presentations, with the opportunity for a few open questions, although wherever possible, questions were saved for the open discussions and breakout groups in order to maintain the flow and schedule of the workshop. Plenary discussion sessions followed each breakout group session.

1.3 Modelling Overview for CO_2 Storage, Isabelle Czernichowski, BRGM & CO_2GeoNet.

This presentation was aimed to explain why modelling is key for CO_2 storage implementation, at stressing that additional efforts are needed to achieve more confidence in modelling results, and that a joint international effort through an IEA GHG network would be highly relevant. A brief summary of BRGM and CO_2GeoNet activities was given as an introduction, with specific focus on modelling activities. CO_2GeoNet, which covers expertise in all areas of CO_2 geological storage, can therefore provide guidance on all aspects, including modelling.

Modelling is widely recognised as playing a key role for the implementation of storage, and it will be necessary to have the ability to assess geological frameworks, with regard to capacity, injectivity, integrity, risks and impacts. Models are needed to provide input and advice to monitoring regimes and schedules, and in turn monitoring results should facilitate refinement of models and generate better understanding of process interactions.

Operators of storage projects must be able to perform dynamic modelling where storage is ongoing or where it is about to start. Static modelling will not provide the level of practical information needed, whereas dynamic modelling allows integration of the associated systems for the entire project.

Modelling is also important in the development of frameworks for legislation; indeed, it is included in the EC Directive on CO_2 Storage of December 2008, in which Annex 1 describes the modelling requirements. Modelling will necessarily involve the collection of data, and the subsequent building of 3D static geological earth modelling. Following from this, will be the characterisation of dynamic behaviour, sensitivity characterisation and risk assessment processes.

The integration of monitoring and modelling allow verification of assumptions made, and Annex 2 of the EC Directive states that the interpretation of these results may lead to recalibration of the model in order to explain the behaviour, and the monitoring programme may be adjusted according to the needs expressed by the new model.

The Risk Assessment Network has asked the question: how confident are we in modelling results? Modelling is a very complex process, with complexities spanning elements such as timescales, spatial scales, geological variation, processes, uncertainties, sensitivities and site specificity. Confidence is therefore an ever-evolving factor, and only through modelling can operators address the necessary issues in order to enable accurate predictions of the behaviour of injected CO_2 at all projects' phases. However it is stressed that model calibration and benchmarking with real field and lab data is a necessity.

In 2002, Lawrence Berkeley National Laboratory (LBNL) held a workshop addressing code comparisons, with the task of comparing different numerical simulation codes for CO_2 storage applications through a set of exercises. A similar workshop was held in 2008 by the University of Stuttgart in Germany. Both workshops were able to come to some agreements, but discrepancies still exist between different codes and modelling approaches. These will need to be addressed in order to progress to commercialisation of CCS projects.

The need for the formation of a modelling network was expressed by all three of the existing storage networks at the Joint Network Meeting in June 2008. The following lists show the modelling needs as expressed by each network:

Wellbore integrity:

- Numerical models of wellbore geochemistry and geomechanics need additional development for providing long-term predictions,
- Numerical models incorporating realistic permeability distributions for wells are needed to evaluate the leakage potential of fields with multiple wells,
- Integrated geomechanical and geochemical experiments / numerical models are needed to capture full range of wellbore behaviour,
- Long-term numerical modelling grounded in enhanced field and experimental data.

Monitoring:

- Recognises the importance of modelling in the various phases of CO_2 storage (site investigation, drilling & well testing, storage operation, site closure)
- The monitoring measurements should be history matched against the predictive flow modelling,
- The main gap is a lack of a “matrix” presenting the common interests among the three networks and the perspective that they are dealt with within each individual network. The objective should be to converge to a common outcome. For example, when a CO_2 risk pathway is identified, are the simulation tools able to calculate it? Which output do they provide? How can this output then be translated into probability of occurrence or severity of consequences?

Risk Assessment:

- How confident are we in modelling results?
- Need for modelling physical / chemical / mechanical phenomena in a way that can be useful for risk assessment.

One comment summarised the general consensus of the 3 storage networks, and this was:

"Yes, I believe there would be a lot of benefit from a modelling network. Significant components of the practice of CO_2 injection and geologic storage can be described only by modelling (e.g. estimated injectivity, injection field design and injection rates, total storage capacity, plume fate and tracking, etc.). Modelling of these technical components will be important in preparing carbon storage permits, and convincing regulators and the public of storage safety and viability. Therefore, a modelling network would contribute to more directly integrating modelling developments with developments in wellbore integrity, monitoring, and risk assessment, and would also promote accurate, dependable, and practical modelling as applied to permitting and monitoring CO_2 geological storage".

1.4 Regulatory Perspectives, Neil Wildgust, IEA GHG.

This presentation was tasked to cover the following 4 regulatory perspectives:

- IPCC GHG Inventory Guidelines,
- London & OSPAR Marine Treaties,
- EU CCS Directive, and
- US EPA Draft Ruling.

The IPCC guidelines demonstrate the methodology of an iterative process, showing the monitoring results with a continual feedback loop to the modelling aspects of the process. The guidelines support the assumption of zero leakage, which emphasises the importance of good site selection and characterisation.

A main highlight of the IPCC Guidelines is the principle of post injection monitoring and its inherent links to modelling, based on the principle that once results from a monitoring programme demonstrate the predicted stabilisation assessment from modelling, then requirements for subsequent monitoring could be dropped or greatly reduced.

The London Convention and Protocol[1] forms a global marine treaty, regulating the disposal of wastes and other matter at sea. CCS activities in geological formations under the seabed are now permitted under amendments to the regulations. OSPAR is a regional treaty, and again has been amended to include guidelines for subsea storage, while highlighting that water column storage is prohibited.

The EU CCS Directive highlights the entire CCS chain, and does not just address the storage element. It is a very prescriptive piece of legislation, and as expected site characterisation and

[1] The London Convention was formed in 1972 and involved 85 countries, and the London Protocol superseded the Convention in 1996, although it was not ratified until 2006 by 35 countries.

selection are highlighted as of great importance. The directive clearly states that the objective is ‘permanent storage’, and that a storage permit will only be granted if there is no significant risk of leakage.

The US EPA draft rule proposes regulation of injection wells where the intention is CO_2 geological storage. The public consultation period closed on the 24th of December 2008, and the final rule will be published late in 2010 or early in 2011.

It can be concluded that the modelling of geological formations and the behaviour of CO_2 injected into them is central to the regulation of geological storage, and to the ability of regulators to make assessments and decisions on the granting of permits.

Session 2: Assessment Objectives

2.1 Storage Capacity, Bert van der Meer, TNO & CO_2GeoNet

Storage capacity and modelling have a clear relationship; modelling of various processes allows estimates to be made of the storage capacity provided by trapping mechanisms. Estimates have varied widely over the years, with variations and total capacity estimates reducing as models become more complex and take more elements into account.

These discrepancies between modelled storage estimates necessitated the development of a conceptual model, depicting both affected and unaffected space. This concept allows for the injected CO_2 to 'push' formation water into the surrounding area, resulting in an increase in formation pressure. The conceptual model as influenced by the geological factors is shown in figure 1.

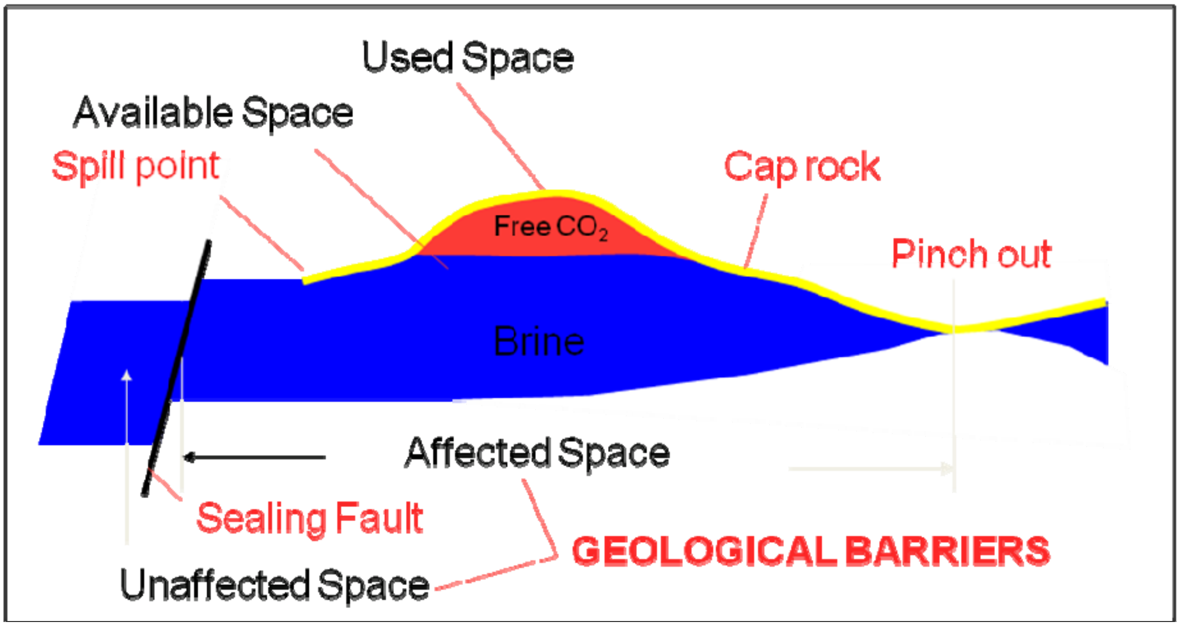


Figure 1: Adapted conceptual model showing geological barriers and factors influencing the extent of the affected space.

As a result of various assessments and reports, 4 controlling factors can be identified for determining the volume of CO_2 that can be stored in a given reservoir:

- Storage capacity; volume and average pressure,
- Potential injectivity; permeability and local pressure,
- Storage efficiency; available and used space,
- Data availability and quality.

2.2 Injectivity, Yann le Gallo, Geogreen

Site selection for geological storage will look at capacity, injectivity, confinement or trapping mechanisms and potential secondary benefits such as EOR[2] opportunities. It is therefore clear that injectivity plays a vital role in the site selection process. Injectivity will drive the number of wells required and possible rate of injection.

Through the knowledge gained from oil and gas exploration, there are several tools available which allow estimation and measurement of injectivity, and also enable prediction of flow behaviours. These tools can be used for the purposes of CO_2 injection modelling as well. However, detailed modelling approaches of the near wellbore region, in order to estimate Injectivity Index, should account for the CO_2 interactions with the reservoir/caprock and their fluids, which may induce different behaviour with respect to:

- Pressure because of dissolution, viscosity/density changes,
- Saturation because of drying out,
- Structure changes because of geochemical interactions

The next steps in order to further our knowledge and understanding can be categorised as requirements for researchers and requirements for industry. Researchers need to develop more of an understanding of coupling effects, the interactions between processes and the petro-physical and textural changes that occur, while switching the focus more from geochemical to geomechanical processes.

Industry must apply models to complex situations, including injection into complex structures and the use of non-vertical well trajectories. Tuning of models therefore appears unavoidable, with field data being integrated into models to fine-tune as necessary for specific CO_2 impacts.

2.3 Plume Evolution and Trapping Phases, Sylvain Thibeau, Total

Although many factors may play the role of primary limiting constraint, we must understand the possibility of plume migration limiting the injection. We must define the initial conditions, and look at developments in saturation, pressure and temperature.

Initial conditions will be defined by salinity, temperature, pressure (intrinsically linked to temperature) and hydro-dynamism. These can all be determined rapidly by sampling/monitoring, with the exception of hydro-dynamism, and this is more of a long term aspect.

The process of drilling can change the temperature at the wellbore, so the initial temperature can be hard to determine. Initial system conditions can be unstable with denser (heavier) formation water on top of less dense (lighter) water.

[2] Enhanced Oil Recovery

This is an unstable position, and will revert to a more stable set of conditions, so how is it possible? Thermal expansion of water is greater than its compressibility, so the temperature gradient can lead to this instability. There are 4 possible explanations of how this situation occurs;

1. There is a lower temperature gradient within the aquifer than in surrounding rocks,
2. The salinity gradient will compensate the temperature gradient,
3. Formation water flow, convective cells and hydro-dynamism,
4. Aquifers may be temperature anomalies (spa) due to hydro-dynamism.

Pressure modelling of aquifer storage is a key issue, as pressure should be kept below defined maximum values and the caprock fracturation pressure. Pressure development in flow models is strongly affected by the simulation domain and its boundary conditions. Care should be taken when defining them, in order not to underestimate pressure increases within the aquifer.

2.4 Caprock Integrity, Brian McPherson, University of Utah.

There are both geomechanical and geochemical processes that can act to degrade caprock integrity, and coupling these processes is a complex procedure. The primary assessment objectives in this area are resolving the uncertainties associated with both the geomechanical and geochemical processes, resolving the competing timescales of the processes, and resolving the special-scaling limitations of the processes.

Reactions with minerals are also key to the processes involved with caprock degradation, and these occur over varying timescales. Some are slow, and will dominate over the long term, whereas the faster reactions will dominate over the short term. Porosity changes due to these reactions are likely to be restricted to the lower few metres of the caprock, highlighting the importance of thicker caprocks wherever possible.

Various geomechanical processes can degrade the caprock integrity, but primarily these can be classified as reactivation of faults, or inducement of fractures. The different types of faults and associated issues that they each cause are covered in the main presentation, but it can be summarised that they will either create or reduce permeability, leading to a resulting strain that is difficult to predict.

Questions / Discussions on 2.1 to 2.4

On opening the questions session, the initial point for discussion was that complexly created models may be too time-consuming for regulators; the application of models will need clarity, efficiency and speed of calculation. Permitting may be required to be a quick process, and complex models may take too much time to be relevant.

Comments in response to, and arising from this were as follows:

- Regulators will ask how much overpressure can be allowed, so how can modellers be ready for this and what should they say?
- Regulators will always go for the lowest value possible, so they may not have time to apply sophisticated models to situations.
- How do you calculate fracture pressure when thermal fracture can see temperature changes of up to ten's of degrees?
- Regulators will insist on determination of the pressure or not allow injection. This is an uncertainty that needs more work.
- With regard to how complex can modelling be acceptable – maybe we are not at a point where we can go to full scale CCS modelling, and must try to understand as much complexity as we can, and then take it to a simpler level for full scale deployment. The same can be said for monitoring; field tests now probably use more monitoring techniques than will eventually be used.
- There is an analogy here with hydrogeology; in the 1960's, models were varied, but became more consistent, so that all parties could use them. Accepted models will be more in line with regulators desires; if there are no questions over the technical model, then there are more likely to be approved projects.
- The impact space is likely to be larger than the permitted area, what happens if an adjoining structure has faults or fractures that will be affected – how large will the permitted area need to be to allow for this scale of effect?
- Neil Wildgust's presentation covered the area of scale, and migration has been focussed on in the past. But pressure can move faster and beyond the CO_2 migration plume, so there must be more focussed research on this topic in the future. However if pressure effects decay logarithmically, where is the boundary where effects can be categorically stated as having ceased? The limit of this effect will need to be established.
- We need to demonstrate a sound knowledge of how the pressure signal develops in both space and time parameters. This could answer the question of the spatial range of effects, and gain confidence of how far we need to look.

2.5 Leakage Through Wellbores, Mike Celia, Princeton University.

Problems with wells and wellbores are well known in the CCS community, and Figure 2 illustrates the density of wellbores from oil and gas exploration and production around the world.

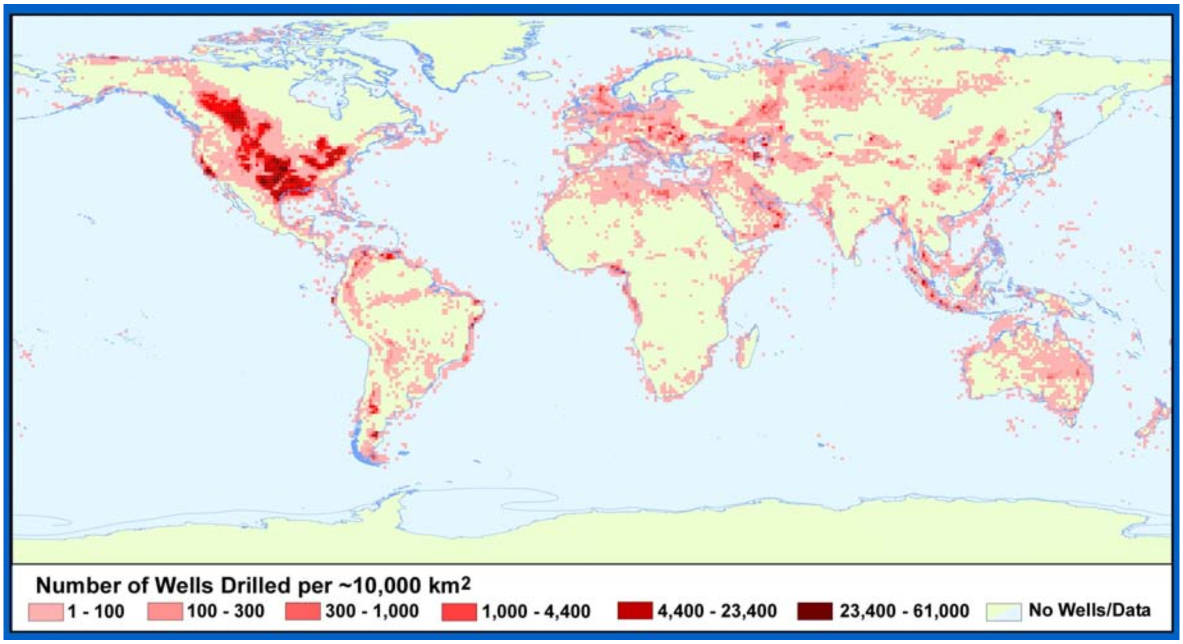


Figure 2: Density of wellbores around the world, with the highest concentrations evident in North America.

It is unavoidable that these wells puncture caprocks, and that many of these caprocks would otherwise be sound. Injected CO_2 can interact with abandoned wellbores and the materials present, leak to overlying layers along the leakage pathway created by the wellbore, and even leak to the surface and the atmosphere.

The abundance of potential leakage pathways through caprocks presents a complexity in itself when it comes to modelling this system. We know that there is a large domain, with leakage pathways, possibly unknown properties of wellbore leakage, and possible degradation of old wellbores which can act to increase any leakage.

One approach to modelling wellbore leakage is the use of analytical modelling techniques. This approach allows models to cater for the extreme scale variability pertaining to storage and wellbore leakage, for example leakage pathways in wellbores may have widths of millimetres, whereas CO_2 plumes may extend laterally for kilometres. Analytical models also facilitate stochastic approaches to modelling, allowing for both uncertainty and natural variability.

2.6 Leakage Through Faults, Andrew Cavanagh, Permedia.

Some predictions of CCS deployment envisage the situation 10 years in the future where we have 500 wells each injecting 1 million tonnes of CO_2 a year. Carried forward, this equates to billions of tonnes of CO_2 in the subsurface by 2050. This highlights the need for accurate modelling of the behaviour of CO_2 once it has been injected into storage reservoirs.

Leakage through faults can be modelled; three types of numerical models can be used to show the processes in and around faults;

- Conceptual/experimental models, looking at a small number of cells,
- Reservoir models , looking at larger areas,
- Reservoir-Basin models, looking at large scales of cells, and large areas.

An example was presented where differing levels of detail on faulting were incorporated into a particular storage scenario. At the extreme of faults being assumed absent, the regional geology model showed the presence of 13 large structural traps and significant storage capacity. At the other end of the scale, inclusion of all mapped faults into the model and conservative assumptions of leaky behaviour implied a complete absence of viable traps.

Questions / Discussions on 2.5, 2.6

Questions were addressed towards the initial conditions; how can operators know what data will be needed, and how sure can the scientific community be of brine conditions before injection commences?

It is difficult to estimate the initial state, and assumptions regarding equilibrium are necessary in order to give this initial state a set of values. There are also problems associated with heterogeneity of the minerals present in the reservoir. The best way to formalise the problem, is to establish an order of reactivities, looking at those that are most reactive first, and then moving on to permeability and other influencing factors. To some extent this will be covered in the presentations of day 2, was recognised as a problem area in need of some methodology in order to be formalised as a best practice.

2.7 Facilitated Plenary Discussion, Results from Breakout Session 1.

The first of the breakout group sessions addressed the following discussion themes:

- Can current coupled models allow adequate modelling of reservoir and caprock behaviour?
- Does current knowledge and uncertainty allow adequate modelling of leakage processes?

Aspects within this theme for more detailed consideration were given as:

- Is there significant divergence in approaches to modelling adopted by different organisations?
- How much confidence can be placed in current approaches and resulting models?
- How modelling technologies can be developed to fulfil likely regulatory requirements?
- What are the current knowledge gaps, and what should be the future focus for research?

The materials presented by each breakout group in the subsequent plenary feedback session are reproduced in appendix 1, with a summary below:

Summary

Discussions in the breakout groups and the subsequent plenary feedback emphasised that despite the availability of various modelling packages, considerable development work remains before modelling will be able to adequately describe storage projects and inform regulators. Gaps in available input data for models was a concern expressed by all the breakout groups, and the debates showed, currently, that there are several modelling topics where increased confidence will require further research and development. Examples include: up-scaling from pore to field scale; coupling of geochemistry and geomechanics for caprock assessment; long term geochemical reactions between injected CO_2 and formation water and minerals; and leakage pathways and rates.

There is a significant divergence in current approaches to modelling and a need for increased sharing of information, and some discussions highlighted the advantages that further benchmarking of models could bring, together with greater consistency of approaches and methodologies.

One ambitious suggestion was that a network could aim to establish a core model, on a modular basis that could be adjusted by all users, without the need to recalculate the initial parameters. An analogue of this concept is weather forecasting; where many agencies use the same basic key elements, but each organisation then extrapolates the data their own way for their own forecast.

Session 3: Processes

3.1 Geological Modelling, Heterogeneities and Scale Relations, Peter Frykman, GEUS and CO_2GeoNet.

Firstly, there are a set of questions that need to be addressed before modelling can begin. Usually, a large site investigation begins with the urgent need for a model. This gives rise to a simple model, and the subsequent stage is a desire to look inside the simple model; to add more information and generate more usefulness. The next stage involves reservoir engineers, and they are asked to add the behavioural properties of CO_2 in the layers shown in the model.

After this stage, the first question to be addressed is what was missed by the model, and this will usually include the spatial area affected; putting the modelled area in the context of the wider geological setting illustrates the effects of pressure outside of the boundaries of the simple model area. Fluvial activity will also extend beyond the modelled area, and scales will need applying to determine the effects of small scale heterogeneities that might not be incorporated in the site scale model.

Further work investigates these limitations, and after addressing the site scale, the regional scale will be looked at. Any pressure effects are sure to pass the boundaries imposed by the site scale model, and the boundary conditions therefore need to be set.

Many experts say modelling is a complex activity, but geo-modelling is comparatively easy. Creating a static model with the tools available is easy, but the potential exists for this model to be totally inaccurate. We should ask for more detailing geological information in the static model in which rules must be established and followed. Static models should then be made available for comparison and testing purposes.

3.2 Multiphase Fluid Flow Modelling, Suzanne Hurter, Schlumberger.

Single fluid flow can be used to look at natural groundwater/formation fluid flow which could have bearing on any storage processes. This can be extended to multiple phases by adding an index for each phase, and replacing absolute with relative permeability, however interactions between fluids can impact on the calculations and different pressures between fluids leads to capillary pressure and flow.

The presentation went on to address the processes; looking at the areal footprint of injected CO_2, and there are many published examples of imagery showing plume development over time, and this can be used to attempt to history match plume geometry. Residual trapping leads on from this, and more recently, the plume extent and impact is receiving more attention as this is an important factor for monitoring and verification purposes. Brine migration/displacement should also be considered at this juncture, as this could have subsequent affects outside the system. Images in Figure 3 show the effects of hysteresis, that its inclusion in models generates more realistic CO_2 caps, as opposed to modelling without hysteresis which results in spikes of concentrated CO_2.

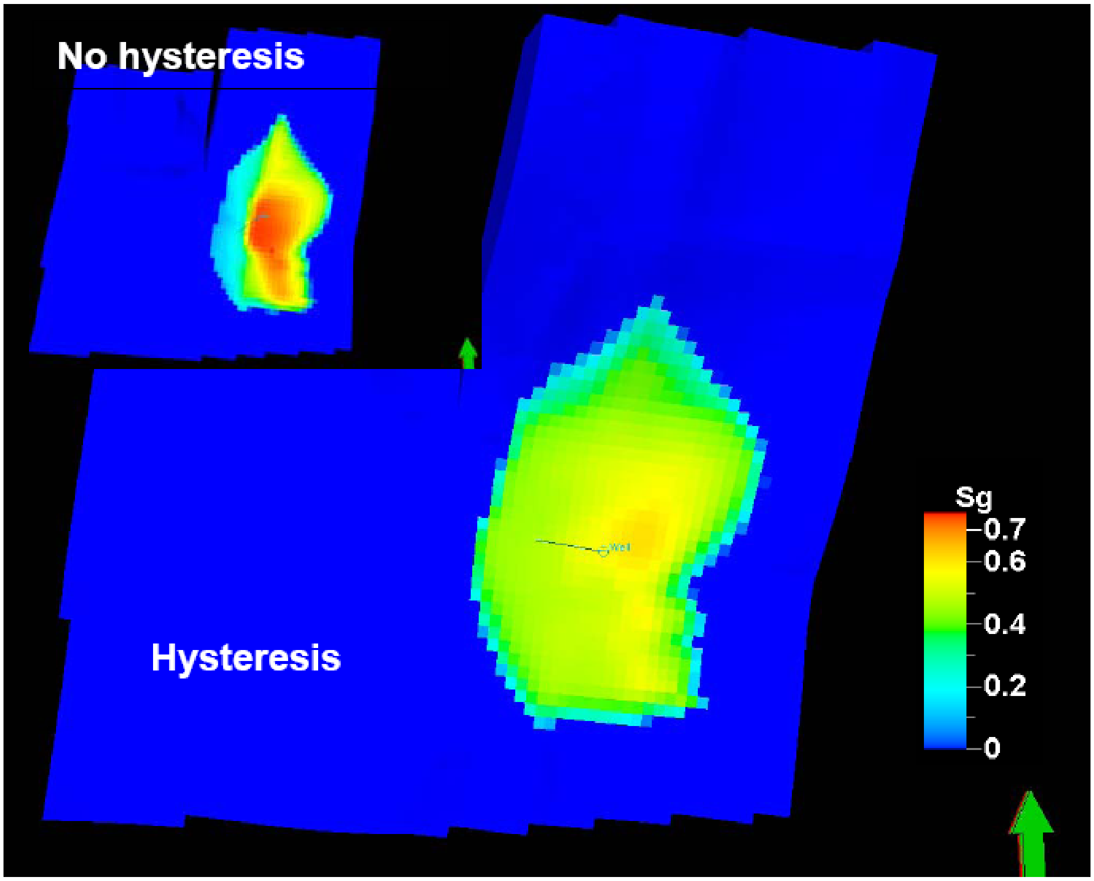


Figure 3: Showing effect of hysteresis in models.

The following list illustrates the elements that should be considered as part of a modelling process.

- The presence of more than 2 fluids,
- Tool and monitoring response develop models,
- Analytical solutions, streamlining models,
- Effects of convection, mixing and stirring,
- Scaling and gridding issues; pore, reservoir and regional,
- The impacts associated with porous versus fractured media,
- Coupling effects with other physical and chemical processes,
- Long term knowledge advancements through operational management.

3.3 Geochemistry and Reactive Transport Modelling, Mohamed Azaroual, BRGM and CO_2GeoNet.

Referring to a slide presented earlier in the workshop, mineral transformations and reactions around a wellbore were explained, and the relationship between these reactions and pore volume was discussed. Differences in the physical properties of various zones were expressed, such that zone 5 (closest to wellbore) contains 100% supercritical CO_2, with maximum heat transfer, whereas zone 1 (furthest from wellbore) contains 100% initial aqueous reservoir fluid with predominantly initial reservoir conditions evident.

The thermodynamics of a complex system such as this arise from disturbance of the gasses, brines, the mineral solubility and the reactions between them when the balance is changed. Capillary pressures can generate a negative internal pressure of water, and some theoretical approaches can be linked to this.

The discrepancies highlighted by the modelled effects of wellbore degradation and field results show the need for more research in this area, and it is expected that coupled geomechanical and geochemical models could go some way towards addressing this gap.

3.4 Geomechanical Modelling, Jonny Rutqvist, LBNL.

This presentation looked at the geomechanical processes incorporated into modelling, and then the calculations of maximum sustainable injection pressures. This included reference to In Salah, where initial injection pressures have been maintained. The geomechanical processes generally included in models are: fault slipping, shear parting, well deviations, hydraulic fracturing and expansion of the aquifer rock.

In order to avoid these processes occurring and threatening the security of storage, there is a need to estimate the maximum sustainable injection pressure. To do this, examples of oil and gas reservoirs where natural over-pressurisation is present and has been sustained have been studied.

In the In Salah project, nearly 1 million tonnes of CO_2 per annum have been injected over a four year period though a series of 3 wells. The bottom hole pressure is limited to below the fracturing gradient, which leads to a maximum pressure increase of approximately 100 bar over the ambient initial formation pressure. This results in a maximum bottom hole injection pressure of about 60% over the initial pressure.

Evolution of stresses and rock deformations has caused small-scale vertical ground displacements which have been measured by satellite of up to 5mm per year, amounting to about 1.5 cm over the first 3 years of injection. This has the potential to increase stresses on the caprock and create induced seismicity. The simulated case also shows uplift as well as the satellite monitored deformations. The calculations of these effects indicate the lowest part of the caprock to be not totally impermeable, giving rise to a additional uplift, but beneficially the permeability area of the lowest part of the caprock is now considered as a secondary storage area.

3.5 Modelling Heat Transfer, Jens Birkholzer, LBNL

The process of heat transfer can be caused by: injection at different temperatures, wellbore heat transfer, water evaporation in the CO_2 stream, evaporative cooling, and many other factors. This illustrates the complexities encountered when attempting to model heat transfer scenarios in CO_2 storage.

Imaging techniques can demonstrate the low temperature profile that forms at the top of the 3-phase zone, and this profile cooling zone is why the CO_2 doesn't just accelerate upwards. Image modelling of $1/8^{th}$ of a 5 spot injection set-up shows the temperature cooling effects around the injection well in both CO_2 and the water around the well after 25 years.

There are many sensitivities when addressing temperature effects of CO_2 injection; CO_2 density is affected by changes in temperature and this could have subsequent effects on the pressure profile at injection wells and density and viscosity may be strongly affected by non-isothermal injection patterns among other effects, however there are very few published studies that address these thermal effects, highlighting an area for future research.

Questions / Discussions on 3.1 - 3.5

Questions over In Salah data were raised regarding the history matching process and if it was possible that CO_2 had moved to higher strata. The question was answered by explaining the details of the sandstones; uplift seems reasonable and a layer on top of the reservoir is known to be fractured with a slightly higher permeability. If this layer was pressurised, there would be substantially greater uplift evident, hence the figures can be confidently agreed.

Another question suggested that although the geomechanical aspects discussed looked good, there are inherent inaccuracies, and these would need addressing in order for validation to allow regulators to issue a storage permit. Although there were no definitive answers or responses to this comment, it was accepted that improvements must be made, and that this supports the formation of an IEA GHG network addressing modelling.

If water promotes crystallisation of minerals, pore volume will decrease, and the net volume containing CO_2 will increase; this is likely to create new pathways and more pore space, so what is the risk? This was deemed a good question as this concept is not taken into account in current models. Current methodologies allow balancing of equations wherever possible, but the reservoir quality must be specified in advance. New path creation leads to new processes to be encountered; it is accepted that the models do not correctly allow for this at the moment, but are open to improvement. Heat extraction is also important in this situation, and this is also required to be included in further model development.

Another problem we will encounter is using saline aquifers as targets; as the least characterised geological formation when compared with oil and gas fields, we will be faced with distributions, but without as much backup. How can this be addressed?

The same answer applies; there is a need for further development, and researchers need to come up with guidelines and best practice as to what needs covering as a minimum, and how do we explain any uncertainty and probabilities when looking for public acceptance; we need to determine how to make uncertainty acceptable to regulators.

There are several tasks within the modelling community with needs for input from the general public and regulators to understand the associated issues without a technical background.

With reference to small scale heterogeneities, is the information we want to extract from small scale just a way of moving towards larger scale and end point data?

If we use core analysis results, we need to understand the scale at which they are useful; up-scaling is a problem, and although we can be optimistic that we can prove additional storage if we have filled the initial available space perfectly with CO_2, heterogeneity will divert CO_2 and we may actually lose storage space.

Upscale parameters will include end point saturations, and this will be needed, starting from small scale parameters, we will need factors to allow up-scaling from small scale structures to the desired end point.

It was highlighted at this point that the study of geology also includes faults, and when they are encountered, we will have the opportunity to validate the models and highlight problem areas for further development and correction.

A comment on the interesting results of initial 3D stress on injection pressure was to suggest a further analysis with 2D techniques. Is it possible to extract 3D conclusions from 2D analysis and can this be verified with repeated 3D techniques?

The experiments used 2D techniques, but with many wells. 3D stress changes can be extrapolated from this using a plain strain model and a series of injecting wells. This is a simplified method, but it works.

3.6 Facilitated Plenary Discussion, Results from Breakout Session 2.

Wednesday morning saw the second of the breakout group sessions, with the following discussion themes:

- What are the processes and parameters that are critical to modelling requirements?
- What knowledge gaps still exist?

The above questions were considered for base geological models, multiphase flow, geochemistry and reactive transport, geomechanics, and thermics. The materials presented by each breakout group in the subsequent plenary feedback session are reproduced in appendix 1, and are summarised below:

Summary

Unsurprisingly, all of the breakout groups identified a variety of issues and parameters that could be considered as 'knowledge gaps' for many of the processes that need to be incorporated into models. Some common themes became evident in the discussions including: problems of coupling processes into models (e.g. geochemical and geomechanical factors for caprock integrity); up-scaling of properties and processes from pore to field scale; and modelling representation of the heterogeneity in geological systems.

Another general point concerned data quality and availability, and the questions were posed: will we ever have enough data, and will we ever be satisfied? The opinion was expressed that there is an inherent reluctance to spend money on data gathering, which will add an extra financial burden to storage projects that may be regarded as costs in their own right.

The discussions also highlighted many examples of more specific technical issues where further knowledge is required to improve modelling. Frequently highlighted examples included relative permeability curves, geochemical reactions and associated kinetics, fault properties and potential reactivation, understanding and measurement of stress fields, and the deformation characteristics and compressibility of storage formations.

Session 4: Special Issues

4.1 Code Comparison Exercises, Holger Class, Stuttgart University.

The background to this presentation was a code comparison study, tasked with setting problem-oriented benchmarks for numerical models and simulators. The problems defined in the benchmarking study included the issue of CO_2 plume evolution and leakage through an abandoned well; whereby the CO_2 plume encounters a leaky well and migrates to an overlying aquifer; and the problems with estimating storage capacity in a reservoir.

In the simulations used, open faults were present and it was assumed that the scenario boundaries were also open. The model sunk an injection well into the reservoir and injected the equivalent of 0.5Mt per year for 50 years. Values for porosity and permeability were determined and entered into models. An isotherm analysis was then plotted on a graph to show the plume evolution over varying lengths of time.

Conclusions from the various models showed a good general agreement, and also that models were able to account for all relevant processes, with minor quantitative variations. The conclusions also highlighted other issues encountered, including errors that were introduced by gridding, incorrect parameters and oversights, and different interpretations of the problems, which led to variations in the assignment of boundary conditions.

4.2 Model Comparison Exercises, Jens Birkholzer, LBNL.

A new US DOE initiative, Sim-SEQ, is tasked with comparison of models for geological storage of CO_2, and aims to evaluate models against real field data sets to generate confidence in the ability to accurately predict the behaviour of CO_2 in the subsurface. Other goals of this initiative are to evaluate model uncertainty stemming from different conceptual model approaches, to provide a forum for multidisciplinary interactive and cooperative research, and to encourage development of new approaches and improvements in modelling and simulation, if necessary. The focus is on the storage reservoir and the seal mechanism, and looks at both the near and far field environments.

Several large-scale CO_2 storage field tests are currently in the planning stages in the United States, involving geologic storage of one million tons of CO_2, at rates on the order of several hundred-thousand tons of CO_2 per year. With carefully developed monitoring strategies in place, these tests will provide a wealth of data on relevant site performance measures, such as the growth and migration of the CO_2 plume, local and large-scale pressure changes, injectivity, stress evolution, brine migration, and geochemical processes. One of these tests will be selected as reference site for the Sim-SEQ initiative, which one is yet to be determined.

Two examples of planned field tests in the United States were presented: the Decatur site in Illinois and the Farnham Dome site in Utah. Both sites will inject into a saline aquifer so the monitoring feedback should prove very interesting. The Decatur site has approximately 300,000 tonnes of CO_2 emissions per year from a nearby food processing plant. Farnham dome is an interesting concept whereby CO_2 will be produced from a gas reservoir and will be stored in an aquifer below the gas reservoir; it is a highly stacked formation with integral coal beds as well.

4.3 Numerical Tools Improvement, Anthony Michel, IFP and CO_2GeoNet.

A definition of a model can be stated as being *'a representation of a system of interest'*, and that modelling can be a key process in the formulation of problems. Numerical modelling software can then solve these problems. Numerical models should be used when the result is close, and most aspects of this are understood. Many models fit into a generic mesh architecture, with models leading from the physics, numerics, geometry and core components.

CPG grids (corner point geometry) are often used, giving more realistic grids, although these are more difficult to solve and work with. Moving geometry can show the growth of a model from simple to complex.

Conclusions that can be drawn from an assessment of the numerical tools available are that there are many different types of software and many hybrid schemes can be developed through these software choices, and there are improvements in general mesh-based models.

4.4 Modelling and Monitoring, Susan Havorka, University of Texas.

Modelling CO_2 injection is not a novel process, however there are improvements to be made due to unprecedented requirements related to the proving of storage permanence. The novel aspect that is being asked is to input observations from the monitoring programme to validate the predictions of future reservoir behaviour.

Once observations have been made, answers will be needed to confirm if the site is performing, whether the predictions are correct, and other operational necessities. The regulatory authority is likely to be hostile; demanding proof that it is working, which leads to the problem of how to prove that something disadvantageous, will not occur at an undefined point in the future.

EOR has been a mass balance process; balancing fluids in with fluids out, which makes for a relatively simple calculation. Geological storage will be more complex process; how do we select tools to show that it is working? We need to have the ability to demonstrate what the anticipated permutations are; to show what is possible, and where the difference exists.

We need to be able to explain in a justifiable manner that not detecting the plume under location 'X' means that the plume is not under location 'X' – i.e. we need to prove that the absence of evidence proves that it is not there, and not that the monitoring does not work. This ability will include the demonstrable precision of the tools, to show how we can detect and map plumes.

4.5 Modelling and Risk Assessment, Rajesh Pawar, LANL.

Communication is highlighted as an important aspect of CCS and modelling of geological storage operations; it is important that the correct information is communicated in the correct manner. Risk assessment is an area that requires particular care as the word 'Risk' endangers certain preconceptions that the operation being considered is inherently dangerous, even when this is not the case.

To this end, definition of Risk is given as: event probability x event consequence, which should assist in communicating that the identification of a risk does not imply that it will occur.

LANL have applied their CO_2PENS model to the SACROC site, and a particular concern for this site is the risk of wellbore leakage, as the site has been subjected to EOR activities. The reservoir model involved a detailed characterisation, and had been subjected to history matching. The only assumption and simplification was that it was an aquifer; it was subsequently modelled for a 50 year period of injection through 34 injection wells, followed by a 50 year period of rest.

Questions / Discussions on 4.1 - 4.5

A question related to the Sim-Seq sites asked whether the project ongoing in the San Juan basin was considered. Of all the possible sites assessed, the US DOE felt that the 2 chosen sites represented the most suitable field test locations. This was at least partly due to the likelihood that future storage operations are more likely to take place in aquifer formations rather than deep coal seams.

Another question for the same test sites queried how long it was likely to take to obtain permits for injection. The Farnham site is presently going through the permitting process, but not with the new class VI wells; the permit will be granted based on class V research wells.

Questions were also raised regarding where the leakage occurred in the model, and whether it is evident in reality. The answer was that the model was not yet validated, but Susan Havorka's group is looking into this, to see if there are any traceable signatures of CO_2 leakage. The group has spent 2 years taking over 100 water samples, and these have been analysed. No leakage signal has been detected in any of these samples, however this is still not seen as evidence that there is not leakage, only that there has been no detected leakage to date. This is an ongoing process aiming to prove the model correct, but so far there is no evidence of leakage.

4.6 Facilitated Plenary Discussion, Results from Breakout Session 3.

The third of the breakout group sessions addressed the following discussion themes:

- How can modelling be used to optimise monitoring strategies and inform risk assessments?
- How confident are we with model predictions?

Regulatory aspects are an important aspect here, and a discussion of the relationship between risk assessment and modelling, especially in the context of risk management frameworks.
The materials presented by each breakout group in the subsequent plenary feedback session are reproduced in appendix 1, and again there is a summary of the session below:

Summary

Beginning with the principle of understanding the purpose of monitoring as having to satisfy regulatory requirements and verify the performance of the storage reservoir, modelling has the ability to assist in the design and decision making processes involved in defining monitoring schedules. The monitoring data then helps to revise and refine the models, making the feedback process inherent to the operation. An important aspect of the relationship between modelling and monitoring is the potential duration of post-injection monitoring requirements and the principle that agreement of monitoring results with predicted, stabilised CO_2 distribution from modelling could be the justification for monitoring to decrease or end.

One view strongly expressed on the question of confidence in current modelling, was that current modelling efforts are often hampered more by limitations in available input data/parameters than understanding of the relevant processes. This situation should improve over the coming few years as more large scale demonstration and possibly commercial storage schemes come into operation, providing data for calibration of processes and models.

Discussions also highlighted the role of modelling – to provide storage performance assessment – as an essential element in the risk assessment process. Also noted was the point that free phase CO_2 provides much greater potential for leakage and associated risks. Assessment of the probability and magnitude of potential leakage is a key area where modelling can feed into the risk assessment process.

Session 5: Aims & Objectives for Modelling Network

Brief presentations were given covering the activities of the existing IEA GHG storage networks, and then the final breakout session was tasked with developing a set of aims, objectives and first steps for the proposed IEA GHG modelling network. Each group came up with very similar ideas, and the following is a synthesis of the ideas raised.

5.1 Aims and Objectives

The overall aim of the network will be to provide an international forum for technical experts to share knowledge and ideas, promoting collaborative projects and contributing to the development of storage performance assessment.
Some specific objectives for the network to provide were identified by the breakout groups:

- Online reference databases – e.g. case studies, modelling parameters
- Online (secure) discussion forums
- Guidance documents for practitioners and non-technical specialists
- Sharing of modelling approaches and data
- Model and code comparison information, or links to benchmarking studies
- Updates on lessons learnt and knowledge gaps
- Provide storage performance assessment input to the risk assessment network
- Identification of the critical processes that require modelling for storage
- Model performance standards
- Online modelling exercises to allow comparison of methods
- Comparison of numerical and analytical modelling approaches

Many of the breakout group discussions emphasised the importance of communication between the networks. Suggestions were made that the network should be used to influence the development and implementation of regulatory regimes, although this might be considered by the risk assessment network, which could act as an overarching network for the modelling, monitoring and wellbore integrity networks and therefore be best placed as the appropriate forum for contact with regulators and other stakeholders.

Some participants also felt very strongly that the network must guard against placing too much emphasis on code development or promotion of particular software packages.

5.2 Next Steps

In addition to organising the next modelling network meeting next year, the following 'next steps' were identified by participants:

- Issue of detailed workshop report to all participants
- Summary presentation of workshop outcomes to risk assessment network
- Modelling network website to include online discussion forum and links to code/model comparison benchmarking studies

The suggestion of a web-based forum was one that was strongly recommended by all groups, so IEA GHG will attempt to action this as a priority before the next meeting.

5.3 Closing Comments

Gabriel Marquette, Schlumberger

This will not be a one-time network as people have expressed the wish to communicate on an ongoing basis; the forum concept is definitely a necessary tool which we will work towards as soon as possible. Schlumberger have a similar system which works very well on a daily basis, so we will look to learn from this and develop a similar system for the IEA GHG modelling network.

Isabelle Czernichowski, BRGM & CO_2GeoNet

Isabelle expressed satisfaction with the outcomes from the workshop, and welcomed the strong involvement from everyone present before announcing the formal establishment of the IEA GHG CO_2 Geological Storage Modelling Network. She acknowledged all those who supported and developed the ideas, with particular thanks to Gabriel Marquette, IEA GHG, John Gale and the IEA GHG ExCo. Neil Wildgust was also motivated by the concept and had organised the process very well, especially the planning and arrangements, organising the steering committee and teleconferences as well as the preliminary working meeting in Washington DC at GHGT9. Thanks were also extended to the steering committee who were instrumental in setting up meeting.

Appendix 1: Notes from Breakout Groups

The following section is a transcription of the notes generated during the breakout discussions. A summary of each session can be found in the relevant section of the main report.

Breakout Session 1

Group 1

Are our models enough?

- All rely on good data and enough of it
- Different approaches have different objectives
- What are you asking?
- SITE specific and RISK specific

Where are the current gaps?

- We have the tools but…
- How to upscale the pore scale to the field
- Gaps in the data e.g. rock water CO_2 interactions over long term
- Lack of clear/consistent METHOD
- Lack of SHARING results/skills

Group 2

Needs:

- Need to step back and examine important processes and phenomena
- Need to understand constraints imposed by regulators
- Small set of benchmarked models accepted by industry and regulators
- Suggestion for developing a single community model (mostly for science)
- Models for scientific research / Models for applications (operators and regulators)
- Working for producing a number of standard model(s) that regulators can use
- Data resolution and quality - Do not put too much emphasis on models results! Always uncertainties

Group 3

- Can current coupled models allow adequate modelling of reservoir and caprock behaviour?

    - Non-consensus: Yes, with a small minority: No.
    - Smaller scale = greater confidence
    - Larger scale, analytical models are probably sufficient / data is limited at a larger scale for numerical models.
    - Both are needed.
    - More coupling means less resolved uncertainty.
    - Try to avoid over-simplification and over-complexity.

- Does current knowledge and uncertainty allow adequate modelling of leakage processes?
    - Unanimously: No, even for smaller scales.
    - Research needed.
- Is there significant divergence in approaches to modelling adopted by different organisations? **YES**
-

Reservoir / Caprock Behaviour	Leakage
General purpose codes, allow coupling of THMCB, limited by data availability.	General purpose
Eclipse – focus on trapping mechanisms,	
"Adequate" = only to resolution of available data – uncertainty and gap analysis. Knowledge of heterogeneity.	
Geo-mechanical processes currently over-simplified – linear poro-elasticity okay for first order.	
Only small / limited size grids	
Different approaches to conceptual modelling reflects bias of individuals	
Eliminate negligible processes	
Missing link: Inverse modelling – what else could explain the observed situation?	

Group 4

- Industry, researchers in group
- Lack of data
- Wellbore leakage model missing? Dynamics of leakage – problem of adequately capturing the physics
- Well leakage monitoring
- Pressure effects very important factor – area of review
- Boundary conditions – geological features or artificial?
- Static geological models are adequate but up-scaling issues
- Modelling of caprock behaviour – coupling of gm and gc not there yet
- Lack of data for geomechanics of caprock
- Shear activation greater concern than existing fractures
- Particular problem for deep saline formations – caprocks effectively unknown properties at local scale
- Models – can they be understood and satisfy regulators? Leakage and pressure are 2 key issues
- Total: 3rd party expertise? Assuming regulators ignorance ignores 3rd party review.
- Models today may not be fully predictive?
- Modelling kinetic geochemistry difficult – no satisfactory models?
- Relative permeability curves

Breakout Session 2

Group 1

	Critical Processes & Parameters	Knowledge Gaps
Geological	• Knowing how to extrapolate • Understanding heterogeneity distribution and scale • …But well developed processes and methods from O&G industry, sedimentology etc… • Focus on fluid flow properties	• Rock physics linked to seismic • Regional scale models using reservoir scale tools • Revision of models & • Full suite of several cases
Multi Phase Flow	• Must have good understanding of mixed gases • Salinity and temperature are critical • Skilled res engineer to know how parameters impact results	• Rel perm curve for cap rocks? • 3 Phase curves • End point saturation
Geochemistry (RTM)	• Reaction rates, surface areas, kinetics (press temp) • Near well bore in short term • Impacts on Seal integrity & capacity (mineral trapping) in long term	• High uncertainty!! • Data base needed for various temps and Pressure scenarios • Cement chemistry? • Properties of high salinity &high temp reservoirs.
Geomechanic	• Existing and potential Fracturing, • initial state, in-situ measurements, regional stress, • rock properties/strength • Being able to upscale core data to field scale • "Full Earth" models into overburden etc…	• Uncertainty in fault properties • COUPLING!! • Costs of core and measurements • Geomechanical effects at the well bore – Damage effects in simulators
Thermics	• Temperature data: Initial uncontaminated measurements • Regional gradients	• Deformation changes resulting from temp changes

*All the above rely on "good data" using the "right" data, and skilled operator

To fill the Gaps we need to have data from the field tests and R&D pilots **SHARING**

Group 2

What are the processes and parameters that are critical to modelling requirements?

- Geological models essential, but choose the appropriate scale
- What should we care for all the scales? What information can we get from all the scales?
- How sensitive large scale plume with respect to different scales?
- How M, C, T effects will modify CO2 flow?
- Look at processes that can create risks (on my area) and focus on them – e.g. brine migration, wells' integrity, faults
- Look at processes having an effect on fluid migration (CO2, brine)
- Have a top-down approach, but how we can decide initially what are the more important processes? Start with experts' opinion (objective ranking needed), then simplified models
- Subsurface is highly uncertain, don't be overwhelmed by details
- Oil industry is used to live with high uncertainty, power companies no
- Reach a common agreement on criteria to decide what processes are important
- How to distinguish numerical artefacts from real physics?

What knowledge gaps still exist?

- Up-scaling, will be different depending on processes (up-scaling geochemistry, up-scaling geomechanics..), up-scaling across processes
- Communication gaps, (1) among scientists/disciplines, and (2) with regulators & policy makers - how do we communicate with regulators and decision makers, and (3) the public
- The best arguments are not enough, emotional factors too, need for a "front" man or woman
- Gaps between what is occurring in the lab and in the field. How do we get representative experimental data?
- Learn more from natural analogues
- Impurities- depending on type of power plants/industry and capture process
- Analogy with meteorological models and calibration
- Consistency in data (e.g. geochemical databases), lack of data for the relevant P,T, Salinity range
- Cement behaviour, thermodynamic/kinetic data
- Computational limits for coupling processes
- Hydrate formation (in case of leakage or highly depressed reservoir) and impact on pore space properties

Group 3

Process, Characterisation Phase	**Risk/Gap**		**Process, Characterisation Phase**	**Risk/Gap**	
Single phase fluid flow			Injectivity change *		
Multi phase fluid flow #	H	H	PVT behaviour variable gas mixtures *#		
Miscibility/wettability effects #			Abnormal pressure development *		
Structural/stratigraphic trapping *	M		Atypical geothermics *#		
Solubility trapping *	M	H	Hydrate development *#		
Mineral trapping *	L	H	Induced seismicity *		
Residual gas trapping *	L	H	Geomech processes at reservoir/pore scale #		
Reactive transport *	M	H	* CO_2 specific		
Diffusion	L		# Oil and gas related		
Fault reactivation *#	H	H			
Compaction/contraction/swelling #	M				
Localised deformation – fractures/faults *	H	H			
Heat flow	L				
Wellbore flow #	M				
Density/buoyancy drive					
Wellbore integrity/degradation *#	H				
Desiccation/brine conc. *	M				

Parameters, Characterisation Phase	**Gap**	**Parameters, Characterisation Phase**	**Gap**
Caprock integrity probing	H	Pressure gradient	
PVT/gas properties/gas mix	H	Capillary pressure	M
Relative permeability	H	Interfacial tension	
Connectivity		Brine chemistry/composition	H
Rock permeability		Thermal conductivity	
Porosity		Seismicity	
End point saturations		Hydraulic diffusivity	
Strength/deformation rock props	H	Seismic properties (velocity)	
Stress state	H	Mineralogy	H
Fault location/characterisation	H	Fracture gradient	
Reservoir heterogeneity	H	Structural/stratigraphic distribution	
Anisotropy		Geochemical reactions	H
Thermal gradient			

Group 4

- Geology, conceptual model, scenarios, containment and capacity, trapping mechanisms, integrity
- How do we identify critical issues?
- Analogues – important way to characterise rock mass – connectivity
- Regulator – integrity is No1 parameter
- Relative permeability
- Kinetics of reactions
- Maximum allowable pressurisation and footprint
- Compressibility of storage formation?
- Boundary conditions of models – worse case
- Geomechanics – in-situ measurements
- Stress is a key input parameter also pore-elastic properties – know how to do it, but not often done
- Up-scaling of mechanical properties a problem
- Caprock petro-physics & mechanical props
- Dual porosity systems – coupling gm and gc
- Can geochem influence injectivity? And long term consequences?
- Geochem – many parameters are uncertain , databases need to be improved
- Long term fault behaviour wrt coupled processes
- Lab test discrepancy with field data e.g. Well cements
- Need for learning from injection projects
- Availability of data from projects

Breakout Session 3

Group 1

How can models be used?

Monitoring	**Risk Assessment**
• How the system behaves at depth: Where to look for it • Will the monitoring tool be able to see the CO_2 : e.g. Fluid substitution modelling for 4D seismic response • Has it stayed in place: Storage inventory assessment • Helps you plan the cheapest, most efficient monitoring options	**Performance** modelling feeds the RISK ASSESSMENT RISK ASSESSMENTS guide the questions you ask of your models, and which models are important, what uncertainties are important.

How confident are we in the results?
Bad question – what results?

Group 2

Why are we monitoring? What is the input from modelling?

- Have to understand the purpose of monitoring
- Satisfying regulatory requirements
- Verify performance
- Modelling helps designing and deciding monitoring
- Monitoring data helps refine/revise models
- Need to model the sedimentary succession from the immediate caprock to the ground surface
- Make sure no impact on potable aquifers
- Need to know the hydrogeology of the shallow aquifers
- Modelling can tell how often you need to monitor and where (frequency and location of monitoring) and which monitoring methods to use
- You reach confidence through your model, then monitoring observations give you some constraints

How confident are we with model predictions?

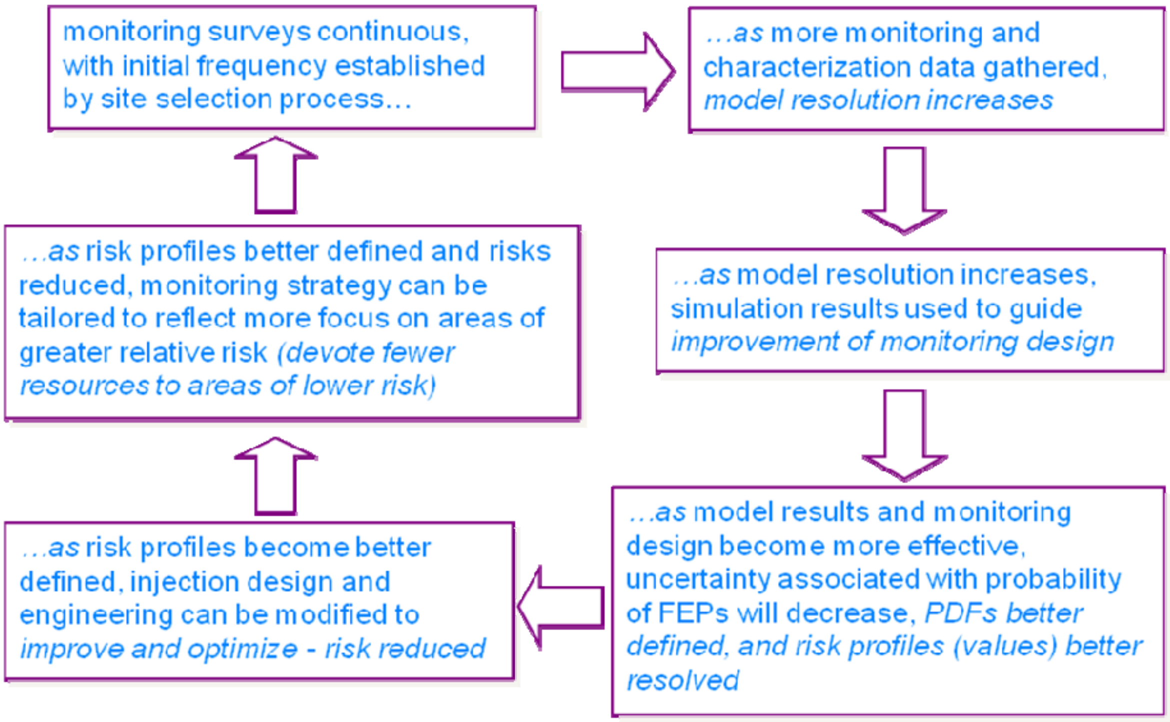
- We are not confident enough
- We are confident about our models and our science, not about parameters
- We are confident if joint modelling and monitoring approach
- Relationship between level of confidence and level of complexity (goes up and down)
- Oil industry has learnt not to be too confident on models, scenarios approach, models always updated

Modelling & Risk Assessment

- Risk assessment should use their proper models – with probabilities and consequences

Group 3

In an 'Ideal World':



Limitations of the 'Ideal World' scenario:

- Too many degrees of freedom, if matching doesn't happen, you will have as many opinions as those involved in discussion,
- Some outcomes may be acceptable, if they are broadly compatible with initial model predictions,
- Model could suggest range of acceptable outcomes, rather than exactly what WILL happen,
- Regulators and public will want to know where the CO_2 is, and this is possible, quantification is a different issue,
- Cannot minimise variation, but can reduce uncertainty,

Risk	Uncertainty
Free Gas, High	Footprint – No, Mass Balance - Yes
Dissolved gas, Low	Distribution - Yes
Everything else, too small to worry about	How much and where - Yes

How confident are we with model predictions?

- A range of confidences...
- Model results are predicated on monitoring technologies,
- Monitoring technologies are subject to limitations,
- Must explicitly state assumptions,
- Describe what model does not inform about,
- Predictions at each stage should indicate what measurements would be ‘surprising’ and what would be within the range of modelling uncertainties, consistent with the conceptual models employed,
- Iterations of the prediction-measurement cycle should result in measurements being consistently unsurprising before the case can be made to walk away from the site,

Group 4

- Regulators: what could go wrong – loss of containment
- Modelling can be used in case of failures. How is this defined? E.g. Earthquake, extreme events
- Initial model for plume extension to define monitoring, importance to baseline
- US partnerships – qualitative FEP analysis
- Monitoring linked to risk analysis
- Weyburn FEP analysis. What is meant by ‘long term’?
- CO_2-PENS attempts to quantify leakage
- Shell project qualitative leakage pathways and ‘stacking’
- Impurities?
- Probabilistic aspect of risk
- Risk versus performance
- Confidence levels for modelling
- Problem of compartmentalisation, e.g. How to quantify risks to shallow groundwater
- Problems of uncertainty
- Risks resulting from brine displacement pressurisation

Appendix 2: Meeting Agenda

Day 1 - Tuesday 10th February	
Session 1 – Introduction	
10.30 to 10.35	Welcome BRGM, Christian Fouillac, Research Director, BRGM and CO_2Geonet
10.35 to 10.45	Welcome and outline agenda, Neil Wildgust, IEA GHG
10.45 to 11.00	Modelling Overview for CO_2 Storage, Isabelle Czernichowski, BRGM and CO_2Geonet
11.00 to 11.20	Regulatory Perspective, IEA GHG
Session 2 – Assessment Objectives for Modelling: Chairs Karsten Pruess and Suzanne Hurter	
11.20 to 11.30	Introduction, Session Chairs
11.30 to 11.45	Storage Capacity, Bert van der Meer, TNO and CO_2GeoNet
11.45 to 12.00	Injectivity, Yann le Gallo, Geogreen
12.00 to 12.15	Plume Evolution and Trapping Phases, Sylvain Thibeau, Total
12.15 to 12.30	Caprock Integrity, Brian McPherson, university of Utah
12.30 to 13.00	Plenary question/discussion session
13.00 to 14.00 Lunch	
14.00 to 14.15	Leakage through wellbores, Mike Celia, Princeton University
14.15 to 14.30	Leakage through faults, Andrew Cavanagh, Permedia
14.30 to 15.50	**Breakout Discussion Session** Theme: Can current coupled models allow adequate modelling of reservoir and caprock behaviour? Does current knowledge and uncertainty allow adequate modelling of leakage processes? Aspects for detailed consideration: • Is there significant divergence in approaches to modelling adopted by different organisations? • How much confidence can be placed in current approaches and resulting models? • How modelling technologies can be developed to fulfil likely regulatory requirements? • What are the current knowledge gaps, and what should be the future focus for research?
15.50 to 16.10 Break	
16.10 to 17.30	**Facilitated Plenary Discussion** Feedback from breakout session and chair summary
Close Day 1 (19.00 Reception)	

Day2 - Wednesday 11th February	
Session 3 – Processes Session Chairs Brian McPherson and Pascal Audigane	
08.30 to 08.40	Introduction, Session Chairs
08.40 to 08.55	Geological modelling, heterogeneities and scale relations, Peter Frykman, GEUS and CO_2GeoNet
08.55 to 09.10	Multiphase fluid flow modelling, Suzanne Hurter, Schlumberger
09.10 to 09.25	Geochemistry and reactive transport modelling, Mohamed Azaroual, BRGM and CO_2GeoNet
09.25 to 09.40	Geomechanical modelling, Jonny Rutqvist, LBNL
09.40 to 09.55	Modelling heat transfer, Karsten Pruess, LBNL
09.55 to 10.15 Coffee Break	
10.15 to 11.45	**Breakout Discussion Session** • What are the processes and parameters that are critical to modelling requirements? • What knowledge gaps still exist? Consider the above questions for base geological models, multiphase flow, geochemistry and reactive transport, geomechanics, and thermics.
11.45 to 13.00	**Facilitated Plenary Discussion** Feedback from breakout groups and chair summary
13.00 to 14.00 Lunch	
Session 4 – Special Issues Session Chiars Sascha van Putten and Tess Dance	
14.00 to 14.05	Introduction Session Chairs
14.05 to 14.20	Code comparison exercises, Holger Class, Stuttgart University
14.20 to 14.35	Model comparison exercises, Jens Birkholzer, LBNL
14.35 to 14.50	Numerical tools improvement, Anthony Michel, IFP and CO_2GeoNet
14.50 to 15.05	Modelling and monitoring, Susan Hovorka, University of Texas
15.05 to 15.20	Modelling and risk assessment, Rajesh Pawar, LANL
15.20 to 15.30 Coffee Break	
15.30 to 16.30	**Breakout Discussion Session** Theme: How can modelling be used to optimise monitoring strategies and inform risk assessments? How confident are we with model predictions? Regulatory aspects are an important aspect here, and a discussion of the relationship between risk assessment and modelling, especially in the context of risk management frameworks.
16.30 to 17.30	**Facilitated Plenary Discussion** Feedback from breakout groups and chair summary
Close Day 2 (19.00 Gala Dinner)	

Day3 - Thursday 12th February	
Session 4 - Aims and objectives for potential modelling network Session Chairs Isabelle Czernichowski and Gabriel Marquette	
08.30 to 08.40	Introduction Session Chairs and Neil Wildgust
08.40 to 08.50	Aims of monitoring network, Neil Wildgust, IEA GHG
08.50 to 09.00	Aims of wellbore integrity network, Toby Aiken, IEA GHG
09.00 to 09.10	Aims of risk assessment network, Neil Wildgust, IEA GHG
09.10 to 10.30	**Breakout Discussion Session** Theme:What should be the aims of a modelling network, objectives and first steps?
10.30 to 10.50 Coffee Break	
10.50 to 12.00	**Facilitated Plenary Discussion** Feedback from breakout groups and chair summary
12.00 to 12.30	Wrap up
Close Day 3	


Orleans

CO_2 Geological Storage Modelling Workshop

10th-12th February 2009

Orleans, France

Organised by

IEA Greenhouse Gas R&D Programme,
BRGM, Schlumberger and CO_2GeoNet

Sponsored by
Total
IFP

10th February 2009 Day 1

09.30 to 10.30 Registration Opens

Session 1 Introduction

10.30 to 10.35 Welcome and Introduction: Christian Fouillac, Research Director, BRGM and CO_2Geonet

10.35 to 10.45 Welcome and outline agenda: Neil Wildgust, IEA GHG

10.45 to 11.00 Modelling Overview for CO_2 Storage: Isabelle Czernichowski, BRGM and CO_2Geonet

11.00 to 11.20 Regulatory Perspective: IEA GHG

Session 2 Assessment Objectives for Modelling: Chairs Karsten Pruess, LBNL and Suzanne Hurter, Schlumberger

11.20 to 11.30 Introduction: Session Chairs

11.30 to 11.45 Storage Capacity: Bert van der Meer, TNO and CO_2GeoNet

11.45 to 12.00 Injectivity: Yann le Gallo, Geogreen

12.00 to 12.15 Plume Evolution and Trapping Phases: Sylvain Thibeau, Total

12.15 to 12.30 Caprock Integrity: Brian McPherson, University of Utah

12.30 to 13.00 Plenary question/discussion session

13.00 to 14.00 Lunch

14.00 to 14.15 Leakage through wellbores: Mike Celia, Princeton University

14.15 to 14.30 Leakage through faults: Andrew Cavanagh, Permedia

14.30 to 15.50 **Breakout Discussion Session**
Theme: Can current coupled models allow adequate modelling of reservoir and caprock behaviour? Does current knowledge and uncertainty allow adequate modelling of leakage processes?
Aspects for detailed consideration:

- Is there significant divergence in approaches to modelling adopted by different organisations?
- How much confidence can be placed in current approaches and resulting models?
- How modelling technologies can be developed to fulfil likely regulatory requirements?
- What are the current knowledge gaps, and what should be the future focus for research?

15.50 to 16.10 Break

16.10 to 17.30 **Facilitated Plenary Discussion**
Feedback from breakout session and chair summary

Close Day 1
18.00 Reception Orleans City Hall

11th February 2009 Day 2

Session 3 Processes Session Chairs Brian McPherson, University of Utah and Pascal Audigane, BRGM and CO_2GeoNet

08.30 to 08.40 Introduction: Session Chairs

08.40 to 08.55 Geological modelling, heterogeneities and scale relations: Peter Frykman, GEUS and CO_2GeoNet

08.55 to 09.10 Multiphase fluid flow modelling: Suzanne Hurter, Schlumberger

09.10 to 09.25 Geochemistry and reactive transport modelling: Mohamed Azaroual, BRGM and CO2GeoNet

09.25 to 09.40 Geomechanical modelling: Johnny Rutqvist, LBNL

09.40 to 09.55 Modelling heat transfer: Karsten Pruess, LBNL

09.55 to 10.15 Break

10.15 to 11.45 **Breakout Discussion Session**

Themes:

- What are the processes and parameters that are critical to modelling requirements?
- What knowledge gaps still exist?

Consider the above questions for base geological models, multiphase flow, geochemistry and reactive transport, geomechanics,and thermics.

11.45 to 13.00 **Facilitated Plenary Discussion**

Feedback from breakout groups and chair summary

13.00 to 14.00 Lunch

Session 4 Special Issues Session Chairs Sascha van Putten, Shell and Tess Dance , CO2CRC

14.00 to 14.05 Introduction: Session Chairs

14.05 to 14.20 Code comparison exercises: Holger Class, Stuttgart University

14.20 to 14.35 Model comparison exercises: Jens Birkholzer, LBNL

14.35 to 14.50 Numerical tools improvement: Anthony Michel, IFP and CO_2GeoNet

14.50 to 15.05 Modelling and monitoring: Susan Hovorka, University of Texas

15.05 to 15.20 Modelling and risk assessment: Rajesh Pawar, LANL

15.20 to 15.40 Break

15.40 to 16.30 **Breakout Discussion Session**

Theme: How can modelling be used to optimise monitoring strategies and inform risk assessments? How confident are we with model predictions?

Regulatory aspects are an important aspect here, and a discussion of the relationship between risk assessment and modelling, especially in the context of risk management frameworks.

16.30 to 17.30 **Facilitated Plenary Discussion**

Feedback from breakout groups and chair summary

Close Day 2

19.00 Gala Dinner at Chateau de la Ferté St Aubin, sponsored by BRGM, Schlumberger, IFP and Total

12th February 2009 Day 3

Session 5 Aims and objectives for potential modelling network Session Chairs Isabelle Czernichowski, BRGM and CO_2GeoNet , Gabriel Marquette, Schlumberger and Neil Wildgust, IEA GHG

08.30 to 08.40 Introduction: Session Chairs

08.40 to 08.50 Aims of monitoring network: Neil Wildgust, IEA GHG

08.50 to 09.00 Aims of wellbore integrity network: Toby Aiken, IEA GHG

09.00 to 09.10 Aims of risk assessment network: Neil Wildgust, IEA GHG

09.10 to 10.30 **Breakout Discussion Session**
Theme: What should be the aims of a modelling network, objectives and first steps?

10.30 to 10.50 Break

10.50 to 12.00 **Facilitated Plenary Discussion**
Feedback from breakout groups and chair summary

12.00 to 12.30 Wrap Up

Close Day 3

IEA GHG CO_2 Geological Storage Modelling Workshop

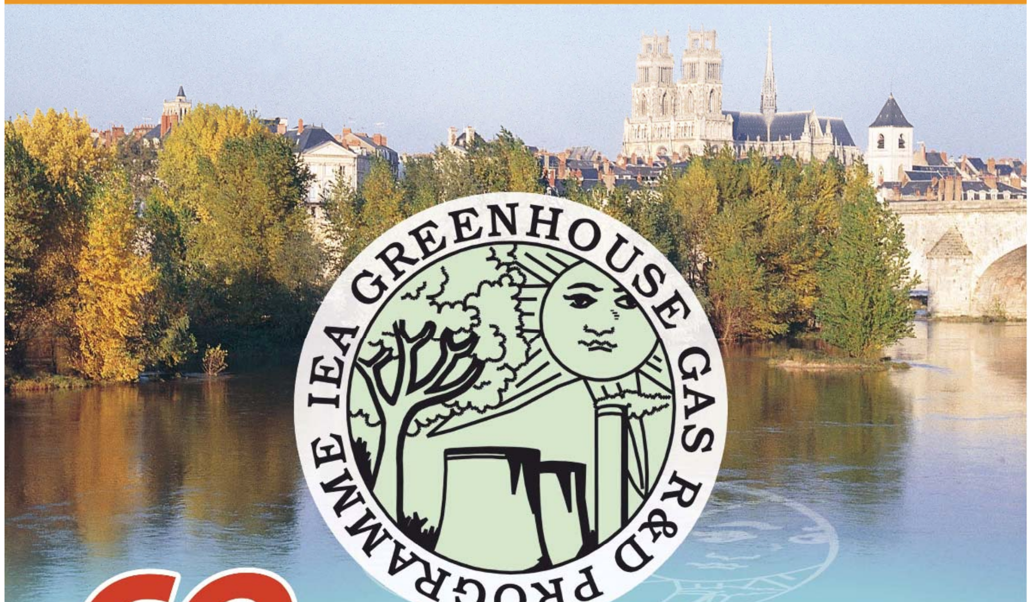
10th-12th February 2009, Orleans, France

Attendee List

Adoración Delgado	RepsolYPF
Alan Rezigh	ConocoPhillips
Alfredo Battistelli	Saipem SpA
Alice Post	Nederlandse Aardolie Maatschappij B.V.
Andre Laurent	BRGM- Water Division
Andreas Kopp	University Stuttgart
Andrew Cavanagh	Permedia Research
Anne Bialkowski	BRGM
Anthony Michel	IFP
Antonin Fabrri	BRGM
Axel-Pierre Bois	CurisTec
Ben Rostron	University of Alberta
Bert van der Meer	TNO
Brian McPherson	University of Utah
Bruno Huet	Schlumberger
Chan Vong	BRGM
Charles Gorecki	Energy & Environmental Research Center
Claus Kjøller	GEUS
Cor Hofstee	TNO
Curt Schneider	ConocoPhillips
Daiji Tanase	J-power
Darius Seyedi	BRGM
Dave Ryan	Natural Resources Canada
Eddy Chui	Natural Resources Canada
Elena Borisova	Schlumberger
Elodie Jeandel	EIFER
Eric Gaucher	BRGM
Karsten Pruess	Lawrence Berkeley National Laboratory
Klaus Udo Weyer	WDA Consultants Inc.
Krzysztof Labus	Silesian University of Technology
Laure Deremble	Schlumberger Carbon Services
Lingli Wei	Shell International Exploration & Production
Marc Lescanne	Total
Marc Paramentier	BRGM
Marie Gastine	BRGM
Martin Iding	StatoilHydro
Matteo Loizzo	Schlumberger Carbon Services
Mayu Otake	INPEX CORPORATION
Michael Celia	Princeton University
Modesto Montoto San Miguel	Oviedo University
Mohamed Azaroual	BRGM
Neil Wildgust	IEA GHG
Ozgur Gundogan	Institute of petroleum engineering
Pascal Audigane	BRGM
Patrick Dobson	US Department of Energy
Peter Fokker	Shell International Exploration and Production
Peter Frykman	GEUS
Peter Olden	Heriot-Watt University
Philip Maul	Quintessa Ltd
Philippe Bigeon	CEA - Delegation ANR/NTE
Pierrick Defossez	BRGM
Quentin Fisher	University of Leeds
Rabih Chammas	OXAND SA
Rajesh Pawar	Los Alamos National Laboratory

Eugene Balbinski	RPS Energy	Remi DREUX	GDF Suez
Fabrice Cuisiat	NGI	Ricardo Juncosa Rivera	Universidade da Coruña
Fabrizio Gherardi	CNR - IGG	Robert Trautz	Electric Power Research Institute
Fco Javier Elorza	Universidad Politecnica de Madrid	Rodrigo Iglesias	Brazilian Carbon Storage Research Center (CEPAC)
Frauke Schaefer	BGR	Saeko Mito-Adachi	RITE
Frederic Bourgeois	TOTAL	Sandrine Grataloup	BRGM
Frederic Pellet	University of Grenoble	Sascha van Putten	Shell International Exploration & Production
Frederic Wertz	BRGM - Water division	Stefan Bachu	Alberta Research Council
Gabriel Marquette	schlumberger	Steve Whittaker	PTRC
Geraldine Picot	brgm	Steven Benbow	Quintessa Ltd
Gerard Mouronval	Total	Steven Smith	Energy & Environmental Research Center
Giovanni Sosio	Schlumberger	Susan Hovorka	Univeristy of Texas, Bureau of Economic Geology
Grzegorz Lesniak	Oil and Gas Institute	Suzanne Hurter	Schlumberger Carbon Services
Hajime Yamamoto	Taisei Corporation	Sylvain Thibeau	Total
Hilde Hansen	StatoilHydro	Sylvie Gentier	ANR
Holger Class	Institut für Wasserbau	Tess Dance	CO2CRC/CSIRO
Isabelle Czernichowski-Lauriol	BRGM, CO2GeoNet	Thalia Vounaki	BGS
Jens Birkholzer	Lawrence Berkeley National Laboratory	Toby Aiken	IEA GHG
Jeremy Rohmer	BRGM	Toshiyuki Tosha	AIST/GSJ
Ji Quan Shi	Imperial College London	Tsuneo Ishido	Geological Survey of Japan, AIST
Jonny Rutqvist	Lawrence Berkeley National Laboratory	Yann Le Gallo	Geogreen
Jorg Aarnes	DNV	Yvi Le Guen	OXAND SA

10th-12th February 2009, Orleans, France



CO_2 Geological Storage Modelling Workshop

Organised by
IEA Greenhouse Gas R&D Programme,
BRGM, Schlumberger and CO_2GeoNet

Sponsored by
Total – IFP

Welcome and Outline of Agenda

CO_2 Geological Storage Modelling Workshop
Orleans, France, February 2009

Contracting Parties and Sponsor Organisations of IEA GHG

Background to this Workshop

- Existing CO_2 storage research networks on risk assessment, wellbore integrity and monitoring
- 2007 proposal from Schlumberger and BRGM to initiate a network on subsurface modelling
- Debated at a joint network meeting in June '08
- Strong support for such a network, but some concerns so workshop agreed as a first step
- We can debate these issues on Day 3

Outline of the Agenda

- Day 1
  - Session 1 Introduction
  - Session 2 Assessment Objectives
  - Evening Reception
- Day 2
  - Session 3 Processes
  - Session 4 Special Issues
  - Gala Dinner
- Day 3
  - Session 5 Modelling Network
  - Tourist tour

Workshop Structure

- Presentations
  - Short duration talks to stimulate discussions
  - Brief questions only – time to debate in discussion sessions
- Discussion Sessions
  - 4 breakout groups, refer to your badge
  - General format – breakout discussions, then plenary feedback/discussions

Practical Arrangements

- Transport
  - Buses to/from hotels
  - Buses to evening reception and gala dinner
  - Shuttles can be arranged to CDG on Thursday afternoon and Friday morning
- Meals
  - Lunches in BRGM canteen
  - Day 1 evening reception – light snacks only

Modelling overview for CO_2 storage

Isabelle Czernichowski-Lauriol
BRGM, Orléans, France
CO_2GeoNet Network Manager

BRGM in brief

- BRGM is France's Public Institution responsible for mobilising the Earth Sciences in the sustainable management of natural resources and the subsurface domain.
- Since 1993, BRGM has been developing expertise on all aspects of CO_2 geological storage, i.e. site selection and characterisation, predictive modelling, monitoring, risk, safety criteria.
- BRGM has earned worldwide recognition for its skills in modelling the chemical interactions between injected CO_2 and the host rock.
- BRGM is a partner of CO_2GeoNet – the European Network of Excellence on CO_2 geological storage.
- As an expert or France's Representative, BRGM gives advice on CCS to French Ministries, national bodies and several international bodies or initiatives (CSLF, IEA-GHG, IEA-WPFF, ZEP, EURACOAL, IPCC, ECCP II, London and Ospar Conventions, G8/IEA/CSLF initiative…).

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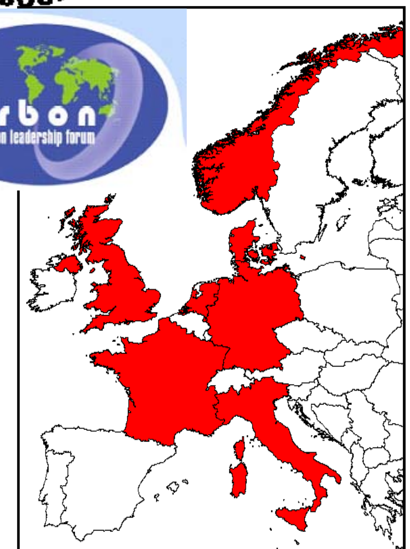
CO_2GeoNet Network of Excellence

CO_2GeoNet is the EU scientific body on CO_2 geological storage:

integrated community of researchers with multidisciplinary expertise, durably engaged in enabling the efficient and safe geological storage of CO_2

- 13 partners over 7 countries, more than 150 researchers
- Activities:
  - Joint research on all storage aspects
  - Training
  - Information / communication
  - Scientific advice
- Created as a FP6 Network of Excellence with EC initial support for 5 years (6 million €, April 2004 – March 2009).
- An Association, legally registered under the French law, has been launched in 2008.



Denmark: **GEUS**
France: **BRGM, IFP**
Germany: **BGR**
Italy: **OGS, URS**
The Netherlands: **TNO**
Norway: **NIVA, IRIS, SPR**
UK: **BGS, HWU, IMPERIAL**

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Outline (as in Joint Network Meeting in New York, June 2008)

1. Modelling is key for CO_2 storage implementation
2. Modelling is very complex
3. Modelling examples
4. Previous initiatives of code comparison
5. Additional efforts needed
6. Towards an IEA GHG modelling network?

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1- Modelling is key for CO_2 storage implementation

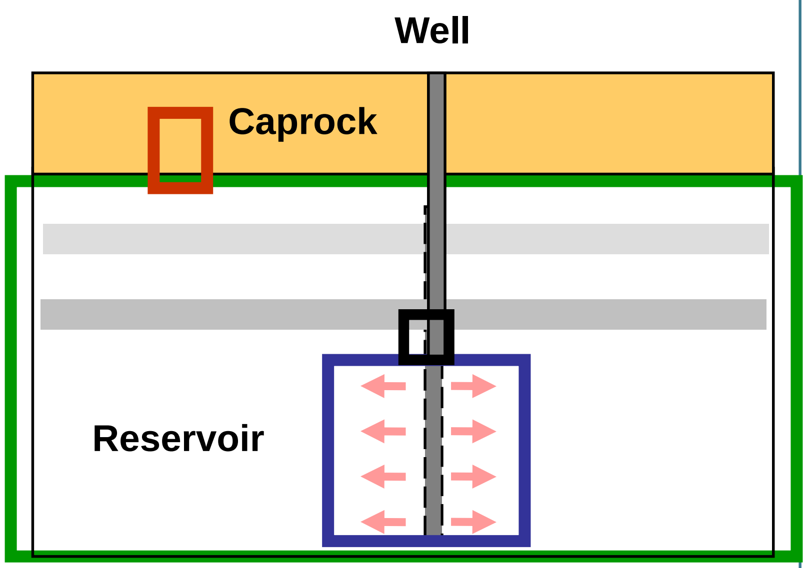
> **Top Necessity for:**

- Assessing the geological framework
- Assessing storage capacity, injectivity, integrity (caprock, faults, wells), risks (leakage, ground movement), impacts
- Advising monitoring (mutual impetus)

> **Only dynamic modelling enables practical conclusions**

> **Modelling will have a top importance in regulatory and legal frameworks**

e.g. EC Directive on CO2 geological storage (2008)



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EC Directive on CO_2 storage (Dec. 2008)

Annex 1 CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF STORAGE SITES

> Step 1: Data collection

- Sufficient data shall be accumulated to construct a *volumetric and static three-dimensional (3-D)-earth model* for the storage site and storage complex

> Step 2: Building the 3D static geological earth model

- Using the data collected in Step 1, a *three-dimensional static geological earth model* shall be built using *computer reservoir simulators*.
- The uncertainty associated with each of the parameters used to build the model shall be assessed by developing a range of scenarios for each parameter and calculating the appropriate confidence limits. Any uncertainty associated with the model itself shall also be assessed.

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EC Directive on CO2 storage (Dec. 2008)

Annex 1 CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF STORAGE SITES

> **Step 3: Characterisation of the storage dynamic behaviour, sensitivity characterisation, risk assessment**

- The characterisations and assessment shall be based on dynamic modelling, comprising a variety of timestep simulations of CO2 injection into the storage site using *the three-dimensional static geological earth model(s)* in the computerised storage complex simulator constructed under Step 2.
- Multiple simulations shall be undertaken to identify the sensitivity of the assessment to assumptions made about particular parameters. The simulations shall be based on altering parameters in the *static geological earth model(s)*, and changing rate functions and assumptions in the dynamic modelling exercise. Any significant sensitivity shall be taken into account in the risk assessment.
- The risk assessment shall comprise hazard characterisation, exposure assessment, effects assessment and risk characterisation, which includes an assessment of the worst-case environment and health impacts. It shall include an assessment of the sources of uncertainty.

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EC Directive on CO_2 storage (Dec. 2008)

Annex 2 CRITERIA FOR ESTABLISHING AND UPDATING THE MONITORING PLAN

- The data collected from the monitoring shall be collated and interpreted. The observed results shall be compared with the behaviour predicted in dynamic simulation of the 3-D-pressure-volume and saturation behaviour undertaken in the context of the security characterisation.
- Where there is a significant deviation between the observed and the predicted behaviour, the 3-D-model shall be recalibrated to reflect the observed behaviour.
- Where new CO_2 sources, pathways and flux rates or observed significant deviations from previous assessments are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly.
- Post-closure monitoring shall be based on the information collected and modelled during the implementation of the monitoring plan

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1- Modelling is Key for CO_2 storage implementation

But « *how confident are we in the modelling results we are generating for CCS projects?* »

(Quotation from Risk Assessment network)

2- Modelling is very complex

- Large timescale range of interest: from hours to thousands of years
- Large spatial scales of interest: from cms to tens of kms
- Various compartments: reservoir, caprock, overburden, faults, wells, surface
- Natural heterogeneities, poor knowledge of the subsurface
- Various dynamic (& coupled) processes: Fluid flow – Geochemistry – Thermics – Geomechanics – Microbiology
- Uncertainty and sensitivity
- Site specificity

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> Only modelling can address such complex issues for enabling to make predictions

- Numerical & Analytical approaches
- Need for efficient computing algorithms and machines
- Conceptual modelling is very important
- Mutidisciplinary teams are needed (all fields of geosciences, mathematics, computer sciences)

> But real data is necessary for model calibration and benchmarking

- Lab & Field experiments
- Field monitoring
- Comparison analytical / numerical models
- Comparison between various numerical codes

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3- Modelling examples

(as shown in Joint Network Meeting in New York, June 2008)

To illustrate why we need models, how complex they are, why we should improve them to increase confidence

- Static geological model
- Fluid flow
- Chemical reactivity
- Geomechanical behaviour
- CO_2 leakage through a well – analytical model

See examples at this Orleans Workshop

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4- Previous initiatives of code comparison

- 2002 Workshop at LBNL, Berkeley, USA: Inter-comparison of numerical simulation codes for geologic disposal of CO2 report (reported in Pruess et al. 2004)

  "Code intercomparison builds confidence in numerical simulation models for geologic disposal of CO2"

  Energy 29 (2004) 1431–1444

- 2008 Workshop at University of Stuttgart, Germany: Numerical Models for Carbon Dioxide Storage in Geological Formations (report to be issued)

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LBNL code intercomparison exercise (2002)

> Participants:

Research Institute	Code(s)
LBNL, USA	TOUGH2 Family
University of Stuttgart, Germany	MUFTE_UG
CSIRO Petroleum, Australia	TOUGH2/ECO2
IFP, France	SIMUSCOPP
University of Stanford, USA	NON BAPTISE
Alberta Research Council (ARC), Canada	GEM
LANL, USA	FLOTRAN, ECLIPSE 300
LLNL, USA	NUFT
Industrial Research Limited (IRL), NZ	CHEM-TOUGH
PNNL, USA	STOMP

> 8 very simplified exercises (1D, 2D radial, schematic & homogeneous media) that probed advective and diffusive mass transport in multiphase conditions, with partitioning of CO2 between gas and aqueous phases; two problems also involved solid minerals and oil phases.

> broad agreement in most areas; bugs corrected, some unexpl. discrepancies

> also points out sensitivities to fluid properties and discretization approaches that need further study.

> It is hoped that future code intercomparisons will address coupled processes in fully 3D heterogeneous media, constrained by actual field observations.

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Univ. of Stuttgart code intercomparison exercise (2008)

> Participants:

Research Institute	Code(s)
University of Bergen/Princeton, Norvège/USA University of Texas/Austin, USA IFP Rueil Malmaison, France University of Stuttgart, Germany RWTH Aachen, Germany BGR Hannover, Germany LANL, USA	Semi-analytical solutions IPARS-CO2 COORES MUFTE TOUGHREACT ROCKFLOW FEHM
University of Stuttgart, Germany	DuMux
BRGM Orléans, France	RTAFF2
HW Edinburgh, UK	ECLIPSE 300
Schlumberger Carbon Services, Paris	ECLIPSE 300
University of Stanford, UK	GPRS

> 3 exercises: focused on fluid flow and numerical aspects, 3D geometries

> Fairly good agreement, but some big discrepancies that need to be further analysed (discretization, numerical algorithm, etc.)

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5- Additional efforts needed

> Needs expressed by IEA GHG Wellbore Integrity Network

- Numerical models of wellbore geochemistry and geomechanics need additional development for providing long-term predictions
- Numerical models incorporating realistic permeability distributions for wells are needed to evaluate the leakage potential of fields with multiple wells
- Integrated geomechanical and geochemical experiments/numerical models are needed to capture full range of wellbore behavior
- Long-term numerical modeling grounded in enhanced field and experimental data

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5- Additional efforts needed

> Needs expressed by IEA GHG Monitoring Network

- Recognizes the importance of modelling in the various phases of CO_2 storage (site investigation, drilling & well testing, storage operation, site closure)
- "The monitoring measurements should be history matched against the predictive flow modelling"
- "The main gap is a lack of a "matrix" presenting the common interests among the three networks and the perspective they are dealt within each individual network. The objective should be to converge to a common outcome. For example, when a CO_2 risk pathway is identified, is /are the simulation tools able to calculate it? Which output they provide? How this output can be then translated in probability of occurrence or severity of consequences".

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5- Additional efforts needed

> Needs expressed by IEA GHG Risk Network

- How confident are we in modelling results?
- Need for modelling physical/chemical/mechanical phenomena in a way that can be useful for risk assessment

> Needs expressed by ZEP - the European Technology Platform for Zero Emissions Fossil Fuel Power Plant:

- R&D area: Long-term modelling of CO2 storage in deep saline aquifers: "Modelling is used to characterise both short-term and long-term storage performance in terms of injectivity, capacity, containment, and quantitative estimation of potential leakage. A dedicated project is needed to develop and demonstrate the capacity of models to adequately predict the storage behaviour and CO2 fate. This will increase confidence in the safe implementation of storage sites and will be useful for optimising the injection operations and the short/long term monitoring strategies".

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6- Towards a IEA GHG modelling network? – Feedback from questionnaire (18 received, 16 with opinion)

> FOR (13), e.g.:

- YES. Modelling is a key component of all CCS projects and thus determining best practises in this area would be very useful.
- YES, it is important to create a place where this community can meet, especially to perform benchmarking
- YES - Definitely. Modelling needs to be performed at several levels, which transcends the scope of the individual networks at present. Our confidence in our ability to model both the small scale and large scale phenomena in the system will be greatly enhanced if we focus effort on this problem and share information that is currently within the domain of the individual network groups.

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6- Towards a IEA GHG modelling network?
– Feedback from questionnaire (18 received, 16 with opinion)

> FOR (13), e.g.:

- YES. I think the results of work done in the other networks can feed the modelling to develop better models, but that this topic is a stand alone issue.
- Simulation and modelling is very important for CCS. So, new network should deal with modelling and simulation
- YES, a new network would be useful on this topic … but Modellers shouldn't be allowed to have more than 2 meetings in a row by themselves! Too susceptible to becoming remote from the "real world"; that is, from addressing issues that matter to other people.

Géosciences pour une Terre durable
brgm

6- Towards a IEA GHG modelling network?
– Feedback from questionnaire (18 received, 16 with opinion)

> AGAINST (2):

- No. I'd rather see effort put into identifying economic monitoring methods that will work when the plants are at full capacity and the years after abandonment (Tools like InSAR).
- NO. Modeling is a crosscutting activity that pertains to all the existing networks.

> MAY BE (1):

- Maybe to some extent

Géosciences pour une Terre durable
brgm

6- Towards a IEA GHG modelling network?

Conclusion is best summarised by one of the answers to the questionnaire:

- "**YES**, I believe there would be a lot of benefit from a modelling network. Significant components of the practice of CO2 injection and geologic storage can be described only by modelling (e.g., estimated injectivity, injection field design and injection rates, total storage capacity, plume fate and tracking, etc.). Modelling of these technical components will be important in preparing carbon storage permits, and convincing regulators and the public of storage safety and viability. Therefore, a modelling network would contribute to more directly integrating modelling developments with developments in WI, M, and RA, and would also promote accurate, dependable, and practical modelling as applied to permitting and monitoring CO2 geologic storage".

Regulatory Perspective on Modelling

Tim Dixon

IEA Greenhouse Gas R&D Programme

Orleans, 10-12 February 2009

Regulation needs modelling

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

IPCC Guidelines for GHG Inventories

- Apr 2006
- Vol 2 Energy, Chp 5 - *CO2 Transport, Injection and Geological Storage*
- Each site will have different characteristics
- **Methodology**

Site characterisation – inc leakage pathways

Assessment of risk of leakage – modelling of CO_2 movement

Monitoring – use results to validate/update modelling

Reporting – inc CO2 inj and emissions from storage site

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

IPCC Guidelines for GHG – cont.

- Geological model of site – site characterisation
- Numerical Modelling – to predict the movement and distribution of the CO_2 – short-term and long-term
- Use models to design monitoring plan
- Sensitivity analysis and uncertainty estimates
- History match against monitoring results
- Important principle - Post-injection monitoring, linked to modelling, may be reduced or discontinued once CO_2 stabilises at its predicted long-term distribution

London Convention and Protocol

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

CCS work

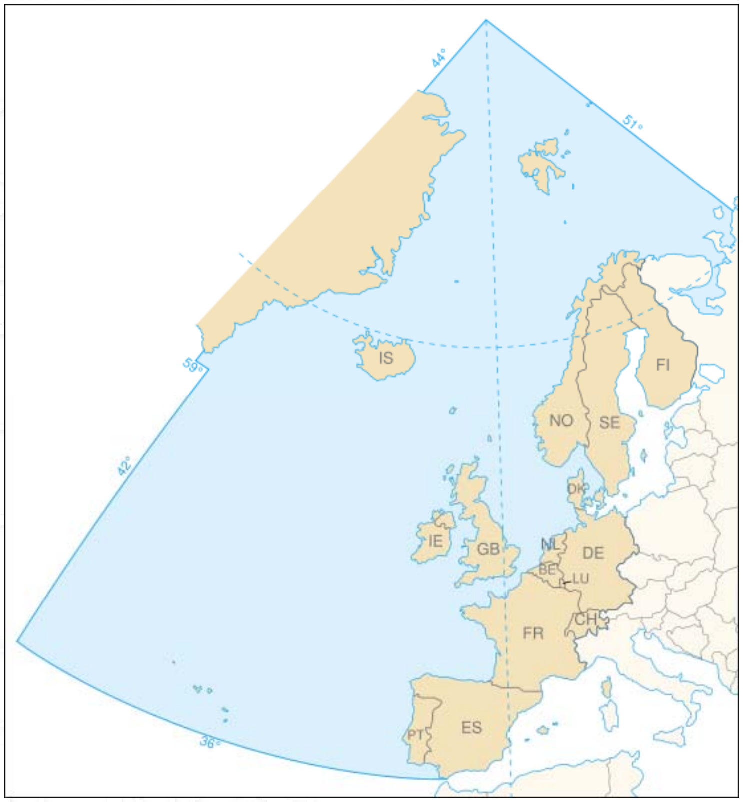
- Assessed by LC Scientific Group
- 2006 - Risk Assessment Framework for CO2

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

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

OSPAR

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



- To allow prohibited CCS configurations - **OSPAR amendments** (to Annexes II and III) for CO2 storage **adopted June 2007** - but need ratification by 7 Parties
- **OSPAR Decision** – requirement to use Guidelines when permitting.
- **OSPAR Guidelines** for Risk Assessment and Management of Storage of CO2 in Geological Formations – includes the Framework for Risk Assessment and Management (FRAM)
- Decision - Storage in water column prohibited

London and OSPAR Guidelines for Risk Assessment and Management

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

EU CCS Directive

Enabling regulatory framework to ensure environmentally sound CCS (proposed 23 Jan 2008)

- Follows IPCC GHG Guidelines and OSPAR
- Objective is permanent storage
- Storage permit only if "no significant risk of leakage"
- Emphasis on site selection and characterisation (details in Annex 1), risk assessment, monitoring plans (details in Annex 2)
- Permit application to include characterisation of site and security
- The draft has been agreed/finalised on 16th December 2008, due for issue within next 2 months

EU CCS Directive – Annex 1 Site Characterisation

1. Data collection
2. Static Simulation
   - 3-d geological earth model, including caprock and hydraulically connected areas, geological structure, geomechanical, geochemical, flow properties of reservoir, overburden and surrounding formations, facture systems. Uncertainties with each parameter assessed with range of scenarios for each and calculating confidence limits.
3. Dynamic simulation
   - security characterisation (ie performance assessment) based on dynamic modelling, including "efficacy of coupled process modelling", reactive processes, over short-term and long-term (decades-millennia), to provide information on range of characteristics including pressure, temperature, plume extent, trapping mechanisms, etc. Sensitivity characterisation.
4. Risk assessment

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

- III.A.1 Geological siting requirements (characterisation) – detailed geological assessment
- III.A.2 Define Area of Review – using computational multiphase fluid flow models for CO_2 and mobilised substances movement, and pressure. Use to develop monitoring plans.
- Informed by EPA Modelling workshop Houston, April 2005.

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

Conclusion

- Modelling of geological formations and CO_2 behaviour is central to the regulation of geological storage and to the ability for regulators to make assessments and decisions on granting permits.

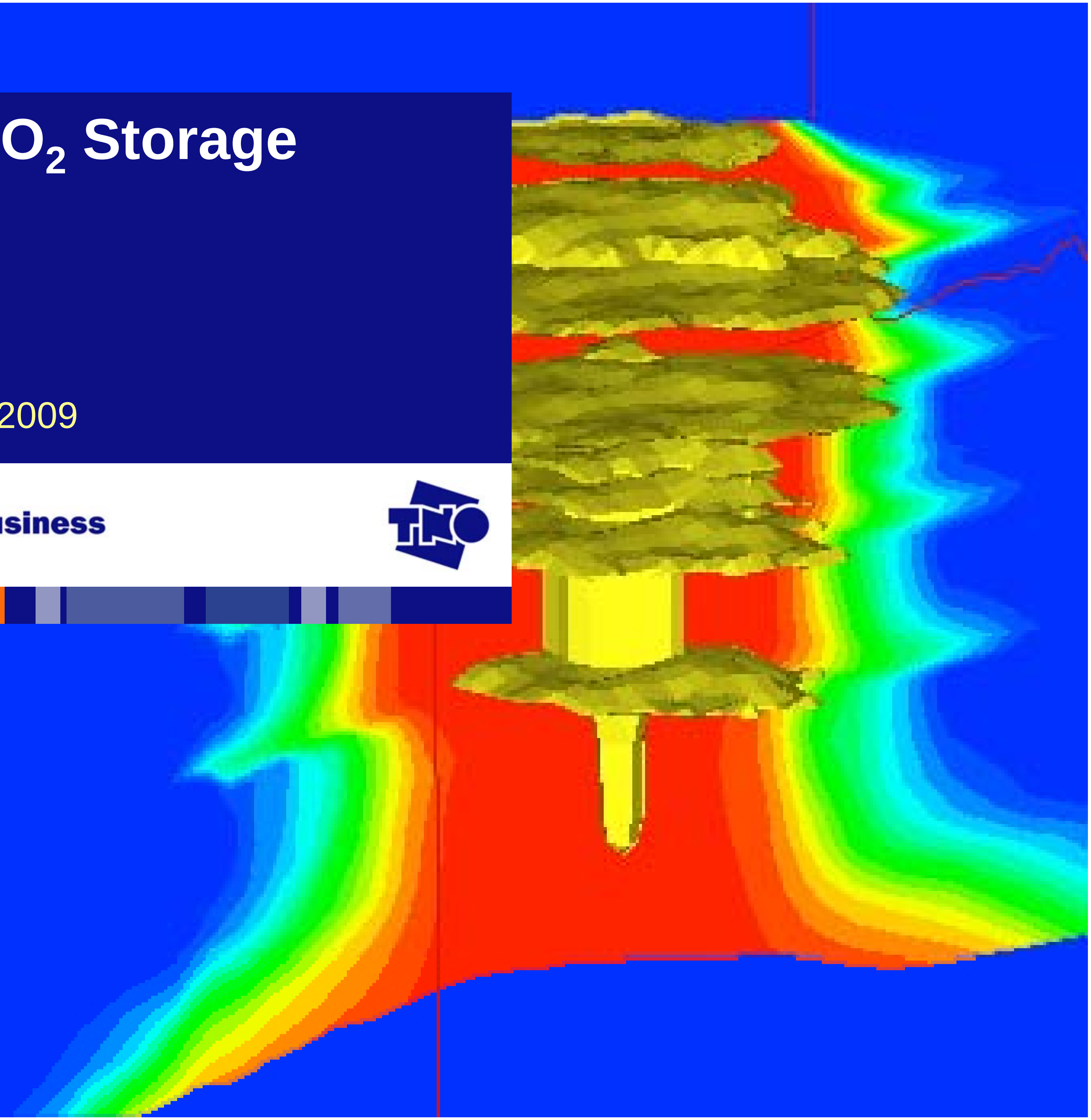
IEA Greenhouse Gas R&D Programme

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

Subsurface CO_2 Storage Capacity

Orléans, 10 Februari 2009

TNO | Knowledge for business



Bert van der Meer

Overview

- Introduction
- Example
- Storage Capacity
- Injectivity
- Storage Efficiency
- Probability of storage
- Conclusions

Overview

- **Introduction** **(only principles)**
- Example
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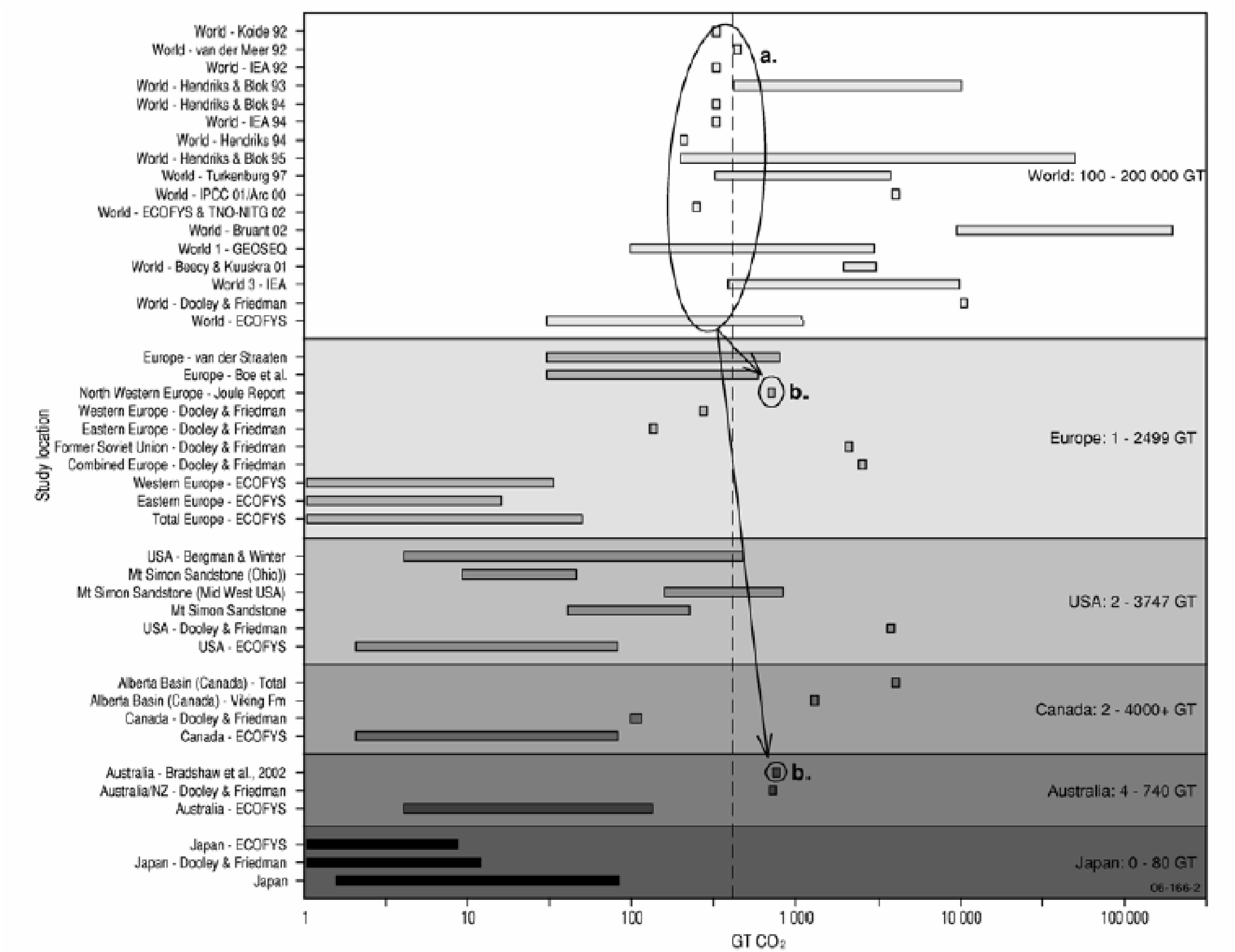
Introduction

After: Bradshaw J. et al, Carbon Sequestration leadership Forum



Introduction

1990 – Dutch solubility approach

- Surface of the Netherlands x aquifer thickness x porosity x solubility

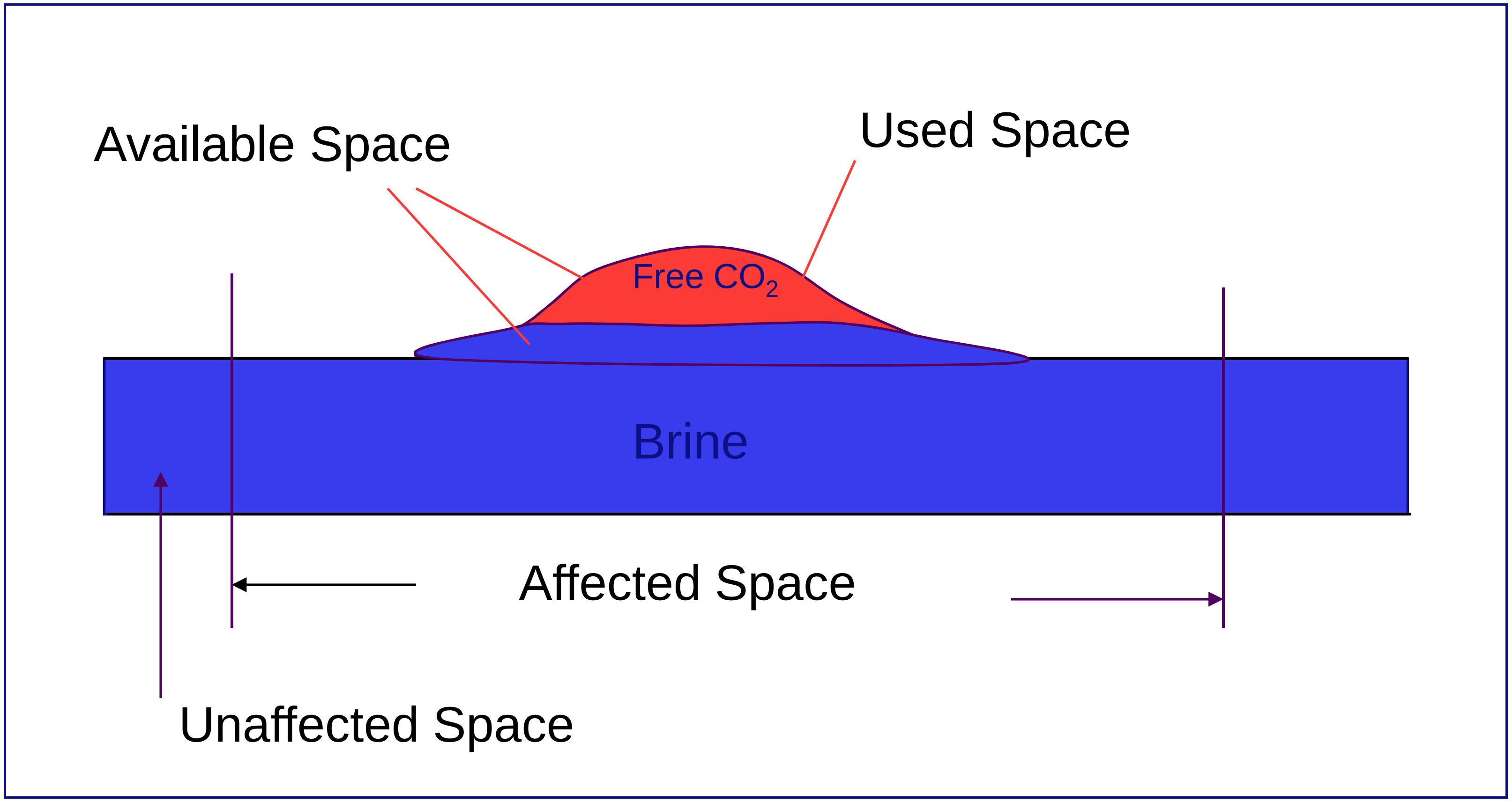
1992 – Amsterdam - not a large open space – 2 % rule

- Disappointing - => up to 6 %

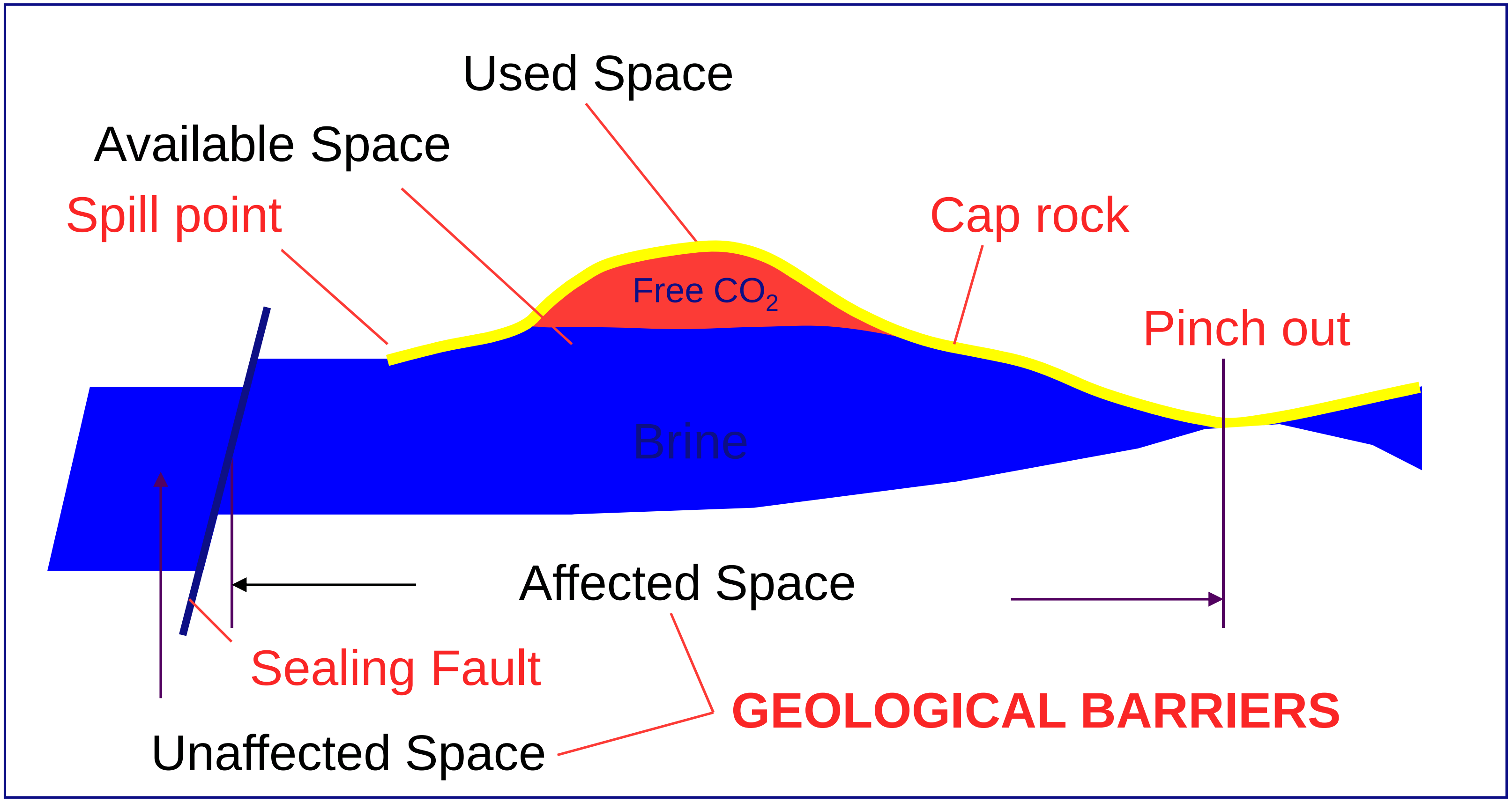
2005 – IPPC Special Report

- Alberta Basin – 4000 $GtCO_2$ – based on solubility
- Permeability is very low

Conceptual Model



Conceptual Model



Overview

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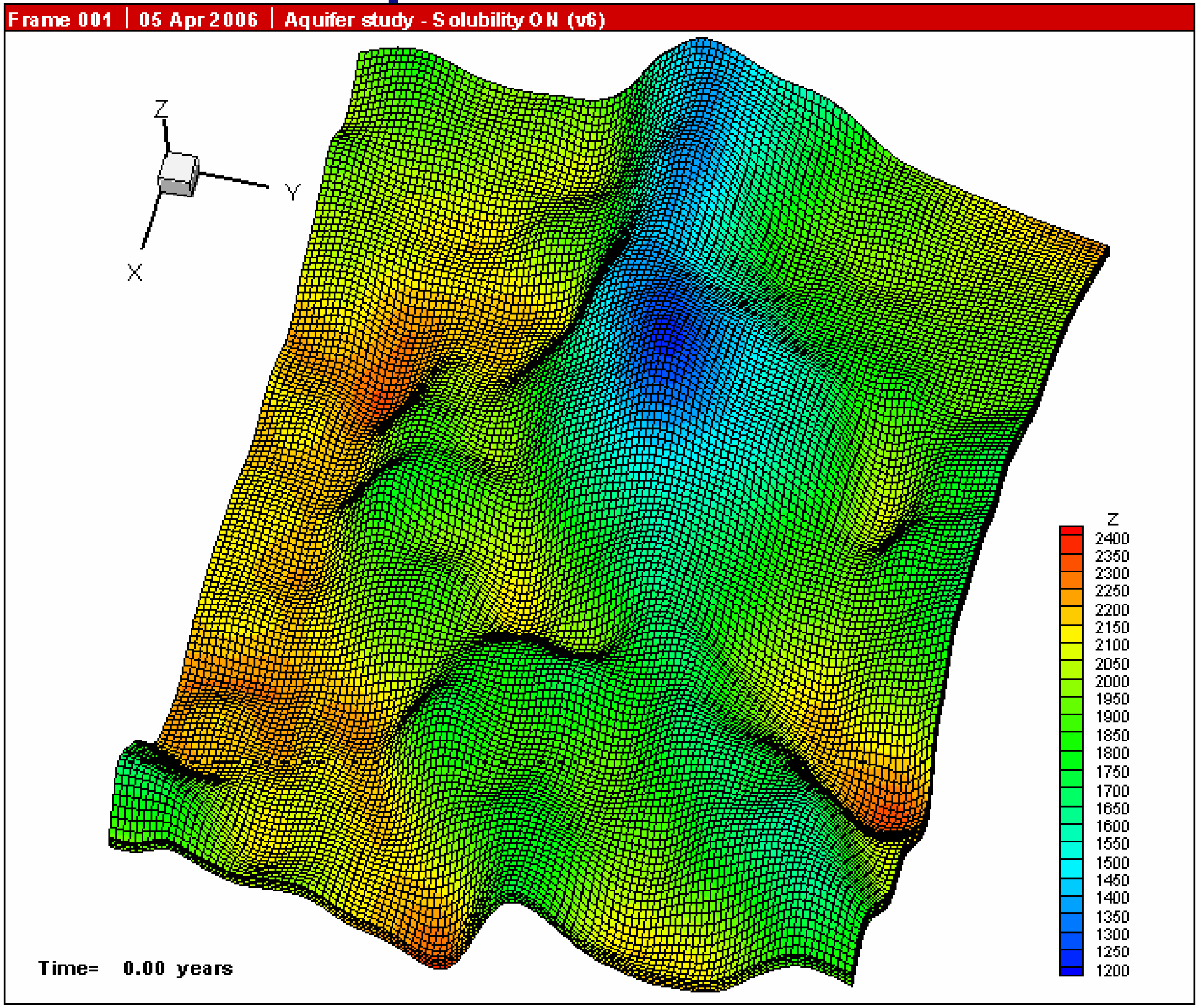
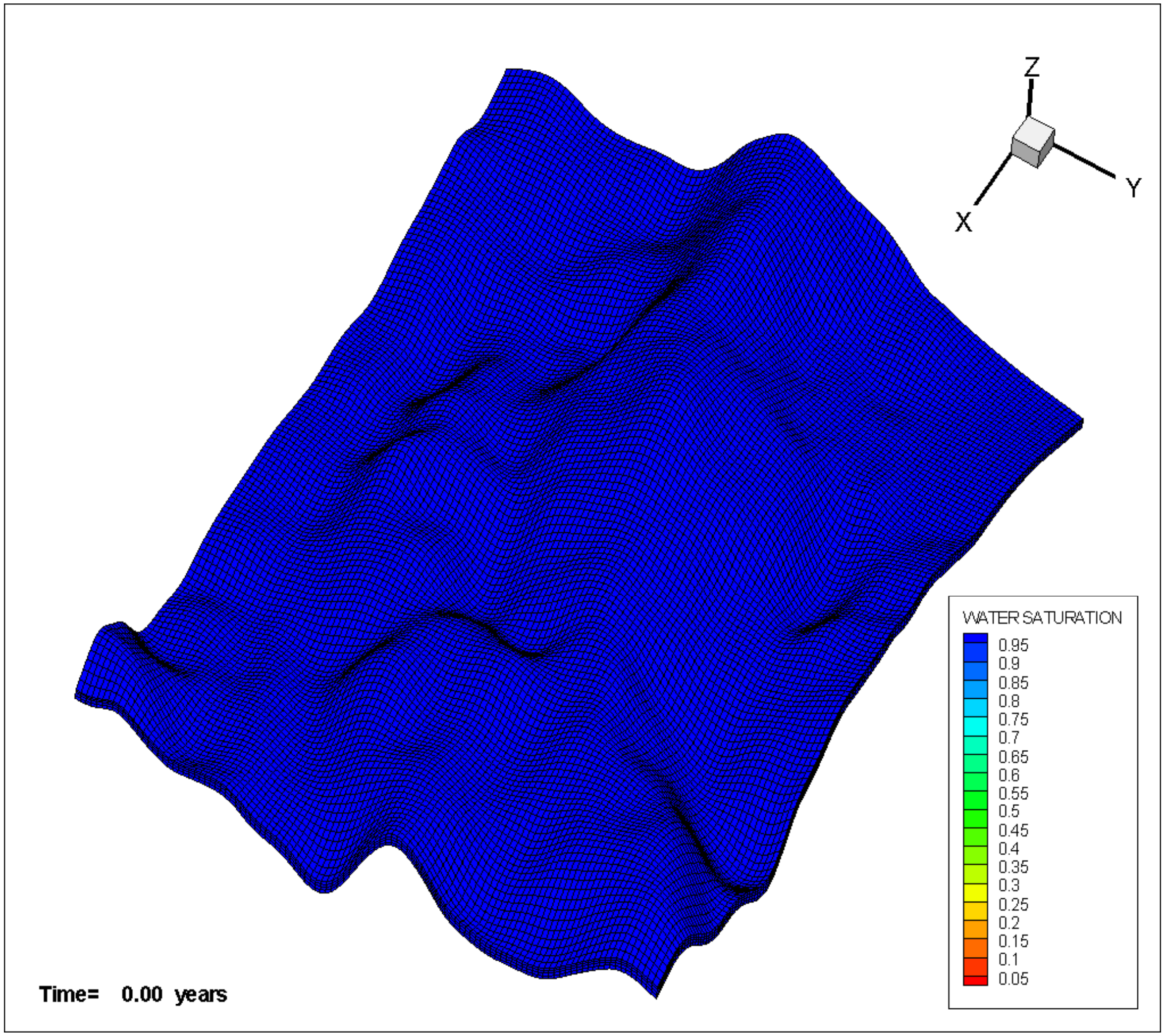
Realistic Example

- Some 46 by 58 km
- 100 m thick
- 200 – 350 mD range
- 10 injectors down dip
- 10 Mt/y
- 400 Mt in 40 years
- Model to small – Average pressure increase of 230 bar (in affected/adopted space)

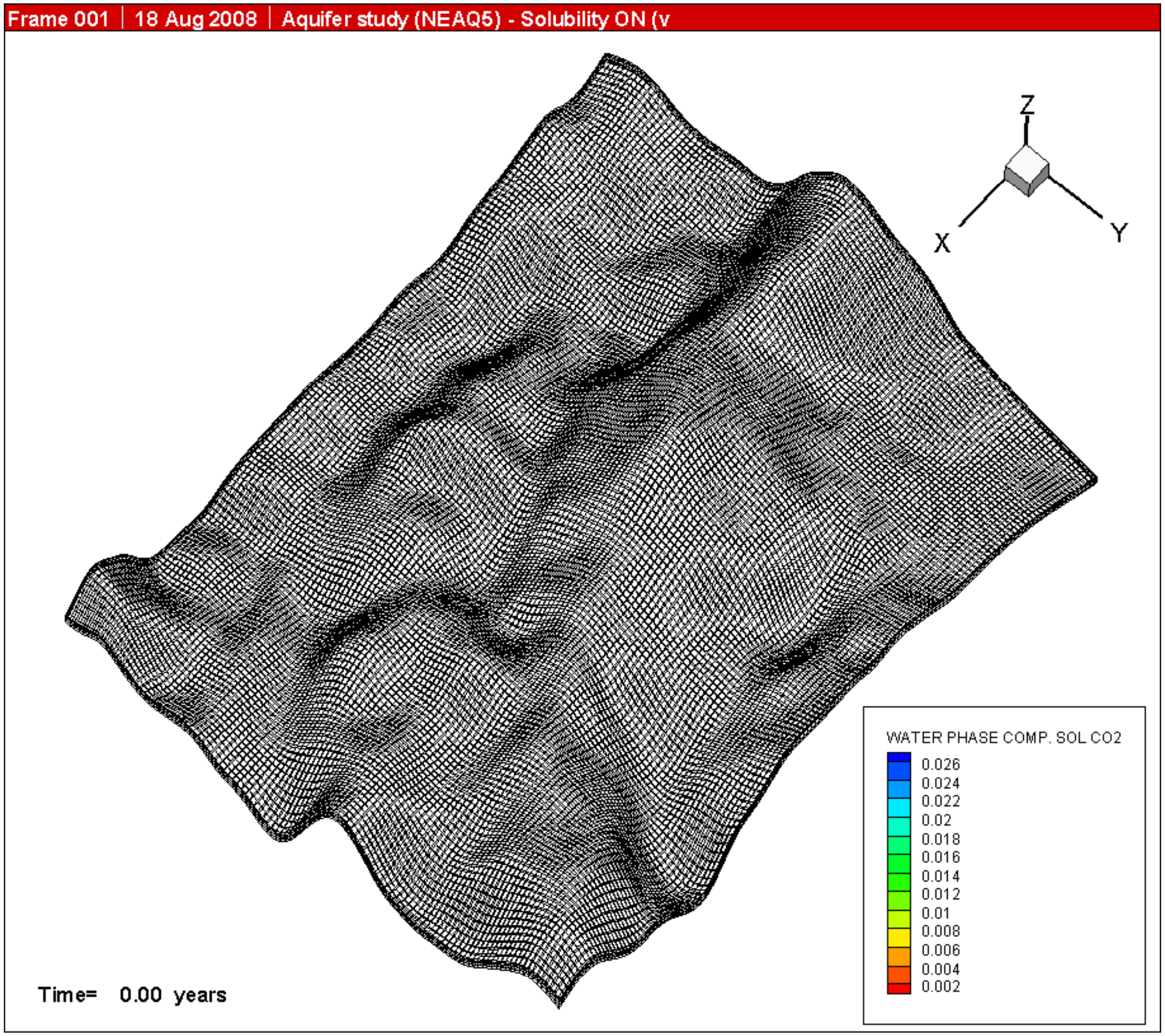
Realistic Example



Example - Free CO2



Example - CO2 Saturated water



Controlling Factors?

