3rd RISK ASSESSMENT NETWORK MEETING

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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

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

The international research network on Risk Assessment is organised by IEA Greenhouse Gas R&D Programme in co-operation with Imperial College, London. The organisers acknowledge the financial support provided by EPRI for this meeting and the hospitality provided by the hosts Imperial College, London.

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

Sevket Durucan, Imperial College
Anna Korre, Imperial College
Rick Chalaturnyk, University of Alberta
Malcolm Wilson, Energy INet
Tony Espie, BP
Elizabeth Scheehle, US EPA
Ton Wildenburg, TNO
Hans Aksel Haugen, Statoil
Larry Myer, Lawrence Berkeley National Laboratory
Jonathan Pearce, British Geological Survey
John Gale, IEA Greenhouse Gas R&D Programme (Chair)
Brendan Beck, IEA Greenhouse Gas R&D Programme

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "3rd Risk Assessment Network Meeting, 2008/1, March and 2008".

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

IEA Greenhouse R&D Programme, Orchard Business Centre, Stoke Orchard, Cheltenham Glos. GL52 7RZ. UK
Tel: +44 1242 680753 Fax: +44 1242 680758
E-mail: mail@ieaghg.org
www.ieagreen.org.uk

THIRD WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

Executive Summary

The IEA Greenhouse Gas R&D Programme (IEA GHG) has been working on the topic of risk assessment for a number of years now. The cornerstone of the IEA GHG Programme's risk assessment work is the IEA GHG International Risk Assessment Network. The Network was formally launched in 2005 in the Netherlands after two preliminary meetings in the UK in 2004 and in Canada in 2005. The purpose of the network is to bring together the key groups working on risk assessment for CO_2 storage from around the world and to address what the regulators are expecting in regard to CCS assurance and whether risk assessment can provide the answers they require. This report provides a summary of the third risk assessment workshop hosted by Imperial College in London, UK between the 15th and 16th August 2007.

The main outcomes from the workshop were:

1. An initial attempt was made to define a set of common terms for use by the international risk assessment community and some progress was made, however this was only the start of the process. The next step in this work is to circulate a questionnaire to people within the industry to try and build consensus on the terms to use and their definition. One suggestion was to set up a *Wikipedia* style website to act as a forum to build an agreed pool of terms.

2. A key issue that the workshop attempted to resolve was on the requirements for site characterization. This is a common theme running throughout the Risk Assessment Networks and was explored in this meeting but not resolved. The issue remaining is determining how much site characterization is enough to satisfy all the stake holders involved in a CCS project.

3. There was a lot of discussion in this network about whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk. The debate concluded that whilst, there might be a desire to have a fully quantitative risk assessment process, currently it would not be possible for anything more than a semi-quantitative or predominantly qualitative process to be used for CO_2 storage simply because we do not know enough about the underground yet to allow us to define probabilities of geological events with confidence.

4. Following the session on the FEP risk assessment process it was concluded that this process is just one tool of many and the general feeling was that it might be better suited as an auditing tool rather than the primary tool for risk assessment.

As well a continuing to work on some of the unresolved issues above there were also a number of additional issues/questions raised over the course of the workshop that need to be addressed. These include:

- Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
- How confident are we in the modelling results we are generating for CCS projects?
- How long do we need to monitor for after the cessation of CO_2 injection?
- What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

These questions will be addressed in future network meetings

THIRD WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

1. Introduction

The IEA Greenhouse Gas R&D Programme (IEA GHG) has been working on the topic of risk assessment for a number of years now. From early discussions on the topic, the key message was that to gain public acceptance of CO_2 capture and storage, two key areas will need to be demonstrated: that the technology is safe and that its environmental impact is limited. Safety can be demonstrated to some extent through monitoring programmes at CO_2 injection operations that are currently underway. However, whilst early results from these injection operations indicate leakage is not occurring, such programmes do not necessarily provide confidence in the long-term i.e. 1000's years after injection has ceased.

The IEA GHG felt that risk assessment studies can assist the development of monitoring programmes for injection sites, relying on predictions of the long-term fate of the injected CO_2 and assessing the potential for leakage in both the short and long-term. To gain public acceptance of CO_2 capture and storage (CCS) the regulators and public will also need to have confidence in the predictions made by the risk assessment studies. To gain such confidence it will be necessary to understand the different approaches being used and the assumptions underlying the results. The results should be produced in an open and transparent manner, so that the results are understood and the implications for ecosystems and human health can be fully appreciated.

The cornerstone of the IEA GHG Programme's risk assessment work is the IEA GHG International Risk Assessment Network. The Network was formally launched in 2005 in the Netherlands after two preliminary meetings in the UK in 2004 and in Canada in 2005. The purpose of the network is to bring together the key groups working on risk assessment for CO_2 storage from around the world and to address what the regulators are expecting in regard to CCS assurance and whether risk assessment can provide the answers they require. The 2nd meeting of the Risk Assessment Network was held in the USA in 2006.

This report provides a summary of the third meeting hosted by Imperial College in London, UK between the 15^{th} and 16^{th} August 2007.

2. Aims and Objectives of Second Workshop

The workshop aimed to provide:

- Overviews of the current status of CCS risk assessment and further develop a number of risk assessment principles
- An assessment of whether it is preferable to use quantitative, qualitative, or simple analytical methods to analyze CCS risk
- A review risk assessment terminology
- An assessment of site characterization needs for RA
- A review of FEP risk assessment methodology

In addition, the workshop provided an overview and status of the well bore integrity based on the work of the International Wellbore Integrity Network also organised by IEA GHG.

3. Workshop Programme

The programme for the workshop is outlined in Table 1.

Table 1 Workshop Programme

Day 1 (15th August 2007)	
08.30 to 09.00	Registration
09.00 to 09.15	Welcome; John Gale, IEA GHG
Session 1: Site Characterisation-How much is enough?	
08.45 to 09.05	**OSPAR/London Convention**; Tim Dixon BERR
09.05 to 09.25	**Sleipner Case Study**; Helga Hansen, Statoil
09.25 to 09.45	**FutureGen**; Tom Grieb
09.45 to 10.15	Panel Discussion
10.15 to 10.30 Break	
Session 2: Site Characterisation	
10.30 to 10.50	**IEA GHG Site Characterization guidelines and IPCC SRCCS**; Brendan Beck, IEA GHG
10.50 to 11.10	**Site Characterization Needs for Risk Assessment**; Mike Stenhouse, Monitor Scientific
11.10 to 11.30	**US Perspective**; Anhar Karimjee, USEPA
11.30 to 11.50	**Australian Perspective**; John Kaldi, CO2CRC
11.50 to 13.00	Panel Discussion
13.00 to 14.00 Lunch	
Session 3: Terminology	
14.00 to 15.00	**Introduction and Presentation of Work**; Anna Korre, Imperial College
15.00 to 16.00	Panel Discussion
16.00 to 16.15 Break	
Session 4: Report from Well Bore Integrity Network	
16.15 to 16.30	**The Role of Wellbore Integrity in Risk Assessment for Geological Sequestration**; George Guthrie, Los Alamos National Laboratory
16.30 to 16.45	**Part 2**; Rick Chalaturnyk, University of Alberta
16.45 to 17.00	Discussion
17.00 to 17.15	**Confidence Building Through Argumentation**; Notio Shigetomi, Mitubushi Research Institute
17.15 to 17.30	**Confidence Building Through Argumentation**; Hiroyasu Takase , Quintessa
Close Day 1	

Table 1 Cont'd

Day 2 (16th August 2007)	
Session 5: Expectations on Different Parts of the CCS Cycle	
09.00 to 09.30	**Introduction - Strawman Proposal**; Tony Espie, BP
09.30 to 09.50	**Risk Assessment Expectations**; Claudia Vivalda, Schlumberger
09.50 to 10.10	**Concerns and Alternatives to Non-Probabilistic Risk Assessment**; Julio freedman, Lawrence Livermore National Laboratory
10.10 to 10.30	**Does Probabilistic Risk Assessment of Long-Term Geological Storage Make Sense?**; Jeroen van de Sluijs, Copernicus Institute, Uterch University
10.30 to 10.45 Break	
10.45 to 11.15	**Keep it Simple**; Lars Olof Hoglund, Kemakta Consultants
11.15 to 12.30	Panel/Strawman Discussion
12.30 to 13.30 Lunch	
Session 6: FEP's - Features, Events, Processes	
13.30 to 14.00	**Using the FEP Approach in Auditing the Comprehensiveness of a Site-Specific Research Programme for CO_2 Storage**; Ton Wildenburg, TNO
13.30 to 14.00	**Using not Abusing FEP's**; Steve Benbow, Quintessa
14.00 to 14.30	**Weyburn Experience of FEP's**; Rick Chalaturyk, University of Alberta
14.30 to 15.00	**Methodological Developments to Define Safety Criteria**; Olivier Bouc, BRGM
	Certification Framework; Curtis Oldenburg
15.00 to 15.15 Break	
15.15 to 16.15	Panel Discussion
16.15 to 17.00	**Wrap up**; John Gale, IEA GHG
Close Day 2	

4. Presentations Summaries and Discussion

4.1. Developments in Risk Assessment

4.1.1. OSPAR/London Convention – Tim Dixon – BERR

Tim Dixon from the UK Department of Business, Enterprise and Regulatory Reform presented an overview of the amendments that have recently been made to the London and OSPAR conventions. The London Convention and Protocol and the OSPAR[1] convention govern various activities in the marine environment and up until now have prohibited most offshore CCS applications. Due to the desire for offshore CCS and the acknowledgement that the conventions were both written without CCS in mind there has been a drive from a number of countries to amend them to allow CCS. It was noted that a number of participants of this network were involved in the amendment process.

The amendments to the OSPAR convention to allow CCS occurred in Annexes II and III of the convention and were accepted by consensus on the 6th of June 2007. However, they will only come into force when they are ratified by 7 Parties. It should also be noted that before a country can ratify they require a CCS regulatory system to be in place domestically. It is also important to note that OSPAR is legally binding unlike the London convention and protocol which are only guidelines.

In conjunction with the amendment to the OSPAR convention they also produced the OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 in Geological Formations which includes the Framework for Risk Assessment and Management (FRAM). OSPAR ruled that it is a requirement to use these guidelines when permitting CCS projects in order to reassure parties of the safety of the CCS process. Although the amendments themselves require ratification, the OSPAR guidelines must be used as of the 15th of January 2008 for all CO_2 storage projects with the exception of EOR.

The Guidelines:

- Provide generic guidance when issuing permits,
- Must be applied as fully as possible by countries,
- Focus on injection and storage,
- Requires countries to report CCS activities to OSPAR,
- Include the FRAM.

The guidelines are intended to be based on common sense and practicalities to ensure they were workable, practical and non-restrictive.

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[1] The OSPAR convention applies to Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, and the European Community.

The amendments to the London Protocol to allow CCS were adopted in November 2006 and came into force in February 2007. Guidelines for Assessment of CO2 Streams for Disposal into Sub-Seabed Geological Formations not completed at time of amendment.

The guidelines will be derived from the London Convention's Risk Assessment and Management Framework (2006). This is the same framework on which the OSPAR FRAM was based.

This London Convention Framework contains:

- Problem Formulation – define bounds, scenarios etc
- Site Selection and Characterisation
- Exposure Assessment – processes and pathways for environmental exposure
- Effects Assessment – of exposure on marine environmental
- Risk Characterisation – integrates exposure with effects and likelihood
- Risk Management – monitoring and mitigation

When producing the London Guidelines a contradiction arose with the need to follow existing waste guidelines. These guidelines look to minimise flow of waste into the environment however a caveat had to be added to explain that this principle doesn't follow in the case of CCS.

Questions:
Q) Who do you anticipate will be the first country to use the OSPAR and London Guidelines?
A) Possibly the UK or Norway as they are moving ahead the quickest on demonstration plants. UK CCS regulations are due to come out as a draft in November of this year. The UK is also looking to see how it can help with regulation building in other countries. The EU regulations may also help fast track the process in member countries.

John Gale made the comment that he is impressed by speed of amendments (which took 3-4 years to be finalized) and it will be interesting to see how quickly other protocols such as the Barcelona convention in the Mediterranean are also amended.

4.1.2. Sleipner case study – Helga Hansen – Statoil

In the second presentation of the session Helga Hansen from Statoil discussed the risk evaluation process that took place prior to injection at Sleipner. Outcomes were also presented from a workshop Statoil held in 2006 that discussed the past, present and future risk associated with the CO_2 injection on Sleipner.

CO_2 storage at Sleipner was an integral part of the development plan at the site so it was included in the original Plan for Development and Operation (PDO) in 1991 so no separate application for CO_2 storage was required. This PDO did not require any quantitative risk evaluation of the site but did mention possible risk associated with the CO_2 storage. These risks included:

- Problems with injectivity and potential over-pressurisation of the formation
- Wet CO_2 corroding the casing in the production wells

- Hydrate formation in the Utsira Formation which was deemed highly unlikely

In addition to highlighting possible risks in the PDO, Statoil did perform an evaluation of a number of other issues prior to injection. The main issues were injectivity, migration of CO2 to the Sleipner wells, and the caprock integrity
In 2006 Statoil invited a number of international CCS experts to a workshop in order to perform a risk evaluation of the Sleipner project. The aim of the workshop was to identify risks of CO2 escape and effects on neighbouring wells and licences, identify mitigating measures, and to evaluate whether the risk associated with the project was within acceptable limits.

This analysis was performed for the current injection rate and at increased injection rate of ten times the current level. Again, no quantitative evaluation was done but rather a qualitative method was used with the experts classifying the severity of the risks.

The project was then divided into three separate categories; the formation, the caprock, and the wells (including the injection and production wells). The results can be put into two categories; risks at current injection rates and, risks increased injection rates of ten times current injection rates.

The results for current injection rates are as follows:

Project component	**Risk**	**Possible risk scenario**
Formation	Medium	• CO_2 migration under the caprock or internal shale layers and into adjacent wells • Low risk of migration under the caprock to up-dip sands and then to the seabed
Caprock	Medium	• Leakage through undetected faults or fractures • A low risk of fractures being crated
Wells	Medium	• CO_2 reaches adjacent exploration wells • A low risk of injection system failure

The results for increased injection rates are as follows:

Project component	**Risk**	**Possible risk scenario**
Formation	Medium	• Injection induced degradation of reservoir • Migration below the caprock or internal shale layers to neighbouring licence blocks • Low risk of reduction/misinterpretation
Caprock	Medium	• Same as current injection rates
Wells	Medium	• Same as current injection rates

A in conjunction with the above results, a number of key conclusions were drawn from the workshop:

- The risk of CO_2 release from Utsira Formation is considered low and acceptable
- Increased injection rates would accelerate the identified risks

- A selection of mitigating measures to reduce risk and improve control of the CO_2 plume are available and have been proposed

Questions:
Q) When the project was divided into wells, formation, caprock. Did you look at the interaction of the risks between these categories? For example; formation subsidence would affect the caprock or undetected faults or fractures.
A) No real interaction was looked at although it was known that there could be some interaction. The division was performed to simplify the process

Q) How could you achieve a ten times increase in injection rate?
A) The increased rate was used in this theoretical process for other projects that may have higher injection. If you were to actually increase injection you would have to do a new risk assessment.

Q) If CO_2 breaks the caprock, will the CO_2 bubble to the surface or pool at the bottom of the ocean?
A) It probably wont reach the ocean floor, but rather be trapped in overlying formations where there is already evidence of accumulated gas.

Q) How did the CO_2 move through the shale levels in the formation?
A) The shale is not continuous. There is often communication around thick levels of shale.

Q) Could you directly measure the fracture grading in the formation?
A) Not directly. High resolution seismic was used to look at the caprock.

Q) What is the smallest volume of CO_2 movement that could you see in seismic? 10Mt?
A) Not sure yet.

Q) Will Statoil do more quantitative analysis in conjunction with seismic?
A) No, there is a focus on seismic and wells, but currently they are giving us confidence in the integrity of the storage.

Q) How good is the temperature control in the well?
A) There is a desire to do measurements for temperature and pressure in the well, but the well is very sensitive.

Q) Will Statoil perform baseline monitoring of the sea floor/environment for the London convention or for OSPAR?
A) No, although work ongoing in Trondheim to model the sea and sea floor at high pressures. The pressure tank will be used to find more about the effects of CO_2 and pH changes on marine environment. Pressure vessel goes to 20bar.

Q) Are there plans to increase the injection rate at Sleipner?

A) Currently we are injecting 1.4Mt per year and there are no plans to increase this although there are discussions about using Sleipner for other projects such as Castor but this would require another well and more risk analysis.

4.1.3. FutureGen case study – Tom Grieb

In April 2007, the FutureGen Alliance completed the Final Risk Assessment Report for the FutureGen Project Environmental Impact Statement (EIS). Tom Grieb from Tetra Tech presented the results. The risk assessment analysis took three months to complete and was performed for all four of the potential FutureGen sites which are all situated in rural communities with low populations in the vicinity.

The FutureGen risk assessment was comprised of a number of different components:

- Conceptual site models
- Human health and ecological risk analysis
- Pre-injection RA
- Post-injection RA
- Risk Screening and Performance Assessment (Characterization)

The FutureGen project has finalised their human health and ecological risk analysis with the final draft of their environmental impact assessment (EIS) being completed. The FutureGen EIS looked at long term storage and analysed four gases; CO_2, NH_3, Radon and H_2S. FutureGen also models aspects of the subsurface and surface, however the modelling provided by the sites wasn't extensive. The human health and ecological risk analysis was then compared to other examples of active and proposed CCS sites at Weyburn, and the Latrobe valley site and Gorgon sites in Australia, however none of these site are yet to fully complete their EIS.

From the analysis it was found that the largest risk associated with this site was upward migration of CO_2 through undocumented deep wells, followed by upward gradual release through the caprock. However it was concluded that overall, the likelihood and consequence of release of CO_2 above the plume footprint are not significant although H_2S releases from abandoned, undocumented, or poorly constructed wells could lead to potential human health risks.

At the conclusion of the FutureGen study, a number of possible uncertainties in their risk assessment results were identified:

- Uncertainties in release rates and their probabilities – wide ranging variables
- Analysis based on affected population remaining constant – this could change over the lifetime over the project
- Design of FutureGen facilities and sequestration methodology evolving – final site won't be selected until end of 2007.
- Exposure and toxicity parameters conservatively chosen
- Peer-reviewed health effect levels not available for CO_2 for all durations

As a result of the FutureGen risk assessment analysis, a number of conclusions have been drawn. Firstly there are potentially serious risks from release of CO_2 to workers in immediate vicinity of pipeline or well-head, in the event of a puncture or rupture. This does not relate to population in the area but rather only to the workers. H_2S releases from pipeline or wellhead could result in health effects to local population at distances up to several kilometres from the release point. The higher the H_2S content in the gas stream the more sever the risk profile. It was found that the likelihood and consequence of releases of CO_2 from above plume footprint are not significant. Lastly it was found that H_2S releases from abandoned, undocumented, or poorly constructed wells lead to potential human health risk. Ultimately the conclusion was that the risks associated with CO_2 are minimal compared to those associated with any H_2S in the stream.

Following the conclusion of the FutureGen risk assessment process, the team gave a number of final impressions about the risks associated with CCS and the FutureGen risk assessment process:

- Potential risks of transport and sequestration in the selected saline formations are quantifiable and manageable
- Transport of compressed gas is a significant consideration
- Well integrity is a key issue
- From the literature we reviewed there was an emphasis on frequencies not probabilities in CCS investigations
- Analogue approach suitable for site risk assessments and basis of developing regulatory framework
- Recommend risk-based MMV program
- Public support for local FutureGen site selection

Questions:
Q) FutureGen used an 8km spacing for safety valves, is this standard? Some are known to have used 30km spacing.
A) This is specified in the design but it is not standard. The analysis was replicated for different scenarios, such as more valves in built up areas.

Q) Won't H_2S absorb quicker than the CO_2 in the subsurface?
A) Yes it will. The H_2S risks mentioned here are during transport and injection rather than leakage from the subsurface.

Q) Did other CO_2 pipelines looked at have similar H_2S content?
A) No, most had lower.

Q) What was the conclusion about the possible affects on groundwater.
A) There was found to be low probability of injected gas coming into contact with ground water.

Q) What caused the video rupture?
A) Backhoe. Most likely cause "whoops" factor – quite high, higher than corrosion.

Q) What were the demographics of the expert group who reviewed the project?

A) All technical, geologists, risk assessors. No NGOs or farmers but this is going on in other parts of the project. Different groups will review the results.

Q) How have you used the safety distance? Did you recommend safety distances?
A) Right now there is not specified distance – 100s of 1000s of pipelines in use now. So there should already be safety distances. They did make recommendations for distances but unsure.
A) Malcolm. Pipeline with 4% H_2S requires a 400m clearance
A) Really there is no general answer.

4.2. Site characterisation – How much is enough?

4.2.1. Site characterisation and the IPCC SRCCS – Brendan Beck – IEA GHG

The first presentation of this session looked to set the scene by outlining how the IPCC Special Report on Climate Change deals with site characterisation. Brendan also outlined some work the IEA GHG is doing in the area of site characterisation guidelines.

The IPCC SRCCS defines the key goals for site characterisation as:

- To assess how much CO_2 can be stored at a potential storage site
- To demonstrate that the site is capable of meeting required storage performance criteria.

These goals require the collection of the wide variety of geological data, much of which will be site-specific. Most data will feed into geological models that will simulate and predict the performance of the site.

Generally the storage site and surroundings need to be characterized by geology, hydrogeology, geochemistry and geomechanics focusing primarily on the trapping mechanisms present. This will include a very good analysis of the sealing horizons and strata above. Site characterization data fed into a three-dimensional geological model. The general site characterization data should include:

- Geological site description from wellbores and outcrops,
- Information on subsurface geological structure, including faults & fractures,
- Formation pressure measurements to map rate and direction of groundwater flow,
- Water quality samples to demonstrate the isolation between deep and shallow groundwater.

It is also noted that oil and gas fields will often be better characterized than saline formations given the history of subsurface exploration associated with these activities.

Brendan then went on to outline the more specific site integrity factors and data requirements that the report identifies in a number of areas including:

- Stratigraphic factors,
- Geomechanical factors,
- Geochemical factors,
- Anthropogenic factors.

Following the outline of the IPCC SRCCS site characterization coverage, Brendan briefly discussed some work that the IEA GHG is doing on Site Characterization Guidelines and their Best Practice Database.

IEA GHG are looking to develop a set of site characterization guidelines to help fast track the development of CCS projects by creating standardized approach to CCS site characterization. The guidelines will be generic to saline aquifers and hydrocarbon fields and will be target oriented rather than being prescriptive. The guidelines will not be regionally focus but rather apply globally. They will then be available for general distribution to encourage uptake of the guidelines in practice. Before the drafting of the guidelines commences a review will be undertaken of the current work in this area to ensure that work is not duplicated.

The guidelines will be underpinned by the IEA GHG Best Practice Database which is being developed in conjunction with the EU CO2ReMoVe project. The database will ensure the most up-to-date practices are available to the project developers and to regulatory bodies. The database has been set up and is ready to go live as soon as a 'critical mass' of information has been gathered.

4.2.2. Site characterization needs for risk assessment – Mike Stenhouse

The second presentation of this session looked specifically at site characterization needs for risk assessment and vice versa and focused specifically on the long term fate of the CO_2. Initially the question was posed; why do risk assessment? The answer given was that risk assessment forms a major part of the confidence building process among stakeholders both technical and public. The goal of risk assessment is to build a sufficiently broad consensus across the stakeholders to proceed to implement a storage project.

There are a number of different requirements to ensuring confidence in a project and these will change depending on the stakeholder in question. A consensus in the technical community that the system (storage system and geosphere) is sufficiently well understood to quantify the ways in which it can evolve with time. Public confidence requires trust that the CO_2 storage community will perform high quality and honest work and is aided by open access to all important information. In both cases, demonstration of robust storage system would enhance confidence.

There are also different risk assessment requirements for the different phases of a CCS project.

- Site Selection: the role of risk assessment would be to screen and compare sites. During Site Characterization: risk assessment will provide guidance as to what data and information will be required.
- Permitting Phase: risk assessment will form the major part of the safety submission.
- Injection phase: The major role of risk assessment will be to refine models with comparison of model using existing data

- Post injection: Risk assessment will help with the long term predictions which require a robust prediction process

Risk assessment and site characterization is an iterative process that requires an active feedback loop to assess and reassess data as it is acquired. It is important to note that baseline data is imperative to differentiate between natural and project based observations.

Specific RA needs from site characterization include the conceptual model of storage system and most importantly data. The conceptual model will reflect the current understanding of the reservoir, the sealing system, leakage pathways, hydrology, hydrochemical and geochemical inputs and wellbore characteristics. The conceptual model will be founded on the current data available and will have to evolve as new data is acquired.

The major question surrounding site characterization of CCS site is deciding when enough is known. There are a number of considerations to take into account when deciding:

- Knowledge increases with additional information and data, but by how much and is the knowledge useful? It is also important to note that certainty doesn't necessarily increase with knowledge.
- Cost of acquiring site characterization information including both direct cost and the indirect or hidden costs.
- Value of information. Reduced uncertainties may make it easier to convince stakeholders of overall safety. Reduced uncertainties could reduce probability of 'negative' surprises by decreasing undetected faults and features.
    - The Probability of conceivable surprises should be possible to bound based on detection limits for characterization techniques.
    - RA can help assess what site properties affect storage integrity
- Stop characterization once the "net gain" of the additional information is zero or negative. A comparison must be made between the value of the increased information and the cost of acquiring it.
- Who decides the value or 'gain' of additional information?

All site characterization information and data must have a useful purpose and this is to improve the understanding of the site and or contribute to the risk assessment needs.

To wrap up the presentation Mike made two key conclusions. Firstly, technical and public confidence is needed as a basis for proceeding with CO_2 storage projects. Technical confidence and good science are prerequisites, but openness and, transparency are also required and can be achieved through the involvement of all stakeholders whenever possible. Secondly, risk assessment can contribute significantly to technical and public confidence as it provides a useful framework for guiding site characterization activities at all stages in the development of a geological CO_2 storage project. As well as identifying what information and data feed directly/indirectly into assessment modelling, RA can also guide decision makers on what information/data are *not* crucial to assessment predictions.

Questions:
Q) The presentation implied that knowledge converges to a finite required amount. Oil and gas doesn't occur this way. Oil and gas estimates often end up well beyond the original estimates. It is not possible to say when enough is enough? Only after a number of years of dynamic performance can you start to properly understand the site.
A) I agree – The presentation described an idealized concept for site characterization knowledge. It is broadly recognised that as you collect data it often leads to lesser relative understanding of the site. You have to look at something like this as one method of deciding when you have enough information
A) Understanding is not the objective; the objective is to reduce the risk to the point where it is acceptable.

Comment) This is very much a question based on where you can make real assessment of risks. One option would be to analyse the worst-case scenarios and if they are acceptable then you can justify large sums of money to develop the project.

Comment) A lot of the risk can be handled by mitigation optimisation

Comment) I can see come scenarios, such as diffuse leakage through a fault which I would question if you can mitigate at all.
A) If no other mitigation option is possible then you always have the choice to ultimately stop injection at the site.

4.2.3. The US perspective – Anhar Karimjee – US EPA

Anhar presented the US perspective of risk assessment and site characterization for CCS projects. In the US, there is a demand for transparent and easily understood risk assessment and it will be important to consider the target audience when developing these approaches. It is understood in the US that site characterization is critical but it can be costly, the key question is "What information is critical and when do we need to have it?" – How much do you need to start injection, how much can you leave to learn as you go? There are currently changing attitudes in the US in regard to climate change and with this change there are been growing interest in CCS.

CCS and US Climate Policy

- Senators Lieberman and McCain requested that EPA estimate the economic impacts of S. 280, the Climate Stewardship and Innovation Act of 2007.
    - The enabling technologies in this analysis for electricity generation are Carbon Capture & Storage (CCS) and Nuclear Power.
- In 2007 alone, there have been at least nine bills presented to congress that are relevant to CCS.
- In addition to the work being done for the federal government, there is also a lot of work going on at state government level in regard to CCS. This has however

led to concerns that the US could be divided into a patch work of different CCS regulation.

In order to establish what regulatory options are appropriate the risks of the process must be identified and evaluated. The method of quantifying risk can vary and be either qualitative or quantitative or a combination of the two. It was proposed that the mean risk, i.e. the most likely outcome, should form the basis of the analysis rather than the worst case scenario. If scientific opinion is divided about the most likely outcome then multiple risk estimates should be presented. Once regulatory options are identified, the relative costs and benefits of each option must be estimated i.e. what will it cost to implement and how will health and environmental risks be reduced?

The costs of regulatory development will change with the level of analysis required. More costly regulations require more extensive analysis. An estimate as to the costs is outlined below:

- <$100M: Preliminary cost analysis
- $100M-$1B: Formal "Regulatory Analysis" including cost-benefits and uncertainty analyses
    - describe uncertainties qualitatively
    - conduct sensitivity analysis
    - identify key parameters where probabilistic analysis may be needed
- >$1B: Regulatory Analysis+
    - conduct formal probabilistic analysis of relevant uncertainties

It is estimated in the US that the cost for CCS regulations may end up in the $100M-$1B range.

Two examples were given of risk assessment approaches in the US. One was for the treatment of waste water where the EPA conducted a relative risk assessment of wastewater disposal options and the other where the EPA performed a vulnerability assessment for CCS.

The EPA is becoming more active with workshops and has recently sponsored two focused specifically on site characterization. The first was the International Symposium on Site Characterization for CO_2 Geological Storage in March 2006 and the second was the EPA Technical "Area of Review" Workshop in July 2007.

In conclusion:

- CCS is a key climate mitigation technology
- There is a high demand for transparent and easily understood risk assessment approaches
- Key Challenges Remain
    - Demonstration
    - Appropriate Regulations
    - Public acceptance

Questions:
Q) In regard to the cost of data acquisition a system model was presented earlier for the Weyburn project saying it would only cost a few million dollars, but Weyburn has so many wells and to recreate that data from scratch would cost ½ to 1bn dollars.
A) This is true, only the additional costs not the total project costs were presented here.

Q) All the site characterization proposed seems to be for the geosphere and not the biosphere – soil gas, ecosystem, and airborne surveys. With no biosphere characterization can evaluate impacts in the future.
A) EPA is considering biosphere characterization and other level 2 attributes in the RA approach but they are currently further along with their geological characterization work.

Q) It was said that the EPA did a study on a US cap and trade system, do you know what the cap was or if it was tight?
A) Not sure what the cap was but it was thought to be neither tight or loose but rather medium.

4.2.4. The Australian Perspective – John Kaldi – CO2CRC

John presented the Australian perspective to CCS risk assessment specifically looking at the methods for quantitative risk assessment and its applications for site characterization. John the presented an update for the Otway Basin project including the future aims and objectives of the project.

The CO2CRC are currently working on a quantitative risk assessment methodology. As part of this process they are looking to develop "best practice" for running quantitative risk-based CCS project analysis underpinned by methods adopted in CO2CRC site characterisation, and monitoring and verification workflows.

John also took the opportunity to present an update on the CO2CRC Otway Basin pilot project announcing that the injection well was drilled at the site earlier this year with injection expected to commence late 2007. John also used the pilot as an example of how site selection could occur outlining some of the factors that led to the choice of the site. A brief explanation was then give to the as to some of the site selection decisions for other CO_2 storage sites.

John then went on to outline some of the issues still remaining with risk assessment for site characterization. This included the composition of the injected gas, the characterisation of existing and future wells, whether the site characterisation requirements will differ for onshore and offshore storage, and what phases of a project site characterisation relate to? Does it only relate to prior injection or does it continue throughout the lifetime of the project? These are all questions that will need to be address in order to achieve a consistent and replicatable methodology for site selection that is adequate for all the stake holders involved in the process.

In conclusion John summarised with a number of key points:

- There is no such thing as the perfect site; they will be fit for purpose….each with own risk assessment criteria
- We need to agree what is meant by "site characterisation", including when it concludes – the title of the section
- We need to have an agreed methodology for storage capacity assessment
- "Characterisation" is site specific, onshore/ offshore specific and storage type specific; it is therefore essential that we identify commonalities and don't just look for differences
- Easy to work out what we can do; more difficult to work out what we don't need to do – otherwise the task will overwhelm us!
- Geology is only one of the features that determines suitability of a site for CO_2 storage

Questions:
Q) Did the monitoring well get completed in terms of all the equipment being set up?
A) Not yet, right now we are waiting for the weather to improve.

Q) How do involve the public at this stage of the Otway project?
A) The CO2CRC ran community meetings from early on in the project. This included open houses, show and tells, and school lectures to kids. We found the best approach was to send the CO2CRC students who are excited about this technology to these sessions rather than the older staff. We found the land owners are quite aware, they knew what their royalty rights were from oil and gas, for them it is just another project but with information they can feel ownership over the benefits. We stress that you need lots on engagement throughout the project.

Q) The CO2CRC definition of site characterization mentions the storage of CO_2 for a "defined period of time", can you elaborate?
A) We will let the regulators will decide what this period of time is.

Q) How do you combine the qualitative (expert panel, public opinion) and quantitative assessment?
A) We work to ensure that the expert panels used involve a large array of different technical and non-technical disciplines.

Q) What is the aim of the Otway Basin Project?
A) The aim is to demonstrate that it can be done to plan, to budget in the Australian environment and with Australian technology.

Discussion:
Q) What is the area that is subject to site characterisation? Air or surface?
A) The EPA has used a fixed radius in the past but for CCS we will have to use modelling to determine an area. The policy makers need support to make a proper decision; they need to know what is practical. There is a need to determine what is actually possible and what isn't.

A) Weyburn used a 10km x 10km project boundary but this could be reduced

Q) Are there any scale up issues of the projects from pilot scale?
A) The FutureGen project goal is to sequester 50Mt over the lifetime of the project. The FutureGen area for site characterization is 1.5mile for all four sites for CO_2 and 40+ miles further for pressure monitoring. You have to invest in monitoring now so you have the data in 20-30 years.

Q) It was good to see consistency across the presentations in this session. In regard to costs, do we have any grasp of the financial uncertainty or hidden costs?
A) There are hidden costs in the site characterisation for Weyburn you are unlikely to have that detail of existing data in any other project.
A) What you need to do is develop an uncertainty plan and find where the uncertainties are.
A) We are good at estimating risk in known experience but are very bad in new scenarios. Also we have no way of apportioning risk over the long time frame.

4.3. Terminology

4.3.1. CO_2 storage risk assessment terminology: Introduction and presentation of work – Anna Korre – Imperial College

Terminology has previously been highlighted as a key issue in the area of risk assessment which led to Imperial College undertaking a body of work in this area for IEA GHG. The objective of this work has been is to develop and propose internationally harmonised generic and technical terms used in CO_2 storage hazard/risk assessment, which will help facilitate the mutual use and acceptance of the assessment of CO_2 storage projects between countries, saving resources for both governments and the industry.

Target groups of users of the harmonised terms are CO_2 storage and environment professionals and political actors at all levels. The harmonised terms may also be used as a basis for preparing other publications primarily aimed at public information and CO_2 storage education. It is not a goal to standardize risk assessments globally, as that is considered to be neither appropriate nor feasible.

Historically there have been two types of risk assessment; first public-health risk assessment and second engineered-systems risk assessment. As their names suggest, the first focuses on the health effects and the second relates to the immediate and delayed effects due to the failure of systems. In both cases, risk assessment involves a search for "causal links" or "causal chains" verified by "objective" analytic and experimental techniques.

In conjunction with risk assessment regulators also apply risk management the difference being; risk assessment is the use of the factual base to define the health effects of exposure of individuals or populations to hazardous materials and situations, where as risk management is the process of weighing policy alternatives and selecting the most appropriate regulatory action, integrating the results of risk assessment with engineering data and with social, economic, and political concerns to reach a decision.

Imperial College has used work done by NRC and IPCS/OECD to define four steps which risk assessment contains some or all of:

- Hazard identification: The determination of whether a particular agent is or is not causally linked to particular adverse effects.
- Dose-response assessment: The determination of the relationship between the magnitude of exposure and the probability of occurrence of the effects in question.
- Exposure assessment: The determination of the extent of exposure before or after application of regulatory controls.
- Risk characterization: The description of the nature and often the magnitude of risk, including attendant uncertainty.

Anna went on to address a number of specific generic terms. Only a selection of the full terminology set were address; these included data-oriented terms such as hazard, agent, risk, effect, and source, and action-oriented terms such as hazard assessment, risk assessment, risk management, and risk analysis. The set of terms presented are part of a greater set of 200 terms that Imperial currently have.

Anna wrapped up her presentation explaining what is next for the CO_2 storage RA terminology development work that they are doing at imperial. All the terms identified and the definitions will be circulated widely (e.g., through IEA GHG RA network, the research community and industry) for review and comments.

Questions and Discussion:
Q) Is this the right group to be engaging on this? If it is we are looking for long term support from the people here to ensure it.
Q) Because this is terminology could we use Wikipedia or a similar style of mechanism to get open and transparent discussion?
A) Wikipedia style approach sounds very possible.
A) Wikipedia is one approach but so it engaging with a working group. The document that is being produced by Imperial will be able to be used as a guide and will evolve with the industry. If we invest some effort now in this it will be an investment for the future.
A) The Wikipedia becomes very attractive. Getting the information in one place is the first and significant step.

Q) The RA that was done for the four areas including Otway calls it quantitative although it includes expert panel attaching numbers to things. Would you call this Qualitative, semi qualitative, semi quantitative?
A) If there is opinion involved in the process then it is qualitative.

Q) What are we looking to achieve? A lot of the definitions used come from very complex projects and relate to specific fields and people. There are a lot of definitions already out there.

A) The goal is to achieve consistency in the way we communicate with each other and the world.

Q) Have the terminology in the OSPAR document been reviewed as it looks like it will be a fairly influential document?
A) This has not been done by Imperial, yet but they will definitely be looking at it and use it in the preparation of the documents that are going to be circulated

Q) There is a project that the DTI funded in the 80's which looked at evidence based analysis.
Q) The nuclear industry did safety assessment and performance assessment is a subset of this. This document came out in the 70s when there was a need to deal with nuclear waste.

C) Part of this process is assembling generic data but the other part is looking at specific CCS terms and how we get them, either from oil and gas or from elsewhere, or our own definition. Closure, abandonment, post-closure have all been pulled from different parts of the industry.

Q) Are we ever going to get to a stage that we will all be using the same terminology?
A) We can try and then it is all out on the table and we know what terms are equivalent.

Q) How long does the list of terms need to be? 200,000 or 20?
A) There was discussion of 50 + 50. Currently Imperial has 200 but this needs to be cut down. Then we will be open for suggestions for things that may need to be added.

Q) The IPCC SRCCS has a glossary, can we use this as the basis for further work?
A) That glossary was just an amalgam of sources and there was no attempt at trying to achieve consensus.
A) IPCC defines risk assessment as "part of a risk management system"
A) London convention and OSPAR both have glossaries and they both come from the IPCC special report.

Q) In the presentation a definition of risk management was given but there was no mention of mitigation.
A) Mitigation would fall into emissions and exposure control.

Q) Risk perception is also an area to look at, as well as probabilistic, non-probabilistic etc.
A) Not all the work done by Imperial was presented today.

Q) Why do people hesitate at performance assessment. Most people these days are try to prove that their system will perform as they expect. Does this not point to performance assessment? There is no talk of X molecules of CO_2 at Y meters which would indicate risk assessment?

A) A risk assessment process can be carried out in separate tiers with tier 1 being potential hazard assessment, tier 2 being exposure assessment, and tier 3 is consequence assessment.
A) Nobody is pushing toward exposure assessment at the moment. If we go by these teirs then we will need to specify exposure limits, in particular with the sub surface. The IPCC numbers 1% over 100 years... that's a performance target.
A) Everyone here is technical and not from health or environment so it is fitting that we discuss technical.
A) This is a concern at the EPA as well. We are not calling it risk assessment because we don't want to give the impression that we can do a quantitative probability assessment. We are using a new term: vulnerability assessment. OMB is extremely politicised organisation and can't be trusted and so is a bad example, they are reacting to politics.
A) This may be the case but Imperial wants to be prepared for tough questions
A) It is a good idea be prepared but don't over sell yourself. We need to manage expectations.

Q) The implication from the discussions is that a certain amount of leakage is acceptable?
A) Perhaps we should talk containment underground rather than containment in a specific formation. Then we don't have to deal with exposure.

Q) How will the data be processed once we give our answers to the terminology survey?
A) It will be presented as a report with review by a small group of experts with the background of all the experts provided in the appendix. It is through this review process that the results will be derived.

Q) We are dealing with many people in the IGCC and pipelines and chemical industry, and all have to deal with other industries so you are not going to get convergence but rather a glossary or translation book.

Q) Glossary is a good idea but we can't make the expectations of storage security so high that in the future we are excluding projects that we need to overcome climate change.

Q) Uncertainty analysis can be reviewed as its own industry with its own terminology.
A) True, this has been considered by Imperial.

Q) What about possible links to the CSLF?
A) George Guthrie and Tim Dixon can provide this network with a link with the CSLF.

Wrap-up) It seems we are in general agreement to go forward and we will send out an abridged list of terms amongst the network before looking into the Wikipedia option. John Gale will look into organising an organising committee.

4.4. Report from the Wellbore Integrity Network

In this session Rick Chalaturnyk from the University of Alberta and George Guthrie for Los Alamos National Laboratory gave an update on the ongoing work of the Wellbore integrity network.

The wellbore integrity network has a number of guiding aims regarding the bringing together of experts in the field and ultimately improving the understanding of the long term performance on well seals, past present and future. To date the wellbore integrity network has worked very well and achieved a lot, in particular since the second meeting where some aggressive objectives were set for what the network hopes to achieve.

The overarching concern is that a CO_2 storage site in an oil or gas reservoir could contain upward of 2000 well penetrations. This means researchers need to better understand the chemistry that occurs in the well and model the implications that these wells may have on site integrity. Current models are unable to deal with this number of wells but it is imperative that people can come up with new models that can because it is not feasible to perform pre-emptive remediation to 2000 wells as this will ruins any cost/benefit analysis for the project.

One of the most interesting findings coming from the network is the comparison of lab results to the observed results from the field. Based on lab experiments there will be rapid degradation of the cements (Portlands) used to plug the well but in practice there are field observations of wells that have been exposed for 90+ years and show very good performance. The question is, how do you reconcile this contradiction? In one case you might say that Portland it fine but in another case you might need very expensive CO_2 resistant materials.

How do we go from performance in the lab to performance in the field? There many variables in the field that we don't completely understand, different cements, different cap rocks. Two approaches are using analogues or using scientific information. These must then combine into probabilistic model.

Another interesting observation involved a sample of well sealing cement taken from the SACROC field. The sample seemed to indicate that there had been some corrosion of the cement at the contact point with the CO_2. It did however indicate that this dissolved cement particles were then forced into the overlying cement creating a very good, impermeable seal.

Conclusions

- Existing wells represent potentially important leakage pathways
- A semi-analytical model allows Monte Carlo simulations for risk assessment
- A comprehensive experimental programme is needed to determine important properties of existing wells.

The next IEA GHG wellbore integrity workshop will be held in Paris in March 2008 and will be hosted by Schlumberger. This is come shortly before the joint network meeting in May in the USA.

Discussion:
Q) How do your wellbore integrity experiments work?
A) The wellbore integrity experiments use reservoir pressure and temperature with a flow CO_2 or CO_2 brine through a made sample which matches result in the field.

Q) How many wells have sustained casing pressure?
A) At Weyburn the safest thing to say is that cases of sustained casing pressure are going up.

Q) Should we avoiding formations with 2000 wells rather than trying to find solutions?
A) Yes perhaps, but reservoirs without wells have their own risks? More wells mean more data?

Q) What is your hypothesis why the degradation rates of cement are quick in the lab and slow in the field.
A) Lab experiments are generally batch experiments which didn't necessarily match the field.

Comment) From a risk assessment standpoint I would have originally said CO_2 resistant cement but not the cement seems to have been redistributed in the well and sealed possible better, although this is one well of one million wells in the basin.

Comment) Maybe we should be concentrating on doing the cement properly. Perhaps we should be looking at cement work rather than the chemistry.

Comment) If you look at SACROC the hypothesis says that fluid flows through a crack to bring material. The resolution to find this is very high. We have to do all our sampling and experiments in a non destructive way before you can fully rely on your results.

4.5. Confidence Building through Argumentation

In the final set of two presentations, Notio Shigetomi from the Mitsubishi Research Institute and Hiroyasu Takase from Quintessa presented some of the work they are doing on confidence building. The two pieces of work that were presented were a workshop that was ran on confidence building and an interactive tool to help pool knowledge on CCS risks.

The workshop was titled confidence building in the long-term effectiveness of CO_2 capture and geological storage and was held in Tokyo in early 2007 in conjunction with the IEA GHG. The objectives of the conference were twofold:

1. To exchange state-of-the-art information, knowledge, expertise and insights on CO_2 capture and geological storage and,
2. To have in-depth discussion among experts in order to build confidence on CO_2 capture and geological storage amongst experts and policy makers.

At the conference four key confidence building questions were identified:

1. Whose confidence do we need?
2. What kind of logics and arguments do we need?
3. Do we have enough evidence for those logics and arguments?
4. How do we communicate with stakeholders?

The second piece of work was the collaborative knowledge networking tool called KNetwork. The KNetwork tool is based around the principle of argumentation – the use critical discussion to arrive at intellectual consensus. The discussion would commence with the proponents posting their hypothesis on the web based KNetwork tool. This could then be accessed by experts via the internet who could pose arguments to the original hypothesis with the proponent and other experts posting counter-arguments. Each argument would then have to be assessed as to how it "links" to the other information presented. It is thought that the critical discussion that it facilitated by the KNetwork tool would help achieve an intellectual conclusion.

Questions:
Q) What is the process of peer review and what is the next step to developing this database?
A) Depends on the interest and the participation. The tool will be ready on the web next month.

4.6. Expectations on different parts of the CCS cycle

4.6.1. BP Introduction –Tony Espie – BP

This session was kicked off by Tony Espie from BP who gave an overview of the BP Alternative Energy Risk Assessment process for CCS. BP is extremely active in the area of CCS having one project in operation at In Salah, three further projects announced (although not all of them may proceed) and three others unannounced. With that many projects in the pipeline BP feel they need to streamline the development processes to focus on what needs to be done rather than what would be nice to have. BP sees this project development as the only way to make serious developments in CCS. It is with this experience that we will build a large enough data set to be able to understand the system.

At In Salah, the primary focus of the risk assessment was on:

- Capacity
- Impact on hydrocarbon operation
- Injectivity

With a secondary focus on:

- Seal capacity (thick regional seal)

- Faulting (no faulting observed above reservoir)
- Well integrity – considered but still needs to be close out.

It is interesting to note here that for the In Salah the reservoir engineering is more of an issue than long term storage. This is due to the fact that the nearest village to the site is 100 miles away and there is no site vegetation so there will be no damage if leakage. The only real risk that relates to leakage is risk to the employees.

At In Salah, BP used a pragmatic, reservoir engineering approach to project development. They only performed minimal qualitative risk assessment but rather decided, given the unique setting of the project, that they can we live with the downsides of not getting the geological characterisation 100% correct.

Currently BP are working on the Australia-NZ Standard for Risk Assessment which sets out a very generic and structured process that applies better to CCS than the chemical industry process. The often quoted analogy with the chemical industry breaks down for CCS because of the vast uncertainties in a CCS system. This is a general concern with numerical models which can be let down because of the uncertainties.

The Australia-NZ Standard for Risk Assessment includes:

- Identification of key risks and event scenarios
- Quantification of risks
- Evaluation of risks (with stakeholder input)
- Process modification to eliminate excess risk
- Monitoring and intervention strategy to manage remaining risk

BP has already developed a structured risk framework that they use internally. There are however some gaps in the current risk assessment process.
These include:

- The criteria that are used for evaluation for example capacity.
- Bust between capacity and rate.
- The robustness of current quantitative Risk Assessment Tools and processes

BP have used the work they are doing with Australia and New Zealand and combined it with their internal experience to develop an approach to assessing CCS projects. Firstly you must design to minimise risk, this means effective site selection criteria and site characterisation. Secondly you must assess the risks that can't be avoided. This would require a risk register and modelling to help understand controls on storage and potential downsides of injection. Thirdly you must manage the risks using monitoring and verification.

This was used for the DF-1 Peterhead project where BP assumed a worst case scenario and looks at the consequences on the marine environment. The scenario looked at was a sub-sea pipeline failure which release 4Mt of CO_2 over the course of a year. This scenario was then modelled with the results show that pH due to the leak is around 0.1 at the sea bed which is one third of the North Seas natural annual fluctuation of 0.3. The pH change at the surface is even less significant. From this study it was deemed that a worst case scenario would have minimal to no effect on the marine environment.

It was also mentioned here that BP have not found FEPs particularly useful in their risk assessment process, and they haven't thrown up any thing unexpected. BP feels that deducting key hazards from 100s of FEPs is a challenge and is better done through reliance on existing experience.

In conclusion, BP are moving into a stage of industrial scale CCS deployment and therefore are boiling down the key requirements for CCS rather than concentrating on all the possibilities and what would be nice to have. However, even at this well developed stage BP feel they are not really in a place to do quantitative analysis and at best can do semi-quantitative risk assessment.

4.6.2. Risk assessment expectations – Claudia Vivalda – Schlumberger

Claudia Vivalda from Schlumberger then presented on risk assessment expectations. Prior to joining Schlumberger Claudia worked specifically on risk assessment so she brings significant expertise and experience to the topic. .

Generally a CCS cycle is broken up into a number of distinct phases which can be seen in the diagram below. Each phase relates differently to the risk assessment process with different risk assessment objectives and methods. The table overleaf outlines of how risk assessment can be applied through each phase using tools that are in use throughout industry today. The methods are aimed at answering the four key questions of risk assessment; these are what can go wrong, how likely is it, what are the consequences, and how confident are we about our answers?

Determining confidence requires an uncertainty analysis to be performed. The objective of the uncertainty analysis is to determine how the uncertainty in the initial conditions affects the results. There are two main types of uncertainty that need to be addressed. These are:

- Aleatory uncertainty which is the inherent variation associated with the physical system or the environment and can never be completely removed.
- Epistemic uncertainty which is due to lack of knowledge of quantities and processes of the system or the environment and so are reducible.

Claudia also talked about the places that uncertainties can be hidden in a project and the need to remember the full range of uncertainties in risk assessment even if we choose not to address them all. The main challenges relating to uncertainties are their representation, aggregation, propagation, and interpretation.

There is much debate about the use of expert judgement in risk analysis. By definition expert judgment is a qualitative risk assessment method but until quantitative methods are development it is often the only option available. When using expert judgement you are looking to build on what people know already, usually on the technical side. Although expert judgement is inherently qualitative, the transparency and reliability of the process

Phase	Objective	Method Examples
Site selection	Maximize performance, minimize risks. Qualitative Risk Assessment	Risk register, what-if analysis, Analytical Hierarchy Process, experts' elicitation, FEP analysis, RIS QUE method
Characterization	Know what is important, to have the risks under control at the best performance. Iterative process. From Qualitative to Quantitative Risk Assessment	•Qualitative: same methods as site selection + others to be identified/developed •Quantitative: to be identified/developed
Design	Assure a robust design vis-à-vis the performance requirements and risks avoidance. Qualitative and/or Quantitative Risk Assessment of the engineered system.	•Qualitative: see above + FMECA, HAZID, HAZOP, etc •Quantitative: FT/ET, Petri Nets, Markov chains, etc. for the engineered system. To be identified/developed for the geological system.
Construction	Build the system as designed, do not introduce additional risks or notify them if unavoidable, minimize operation risks. Qualitative/Quantitative Risk Assessment.	e.g. risk register, HARC, what-if analysis
Preparation	No induced risks, proceed according to the procedures. Qualitative risk assessment.	•Qualitative/Quantitative: risk register, risk avoidance procedures, HAZOP
Injection Note: one of the most important phases for risk control	Optimize operations to achieve the foreseen performance and to keep the risks under control. Update qualitative and quantitative risk assessment. Risk management.	•Qualitative/Quantitative: risk register update, RCM
Decommissioning Note: here in particular we need to ensure the work is well done because you will not be around to fix it.	Optimize plugging design to minimize long term risks, minimize operation risks, and minimize geological system risks. Qualitative and Quantitative Risk Assessment.	•Qualitative: risk register, what-if analysis, Analytical Hierarchy Process, experts' elicitation, FMECA, HAZID, HAZOP, etc •Quantitative: FT/ET, etc. for the engineered system. To be identified/developed for the geological system.
Surveillance	Monitor/survey what is important, to have the risks under control. Update Qualitative and Quantitative Risk Assessments.	Approach: region/site specific. No universal recipe at the current state of the art.

can be improved through a formalized expert judgment process. The nuclear industry uses a four step process:

- Identifying the elicitation issues and information needs
- Selecting the experts
- Training the experts
- Carrying out the elicitation sessions – maybe we need to explore more robust methods of assembling expert judgement. Beyond workshop.

In conclusion it is believed that for the first years of a project, a site customized procedure for risk assessment should be able to reasonably answer the four questions initially raised, e.g. what wrong, how often, what consequences, what confidence using a combination of qualitative and quantitative methods. Simulation models should be built taking into account quantitative risk assessment needs and all the uncertainties should be considered even if they are not quantifiable. Finally there is a need for a set of models that when combined together can be used to build the "risk model" of a specific site – CO_2 storage is not in a system that we can fully control? What we know about the system is through simulations.

Questions:
Comment) This comment was made in regard to the two previous presentations. When you are dealing with CO_2 storage it is the long-term risk which is unique. The two options you have are to continue monitoring and verification for ever or to decide when you stop. During your operational period you build confidence and use short-term operation for further long-term prediction. At some moment some state authority will ask how they can take over liability for the site.

4.6.3. Concerns and alternatives to non-probabilistic risk assessment – Julio Freedman – Lawrence Livermore National Laboratory – Presented by John Gale

The next presentation in this session was written by Julio Friedmann from Lawrence Livermore National Laboratory and was on the concerns and alternatives to non-probabilistic risk assessment, unfortunately Julio was unable to attend the event in person so John Gale from the IEA GHG presented his slides on his behalf.

Julio is putting forward a new approach for risk assessment which is based around the identification of hazards rather than risks. The change in approach was brought about through the concern that there are too many uncertainties related to traditional risk assessment. The outcomes of this hazard based process are called operation protocols and place an emphasis on earth and atmospheric hazards.

The reasons for using operational protocols are that they should help operators & regulators make decisions based on sound technical constraints across a range of geological circumstances. Protocols for CCS should also help stimulate development of both commercial projects and evolving regulations. And finally they should guide operators in terms of selecting and maintaining site effectiveness, esp. regarding key hazards and risks.

The focus for operational protocols should be hazards first, risks second. Hazards are easily mapped & understood, providing a concrete basis for action whereas risks are often difficult to determine. With risk defined as probability multiplied by consequence, it can be difficult to define either of these terms from first principles. Also there is a current dearth of large, well-studied projects prevents empirical constraint.

Hazards are defined as a set of possible features, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts. The table below lists a number of hazards and associated features, mechanisms, and conditions.

Hazard	**Atmospheric release**	**Groundwater degradation**	**Crustal deformation**
Feature, Mechanism, or Condition	Well leakage	Well leakage	Well failure
	Fault leakage	Fault leakage	Fault slip/leakage
	Caprock leakage	Caprock leakage	Caprock failure
	Pipeline/ops leakage		
			Induced seismicity
			Subsidence/tilt

Taking this example of a hazard list, a process of prioritization can be done for any site with a combination of expert knowledge, scientific evidence and experience. Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases. After the prioritization is complete the results can be used to tailor the monitoring programme. The monitoring suite design and integration should focus on the hazards. In the case of the Illinois basin, the protocol should focus on ground water hazards, and in particular wells.

A two-phase technical program can help provide insight needed to develop CCS protocols. First, simulations should provide constraints on CCS operating conditions and second, a field program must be used to substantiate these constraints. The program should focus on earth & atmospheric hazards of greatest relevance and provide.

The E&A hazards and need for protocols leads to a few important questions

- What is the technical basis for developing a risk hierarchy? How can that basis be improved?
- If wells represent the greatest risk, how can that risk be quickly characterized, quantified, and managed?
- If geomechanics represent substantial risks, what are the minimal data necessary to properly characterize those risks
- What science is necessary to understand the potential risks to fresh groundwater?
- What is the least monitoring necessary to serve the needs of all stakeholders?

The full list of E&A hazards suggests a need to rank, quantify, and respond to risk elements to inform operators and regulators on what actions to take for preparing a site.

Given the lack of empirical data, other approaches are needed.

- Use of analogues:
  - Industrial analogues (NG storage)
  - Natural analogues (HC systems, CO_2 domes)
- Simulation:
  - Key features & processes
  - Must be accurate, but not unduly complex
- Lab experimentation:
  - Focus on most relevant problem
  - Experimental design is key
- Scenario development:
  - Max/min cases can be defined and tested
- Risk assessment methodology:
  - Requires integration of results
  - Some probabilistic methods as appropriate

4.6.4. "Useless arithmetic" or "the best of our knowledge"? – Does probabilistic risk assessment of long-term geological storage of CO_2 make sense? – Copernicus Institute, Utrecht University – Jeroen van der Slujis

The next presentation in this session was from Jeroen van der Slujis from the Copernicus Institute at Utrecht University. Jeroen looked at when and how probabilistic risk assessment can be used in conjunction with the long-term storage of CO_2.