4 Important factors controlling the volume of CO_2 we can store in a predefine subsurface space

- Storage Capacity (Volume - Average Pressure)
- Potential Injectivity (Permeability - Local Pressure)
- Storage Efficiency (Available Space - Used Space)
- Data Available and Quality

Overview

- Introduction
- Example
- **Storage Capacity**
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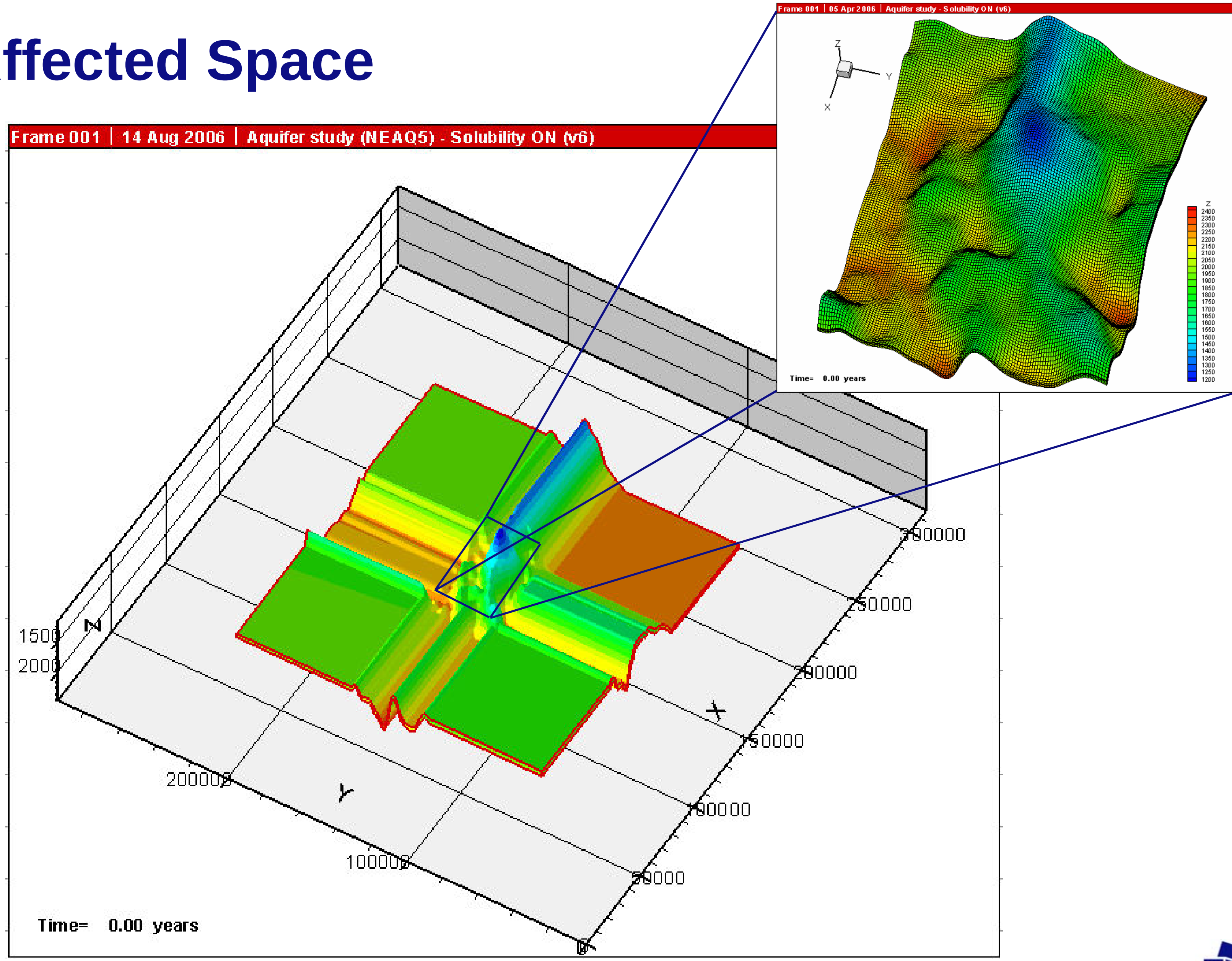
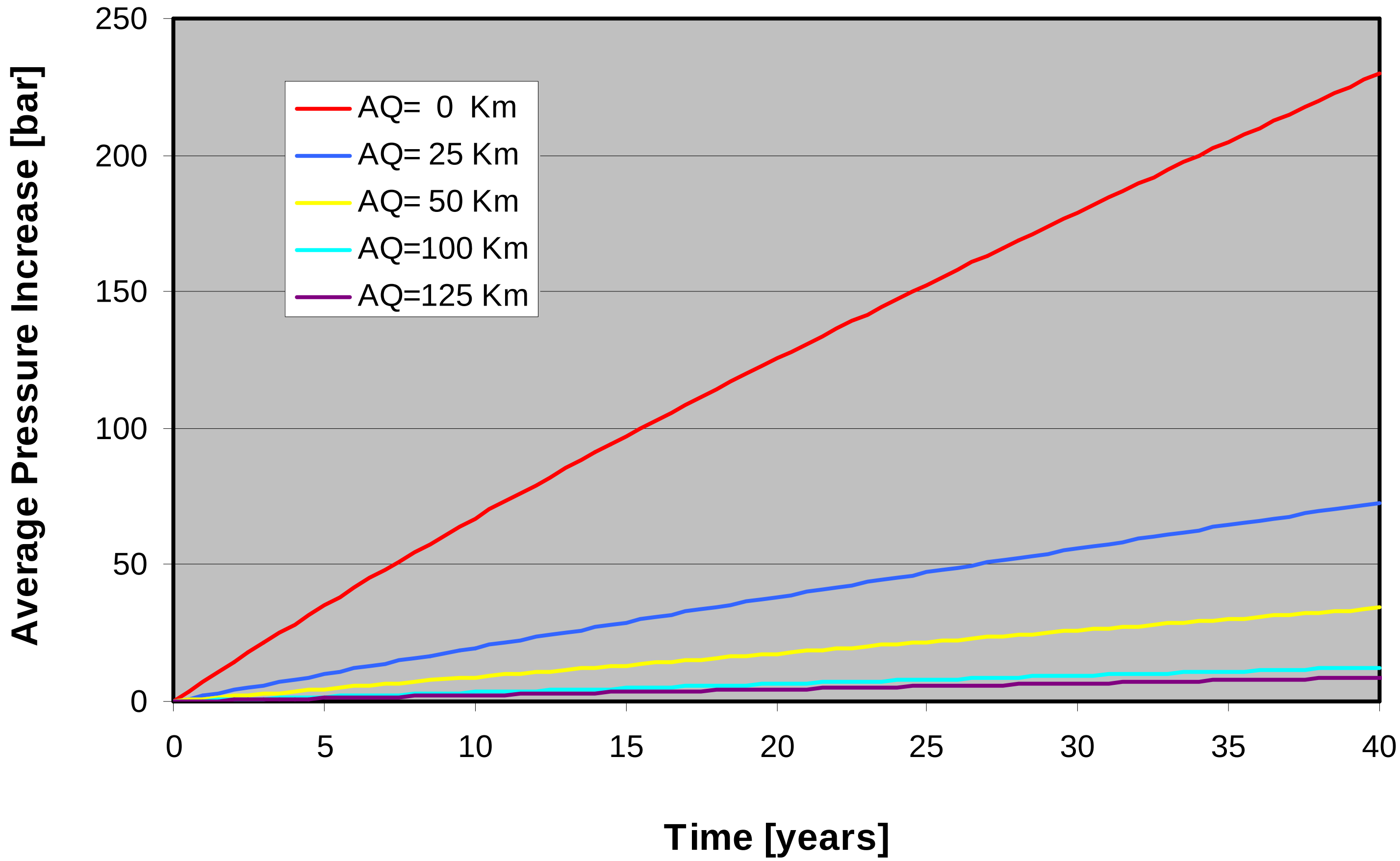
Affected Space



Affected Space – Average Pressure Respond



Conclusions (Storage Capacity)

- Affected space is full (rock and water)
- More space via pressure increase and compressibility
- length * width * height * N/G * poro - (Cw +Cr) * Pavg
- Pavg = Allowed average pressure increase in affected area
- If pressure increase too large => more affected space or less CO_2
- In example nearly 300 x 300 km, 400 Mt is 10.5 bar increase in average volume weighted pressure
- (2×10^{-5} 1/bar * 10 bar => 0.0002 % Earlier calculations with 100 bar via the geostatic approach/limitation max. 2 %)

Overview

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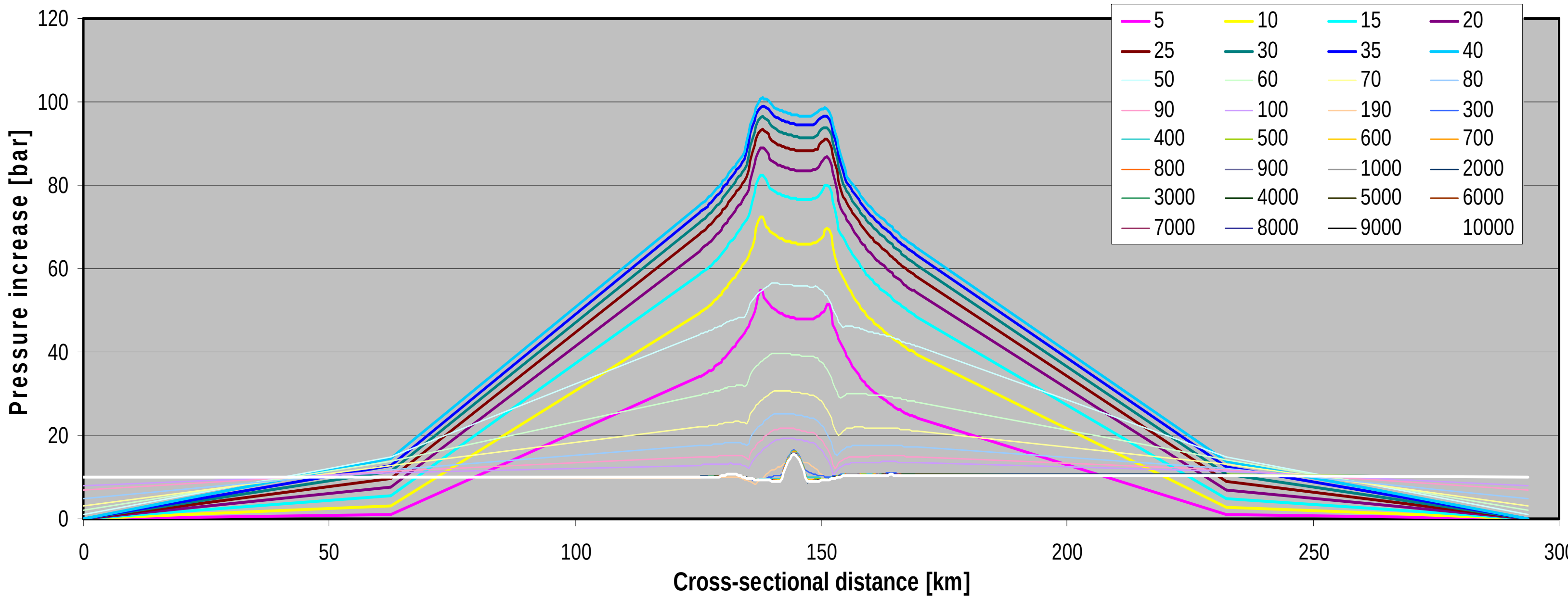
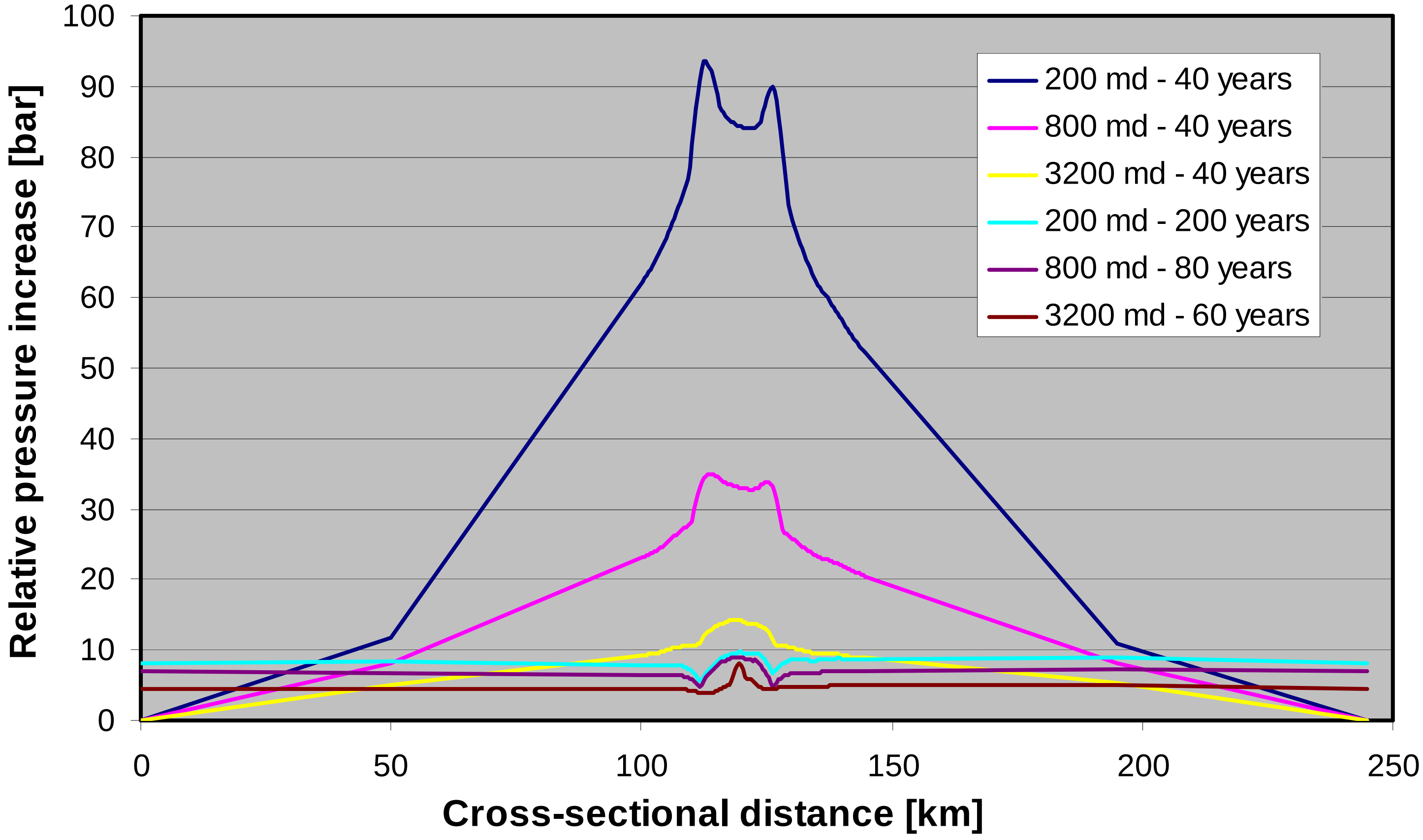
Potential Injectivity 1 (Permeability vs. Local Pressure)



Potential Injectivity 2 (Permeability vs. Local Pressure)



Conclusion (Potential Injectivity)

- Permeability (transmissibility) can reduce the total injection rate
- The higher the permeability the better
- Thicker also
- Pressure dispersion is important
- We developed a simple model to estimate pressure profile and maximum injection pressure
- Total injection volume rate important above individual well rate

Overview

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- **Storage Efficiency**
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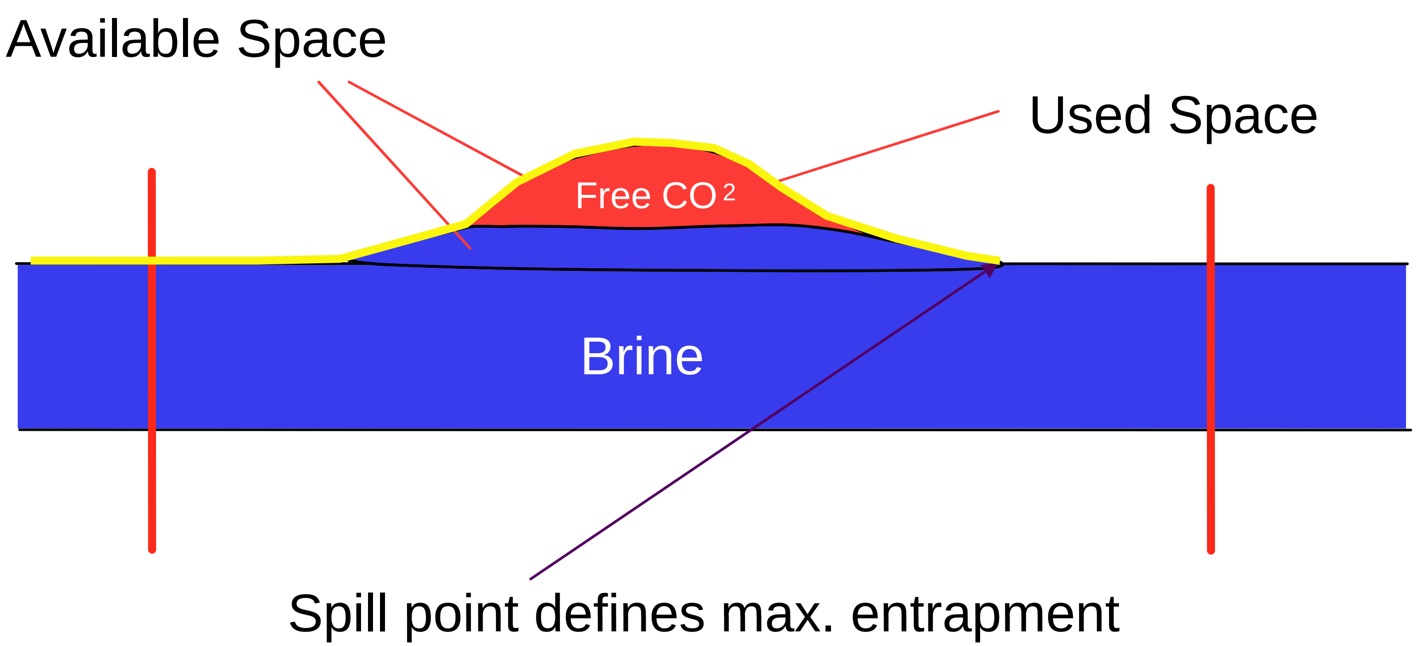
Storage Efficiency (Available Space vs. Used Space)



Conclusions (Storage Efficiency)

- Storage space defined by containment boundary and a spill point
- Storage Efficiency = Used Space / Available Space * 100 %
- Due to the solubility of CO_2 in water the Storage Efficiency could be specified in a form of a dynamic parameter

Overview

- Introduction
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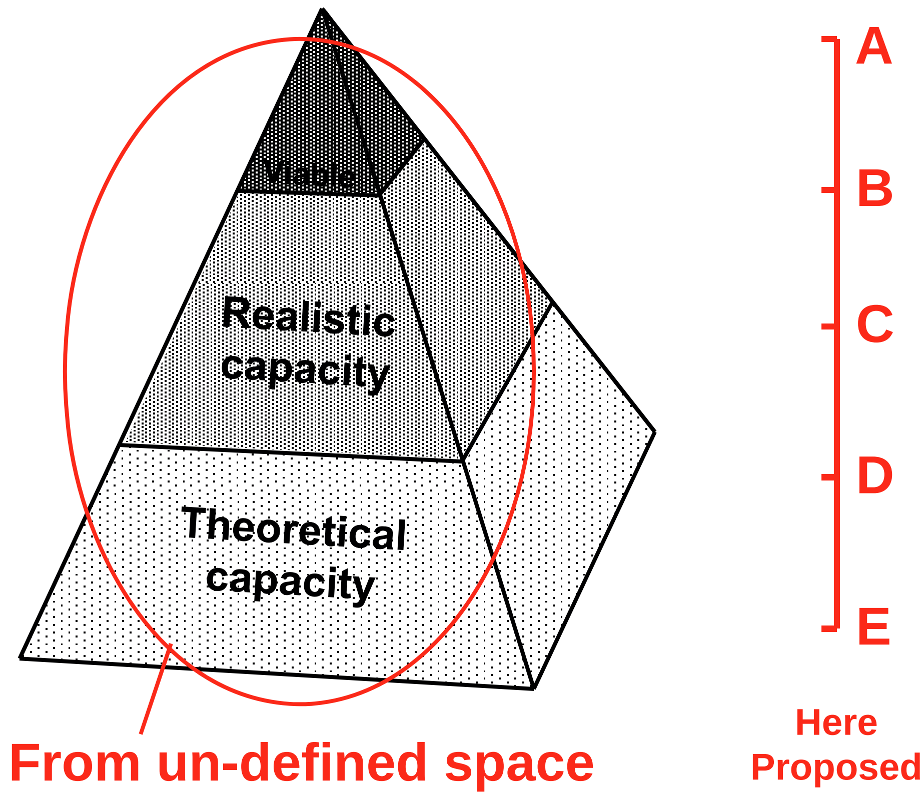
- Injectivity
- Storage Efficiency
- **Probability of storage**
- Conclusions

Data and probability of results

Classificati on	Description
A (Absolute)	All data used is b averaging is base methods. The dat Description of the and geological stu by sufficient well
B	As “A”, with the e two important par permeability. The situation.
C	The main descrip estimation is mad some uncertainty they are not be ba
D	Measurements in as a storage loca speculations or b permeability, seal
E (Estimate)	All data items are



Techno-Economic Resource Pyramid, after Bradshaw

Conclusions

- Subsurface is full (rock and water)

- More space via pressure increase and compressibility

We have specified:

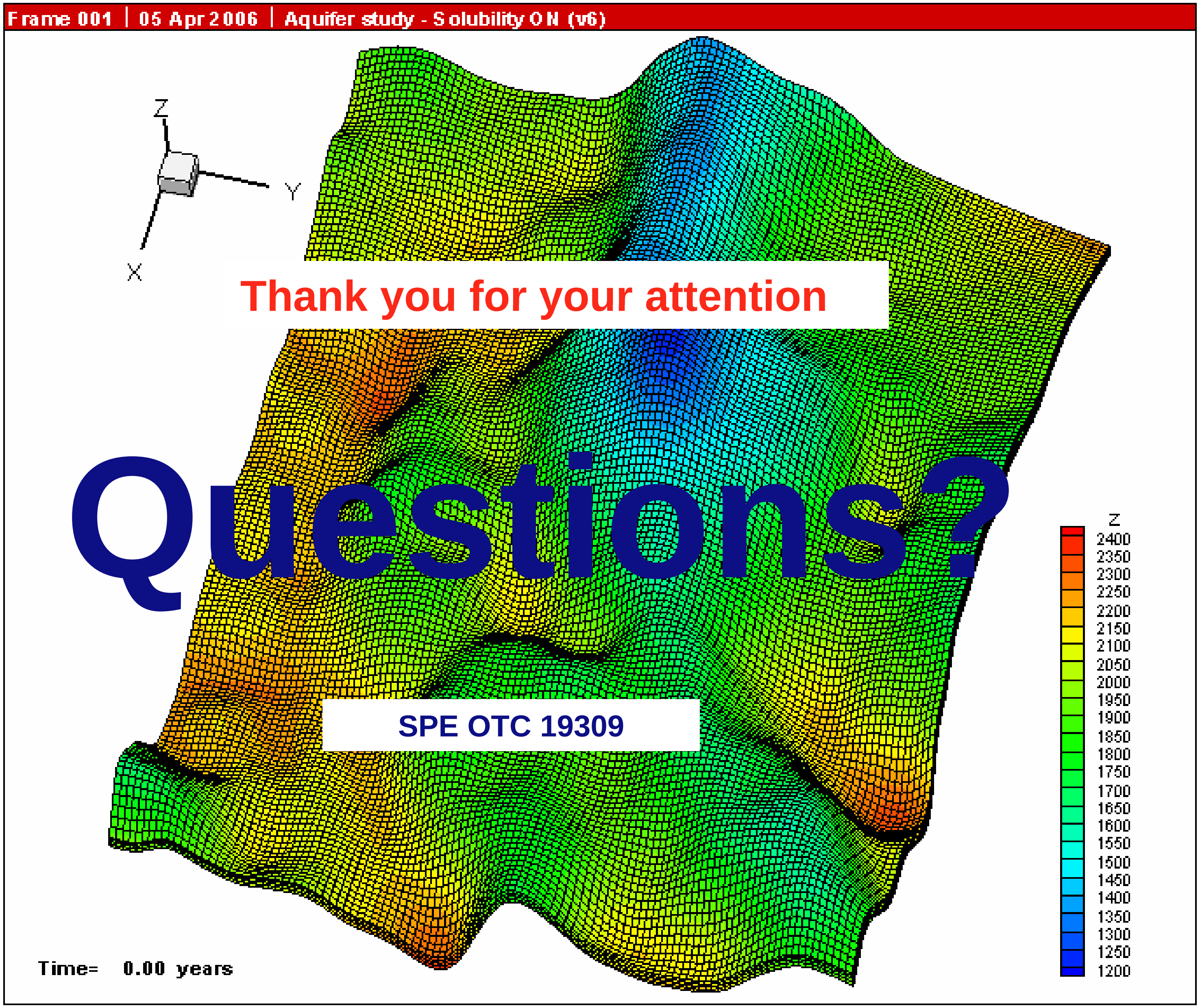
- Affected Space (effect of activity is felt, needed for space)
- Storage Capacity (Volume vs. Average Pressure)
- Potential Injectivity (Permeability vs. Local Pressure)
- Storage Efficiency (Available Space vs. Used Space)
- Data / information probability schema

- For Calculations see paper (OTC 19309)

Thank you for your attention

Questions?

SPE OTC 19309



Engineering for CO_2 geological storage

Injectivity

Y. Le Gallo

Outline

❶ Injectivity issues

❷ Current approaches

❸ Way forward

Geogreen strength: Shareholders

Synergy between three key players

- Géostock, an international reputed company involved in gas and liquid hydrocarbon underground storage operations *40%*
- IFP, involved in R&D and all important CCS projects (CASTOR) *40%*
- The Bureau for Geological and Mining Research (BRGM), involved in R&D and in expertise for Public Authorities *20%*

Geogreen strategy

Safety and quality →
- Target: ISO9001 end 2009

Independence →
- No technology provision

Long term approach →
- Owner's engineering

Pragmatism →
- Visibility
- Shareholders' know-how
- Internal resources
- Link with shareholders' offices abroad
- Cooperation with major engineering companies

Software

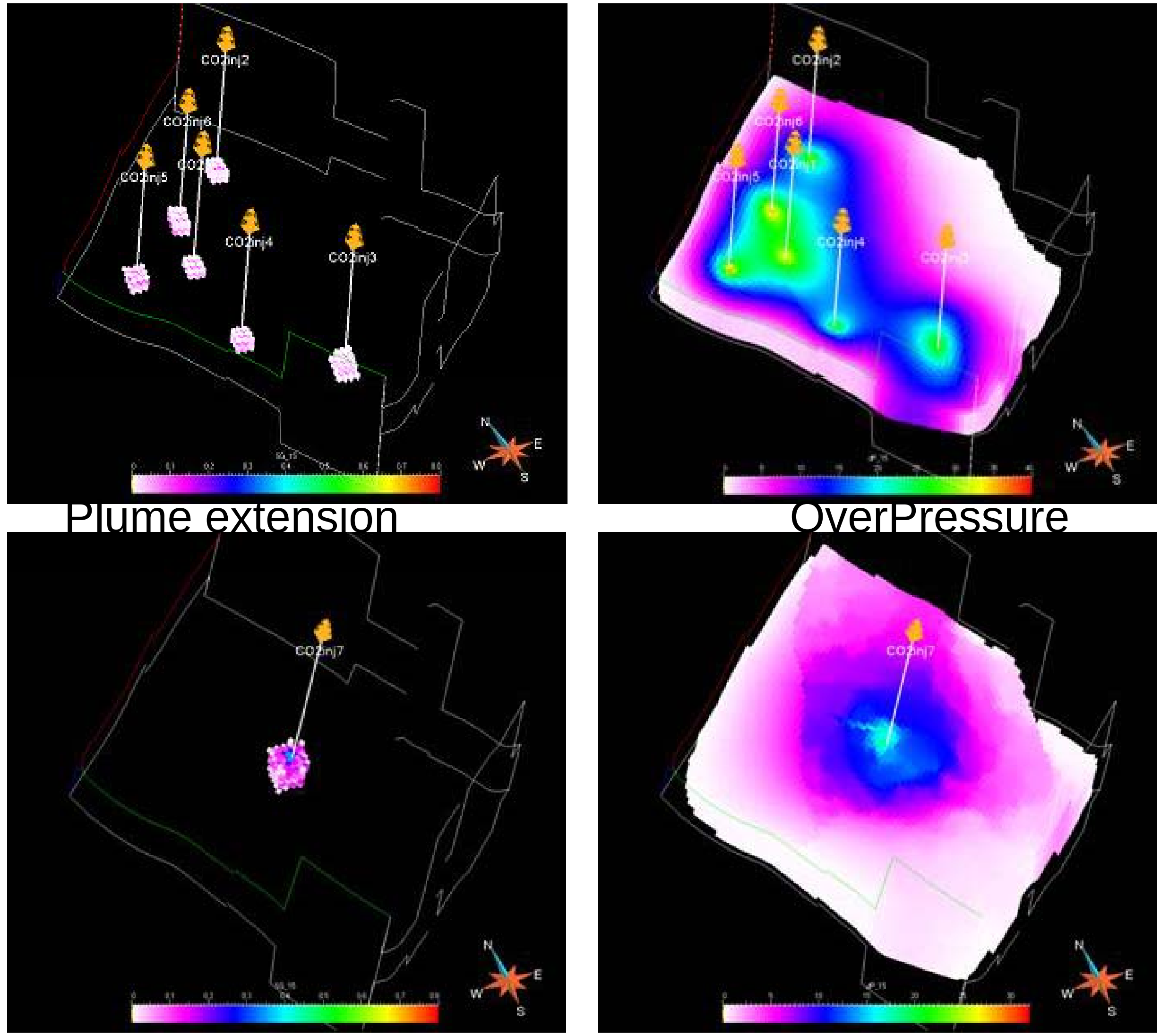
- All reservoir software developed by IFP and marketed by Beicip-Franlab (RML™, Easytrace™, Interwell™, CondorFlow™, PumaFlow™)
- IFP dedicated prototype software COORES™
- Additional software:
  - Petrophysics: Elan™
  - Geological modeling: Petrel™
  - Seismic interpretation: Charisma™ workstation
  - Geomechanics: Abaqus™
  - Well performance: Prosper™
  - Static modeling: MATBAL™
  - Reservoir dynamic modeling: ECLIPSE™
  - Sensitivity Analysis: COUGAR™
  - Process: HYSIS™
  - Life Cycle Analysis: GaBi4™ (Energy and GHG Performance Analysis for complex processes)

Storage Site selection study

- Technical criteria: the storage
  - Capacity
  - Injectivity
  - Confinement / trapping (Safety Management)
  - Potential EOR option for depleted fields
- Other criteria: the regional and local environment – Operational constraints
  - Seismic risk exclusion, major faults
  - Competition with other underground activities: Oil & gas exploration / production, geothermal well, underground gas storage, ...
  - Environmental exclusion (urban and industrial areas, water resources, classified sites)
  - Potential operational difficulties (from licensing instruction / to injection, protection of fauna and flora, waste disposal, existing wells, faults…)

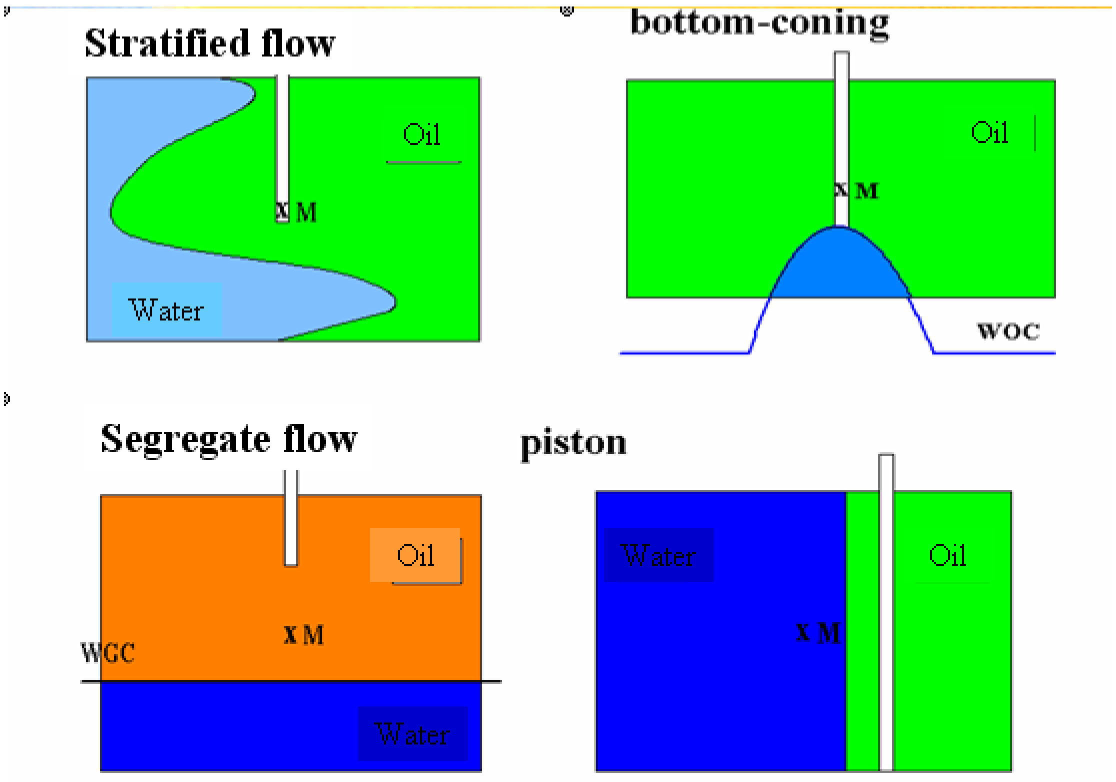
Key drivers for CCS project economics

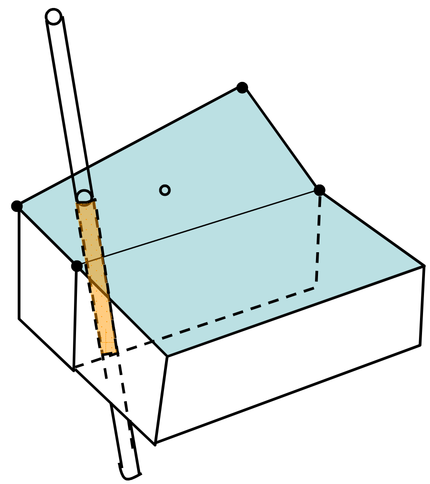
- Number of wells
- Rate of injection



Injectivity… an old problem

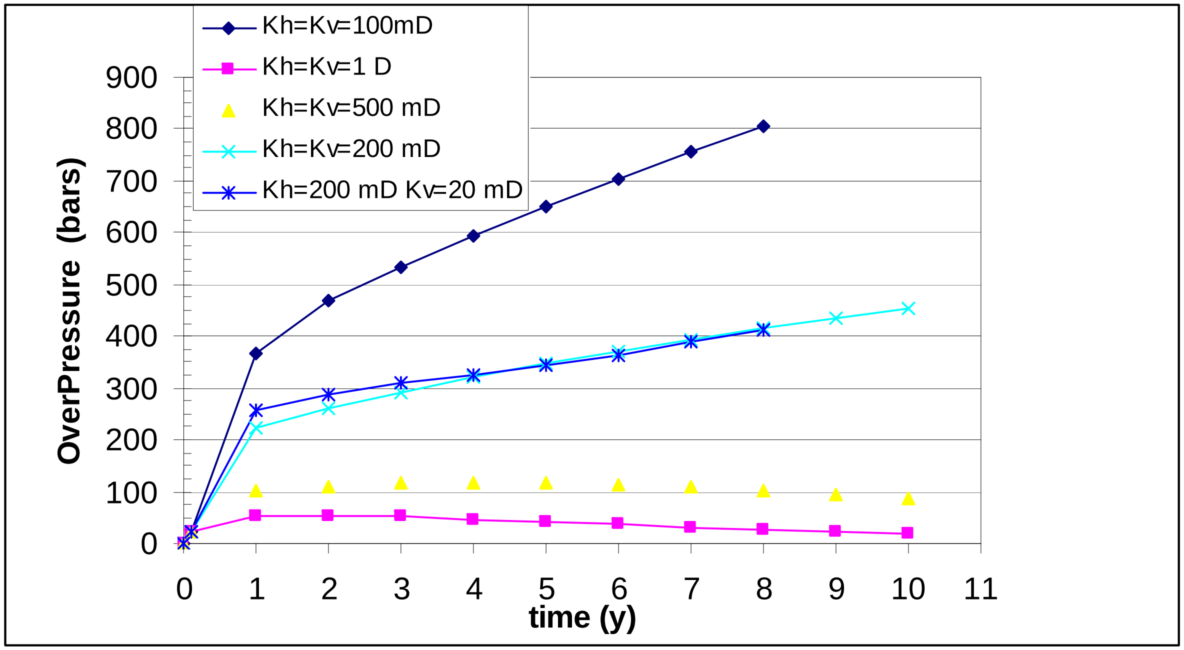
- Injectivity is common issue in O&G => several commercial tools are available for non reactive gases
- Detailed modeling approaches of the near wellbore region are commonly performed to estimate Injectivity Index for use in reservoir model.
  - Key issues: matching pressure (and flow rate)
  - Usual suspects: K, kr, (Pc), skin
- Water compatibility (scaling) is modeled with (a few) dedicated commercial tools

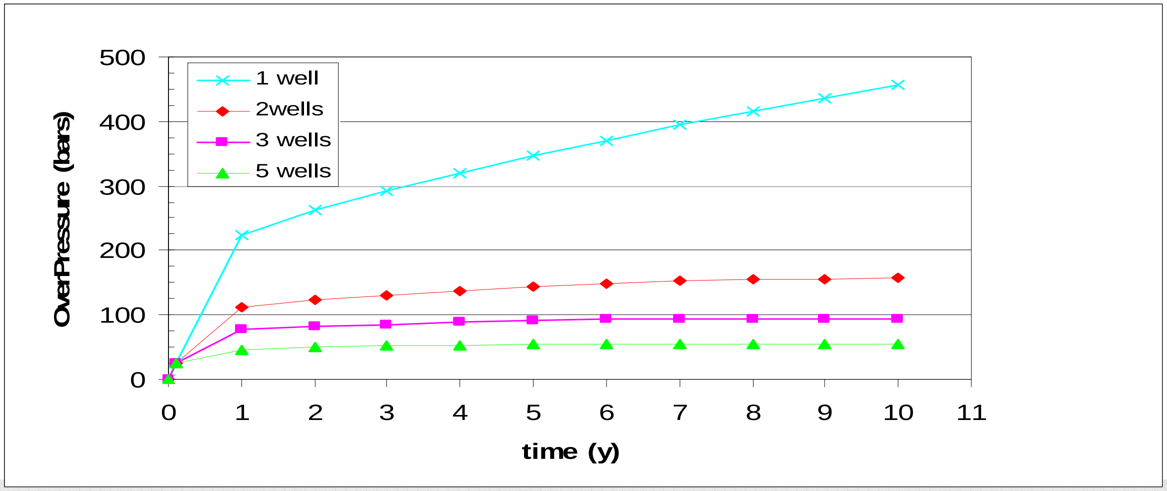




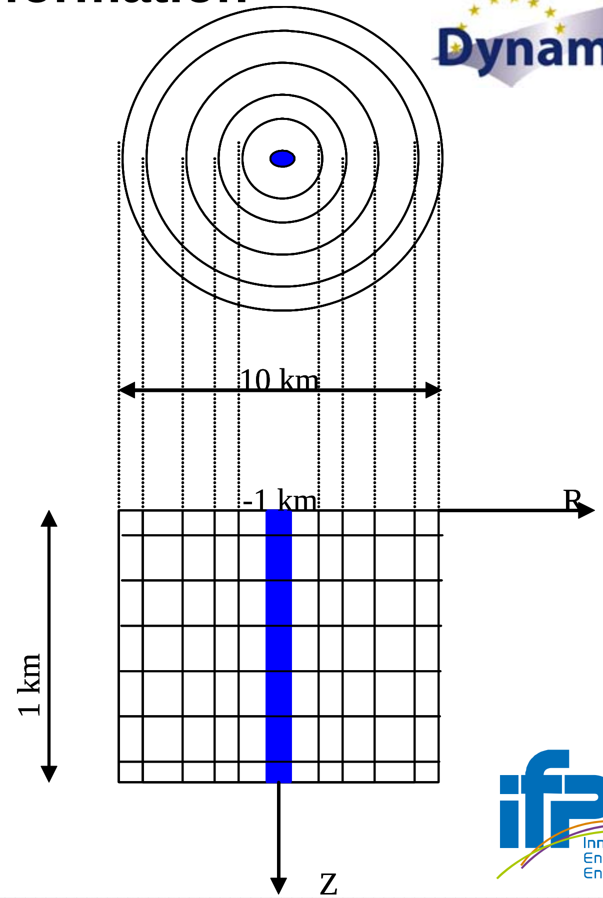
Modify end-point or kr function
Use Local Grid Refinement
Compute off-center Injectivity Index

Influence of injectivity/permeability on pressure

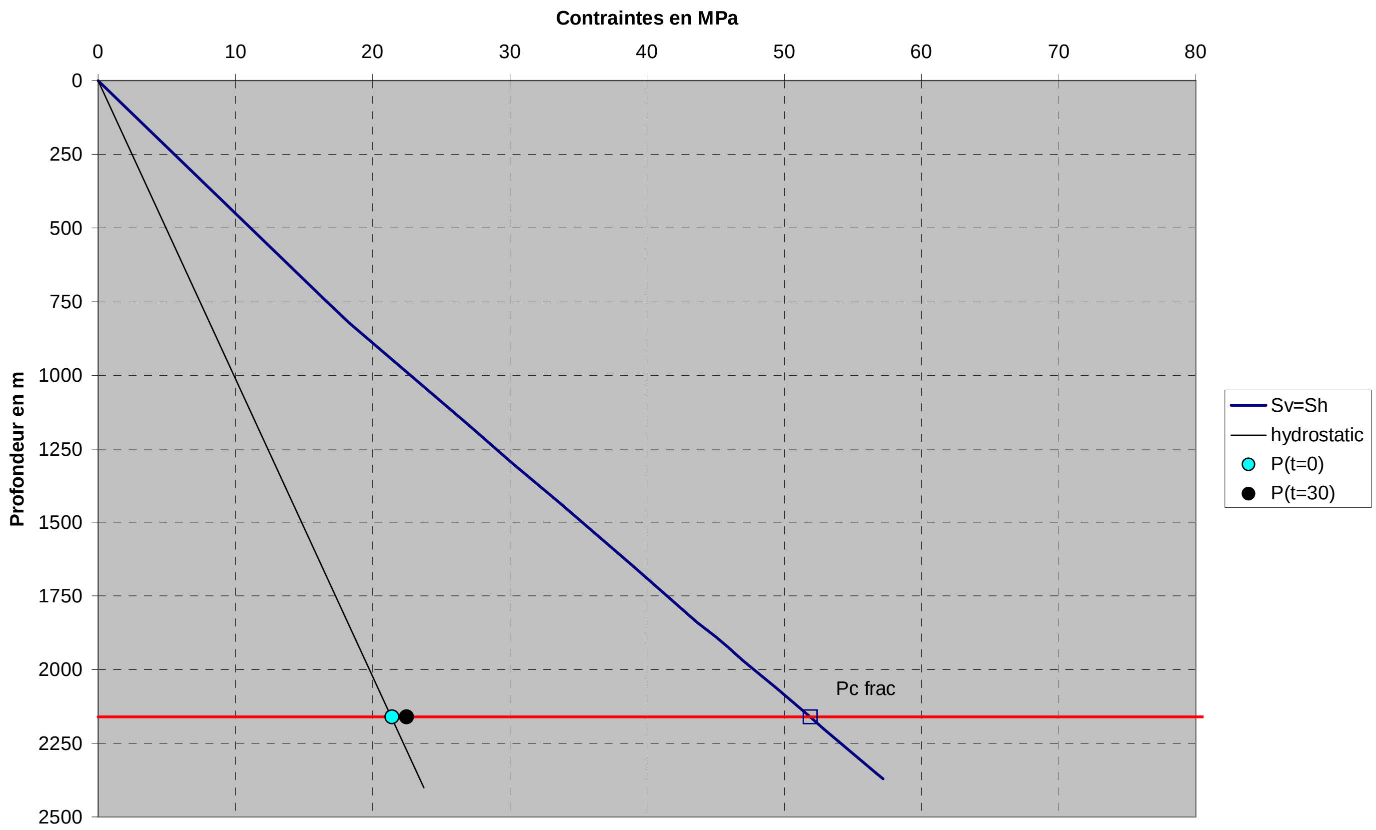




Rate of injection 2.5 Mt/y with 1 vertical well in a cylindrical infinite saline formation



Pressure constraints



Injectivity… a new concern

- CO_2 stream interactions with the reservoir/cap rock and fluids may induce different behavior from non reactive gases:
  - Pressure… because of dissolution, viscosity/density changes
  - Saturation… because of drying out and salting out
  - Salinity… because of salting out
  - Structural changes … because of geochemical interactions

Major impacts occur in the near well bore region

- Detailed modeling approaches of the near wellbore region to estimate Injectivity Index rely (mostly) on research modeling tools
  - Key issues: matching pressure (and flow rate)
  - Usual suspects: K, kr, (Pc), skin
  - New comers: salinity and mineral

Injectivity Control

$$II = Injectivity\ Index = \frac{\text{Flow Rate}}{Pinj - Pres} \propto \frac{K\,K_r}{\mu}$$

Fluid in place / injected

TRANSPORT
- Forsheimer effects
- fines
- drying
- Kr hysteresis

GEOCHEMISTRY
- rock / fluid interactions
- dissolution
- precipitation

$$II \propto \frac{K\,K_r}{\mu}$$

MECHANICAL
- Elastic properties
- Fracture properties

Géocarbone INJECTIVITE CO2

Lombard et al., 2007

Outline

❶ Injectivity issues

❷ Current approaches

❸ Way forward

Experiment-Model workflow

Petrophysical Analysis

Batch Experiments

Reactive Surface Area

K - phi

Kinetics

Literature data

Multiphase + Geochemical Model

Comparaison

exp / computation

Estimate prediction degree

Géocarbone

INJECTIVITE

CO2

Other rate, P, T, ...

Flow-through Experiments

Lombard et al., 2007

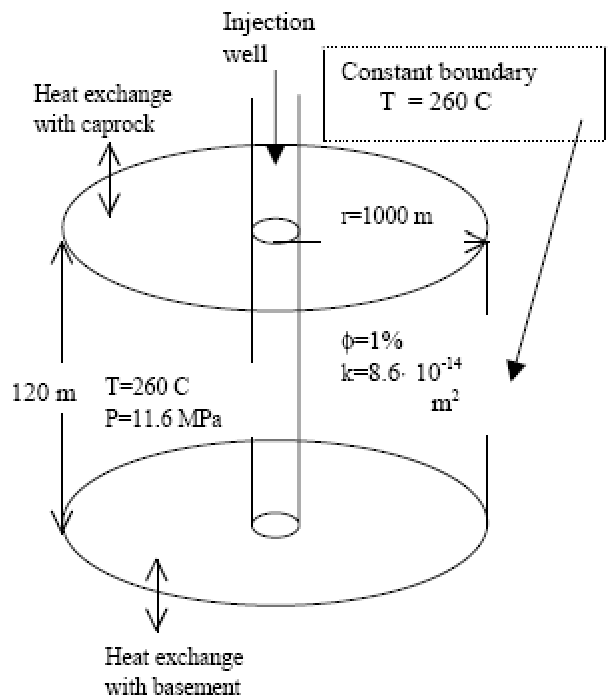


Fig. 2. Simplified conceptual model for injection well Nag-67.

Porosity variations

T. Xu et al. / Computers & Geosciences 32 (2006) 145–165 153

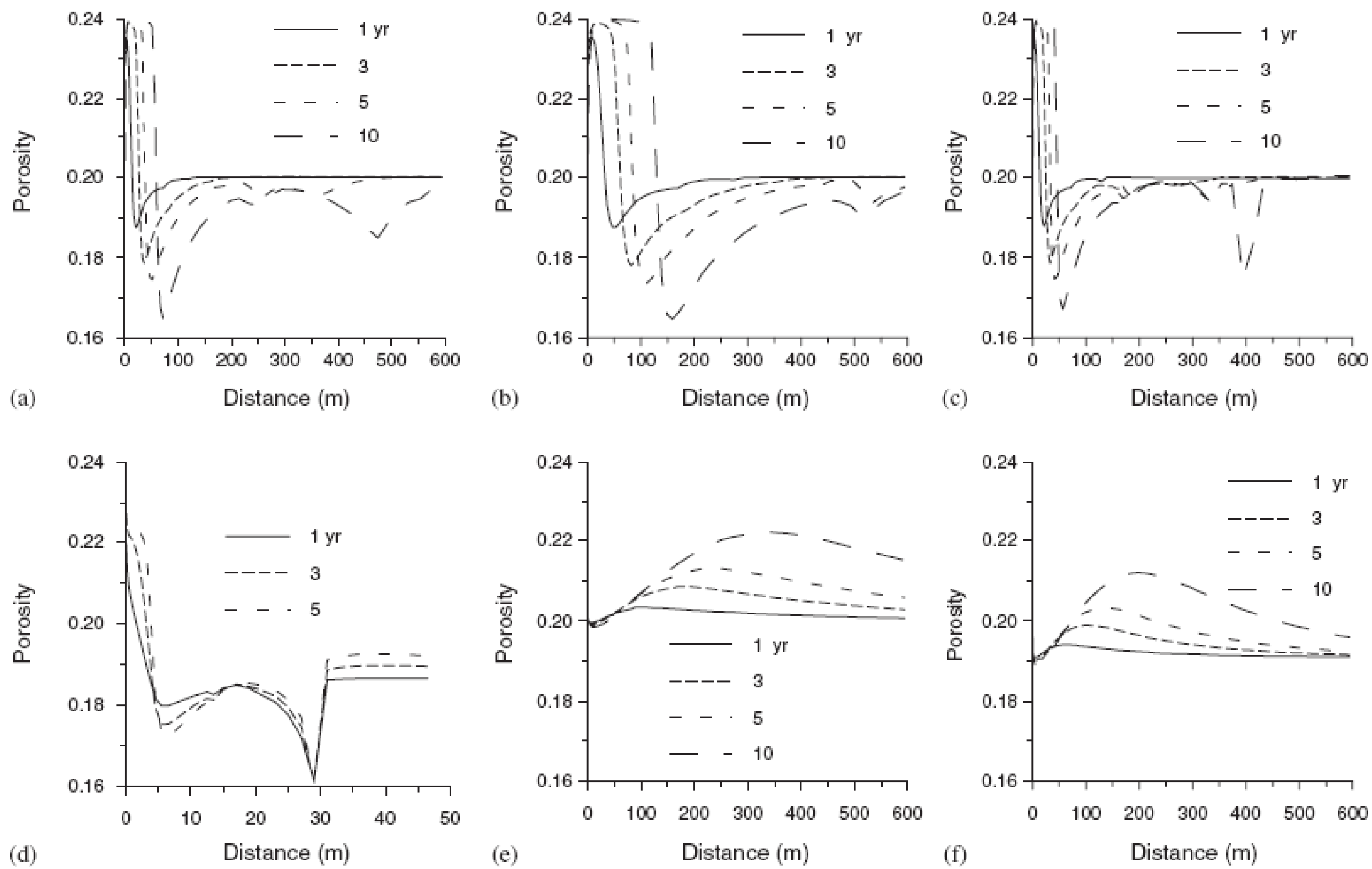


Fig. 3. Distribution of porosity obtained from all six different simulations. (a) Simulation 1 (Base case). (b) Simulation 2 (Over-pressure). (c) Simulation 3 (Verma-Pruess). (d) Simulation 4 (Swelling). (e) Simulation 5 (pH 7). (f) Simulation 6 (Mixing).

T. Xu et al. / Computers & Geosciences 32 (2006) 145–165

Permeability variation in near well bore region in Geothermal reservoir

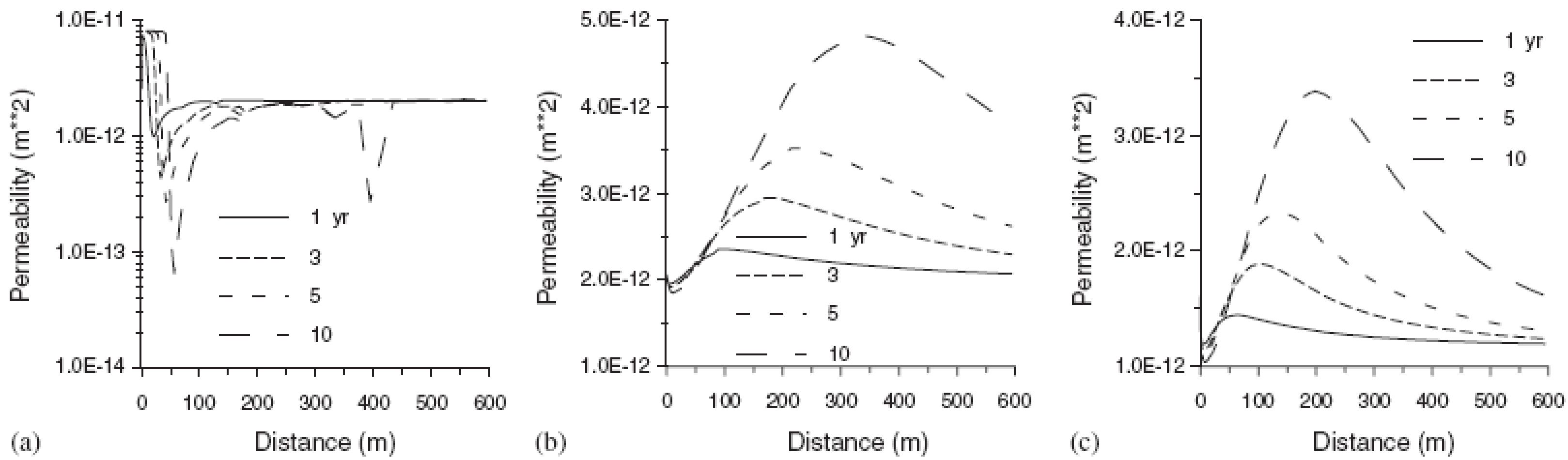
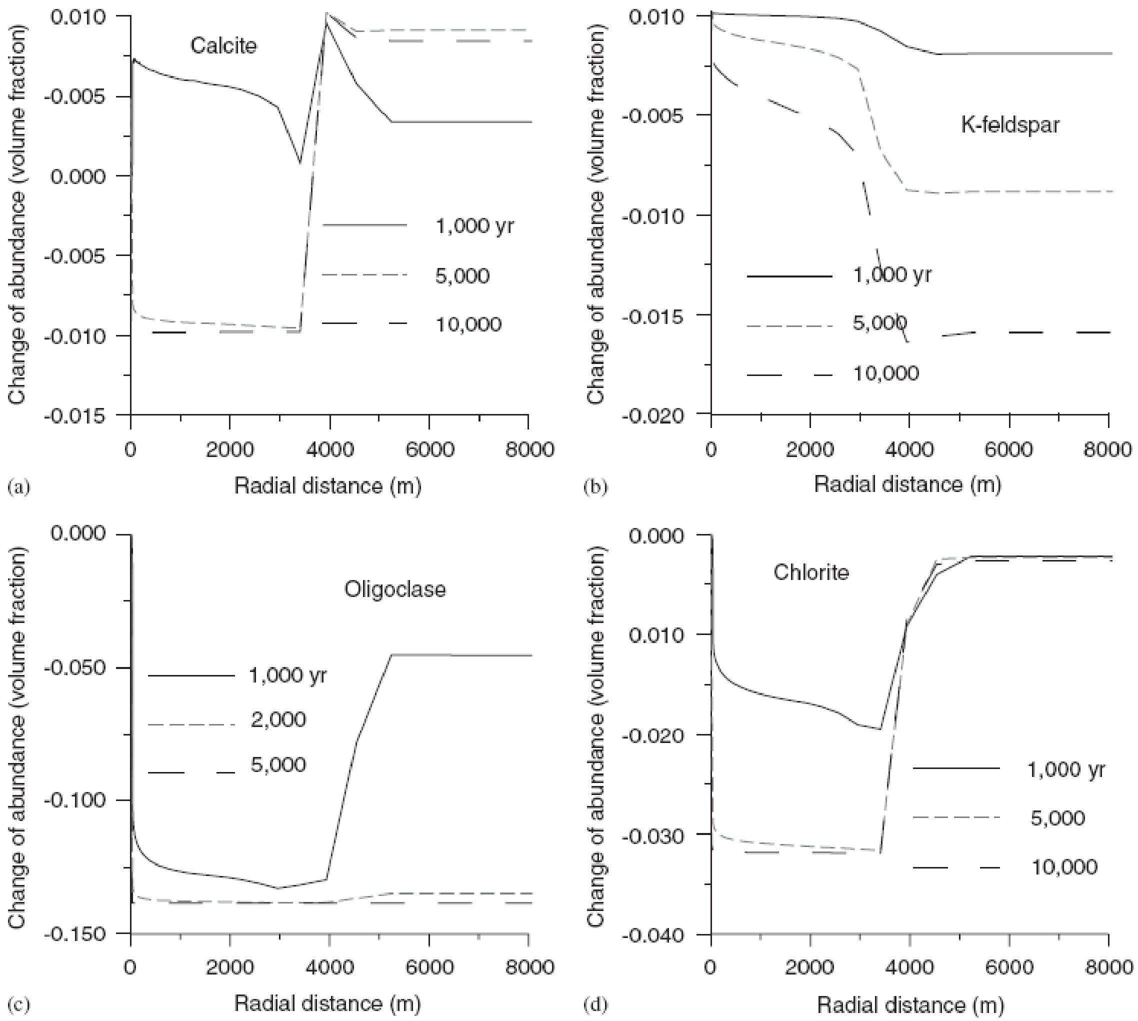


Fig. 4. Distribution of permeability obtained from three different simulations. (a) Simulation 3 (Verma-Pruess). (b) Simulation 5 (pH 7). (c) Simulation 6 (Mixing).

T. Xu et al. / Computers & Geosciences 32 (2006) 145–165

Mineral change in near wellbore region during CO_2 injection

T. Xu et al. / Computers & Geosciences 32 (2006) 145–165



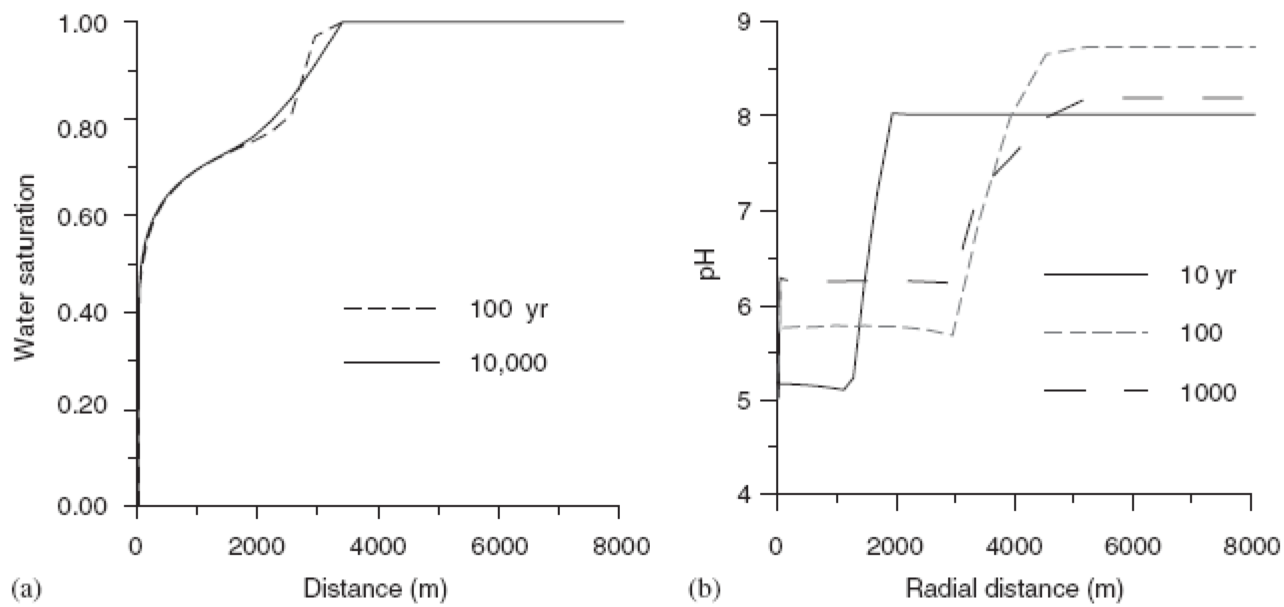
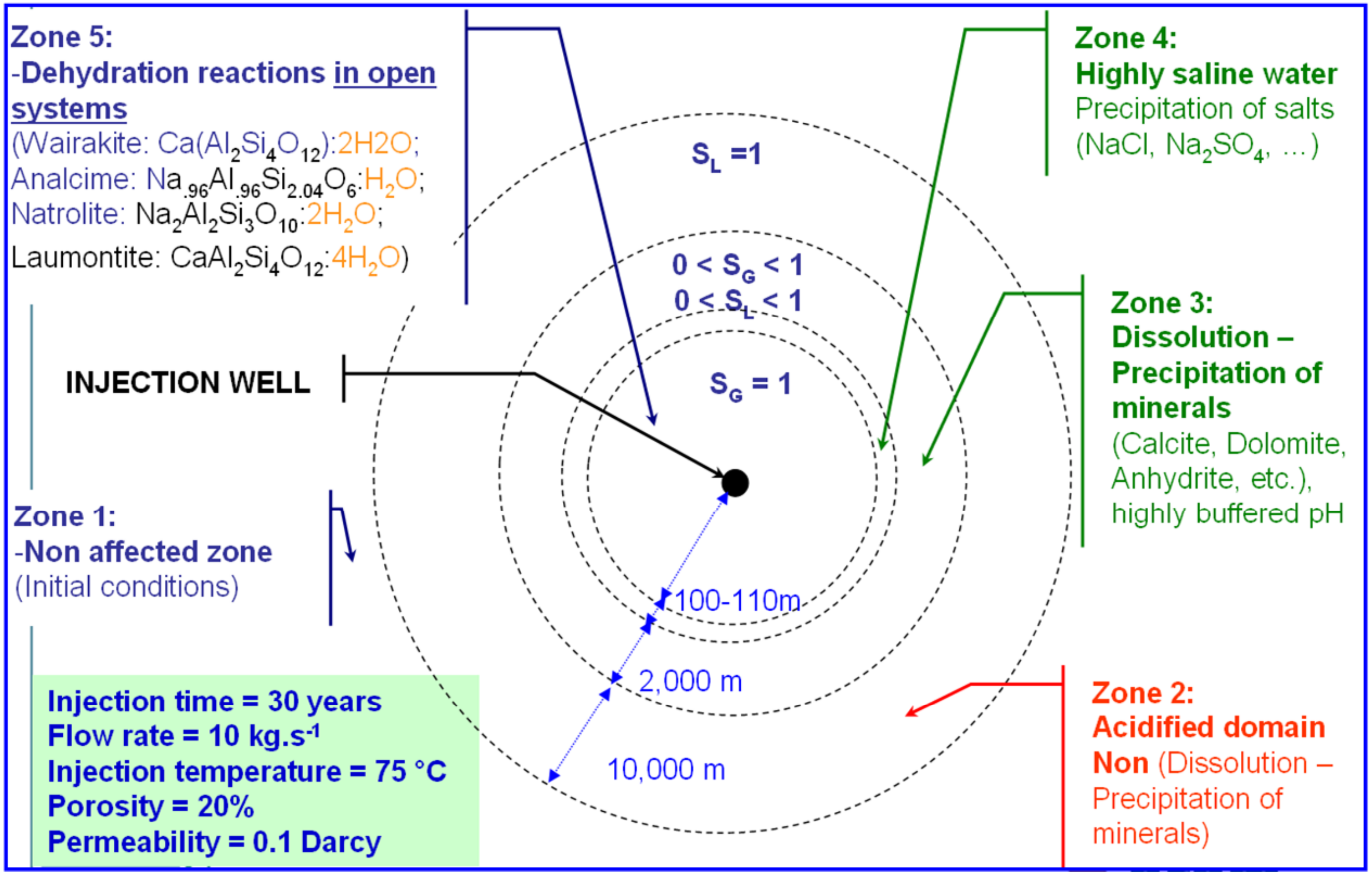


Fig. 8. Water saturation and pH at different times for 1-D radial CO_2 injection problem.

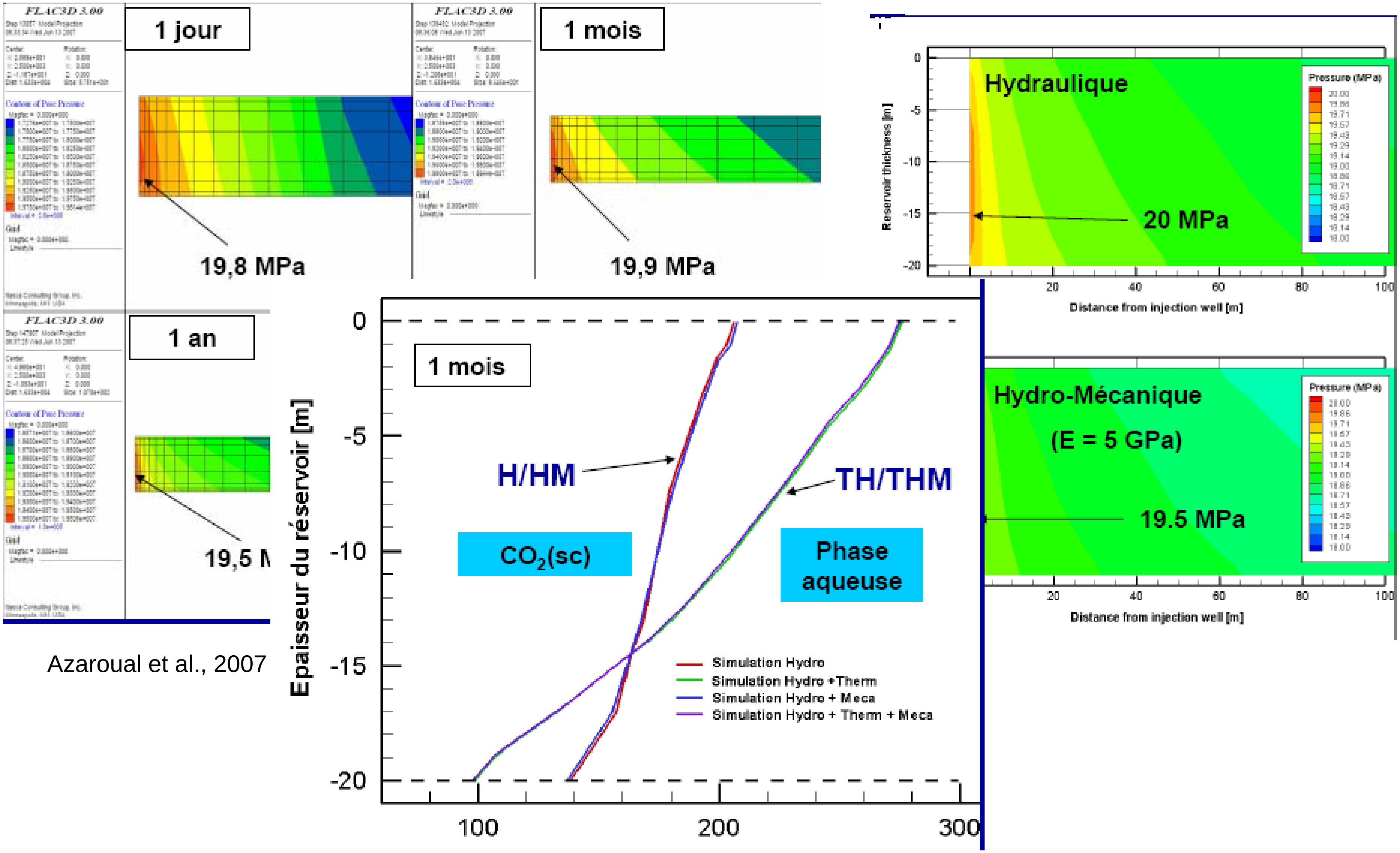
T. Xu et al. / Computers & Geosciences 32 (2006) 145–165

Near well bore effects



Azaroual et al., 2007 ; André et al., 2008

Other interactions



Azaroual et al., 2007

Outline

❶ Injectivity issues

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❸ Way forward

Challenging Injectivity

- Research
  - Account for all couplings: P, T, geochemical, geomechanical… no so obvious => coupling methodology challenges
  - Account for coupling interactions
  - Account for petrophysical and textural changes
  - Focus on more on geomechanical and less on geochemical
- Industry
  - Complex formation (carbonates) and structure (fluvial), and well trajectory => detailed near wellbore characterization both petrophysical and mineralogical
  - Tuning currently looks unavoidable either with field data or with lab data to account for CO_2 specific impact

Reservoir modeling of CO_2 aquifer storage

S.Thibeau – CO_2 Geological Storage Modelling Workshop – Orléans – 10-12/02/2009

TOTAL

Key issues

① Definition of initial conditions

② Saturation development

③ Pressure development

④ Temperature development

Key issues

① Definition of initial conditions

② Saturation development

③ Pressure development

④ Temperature development

TOTAL

Initial conditions - principle

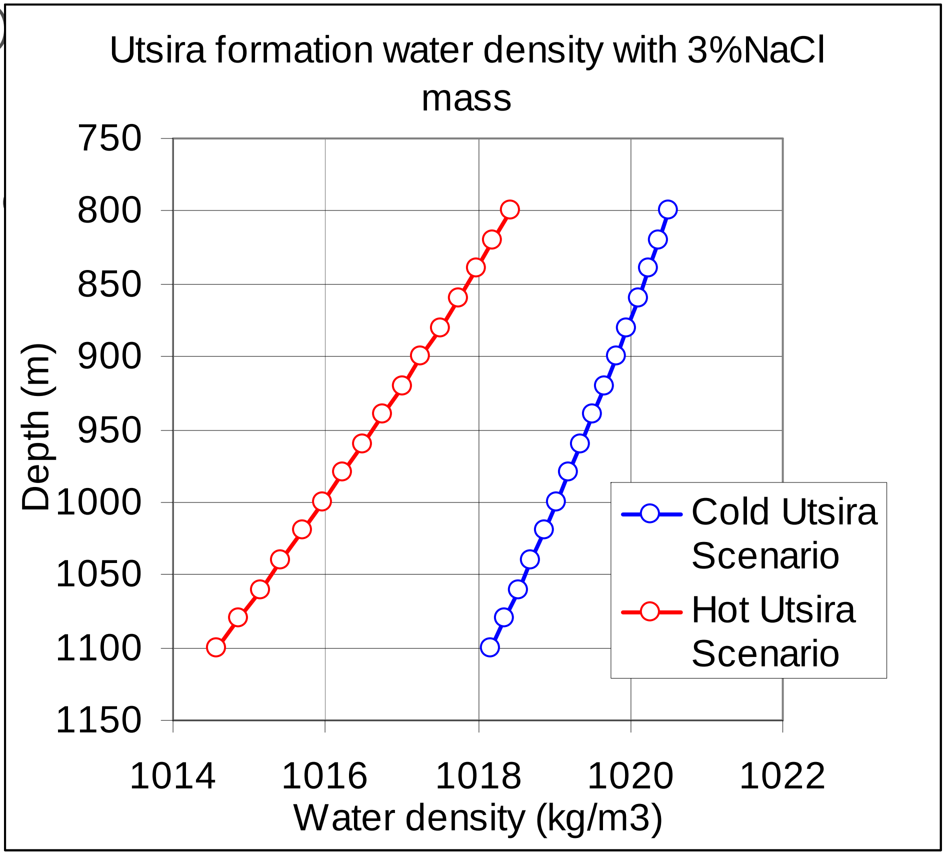
Aquifer initial conditions (at an injection site) defined by

- salinity ➲ water sample or production
- temperature ➲ measurement or regional data (gradients)
- hence, pressure ➲ pressure at datum + density calculation
- hydrodynamism ➲ complex assessment, may be not relevant to qualify an injection site

TOTAL

Initial conditions – Utsira example

- **Two reference temperatures considered (uncertainty)**
  - 37°C @ 1058 m bmsl (cold scenario)
  - 45°C @ 1058 m bmsl (hot scenario)
- **Formation water density calculati**
  - 3% NaCl mass
  - Rowe & Chou model



➢ **Unstable solution !**
  - Denser water on top

Initial conditions – Issues

- **Formation water properties at 100 bar and 40°C (3% mass NaCl)**
  - Thermal expansion: 4.1 10^{-4} / C
  - Compressibility: 4.2 10^{-5} /bar
  - ➢ If temperature gradient over 0.1 C/bar (0.01 C/m), unstability obtained
- **Possible explanations**
  - Lower temperature gradient within aquifer than other rocks (locally ?)
  - Salinity gradient to compensate for temperature gradient
  - Formation water flow (convective cells / hydrodynamism)
  - Aquifers may be temperature anomaly (spas) due to hydrodynamism
- **Beware when entering formation water properties versus pressure !**
  - For an injection site
  - Even more complex at larger scale

TOTAL

Key issues

① Definition of initial conditions

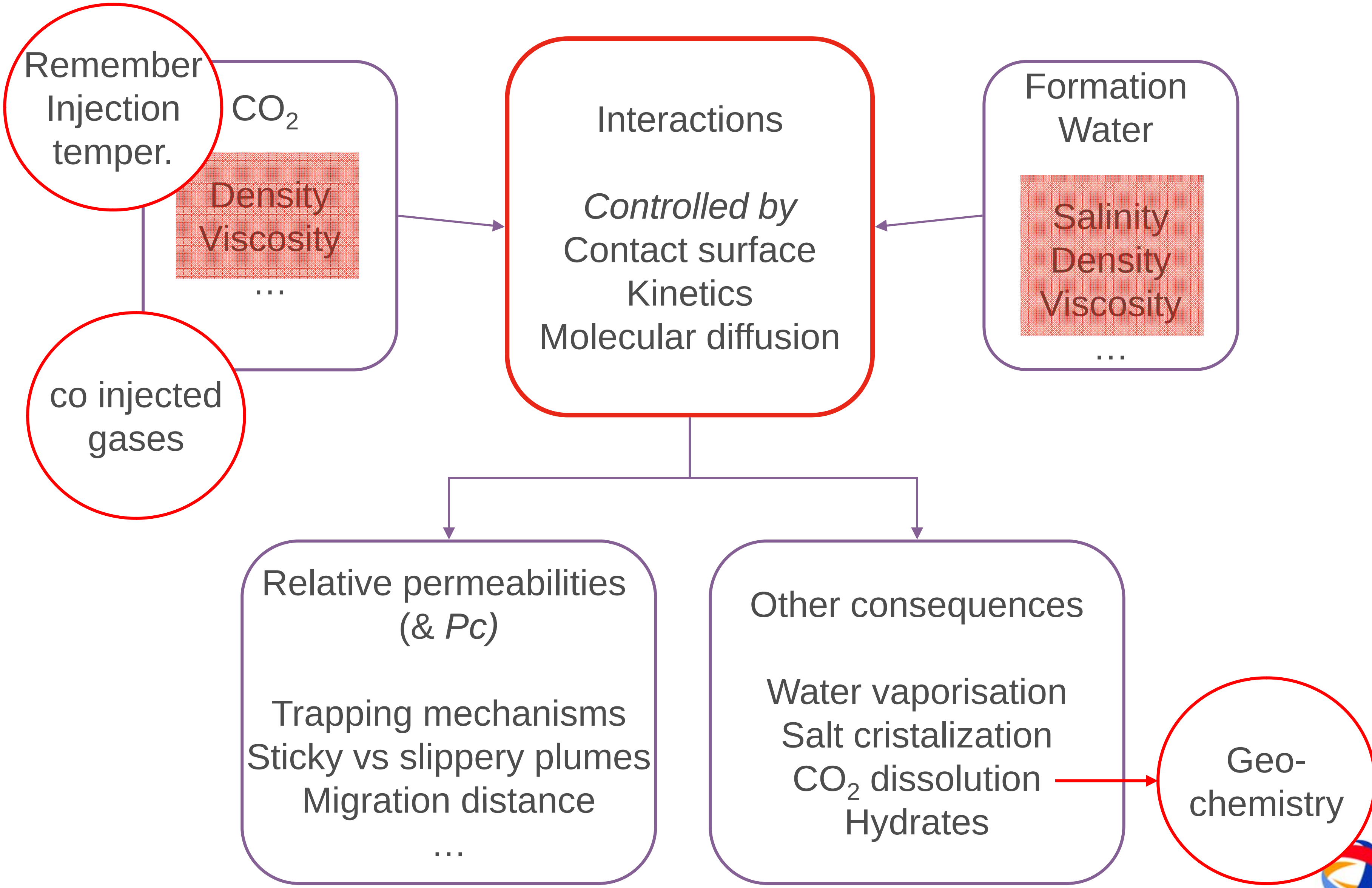
② Saturation development

③ Pressure development

④ Temperature development

TOTAL

Saturation development (CO_2 plume)



TOTAL

Saturation developments

- **A model should be fit for purposes**

- **Several possible objectives**
  - Ensure CO_2 volume will be injected / injectivity issues
  - Define monitoring strategy
  - Evaluate migration distance (tilted aquifers), connection to other wells/faults
  - Evaluate long term fate of CO_2 (dissolution, mineralization)

- **Selection of relevant effects based on objective**
  - Where ? (near well effect, far away migration)
  - What physics ?
  - What time frame ?

- **A lot of very good literature on various effects**

TOTAL

Key issues

① Definition of initial conditions

② Saturation development

③ Pressure development

④ Temperature development

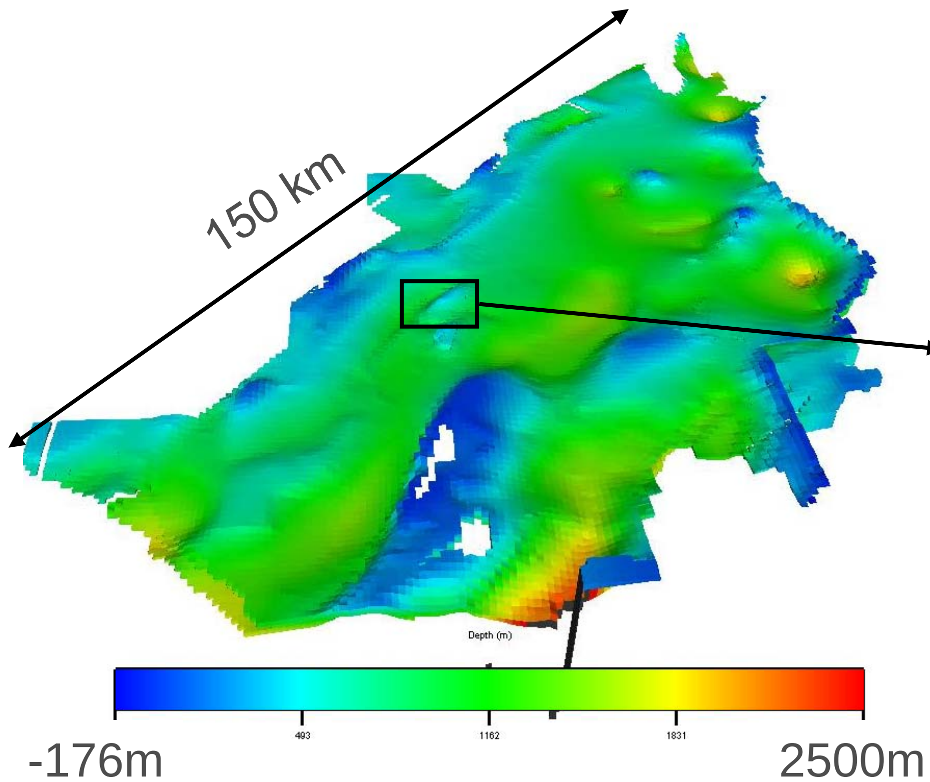
Pressure development – Technical issues

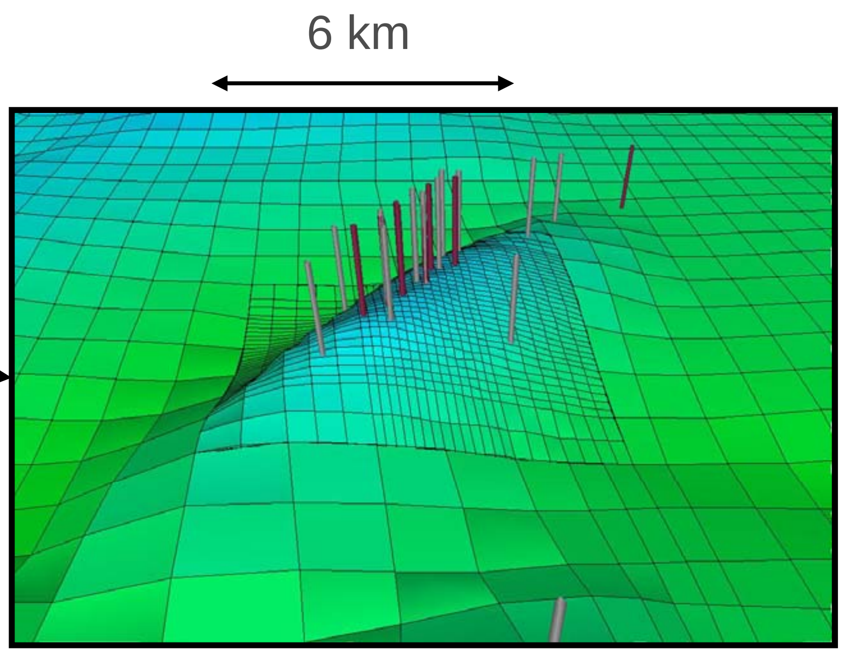
- **CO_2 injection leads to formation water pressure build up**
  - low water and rock compressibility
  - huge CO_2 volumes to be injected if CO_2 storage becomes a global solution
  - expected water pressure build up at basin scale (it is not a local, site effect)
- **Pressure (gas and formation water) should not exceed**
  - Hydraulic fracturation pressure of the cap rock or fault activation pressure
  - at the injector (bottom hole flowing pressure) or anywhere in the aquifer
- **Formation water pressure development controlled by**
  - water in place within the simulation domain
  - connectivity (permeability, thickness) within the simulation domain
  - Flow out of the simulation domain
- **As a consequence**
  - ➢Importance of the size of the simulation domain and its heterogeneities
  - ➢injection site behaviour largely dependent on flow boundary conditions

TOTAL

Size of the simulation domain

- **Option 1: Incorporate basin scale features and flow model**
  - Can incorporate geological knowledge
  - Can use simplified geometry to capture connected water pore volume and KH
  - Injection should have no effect close to boundaries, (no water fluxes, no pressure change)





TOTAL

Size of the simulation domain

- **Option 2: Side boundary conditions**
  - Reservoir size limited to injection site
  - Size defined to capture CO_2 plume migration
- **Requires boundary conditions in order to model pressure dissipation**
  - Constant pressure boundaries are very optimistic !
  - To check the impact of boundary conditions, compare no flow versus constant pressure
  - Approach identical to analytical aquifer should/could be used
    - Water volume of the aquifer connected to the injection site
    - Connectivity (KH) in the connected analytical aquifer
- **Pressure developments (for large scale injections) very sensitive to the size of the simulation domain and type of boundary conditions**

TOTAL

Pressure development – other issues

- **Will formation water flow into the cap rocks ?**
  - If this effect is expected, it should be properly modeled
- **Will hydrodynamism interact with the CO2 injection**
  - Open aquifers ?
  - Hydrodynamically active aquifers ?
- **Interference within the basin**
  - Geothermal projects ; Gas storage ; …

Key issues

① Definition of initial conditions

② Saturation development

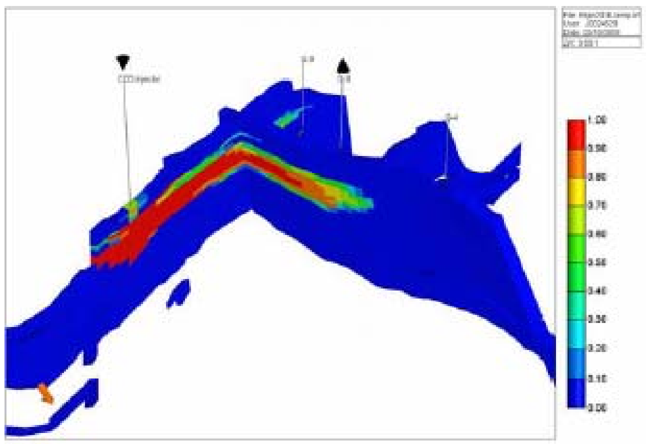
③ Pressure development

④ <u>Temperature development</u>

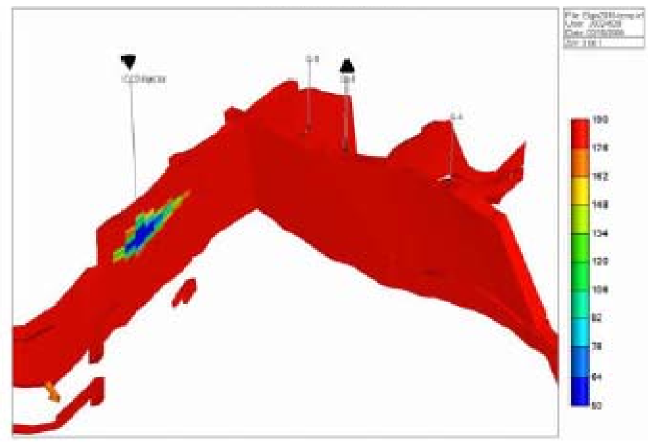
TOTAL

Temperature modeling

- **Expected impacts**
  - CO_2 injectivity (mobility)
  - CO_2 migration in the cooled area
  - thermal fracturing
  - impact on geochemical reactions
  - CO_2 hydrates
- **Cooled area eventually smaller than flooded area**



CO_2 molar fraction
(injection in a gas reservoir)



Temperature

Modeling Caprock Integrity: Assessment Objectives

Presented by
Brian McPherson
University of Utah

IEA-GHG CO_2 GEOLOGICAL STORAGE MODELLING WORKSHOP
Orleans, France – February 10, 2009

Acknowledgements

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- Many other scientists in the Southwest Regional Partnership on Carbon Sequestration

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- U.S. Department of Energy
- National Energy Technology Laboratory
- University of Utah

Outline

- **Assessment Objectives**
- **Geochemical Impacts on Caprock Integrity**
- **Geomechanical Impacts on Caprock Integrity**
- **Coupling Geochemical and Geomechanical Processes: Competing Roles**
- **Assessment Objectives**

Outline

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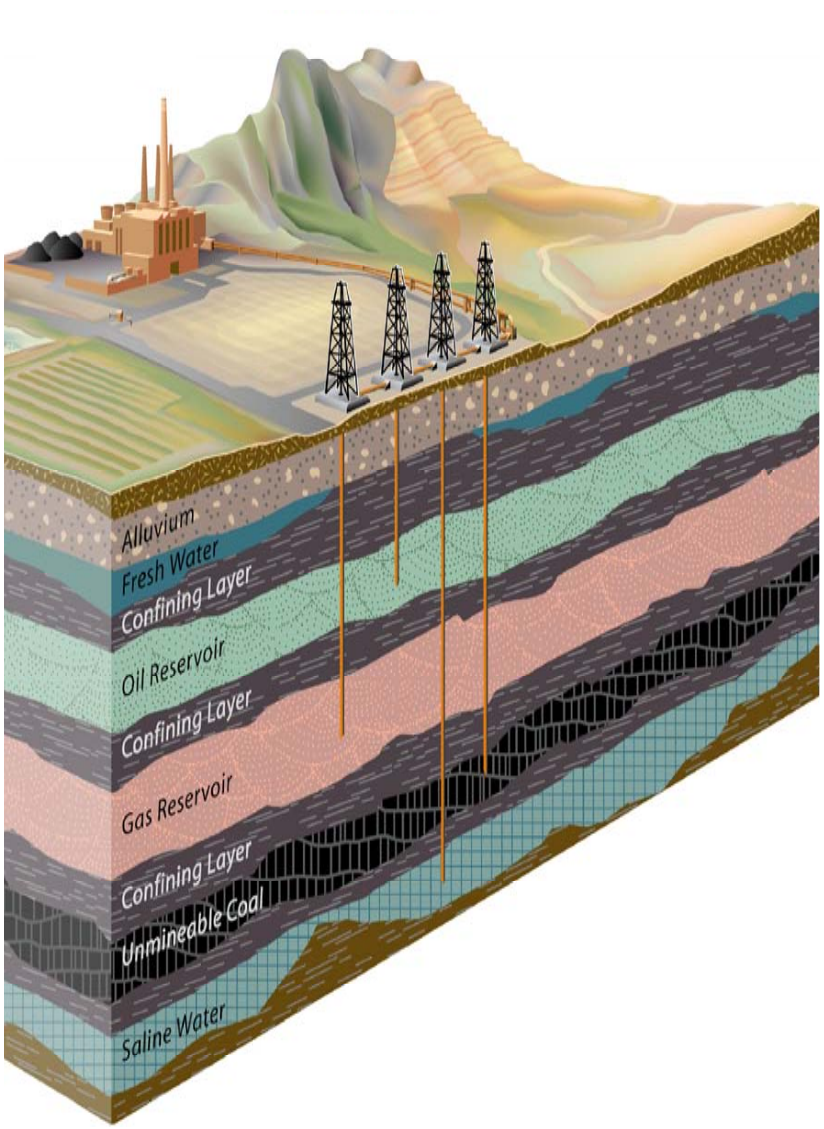
Primary Assessment Objectives



- geochemical (**GC**) processes that degrade caprock integrity
- geomechanical (**GM**) processes that degrade caprock integrity
- **coupling** GM and GC
- **resolving uncertainties** associated with subsurface properties, GM and GC
- **resolving competing time-scales** of GM and GC
- **resolving spatial-scaling limitations** (e.g., calibration using lab-scale data)

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- Assessment Objectives
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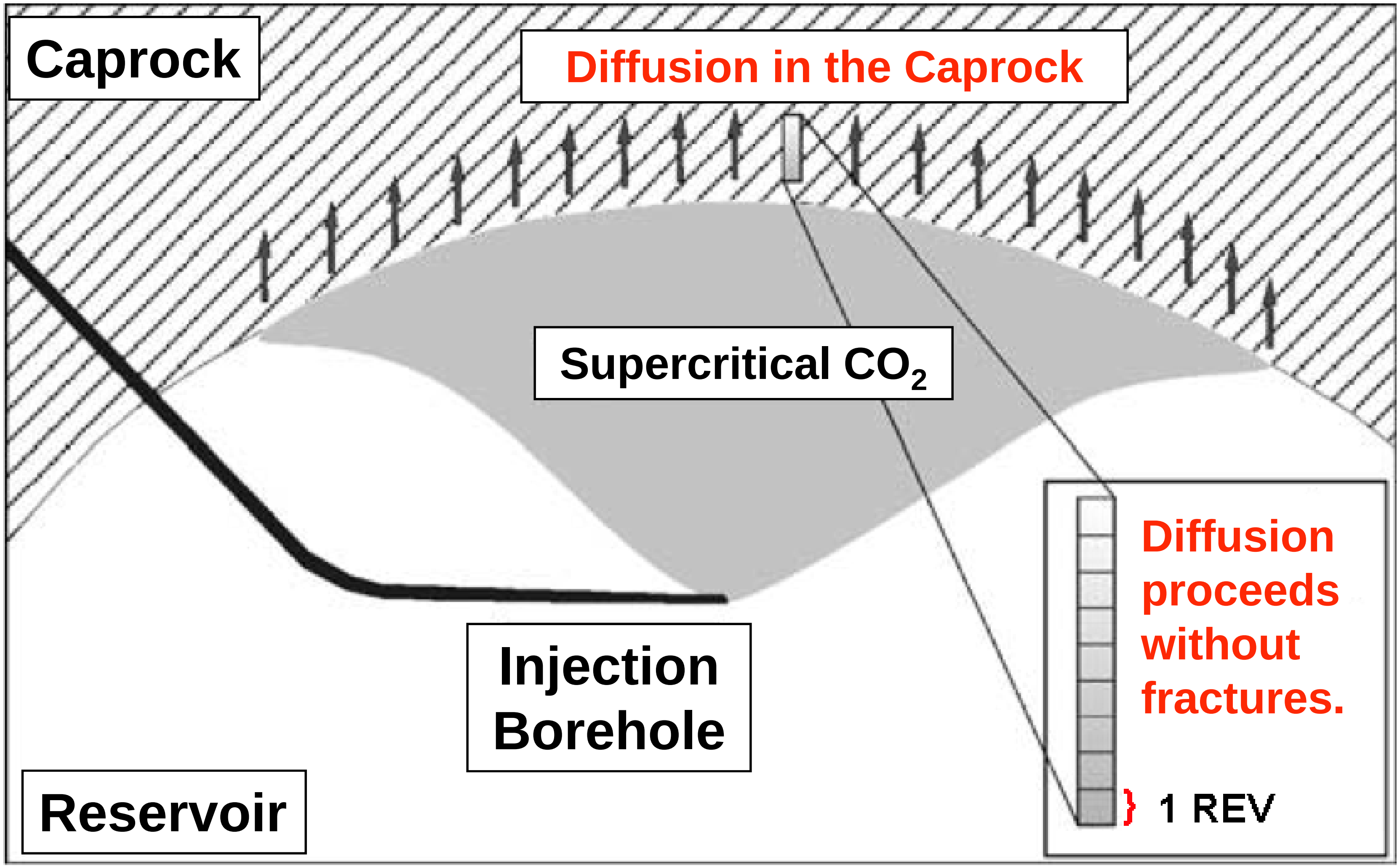
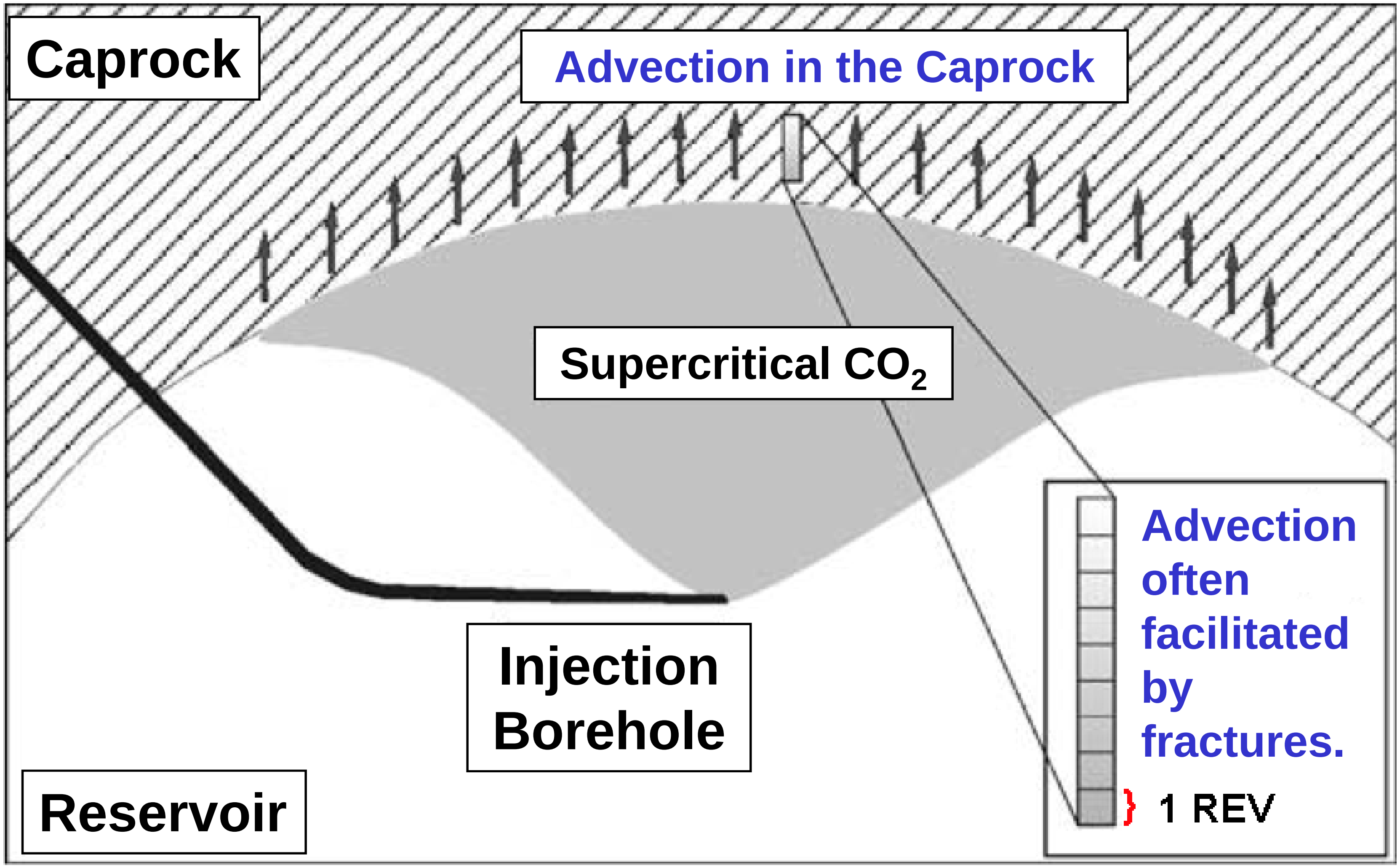
Geochemical Reactions that Degrade Caprock Integrity: Flow Processes



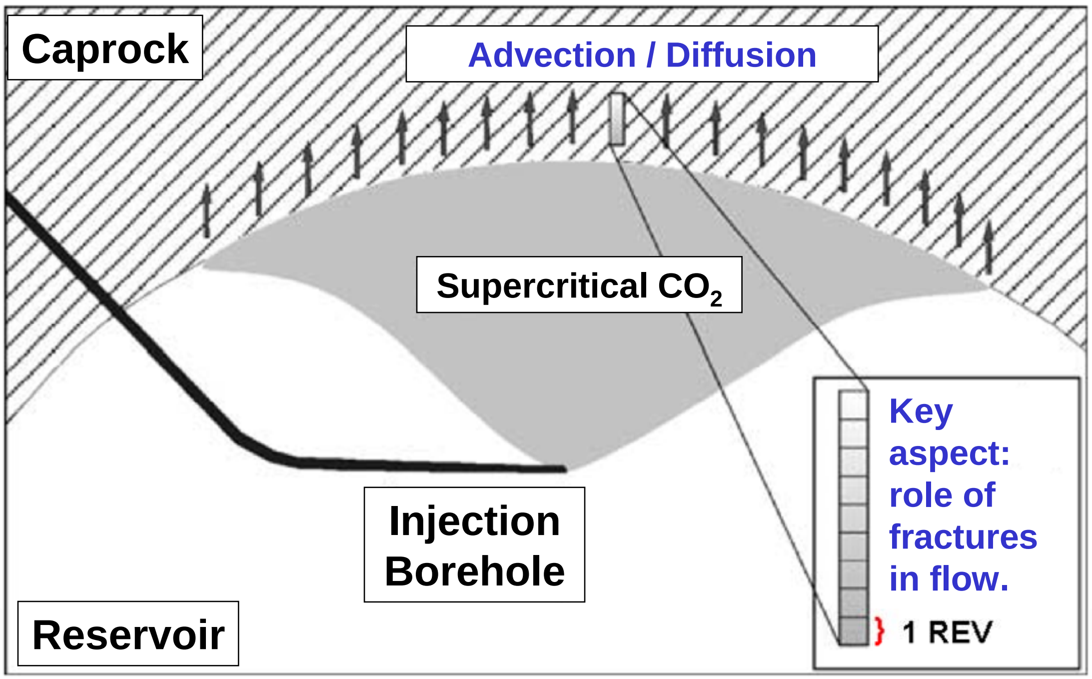
Adapted from Gaus, Azaroual, and Czernichowski-Lauriol (2005)

Geochemical Reactions that Degrade Caprock Integrity: Flow Processes



Adapted from Gaus, Azaroual, and Czernichowski-Lauriol (2005)

At Least Three General Flow Scenarios



Adapted from: Gaus, Azaroual, and Czernichowski-Lauriol (2005)

1) **Matrix diffusion only**

2) **Matrix diffusion plus advection, with some forcing by capillary pressure**

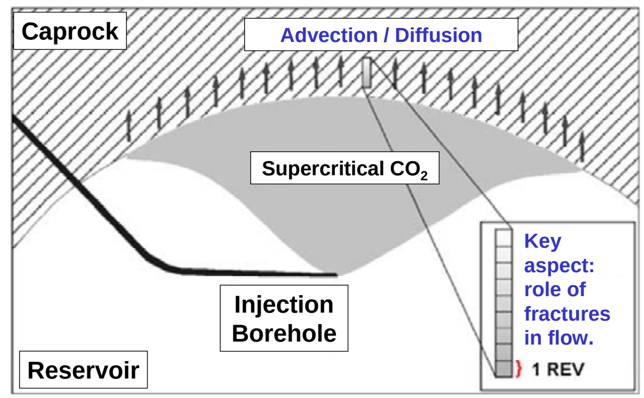
3) **Fracture flow** ***(Coupling of geochemical and geomechanical processes is important)***

Some Common Observations

(based on both experimental and modeling results)

1) **In many cases, carbonate reactions dominate the short-term**

2) **Magnesite and siderite - also relatively "fast" kinetic reaction rates, e.g.,**



Adapted from: Gaus, Azaroual, and Czernichowski-Lauriol (2005)

$$HCO_3^- + Ca^{2+} \Leftrightarrow CaCO_3 + H^+ \quad \text{calcite (fast reaction)}$$

$$HCO_3^- + Mg^{2+} \Leftrightarrow MgCO_3 + H^+ \quad \text{magnesite (fast rxn)}$$

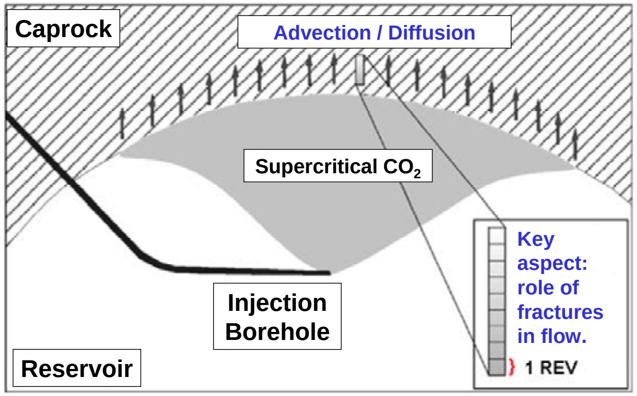
$$HCO_3^- + Fe^{2+} \Leftrightarrow FeCO_3 + H^+ \quad \text{siderite (fast reaction)}$$

Rates of these <u>bicarbonate-consuming reactions</u> are relatively fast but depend on reactant concentrations, pH, temperature and salinity

Some Common Observations

(based on both experimental and modeling results)

3) **Feldspars, clays and other reactions tend to follow, and dominate over the long term, e.g.,**



$$CaSiO_3 + 2H^+ + H_2O \Leftrightarrow Ca^{2+} + H_4SiO_4$$

wollastonite (slow) (neutralizes acidity)

$$Mg_2SiO_4 + 4H^+ \Leftrightarrow 2Mg^{2+} + H_4SiO_4$$

forsterite (slow) (neutralizes acidity)

$$Fe_2SiO_4 + 4H^+ \Leftrightarrow 2Fe^{2+}\ H_4SiO_4$$

fayalite (slow) (neutralizes acidity)

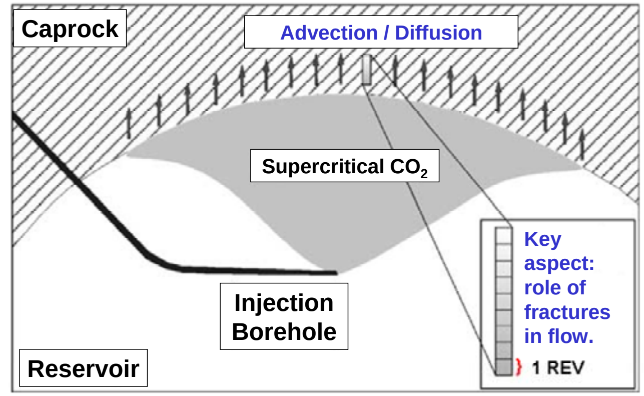
$$CaAl_2Si_2O_8\ (anor) + CO_2 + 2H_2O \Leftrightarrow CaCO_3 + Al_2Si_2O_5\ (OH)_4$$

kaolinite (slow)

Some Common Observations

(based on both experimental and modeling results)

4) **In many systems, concentration of pore-water due to CO_2 interactions will change reactivity** (albeit over the very long term)



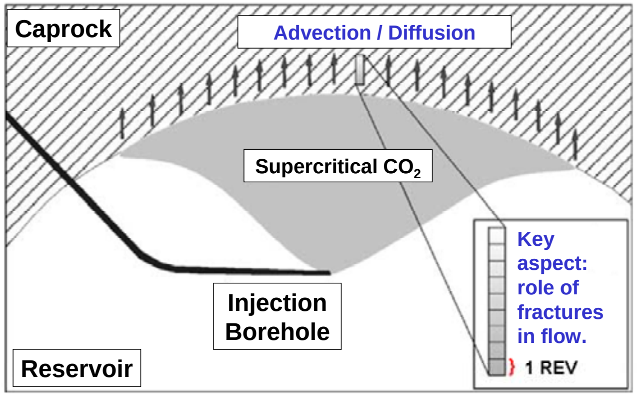
5) **Dessication of clays (leading to caprock degradation) may occur** via consumption of water by reactions or by supercritical CO_2

6) **Capillary entry pressure (CEP) will drive advection processes** (and may accelerate the diffusion-to-advection transition) and thus should not be neglected

Some Common Observations

(based on both experimental and modeling results)

7) **Porosity changes in caprocks, in most systems, will be restricted to the lower portion (few metres) of the caprock – thick is better**

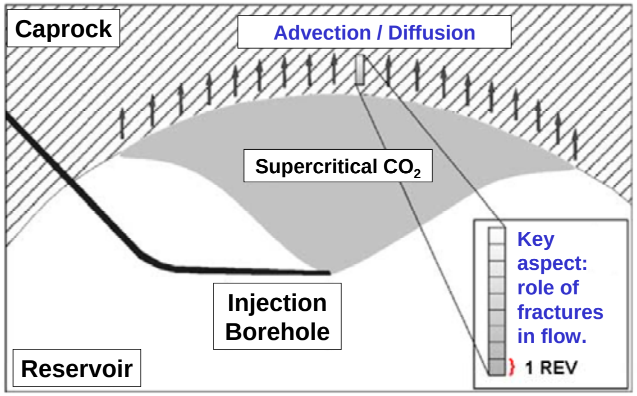


8) **The extent of caprock degradation (or changes in general) will depend on competing diffusion and reaction rates** (except in the case of fractured caprocks)

9) **Mineralization (mineral trapping) in caprocks is largely negligible**

Some Common Observations

(based on both experimental and modeling results)



10) in general, non-carbonate mineralogical transformations in caprock are mostly negligible for hundreds of years

11) calcite reactions overwhelm reactions of Al-silicates, clays, and forming of new minerals (e.g., dawsonite)

Some Sources of Uncertainty

(based on both experimental and modeling results)

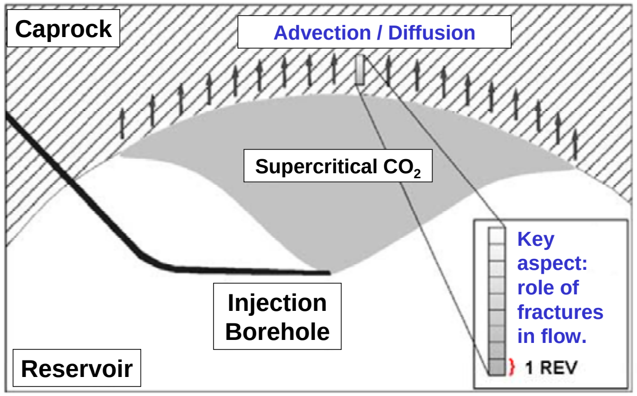
1) **Heterogeneity of caprock and in situ fluid composition** (e.g., pH buffering)

2) **Kinetic reaction rate constants**

3) **Specific surface area data**

4) **Diffusion coefficients** (including variability among species)

5) **Exact composition of specific components** – e.g., plagioclase (albite vs. anorthite, etc.), clays (e.g., kaolinite vs. illite, etc.)