Probabilistic risk assessment is used widely in a number of different fields. The strength of this risk assessment approach is as follows.

- Integrative and quantitative approach
- Allows ranking of issues and results, explicit treatment of uncertainties, and optimisation
- Can be used to both enhance safety and manage operability.
- Results and decisions can be communicated on a clearly defined basis – as it has been used for a number of decades, it is well understood
- Its use is beneficial even if the models generated are not (fully) quantified
- Lack of accuracy of the data does not hamper the use of probabilistic approaches as comparative tools to rank alternatives

There are however, a number of weaknesses also associated with the approach that must be acknowledged such as:

- It can be complex, time consuming, and data-intensive
- It unavoidably requires mixtures of 'subjective' (expert judgement) and 'objective' data (observations, measurements) which limits scientific rigor of result.
- There is large potential for misunderstanding of scientific status of the outcomes possibly resulting in an undue sense of certainty

- Models of open (uncontrolled) systems can never be validated, only ‘confirmed’ by non-contradiction between observation and prediction (Oreskes et al. 1994)
- There are dangers of standardization & benchmarking too early

Probabilistic risk assessment has been used to assess the reliability of these industrial installations. There are however some key differences which set apart the geological CO_2 storage from industrial installations which will affect the validity of probabilistic risk assessment.

- Natural reservoir are much less defined and significantly more heterogeneous that industrial storage
- A natural CO_2 storage reservoir is not an engineered system
- Geological CO_2 storage is looking at a much longer time horizon - the longer the time horizon, the more open the system is
- Geological CO_2 storage involved significantly larger volumes of CO_2
- There is much more past experience for industrial gas storage
- Geological CO_2 storage requires a much larger dependency on expert judgement

All these factors combined amplify the weaknesses of probabilistic risk assessment for geological CO_2 storage.

Jeroen described three different ways that you can look at uncertainty, these are the deficit view, the evidence evaluation view and the complex systems, or post-normal view. He also outlines the different dimensions of uncertainty,

- Technical uncertainty (inexactness)
- Methodological uncertainty (unreliability)
- Epistemological uncertainty (ignorance)

And,

- Societal uncertainty (limited social robustness)

A process that can be used to help identify and quantify uncertainty is the NUSAP approach which stands for: Numeral, Unit, Spread, Assessment, and Pedigree. Looking at the final two components, assessment uses expert judgement to assess unreliability and pedigree evaluates the strength of a piece of data by looking at a number of factors including the background history by which the number was produced and the underpinning and scientific status of the number. Pedigree can be evaluated using a pedigree matrix to document and to communicate the level of certainty and reliability of pieces of information or criteria.

When assessing uncertainty it is also important to assess the quality of your model. It is I important to note that models are tools and not truths; you should concentrate of whether it is fit for purpose. Untrue tools can be very useful for example, the London underground map. A model is not good or bad but there are ‘better’ and ‘worse’ forms of modelling practice. Models are ‘more’ or ‘less’ useful when applied to a particular problem. By performing model quality assessment you can provide insurance against pitfalls in process and insurance against irrelevance in application. It is also important to note that as a model become more complex then the data error becomes larger even though the model error decreases. This means that an optimum must be found.

Taking into account the pros and cons of probabilistic risk assessment, valid and invalid uses can be defined for geological CO_2 storage. Valid uses of probabilistic risk assessment of geological CO_2 storage:

- Comparative assessment of different reservoirs and storage options
- "Validation" of simpler methods – use complex methods to test simple methods
- Gain insight in key-characteristics that determine reservoir safety
- Gain insight in what factors should be monitored for early detection of leakage risks
- Improvement of operational practices
- Support of safer designs
- Informed debate with regulators and society (but it is essential to make pedigree of results explicit!)

Uses of probabilistic risk assessment that are not so straight forward with the present state of knowledge are:

- Demonstration of compliance to a quantified safety requirement
- Comparison to other (e.g. industrial) risks

And finally invalid uses of probabilistic risk assessment of geological CO_2 storage with the present state of knowledge are:

- Demonstration of safety
- Interpreting outcomes as absolute

Following this analysis of probabilistic risk assessment and its application to geological CO_2 storage a number of conclusions can be drawn:

- Specific characteristics of CO_2 storage amplify all generic weaknesses of probabilistic risk assessment
- Probabilistic risk assessment currently has a strong dependence on expert judgement – we need to document the experts decision process
- There is a need for systematic reflection on knowledge quality – and on the numbers that we use.
- There is a need for systematic elicitation and documentation of the arguments behind each judgment by each expert
- You must be very open and very transparent about uncertainty and pedigree of results
- You must be explicit about all assumptions on which outcomes are conditioned
- You must avoid mismatch between regulatory requirements and the limited level of rigor that state-of-the-art science can realistically achieve
- There are some alternatives risk assessment options for regulators to consider including the Precautionary Principle and the Maximum Credible Accident or Worst Case Scenario approach.

4.6.5. Keep it simple! – Performance Assessment applied to Geological Carbon Dioxide Capture – Lars Olof Hoglund – Kamakta Consultants

Lars Olof's presentation looked at performance assessment for geological CO_2 storage and stressed the need to keep it simple.

First of all the principles of a performance assessment methodology were described stressing the need to keep it simple. The methodology should be simple but robust, based on fundamental and well-established scientific principles, e.g. mass-balances or thermodynamics. Using these fundamental mechanistic approaches allows reliable extrapolation in time; this is not the case with lumped knowledge.

Use an iterative approach, avoiding unnecessary detail in the first rounds of iteration. Only go into more detail with issues that you judge to have potential global impact. Discard processes/features/scenarios that are obviously irrelevant or can be discarded based on simple estimates. It is important to be quantitative where ever possible – try to pin down some numbers that can be refined.

Always document exactly what you are doing and why you are doing it. It doesn't take too much extra time but it can save years if you need to come back to the work you have done. Issues to document include:

- What has been studied (purpose and scope of investigation, the studied site and storage system etc)
- Which assumptions that were made
- Quantitative parameterization – why you used the numbers and what are their sources?
- Judgments made based on the quantitative results
- Sensitivity of results to parameter uncertainty – parameter uncertainty is less than conceptual uncertainty
    - Is the uncertainty expected to be of importance?
- Who made the judgments

Try to keep the overall aim in focus – what are we really trying to do? Are we trying to get the exact number of kilograms of CO_2 are entering the atmosphere or counting how many salmon die or are we trying to save the earth? The results of your assessment must be compared with field and laboratory observations, using any deviations to improve the understanding of the system. Results should also be compared to observations of natural analogues to address long-term and/or large scale processes. These comparisons work as feedback to the design and help improve and optimise the process.

There are some issues of potential importance that should be kept in mid when generating a performance assessment methodology.

- Scale-effects may be important. What is not observed in small scale experiments/ applications may well occur in large scale applications. An example of this is rock heterogeneity at different scales which will affect the mechanical impacts of CO_2 pressure or the buoyancy effect.
- Impact on groundwater systems. Effects due to dissolution and hydrolysis of $_{CO2}$ can include pH effects, dissolution/precipitation of minerals and mobilisation of heavy metals. There is also the issue of displacement of saline groundwater which may impact water a long way away. This can result in huge volumes

displaced by injected CO_2, high pressure gradients created, and possible impacts on fresh groundwater aquifers.

- In all cases risk assessments should be used to address possible effects. This process should include identifying:
    - Which processes/features may be critical?
    - What are the potential consequences?
    - Would the consequences be acceptable? – if they are…no problem.
    - What would be required for this to happen? Is this reasonable?
    - Can it be avoided/minimised?

In conclusion it was highlighted that CCS will be required to meet the significant mitigation requirements to avoid serious climate change, particularly for the growth emissions in India and China. It was stressed that we should not wait for the perfect solution and complete knowledge of all details about CCS, because by this time it may be too late to contribute to the solution. Instead we should be prepared for the certain surprises that will arise in the development of CCS. The performance assessment methodology can be applied to address, foresee and possibly avoid some of these difficulties.

Discussion:
Q) The approach of working backwards from a possible event is good but it requires judgement of the likelihood of it happening. For example Lake Nyos would have been deemed very very unlikely to occur but it did kill1800.
A) True but we have more knowledge than in the natural system. If the Lake Nyos was monitored and understood then we could probably have predicted it.

Q) In terms of communicating to the public the maximum credible accident approach works. This has to be the way forward for building confidence.
A) Yes. You may not know what the worst case is.

Q) Whatever scenario you choose, it is very hard to come up with a significant accident with CO_2, so it is hard to come up with a worst case scenario.
A) Worst case scenarios are often extrapolated by non technical people to something that is not very realistic.

Comment) We need to look at the risk of not doing CCS as well and compare these to the risks associated with it.

Comment) The experience from Sleipner indicates that the probability that anything escapes from the Utseria formation is likely to go downwards because of dissolution. Risk profile can improve over time although this is over thousands of years.

Comment) People can't comprehend 1000+ years.

Comment) Listening to the conversation we don't have a definition of risk. What is it that we are worried about? People, climate change, fish? Maybe we don't have just one single type of risk?

Comment) Changing levels of pH as an example and playing devils advocate. Why did the pH change occur? You have to be very careful to identify all the risks and measures.

Comment) The BP rupture model would not pass the credibility test because it wouldn't happen.

Comment) If you have a lot of projects or the ocean behaves differently than we think then the results may be worse than we think.

Session Conclusions

To wrap up this session John Gale summarised the major conclusions. He stated that we have achieved a consensus of sorts. The question from the session was; What are we really trying to do? The answer; what we are really trying to do is stop global warming and CCS technology should be looked at and assessed in this context.

There is a drive from regulators to describe impacts but this would require us to define flux rates and multiply it out but we can't do this yet so we shouldn't focus on it. We should instead concentrate on the fact that climate change is the big issue.

If we are going to experience leakage it will be from the engineered system – pipelines, well, infrastructure. We do have history on this so to some extent we can history match and use past experience. This in turn would allow us to use a quantitative analysis. The engineering design will be the same irrespective of the storage site. We are able to predict with some degree of confidence the likelihood of the risk for this part of the process.

In regard to the storage reservoir; we don't feel that we are going to experience any serious leakage from the storage reservoir. We can't really quantify that any further at this stage because we don't really have the analytical data to support it. We can however run worst case scenario. We can also try to minimise the risk of the event occurring. In the early days we may have to over engineer, by isolating the project to reduce risk. This could be done by placing the project out at sea, like Sleipner, or in uninhabited places, like In Salah. The best we can do at this stage is a semi-quantitative process while we keep working on the models and on a full quantitative process.

Comment) Would this be enough for regulators and public? What more can we offer them?

Comment) If you have a 1 in 100000 chance of an event happening, people don't understand that, people buy lottery tickets. We must put this information out so that people are not scared about it. Before we have a realistic evaluation we need 50+ years of experience. The regulators are going to listen to the voters so it is important to inform the voters properly. This is the way that they approached it in Australia.

Comment) Without large scale injection we are going nowhere, modelling is not going to get us any further.

Comment) You need the money for the CO_2 from somewhere. But people are not going to pay if we can't prove to the spender that we know where it is going otherwise this is going to devalue storage to five from twenty five.

Comment) Public don't trust industry. We also need to know how long we monitor before hand over.

Comment) In Nuclear they foresee monitoring for 300+ years. We want to avoid this.

Comment) Once there is a convergence of the model and the monitored data, that is when we can hand over the site.

Comment) There is another piece missing from this discussion. In nuclear there are limits to nuclear exposure. What we are missing is how much leakage is acceptable. At the moment we have 100% leakage. We want to go to the regulators and the public and convince them that CCS is good.

Comment) Leakage is acceptable up to 500ppm in the atmosphere.

Co_2mment) To be honest with CCS it can be impossible to get the CO_2 back out of the reservoir again, even if we wanted to.

4.7. FEPs – Features, events, processes

4.7.1. Using the FEP approach in auditing the comprehensiveness of a site-specific programme for CO_2 storage – Ton Wildenburg – TNO

This presentation looked at how FEPs or Feature, Event, and Processes analysis can be used in an auditing capacity for the De Lier project in the Netherlands. The De Lier project currently involves the capture of CO_2 from a refinery and the use of the CO_2 in greenhouses in the region. The CO_2 is almost pure as it comes from the refinery however the CO is only required in the summer months because in winter the CO_2 required is generated from the diesel engines used to heat the greenhouses. It has been proposed that during the winter months the CO_2 could be diverted into a geological storage reservoir.

The objective of the feasibility study was to evaluate the feasibility of safe and effective storage of CO_2 in the depleted De Lier gas field near the village of De Lier. The emphasis of this study was on the integrity of containment or hazards rather than on the consequences of a potential leak.

The eight specific studies involved were:

1. Well integrity
2. Subsurface model

3. Caprock and fault integrity
4. Spill risk
5. Reservoir compatibility
6. Monitoring programme
7. Surface design, including risks and mitigation
8. Qualitative hazard assessment

Study number eight, qualitative hazard assessment, is relevant to this network. The objective of this study is to try and achieve qualitative consensus on possible leakage scenarios of CO_2 out of containment and to evaluate the comprehensiveness of the initial programme of technical studies.

To assess the hazards and risks initially the bowtie concept was used however for this study only one half of the bowtie was addressed with the focus on hazards rather than consequences.

The FEP process was then used as part of a greater scenario-based assessment method. The scenario based assessment process includes:

1) Definition of the assessment basis
2) FEP analysis
    - Identifying any potential risk posed to your storage site.
    - Ranking the risks identified
3) Scenario formation
4) Development of dedicated models for simulation of safety scenarios
5) Risk evaluation against HSE effects

The first step, defining assessment basis, in this case relates to the De Lier reservoir and surroundings. The assessment basis will include the geographical and geological setting, the containment concept, the assessment target, the temporal and special scale and the assessment procedure.

The second step is FEP identification. Currently the FEP database contains 657 FEPs. TNO's first step then was to narrow down this list, removing any redundant FEPs or FEPs that didn't relate to this particular project. This pre-selection process brought the list of FEPs down to 200. These 200 were then grouped according to what they related to. The groups were:

• Chemical reactions • CO_2 behaviour • Faults and fractures • Fluid Flow • Human flaws • Injection • Mineral dissolution and precipitation	• Natural changes of the system • Petrophysics • Anthropogenic activities • Rock mechanics • Seal integrity • Thermal processes • Well Integrity

The list of 200 grouped FEPs were then circulated via email to 13 experts who were asked to identify their top 20 FEPs that could impact this project. After combining the top 20 FEPs from each expert, 67 unique FEPs were identified in total.

The next step in the process was the scenario formation workshop which brought the experts together in person to reach a consensus on the selected FEPs. The workshop also allowed the experts to combine the FEPs into meaningful cause-consequence relations and to review the completeness of the whole De Lier feasibility study. Following the workshop 42 FEPs remained for further (quantitative) assessment. Scenarios were also defined for three stages, pre-injection, injection and post injection.

Each of the stages included a flow chart that outlines the process and categorised each element. The scenarios for each stage are as follows:
Pre-injection:

- Effect of production on well, reservoir and seal

Injection:

- Pressure
- Temperature
- Compositional change

Post injections

- Pressurized reservoir
- Buoyancy
- Reactions

In conclusion, the FEP process was found to provide a structured way of how to define possible leakage scenarios within limited time. In this process it was found that splitting the time domain into pre-injection, injection, and post-injection made the scenario definition less complicated. It was also noted that most of the selected FEPs were included in the initial risk assessment programme. It was also noted that although this process does involved some expert judgement, a lot of quantitative analysis is also involved in this process. In the end it was found that parts of the FEP approach are really adding to this work and the whole assessment took two weeks so it isn't too tedious.

In regards to the case study it was found that the field has over 50 wells penetrating it and in Dutch law there is no requirement for a well going to an underlying stacked field to have a cement lining as it passes through the overlying fields. These two factors combined with the close proximity to populated areas means the field was deemed to high risk and will not be pursued, however another site has been identified in the area.

Questions:
Q) How did you choose the experts? Could you be accused of bias in the selection of the expert panel? Were they CCS people? If not did you have to bring their level of knowledge up to a certain level before you could proceed?

A) The main bias is that they were people from the organisation developing the project. Technically they covered the range of experience required. You could say that an independent panel of experts should be used. Perhaps this could be a step to follow the internal review process.

Q) In regard to the expert workshop consensus building process, this is a very uncertain area with a lot of ignorance. Did you analyse where the experts disagree and the process used to reach consensus?
A) We have looked at all the FEPs and documented why they are excluded however it could have been done in a more systematic way. The process could be formalized. Lots of people think the FEP process is a tedious approach. In this case it worked. FEP is just a name; you could call it hazard identification instead. This is inline with many other industries such as oil and gas.

Q) In the Weyburn context, the concern is that with the experts TNO assembled end up answering the wrong questions. The questions will be posed by regulators and the public and if you only consult experts you will miss all these important questions.
A) Agreed, we weren't ready to go public but there will have to be a dialogue. If the public do pose different problems then you will have to redo the FEPs process with the new issues. It could be an iterative process. This is not the end point, this could be used for the internal screening.

Q) People will argue that all these other stake holders should be part of this process.
A) The critical question is when do you bring other people in? In Australia we tried to sort out as many of the technical issues as possible before we went to the community. The community also involved EPA and government. You can't bring the people in until you have answers for them.
A) In FutureGen the technical analysis was done as part of the EIS which then lead to public consultation.
A) The clarity of how you present it is very important.

4.7.2. Using (not abusing) FEPs – Steve Benbow – Quintessa

This presentation gave a background to the FEP process, showed some of the possible usage options and how FEPs could be applied to natural analogue systems.

There are many slightly different formal definitions for FEPs but basically they are:

- Feature – a physical component of a system or a physical entity that influences a system. This also involves concentrations and pressures.
- Event – a process influencing system evolution over a short time period compared to the time frame being considered
- Process – a dynamic interaction between "Features", which may operate over any particular time interval of interest.

FEP databases are collections of FEPs and should not be used or described as modelling tools. They do however attempted to be more than just lists of FEPs. FEP databases can be used in a number of applications. They can be used to aid model and scenario development, describing key scenarios and providing us with a language and terminology to use. They can act as auditing tools for system-level models. They provide a knowledge base for storage studies, giving an explanation of the FEP, sources, descriptions and links. They also stimulate discussions among experts. Project specific FEP databases indicate the range of phenomena that have been considered and build confidence in thoroughness and logic of a safety assessment.

For Weyburn, Quintessa came up with a generic FEPs database. The database was developed initially during the Weyburn Project between 2001 and 2004 and tried to create a core set of FEPs that broadly described the project. Initially this database contained between 100 and 200 FEPs. This database has since been expanded and is available from the IEA GHG website – www.co2captureandstorage.info/riskscenarios/riskscenarios.htm. Each FEP contains a description, its relevance to safety, references, links and an area where suggested improvements can be made.

FEP databases can be used in two ways, 1) the Bottom-up approach and 2) the Top-down approach.

In the bottom-up approach the database is used directly in the development of assessment models, e.g. process influence diagrams and interaction matrices. If the database is used as a starting point, then all possible FEPs and relationships must initially be considered which potentially results in huge complexity. There is also the issue of where to begin?
If the bottom-up approach is used, there is a tendency to reach for probabilistic tools in order to cope with the complexity. This is fine if good PDFs are available for all likely FEPs and interactions, if they are not available there is a danger of "risk dilution". Risk dilution is a situation where an increase in the uncertainty in the values of input parameters to a model leads to a decrease in calculated risk. This generally involves the risk being spread out in time or space. Examples of risk dilution are ignoring parameter correlations or when a PDF is inappropriately wide or biased to low consequence outcomes. There is also an issue with sampling, how many runs do we need to convince ourselves that we've covered all relevant possibilities? We must not only choose which relationships to include, but also how to include them.

In the Top-down approach the database is used as an audit tool and modelling aid to ensure all relevant FEPs are in the model and to document why other FEPs are screened-out. To help explain the top down approach better, the CO2GeoNet study of the Latera analogue was used. This was not a performance assessment but rather a modelling study. However the approach to modelling the system is similar to a performance assessment.

The objective of the study was to simulate:

- The CO_2 fluxes to the surface and near-surface aquifers
- The overall mass balance for the near surface part of the system
- The soil gas concentrations
- The potential impacts to flora

The plan was to use this to develop a probabilistic assessment model and run it 1000 times so the model can not be too complex. To reduce the complexity a system-level model was produced.

The top down approach is used to identify the key subsystems and "project FEPs" using information from detailed site characterisation. These project FEPs were then audited using the larger FEP database to document "project-specific" details for relevant FEPs, give reasons for all screened-out FEPs, and to ensure that we've not missed anything. Following this process we can identify the "base case" and the scenarios that we want to model with the aim of covering the range of "interesting" possibilities, both central and worst cases. Only after this process is complete can we develop a model. The "knowledge" in the database can help us in creating the model however the database is only ever used to assist in developing models/scenarios and as an audit tool. It is never used as a "model generator".

When developing a model it must be decided on an appropriate level of detail when modelling, full complex reservoir models should feed into simpler broader models. It may be suitable to model some aspects of the system in "less detail" than others (e.g. the ecosystem). "Less detail" means less detailed representation of processes and/or geometry. Other aspects may need to be modelled in more detail (e.g. the multiphase flow of CO_2 and water). There is a balance to be struck as less detail can lead to less accuracy, but the model runs faster which means more scenarios are possible. More detail leads to greater accuracy but slower runs so fewer scenarios are possible. The outcome is that the least amount of detail should be used that still provides sufficient accuracy. The choice of detail level could also be limited by what is possible in our programming code chosen.

The two key models used in this example were the CO_2 transport model and the ecosystem model which was intentionally fairly simple. The results of the two models mapped CO_2 fluxes at the surface and the resulting effects on vegetation.

In conclusions it was found that FEPs are good to audit and allow us to talk about models, but should not be used to create them.

We have demonstrated our approach to using FEPs and FEP databases in the system level modelling approach:

- Example QPAC systems-level model was discussed
- System was broken down in to "subsystems" corresponding to key project FEPs
- Processes relevant to each subsystem are modelled in appropriate detail
- Subsystems are joined by common CO_2 fluxes at the surface
- FEP audit reveals comprehensiveness of the model and identifies areas for consideration in future modelling studies.

The “FEP approach” is not “fancy” - it just gives us a logical way to structure our modelling study. It is important to note however that databases need to be kept up to date if they are to continue to provide a useful knowledge base.

Questions:
Q) Is the model a good tool?
A) It is a prototype tool, a reasonable stab at reproducing field results in terms of flux profiles and vegetation response.

Q) Did you use geomechanical and chemical modelling?
A) Not yet.
A) This is the first time to try and link the surface and the subsurface modelling and it pretty accurately matches what is happening in the field. Quintessa is happy with the results from this study to date.

4.7.3. Weyburn experience of FEPs – Rick Chalaturnyk – Alberta University

The final phase of IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project is to go ahead 3 years after phase 1 finished. The final phase will contain both technical and non-technical components. The non-technical component will look at regulation, public communication, and fiscal policy. The technical component will look at geological integrity, wellbore integrity, storage monitoring methods (Geophysics and Geochemistry) and risk assessment.

Risk assessment forms the 4th theme of the programme and will look specifically at storage & trapping mechanisms, remediation measures, and HSE. There are a number of knowledge gaps that will act as a driver for this work programme. There is a need to find consensus on risk/performance methodologies suitable for site approval for operations and for earning (storage) credits. There is a need for appropriate risk assessment methods and risk mitigation measures for confirming the safety and reliability of geological storage of CO_2. There is a strong need to rationalize the selection of cost and time-effective methodologies for risk assessment of the long-term fate of stored CO_2. Finally there needs to be recognition that risk/performance assessment is critical for the development of future regulations and/or identifying and addressing gaps that may exits in existing regulatory frameworks

In the final phase there are a number of objectives.

- A number of risk assessment techniques will be used to complete a full field risk assessment of the Weyburn Storage site, Region B. This will include FEP analysis, Bow-Tie Method and URS Method
- A peer review of Phase I dataset in order to establish a collection of data and information for use in quantitative/semi-quantitative risk analysis – this is necessary to demonstrate traceability of the data and contribute to the transparency of the RA process.
- A peer review evaluation of the Base and Alternate Scenario’s developed in Phase I to ensure integration of the final geoscience/reservoir data into the performance

assessment model. There is a need to update and refine the geosphere model based on the latest interpretation of geological and hydrogeological information.

- Reconciling Reservoir/Geosphere/Biosphere Modelling Issues
- Perform FEP and Scenario Development for Midale
- Conduct a semi-quantitative risk assessment utilizing experts and Phase I work in order to frame the entire risk assessment process.
    - This will engage a multidisciplinary panel of experts and stakeholders for input
    - The goal is to complete even a qualitative risk assessment that identifies the major issues that include both likelihood and consequence and provide a framework for configuring the more detailed and comprehensive analysis tasks required for completion of a quantitative risk assessment.

Finally, one other technique for assessing risk in CO_2 storage projects that was developed in Australia and that is called the RISQUE Method. This technique addresses the need to compare relative risks between projects. This will enable the Weyburn project to be placed in the context of other international projects. The expert panel is a critical resource in the RISQUE method. The quality of information used in the assessment is dependent on the level of skill and knowledge of the expert panel and to a lesser extent, on the ability of the risk analyst to effectively guide the panel through the process. This will be done first and use it to drive more quantitative work later on. Spend the money solving the questions that need answering.

Questions:
Q) Now you are doing this for Weyburn, what are you going to do at Midale?
A) Nothing really, there is some stuff that they would like to do but they don't have the resources. Midale is a field just east. Apache want to make money, Encana are in it for the storage.

4.7.4. Methodological developments to define safely criteria – Olivier Bouc – BRGM

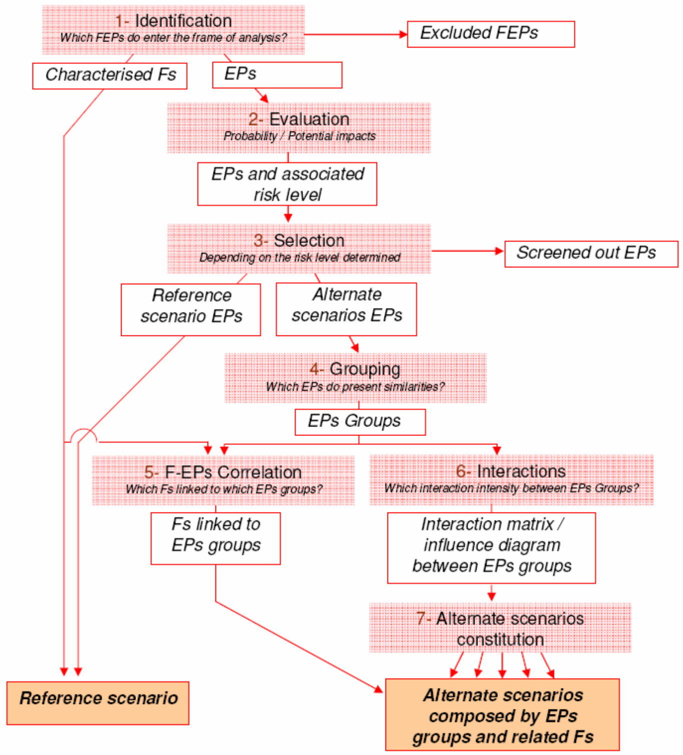
In this presentation Olivier describes some of BRGM's research about safety criteria for CO_2 Geological storage, in particular, qualitative/quantitative approach of risk scenarios. The findings are based on a 3 year cooperative research project which is funded by government, industry and a number of universities.

This study is looking to address safety criteria which are distinct from performance objectives. Safety criteria relate to the requirements to ensure near-zero local impacts on health, safety and the environment in the short, middle and long term. Qualitative assessment will be used for the generic criteria with quantitative when possible for the site specific criteria.

The aim of the study is to contribute to demonstrating safety of CO_2 geological storage by providing a simple workflow to evaluate safety in a licensing process. This will involve building long-term evolution scenarios, evaluating potential targets exposure using simple models and ultimately determining safety criteria. It is important to note that this is not a risk assessment, but rather gives keys to control a risk assessment.

The first step in the process was to build scenarios which are where FEPs were used. The scenarios were based around an hypothetical storage site, in the Dogger Aquifer underneath the Paris basin, in France.

FEPs database workflow used can be seen in the flow chart below:



The Quintessa online FEPs database was used for the study and the workflow closely followed that used by Vattenfall and TNO in the CO2STORE project.

The results of the study defined 6 leakage scenarios

A) Well degradation
B) Caprock fracturing due to overpressure
C) Leakage through buoyancy
D) Leakage through fault
E) Reservoir water migration
F) Open hole leakage e.g. future drilling

Following the study they review the use of FEPs. They found that the method was not optimal as it was tedious and time consuming, and identified very little compared to investment, i.e. could have achieved the same results cheaper. They also found their results were very close to the results of the CO2STORE study.

More specifically they found some of the steps involved in the FEPs process to be unnecessary. Steps 1-3 are fine, Step 4 (grouping) they found questionable and very subjective and they also had concerns about Step 7 (Deducing scenarios from influence diagram). Ultimately they found that the same results could be achieved even without steps 4-7. They do however acknowledge that there are some restrictions to their criticism which are, this was only a test and their first use of the tool, they used a hypothetical site so had no real data, they did not bring together an actual expert panel, they used the Quintessa Database where the TNO may be more suitable for this method.

The main advantages of the FEPs process were its comprehensiveness and it systematic documentation of the evaluation process. They feel however that it may be better suited as an auditing tool rather than a scenario-building tool.

Questions:
Q) Did you consider using a correlated variable to address the uncertainty of compartmentalised models?
A) We are trying not to represent everything by probability functions. People are working on showing what we know using fuzzy logic. We don't want to represent more than what we know. They will then look at how to propagate it through the model.

Sessions Conclusions:
To summarise this session on the used of FEPs in risk assessment John Gale noted that FEPs are a tool, one of many, and ultimately it will be a developer's choice as to which tool they use. He also said that the consensus seems to be that FEPs are a very good audit tool and noted that we have learnt a lot from the application of FEPs until now.

4.7.5. Geological CO_2 Storage Certification Framework – Curt Oldenburg

The final presentation of the network meeting was from Curt Oldenburg who described the CCP2 study to develop a simple framework for evaluating leakage risk for certifying operation and decommissioning of geological CO_2 storage systems. They believe that having a simple, transparent, and accepted basis for regulators and stakeholders to certify that the risks of geologic CCS projects to HSE and resources are acceptable is critical to the large scale deployment of CCS.

Certification Framework Overview

- Theory and Philosophy of Certification Framework
    - Effective Trapping requirement – We don't want to say 100% storage so we need a framework that will allow some CO_2 leakage.
    - The Certification Framework is based on CO_2 Leakage Risk
    - Compartment concept
    - Broad classes of features
    - Catalogue of model results
    - Model results are from sophisticated modelling of simplified systems
    - The Certification Framework is probabilistic in existence of flow pathways and deterministic in flow along the pathway
- Inputs are properties and definitions of the injection system

- Outputs are CO_2 Leakage Risk numbers for impacts to various compartments

As part of the development, existing Underground Injection Control (UIC) regulations were looked at which address the injection of hazardous liquid waste. The requirement for this certification is projection that no migration will occur from the injection zone while the waste remains hazardous (or for 10,000 years). The main concern of the UIC regulations is the protection of underground sources of drinking water or USDW rather than migration to the surface. This is because these, Class I, wells inject below the USDW and the injected fluids are nearly always denser than native fluids. Under these conditions, the non-migration requirement is relatively easy to meet.

CO_2 injection however differs from hazardous liquid waste injection in some key areas such as CO_2 being less dense than the reservoir brine and CO_2 will be injected in much larger volumes and higher injection rates. This means that CO_2 has tendency to migrate upwards and the CO_2 area of review may be very large.

Part of the Certification Framework is a method of leakage risk calculation which was shown using a hypothetical storage site to illustrate. The hypothetical site included a number of oil and explorations wells, a number of water wells, and a CO_2 injection well. The wells and faults contained a mixture of active and non-active.

The project was simplified into a mixture of conduits (wells, faults and fractures) and compartments (Hydrocarbon and mineral resources, USDW, HSE (Health, Safety and the Environment), and ECA (Emissions credits and atmosphere). The simplified model also contained a CO_2 source.

Using this as the basis for the analysis, the CO_2 leakage risk is calculated using the multiplication of impacts and probability. Examples of impacts could be:

- Exceeding the concentration limit of a compartment e.g. 0.4% in air in an HSE compartment (indoors, local)
- Exceeding flux limits e.g. CO_2 flux greater than 100 times background to the USDW compartment
- Exceeding time-integrated concentration or flux e.g. concentration of CO_2 exceeds ten days of greater than 0.1% in an HSE compartment (outdoors, local)

Thresholds for individual compartments would pertain to the probability of occurrences of exceeding limits. The impacts would relate to defined limits and thresholds. The probabilities considered by the Certification Framework are the probabilities of conduits (wells, faults and fractures) intersecting the CO_2 source and the compartments (Hydrocarbon and mineral resources, USDW, HSE and ECA).

In short, certification of a storage system will be allowed only if the CO_2 leakage risk is below thresholds established for the probability that a limit will be exceeded for concentrations or fluxes at all compartments. When the CO_2 leakage requirement is below all thresholds, the effective trapping requirement will be met.

Ongoing efforts relating to the Certification Framework include:

- Reservoir simulation catalog
- Case studies
- Fault and well flow model
- Fault intersection and characterization
- Above-ground CO_2 migration
- Interaction with regulators, guidance on impact thresholds and risk limits
- Uncertainty by fuzzy membership models
- Rapid Prototype in GoldSim

Lastly Curt wanted to make one last comment about probability. For years people have tried to avoid it and focus on impacts but there is a steady drum beat of demand for probabilistic risk assessment. It is something that is inevitable as we need to portray how likely things are.

Questions:
Q) Are you only looking at subsurface? We will have to deal with operational venting because no one wants to talk about it.
A) Our experience is only in storage

Q) What about the spill point?
A) We are assuming that the site was chosen to avoid meeting the spill point.

Q) This is a process for permitting but do you foresee that operators will have to measure the fluxes when they are operating?
A) We have been thinking that monitoring is a secondary overprint so no, we do not expect the operators to do this.

Q) Do you have a model for each part?
A) We have 2 models, one complex and one more simple. We have run 1000 iterations with generic data depth, etc. We are trying to push the Framework not the model.

Q) Do you want to benchmark this about actual projects?
A) Yes.

Q) Who would be doing this?
A) The developer or a consultant hired for the developer.

Q) If the developer does it then you can’t separate out the monitoring.
A) Yes, perhaps then the monitoring would have to be imposed as an overlay. It could turn out that the performance is so good that monitoring requirements are minimal.

5. Summary and Outcomes

Following the final presentations John Gale gave a brief outline of what we have achieved at this meeting and what further issues and questions have been identified for future focus.

In regard to risk assessment technology, Imperial College performing a study that tries to identify and define key terms that are integral to CCS risk assessment communication. The terms identified are drawn from CCS literature and associated industries. The next step in this work is to circulate a questionnaire to people within the industry to try and build consensus on the terms to use and their definition. One suggestion was to set up a *Wikipedia* style website to act as a forum to build an agreed pool of terms.

A key discussion from this workshop was around the process of site characterization. This is a common theme running throughout the Risk Assessment Networks and was explored in this meeting but not resolved. The issue remaining is determining how much site characterization is enough to satisfy all the stake holders involved in a CCS project.

There was a lot of discussion in this network about whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk. The debate seemed to conclude that it would be ideal to have a fully quantitative risk assessment process but currently it would not be possible for anything more than a semi-quantitative or predominantly qualitative process to be used. This led to a discussion on the use of expert panels in risk assessment which was seen as a process that needs formalization.

Following the session on the FEP risk assessment process it was found that this process is just one tool of many and the general feeling was that it was better suited as an auditing tool rather than the primary tool for risk assessment.

6. Next Steps

There were also a number of additional issues/questions raised over the course of the network that need to be addressed. These include:

- Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
- How confident are we in the modelling results we are generating for CCS projects?
- How long do we need to monitor for after the cessation of CO_2 injection?
- What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

Finally John announced the first Joint Network meeting that will involve the Risk Assessment Network, the Monitoring Network and the Wellbore Integrity Network. This meeting will be held in New York in June 2008. The 4th Risk Assessment Network meeting will be held in Australia and hosted by the CO2CRC. The date for this meeting has not been confirmed but will most likely be early 2009. The 5th Risk Assessment Network meeting will be in France, hosted by Schlumberger.

Imperial College, London

3rd Risk Assessment Network Meeting

15th—16th August 2007

Imperial College, London, UK

Organised by

IEA Greenhouse Gas R&D Programme.

Hosted by

Imperial College

Imperial College London

15th August 2007 Day 1

08.00 to 08.30 Registration
08.30 to 08.45 Welcome Address; John Gale, IEA GHG

Session 1– Developments in Risk Assessment

08.45 to 09.05	OSPAR/London Convention; Tim Dixon, BERR
09.05 to 09.25	Sleipner Case Study; Helga Hansen, Statoil
09.25 to 09.45	FutureGen; Tom Grieb, Tetra Tech
09.45 to 10.15	Panel Discussion

10.15 to 10.30 Coffee Break

Session 2- Site Characterization - How much is enough?

10.30 to 10.50	IEA GHG site characterisation guidelines and IPCC SRCCS; Brendan Beck, IEA GHG
10.50 to 11.10	Site Characterization Needs for Risk Assessment; Mike Stenhouse, Monitor Scientific
11.10 to 11.30	US Perspective; Anhar Karimjee, US EPA
11.30 to 11.50	Australian Perspective; John Kaldi, CO2CRC
11.50 to 13.00	Panel Discussion

13.00 to 14.00 Lunch

Session 3—Terminology

14.00 to 15.00	CO2 Storage Risk Assessment Terminology: Introduction and Presentation of work; Anna Korre, Imperial College
15.00 to 16.00	Panel Discussion

16.00 to 16.15 Coffee Break

Session 4—Report from Well Bore Integrity Network

16.15 to 16.30	The Role of Wellbore Integrity in Risk Assessment for Geologic Sequestration; George Guthrie, LANL
16.30 to 16.45	Wellbore Integrity Part II; Rick Chalaturnyk, Weyburn
16.45 to 17.00	Panel Discussion
17.00 to 17.15	Confidence Building Through Argumentation; Norio Shigetomi, Mitsubishi Research Institute

Close Day 1

16th August 2007 Day 2

08.30 to 09.00 Coffee

Session 4—Expectations on different parts of the CCS cycle

09.00 to 09.30	Introduction - Strawman proposal;Tony Espie, BP.
09.30 to 09.50	Risk Assessment Expectations; Claudia Vivalda, Schlumberger
09.50 to 10.10	Concerns and Alternatives to Non-Probablistic Risk Assessment; Julio Freedman, Lawrence Livermore National Laboratory
10.10 to 10.30	Does probabilistic risk assessment of long-term geological storage of CO2 make sense?; Jeroen van der Sluijs, Copernicus Institute, Utrecht University

10.30 to 10.45 Coffee Break

10.45 to 11.15	Keep it Simple; Lars Olof Hoglund Kemakta Consultants Co.
11.15 to 12.30	Panel/Strawman Discussion; Tony Espie, BP

12.30 to 13.30 Lunch

Session 5– FEPs - Features, Events, Processes

13.30 to 14.00	Using the FEP approach in auditing the comprehensiveness of a site-specific research programme for CO2 storage; Ton Wildenburg, TNO
14.00 to 14.30	Using not abusing FEPs; Steve Benbow, Quintesssa
14.30 to 15.00	Weyburn Experience of FEPs; Rick Chalaturnyk, Weyburn
15.00 to 15.30	Methodological developments to define safety criteria; Olivier Bouc, BRGM

15.45 to 16.00 Coffee Break

16.00 to 16.45	Panel Discussion
16.45 to 17.00	Wrap up; John Gale, IEA GHG

Close Day 2

Attendee list for the 3rd Risk Assessment Network Meeting, Imperial College London, 15th- 16th August 2007

Claudia Vivalda	Schlumberger	John Kaldi	CO2CRC
Malcolm Wilson	University of Regina	Cutis Oldenburg	Lawrence Berkeley National Laboratory
Olivier Bouc	BRGM	Tom Grieb	Tetra Tech, Inc.
Jeremy Colls	The University of Nottingham, UK	Hiroyasu Takase	Quintessa Japan
David Savage	Quintessa Limited	Christian Bernstone	Vattenfall Research and Development AB
John Gale	IEA GHG	Anna Korre	Imperial College London
Brendan Beck	IEA GHG	Sevket Durucan	Imperial College London
Mike Stenhouse	MONITOR SCIENTIFIC	Claire Imrie	Imperial College London
Sohei Shimada	University of Tokyo	Norio Shigetomi	Mistubishi Research Institute, Inc.
Steve Benbow	Quintessa Limited	Marie Gastine	BRGM
Helga Hansen	Statoil	Hubert Fabriol	BRGM
John Barker	University of Southampton	Joris Koornneef	Copernicus Institute - Utrecht Univeristy
Hans Aksel Haugen	Statoil	Rajesh Pawar	Los Alamos National Laboratory
Lars Olof Hoglund	Kemakta Consultants	Tsukasa Kumagai	JGC Corporation
Hanspeter Rohner	Schlumberger	Rabih Chammas	OXAND SA
Tony Espie	BP	George Guthrie	LANL
Martin Jagger	Shell E&P	Anhar Karimjee	USEPA
Guenter Borm	GeoForschungsZentrum Potsdam	Kojiro Katsukura	RITE
Koorosh Asghari	University of Regina	Andrea Ballouk	Forschungszentrum Juelich GmbH
Alberto Mazzoldi	University of Nottingham	Tim Dixon	UK Dept BERR (formerly DTI)
Sarah Stiff	E.ON UK	Jeremie Saint-Marc	TOTAL
Andrew Garnet	PTC / CO2 Projects	Alex Bond	Quintessa
Rick Chalaturnyk	University of Alberta	Tony Booer	Schlumberger Carbon Services
Nicolas Aimard	Total E&P	Ton Wildenburg	TNO
Magnus Pettersson	Vattenfall Power Consultant	Julia West	BGS
Runar Nygaard	University of Calgary	Jeroen van der Sluijs	Copernicus Institute, Utrecht University
Ji Quan Shi	Imperial College, London	Mike Carpenter	DNV Research & Innovation
David Jones	BG Group	Sian Twinning	IEA GHG

OSPAR, and London Convention, Risk Assessment and Management Guidelines

Tim Dixon
Cleaner Fossil Fuels and Hydrogen Team
UK Department for Business, Enterprise & Regulatory Reform
15 Aug 2007

OSPAR

- **OSPAR amendments** (to Annexes II and III)
- **OSPAR Decision** – requirement to use Guidelines when permitting, including risk assessment and management process
- **OSPAR Guidelines** for Risk Assessment and Management of Storage of CO2 in Geological Formations – includes the **Framework for Risk Assessment and Management (FRAM)**

OSPAR Guidelines for Risk Assessment and Management

- Provide generic guidance when issuing permits
- Parties to ensure applied to the extent possible
- Focus on injection and storage
- Reporting to OSPAR
- Permit information
- Include the FRAM

OSPAR FRAM

- Although permanent containment is objective, it is necessary to show that if leakage does occur it will not lead to significant adverse consequences
- Project initiator to : characterise site; characterise risks to marine environment; provide information and develop strategy to manage and minimise risks
- Definition of CO2 stream – may contain incidental associated substances from source material, processes, and substances added to enable the processes.
  - Nothing to be added for disposal
  - Acceptable concentrations should be related to their potential impacts on transport and site integrity, risk to the marine env, and to applicable EU regulations

OSPAR FRAM - contents

- Problem Formulation – scope
- Site characterisation – capacity, integrity, leakage pathways, monitoring options, surrounding area
- Exposure assessment – properties of CO2 stream, exposure processes and pathways, likelihood, scale
- Effects assessment – consequences
- Risk characterisation – Impact Hypothesis (with performance criteria, qualitative or quantitative)
- Risk management – leak prevention, monitoring of CO2 streams within and above formations – link to Impact Hypothesis (peformance monitoring) and migration detection, and monitoring seafloor, water and biological if leakage is suspected - mitigation

OSPAR FRAM - contents

Information needs

- Characterisation of CO_2 stream
- Existence of biological features and other uses of maritime area
- Geological setting
- Reservoir/seal evaluation
- Marine environment
- Economic/regulatory factors

Issues for further research

- Risk management
- Exposure assessment
- Effects assessment

OSPAR

- **OSPAR amendments -** come into force after ratification by 7 Parties
- **OSPAR Decision and Guidelines** – comes into force 15 Jan 08 for all CO_2 storage (except EOR)
- Applies to Belgium , Denmark , Finland , France , Germany , Iceland , Ireland , Luxembourg , the Netherlands , Norway , Portugal , Spain , Sweden , Switzerland , United Kingdom , European Community

London Convention/Protocol

- Amendment adopted Nov 06, came into force Feb 07.
- Guidelines for Assessment of CO2 Streams for Disposal into Sub-Seabed Geological Formations not completed at time of amendment
- Derived from LC's **Risk Assessment and Management Framework** (2006), on which the OSPAR FRAM was based. For advice only.
- Will be no legal requirement to use Guidelines, but Parties encouraged to use for guidance when issuing permits.

London Risk Assessment and Management Framework

Content

- Problem Formulation – define bounds, scenarios etc
- Site Selection and Characterisation
- Exposure Assessment – processes and pathways for env exposure
- Effects Assessment – of exposure on marine env
- Risk Characterisation – integrates Exposure w Effects and likelihood
- Risk Management – monitoring and mitigation

London Guidelines

Follows standard LC format

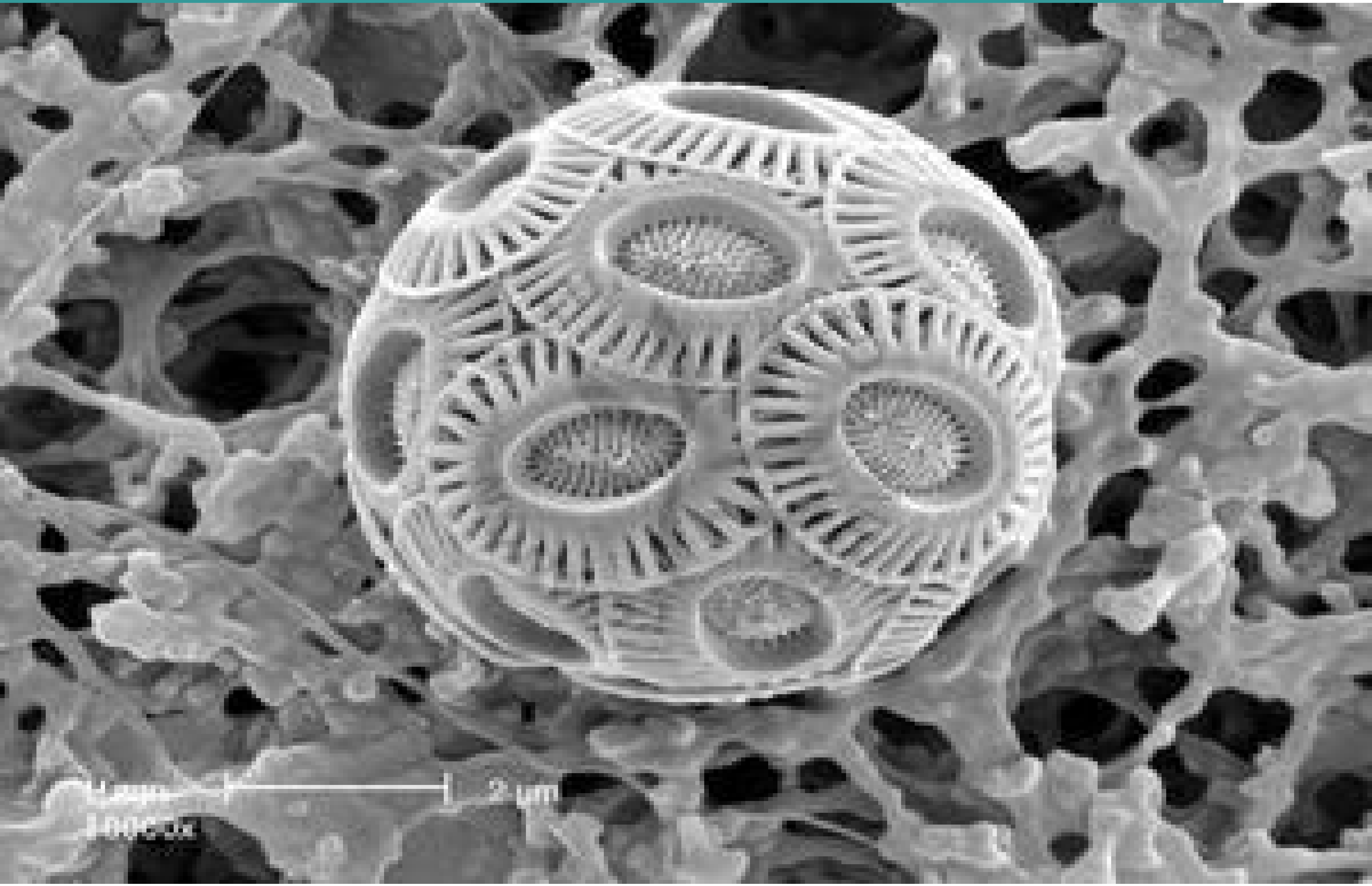
- Introduction – scope, how to use
- Waste Prevention Audit
- Consideration of Waste Management Options
- Chemical and Physical Properties
- Action List
- Site Characterisation
- Potential Effects
- Monitoring and Risk Assessment
- Permit Conditions

London Guidelines

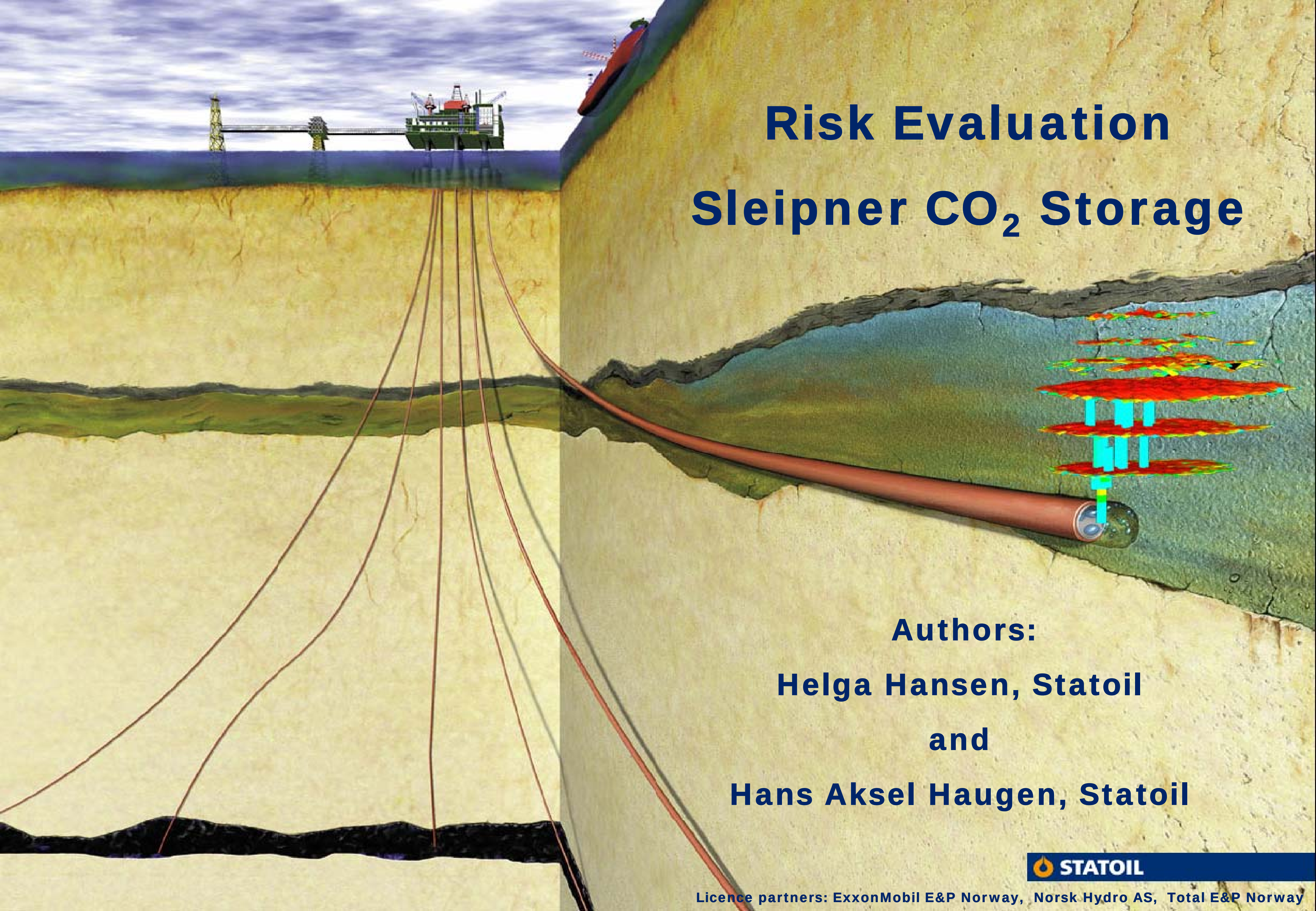
- Draft Guidelines agreed by Scientific Group Jun 2007, for adoption by LC/LP in Nov 2007.