Some Sources of Uncertainty

(based on both experimental and modeling results)

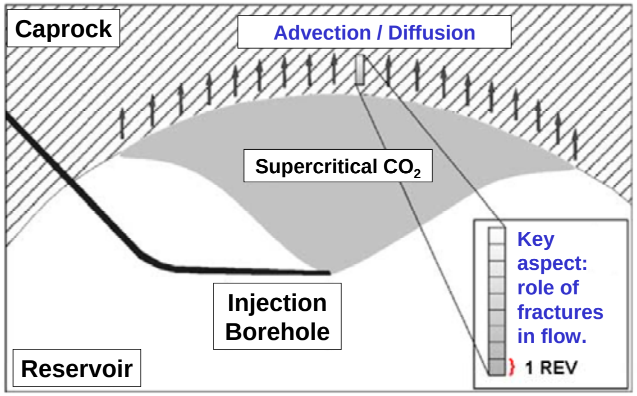
6) **Capillary entry pressure data**

7) **Impurities of input CO_2 stream**

8) **Existence of fractures/faults**

9) **Secondary mineral assemblages**
(non-uniqueness)

10) **Grid-orientation and scaling effects**
(gridding methods in large-scale models, or in areas with structural variability, induce a great deal of uncertainty; *scaling and calibration limitations of both*)



Outline

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Some Geomechanical Processes that Degrade Caprock Integrity

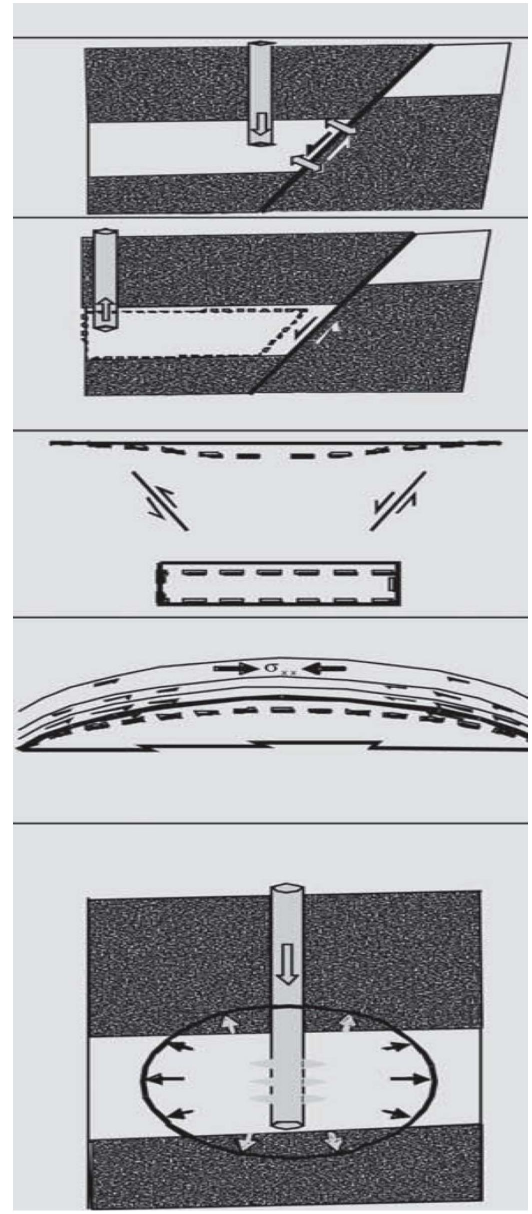
(1) Reactivation of faults via pressure changes in the fault plane

(2) Reactivation of faults via pressure increases within the reservoir (pressure migration)

(3) Reactivation of faults within the overburden (or just the caprock)

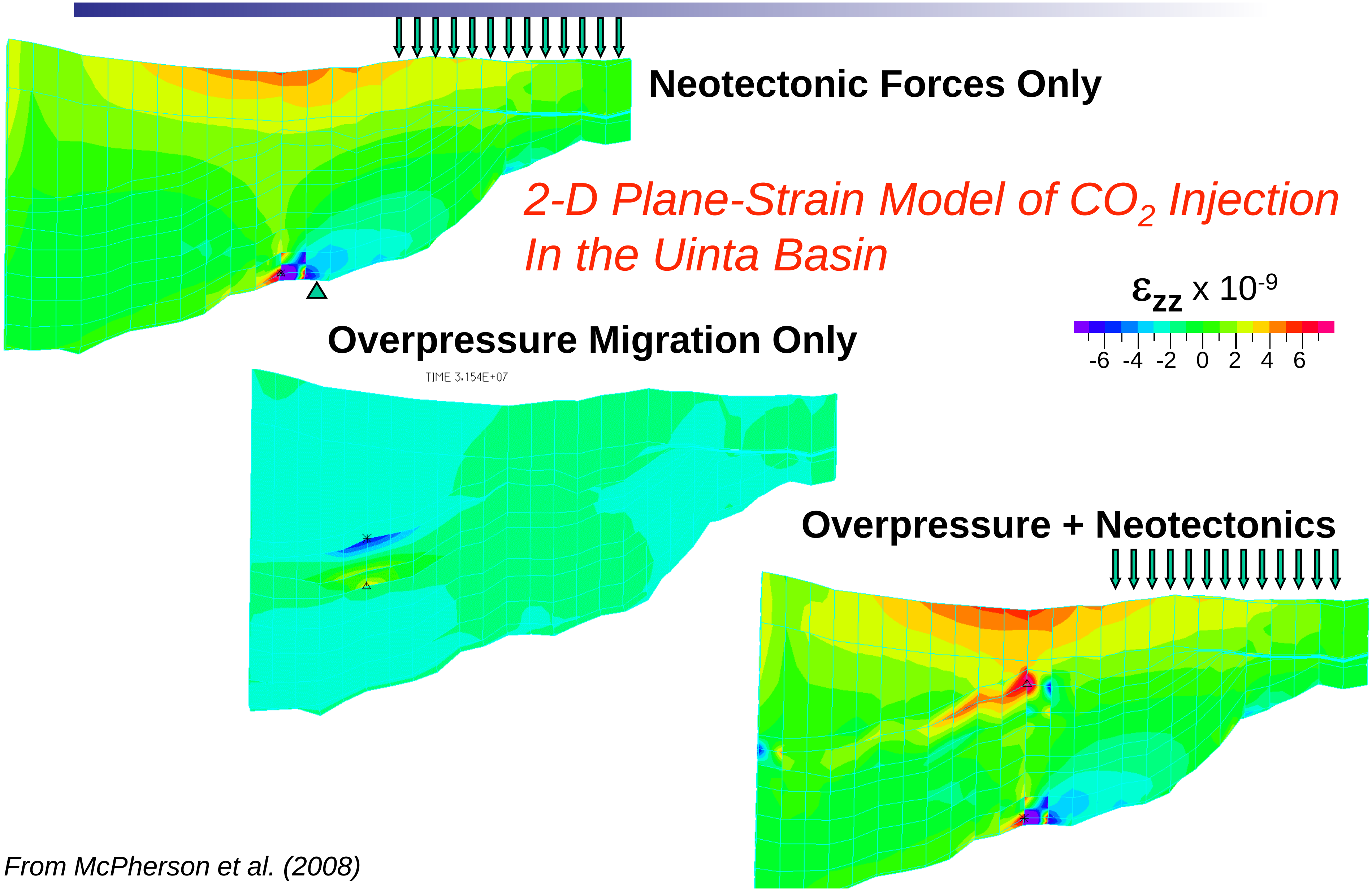
(4) Induced shear failure (fractures)

(5) Out-of-zone hydraulic fractures
- those that exist prior to CO_2 injection, but are unknown
- those induced during CO_2 injection (via pressure migration)



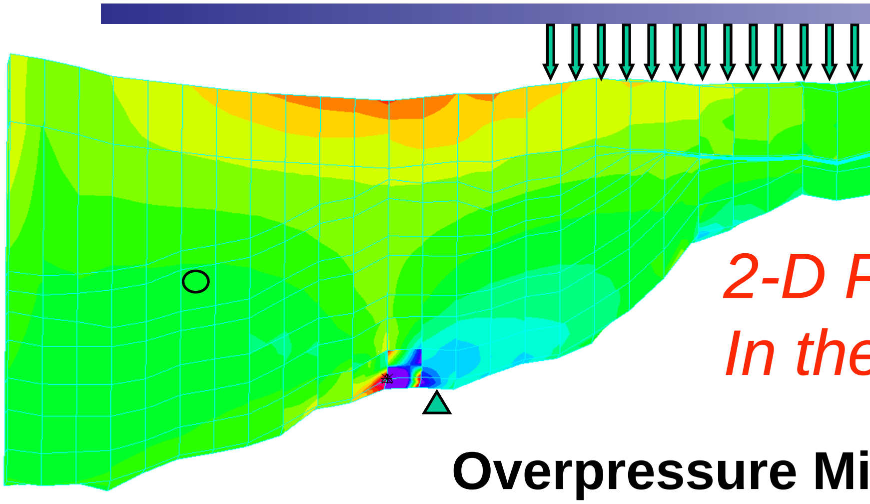
From: Hawkes, Bachu and McLellan (2005)

Fluid Pressure Migrates – So Do Stress and Strain



From McPherson et al. (2008)

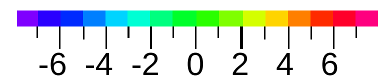
Neotectonic Forces (Current Stress-State) Must Be Addressed



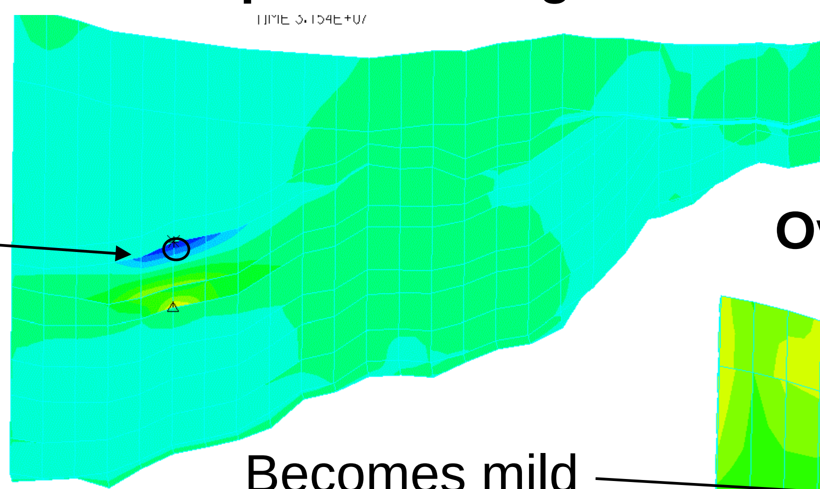
Neotectonic Forces Only

2-D Plane-Strain Model of CO_2 Injection In the Uinta Basin

ε_{zz} x 10^{-9}

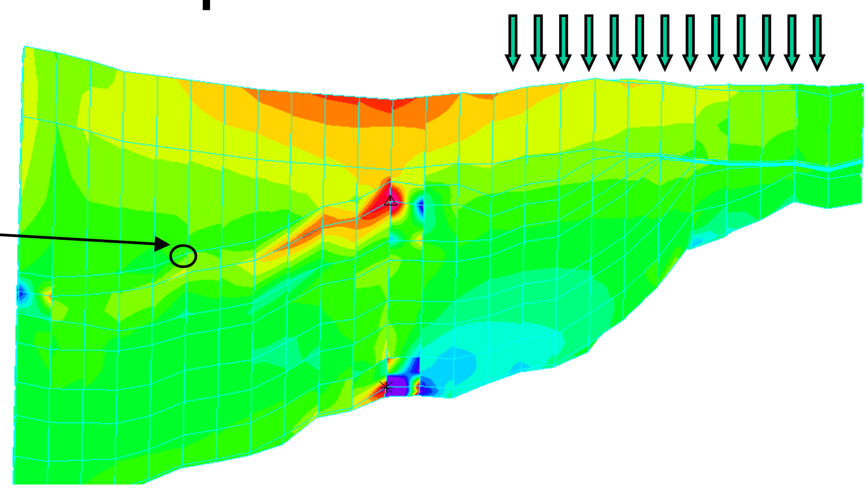


Overpressure Migration Only



Note forecasted compression of caprock during injection

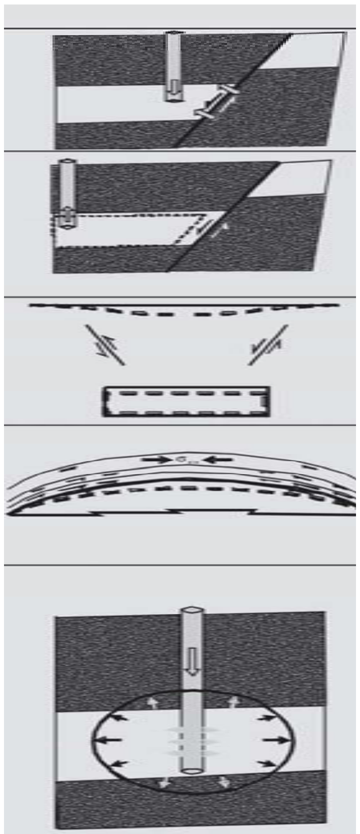
Overpressure + Neotectonics



Becomes mild tensile deformation with neo-tectonic forces included

From McPherson et al. (2008)

Some Specific Types of Fractures/Faults



From: Hawkes, Bachu and McLellan (2005)

(1) A discontinuity that dilates (or contracts) normal-to-its-plane only, creating a high (or low) permeability conduit

(2) A discontinuity that dilates due to shear with a moderate normal stress, initially increasing permeability, but then sealing as fault gouge is produced

(3) A discontinuity that shears under high compressive stress, forming a low permeability barrier

Because of the relationship between permeability, in-situ stress, and resulting strain is fundamentally critical.

Some Sources of Uncertainty
(based on both experimental and modeling results)

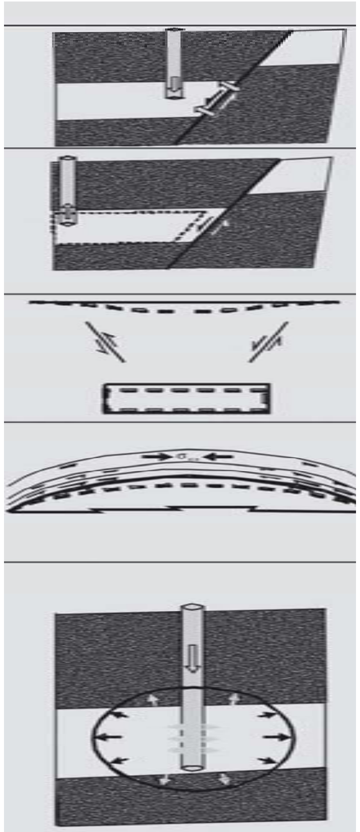
1) **Initial stress state** – vertical, minimum horizontal, maximum horizontal, stress orientation

2) **Elastic / mechanical data** - including Young's modulus, Poisson's ratio, Biot's parameter, compressive/tensile rock strength

3) **Rock porosity, permeability, density**

4) **Presence of pre-existing fractures / faults**

5) **Capillary entry pressure data**



From: Hawkes, Bachu and McLellan (2005)

Some Sources of Uncertainty

(based on both experimental and modeling results)

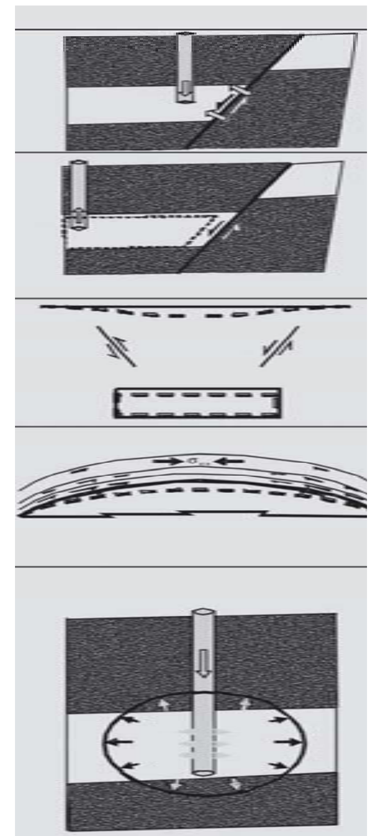
6) **Multiphase data in general** - capillary pressure functions, relative permeability, irreducible saturations, etc.

7) **Stress-sensitivity of permeability and porosity**

8) **Hydraulic diffusivity** - for forecasting pressure propagation in the reservoir and within the caprock above/below it

9) **Lack of quantitative correlation between deformation and induced seismicity** – e.g., whether seismicity will be induced and its magnitude

10) **Discrete versus Continuum Approaches –** *general lack of data for both; grid-effects in both; scaling and calibration limitations of both*



From: Hawkes, Bachu and McLellan (2005)

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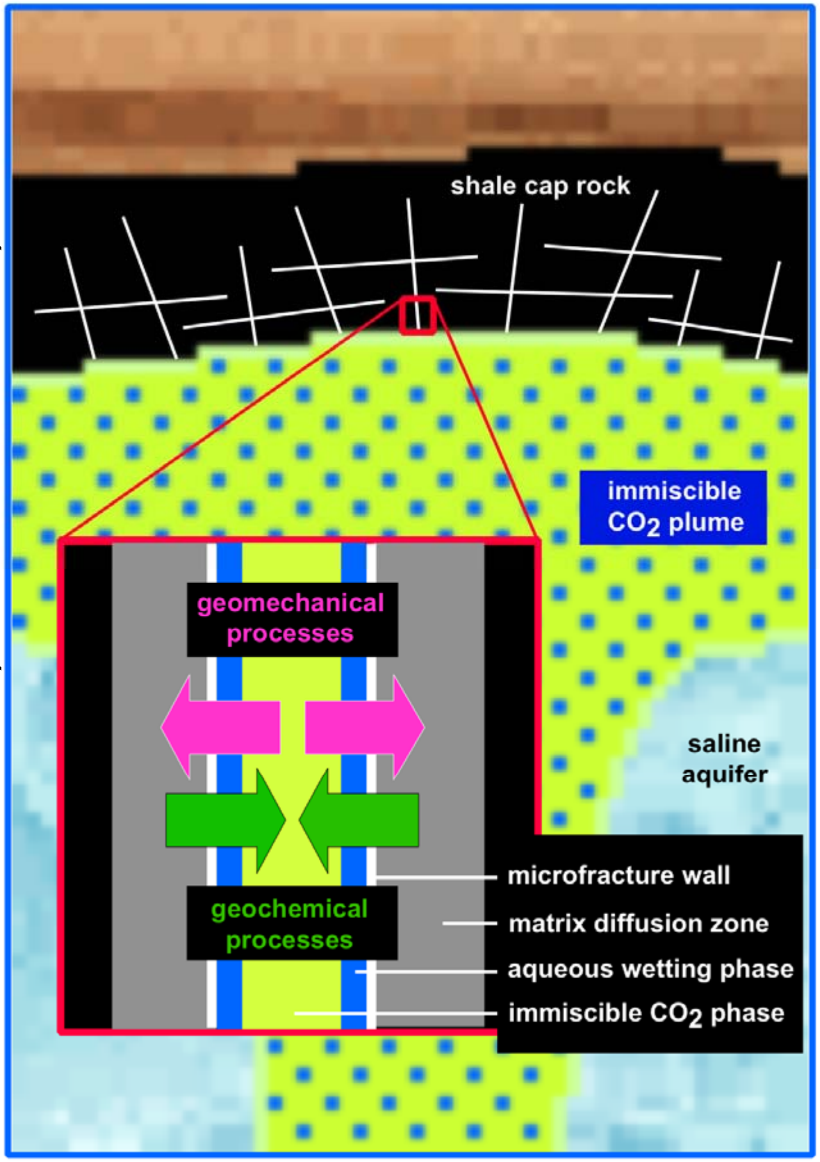
Geochemistry (GC) and Geomechanics (GM): Competing Processes

From Johnson, Nitao and Morris, 2004



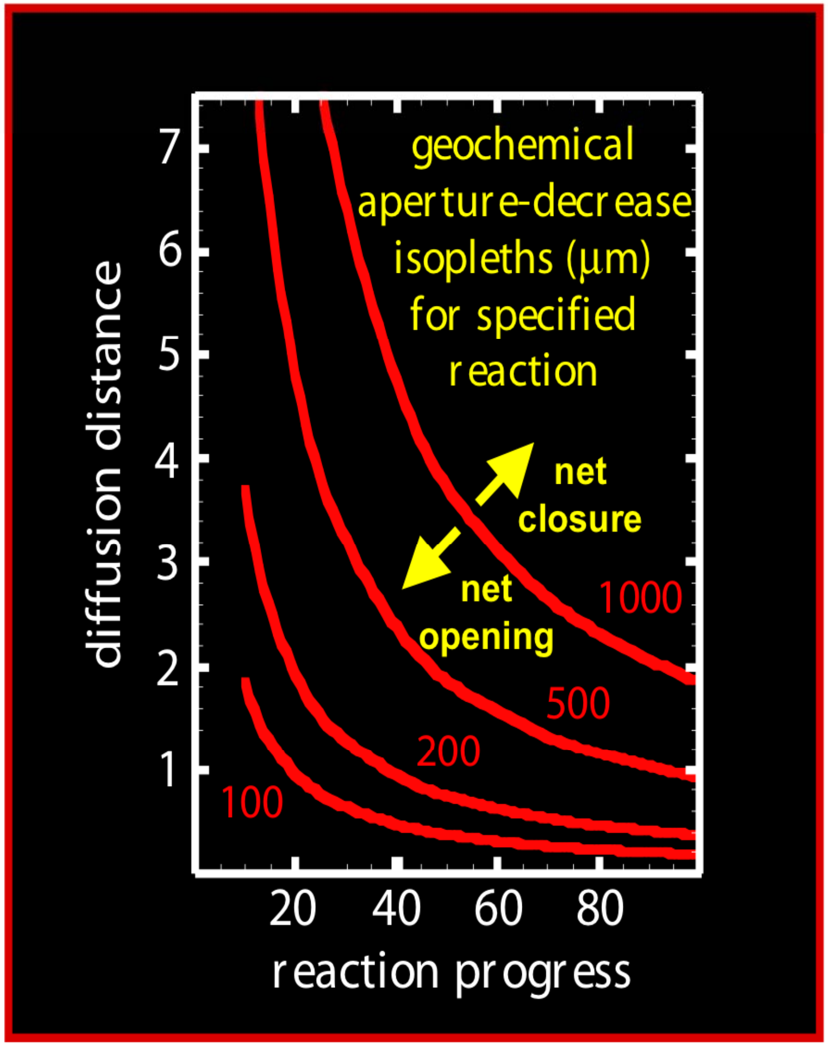
- **Forecasting geomechanical processes is possible**
  (uncertainty can be estimated)

- **Forecasting geochemical processes is possible**
  (uncertainty can be estimated)

- **Forecasting competing roles is possible for specific sites**
  (generalized coupling behavior not established yet)

Geochemistry (GC) and Geomechanics (GM): Competing Processes

From Johnson, Nitao and Morris, 2004



Johnson et al. (2005) concluded that the competing geomechanical deformation and geochemical changes may counterbalance each other.

However:
Time-scales of both must be resolved well

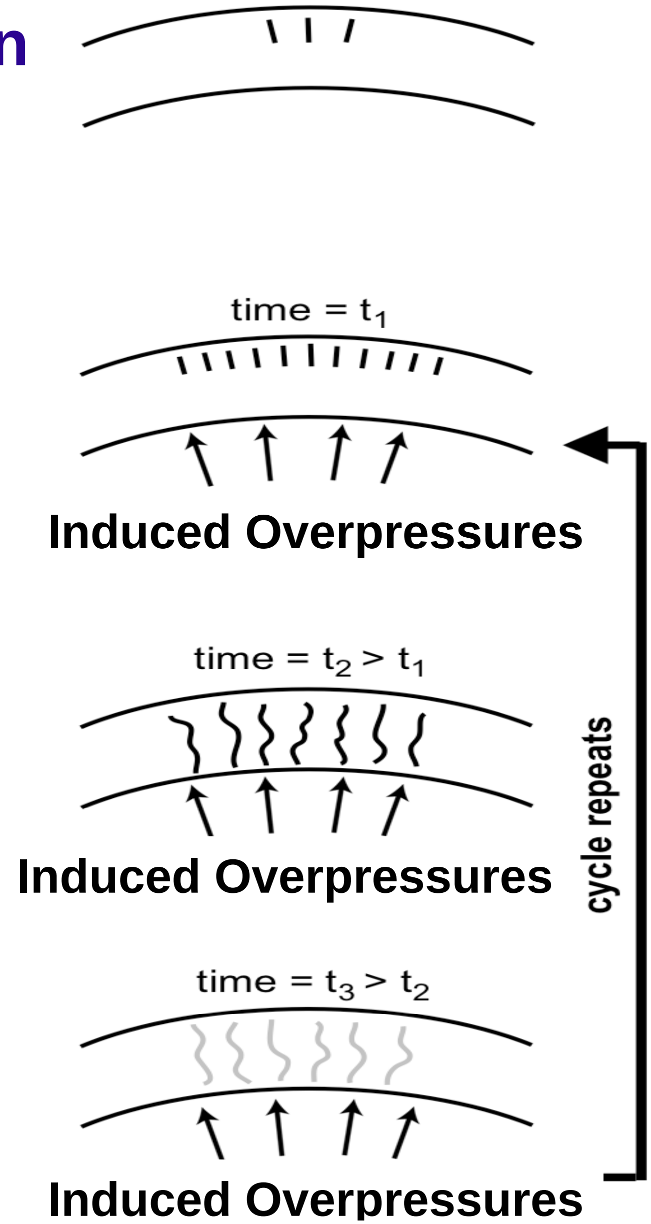
Example of Coupled GM and GC: the "Fracture Valve" Conceptual Model

(1) Overburden minimizes extension and fracturing.

(2) Injection pressure reduces effective stress and offsets overburden, causing fracturing.

(3) As CO_2 is injected, $CaCO_3$-laden fluid migrates into open fractures.

(4) pCO_2 in fractures < pCO_2 in HC zone, therefore $CaCO_3$ precipitates and seals fractures.



From McPherson et al. (2008)

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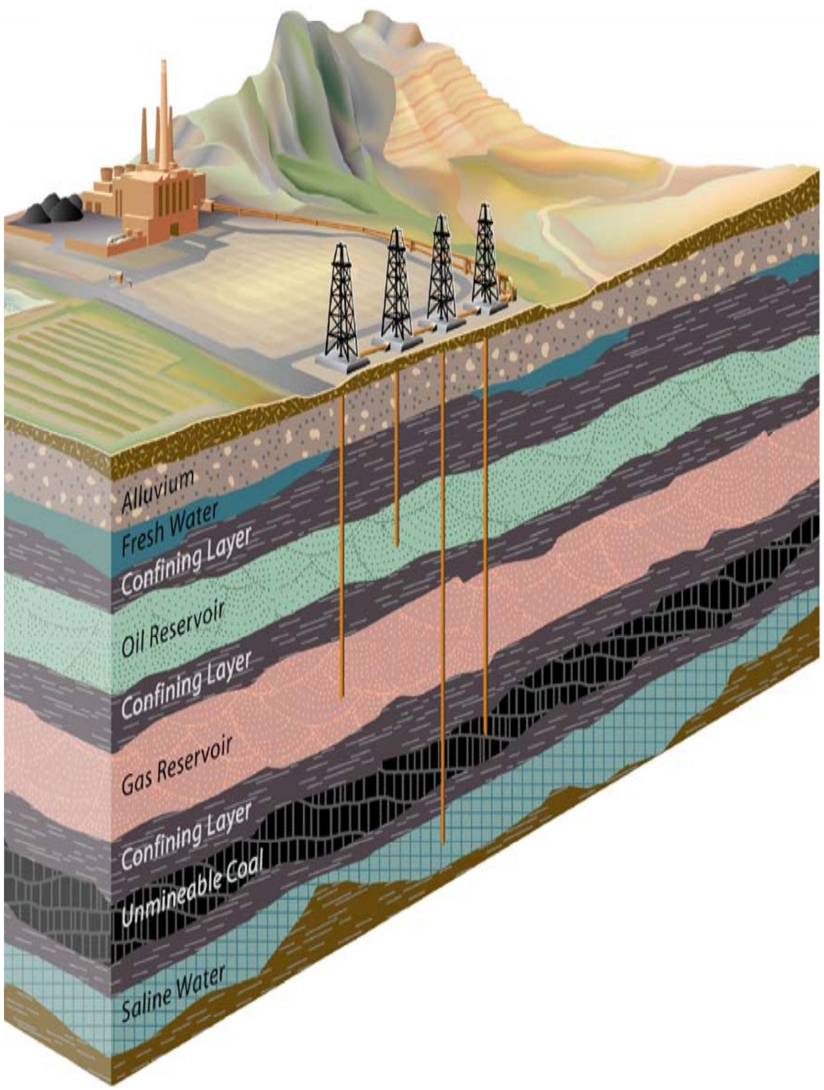
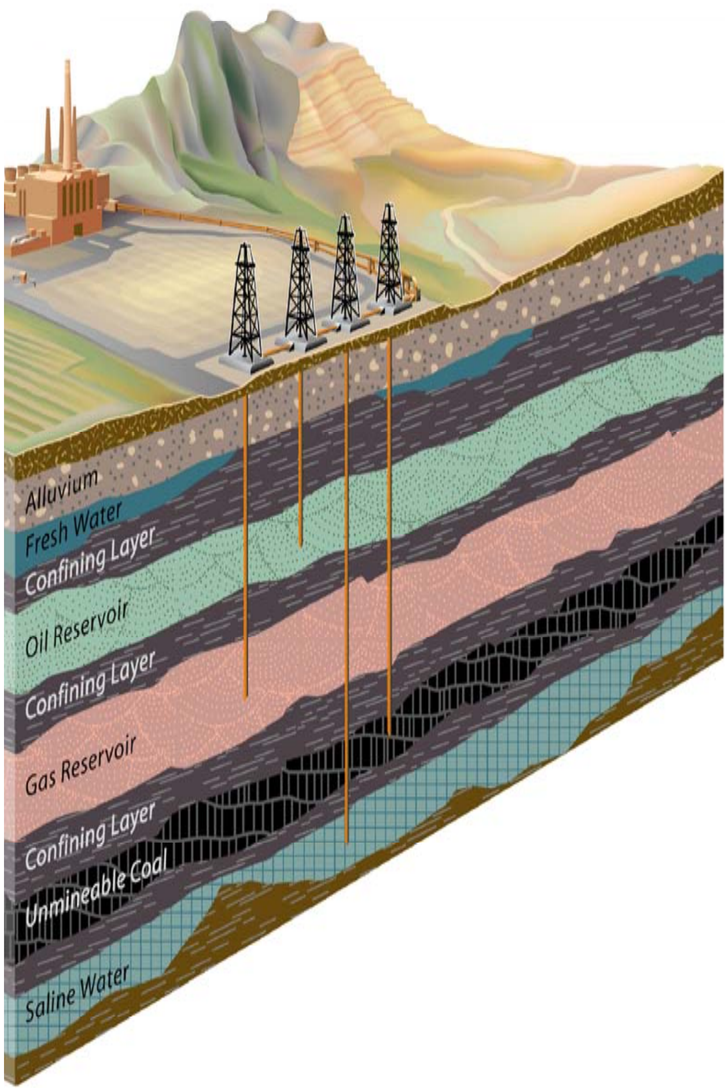
Primary Assessment Objectives



FOR EACH SITE:

- geochemical (**GC**) processes that degrade caprock integrity
- geomechanical (**GM**) processes that degrade caprock integrity
- **coupling** GM and GC
- **resolving uncertainties** associated with subsurface properties, GM and GC
- **resolving competing time-scales** of GM and GC
- **resolving spatial-scaling limitations** (e.g., calibration using lab-scale data)

Interested in additional discussion? Many authors of caprock studies here. Some are:



Sylvain Thibeau -- wettability alteration of caprock minerals and interfacial tensions between CO_2 and brine

Isabelle Czernichowski-Lauriol -- reactive transport in the Sleipner caprock

Mohamed Azaroual -- reactive transport in the Sleipner caprock

Johnny Rutqvist - deformation effects of injection; focused work on caprock/reservoir systems

Jens Birkholzer -- deformation effects of injection

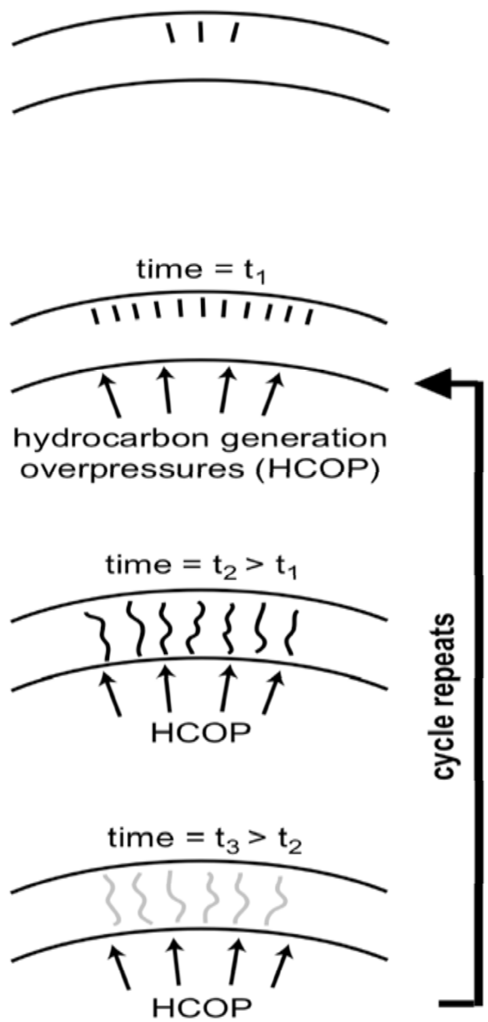
Stefan Bachu – geomechanics of caprocks

Several others -

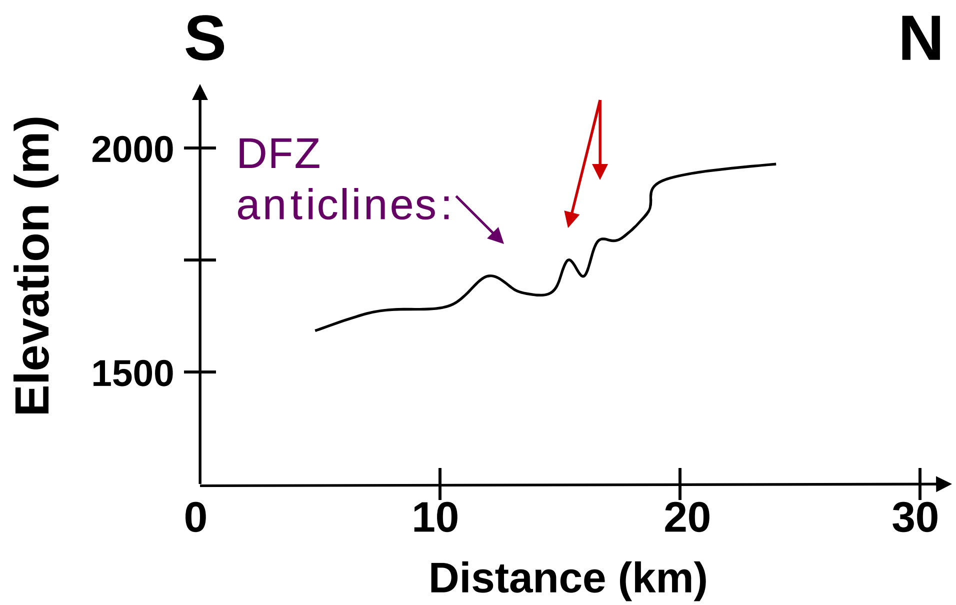
[redacted]

Data Supporting the Conceptual Model

Conceptual Model



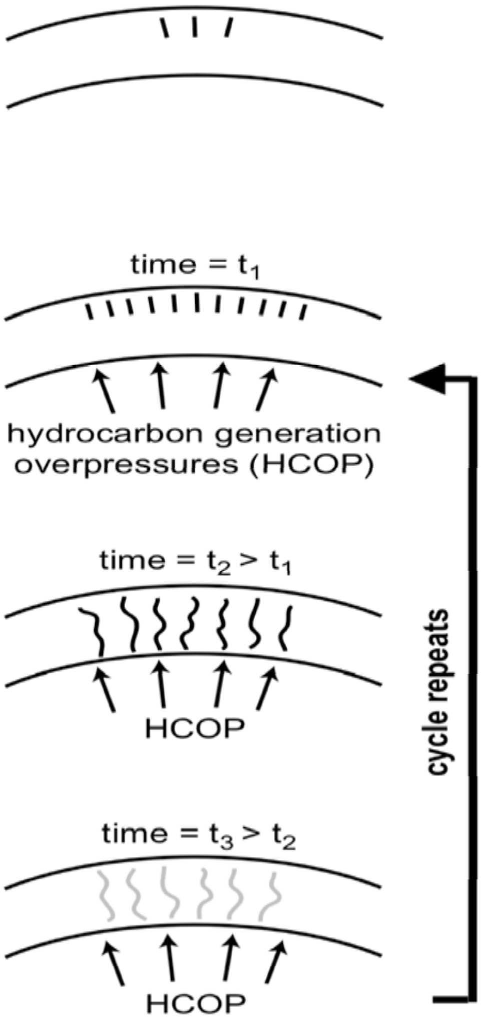
Surface Elevation



- Local flexure = anticline
- DFZ anticline shows intense fracturing

Data Supporting the Conceptual Model

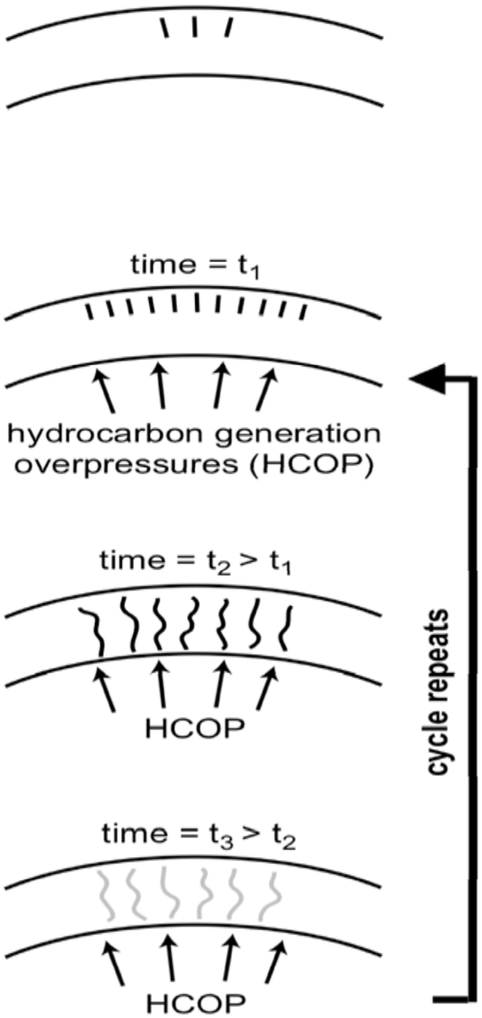
Conceptual Model



- **One of the major offsets within the DFZ**
- **several mounds in this area show tufa deposits cropping out at surface**

Data Supporting the Conceptual Model

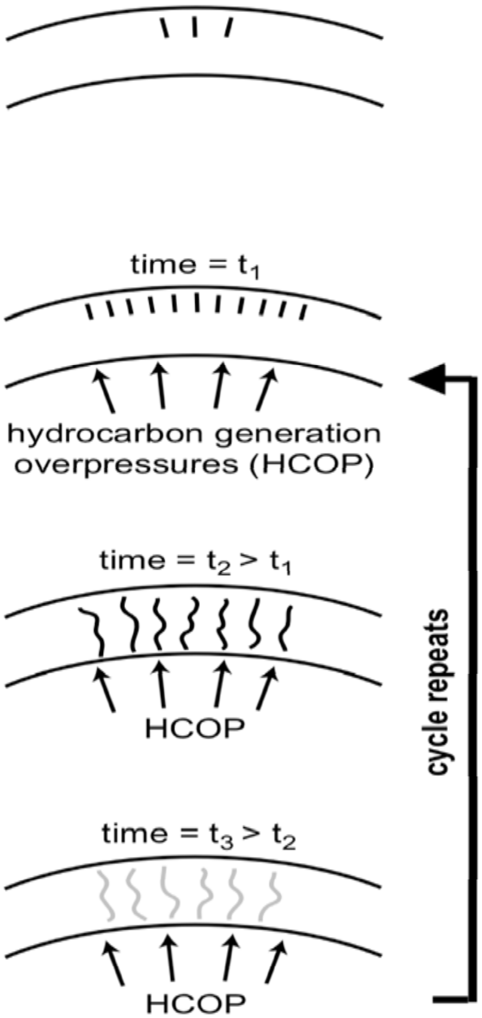
Conceptual Model

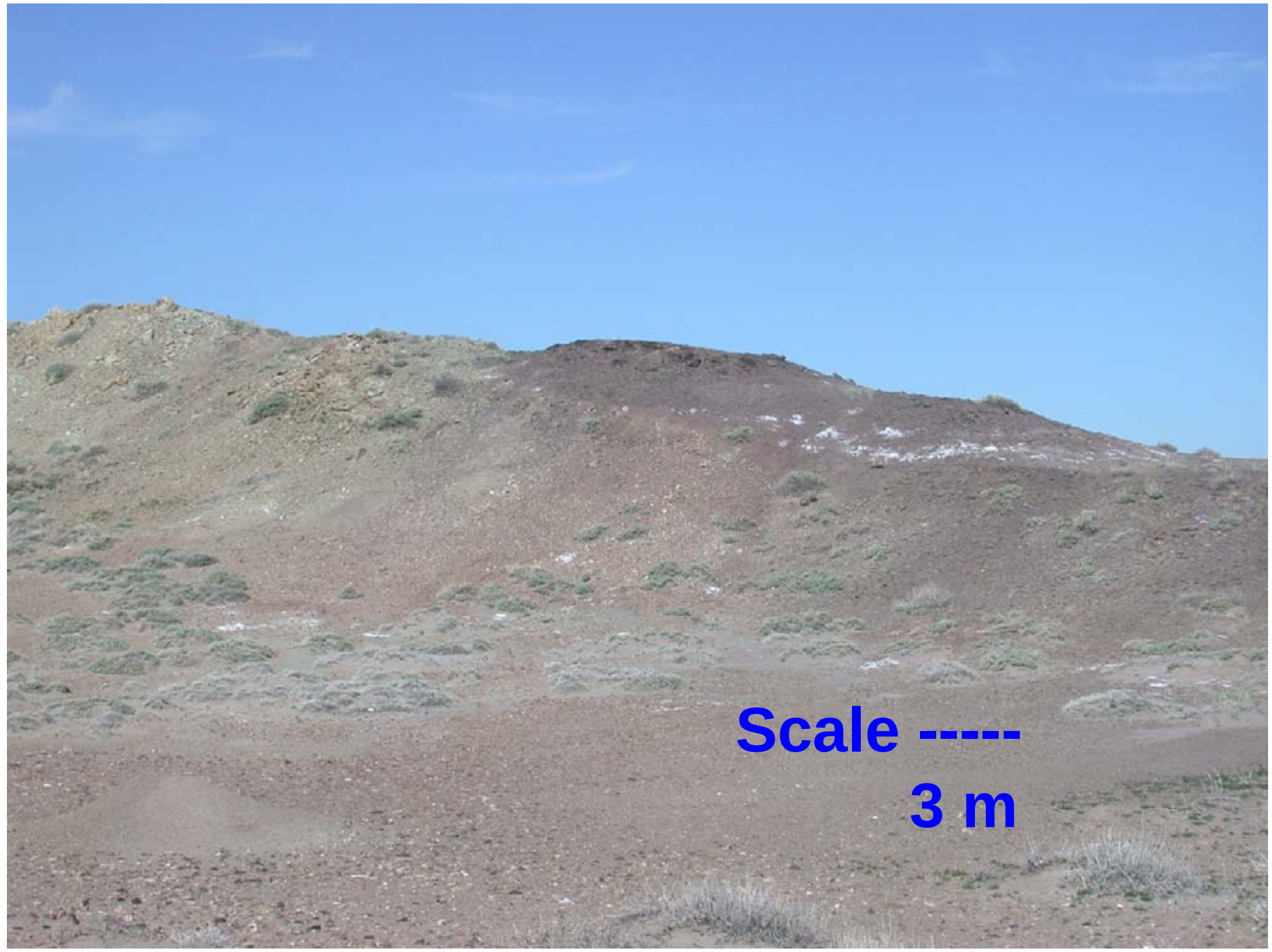


- **concretions at surface also observed in several areas of the DFZ**

Data Supporting the Conceptual Model

Conceptual Model

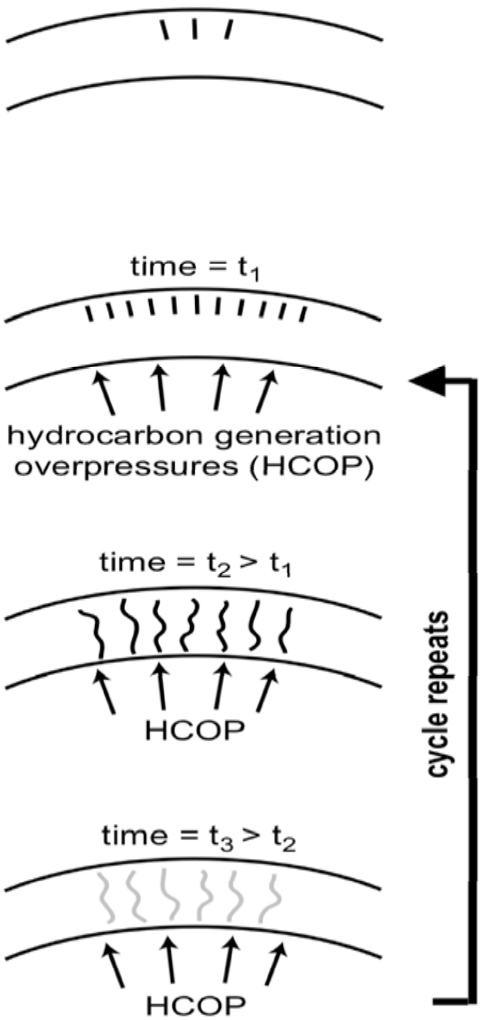




- **Facies change and tufa deposits at surface**

Data Supporting the Conceptual Model

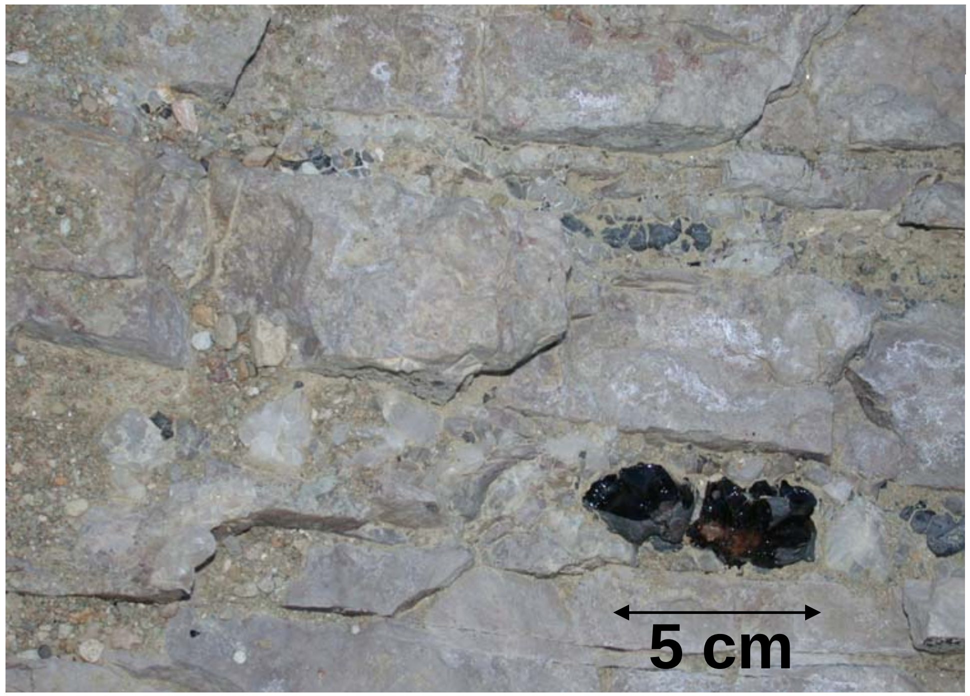
Conceptual Model



- **Small calcite veinlets, Duchesne Graben area**

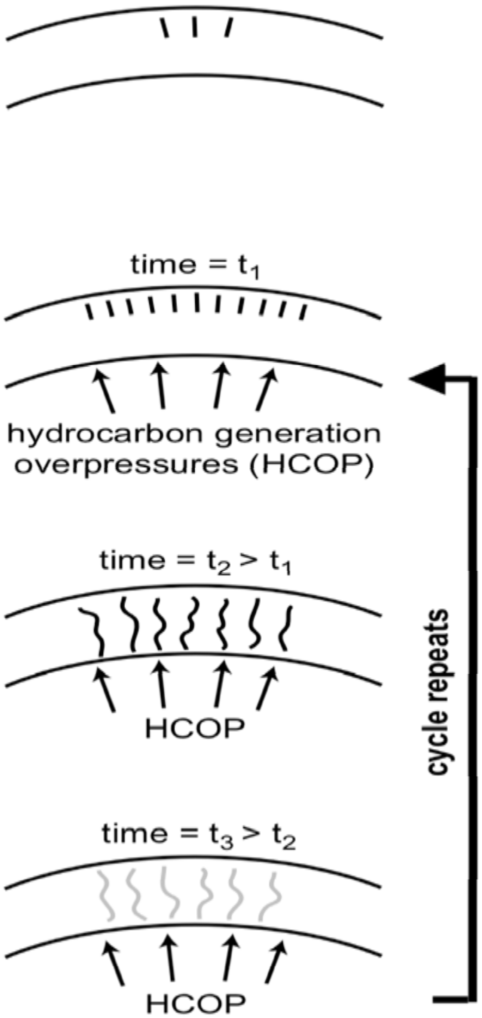
Data Supporting the Conceptual Model

Multiple Stages of Fluid Flow: (1) east-west trending fractures in Duchesne Graben have calcite filled fractures with gilsonite "injected"



Data Supporting the Conceptual Model

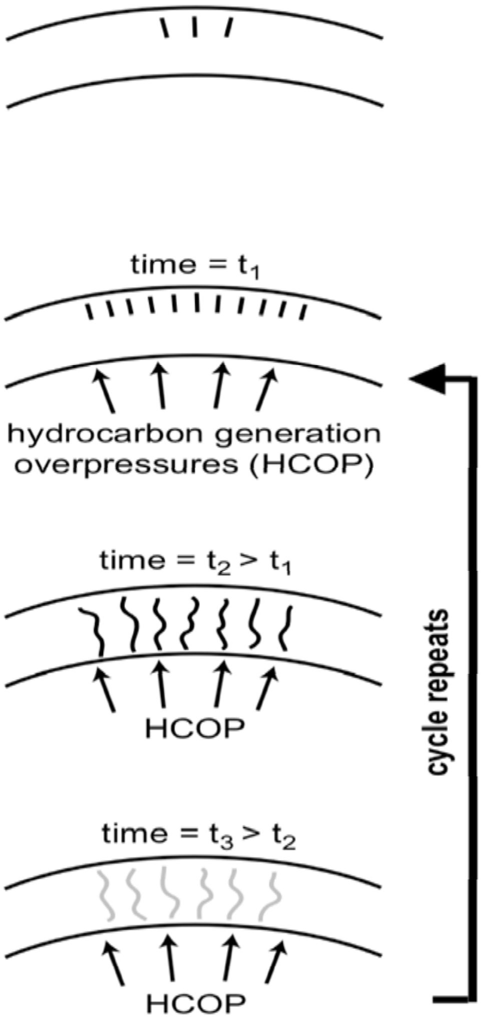
Conceptual Model



Multiple Stages of Fluid Flow:
(2) north-south trending fractures in Duchesne Graben have gilsonite only (no calcite)

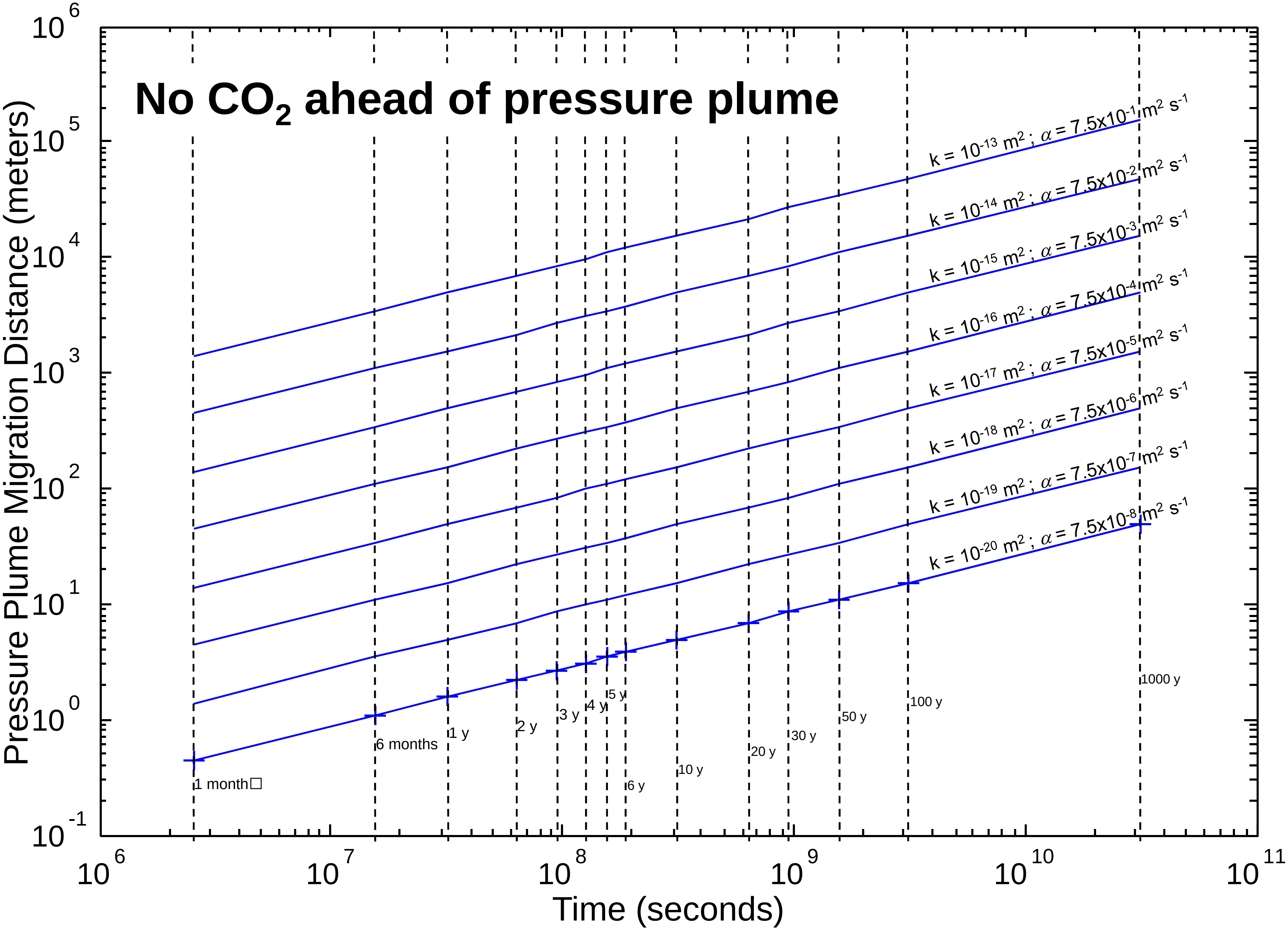
Data Supporting the Conceptual Model

Conceptual Model

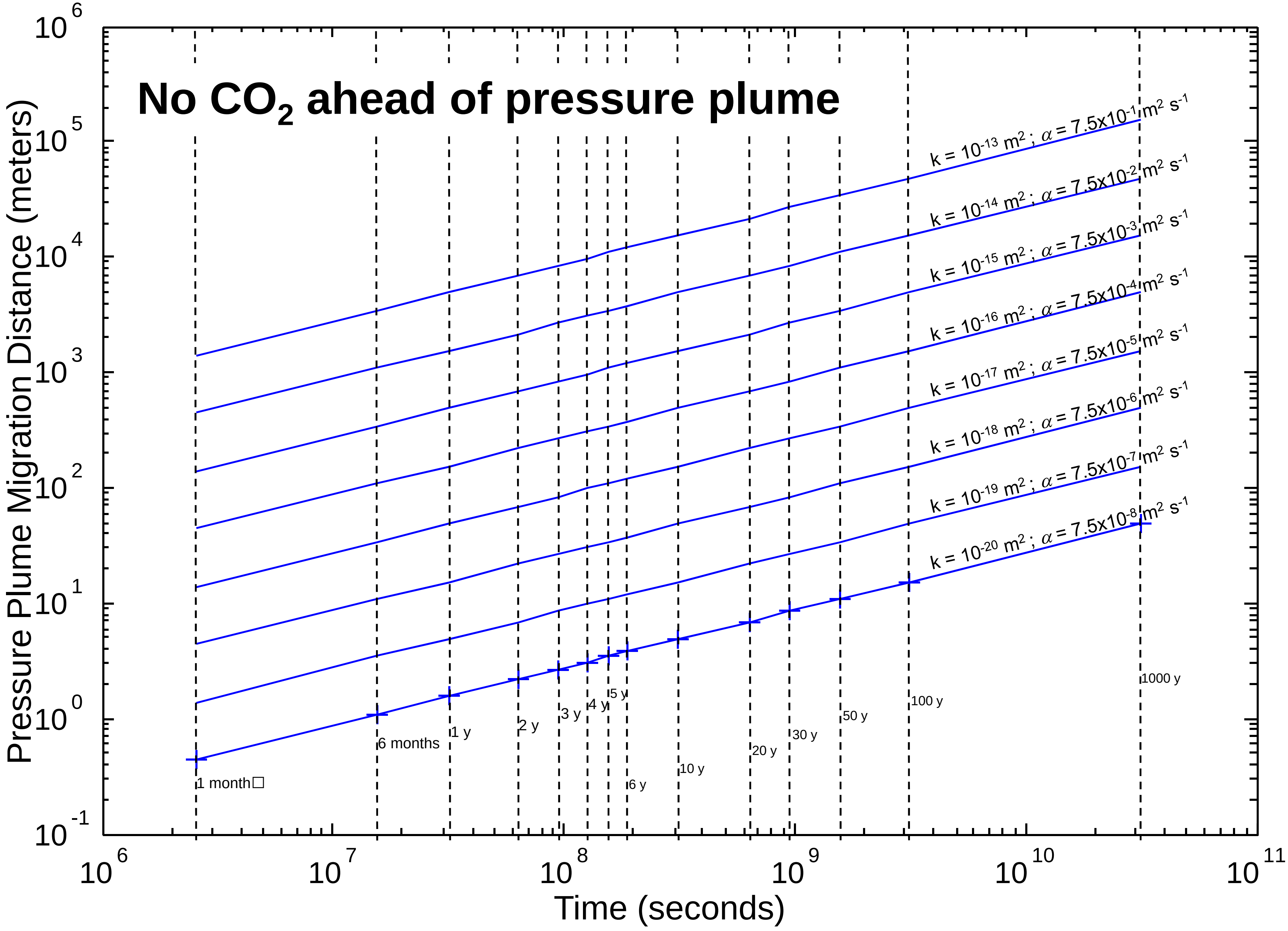


Also: outcrop examination (left) and thin-sections suggest multiple stages of fluid flow, evidenced by two+ stages of calcite mineralization

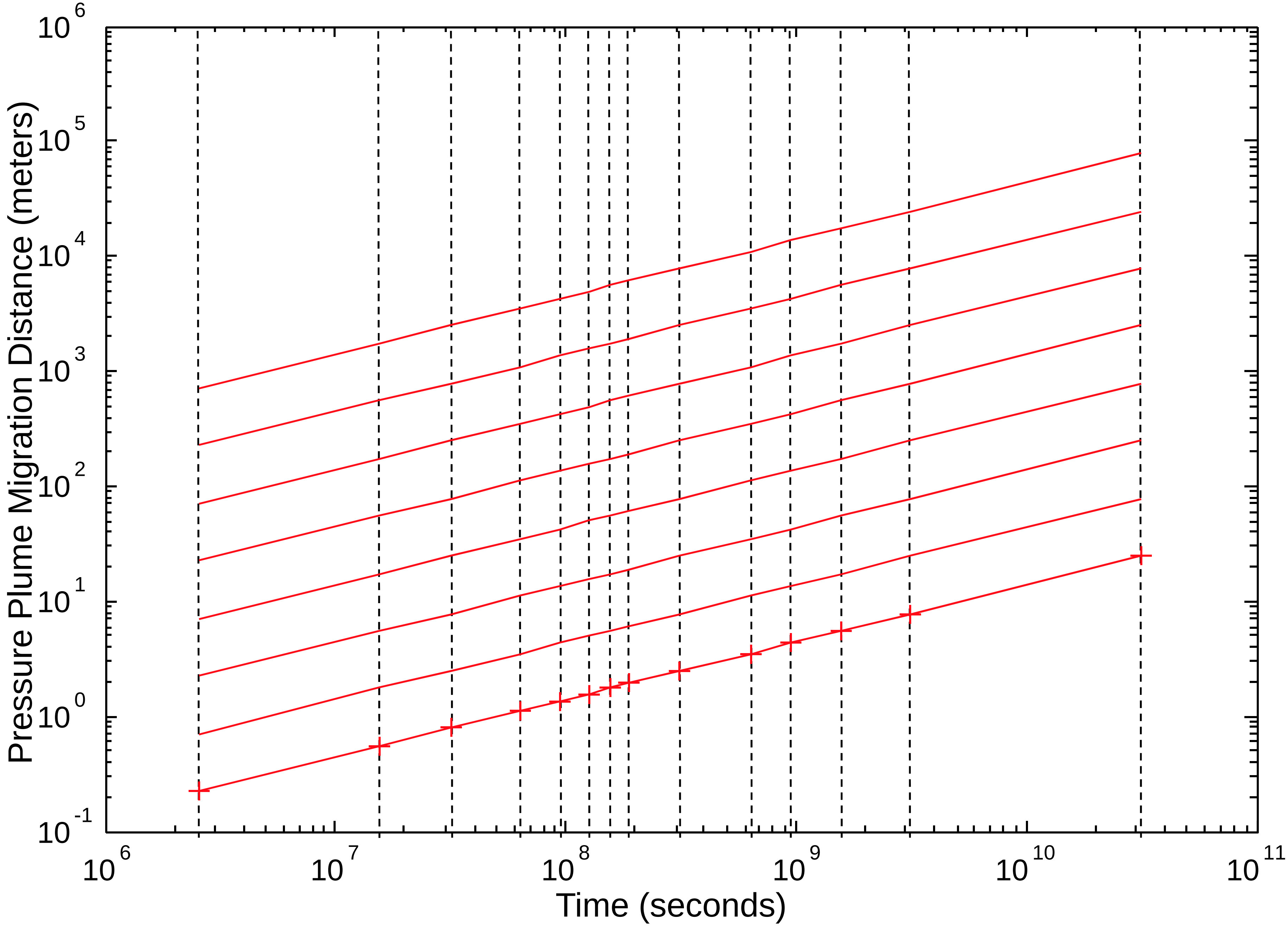
General Simulation Results: Pressure Propogates Consistent With $l = \sqrt{\alpha t}$



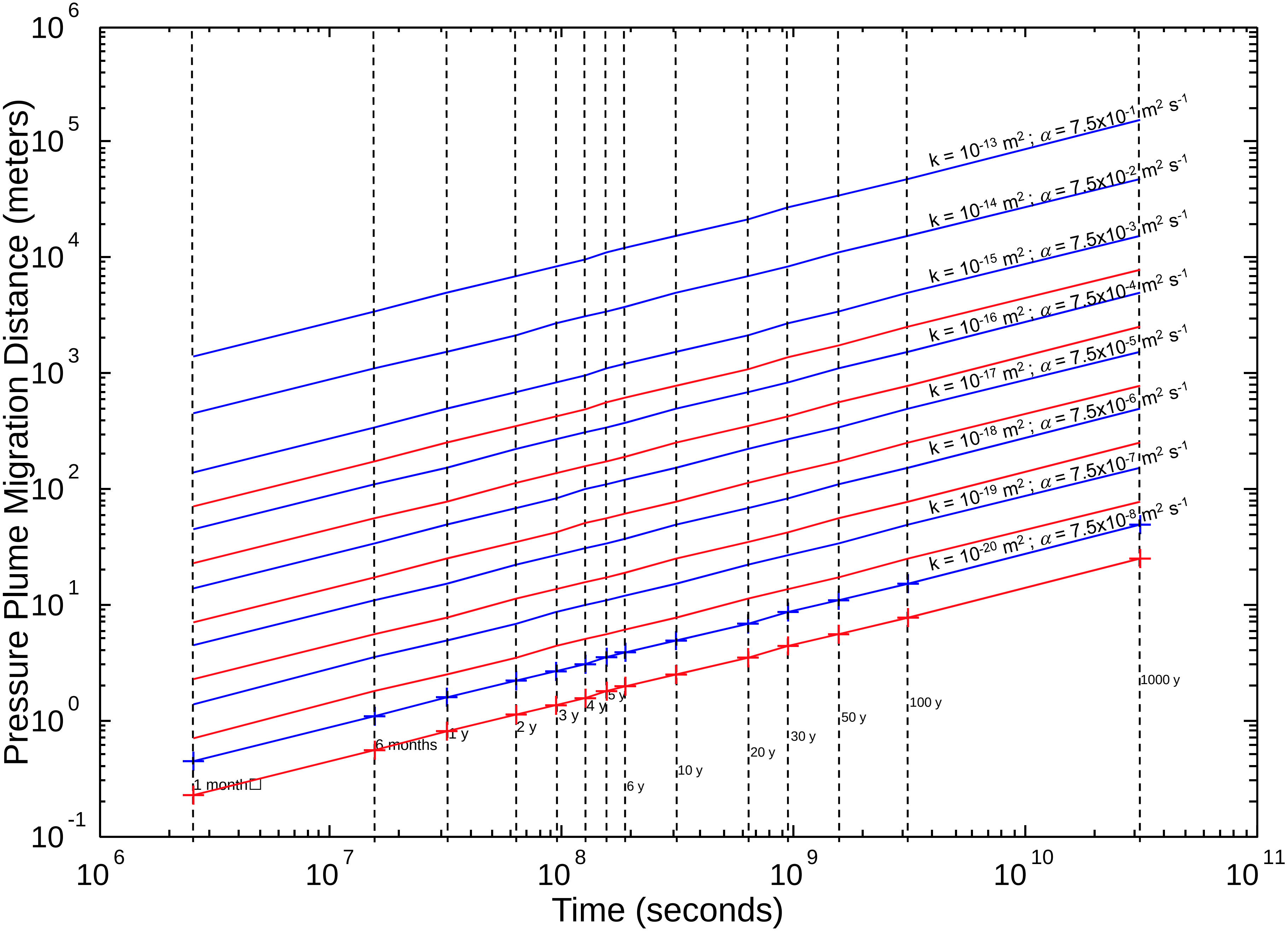
For Brine-Saturated Strata: Pressure Propogates Consistent With $l = \sqrt{\alpha t}$



For CO_2-Saturated Strata: Pressure Propogates Consistent With $l = \sqrt{0.1\alpha t}$



Comparison: Pressure Propagation with and without CO_2



Useful Analytical Equations

In general, after calibrating injection site reservoir simulation models with observed pressure trends and with tracer data, we found that the simulation results are generally consistent with the following analytical equations for forecasting pressure propagation:

***Using Standard Hydraulic Diffusivity*:**

$$l = \sqrt{\alpha t}$$

Brine-saturated media

$$l = \sqrt{0.1 \alpha t}$$

CO_2-saturated media

Using Hydraulic Diffusivity Based on CO_2 Properties:

$$l = \sqrt{0.001 \alpha_{CO2} t}$$

CO_2-saturated media

Aqueous Trapping

First, CO_2 becomes carbonic acid

CO_2 (g) + H_2O = H_2CO_3 (slow reaction)

Followed by rapid dissociation

H_2CO_3 = H^+ + HCO_3^- (very fast reaction)

Models for Wellbore Leakage

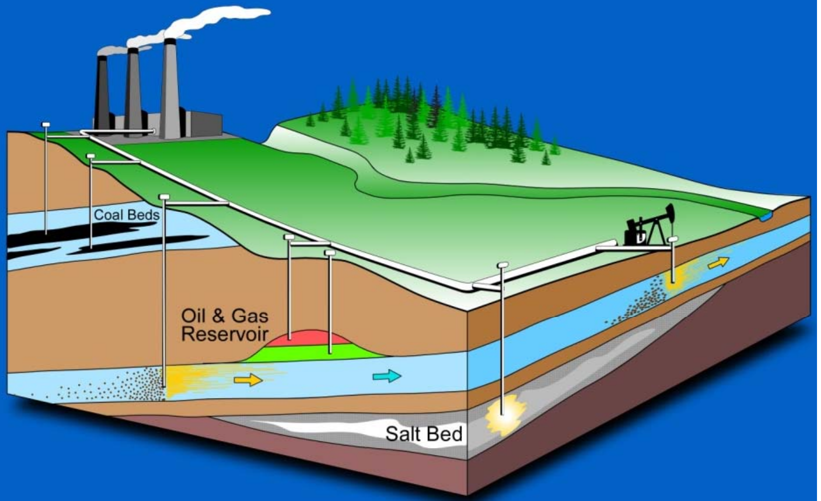
Michael A. Celia
Princeton University

Jan Nordbotten (*U. Bergen and Princeton U.*)
Stefan Bachu (*Alberta Research Council*)
Mark Dobossy (*Princeton U.*)

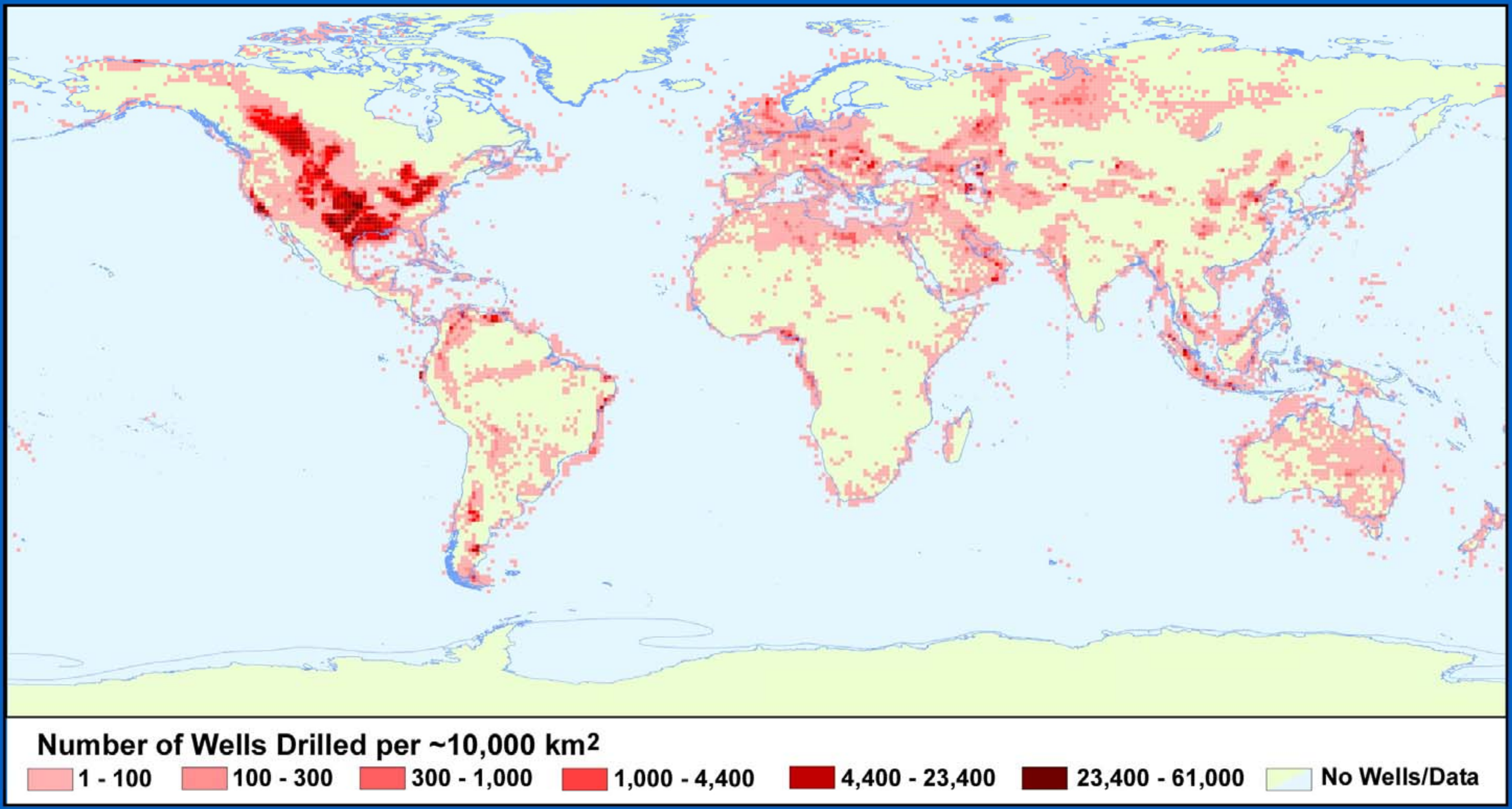
Princeton University

Outline

- Challenges of the Well Leakage Problem
- Our Modeling Approach
- Numerical, Analytical, and Semi-analytical Models
- Concluding Comments



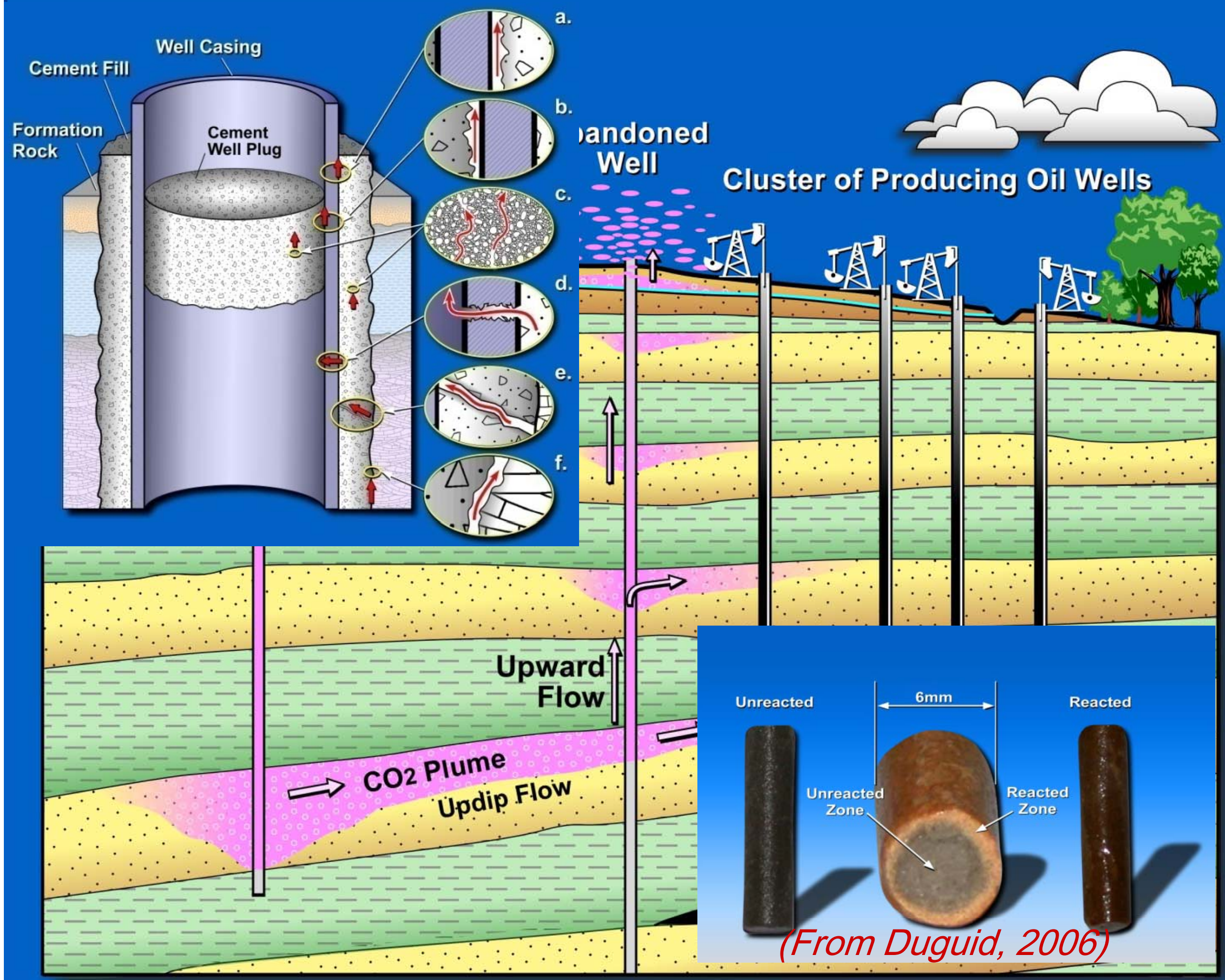
Worldwide Density of Oil and Gas Wells



End of 2004

From IPCC SRCCS, 2005

Injection and Leakage



- How to model this system?
- Domain Size:
  1,000 km^2
- Leakage Pathways:
  0.001 m^2.
- Flow Properties along well highly uncertain.
- Possible Material Degradation.

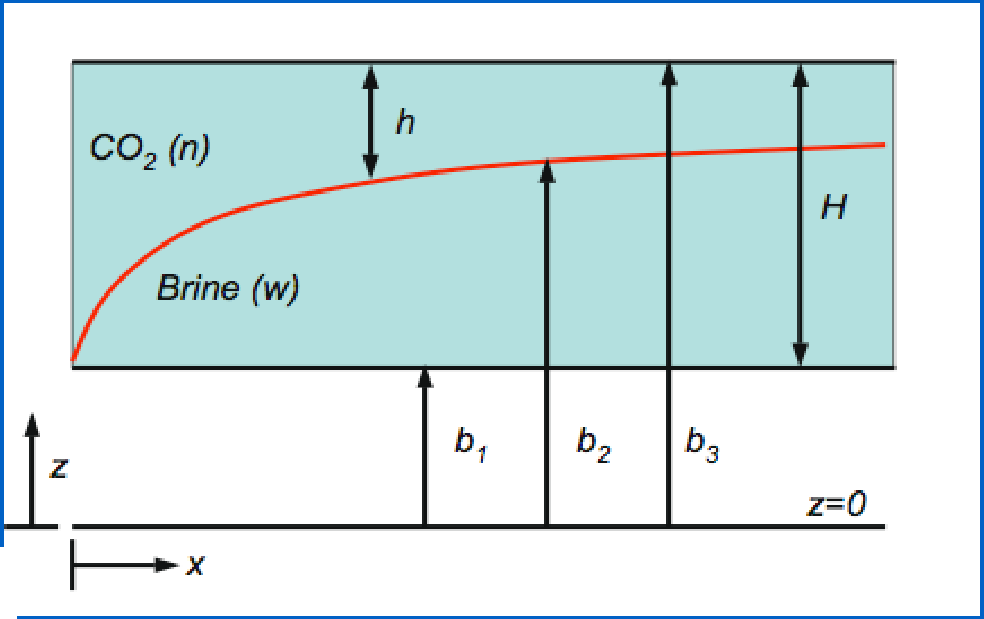
Our Approach to Modeling

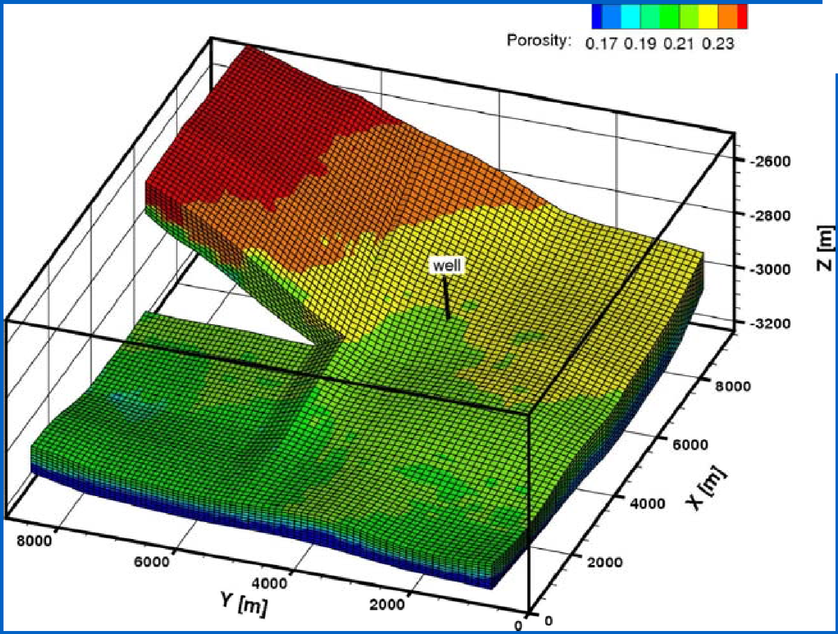
- Simplify the system (but not too simple)
  - Macroscopic sharp interface (buoyant segregation)
  - Vertical equilibrium / Structured vertical velocity
  - Focus on early time → Max risk of leakage
    - Two-phase flow physics dominates
    - Ignore geochemistry, non-isothermal effects
- Develop very fast analytical, semi-analytical, and hybrid numerical-analytical solutions.
- Apply simulation tools in a Monte Carlo framework.
- Combine models into 'hierarchical' framework

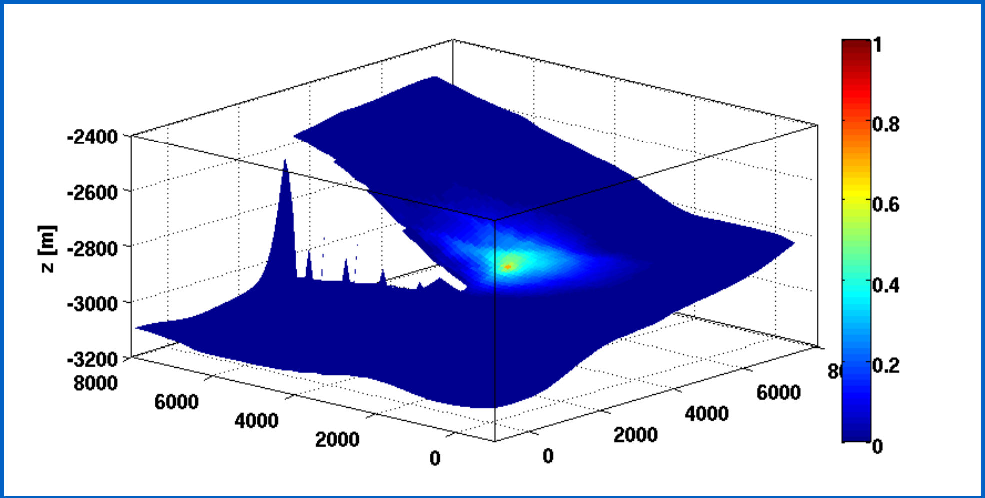
See: Celia, M.A. and J.M. Nordbotten, "Practical Modeling Approaches for Geological Storage of Carbon Dioxide", under review, *Ground Water*, 2009.

Numerical Solutions

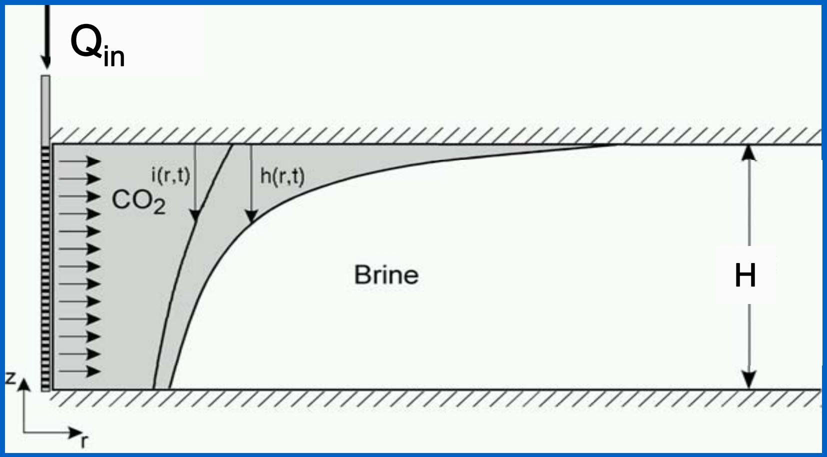
Solve for $p(x,y,t)$, $h(x,y,t)$







Analytical Solution



$$\Gamma \equiv \frac{2\pi\Delta\rho g k \lambda_w H^2}{Q_{in}}$$

$$\tau \equiv \frac{Q_{in} t}{2\pi H \varphi \left(1 - S_{res}\right)}$$

$$\lambda_1 \equiv \frac{\lambda_c}{\lambda_w}, \quad \lambda_2 \equiv \frac{\lambda_{cw}}{\lambda w}, \quad \vartheta \equiv \frac{\rho_{cw} - \rho_c}{\rho_w - \rho_{cw}}$$

$$h' \equiv \frac{h}{H}, \quad i' \equiv \frac{i}{H}$$

$$\chi \equiv r^2 / \tau$$

$$\frac{dh'}{d\chi} = \frac{4\Gamma\gamma_1}{\chi}\frac{d}{d\chi}\left((1-h')\chi\frac{dp'}{d\chi}\right)$$

$$-\frac{di'}{d\chi} = \frac{4\gamma_2\Gamma\lambda_1}{\chi}\frac{d}{d\chi}\left(i'\chi\frac{d}{d\chi}(p'+h'+\vartheta i')\right)$$

$$-\frac{d}{d\chi}(h'-i') = \frac{4\Gamma\lambda_2}{\chi}\frac{d}{d\chi}\left((h'-i')\chi\frac{d}{d\chi}(p'+h')\right) + \frac{4(1-\gamma_2)\Gamma\lambda_1}{\chi}\frac{d}{d\chi}\left(i'\chi\frac{d}{d\chi}(p'+h'+\vartheta i')\right) + \frac{4\Gamma(1-\gamma_1)}{\chi}\frac{d}{d\chi}\left((1-h')\chi\frac{dp'}{d\chi}\right)$$

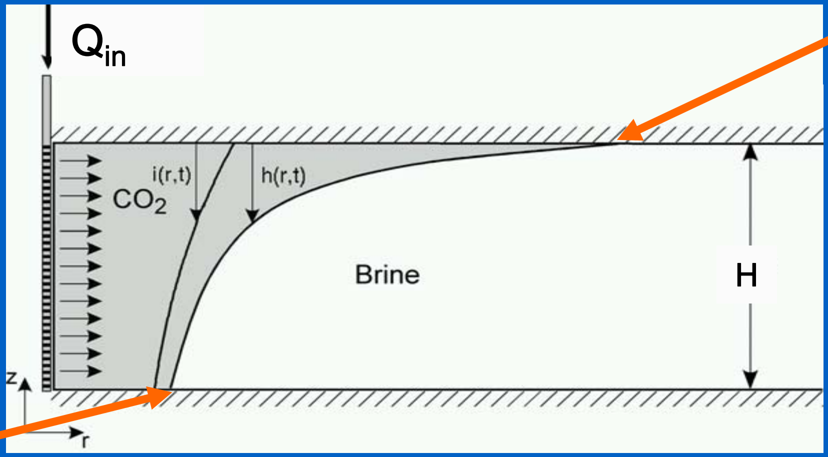
(From Nordbotten and Celia, *JFM*, 2006; See Celia and Nordbotten, 2009)

Similarity Solution: Simplified

When Γ<0.5:

$$h'(\chi) = \frac{h(\chi)}{H} = \frac{1}{\lambda - 1}\left(\sqrt{\frac{2\lambda}{\chi}} - 1\right)$$

$$\chi_{max} = 2\lambda$$

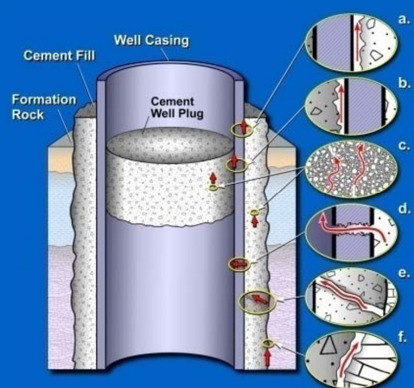


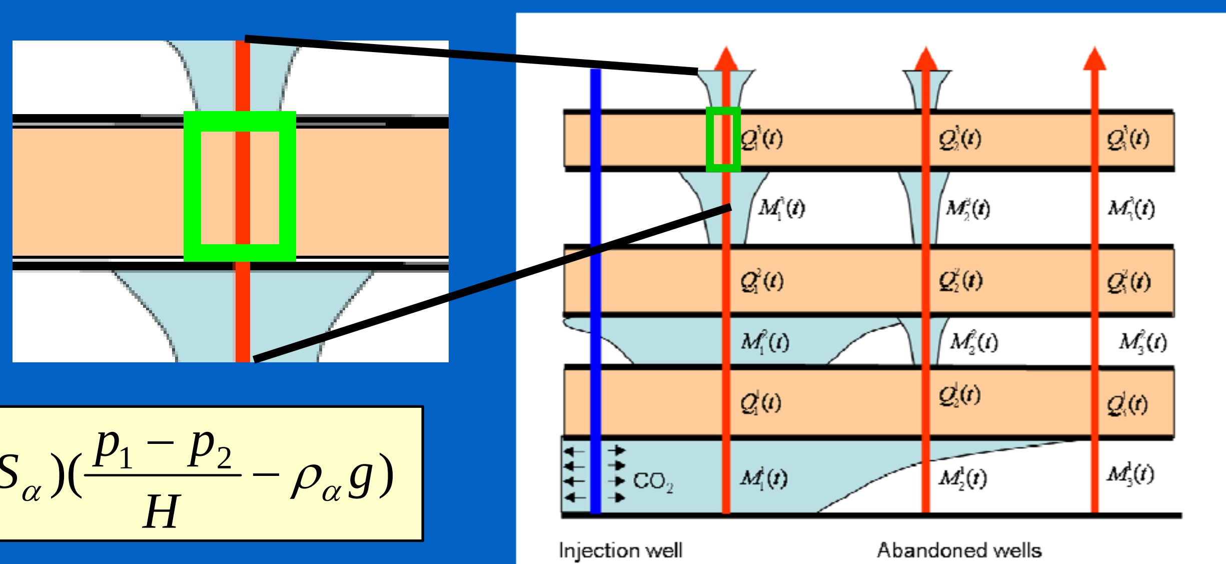
$$\chi_{min} = \frac{2}{\lambda}$$

(From Nordbotten and Celia, *JFM*, 2006)

A Semi-analytical Model

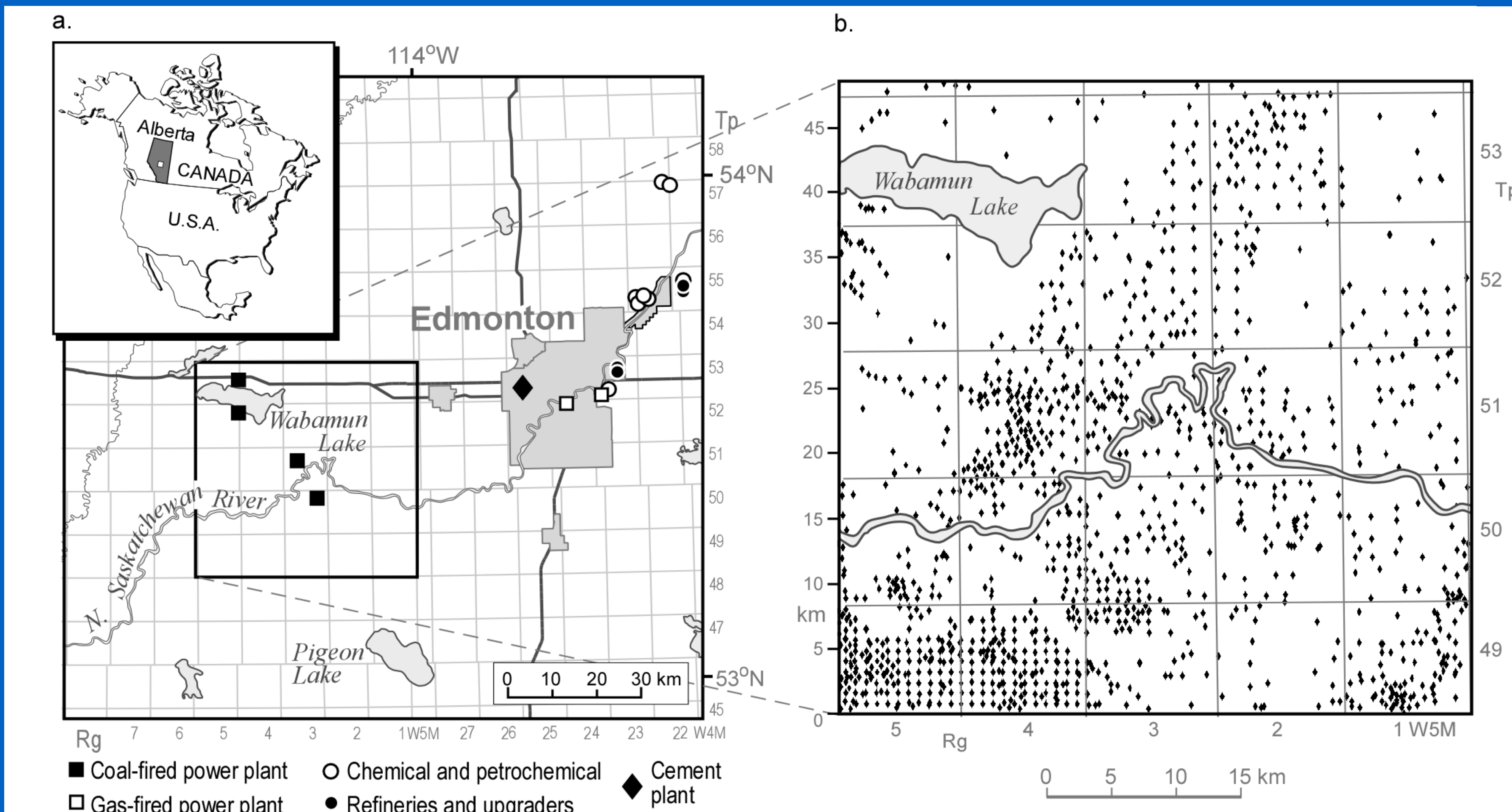
1. Injection Plume, Secondary Plumes and Pressure Fields: Similarity Solution (*Nordbotten and Celia, JFM, 2006*)
2. Leakage Dynamics: Multi-phase Darcy Flow along Leaky Well Segments (*Nordbotten et al., ES&T, 2005, 2008*)
3. Upconing around Leaky Wells (*Nordbotten and Celia, WRR, 2006*)
4. Grid-free solutions: We can now solve 50 years of injection over 2,500 km^2, 12 layers, and 1,200 wells in about 15 minutes.

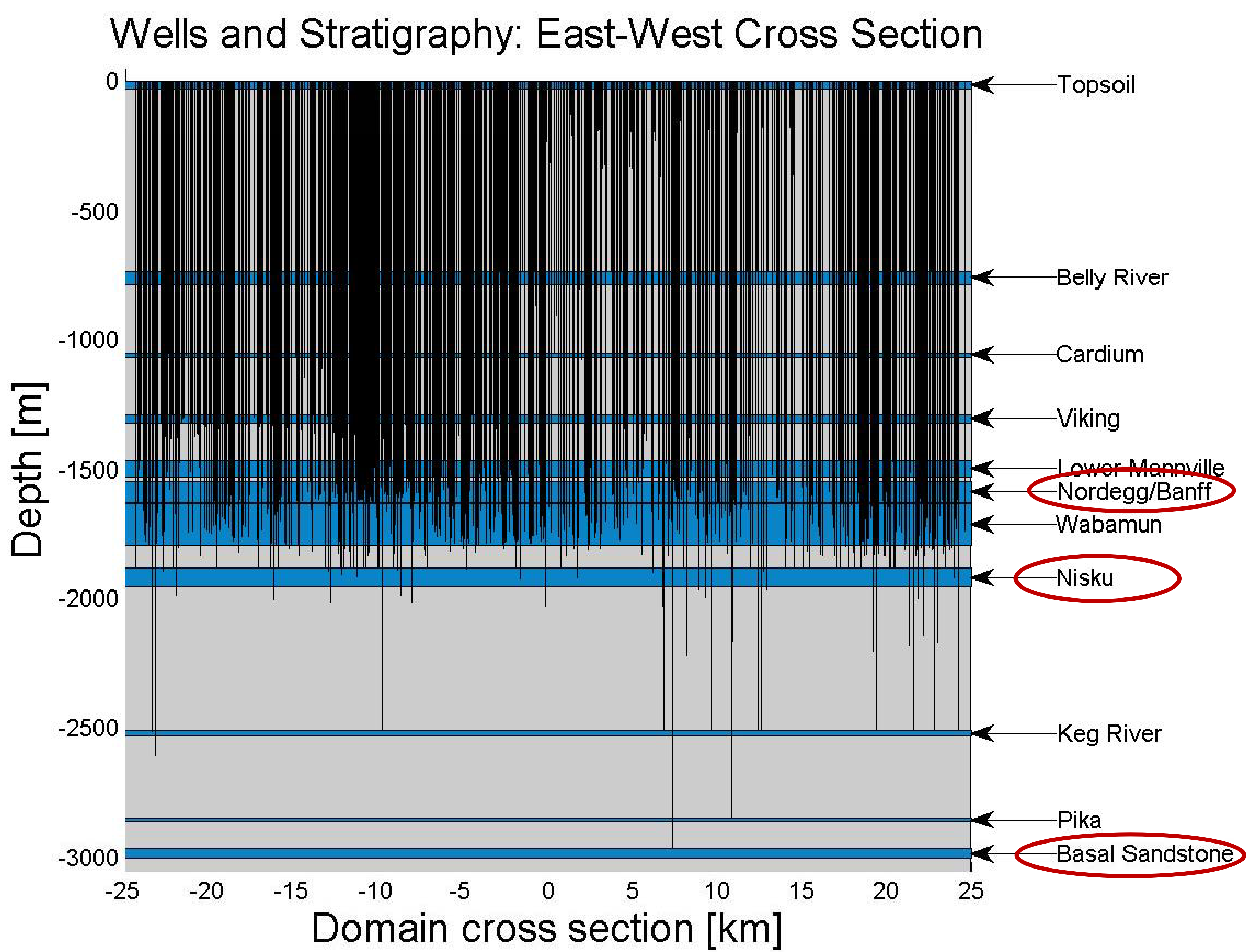




$$Q_{well} \propto K_{well} k(S_\alpha)\left(\frac{p_1 - p_2}{H} - \rho_\alpha g\right)$$

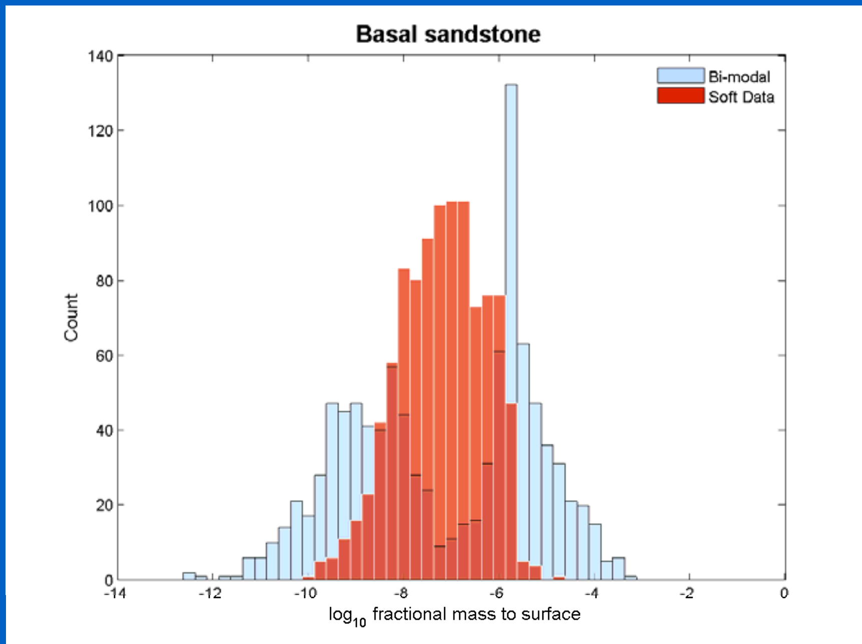
Study Area around Edmonton – Wabamun Lake

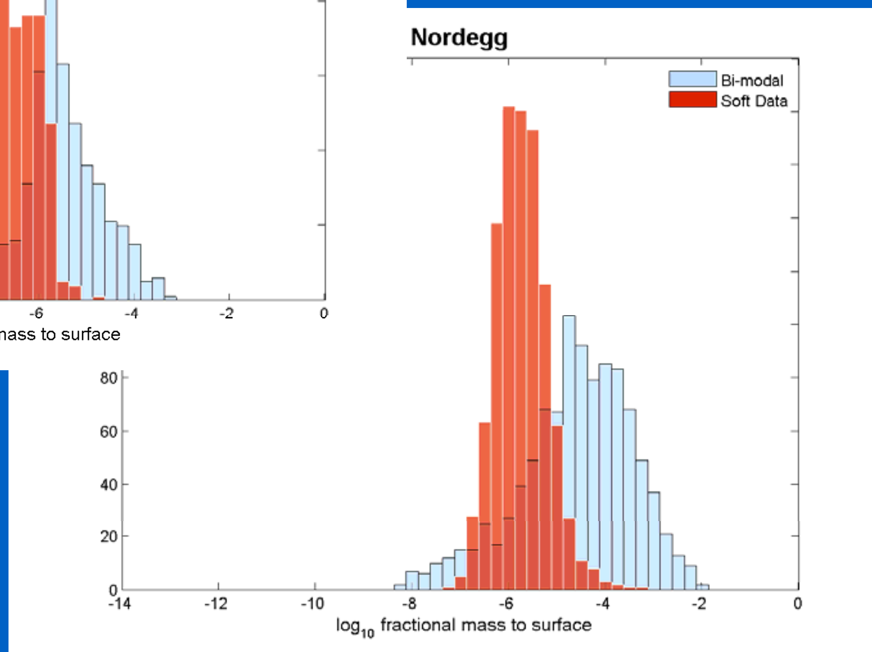


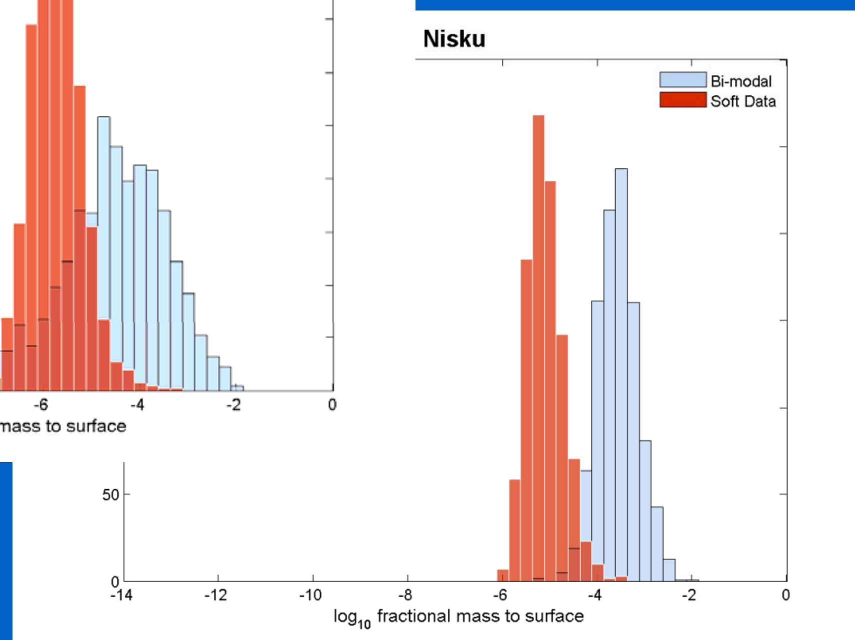


Wells and Stratigraphy: East-West Cross Section
Depth [m]
0
-500
-1000
-1500
-2000
-2500
-3000
-25
-20
-15
-10
-5
0
5
10
15
20
25
Domain cross section [km]
Topsoil
Belly River
Cardium
Viking
Lower Mannville
Nordegg/Banff
Wabamun
Nisku
Keg River
Pika
Basal Sandstone

Model Results







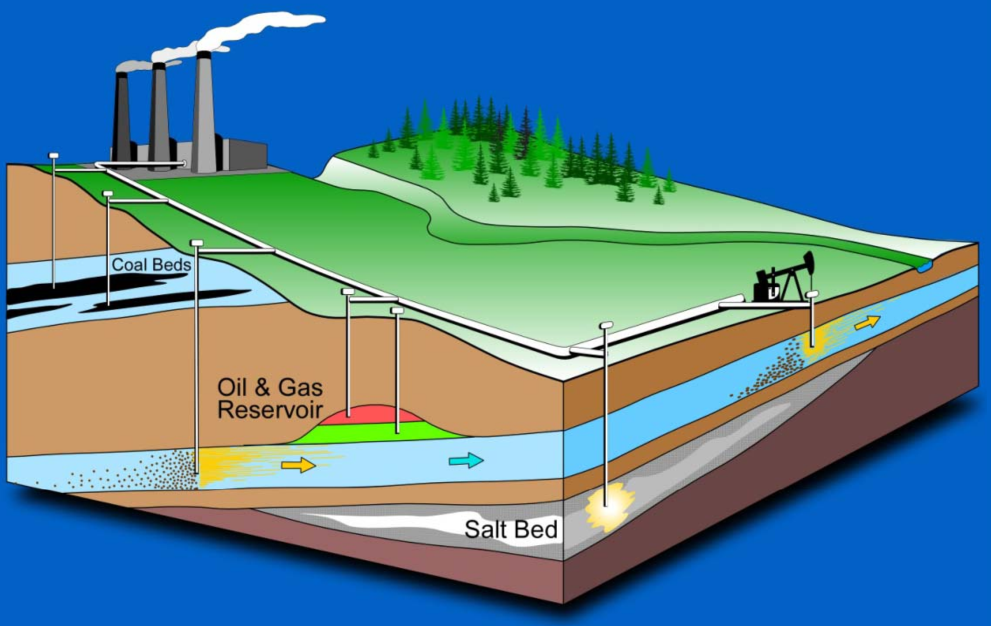
Recent Developments

- High-performance Implementation (Elsa)
  - Complete re-implementation of code in C++
  - Highly modular, very efficient
- Expanded Physics in Semi-analytical Model
  - Diffuse leakage of brine through caprock formations
  - Improved similarity solutions for low flow rates
- User-friendly Interaces
  - Web-based interface for simple systems
  - Multiple formats for input
- Separate numerical sharp-interface code (VESA)
- Designs for a hierarchical modeling platform.

Concluding Remarks

- Simplified models can be reasonable because:
  - Buoyancy provides strong vertical segregation
  - Space- and time-scale separation for critical processes
  - Large uncertainties in critical leakage parameters make detailed fine-scale simulation unnecessary
- Fully coupled detailed models are appropriate for:
  - Fine resolution along critical leakage pathways
  - Computational upscaling for bulk parameters
  - Basic Science investigations
- Important practical questions require practical models.

Thank You!



Publications

Celia, M.A. and J.M. Nordbotten, "Practical Modeling Approaches for Geological Storage of Carbon Dioxide", under review, *Ground Water*, 2009.

Nordbotten, J.M., D. Kavetski, M.A. Celia, S. Bachu, A Semi-analytical Model Estimating Leakage associated with CO_2 Storage in Large-scale Multi-layered Geological Syatems with Multiple Leaky Wells", published online 17 December 2008, *Environmental Science and Technology*, 2008.

Celia, M.A., J.M. Nordbotten, S. Bachu, M. Dobossy, and B. Court, "Risk of Leakage versus Depth of Injection in Geological Storage", Proc. GHGT-9, Washington, DC, November 2008.

Bachu. S. and M.A. Celia, "Assessing the Potential for CO2 Leakage, Particularly through Wells, from CO2 Storage Sites", to appear, *The Science and Technology of Carbon Sequestration*, AGU Monograph, 2008.

Gasda, S., J.M. Nordbotten, and M.A. Celia, "Upslope Plume Migration and Implications for Geological CO_2 Storage in Deep Saline Aquifers", *IES Journal of Civil Engineering, Vol. 1, No. 1*, page 1, 2008.

Gasda, S., J.M. Nordbotten, and M.A. Celia, "Determining Effective Wellbore Permeability from a Field Pressure Test: A numerical Analysis of Detection Limits", *Environmental Geology*, published online 18 July 2007.

Nordbotten, J.M. and M.A. Celia, "Similarity Solutions for Fluid Injection into Confined Aquifers", *Journal of Fluid Mechanics*, *561*, 307-327, 2006.

Nordbotten, J.M. and M.A. Celia, "Interface Upconing around an Abandoned Well", *Water Resources Research*, *42*, (doi:10.1029/2005WR004738), 2006.

Celia, M.A., S. Bachu, J.M. Nordbotten, D. Kavetski, and S. Gasda, "A Risk Assessment Modeling Tool to Quantify Leakage Potential through Wells in Mature Sedimentary Basins", *Proc. 8th Int. Conf. on Greenhouse Gas Control Technologies*, Trondheim, Norway, 2006.

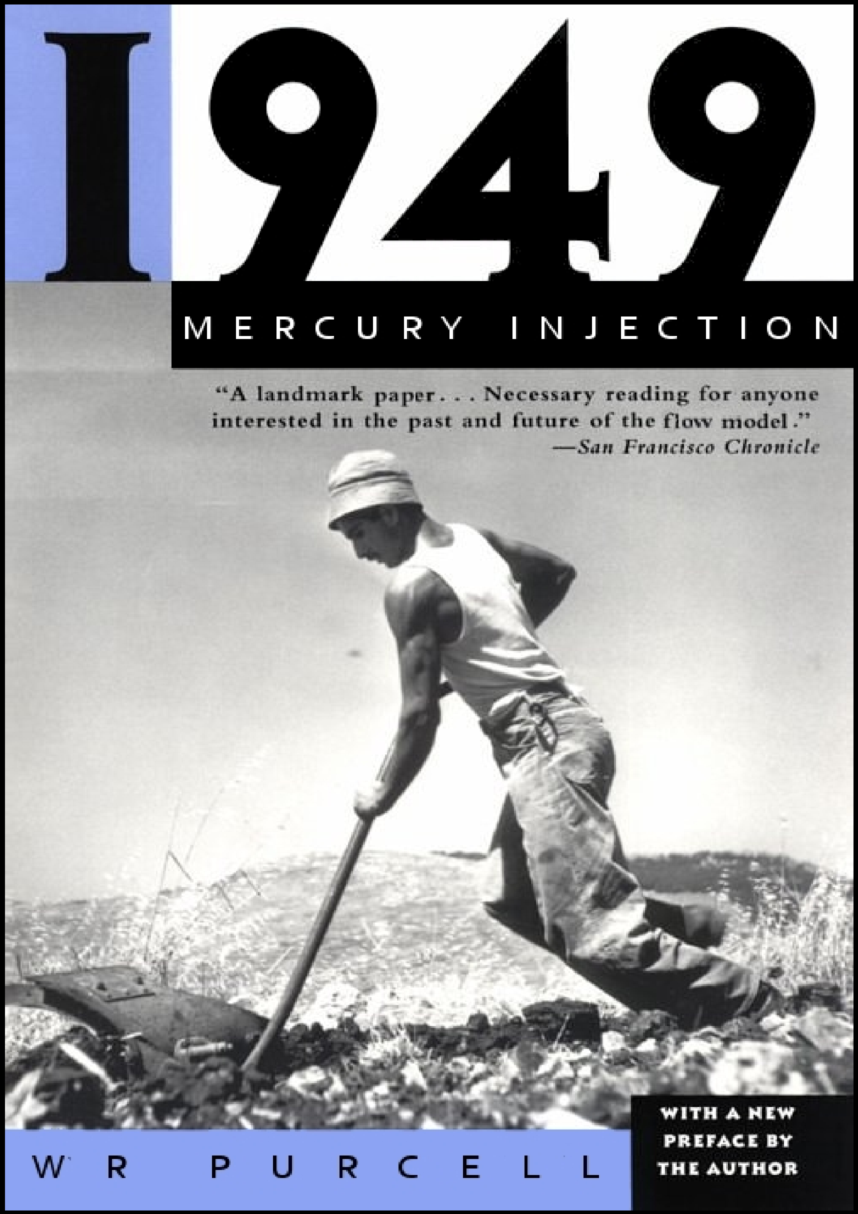
Critical Parameters

- Reservoir Formations (Upscaled):
  - Permeability (k), Porosity (φ), and Thickness (H)
  - Residual Saturations (S_{res})
  - Endpoint Relative Permeability (k_{rel})
- Caprock Formations:
  - Permeability
  - Thickness
  - Preferential Flow Paths
- Old Wells (and Faults):
  - Depth
  - Effective Permeability (k_{well})
  - Geochemical reactions, other local nonlinear processes

Leakage through Faults

Andrew Cavanagh
The Permedia Research Group

CO2Toolkit
by Permedia



'Capillary pressure - their measurements using mercury and the calculation of permeability therefrom'
Purcell, W. R. 1949. AIME Petroleum Trans., 186, 39-48.