DEPARTMENT FOR
BUSINESS, ENTERPRISE & REGULATORY REFORM

defra
Department for Environment
Food and Rural Affairs



Calcifying Phytoplankton - Coccolithophores



Risk Evaluation Sleipner CO_2 Storage

Authors:

Helga Hansen, Statoil

and

Hans Aksel Haugen, Statoil

STATOIL

Licence partners: ExxonMobil E&P Norway, Norsk Hydro AS, Total E&P Norway

Outline

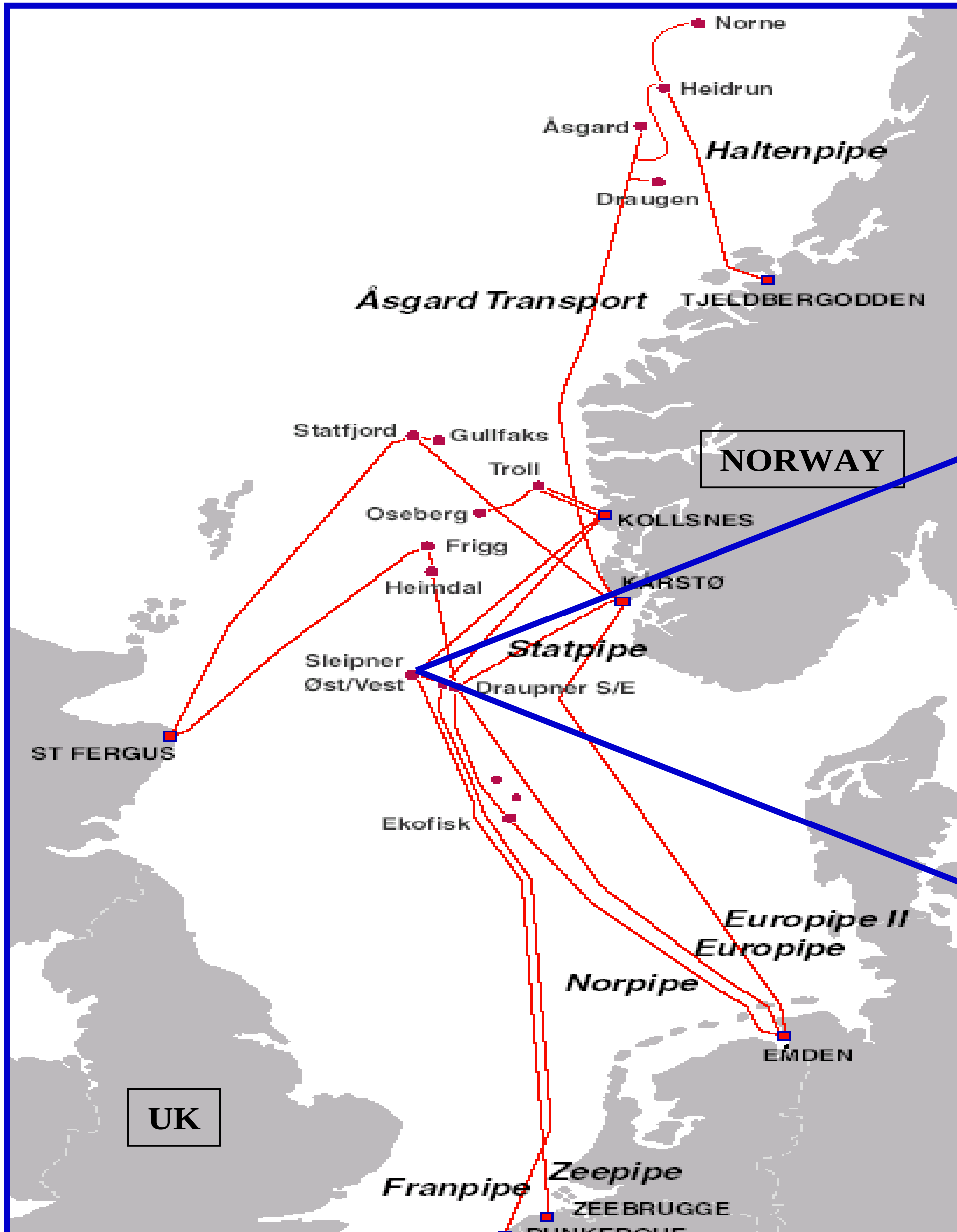
1. Introduction

3.
EU- and industry-funded
SACS, SACS2 and CO2STORE

2.
Risk evaluation
pre-injection

4.
Risk evaluation **post**-drilling,
after ten years of injection

5. Further work



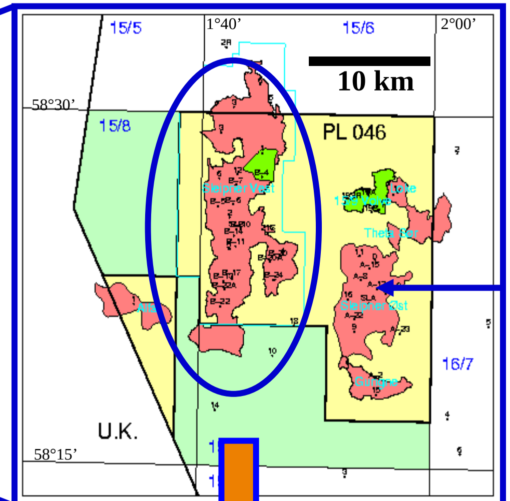
Sleipner Vest

Production start 1996

Natural gas with
9 mol% CO_2

GIIP: 5.6 TSft³
(160 GSm³)

CIIP: 427 mill.bbl
(70 MSm³)

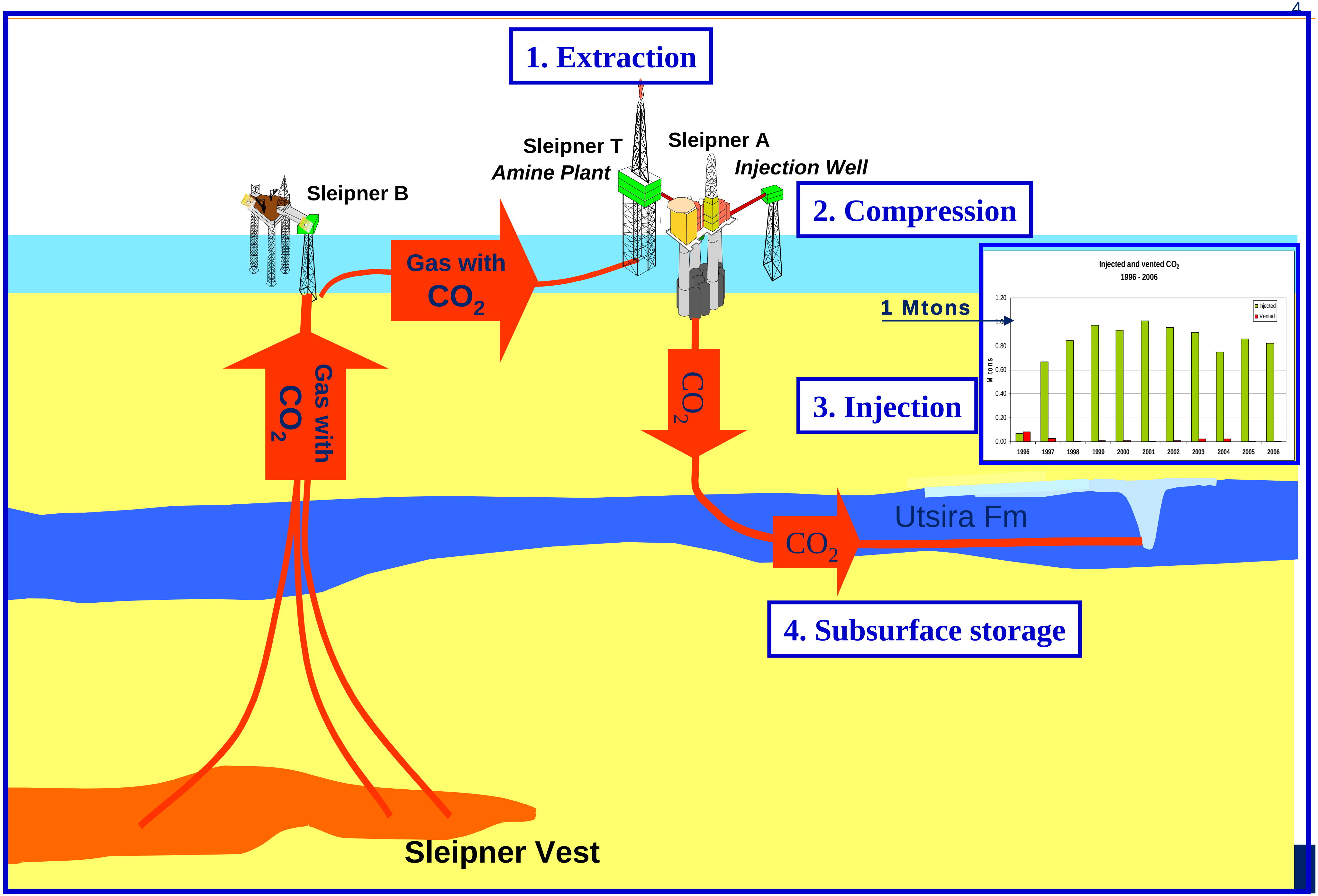


Sleipner Øst

Production start 1993

Natural gas with
< 1 mol % CO_2

Gas sales specifications:
< 2.5 mol% CO_2


1. Extraction
Sleipner T
Amine Plant
Sleipner A
Injection Well
Sleipner B
2. Compression
Gas with CO2
Gas with CO2
CO2
1 Mtons
Injected and vented CO2
1996 - 2006
1.20
1.00
0.80
0.60
0.40
0.20
0.00
M tons
Injected
Vented
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
3. Injection
Utsira Fm
CO2
4. Subsurface storage
Sleipner Vest

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Approval from the Norwegian Authorities:

- Plan for Development and Operation (PDO) for the Sleipner Vest field (1991)

  → No separate application

- No Quantitative Evaluation

  Risks mentioned:

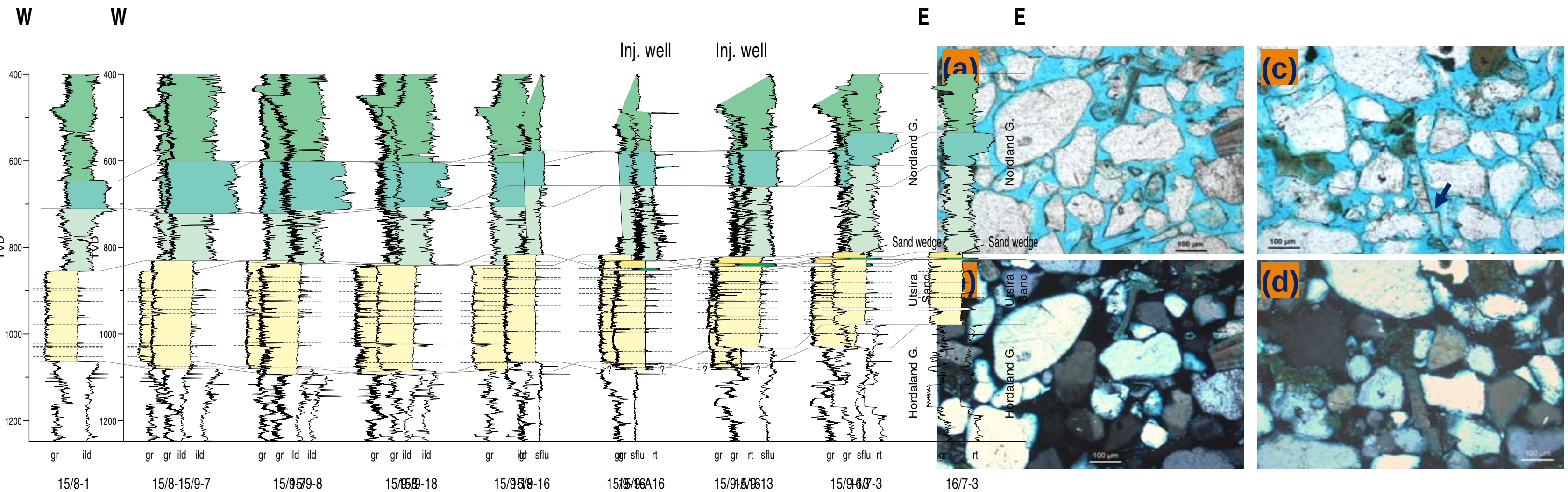
  - injectivity, potential overpressure
  - wet CO_2 corroding the casing in the production wells
  - hydrate formation in the Utsira Formation → unlikely

Main issues focused on prior to injection

- Evaluation of injectivity
  - → **Petrophysical evaluation**
  - → **Reservoir Simulation**
- No migration of the CO_2 back to the Sleipner wells
  - → **Mapping of the Top Utsira Fm important to locate the optimal injection point**
- Caprock
  - → **Cuttings and geophysical well logs**
  - → **Gas seapage study**

Main issues focused on prior to injection - **INJECTIVITY**

→ **Petrophysical evaluation of the Utsira Fm based on six wells; main results were Net sand and Porosity for seven different zones**



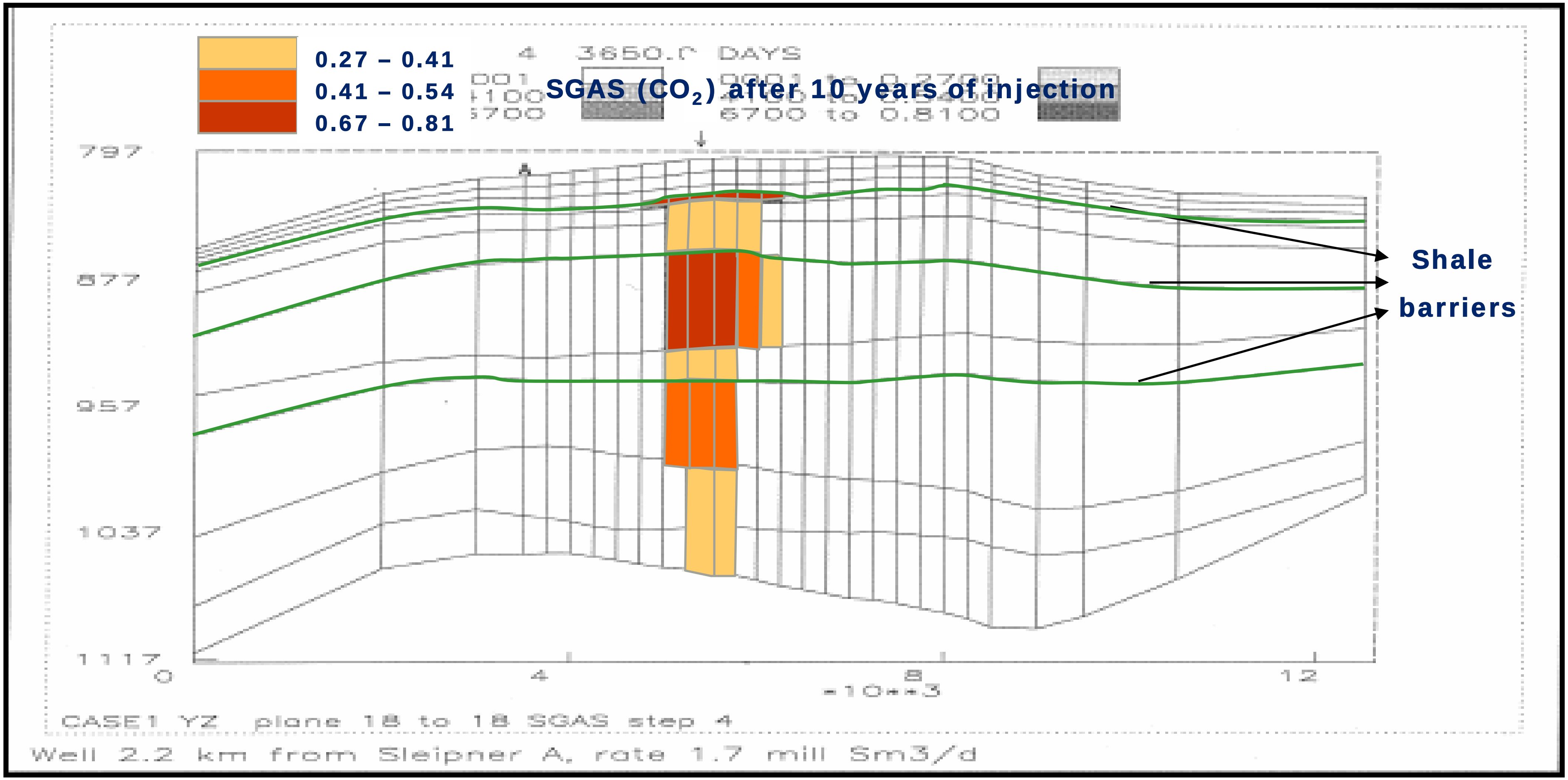
Net Sand (%)	Porosity (%)	Horizontal permeability *
90 – 98	~ 38	1-8 D

* estimated

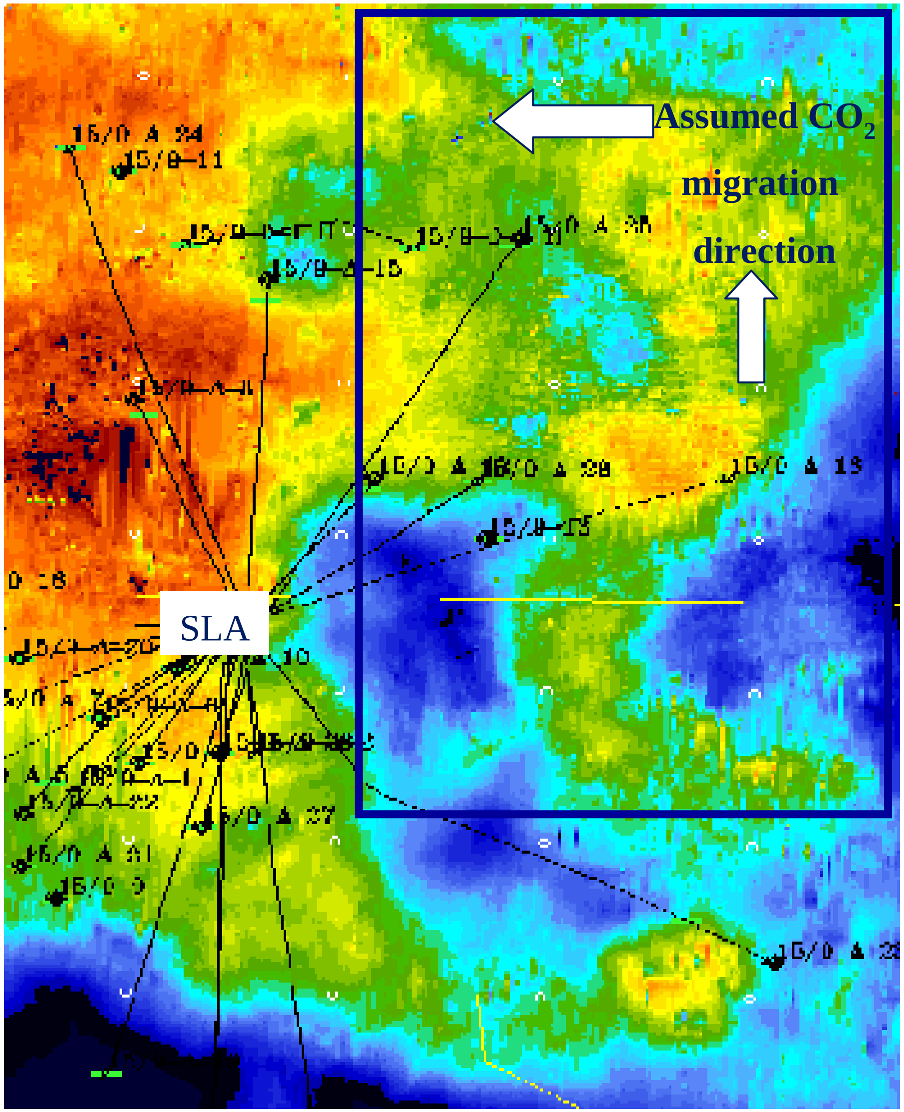
Main issues focused on prior to injection - **INJECTIVITY**

→ **Reservoir Simulation (black oil, oil-gas model)**

Temperature critical, 27 ^{0}C



Main issues focused on prior to injection - **MIGRATION**



No migration of the CO_2 back to the Sleipner wells

- **New seismic survey in 1994 → changed the location from NW to 2.8 km NNE of the SLA (the current location)**
- **Structural trap identified, saddle area northwards Predicted migration direction → northwards**
- **Base Utsira Fm shows shale diapirs east of SLA → expected to reduce the horizontal distribution of the CO_2 towards the SLA**

Main issues focused on prior to injection - **CAPROCK**

- Cuttings and geophysical well logs of the Nordland shales

→ no detailed studies performed, considered an effective seal

- Gas seapage study performed in 1994

→ Mapped existing shallow gas accumulations and pre-existing gas pathways around the storage site.

Concluded that there are no indications of gas seepage which may signify a leakage risk from the CO_2 storage site.

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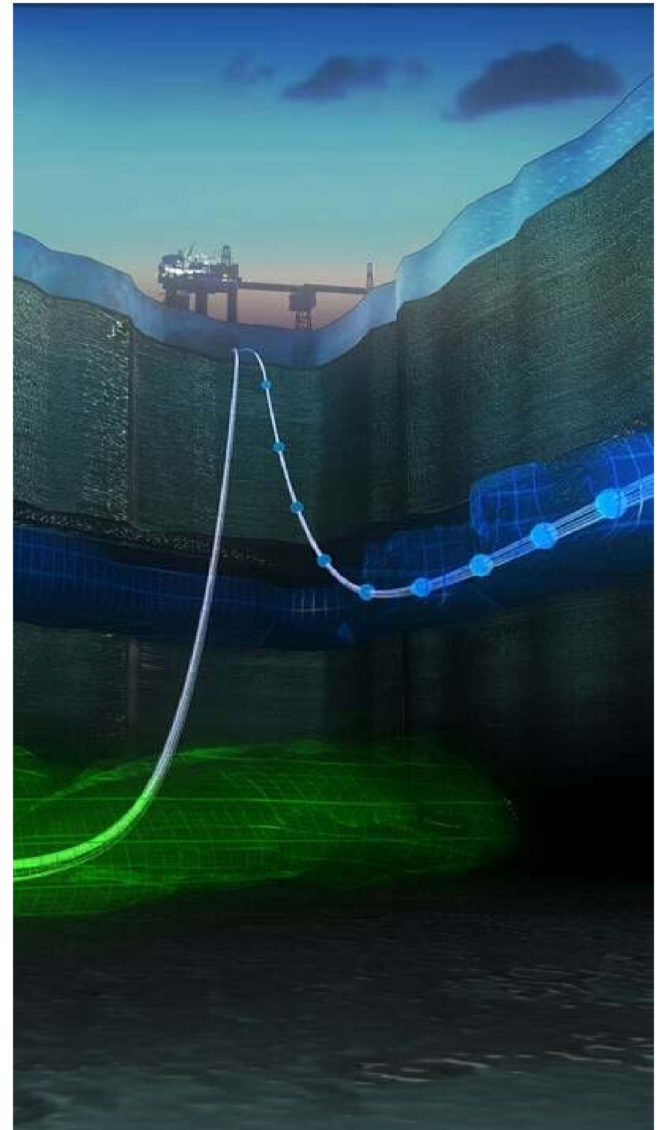
SACS-project - a multi-institutional research project

The project has been divided into 5 scientific work areas:

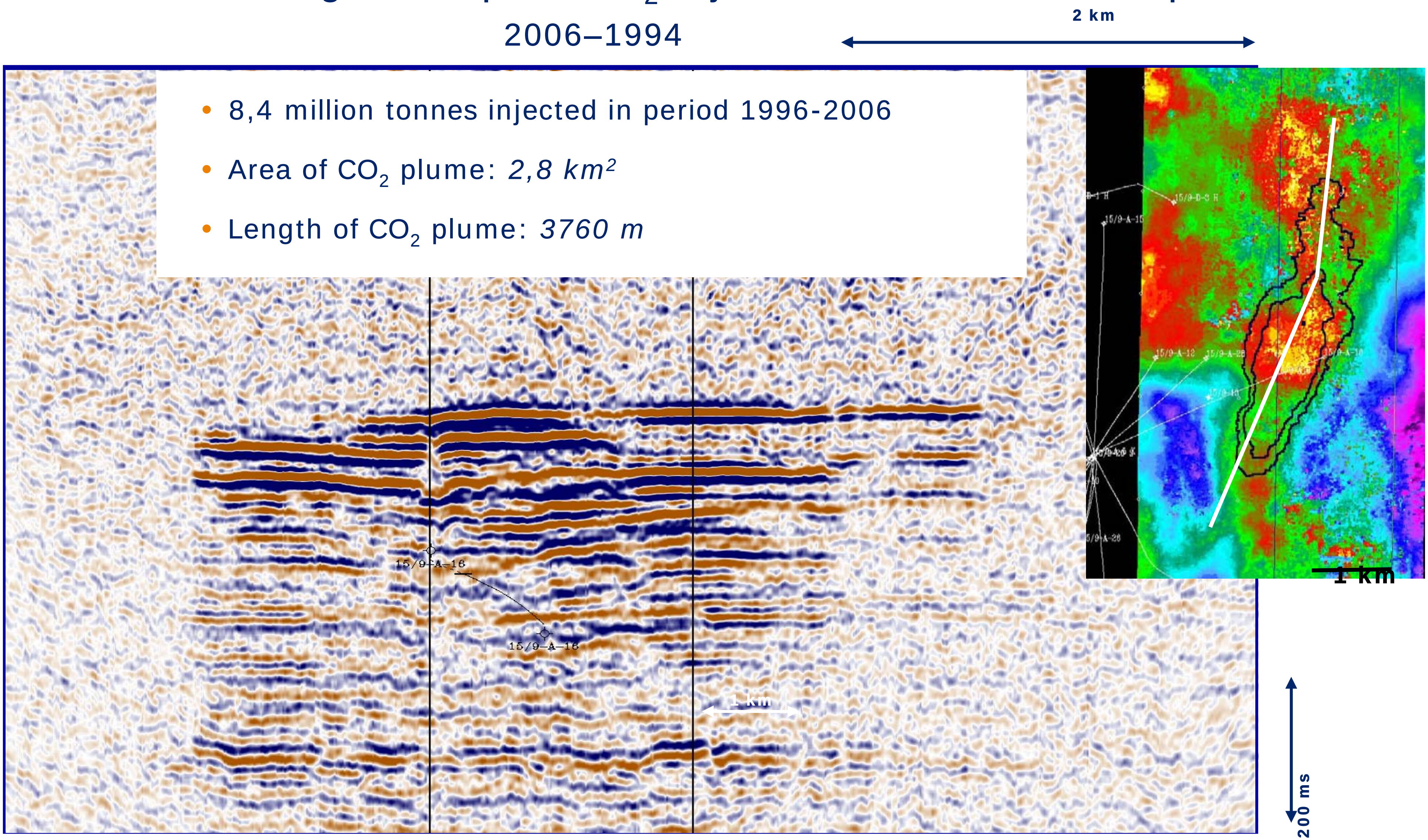
- Regional geology and reservoir characterisation
- Geochemistry
- Monitoring Well
- Geophysics
- Reservoir Simulations



Seismic monitoring of Sleipner CO_2 injection – difference maps

2006–1994

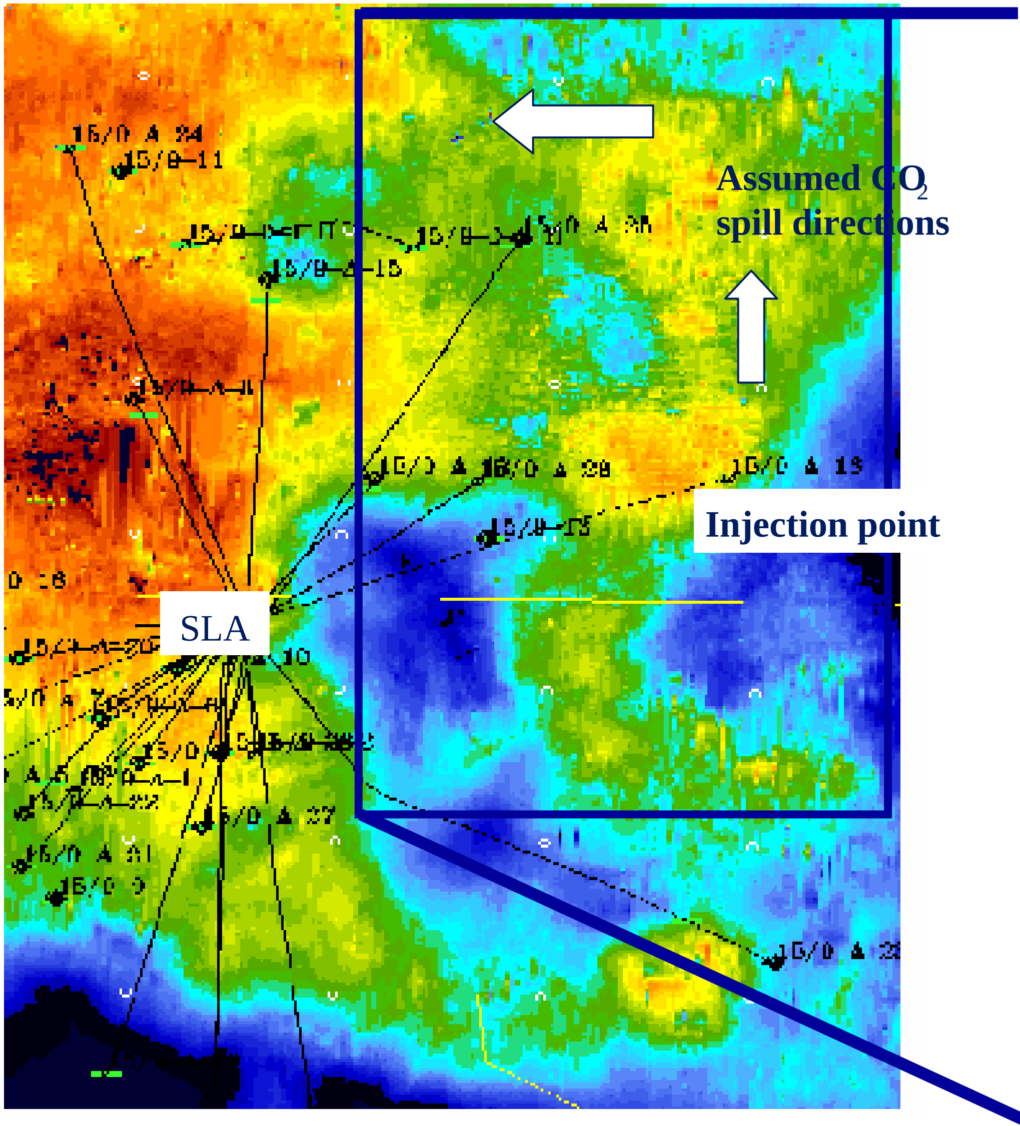
- 8,4 million tonnes injected in period 1996-2006
- Area of CO_2 plume: *2,8 km²*
- Length of CO_2 plume: *3760 m*

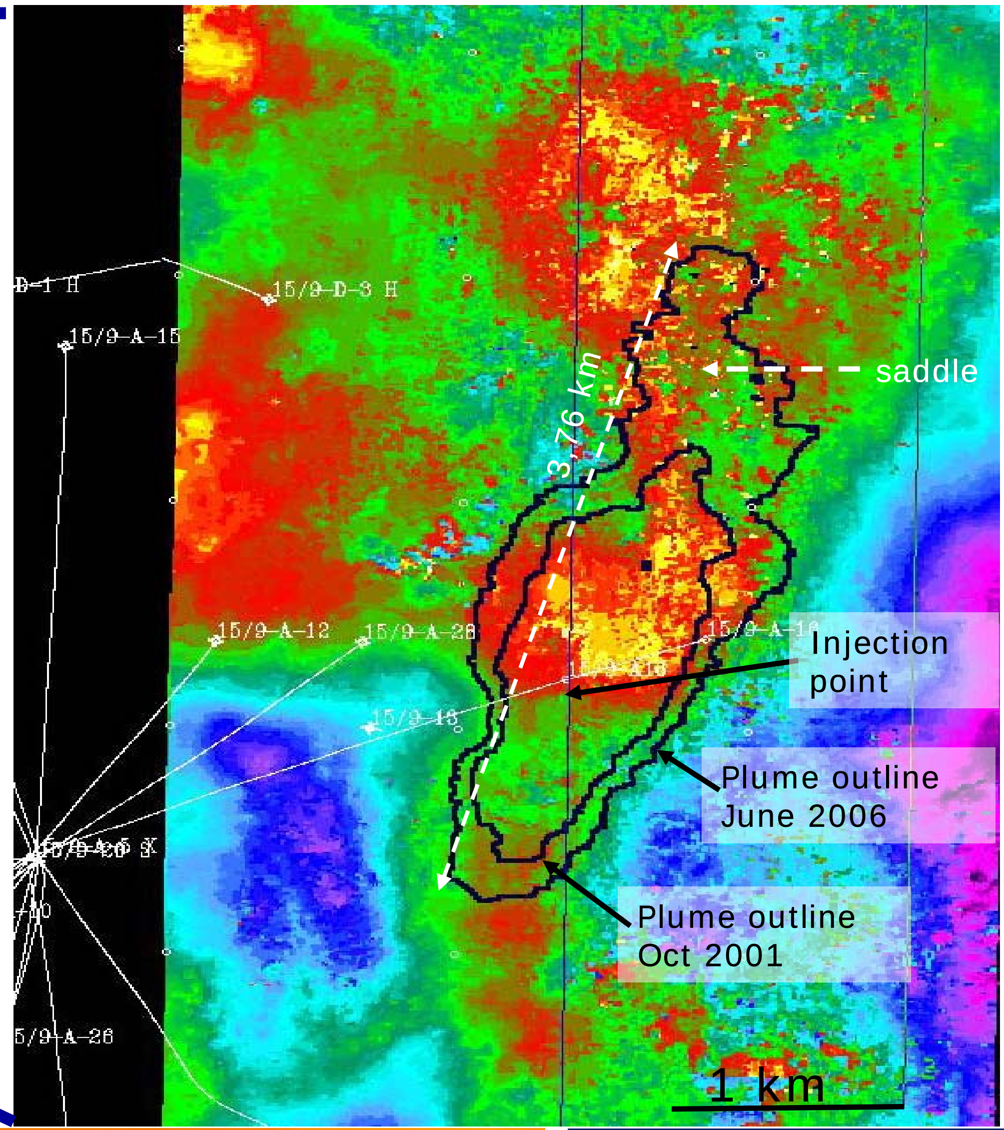


Sleipner Area:
Top Utsira Time Map

Plume extension & top Utsira time map

Summed amplitudes





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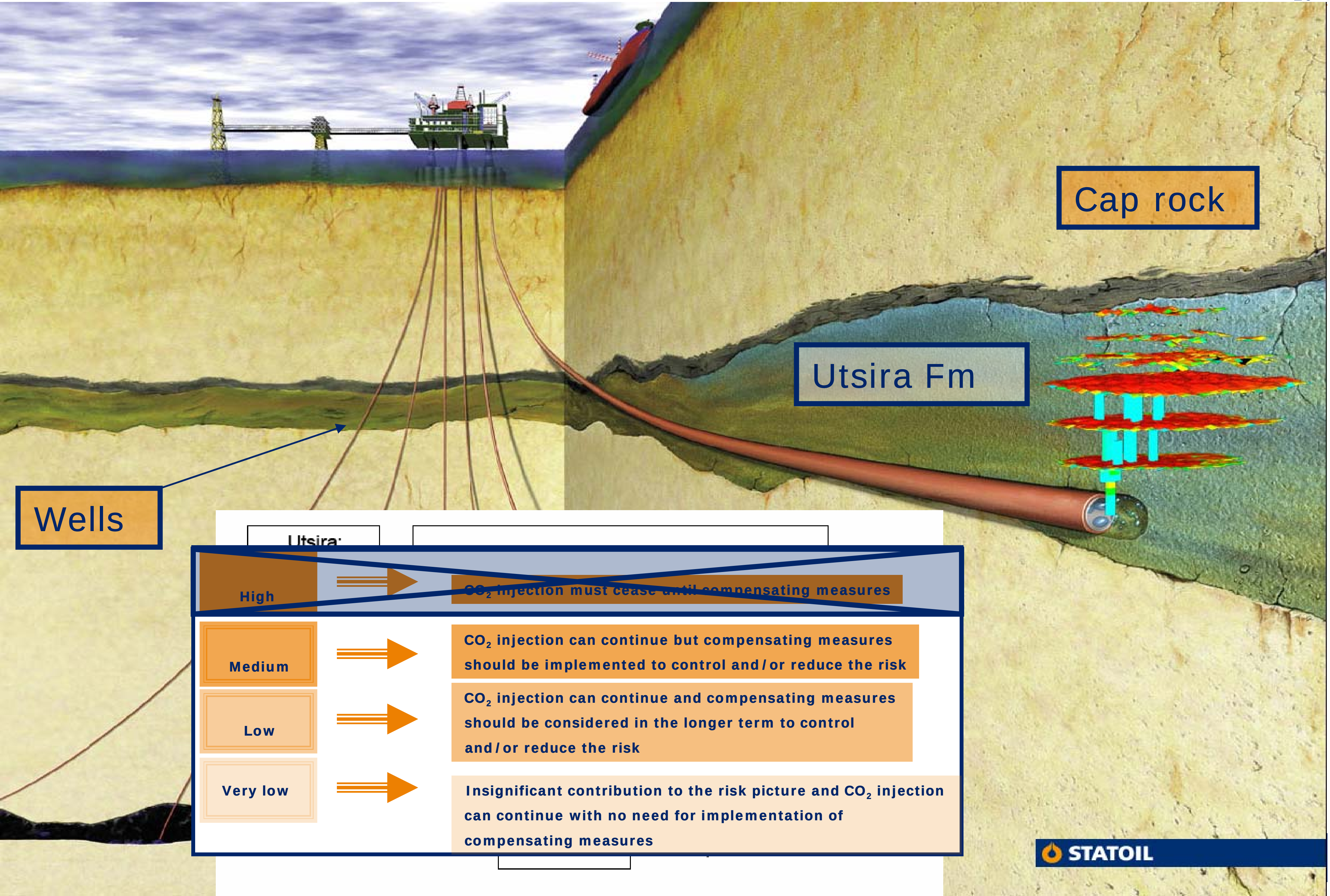
The Risk Evaluation Process

- A group of experts, including international expertise, were invited to join a workshop on risk associated with the CO_2 injection on Sleipner, 29. and 30. May 2006

- Aim of workshop:
  - Identify risks of CO_2 escape and effects on neighbouring wells and licences
    - → Current injection rates
    - → Increased injection rates
  - Identify mitigating measures
  - Evaluate whether risk is within acceptable limits

Risk classification

High	CO_2 injection must cease until compensating measures have been performed
Medium	CO_2 injection can continue but compensating measures should be implemented to control and / or reduce the risk
Low	CO_2 injection can continue and compensating measures should be considered in the longer term to control and / or reduce the risk
Very low	Insignificant contribution to the risk picture and CO_2 injection can continue with no need for implementation of compensating measures



High	CO_2 injection must cease until compensating measures
Medium	CO_2 injection can continue but compensating measures should be implemented to control and / or reduce the risk
Low	CO_2 injection can continue and compensating measures should be considered in the longer term to control and / or reduce the risk
Very low	Insignificant contribution to the risk picture and CO_2 injection can continue with no need for implementation of compensating measures

Increased* injection rates, Utsira Fm

* ~ 10 times current injection rates

Risks affecting the Sleipner Licence

Medium risk:

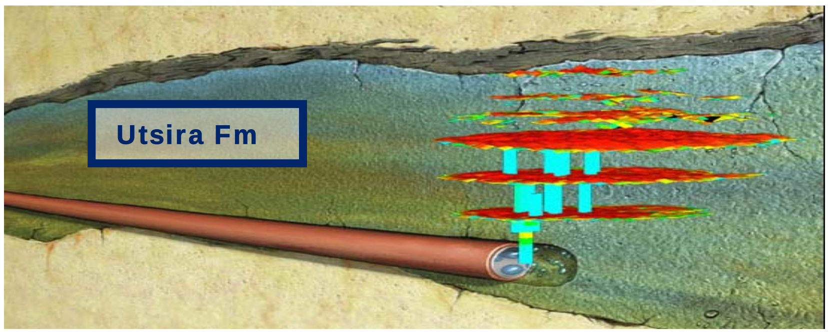
• Migration below Top Utsira Fm or internal shale layers to adjacent wells

Medium risk:

• Injection induced degradation of reservoir, e.g.subsidence

Low risk:

Reduce / misinterpret storage capacity due to degradation or other unknown factors



Risks affecting neighbouring licences

Medium risk:

• Migration below Top Utsira Fm or internal shale layers to neighbouring licence blocks:

- problems for future exploration wells (gas pockets, corrosive environment)
- destroy seismic response below plume

Low risk:

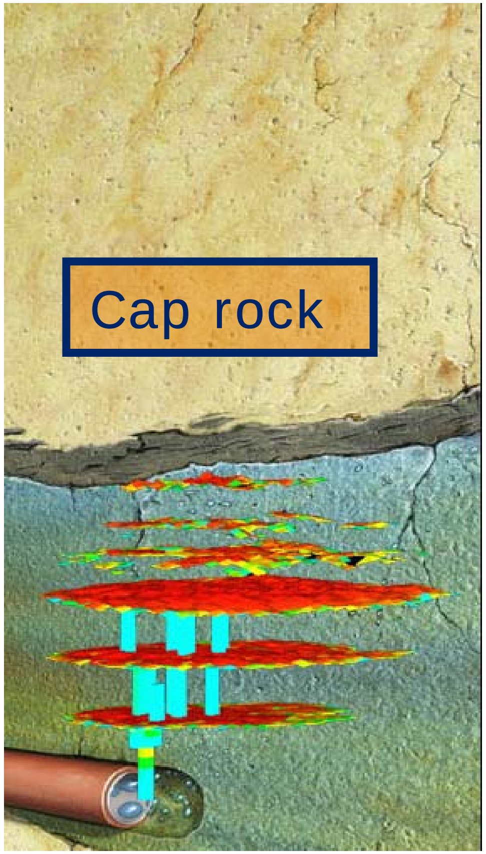
• Migration below Top Utsira Fm to up-dip sands in cap rock seal → seabed

• Compromise future use of Utsira water for injection purposes

Increased* injection rates, cap rock

*** ~ 10 times current injection rates**

Risks affecting the Sleipner Licence



Risks affecting neighbouring licences

Medium risk:

- **Leakage through undetected faults/fractures:**
→ to shallow fms → seabed

Low risk:

- **Differential pressure due to buoyancy effects creates fractures**
- **Migration through sand injections (pre-existing permeable zones)**

Increased injection rates, wells

* ~ 10 times current injection rates

Risks affecting the Sleipner Licence

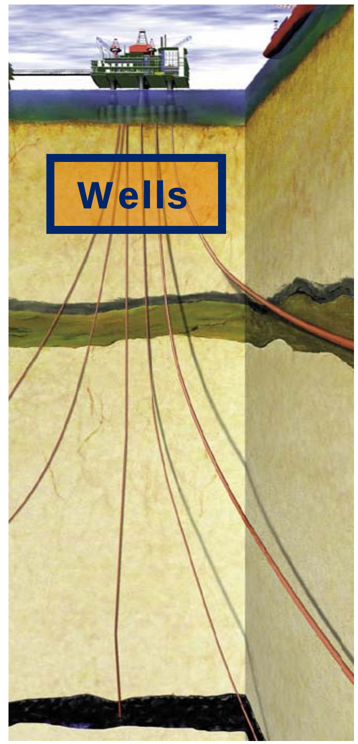
Risks affecting neighbouring licences

Medium risk:

• CO_2 reaches adjacent exploration and production wells

- loss of well integrity
- leakage outside / inside casing

→ surface



Low risk:

• Injection system failure

→ leakage back to SLA through injection well – risk to personnel

Key findings from the workshop

The risk of CO_2 release from Utsira Formation is considered low and acceptable

Increased injection rates would accelerate the identified risks

A selection of mitigating measures to reduce risk and improve control of the CO_2 plume were proposed

Further work

EU- and industry-funded
SACS, SACS2 and CO2STORE

Risk evaluation post-drilling,
after ten years of injection

CO2ReMoVe

Mitigating measures

- **Time lapse seismic surveys are the main monitoring tool**
- **Update the Top Utsira Depth map based on the time lapse seismic survey**
- **Update the reservoir simulation model based on the Top Utsira map**
  → update CO_2 migration prognosis
- **Evaluation of the exposure and long-term integrity of wells in the area**

Site Characterization:
The IPCC SRCCS & The IEA GHG Guidelines

IEA GHG Risk Assessment Network

Imperial College, London

15th-16th August 2007

Overview

- IPCC SRCCS - Site Characterization
- IEA GHG work
  - Site Characterization Guidelines
  - Data Accessibility
  - Best Practice Database

IPCC SRCCS

- Site Characterization Goals
- Site Integrity factors
  - Stratigraphic
  - Geomechanical
  - Geochemical
  - Anthropogenic
- Types of data for Site Characterization

Site Characterization Goals

- Key goals for geological CO_2 storage site characterization are:
  - To assess how much CO_2 can be stored at a potential storage site
  - To demonstrate that the site is capable of meeting required storage performance criteria.
- These goals require the collection of the wide variety of geological data
  - Much of the data will be site-specific.
  - Most data will feed into geological models that will simulate and predict the performance of the site.

Site Characterization

- The storage site and surroundings need to be characterized by:
  - geology,
  - hydrogeology,
  - geochemistry,
  - geomechanics,
- Storage site requirements depend on trapping mechanism and geological medium,
- Oil and gas fields will often be better characterized than saline formations,
- Focus on sealing horizons and strata above,
- Site characterization data fed into a three-dimensional geological model,
- A lot of the site characterization data will be site specific,

Site Characterization

- General site characterization data:
  - Geological site description from wellbores and outcrops,
  - Information on subsurface geological structure, including faults & fractures,
  - Formation pressure measurements to map rate and direction of groundwater flow,
  - Water quality samples to demonstrate the isolation between deep and shallow groundwater.

Site Integrity: Stratigraphic factors

- Ideally, a sealing rock unit should be regional in nature and uniform in lithology, especially at its base,
- Where there are lateral changes in the basal units of a seal rock, the chance of migration out of the primary reservoir into higher intervals increases,
- For a good seal rock (uniform, regionally extensive and thick) the main issues are:
  - Physical rock strength,
  - Natural or anthropomorphic penetrations (faults, fractures, wells),
  - Potential CO_2-water-rock reactions that could weaken the seal rock or increase its porosity and permeability.

Site Integrity: Geomechanical factors

- Pressure from injecting CO_2 could lead to deformation of the reservoir rock or the seal rock creating weak points
- Geomechanical modeling can determine the maximum formation pressures for the storage site,
- Information required for modeling:
  - Pore fluid composition,
  - Mineralogy,
  - *In situ* stresses,
  - Pore fluid pressures,
  - Pre-existing fault orientations and their frictional properties.

Site Integrity: Geomechanical factors

- Effectiveness of oil or gas caprock can be characterized by:
  - capillary entry pressure,
  - potential hydrocarbon column height that it can sustain,
- Depletion and subsequent CO_2 injection may affect the integrity of the caprock due to compaction or pore collapse
  - This may reduce the max pressure you can inject, reducing the storage capacity,
  - In Weyburn, the maximum injection pressure is 90% of the sealing rock fracture pressure.

Site Integrity: Geochemical factors

- The mixing of CO_2 and water will create dissolved CO_2, carbonic acid and dicarbonate ions,
- Acidification of the pore water reduces the amount of CO_2 that can be dissolved.
  - Rocks that buffer the pore water pH, facilitate the storage of CO_2 as a dissolved phase,
- CO_2 rich water may react with reservoir, caprock, borehole cements and steels which could increase the risk of leakage,
- A carbonate mineral formation stores the CO_2 in an immobile phase

Site Integrity: Anthropogenic factors

- Active wells, mine shafts and subsurface production should all be documented and understood,
- Abandoned wells that penetrate the storage reservoir are of particular concern and may provide a path for CO_2 to quickly reach the surface.
  - Therefore all abandoned wells must be located assessed and resealed if necessary.

Types of data for Site Characterization

- Seismic profiles,
  - preferably three-dimensional or closely spaced two-dimensional surveys,
- Structure contour maps of reservoirs, seals and aquifers,
- Detailed maps of the structural boundaries where the CO_2 will accumulate, highlighting potential spill points,
- Maps of the predicted pathway along which the CO_2 will migrate from the point of injection,

Types of data for Site Characterization

- Documentation and maps of faults and fractures,
- Facies maps showing any lateral facies changes in the reservoirs or seals,
- Core and drill cuttings samples from the reservoir and seal intervals,
- Well logs, preferably a consistent suite, including geological, geophysical and engineering logs,
- Fluid analyses and tests from downhole sampling and production testing;
- Oil and gas production data (if a hydrocarbon field),

Types of data for Site Characterization

- Pressure transient tests for measuring reservoir and seal permeability;
- Petrophysical measurements, including porosity, permeability, mineralogy (petrography), seal capacity, pressure, temperature, salinity and laboratory rock strength testing;
- Pressure, temperature, water salinity;
- *In situ* stress analysis to identify the maximum sustainable pore fluid pressure during injection;

Types of data for Site Characterization

- Hydrodynamic analysis to identify the magnitude and direction of:
  - water flow,
  - hydraulic interconnectivity of formations
  - pressure decrease associated with hydrocarbon production;
- Seismological data, geomorphological data and tectonic investigations to indicate neotectonic activity.

Note: Financial constraints may limit the types of data that can be collected as part of the site characterization and selection process.

IEA GHG Site Characterization Guidelines

- To fast track the development of CCS projects by creating standardized approach to CCS site characterization
- Guidelines will be:
  - Generic to saline aquifers and hydro-carbon fields
  - “Non prescriptive”
  - Step-wise
  - Underpinned on current best practice (IEA GHG Best Practice Database)
  - Drafted Internally
  - Guided by Risk Assessment network

Scope of Guidelines

- The formation setting and character
- The formation geology and hydrogeology
- The sealing formations above and below the formation
- The formation overburden
- Faulting/fracturing of the formation and overburden
- Well intrusions, operational and abandoned
- Overlying aquifers and seals
- Surface features and characteristics
- Etc…

Other work being done

- IPCC SRCCS
- CO2STORE
- Weyburn
- US Environmental Protection Agency
- World Resource Institute
- International Risk Governance Council
- BRGM
- DNV

IEA GHG Data Accessibility

- Facilitate better access to the quality information that is available, including the SRCCS.
- Looking into possible structures
- Using SRCCS initially
- Will be expanded to include other sources of information.

SRCCS – SC Link Table

								FACTORS WHICH INFLUENCE SUITABILITY FOR THE CRITERION											
ITEM TO CHARACTERISE	PAGE	LINES	Preferred methods	PAGE	LINES	Details to be generated	General Acceptance Criteria	POSITIVE FACTORS	PAGE	LINES	NEUTRAL FACTORS	PAGE	LINES	NEGATIVE FACTORS	PAGE	LINES	EXCLUSION FACTORS	PAGE	LIN
Tectonic activity	213	20,21	Mapping of plates			Location on continental plate	Location not in seismically active area	1 Mid continent	213	33-33				1. Edges of plates where subduction is occurring	214	1-3	1. Volcanically active regions		
			Seismic activity maps					2 Edge of stable continental plates	213	22-24				2. Between active mountain ranges	214	1			
														3. Tectonically active areas	213	40-43			
Adequate capacity	213	18	Estimate volumetric trapping	220	110-112	pore space, in situ density of CO2		Low temperature gradient	215	23-24				1.Thin <1000m	214	8/9			
	220	100-107	Estimate Solubility trapping	220	113-115	Amount of CO2 which can be dissolved								2. Poor reservoir seal relationship	214	9			
	221	1-3	Estimate Adsorption trapping	220	116-117	Coal volume times CO2 adsorbing capacity								3. Highly faulted and fractured	214	10			
			Estimate Mineral trapping	221	1-3	Available minerals for carbonate precipitation and CO2 amount used in reactions								4. Within fold belts	214	10			
														5. Strongly discordant sequences	214	11			
														6. Have undergone significant diagenesis	214	12-13			
														7. Have over pressured reservoirs	214	13			
Stress change induced compaction or pore collapse	227	54-56	Not stated			Not known													
Satisfactory caprock seal	213	19	DETAILS BELOW					Cap of shale, anhydrite or salt	214	35-39				Extensive faulting	213 214	39-40 1-3	Faulting and fracturing in seismically active area		

SRCCS – SC Link Table

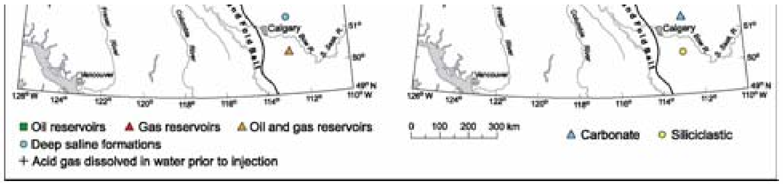


Figure 5.13 Locations of acid gas injection sites in the Alberta Basin, Canada: (a) classified by injection unit; (b) the same locations classified by rock type (from Bachu and Haug, 2005).

accumulations have been stored for up to 1400 million years. However, some natural traps do leak, which reinforces the need for careful site selection (Section 5.3), characterization (Section 5.4) and injection practices (Section 5.5).

5.3 Storage formations, capacity and geographical distribution

In this section, the following issues are addressed: In what types of geological formations can CO_2 be stored? Are such formations widespread? How much CO_2 can be geologically stored?

5.3.1 General site-selection criteria

There are many sedimentary regions in the world (Figures 2.4–2.6 and Figure 5.14) variously suited for CO_2 storage. In general, geological storage sites should have (1) adequate capacity and injectivity, (2) a satisfactory sealing caprock or confining unit and (3) a sufficiently stable geological environment to avoid compromising the integrity of the storage site. Criteria for assessing basin suitability (Bachu, 2000, 2003; Bradshaw *et al.*, 2002) include: basin characteristics (tectonic activity, sediment type, geothermal and hydrodynamic regimes); basin resources (hydrocarbons, coal, salt), industry maturity and infrastructure; and societal issues such as level of development, economy, environmental concerns, public education and attitudes.

The suitability of sedimentary basins for CO_2 storage depends in part on their location on the continental plate. Basins formed in mid-continent locations or near the edge of stable continental plates, are excellent targets for long-term CO_2 storage because of their stability and structure. Such basins are found within most continents and around the Atlantic, Arctic and Indian Oceans. The storage potential of basins found behind mountains formed by plate collision is likely to be good and these include the Rocky Mountain, Appalachian and Andean basins in the Americas, European basins immediately north of the Alps and Carpathians and west of the Urals and those located south of the Zagros and Himalayas in Asia. Basins located in tectonically active areas, such as those around the Pacific Ocean or the northern Mediterranean, may be less suitable for CO_2 storage and sites in these regions must be selected carefully because of the potential for CO_2 leakage (Chiodini *et al.*, 2001; Granieri *et al.*, 2003). Basins located on the edges of plates

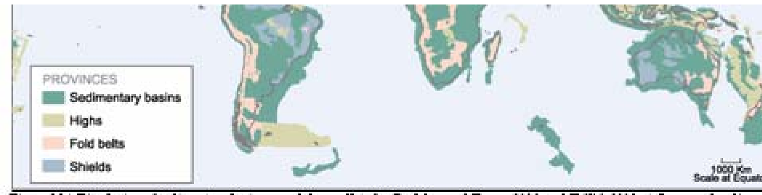


Figure 5.14 Distribution of sedimentary basins around the world (after Bradshaw and Dance, 2005; and USGS, 2001a). In general, sedimentary basins are likely to be the most prospective areas for storage sites. However, storage sites may also be found in some areas of fold belts and in some of the highs. Shield areas constitute regions with low prospectivity for storage. The Mercator projection used here is to provide comparison with Figures 5.1, 5.11 and 5.27. The apparent dimensions of the sedimentary basins, particularly in the northern hemisphere, should not be taken as an indication of their likely storage capacity.

where subduction is occurring or between active mountain ranges, are likely to be strongly folded and faulted and provide less certainty for storage. However, basins must be assessed on an individual basis. For example, the Los Angeles Basin and Sacramento Valley in California, where significant hydrocarbon accumulations have been found, have demonstrated good local storage capacity. Poor CO_2 storage potential is likely to be exhibited by basins that (1) are thin (≤1000 m), (2) have poor reservoir and seal relationships, (3) are highly faulted and fractured, (4) are within fold belts, (5) have strongly discordant sequences, (6) have undergone significant diagenesis or (7) have overpressured reservoirs.

The efficiency of CO_2 storage in geological media, defined as the amount of CO_2 stored per unit volume (Brennan and Burruss, 2003), increases with increasing CO_2 density. Storage safety also increases with increasing density, because buoyancy, which drives upward migration, is stronger for a lighter fluid. Density increases significantly with depth while CO_2 is in gaseous phase, increases only slightly or levels off after passing from the gaseous phase into the may even decrease with a further increase in depth, depending on the temperature gradient (Ennis-King and Paterson, 2001; Bachu, 2003). 'Cold' sedimentary basins, characterized by low temperature gradients, are more favourable for CO_2 storage (Bachu, 2003) because CO_2 attains higher density at shallower depths (700–1000 m) than in 'warm' sedimentary basins, characterized by high temperature gradients where dense-fluid conditions are reached at greater depths (1000–1500 m). The depth of the storage formation (leading to increased drilling and compression costs for deeper formations) may also influence the selection of storage sites.

Adequate porosity and thickness (for storage capacity) and permeability (for injectivity) are critical; porosity usually decreases with depth because of compaction and cementation, which reduces storage capacity and efficiency. The storage formation should be capped by extensive confining units (such as shale, salt or anhydrite beds) to ensure that CO_2 does not escape into overlying, shallower rock units and ultimately to the surface. Extensively faulted and fractured sedimentary basins or parts thereof, particularly in seismically active areas, require

careful characterization to be good candidates for CO_2 storage, unless the faults and fractures are sealed and CO_2 injection will not open them (Holloway, 1997; Zarlenga *et al.*, 2004).

The pressure and flow regimes of formation waters in a sedimentary basin are important factors in selecting sites for CO_2 storage (Bachu *et al.*, 1994). Injection of CO_2 into formations overpressured by compaction and/or hydrocarbon generation contain a reactive and potentially buoyant fluid such as CO_2. Therefore, the condition of wells penetrating the caprock must be assessed (Winter and Bergman, 1993). In many cases, even locating the wells may be difficult and caprock integrity may need to be confirmed by pressure and tracer monitoring.

The capacity of a reservoir will be limited by the need to avoid exceeding pressures that damage the caprock (Section 5.5.3). Reservoirs should have limited sensitivity to reductions

Box 5.6 The Rangely, Colorado, CO_2-EOR Project.

The Rangely CO_2-EOR Project is located in Colorado, USA and is operated by Chevron. The CO_2 is purchased from the Exxon-Mobil LaBarge natural gas processing facility in Wyoming and transported 283 km via pipeline to the Rangely field. Additional spurs carry CO_2 over 400 km from LaBarge to Lost Soldier and Wertz fields in central Wyoming, currently ending at the Salt Creek field in eastern Wyoming.

The sandstone reservoir of the Rangely field has been CO_2 flooded by the water alternating gas (WAG) process, since 1986. Primary and secondary recovery, carried out between 1944 and 1986, recovered 1.9 US billion barrels (302 million m³)

Possible Next Step

- Combine data accessibility work and site characterization guidelines
  - Site Characterisation Tool
  - Eventually lead to a similar tool to the monitoring selection tool

Best Practice Database

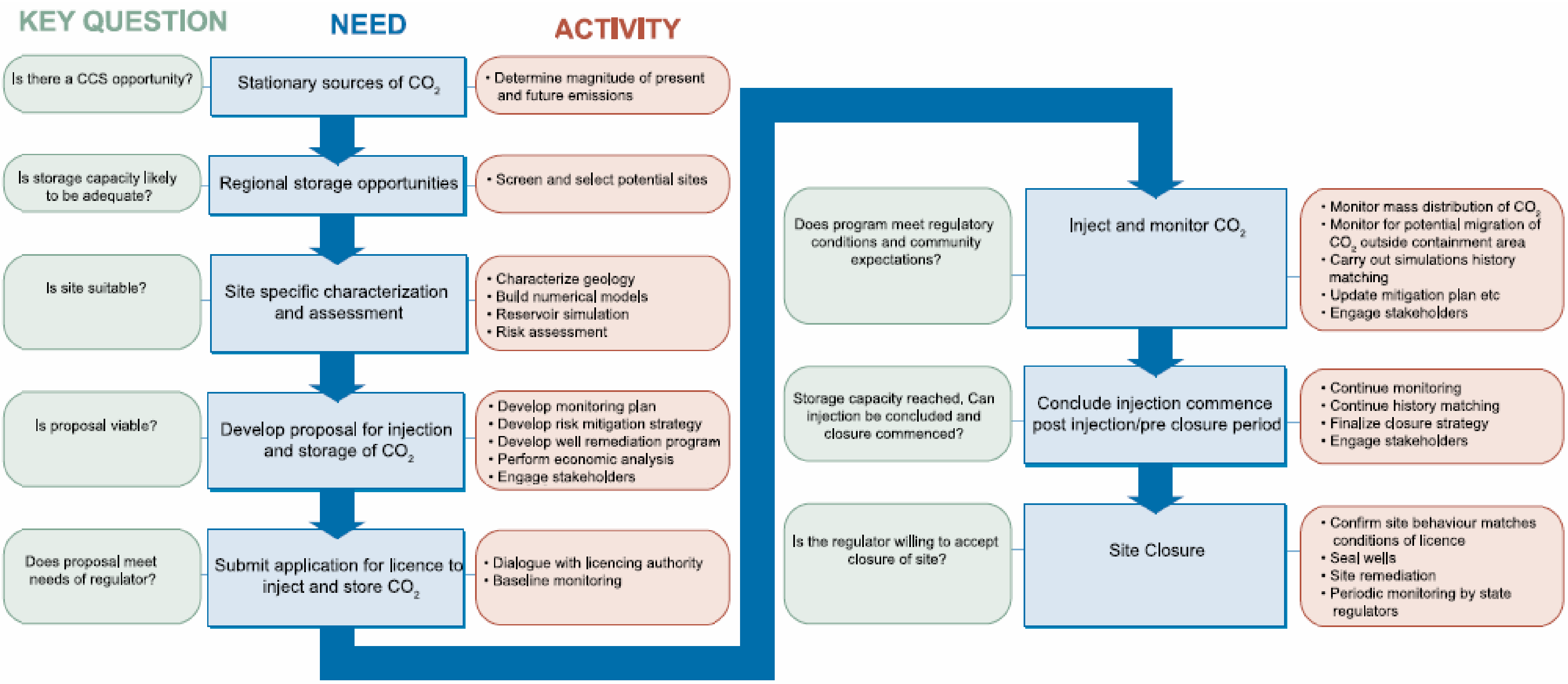
- Developed in conjunction with the EU CO2REMOVE project
- Underpins SC guidelines
  - ensures the most up-to-date practices are known to project developers and regulatory bodies.
- The database has been set up and is ready to go live as soon as a 'critical mass' of information has been gathered,
- If the database is launched without enough information, it will loose credibility as a information source.

IEA Greenhouse Gas R&D Programme

Best Practice Database

- Please send documents to Brendan@ieaghg.org

Life cycle of a CO2 storage project



IEA GHG Risk Assessment Workshop
Imperial College, London
August 15-16, 2007

Site Characterization Needs for Risk Assessment

Mike Stenhouse, Wei Zhou, Randy Arthur

Monitor Scientific, LLC
Denver, Colorado, USA
mstenhouse@monitorsci.com

MONITOR SCIENTIFIC

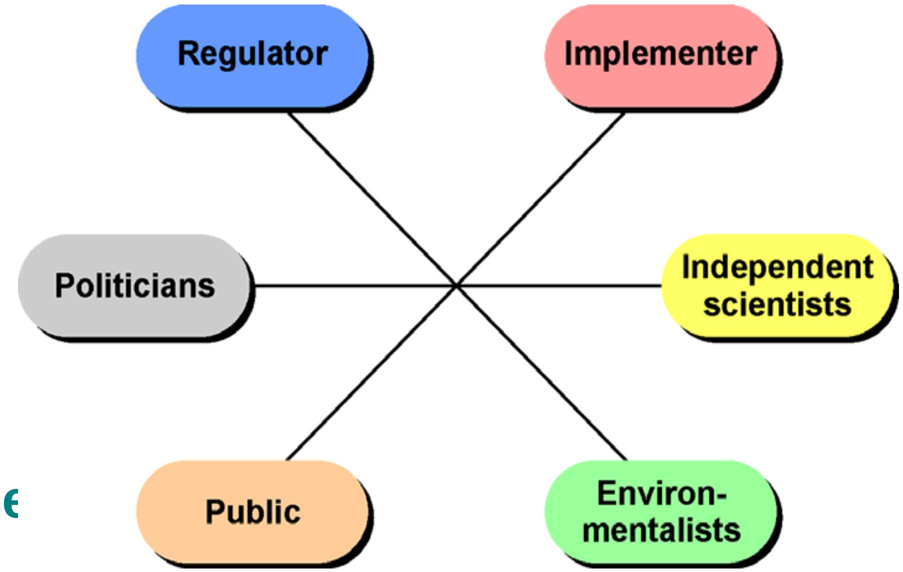
Outline of Presentation

- Introduction - Role of RA
- Site characterization needs <=> RA
- When to stop (site characterization)?
- Conclusions

Monitor Scientific

Why Risk Assessment?

- Part of the process of **building confidence** among stakeholders......many stakeholders are involved....
  - Technical AND public confidence
  - Aiming for a sufficiently broad consensus to procee to implement a storage project



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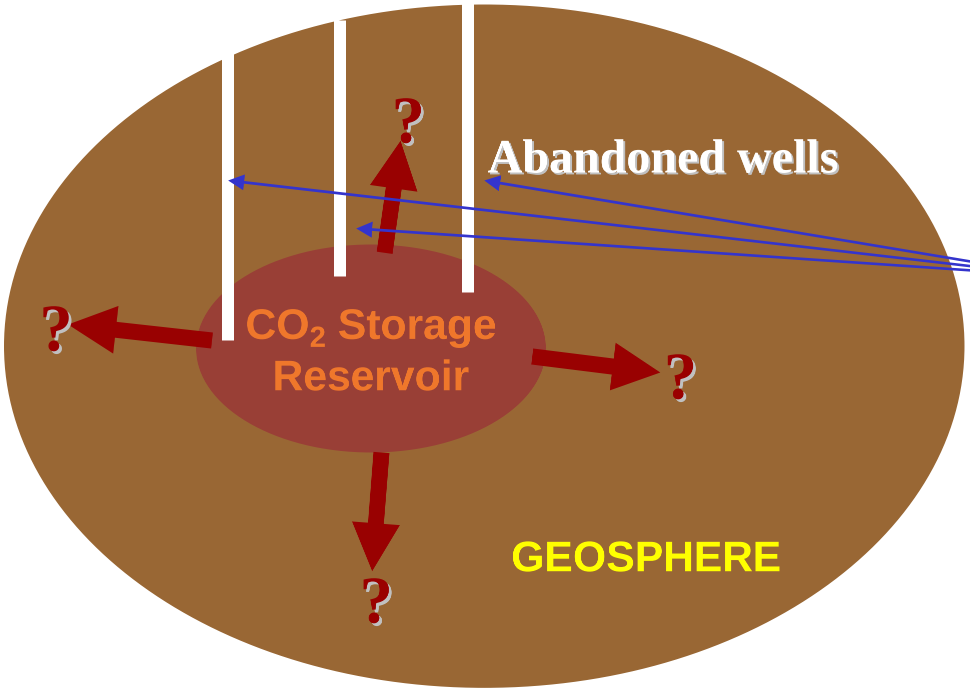
CO_2 Storage System - Schematic



- Reservoir 'infrastructure'
- Ideally, vertical leakage = 0!

What Ensures Confidence in Project?

- **Technical confidence**
  - **A consensus in the technical community that the system is sufficiently well understood to *quantify* the ways in which it can evolve with time**
- **Public confidence**
  - **Trust that the CO_2 storage community will perform high quality and honest work**
  - **Open access to all important information**
- **Demonstration of robust storage system would enhance both technical and public confidence**
  - **Simple geology, hydrogeology, chemistry**
  - **Large safety factors**
    - ***Some degree of redundancy in terms of sealing system***

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Role of RA in CO_2 Storage Project

RA role | Data needs (SC)

Site selection

Minimal subsurface information

Screening / comparison purposes

Existing site and generic data

Role of RA in CO_2 Storage Project

RA role

Data needs (SC)

Site selection

Site characterization (SC)

=> Subsurface

Guidance: what data / information

Site data primarily supported by generic data

Role of RA in CO_2 Storage Project

RA role **Data needs (SC)**

Site selection

Site characterization

Permitting phase

Need to satisfy regulators

Major part of safety submission

Site data primarily

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Role of RA in CO_2 Storage Project

RA role | Data needs (SC)

Site selection

Site characterization

Permitting phase

Injection phase

Opportunity to improve understanding and test predictions

Major role; update model if necessary

Site data Monitoring data

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Role of RA in CO_2 Storage Project

RA role | **Data needs (SC)**

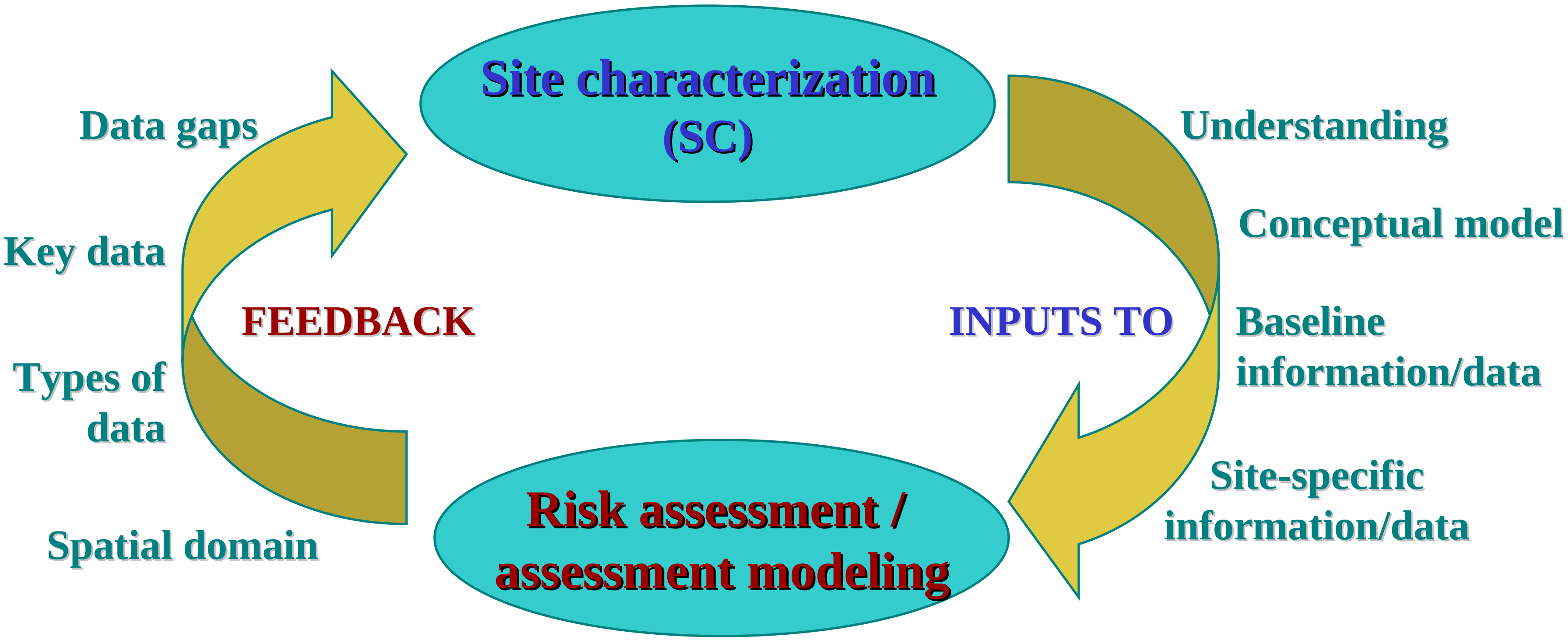
- Site selection
- Site characterization
- Permitting phase
- Injection phase
- **Post-injection phase**

Major role; Final (long-term) predictions

Site data Monitoring data

Shown here as one direction, but……

RA - SC: Iterative Process



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Risk Assessment Methodology

- **Framework of *Scenario Analysis***
  - **Scenarios are plausible/credible ways in which the storage reservoir and its surroundings might evolve**
  - **Scenarios are supported by consideration of *features*, *events*, and *processes* (*FEPs*)**
    - ***FEPs are those factors that need to be considered when modeling the integrity of the CO_2 storage system***
  - **Generic and some site-specific FEP databases are available containing descriptions of different FEPs**

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Extract from generic FEP database

Click on the links below to view the FEP records.

0 Assessment Basis
- 0.1 Purpose of the assessment
- 0.2 Endpoints of interest
- 0.3 Spatial domain of interest
- 0.4 Timescales of interest
- 0.5 Sequestration assumptions
- 0.6 Future human action assumptions
- 0.7 Legal and regulatory framework
- 0.8 Model and data issues

1 External Factors
- 1.1 Geological factors
  - 1.1.1 Neotectonics
  - 1.1.2 Volcanic and magmatic activity
  - 1.1.3 Seismicity
  - 1.1.4 Hydrothermal activity
  - 1.1.5 Hydrological and hydrogeological response to geological changes

http://www.quintessa-online.com/CO2

4 Geosphere
- 4.1 Geology
  - 4.1.1 Geographical location
  - 4.1.2 Natural resources
  - 4.1.3 Reservoir type
  - 4.1.4 Reservoir geometry
  - 4.1.5 Reservoir exploitation
  - 4.1.6 Cap rock or sealing formation
  - 4.1.7 Additional seals
  - 4.1.8 Lithology
    - 4.1.8.1 Lithification/diagenesis
    - 4.1.8.2 Pore architecture
  - 4.1.9 Unconformities
  - 4.1.10 Heterogeneities
  - 4.1.11 Fractures and faults
  - 4.1.12 Undetected features
  - 4.1.13 Vertical geothermal gradient
  - 4.1.14 Formation pressure
  - 4.1.15 Stress and mechanical properties
  - 4.1.16 Petrophysical properties
- 4.2 Fluids

Specific RA Needs From Site Characterization

- Conceptual model of storage system
  - Reflecting 'current' understanding
    - *Reservoir itself*
    - *Sealing system*
    - *Preferential pathways for CO_2 migration*
      - Natural (faults)
      - Man-made (wellbores)
    - *Hydrogeological regime(s)*
      - Aquifers / aquitards
    - *Hydrochemical / geochemical inputs*
      - Mineral-water-CO_2 reactions => +ve or -ve
      - Near-surface aquifer hydrochemistry
    - *Wellbore characteristics*
- DATA!
  - Input data for RA

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The Weyburn Geological Model

- Represented in assessment modeling as………..

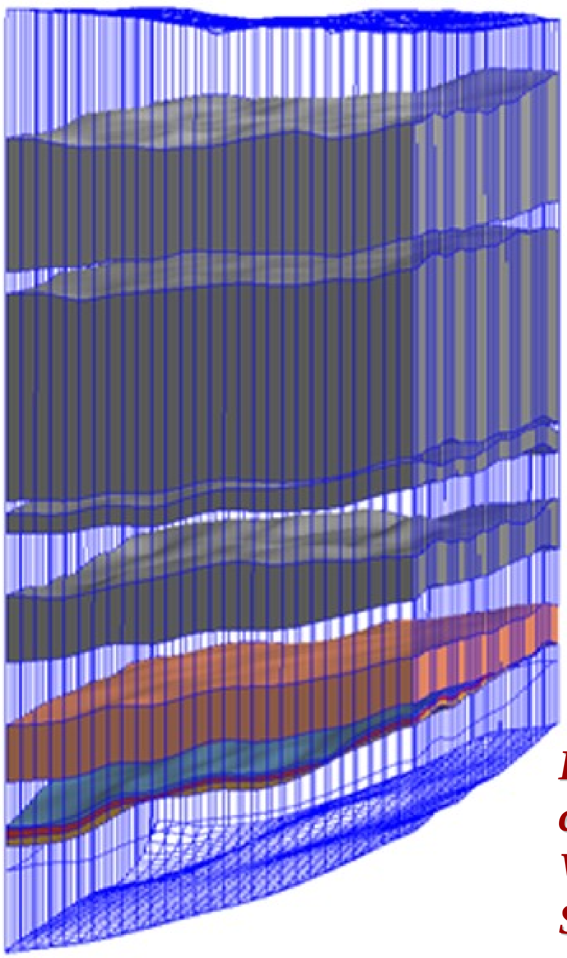

Diagram courtesy of Steve Whittaker, SIR, Regina

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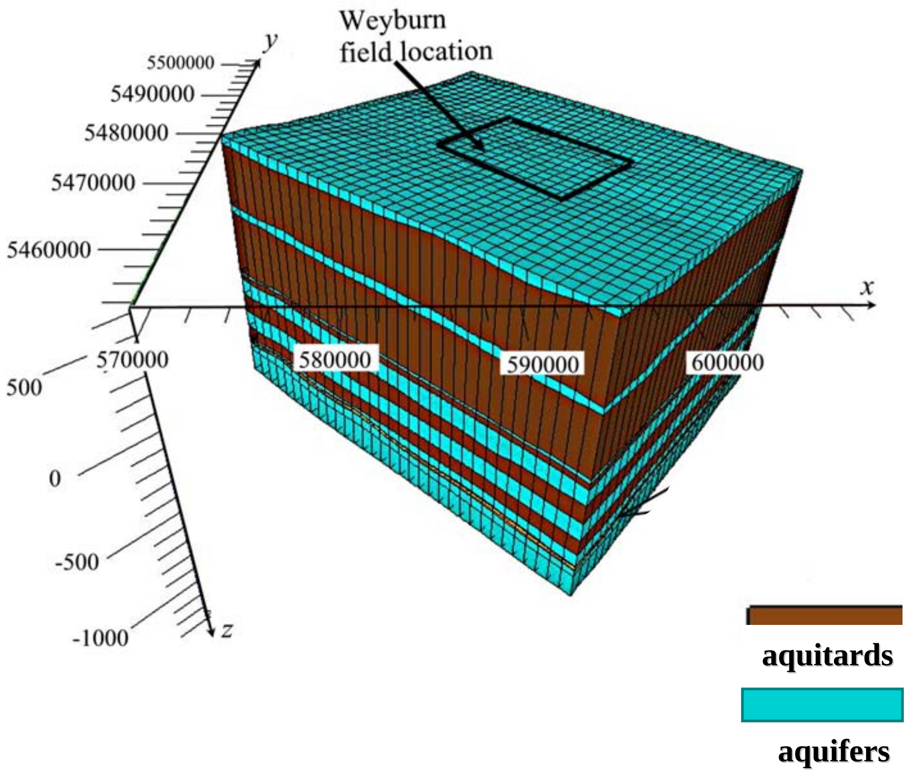
Weyburn Assessment Model



- Hydraulic units represented by series of aquifers and aquitards
- CO_2 migration *may* occur laterally as well as vertically upwards and downwards
- Biosphere starts with deepest potable aquifer

Monitor Scientific

Deciding When Enough is Known

- Knowledge (hopefully!) increases with more information and data – but how much and <u>is it useful knowledge</u>?
- Stop characterization once ”net gain” is zero or negative
  - Value of increased information *vs*. cost of acquiring it
- Cost of acquiring site characterization information
  - Direct costs
  - Indirect / hidden?
- Value of information
  - Reduced uncertainties may make it easier to convince stakeholders of overall safety
  - “Diminishing return” in investigation / assessment efforts
  - Reduce probability of ‘negative’ surprises (transmissive fault)!
  - Judgmental!
- Who decides ‘gain’?
  - Use formal decision making?

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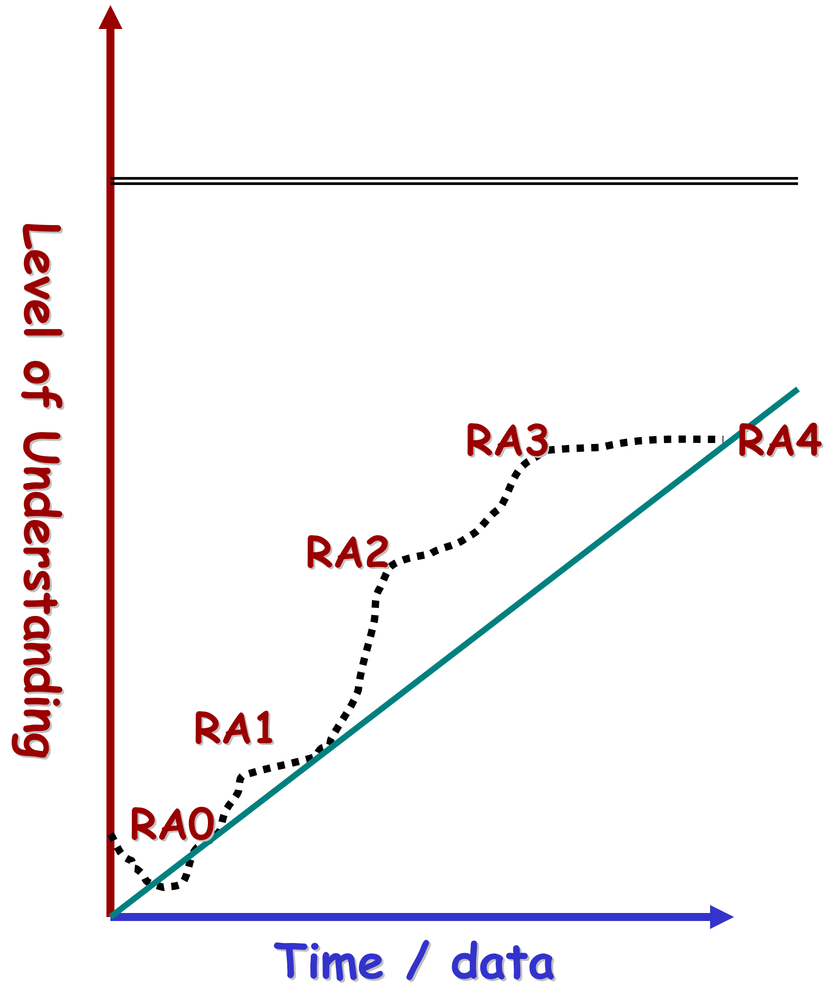
When is Enough Enough?!?



All site characterization information and data must have a useful purpose — => *improve understanding and/or contribute to RA needs*

Value of New Information?

- What site properties affect storage integrity?
  - => Key safety features associated with long-term predictability (feedback from RA)
  - Importance of information not always the same as the resources needed to acquire it!
- Understanding and "surprises"
  - Probability of conceivable surprises should be possible to bound based on detection limits for characterization techniques

Conclusions

- Technical and public confidence are <u>both</u> needed as a basis for proceeding with CO_2 storage projects
  - Good science is a prerequisite – but <u>not sufficient</u>
  - Openness, transparency are also required, and involvement of all stakeholders whenever possible
- Risk assessment can contribute significantly to technical and public confidence
  - Provides a useful framework for guiding site characterization activities at all stages in the development of a geological CO_2 storage project.
  - Besides identifying what information and data feed directly/indirectly into assessment modeling, RA can also guide decision makers on what information/data are *not* crucial to assessment predictions.

MONITOR SCIENTIFIC

Risk Assessment and Site Characterization: A US Perspective

Anhar Karimjee

Climate Change Division

US Environmental Protection Agency

Overview

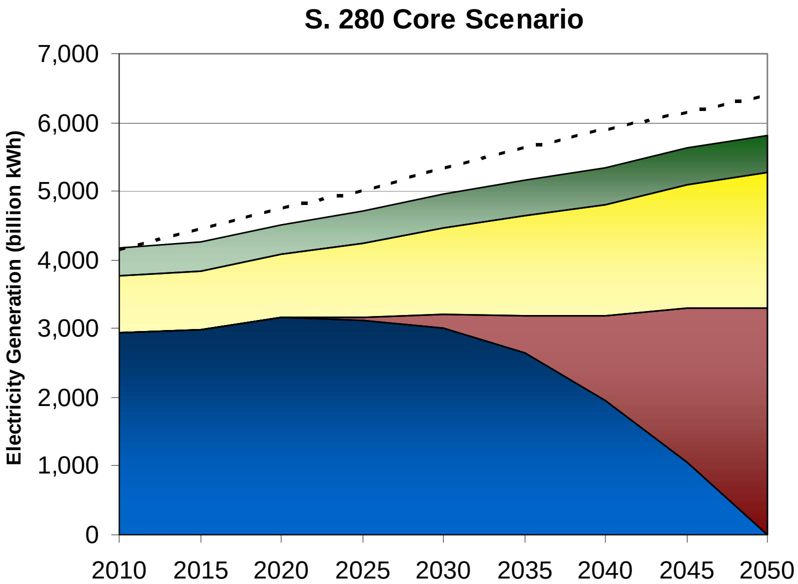
- In the US, there is a demand for transparent and easily understood risk assessments
  - Legislatures, Regulators, Investors, Public
- It will be important to consider the audience when developing these approaches
  - What is the question, who is asking it, and what is their motivation?
  - Approaches and level of analysis may vary
- Site characterization is critical but can be costly
  - "How much is enough?" → "What information is critical and when do we need to have it?"

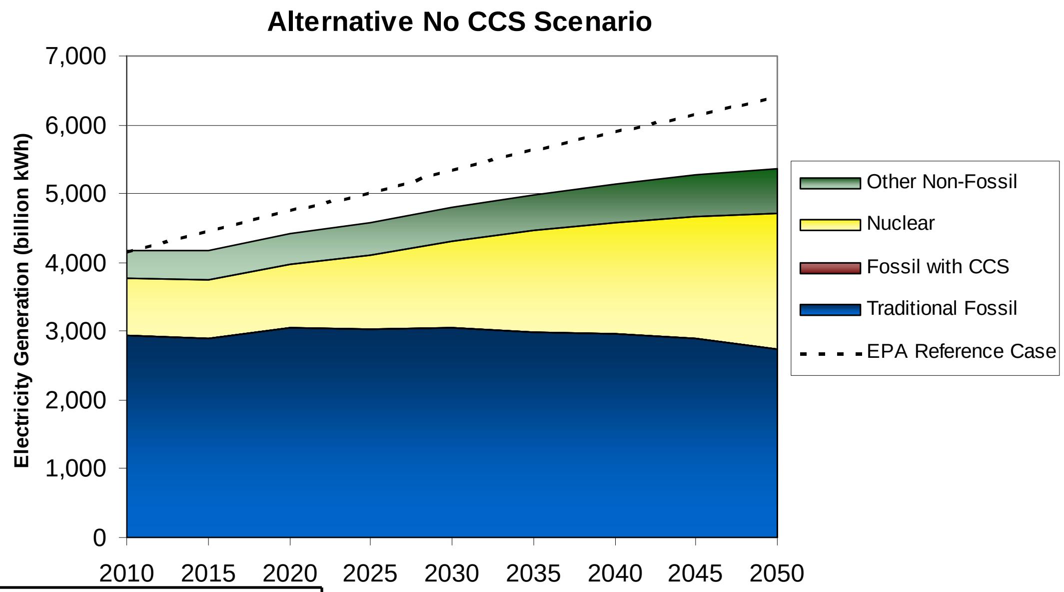
Background: CCS and US Climate Policy

- Senators Lieberman and McCain requested that EPA estimate the economic impacts of S. 280, the Climate Stewardship and Innovation Act of 2007.
- The enabling technologies in this analysis for electricity generation are Carbon Capture & Storage (CCS) and Nuclear Power.
- If neither CCS nor nuclear are available at large scales at the cost used in this analysis then the allowance prices and the costs to the economy would increase significantly.

http://www.epa.gov/climatechange/downloads/s280fullbrief.pdf

Results: Additional Scenarios (7) No CCS Technology (ADAGE)





	2030		2050	
	S. 280 Senate Scenario	S. 280 No CCS Scenario	S. 280 Senate Scenario	S. 280 No CCS Scenario
GDP (% change from BAU)	-0.55%	-0.97%	-1.07%	-1.82%
Allowance Price (2005 $/t$CO_2$e)	$26.59	$39.90	$70.33	$105.23

- Assumes no CCS technology is available
- Results in 50% higher allowance prices
- Results in reduced electricity generation

Note: Other non-fossil includes nuclear, hydro, geothermal, wind, solar, biomass and municipal solid waste.

US Congress and CCS

BILL TITLE	SPONSOR	DATE	RELEVANCE TO CCS
S. 309 – Global Warming Pollution Reduction Act	Sanders and Boxer	January 16, 2007	▪ Competitive grant program for CCS ▪ EPA to develop guidelines for CCS
S. 731 - National Carbon Dioxide Storage Capacity Assessment Act of 2007	Salazar	March 1, 2007	▪ DOI to develop methodology for assessing U.S. capacity for geologic storage of CO_2, accounting for potential risk
S. 962 - Department of Energy Carbon Capture and Storage Research, Development and Demonstration Act of 2007	Bingaman	March 22, 2007	▪ Research and development, including testing to perform quantitative risk assessments ▪ Regional partnerships ▪ Large-volume test projects
S. 1168 - Clean Air/Climate Change Act of 2007	Alexander and Lieberman	April 19, 2007	▪ Cap-and-trade with CCS offset option
S. 1201 – Clean Power Act of 2007	Sanders	April 24, 2007	▪ Cap-and-trade ▪ EPA to establish guidelines for CSS ▪ Guidelines to address risk assessment
S. 1227 – Clean Coal Act of 2007	Kerry	April 26, 2007	▪ Bans new coal-fired power plants without CCS capability
H.R. 2337 – Energy Policy Reform and Revitalization Act	Rahall	May 16, 2007	▪ DOE to assess risk and capacity associated geologic storage of CO_2 in U.S.
S. 1766 – Low Carbon Economy Act of 2007	Bingaman and Specter	August 11, 2007	▪ Report to Congress on risk associated with CCS
America's Climate Security Act of 2007	Lieberman and Warner	Forthcoming this Fall	▪"Legal framework" for CCS ▪EPA to issue CCS regulations that minimize potential risk

States and CCS

Montana H.B. 0828 – Carbon Sequestration Study. *Tabled in committee.* Requires the state to conduct a study to examine the costs, benefits, capacity for, and risks of CCS. **S.B. 0105 – Tax Break for Equipment to Sequester Carbon Dioxide**. *Tabled in committee*. Establishes a tax exemption for CO_2 sequestration equipment.

Minnesota H.F. 1666 – Carbon Sequestration Assessment. *In committee*. Requires the state to conduct an assessment of the state's capacity for geologic storage of CO_2.

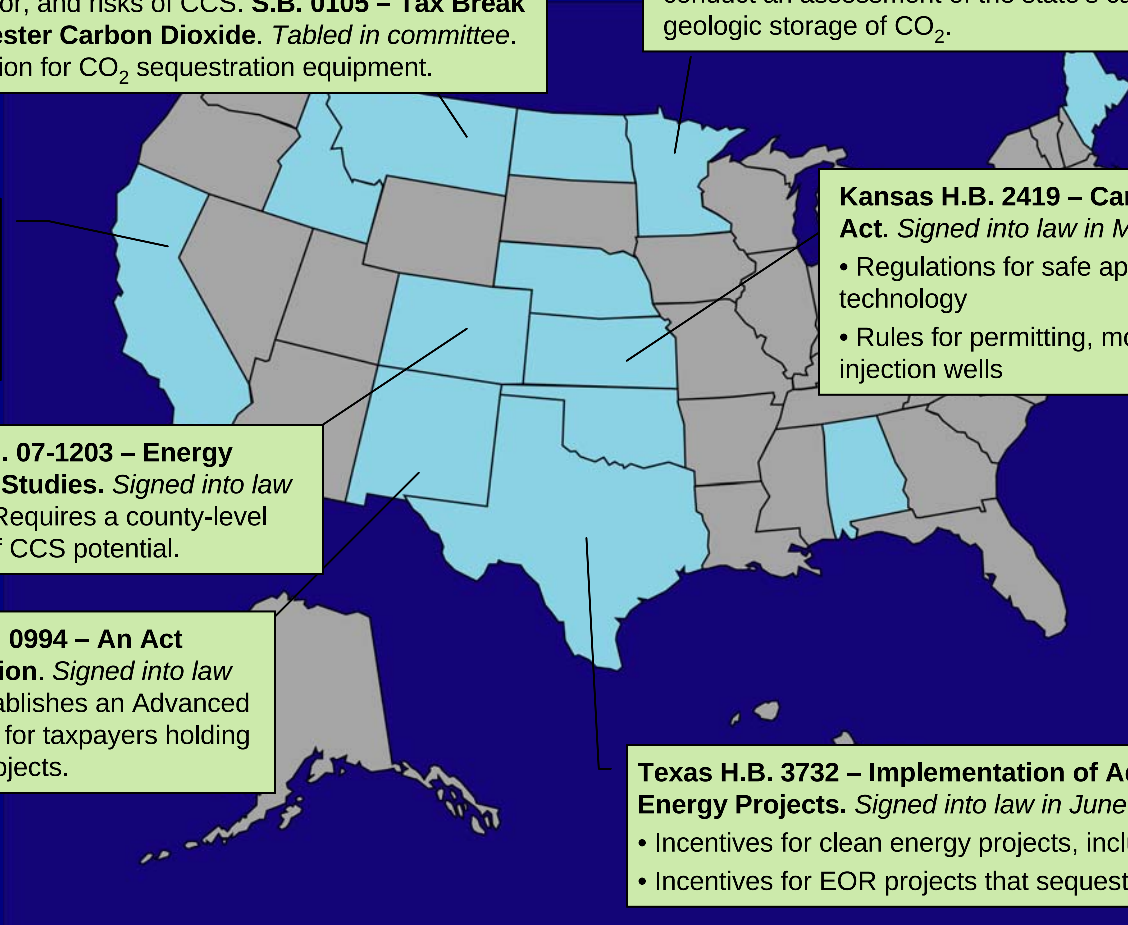
California A.B. 705 – Geologic Carbon Sequestration. *Bill repealed in April 2007.* Regulations for CCS projects.

Kansas H.B. 2419 – Carbon Dioxide Reduction Act. *Signed into law in March 2007*.

- Regulations for safe application of CCS technology
- Rules for permitting, monitoring, and inspecting injection wells

Colorado H.B. 07-1203 – Energy Management Studies. *Signed into law in May 2007*. Requires a county-level assessment of CCS potential.

New Mexico. S.B. 0994 – An Act Relating to Taxation. *Signed into law in April 2007*. Establishes an Advanced Energy Tax Credit for taxpayers holding interest in CCS projects.



Texas H.B. 3732 – Implementation of Advanced Clean Energy Projects. *Signed into law in June 2007*.

- Incentives for clean energy projects, including CCS
- Incentives for EOR projects that sequester CO_2.

Highlighted states are pursuing CCS in legislative activity

The Role of Risk Assessment in Regulatory Development

- Risks must be identified and evaluated in order to establish regulations
- Once regulatory options are identified, the relative costs and benefits of each option are estimated
  - What will it cost to implement and how will health and environmental risks be reduced?
- Methods can vary and be qualitative or quantitative
  - Expert judgment can be used
  - Uncertainty should be addressed
- Mean risk estimates are basis of benefits analysis
  - Goal is to estimate most likely outcome or present multiple risk estimates if scientific opinion is strongly divided

Level of Analysis Required

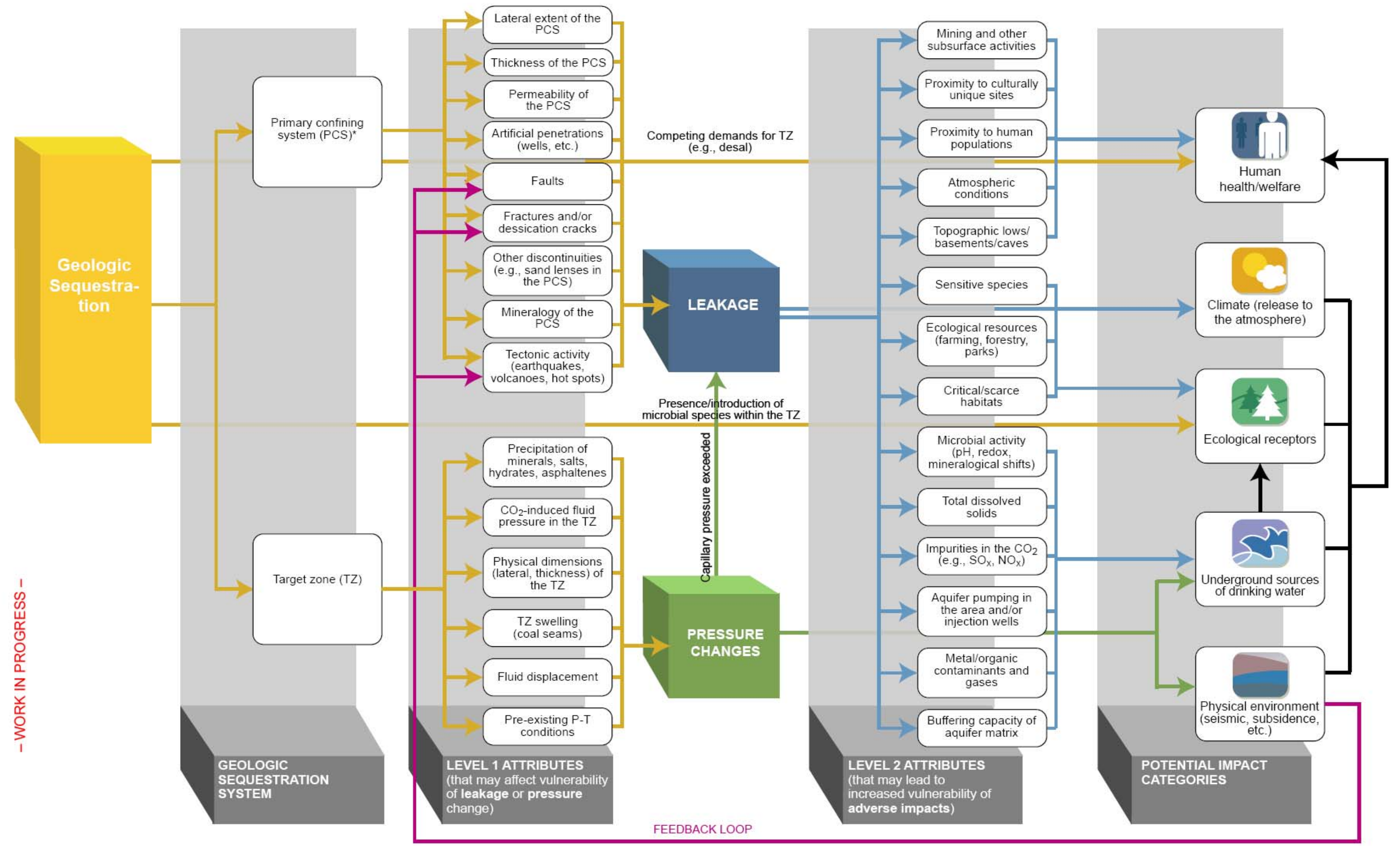
- More costly regulations require more extensive analysis
  - <$100M: Preliminary cost analysis
  - $100M-$1B: Formal “Regulatory Analysis” including cost-benefits and uncertainty analyses
    - describe uncertainties qualitatively
    - conduct sensitivity analysis
    - identify key parameters where probabilistic analysis may be needed
  - >$1B: Regulatory Analysis+
    - conduct formal probabilistic analysis of relevant uncertainties

Risk Assessment Approaches: Relative Risks for Treated Wastewater

- EPA conducted a relative risk assessment of wastewater disposal options in Florida
  - Deep well injection, aquifer recharge, discharge to ocean outfalls, and discharge to other (non-ocean) surface water bodies
- Each option had specific stressors, exposure pathways, receptors, and potential effects
- A strictly quantitative comparison between the four options was not possible
- Individual risk assessments were conducted with overall comparisons and conclusions presented as relative risk assessment matrices

http://www.epa.gov/region4/water/uic/downloads/ra/08-relative_risk.pdf

Risk Assessment Approaches: Vulnerability Assessment for CCS



** Secondary containment system(s) should also be evaluated using the level 1 leakage attributes.*

EPA Sponsored Site Characterization Workshops

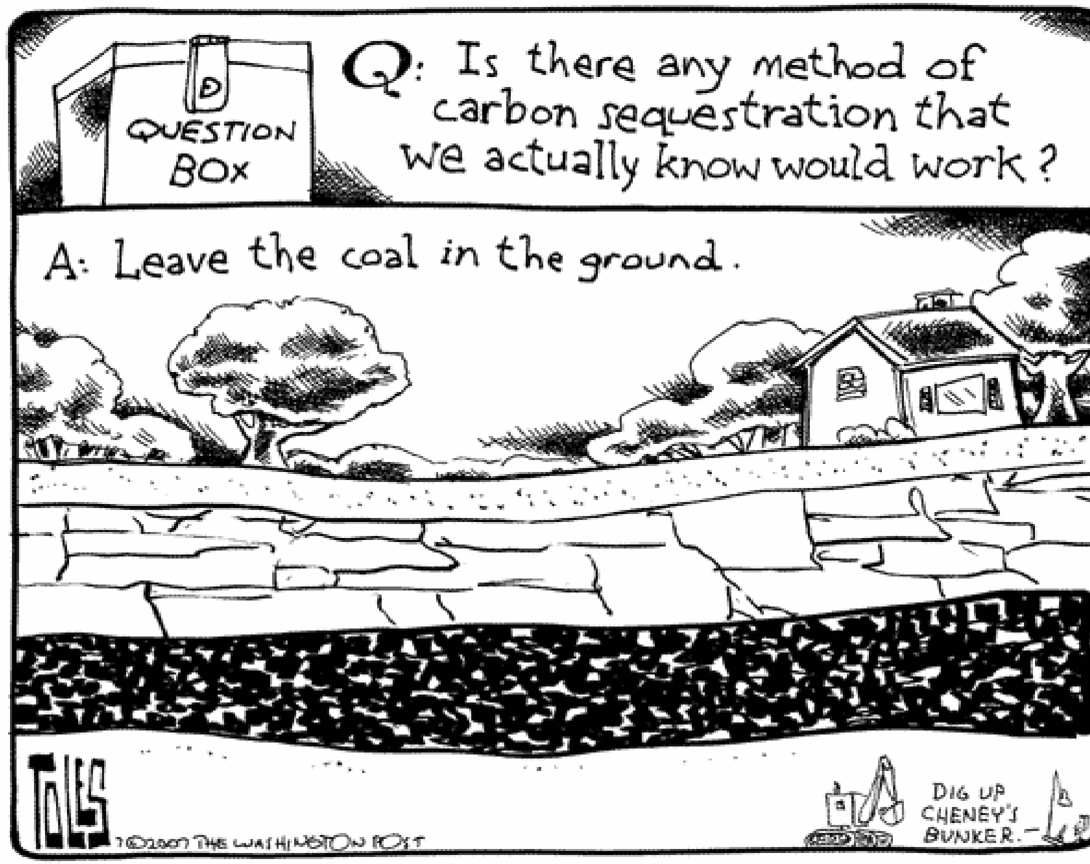
- CO2SC 2006: International Symposium on Site Characterization for CO_2 Geological Storage
  - Berkeley, CA, March 20-23, 2006
- EPA Technical "Area of Review" Workshop:
  - Washington, DC, July 10-11, 2007

Workshop Findings

- Key attributes for site characterization: Containment Effectiveness, Injectivity, Storage Capacity
- Need to identify critical variables for regulators
  - There may be additional site characterization needs for risk assessment/management
  - Data required for pilot or research projects should not become the de facto standard
- Site characterization can be an iterative process
  - Basic “high-level” screening as first step
  - Additional characterization driven by the complexity of the site and project performance
- Other issues raised:
  - Monitoring after injection may be more appropriate than extensive well mitigation prior to injection
  - Some leaks may be acceptable if there are no impacts to human health and the environment

Final Thoughts

- CCS is a key climate mitigation technology
- There is a high demand for transparent and easily understood risk assessment approaches
- Key Challenges Remain
  - Demonstration
  - Appropriate Regulations
  - Public acceptance



Background Slides

CCS in State Legislation

STATE	BILL TITLE	RELEVANCE TO CCS	RECENT ACTION
California	A.B. 705 – Geologic Carbon Sequestration	▪ Regulations for CCS projects	Bill repealed in April 2007
Colorado	H.B. 07-1203 – Energy Management Studies	▪ Requires a county-level assessment of CCS potential	Signed into law in May 2007.
Kansas	H.B. 2419 – Carbon Dioxide Reduction Act	▪ Rules for permitting, monitoring, and inspecting injection wells	Signed into law in March 2007
Minnesota	H.F. 1666 – Carbon Sequestration Assessment	▪ Requires the state to conduct an assessment of the state's capacity for geologic storage of CO_2	In committee
Montana	H.B. 0828 – Carbon Sequestration Study	▪ Requires the state to conduct a study to examine the costs, benefits, capacity for, and risks of CCS	Tabled in committee
	S.B. 0105 – Tax Break for Equipment to Sequester Carbon Dioxide	▪ Establishes a tax exemption for CO_2 sequestration equipment	Tabled in committee
New Mexico	S.B. 0994 – An Act Relating to Taxation	▪ Establishes an Advanced Energy Tax Credit for taxpayers holding interest in CCS projects	Signed into law in April 2007.
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CO2 CRC COOPERATIVE RESEARCH CENTRE FOR GREENHOUSE GAS TECHNOLOGIES

Reducing greenhouse gas emissions to the atmosphere

Risk Assessment for Site Characterisation: An Australian Perspective

John Kaldi, Max Watson, Peter Cook

CO2CRC

Adrian Bowden, Donna Pershke,
URS

Special thanks to Andy Rigg (formerly CO2CRC)

3rd MEETING of the RISK ASSESSMENT NETWORK
15th-16th August 2007, Imperial College, London, UK

CRC

CO2CRC Participants

Supporting participants: Australian Greenhouse Office | Australian National University |
| CANSYD | Meiji University | The Process Group | University of Queensland | Newcastle University |

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

Presentation Outline

- **About QRA Method**
- **Site Characterisation**
- **Linking RA to stages of site characterisation**
- **Risk-based Decision Making in CCS Project Development**
- **Update on Otway Basin Project**
- **RA for site characterisation: gaps**
- **The Future: Aims & Objectives**
- **Conclusions**

About QRA Methodology

- Develop "best practice" to run complete quantitative risk-based CCS project
  - Underpinned by methods adopted in CO2CRC Site Characterisation, and Monitoring and Verification workflows
- Utilise URS's RISQUE™ method as basis for each phase of risk assessment
  - Storage capacity
  - Injectivity potential
  - Containment
  - Site details
- Use "expert Panel"
- Incorporate technical uncertainty of geological data
- Include technical, economic, regulatory and social risks
- Assist communication of risk to stakeholders

Scales of Investigation

- Country/State/Region Screening
- Basin Assessment
- Site Characterisation
- Site Deployment)

What project outcomes do stakeholders want?

- X tonnes of CO_2 stored for Y years with a Z percent confidence level at an acceptable cost of D dollars per tonne CO_2. Plus, confirmation the site meets regulatory HSE and other requirements, through technical assessment and extended monitoring and verification.

How will stakeholders measure project success?

- A happy ‘customer’(regulator, company)
- An accepting community.
- A well conducted project with no incidents/problems- that will help smooth the path of the next project.
- A real decrease in CO_2 emissions to the atmosphere

Site Characterisation

Definition

US Regulatory Commission

The US Nuclear Regulatory Commission defines site characterization in relation to Yucca Mountain as follows:

"Site characterization means the program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions and the ranges of those parameters of the Yucca Mountain site, and the surrounding region to the extent necessary, relevant to the procedures under this part.

Site characterization includes borings, surface excavations, excavation of exploratory shafts and/or ramps, limited subsurface lateral excavations and borings, and in situ testing at depth needed to determine the suitability of the site for a geologic repository."

See http://www.nrc.gov/reading-rm/doc-collections/cfr/part063/part063-0002.html

Site Characterisation
(after CO2CRC, 2006)

"The collection, analysis and interpretation of subsurface, surface and atmospheric data (geoscientific, spatial, engineering, social, economic, environmental) and the application of that knowledge to judge, with a degree of confidence, if an identified site will geologically store a specific quantity of CO_2 for a defined period of time and meet all required health, safety, environmental and regulatory standards".

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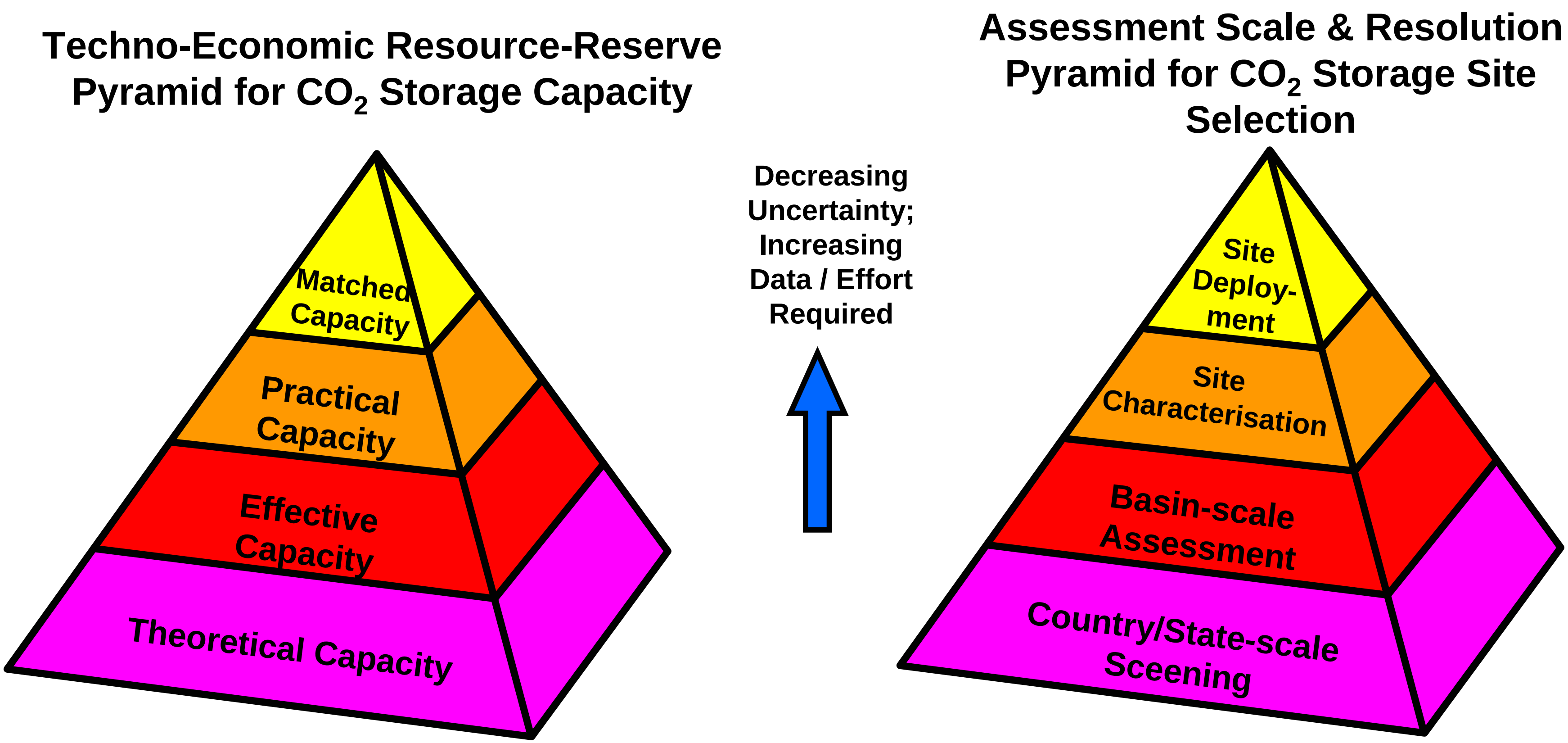
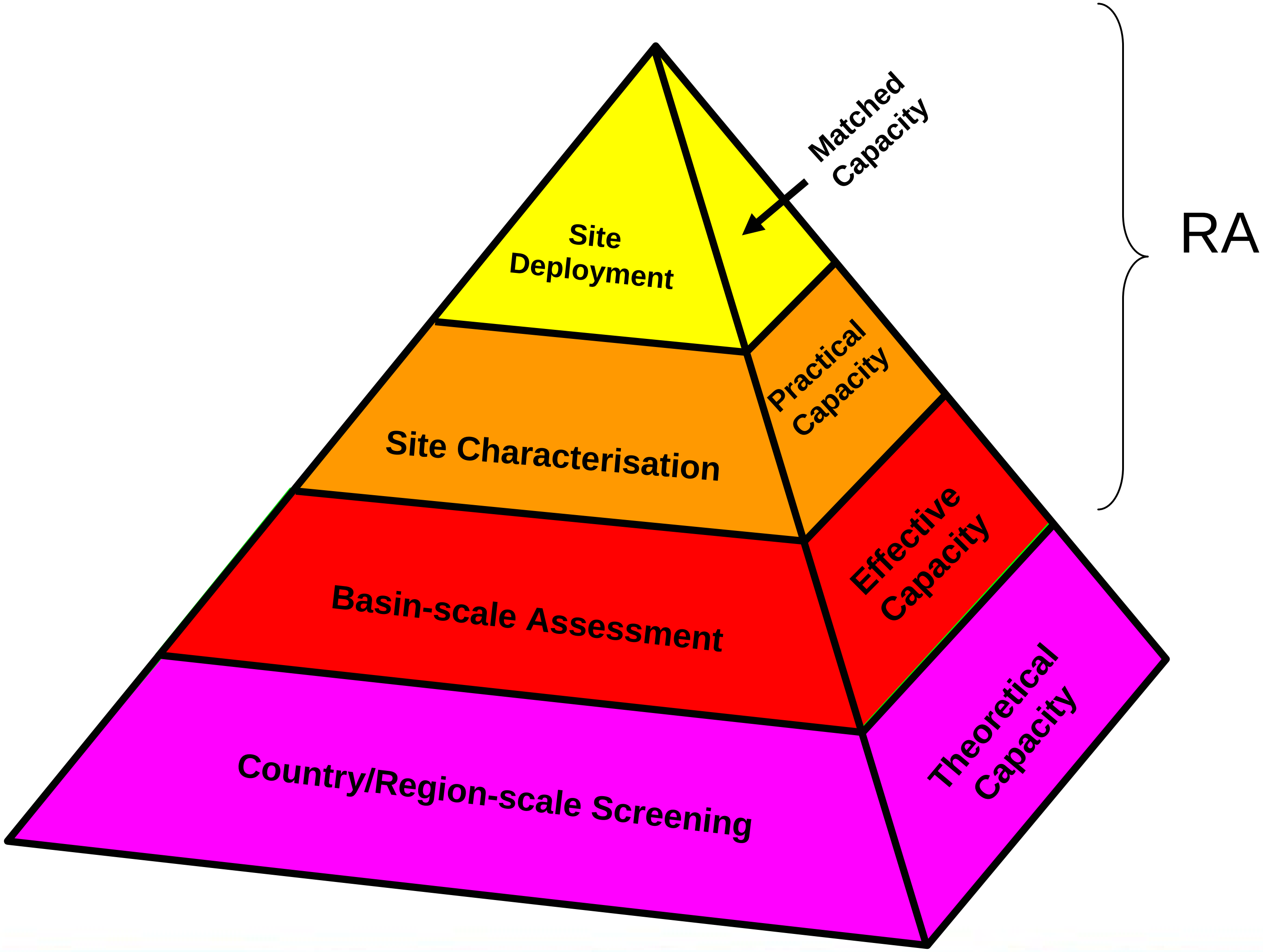
Resource & Site Pyramids