Young-Laplace equation

$\Delta P = 2\gamma.\cos\theta/r$

Darcy's law

$Q/A = -\nabla P.k/\mu$

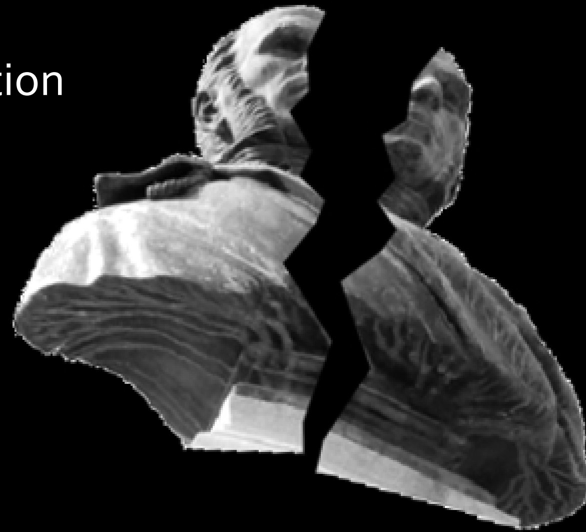
Henry Philibert Gastard Darcy, 1803-1858

Thomas Young, 1773-1829

Pierre-Simon Laplace, 1749-1827

Young-Laplace equation

$\Delta P = 2\gamma.\cos\theta/r$



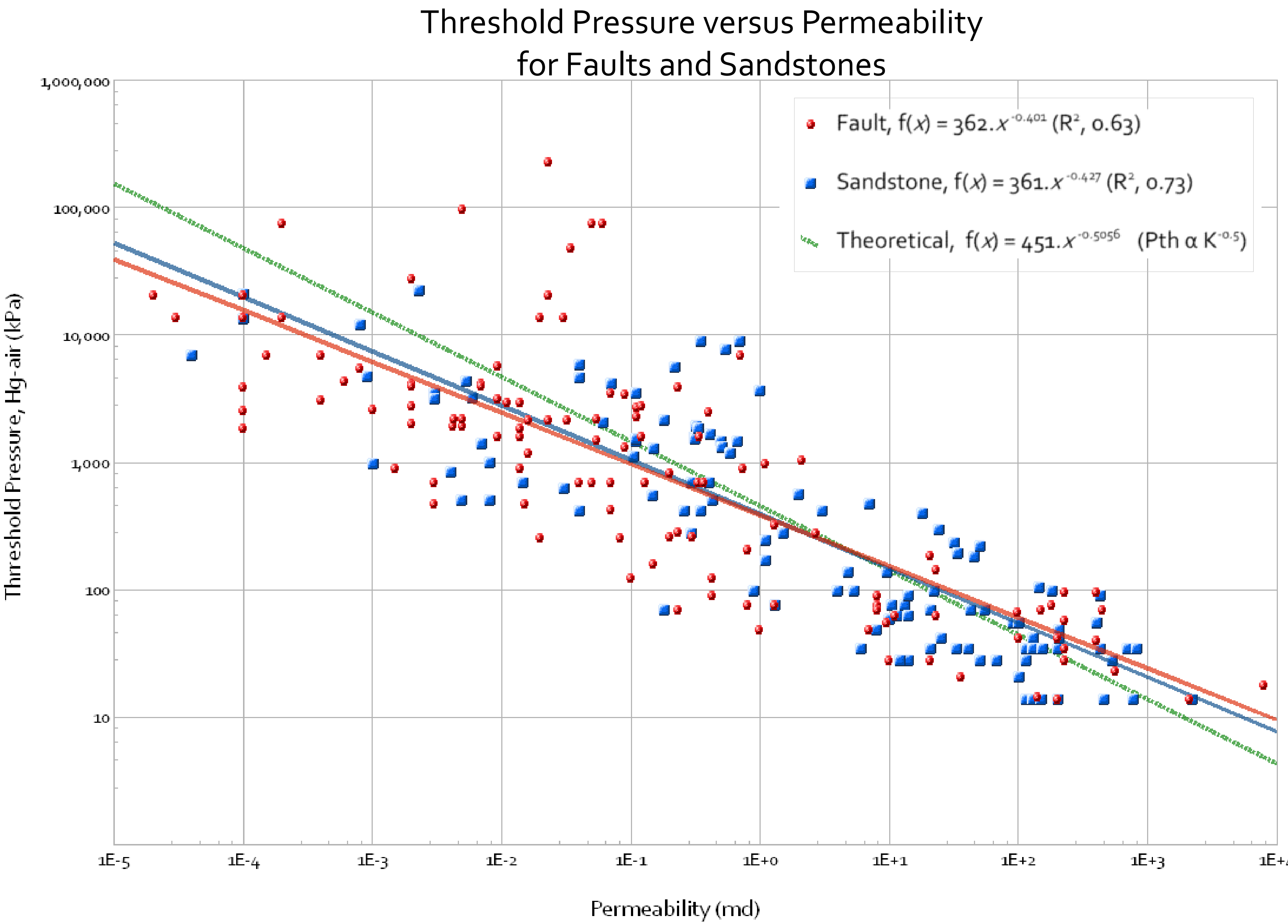
Darcy's law

$Q/A = -\nabla P.k/\mu$

Capillary Number, Ca < 0.0001

Thomas Young, 1773-1829

Pierre-Simon Laplace, 1749-1827



(After Harper & Lundin 1997; Sperrevik et al. 2002; Sorkhabi & Tsuji, 2005)

CO_2 Sequestration in Faulted Environments

Injection of CO_2 into geological formations gives rise to a variety of coupled chemical and physical processes. CO_2 injection **can induce fault instability**, leading to seismic activity within and around a storage site.

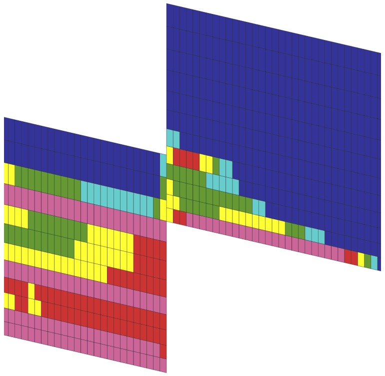
A sequential coupling approach for a recent numerical study (Li *et al* 2004) investigated the behavior of the CO_2 sequestration system for temperature, effective stress, injection pressure and CO_2 buoyancy to further understand the effect of CO_2 injection on the mechanical behavior of faults.

The numerical results showed that **fault seal is highly sensitive to injection pressure**. At the initial stage of the sequestration process, injection pressure may play a key role in the pore pressure of the formations.

However, as time continues, CO_2 buoyancy dominates the pore pressure regime of the formations. **For buoyant flow, thermo-mechanical factors are unlikely to affect the mechanical stability of formations and faults.**

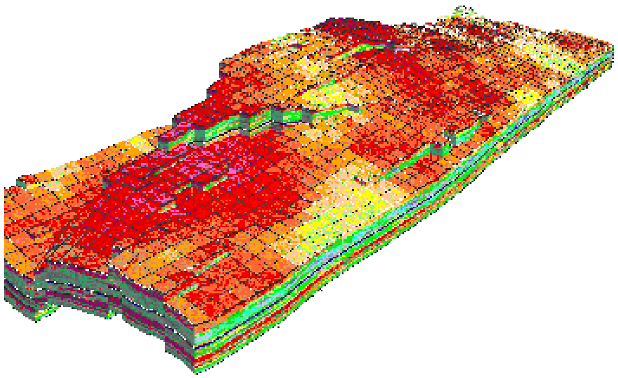
Adapted from Li *et al. 2006,* Pure and Applied Geophysics

Conceptual
Experimental
1,000 – 100,000 cells



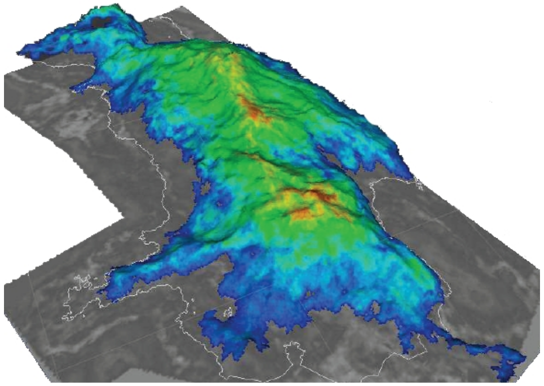
PERM
Imperial College

Reservoir
Matrix Solver
100,000 – 10,000,000 cells



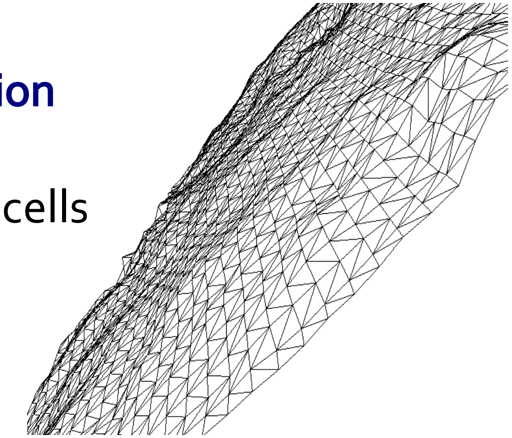
TrapTester
Fault Analysis Group

Reservoir-Basin
Geometric Solver
10,000,000 – 1,000,000,000 cells



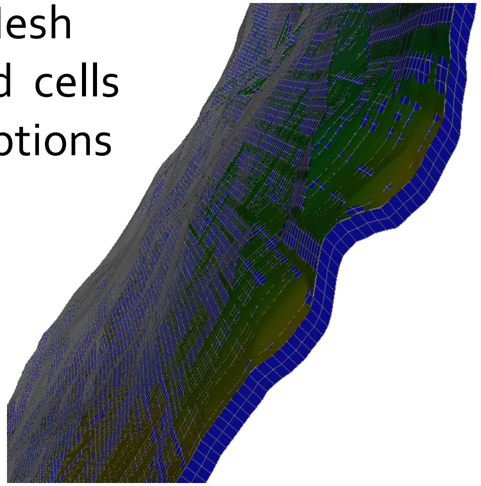
MPath Migration
Permedia Research and BP

Simple Fault Representation
2D Faults in a 3D mesh
Unique surfaces between cells
Boundary conditions



Fault Flow Simulation
Thickness and Permeability Modifiers
Transmissibility Multipliers
Geomechanics, Geochemistry…

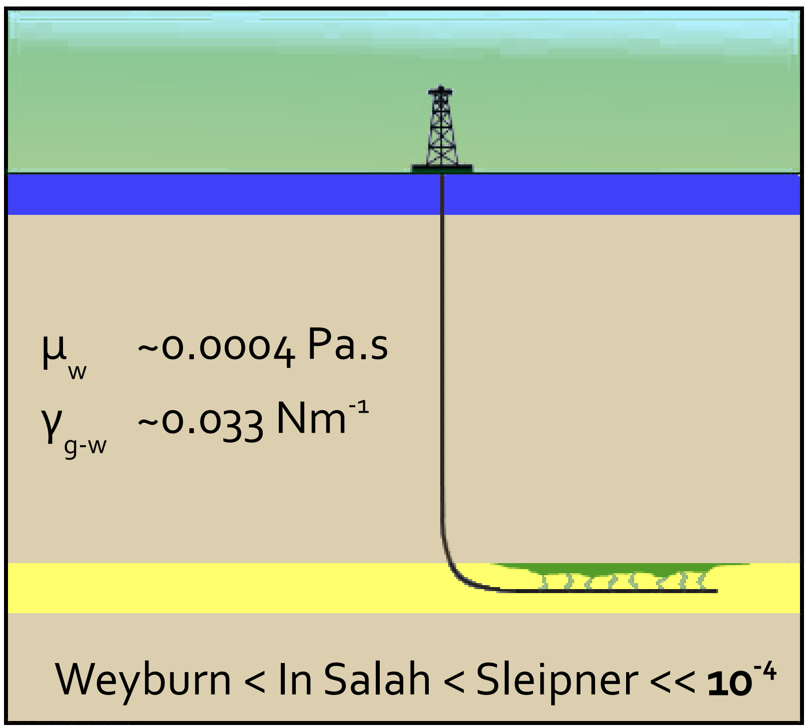
Complex Fault Representation
3D Faults in a 3D Mesh
Paired surfaces and cells
Lithological descriptions



$Ca = \mu . q / \gamma$	[/]
μ, viscosity	
q, flux	
γ, interfacial tension	

So you think a million tonnes/year is fast?

1 Mt/yr = 50 litres/second… (635 kg/m^3 and 31,556,700 s/yr) [Q]



Capillary number calculation

Perforation length: ~50 meters

Injection rate: ~1 litre/meter/second

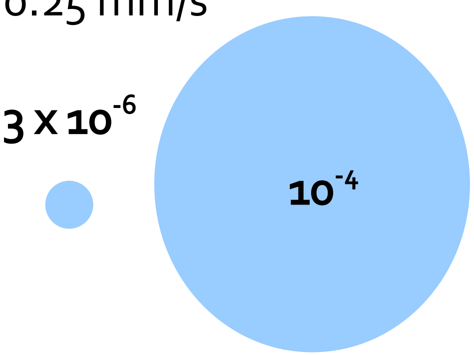
Plume ascent width: ~25 cm [?]

Area of frontal advance: 0.25 m^2 [A]

Flux at well: 1 litre/0.25 m^2/second [Q/A]

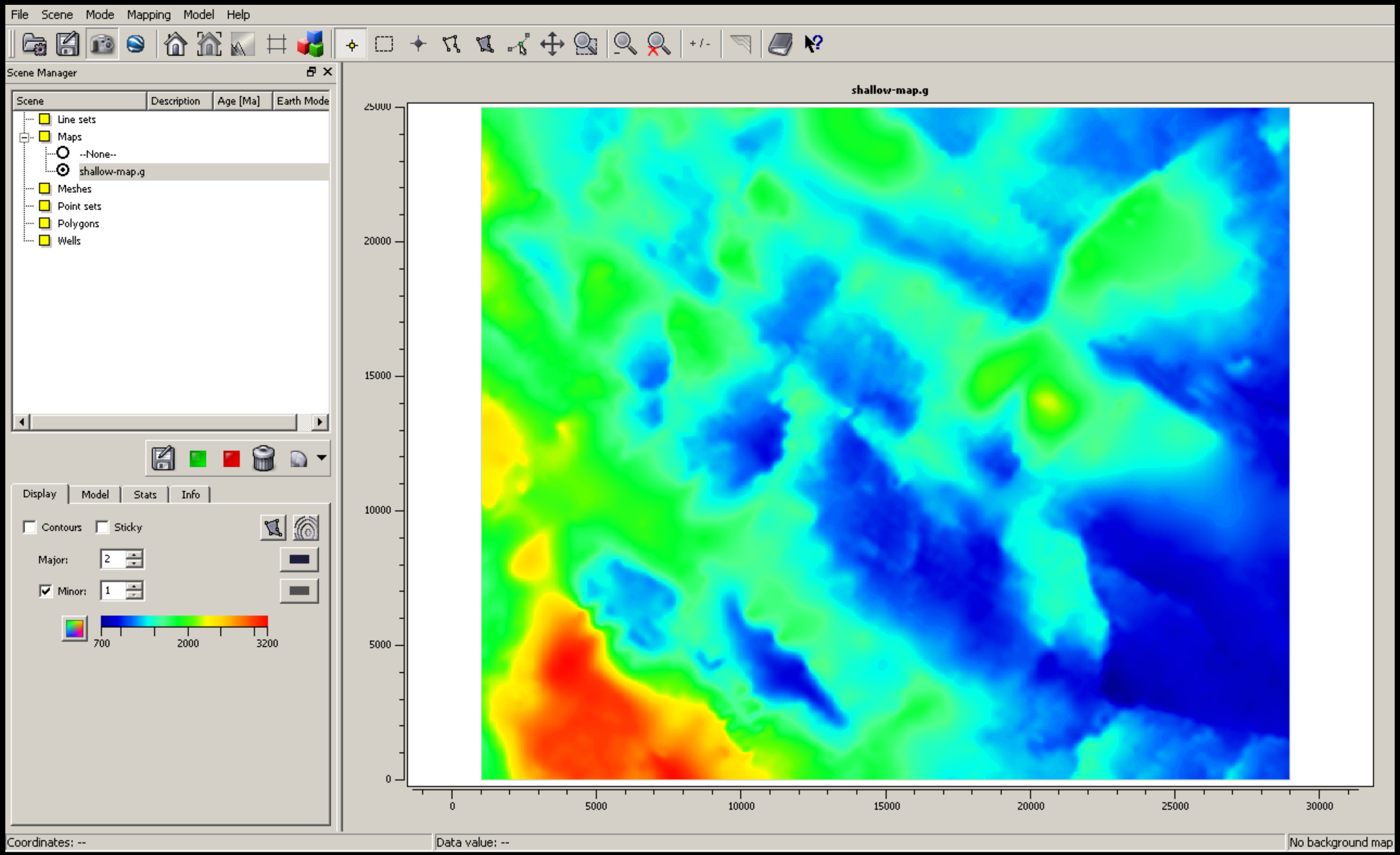
0.25 mm/s [q]

Capillary number: $\mathbf{3 \times 10^{-6}}$ [/]

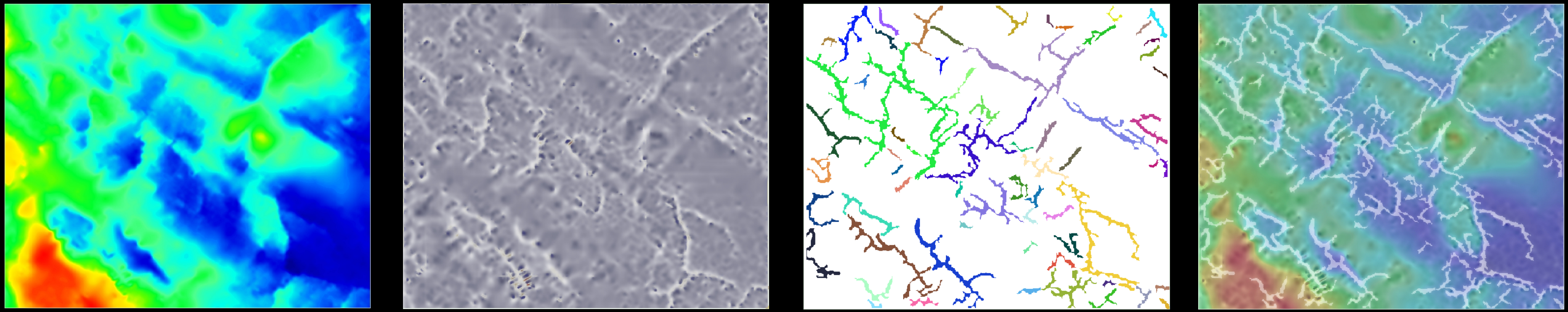


An injection rate of one million tonnes/year/well is about thirty times **too slow** to break the boundary condition of invasion percolation

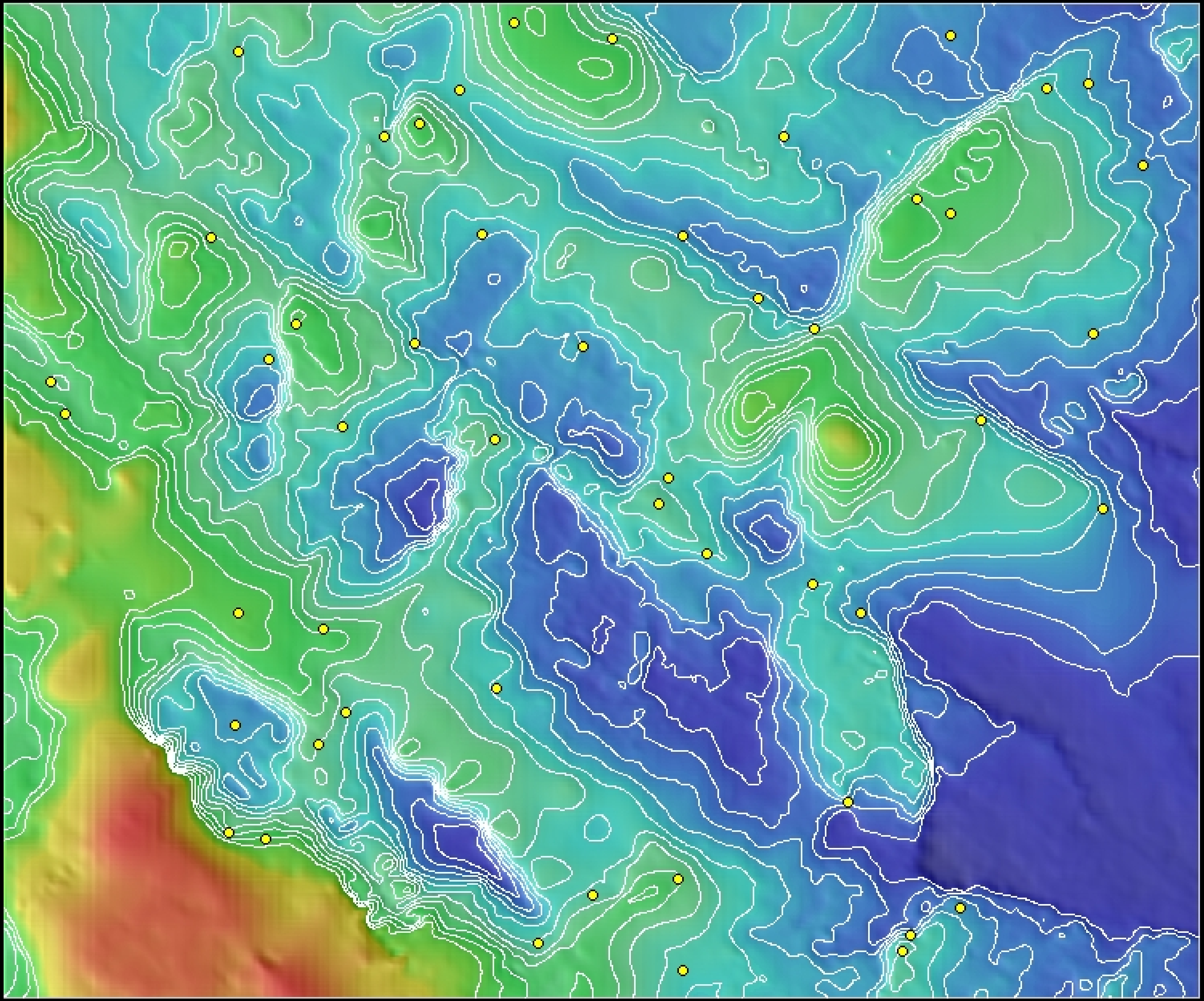
Regional Flow Model



Curvature Analysis



Site location? Trap size? Storage volume?



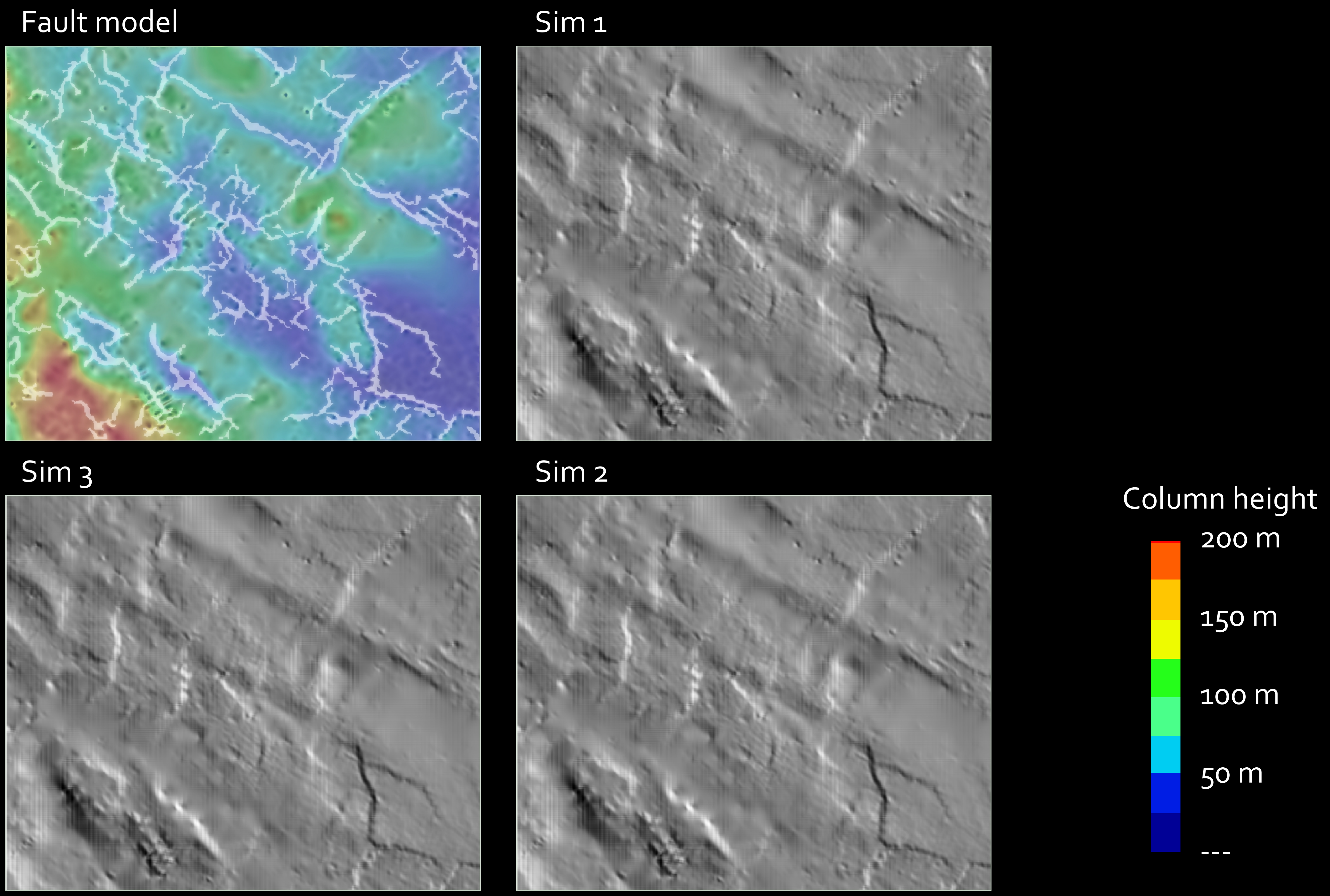
Scenario
Regional aquifer
Mudstone cap rock
Two fault trends

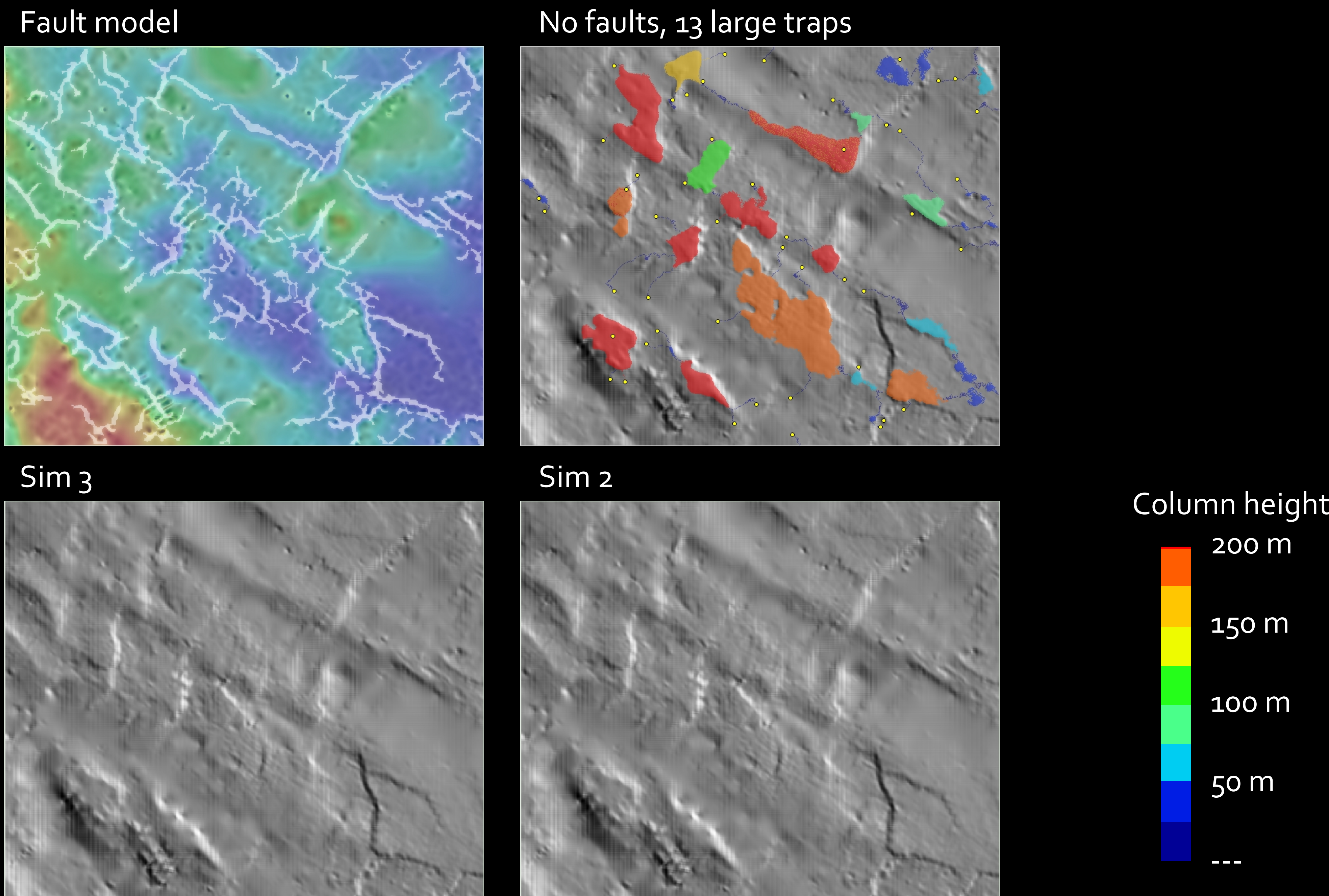
Area: 30 x 25 km
Depth: 700 - 3200 m

CO_2 ceiling: 1000 m
CO_2 floor: 2000 m
Injection wells: 50

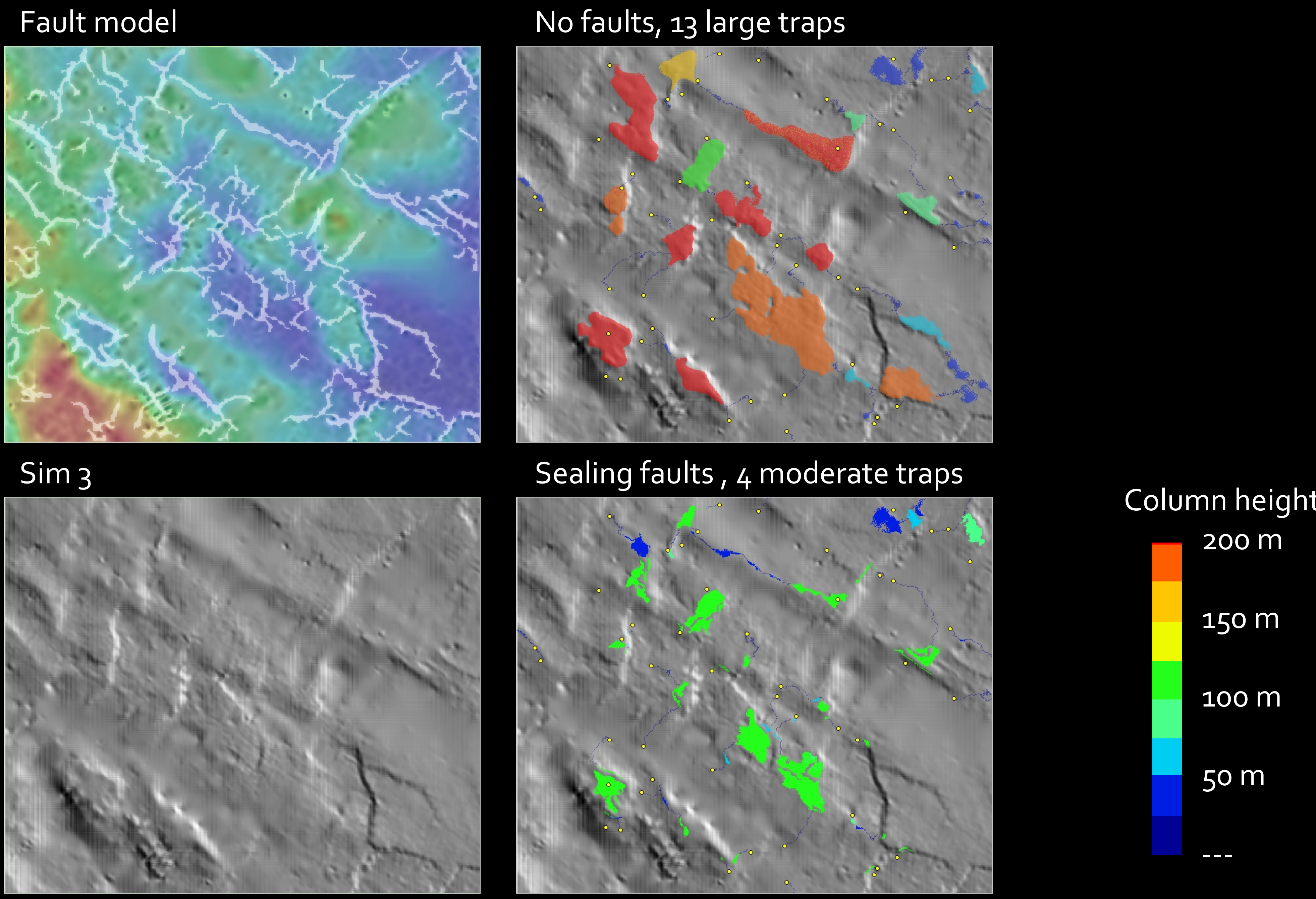
Sim 1: no faults
Sim 2: sealing faults
Sim 3: leaky faults

Column heights
Mudstone: 200 m
Sealing faults: 100 m
Leaky faults: 50 m

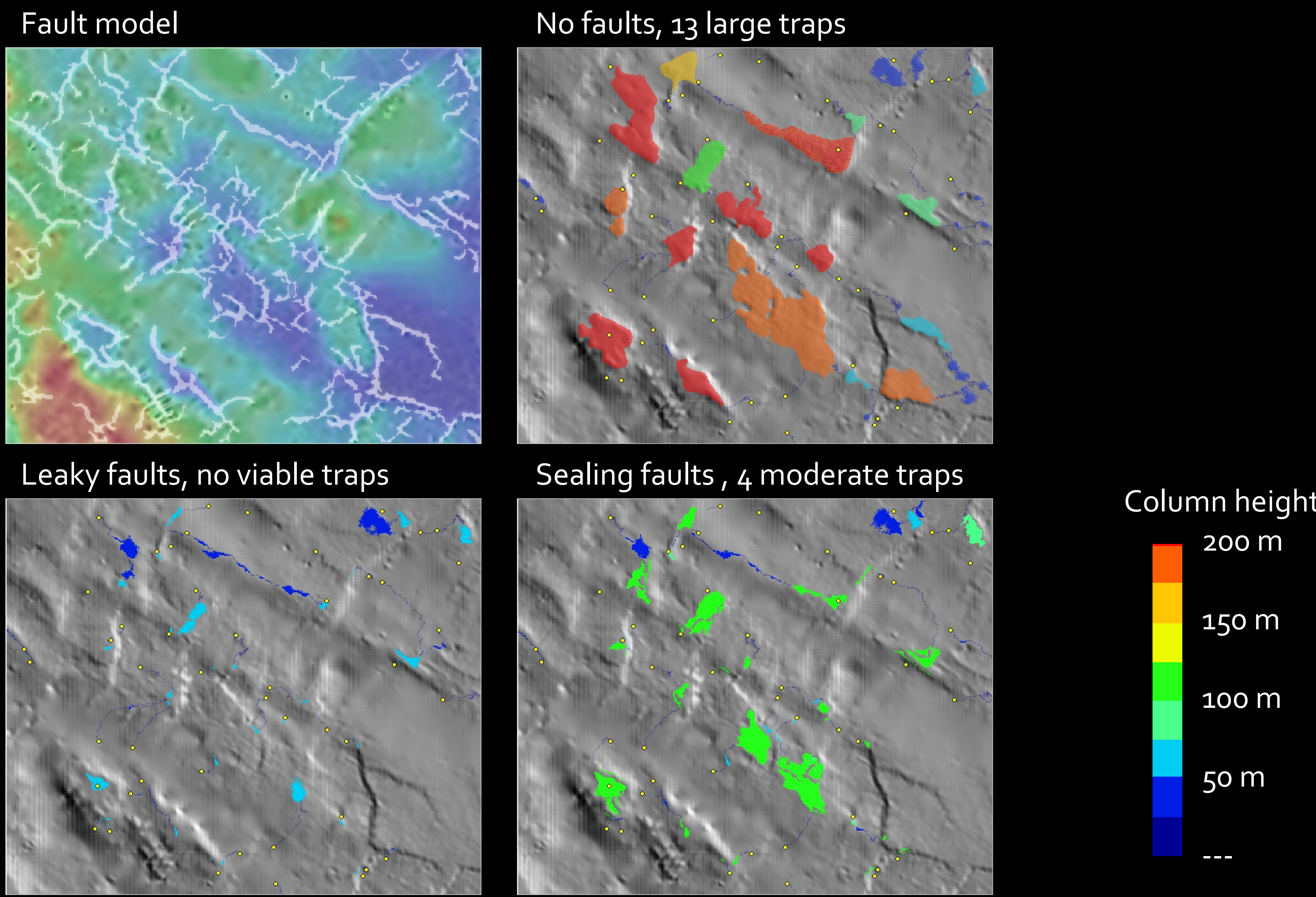

Fault model
Sim 1
Sim 3
Sim 2
Column height
200 m
150 m
100 m
50 m

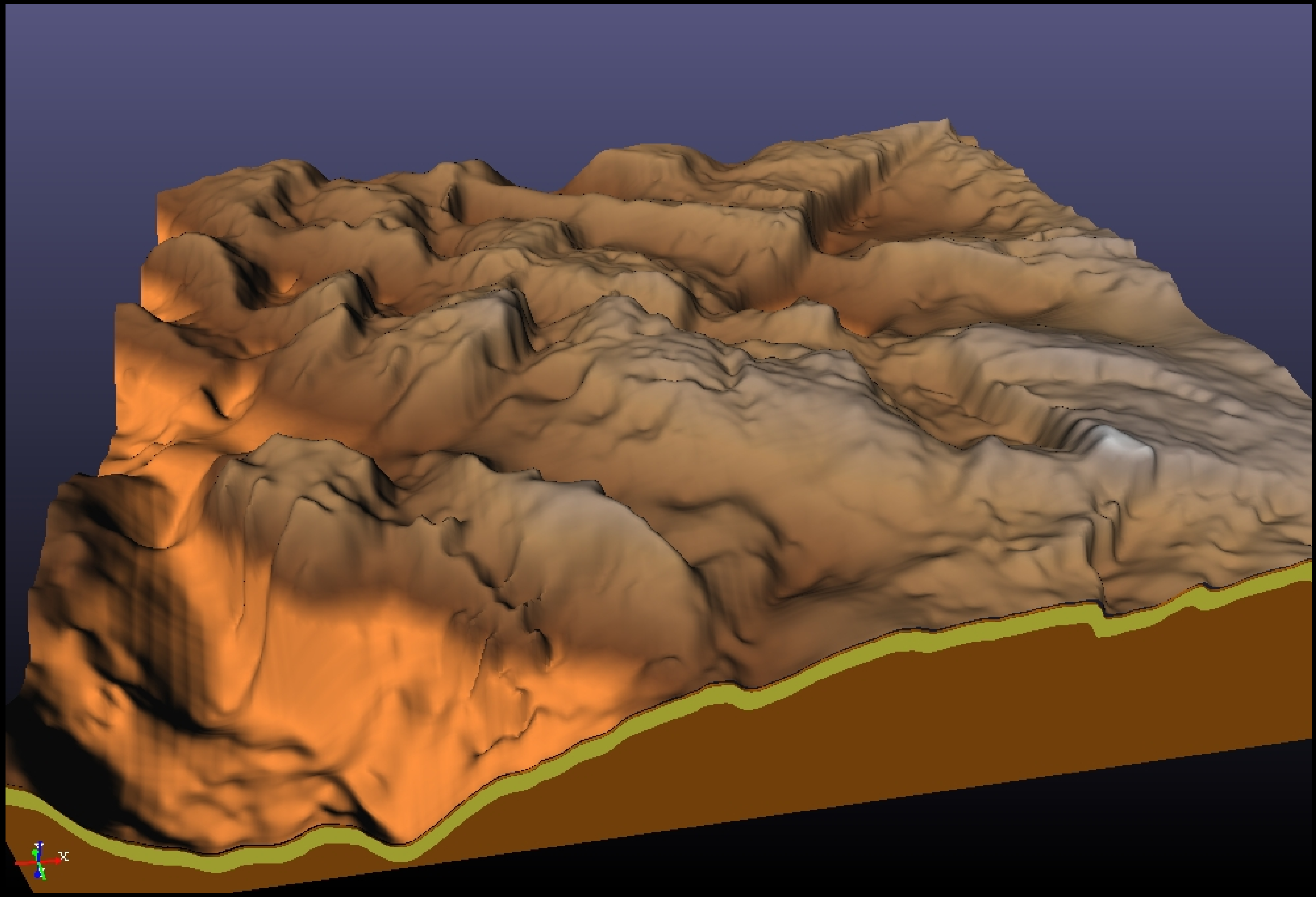


Fault model
No faults, 13 large traps
Sim 3
Sim 2
Column height
200 m
150 m
100 m
50 m



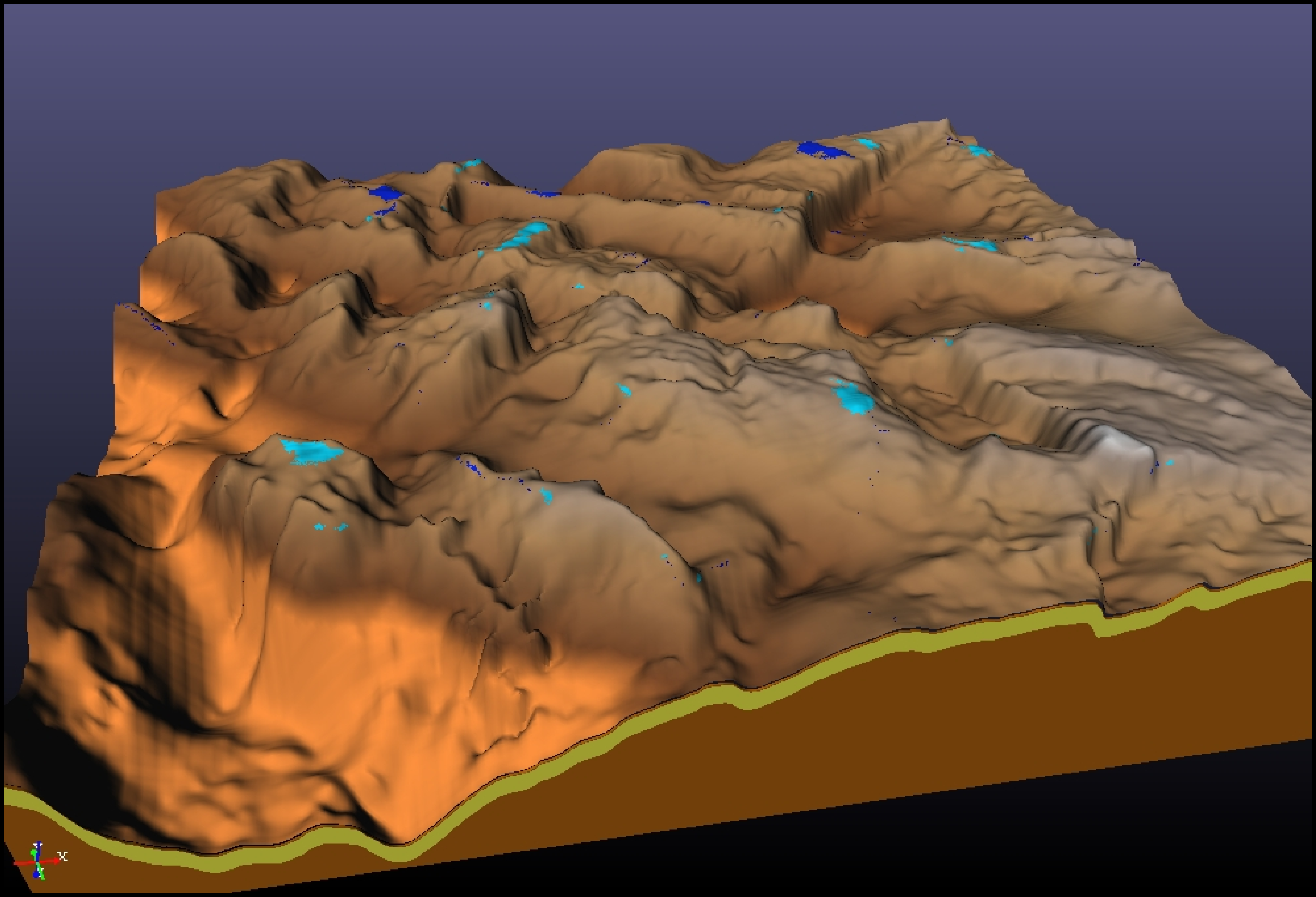
Fault model
No faults, 13 large traps
Sim 3
Sealing faults , 4 moderate traps
Column height
200 m
150 m
100 m
50 m


Fault model
No faults, 13 large traps
Leaky faults, no viable traps
Sealing faults , 4 moderate traps
Column height
200 m
150 m
100 m
50 m



'Analyses of leaky faults are commonly addressed superficially in seal evaluation. The result may well be overlooked exploration opportunities and failed exploration wells.'

Hermanrud *et al.* Seal Failure Related to Basin Scale Processes. AAPG (2005).



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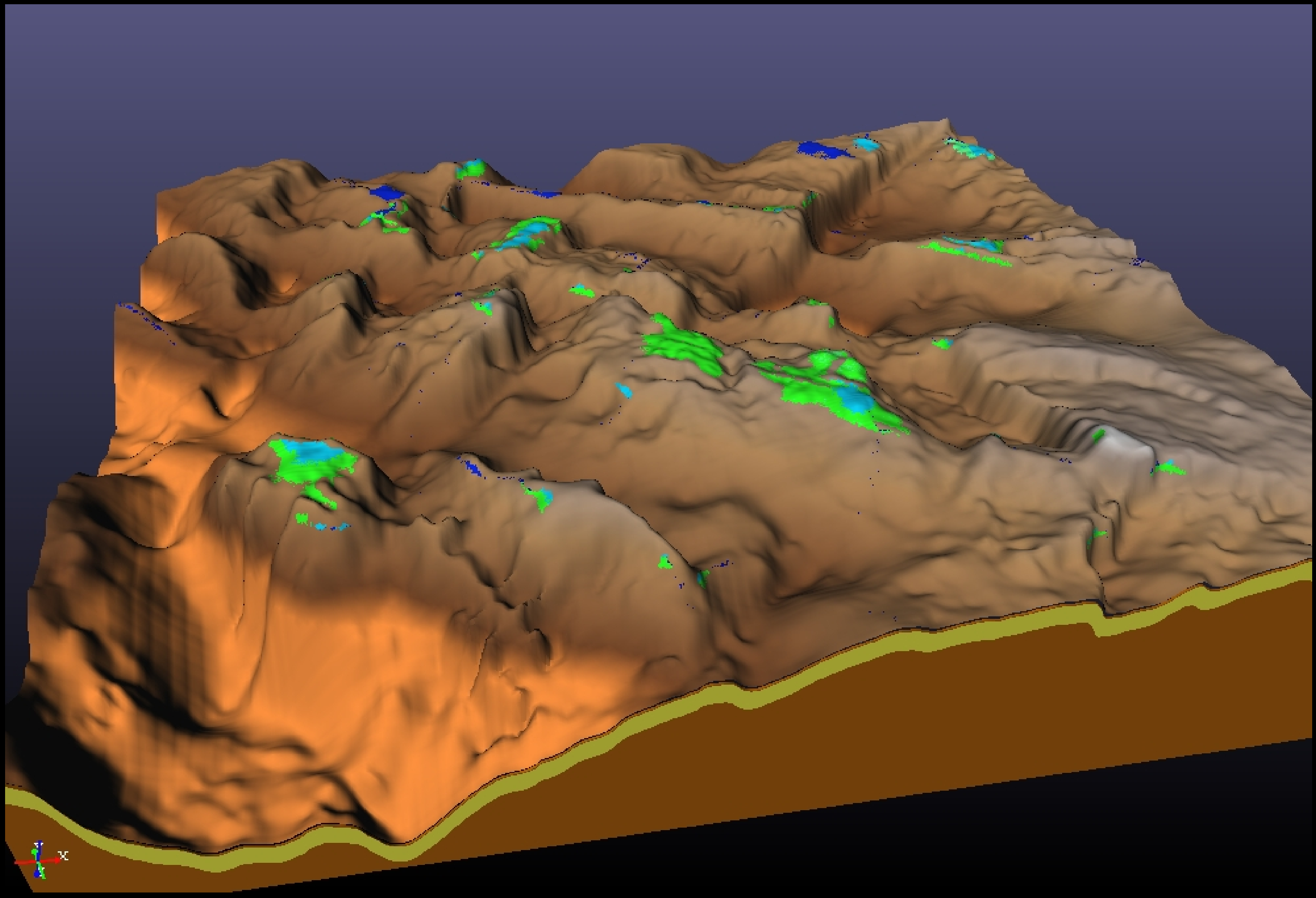

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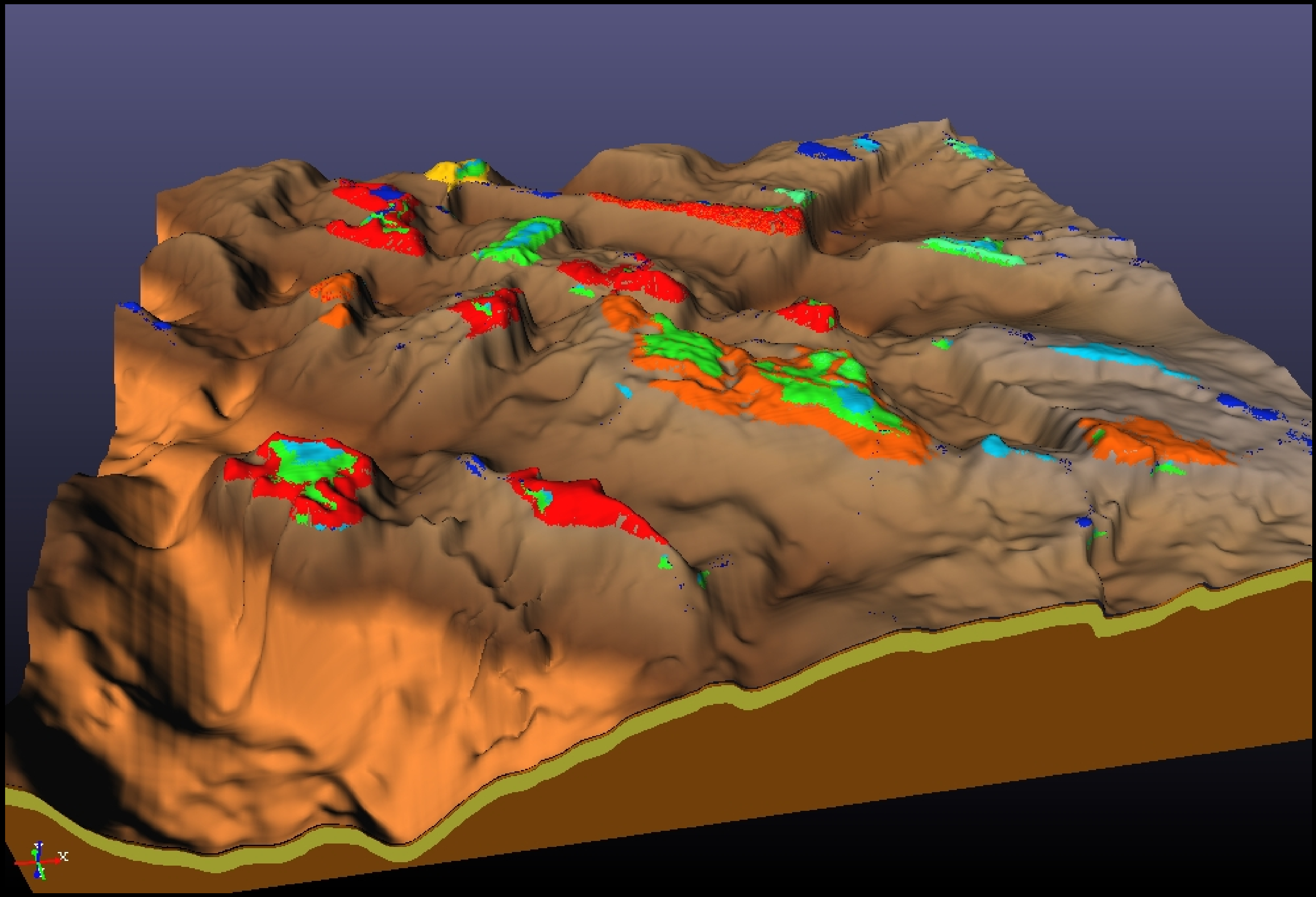

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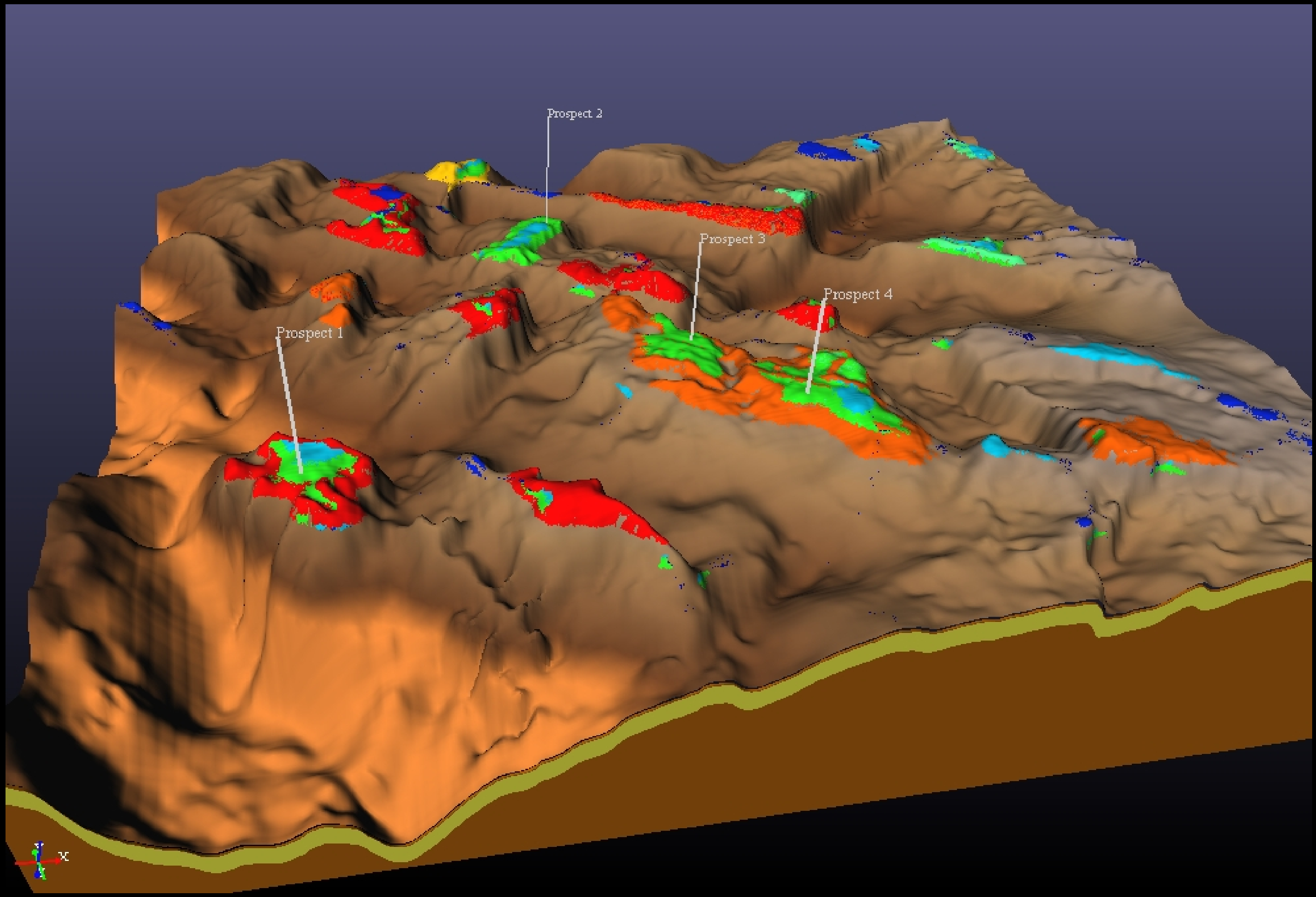

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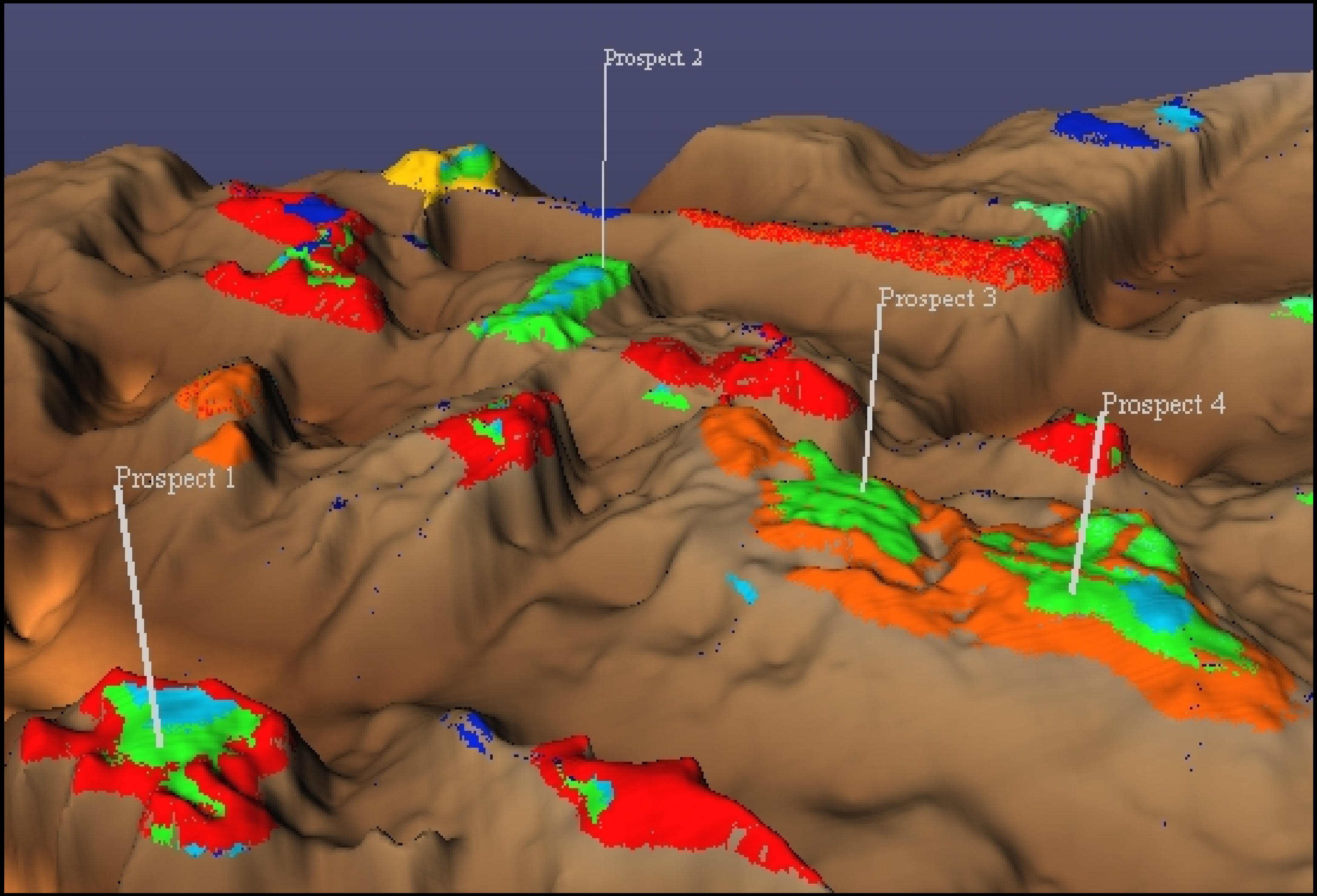

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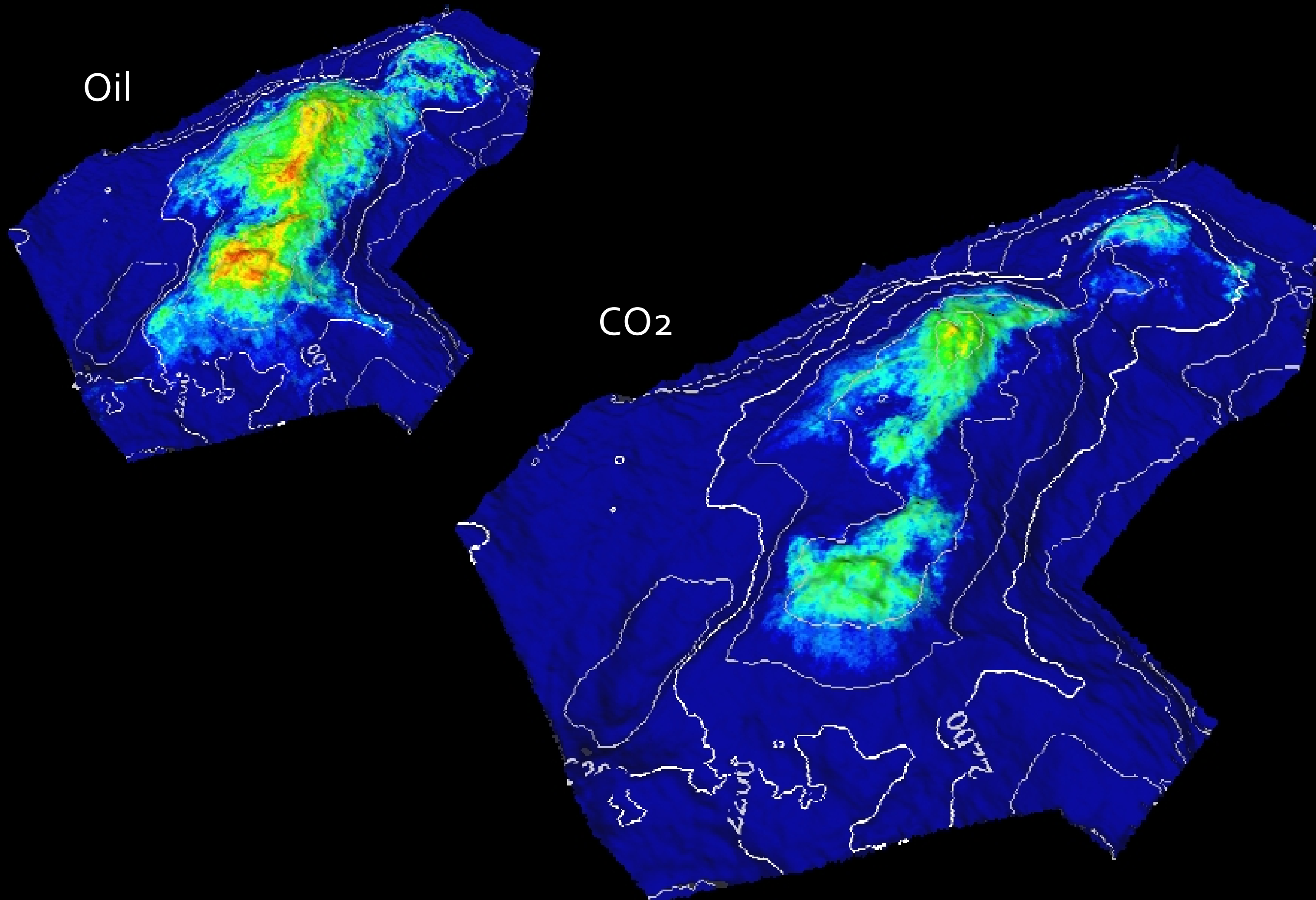

Forties Field, North Sea: Oil STOOIP and CO_2 Storage Comparison
Bunney & Cawley, AAPG Hedberg 2007.

Faults and Fluid Flow in Petroleum Systems

- AAPG Memoir 85: Faults, Fluid Flow and Petroleum Traps (2005).
- AAPG Hedberg Series 2: Evaluating Fault and Caprock Seals (2005)

Colorado Plateau Analogues

- Dockrill & Shipton. Structural controls on leakage from a natural CO_2 geologic storage site: AAPG Special Publication (2009).

- Nelson *et al*. An analogue for the failure of geologic sequestration: the Hurricane Fault at Pah Tempe Hot Springs. GSA Bulletin (2009).

The In Salah Project

- Ringrose *et al.* First Break (2009).

Fault Leakage

- Manzocchi *et al.* Petroleum Geoscience (1998-2008).
- Hermanrud *et al.*, AAPG Hedberg Series 2 (2005).

Invasion Percolation Theory

- Carruthers (2003).
- Boettcher (2002).
- Meakin (2000).
- England (1987).

CO_2Toolkit by Permedia™

Group 1

Are our models enough?

- All rely on Good Data and enough of it
- Different approaches have different objectives
- What are you asking?
- SITE specific and RISK specific

Group 1

Where are the current gaps?

- We have the tools but…
- How to upscale the pore scale to the field
- Gaps in the data eg rock water CO2 interactions over long term
- Lack of clear/consistent METHOD
- Lack of SHARING results/skills

Group 2

Needs

- Need to step back and examine important processes and phenomena
- Need to understand constraints imposed by regulators
- Small set of benchmarked models accepted by industry and regulators
- Suggestion for developing a single community model (mostly for science)
- Models for scientific research / Models for applications (operators and regulators)
- Working for producing a number of standard model(s) that regulators can use
- Data resolution and quality - Do not put too much emphasis on models results! Always uncertainties

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Session 2 Breakout

Breakout Group 4

- Industry, researchers in group
- Lack of data
- Wellbore leakage model missing? Dynamics of leakage – problem of adequately capturing the physics
- Well leakage monitoring

- Pressure effects very important factor – area of review
- Boundary conditions – geological features or artificial?
- Static geological models are adequate but upscaling issues
- Modelling of caprock behaviour – coupling of gm and gc not there yet

- Lack of data for geomechanics of caprock
- Shear activation greater concern than existing fractures
- Particular problem for deep saline formations – caprocks effectively unknown properties at local scale
- Models – can they be understood and satisfy regulators? Leakage and pressure are 2 key issues

- Total: 3rd party expertise? Assuming regulators ignorance ignores 3rd party review.
- Models today may not be fully predictive?
- Modelling kinetic geochemistry difficult – no satisfactory models?
- Relative permeability curves

Geological modelling, heterogeneities and scale relations

Peter Frykman

GEUS - Geological Survey of Denmark and Greenland

GEUS

Motivation

- Given the complexity of geology, and a toolbox of modelling tools:

  - How to best represent the most influential geological features in a model that can be used for flow simulation and prediction of CO_2 injection and site performance

COMMISSION OF THE EUROPEAN COMMUNITIES

Brussels, 23.1.2008
COM(2008) 18 final

2008/0015 (COD)

Proposal for a

DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

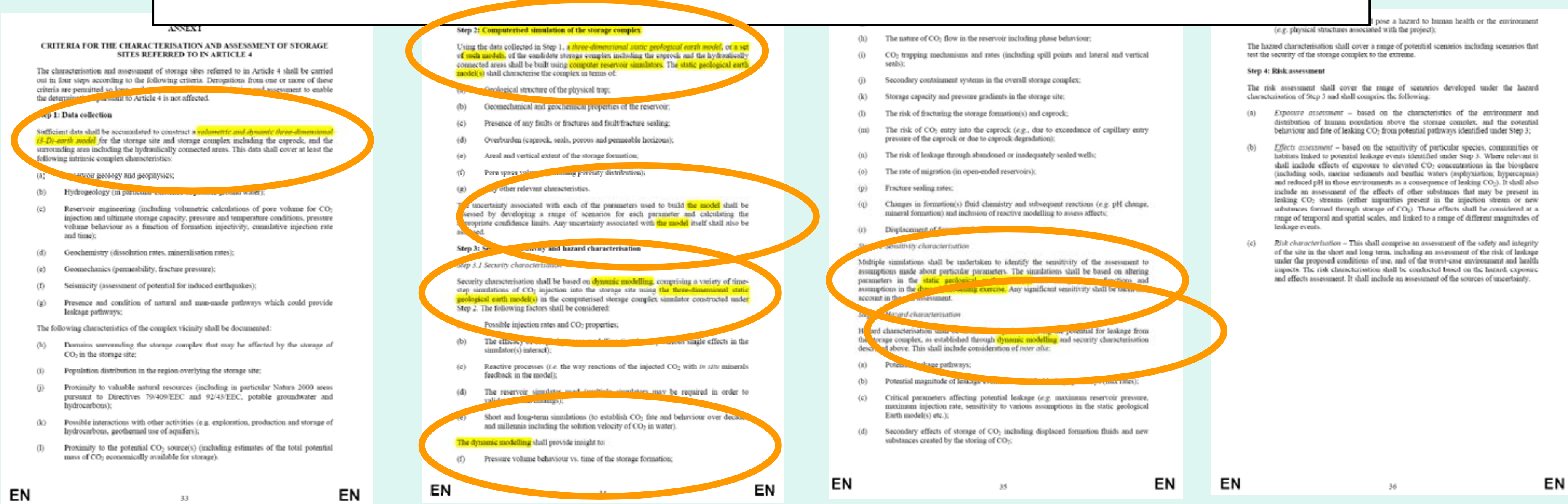
on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006

Important?

model, modelling

ANNEX I

CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF STORAGE SITES REFERRED TO IN ARTICLE 4

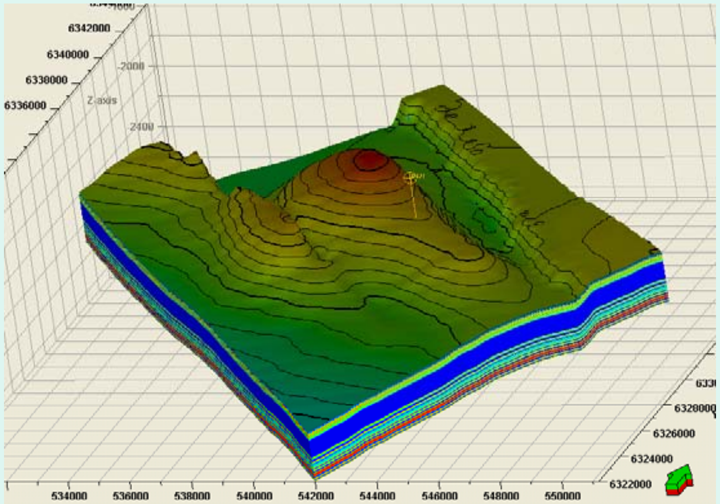


Before you start the modelling -

- How large a model area/volume is necessary?
- Which process do we study?
- At which scale is the process important?
- Can we monitor the real system and make use of the data for history matching and verification?

Typical start of a large project –
1) **Make a model – quick – we need it tomorrow!**

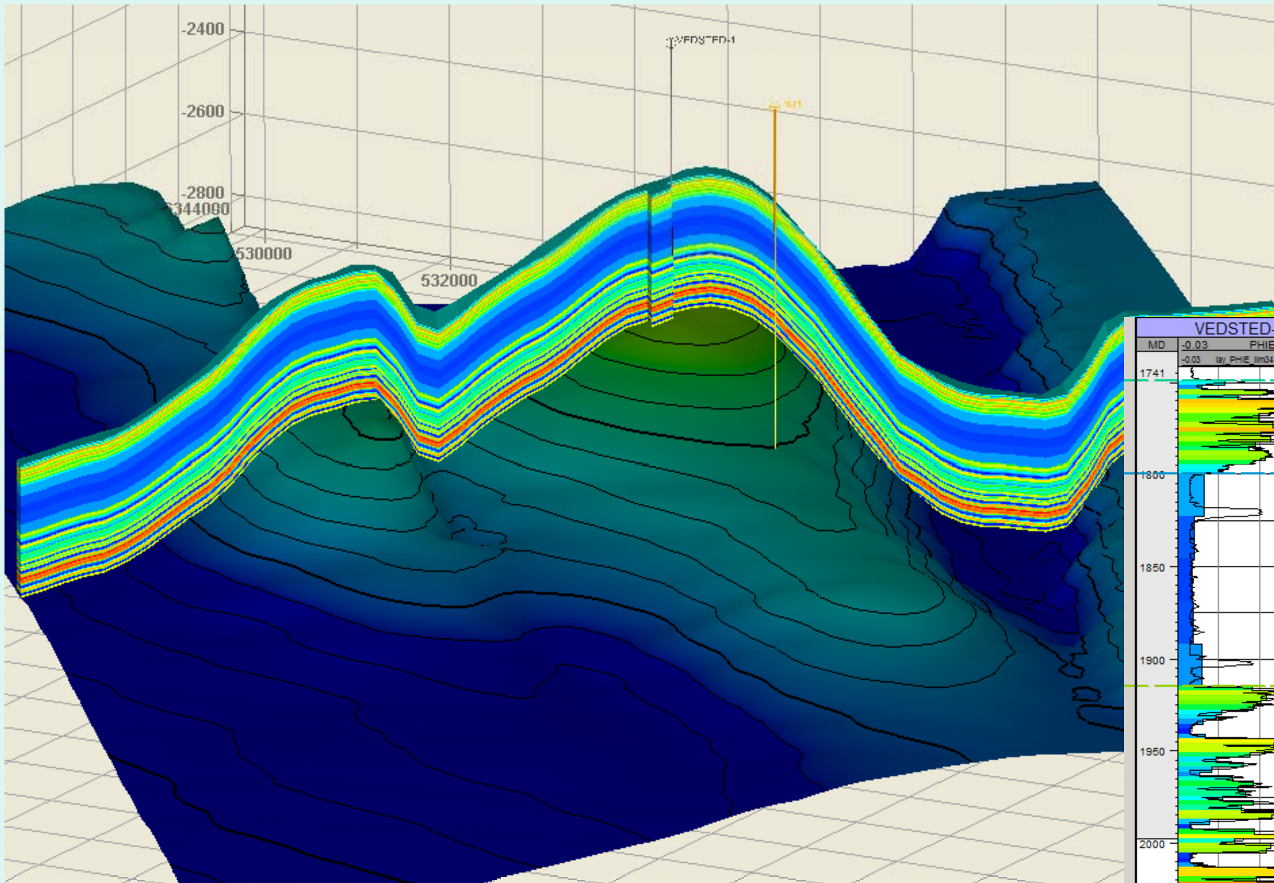
12x19 km site model

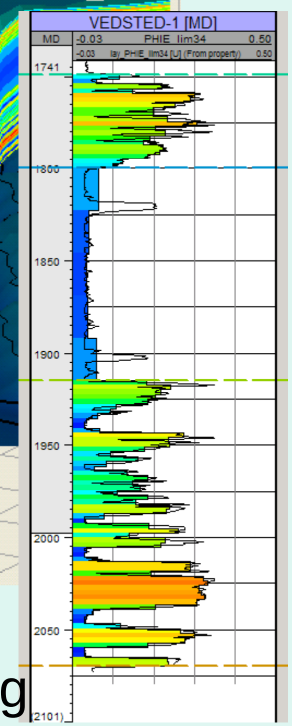


Next –

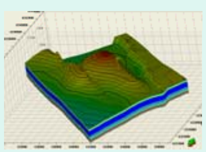
1) Make a model – quick – we need it tomorrow!

2) **OK looks good – what is inside?**





Porosity log



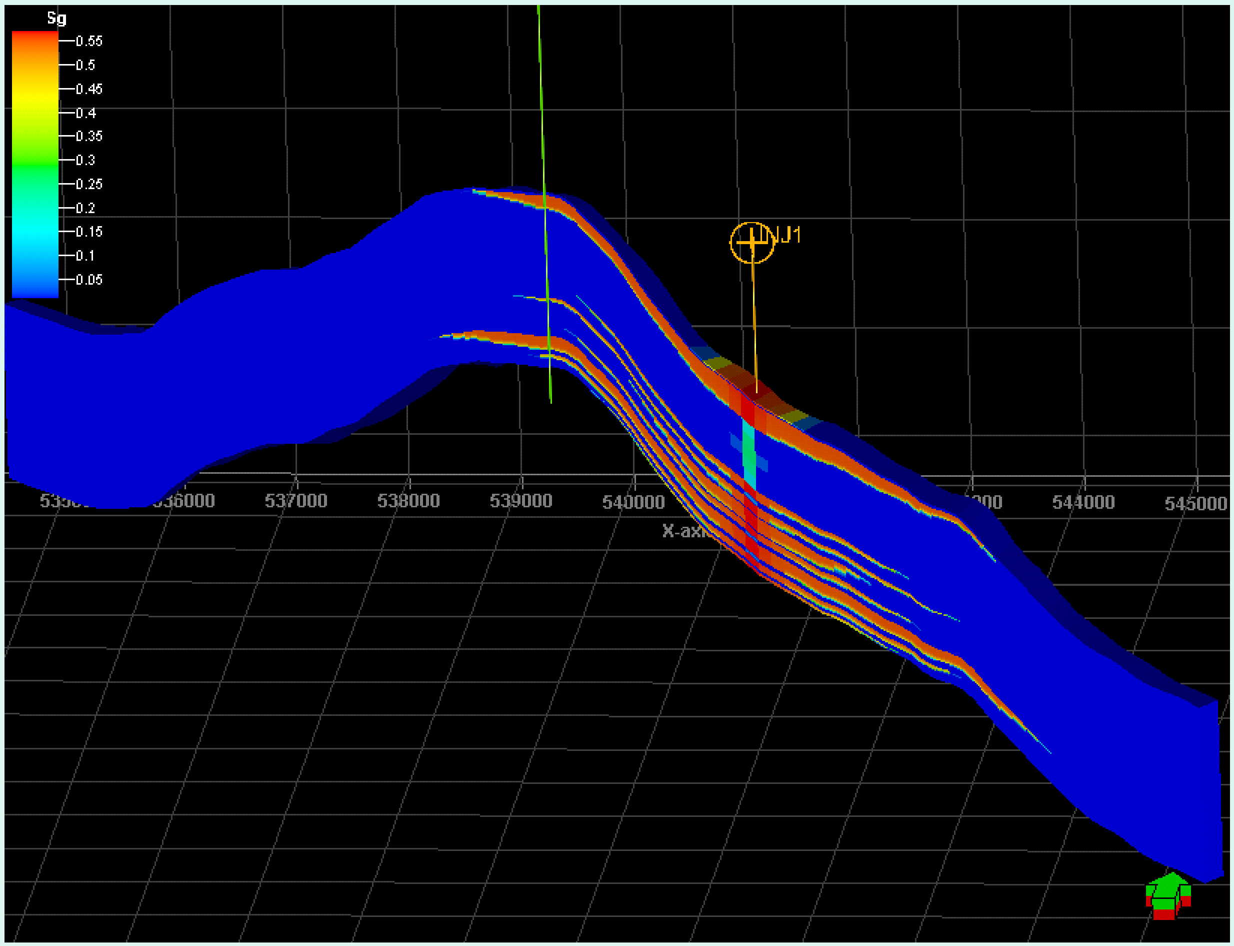
12x19 km site model

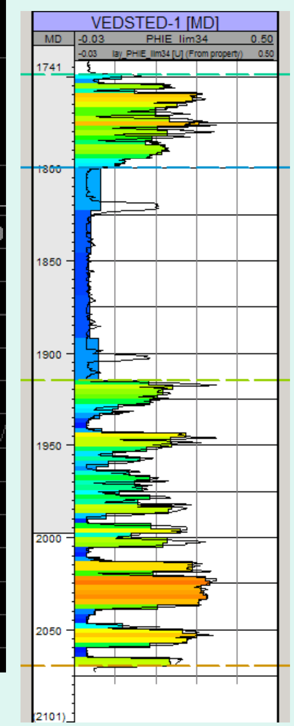
Typical continuation –

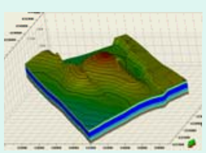
1) Make a model – quick – we need it tomorrow!

2) OK looks good – what is inside?

3) **How does the CO_2 behave?**





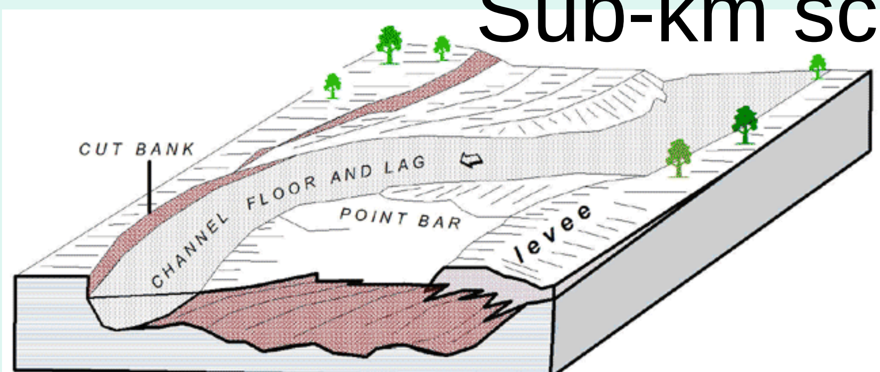


12x19 km site model

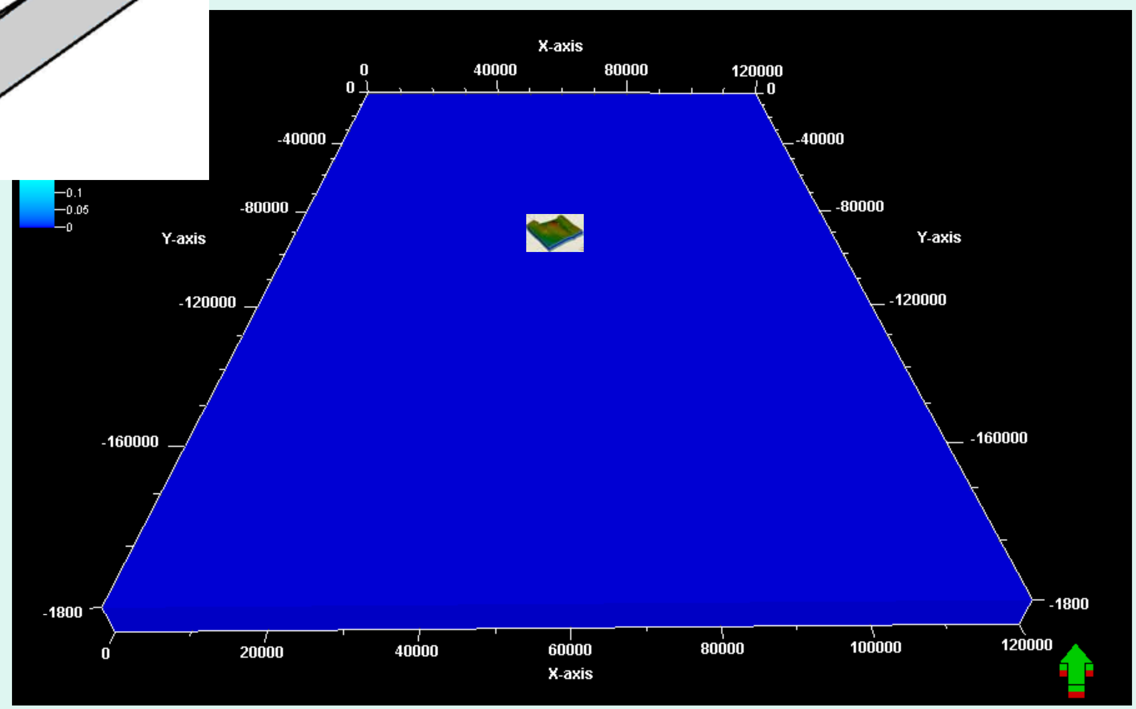
1. Make a model – quick – we need it tomorrow!
2. OK looks good – what is inside?
3. how does the CO_2 behave?

4. **Hey – what did we miss?**

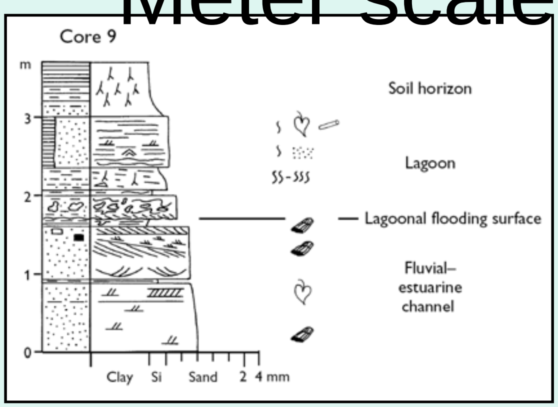
Sub-km scale



Region scale

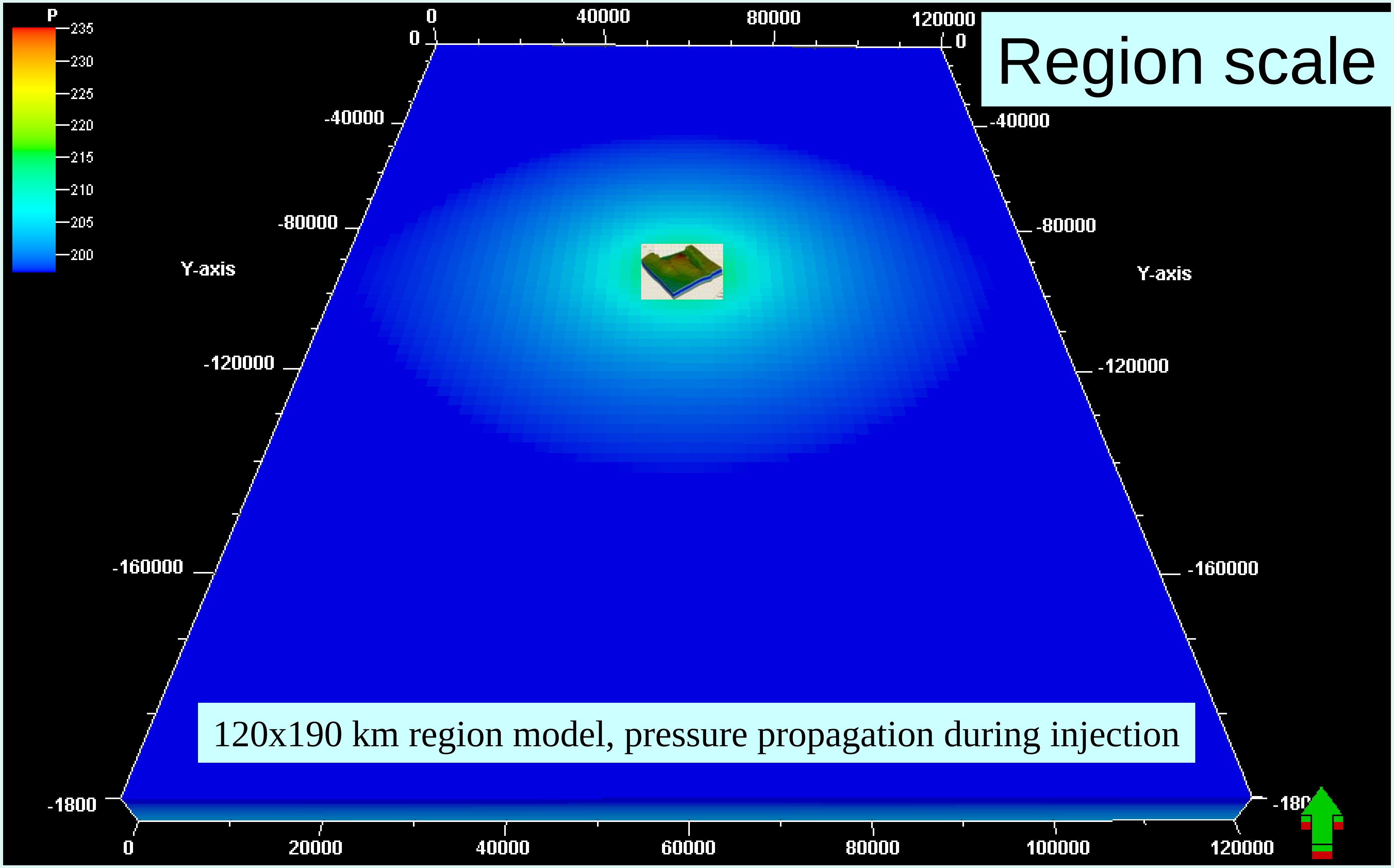


Meter scale



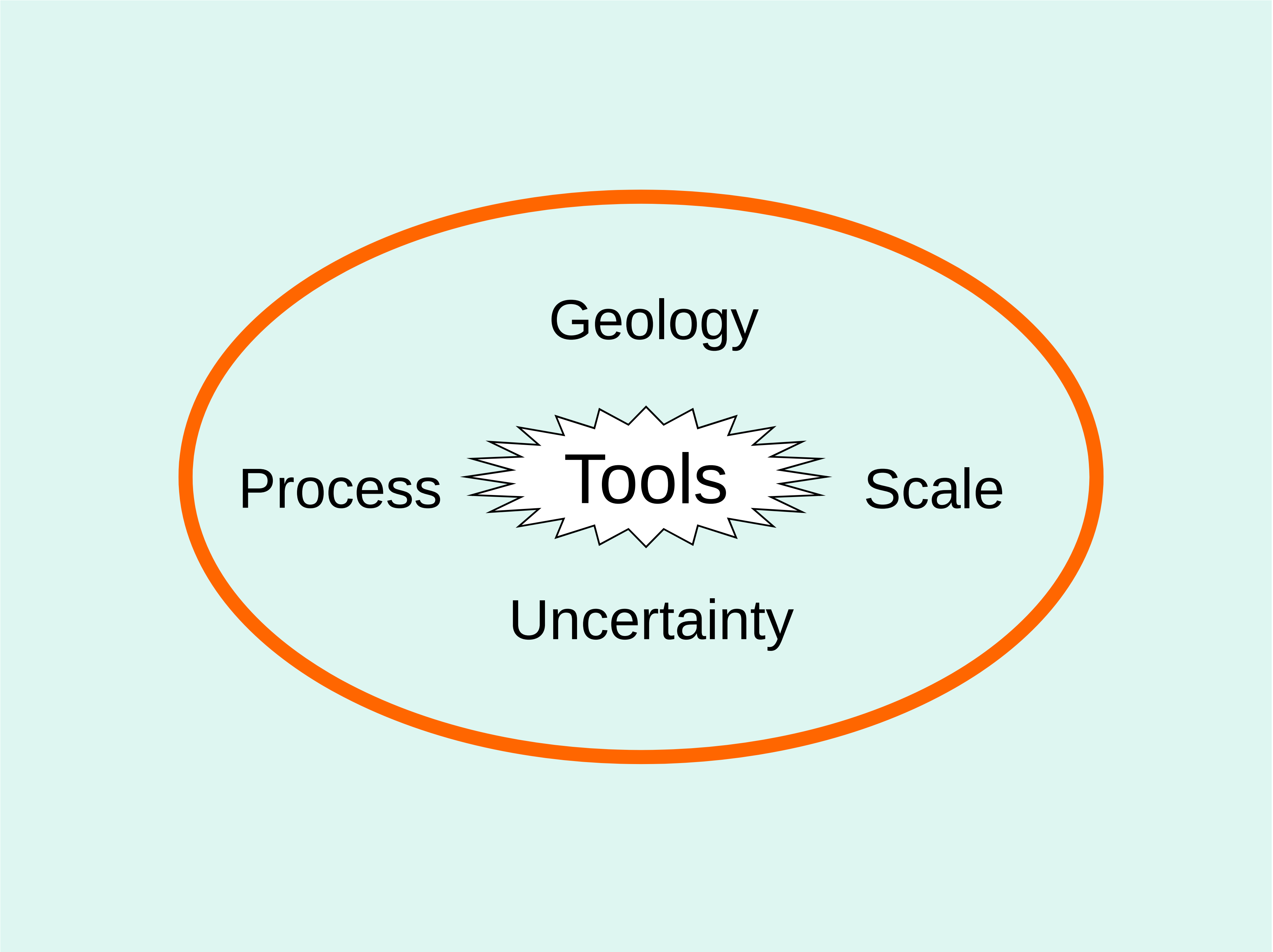
120x190 km region model

Region scale

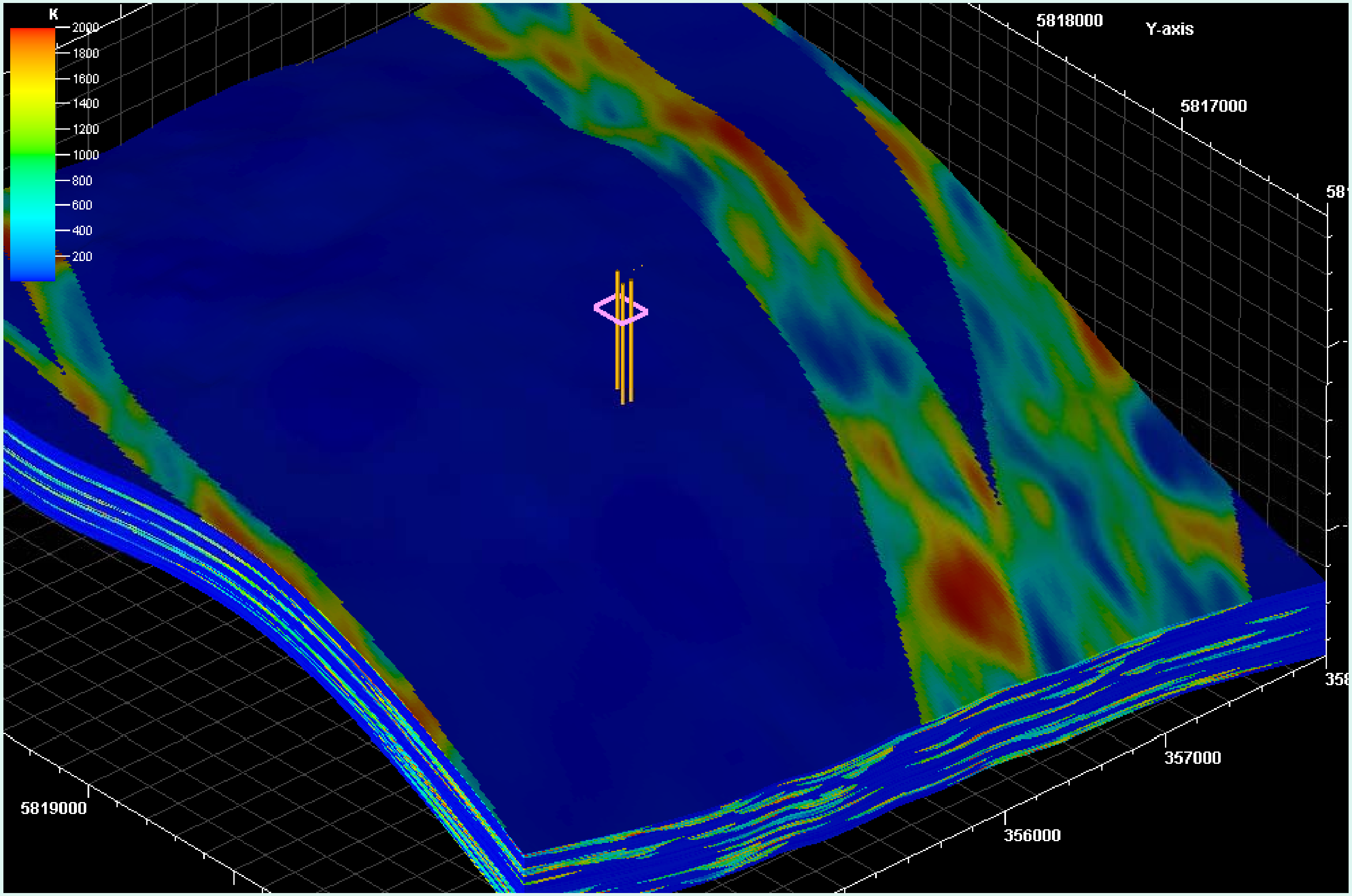


120x190 km region model, pressure propagation during injection

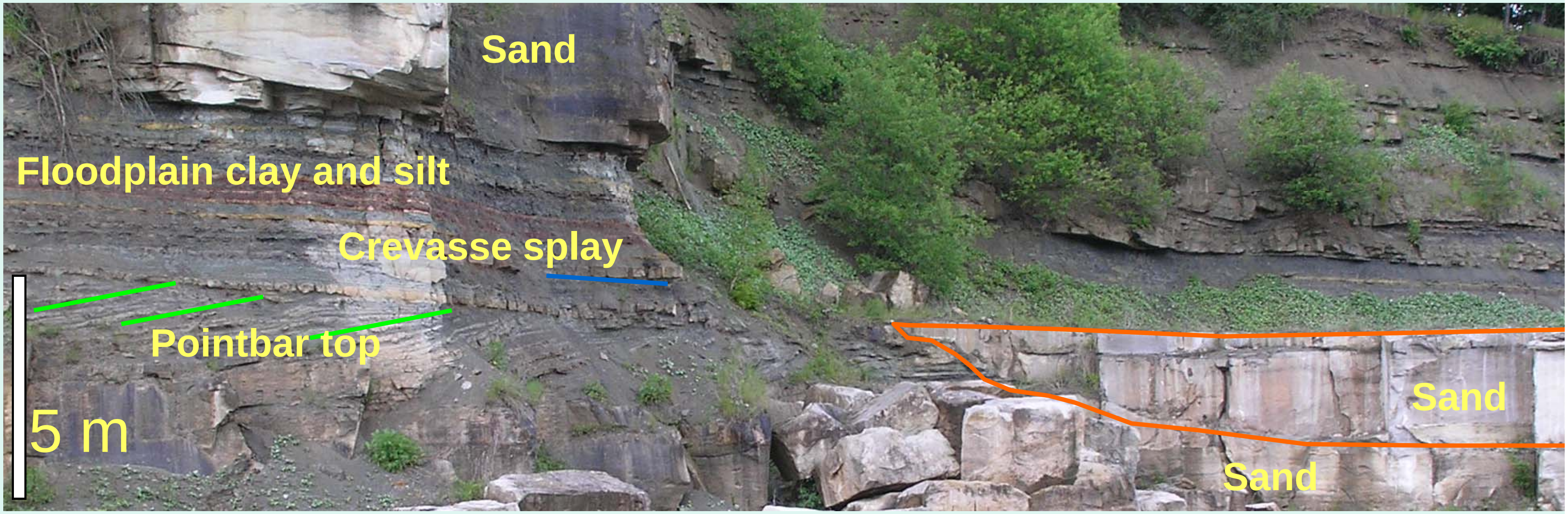
For running the site model as stand-alone we need the correct boundary conditions for pressure development


Geology
Process
Tools
Scale
Uncertainty

Even a single well supplies information to the geologist to extrapolate geometry and variability into the full model

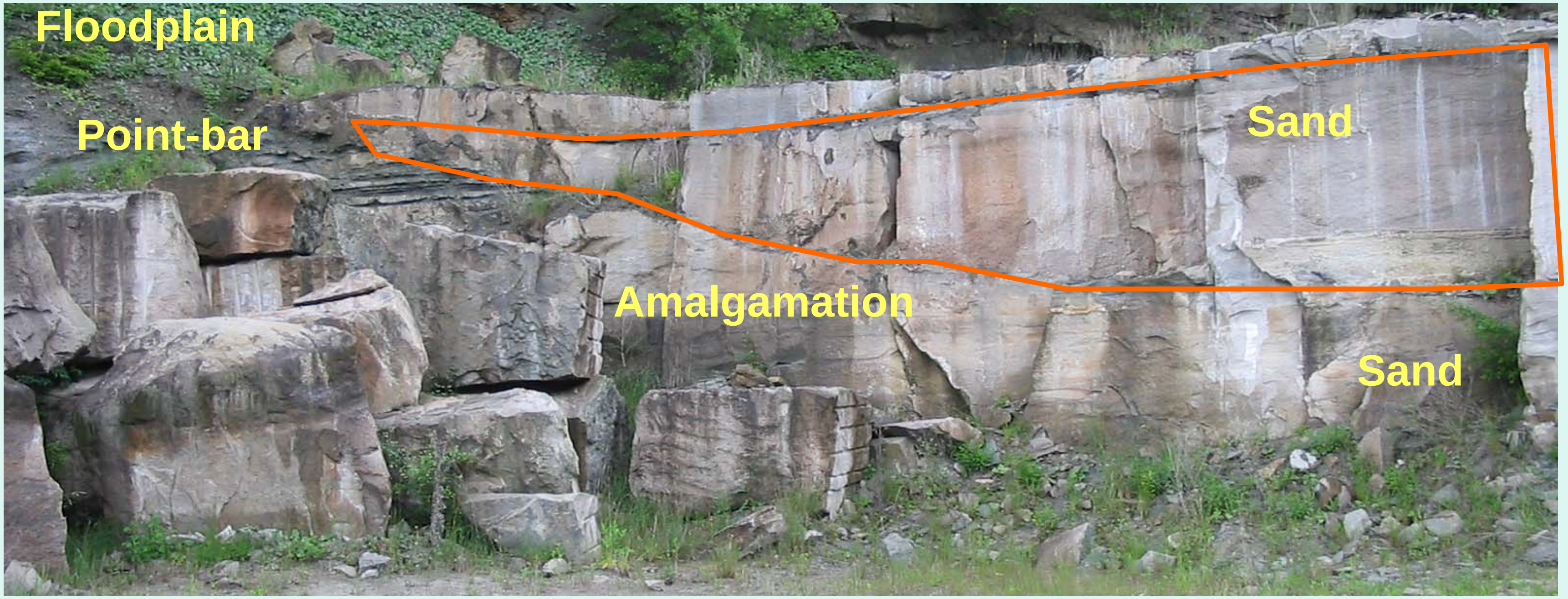


Heterogeneities
Fluvial system

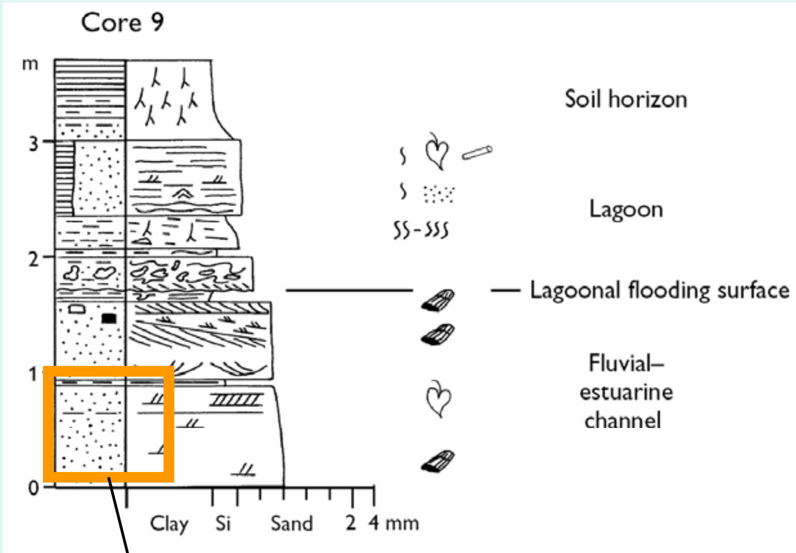


Information from:
Analogue outcrops
Studies of analogue reservoirs

Triassic fluvial channel margin

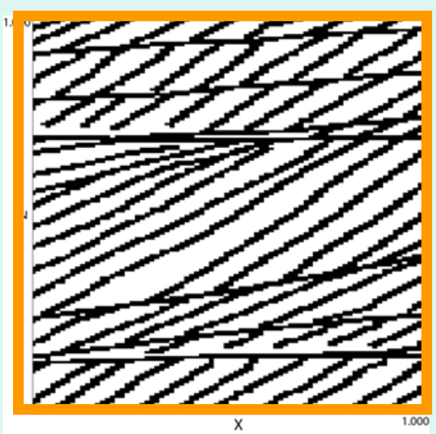


Even crossbedding matters

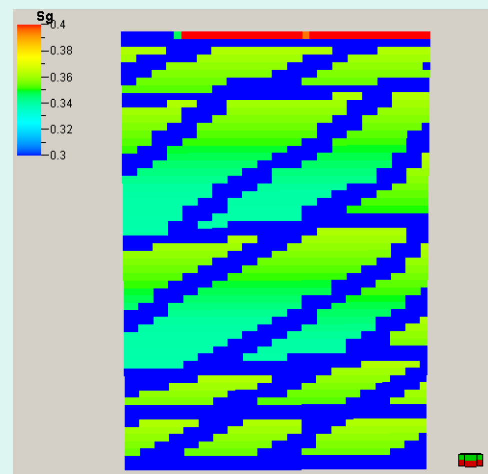


Capillary trapping
+ heterogeneity trapping

Small-scale effects due to
sub-meter scale heterogeneities



Flow simulation:
1) Fill with CO_2
2) Let aquifer move in from below
3) Notice the above-endpoint residual saturations in the sand compartments –
Extra trapping !

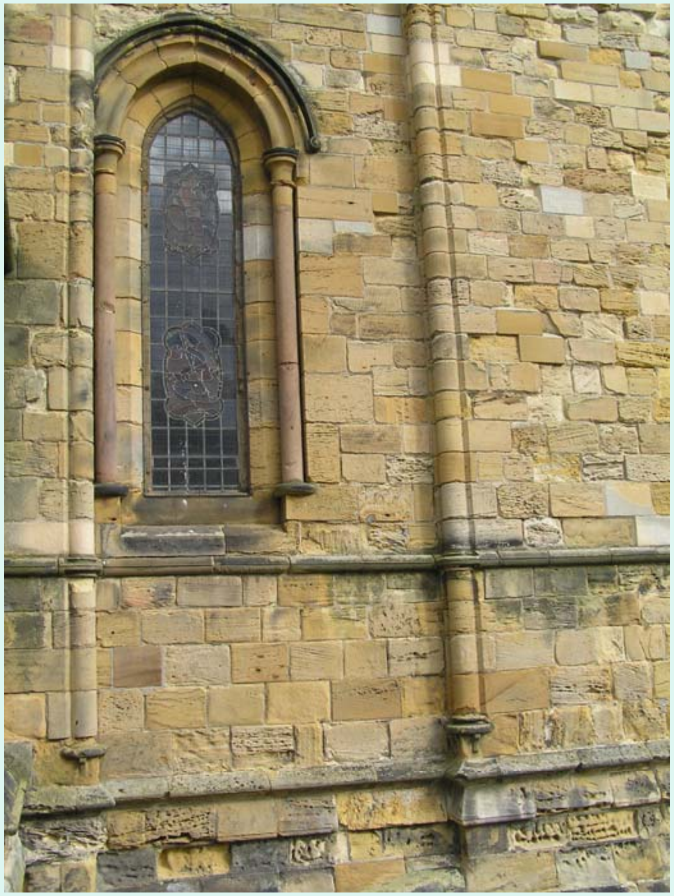


Future for modelling network

- *”Modelling is very complex”* (Isabelle)
- No, in fact geomodelling is much too easy! Even an ignorant can create a very nice static model with modern tools, being totally wrong
- So -
- Ask for more and better geology in the static model
- Develop ”rules of engagement”, guidance and discipline
- Share static models for testing purposes

Conclusions

- Geology is usefull!
- Mind the scale
- Be aware of the link between size/scale and process



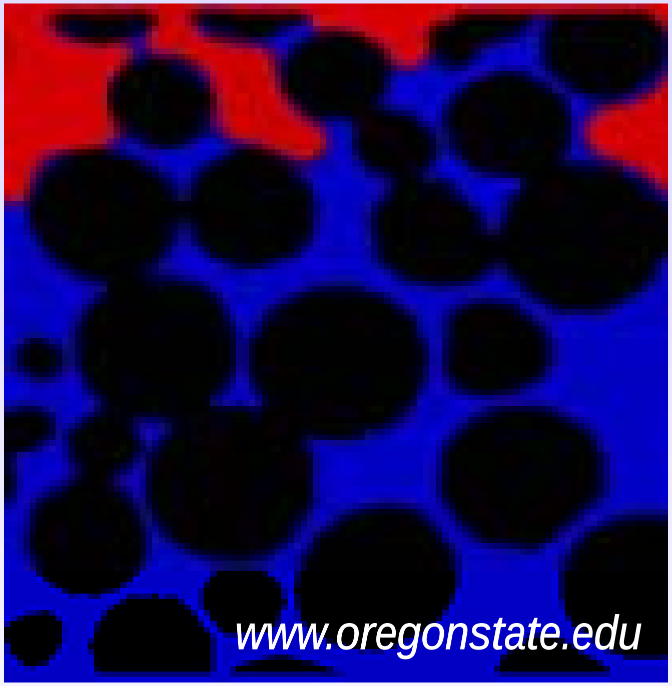
St Mary's Church, Scarborough
Ca. 1150
Fluvial sandstone

Multiphase Flow for CO_2 Storage

Suzanne Hurter, SCS

Contents - Keywords

- A little bit of physics
  - Darcy's Law for multiple fluids
  - Capillary Pressure
  - Relative Permeability
  - Hysteresis
- CO_2 Storage: which processes?
- Examples
- Laundry List and Gaps?



Multiphase Flow Physics (I)

Darcy's Law:

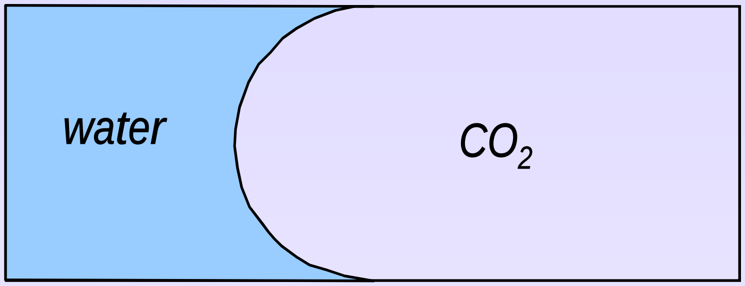
$$Q_{*} = \frac{k_{*} \cdot A}{\mu_{*}} \cdot \frac{\Delta p}{L}$$

single fluid flow: natural groundwater / formation fluid flow

extended to multiple phases, by adding an index for each phase and replacing the absolute permeability by the relative permeability, *kr*

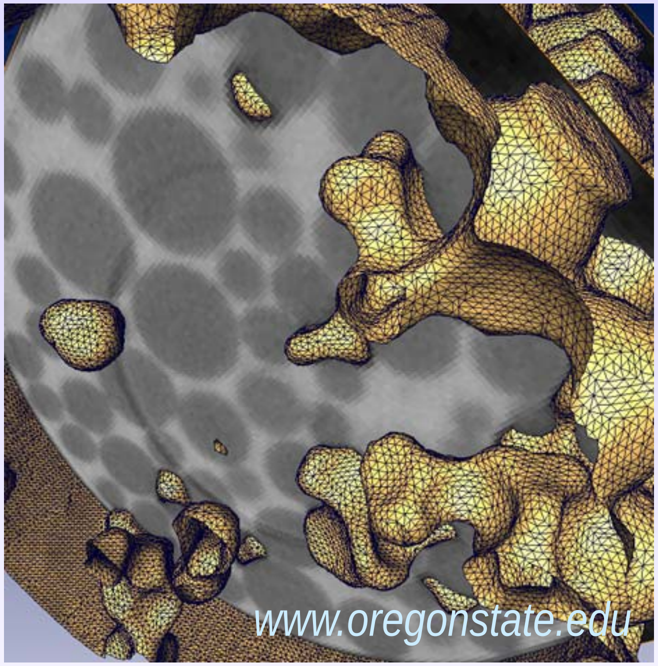
Relative Permeability $$k_{ri} = \frac{k_i}{k}$$

Multiphase Flow Physics (II)



Capillary Pressure

$$P_c = \frac{2 \cdot \sigma}{r} \cdot \cos\theta$$



wetting angle:

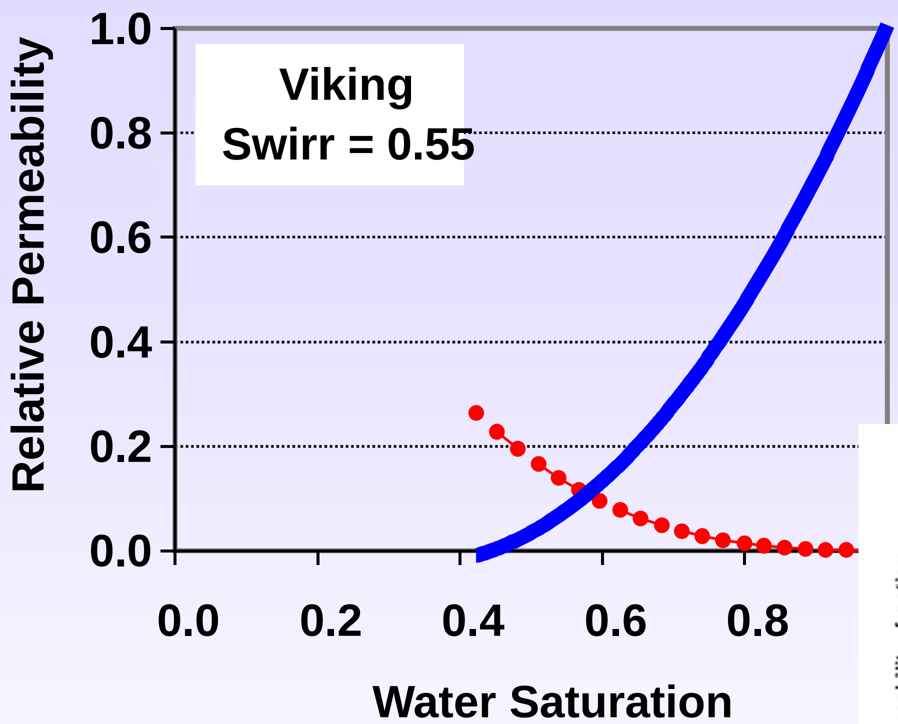
wetting $0 < \theta < 90°$

non-wetting $90° < \theta < 180°$

surface tension, σ

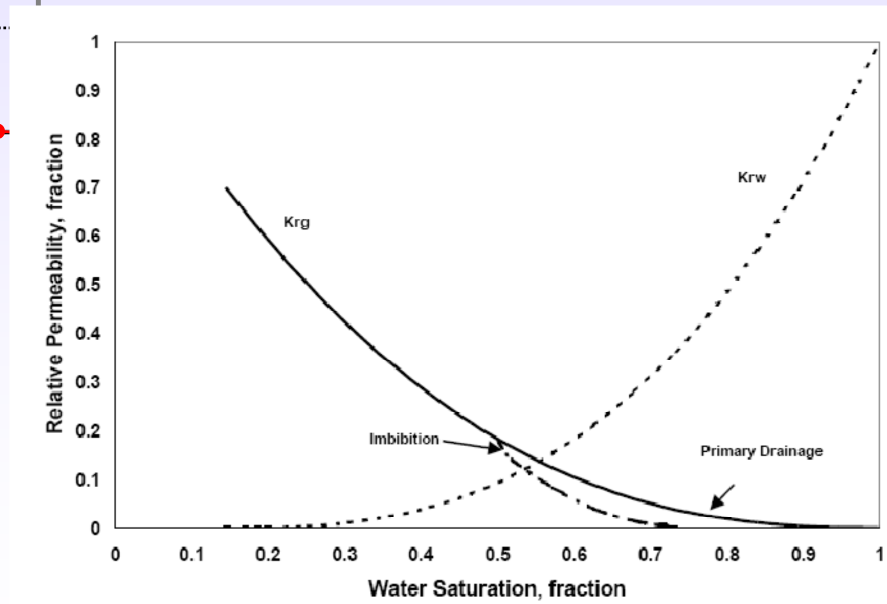
pore throat radius, r

Relative Permeability Hysteresis

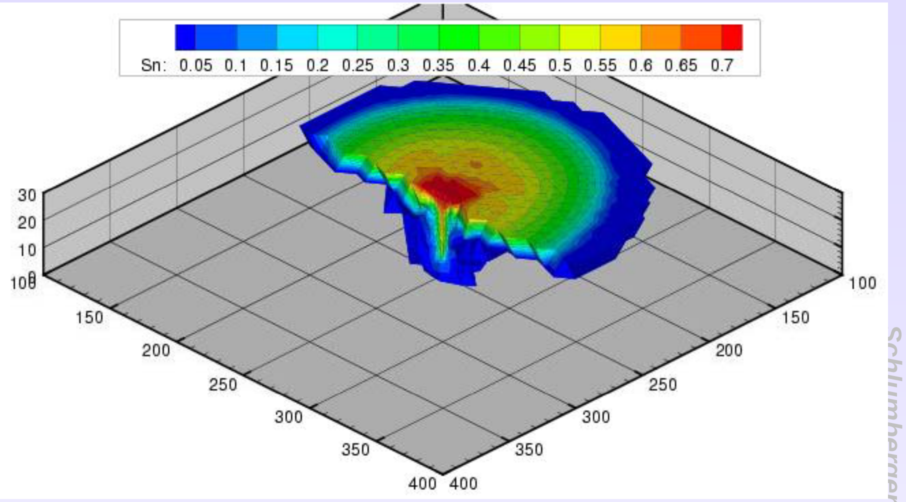


Lack of data
Analogs Library

Explore Scenarios



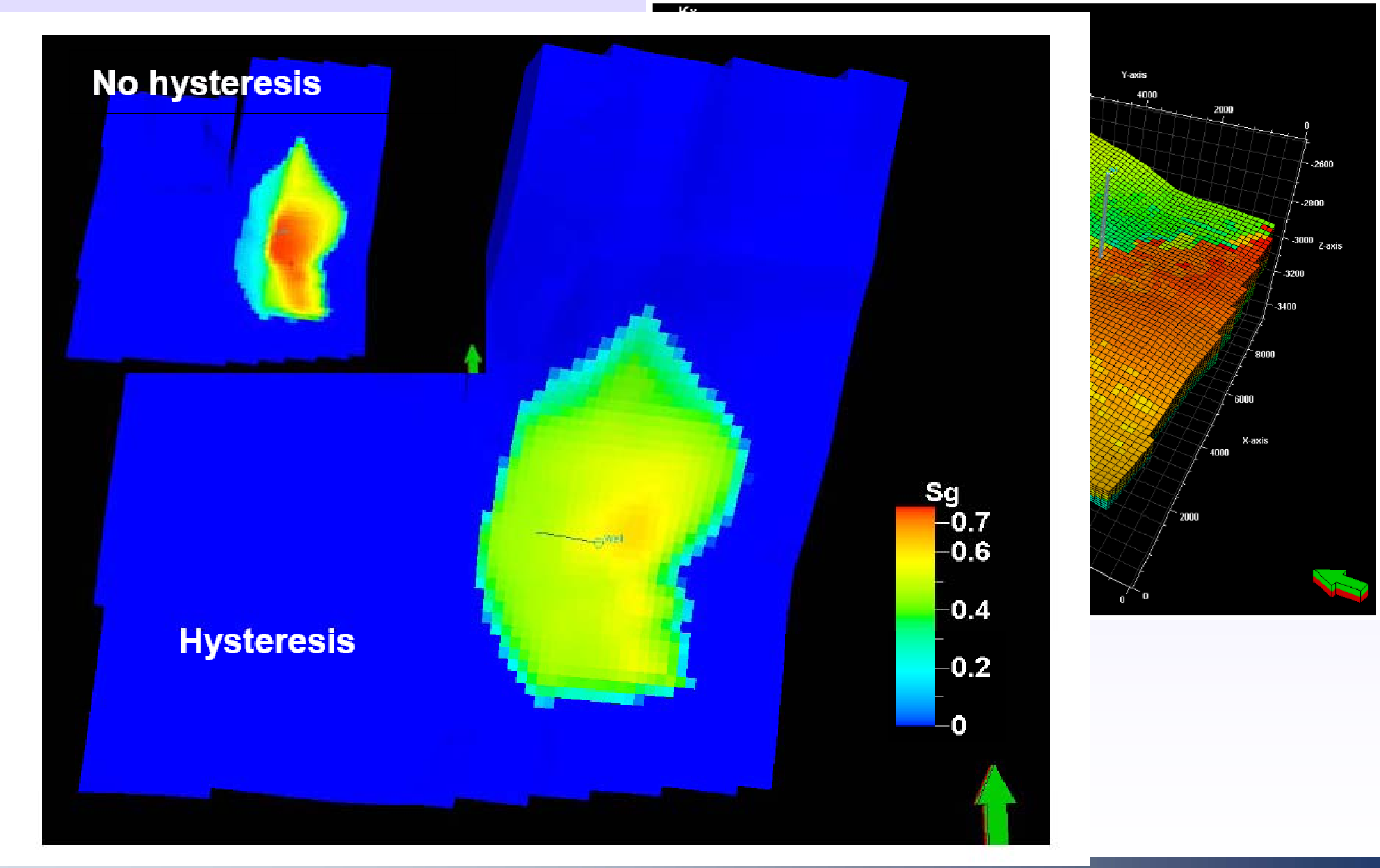
Processes that can be addressed?



Bielinski, University of Stuttgart

- Injected CO_2 footprint
  - plume extent, front location
  - plume geometry
- Trapped CO_2 (residual)
- Pressure distribution and management
  - in the reservoir
  - at specific locations (wells, faults)
  - pressure plume geometry and extent
- History Matching and Joint Inversion (Monitoring and Verification)
- Brine migration!

Effect of Hysteresis



Monitoring Needs?

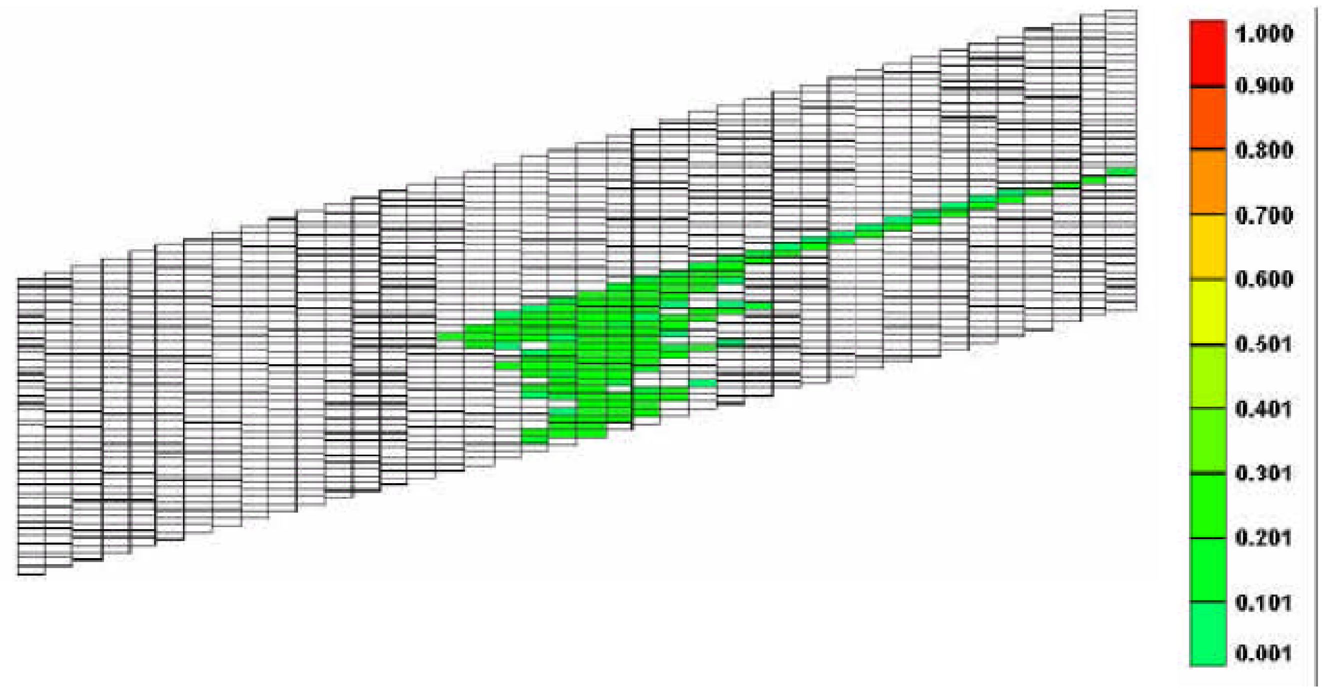


Figure 2.2.3.7.1 (25) Gas Saturation at 1000 years in a layered aquifer with high permeability at the top of the injection interval.

(Pope et al.,2003)

Streamline Simulators (coupled?)

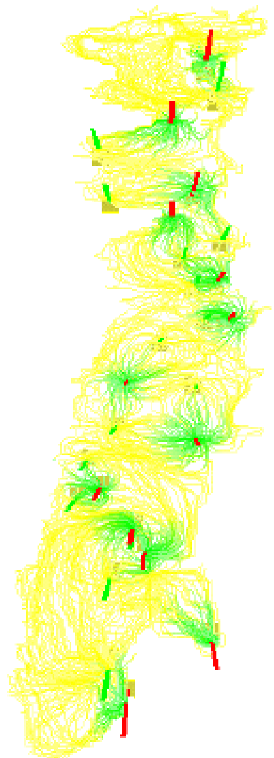
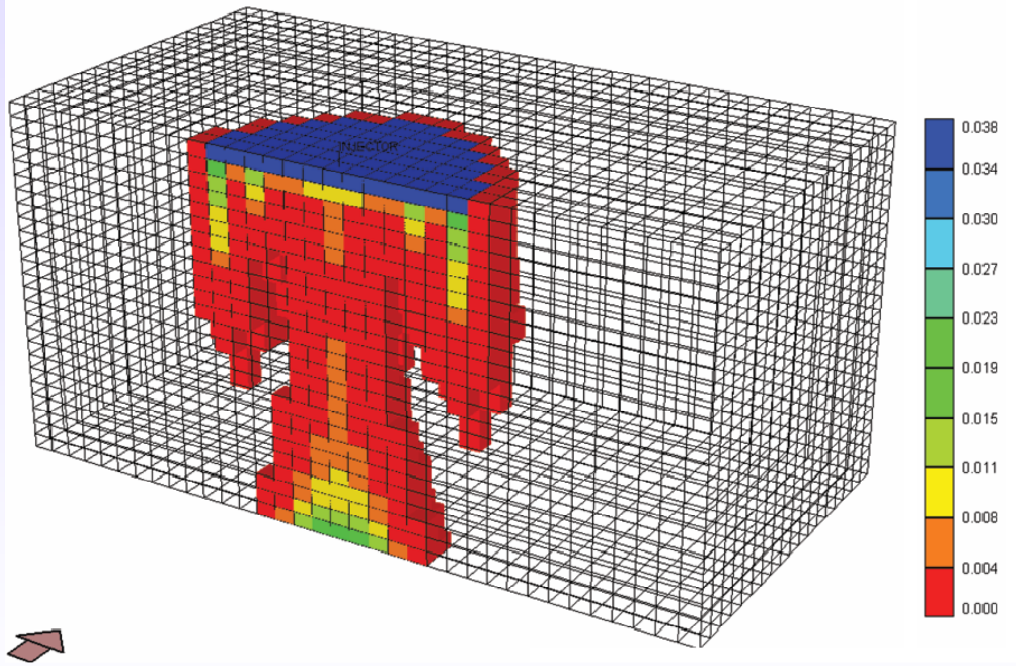


Fig. 2 - Wells positions

Samier et al., 2001

b) CO_2 mole fraction in aqueous phase

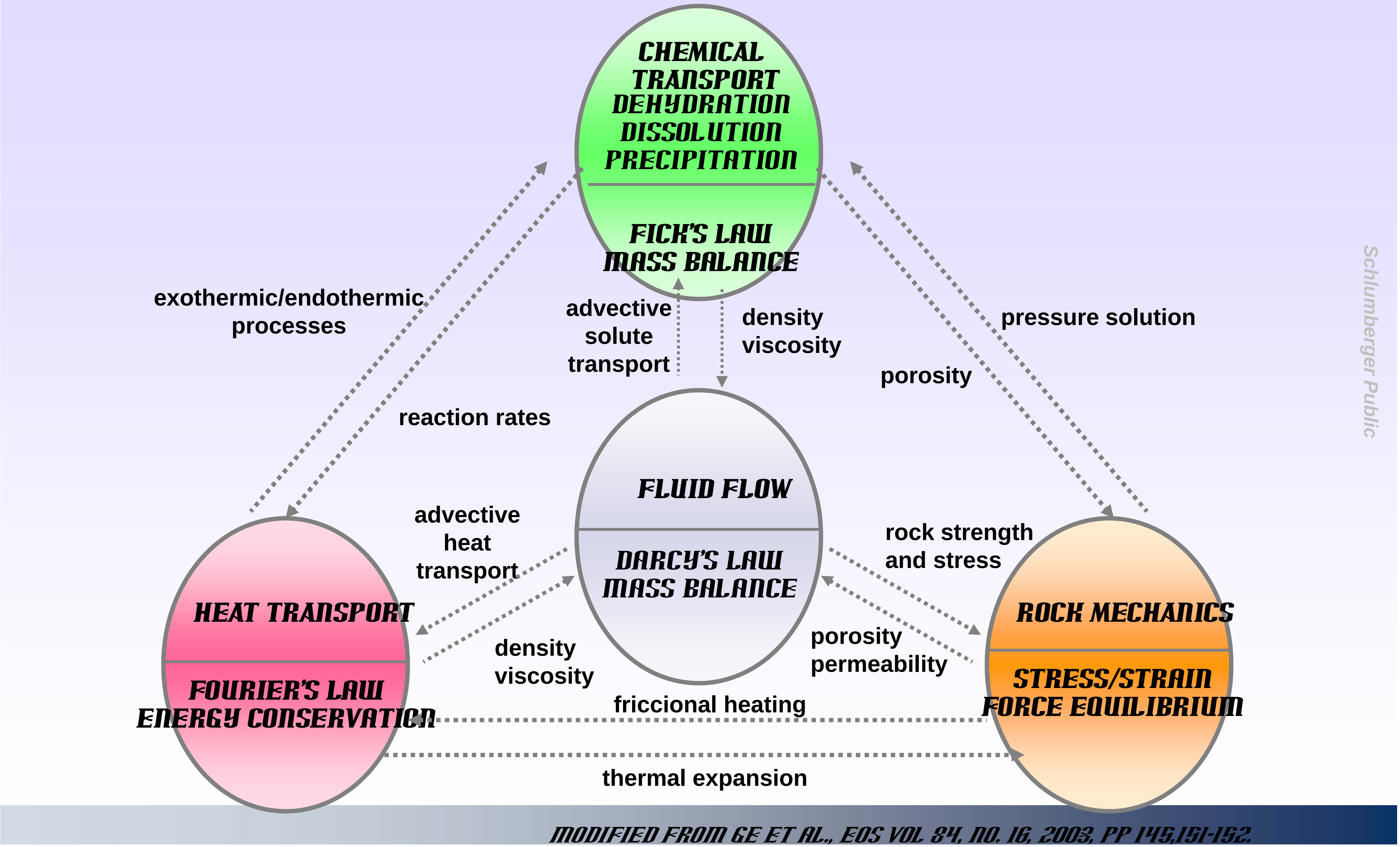


Gambari et al., 2003

[Numerical] Tools

- Conventional Codes (finite dif, finite el, finite vol)
- Streamline
- Semi-analytical (built in)
- Analytical

Coupling ?



CHEMICAL TRANSPORT
DEHYDRATION
DISSOLUTION
PRECIPITATION
FICK'S LAW
MASS BALANCE
exothermic/endothermic processes
advective solute transport
density viscosity
pressure solution
porosity
reaction rates
FLUID FLOW
DARCY'S LAW
MASS BALANCE
advective heat transport
rock strength and stress
HEAT TRANSPORT
FOURIER'S LAW
ENERGY CONSERVATION
density viscosity
porosity permeability
ROCK MECHANICS
STRESS/STRAIN
FORCE EQUILIBRIUM
friccional heating
thermal expansion
MODIFIED FROM GE ET AL., EOS VOL 84, NO. 16, 2003, PP 145,151-152.

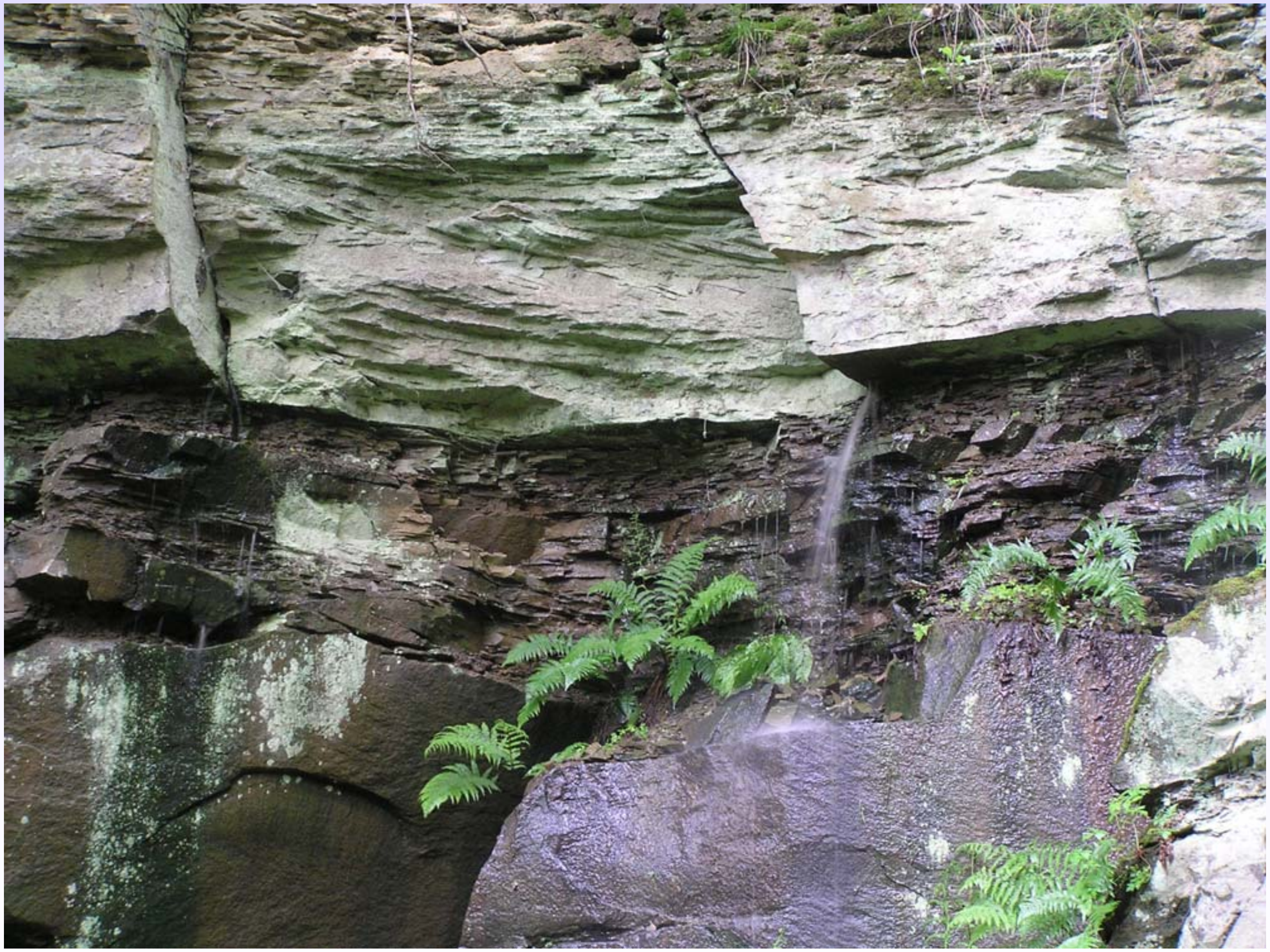
Associated Concerns

- what goes into the models?
  - PVT, gas mixtures (EOS)
  - relative perms (lab)
- how to build in monitoring results ?
- well representation at each scale?
- process for model building
  - expand scenarios (select reference case and others)
  - narrow down number of scenarios systematically
  - integrate over various scales

Keywords

- more than 2 fluids
- tool / monitoring response forward models
- analytical solutions, streamlines, et al.
- convection, mixing, stirring
- pore scale, reservoir scale, regional scale
- gridding and upscaling
- porous vs fractured media
- coupling with other physics/chemistry
- knowledge gain, operation management, long-term

courtesy Peter Frykman



Geochemistry and Reactive Transport Modeling of CO_2 Storage

Mohamed Azaroual

BRGM – Water Division, Orléans

Contributors: Laurent André, Arnault Lassin, Christophe Kervévan, Marc Parmentier

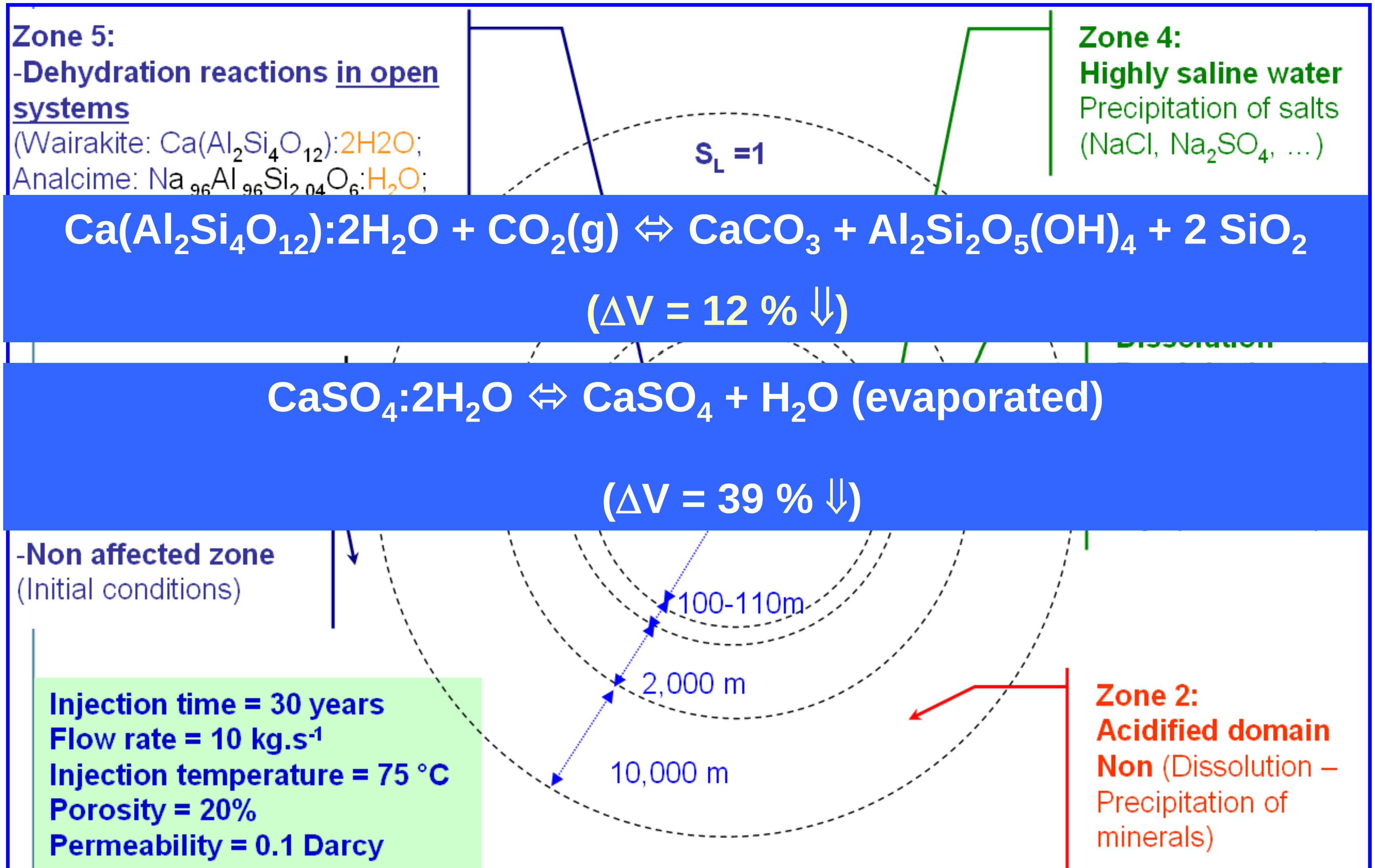
Géosciences pour une Terre durable

brgm

Outline

- **Physical & chemical processes affecting the near well of CO_2 injection**
- **Thermodynamic of complex systems (brine – gas – minerals)**
- **Thermodynamic of capillary waters (stability and internal negative pressure)**
- **CO_2 quality and reactivity of co-injected components**
- **Mineral dissolution/precipitation kinetics**
- **Cold CO_2(sc) injection; temperature effect on minerals reactivity**
- **Cap rock integrity**
- **Well cement degradation**
- **Development of biofilms**
- **Knowledge limitations and some research targets**

Physical & chemical processes affecting the near well



$$Ca(Al_2Si_4O_{12}):2H_2O + CO_2(g) \Leftrightarrow CaCO_3 + Al_2Si_2O_5(OH)_4 + 2\ SiO_2$$

($\Delta V = 12\ \% \Downarrow$)

$$CaSO_4:2H_2O \Leftrightarrow CaSO_4 + H_2O \text{ (evaporated)}$$

($\Delta V = 39\ \% \Downarrow$)

Azaroual M., Pruess K., Fouillac C. (2007) - In Proceedings of the Engine Workshop 2 - Exploring high temperature reservoirs: new challenges for geothermal energy – Volterra (Italy), 1-4 April 2007 – p.47

Structure of the near well bore of CO_2 injection (main physical & geochemical processes)

CO_2 Injection well

Moving and growing zones

Zone 5	Zone 4	Zone 3	Zone 2	Zone 1
$S_G = 100\ \%$	$S_G = 98\ \%$ $S_L = 2\ \%$	$2 < S_L < 100\ \%$ $0 < S_G < 98\ \%$	$S_L = 100\ \%$	
Desiccation ↓ Mineral dehydration	Desiccation (Evaporation) ↓ High saline pore water ↓ Massive precipitation of salts in micropores	Two phase mixture ↓ pH buffered by pCO_2 (3.5 to 5.5) ↓ Mineral dissolution - precipitation	Acidified aqueous CO_2 rich solution ↓ Mineral dissolution (carbonate, alumino-silicates	Initial aqueous solution ↓ Thermodynamic equilibrium (mineral – aqueous solution)
Maximum heat transfer	*Increase of exchange surface*	*Very reactive zones*		*Initial conditions*

Thermodynamic of complex systems (brine – gas – minerals)

Gas

(CO_2, SOx, NOx, Ar, N_2, H_2S, H_2O, etc.)

(EOS & fugacity correction)

Brines

(Na^+, Ca^{2+}, Sr^{2+}, Ba^{2+}, F^-, CO_2, SO_4^{2-}, Cl^-, HCO_3^-, etc.)

(Mass Action Law & activity coefficient)

Mineral solubility

(Calcite, Gypsum, Anhydrite, etc.)

(Solubility product, Ks)

Equilibrium: CO_2 gas ⇔ CO_2 dissolved

$$\frac{a_i}{f_i} = K(T,P)$$

Fugacity & solubility: $f_i = \Phi_i X_i P$

Activity & speciation: $a_i = \gamma_i m_i$

$$m_i = \frac{K(P,T)\,\Phi_i\,X_i\,P}{\gamma_i}$$

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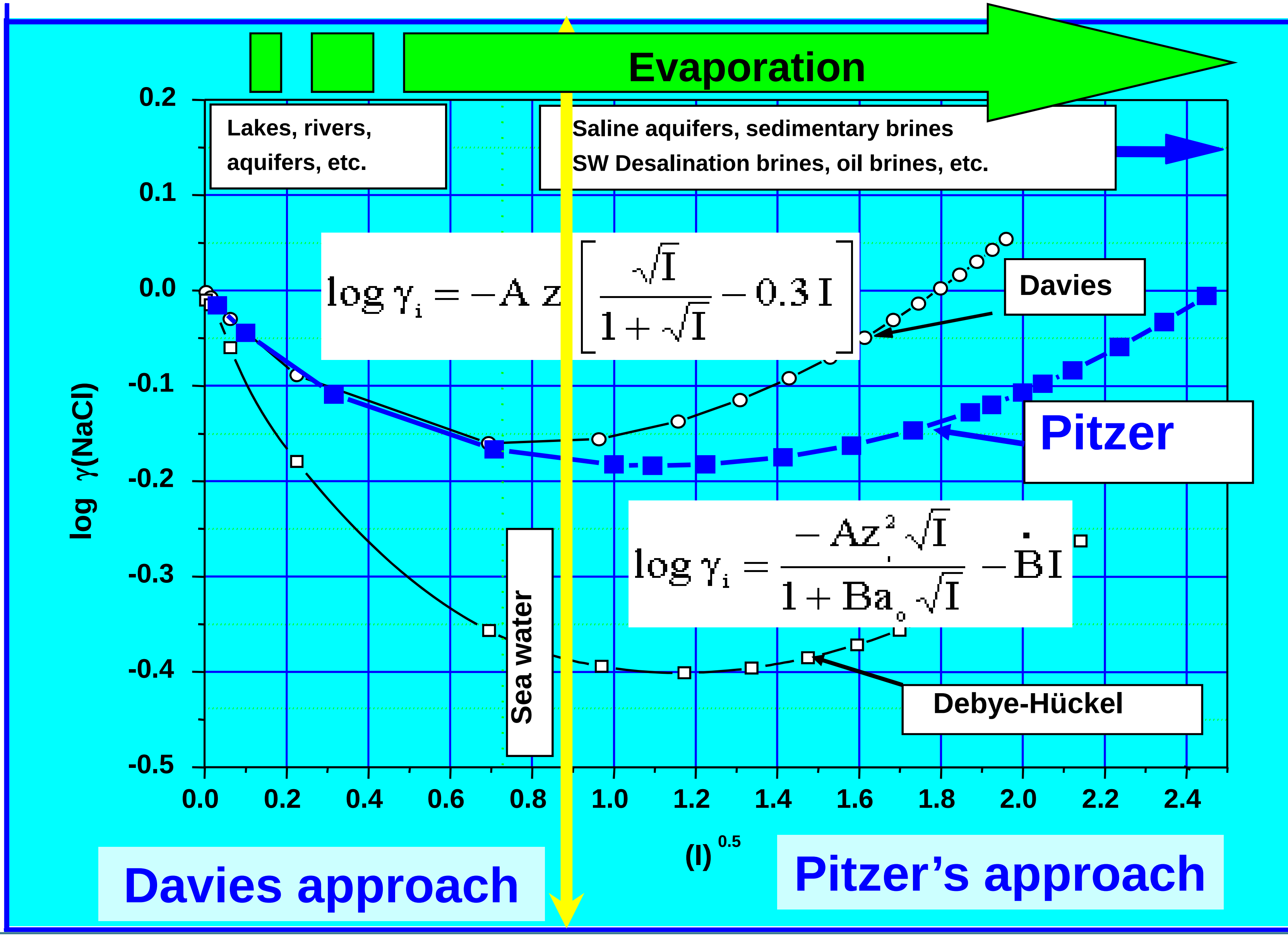
NaCl activity coefficient *vs* Ionic Strength (@ 25°C)



Thermodynamic of capillary waters (internal negative pressure of water)

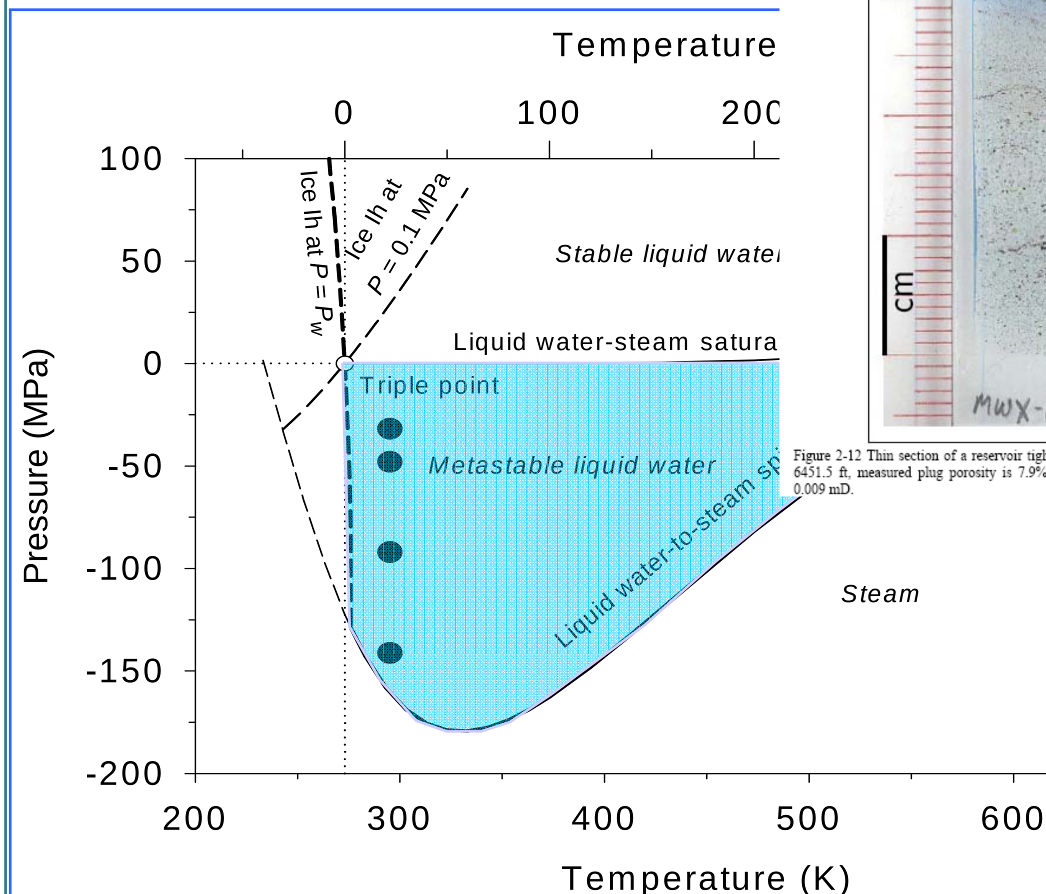


Figure 2-12 Thin section of a reservoir tight gas sandstone sample (R-6451.5V). Depth 6451.5 ft, measured plug porosity is 7.9% and Klinkenberg corrected permeability is 0.009 mD.

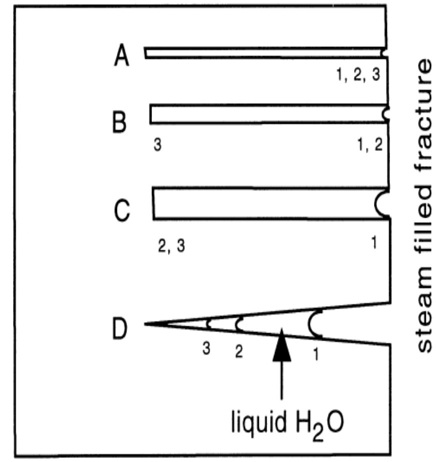


Fig. 2. Idealized geometry of pores in a matrix block.

Thermodynamic of osmotic and capillary processes

$$a_w = \frac{RH}{100} = \frac{p}{p_0}$$

$$RT\ln\frac{RH}{100} = RT\ln\frac{p}{p_0} = RT\ln a_w + \int_{P_r}^{P} V_w \cdot dP$$

Lassin *et al.* (2005) *Geochim. Cosmochim. Acta*, Vol. 69, p. 5187-5201.

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CO_2 quality and co-injected component reactivity

- CO_2 (90-95%) + (N_2, Ar, O_2, SOx, NOx, CH_4, H_2S, H_2, CO) + H_2O
- Needs of relevant solubility data in highly saline waters and EOS integrating complex fluid mixing (fugacity coefficient and mixing parameters)
- Petrophysical properties (k, kr, Pc, IFT, etc.)
- Highly reactive (aggressive) against well cement, host rock and cap rock ($pH_{(CO2)}$ ➔ 3.5-5.5 with impurities $pH_{(CO2 + SO2+O2+CO)}$ ➔ -1 to 2!)

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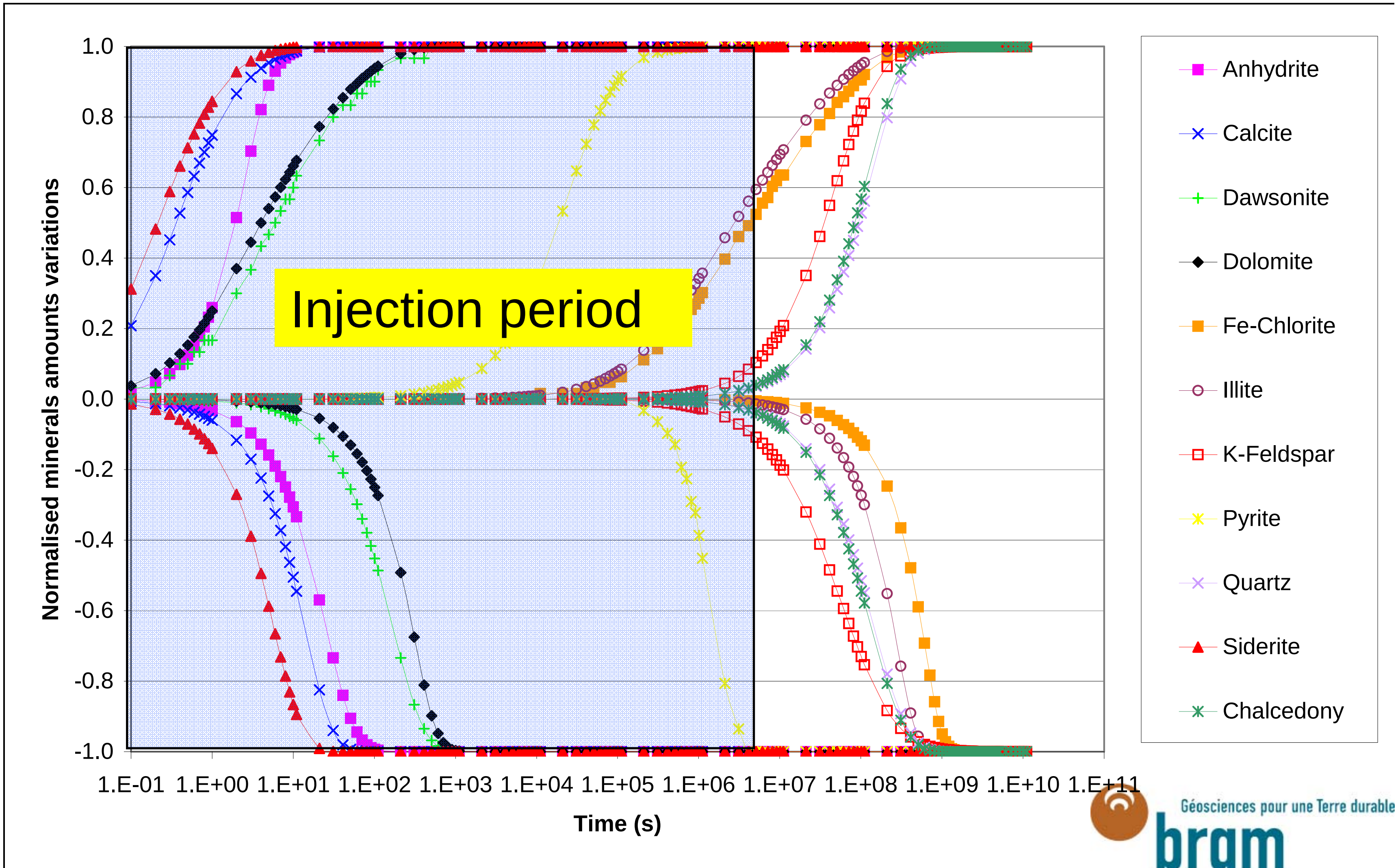
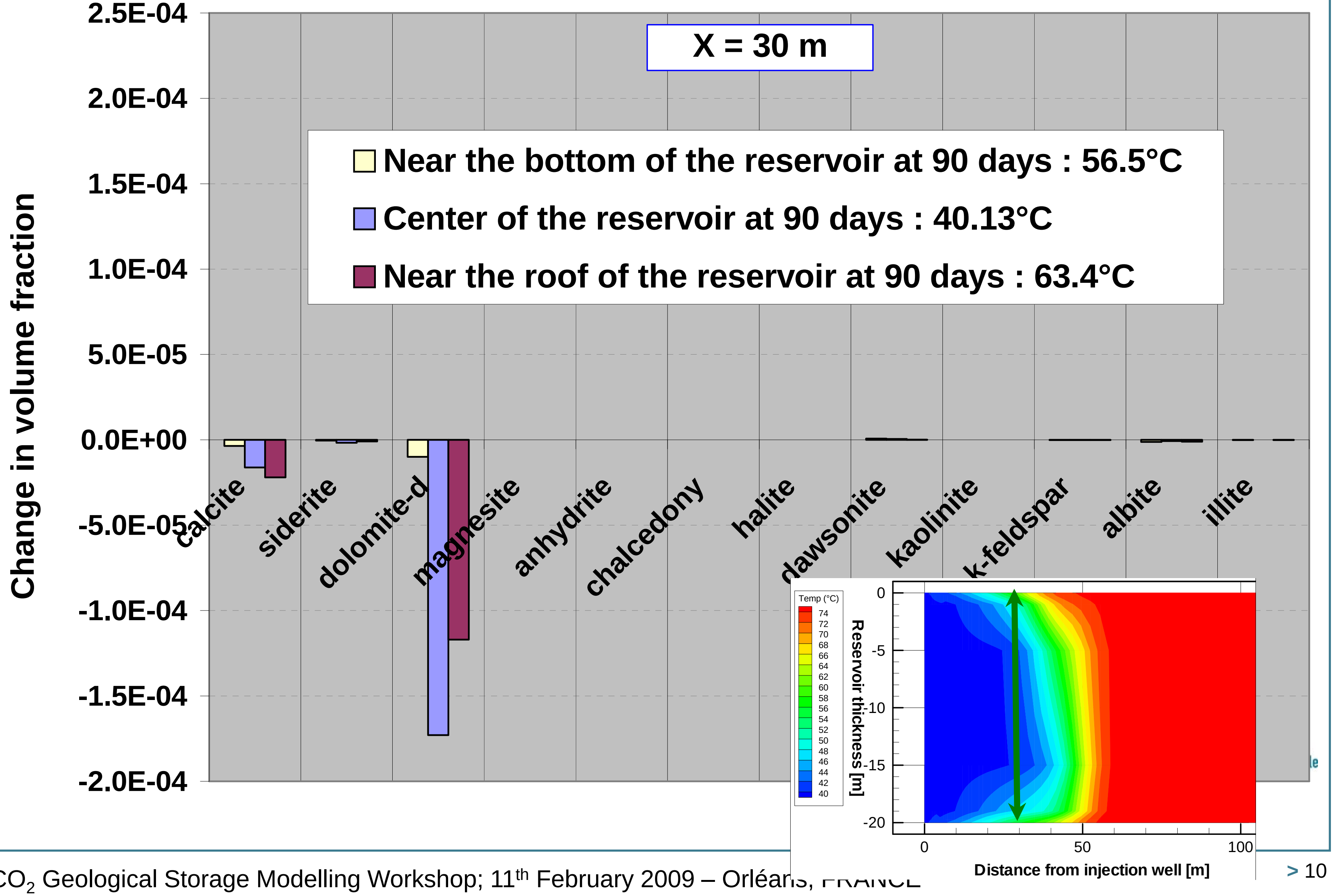
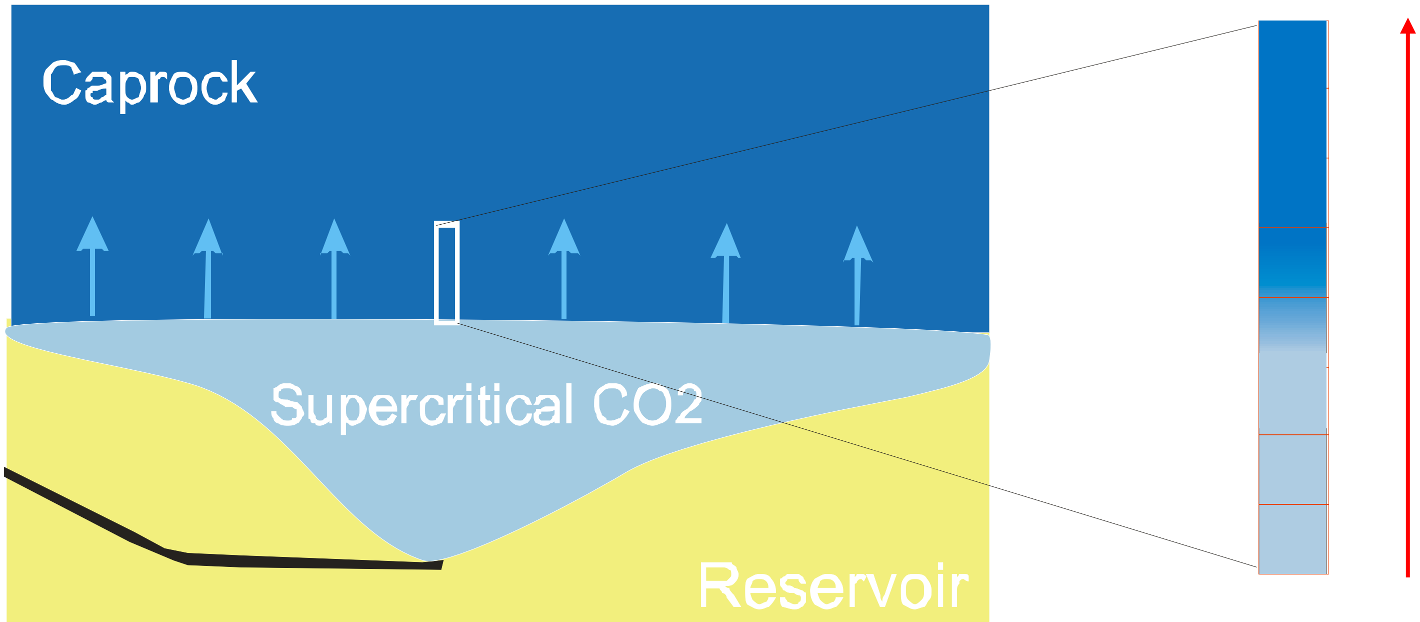
Evolution of normalised mineral rate dissolution - precipitation (50°C, pCO_2 = 80 bar)



Cold CO_2(sc) injection: geochemical impact and minerals reactivity



Cap rock integrity



Diffusion of dissolved CO_2 affecting cap rock mineralogy through geochemical interactions and mass exchanges

Identification of:

- **Geochemical processes and key reactions**
- **Amount of CO_2 permanently sequestered**
- **Key physicochemical parameters**
- **Petrophysical properties (k, kr, Pc, IFT, …)**
- **Possibility of biofilm development, …**

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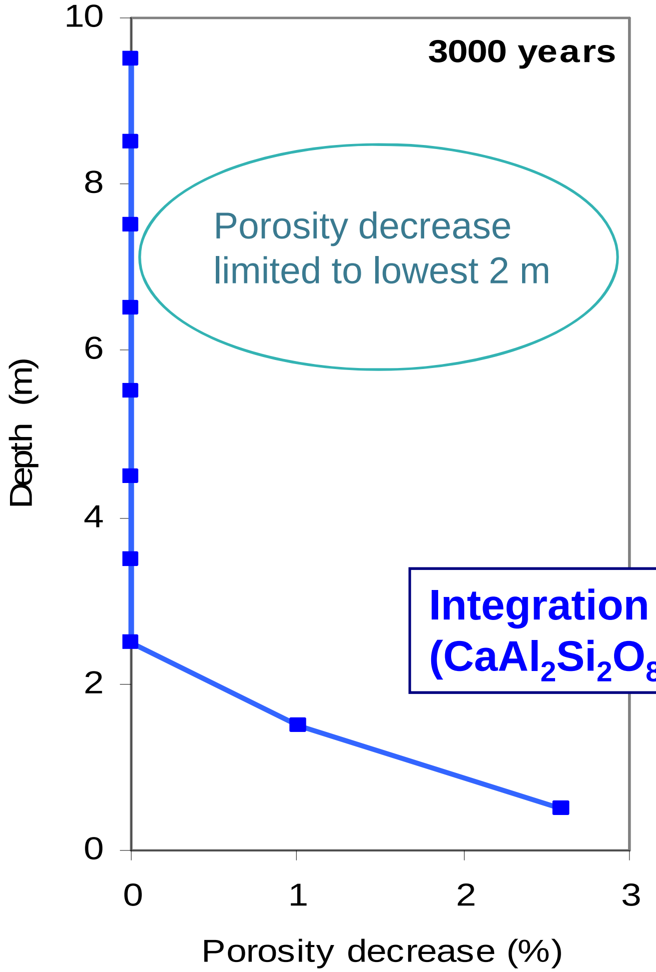
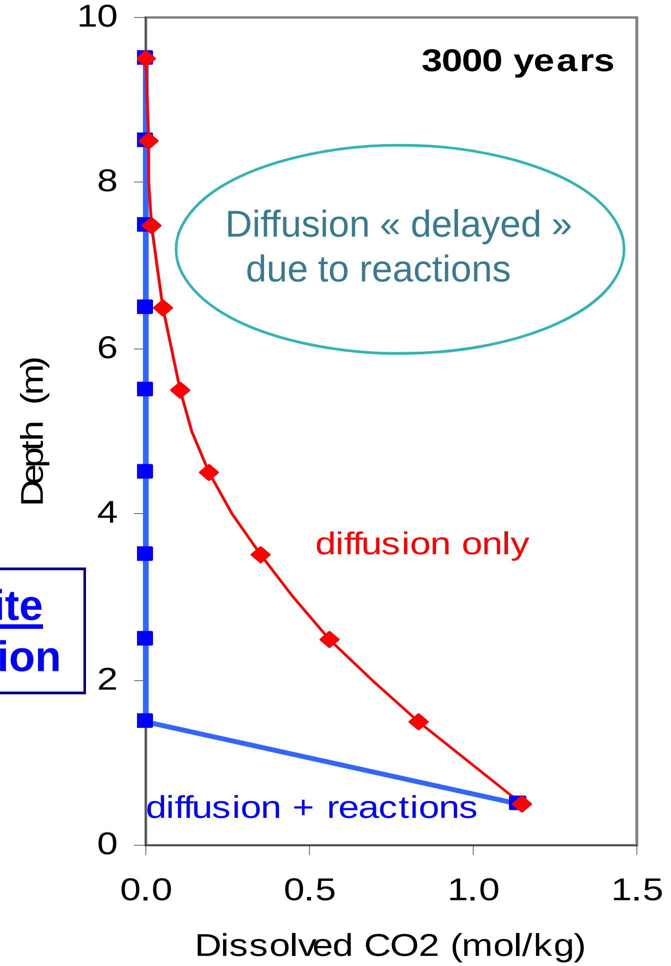
Porosity and diffusive reactive transport in the Cap Rock

Porosity change profile



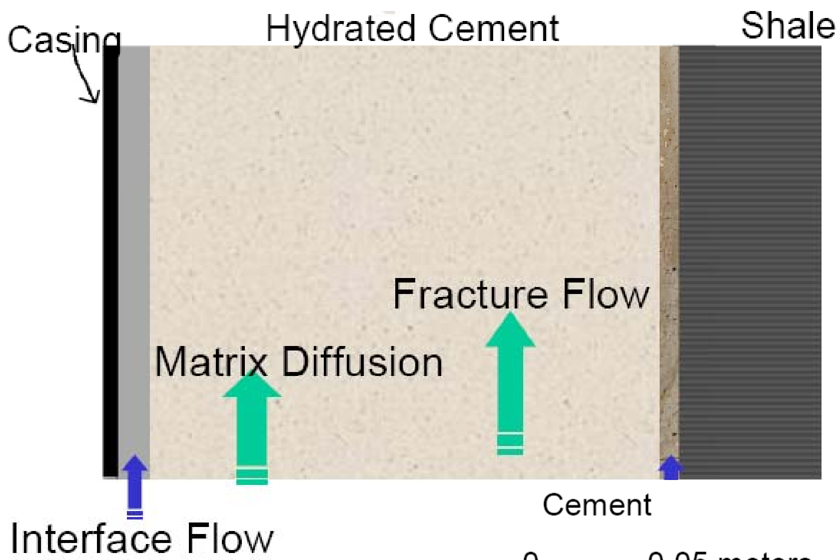
Diffusion profile



Integration of anorthite ($CaAl_2Si_2O_8$) dissolution

After Gaus et al. (2005)

Well cement degradation (after 30 years)



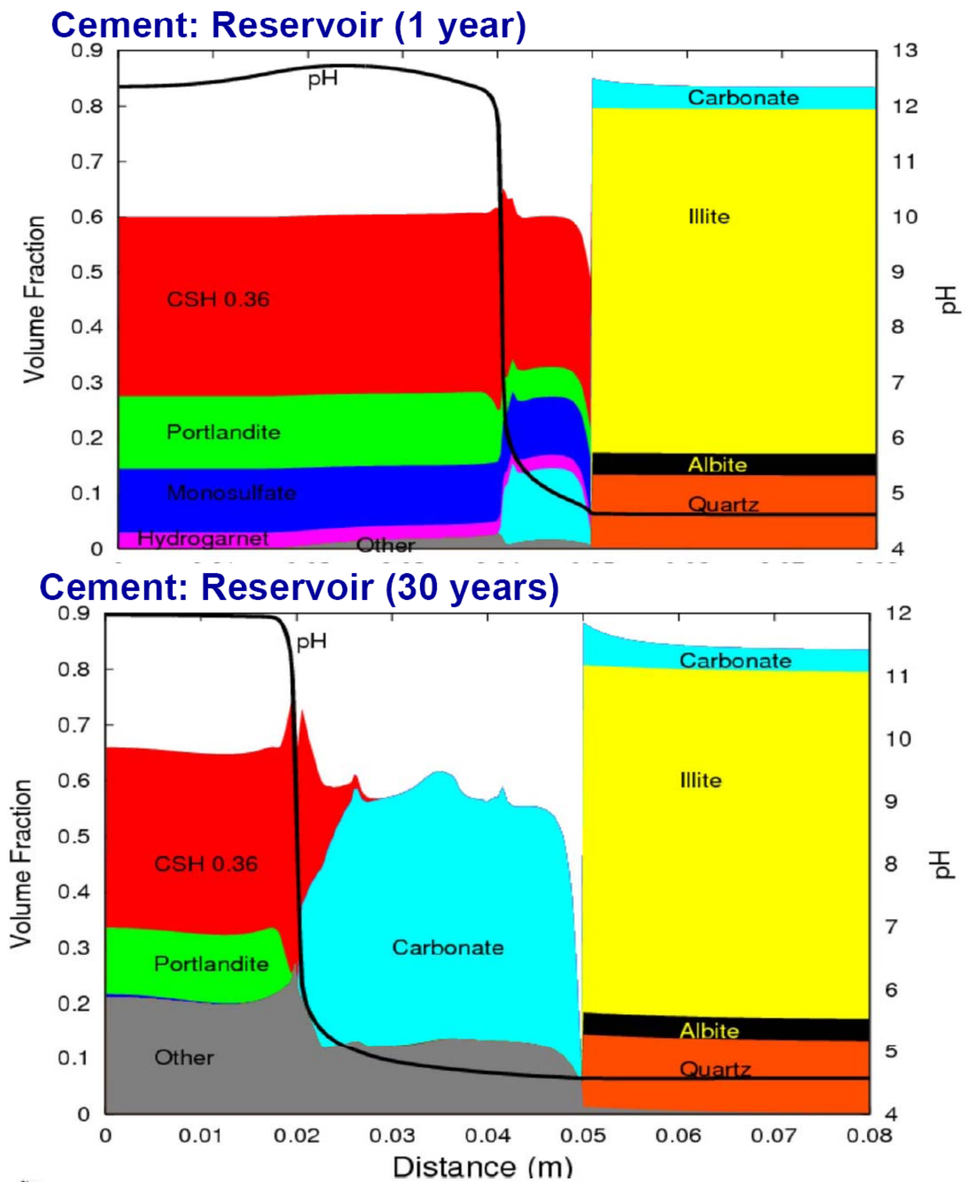
38% C-S-H (x_{SiO2}=0.36, Ca/Si = 1.78)
15% portlandite
14% monosulfate
3% hydrogarnet
30% porosity

20% illite
7% quartz
1% kaolinite
1% calcite
1% dolomite
70% porosity

- 1-D diffusion of CO_2-saturated brine into cement
- 25 °C and 179 bars P(CO_2)
- Variables: Porosity, tortuosity, reaction rates, and solid solution model [Carey & Lichtner (2007) American Ceramic Society]

Carey et al. (2007) Analysis and performance of oil well cement with 30 y of CO2 exposure from the SACROC Unit …. IJGGC, vol. 1, 75-85

Well cement degradation (numerical modeling results)

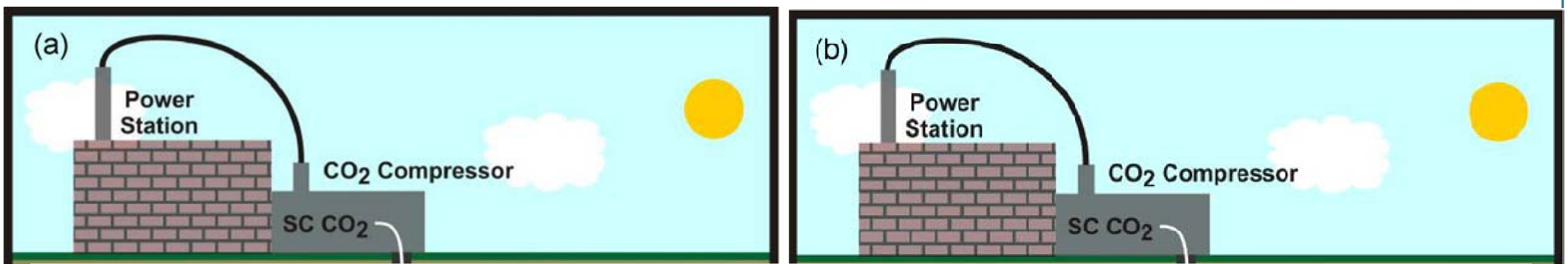


Carey et al. (2007) Well bore Integrity Workshop; Buzmann

> **Needs research because currently available results are contradictory?**

> **Needs coupling models: geochemical – geomechanical?**

Biofilm development? (what are P, T, x conditions?, …)



Biomasse Concentration (g L^{-1})

Respiration Reaction Rate (mol L^{-1} s^{-1}) → $$v = k[X]F_D\,F_A\,F_T$$ ← Thermodynamic Potential of the reaction

Kinetic Constant (mol g^{-1} s^{-1}),

Factors dependent on concentrations of electron donors and acceptors

- **The factor (F_T) is a function of redox reaction enthalpy:**

$$F_T = 1 - \exp\left(\frac{\Delta G_{redox} + m\Delta G_P}{\chi RT}\right)$$

$$\Delta G_{redox} = \Delta G^0_{redox} + RT\ln\left(\frac{\prod_{D^+} a_{D^+}^{\nu_{D^+}} \prod_{A^-} a_{A^-}^{\nu_{A^-}}}{\prod_{D} a_{D}^{\nu_{D}} \prod_{A} a_{A}^{\nu_{A}}}\right)$$

Mitchell et al. (2009) Biofilm enhanced geologic sequestration of sc-CO_2. IJGGC, vol. 3, 90-99. ➔ T = 32°C, P = 8.9 MPa

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Knowledge limitations and some research targets

- ***Pitzer Formalism:*** **for highly saline waters and needs detailed specific interactions between aqueous species (Al, Si, …)**
- ***Gas Mixes:*** **we need more powerful and comprehensive EoS for CO_2 impurities**
- ***Geobiochemical Processes:*** **very complex niches with synergies between micro-organisms communities (topic at the infancy stage with many questions?)**
- ***Fundamental Processes, Available Approaches and Performances:*** **feedbacks, coupled & interdependent processes, complex reaction networks ➔ coupling THCMHT?**
- ***Geochemical Software Benchmarking:*** **some cases were envisaged but it is very difficult to establish case studies because of thermodynamic databases "inconsistencies", corrections of the excess properties of aqueous, solids, and gas sub-systems, etc.**

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Geomechanical Modeling Associated with Geological CO_2 Sequestration

Jonny Rutqvist

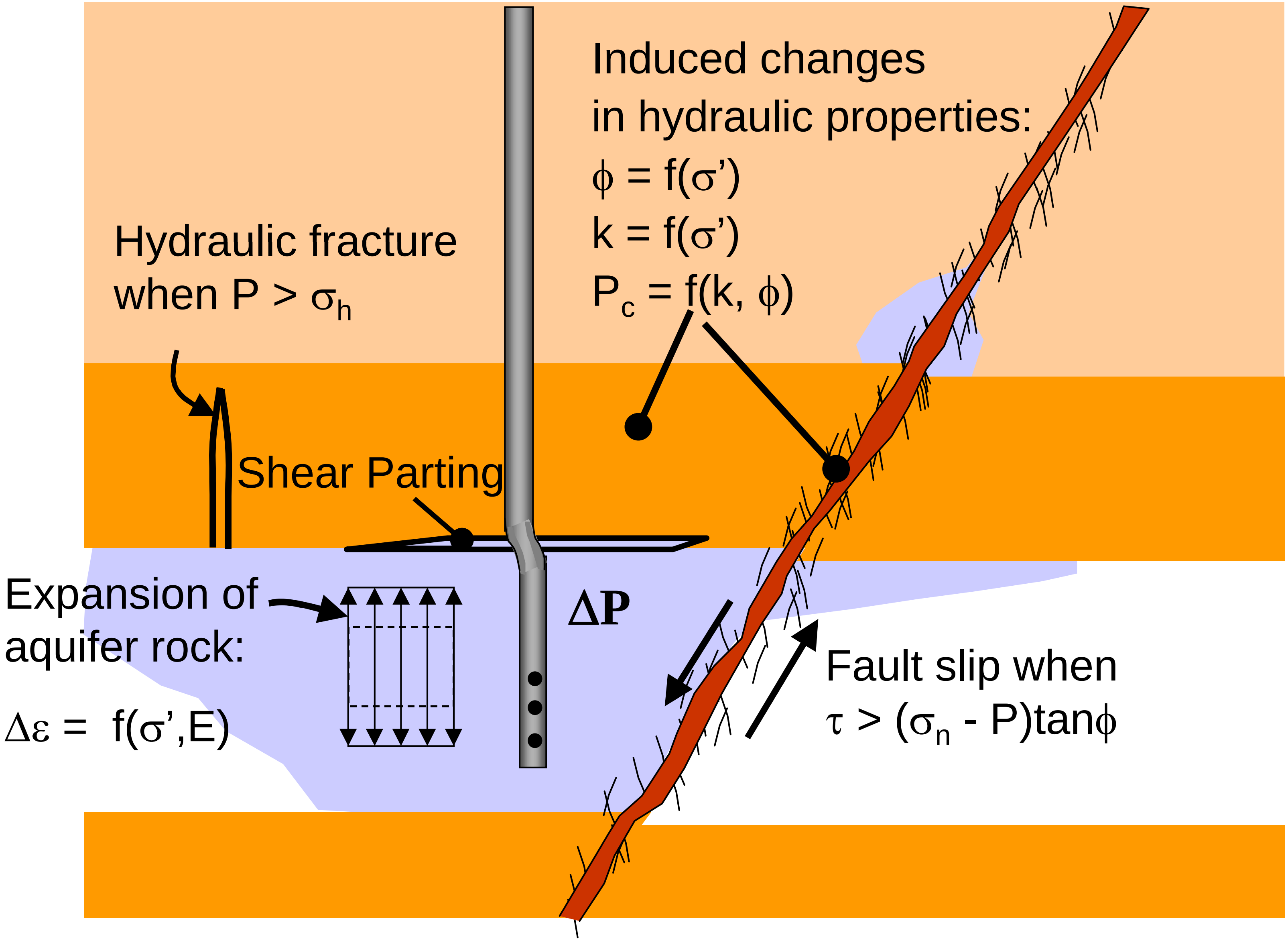
Lawrence Berkeley National Laboratory

Acknowledgements:
U.S. Department of Energy, through the National Energy Technology Laboratory (NETL) for funding and support.

OUTLINE

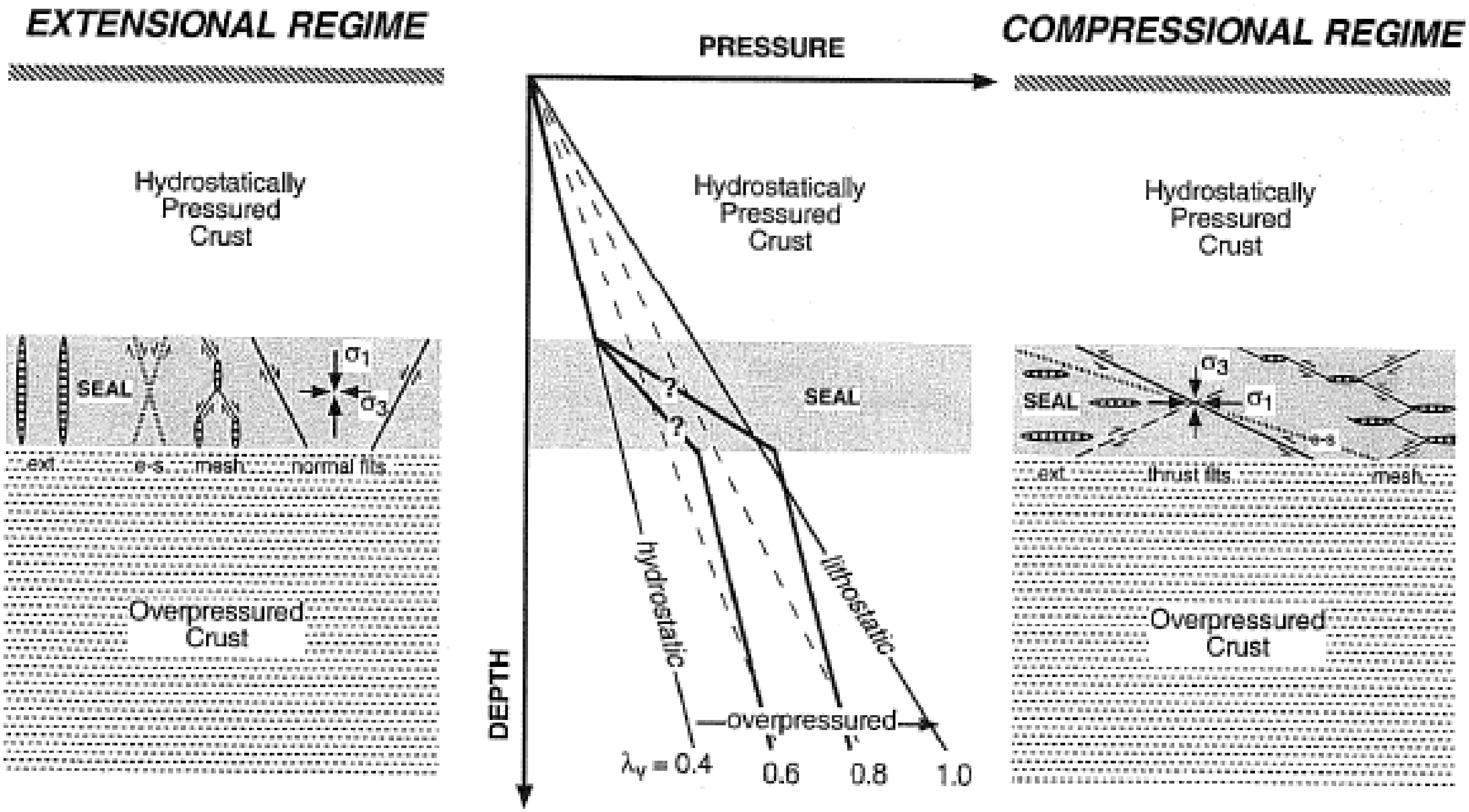
- Geomechanical processes associated with CO_2 injection
- Estimating maximum sustainable injection pressure and shear reactivation
- Ongoing application of coupled geomechanical modeling to the In Salah CO_2 storage project
- Concluding remarks

Geomechanical Processes in CO_2 Storage



What is the maximum sustainable injection pressure?

NATURALLY OVERPRESSURED SEDIMENTS AND GAS RESERVOIRS

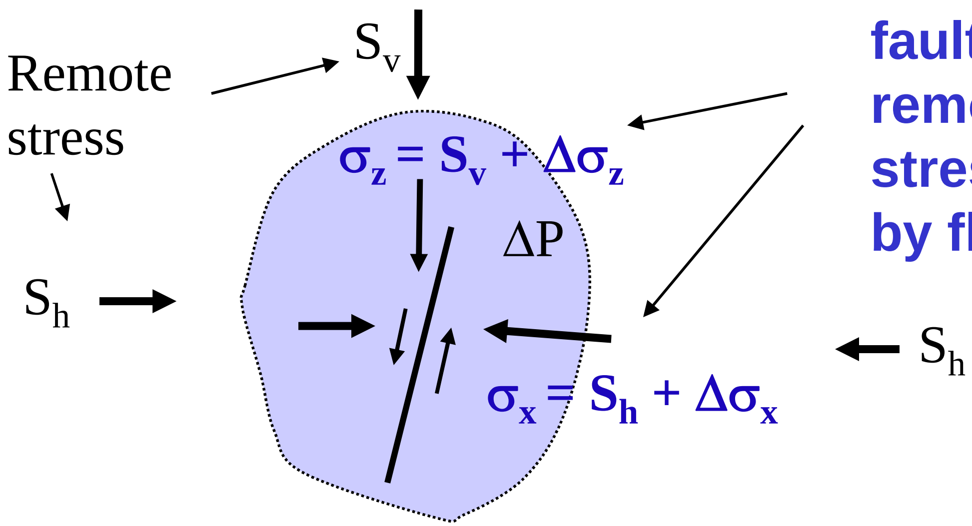


- Reshear of cohesionless faults favorably oriented for frictional reactivation provides the lower limiting bound to overpressures (Sibson, AAPG, 2003).

⇒ Geomechanical analysis of fault slip (not just fracturing) is essential for estimating maximum sustainable pressure at a CO_2 injection site.

SHEAR REACTIVATION OF EXISTING FRACTURES

During underground fluid injection, the *in situ* stress field does not remain constant, but rather evolves in time and space, controlled by the evolutions of injection- induced changes in fluid pressure and temperature.



Local stresses across fault are the sum of remote (initial) stress + stress changes caused by fluid injection

Injection-induced (poro-elastic) stresses depends on the geometry of the pressurized zone and the poro-elastic properties of the reservoir and its surroundings.

Injectin induced stresses may be estimated using analytical/semi-analytical solutions (for certain geometries) or modeled in a coupled reservoir-geomechanical numerical analysis.

A CONSERVATIVE STRESS CRITERION FOR ESTIMATING MAXIMUM SUSTAINABLE PRESSURE

Coulomb criterion for a single fault of known orientation ⇒ $$\tau = C + \mu(\sigma_n - p)$$

⇓

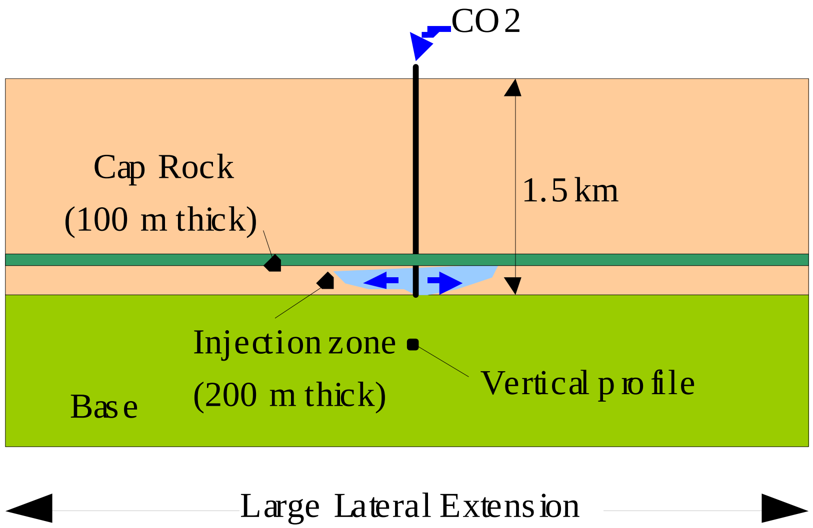
Assume that a fault (or pre-exiting fracture) could exist at any point with any orientation a zero cohesion and a friction angle, φ = 30° ⇒ $$\sigma_1' < 3\sigma_3'$$

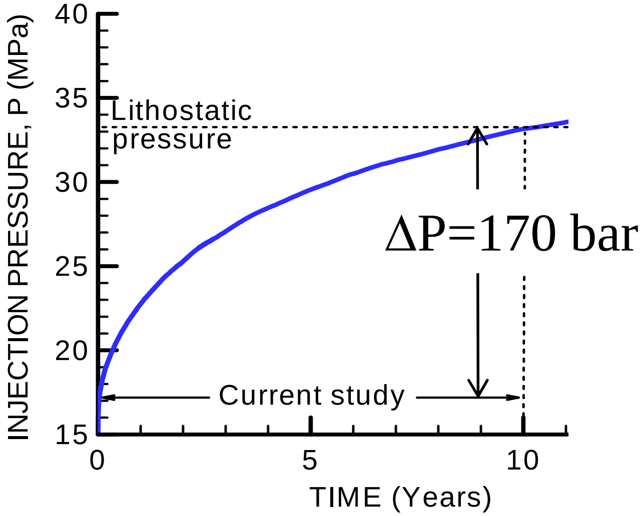
Max principal effective stress (σ_1')

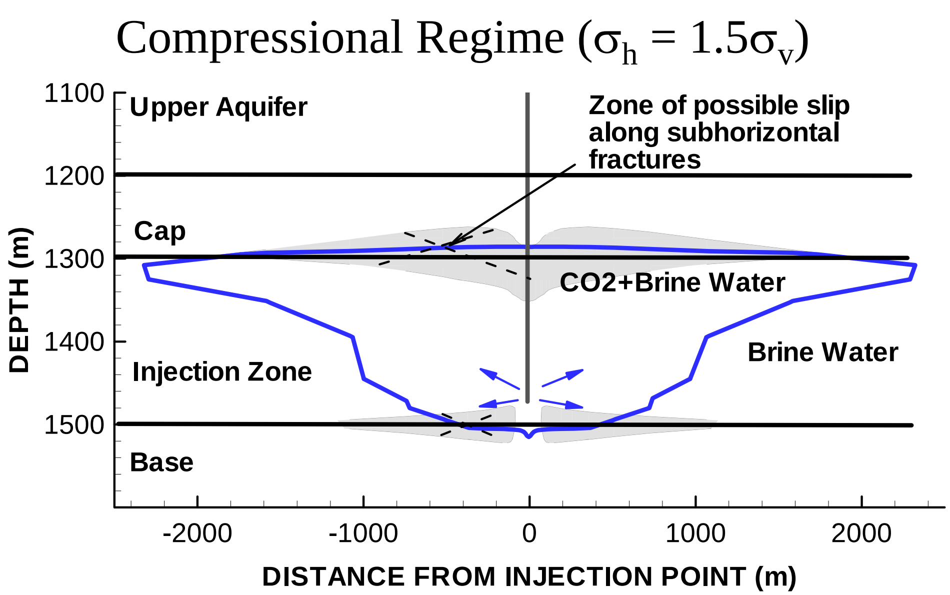
Min principal effective stress (σ_3')

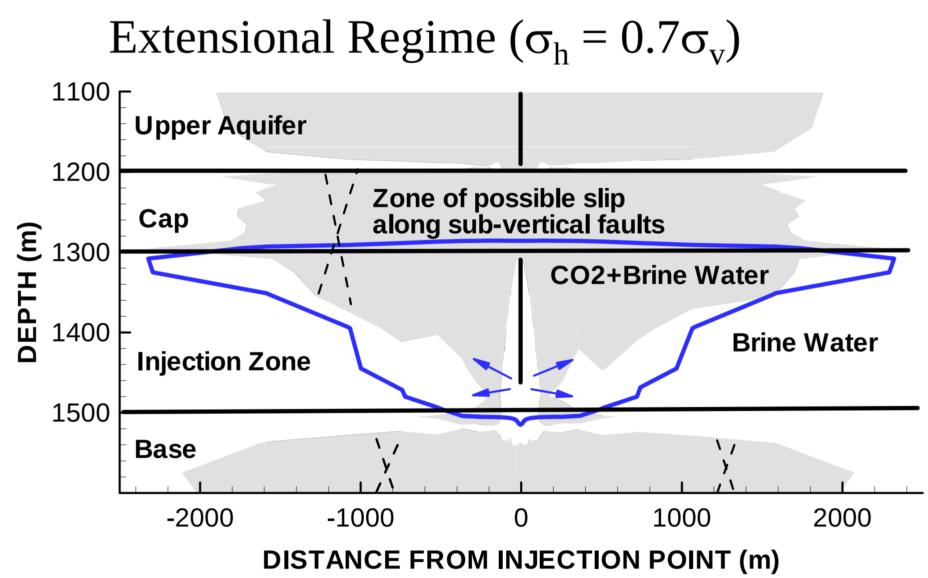
μ = tan30° ≈ 0.6 is a lower-limit value observed for hydraulic conducting fractures and their correlation with maximum shear stress in fractured rock masses (e.g. Barton et al., 1995)

POTENTIAL FOR SHEAR ALONG EXISTING FRACTURES





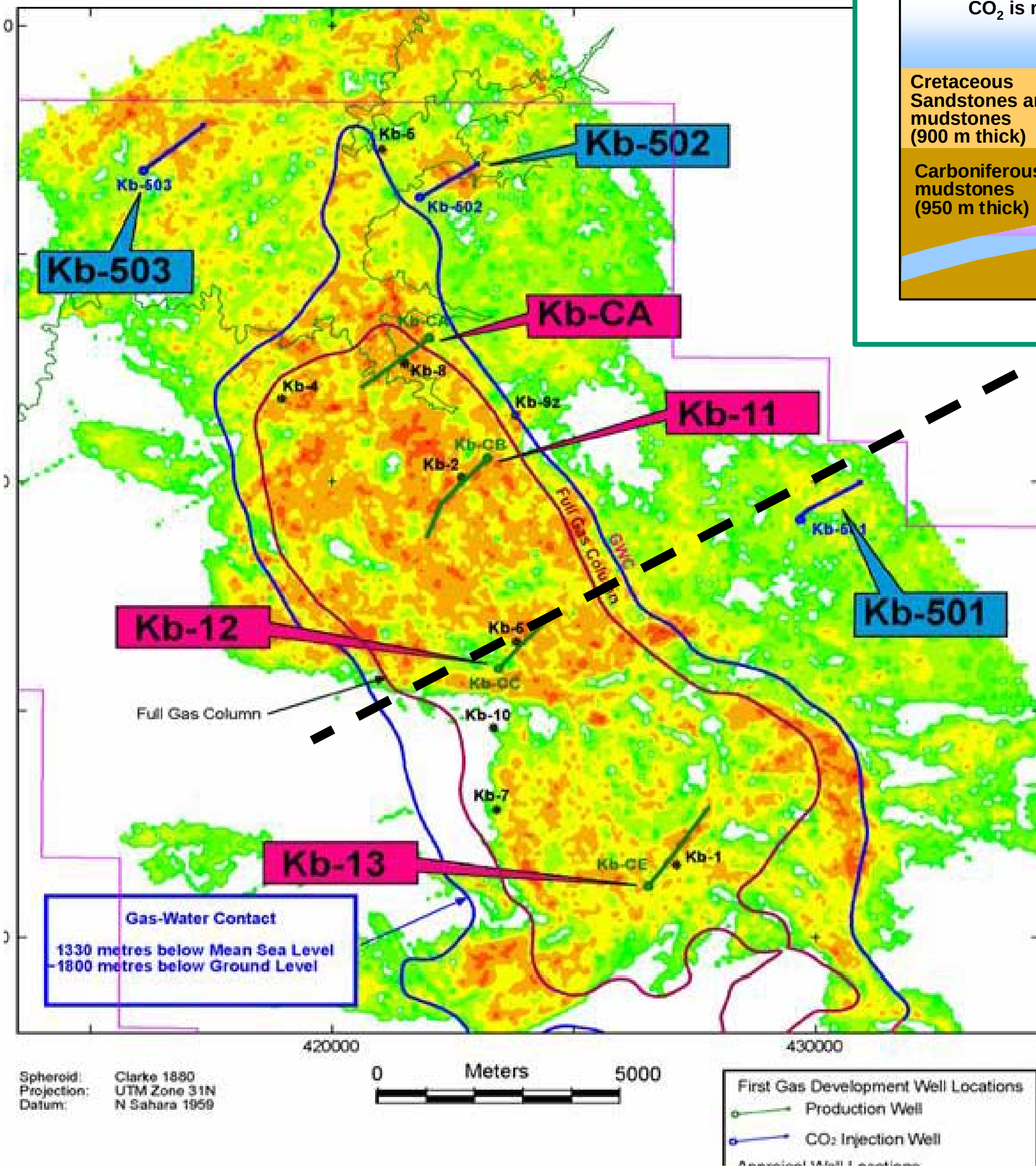


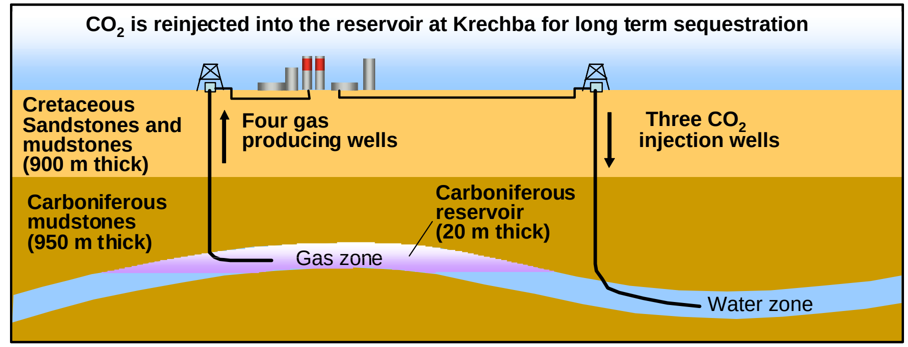


⇒ Remote (initial) stress field a very important factor

Application of Geomechanical Modeling to The In Salah CO_2 Storage

Plane view of Krechba gas field



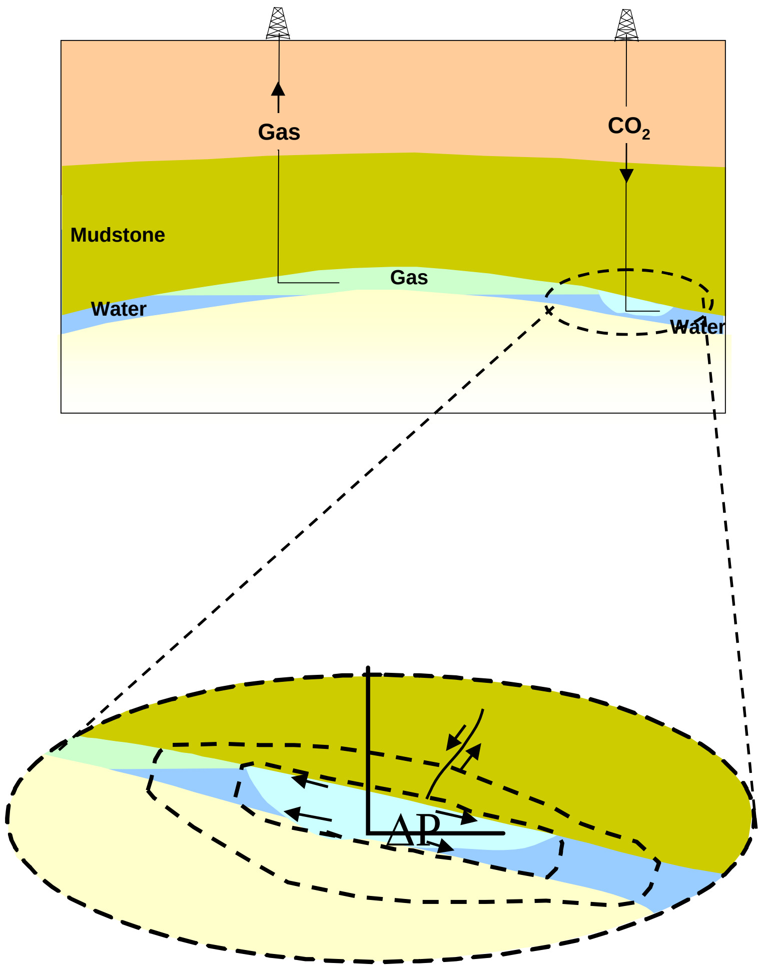


- Nearly one million tonnes CO_2 per year have been injected over the past four years at 3 injection wells (KB501, KB502, and KB503).
- The bottom hole pressure is limited to below the fracturing gradient leading to a maximum pressure increase of about 100 bar above the ambient initial formation pressure.

$\Rightarrow$ Maximum bottom hole injection pressure is about 60% above initial pressure.

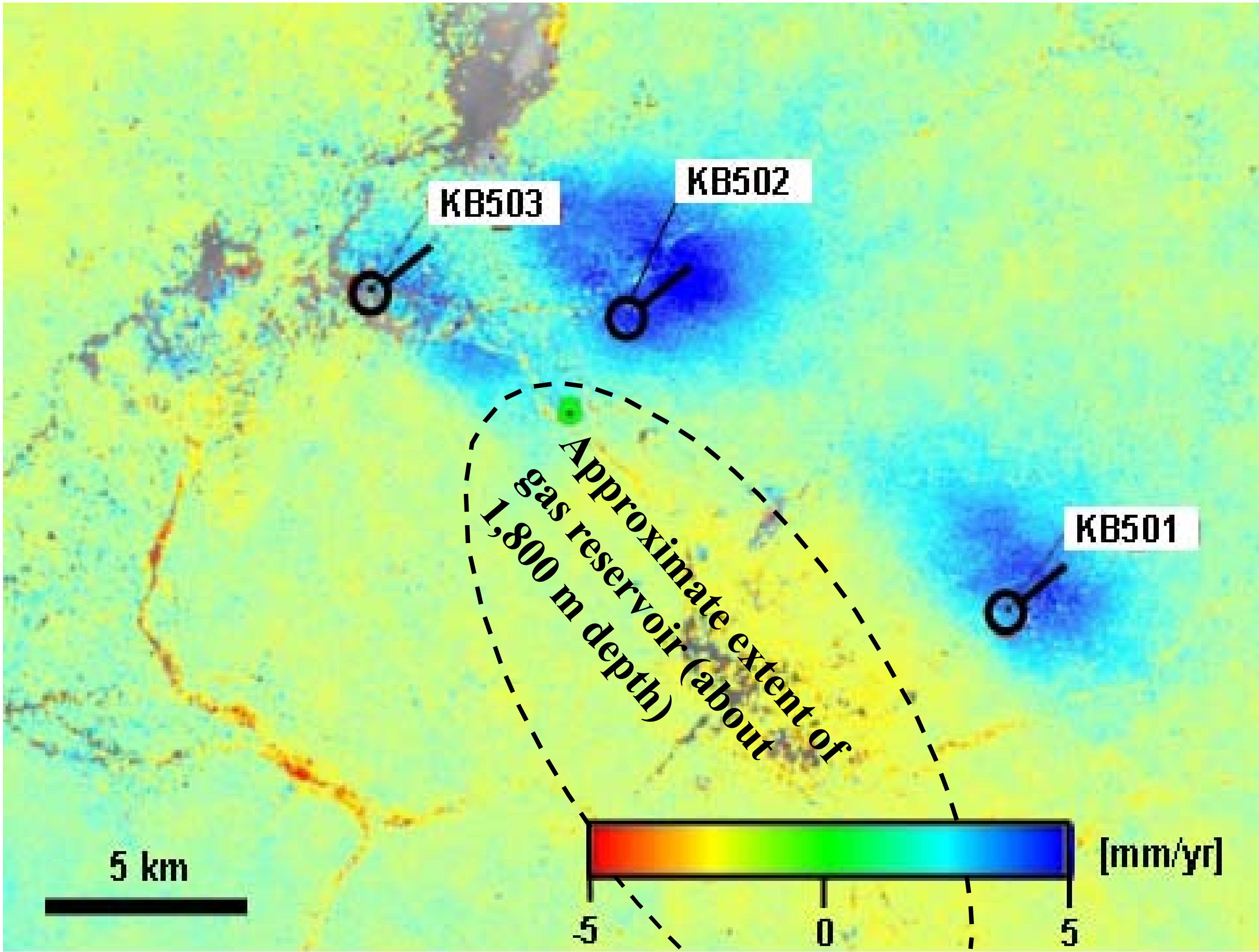
Coupled Reservoir-Geomechanical Numerical Analysis of In Salah

CO_2 injection into a narrow (20 m thick) reservoir at a relatively high injection pressure over a large area (several square kilometers)

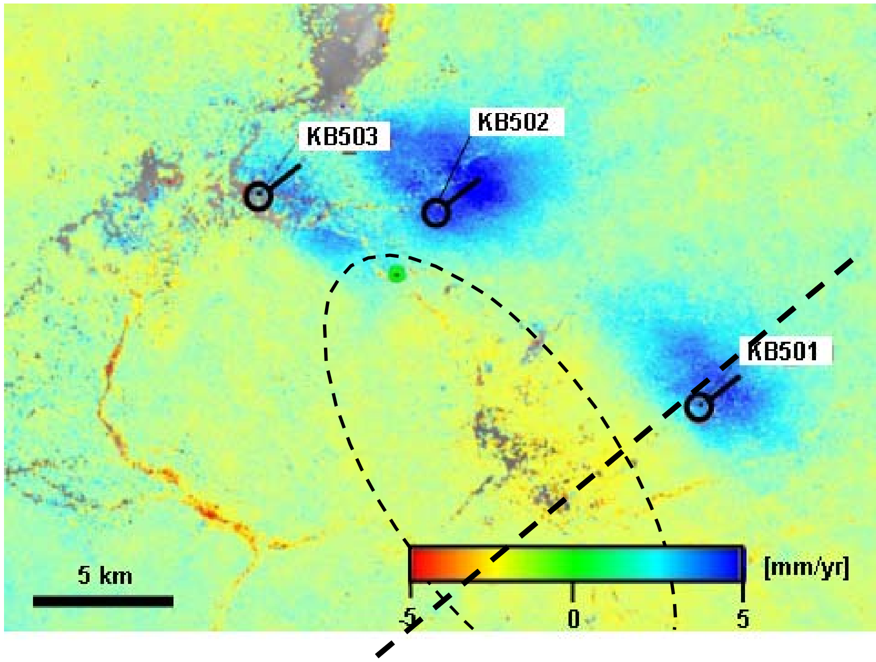


- Evolution of stresses (effective and poro-elastic stresses) and rock deformations
- Pressure (effective stress) dependent permeability and its effect on injectivity
- Potential for tensile or shear parting (at reservoir-caprock interface).
- Potential of shear slip along fractures (induced seismicity?)
- Potential for development of new leakage path through caprock
- Study potential leakage detection from injection well data, deformation pattern or by measurable geophysical changes
- Surface deformation (detectable?)

Vertical Ground Surface Displacements from Satellite

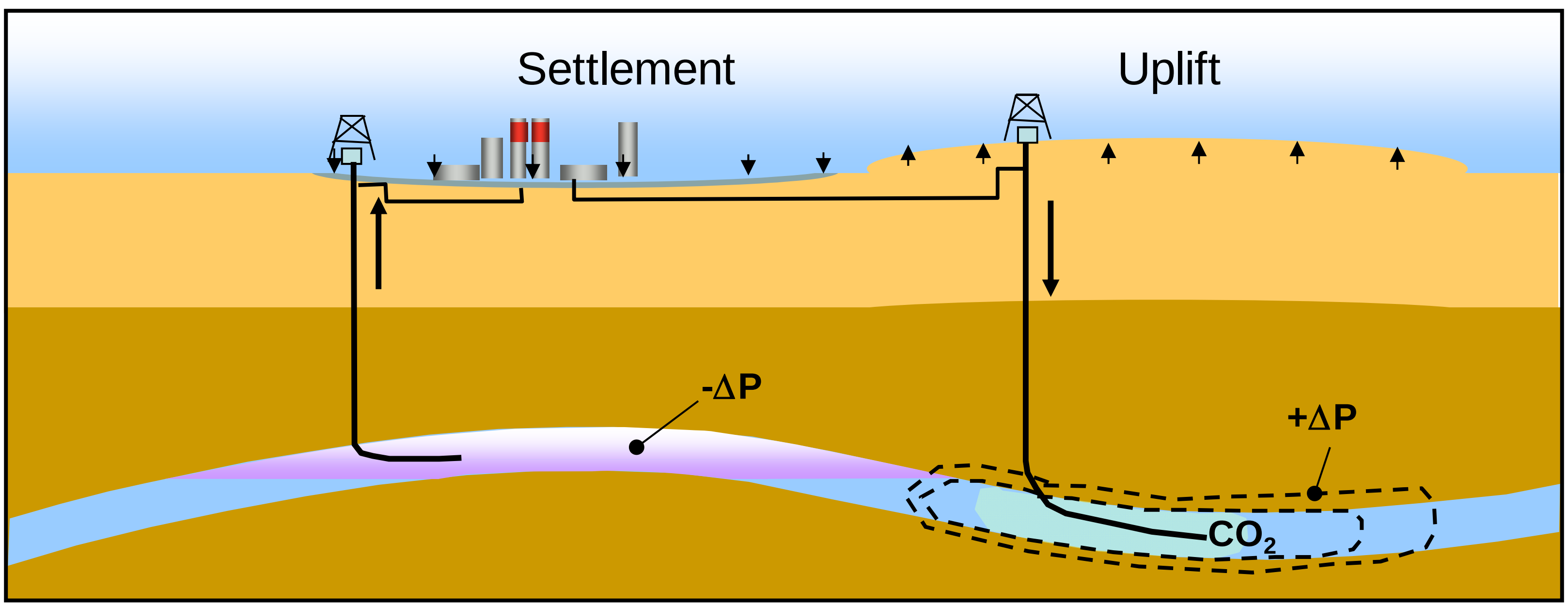


Measured Vertical Displacement

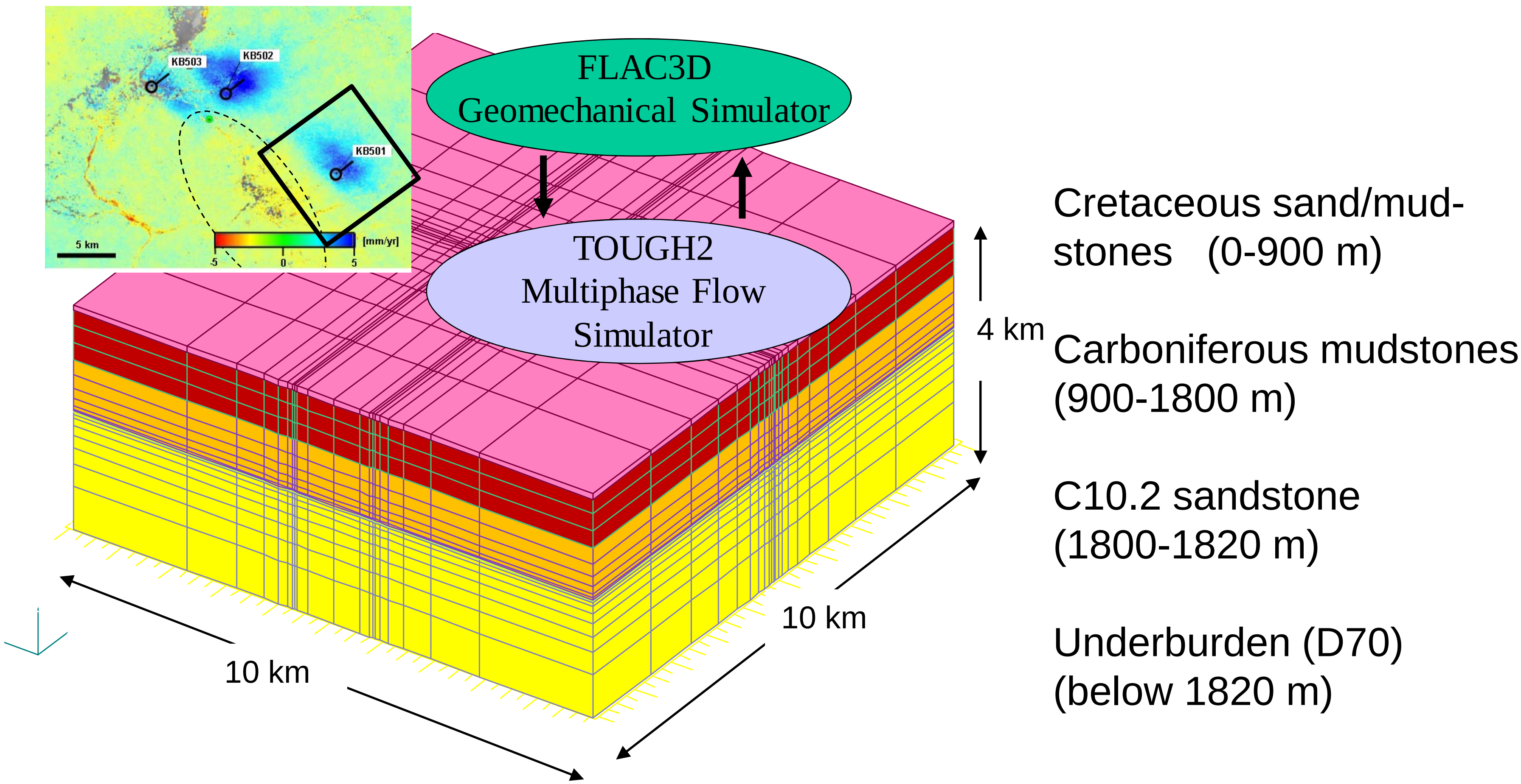


- 5 mm yearly uplift above injection wells

Settlement above the depleting gas field



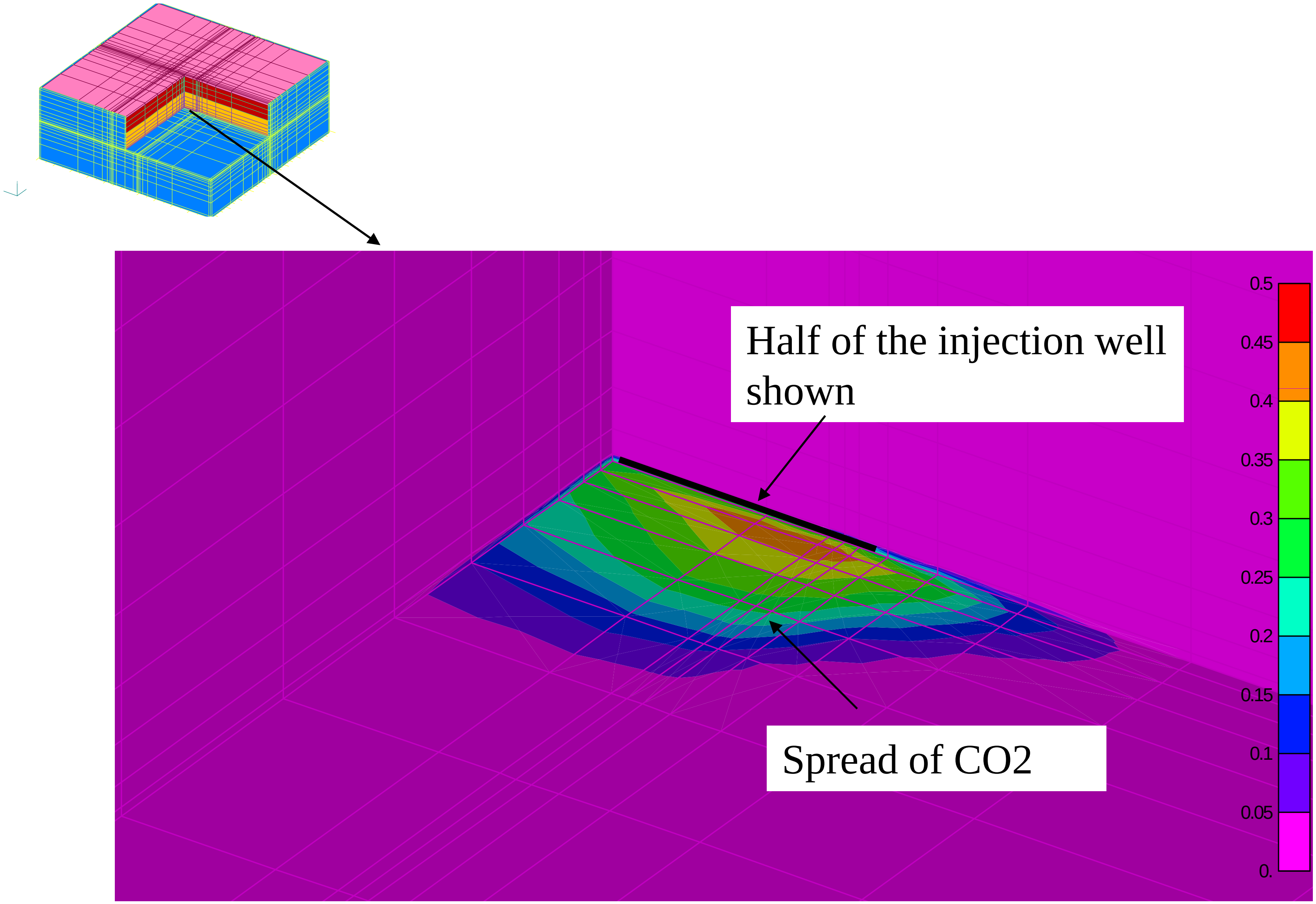
COUPLED RESERVOIR-GEOMECHANICAL MODELING OF CO2 INJECTION



Elastic properties (E = 6 GPa, ν = 0.2) of C10.2 sandstone consistent with laboratory measurements conducted by University of Liverpool (Faulkner and Mitchell) at relevant confining stress level.

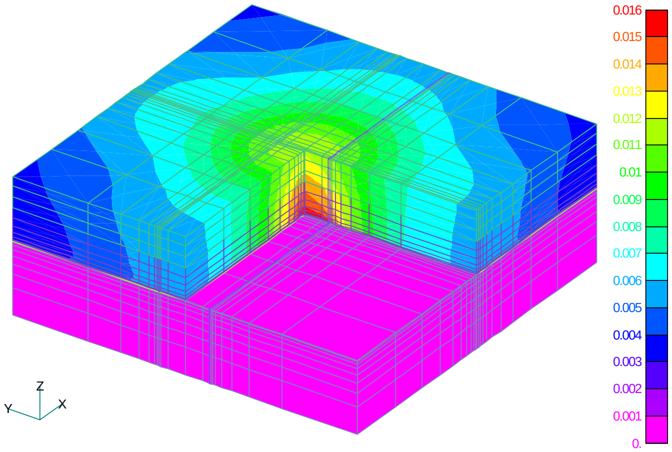
Elastic properties of other layers estimated from vertical profiles of sonic log results $\Rightarrow$ somewhat stiffer caprock (900-1800 m) and softer near surface layer (0 – 900 m)

TOUGH-FLAC MODELING OF CO2 INJECTION



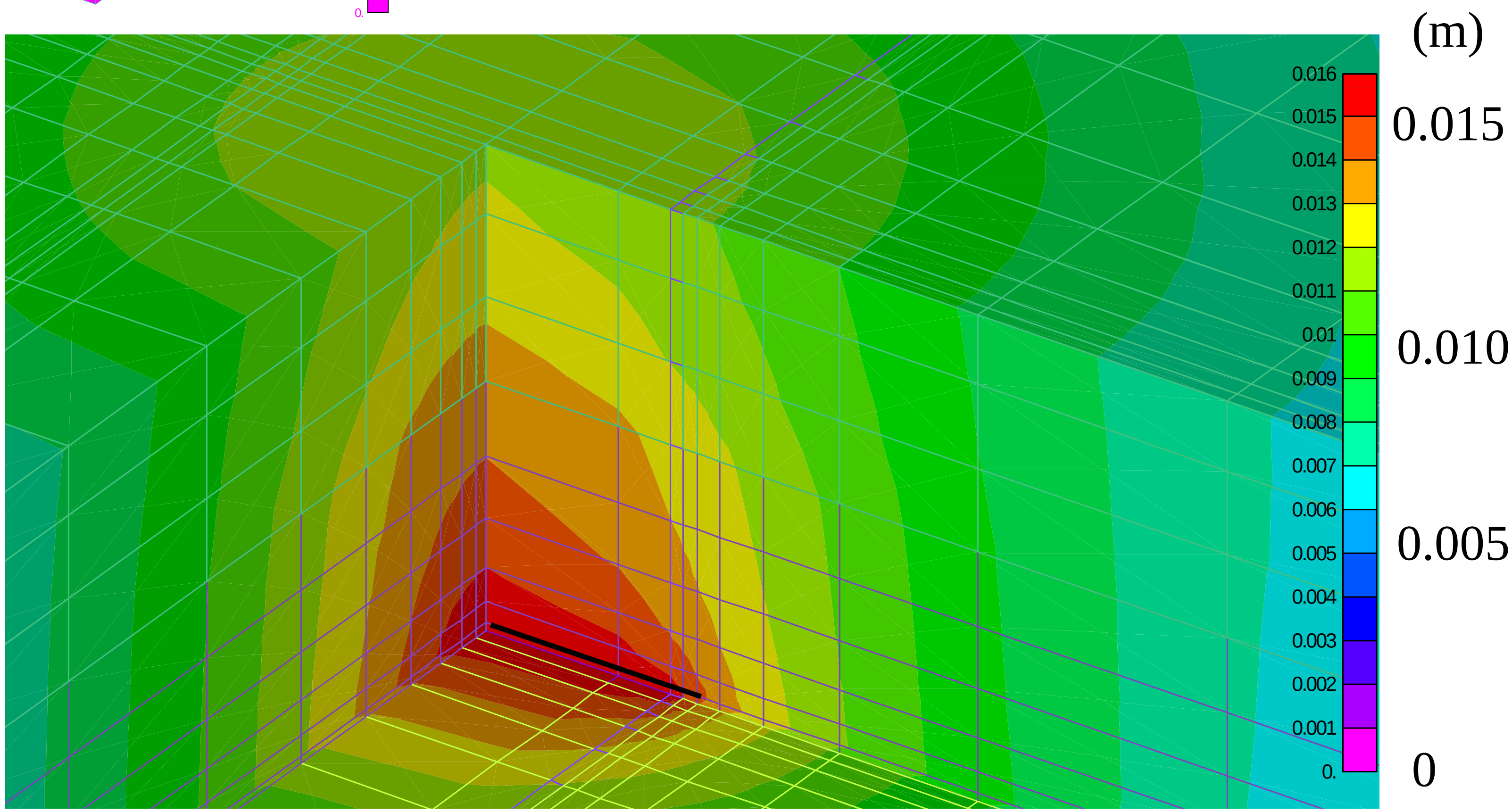
(a) Close up view showing the saturation of the CO_2 fluid phase (half of the CO_2 injection well is indicated by the black line).