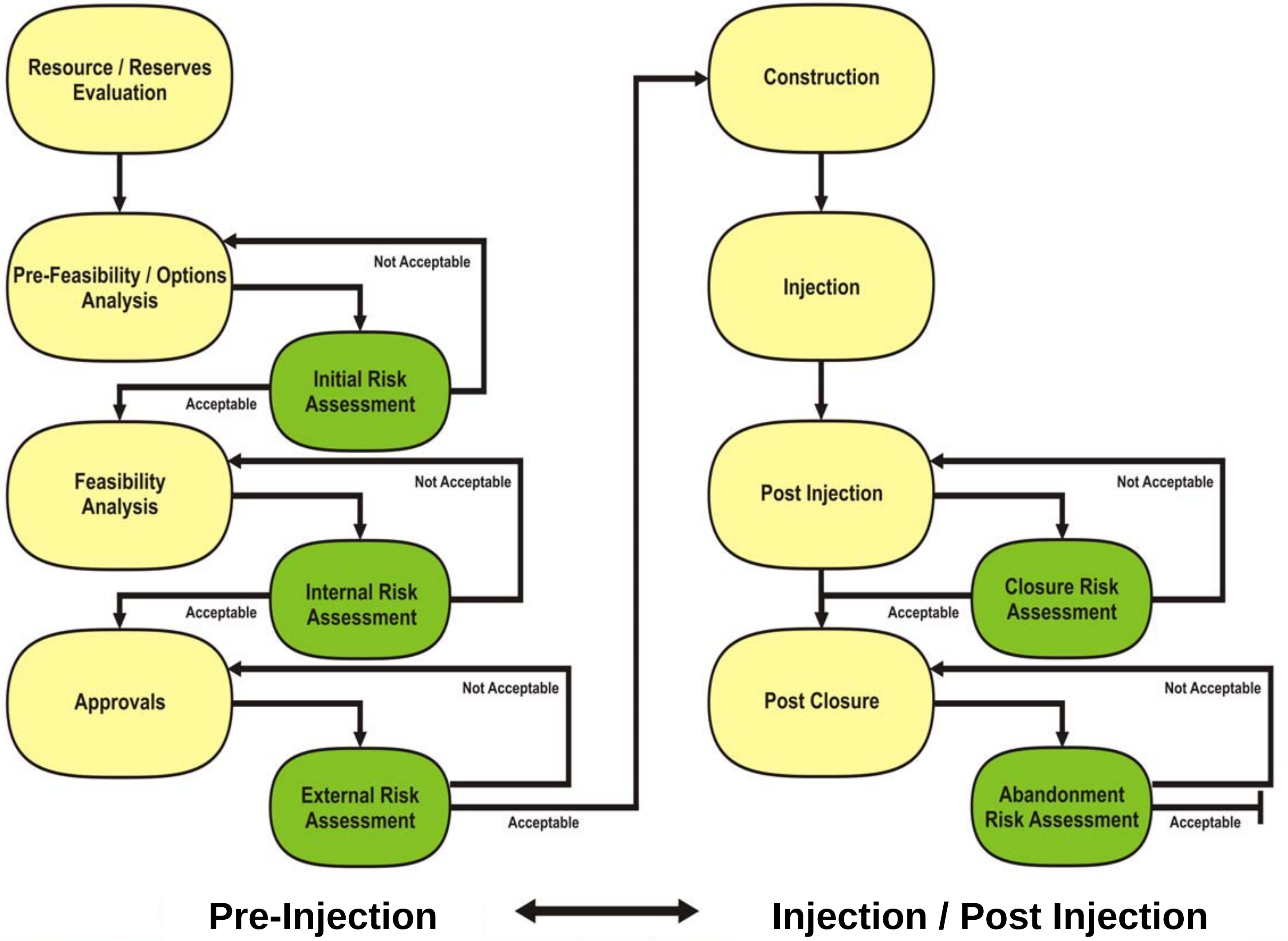


Bachu et al., CSLF, 2005

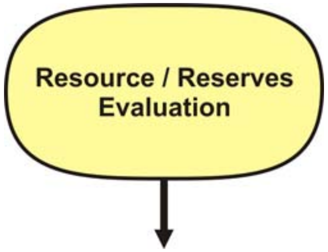
Combined Site & Capacity Pyramid



Risk-Based Decision Making in CCS Project Development



CO2CRC

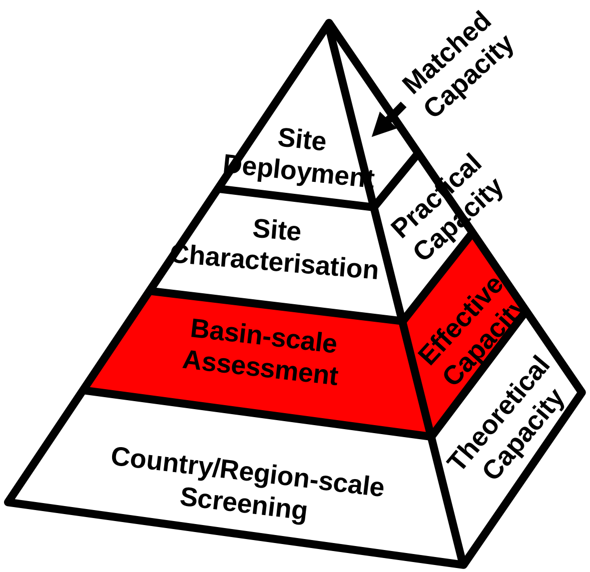


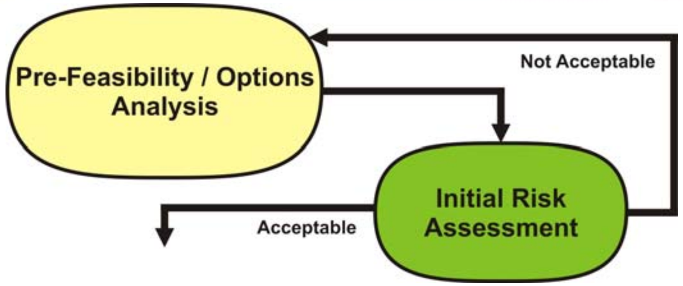
Resource / Reserve Evaluation

Aim: Approval for permit release / acquisition for CCS

Requirements

- **Qualitative evaluation of specific CCS requirements** *(See Bradshaw et al, 2002)*
  - **Storage capacity** (> required volume)
  - **Injectivity potential** (sufficiently high K)
  - **Site details** (chance economically and technically)
  - **Containment**
    - ➢ Geohazards (i.e. volcanism, earthquake)
    - ➢ Effective trap and seal
  - **Existing natural resources** (chance of compromising)





Pre-Feasibility / Options Analysis (expert panel)

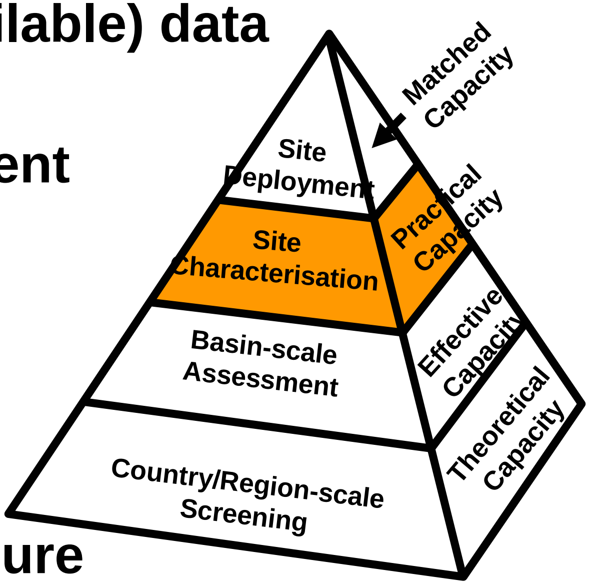
Aim: Approval for commercialisation assessment internally

Initial Quantitative Risk Analysis *(See Bowden and Rigg, 2003)*

- **Performance assessment on basic (typically available) data**
  - **Initial Containment Risk Assessment**
  - **Initial Technical Effectiveness Risk Assessment**

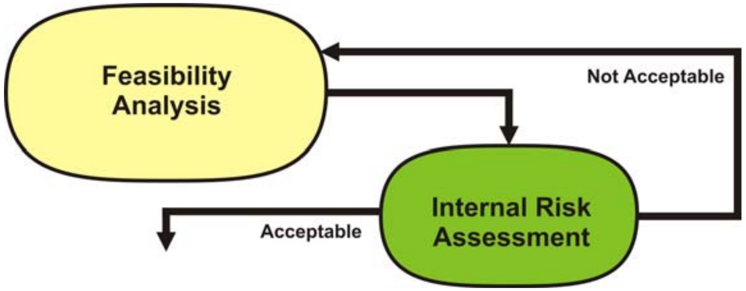
Red flag any:

- **Environmental and social risks**
- **Natural resource risks**
- **Data gap / high uncertainty areas**



Preliminary estimate of project cost including closure

Probabilistic assessment of 'Practical Storage Capacity'

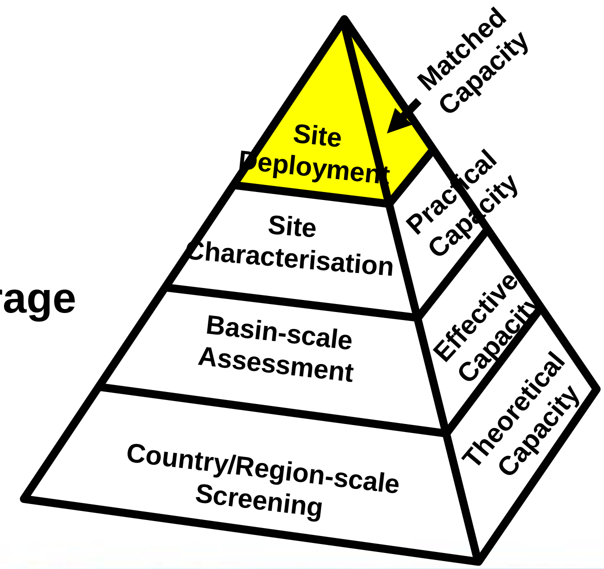


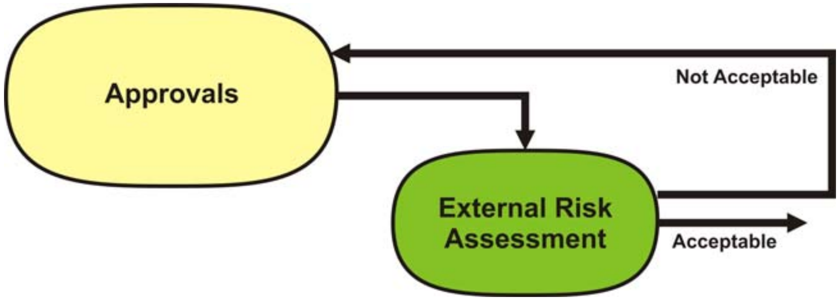
Feasibility Analysis (expert panel + modelling)

Aim: Internal Approval for Commercialisation

Detailed, Quantitative Risk Assessment incorporating:

- **Performance assessment, including newly acquired data, with modelling results**
  - **Detailed Containment Risk Assessment**
    - **leakage from primary container**
  - **Detailed Technical Effectiveness Risk Assessment**
  - **Consequence analysis**
  - **Mitigation and remediation analysis**
  - **Probabilistic and modelled assessment of 'Matched Storage Capacity'**
- **Mitigation for regulatory/social risks**
  - **Environmental Impact Analysis**
  - **Initiate Stakeholder Engagement Program**



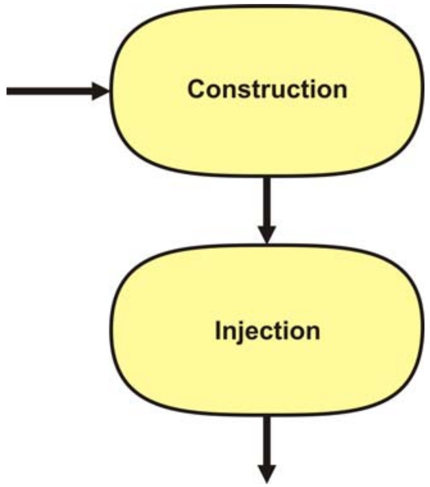


Approvals

Aim: External (Regulatory) Approval for <u>Commercialisation</u>

Transparent External <u>Qualitative</u> Risk Assessment (i.e. Environmental Impact Assessment) incorporating:

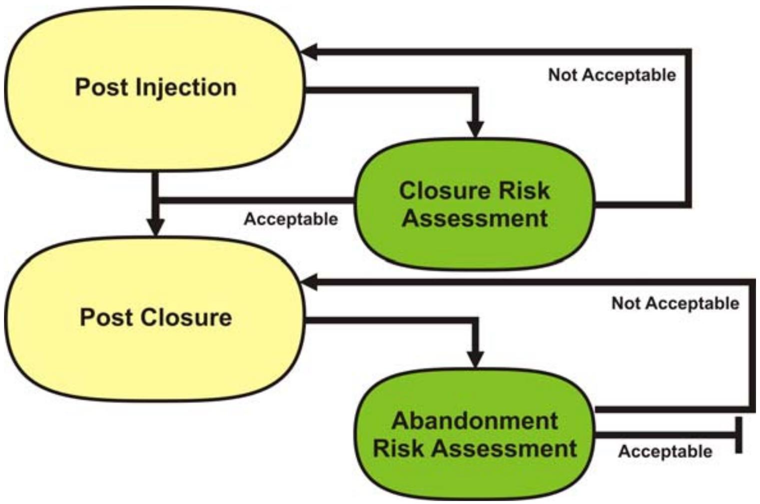
- **<u>Leakage</u> Risk Assessment on all data available**
  - **Leakage to surface / near surface / existing resources**
- **Consequence analysis**
- **Mitigation and remediation analysis (technical)**
- **Mitigation for social risks**
  - **Finalise stakeholder engagement program**
  - **Clarify liability pathways**



Construction and Injection (Deployment)

Aim: Safely develop injection site and safely inject CO_2

- **Standard industry equipment with standard procedures to manage and minimise risk of fugitive leakage.**
- **Initial gathering of injection and monitoring data**



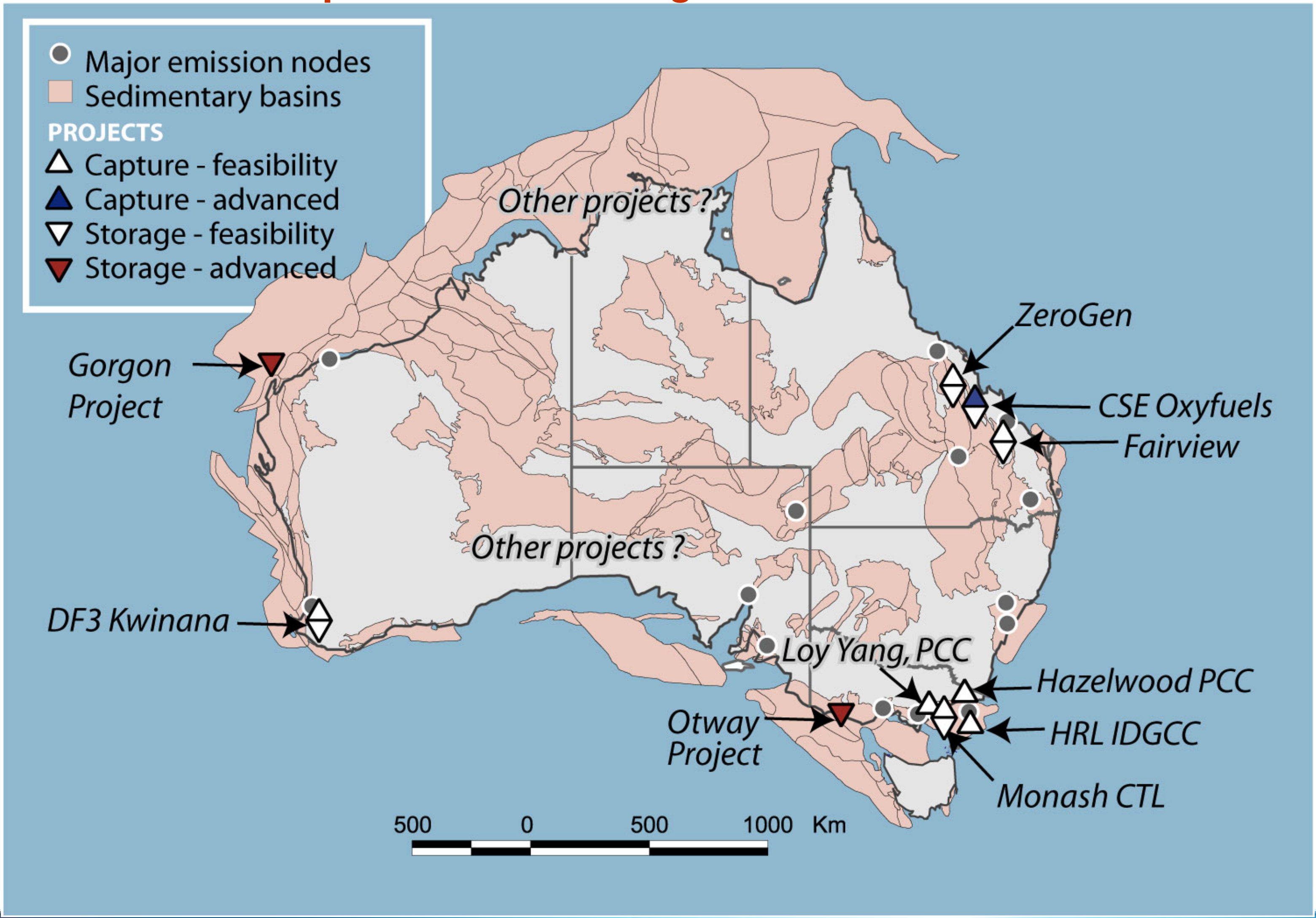
Post-Injection and Post Closure

Aim:

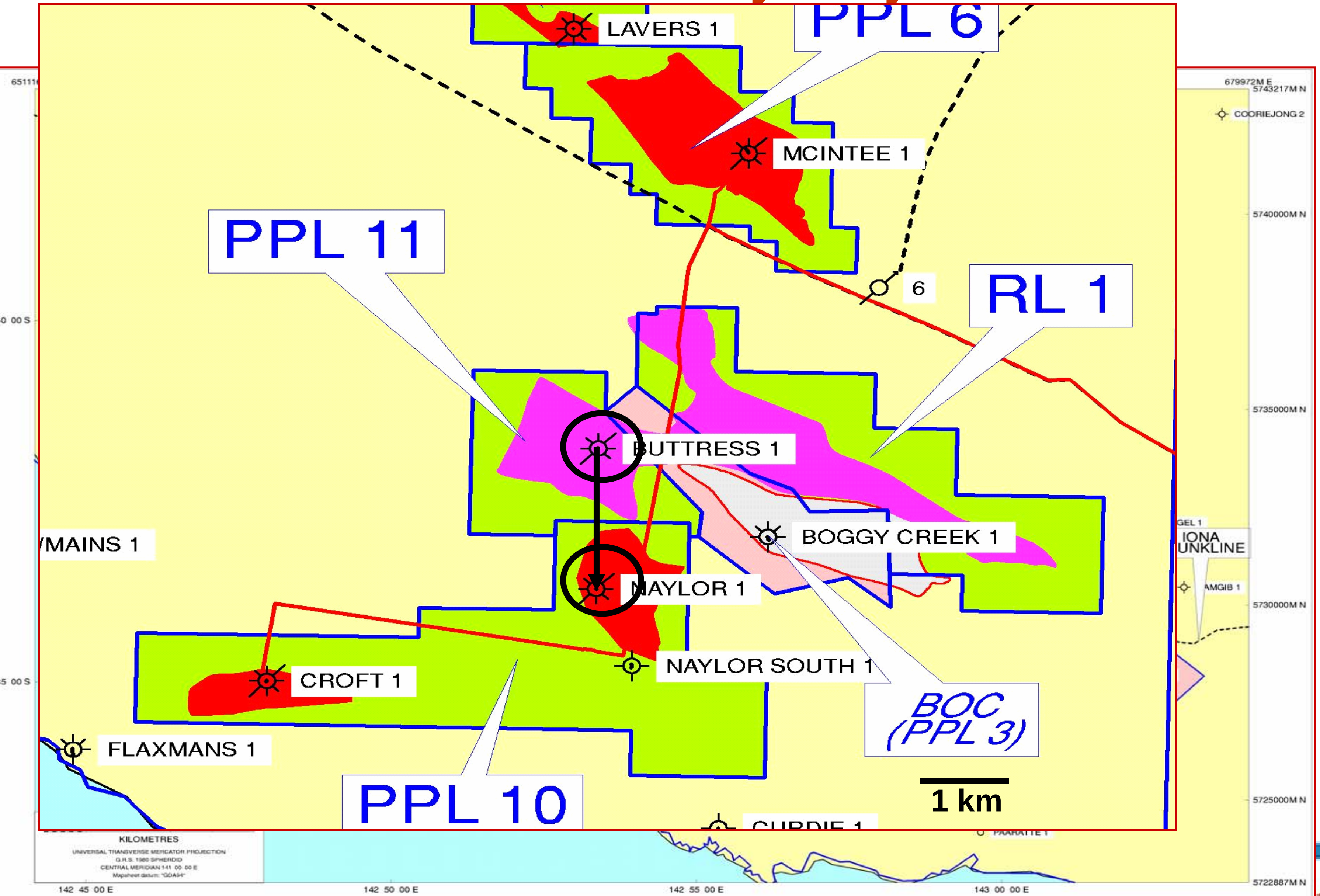
1. Internal Approval for <u>Site Closure</u>
2. Regulator Approval for <u>Abandonment</u>

- Demonstration of risk reduction through MMV
- Based on verification that injected CO_2 complies with modelling
  - Refinement of quantitative risk assessment model
  - Revision of monitoring practices

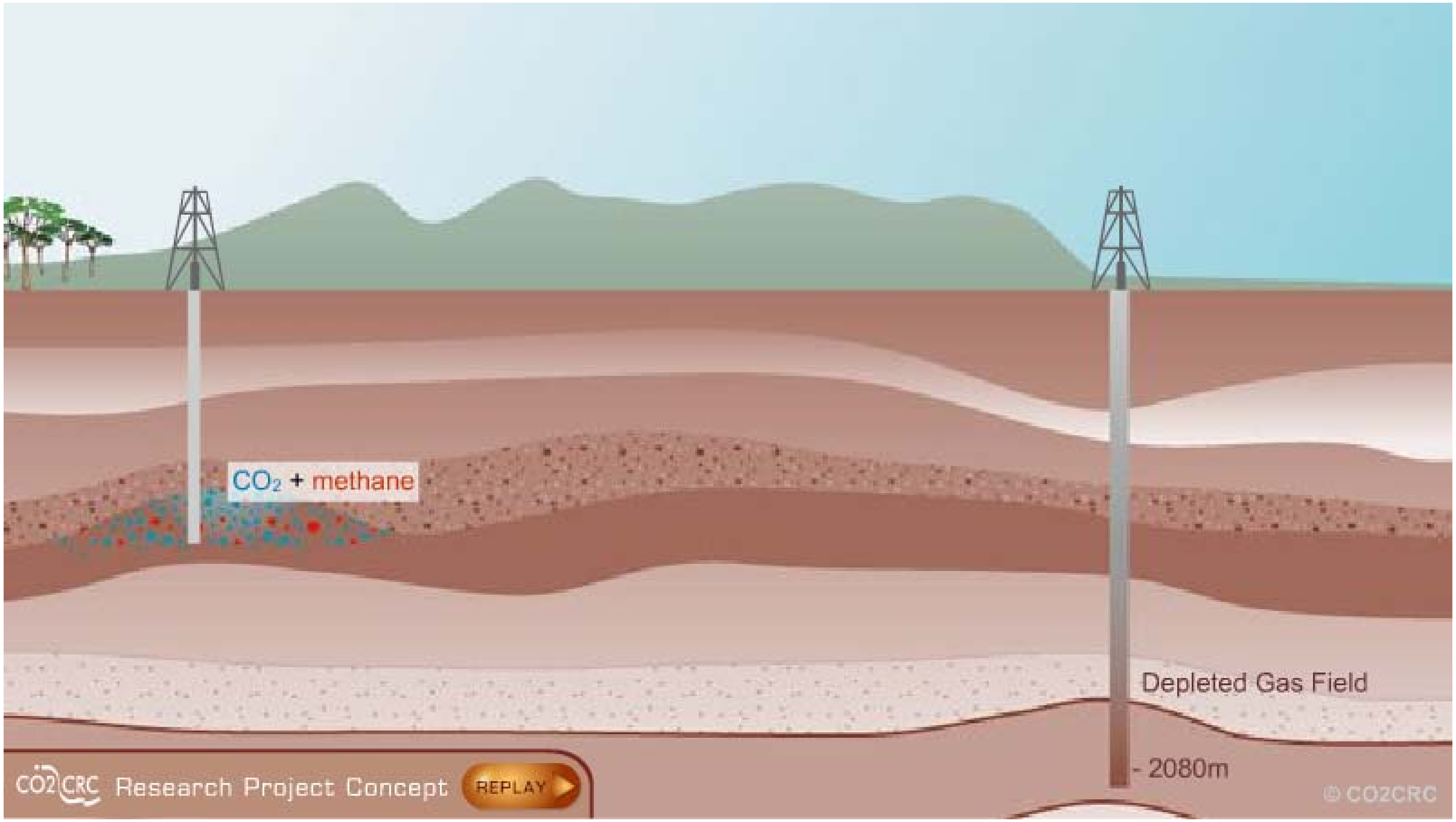
The Australian Scene: Projects and potential projects involving capture and/or storage of carbon dioxide



CO2CRC Otway Project



CO2CRC Otway Project concept



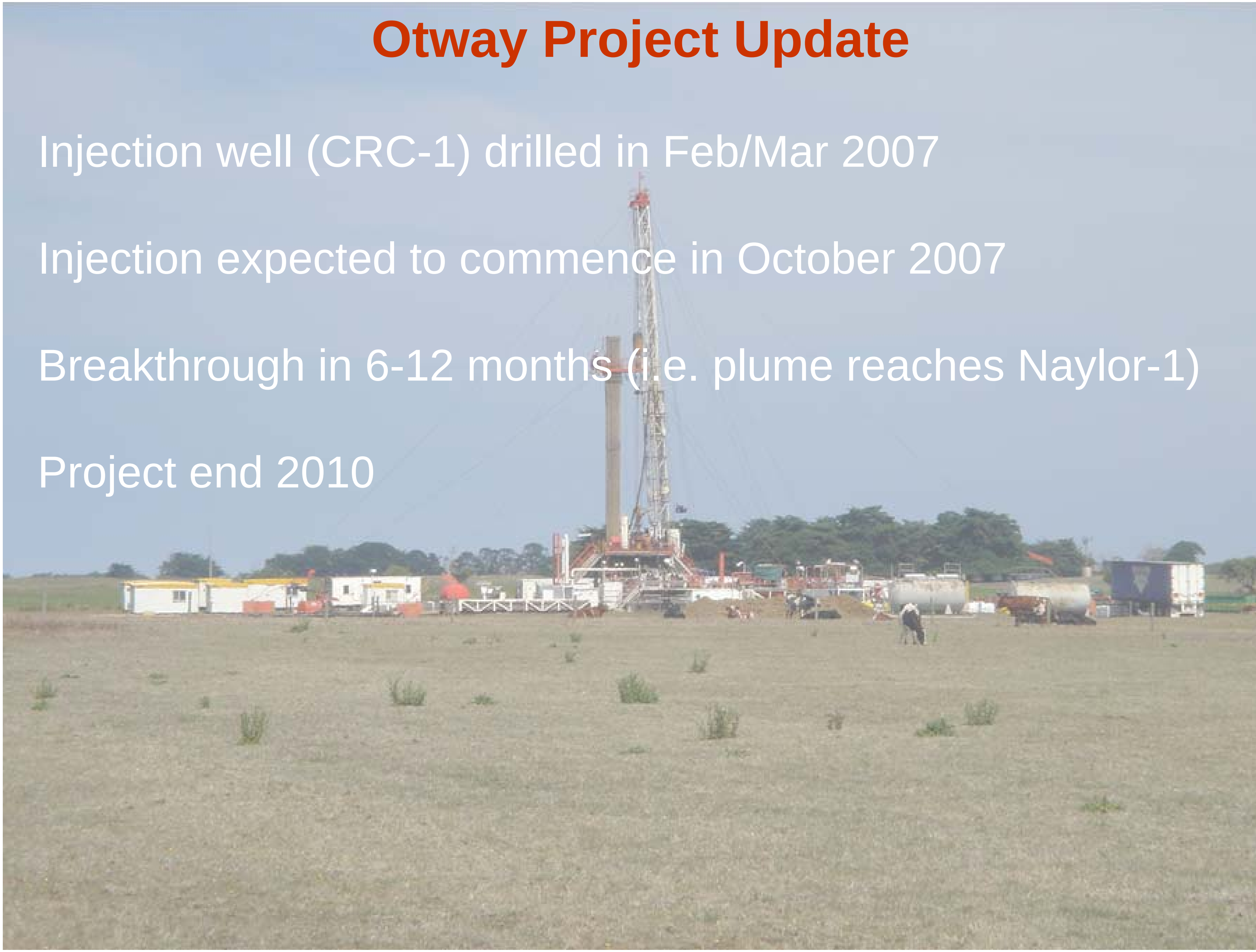
Otway Project Update

Injection well (CRC-1) drilled in Feb/Mar 2007

Injection expected to commence in October 2007

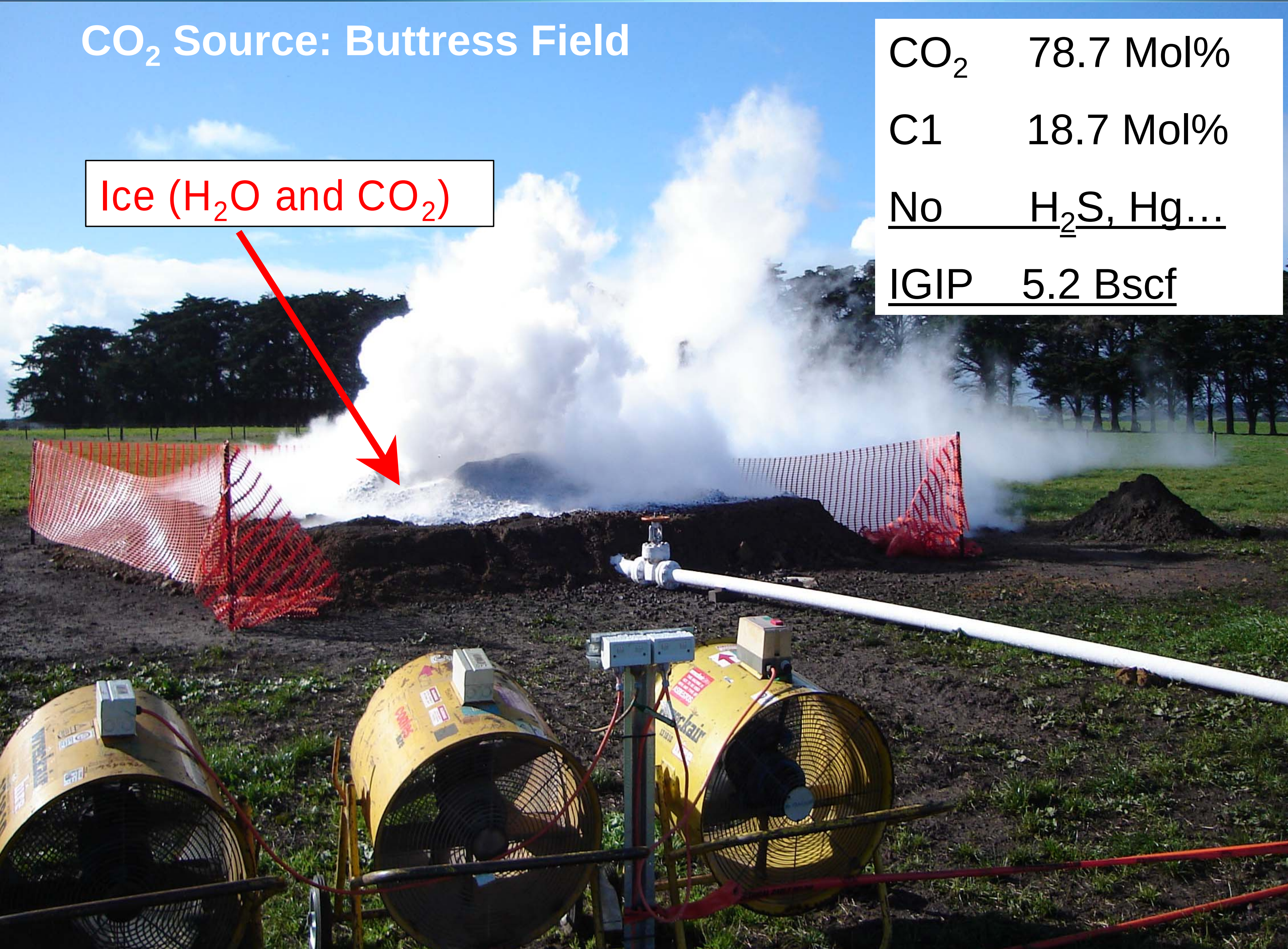
Breakthrough in 6-12 months (i.e. plume reaches Naylor-1)

Project end 2010



CO_2 Source: Buttress Field

CO_2	78.7 Mol%
C1	18.7 Mol%
No	H_2S, Hg…
IGIP	5.2 Bscf



What were factors that led to the choice of the Otway Project site?

- A <u>source</u> of carbon dioxide
- Oil and gas tenements <u>available</u> at an affordable price
- Large amount of exploration and production <u>data</u>
- <u>Infrastructure</u> in place
- Gas had demonstrably been trapped for a long time
- Community <u>familiar</u> with the oil industry (plus and minus)
- <u>Accessible</u>
- Geology suitable for required <u>storage capacity</u>

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What dictated the storage site at some commercial projects?

(in addition to adequate storage capacity/suitable geology)

Sleipner

- Need to avoid carbon tax
- Existing infrastructure (offshore platform)
- Minimal transport distance

Weyburn

- EOR commercial opportunity
- CO_2 source
- Supportive government

In Salah

- Company ethos (and technical benefits?)
- Existing infrastructure
- Minimal transport distance

Gorgon

- Onshore location
- Existing infrastructure
- State expectations (and minimization of financial risk to a long term project)

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RA for Site Characterisation: Gaps (cont.)

- Should we also characterise the CO_2 (the injection gas) in terms of composition, given that differing compositions may react with the storage formation in different ways?
- Existing wells must be considered as part of “site characterisation”, but what about planned future wells?
- Will RA for onshore and offshore characterisation need to meet different requirements?

RA for Site Characterisation: Gaps (cont.)

Will RA for onshore and offshore characterisation need to meet different requirements, given the significant differences?

For example………

- **Data type and availability**
- **M&V technologies that can be deployed**
- **Remediation options that may be used**
- **The economics of storage will differ**
- **The scale of operation will be different**
- **The opportunity for test wells prior to injection**
- **The use of existing infrastructure**
- **The environmental impact**
- **The jurisdictional issues State/Federal**

RA for Site Characterisation: Gaps (cont.)

- Is characterisation an activity that occurs only prior to commencement of CO_2 injection?
- Or does it also continue (and is refined) throughout the injection phase, and during later monitoring and verification stages?
- Should we be defining site characterization into 3 phases?

  - pre-injection
  - injection
  - post injection??

Alternatively, is "site characterisation" the pre-injection phase & "site verification" (M & V) the injection/post injection phase?

The Future: Aims & Objectives

- Develop and get sign-off from all stakeholders on “best practice” for:
  - Developing a risk assessment scheme to optimise characterising storage sites and estimating storage capacity of those sites
  - Assuring consistency in data compilation, interpretation, modelling etc, to the extent that this is possible, given the variability in the extent and quality of geological & geophysical data
  - Ensuring consistency in characterising storage sites and determining storage capacity across state boundaries, between offshore and onshore, between Australia and New Zealand, or elsewhere
- Develop a consistent and readily useable methodology that will ultimately deliver the basis for bankable storage projects in an economical, credible and timely fashion.
- Potentially develop “roadmap to certification”!

Conclusions

- There is no such thing as the perfect site; they will be fit for purpose….each with own risk assessment criteria
- We need to agree what is meant by "site characterisation", including when it concludes
- We need to have an agreed methodology for storage capacity assessment
- "Characterisation" is site specific, onshore/ offshore specific and storage type (saline fmn, coal etc) specific; it is therefore essential that we identify commonalities and don't just look for differences (lumpers versus splitters!)
- Easy to work out what we can do ("stamp collecting"); more difficult (and more essential?) to work out what we don't need to do- otherwise the task will overwhelm us!
- Geology is only one of the features that determines suitability of a site for CO_2 storage

CO2CRC

CO_2 Storage Risk Assessment Terminology:
Introduction and Presentation of work

Anna Korre, Sevket Durucan
Department of Earth Science and Engineering

Imperial College
London

Outline

- Objectives of this work
- Risk assessment and Performance Assessment
- Approach to the generic terminology
    - Data oriented terms
    - Action oriented terms
- Risk Assessment vs Risk Management
- Standards for Risk Assessment
- CO_2 Storage RA terminology – What happens next …

Objectives

The objective of this work has been is to develop and propose internationally harmonised generic and technical terms used in CO_2 storage hazard/risk assessment, which will help facilitate the mutual use and acceptance of the assessment of CO_2 storage projects between countries, saving resources for both governments and the industry.

Target groups of users of the harmonised terms are CO_2 storage and environment professionals and political actors at all levels. The harmonised terms may also be used as a basis for preparing other publications primarily aimed at public information and CO_2 storage education.

Objectives

It is not a goal to standardize risk assessments globally, as that is considered to be neither appropriate nor feasible.

Instead, harmonisation is thought of as an effort to strive for consistency among approaches and to enhance understanding of the various approaches to CO_2 storage risk assessment worldwide.

Thus, harmonisation is defined, in a step-wise fashion, as an understanding of the methods and practices used by various countries and organizations so as to develop confidence in, and acceptance of, assessments that use different approaches.

Types of Risk Assessment

Historically, risk assessment has been dominated by two parallel methodological developments:

public-health risk assessment, focus on the health effects of chronic exposures to chemicals, contaminants, and pollutants in the water, the air and the food.

engineered-systems risk assessment, focus on immediate and delayed effects due to the failure of systems, (e.g. aerospace vehicles, chemical process plants, and nuclear power plants).

More recently there has been heightened interest in other risks including

ecological risks (e.g. the degradation of ecological systems due to nonnative invasive species, global warming, and genetically modified organisms);

risks related to severe natural phenomena (e.g. hurricanes, earthquakes, fires, and floods); and

risks associated with malicious human acts (terrorism).

What does Risk Assessment involve?

Risk assessment, in both cases, involves a search for “causal links” or “causal chains” verified by “objective” analytic and experimental techniques.

public-health risk assessment

exposure and dose-response data

engineered-systems risk assessment

quantifying the behavior of various elements (e.g. pumps, valves, operators) in terms of failure-rate data

Each field has generated its own analytic methods and experimental protocols, with the common goal of quantifying overall system performance in terms of valued consequences.

US National Research Council, 2007

What is the Risk Assessment focus?

public-health risk assessment

What are the consequences in terms of exposure assessment and dose-response assessment?

Uses quantitative estimates of behaviours like ingestion and metabolism.

engineered-systems risk assessment

What can go wrong?

How likely is it to happen?

The analysis is typically organized around fault and event trees, delineating the impacts of initiating events and failure rates.

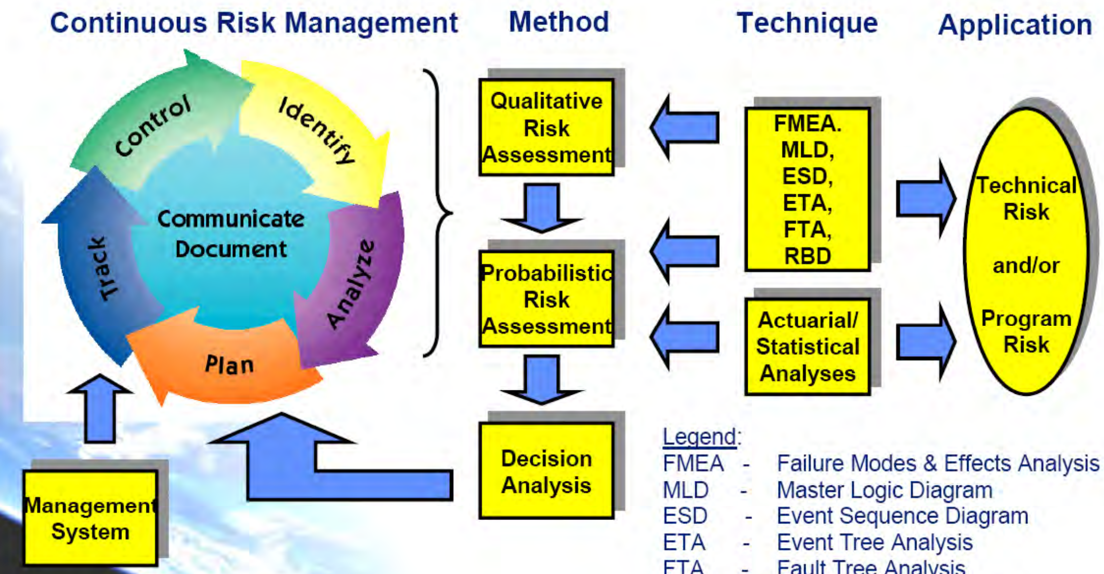
US National Research Council, 2007

Table of Synonymous terms in Risk Assessment

ILSI RSI MRA[1]	EPA ECOLOGICAL RA[2]	NAS NRC RA[3]	CODEX RA[4]	OIE IMPORT RA[5]
Problem Formulation A systematic planning step that identifies the goals, breadth, and focus of the pathogen risk assessment, the regulatory and policy context of the assessment, and the major factors that need to be addressed for the assessment.	**Problem Formulation** A process for evaluating the nature of the problem, refining objectives for the ecological risk assessment, and generating a plan for analyzing data and characterizing risk.	**Hazard Identification** Determination of whether a specified chemical causes a particular health effect. Four classes of information used in this step are epidemiological data, animal-bioassay data, data on in vitro effects, and comparison of molecular structure.	**Hazard Identification** The identification of biological, chemical, and physical agents capable of causing adverse health effects and which may be present in a particular food or group of foods.	**Hazard Identification** The process of identifying the biological agents that could potentially be introduced into the commodity considered for importation.
Analysis Phase Technical examination of data concerning potential pathogen exposure and associated human health effects. Elements of this process are:	**Analysis Phase** Examination of the two primary components of risk—exposure and effects—and the relationships between each other and ecosystem characteristics. Elements of this process are:			**Release Assessment** A description of the biological pathway(s) necessary for a risk source to introduce biological agents into a particular environment, and a qualitative or quantitative estimate of that complete process occurring.
Characterization of Exposure Evaluation of any interactions between the pathogen, the environment, and the human population. Steps include pathogen characterization, pathogen occurrence, and exposure analysis; the result is an exposure profile.	**Characterization of Exposure** Evaluation of the interaction of the stressor with one or more ecological entities, including measures of exposure, ecosystem and receptor characteristics, and exposure analysis. The objective is to produce an exposure profile.	**Exposure Assessment** Determination of the extent of human exposure before or after application of regulatory controls.	**Exposure Assessment** The qualitative and/or quantitative evaluation of the likely intake of biological, chemical, and physical agents via food as well as exposures from other sources if relevant.	**Exposure Assessment** A description of the biological pathway(s) necessary for exposure of animals and humans to the hazards released from a given risk source, including a qualitative or quantitative estimation of the probability of that exposure occurring.
Characterization of Human Health Effects Evaluation of the ability of a pathogen to cause adverse human health effects under a particular set of conditions. Steps include host characterization, evaluation of human health effects, and quantification of the dose-response relationship; the result is a host-pathogen profile.	**Characterization of Ecological Effects** Evaluation of the ability of the stressor to cause adverse effects under a particular set of conditions. Elements include measures of effects, ecosystem and receptor characteristics, and ecological response analysis; the result is a stressor-response profile.	**Dose-Response Assessment** Determination of the relationship between the magnitude of exposure and the probability of occurrence of the health effects in question. Methods include low-dose extrapolation and animal-to-human extrapolation.	**Hazard Characterization** The qualitative and/or quantitative evaluation of the nature of the adverse health effects associated with the hazard, including a dose-response assessment.	**Consequence Assessment** A description of the relationship between specified exposures to a biological agent and the consequences of those exposures.
Risk Characterization Estimation of the likelihood of adverse human health effects occurring as a result of a defined exposure to a microbial contaminant or medium.	**Risk Characterization** Integration of the exposure and stressor-response profiles to evaluate the likelihood of adverse ecological effects associated with exposure.	**Risk Characterization** Description of the nature and often the magnitude of human risk, including attendant uncertainty.	**Risk Characterization** The qualitative and/or quantitative estimation, including attendant uncertainties, of the probability of occurrence and severity of known or potential adverse health effects in a given population based on the above steps.	**Risk Estimation** A qualitative and/or quantitative summation of the previous steps to produce overall measures of the potential outcome from the health, environmental and economic risks, given the hazard identified at the outset.

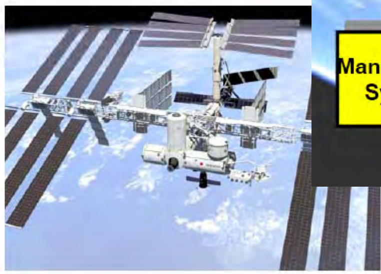
Risk Science Institute of the International Life Sciences Institute, 2000

Relationship Between Risk Management and Probabilistic Risk Assessment (PRA)



Legend:
FMEA - Failure Modes & Effects Analysis
MLD - Master Logic Diagram
ESD - Event Sequence Diagram
ETA - Event Tree Analysis
FTA - Fault Tree Analysis
RBD - Reliability Block Diagram

PRA Applications at NASA



- For Upgrades (Space Shuttle)
- For Development, construction and assembly (e.g., International Space Station)
- When there are requirements for Safety Compliance (e.g., nuclear missions like Mars '03; Project Prometheus, Mars Sample Return)
- In Design and Conceptual Design (e.g., Orbital Space Plane, Mars missions, Project Prometheus)

What is the Performance Assessment?

As defined by US DOE M 435.1-1, a performance assessment is

“An analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will not be exceeded following closure of the facility.”

In addition, DOE M 435.1-1 also states that the method used for the performance assessment must include uncertainty analyses. A method that addresses these requirements has been used for the Waste Isolation Pilot Plant (DOE, 1996), the Yucca Mountain Project (DOE, 1998), and the intermediate-depth Greater Confinement Disposal Boreholes (Cochran et al., 2001) to assess the long-term performance of nuclear waste repositories.

Performance Assessment of Monticello Mill Tailings Repository

Performance Assessment of Lakeview Mill Site

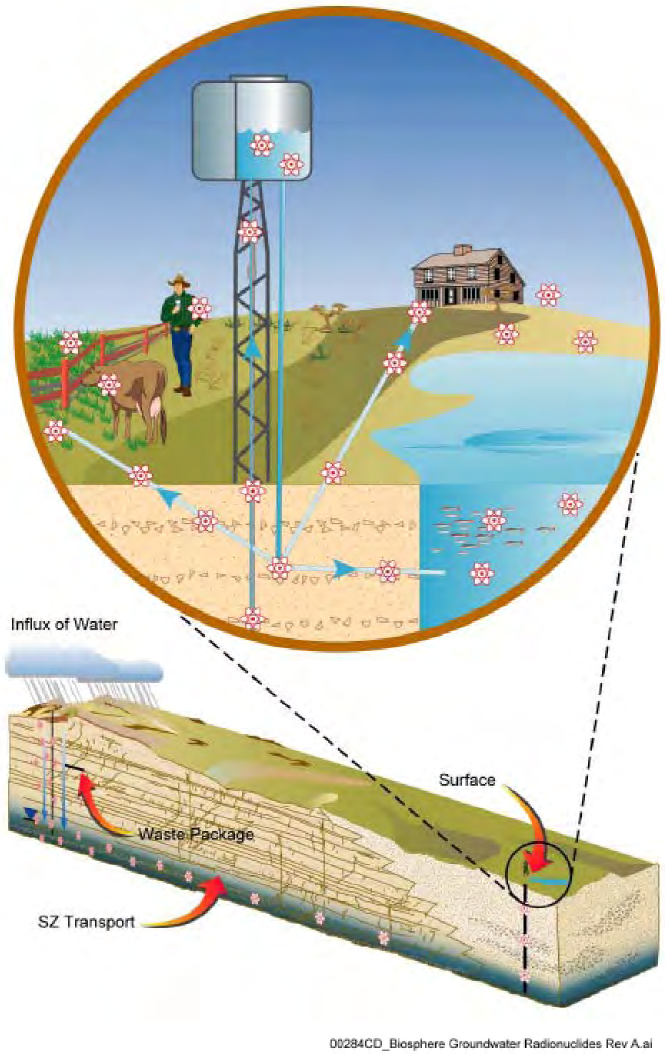
Performance Assessment of the Mixed Waste Landfill (2007)

What is the Performance Assessment?

Simulation of an environmental system that includes some man-made components (e.g., a waste disposal facility) in which one is attempting to predict the performance or the degree of safety or reliability of the system.

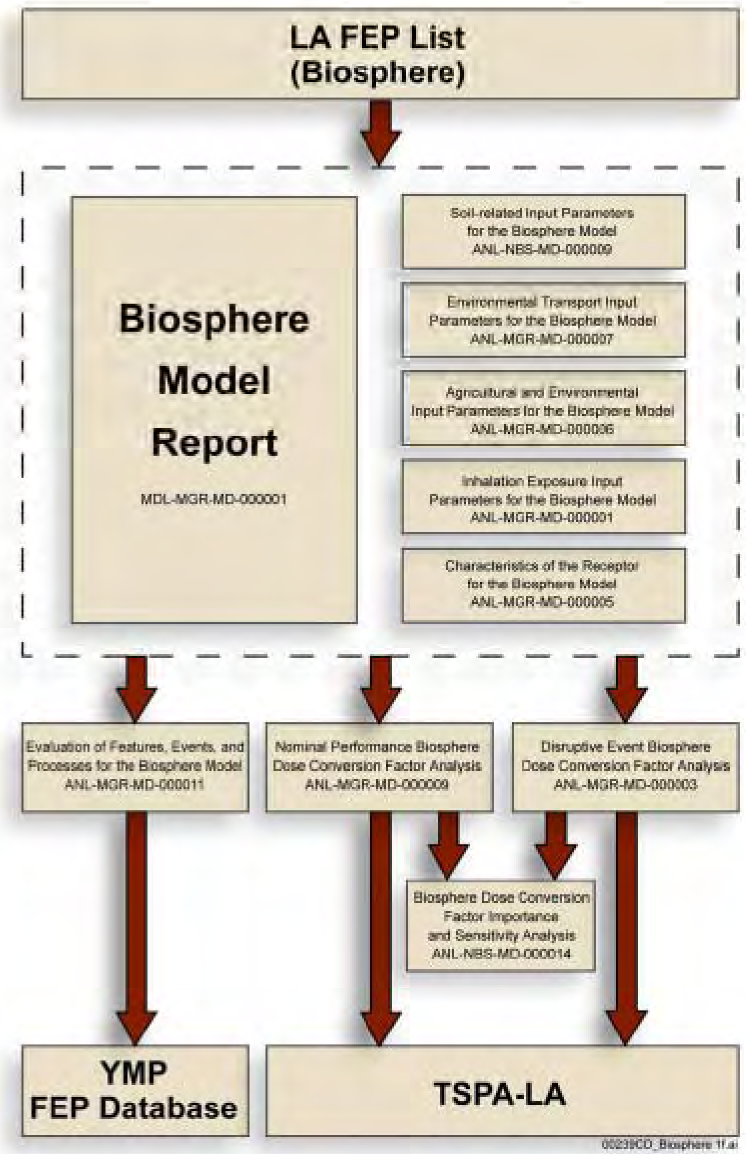
http://www.goldsim.com/Solutions/probPA.htm.

US DOE Yucca Mountain Repository Analysis and reports



NOTE: SZ = saturated zone.

Figure 6.3-1. Graphical Representation of the Biosphere System for the Groundwater Contamination

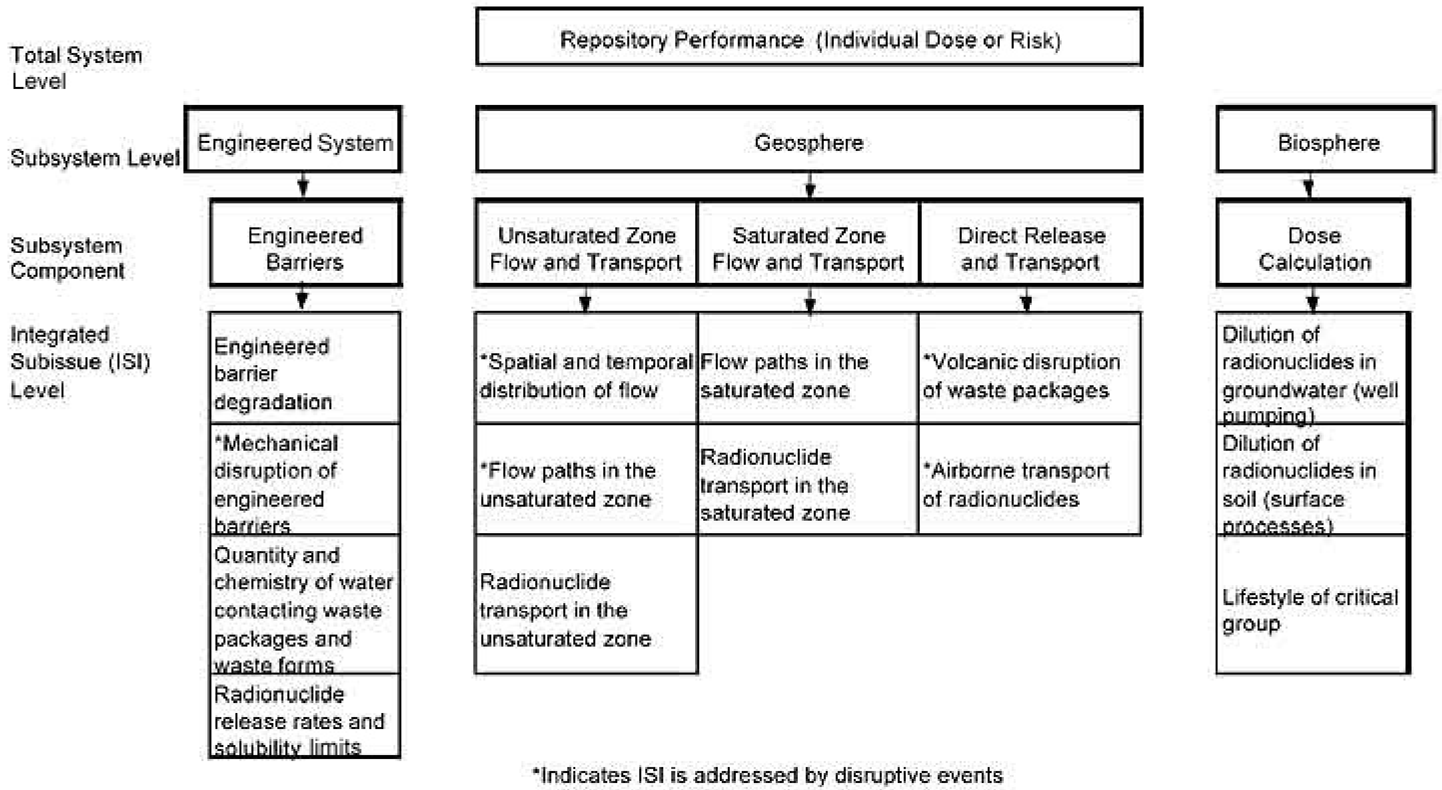


Overview of the Yucca mountain biosphere model documentation

Civilian Radioactive Waste Management System
Management & Operating Contractor
Disruptive Events Process Model Report

TDR-NBS-MD-000002 REV 00 ICN 01

July 2000



Source: NRC 2000, Figure 3

Figure 4-1. Hierarchical System for Reviewing Subissue 3, Model Abstraction

Prepared for: U.S. Department of Energy
Yucca Mountain Site Characterization Office

Which principal term should we use for CO_2 storage?

Risk Assessment

or

Performance Assessment

Risk Assessment vs. Risk Management

Regulatory actions are based on two distinct elements:

Risk assessment is the use of the factual base to define the health effects of exposure of individuals or populations to hazardous materials and situations.

Risk management is the process of weighing policy alternatives and selecting the most appropriate regulatory action, integrating the results of risk assessment with engineering data and with social, economic, and political concerns to reach a decision.

Both scientific judgments and policy choices may be involved in selecting from among possible inferential bridges. The term risk assessment policy is used to differentiate those judgments and choices from the broader social and economic policy issues that are inherent in risk management decisions.

NRC, 1983

Risk Assessment steps

Risk assessments contain some or all of the following four steps:

Hazard identification: The determination of whether a particular agent is or is not causally linked to particular adverse effects.

Dose-response assessment: The determination of the relationship between the magnitude of exposure and the probability of occurrence of the effects in question.

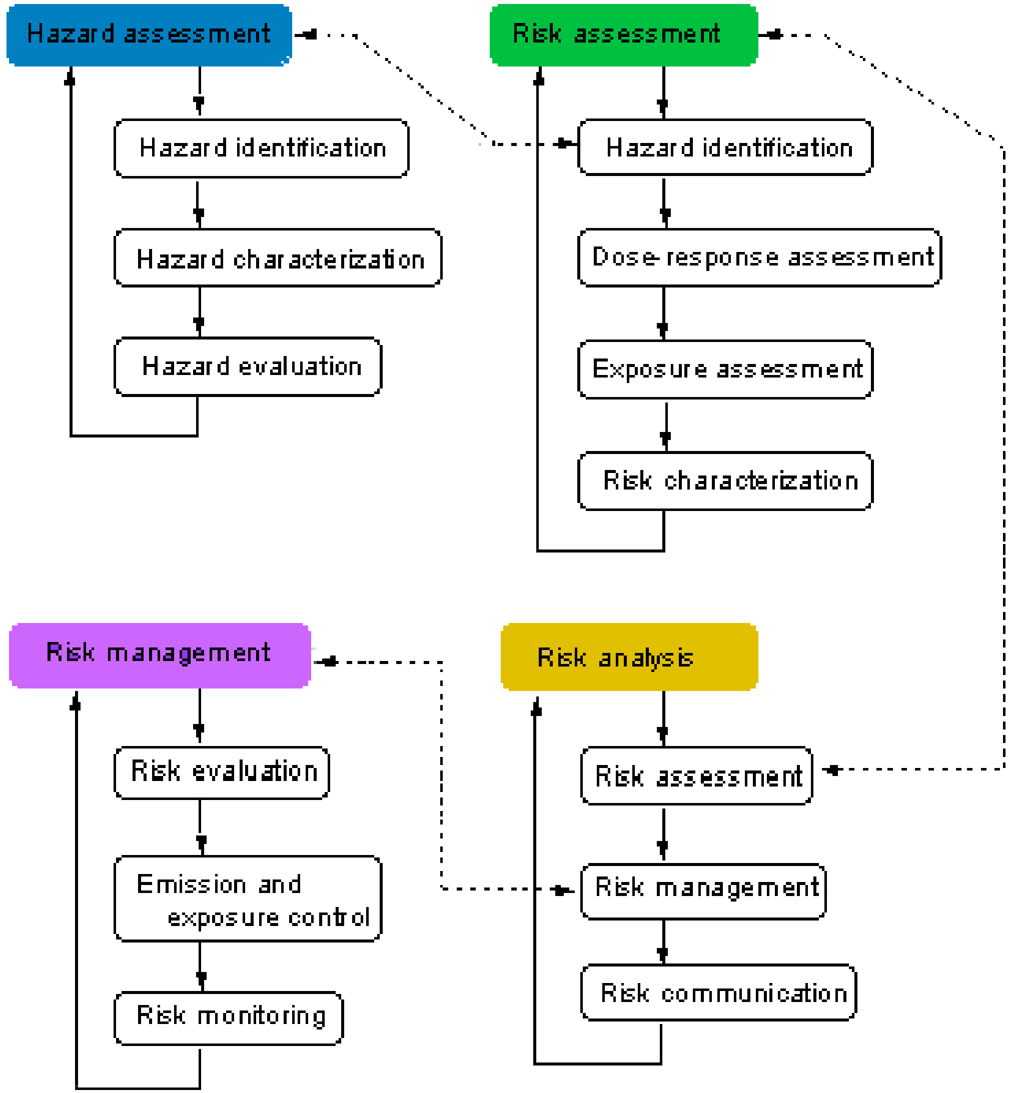
Exposure assessment: The determination of the extent of exposure before or after application of regulatory controls.

Risk characterization: The description of the nature and often the magnitude of risk, including attendant uncertainty.

NRC, 1983; IPCS/OECD, 2004

How do the Risk Assessment steps relate with Risk Management and Risk Communication

International Program on Chemical Safety/ Organization for Economic Cooperation and Development, 2004



Approach to the generic terminology

Consider each term in the appropriate conceptual environment.

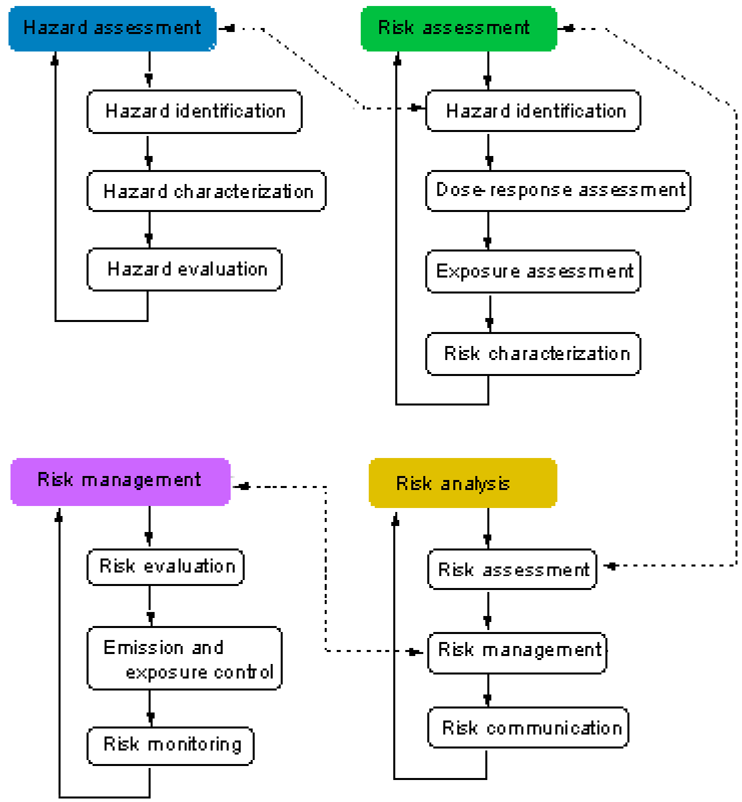
Defined as the base terms "data-oriented terms" and their combinations with action concepts "action-oriented terms".

1. Data-oriented terms

   "Risk" and "hazard" are the key data-oriented terms, and there are clusters of related terms around them.

2. Action-oriented terms

   These are terms used in conjunction with single-word terms, except for "assessment", which is defined in isolation also.



(IPCS/OECD, 2004)

Data oriented terms

Hazard; Agent, Stressor

vs

Risk

Hazard:

1. inherent property of an agent or situation capable of having adverse effects on something. Hence, the substance, agent, source of energy, or situation having that property (IPCS, 2004)
2. a condition or physical situation with a potential for an undesirable consequence (SRA, 2007)

Agent:

Any physical, chemical, or biological entity that can induce an adverse response (synonymous with stressor). (USEPA, 2007)

Data oriented terms

Hazard; Agent, Stressor

vs

Risk

Risk:

1. the probability of adverse effects caused under specified circumstances by an agent in an organism, a population, or an ecological system (IPCS, 2004)
2. The expected frequency or probability of undesirable effects resulting from exposure to known or expected stressors. (USEPA, 2007)
3. The potential for realization of unwanted, adverse consequences to human life, health, property, or the environment; estimation of risk is usually based on the expected value of the conditional probability of the event occurring times the consequence of the event given that it has occurred. (SRA, 2007)

Data oriented terms

Concentration vs Dose

Concentration:

1. Amount of a material or agent dissolved or contained in unit quantity in a given medium or system. (IPCS, 2004)

Dose:

1. Total amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population. (IPCS, 2004)
2. The amount of a contaminant that is absorbed or deposited in the body of an exposed organism for an increment of time--usually from a single medium. Total dose is the sum of doses received resulting from interaction with all environmental media that contain the contaminant. Units of dose and total dose (mass) are often converted to units of mass per volume of physiological fluid or mass of tissue. (NRC, 1994)

Data oriented terms

Concentration vs Dose

Dose:

3. The amount of a substance available for interactions with metabolic processes or biologically significant receptors after crossing the outer boundary of an organism. The POTENTIAL DOSE is the amount ingested, inhaled, or applied to the skin. The APPLIED DOSE is the amount presented to an absorption barrier and available for absorption (although not necessarily having yet crossed the outer boundary of the organism). The ABSORBED DOSE is the amount crossing a specific absorption barrier (e.g. the exchange boundaries of the skin, lung, and digestive tract) through uptake processes. INTERNAL DOSE denotes the amount absorbed without respect to specific absorption barriers or exchange boundaries. The amount of the chemical available for interaction by any particular organ or cell is termed the DELIVERED or BIOLOGICALLY EFFECTIVE DOSE for that organ or cell. (USEPA, 2007)

Data oriented terms

Effect

vs

Response

Effect:

1. Change in the state or dynamics of an organism, system, or (sub)population caused by the exposure to an agent. (IPCS, 2004)
2. A biological change caused by an exposure. (SRA, 2007)

Response:

1. Change developed in the state or dynamics of an organism, system, or (sub)population in reaction to exposure to an agent. (IPCS, 2004)
2. The proportion or absolute size of a population that demonstrates a specific effect. May also refer to the nature of the effect. (SRA, 2007)

Data oriented terms

Cluster of related terms

Adverse ecological effects :

1. Changes that are considered undesirable because they alter valued structural or functional characteristics of ecosystems or their components. An evaluation of adversity may consider the type, intensity, and scale of the effect as well as the potential for recovery. (USEPA, 2007)

Adverse Effect (of an organism):

1. Change in the morphology, physiology, growth, development, reproduction, or life span of an organism, system, or (sub)population that results in an impairment of functional capacity, an impairment of the capacity to compensate for additional stress, or an increase in susceptibility to other influences. (IPCS, 2004)
2. A biochemical change, functional impairment, or pathologic lesion that affects the performance of the whole organism, or reduces an organism's ability to respond to an additional environmental challenge. (USEPA, 2007)

Data oriented terms

Source :

1. An entity or action that releases to the environment or imposes on the environment a chemical, physical, or biological stressor or stressors. (USEPA, 2007)

Source term :

1. The release rate of hazardous agent from a facility or activity. (SRA, 2007)
2. As applied to chemical stressors, the type, magnitude, and patterns of chemical(s) released. (USEPA, 2007)

Data oriented terms

Release :

1. A "release" is defined by CERCLA as "any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment (including the abandonment or discarding of barrels, containers and other closed receptacles containing any hazardous substance or pollutant or contaminant". (USEPA, 2007)

Release rate :

1. The quantity of a pollutant released from a source over a specified period of time. (SRA, 2007)

Data oriented terms

Bias:

1. Systematic deviation between a measured (observed) or computed value and its “true” value. Bias is affected by faulty instrument calibration and other measurement errors, systematic errors during data collection, and sampling errors, such as incomplete spatial randomization during the design of sampling programs. (NRC, 2007)
2. Any difference between the true value and that actually obtained due to all causes other than sampling variability. (SRA, 2007)

Data oriented terms

Uncertainty :

1. Imperfect knowledge concerning the present or future state of the system under consideration; a component of risk resulting from imperfect knowledge of the degree of hazard or of its spatial and temporal distribution. (USEPA, 2007)
2. Imperfect knowledge concerning the present or future state of an organism, system, or (sub)population under consideration. (IPCS, 2004)

Variability :

1. Observed differences attributable to true heterogeneity or diversity and the result of natural random processes—usually not reducible by further measurement or study (although it can be better characterized). (NRC, 2007)

Data oriented terms

Cluster of related terms

Concentration – Effect relationship:

1. Relationship between the exposure, expressed in concentration, of a given organism, system, or (sub)population to an agent in a specific pattern during a given time and the magnitude of a continuously graded effect to that organism, system, or (sub)population. (IPCS, 2004)

Concentration – Response Curve:

1. A curve describing the relationship between exposure concentration and percent of the test population responding. (USEPA, 2007)

Data oriented terms

Cluster of related terms

Dose – Response relationship:

1. The relationship between a quantified exposure (or dose) and a quantified effect. (NRC, 2007)
2. The relationship between the amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population and the change developed in that organism, system, or (sub)population in reaction to the agent. (IPCS, 2004)
3. The relationship between a quantified exposure (dose) and the proportion of subjects demonstrating specific biologically significant changes in incidence and/or in degree of change (response). (USEPA, 2007)

Dose – Response Curve

1. A graphical presentation of the relationship between degree of exposure to a substance (dose) and observed biological effect or response. (NRC, 1994).

Data oriented terms

Cluster of related terms

Dose-related effect:

1. Any effect to an organism, system, or (sub)population as a result of the quantity of an agent administered to, taken up by, or absorbed by that organism, system, or (sub)population. (IPCS, 2004)

Dose – effect:

1. Relationship between the total amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population and the magnitude of a continuously graded effect to that organism, system, or (sub)population. (IPCS, 2004)
2. The relationship between dose (usually an estimate of dose) and the gradation of the effect in a population, that is a biological change measured on a graded scale of severity, although at other times one may only be able to describe a qualitative effect that occurs within some range of exposure levels. (SRA, 2007)

Data oriented terms

Threshold:

1. A pollutant concentration [or dose] below which no deleterious effect occurs. (SRA, 2007)
2. The dose or exposure concentration of an agent below which a stated effect is not observed or expected to occur. (IPCS, 2004; USEPA, 2007)

Threshold dose :

1. The minimum application of a given substance required to produce an observable effect. (SRA, 2007)

Data oriented terms

Chronic Effect:

1. An effect that occurs as a result of repeated or long term (chronic) exposures. (USEPA, 2007)

Chronic Exposure :

1. Long-term exposure usually lasting 1 year to a lifetime. (NRC, 2007)
2. Repeated exposure by the oral, dermal, or inhalation route for more than approximately 10% of the life span in humans (more than approximately 90 days to 2 years in typically used laboratory animal species). (USEPA, 2007)

Data oriented terms

Acute toxicity:

1. Any poisonous effect produced within a short period of time following exposure, usually up to 24-96 hours, resulting in biological harm and often death. (SRA, 2007)
2. Any poisonous effect produced within a short period of time following an exposure, usually 24 to 96 hours. (USEPA, 2007)

Acute inhalation toxicity :

1. The adverse effect caused by a substance following a single uninterrupted exposure by inhalation over a short period of time (24 hours or less) to a substance capable of being inhaled. (USEPA, 2007)

Data oriented terms

Endpoint :

1. An observable or measurable biological event or chemical concentration (e.g., metabolite concentration in a target tissue) used as an index of an effect of exposure. (USEPA, 2007)

Data oriented terms

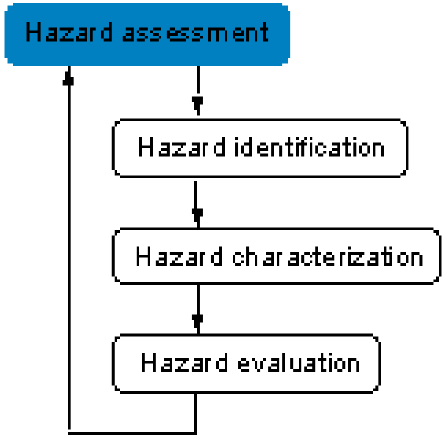
de minimis contamination limit :

1. A level of contamination below which the effects are not considered by regulators to warrant regulatory control. (NRC, 1994)

de minimis risk :

1. From the legal maxim "de minimis non curat lex" or "the law is not concerned with trifles." (SRA, 2007)

Action oriented terms



Hazard assessment :

An analysis and evaluation of the physical, chemical and biological properties of the hazard. (SRA, 2007)

Hazard Identification :

The process of determining whether exposure to a stressor can cause an increase in the incidence or severity of a particular adverse effect, and whether an adverse effect is likely to occur. (USEPA, 2007)

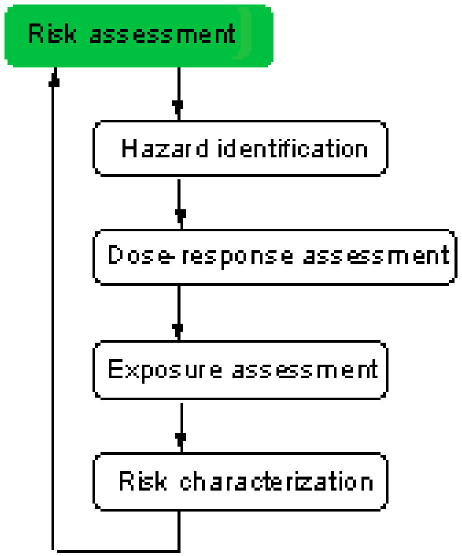
Hazard characterization :

The qualitative and, wherever possible, quantitative description of the inherent property of an agent or situation having the potential to cause adverse effects. This should, where possible, include a dose–response assessment and its attendant uncertainties. (IPCS, 2004)

Hazard evaluation :

The determination of the qualitative and quantitative relationship between exposure to a hazard under certain conditions, including attendant uncertainties and the resultant adverse effect. (IPCS, 2004)

Action oriented terms



Risk assessment :

An analysis and evaluation of the physical, chemical and biological properties of the hazard. (SRA, 2007)

Dose–response assessment :

Analysis of the relationship between the total amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population and the changes developed in that organism, system, or (sub)population in reaction to that agent, and inferences derived from such an analysis with respect to the entire population. (IPCS, 2004)

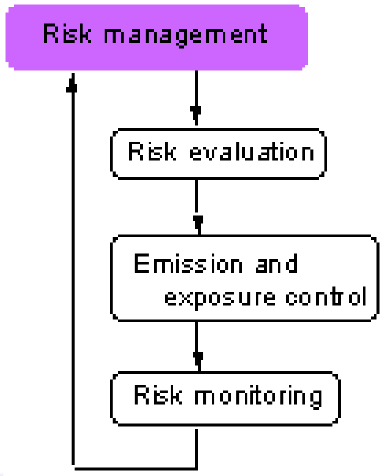
Exposure Assessment :

The process of characterizing the magnitude, frequency, and duration of exposure to an agent, along with the number and characteristics of the population exposed. Ideally, it describes the sources, pathways, routes, and uncertainties in the assessment. (NRC, 2007)

Risk characterization :

The qualitative and, wherever possible, quantitative determination, including attendant uncertainties, of the probability of occurrence of known and potential adverse effects of an agent in a given organism, system, or (sub)population, under defined exposure conditions. (IPCS, 2004)

Action oriented terms



Risk management :

Decision-making process involving considerations of political, social, economic, and technical factors with relevant risk assessment information relating to a hazard so as to develop, analyse, and compare regulatory and non-regulatory options and to select and implement appropriate regulatory response to that hazard. (IPCS, 2004)

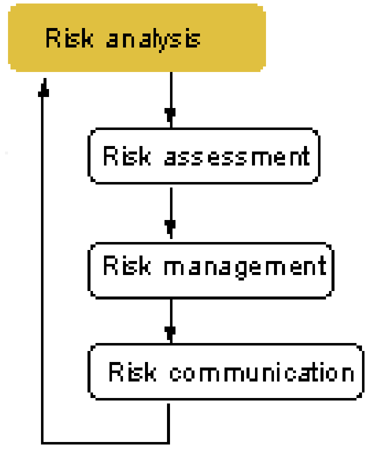
Risk evaluation :

Establishment of a qualitative or quantitative relationship between risks and benefits of exposure to an agent, involving the complex process of determining the significance of the identified hazards and estimated risks to the system concerned or affected by the exposure, as well as the significance of the benefits brought about by the agent. (IPCS, 2004)

Risk monitoring :

Process of following up the decisions and actions within risk management in order to ascertain that risk containment or reduction with respect to a particular hazard is assured. (IPCS, 2004)

Action oriented terms



Risk analysis :

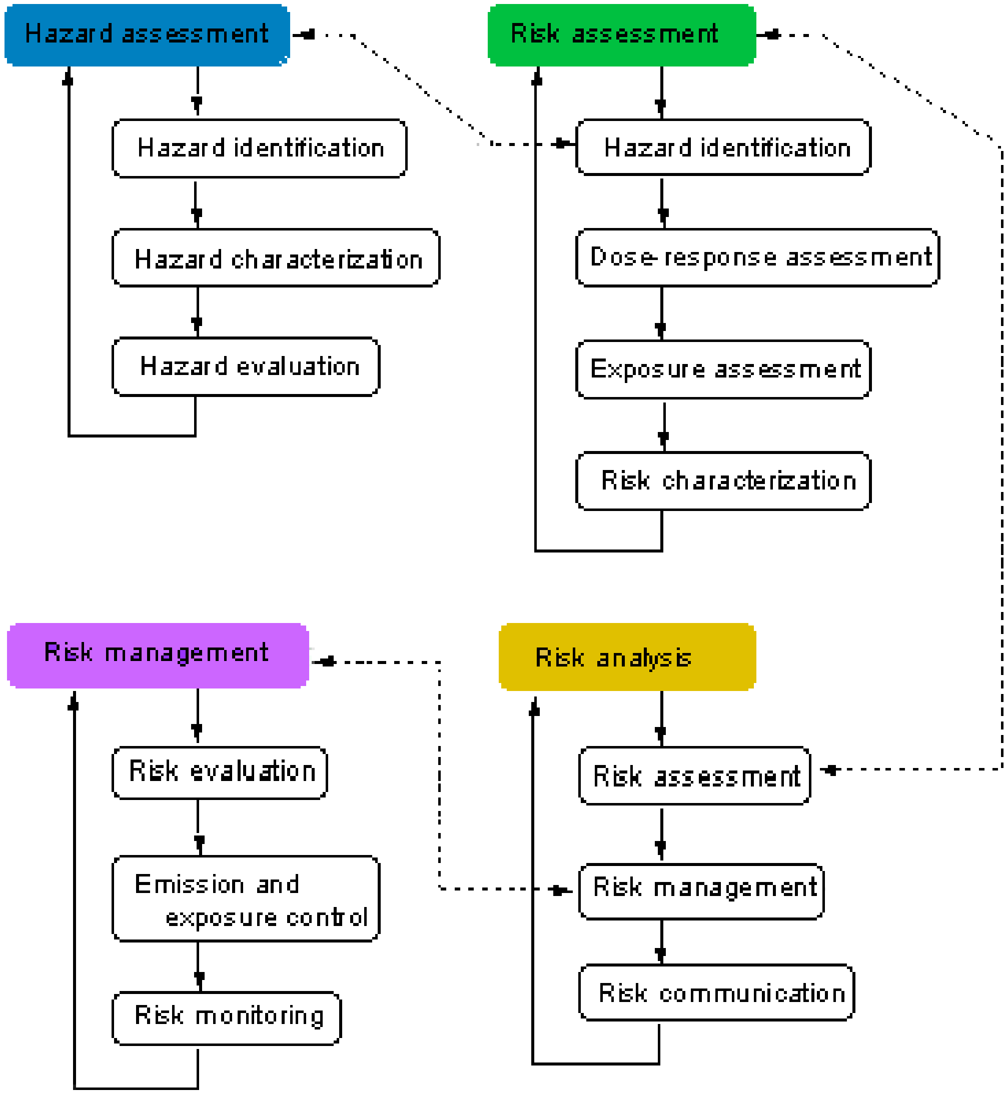
A detailed examination including risk assessment, risk evaluation, and risk management alternatives, performed to understand the nature of unwanted, negative consequences to human life, health, property, or the environment; an analytical process to provide information regarding undesirable events; the process of quantification of the probabilities and expected consequences for identified risks. (SRA, 2007)

Risk communication :

interactive exchange of information about risks among risk assessors, managers, news media, interested groups, and the general public. (IPCS, 2004)

How do the Risk Assessment steps relate with Risk Management and Risk Communication

International Program on Chemical Safety/ Organization for Economic Cooperation and Development, 2004



Standards for Risk Assessment ?

The US Office of Management and Budget (OMB), in consultation with the Office of Science and Technology Policy (OSTP), proposed to issue new technical guidance FOR PEER REVIEW AND PUBLIC COMMENT on risk assessments produced by the US federal government in January 2006.

The General Risk Assessment and Reporting Standards proposed, included:

1. Standards Relating to Informational Needs and Objectives
2. Standards Relating to Scope
3. Standards Related to Characterization of Risk
4. Standards related to Objectivity
5. Standards Related to Critical Assumptions
6. Standards Related to the Executive Summary
7. Standards Related to Regulatory Analysis

Standards for Risk Assessment ?

The US Office of Management and Budget (OMB), in consultation with the Office of Science and Technology Policy (OSTP), proposed to issue new technical guidance FOR PEER REVIEW AND PUBLIC COMMENT on risk assessments produced by the US federal government on 9 January 2006.

In addition Special Standards for Influential Risk Assessment proposed, included:

1. Standard for Reproducibility
2. Standard for Comparison to other Results
3. Standards for Presentation of Numerical Estimates
4. Standard for Characterizing Uncertainty
5. Standard for Characterizing Results
6. Standard for Characterizing Variability
7. Standard for Characterizing Human Health Effects
8. Standard for Discussing Scientific Limitations
9. Standard for Addressing Significant Comments

26 page document

Standards for Risk Assessment ?

The US Office
Technology P
PUBLIC COM

Scientific Review of the Proposed Risk Assessment Bulletin from the Office of Management and Budget

Committee to Review the OMB Risk Assessment Bulletin, National Research Council

ISBN: 0-309-66876-X, 302 pages, 6 x 9, (2007)

;cience and
:VIEW AND
ı 9 January 2006.

COMMITTEE'S CONCLUSIONS AND RECOMMENDATIONS

On the basis of its review, the committee concludes that the OMB bulletin is fundamentally flawed and recommends that it be withdrawn.

Although the committee fully supports the goal of increasing the quality and objectivity of risk assessment in the federal government, it agrees unanimously that the OMB bulletin would not facilitate reaching this goal.

What went wrong ?

1. Definition of Risk Assessment that conflicts with long-term established concepts and practices.
2. Goals: indicate that a risk assessment should be tailored to the specific need for which it is undertaken; balanced in scope, time and cost with the importance of the issue; and peer reviewed and released for public comment.

Emphasis on efficiency

Thus not entirely support technical quality and objectivity

3. Standards for Influential Risk Assessments vs General Risk Assessments: the structure was found problematic and many standards unclear or flawed.

It is not possible to know at the outset whether an analysis will constitute an influential risk assessment

4. Characterization of uncertainty and variability is oversimplified.
5. The definition of adverse effects implies an apparent effect and ignores the scientific reality that adverse effects may manifest along a continuum.

Standards for Risk Assessment ?

Scientific Review of the Proposed Risk Assessment Bulletin from the Office of Management and Budget
Committee to Review the OMB Risk Assessment Bulletin, National Research Council
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COMMITTEE’S CONCLUSIONS AND RECOMMENDATIONS

- Risk assessment is not a monolithic process or a single method.
- Different technical issues arise in assessing the probability of exposure to a given dose of a chemical, of a malfunction of a nuclear power plant or air-traffic control system, or of the collapse of an ecosystem or a dam.
- Any guidance on risk assessment should provide a definitions which are compatible with previous NRC documents and guidelines of other expert organizations; preserves the clear conventional distinctions between risk assessment and risk management.
- The committee strongly recommends that discussion of uncertainty and variability, presentation of risk results, definition of adversity, and other similar topics be reserved for the technical guidance to be developed by the agencies.

CO_2 storage RA terminology development: What happens next …

Generic terms :

1. The definitions for the higher-priority generic terms extracted from the "key documents and sources" will be circulated widely (e.g., through IEA GHG RA network, the research community and industry) for review and comments. Respondents will be asked to:
   - identify or provide their preferred definition for each term
   - identify terms considered as synonyms
   - indicate whether any important key documents or sources were omitted.

CO_2 storage RA terminology development: What happens next …

Specific terms :

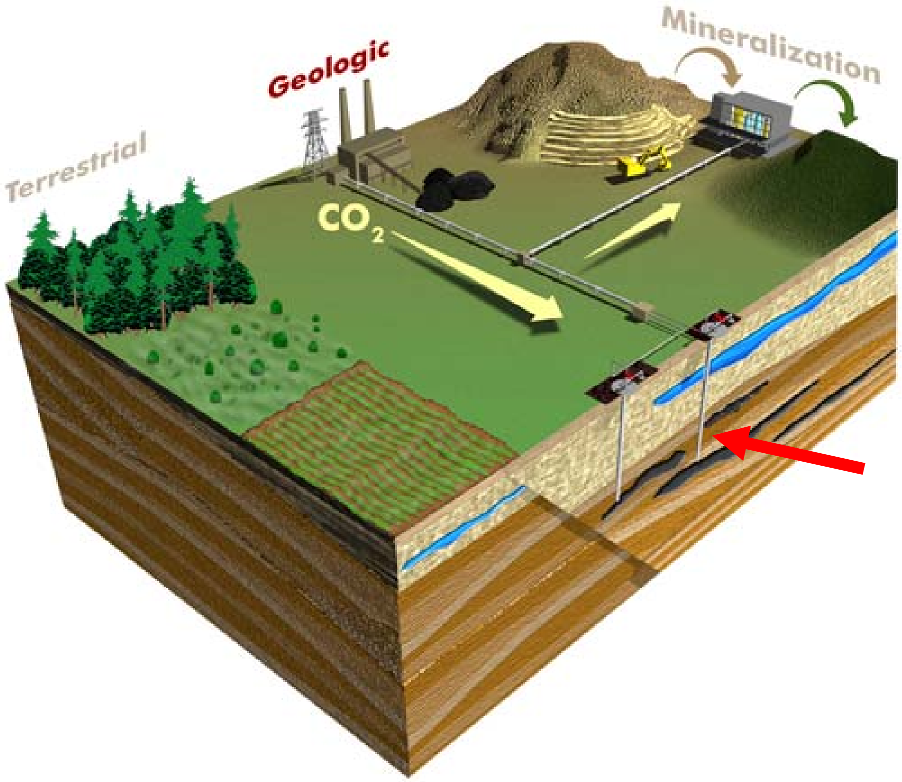
Technical terms are defined as those terms used in reservoir performance, human health and environmental hazard and risk assessment, including scientific–technical terms used in effects assessment (e.g., nomenclature for storage site features and technical terms used in hazard characterization, such as cap rock failure and effects on the biosphere).

These terms are based on the review of the literature on CO_2 storage monitoring, performance and risk assessment for projects and field laboratories worldwide.

These will be circulated for review in the same way as the generic terms.

Looking forward to your comments and recommendations ….

EOR Experience and a Science-Based Treatment of Wellbore Integrity in a CO_2 Storage System



Sample Recovery; Field History

- Pete Hagist, Scott Wehner (Whiting)
- Mike Raines (PetroSource)
- Mike Hirl (KinderMorgan CO_2)

Cement Integrity

- Bill Carey, Peter Lichtner, Marcus Wigand, Steve Chipera, Giday WoldeGabriel
- Bob Svec (NMT)
- Brian Strazizar, Barbara Kutchko (NETL), Niels Thaulow

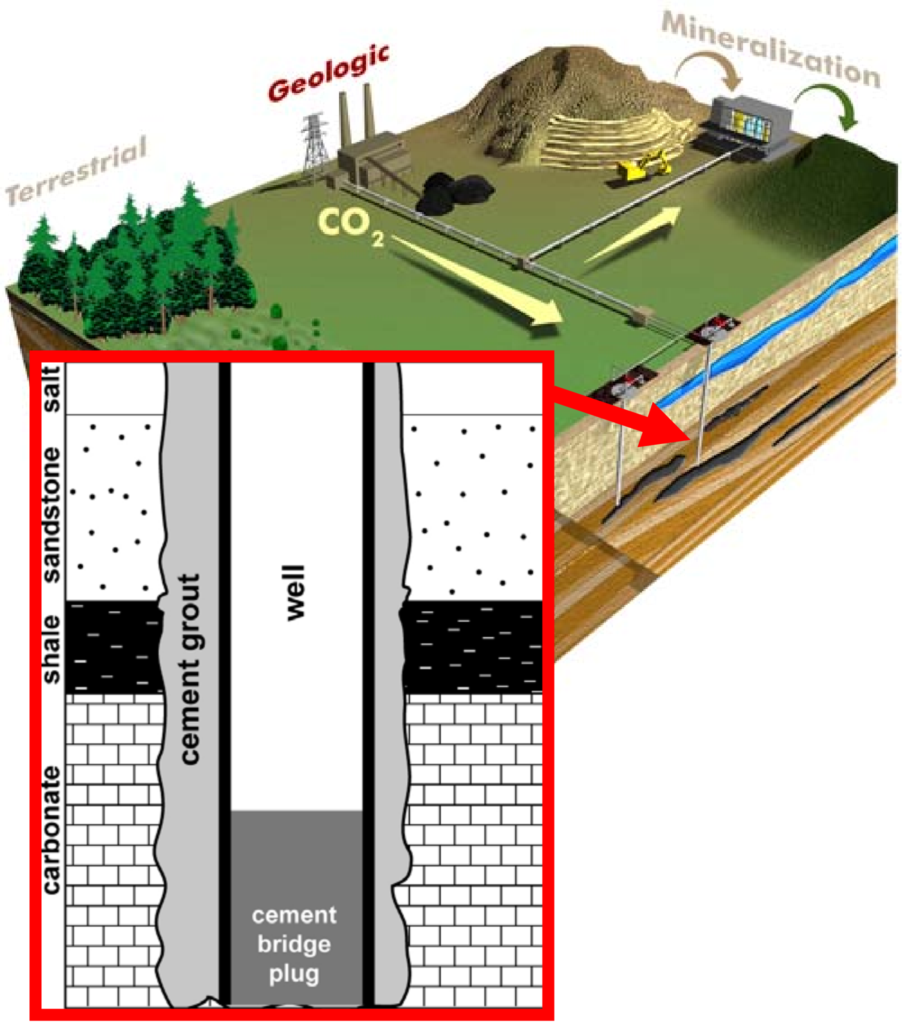
Science-Based System Modeling

- Rajesh Pawar, Phil Stauffer, Hari Viswanathan, Seth Olsen, John Kaszuba, Gordon Keating, Tom McTighe, Richard Middleton
- Dmitri Kavetski, Mike Celia (Princeton)
- [Stefan Bachu, AEUB]
- [Grant Bromhal, Anthony Cugini (NETL)]
- [Howard Herzog (MIT)]

George Guthrie

Program Director
Fossil Energy and Environment
Los Alamos National Laboratory

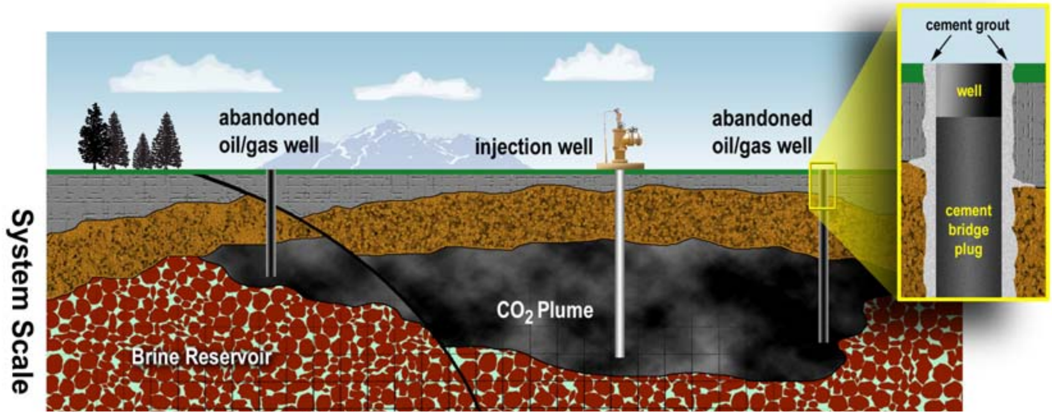
Wellbore integrity is important in long-term CO_2 storage.



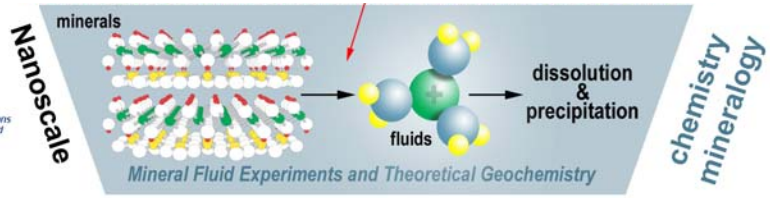
- Wellbores are typically completed & plugged with portland-based cement
  - hydrated portland cements contain calcium hydroxide (a base) and other acid sensitive materials
  - CO_2 + water => carbonic acid
  - batch experiments suggest rapid degradation of cement by carbonic acid
- Integrity of cement has important implications for long-term fate of CO_2
  - potential release pathway?
- Must scale fundamental physics and chemistry to system level
  - must know brine-CO_2-cement interaction mechanisms, including impact on permeability
- EOR sites provide direct information on cement integrity in the field
  - samples allow development and validation of our predictions

Upscaling from molecular processes to system behavior is grand challenge for predicting long-term fate of CO_2.

Predicting and Engineering Natural Systems

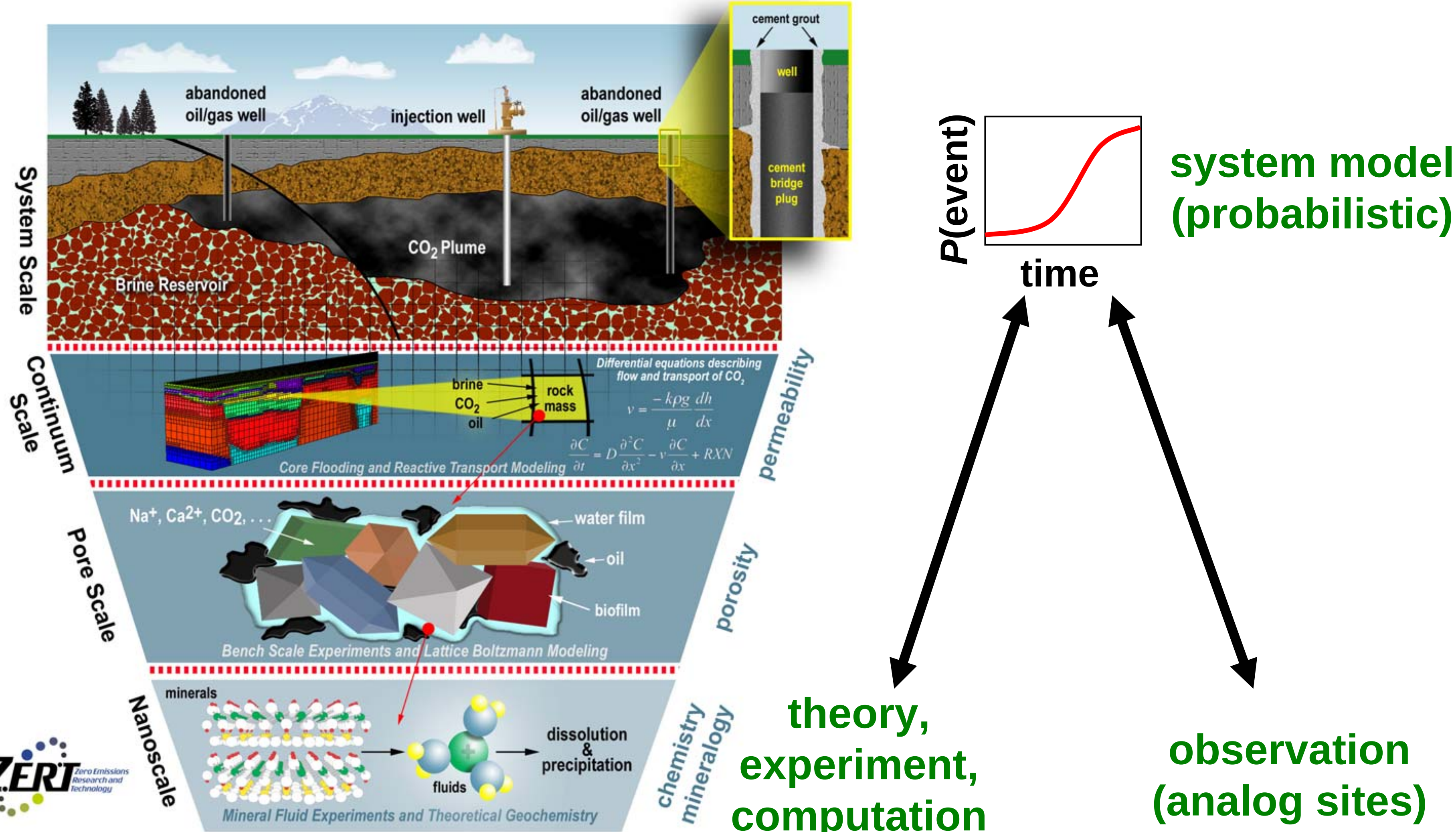


?

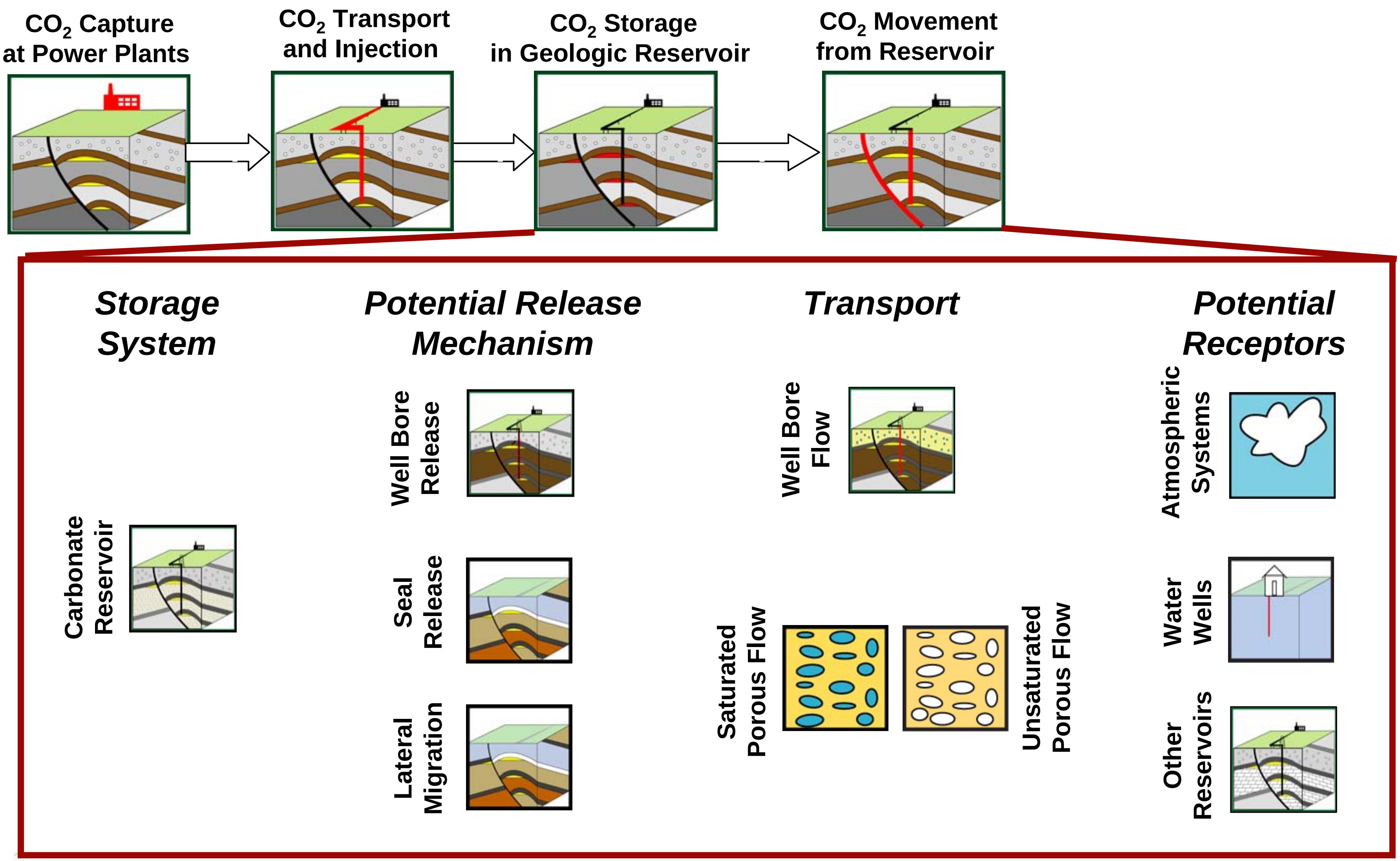


- Site specific complexity, heterogeneity, & uncertainty
- Poorly defined phenomena (e.g., hydrogeochemical processes)
- Wide range in length scale (nanoscale processes control reservoir-scale behavior)
- Wide range in time scale (days to millennia)

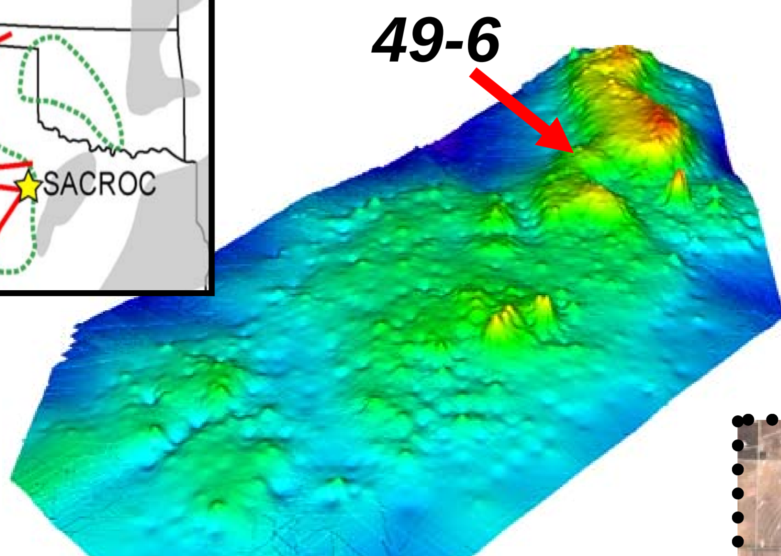
Science based prediction of natural system performance requires system-level probabilities based on process level phenomena.

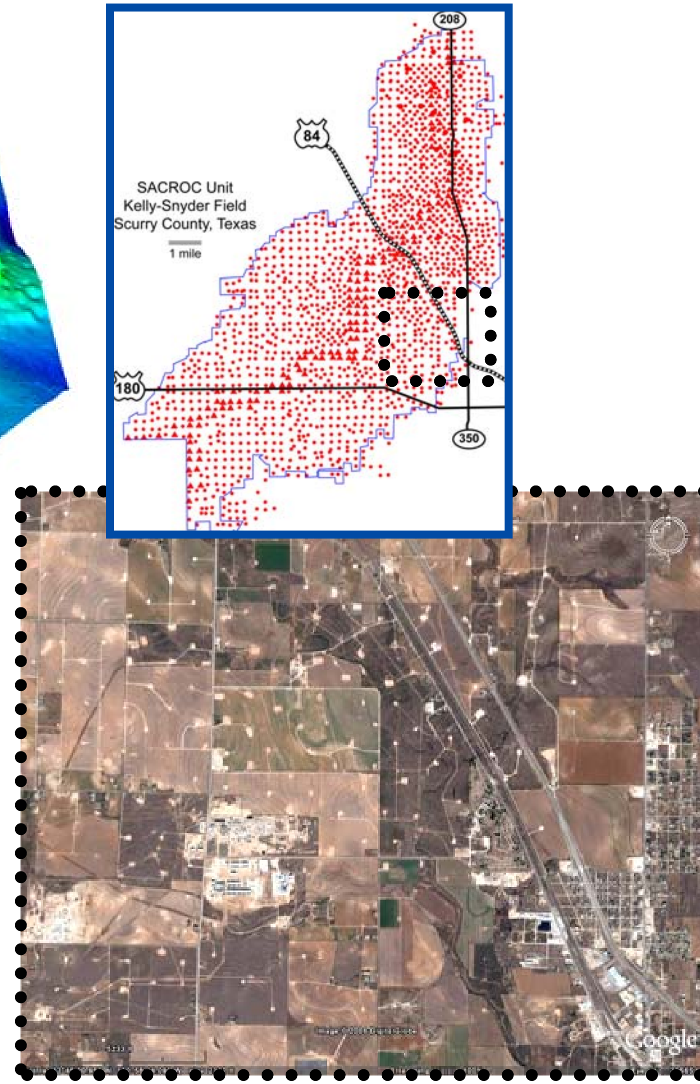


Initial version of CO_2-PENS system model has several modules associated with wellbore release.



CO_2-EOR operations routinely utilize wellbore technology to place (and to contain) fluids within the reservoir.





SACROC is one of several industrial-scale examples in the Permian Basin

- **~13.5 million tonnes of CO_2/yr injected**
- **(~6-7 million t/yr of new CO_2)**
- **~ 70 million tonnes CO_2 accumulated (>30 million tonnes anthropogenic)**
- **CO_2 injection since 1972**

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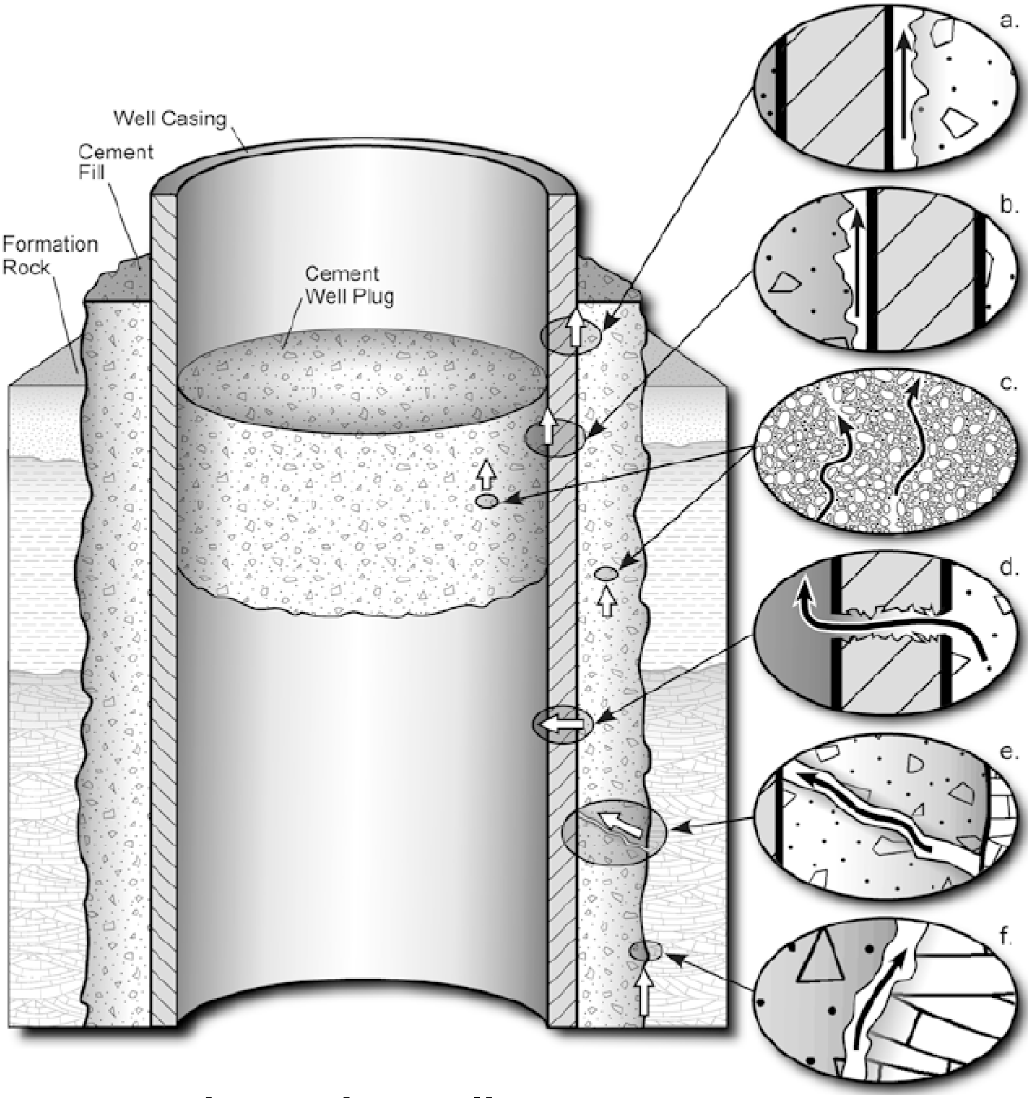
Carey et al., 2007

Several processes have the potential to contribute to CO_2 release from wellbores.



0. dissolution/corrosion of cement

1. flow between cement & casing
(Gasda et al. mechanisms A & B)

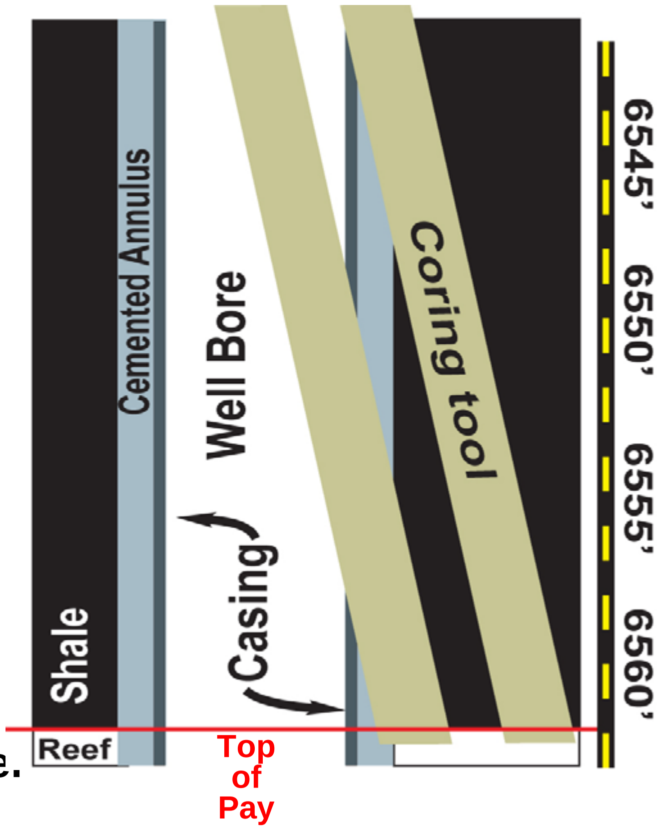
2a. diffusion through cement
(Gasda et al. mechanism C)

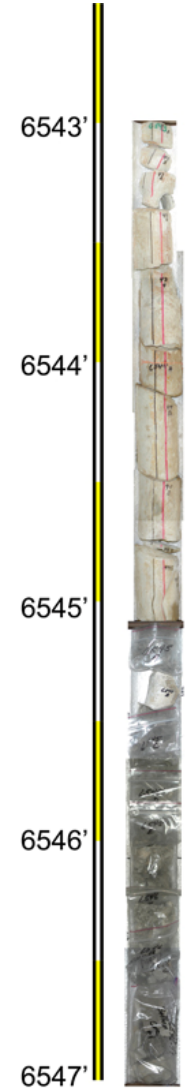
2b. fracture flow through cement
(Gasda et al. mechanism E)

3. flow between cement & shale
(Gasda et al. mechanism F)

Gasda, Bachu, Celia, 2004
Princeton CMI

Whipstock drilling at SACROC 49-6 provided recovery of core through cemented annulus to within 12' of top of pay.





- Drilled/completed 1950
- Water flood initiated 1954
- First direct CO_2 exposure 1975
  - 10 yrs as injector; 7 yrs as producer

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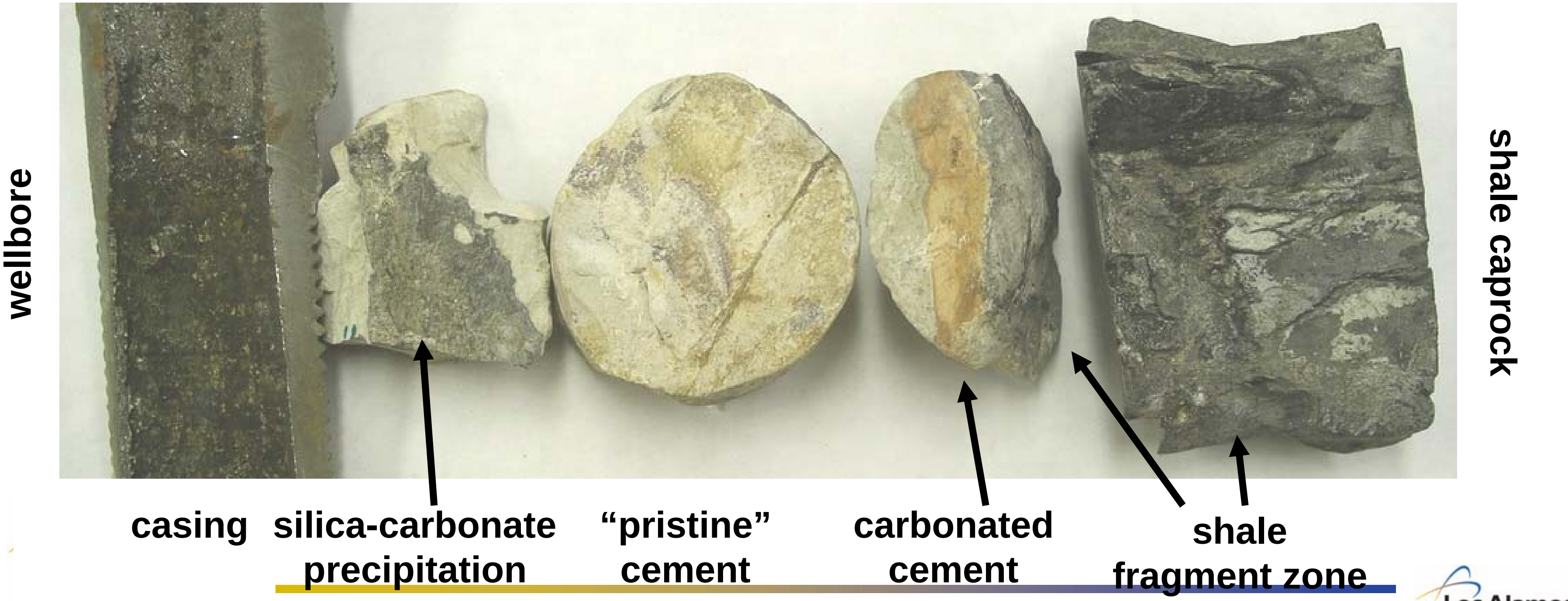
LA-UR-06-5429

Carey et al., 2005, *SPE*; Guthrie et al., 2005, Midland CO_2 Conf.