SIMULATION RESULTS FOR BASE CASE PROPERTIES

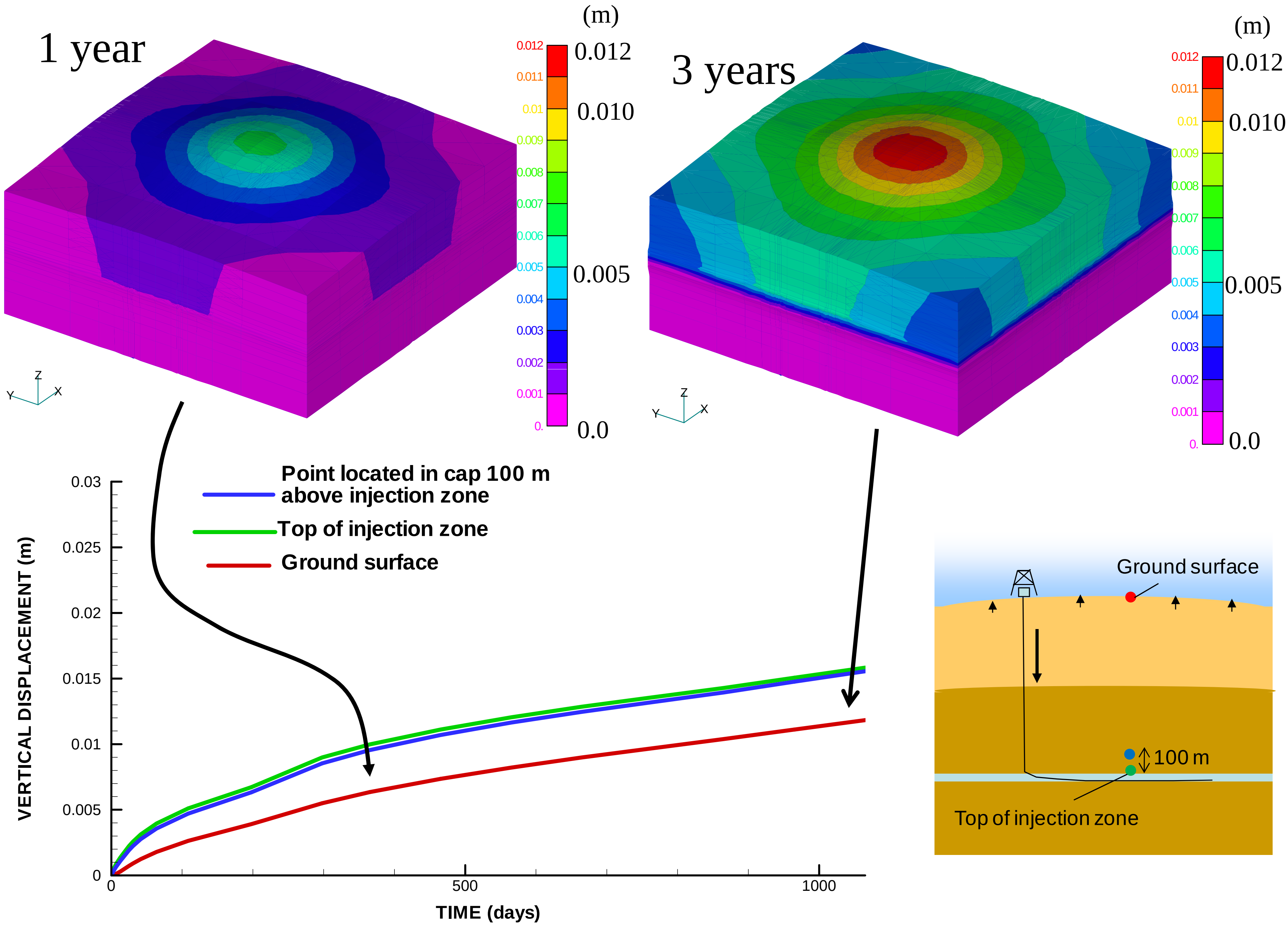


KB501 like CO_2 injection: Average rate 15 MMscfd used and permeability set to 13 mDarcy leading to a pressure increase of about 100 bar

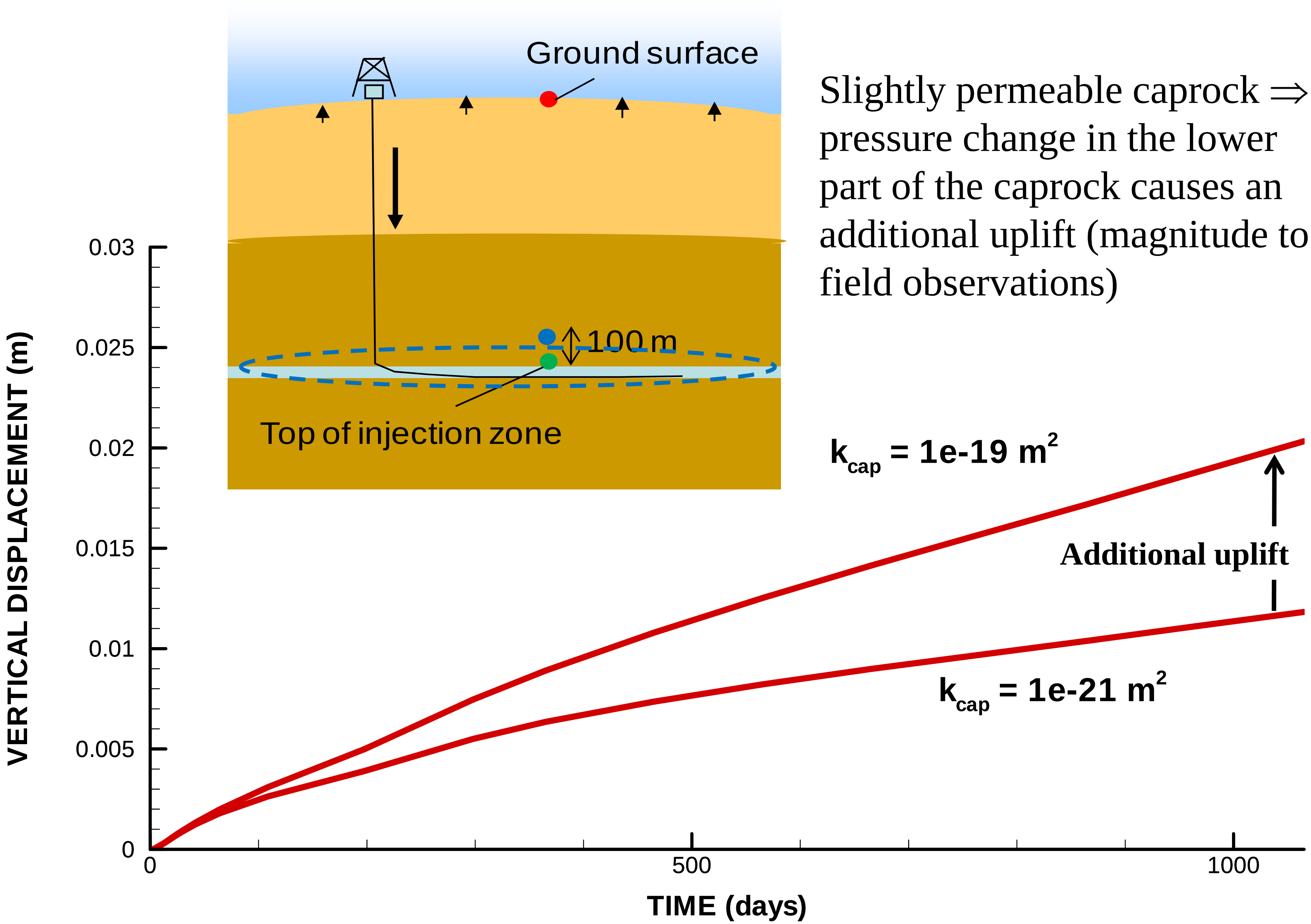
Results: about 1.2 cm ground uplift after 3 years (when caprock considered impermeable)



SIMULATION RESULTS FOR BASE CASE PROPERTIES



IF CAPROCK IS NOT PERFECTLY IMPERMEABLE



Slightly permeable caprock ⇒ pressure change in the lower part of the caprock causes an additional uplift (magnitude to field observations)

Lower part of caprock fractured and now considered to be a secondary storage zone

IN SALAH COUPLED GEOMECHANICAL MODELING

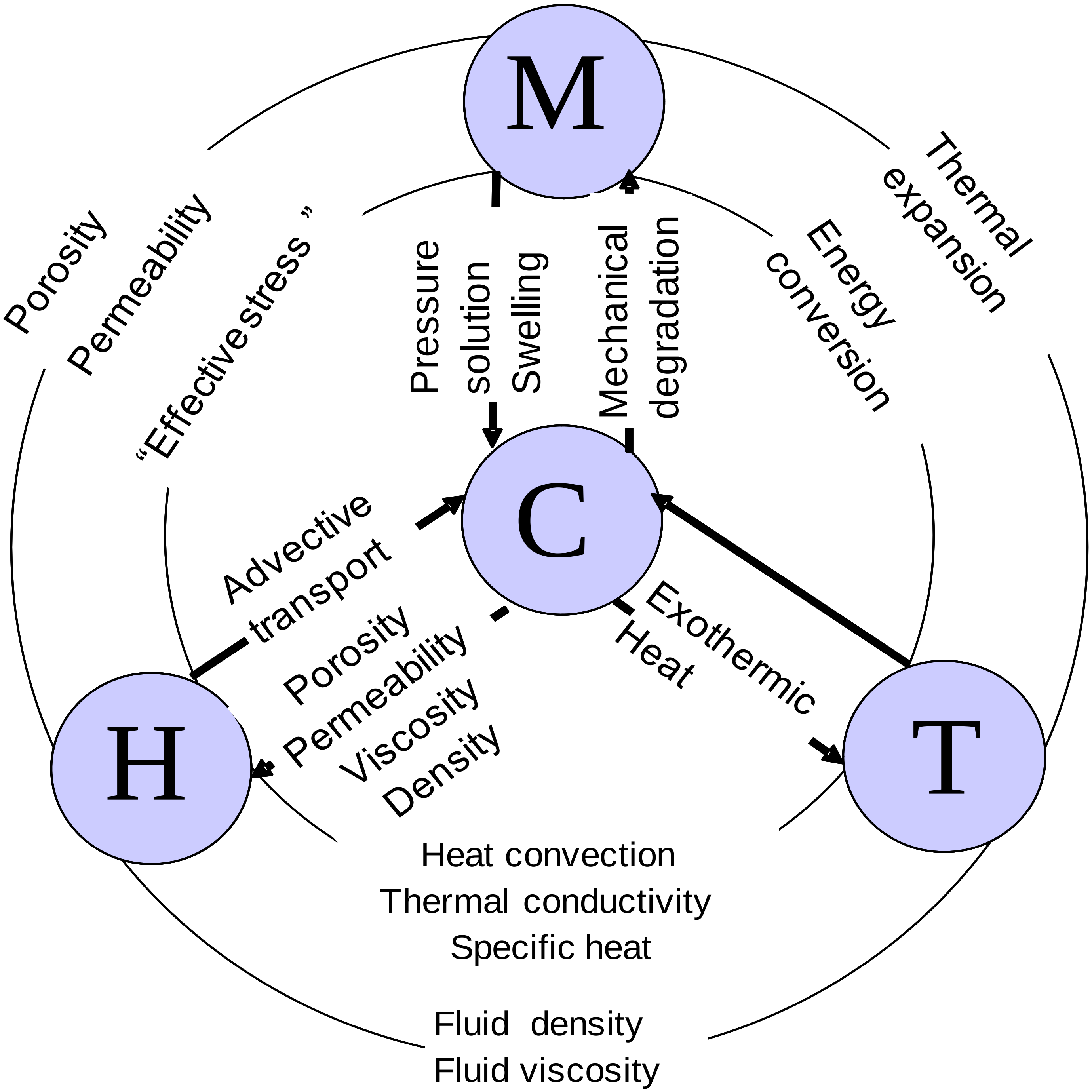
- Reservoir poro-elastic properties constrained by observed surface deformations
- The regional in situ stress estimated from leak-off tests and borehole break-out data etc.
- Next step is to study the evolution of injection-induced effective and poro-elastic stresses (depends on poro-elastic properties and pressure change)
- Evaluate the potential for shear slip reactivation (and induced seismicity) from the stress evolution
- Down hole seismic monitoring to be deployed
- Continued refined analysis of surface uplift rate

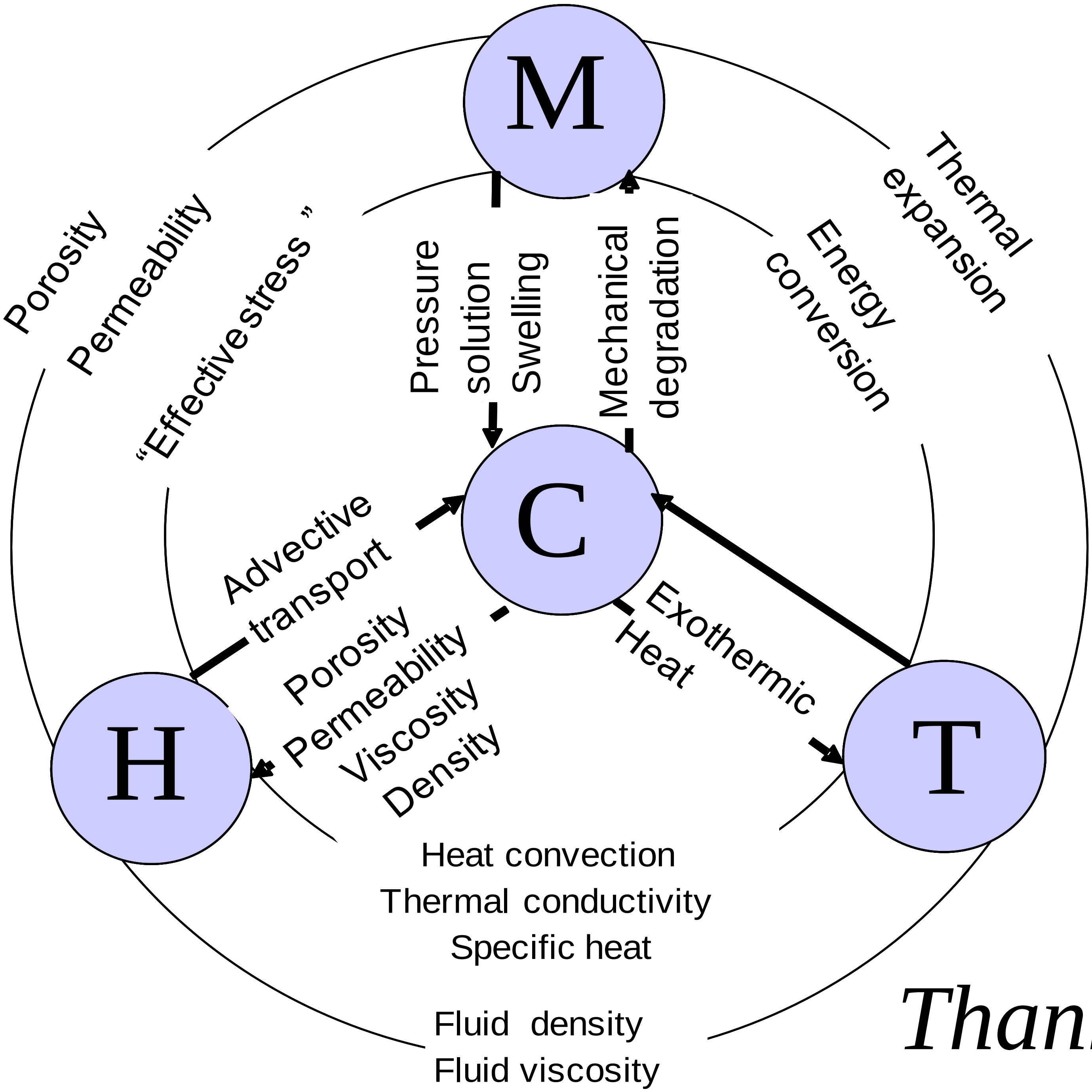
CONCLUDING REMARKS (1)

- Simplified linear poro-elastic analysis of injection-induced evolution of the 3D stress field and a conservative shear-slip based stress criterion may be used for a conservative estimate of the maximum sustainable injection pressure.
- The conservative stress criterion ($\sigma'_1 < 3\ \sigma'_3$) is based on field observations of long term containment in over-pressured reservoirs, observations of hydraulic conducting fractures in relation to maximum shear stress, and a conservative assumption that (unknown) fractures of any orientation could exist in the caprock.
- The estimated maximum sustainable injection pressure using such analysis will critically depend on the initial 3D stress field as well as on the poro-elastic properties of the reservoir.

CONCLUDING REMARKS (2)

- More complex geomechanical analysis of actual fracture propagation and shear reactivation with associated permeability change may be performed to investigate what are the potential consequences of exceeding such a conservative bound of the maximum injection pressure.
- Coupled geomechanical modeling of a CO2 injection operation (i.e. different injection scenarios or well locations) may be used to optimizing injection while minimizing the risk of unwanted damaging geomechanical changes.


M
C
H
T
Porosity
Permeability
"Effective stress"
Pressure solution
Swelling
Mechanical degradation
Energy conversion
Thermal expansion
Advective transport
Porosity
Permeability
Viscosity
Density
Exothermic Heat
Heat convection
Thermal conductivity
Specific heat
Fluid density
Fluid viscosity


M
C
H
T
Porosity
Permeability
“Effective stress”
Pressure solution
Swelling
Mechanical degradation
Energy conversion
Thermal expansion
Advective transport
Porosity
Permeability
Viscosity
Density
Exothermic Heat
Heat convection
Thermal conductivity
Specific heat
Fluid density
Fluid viscosity

Thank You!

Modeling of Non-isothermal Effects in CO_2 Storage

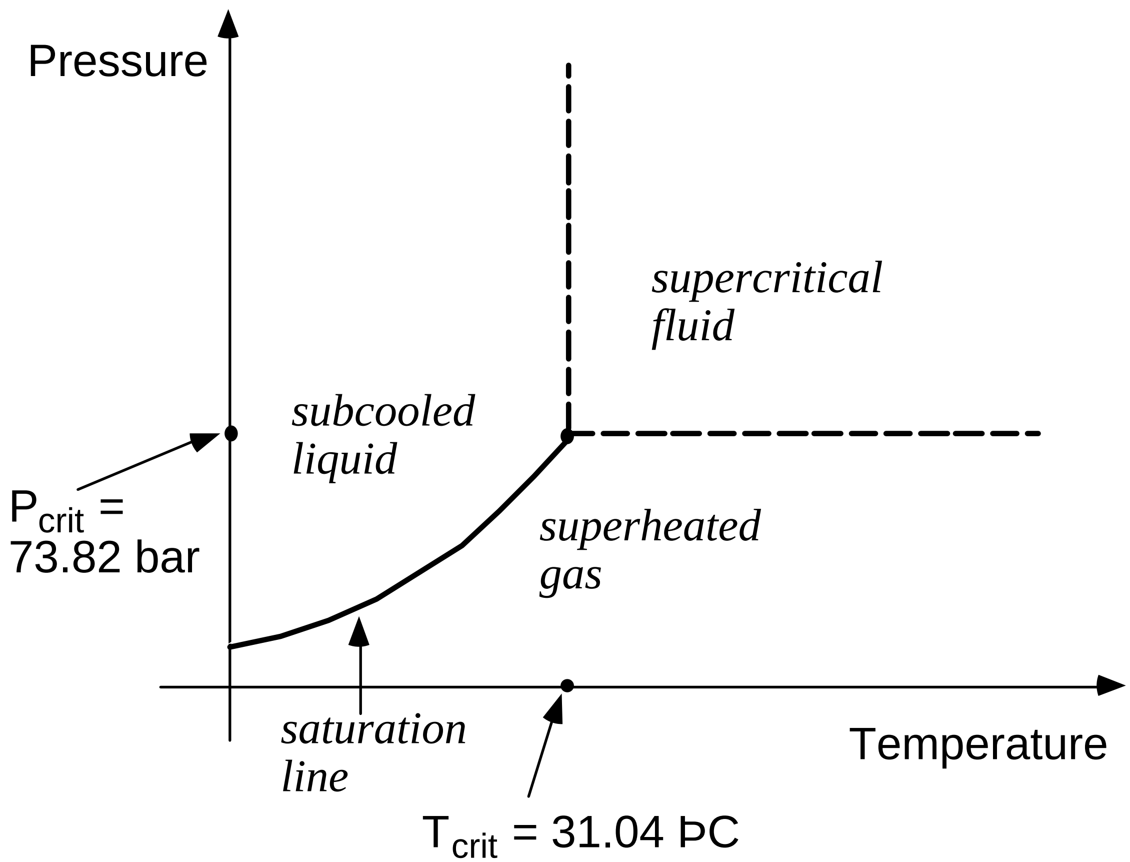
Karsten Pruess

Earth Sciences Division
Lawrence Berkeley National Laboratory

Sources of Non-isothermal Behavior

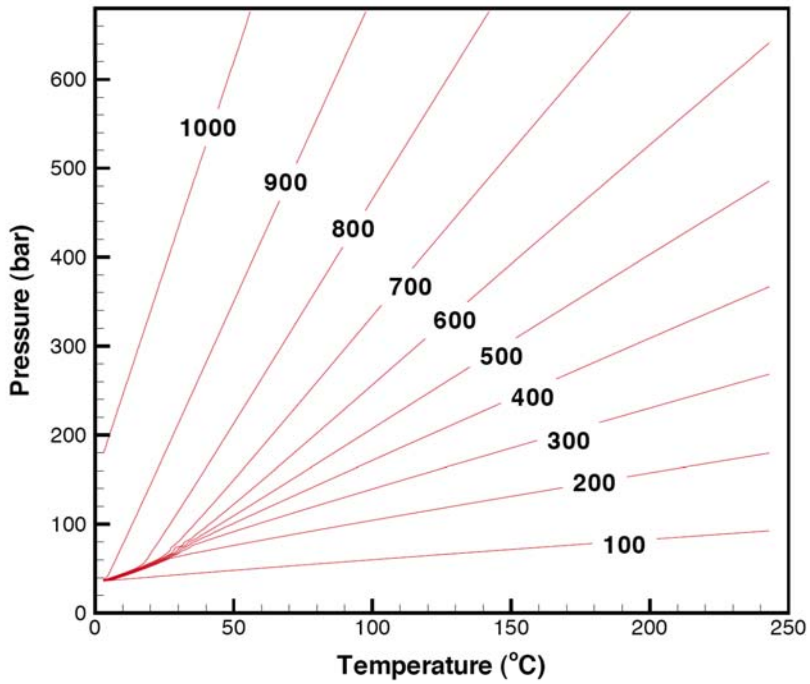
- Injecting at a temperature different from target formation
- Wellbore heat transmission
- Evaporation of water into the CO_2 stream
- Heat-of-dissolution effects as CO_2 dissolves into aqueous phase
- Heat effects in fluid-mineral reactions
- Joule-Thomson cooling when CO_2 flows down a pressure gradient and expands
- Latent heat effects as liquid CO_2 boils into gas

Phase States of CO_2

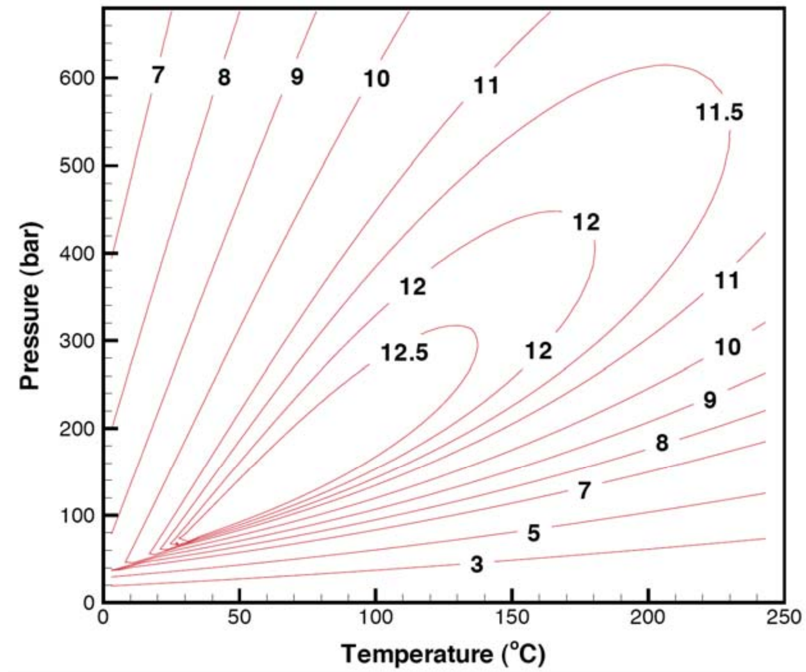


CO_2 Thermophysical Properties

Density (kg/m^3)



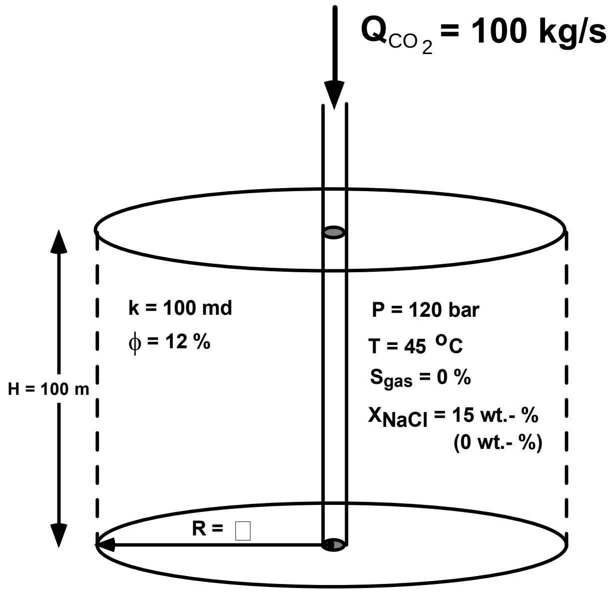
(Density/Viscosity) (10^6 s/m^{-2})



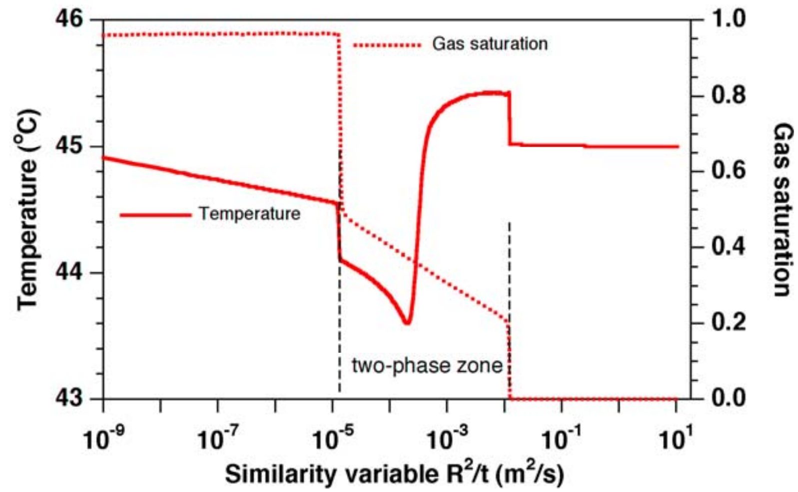
- strong temperature dependence of CO_2 density means that pressure gradients in CO_2 injection wells will be temperature-sensitive
- CO_2 mobility (= density/viscosity) also has significant temperature dependence, but impacts are likely minor, because relative permeability effects will be dominant

Radial Flow from a CO_2 Injection Well

(Sample Problem #2 for TOUGH2/ECO2N)



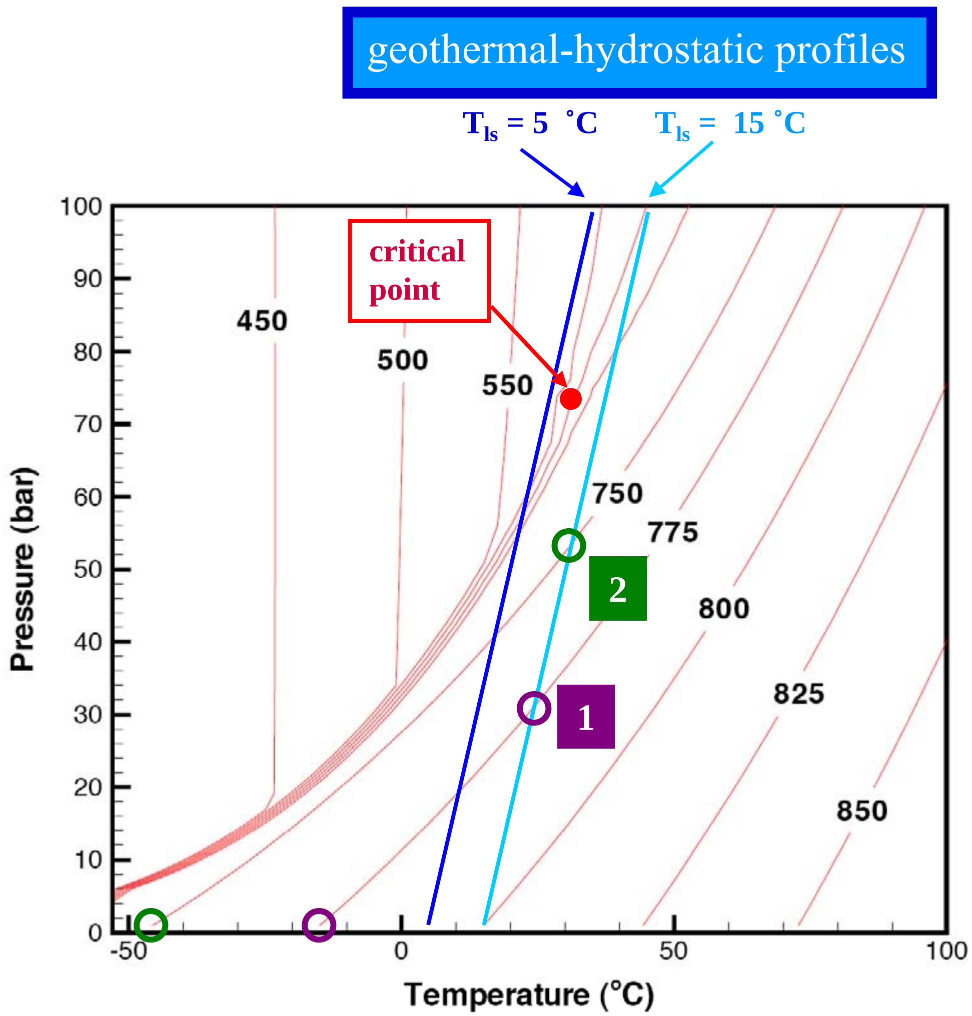
Similarity property: system evolution depends on radial distance and time only through R^2/t



- temperature effects are generally small
- temperatures decline in inner part of two-phase zone, due to water evaporating
- at outer end of two-phase zone, have temperature increase from heat-of-dissolution of CO_2
- in outer part of two-phase zone, temperatures "interpolate" between evaporative cooling and warming from CO_2 dissolution
- behind two-phase zone, temperatures increase towards injection temperature of 45 °C

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.

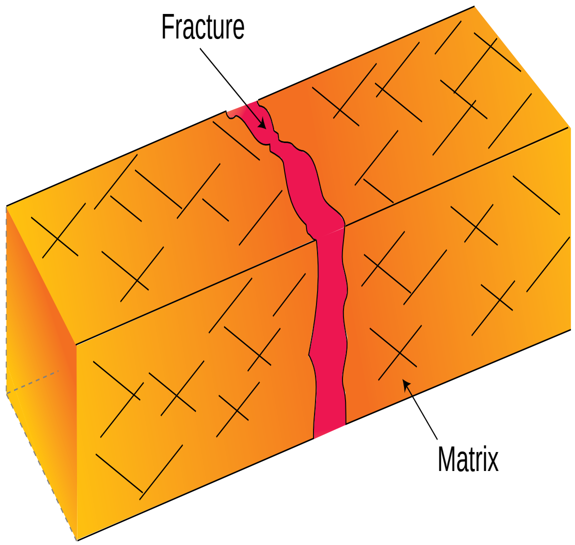
CO_2 Blowouts in Oil Wells

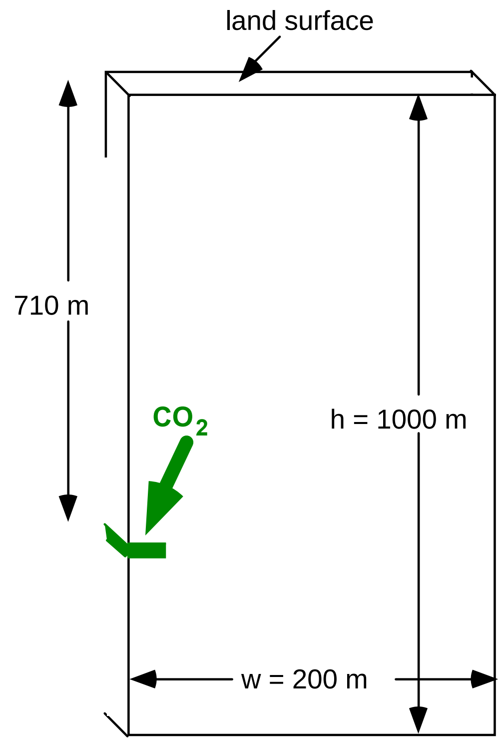
Fig. 2. Vapor cloud from water in the air condensed by cold CO_2 reduces visibility near wellbore, hindering hand-signal communications.

Fig. 4. Accumulation of dry ice and hydrates on the pump unit skid and gear box, plus 1 to 2 in. accumulation on the ground.

Les Skinner, *World Oil*, Vol. 224, No. 1, 2003

CO_2 Leakage through an Idealized Fault (Fracture) Zone

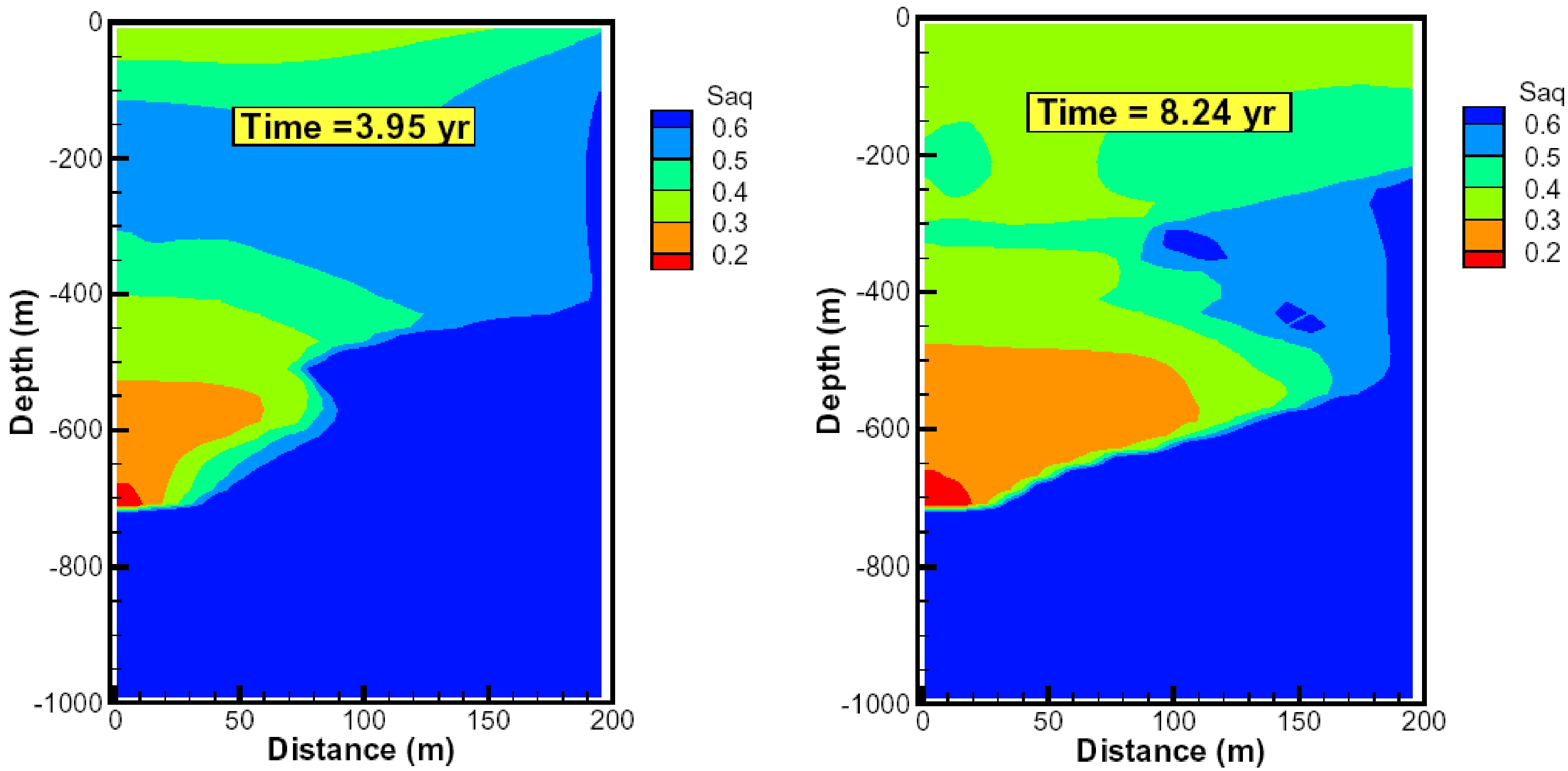




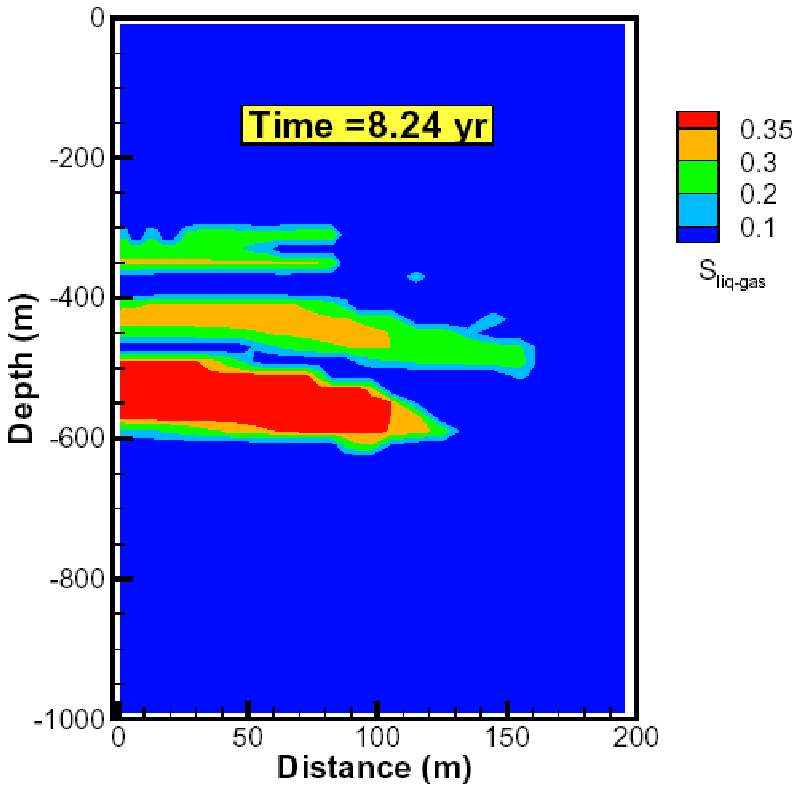
- homogeneous medium embedded in impermeable country rock
- start from natural water-saturated, geothermal/hydrostatic conditions
- apply CO_2 overpressure (80 bar @ 710 m depth, compared with hydrostatic pressure of 70.5 bar)

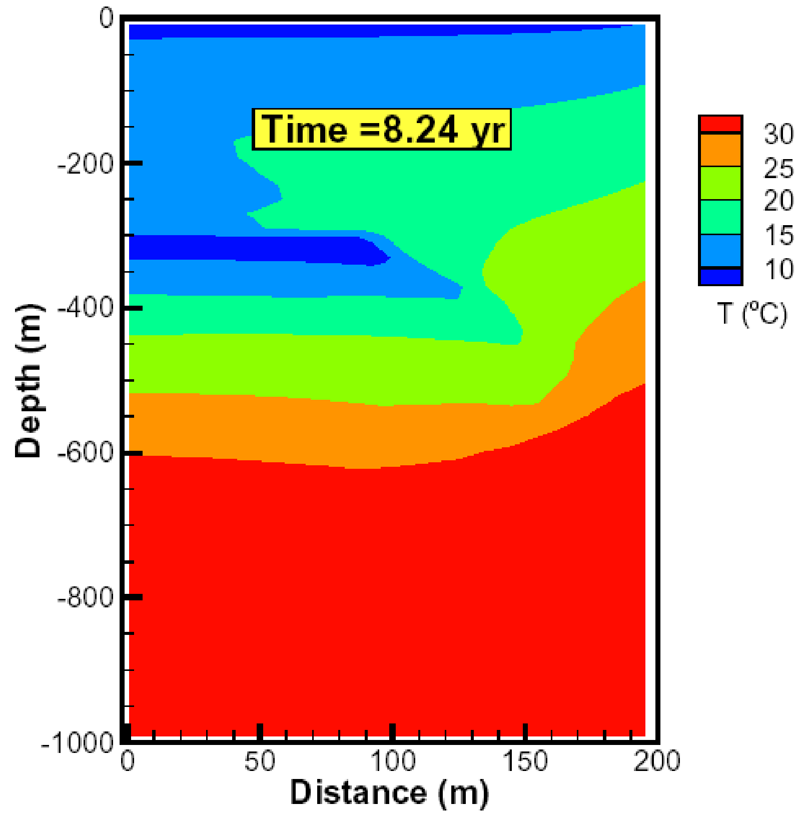
CO_2 Plumes at Two Different Times

(1 m thick fracture zone)



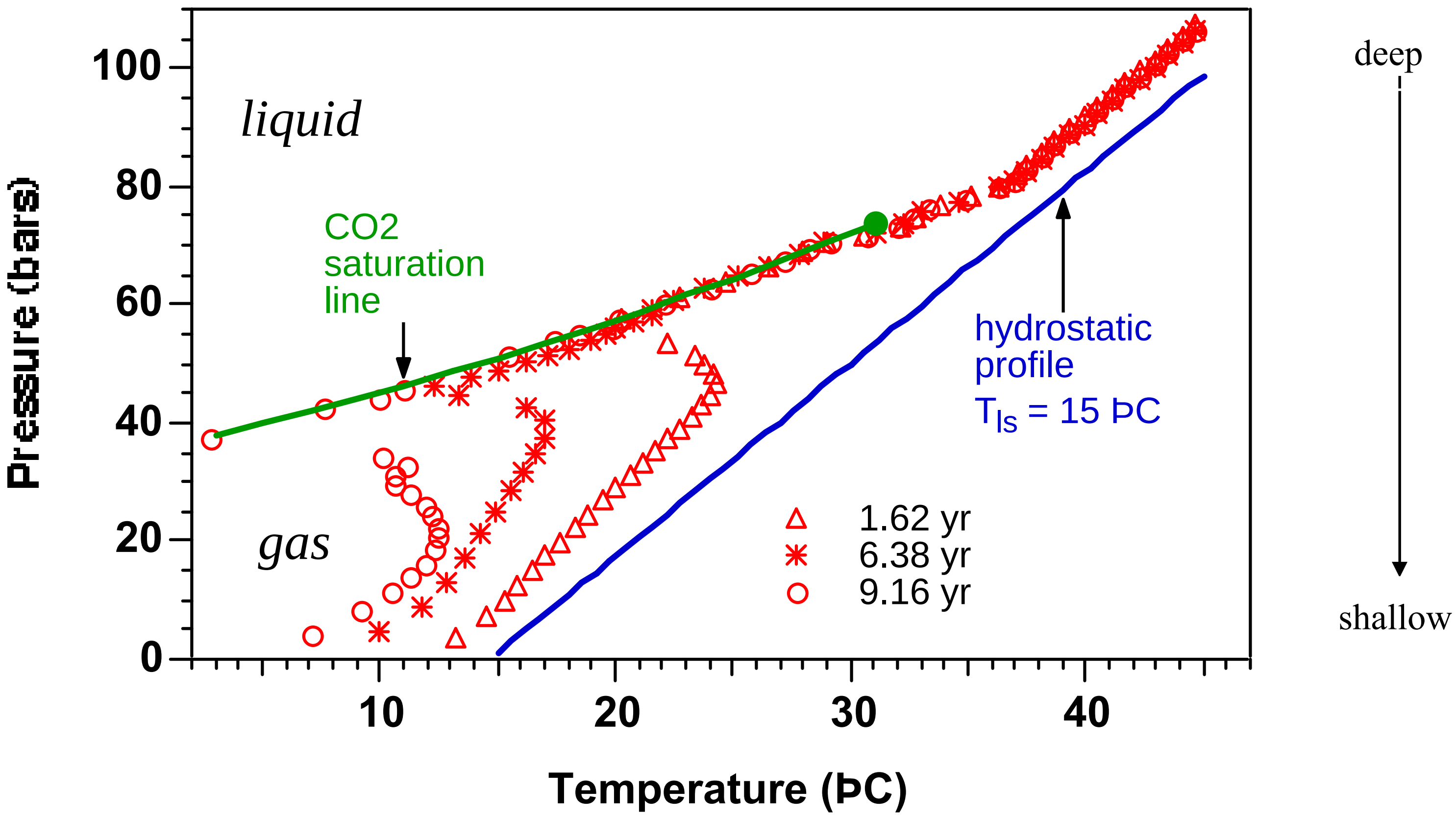
Low Temperatures at Top of 3-phase Zone





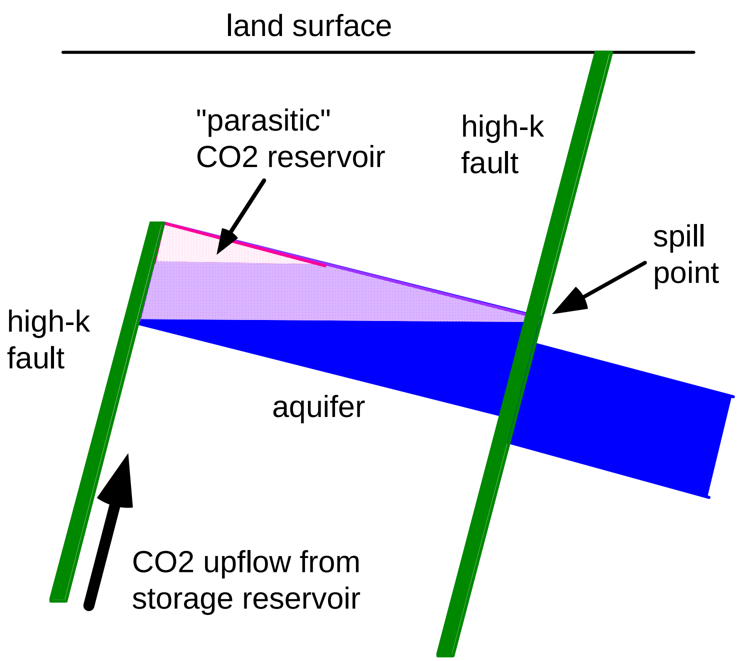
$$S_{liq-gas} = \sqrt{S_{liq} \cdot S_{gas}}$$

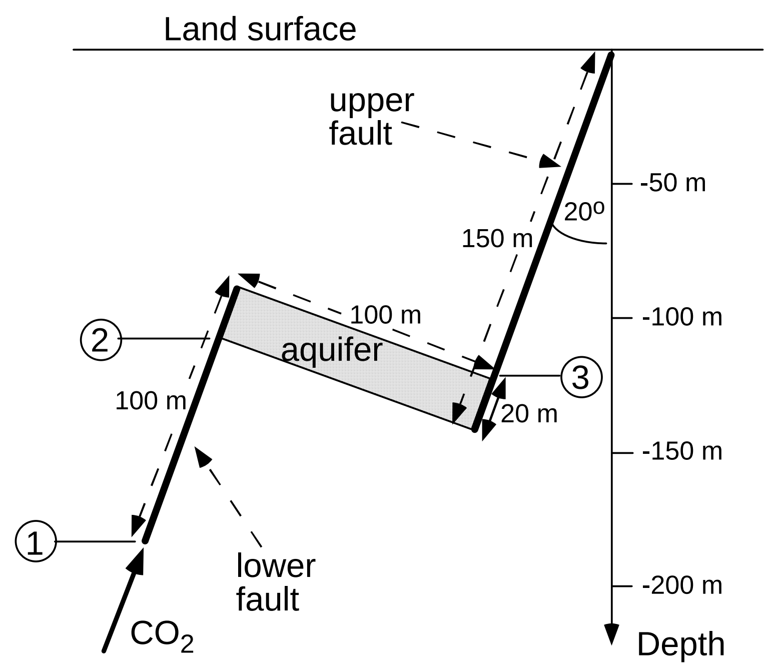
Low Temperatures at Top of 3-phase Zone



Role of Secondary Accumulation at Shallow Depth

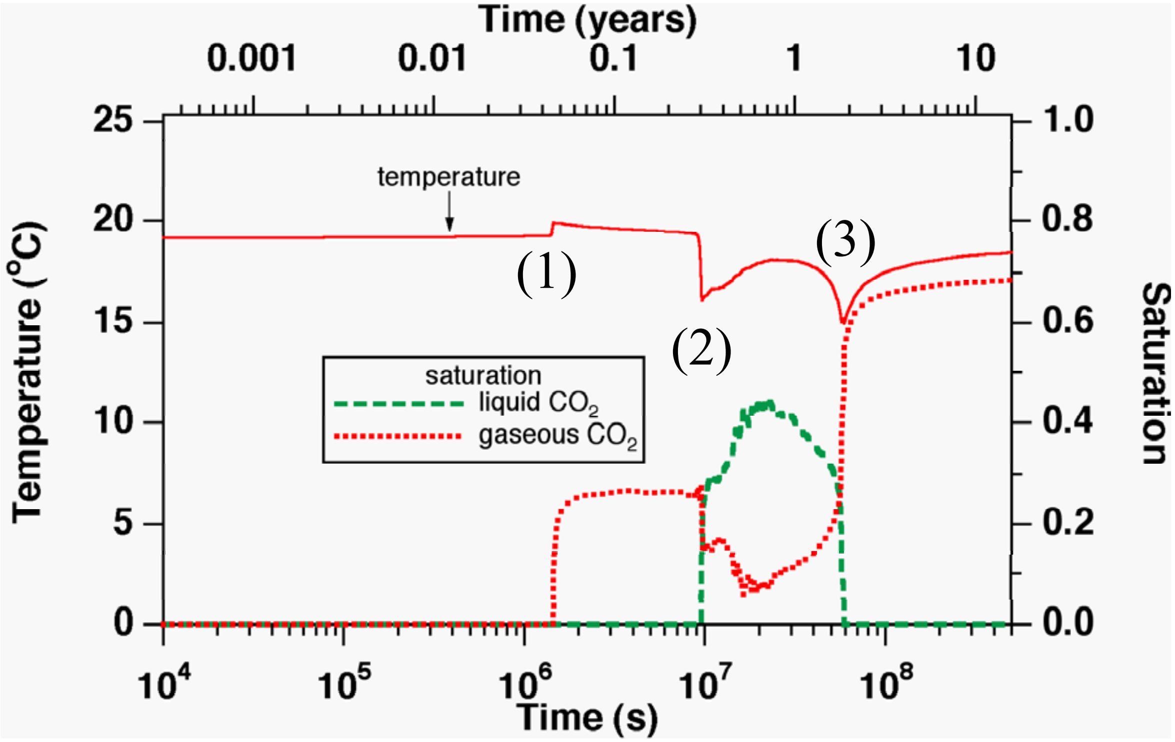
Fault or fracture zones





(Pruess, *IJGGC*, 2008)

Evolution of Temperatures and CO_2 Saturations at Monitoring Point (2)



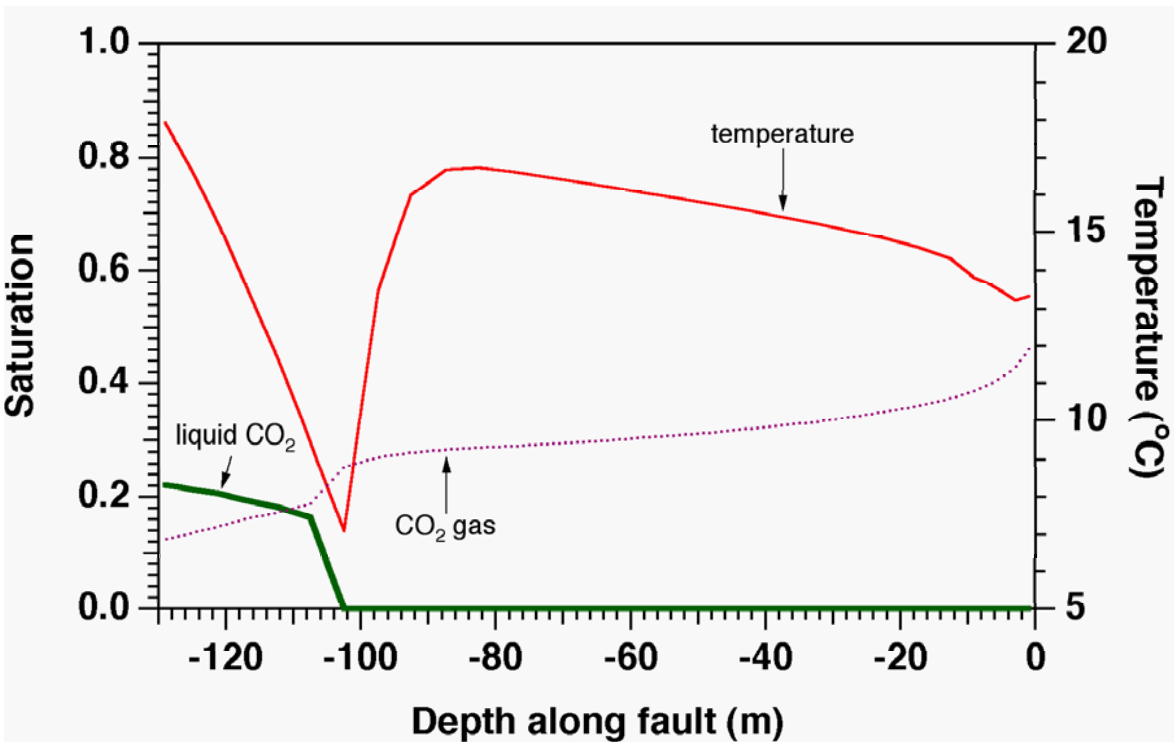
(1) heat-of-dissolution

(2) liquid CO_2 boiling into gas

(2)-(3) $T = T_{sat}(P)$

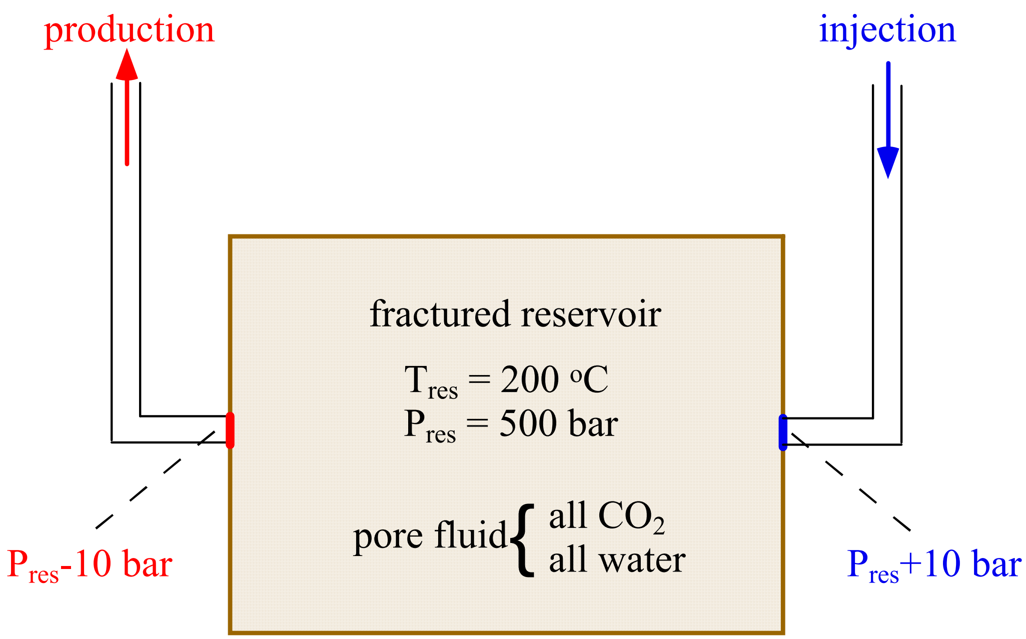
(Pruess, *IJGGC*, 2008)

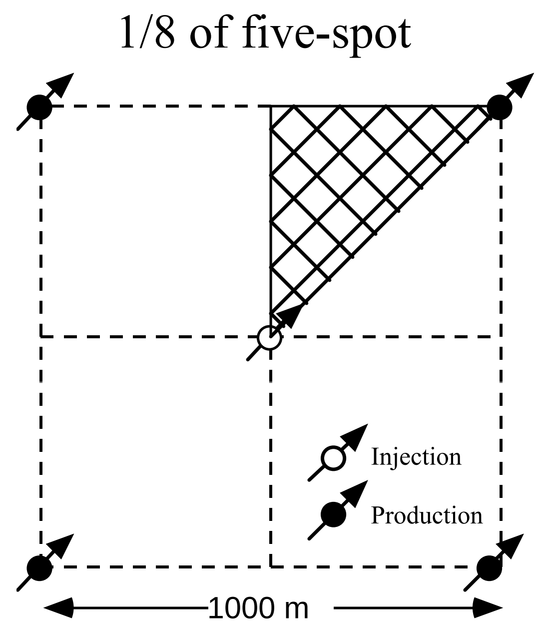
Profile of Temperatures and CO_2 Saturations in Upper Fault after 1.5 yr



(Pruess, *IJGGC,* 2008)

Enhanced Geothermal Systems (EGS): Comparing Operating Fluids CO_2 and Water

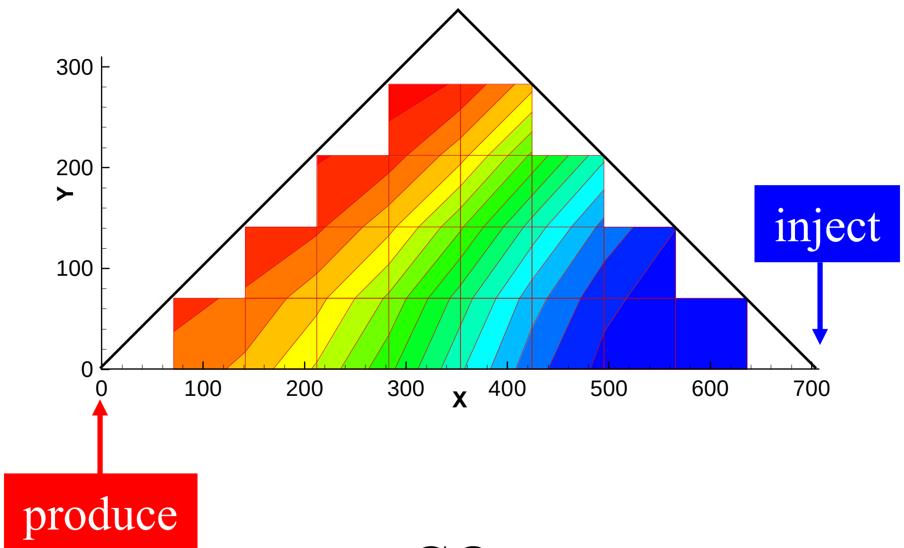




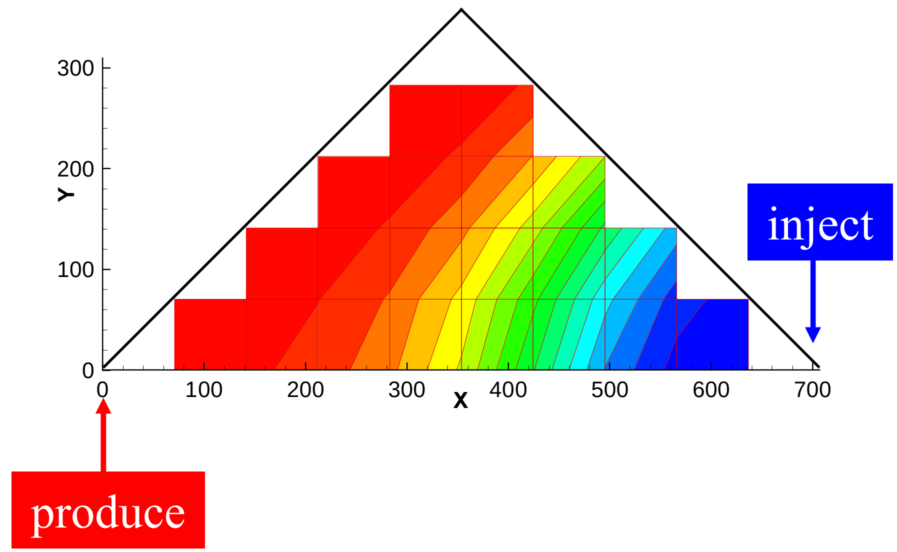
➢ monitor mass flow, heat extraction rates

1/8 of a Five-Spot - Temperatures after 25 Years

T_{res} = 200 °C, P_{res} = 500 bar, T_{inj} = 20 °C



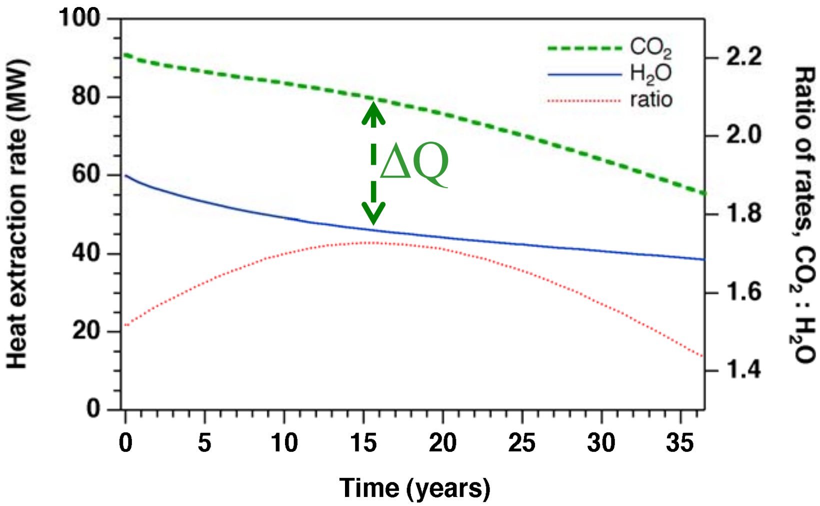
CO_2

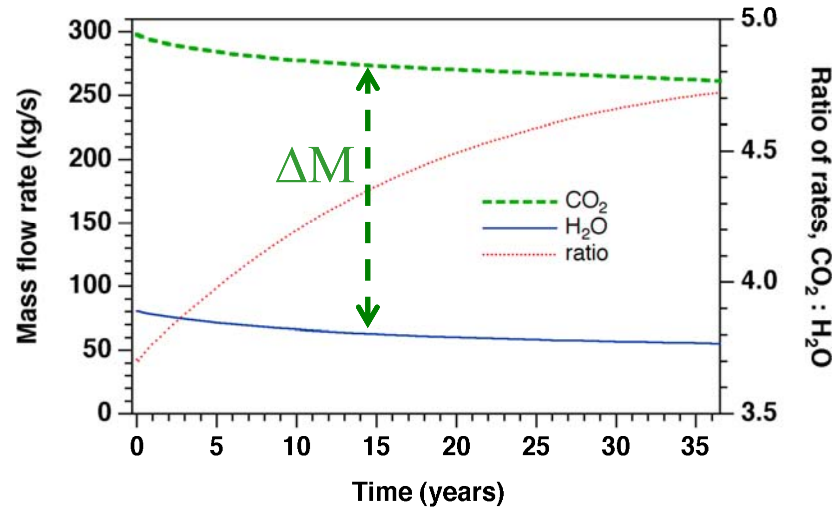


water

Heat and Mass Production

$T_{res} = 200\ ^{\circ}C$, $P_{res} = 500$ bar, $T_{inj} = 20\ ^{\circ}C$





(Pruess, *Geothermics*, August 2006)

Temperature Sensitivities

- Strong temperature dependence of CO_2 density may affect pressure profiles in injection wells.
- Non-isothermal injection may have strong effects on CO_2 density and viscosity.
- Other non-isothermal effects for CO_2 storage tend to be weak (CO_2 dissolving into water, water evaporating into CO_2 stream, fluid-mineral reactions).
- Very strong non-isothermal effects are possible in CO_2 leakage: Joule-Thomson effect; boiling of liquid CO_2.
- Very few published studies address thermal effects.

	Critical Processes & Parameters	Knowledge Gaps
Geological	•Knowing how to extrapolate •Understanding heterogeneity distribution and scale •…But well developed processes and methods from O&G industry, sedimentology etc… •Focus on fluid flow properties	•Rock physics linked to seismic •Regional scale models using reservoir scale tools •Revision of models & •Full suite of several cases
Multi Phase Flow	•Must have good understanding of mixed gases •Salinity and temperature are critical •Skilled res engineer to know how parameters impact results	•Rel perm curve for cap rocks? •3 Phase curves •End point saturation
Geochemistry (RTM)	•Reaction rates, surface areas, kinetics (press temp) •Near well bore in short term •Impacts on Seal integrity & capacity (mineral trapping) in long term	•High uncertainty!! •Data base needed for various temps and Pressure scenarios •Cement chemistry? •Properties of high salinity &high temp reservoirs.

Geomechanic	•Existing and potential Fracturing, •initial state, insitu measurements, regional stress, •rock properties/strength •Being able to upscale core data to field scale •"Full Earth" models into overburden etc…	•Uncertainty in fault properties •COUPLING!! •Costs of core and measurements •Geomechanical effects at the well bore – Damage effects in simulators
Thermics	•Temperature data: Initial uncontaminated measurements •Regional gradients	•Deformation changes resulting from temp changes

CONCLUSIONS FOR ALL:

*All the above rely on "good data" using the "right" data, and skilled operator
To fill the Gaps we need to have data from the field tests and R&D pilots **SHARING**

What are the processes and parameters that are critical to modelling requirements?

- Geological models essential, but choose the appropriate scale
- What should we care for all the scales? What information can we get from all the scales?
- How sensitive large scale plume with respect to different scales?
- How M, C, T effects will modify CO_2 flow?
- Look at processes that can create risks (on my area) and focus on them – e.g. brine migration, wells' integrity, faults
- Look at processes having an effect on fluid migration (CO_2, brine)
- Have a top-down approach, but how we can decide initially what are the more important processes? Start with experts' opinion (objective ranking needed), then simplified models
- Subsurface is highly uncertain, don't be overwhelmed by details
- Oil industry is used to live with high uncertainty, power companies no
- Reach a common agreement on criteria to decide what processes are important
- How to distinguish numerical artefacts from real physics?

What knowledge gaps still exist?

- Upscaling, will be different depending on processes (upscaling geochemistry, upscaling geomechanics..), upscaling across processes
- Communication gaps, (1) among scientists/disciplines, and (2) with regulators & policy makers - how do we communicate with regulators and decision makers, and (3) the public
- The best arguments are not enough, emotional factors too, need for a “front” man or woman
- Gaps between what is occurring in the lab and in the field. How do we get representative experimental data?
- Learn more from natural analogues
- Impurities- depending on type of power plants/industry and capture process
- Analogy with meteorological models and calibration
- Consistency in data (e.g. geochemical databases), lack of data for the relevant P,T, Salinity range
- Cement behaviour, thermodynamic/kinetic data
- Computational limits for coupling processes
- Hydrate formation (in case of leakage or highly depressed reservoir) and impact on pore space properties

Group 3

Process, Characterisation Phase	Risk / Gap	
Single phase fluid flow		
Multi phase fluid flow #	H	H
Miscibility / wettability effects #		
Structural /stratigraphic trapping *	M	
Solubility trapping *	M	H
Mineral trapping *	L	H
Residual gas trapping *	L	H
Reactive transport *	M	H
Diffusion	L	
Fault reactivation * #	H	H
Compaction / contraction / swelling #	M	
Localised deformation – Fractures /faults *	H	H
Heat flow	L	
Wellbore flow #	M	
Density / Buoyancy drive		
Wellbore Integrity / Degradation * #	H	
Desiccation / brine conc. *	M	

Process, Characterisation Phase	Rank / Gap	
Injectivity Change *	M	
PVT Behaviour of variable gas mixtures * #	M	
Abnormal pressure development *	H	H
Atypical geo-thermics * #	L	H
Hydrate dev. *#	L	
Induced seismicity *	H	H
Geo-mechanical processes @ reservoir / pore scale #	M	H

* = CO_2 Specific
# = Oil and Gas related

Group 3

Parameters, Characterisation Phase	Gap
Caprock integrity probing	H
PVT / gas properties / gas mix	H
Relative permeability	H
Connectivity	
Rock permeability	
Porosity	
End point saturations	
Strength / Deformation rock properties	H
Stress state	H
Fault location / characterisation	H
Reservoir heterogeneity (all parameters)	H
Anisotropy	
Thermal gradient	
Pressure gradient	
Capillary pressure	M
Interfacial tension	
Brine chemistry / composition	H
Thermal conductivity	
Seismicity	

Process, Characterisation Phase	Gap
Hydraulic diffusivity	
Seismic properties (velocity)	
Mineralogy	H
Fracture gradient	
Structural stratigraphic distribution	
Geo-chemical reactions	H

Session 3 Breakout

Breakout Group 4

- Geology, conceptual model, scenarios, containment and capacity, trapping mechanisms, integrity
- How do we identify critical issues?
- Analogues – important way to characterise rock mass – connectivity
- Regulator – integrity is No1 parameter
-

- Relative permeability
- Kinetics of reactions
- Maximum allowable pressurisation and footprint
- Compressibility of storage formation?
- Boundary conditions of models – worse case
- Geomechanics – in-situ measurements

- Stress is a key input parameter also pore-elastic properties – know how to do it, but not often done
- Upscaling of mechanical properties a problem
- Caprock petrophysics & mechanical props
- Dual porosity systems – coupling gm and gc
- Can geochem influence injectivity? And long term consequences?

- Geochem – many parameters are uncertain , databases need to be improved
- Long term fault behaviour wrt coupled processes
- Lab test discrepancy with field data e.g. Well cements
- Need for learning from injection projects
- Availability of data from projects

Processes	Geology				
Characterisation	Conceptual model, scenario building				
Injection					
Post Injection					

Numerical Investigation of CO_2 Sequestration in Geologic Formations - Problem Oriented Benchmarks

Holger Class, Anozie Ebigbo, Rainer Helmig, Andreas Kopp, Melanie Darcis, Bernd Flemisch

Universität Stuttgart

Orleans, Feb.11, 2009

GEOTECHNOLOGIEN

Aims and Overview of the Study

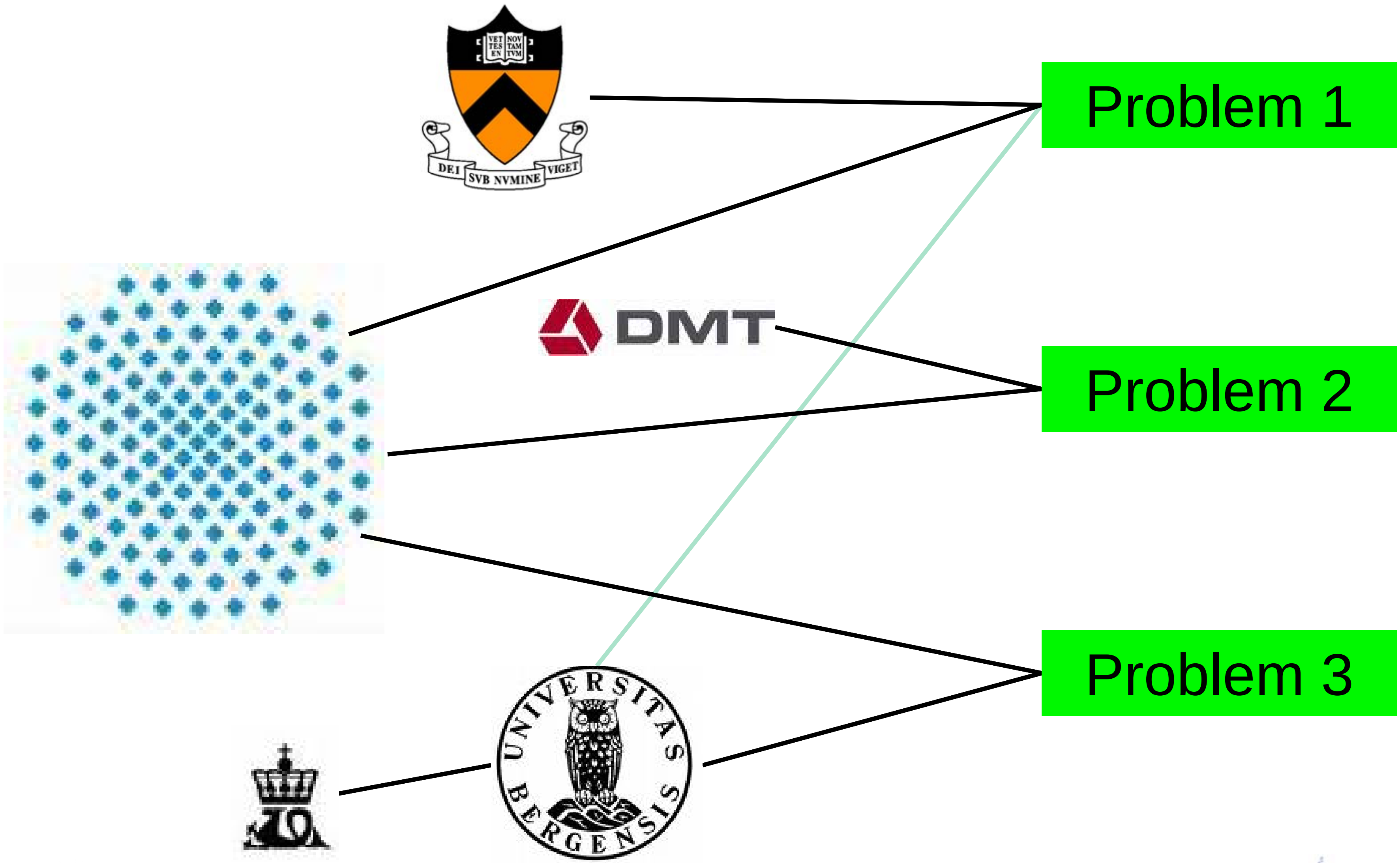
Formulation of problem-oriented benchmarks for mathematical and numerical models and simulators

- to improve the understanding of the complex coupled processes taking place during and after injection of CO2 in geological formations,
- to explore the accuracy and reliability of model predictions.

3 Benchmark problems, covering:

- Injection into saline formations including leakage through a leaky well and large-scale computation in a heterogeneous formation.
- Injection into a gas reservoir (EGR scenario).
- 3D, reservoir-scale problems.
- Non-isothermal and multiphase multi-component processes included.

Groups Contributing to Problem Definitions



Workshop on Numerical Models for Carbon Dioxide Storage in Geological Formations

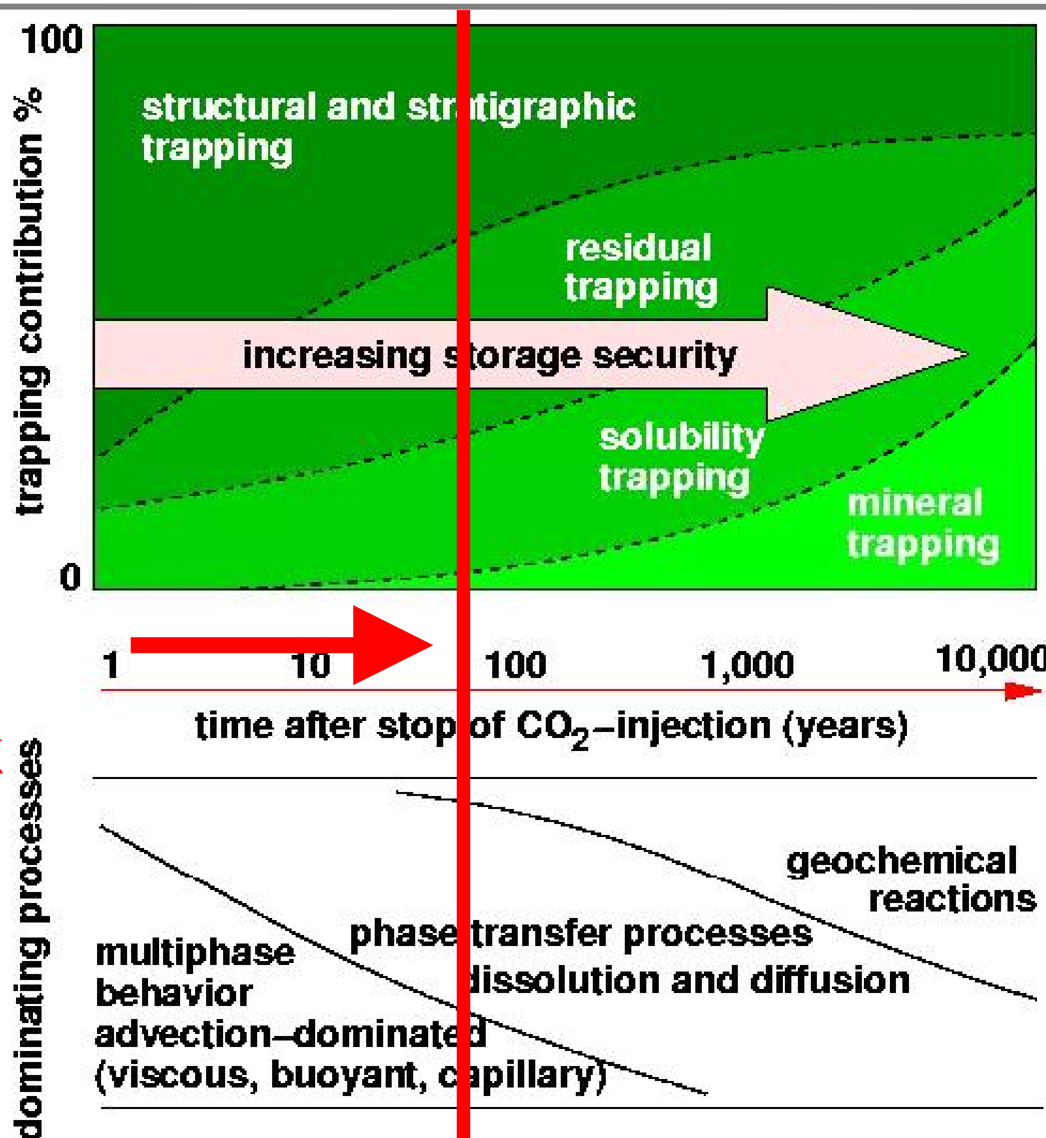
Stuttgart, 2nd - 4th April, 2008

Full description of the benchmark problems available under:

http://www.iws.uni-stuttgart.de/co2-workshop

Universität Stuttgart Institut für Wasserbau, Lehrstuhl für Hydromechanik und Hydrosystemmodellierung

Trapping Mechanisms & Time-Scales



Time-scale of the benchmark problems

modified after IPCC 2006

List of Participants

Name(s)	Institution	Country
M. Jin, G. Pickup, E. Mackay	Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh	Scotland
S.G. Thomas, M. Delshad, M.F. Wheeler	Institute for Computational Engineering and Sciences, University of Texas, Austin	USA
L. Trenty, A. Fornel, C. Kada Kloucha, Y. Le Gallo	Technology, Computer Science and Applied Mathematics Division, Institut Français du Pétrole, Rueil-Malmaison	France
S.E. Gasda, J.M. Nordbotten, M.A. Celia	Department of Civil and Environmental Engineering, Princeton University	USA
J.M. Nordbotten, M.A. Celia, S. Bachu, H.K. Dahle	Department of Mathematics, University of Bergen; Department of Civil and Environmental Engineering, Princeton University; Alberta Geological Survey, Alberta Energy und Utilities Board, Edmonton	Norway, USA, Canada

List of Participants

Name(s)	Institution	Country
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M.A. Sbai, P. Audigane	French Geological Survey (BRGM), Water Department, Orléans	France
A. Naderi Beni	Applied Geophysics and Geothermal Energy, E.ON Energy Research Center, RWTH Aachen	Germany
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List of Participants

Name(s)	Institution	Country
J. Ennis-King	CRC Greenhouse Gas Technologies, CSIRO	Australia
Lingli Wei	Shell, Rijswijk	Nether-lands
D. Labregere, S. Hurter	Schlumberger Carbon Services	France

List of Mathematical/Numerical Models

Code	Acronym
ECLIPSE 300 simulation package	ECLIPSE (Heriot-Watt, Schlumberger)
Integrated Parallel Accurate Reservoir Simulation	IPARS-CO2 (Uni Texas/Austin)
CO_2 Reservoir Environmental Simulator	COORES (IFP)
Vertical-Averaged Numerical Model for CO_2 Injection into deep, saline formations	VESA (Princeton Uni)
Semi-Analytical Solution for CO_2 Plume Evolution During Injection	ELSA (Uni Bergen/Princeton Uni)
Finite Element Heat and Mass Transfer Code	FEHM (Los Alamos NL)
General Purpose Research Simulator	GPRS (Stanford Uni)
Multiphase Flow, Transport and Energy Model	MUFTE (Uni Stuttgart)
Reactive Transport and Fluid Flow	RTAFF2 (BRGM)

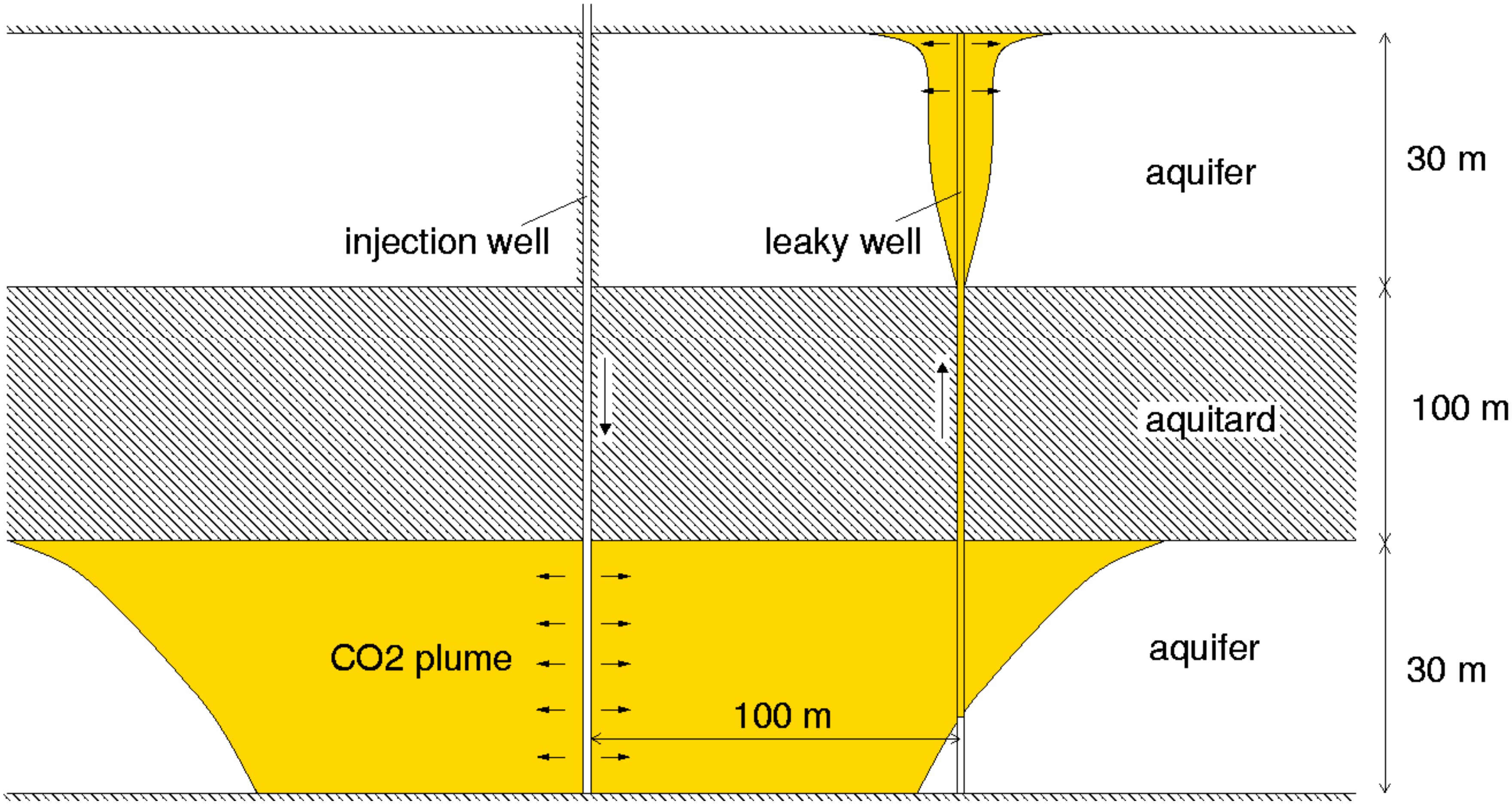
List of Mathematical/Numerical Models

Code	Acronym
DUNE for Multi-(physics, phase, component, scale) Flow in Porous Media	DuMu^x (Uni Stuttgart)
Flow, Heat and Mass Transport in Fractured Porous Media	RockFlow (BGR)
Transport of Unsaturated Groundwater and Heat	TOUGH2 (RWTH Aachen, CSIRO, BRGM)
Shell in-house reservoir simulator	MoReS (Shell)
Generalized Equation-of-state Model compositional reservoir simulator	GEM (Heriott-Watt)

Problem 1

- *Title:* CO_2 plume evolution and leakage through an abandoned well
- *Authors:* A. Ebigbo[1], J.M. Nordbotten[2], H. Class[1]
  - [1] Dept. of Hydromechanics and Modelling of Hydrosystems, Universität Stuttgart
  - [2] Dept. of Applied Mathematics, University of Bergen
- *Problem description:*
  - CO_2 injection into an aquifer which is penetrated by a leaky well
  - Leakage occurring through well up to a higher aquifer
  - Two variations with different depths and assumptions
- *Ebigbo, Class, Helmig: Computational Geosciences (2006)*

Problem 1



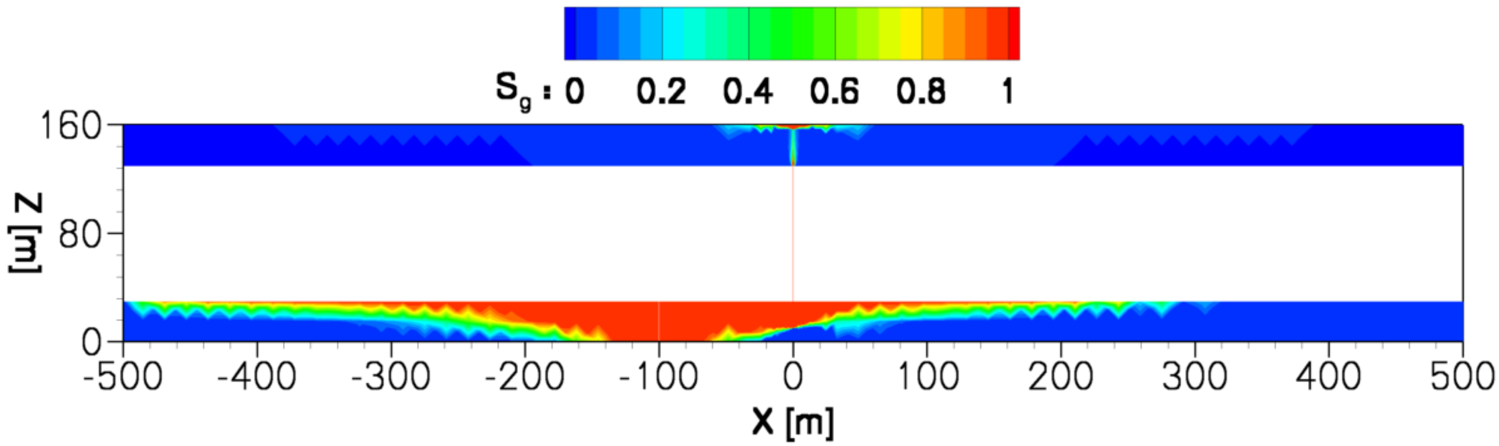
Leakage scenario as described in *J.M. Nordbotten et al., 2005*

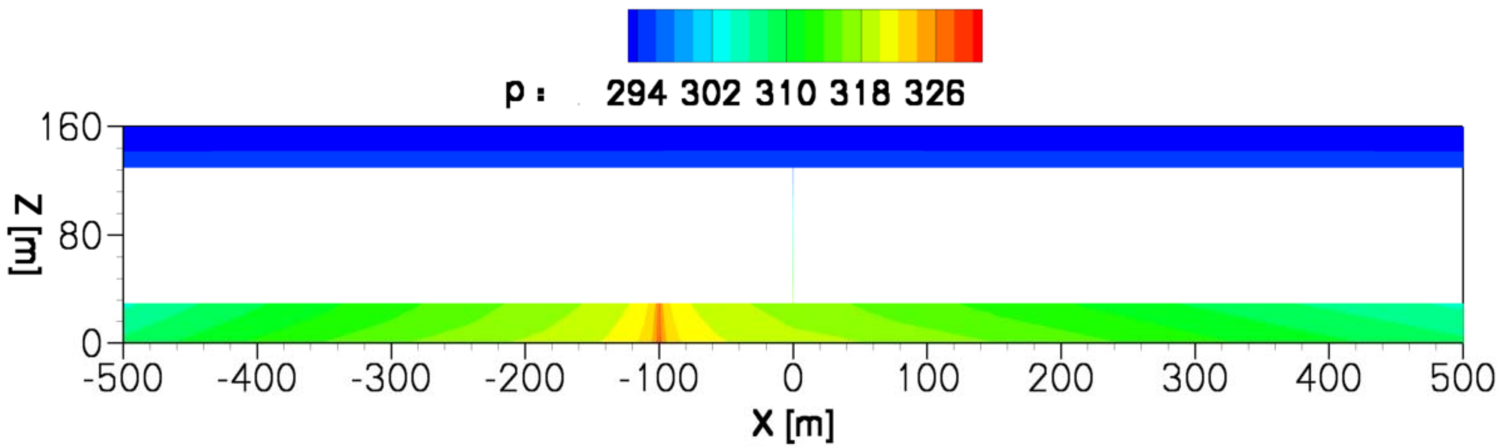
Problem 1: Description

Domain dimensions	1000 m x 1000 m x 160 m	
Injection rate	8.87 kg/s	
Porosity	0.15	
Permeabilities	Aquifer	20 mD
	Leaky well	1000 mD
	Problem 1.1	Problem 1.2
Depth	2840 m - 3000 m	640 m - 800 m
Fluid properties	constant	variable
Relative permeabilities	linear	non-linear
Residual saturations	no	yes
Capillary pressure	no	yes

Problem 1.1: Simulation (t = 80 days)

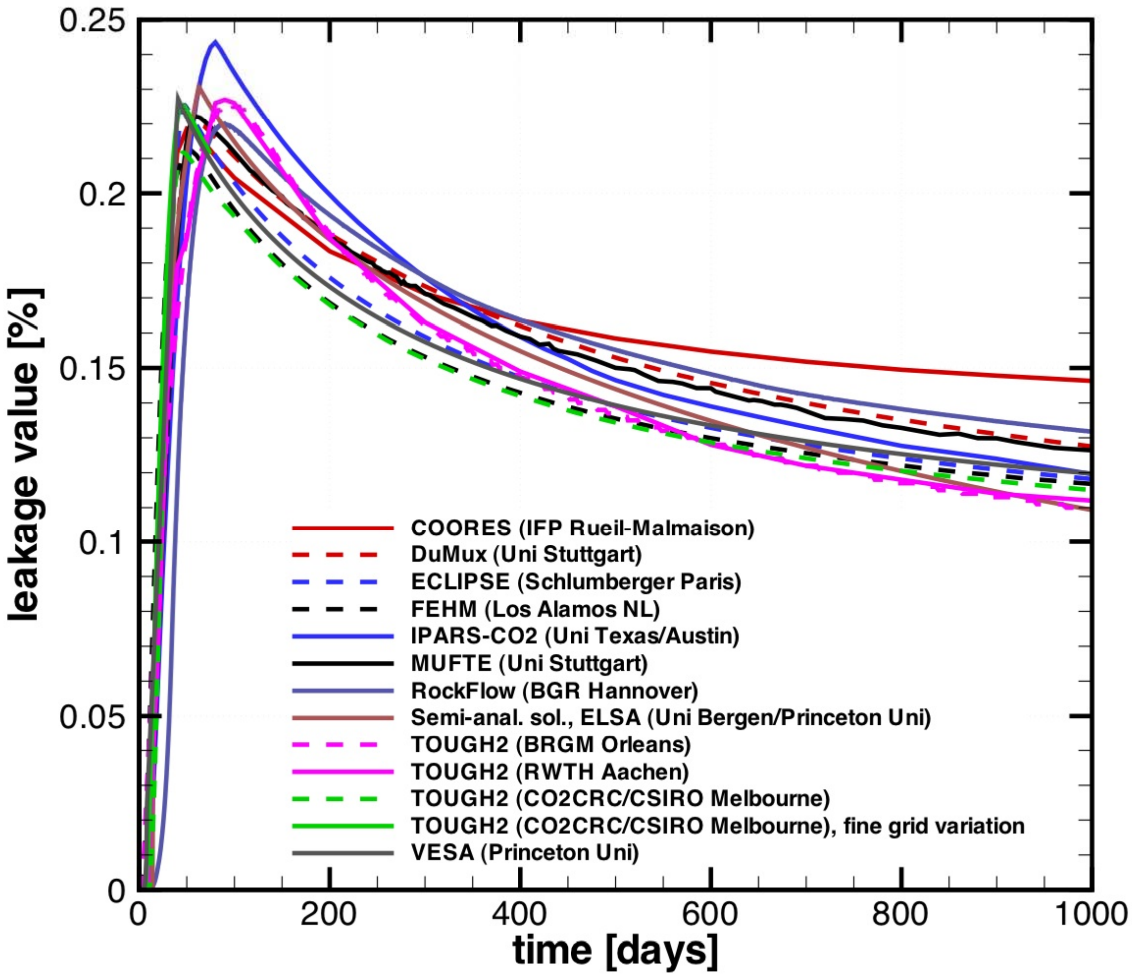
Saturation





Pressure [bar]

Problem 1.1: Comparison



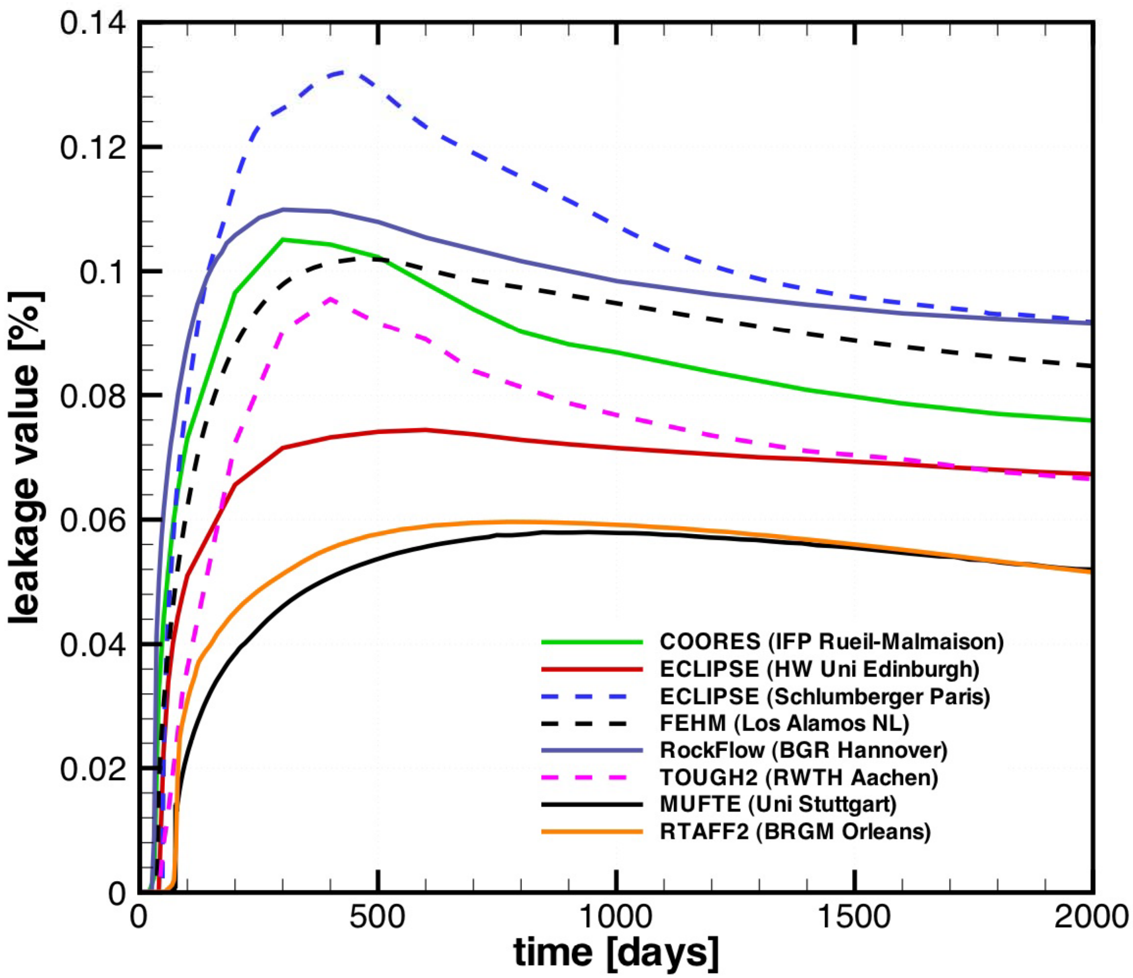
Problem 1.1: Comparison

Code	Max. leakage [%]	Time at max. leakage [days]	Leakage at 1000 days [%]	Arrival time [days]
ELSA (Uni Bergen/Princeton Uni)	0.231	63	0.109	14
MUFTE (Uni Stuttgart)	0.222	58	0.126	8
IPARS-CO2 (Uni Texas/Austin)	0.243	80	0.120	10
COORES (IFP)	0.219	50	0.146	8
TOUGH2 (RWTH Aachen)	0.227	89	0.112	9
RockFlow (BGR)	0.220	74	0.132	19
FEHM (Los Alamos NL)	0.216	53	0.119	4

Problem 1.1: Comparison

Code	Max. leakage [%]	Time at max. leakage [days]	Leakage at 1000 days [%]	Arrival time [days]
DuMux (Uni Stuttgart)	0.220	61	0.128	6
ECLIPSE (Schlumberger)	0.225	48	0.118	8
TOUGH2/ECO2N (BRGM	0.226	93	0.110	4
TOUGH2/ECO2N (refined grid)	0.212 0.225	46 45	0.115 -	10 8
VESA (Princeton Uni)	0.227	41	0.120	7

Problem 1.2: Comparison



Remember:

Changes compared to Problem 1.1

- Shallower depth, 640 – 800m
- Variable fluid properties
- With capillary pressure
- Nonlinear relative permeabilities

Problem 1.2: Comparison

Code	Max. leakage [%]	Time at max. leakage [days]	Leakage at 2000 days [%]	Arrival time [days]	ΔT at z=670m [K]
RTAFF2 (BRGM)	0.060	776	0.052	74	1.87
MUFTE (Uni Stuttgart)	0.058	941	0.052	75	1.91
FEHM (Los Alamos NL)	0.102	471	0.085	37	1.20
COORES (IFP)	0.105	300	0.076	31	Isothermal
ECLIPSE (Heriot-Watt)	0.074	600	0.067	42	isothermal
RockFlow (BGR)	0.11	279	0.09	30	isothermal

Problem 1.2: Comparison

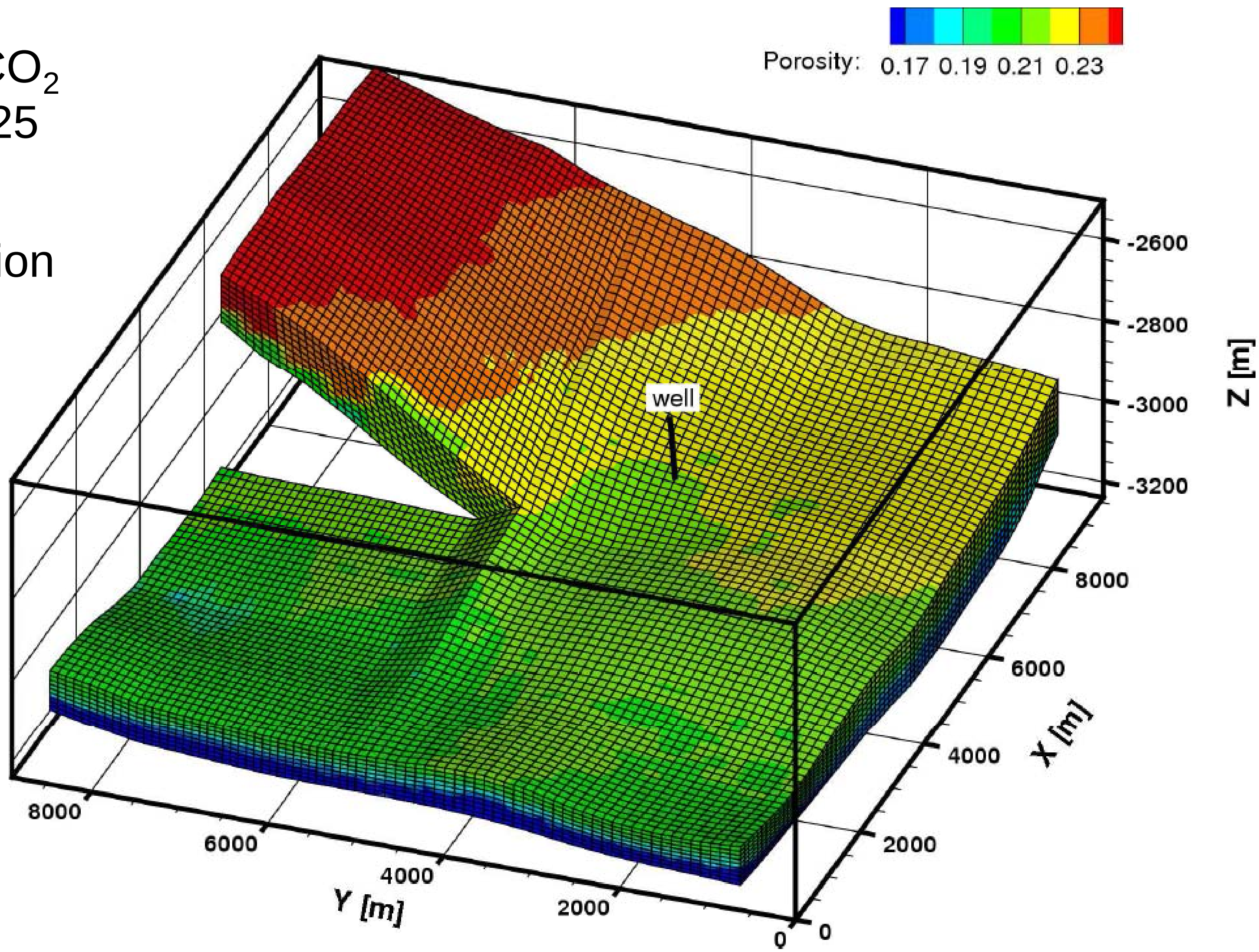
Code	Max. leakage [%]	Time at max. leakage [days]	Leakage at 2000 days [%]	Arrival time [days]	ΔT at z=670m [K]
ECLIPSE (Schlumberger)	0.132	437	0.092	48	Isothermal
TOUGH2 (RWTH Aachen)	0.096	400	0.067	46	Isothermal

Problem 3

- *Title:* Estimation of the CO_2 storage capacity of a geological formation
- *Authors:* H. Class[1], H. Dahle[2], F. Riis[3], A. Ebigbo[1], G. Eigestad[2]
  - [1] Dept. of Hydromechanics and Modelling of Hydrosystems, Universität Stuttgart
  - [2] Dept. of Applied Mathematics, University of Bergen
  - [3] Norwegian Petroleum Directorate
- Geological data based on a study of the Johansen formation by the Norwegian Petroleum Directorate

Problem 3: Set-up

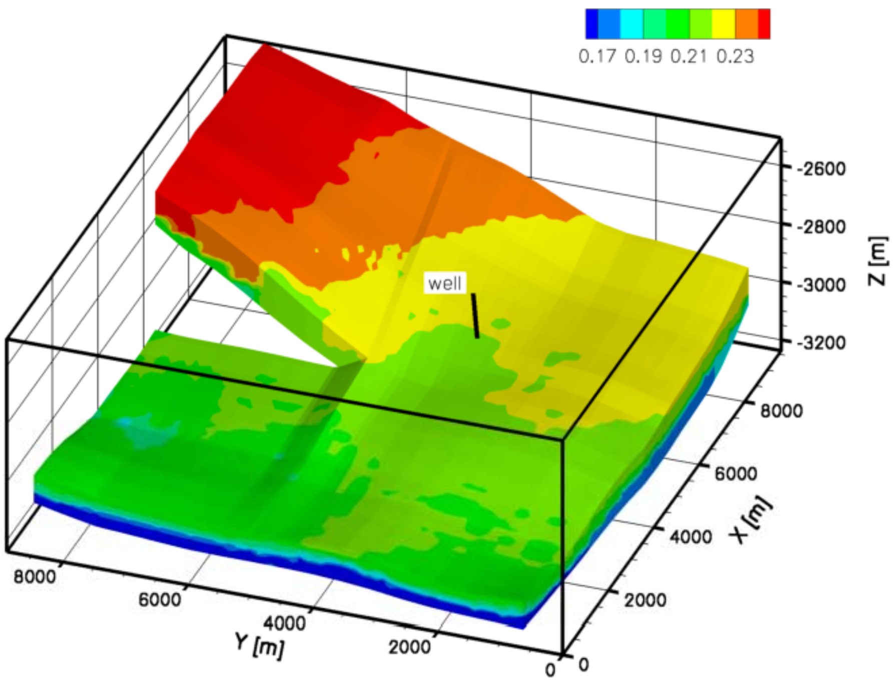
- Injection of CO_2 at 15 kg/s for 25 years
- Total simulation time: 50 years
- Storage capacity and mechanisms
- Effects of hysteresis

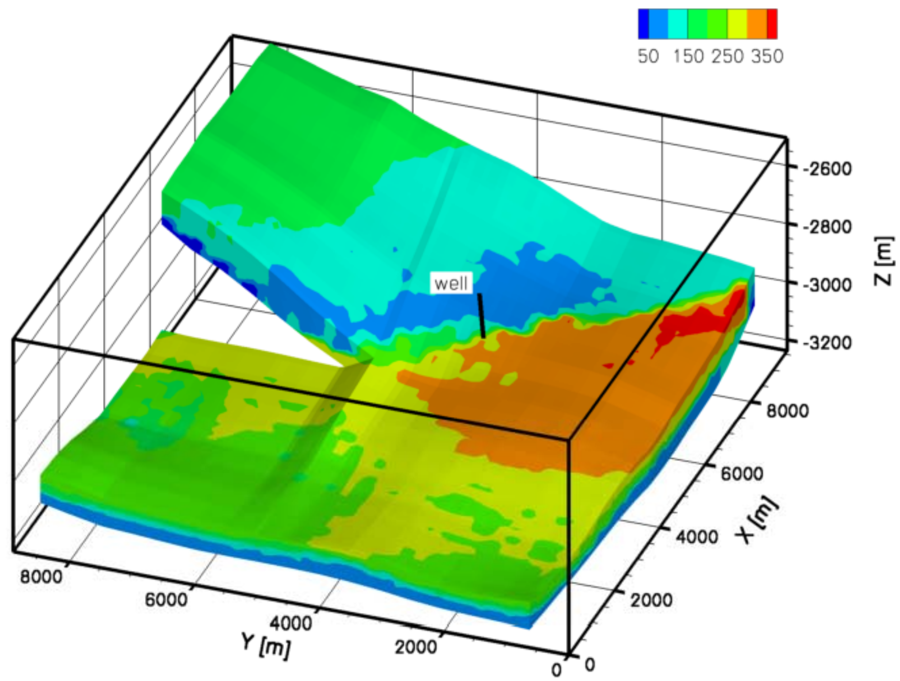


Problem 3

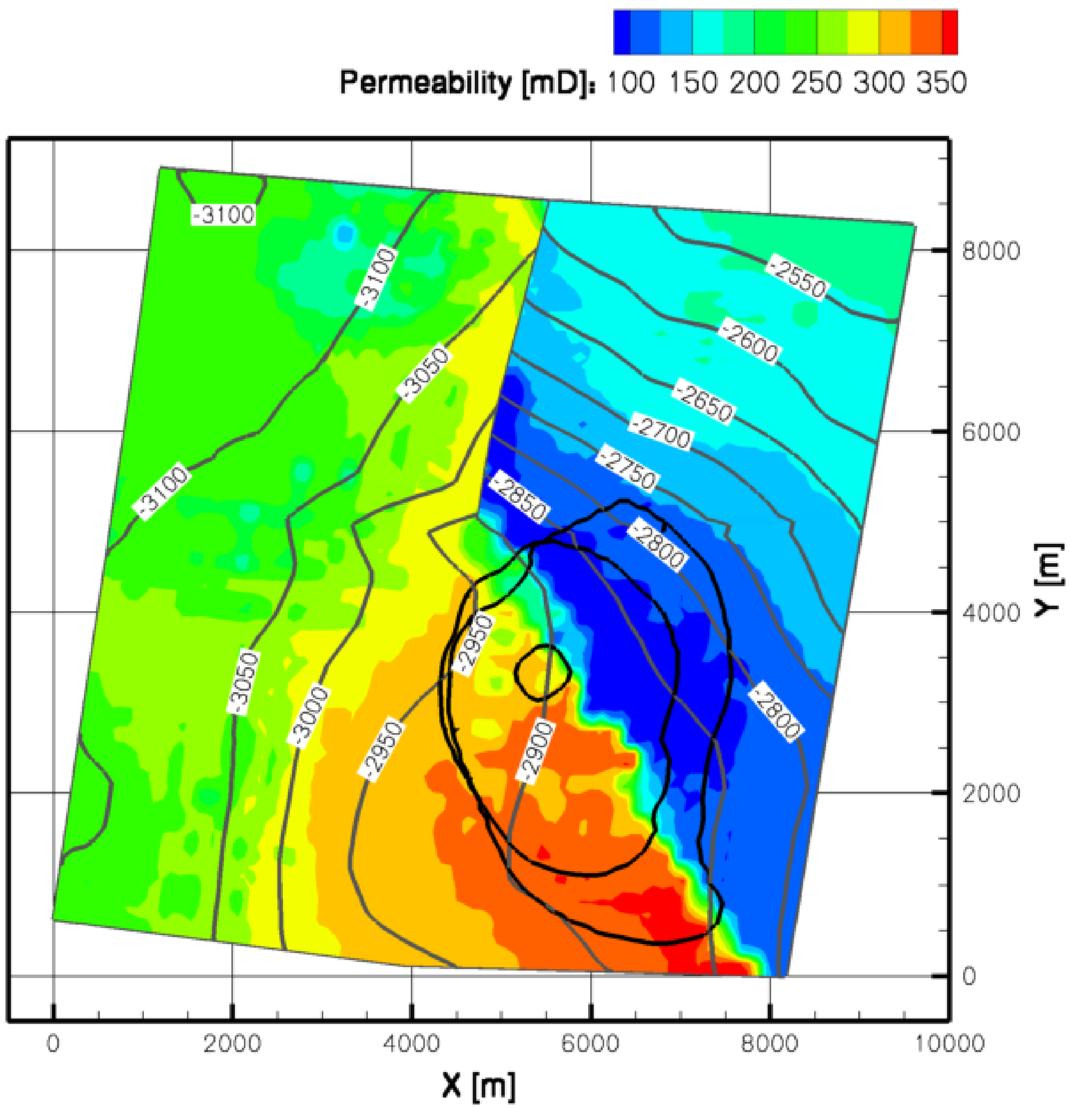
Porosity

Permeability [mD]

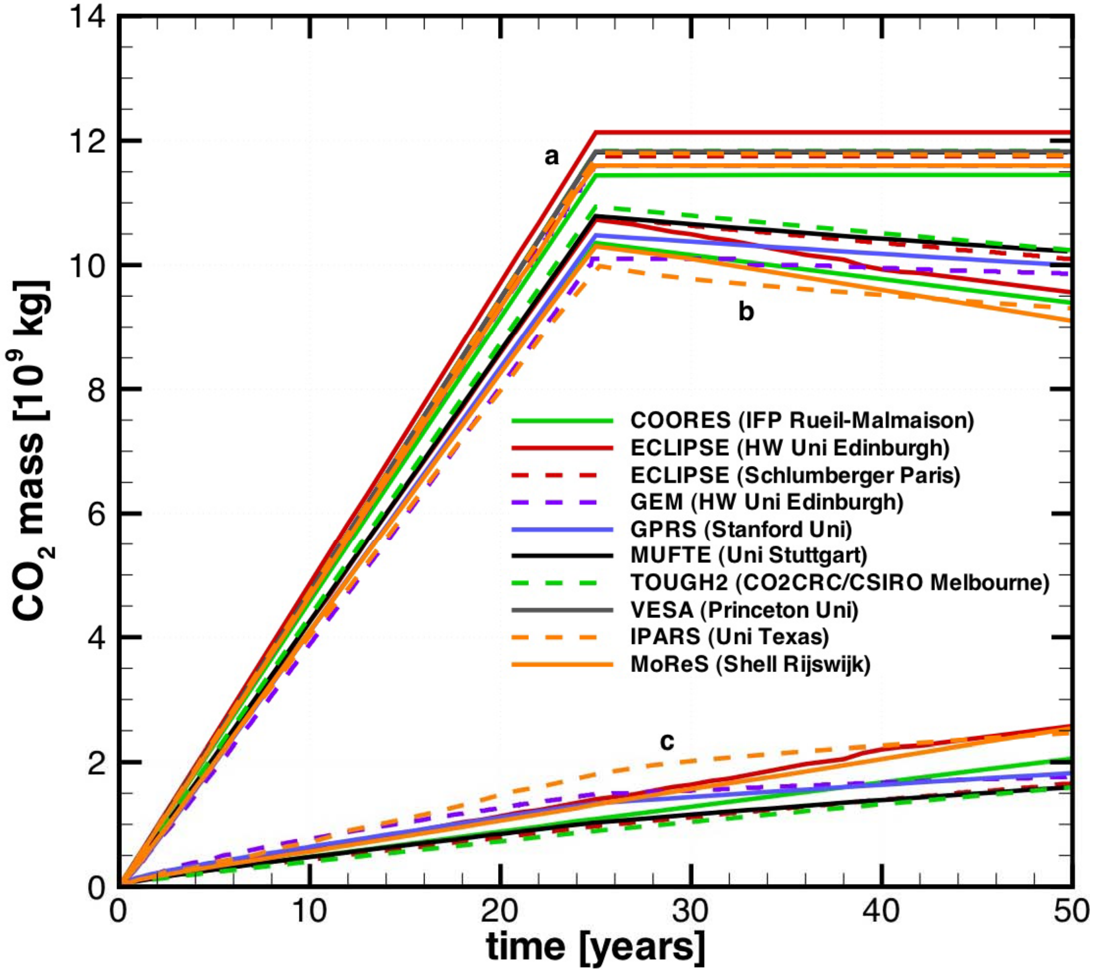




Problem 3.1: Simulations (t = 1, 25 and 50 yrs)



Problem 3.1: Mass Distribution



a:
Total injected mass of CO2

b:
Mass of CO2 in gas phase

c:
Mass of CO2 dissolved in brine phase

Problem 3.1: Mass Distribution (cont'd)

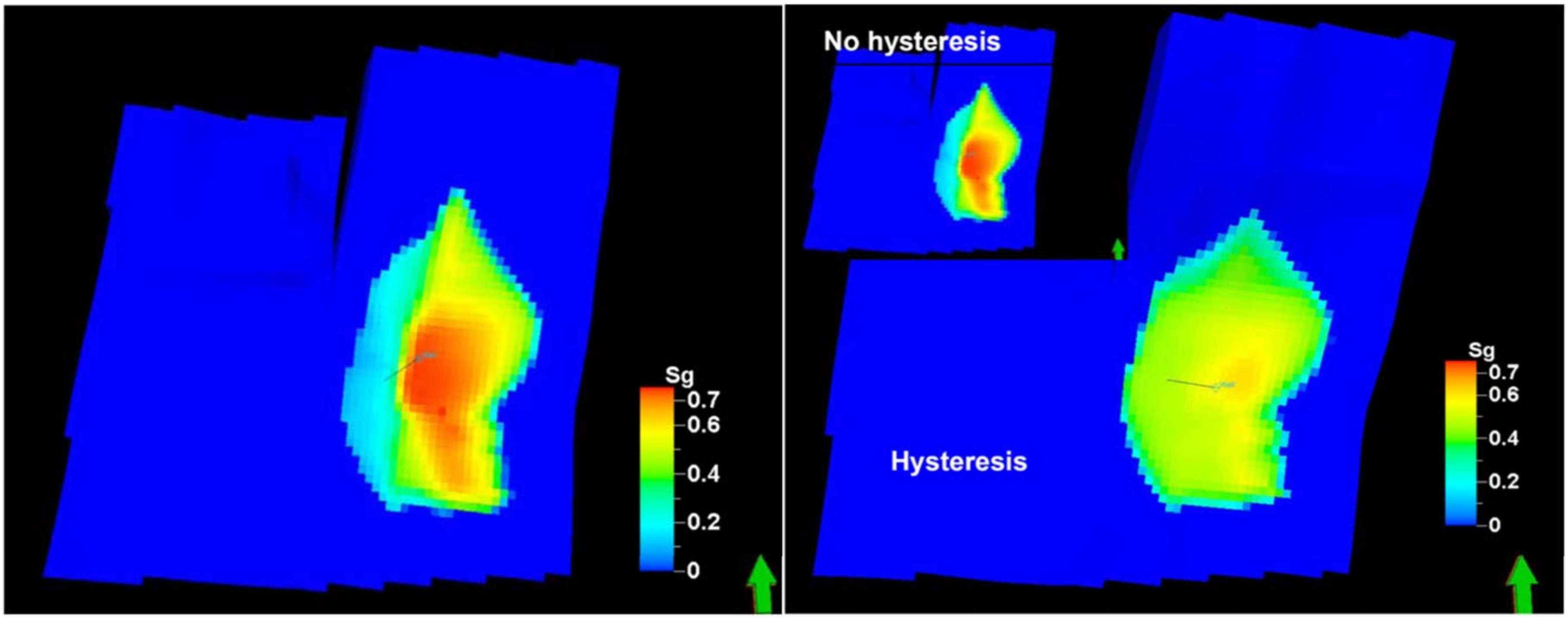
Code	CO_2 in phase at t=50 yrs [% of total stored mass]	CO_2 in brine at t=50 yrs [% of total stored mass]
COORES (IFP)	82.0	18.0
ECLIPSE (Heriot-Watt)	78.8	21.2
VESA (Princeton Uni)	100.0	-
MUFTE (Uni Stuttgart)	86.5	13.5
GPRS (Stanford Uni)	84.6	15.4