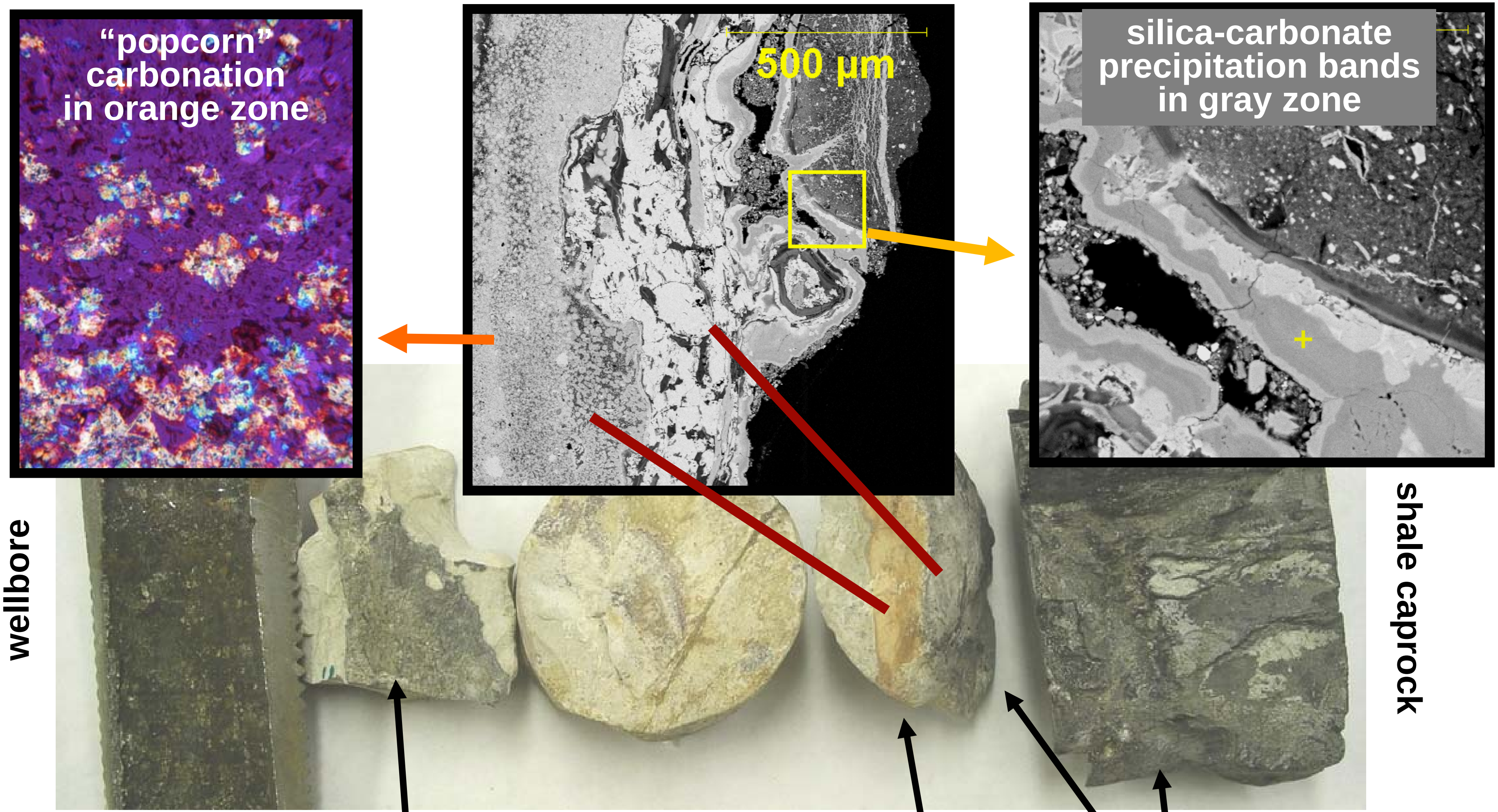
Core recovery spans from casing through pristine cement, through an altered zone, and finally into shale caprock.



LA-UR-06-5429

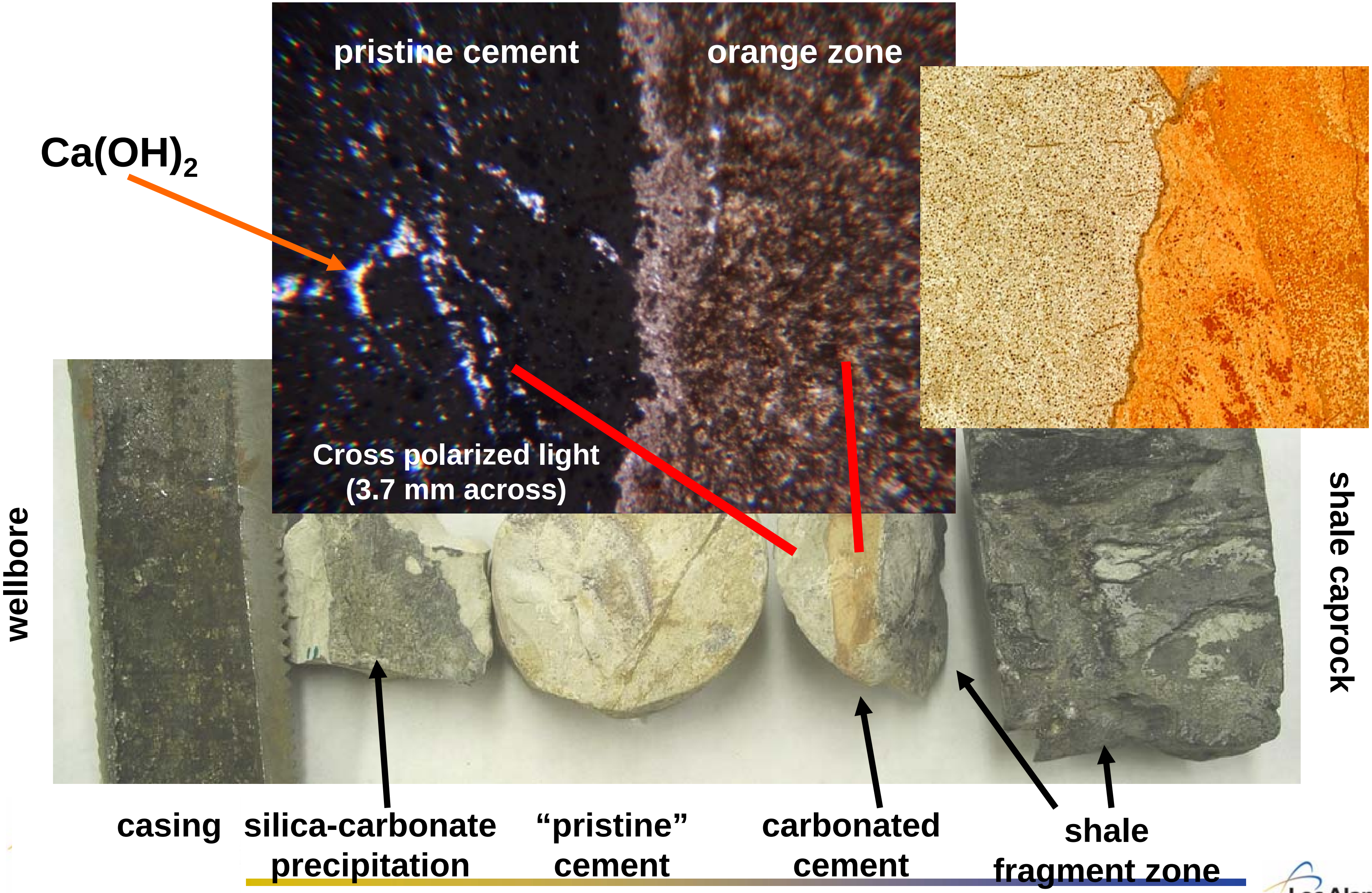
Carey et al., 2007, IJGGC; Guthrie et al., 2005, Midland CO_2 Conf.

Altered zone shows evidence of cement carbonation (via diffusion) and silica-carbonate precipitation (from fluid).



(Kutchko, Thaulow, and Strazizar, pers. comm.)

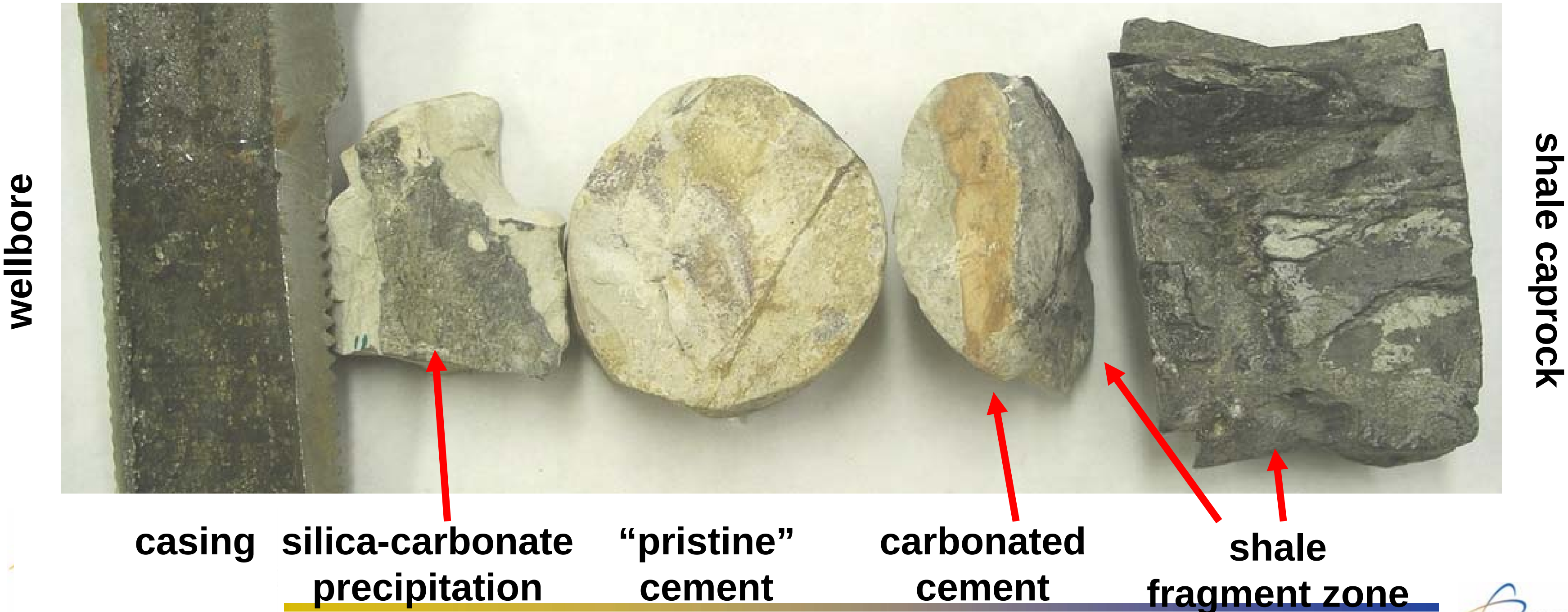
Unaltered cement zone still contains veins of portlandite, indicating no exposure to CO_2 bearing fluids.



Kutchko, Thaulow, and Strazizar, pers. comm.)

Cement sample from SACROC 49-6 (6550' near top of pay) was exposed to CO_2 for ~ 30 years (~110,000 tonnes).

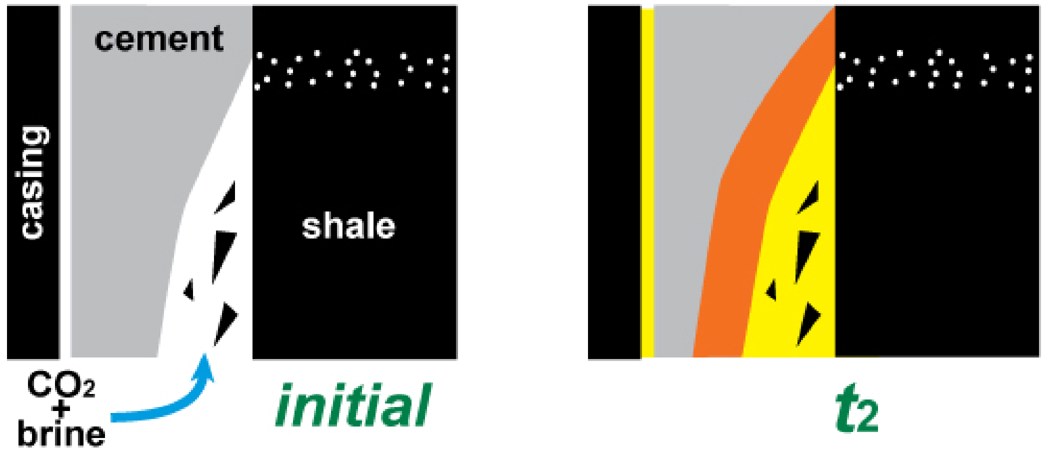
- "pristine" hydrated cement, containing portlandite ($Ca(OH)_2$) both in matrix and in veins➔precludes complete dissolution & Gasda et al. mechanisms C&E
- thin carbonated zone between cement and casing (Gasda et al. mechanism A)
- orange carbonated cement ("popcorn" texture) (Gasda et al. mechanism F)
- gray carbonated vein➔fluid flow followed by precipitation of silica/carbonate

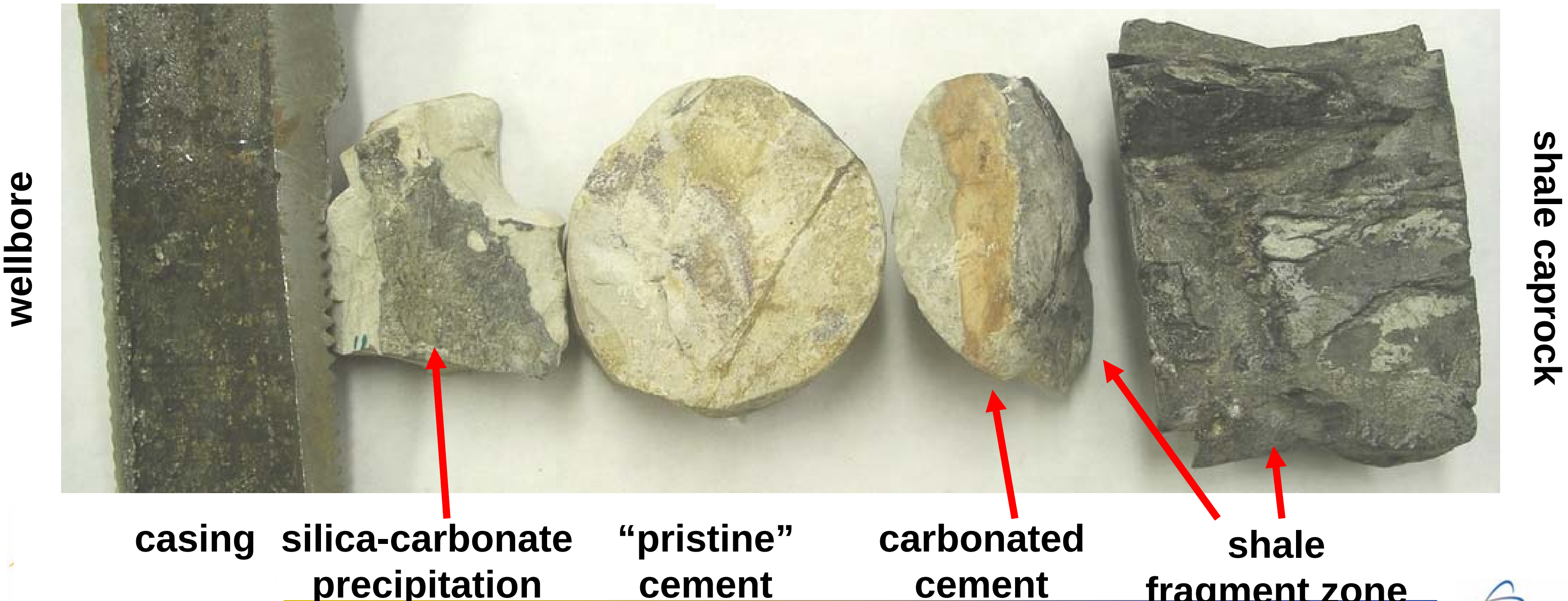


Carey et al., 2007, *Int. J. GHG Control*, 1:75-85

Observations suggest initial flow along interfaces followed by precipitation of silica and carbonate phases.

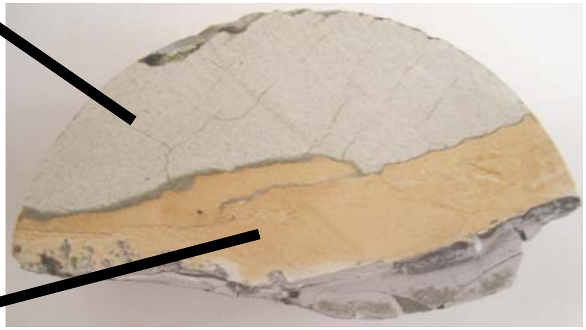
- **fluid flow along interface into sandy unit in shale**
- **diffusion-driven carbonation of cement to form orange zone**
- **precipitation of silica and carbonate from brine in "yellow" zones**





Air-Permeability Measurements of Cement and Shale

Zone	Air Dried (mD)	Oven Dried (mD)
Upper Cement	0.09	74.00
Gray Zone		0.10
Gray Zone (A1)	0.09	30.54
Gray Zone (A2)	0.07	48.22
Gray Zone (A3)	0.11	18.94
Gray Zone (B1)		5.75
Gray Zone (B2)		3.33
Gray Zone (B3)		8.40
Orange Zone (A1)	0.38	0.43
Orange Zone (A2)	0.19	0.19
Orange Zone (A3)	0.11	0.05
Orange Zone (B1)		0.17
Orange Zone (B2)		0.14
Orange Zone (B3)		0.22
Orange Zone (B4)		1.22
Shale along layers		8.57



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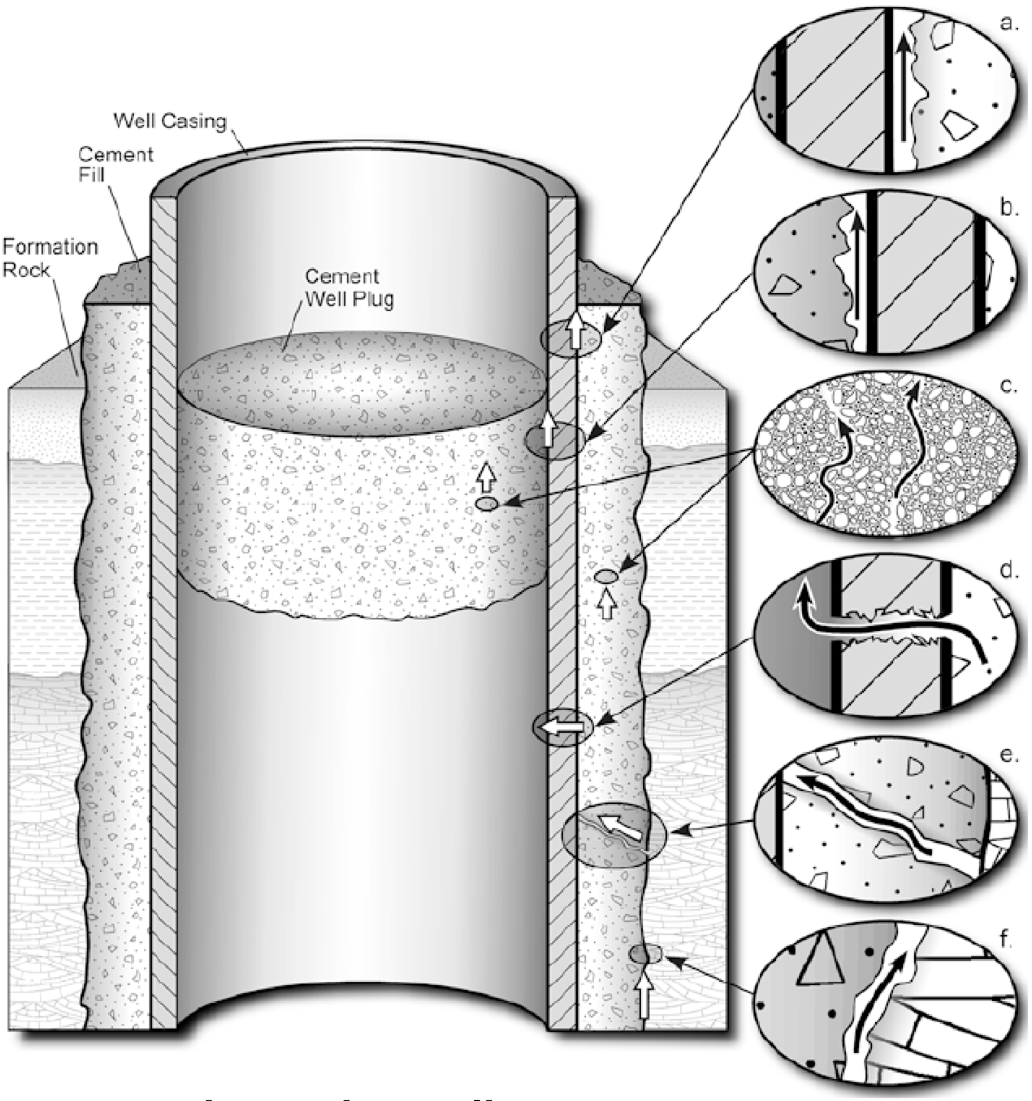
LA-UR-06-5429

Measurements courtesy of Bob Svec, New Mexico Tech

Summary of major processes occurring at wellbore 49-6.



0. ~~dissolution/corrosion of cement~~

1. **flow between cement & casing (Gasda et al. mechanisms A & B)**
   - precipitation along interface

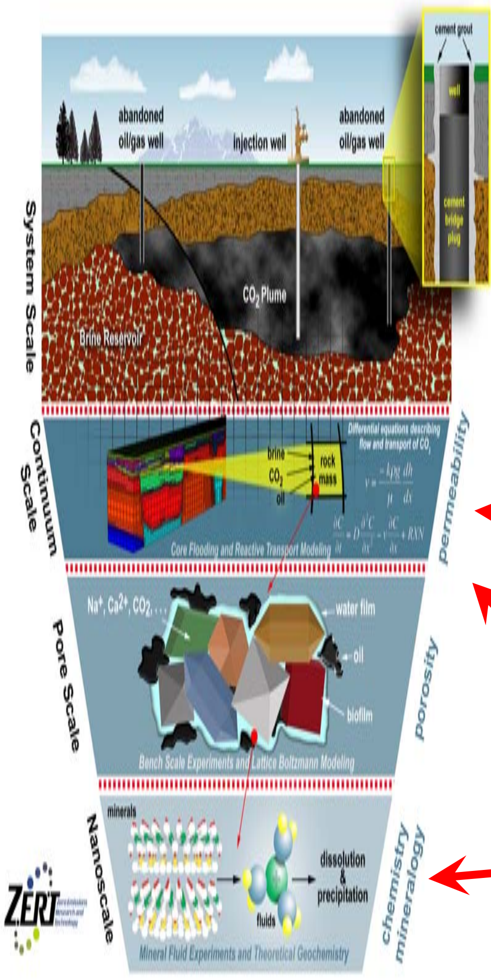
2a. **diffusion through cement (Gasda et al. mechanism C)**
   - minimal—$Ca(OH)_2$ preserved

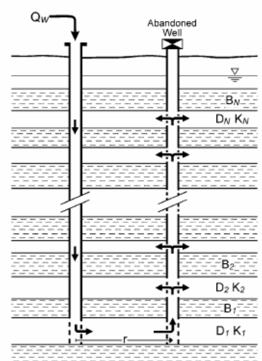
2b. **fracture flow through cement (Gasda et al. mechanism E)**
   - minimal—$Ca(OH)_2$ along fractures

3. **flow between cement & shale (Gasda et al. mechanism F)**
   - cement alteration;
   - precipitation filling voids

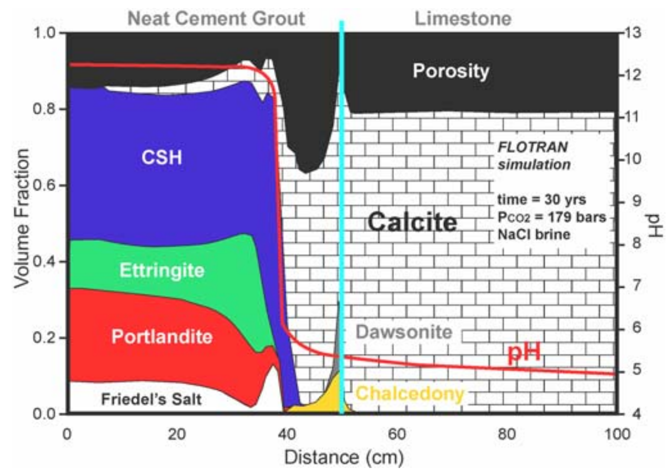
Gasda, Bachu, Celia, 2004
Princeton CMI

Using EOR Experience to Develop a Multiscale Model for the Role of Cement Integrity in a CO_2 System





Semi-analytical model
for wellbore release
(LANL team w/ Princeton CMI)



predictive modeling of cement-CO2 reactions and rates
(Carey and Lichtner, in press; LANL)

EOR (SACROC)

experiment (M. Wigand, LANL)

observations and experiments to determine reactions, rates, & impact
(LANL and NETL)

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IEA Risk Assessment Meeting

15th – 16th August, 2007

Imperial College, London, UK

Wellbore Integrity – Part II

Rick Chalaturnyk
Geological Storage Research Group
University of Alberta, Edmonton, Alberta

Objective of Well Integrity Network

- Determine the impact of CO_2 interactions with wellbore materials (cement, steel, etc.) on the long term effectiveness of geological storage of CO_2,
- Bring together experts working within the CCS area and related CO_2 -rich geologic environments including industry, academia, government laboratories, and policy makers,
- Determine the current level of understanding and assess the current state of knowledge with regard to CCS and wellbore / CO_2 interactions,
- Collect and assess field experience of CO_2-wellbore interactions including enhanced oil recovery sites and natural CO_2 reservoirs,
- Evaluate and provide recommendations on field monitoring and evaluation methods for wellbore integrity,
- Evaluate and provide recommendations on remediation methodologies for wellbores,
- Foster and provide leadership on essential experimental and numerical studies of wellbore performance in CO_2-rich environments,
- Provide guidance on the development of policies and regulations for wellbore performance in CCS

Areas of Interest for further work:

- Investigate the discrepancies observed between laboratory work and field research, and if necessary, design new laboratory experiments to better replicate the conditions experienced in the field.
- Initiate practical test projects in both new and existing CO_2 field sites, utilising recent advances in knowledge and allowing integration of further technological advancements and breakthroughs,
- Design complimentary field studies with supporting laboratory testing and modelling / simulations to demonstrate matching of theoretical data with practical data obtained from the field to improve confidence in modelling techniques.
- Instigate discussions and investigations into views on models / simulations used in the implementation of field projects.
- Foster collection and analysis of industrial experience with wellbore integrity through studies of the performance of oil and gas fields.

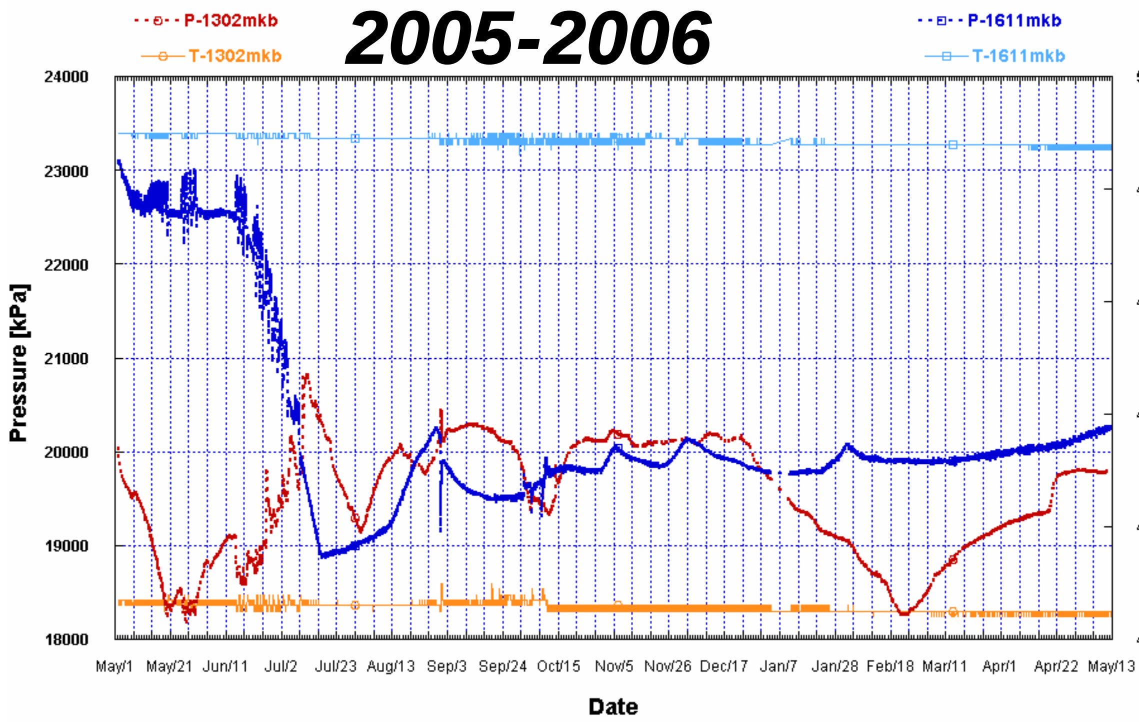
On a basic level, the two contrasting views towards modelling suggest either:

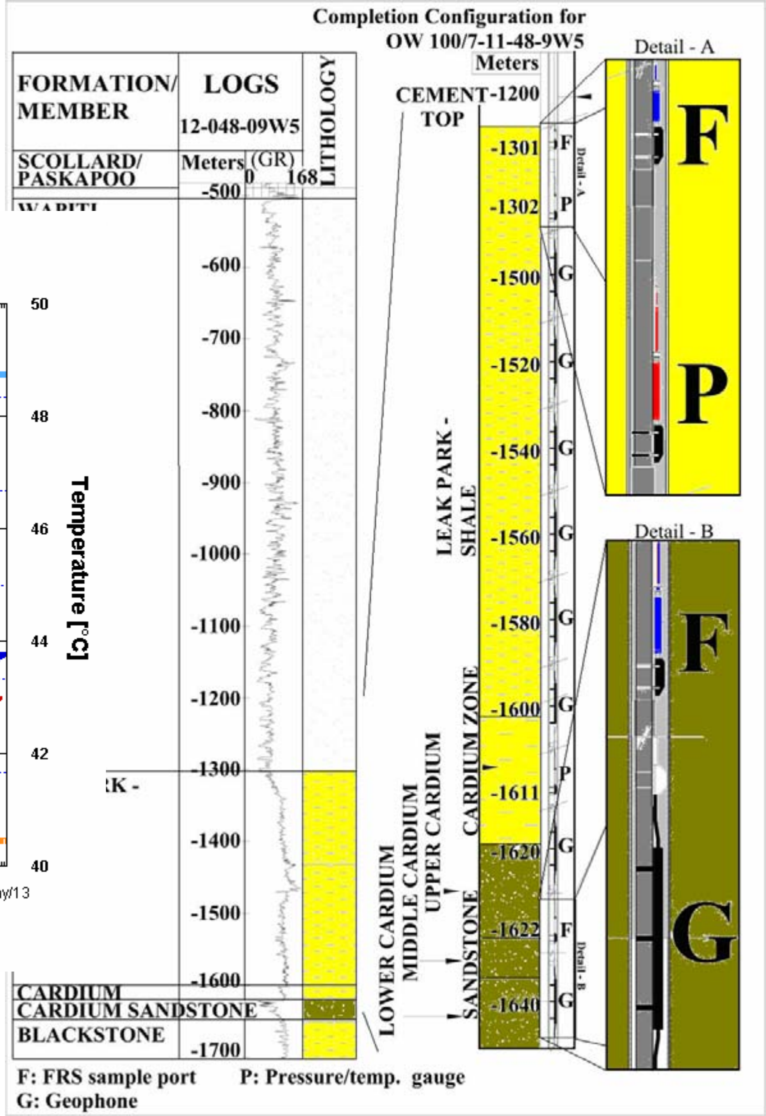
- Utilising a complex and comprehensive model covering all aspects of a project and the oil / gas fields involved which would then be adapted to predict the behaviour of each individual well, or
- Using a simpler analytical model which covers the broad aspects in detail, which could then be adapted as necessary to allow for variance between wells in a field

Purpose of Monitoring.....

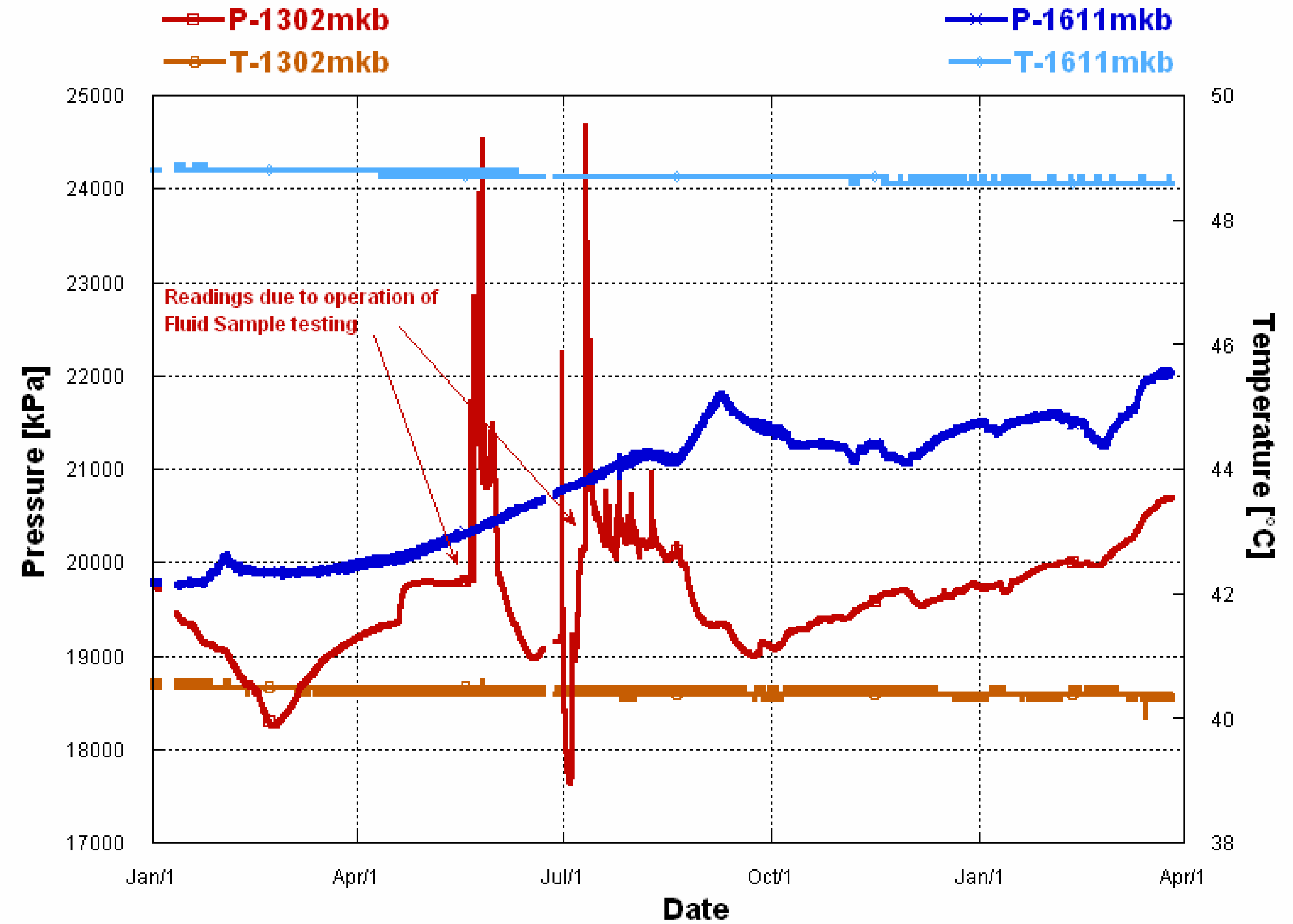
- To “truth” or validate the predictive capability of the simulators
- To validate the physics of the storage process
- To mitigate uncertainty associated with reservoir parameters
- To identify and validate different categories of storage mechanisms in geological horizons
- To correlate operational issues with aquifer and caprock response, trigger contingency plans and mitigation activities
- To satisfy regulatory requirements.

Observation Well 100/07-11

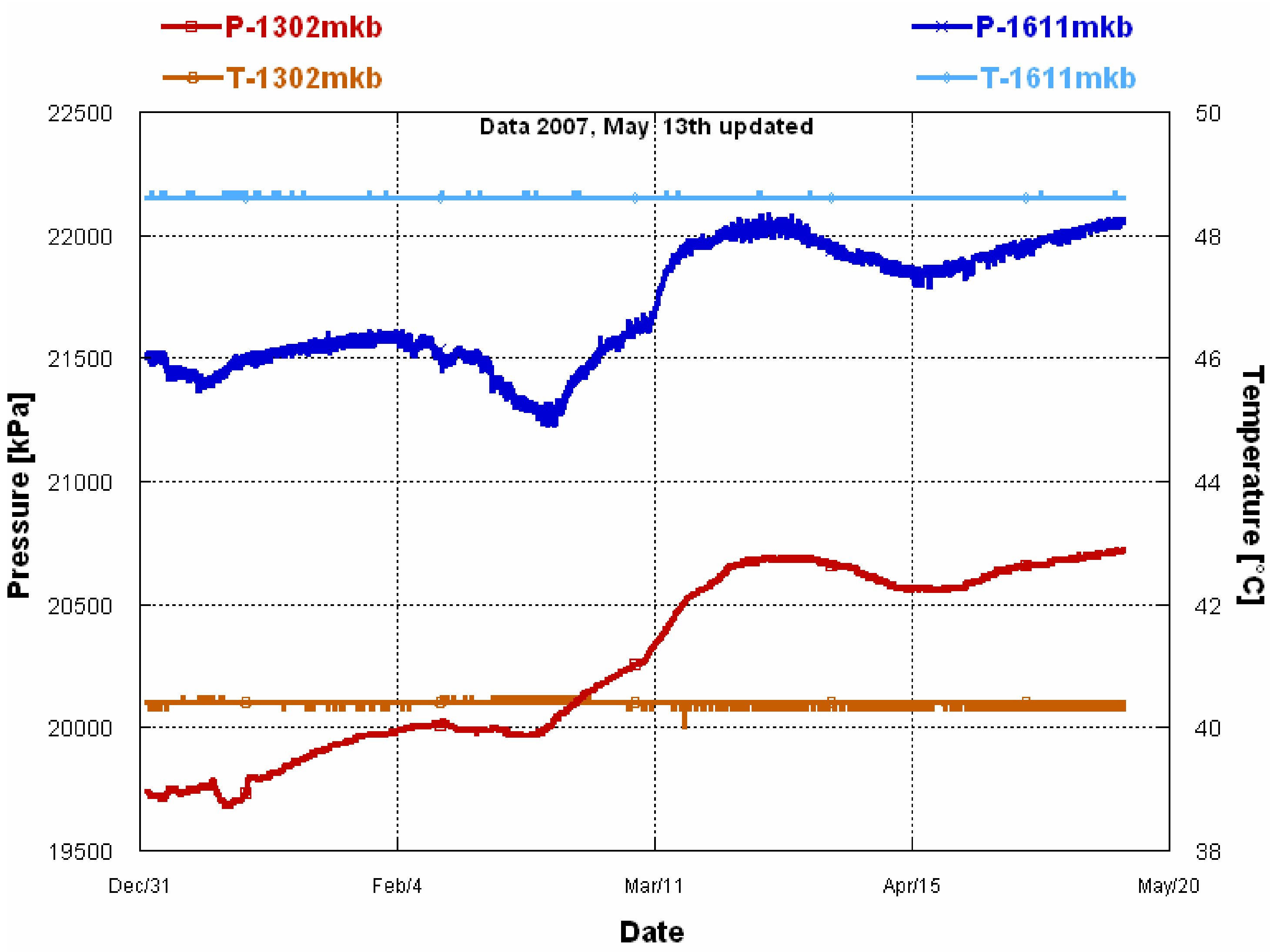


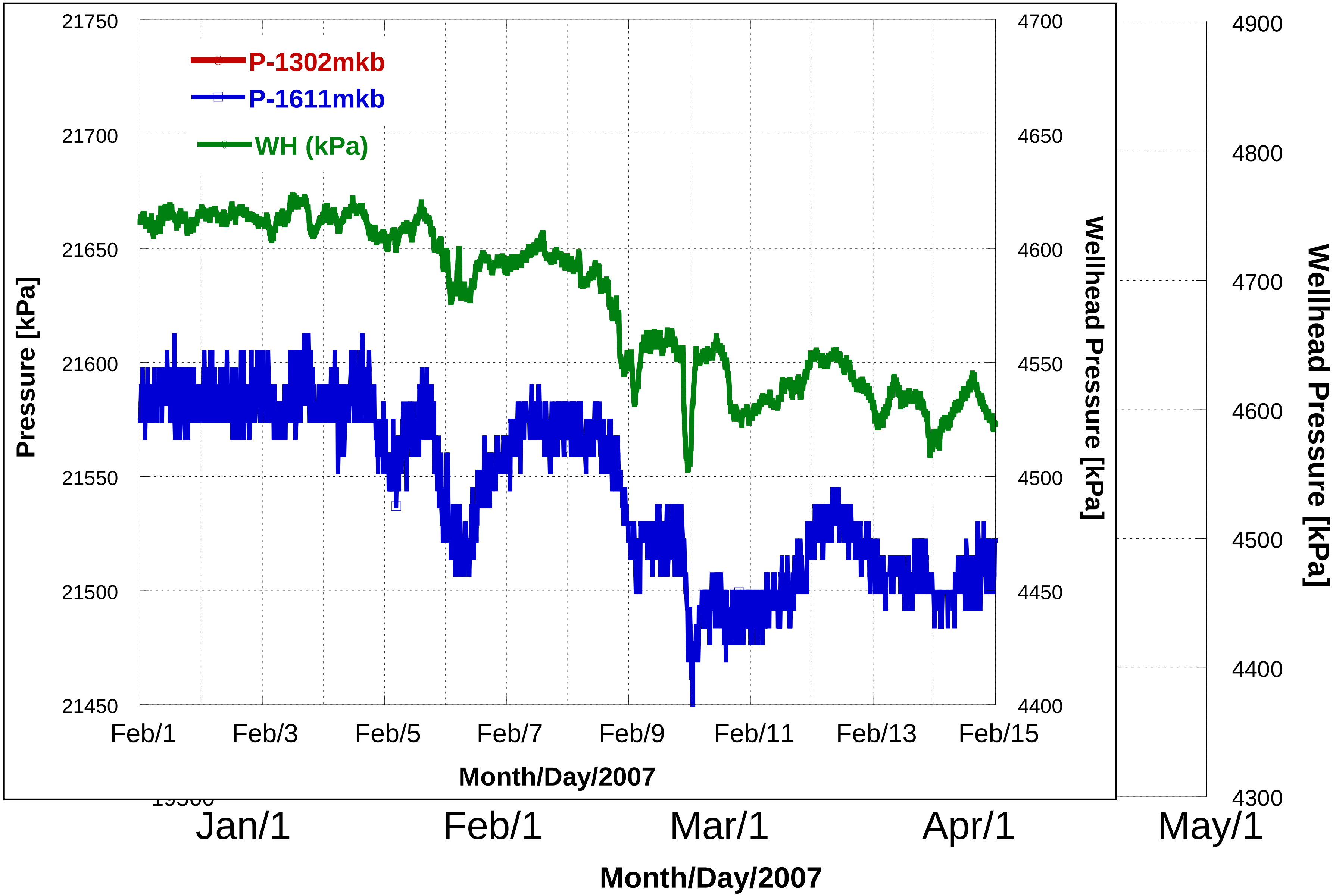


Pressure and Temperature 2006 - 2007



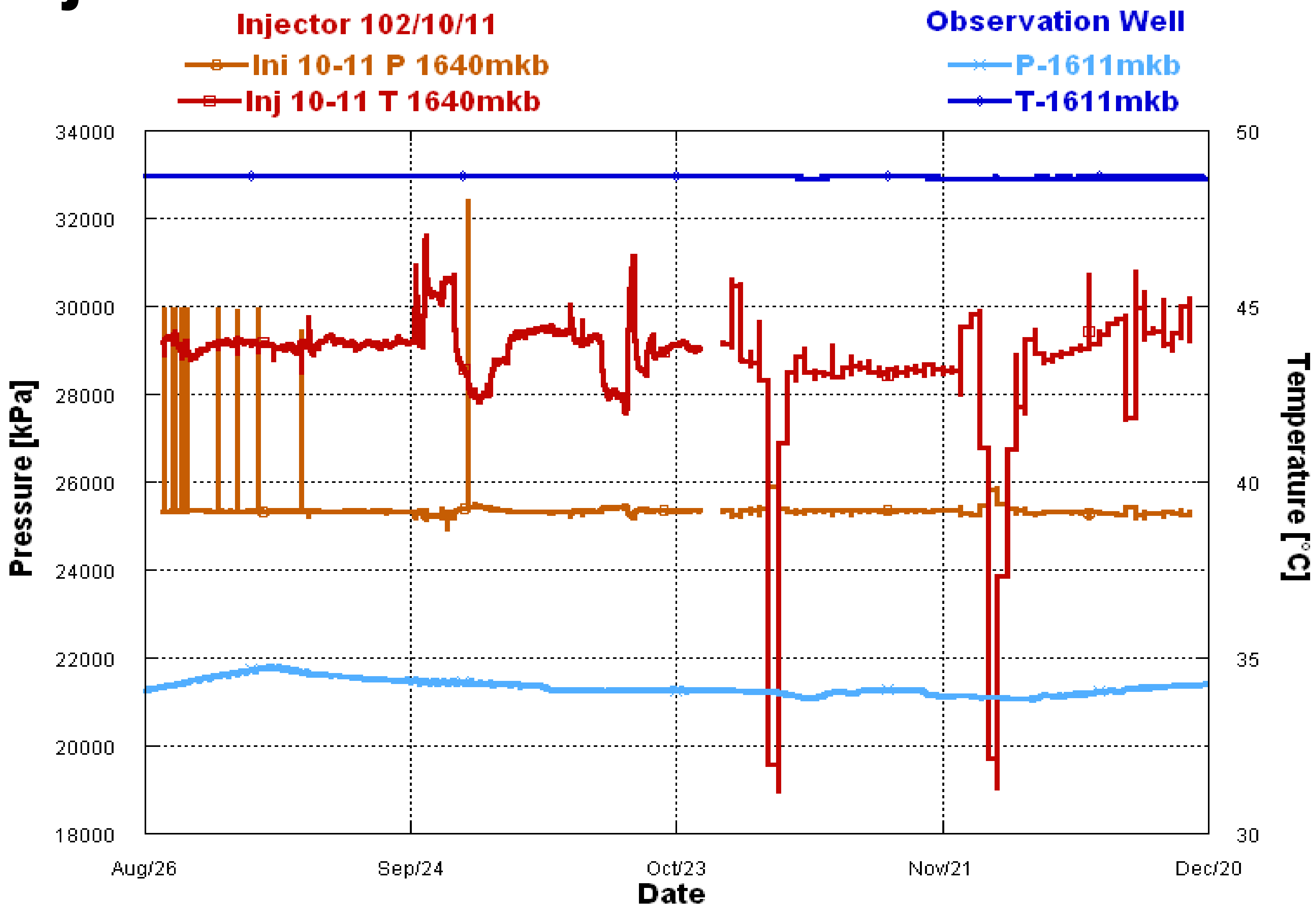
Pressure and Temperature 2007





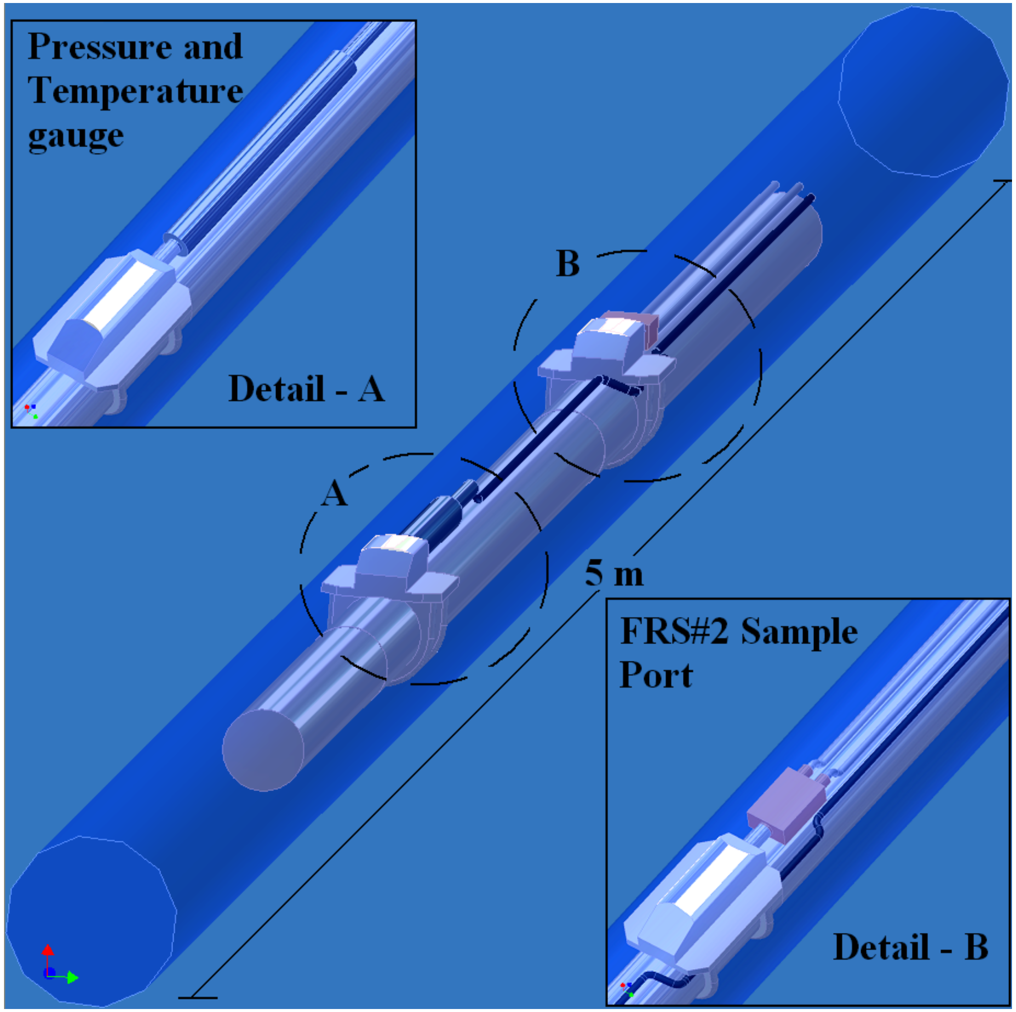
P-1302mkb
P-1611mkb
WH (kPa)
Pressure [kPa]
21750
21700
21650
21600
21550
21500
21450
4700
4650
4600
4550
4500
4450
4400
Wellhead Pressure [kPa]
4900
4800
4700
4600
4500
4400
4300
Wellhead Pressure [kPa]
Feb/1
Feb/3
Feb/5
Feb/7
Feb/9
Feb/11
Feb/13
Feb/15
Month/Day/2007
Jan/1
Feb/1
Mar/1
Apr/1
May/1
Month/Day/2007