Problem 3.1: Mass Distribution (cont'd)

Code	CO_2 in phase at t=50 yrs [% of total stored mass]	CO_2 in brine at t=50 yrs [% of total stored mass]
GEM (Heriot-Watt)	84.8	15.2
ECLIPSE (Schlumberger)	85.9	14.1
IPARS (Uni Texas)	79.1	20.9
MoReS (Shell)	78.4	21.6
TOUGH2/ECO2N (CO2CRC/CSIRO)	86.5	13.5

Problem 3: ECLIPSE (Schlumberger)

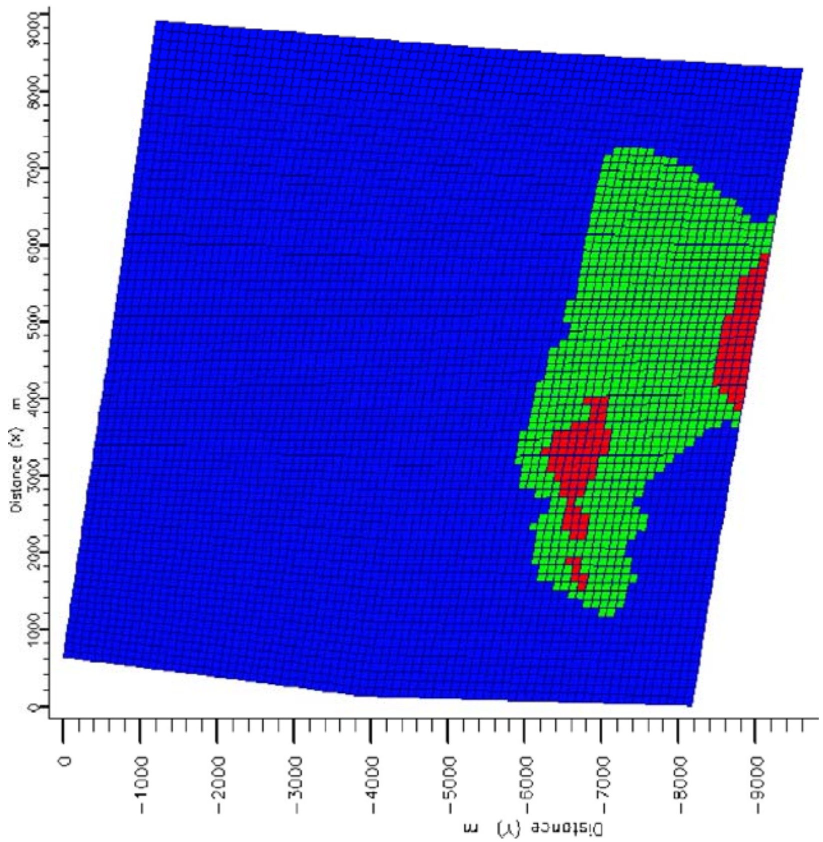
Problem 3.1 | Problem 3.2



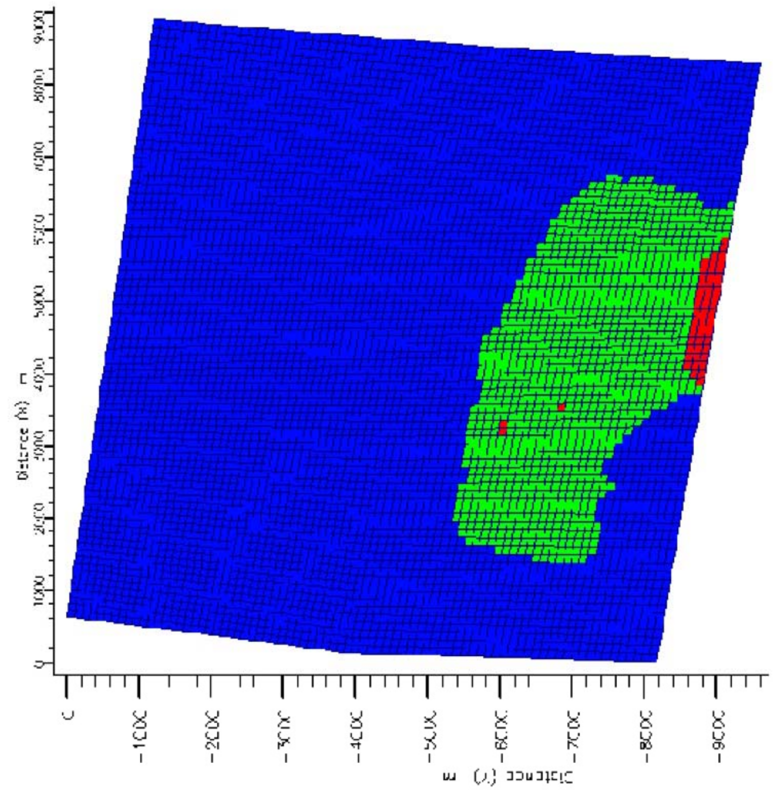
50 years

Problem 3: ECLIPSE (Heriot-Watt)

Problem 3.1



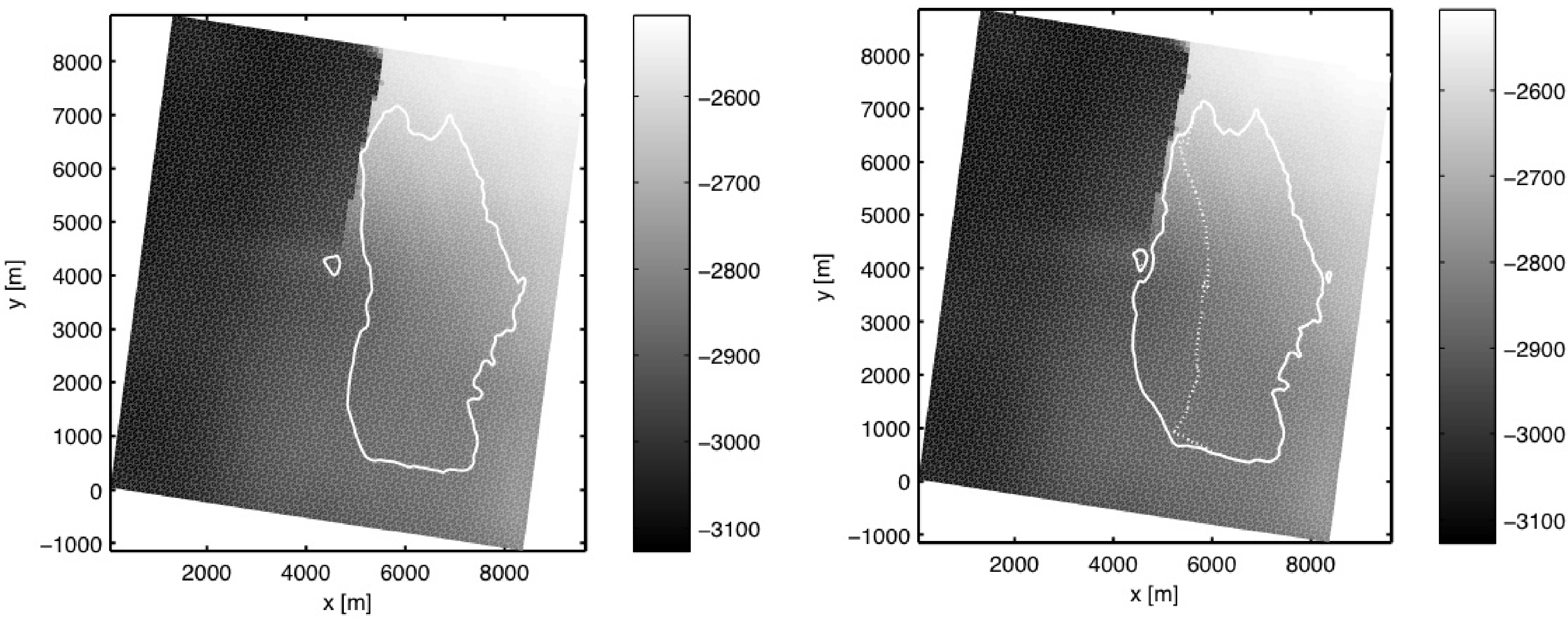
Problem 3.2



50 years

Problem 3: VESA (Princeton Uni)

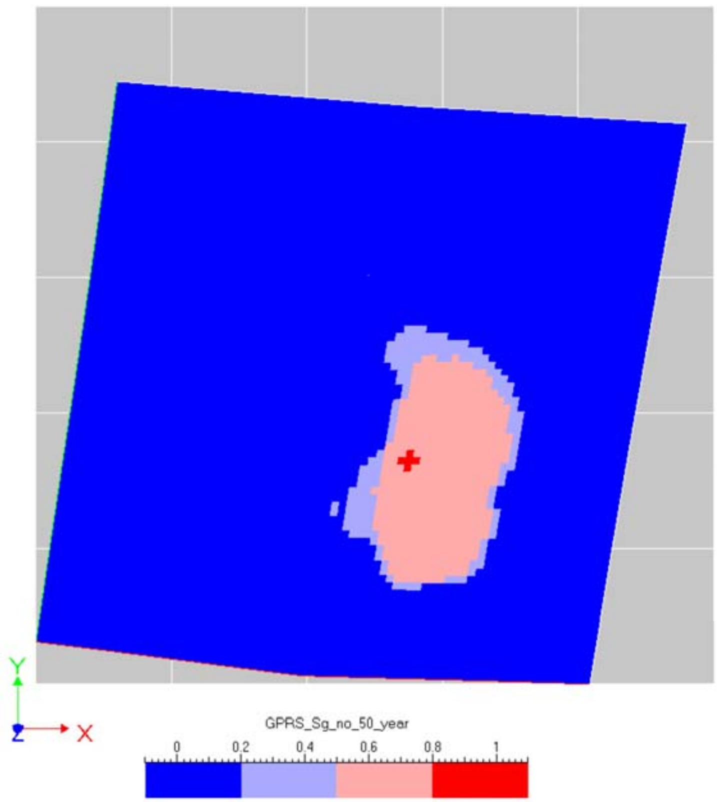
Problem 3.1 | Problem 3.2



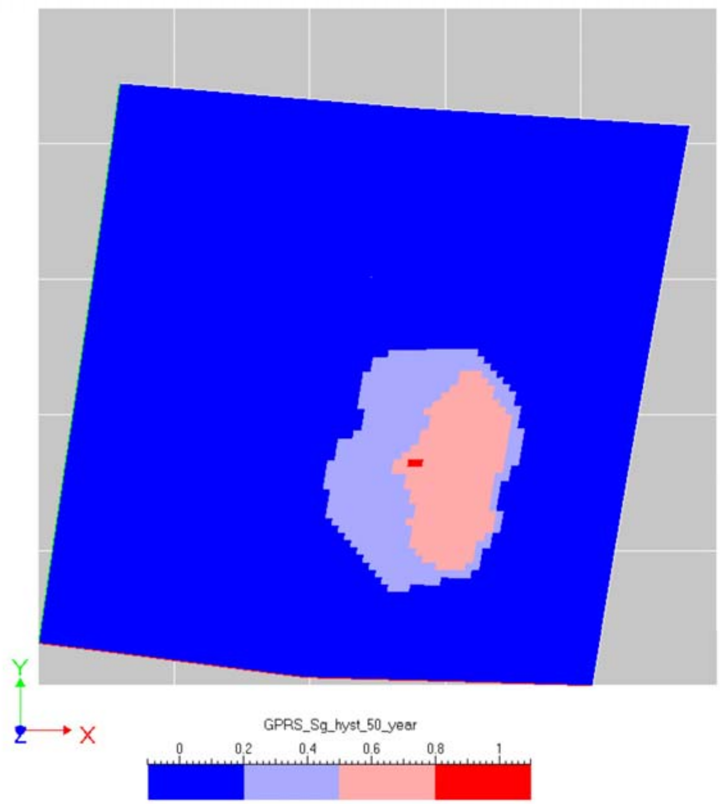
50 years

Problem 3: GPRS (Stanford Uni)

Problem 3.1



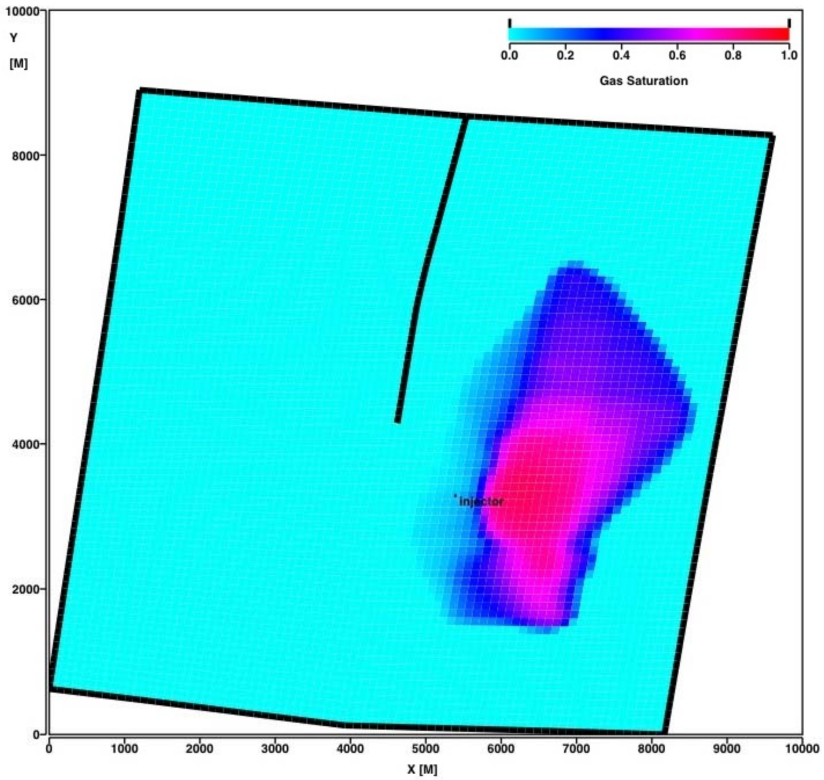
Problem 3.2



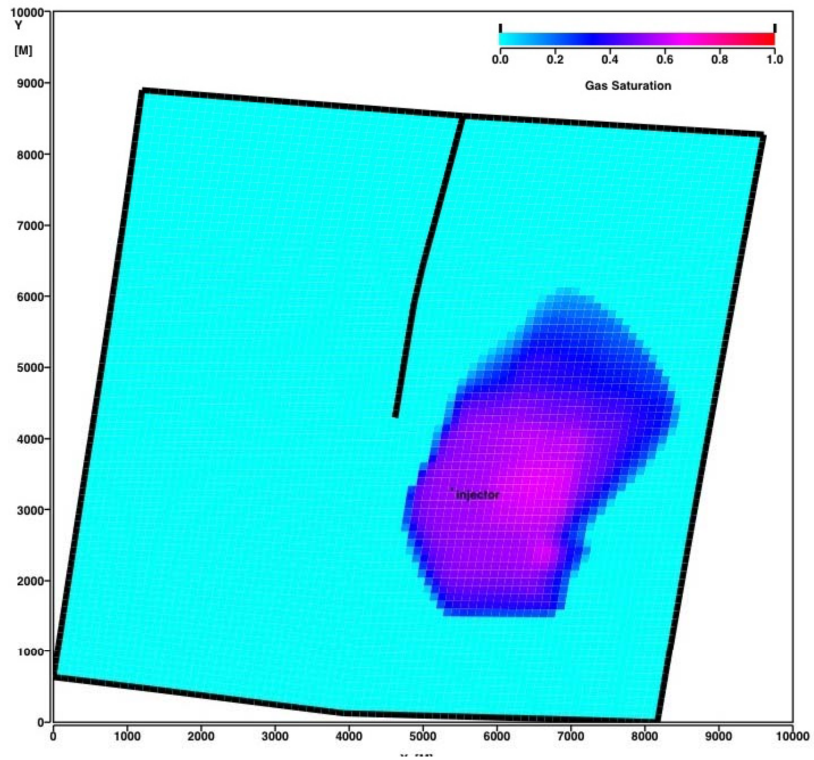
50 years

Problem 3: MoReS (Shell)

Problem 3.1



Problem 3.2



50 years

Summary and Conclusions

- Fairly good agreement of model predictions in all cases
  - Available models capable of accounting for relevant processes, parameters, and properties with only minor quantitative deviations
  - Uncertainties arising from geological input data are in general much larger than differences between simulation codes
  - **BUT**: in parts strongly deviating results in the preliminary comparison at the benchmarks workshop in April 2008
    - Errors introduced by gridding
    - Wrong parameters, oversights
    - Different interpretations of problems leading, for example, to a different assignment of boundary conditions

Summary and Conclusions

- Quality control and assessment is of highest importance and code intercomparison is useful to detect user-induced errors
- Benchmark problem 3 revealed that once realistic heterogeneities and uncertainties are introduced, the model predictions diverge
- Numerical performance of participating simulators is very different!
- The process of formulating benchmark problems and evaluating/comparing results is a delicate issue, in particular explaining WHY certain deviations occur

Special Issue of ***Computational Geosciences***

Numerical Models for Carbon-Dioxide Storage in Geologic Formations

Editors: Rainer Helmig, Helge Dahle, Holger Class

including

Class H, Ebigbo A, Helmig R, Dahle H, Nordbotten JM, Celia MA, Audigane P, Darcis M, Ennis-King J, Fan Y, Flemisch B, Gasda S, Jin M, Krug S, Labregere D, Naderi A, Pawar RJ, Sbai A, Thomas SG, Trenty L, Wei L:

A benchmark study on problems related to CO2 storage in geologic formations – summary and discussion of the results

to appear 2009

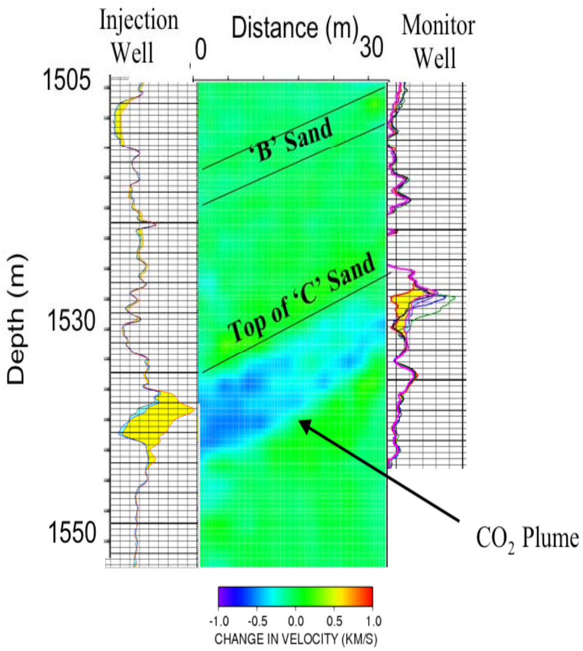
Model Comparison and Evaluation Using Results from CO_2 Field Tests

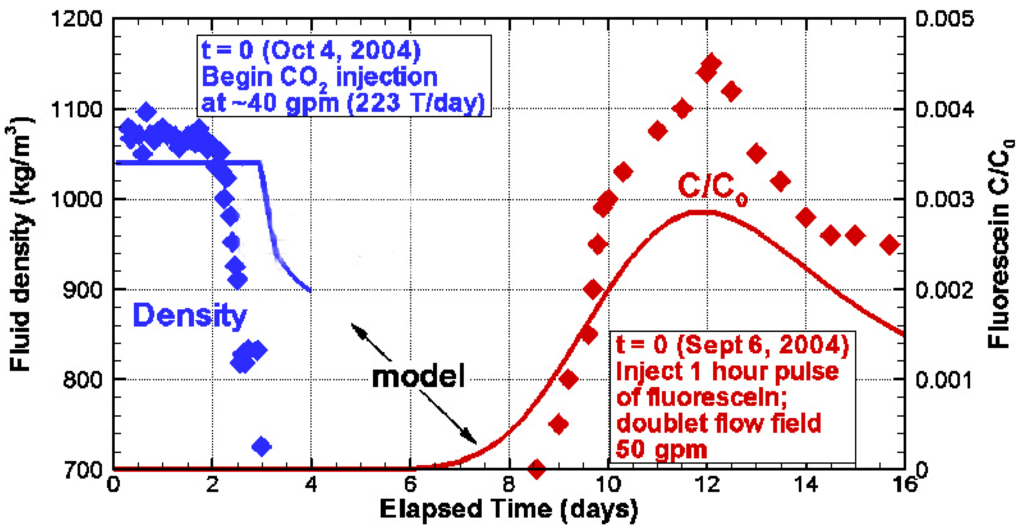
Jens Birkholzer, LBNL

IEA GHG Modelling Workshop, February 11, 2009

This Talk Is About ….

Model Evaluation and Comparison Against Measured Data





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

NOT Code Comparison and Verification Against Benchmark Tests

Model Challenges in CO_2 Storage

- **Processes are coupled and highly nonlinear**
- **Vastly differing time scales for multiphase flow and geomechanical versus chemical effects**
- **Heterogeneities on different scales**
- **Sparsity of data in field situations**
- **Difficult-to-measure and uncertain parameters**

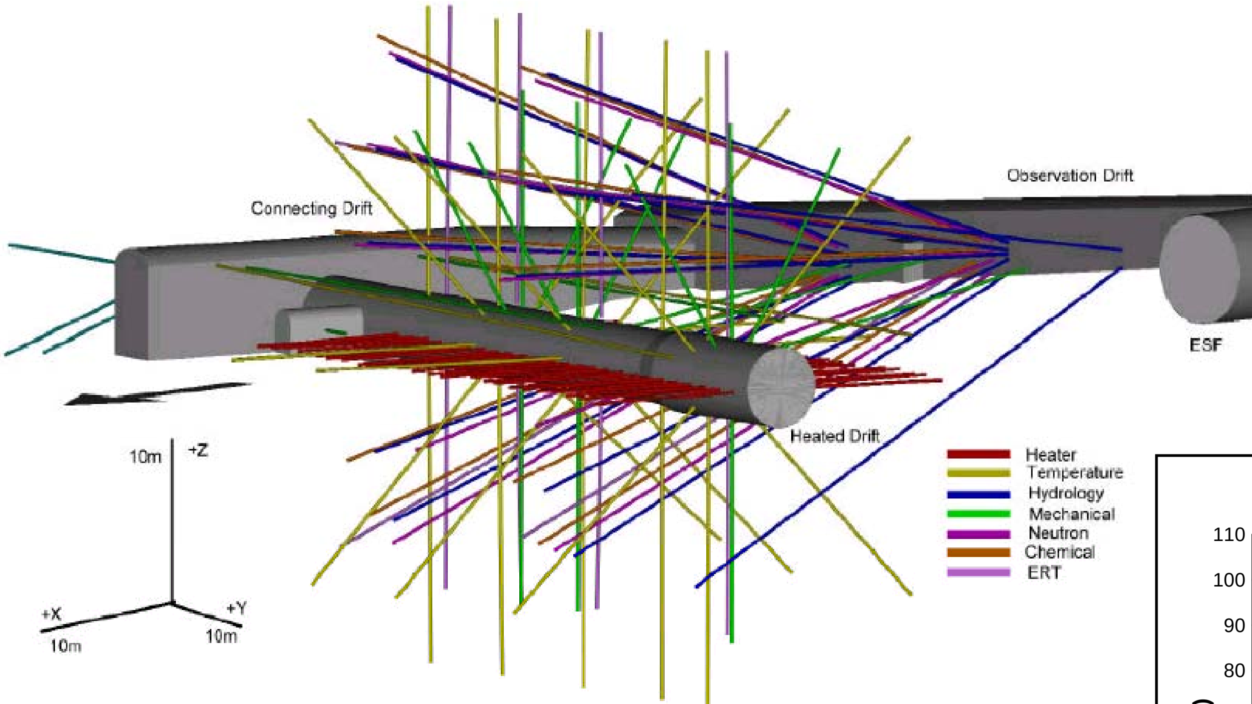
➢ **Wide range of predictions because of different modeling techniques, coupling methods, approaches for multiphase behavior, interpretations of site data**

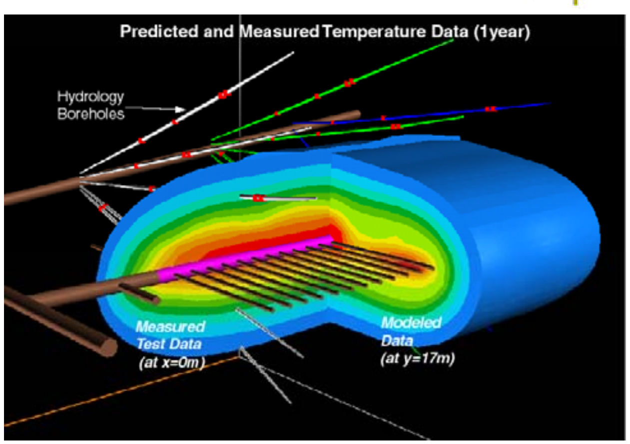
➢ **Uncertainty about performance assessment predictions**

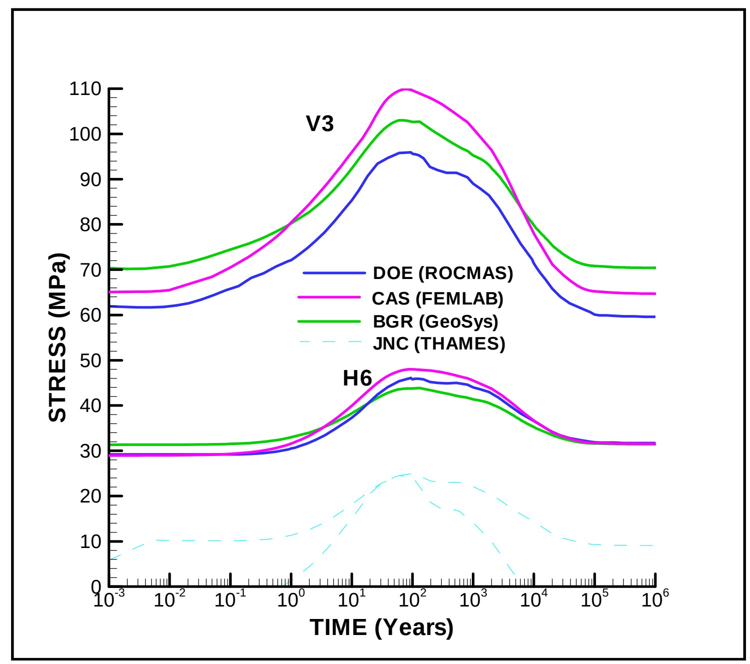
➢ **Model comparison exercises can be very useful, as shown by successful DECOVALEX project**

DECOVALEX Example Case

Underground heater test with measurement of THMC response in rock mass







Sim-SEQ

A New 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 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 is facilitated by LBNL team (Jens Birkholzer) and embedded in DOE's simulation and risk assessment working group (Brian McPherson)
- Participants convene regularly via videoconferences and workshops
- DOE's initiative currently includes domestic modeling groups, but international groups are welcome to join
- Sim-SEQ is currently in start-up phase

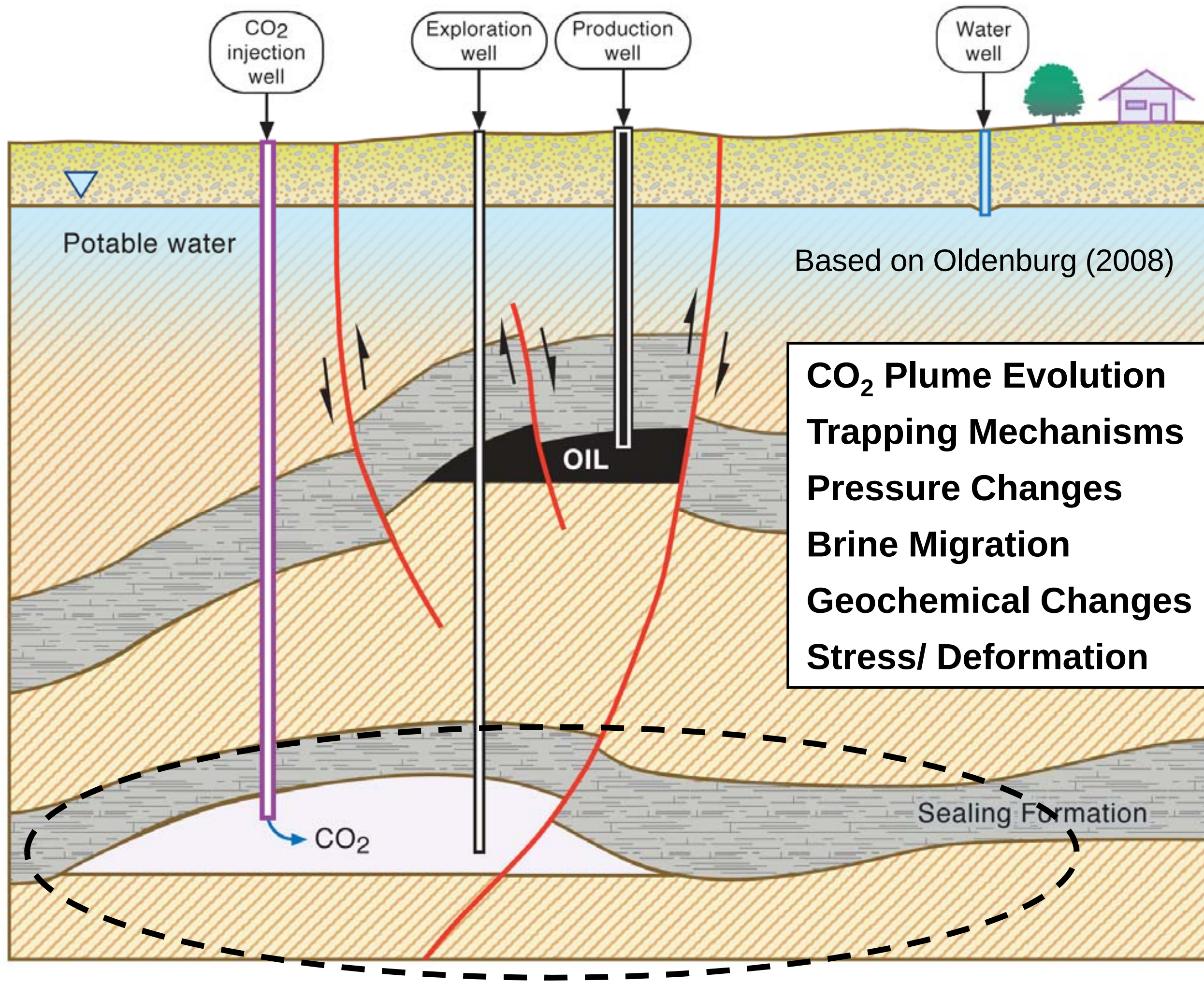
Sim-SEQ Focus

Atmosphere

USDW

Above-Zone Unit

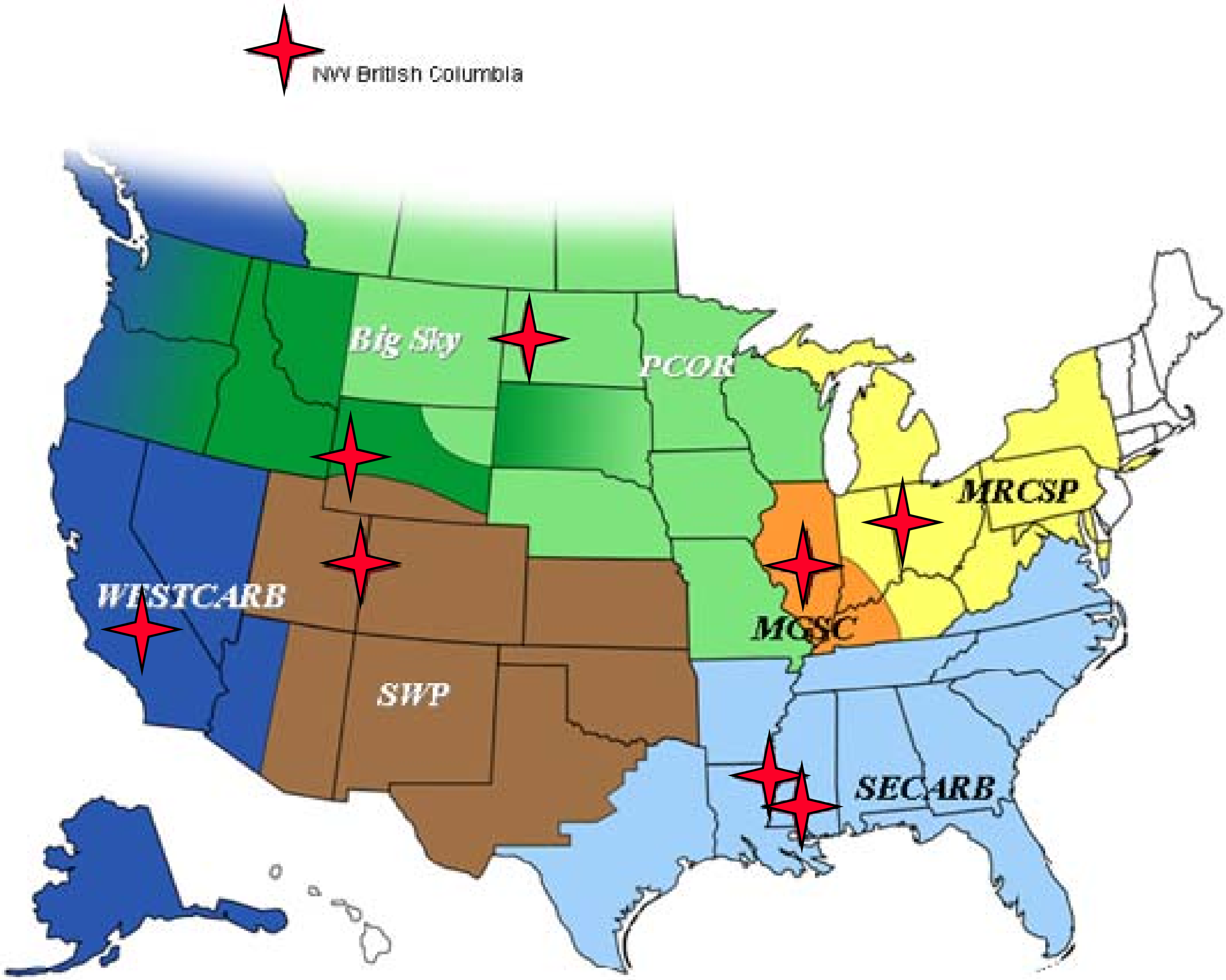
Storage Reservoir and Seal



CO_2 Plume Evolution
Trapping Mechanisms
Pressure Changes
Brine Migration
Geochemical Changes
Stress/ Deformation

Near-Field and Far-Field

Large Field Tests Planned in US



Based on NETL, 2008

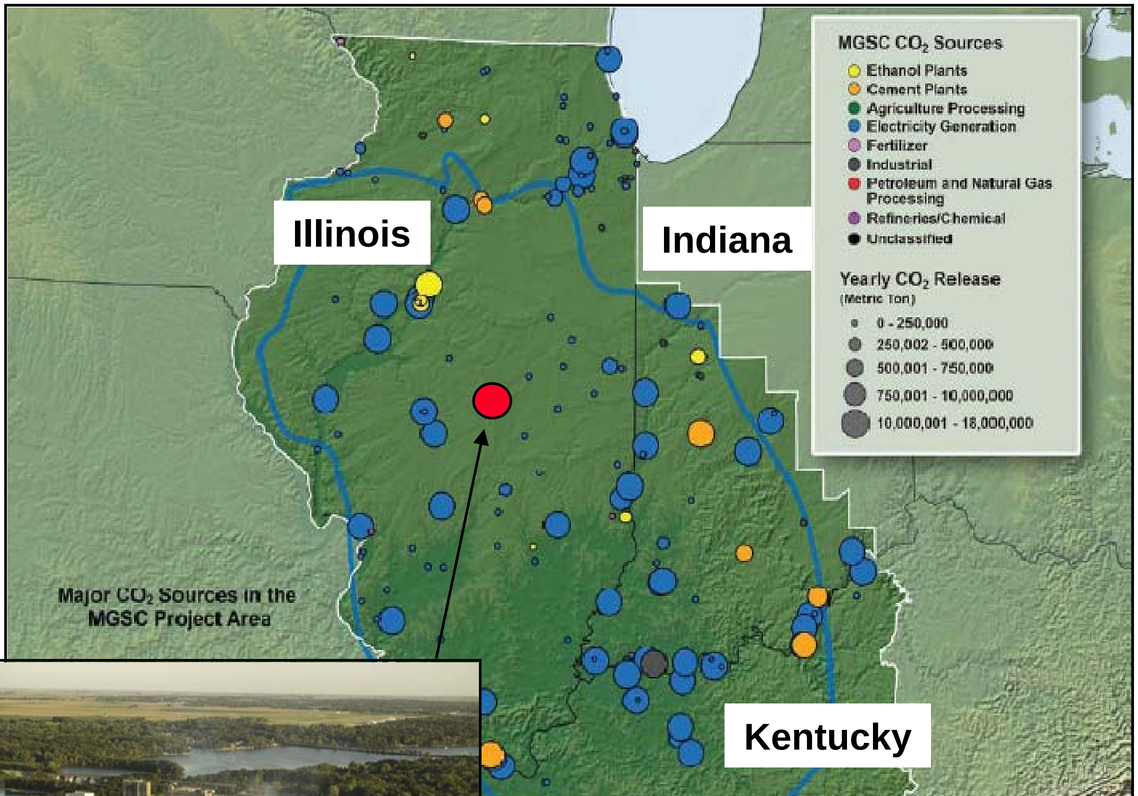
Sim-SEQ Field Test Sites

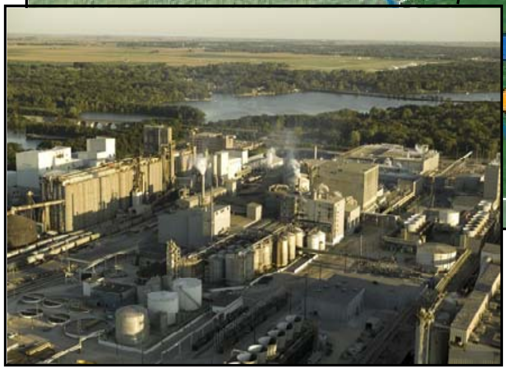
RCSP	Site	Phase	Type	Injection Volume	Expected Drill Date	Expected Injection Start	Data Avail. Before Injection
MGSC	Decatur	3	saline	1 Million tons over 3 years	Ongoing	Dec-09	Sparse (based on seismic, few wells)
SECARB	Cranfield	3	saline near EOR	1.5 Million tons per year over 1.5 years	Early 2009	Summer 2009 (?)	Moderate to good from neaby EOR
MRCSP	Greenville (TAME)	3	saline	1 Million tons over 4 years	Jul-09	2010	Sparse (based on seismic, few wells)
WESTCARB	Kimberlina	3	saline	1 Million tons over 4 year	2009	2012	Sparse (based on seismic, few wells)
Big Sky	Riley Ridge	3	saline	1 to 3 Million tons per year for 3 years	Summer 2010	2011	Moderate (existing nearby wells, outcrop)
SWP	Farnham Dome	3	saline	Up to 1 Million tons per year for 4 years	Begins in April 2009	Late 2009	Moderate (twelve existing and 6 new wells, seismic)
SECARB	Cranfield	2	EOR	0.5 Million tons per year	Done	Started in 2008	Very good data from EOR operations
MRCSP	Gaylord, Mich.	2	saline	50000 tons over 500 days	Done	Ongoing	Sparse (based on seismic, few wells)
SWP	SACROC	2	EOR	0.3 Million tons per year for 3 to 5 years	Done	Started in 2008	Very good from 30 years of EOR

Sim-SEQ sites were selected during workshop in Berkeley (12/2008) and in discussions thereafter. Criteria included large injection volume, timely test start, preference for saline formations, and site characterization/monitoring concepts.

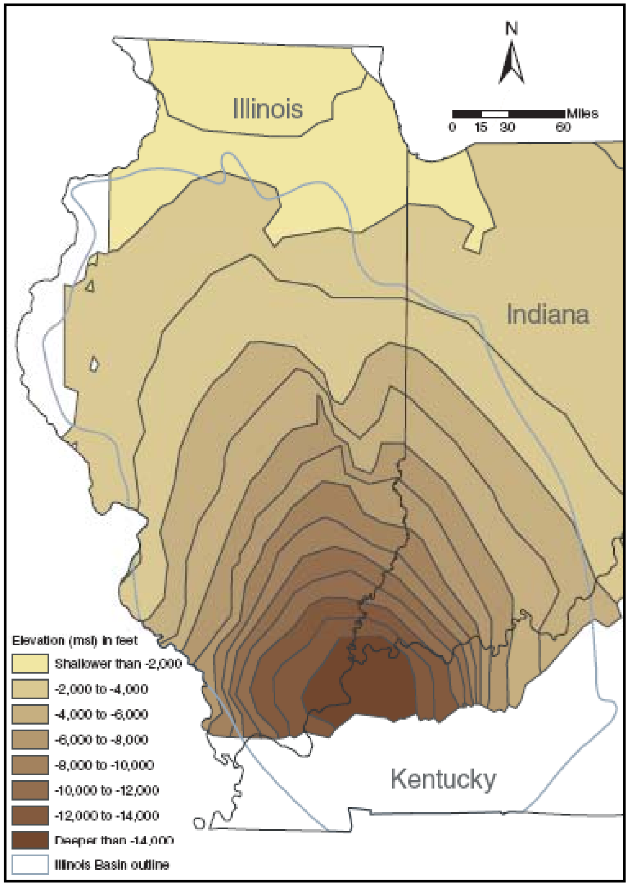
The Decatur Site in the Illinois Basin

Annual CO_2 Emissions from Stationary Sources
300 million tons (MT)





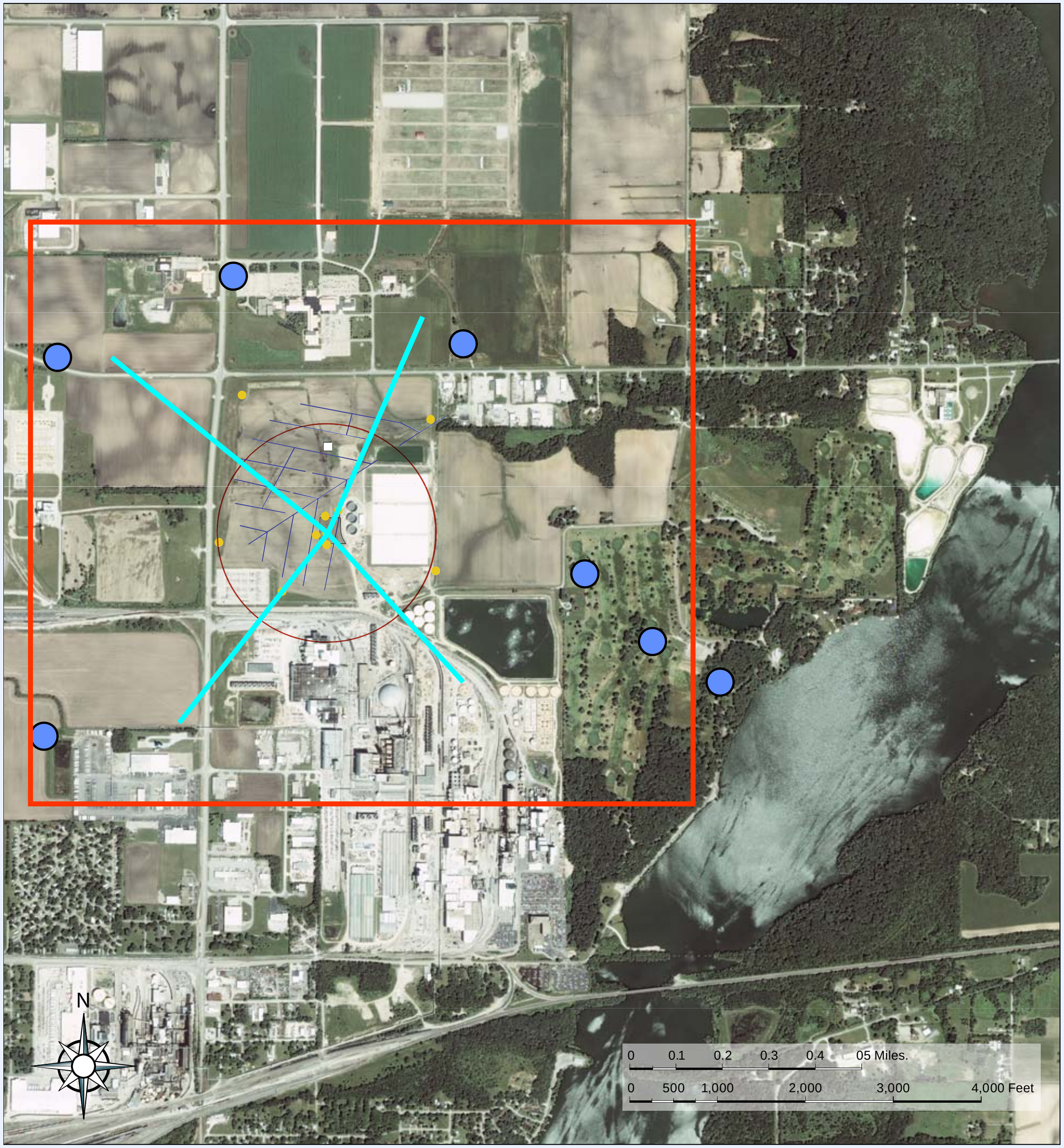
Mount Simon Sandstone as Deep Saline Storage Target



ADM Food Processing Plant at Decatur, Illinois

Courtesy of Hannes Leetaru, MGSC

Plume Monitoring



Shallow ground water

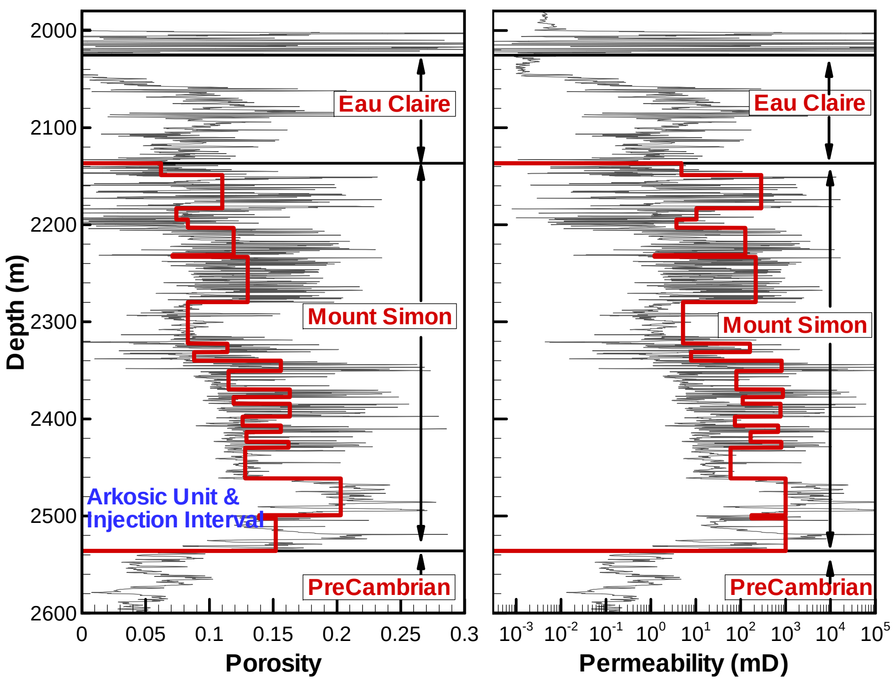
CIR satellite Imagery

Radial repeat vertical seismic profiles

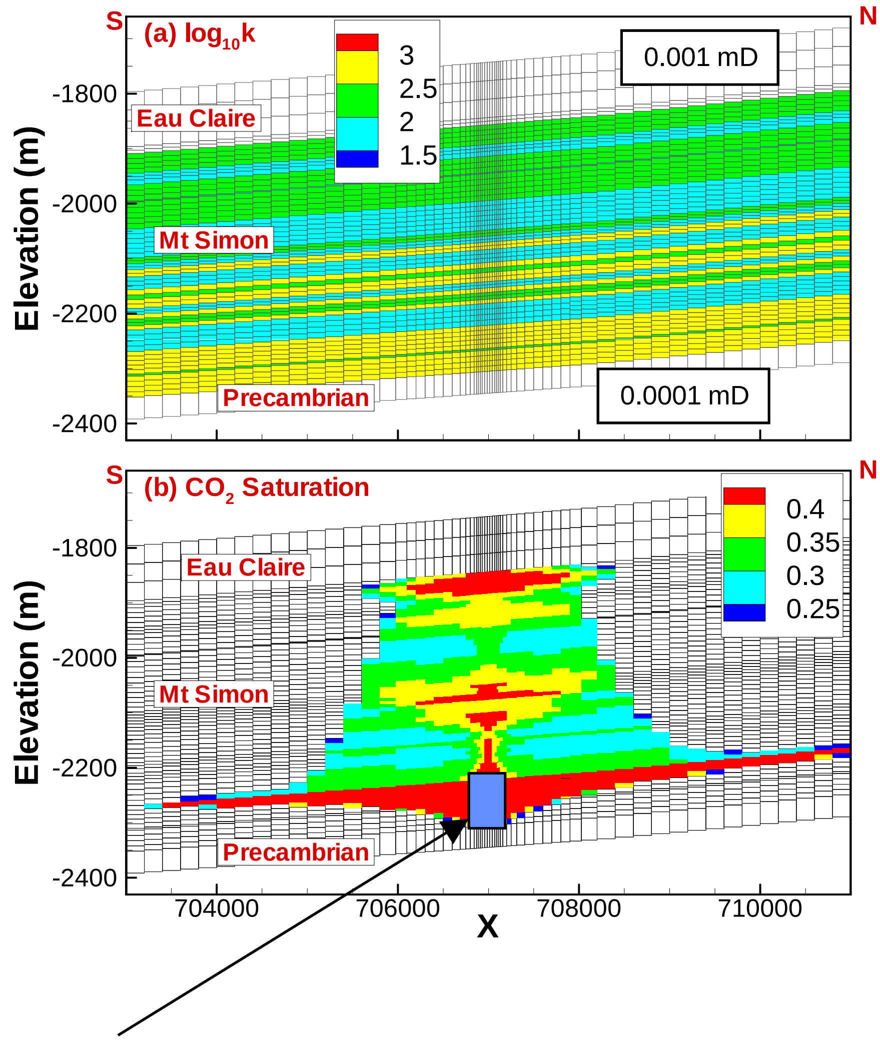
Two deep verification wells

Courtesy of Hannes Leetaru, MGSC

Mount Simon: A Thick Sandstone with Depositional Variability

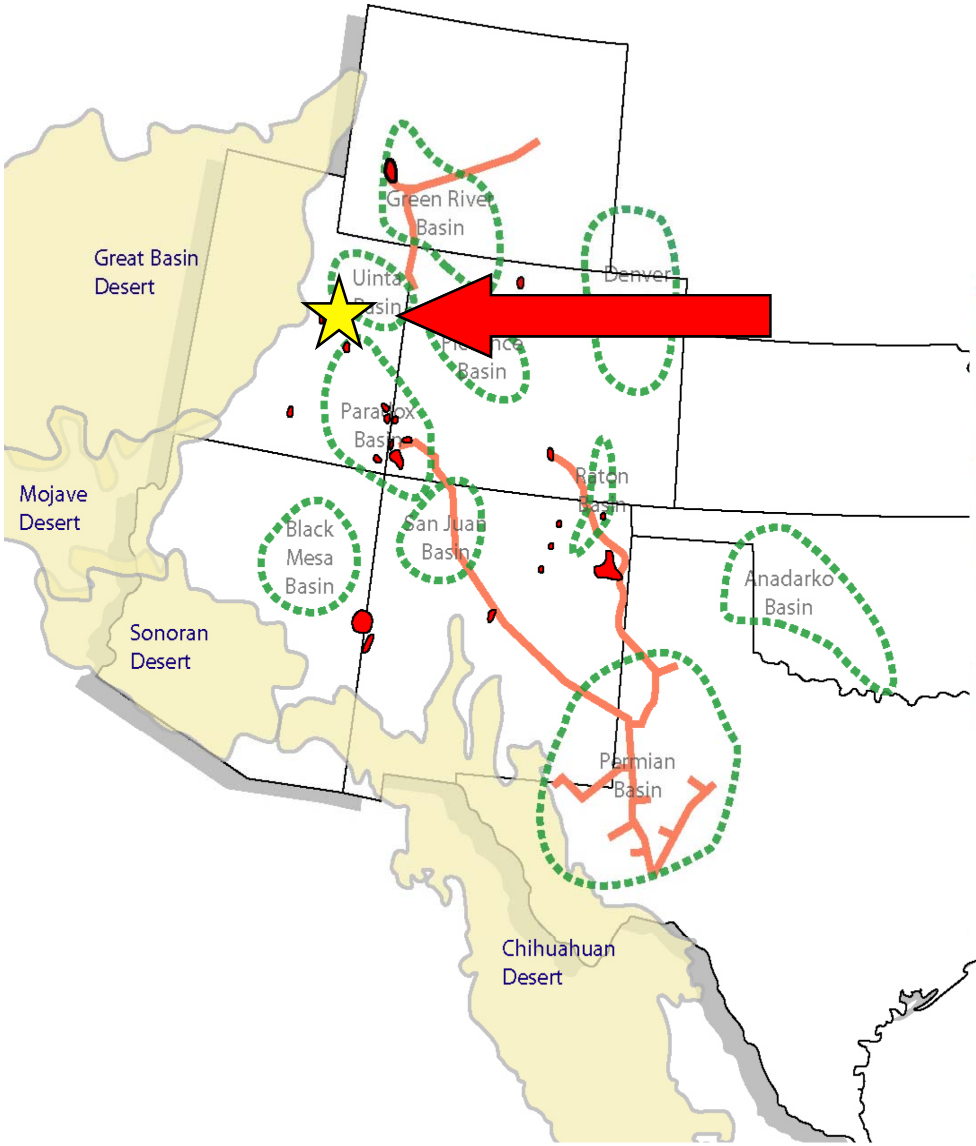


Courtesy of Hannes Leetaru, MGSC



Example simulation: Injection of 5 million tons/year

Farnham Dome in Utah



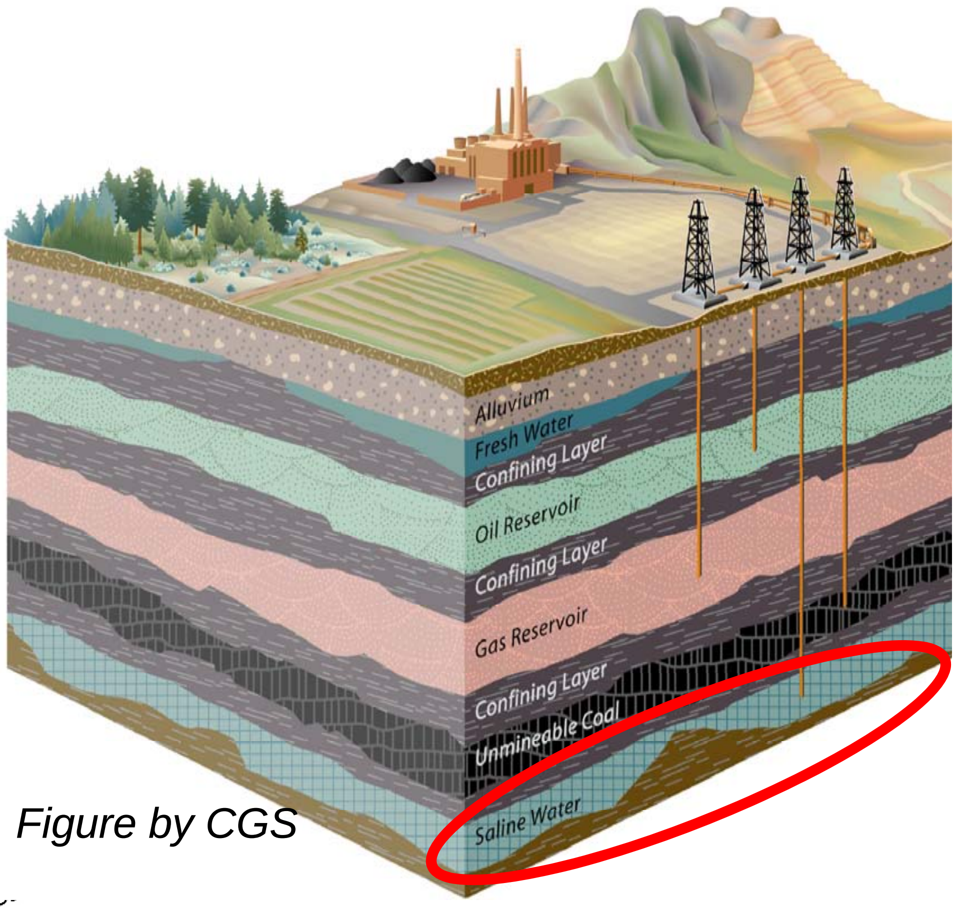
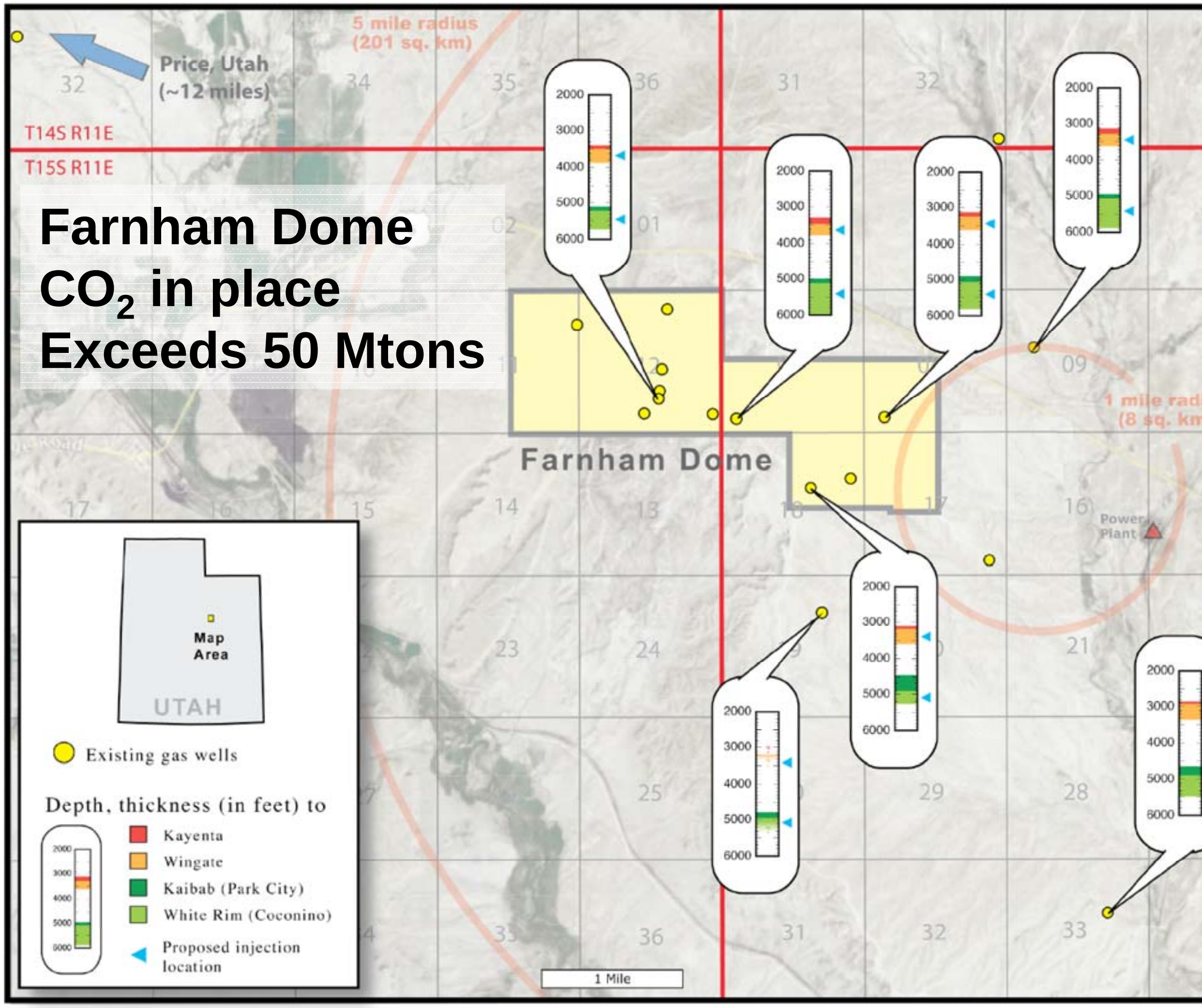
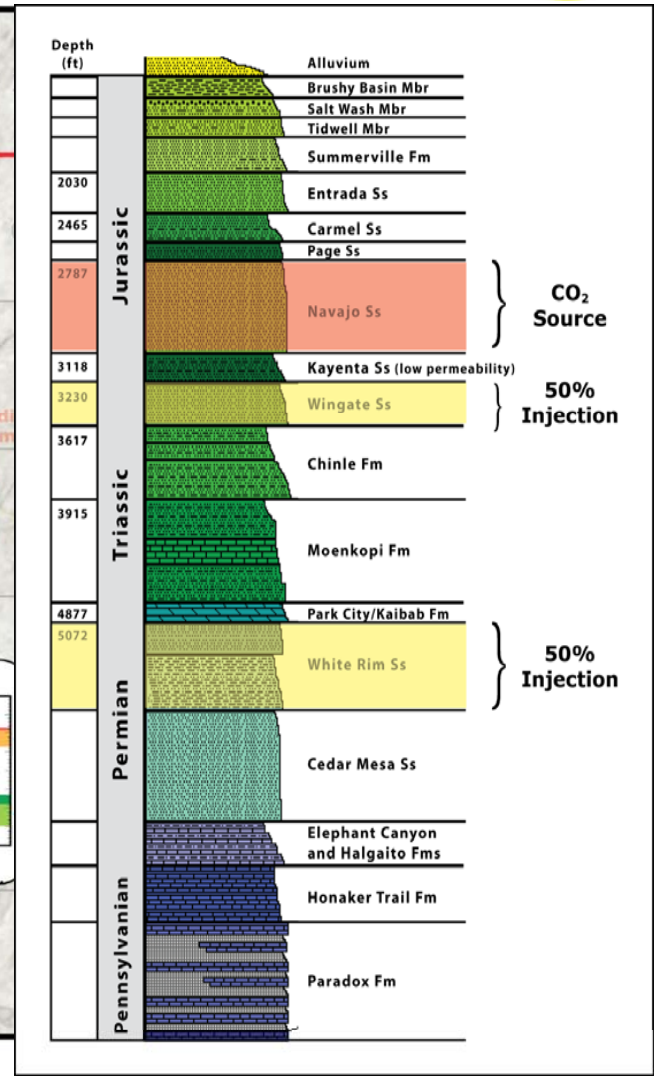


Figure by CGS

Courtesy of Brian McPherson, SWP

Site Characterization

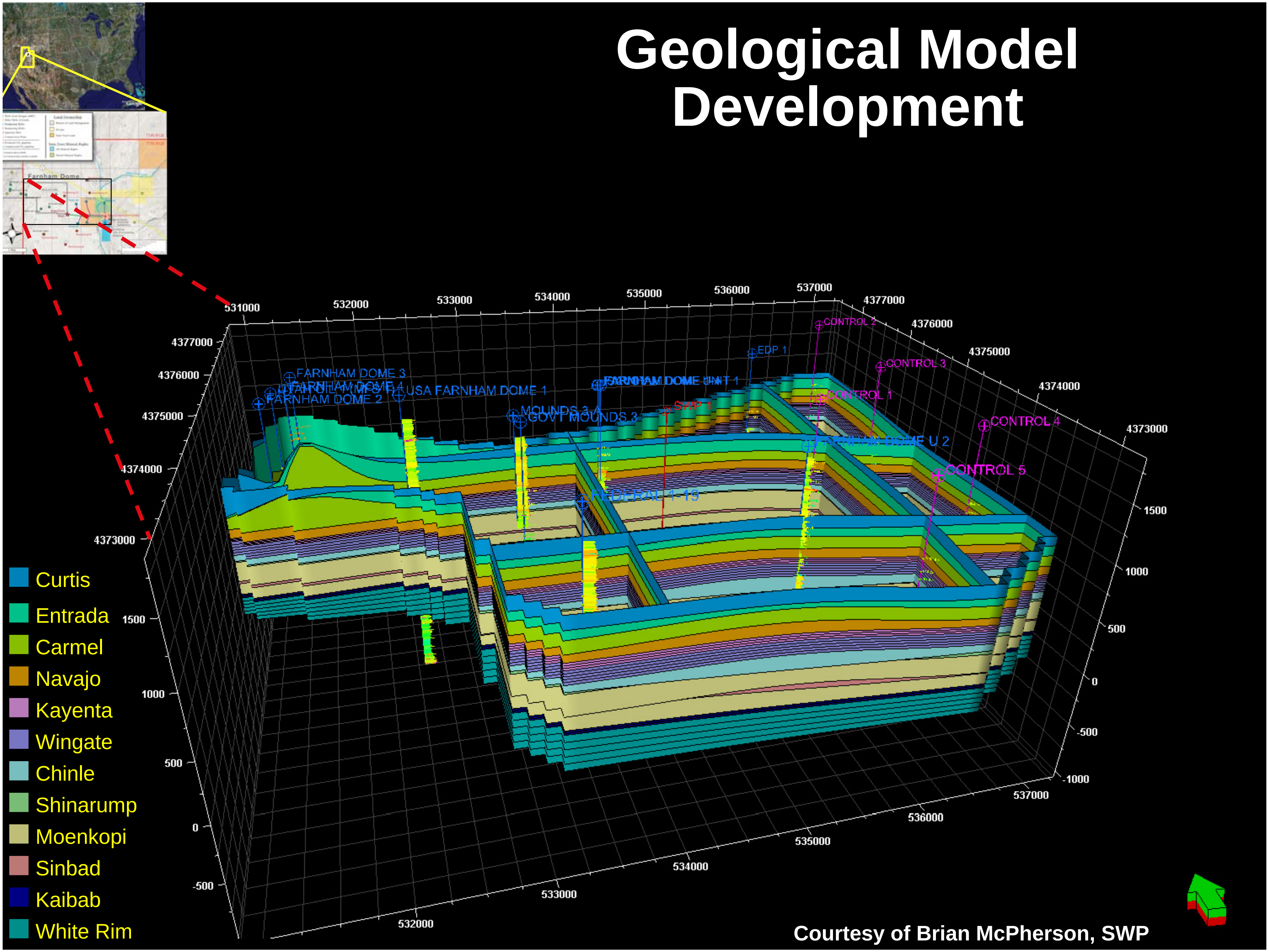




Site has 12 existing wells, up to 6 more injection and monitoring wells will be drilled

Courtesy of Brian McPherson, SWP

Geological Model Development



Courtesy of Brian McPherson, SWP

Sim-SEQ Fields Test Sites

Decatur, Illinois

- Large field test with 1 million tons over 3 years (starting Dec 2009)
- Saline formation with huge thickness and lateral extent
- Offers opportunity to study impact of vertical heterogeneity
- Sparse site information from up to 3 deep wells
- Wide range of monitoring techniques employed

Farnham Dome, Utah

- Very large test with 1 million tons annually over 4 years (from late 2009)
- Stacked reservoir with injection into saline formations under a formation holding natural CO_2
- Offers opportunity to compare attributes of natural analog for storage versus engineered storage
- Moderately good site information from up to 18 wells
- Wide range of monitoring techniques employed

Status and Path Forward

- **Identify Technical Team members***
- **Status review on modeling capabilities**
  - **Current modeling plans and prediction results of participating groups, conceptual models, couplings, expected challenges**
  - **Simulators used, their capabilities, and possible gaps**
- **Selection of field test sites for model comparison***
- **Preparation of information packages for modeling groups**
- **Development of performance metrics for model comparison**

Starting Fall 2009

- **Participants start predictive modeling prior to field tests**
- **Monitoring feedback and iterative model improvement**
- **Comparative evaluation of ongoing model activities**
  - **Conducted over multiple years, prior to and in parallel with field tests**
  - **LBNL-team monitors activities, extracts and summarizes relevant information**
  - **Regular Technical Team meetings with presentations on recent results, model assessment, and discussion about improvements and lessons learned**

* Additional field tests sites and models can be added, if there is interest.

International Interest?

Please contact Jens Birkholzer

jtbirkholzer@lbl.gov

http://esd.lbl.gov/research/projects/sim_seq/

Backup Slides

A Collaborative Effort

LBNL-Team:

Manages and coordinates model evaluation effort

Jens Birkholzer
Stefan Finsterle, Support Staff

External Scientific Advisor: TBA

Sim-SEQ Technical Team:

Comprises modeling team members from each partnership

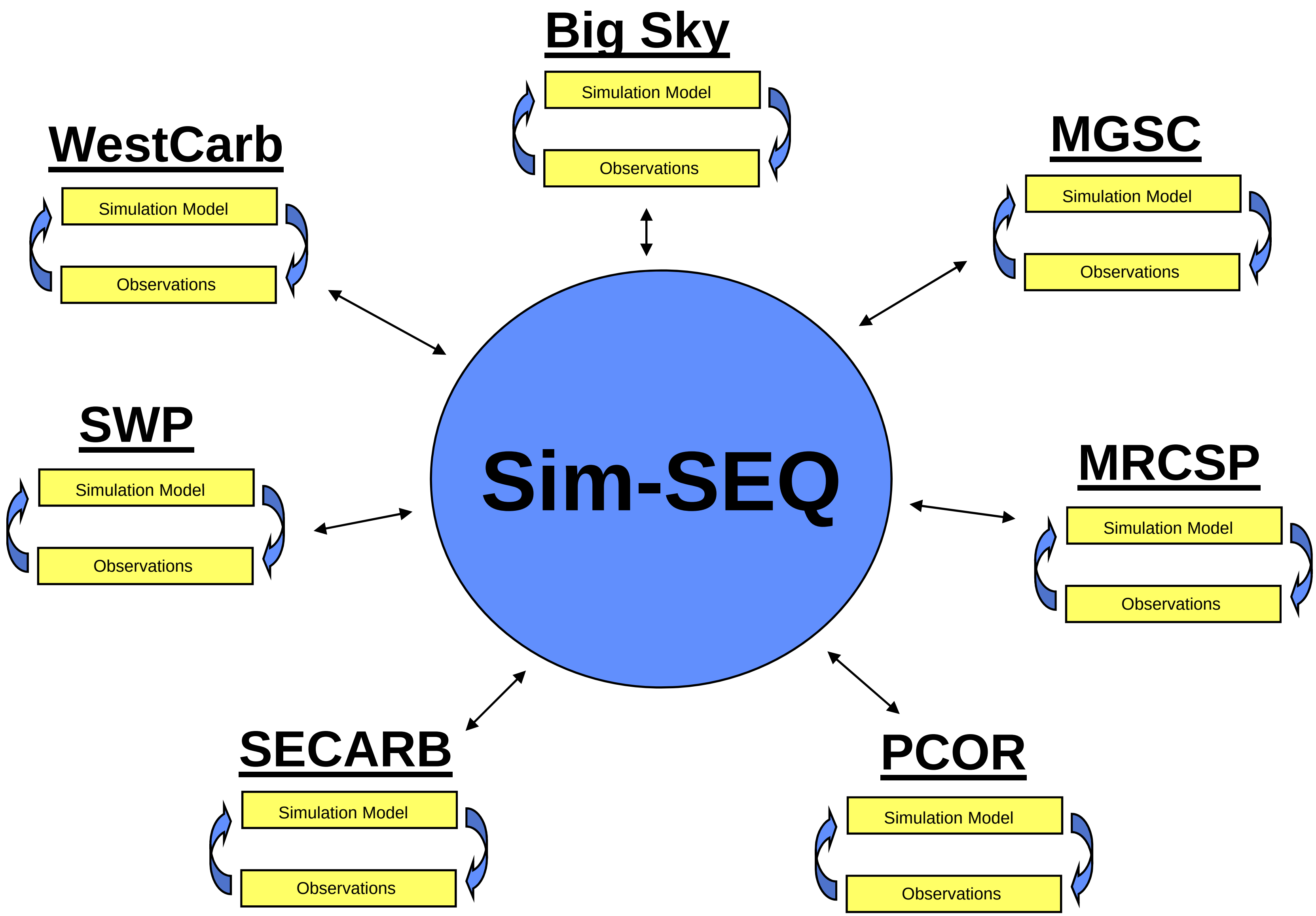
Convenes regularly via video-conferences and workshops

Provides main venue for presentation, discussion, and evaluation of models and results

Multi-Year Effort During Phase III

Integrated in and coordinated with *National Risk Assessment Program* and *Simulation and Risk Assessment Working Group*

A Collaborative Effort



Codes, Capabilities, and Gaps

	Big Sky	MGSC	MRCSP	NETL	PCOR	SECARB	SWP	WESTCARB
ABACUS							●	
CO2-PENS	●						●	
COMET			●			●	●	
COMSOL							●	
Eclipse	●				●	●	●	
FEHM							●	
GEM-GHG						●	●	
GC Workbench	●	●						
GMI - SFIB								
MASTER				●				
NEFLOW-FRACGEN				●				
NUFT	●	●						
PFLOTRAN							●	
PHREEQC					●			
PSU-COALCOMP				●				
STOMP			●					
TOUGH2 (aka as TOUGH+)							●	●
TOUGH-FLAC								●
TOUGHREACT							●	●

From RCSP Interpartnership Simulation and Risk Assessment Workgroup

Numerical tools improvement for CO2 Geological Storage Modelling

A.Michel, J-M.Gratien, L.Trenty

Innovation Energie Environnement

IEA-GHG 10th-12th February 2009, Orléans

Numerical Modelling Concepts

- A model is a representation of a system of interest
  - Give a point of view
  - Focus on a system
  - Make assumptions
- Modelling is a key process in formulating problems
  - Define Variables = Degrees of freedom
  - Define Equations = Constraints
- Many physical problems can be solved (approximately) by using numerical modelling softwares

Innovation
Energie
Environnement

Numerical Modelling Software Solutions

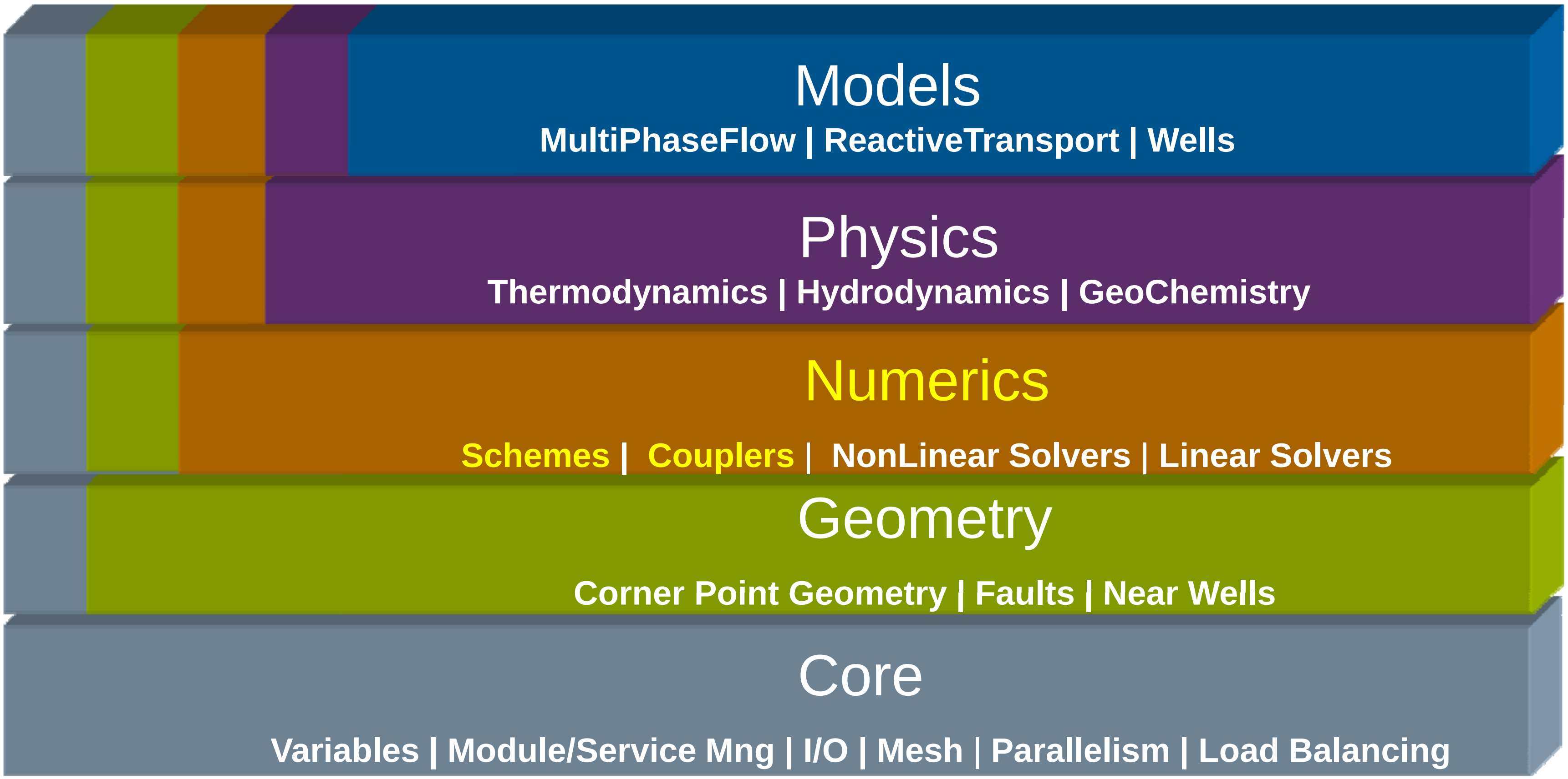
- Spreedsheat Models
- Semi-Analytical Models
- Specialized Mesh-Based Models
  - StreamLines
  - Invasion-Percolation

- <u>General Mesh-Based Models</u>
  - Thermal Multiphase Flow
  - Reactive Transport
  - Geomecanics
  - Coupled Models

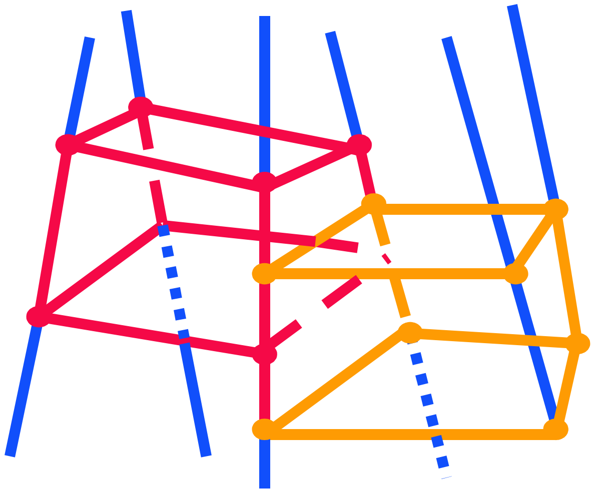
- Hybrid Models

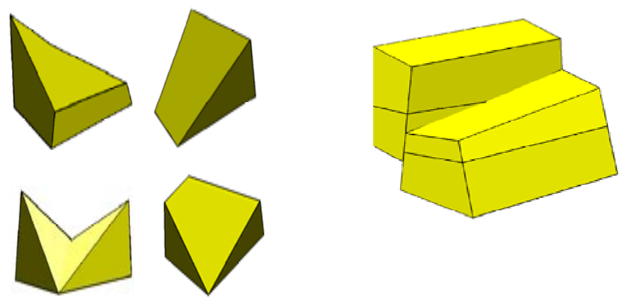
Innovation Energie Environnement

General Mesh-Based Models Architecture

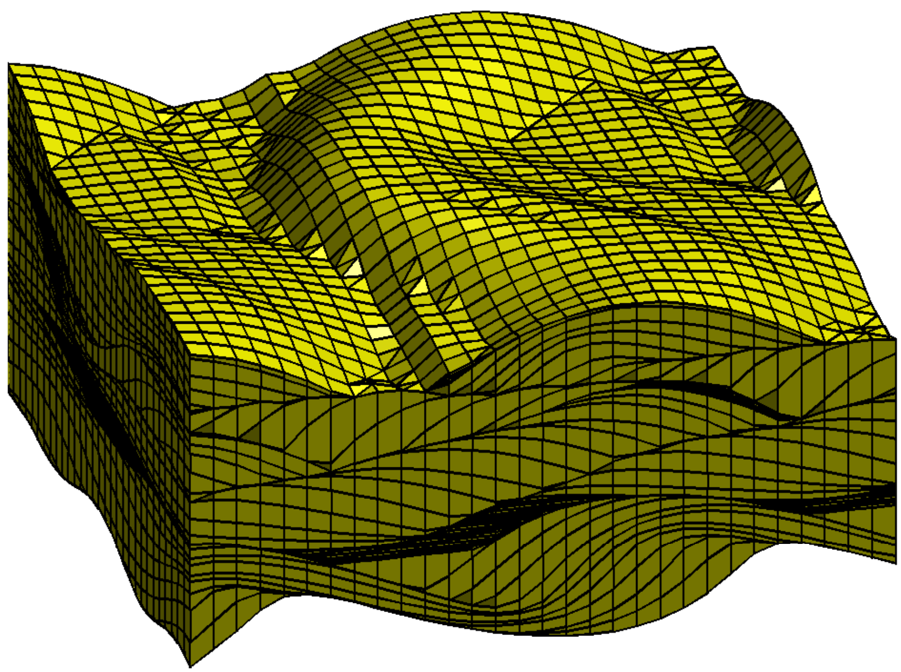


Geometry
CPG Grids



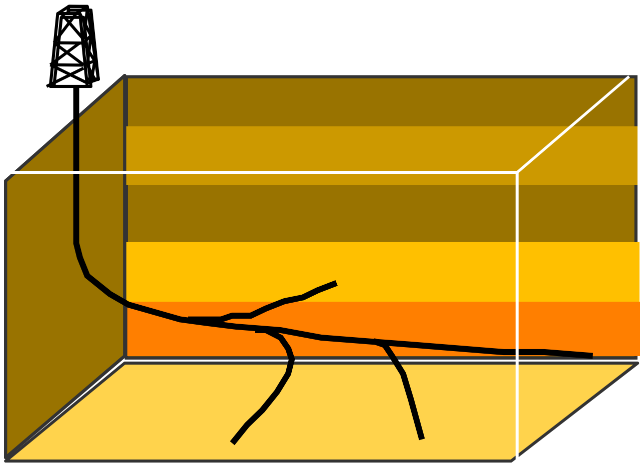


- Erosions
- Local Grid Refinement
- Faults

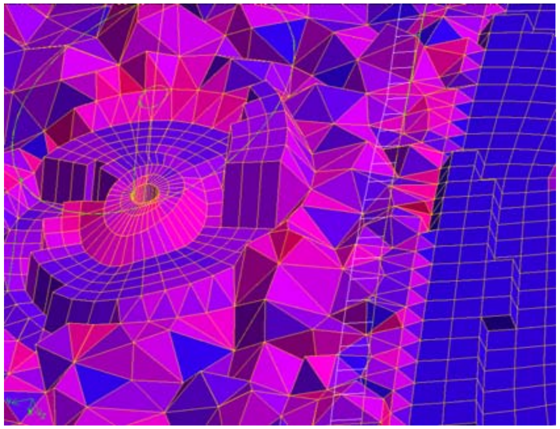


Geometry
Near Wellbore Meshes

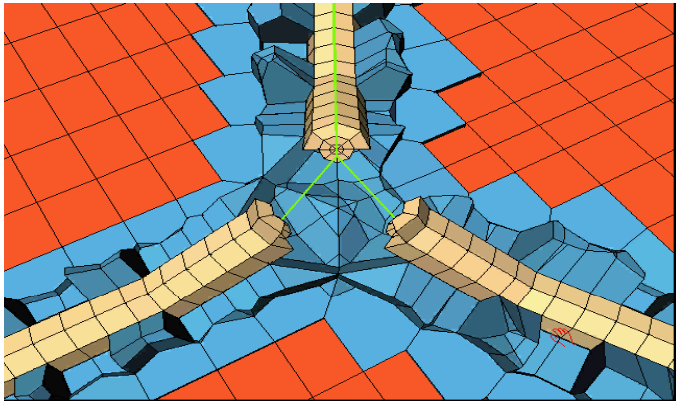
Multi-branch Wells



Pyramid and Tetraedron Approach

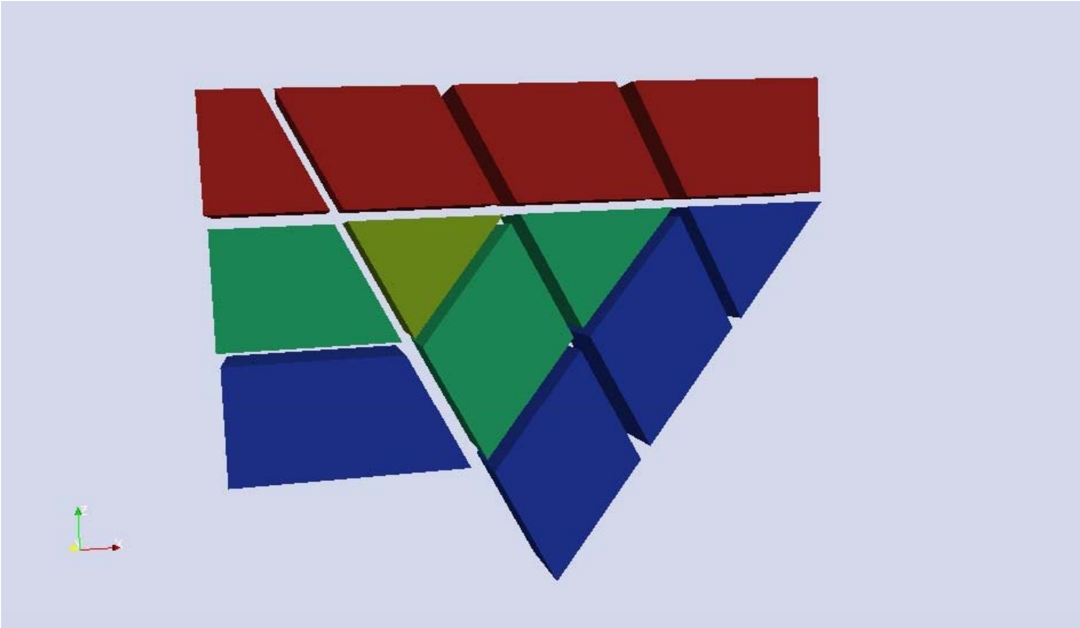


Voronoï Approach



Geometry
Evolutive Mesh

- **Driven by a kinematic model**
  - **Sedimentation, Erosion, Compaction...**
- **Non CPG topology : fully unstructured mesh**

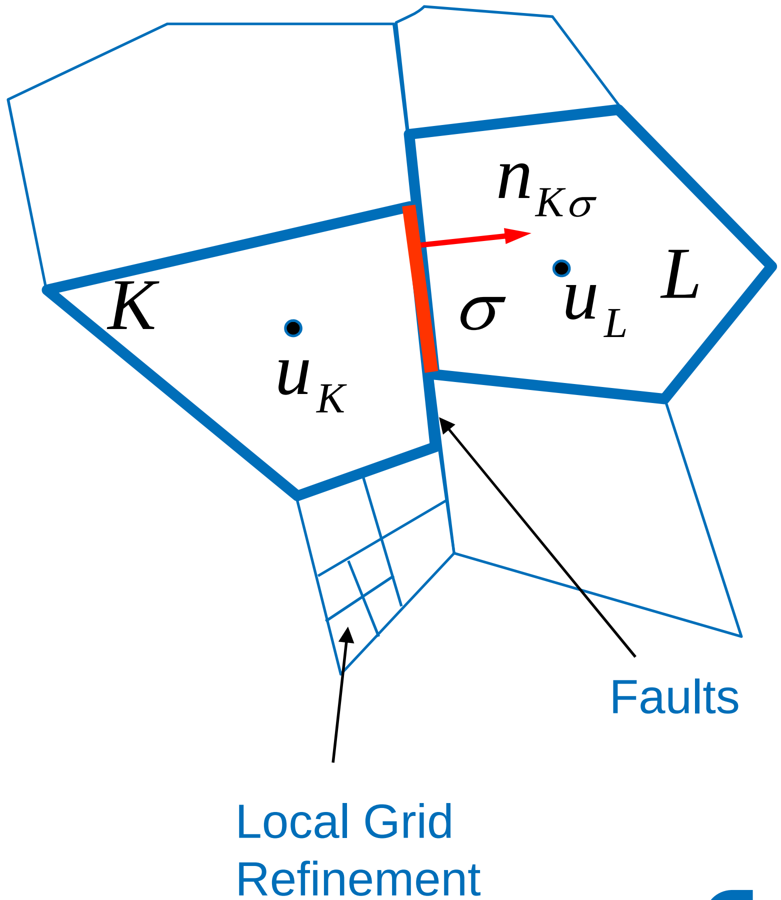


Discrete Operators
Diffusion Schemes

$\mathrm{div}\,(-\,\mathbf{K}\ \mathrm{grad}\,(P)\,)$

$\mathrm{div}\,(-\,\mathbf{D(v)}\ \mathrm{grad}\,(c)\,)$

$\mathrm{div}\,(-\,\lambda\ \mathrm{grad}\,(T)\,)$

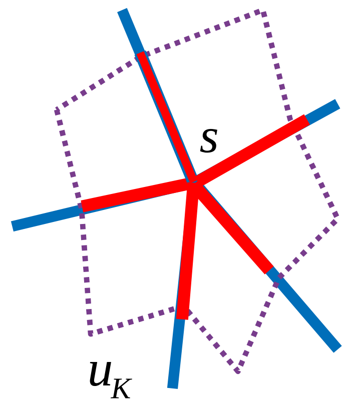


- **General meshes**
- **Anisotropic Heterogeneous Diffusion Tensors**
- **Reduced Cost**

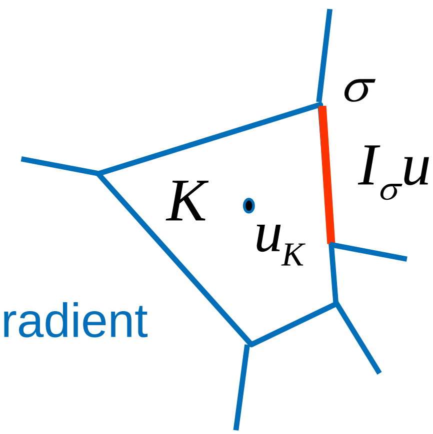
Discrete Operators

Finite Volume Schemes for Diffusion

O-scheme
L- scheme
G-scheme

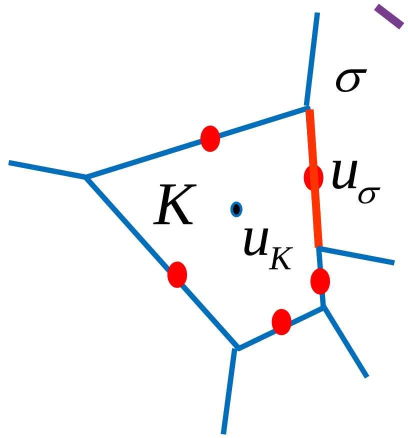


Cell-centered schemes



Cell Gradient

Mimetic Finite Difference
Hybrid Finite Volume
Mixed Finite Element



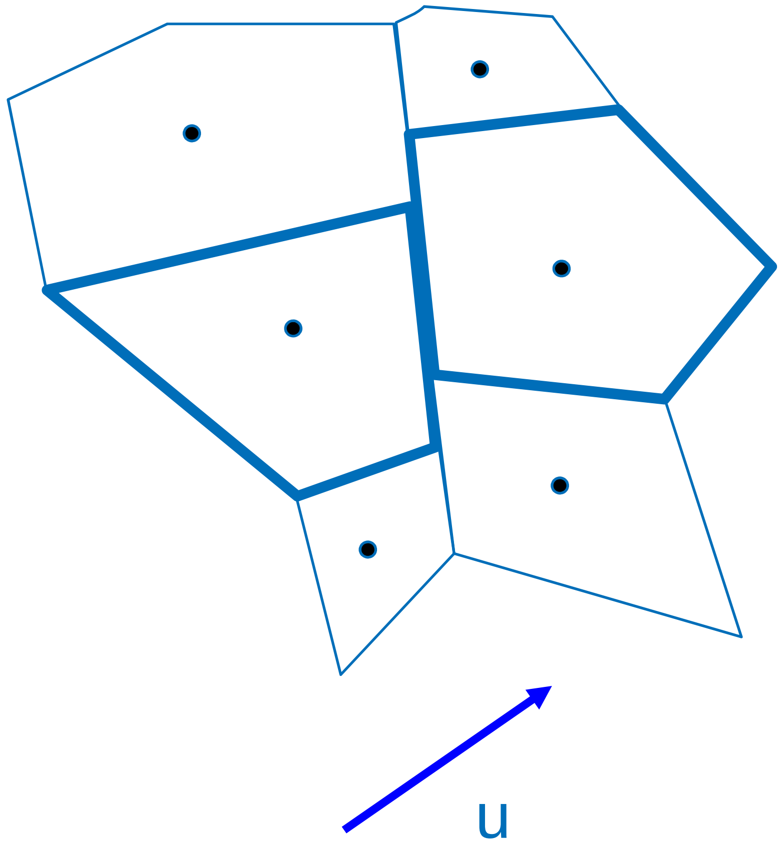
Hybrid methods

Discrete Operators
Advection Schemes

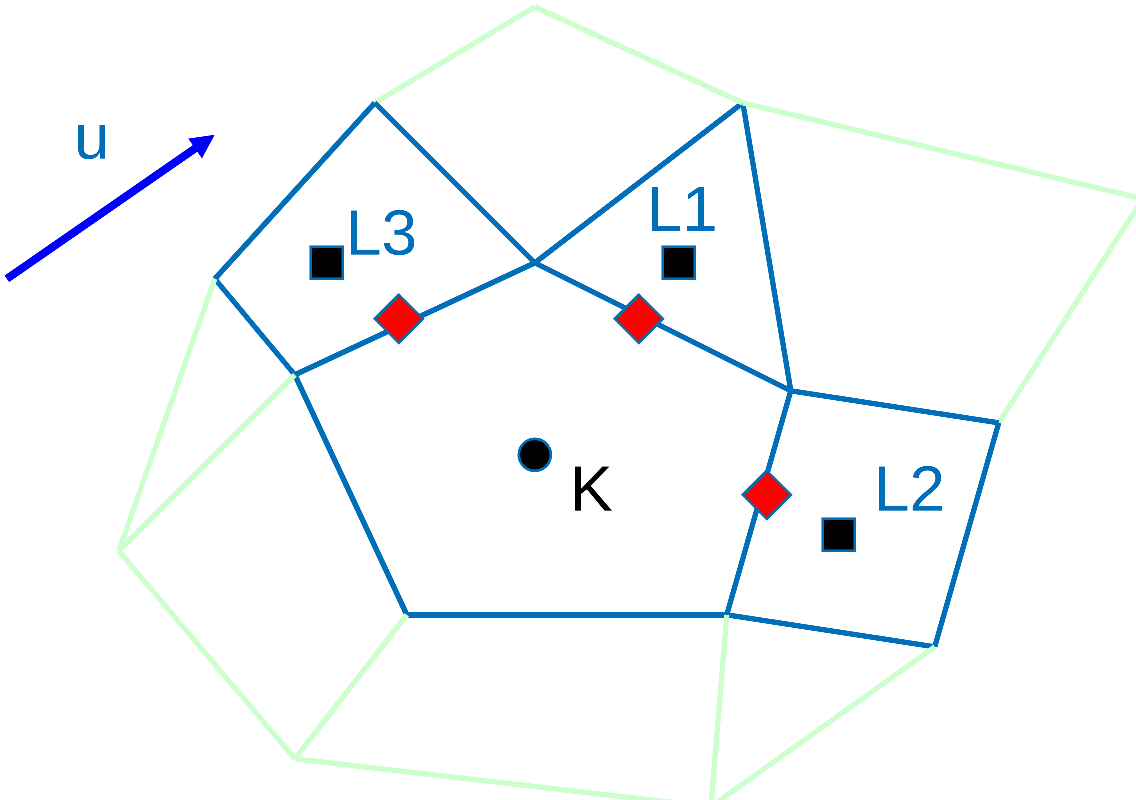
div (ρ **v**)

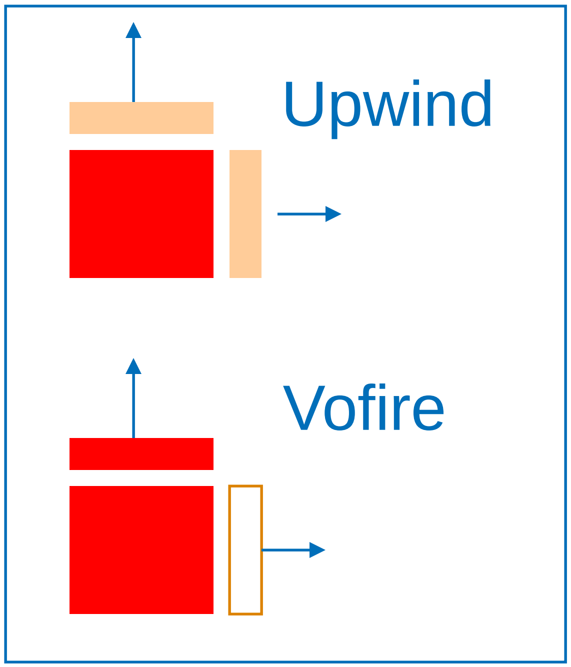
div (ρ∗xi **v**)

- General meshes
- Avoid Numerical Diffusion
- Second Order and Stability
- Multi-Species Transport
- Reduced Cost



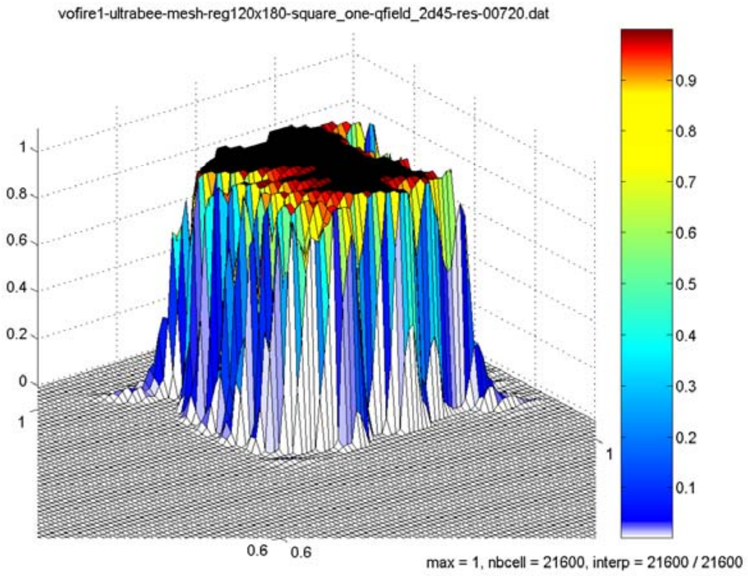
Discrete Operators
VOFIRE Upwind Schemes



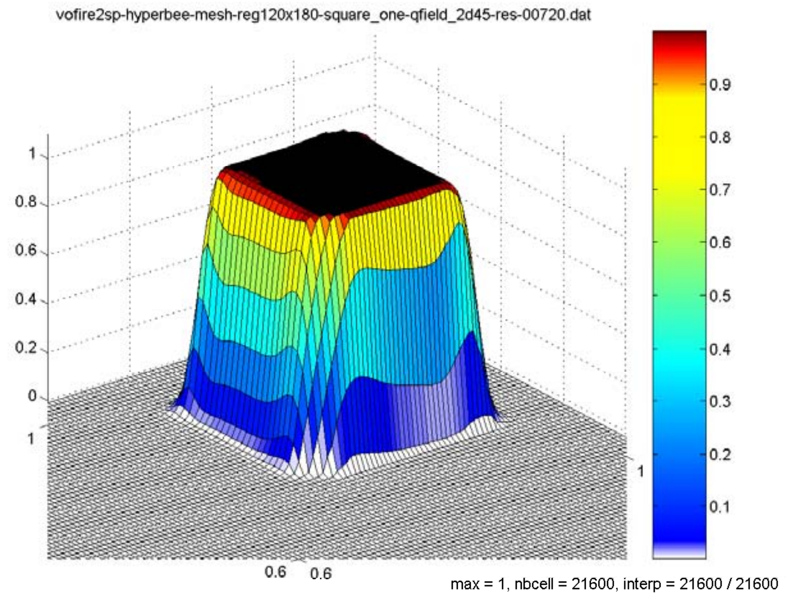


Conservative transverse
Outflow reconstruction

Discrete Operators
VOFIRE Upwind Schemes



VOFIRE Scheme



Modified VOFIRE Scheme

Coupling Models

- **Coupling Numerical Models**
  - **External Coupling**
  - **Multi-Models Platforms**

- **Decoupling Systems of Equations**
  - **Sequential Iterative Splitting Strategies**
  - **Time-Space Domain Decomposition**
  - **Waveform Relaxation**

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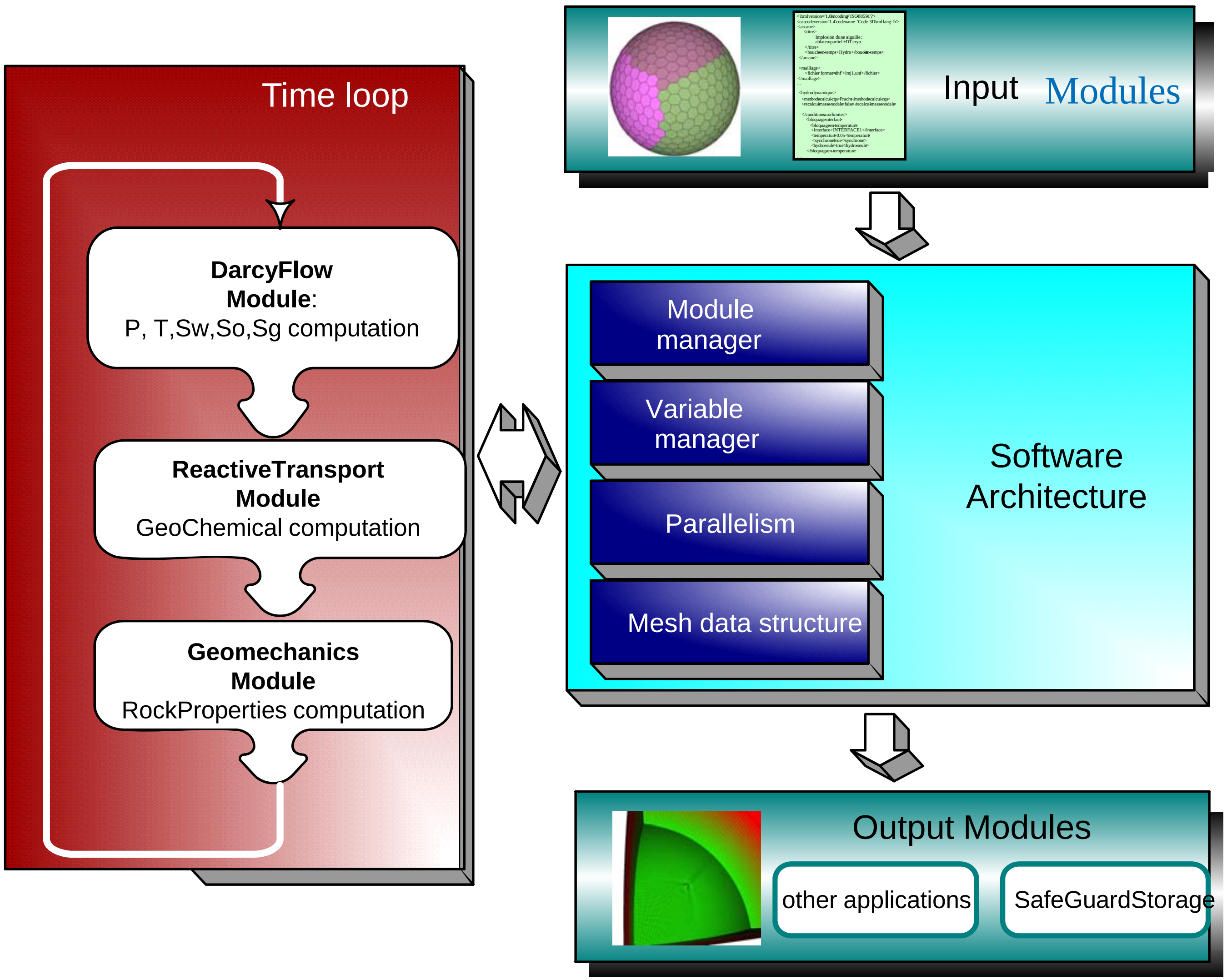
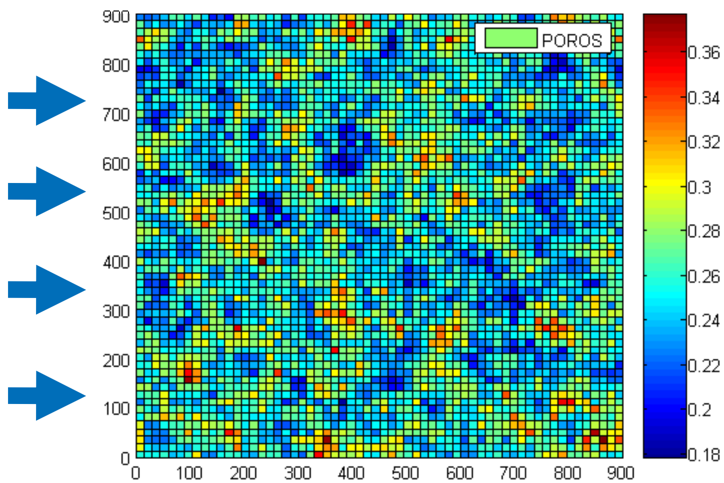
Coupling Numerical Models

Multi-Models Platforms



Reactive Front Tracking
Heterogeneous Chemical Setting

Acid Water



Kinetic Minérals

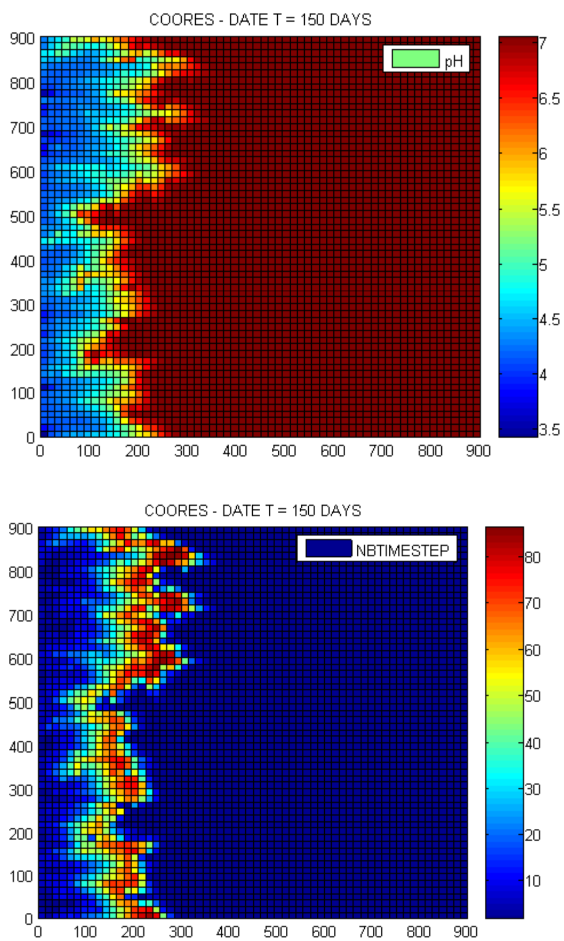
clinochlore
k-feldspath
kaolinite
low-albite
quartz
siderite

Geostatistical distribution of
mineral composition and porosity

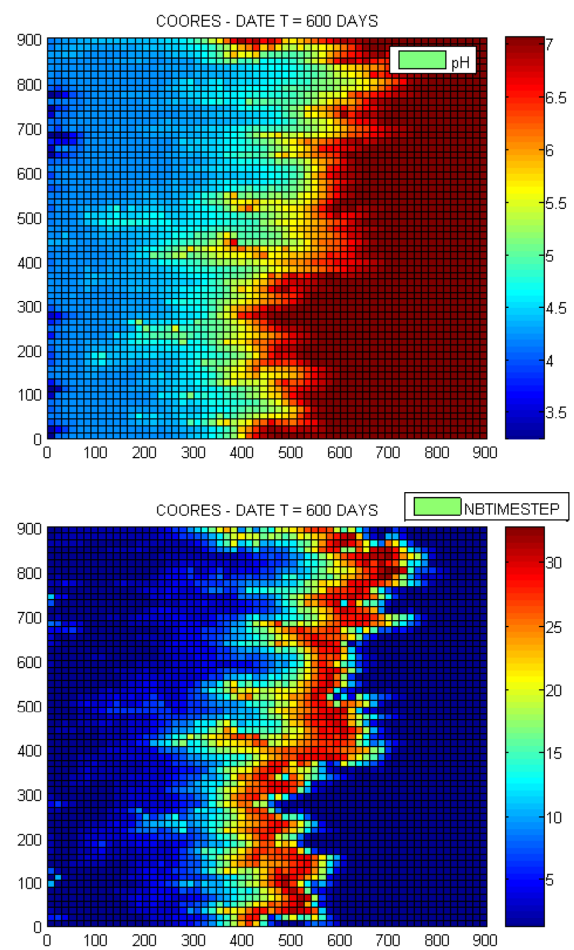
[F.Diedro, ENSMSE, PhD Thesis]

Reactive Front Tracking

Time Step and Reactivity



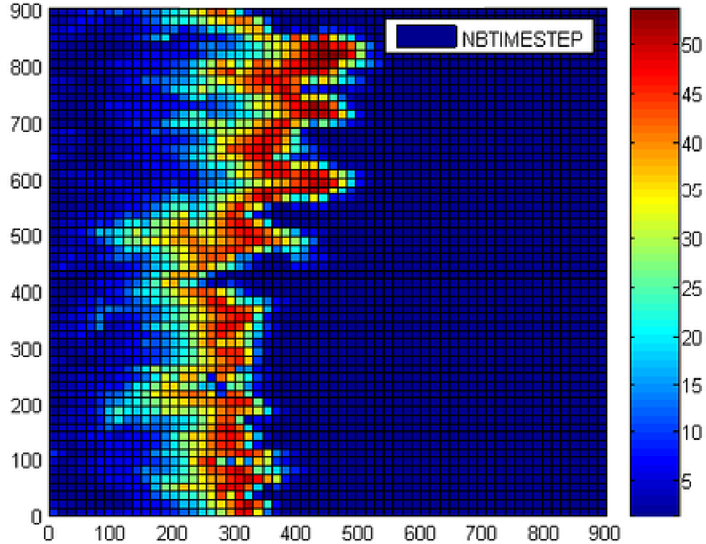
T = 150 days



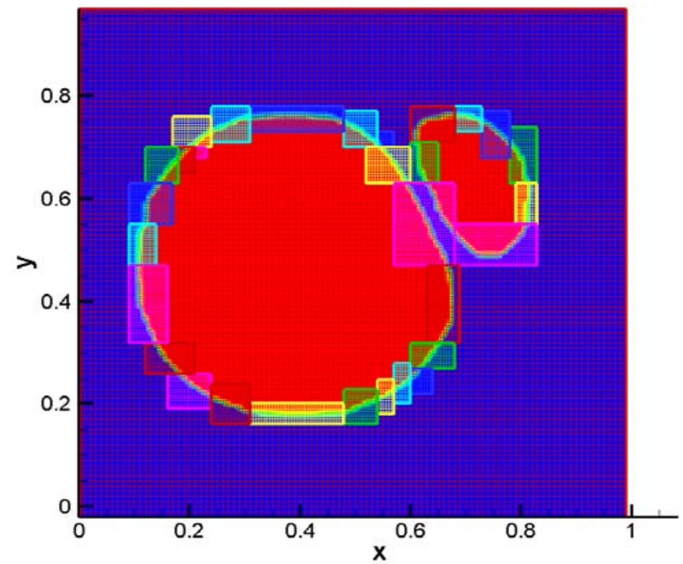
T = 600 days

Reactive Front Tracking
Numerical Tools

- Front Tracking
- Local Time Stepping
- Adaptive Mesh Refinement



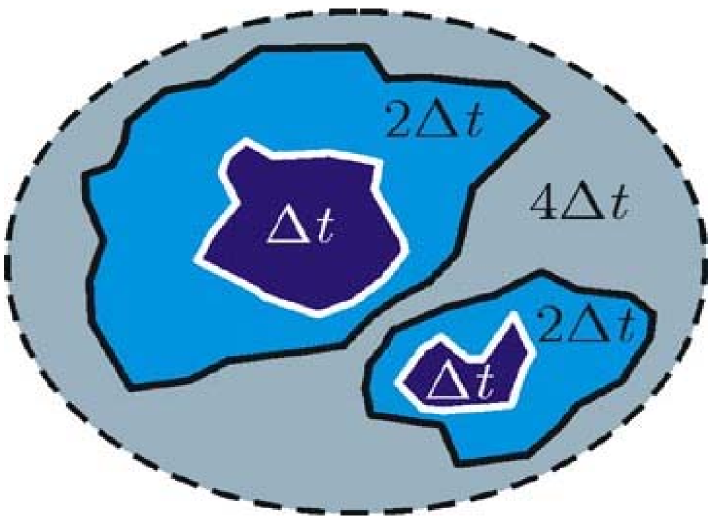
Fast Upwind + Local Solver



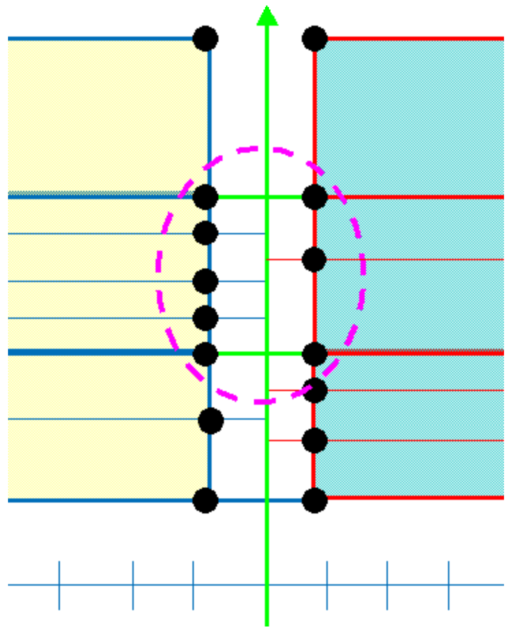
Anti-diffusive Scheme + AMR

[J.Ryan, ONERA and Paris13]

Time-Space Domain Decomposition
Coupling Conditions



Sub-Domains



Time-Space Coupling Interface

Time-Space Domain Decomposition
Introducing Nonlinear Optimal Conditions

$$\begin{cases} \partial_t u - \nu \Delta u + f(u) = 0, & \text{dans } \mathbb{R}^2 \times]0,T[, \\ u = u_0, & \text{pour } t = 0. \end{cases}$$

$f(u) \longrightarrow \varphi(u)$ = Nonlinear Optimal Parameter

Boundary Conditions Domain 1

$$\frac{\partial u_1^{k+1}}{\partial n_1} + \varphi(u_1^{k+1}) u_1^{k+1} = \frac{\partial u_2^k}{\partial n_1} + \varphi(u_2^k) u_2^k \quad \text{sur} \quad \Gamma \times]0,T[.$$

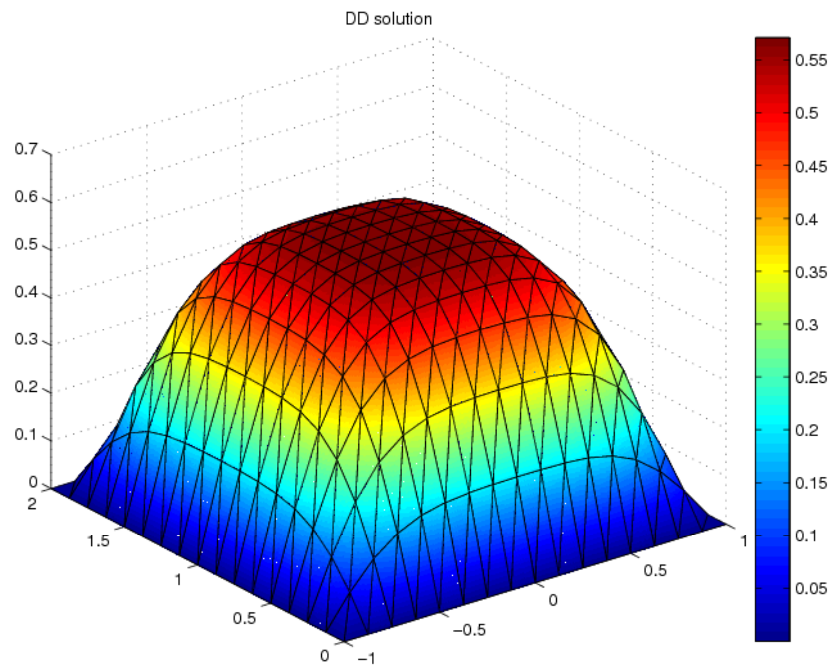
Boundary Conditions Domain 2

$$\frac{\partial u_2^{k+1}}{\partial n_2} + \varphi(u_2^{k+1}) u_2^{k+1} = \frac{\partial u_1^k}{\partial n_2} + \varphi(u_1^k) u_1^k \quad \text{sur} \quad \Gamma \times]0,T[.$$

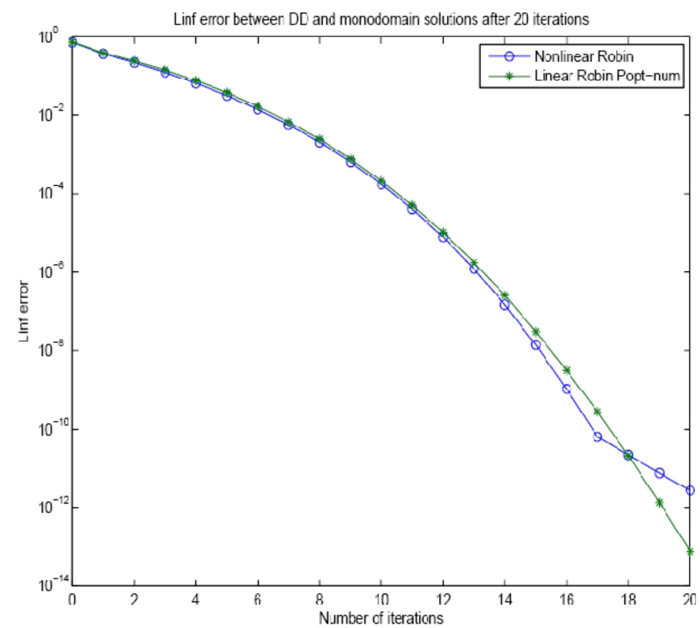
Innovation Energie Environnement

Time-Space Domain Decomposition
Nonlinear Optimal Robin Conditions

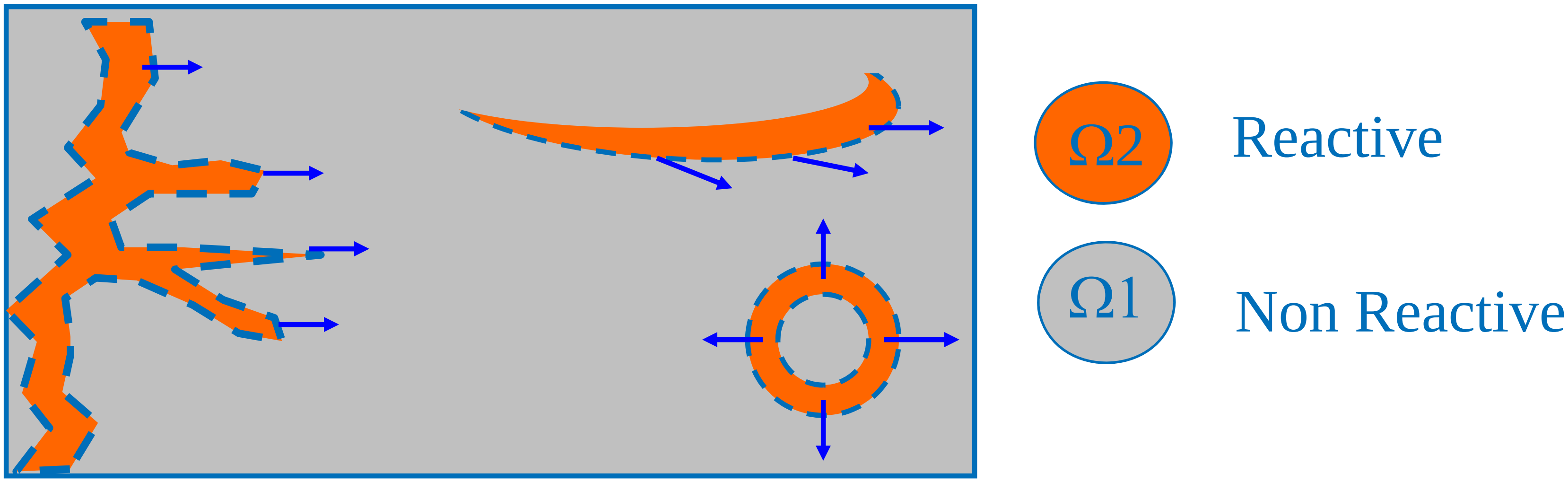
Solution after 20 iterations

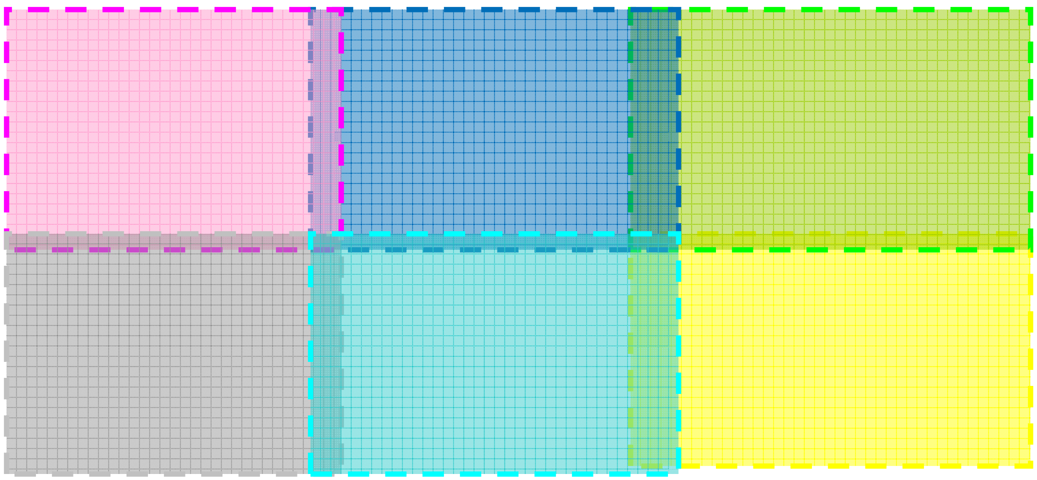


Optimal parameter vs Nonlinear Optimal



Time-Space Domain Decomposition
Parallel Dynamic Load Balancing





+ Distributed Memory

Conclusions

- Different types of numerical modelling software
- Hybrid strategies can be interesting

- Improvement of General Mesh-Based Models
  - Coupling facilities in the core of the platform
  - Complex dynamic meshes
  - Accurate discrete operators
  - Dynamic front tracking and AMR
  - Time-space domain decomposition
  - Parallel Dynamic Load Balancing

- It is enough or is it too much ?

Innovation
Energie
Environnement

A novel problem in the geosciences: combination of field monitoring and modeling to verify permanence of geologic sequestration of CO_2

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

Gulf Coast Carbon Center

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

BUREAU OF ECONOMIC GEOLOGY

Presented to 1st IEA Modeling Network Meeting
11 February, 2008, Orléans, France

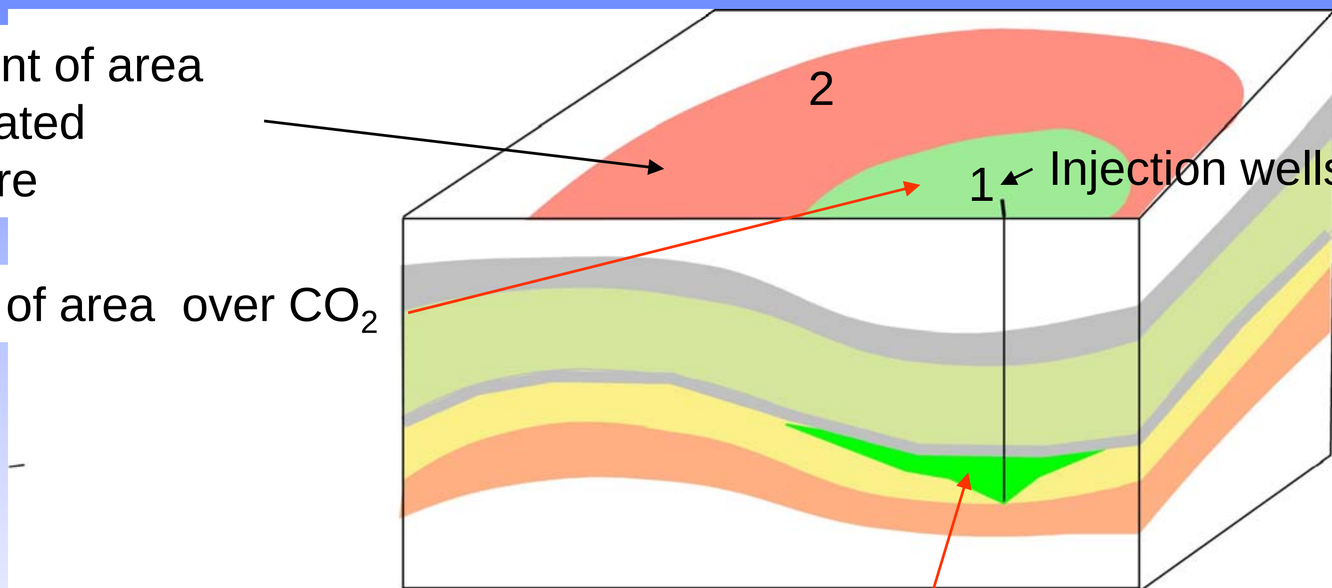
Why is This Novel?

- Modeling CO_2 injection in the subsurface is not novel (Never-the-less many improvements to be made)
- Unprecidented Modelling requirements: Input observations from monitoring to validate predictions of future performance
  - Confirm characterization and model approach – injection can continue
  - Post closure prediction “ approaching stablization”
  - Regulatory environment

Why Model?

- Modeling to predict
  - – Site selection, permitting
- Modeling as an experiment
  - – Injection design, selection of monitoring tools
- Modeling to determine what happened
  - – Observations have been made
    - Is the site performing as required
    - Are predictions correct?

Modeling for Site Selection and Permitting –
Two Areas Predicted - CO_2 and Elevated Pressure



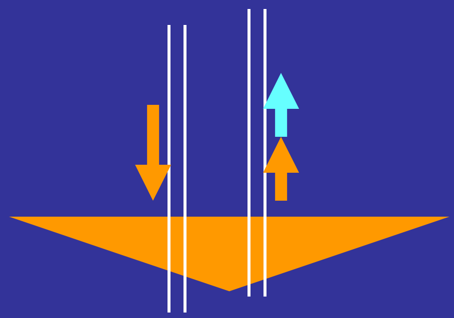
Most workers in CCS are most concerned about area (1).

US regulation traditionally has been concerned about area 1 +2 = Area of Review

Comparing EOR to Sequestration

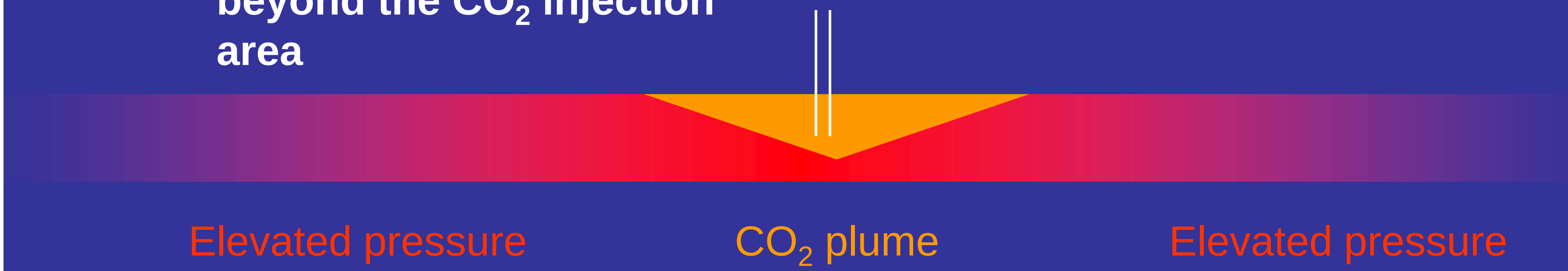
EOR

CO_2 injection is approximately balanced by oil, CO_2, and brine production no pressure plume beyond the CO_2 injection area



Sequestration

(with no production) pressure plume extends beyond the CO_2 injection area



Selection of Monitoring Tools (via modeling)

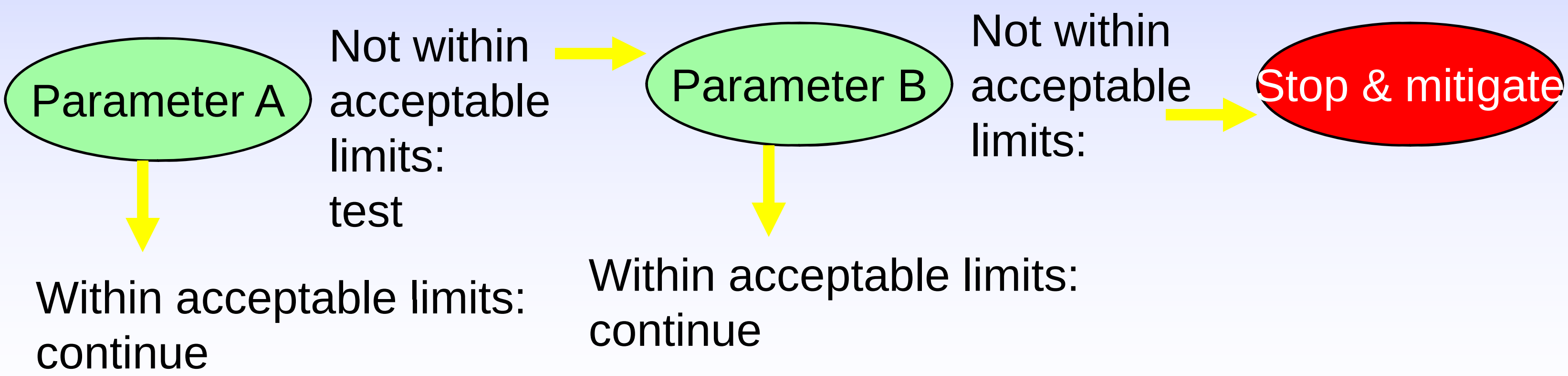
- Selection of monitoring tools
  - Can selected tools show that the site is performing correctly?
    - Numerous model experiments needed - would the expected or possible perturbation of the subsurface be detectable?
  - Would detections adequately constrain model?
    - Explicit statement of assumptions

Correct Performance of Site

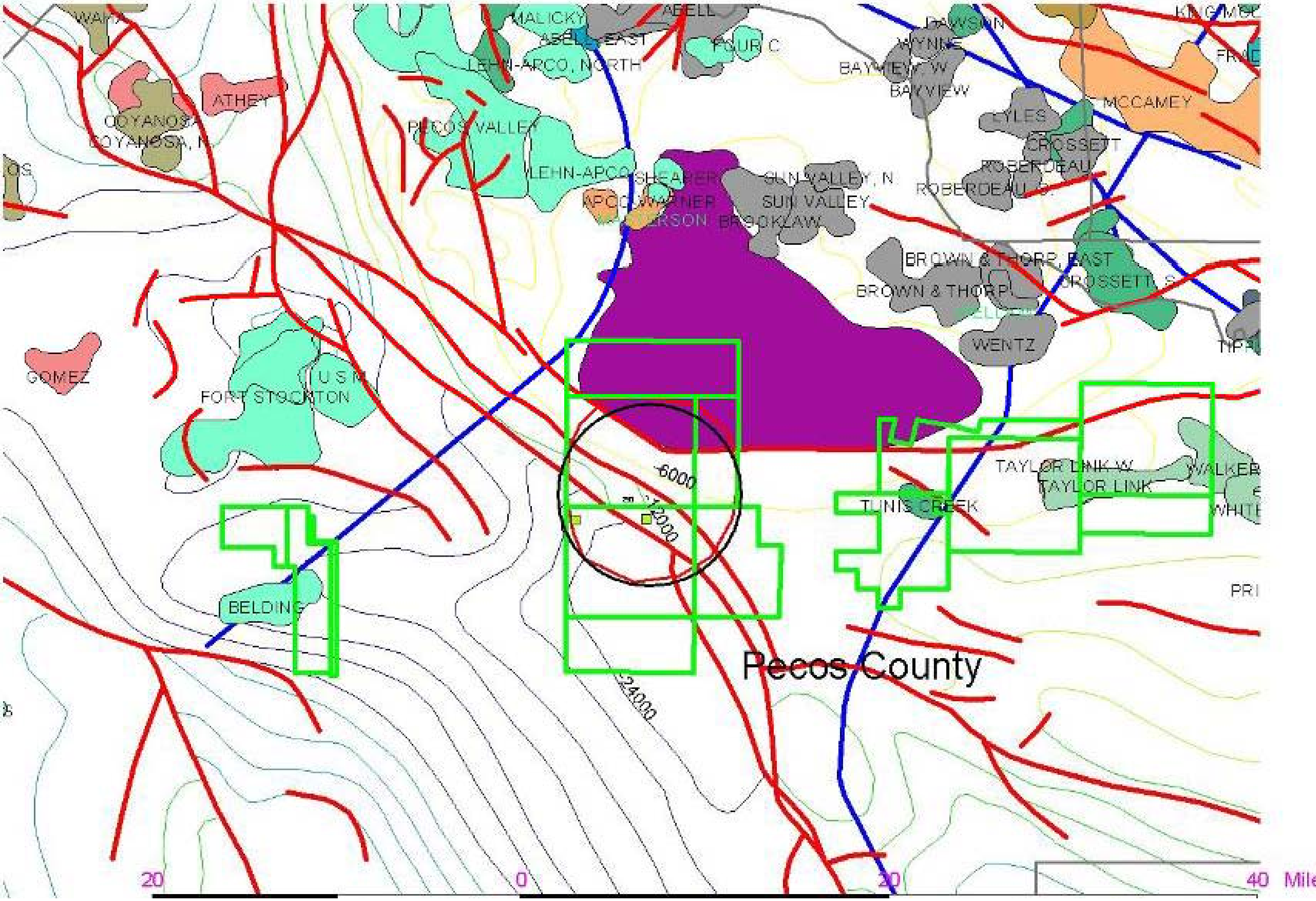
- Limited number of measurements made – how many possible conditions can these measurements fit? (inverse modeling)
- How to cope with miss-matches between expected (modeled) and observed conditions?
  - What parameters count?

Need for Parsimonious Monitoring Program in a Mature Industry or ‘less said, soonest mended”

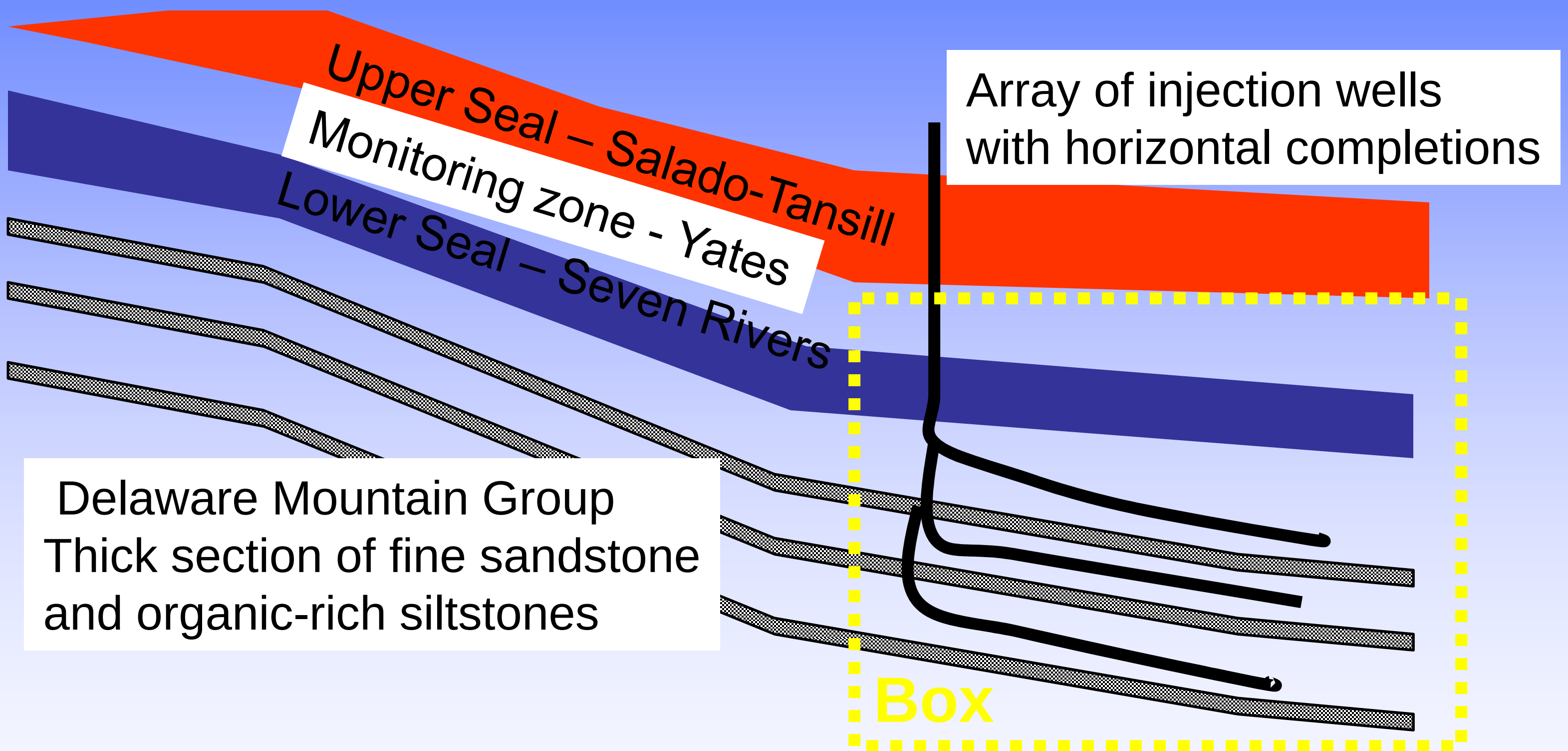
- Standardized, dependable, durable instrumentation
  - reportable measurements
- Possibility above-background detection:
  - Follow-up testing program
  - assure public acceptance and safe operation
- Hierarchical approach:



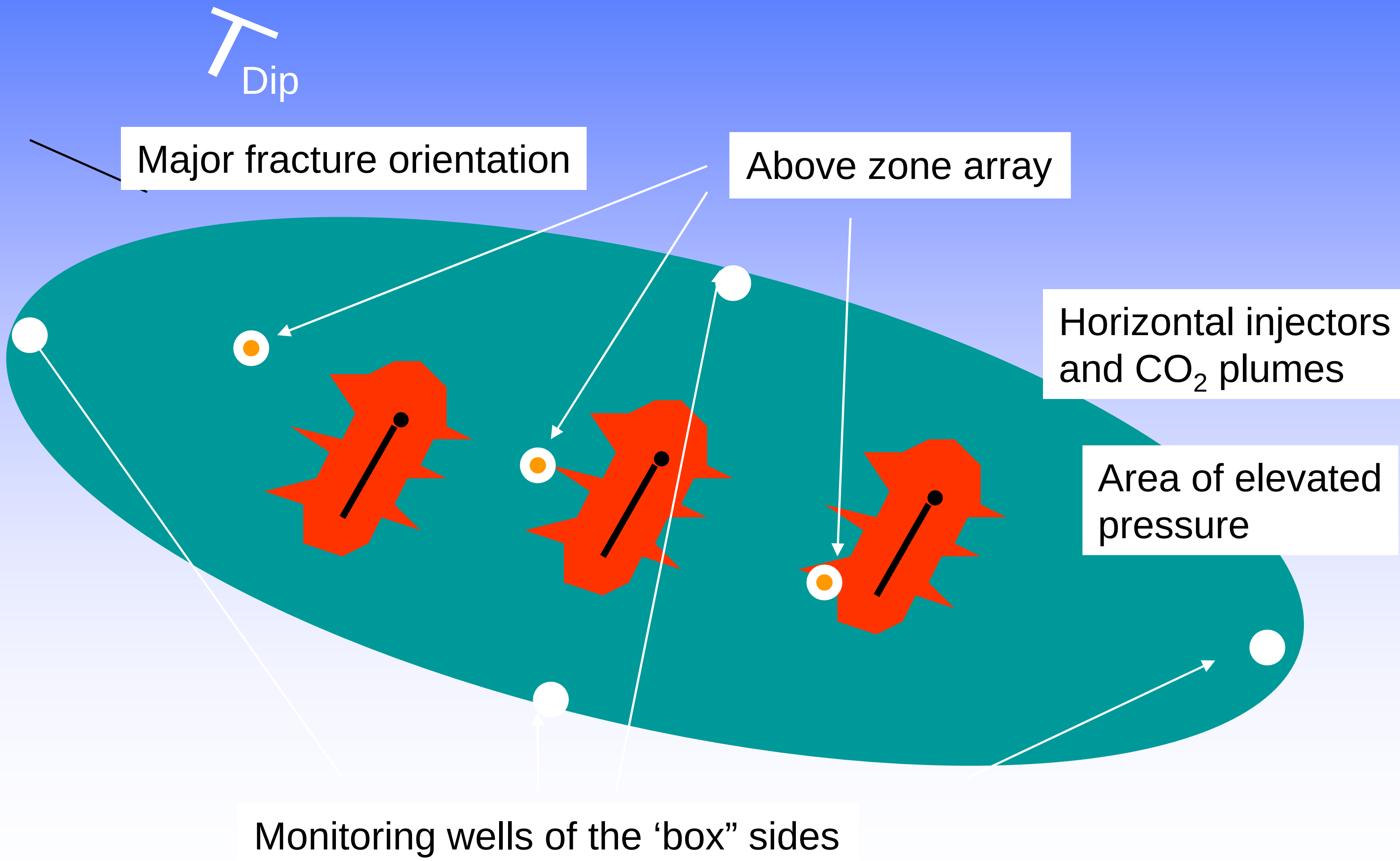
Case example 1 - Dipping saline formation



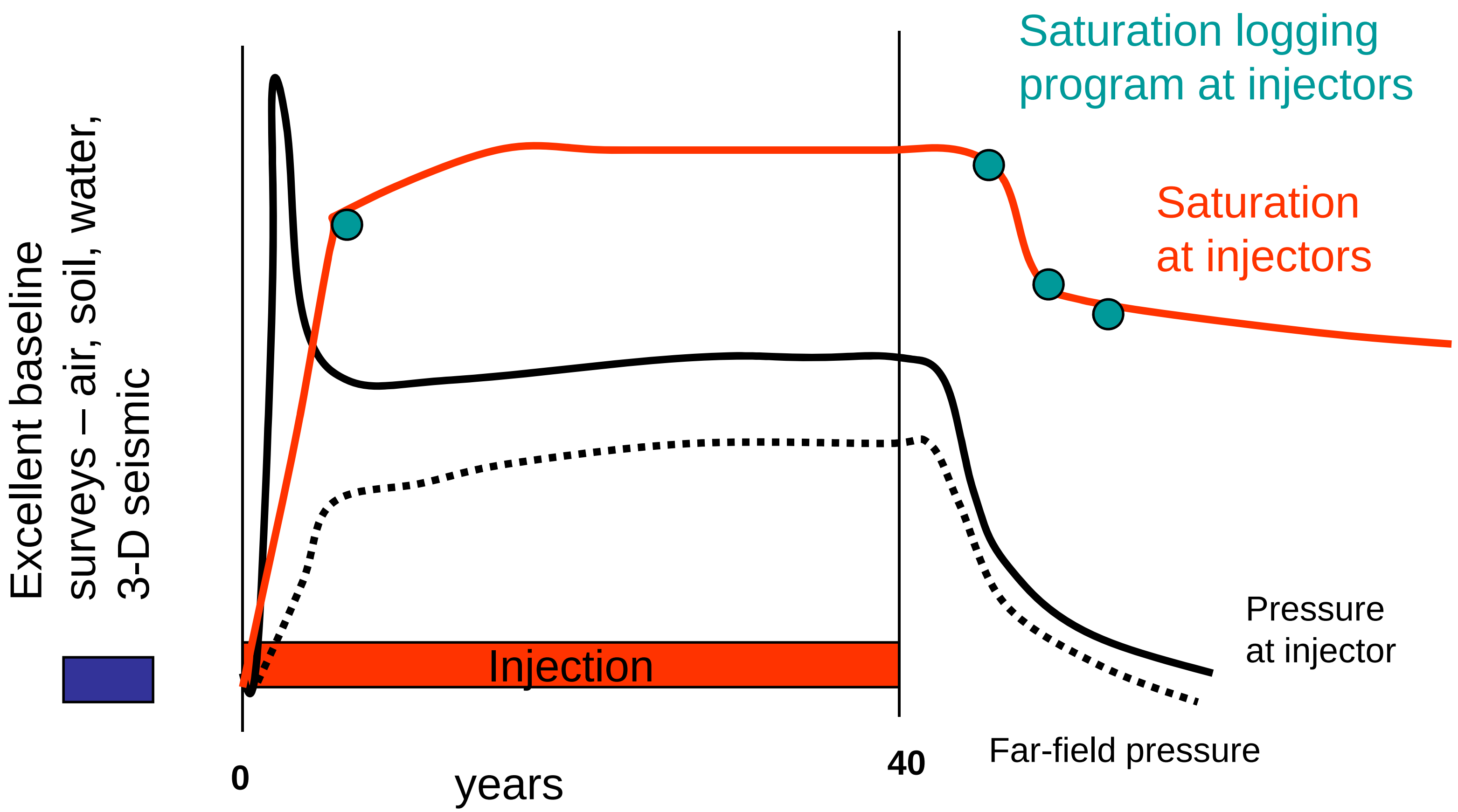
Cross section - Large volume injection proposal



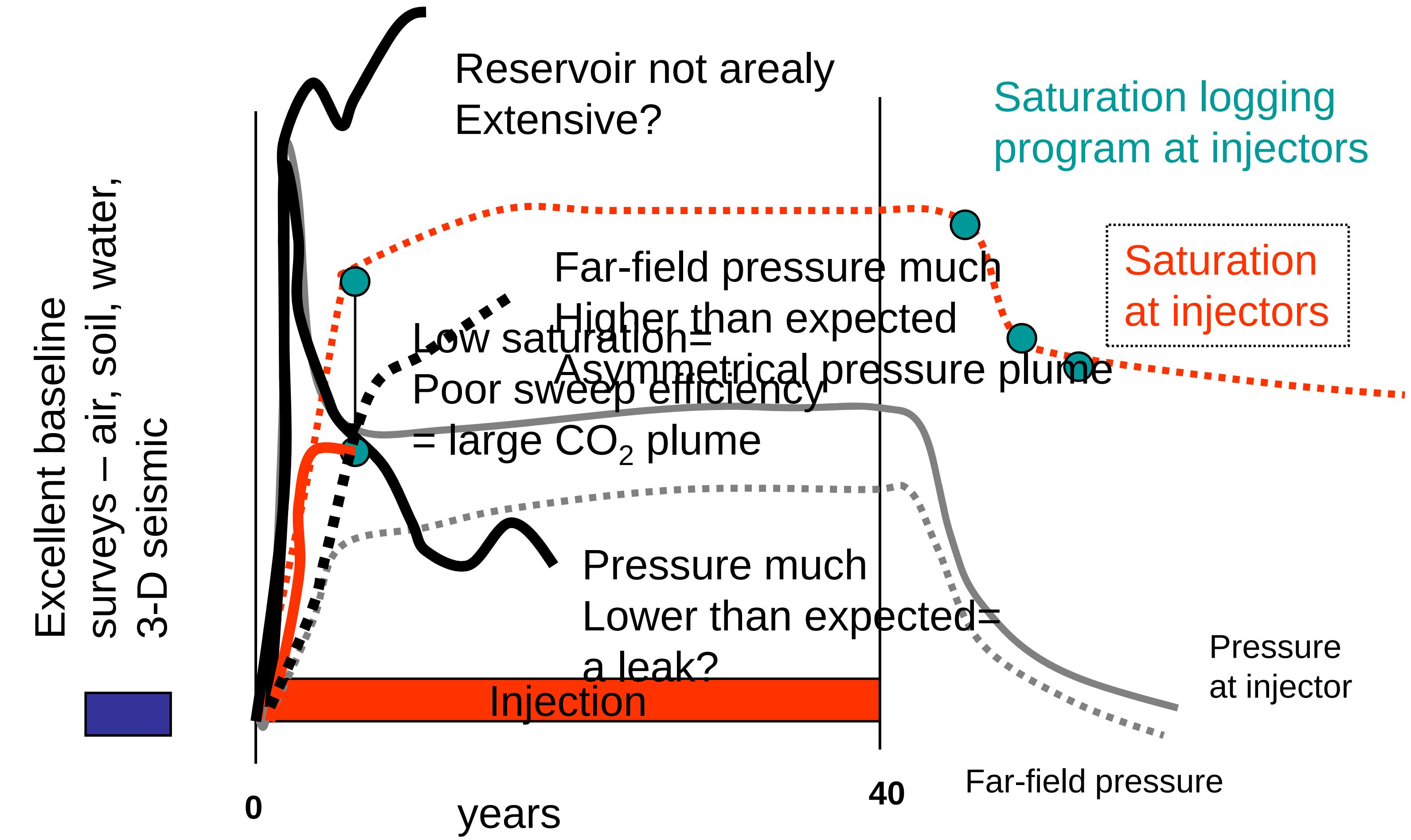
Map view-Large Volume Monitoring Proposal



Monitoring Plan



Monitoring Plan – finds unacceptable response



Next Field Experiment- Cranfield MS, Phase III - 1 MMT/year

(1) Sweep efficiency – how effectively are pore volumes contacted by CO_2?
- High injection rates in brine
- How much CO_2 is dissolved? Compare brine to EOR
- Cross-well program to assess sweep at high injection rates

(2) Injection volume is sum of fluid displacement, dilatancy, dissolution, and rock+fluid compression
- Downhole tilt and micro seismic
- Bottom hole pressure mapping to estimate fluid displacement
- Real-time cross-well program to map plume – pressure relationships

(3) Surface test plan – assess the effectiveness of surface monitoring in an area of deep water table

Conclusions – Model Issues need resolution *

* from the perspective of field observations

- Many forward models
  - Tool sensitivity to expected conditions
  - Tool sensitivity to unexpected conditions
    - Leaks
    - characterization errors and uncertainty
- Many inverse models
  - Observations made, how many realizations can this represent?

Gulf Coast Carbon Center (GCCC)

Gulf Coast Carbon Center

www. gulfcoastcarbon.org

Bureau of Economic Geology

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environmental defense finding the ways that work
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA
The University of Texas at Austin John A. & Katherine G. JACKSON SCHOOL OF GEOSCIENCES

Bureau of Economic Geology -100 Years of Scientific Impact

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

1909-2009

Risk Assessment & Numerical Modeling

Rajesh J. Pawar

Los Alamos National Laboratory

Contributors

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- **External**
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  - University of Utah (Brian McPherson, Weon Shik Han)
  - Harvard

Developing confidence in effectiveness of large- scale geologic storage of CO_2

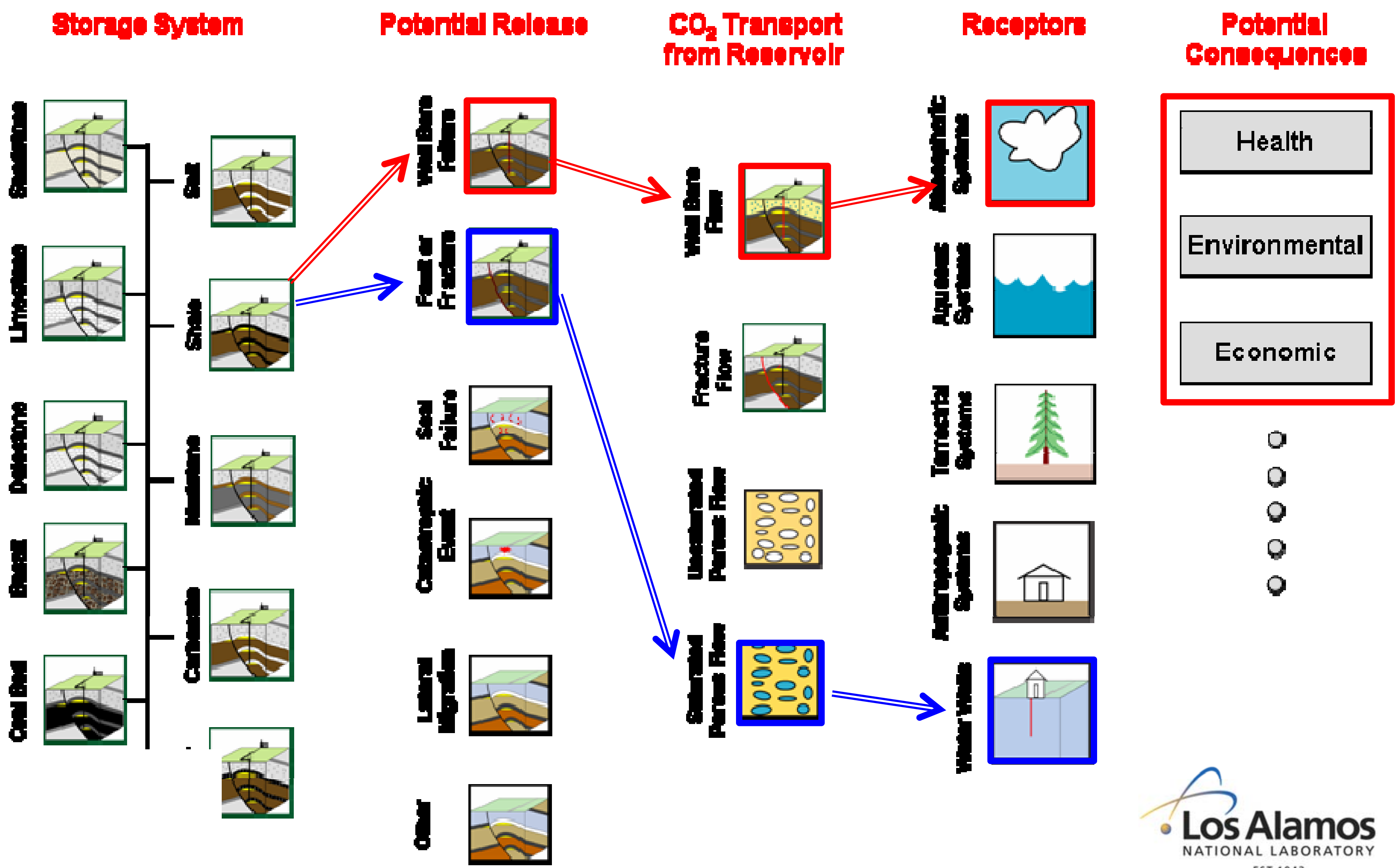
- Need a comprehensive framework/approach to predict long-term performance and quantify risks
  - Must be based on fundamental physical & chemical processes
- Need to take into account various drivers:
  - Effectiveness (capacity, injectivity, long-term storage)
  - HSE Risks
  - Economics
  - Public policy
- Need a systems level description that captures uncertainty and complexity
  - Very little known about saline aquifers
- Need a transparent process for effective communication

Risk Assessment: Some Definitions

- **Features/Events/Processes (FEPs) Analysis**
  - Systematic development of all possible features/events/processes controlling the performance of any natural system
- **Performance Assessment (PA)**
  - Estimates probability of a system exceeding certain performance metric
  - Does not address risk directly
- **Quantitative Risk Assessment (QRA)**
  - Combines performance assessment with consequence analysis
  - Quantifies effect of inherent uncertainties in natural system
  - Allows for decomposition of results into their important contributors

Risk = Event Probability x Event Consequence

CO_2-Prediction of Engineered Natural Sites (CO_2-PENS) framework for geologic storage



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Key aspects of risk assessment

- **What input is needed for risk analysis?**
  - Probabilistic representation of system performance (to be coupled with consequence analysis)
  - What is the risk metric?
- **How do you effectively represent processes and resulting changes?**
  - How does CO_2 migrate and what are the resulting interactions?
- **How do you integrate multiple components (with different physics)?**
  - Single numerical model versus system level model
- **Probabilistic approaches**
  - Capture heterogeneity/uncertainty
- **Identify factors that affect overall risks**
  - Risk management, risk mitigation, monitoring
- **Computational efficiency / simplicity against accurate representation of processes**

CO_2-PENS for comprehensive assessment of sequestration operations

- **At LANL we have developed CO_2-PENS (CO_2-Prediction of Engineered Natural Sites), a science based approach and systems level model, that can be used as part of a comprehensive risk analysis**
  - Simulate CO_2 transport & migration from sources to storage & beyond.
  - Modular, systems level model (components include reservoir, wells, faults, shallow aquifers, atmosphere, etc.)
  - Integrates modules that are governed by different physics and are described by analytical/semi-analytical/detailed numerical models or look-up tables.
    - ECLIPSE, FEHM: reservoir simulators
    - Princeton semi-analytical wellbore model
    - PSU-COMP for coal (in collaboration with NETL)
    - PHREEQC for groundwater chemistry

- Further details:
  - Pawar et al.: 2006 GHGT-8
  - Viswanathan et al: 2008 ES&T
  - Stauffer et al: 2009 ES&T

Examples: CO_2-PENS Application

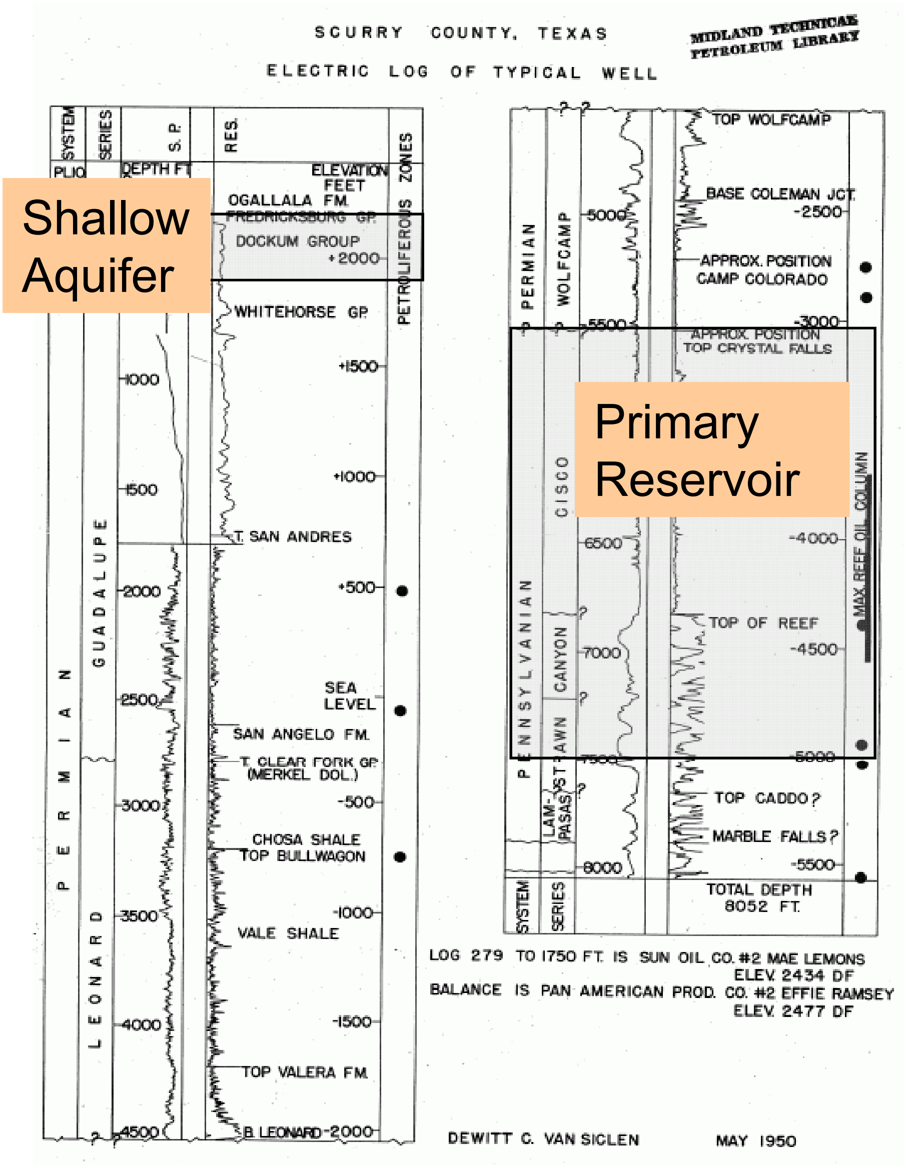
CO_2-PENS application to SACROC: leakage assessment example

- **SACROC is one of several industrial-scale CO_2 storage analogs in the Permian Basin**
  - CO_2 injection since 1972 (oldest operation in US)
  - ~13.5 million tons of CO_2/yr injected (~6-7 million t/yr of new CO_2)
  - ~ 55 million tons CO_2 accumulated
- **Multiple CO_2 sequestration related projects focused around SACROC**
  - LANL in collaboration with Kinder-Morgan has collected the first ever CO_2 exposed cement sample from the field (Carey et al., IJGGC, 2007)
  - SW Regional Partnership is performing monitoring and modeling studies to understand long-term storage related issues
- **This example demonstrates an application of the CO_2-PENS approach**
  - Focused on one of the potential risks in CO_2 sequestration operations: CO_2/brine migration through wellbores and subsequent impact (~ 2000 wells)
  - Inject CO_2 over 50 years, simulate performance for 100 years
  - Assumes all of the existing wells are plugged with cement of uncertain permeability

Pawar et. al: 2008 US DOE CO_2 Conference, Pittsburgh

Stauffer et. al: 2008 AGU Fall Meeting, San Francisco

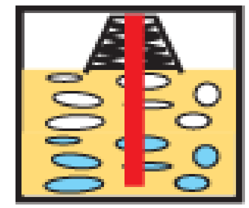
Coupled sub-systems in SACROC CO_2-PENS model



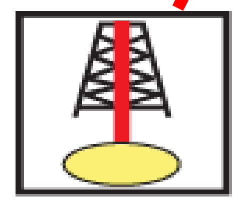
- **Focused on north platform area**
- **Primary reservoir and shallow aquifer separated by thick shale and some intermediate brine aquifers**
- **System model components include:**
  - Target reservoir (Cisco & Canyon)
  - Wellbore
  - Shallow aquifer (Dockum): assumed confined
  - CO_2 migration in intermediate brine aquifers ignored in this example (worst case scenario)

Coupled system level calculations: migration out of reservoir

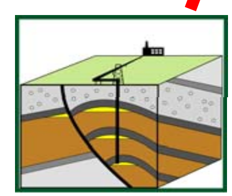
3 Analytical function describes movement of fluids into the shallow aquifer



2 Multiphase wellbore flow model is used to calculate leakage rates



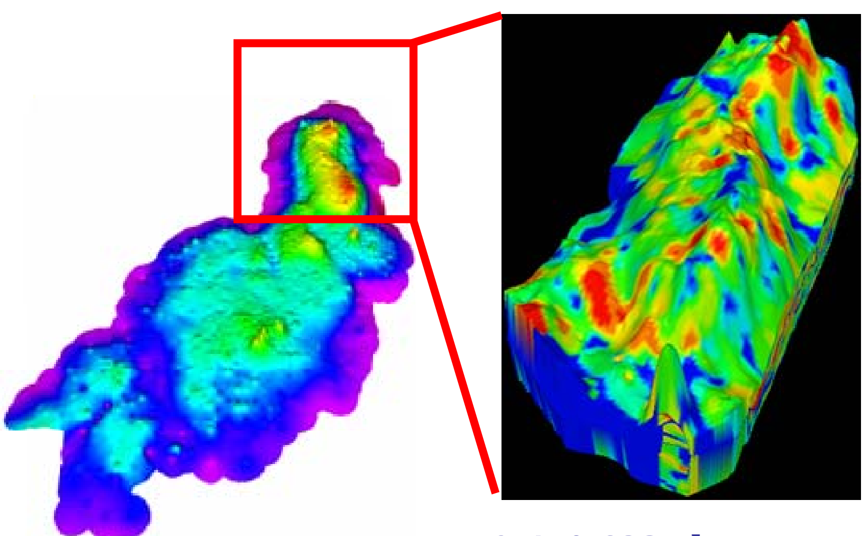
1 Detailed reservoir model predicts pressure and saturation at reservoir/caprock interface



Assume mass traveled across sub-system boundary does not significantly affect mass balance within individual sub-systems

Detailed Reservoir Calculations: CO_2 Injection & Migration

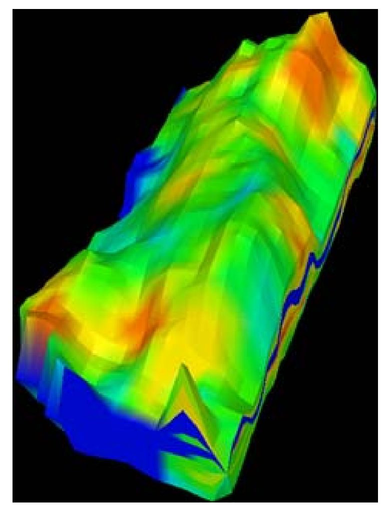
- Reservoir Model (Han & McPherson, AGU 2007)
  - ~32 km^2 areal extent (500m x 500m grid-block size)
  - Detailed characterization and geologic model built by Texas BEG
  - History matched for CO_2 injection and production performance
  - Multi-phase, CO_2 injection 50 years followed by 50 years relaxation
    - 34 injectors, injection pressure constrained @ 50 MPa



9,450,623 elements Mean 5.62E-15 m^2

Std. 4.20E-14

N. Platform Upscaled Model



15,470 elements Mean 5.86E-16 m^2

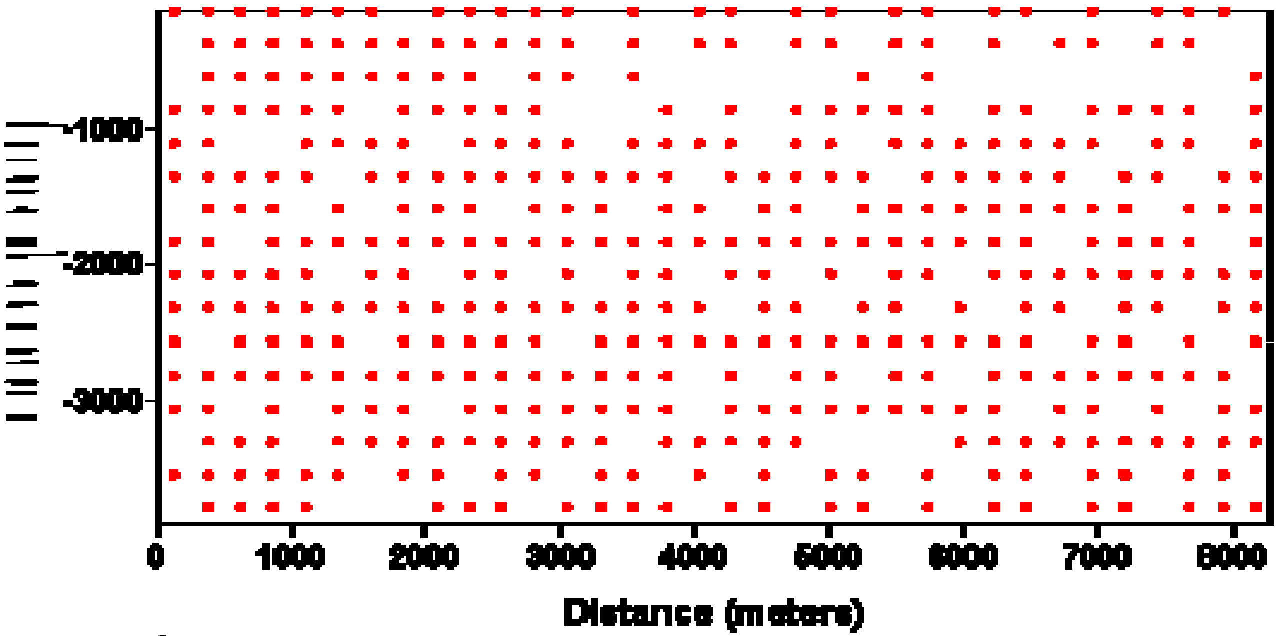
Std. 3.94E-15

Detailed Reservoir Simulation Output: Abstraction

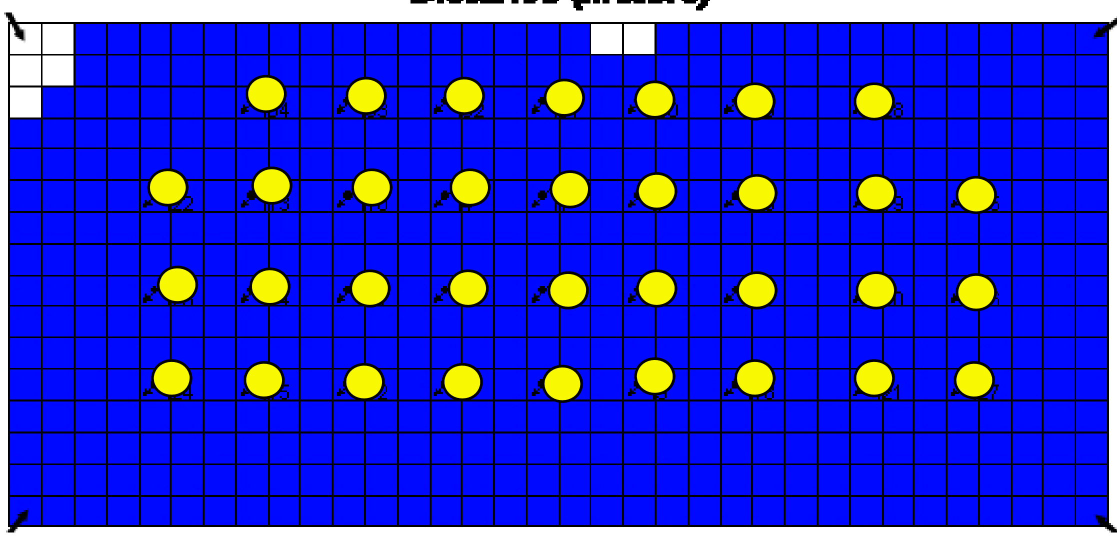
- **P and S at the reservoir/caprock interface (lookup table)**
  - **Each year for the first 10 years to capture pressure wave**
  - **Every 10 year increment to follow saturation to 100 years**
  - **543 grid locations at 20 points in time**
- **Permeability and porosity are also in lookup tables**
- **Uncertainty in these values is included in the System Level by adding in ±20%**

LA-UR-09-00750

At the North Platform of SACROC there are 524 existing wells



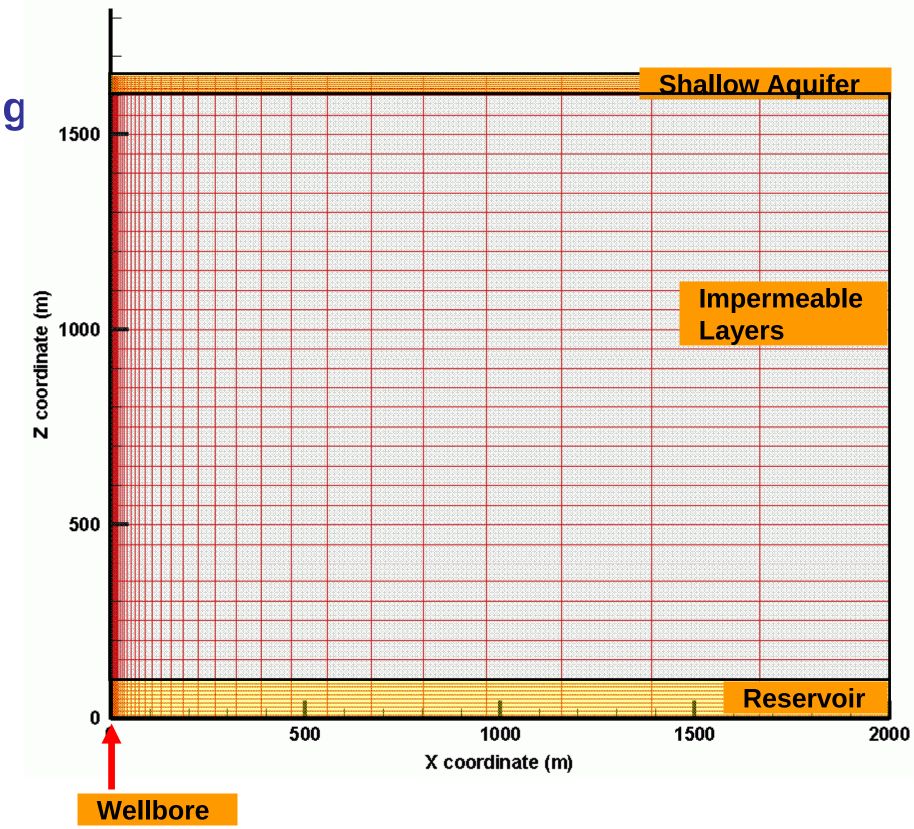
Existing Well Locations

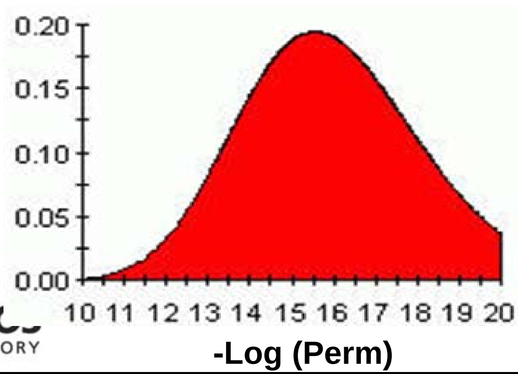


Injection Well Locations

Wellbore Leakage Calculations

- **Wellbore flow modeled using FEHM (LANL's multi-phase fluid flow simulator)**
- **Simulated flow through wellbore including CO_2 phase change**
  - Complex coupled processes including phase change, heat transfer
- **2-D radial grid with 4 inch diameter well with 2 km radial extent**
  - 2 aquifers at top and bottom separated by impermeable layers
  - Wellbore simulated using porous media approximation
- **Model initialized at hydro-stratigraphic equilibrium conditions**
  - 0.6 MPa at top (Gas Phase CO_2)
  - ~16 MPa at bottom (SC CO_2)





Hypothetical Wellbore Permeability Distribution: One measurement on field cement sample Another on way!!

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Abstraction of Wellbore Leakage

- **~150 runs with different starting conditions and parameters**
  - Reservoir pressure (20 MPa – 32 MPa)
  - Reservoir CO_2 saturation (0 – 1)
  - Wellbore permeability (10^{-16} m^2 – 10^{-10} m^2)
  - Reservoir permeability (10^{-14} m^2 – 10^{-12} m^2)
  - Shallow aquifer permeability (10^{-14} m^2 – 10^{-12} m^2)
- **Generated a table of CO_2 & brine mass flow rate in shallow aquifer as a function of all parameters**

Example results of CO_2 Mass Flow (kg/s) for wellbore permeability 10^{-12} m^2

CO_2 Sat ↓ Pressure (MPa) →	20	22	24	26	28	30	32
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2	3.7 e^{-5}	6.1 e^{-5}	7.9 e^{-5}	9.8 e^{-5}	1.2 e^{-4}	1.35 e^{-4}	1.55 e^{-4}
0.4	6.2 e^{-5}	9.5 e^{-5}	1.1 e^{-4}	1.4 e^{-4}	1.6 e^{-4}	2.0 e^{-4}	2.3 e^{-4}
0.6	7.4 e^{-5}	1.1 e^{-4}	1.3 e^{-4}	2.3 e^{-4}	2.4 e^{-4}	3.2 e^{-4}	3.8 e^{-4}
0.8	1.2 e^{-4}	1.7 e^{-4}	2.0 e^{-4}	2.7 e^{-4}	3.3 e^{-4}	4.1 e^{-4}	4.6 e^{-4}
1.0	2.6 e^{-4}	3.9 e^{-4}	5.3 e^{-4}	6.7 e^{-4}	8.1 e^{-4}	9.3 e^{-4}	1.0 e^{-3}

Abstraction of aquifer migration

- **Nordbotten analytical solution**
  - Gives plume radius and thickness as a function of injection volume

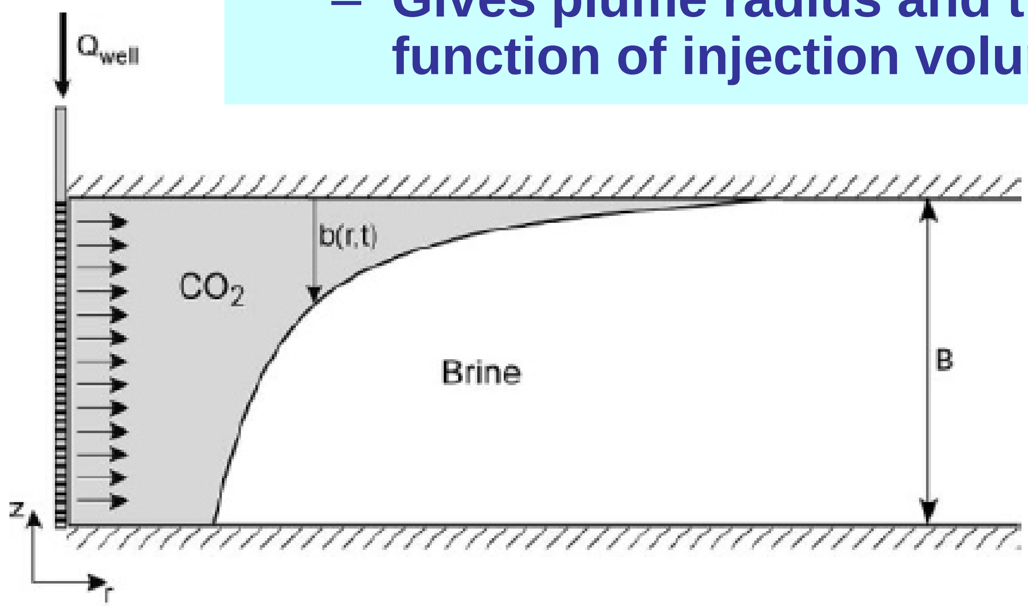


FIGURE 3. Schematic of sharp-interface representation of injected CO_2 plume. (Nordbotten et al., 2005 ES&T)

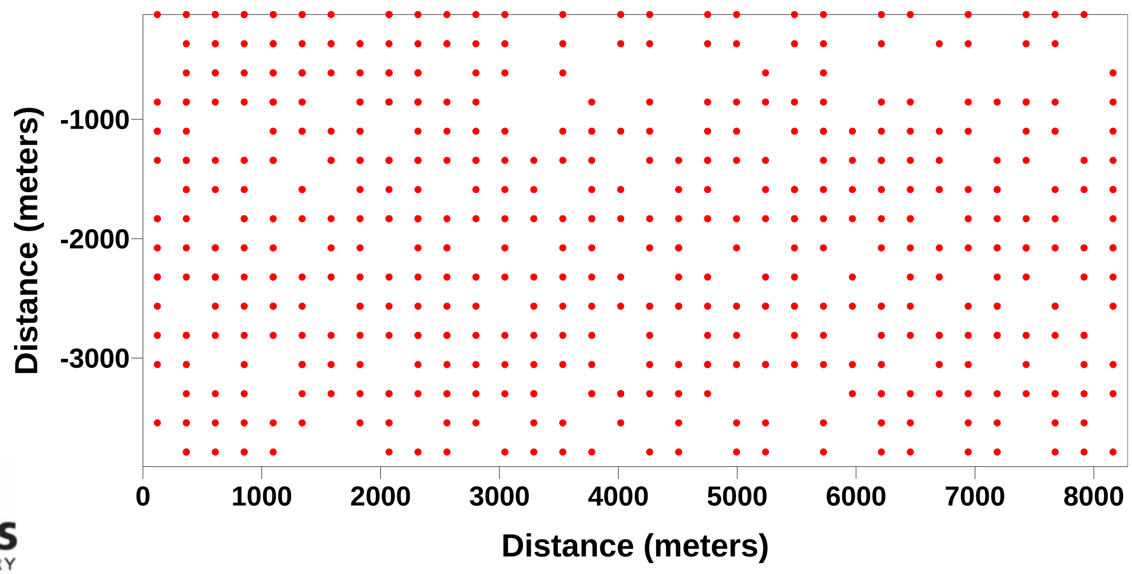
$$\lambda = k_{rel}/\mu$$

$$r = \sqrt{\frac{\lambda_c V_t}{\lambda_w \phi \pi B}}$$

$$b(r,t) = B\left(\frac{1}{\lambda_c - \lambda_w}\right)\left(\sqrt{\frac{\lambda_c \lambda_w V_t}{\phi \pi B r^2}} - \lambda_w\right)$$

Coupled calculations

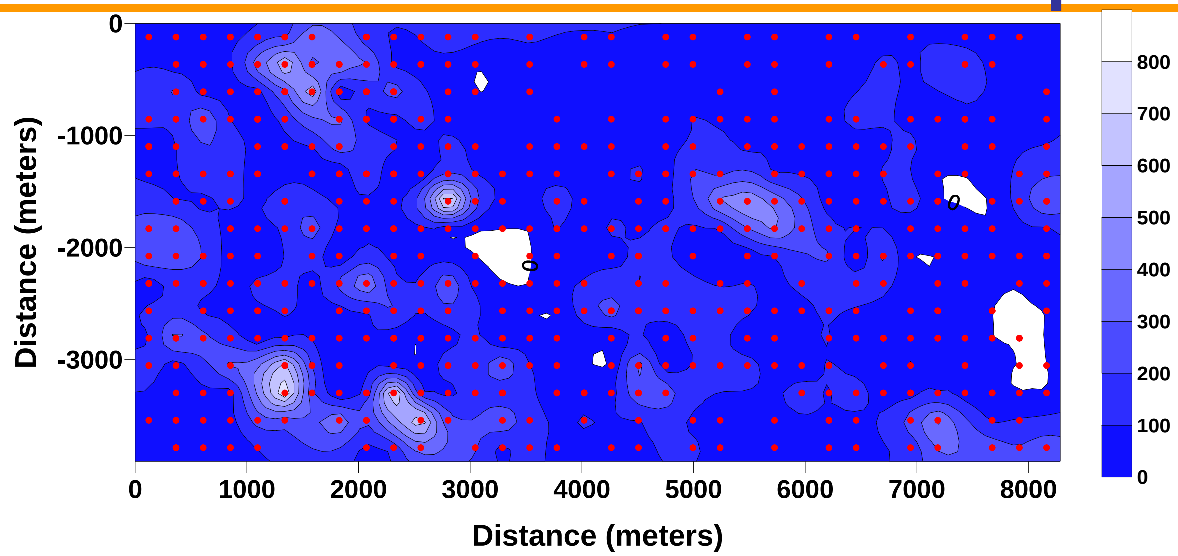
- Monte Carlo simulations: 1000 realizations, Latin Hyper Cube sampling of uncertain variables
- Uncertain variables:
  - Reservoir pressure, permeability, and saturation are assigned 20% variability to account for reservoir uncertainty
  - Wellbore permeability: only one field measurement (10^{-16} m^2), assigned a hypothetical distribution
  - Shallow aquifer uncertainty in thickness, permeability, and porosity



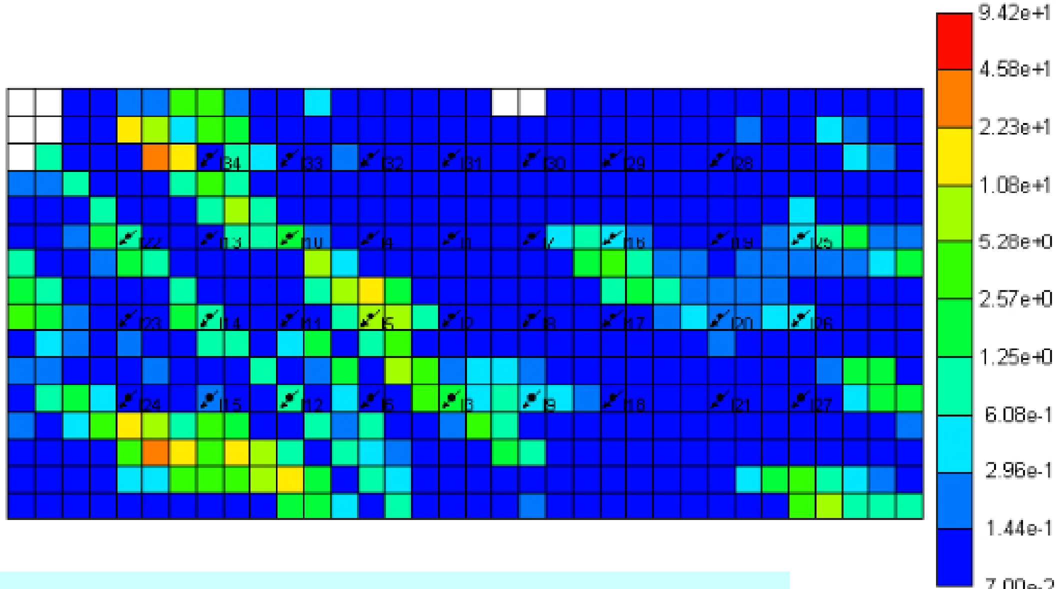
524 existing wells in the model domain

LA-UR-09-00750

Spatial variability in predicted rate of BRINE flow in shallow aquifer



Mean Leak Rate (kg/yr)

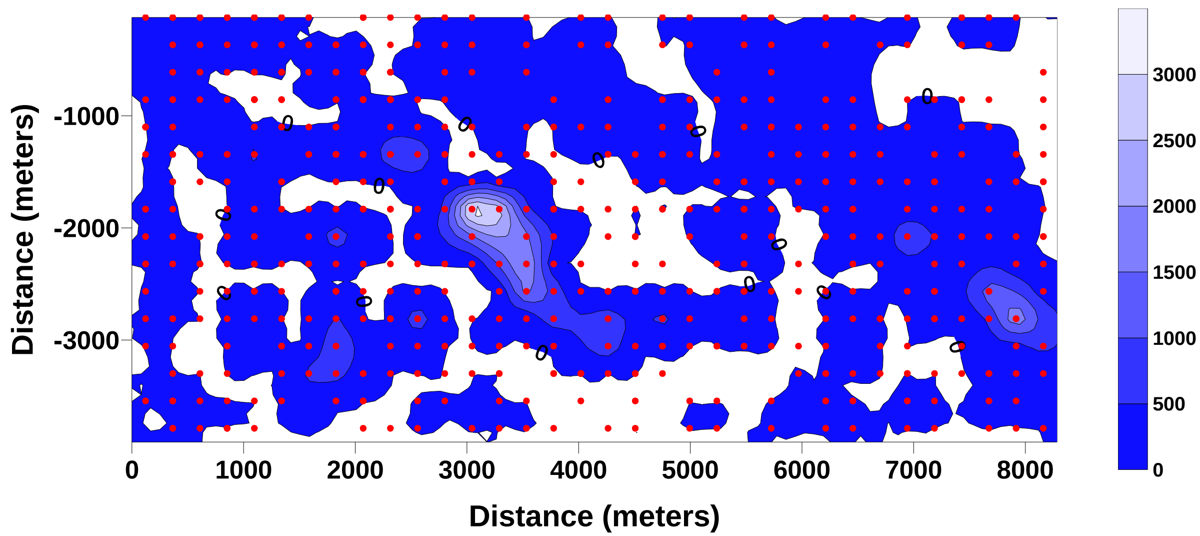


Caprock Interface Permeability md

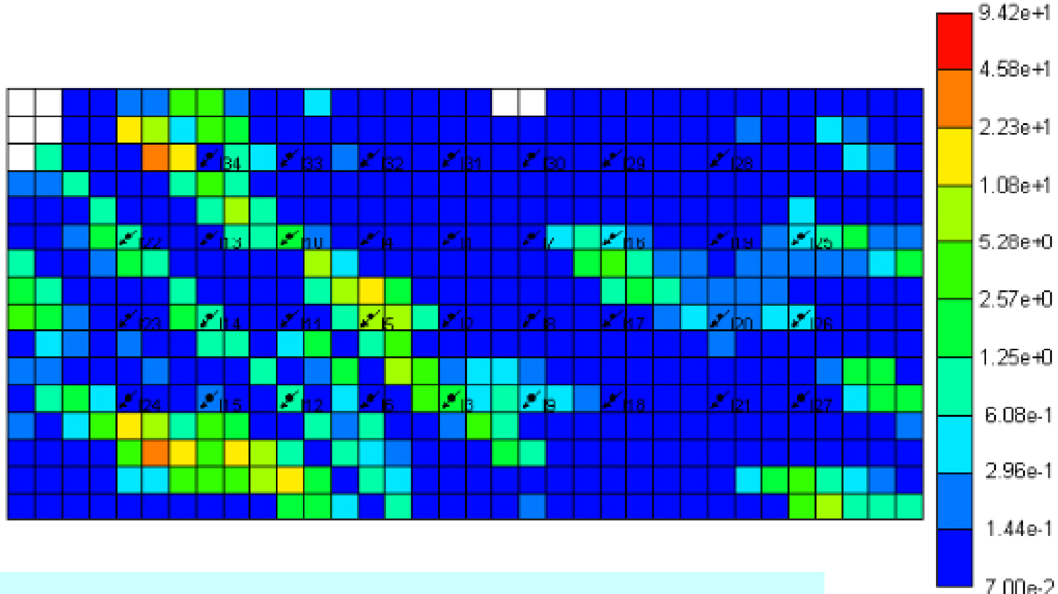
Los Alamos

Brine flow depends mainly on caprock permeability

Spatial variability in predicted rate of CO_2 flow in shallow aquifer

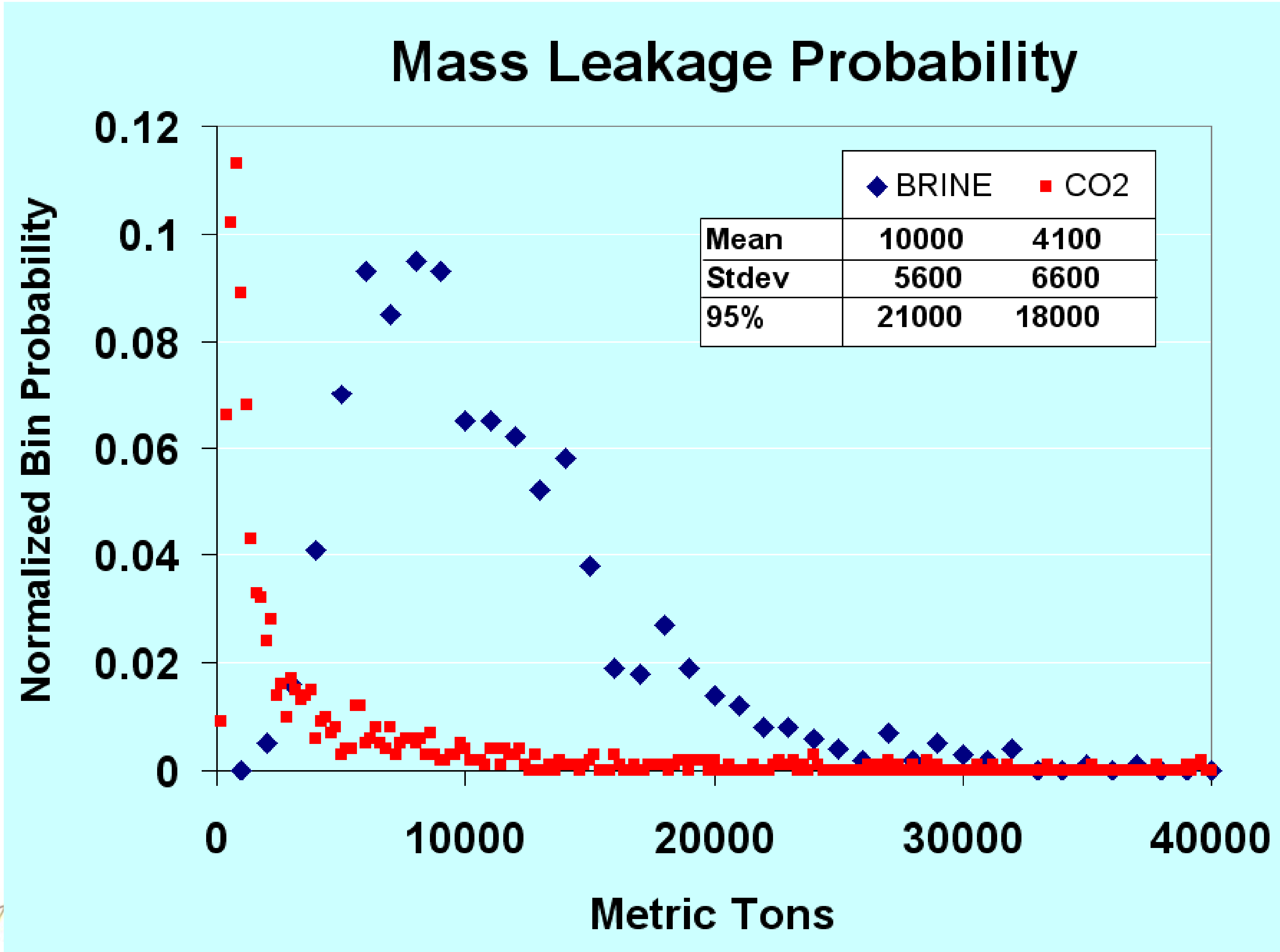


Mean Leak Rate (kg/yr)



Caprock Interface Permeability md

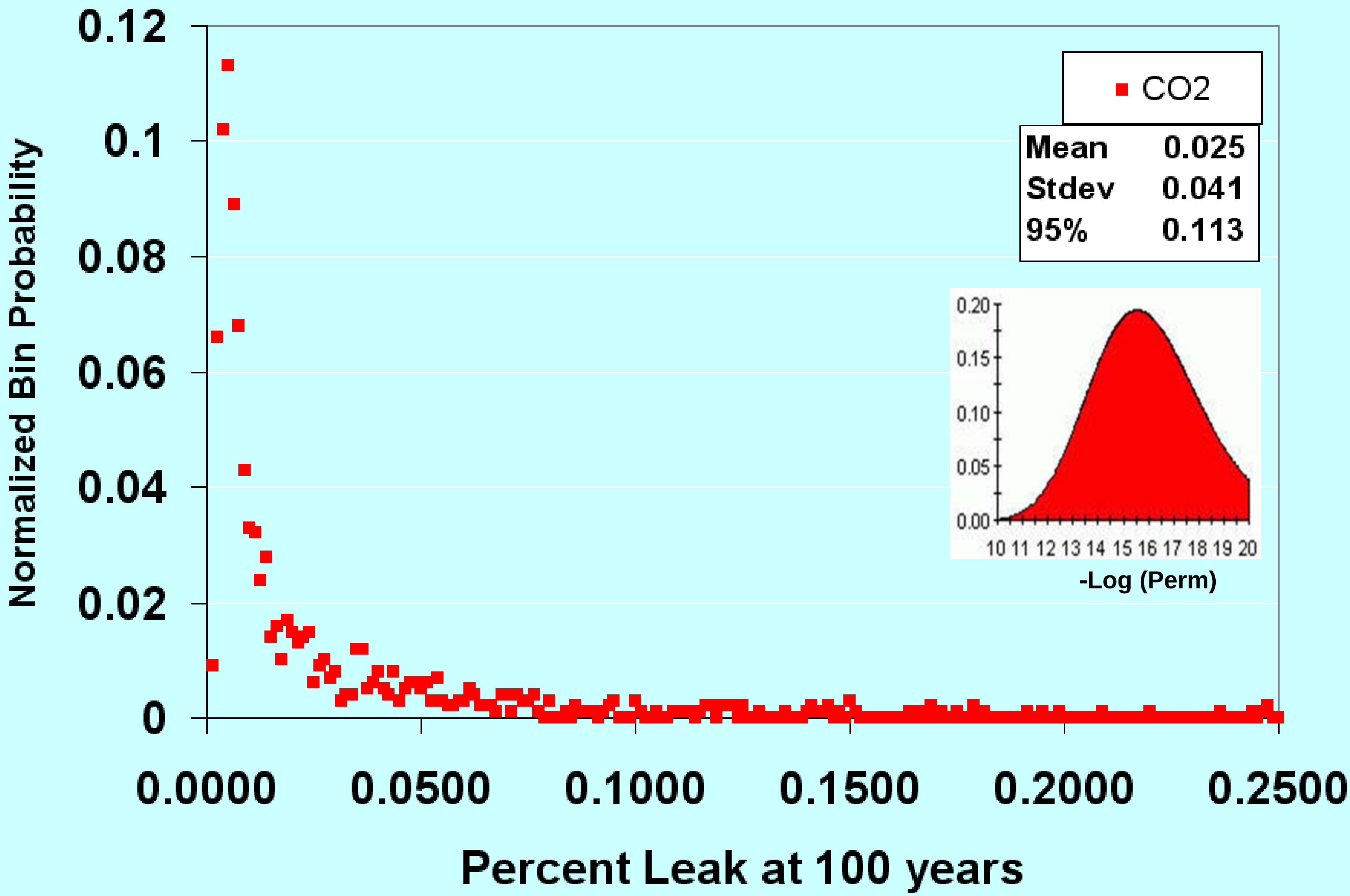
CO_2 leakage depends on cap geom, perm, and sat



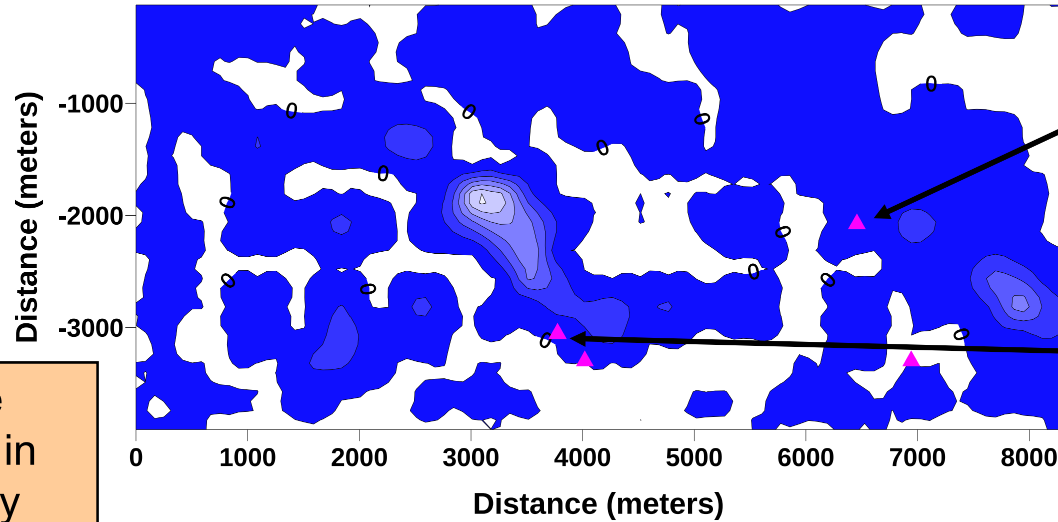
Mass Leakage Probability
Normalized Bin Probability
Metric Tons
0.12
0.1
0.08
0.06
0.04
0.02
0
0
10000
20000
30000
40000
BRINE
CO2
Mean 10000 4100
Stdev 5600 6600
95% 21000 18000

EST.1943

Mass Leakage: Percent Injected CO_2



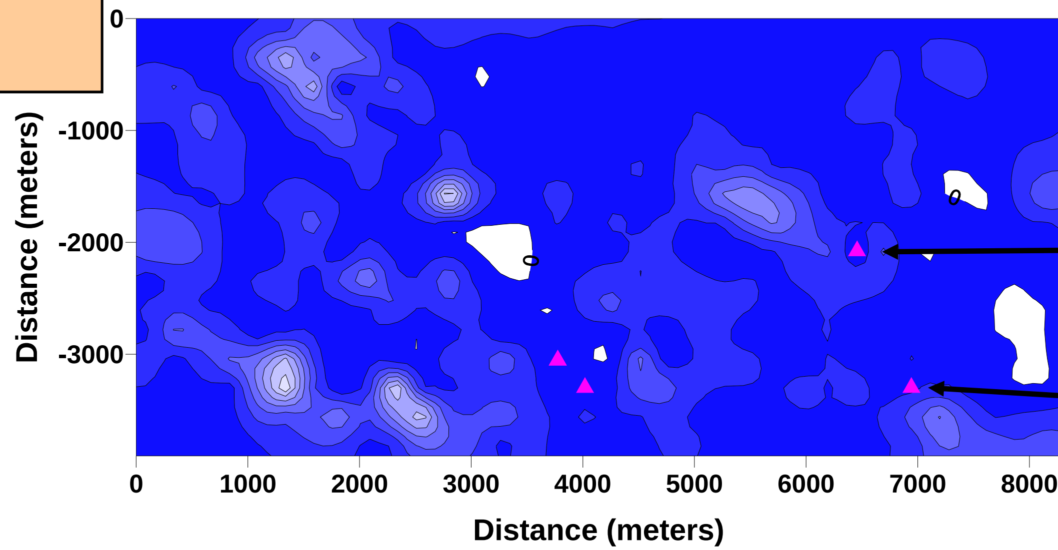
Impacts: Locations of shallow wells in the vicinity of leaked Brine & CO_2



Shallow Wells

Should be monitored for potential CO_2 impact

Region that should be monitored for change in groundwater chemistry due to CO_2 and brine could be different

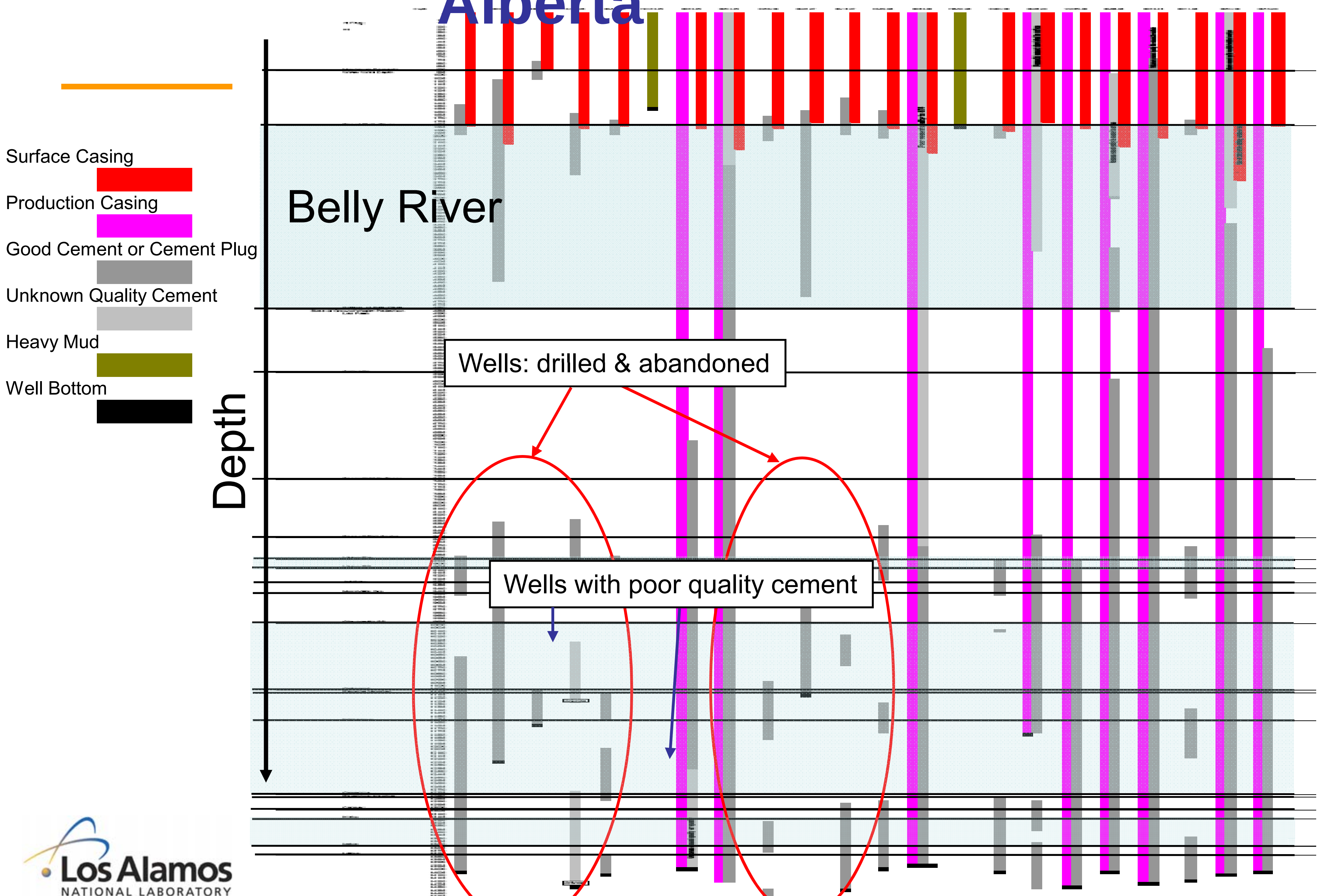


Should be monitored for potential brine impact

Los Alamos NATIONAL LABORATORY EST.1943

Things are never simple !!

Example Well Tracks at a Site in Alberta



Acknowledgement

Development of CO_2-PENS has been supported by US-DOE through the Zero Emission Research & Technology (ZERT) project

Q: How can models be used?

Monitoring	Risk Assessment
•How the system behaves at depth: Where to look for it • Will the monitoring tool be able to see the CO_2 : eg. Fluid substitution modelling for 4D seismic response •Has it stayed in place: Storage inventory assessment •Helps you plan the cheapest, most efficient monitoring options	**Performance** modelling feeds the RISK ASSESSMENT RISK ASSESSMENTS guide the questions you ask of your models, and which models are important, what uncertainties are important.

Q: How confident are we in the results?

A: Crap question! What results?

Why are we monitoring? What input from modelling?

- Have to understand the purpose of monitoring
- Satisfying regulatory requirements
- Verify performance
- Modelling helps designing and deciding monitoring
- Monitoring data helps refine/revise models
- Need to model the sedimentary succession from the immediate caprock to the ground surface
- Make sure no impact on potable aquifers
- Need to know the hydrogeology of the shallow aquifers
- Modeling can tell how often you need to monitor and where (frequency and location of monitoring) and which monitoring methods to use
- You reach confidence through your model, then monitoring observations give you some constraints

How confident are we with model predictions?

- We are not confident enough
- We are confident about our models and our science, not about parameters
- We are confident if joint modelling and monitoring approach
- Relationship between level of confidence and level of complexity (goes up and down)
- Oil industry has learnt not to be too confident on models, scenarios approach, models always updated

Modelling & Risk Assessment

- Risk assessment should use their proper models – with probabilities and consequences

In An "IDEAL" World

monitoring surveys continuous, with initial frequency established by site selection process…

…*as* more monitoring and characterization data gathered, *model resolution increases*

…*as* model resolution increases, simulation results used to guide *improvement of monitoring design*

…*as* model results and monitoring design become more effective, uncertainty associated with probability of FEPs will decrease, *PDFs better defined, and risk profiles (values) better resolved*

…*as* risk profiles become better defined, injection design and engineering can be modified to *improve and optimize - risk reduced*

…*as* risk profiles better defined and risks reduced, monitoring strategy can be tailored to reflect more focus on areas of greater relative risk *(devote fewer resources to areas of lower risk)*

Limitations of Ideal World Scenario

•Too many degrees of freedom, if matching doesn't happen, you will have as many opinions as those involved in discussion,

•Some outcomes may be acceptable, if they are broadly compatible with initial model predictions,

•Model could suggest range of acceptable outcomes, rather than exactly what WILL happen,

•Regulators and public will want to know where the CO_2 is, and this is possible, quantification is a different issue,

•Cannot minimise variation, but can reduce uncertainty,

Limitations of Ideal World Scenario

Risk	Uncertainty
Free Gas, High	Footprint – No, Mass Balance - Yes
Dissolved gas, Low	Distribution - Yes
Everything else, too small to worry about	How much and where - Yes

Breakout Group 3

- How confident are we with model predictions?
  - A range of confidences...
  - Model results are predicated on monitoring technologies,
  - Monitoring technologies are subject to limitations,
  - Must explicitly state assumptions,
  - Describe what model does not inform about,
  - Predictions at each stage should indicate what measurements would be 'surprising' and what would be within the range of modelling uncertainties, consistent with the conceptual models employed,
  - Iterations of the prediction-measurement cycle should result in measurements being consistently unsurprising before the case can be made to walk away from the site,

Session 4 Breakout

Breakout Group 4

- Regulators: what could go wrong – loss of containment
- Modelling can be used in case of failures. How is this defined? E.g. Earthquake, extreme events
- Initial model for plume extension to define monitoring, importance to baseline
- US partnerships – qualitative FEP analysis

- Monitoring linked to risk analysis
- Weyburn FEP analysis. What is meant by ‘long term’?
- CO_2-PENS attempts to quantify leakage
- Shell project qualitative leakage pathways and ‘stacking’
- Impurities?
- Probabilistic aspect of risk

- Risk versus performance
- Confidence levels for modelling
- Problem of compartmentalisation, e.g. How to quantify risks to shallow groundwater
- Problems of uncertainty
- Risks resulting from brine displacement pressurisation

IEA Greenhouse Gas R&D Programme

IEA GHG Monitoring Network

CO_2 Geological Storage Modelling Workshop

Orleans, France, February 2009

CO_2 Storage Monitoring

- Can be deep focussed (performance) or shallow (leakage/impacts)
- Required during various phases and for different storage scenarios
- Required for stakeholder confidence, regulatory approval and verification

History of Monitoring Network

- First meeting held in California, 2004
- Subsequent annual meetings:
  - Rome, 2005
  - Melbourne, 2006
  - Edmonton, 2007
  - Joint network meeting, New York 2008
- Next meeting: Japan, June 2009

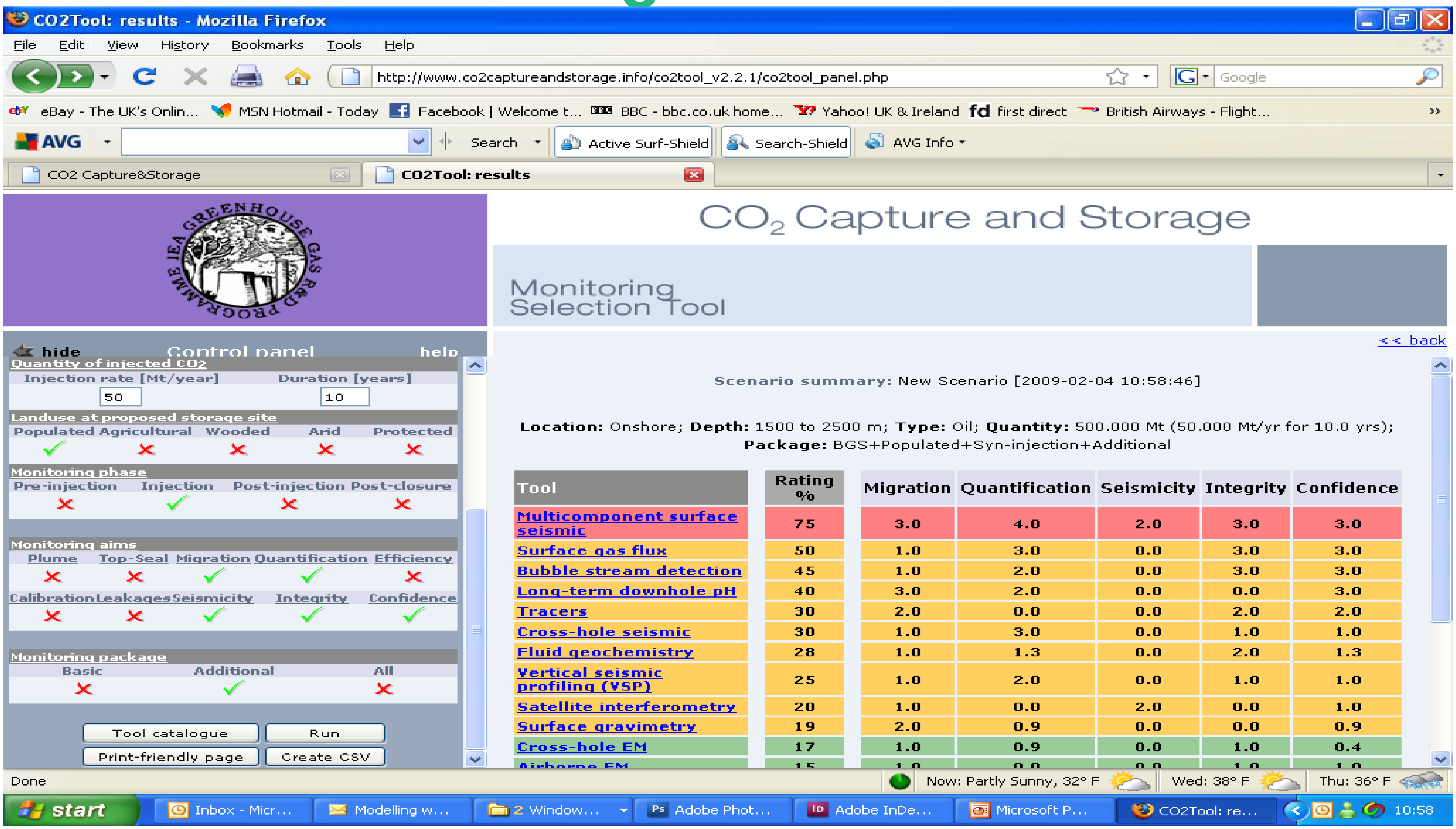
Aims and Objectives

- Overall aims:
  - Facilitate exchange of ideas between experts
  - Improve design and implementation
- Specific objectives:
  - Determine accuracy, applicability and limitations of existing and new techniques
  - Disseminate information from R&D and pilots
  - Develop monitoring guidelines

Range of Available Tools

- First network meeting identified a large range of monitoring tools available
- Subsequent discussions focussed on integration of techniques into programmes
- Confidence building and cost considerations
- Web based Monitoring Selection Tool (BGS)
- www.co2captureandstorage.info

Monitoring Selection Tool



Tool	Rating %	Migration	Quantification	Seismicity	Integrity	Confidence
Multicomponent surface seismic	75	3.0	4.0	2.0	3.0	3.0
Surface gas flux	50	1.0	3.0	0.0	3.0	3.0
Bubble stream detection	45	1.0	2.0	0.0	3.0	3.0
Long-term downhole pH	40	3.0	2.0	0.0	0.0	3.0
Tracers	30	2.0	0.0	0.0	2.0	2.0
Cross-hole seismic	30	1.0	3.0	0.0	1.0	1.0
Fluid geochemistry	28	1.0	1.3	0.0	2.0	1.3
Vertical seismic profiling (VSP)	25	1.0	2.0	0.0	1.0	1.0
Satellite interferometry	20	1.0	0.0	2.0	0.0	1.0
Surface gravimetry	19	2.0	0.9	0.0	0.0	0.9
Cross-hole EM	17	1.0	0.9	0.0	1.0	0.4
Airborne EM	15	1.0	0.0	0.0	1.0	1.0

Future Network Focus

- Results from pilots and demonstration projects
- Update Monitoring Selection Tool
- Potential for accurate quantification
- Maximisation of data derived from seismic surveys and integration with other techniques
- Adequacy of monitoring techniques
- Duration of post-injection monitoring

IEA GHG Wellbore Integrity Network

CO_2 Geological Storage Modelling Workshop
Orleans, France, February 2009

History of Wellbore Integrity Network

- First meeting held in Houston, USA, 2005
- Subsequent annual meetings:
  - Princeton, USA, 2006
  - Santa Fe, USA, 2007
  - Paris, France, 2008
  - Joint network meeting, New York 2008
- Next meeting: Calgary, Canada, May 2009

Aims and Objectives

- Long term network objectives:
  - Determine impact of CO_2 interactions with wellbore materials,
  - Bring together experts working in area,
  - Determine current level of understanding,
  - Collect and assess experience from lab and field studies,
  - Provide guidance on policy and regulation development for wellbore performance.

Age, Quantity and Quality of Wells

- Issues identified include levels of knowledge and number of old wells:
  - Texas: Over 1 million wells, some limitations to data,
  - Alberta: Over 300,000 wells, good data repository.
- Legislation aims:
  - Historically legislation did not consider CCS, therefore completion and abandonment procedures not necessarily best practice for CO_2 containment,
  - New wells, purpose built, and abandoned in line with CCS security objectives

Wellbore Performance

- Differences between laboratory and field studies still evident, but gap is becoming narrower,
- CO_2 resistant cements, although more expensive options, provide great improvements in wellbore integrity.
- It is hoped that future development of resistant cements will lower the costs involved and result in more widespread use.

2009 IEA GHG Study on Wellbore Integrity

- Study being undertaken by TNO,
- Reviewing abandonment practices around the world,
- Recommending a best practice for abandonment,
- Will be presented at the Wellbore Integrity Meeting in Calgary,
- Published later in 2009.

Future Network Focus

- Recommendations came from the 2008 Joint Network Meeting,
- Network to discuss future at Calgary meeting, to determine best way forward,
- Focus for 2009 meeting on new results and previously un-presented work.

IEA GHG Risk Assessment Network

CO_2 Geological Storage Modelling Workshop
Orleans, France, February 2009

History of RA Network

- First meeting held in Netherlands, 2005
- Subsequent annual meetings:
  - California, 2006
  - London, 2007
  - Joint network meeting, New York 2008
- Next meeting: Melbourne, April 2009

Aims and Objectives

- Overall aim:
  - Facilitate exchange of ideas between experts
- Specific objectives:
  - Allow RA approaches to be compared
  - Forum for international collaboration
  - Identify knowledge gaps and R&D required
  - Maintain dialogue with regulators

CO_2 Storage Risk Assessment

- Risk can be defined as the product of the probability of an adverse event occurring and the severity of the impact that would result
- RA provides structured assessment framework
- In the context of CO_2 storage, RA needs to demonstrate safety and acceptable environmental impacts
- Present knowledge restricts use of quantitative RA

Risk Management

- Frameworks can involve several stages, e.g.
  1. Hazard identification (scenarios)
  2. Hazard assessment (review of hazards)
  3. Risk estimation (leakage probability/rates and impacts)
  4. Risk evaluation (magnitude and consequence)
  5. Risk control
- Risk Assessment = stages 1 to 4
- Risk Reduction = stages 4 to 5

Natural Analogues

- Important for confidence building in storage: communicating the safety of storage
- Understanding of trapping and leakage
- Verification of modelling
- Interpretation and risk management

Natural Analogues

CO2 leaks, what are they like and where do we find them?

- spot like
- localised along faults (preferentially at the intersection of fractures / faults)

Gas vent at Latera caldera

2006 IEAGHG Study on RA

- Study sought feedback on RA from regulators
- Briefing document supplied with questionnaires
- Main findings:
  - RA will be key requirement of regulations
  - Storage RA needs to predict long timescales
  - Quantification of seepage rates may be needed, linked to receptors and impacts
  - No consensus on RA methodology

Future Risk Network Focus

- Standardised terminology
- RA guidelines/best practice
- Environmental impact assessment
- Wider risk management, including mitigation
- Duration of post-injection monitoring
- Regulatory perspectives

Session 5 Breakout

- Your ideas on aims, objectives and next steps for IEA GHG modelling network

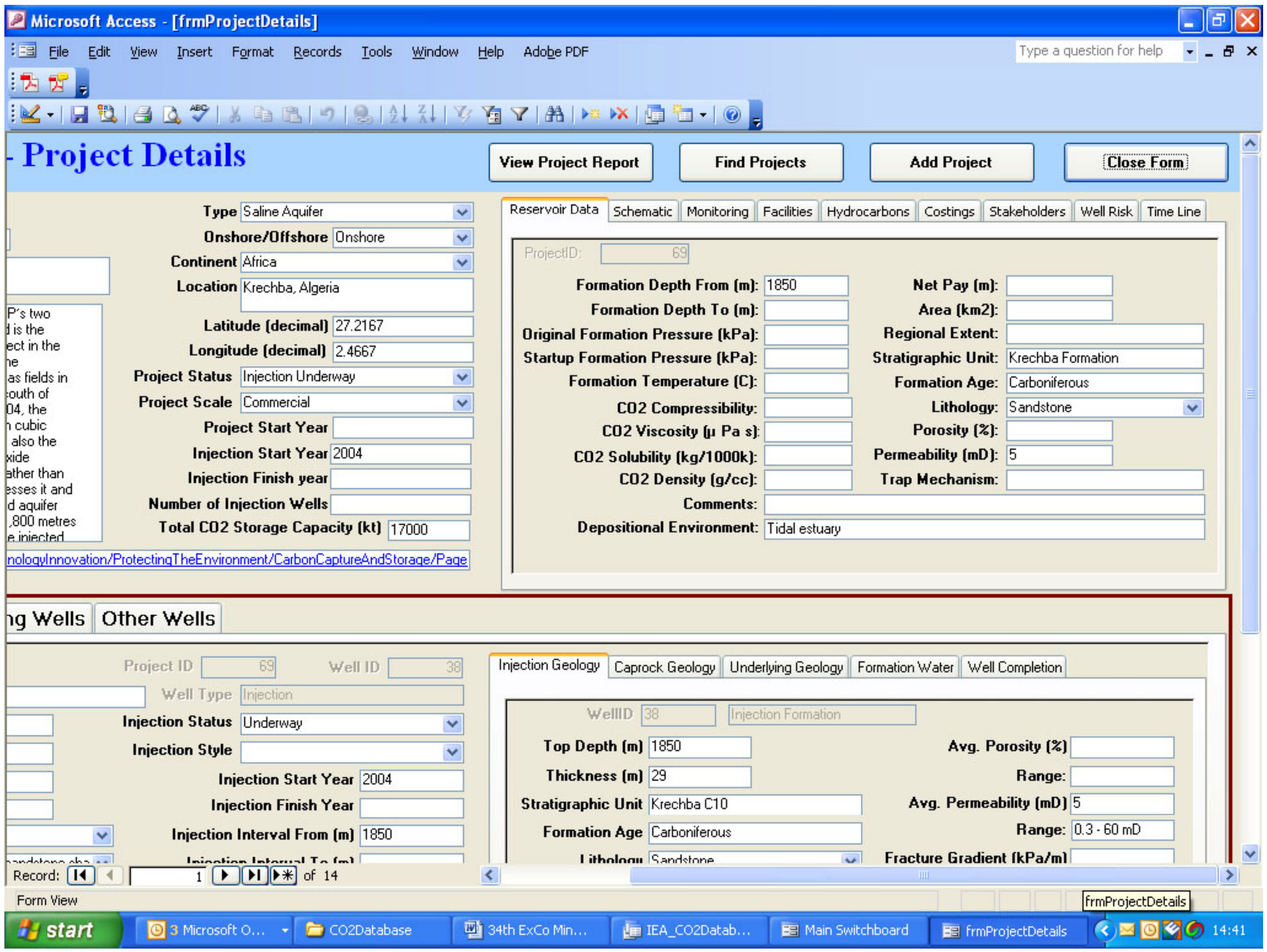
- Some reminders on IEA GHG role
  - Evaluate technologies (don't promote)
  - Work is policy relevant not prescriptive

Some ideas........

- Aims – general – open forum, sharing of information, evaluation of modelling techniques
- Objectives, e.g.
  - Performance assessment of storage
  - Identification of knowledge gaps
  - Support/advice to IEA GHG RA network
  - Online information – databases, modelling guidelines (non-practitioners)
  - Regulatory dialogue

IEA Greenhouse Gas R&D Programme

Aquifer Storage Database



www.ieagreen.org.uk

Some more ideas.....

Possible next steps:

- 2009 workshop report
- Report to 2009 RA network in Melbourne
- Links to online database on saline aquifer properties
- CO2GeoNet
- Establish links with US Regional Partnerships
- 2010 meeting

Overall: facilitate exchange between experts

Specific:

- Performance assessment of storage
- Knowledge gaps
- Support to RA network
- Online info, guidance, databases
- Regulatory dialogue
- Get feedback from stakeholders (those that use model results)

Specifics

- Reference database on modeling studies
- Focused guidance on assessment objective (e.g., capacity, leakage) versus which models to use versus confidence/gaps
- Assemble additional model comparison/ code comparison/ sample cases
- Guidance on model performance metrics (what is good enough, what is needed in terms of impact?)
- Education of users (what can you expect from models)

Specifics

- Would a guidance document on modeling even be useful (i.e., can there be a simple checklist, generally applicable?)
- Lessons learned from ongoing or past pilots/demonstration projects (including pitfalls)
- Develop plan for closing of knowledge gaps (e.g., a commissioned study on consistent thermodynamic database, guidance on data improvements)
- Use of model results for public outreach?
- Modeling and site characterisation?

- Action list till next meeting (sub-groups working on special assignments? Which ones?)

What should network avoid?

- Do not be prescriptive or self-promoting
- No software trade show
- Focus is not on solver/code development

Group 2

Modelling Network

- **Overall objective:**
  - **International forum for modellers to exchange ideas, information, data, methods, experience**
  - **The only forum dedicated to modelling!**

- **Specific Objectives:**
  - **Reach an agreement on which processes are important or not important**
  - **Perform modelling studies that will help to identify important processes and important coupled processes**
  - **Identify what data need to be collected and acquired for improving confidence**
  - **Share data**
  - **Sharing of our modelling predictions on field cases**
  - **Sharing how to build models**
  - **Identify what to model, and how to model**
  - **Inform risk assessment, but this is not the only aim of modelling**
  - **Propose guidelines to tackle uncertainties**
  - **Trans-Atlantic and Trans-Pacific collaboration – storage conditions are often different, such a variability that it is important to achieve international collaboration**
  - **Learn about modelling experience from various countries, avoid to reinvent the wheel**

Group 2

Modelling Network

- **Specific Objectives (continued):**
  - identify which level of detail we are looking for
  - mix of discussions about technical details & wider discussions (have parallel sessions on specific topics)
  - attract also a group of more technical people
  - invite also users
  - bring together model developers and model users
  - emphasize the difference between modelling for oil industry and modelling for CO_2 storage
  - how to best capture the reality, i.e. the geology (need to share field data)
  - communicate our existence to regulators
  - bring the regulators to participate
  - work towards consensus internally (on our approaches, methodologies, tools)
  - web-based guidelines/database on modelling
    - Database of tools, conditions of uses, contacts
    - level of support
    - information on modelling approaches for non-practitioners
    - capabilities of individual models and how they can connect

Aims and Objectives

- Maintain dialogue with regulators and NGO's,
- Allow models and codes to be compared / benchmarked,
- Forum for international collaboration,
- Identify gaps and R&D required to address,
- Provide input and feedback to RA and monitoring networks,
- Joint meetings of networks or organising committees on annual basis,
- More focus on reactive transport and co-contaminants,
- Create database of reference cases,

Expectations / Hopes:

- Interest in meeting people with similar technical interest and skills, exchange views – make life easier,
- Wikipedia style set-up or web-blog / forum,
- Detailed discussions – ‘technical clinic’,
- Code comparisons – opportunity to develop new links and share experiences, avoid duplication of efforts,
- Links with other networks / working groups,
- Access to information – via internet, face-to-face etc.,
- Sub-groups to deal with specific issues / topics,
- Clearing house of information from sub-groups, dissemination to wider audience,
- User id / password log-in to post data to forum,

Expectations / Hopes:

- Anticipate sub-groups in advance?
  - Merge reservoir engineer and hydro-geologist views,
  - Code comparison,
  - Non-technical group / forum to provide information at simple level to non-specialists (regulators),
  - Parameter / boundary conditions determination,
  - Gallery of results from various models / case studies… however limitations / availability of data could prove problematic here,
  - Critical discussion group – critical comments with no offence,
  - Geo-mechanical aspects,
  - Sub-groups generated as a result of gaps identified,

First Steps:

- Build website capability with partial security and disclaimer!
- Suggest voluntary regulatory sub-committee covering all networks,
- Determine sub-groups – not too many,
- Establish method for cross-network communication,

Session 5 Breakout

Breakout Group 4

Aims, objectives

- Important that work not duplicating RA network
- Modellers from different fields talking together
- Website forum for discussions
- Benchmarking of models
- Databases
- Link to Stuttgart code comparison excercise

- Benchmarking, model guidelines and standardised approaches
- Modelling guidelines online guidance
- Network should not endorse code, but can evaluate codes according to benchmark
- Existing benchmarking studies – LBNL, Stuttgart

- Role for network fostering views and subgroups – people need to volunteer their time
- Knowledge gaps
- Lessons learnt
- Focus on containment issues
- Analytical models
- Feedback from CO2GeoNet

Next Steps

- 2009 workshop report
- 2010 network meeting organisation
- Website forum
- Small well-defined problem posted on website?
- Contact with Holger (code) and Jens (Model) comparison excercises
- Summer schools/student participation