Injection Pressures

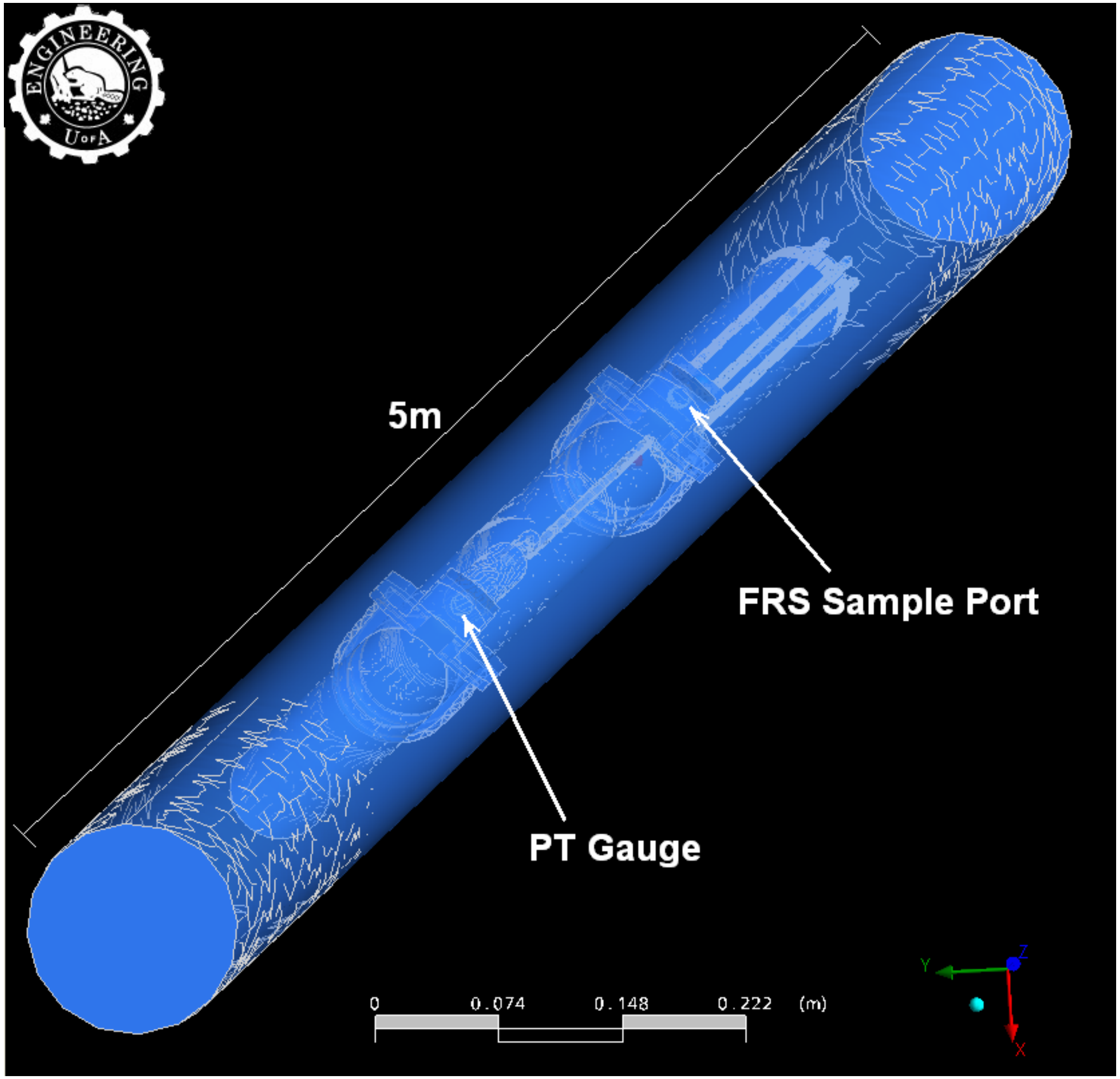


Preliminary 3D CFD Simulation of Cement Displacement

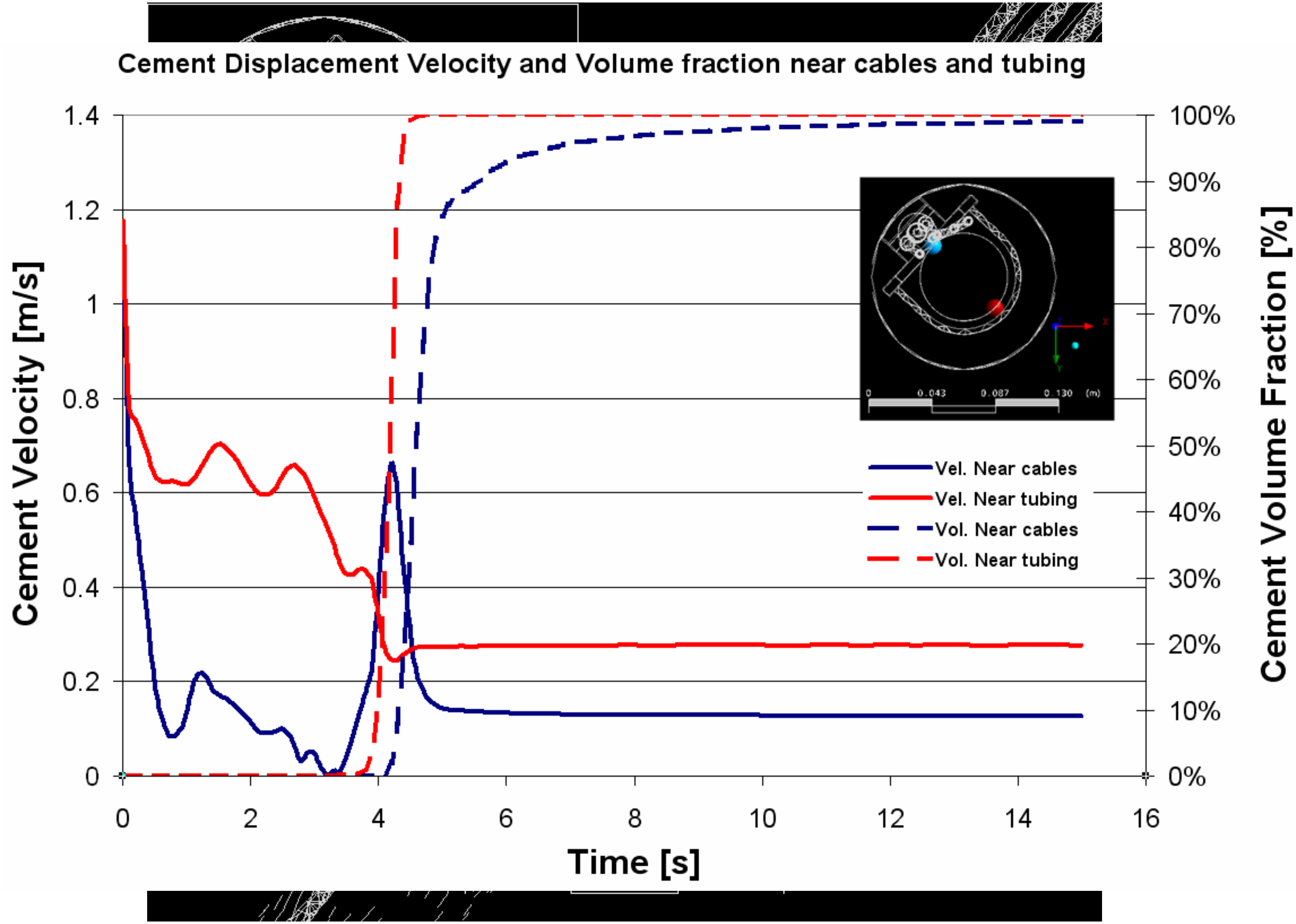
- **Geometry Definition**



Grid Generation



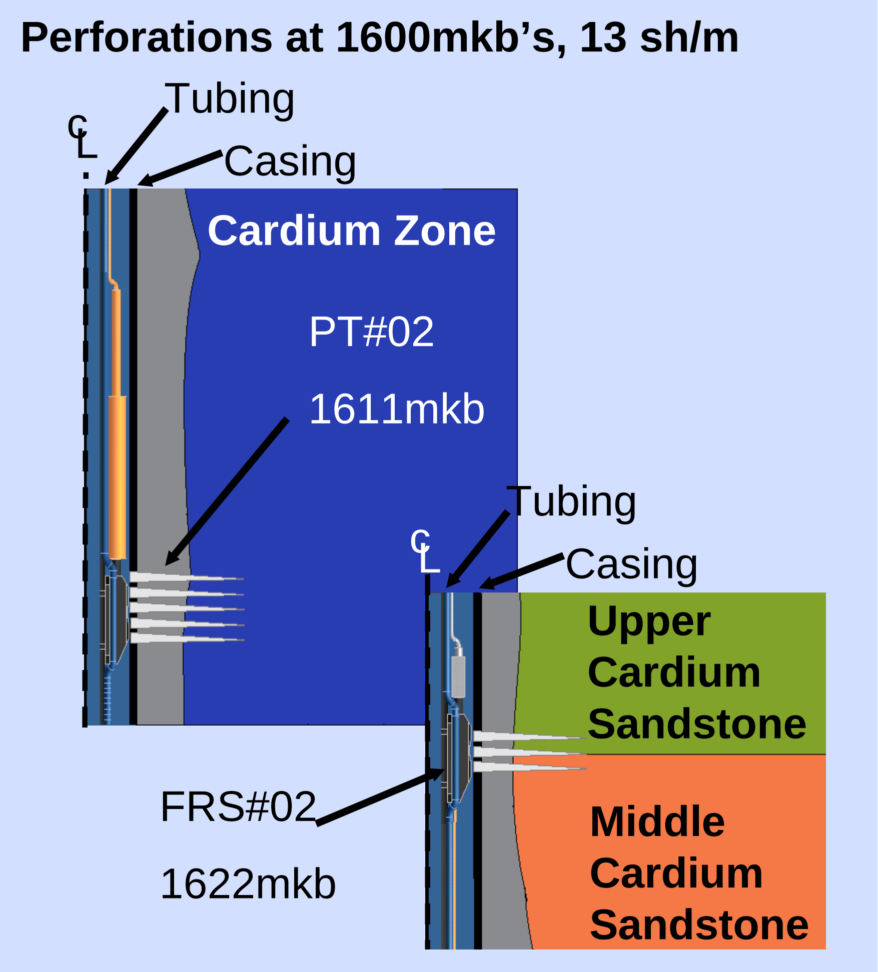
Results and Discussion

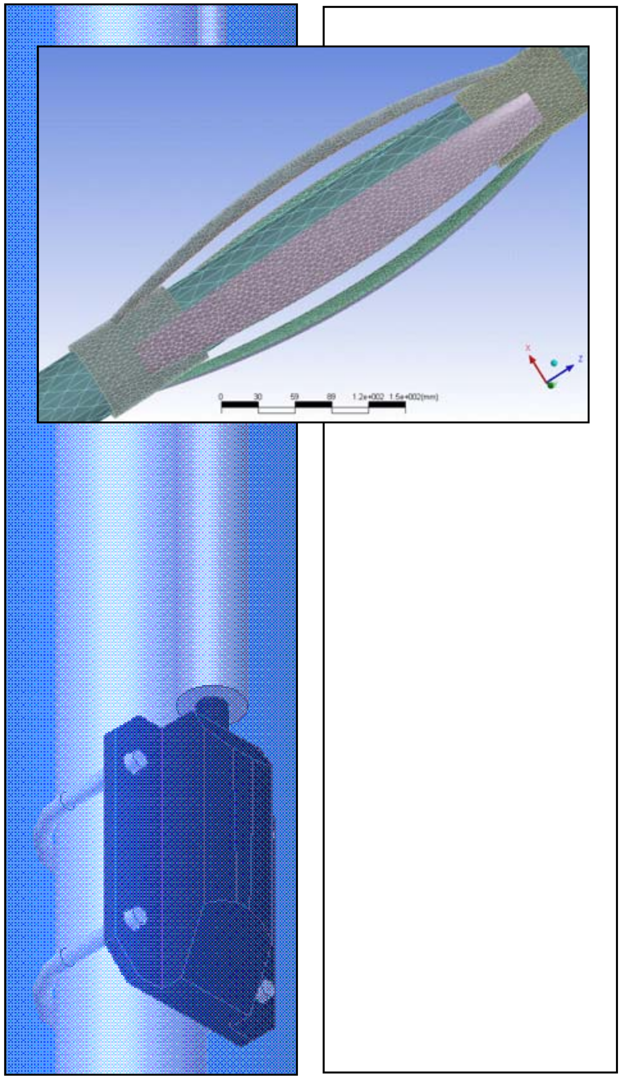


Detailed Near-Well Modeling

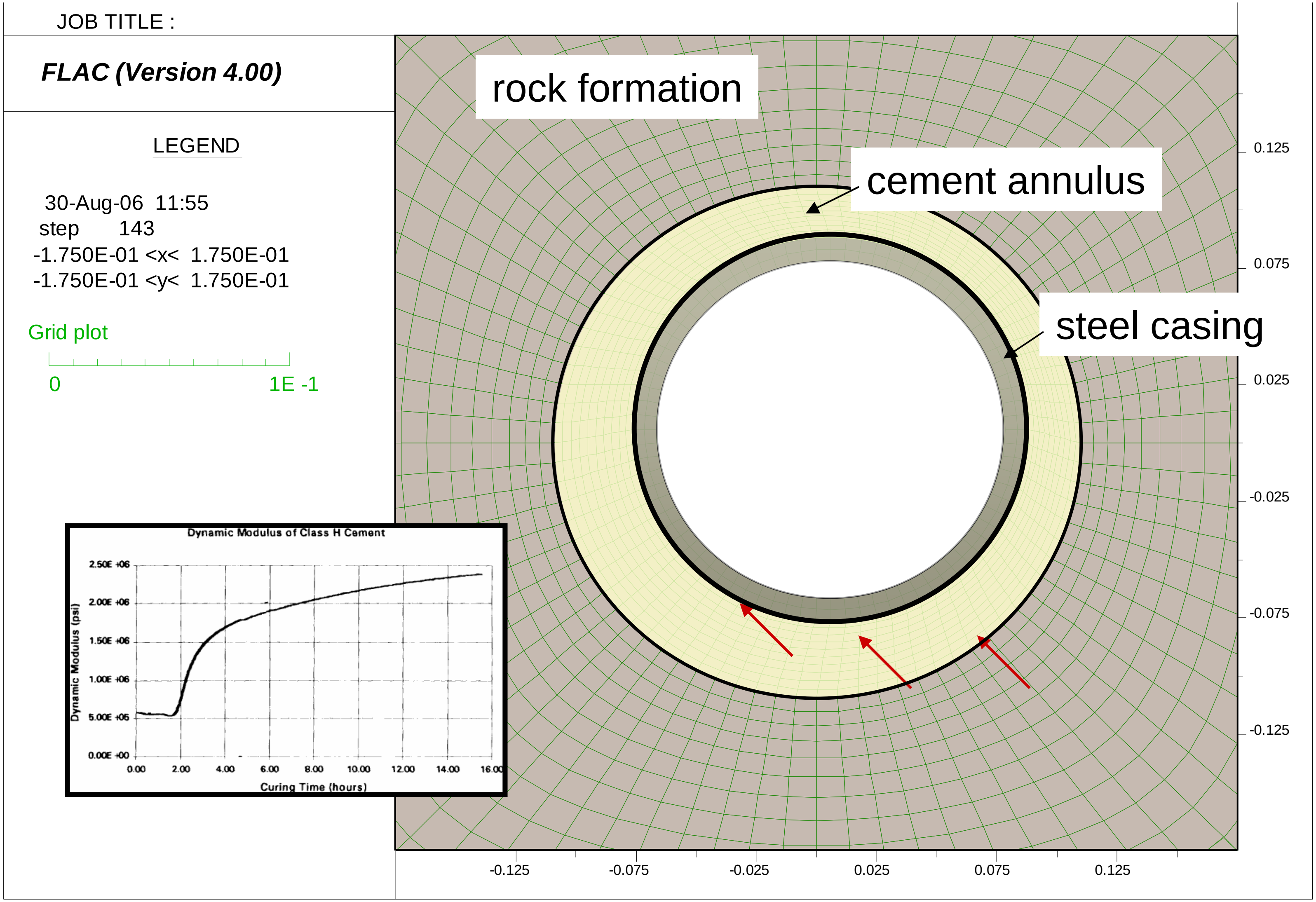
Movie #1

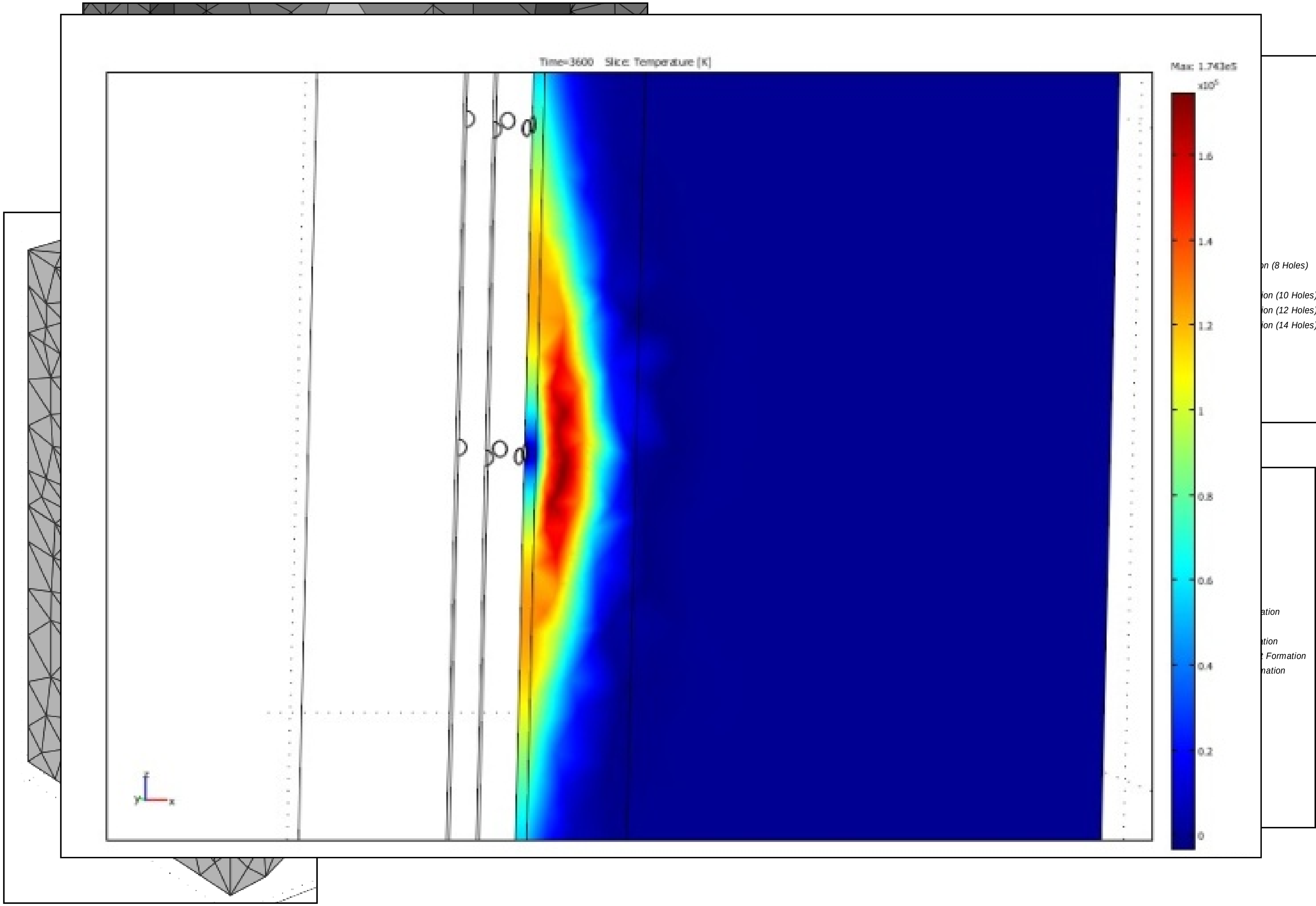
Movie #2





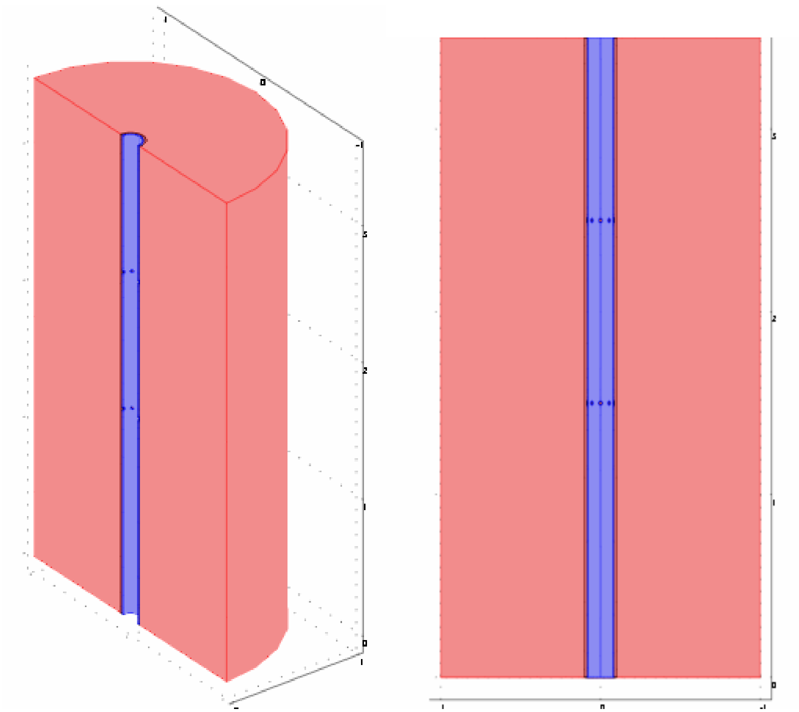
Detailed Near-Well Modeling

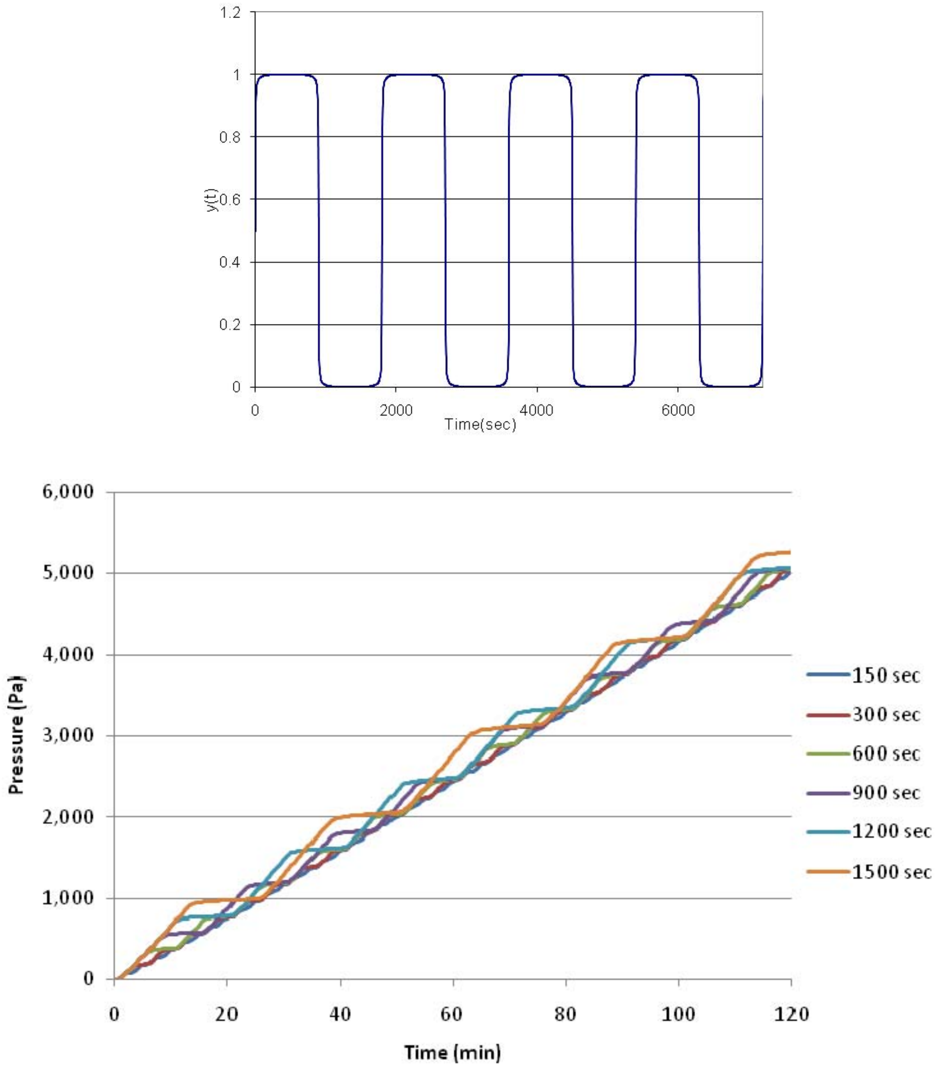


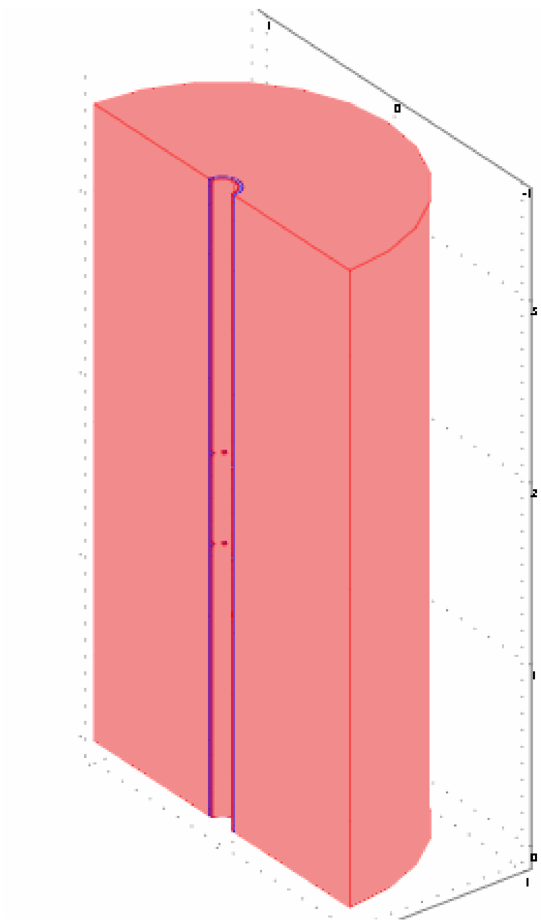


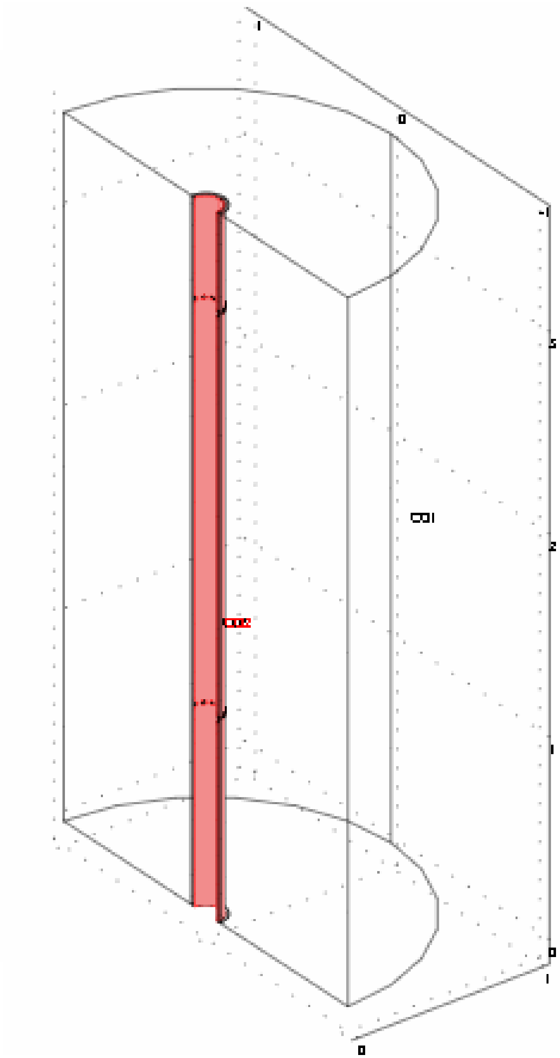
Time=3600 Slice: Temperature [K]
Max: 1.743e5
x10^5
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

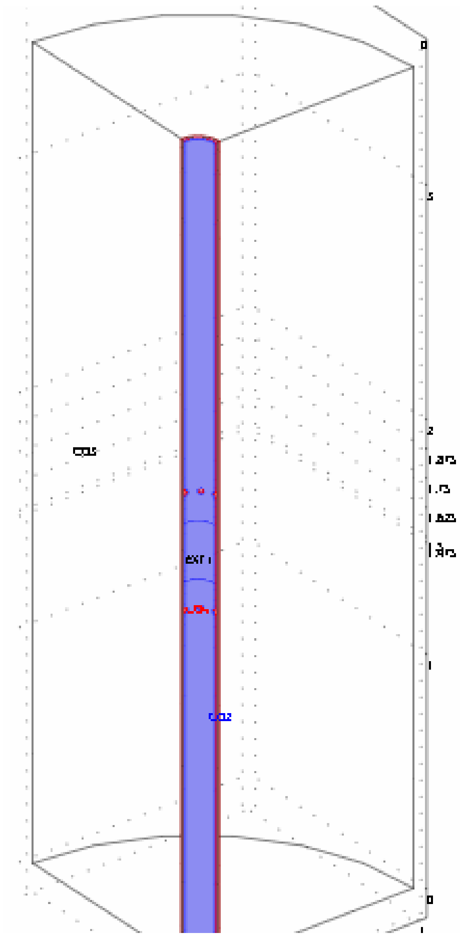
Frequency of Pressure Pulsing

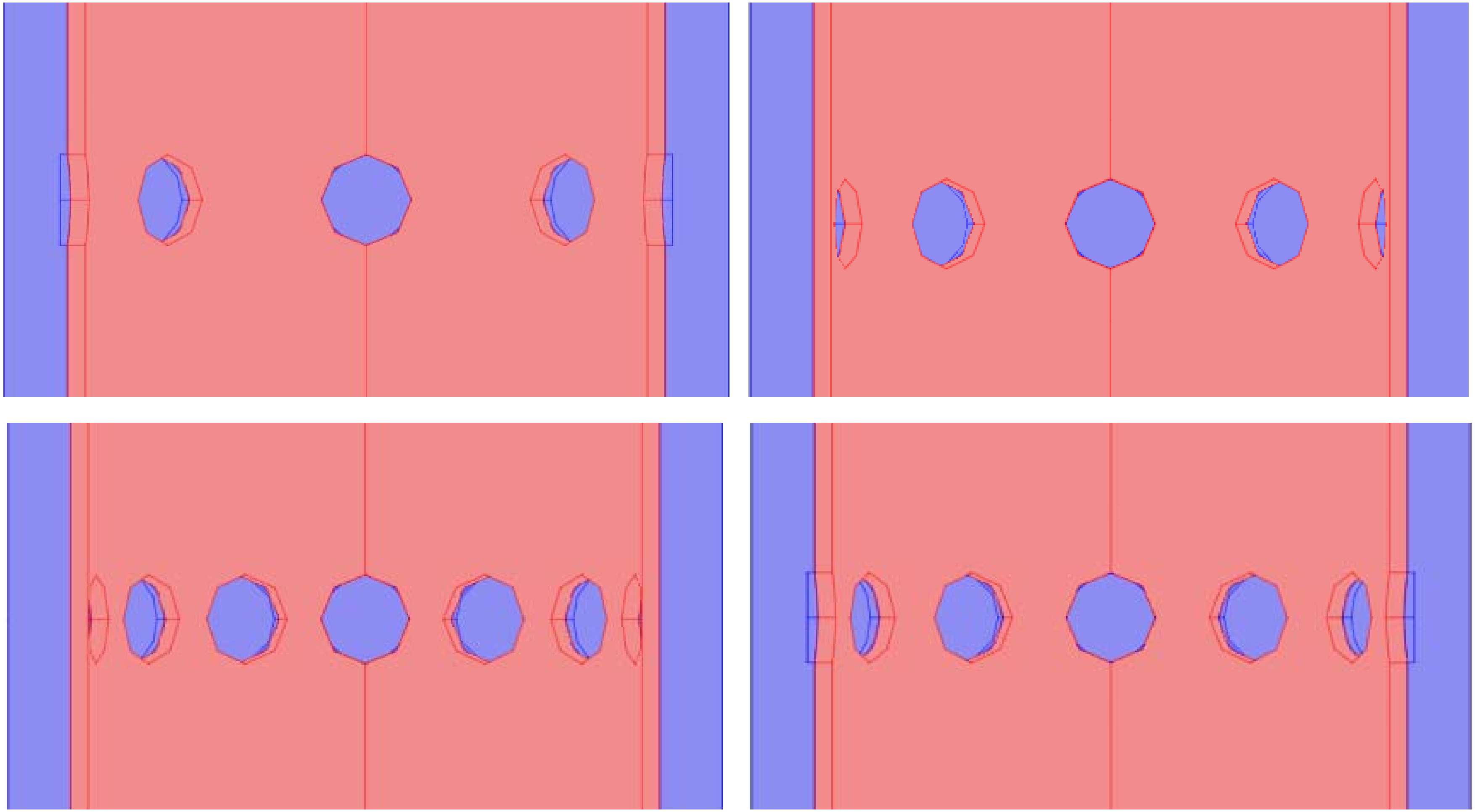


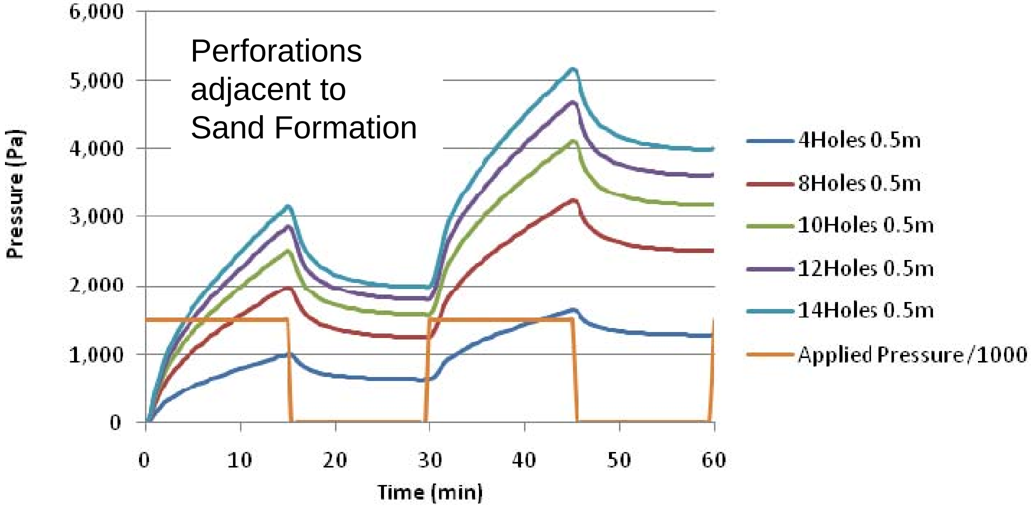


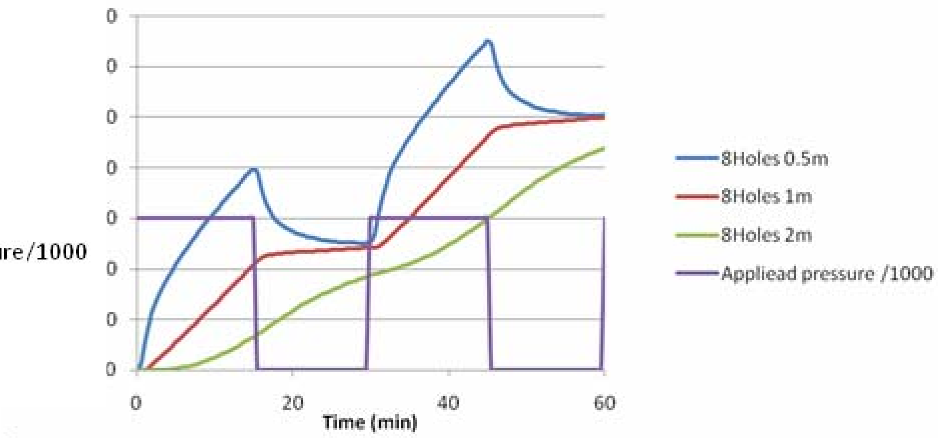


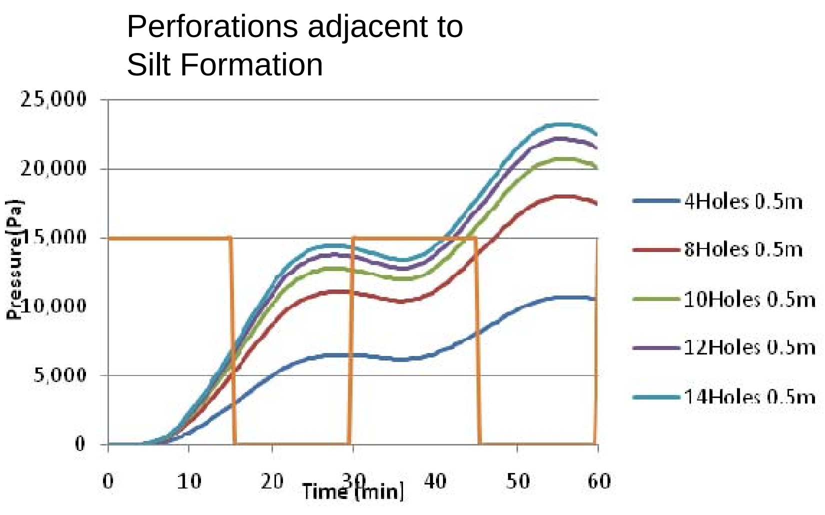


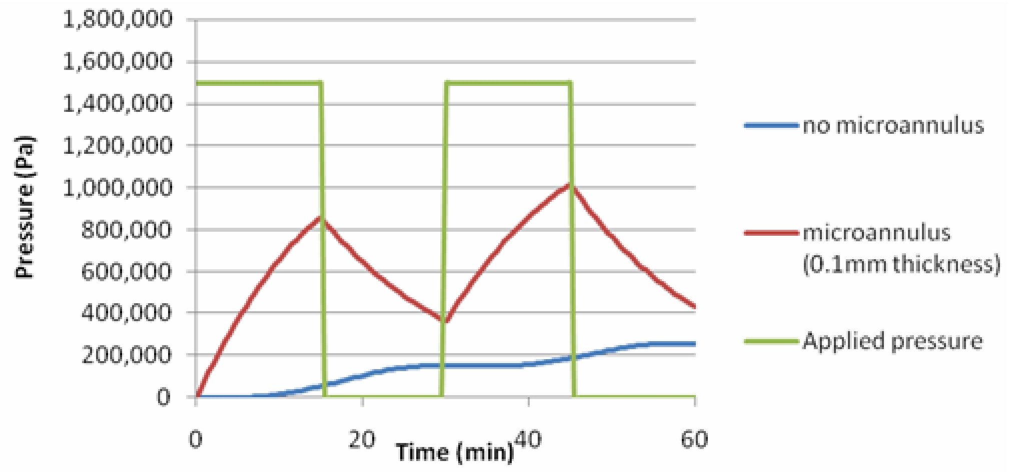




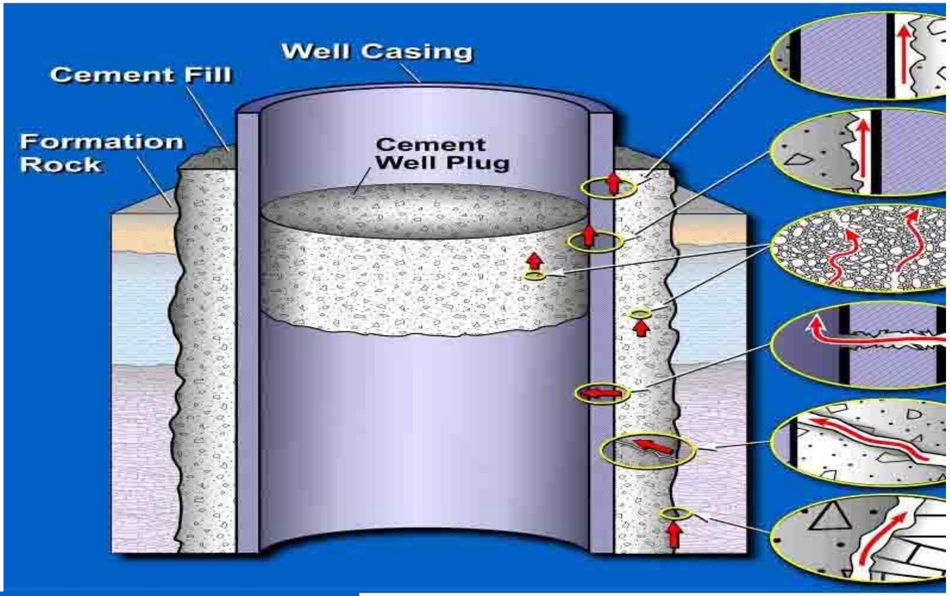

Perforations
adjacent to
Sand Formation
6,000
5,000
4,000
3,000
2,000
1,000
0
Pressure (Pa)
0
10
20
30
40
50
60
Time (min)
4Holes 0.5m
8Holes 0.5m
10Holes 0.5m
12Holes 0.5m
14Holes 0.5m
Applied Pressure/1000

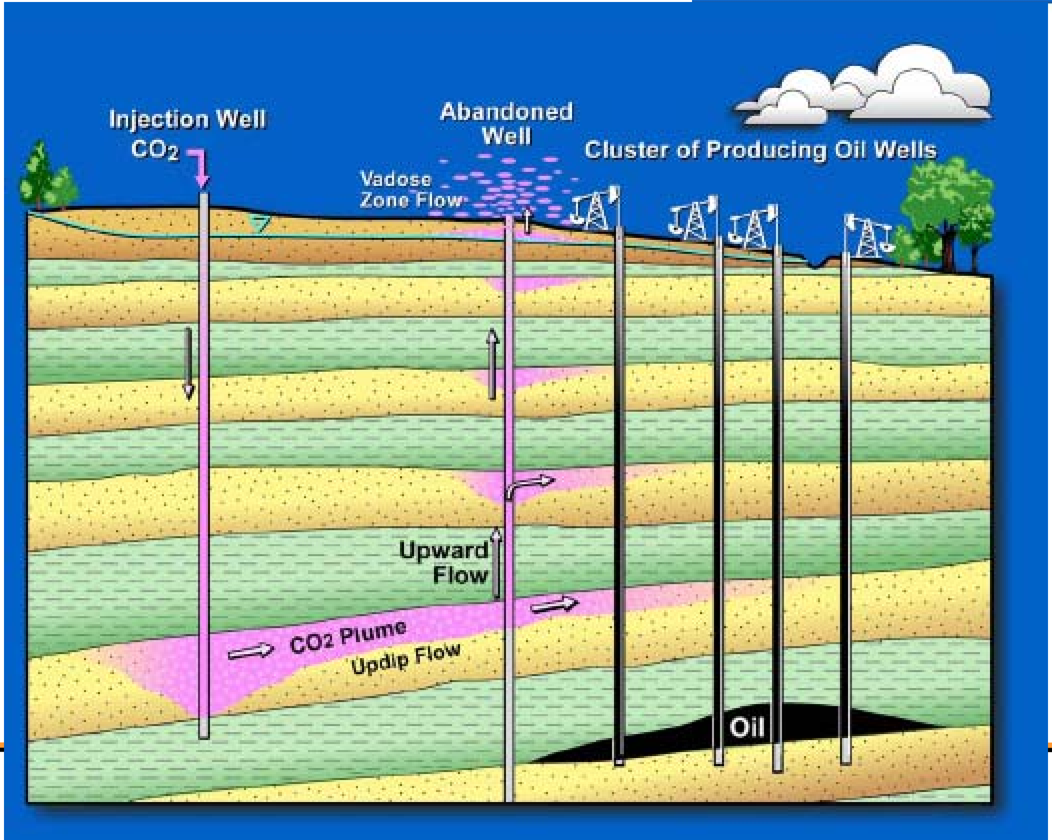

0
20
40
60
Time (min)
8Holes 0.5m
8Holes 1m
8Holes 2m
Appliead pressure /1000


Perforations adjacent to
Silt Formation
25,000
20,000
15,000
10,000
5,000
0
Pressure (Pa)
0
10
20
30
40
50
60
Time (min)
4Holes 0.5m
8Holes 0.5m
10Holes 0.5m
12Holes 0.5m
14Holes 0.5m


1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
Pressure (Pa)
0
20
40
60
Time (min)
no microannulus
microannulus
(0.1mm thickness)
Applied pressure

Why?

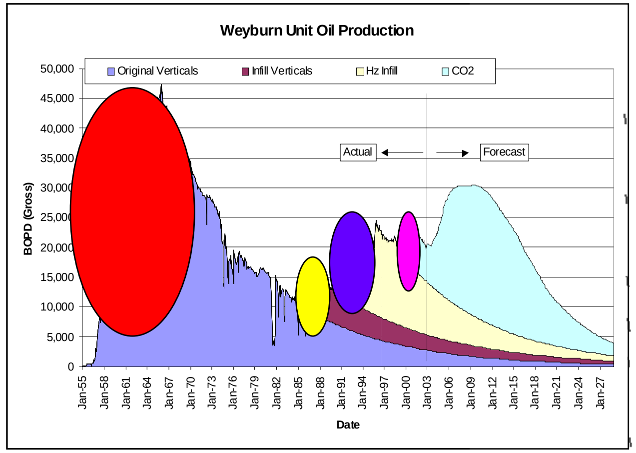

Well Casing
Cement Fill
Formation Rock
Cement Well Plug

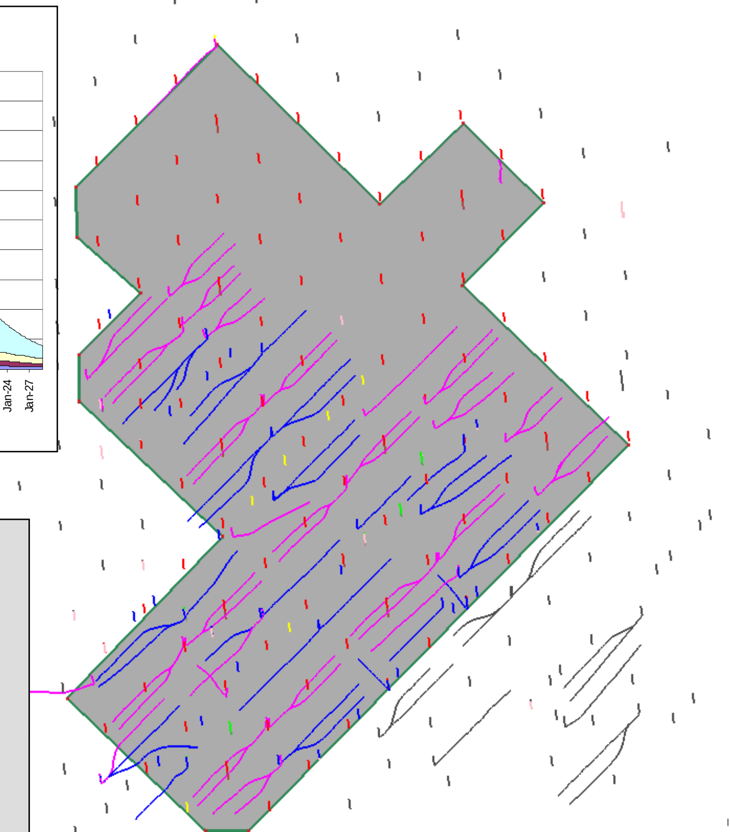

Injection Well
CO_2
Abandoned Well
Cluster of Producing Oil Wells
Vadose Zone Flow
Upward Flow
CO_2 Plume
Updip Flow
Oil

Conclusions

- Existing wells represent potentially important leakage pathways
- A Semi-analytical model allows Monte Carlo simulations for risk assessment.
- A comprehensive experimental program is needed to determine important properties of existing wells.

Wells in Phase 1a



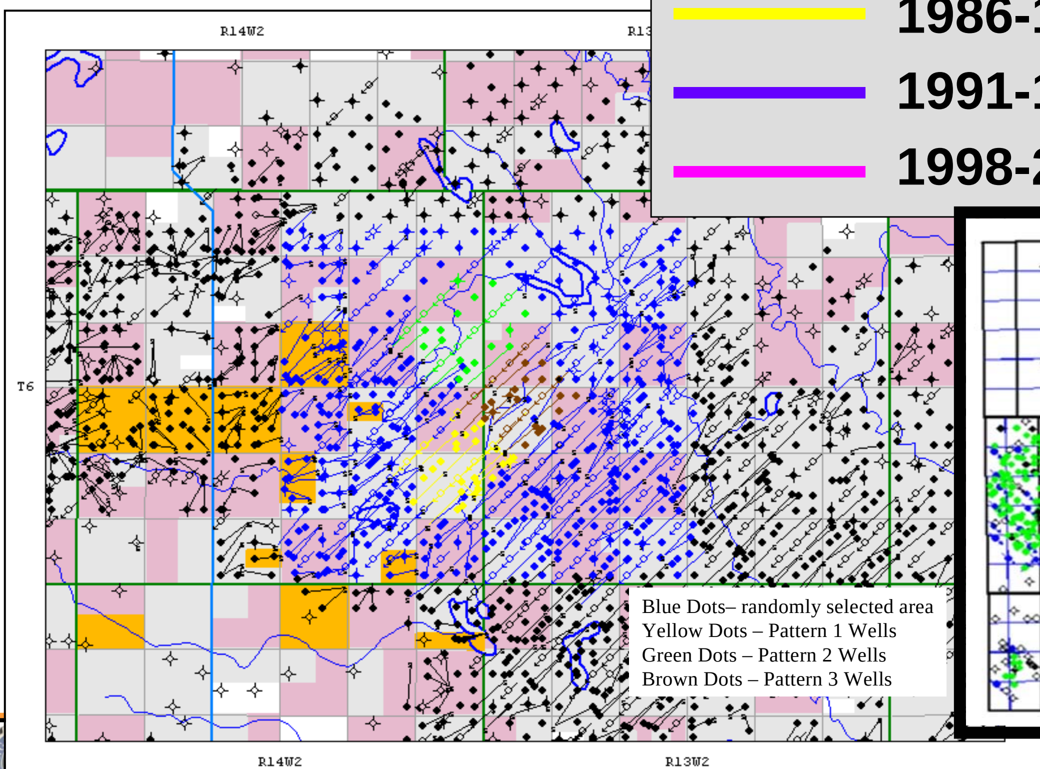


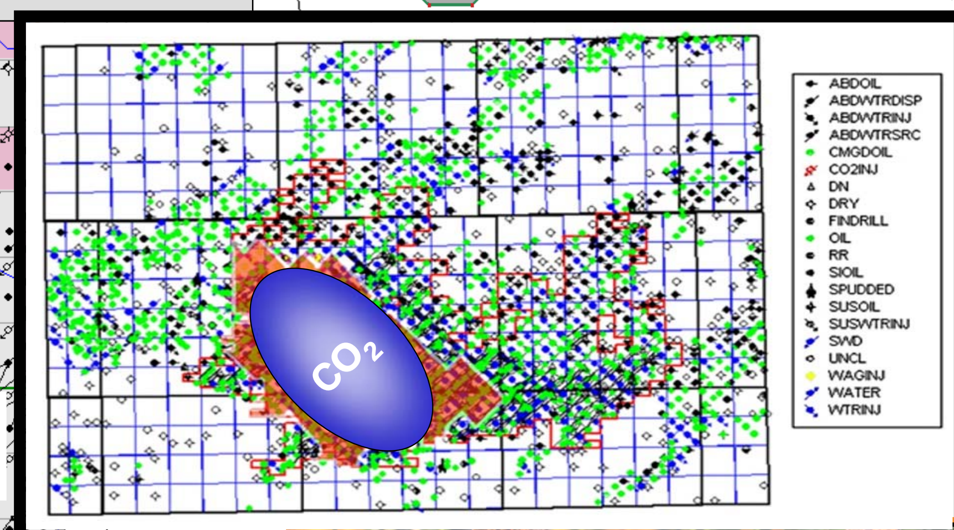
1956-1967

1986-1987

1991-1995

1998-2001





University of Alberta

4th IEA Wellbore Integrity Meeting

- Paris, France in the spring of 2008, and Schlumberger have agreed to host the meeting

Confidence Building through Argumentation

Results summary of Workshop on Confidence Building in the long-term Effectiveness of CCS in Tokyo

Norio SHIGETOMI

Mitsubishi Research Institute, Inc.

MITSUBISHI RESEARCH INSTITUTE, INC.

3rd Meeting of the Risk Assessment Network
15-16 August, 2007
Imperial College, London, UK

Contents

- Background of Tokyo Workshop
- Objectives
- Program
- Summary

Background of Tokyo Workshop 1/2

(September, 2006)
Suggestion at IEA GHG 30th Executive Committee Meeting by Japanese METI.

1. **Discuss about international cooperation and means of implementation regarding Confidence Building at IEA GHG R&D Programme' 2nd Risk Assessment Network Meeting (October 2006)**
2. **Hold an international workshop on Confidence Building in Tokyo in January 2007**

Suggestions accepted

(October, 2006)
Suggestion at IEA GHG 2nd Risk Assessment Network Meeting by Japanese Delegation.

1. **Development of methodology and international cooperation on Confidence Building by accumulating experts' comments though ESL (Evidential Support Logic)**

RA Network's cooperation on Development of Confidence Building Methodology

Background of Tokyo Workshop 2/2

Workshop on Confidence Building in the long-term effectiveness of Carbon Dioxide Capture and Geological Storage in Tokyo, Japan

Organized by: Ministry of Economy, Trade and Industry of Japan (METI) in collaboration with IEA Greenhouse Gas R&D Programme

Date: 24 and 25 January, 2007
Venue: Mitsubishi Research Institute, Inc.
Participants: More than 40 CCS Experts and policy makers.

Objectives

- To exchange state-of-the-art information, knowledge, experience and insights on Carbon Dioxide Capture and Geological Storage

- To have in depth discussion among experts in order to build confidence on Carbon Dioxide Capture and Geological Storage amongst experts and policy makers.

■Program (1/2)

DAY1: 24 January 2007

8:30 - 9:00	Registration	
Opening		
9:00 - 9:05	Welcome Address	Kentaro Endo, METI
9:05 - 9:15	Workshop Objectives	Norio Shigetomi, MIRI
Confidence Building in CCS 1, Chair: Makoto Akai, AIST		
9:15 - 10:05	Proposals for Confidence Building	Hidemitsu Shimada, JGC Corporation Quintessa Japan
10:05 - 10:55	Current Status of IEA GHG's Efforts toward CCS Confidence Building	Harry Audus,IEA GHG R&D Programme
10:55 - 11:15	Coffee break	
Case study 1, Chair: Sally Benson, LBNL		
11:15 - 12:05	Approach to Building Confidence Concerning Geological CO2 Storage	Michael Stenhouse, Monitor Scientific LLC
12:05 - 12:55	European Efforts towards CCS and Confidence Building	Isabelle Czernichowski-Lauriol, CO2GeoNet_BRGM
12:55 - 14:30	Lunch	MIRI
Confidence Building in CCS 2, Chair: Isabelle Czernichowski-Lauriol, CO2GeoNet_BRGM		
14:30 - 15:20	Knowledge about the CCS risk learnt from natural analogues	Koji Yamamoto, Mizuho Information and Research Institute
15:20 - 16:10	Natural Analogues for Confidence Building in CCS	Sally Benson, Lawrence Berkley National Laboratory, Mizuho Information and Research Institute
16:10 - 16:30	Coffee break	

Program (2/2)

DAY1: 24 January 2007

Confidence Building in CCS 3, Chair: Harry Audus, IEA GHG		
16:30 – 17:00	Common Arguments on CCS	Kenshi Itaoka, Mizuho Information and Research Institute
17:00 - 18:00	Discussion	
Close Day 1		
18:00 - 20:00	Reception	MIRI

DAY2: 25 January 2007

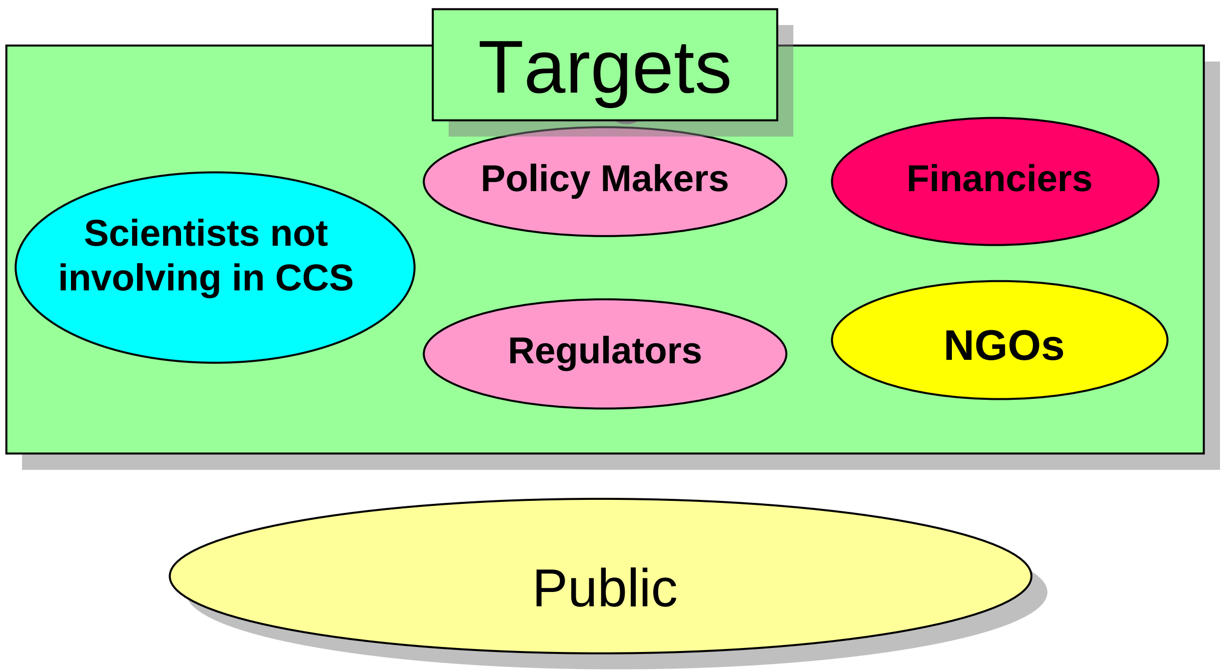
8:30 - 9:00	Registration	
Confidence Building in CCS 4, Chair: Harry Audus, IEA GHG		
9:00 - 9:45	A Structured Approach to Building and Sharing Confidence	JGC Corporation Hiroyasu Takase, Quintessa Japan David Savage, Quintessa
9:45 - 11:45	Discussion	
11:45 - 12:00	Resume of workshop	Makoto Akai, AIST
Close Day 2		

Four key questions

1. Whose confidence do we need?
2. What kind of logics and arguments do we need?
3. Do we have enough evidence for those logics and arguments?
4. How do we communicate with stakeholders?

■Whose confidence do we need?

Importance of focusing on policy makers and scientists as the first target of confidence building followed by a confidence building for general public and a necessity to conduct an awareness survey on CCS including general public.



Confidence building through argumentation

Hiroyasu Takase (Quintessa Japan)
David Savage (Quintessa UK)
Tsukasa Kumagai (JGC Corporation)
Norio Shigetomi (Mitsubishi Research Institute)

Background

Objectives of confidence building / uncertainty management

- A number of arguments to support effectiveness of confinement
- Strategy to dealing with uncertainties that could compromise effectiveness
- Assessment of our confidence in performance of the system in the presence of uncertainty

Adequate level of confidence to support decision at hand (rather than a rigorous quantitative "proof")

Iterative process of decision making

"Duality" between confidence building and uncertainty management

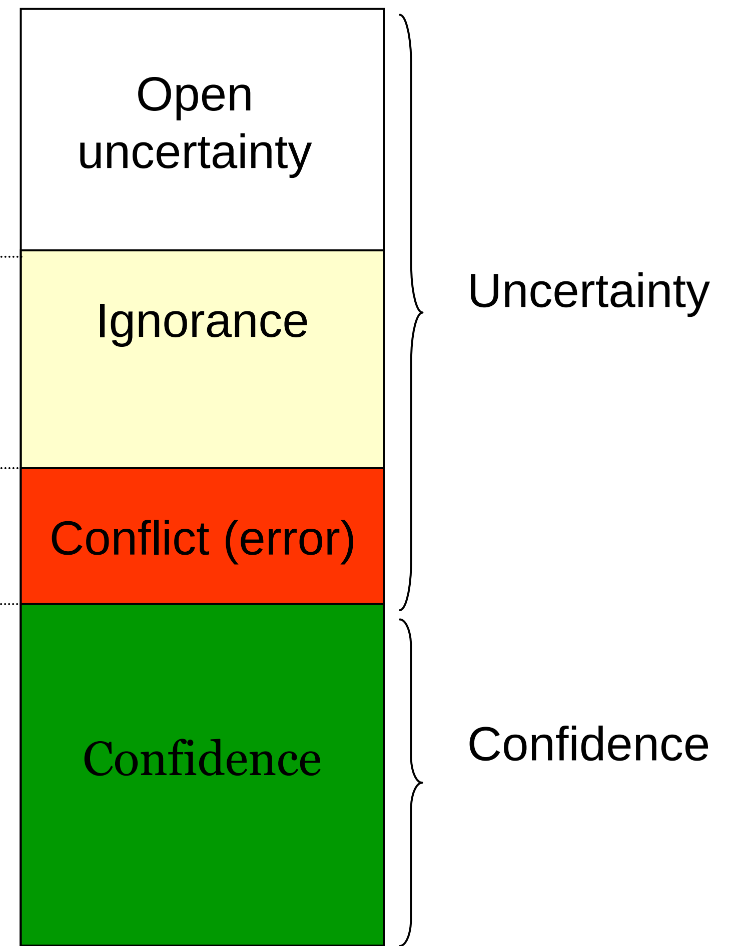
Confidence building / Uncertainty management

- "What if" analysis to bound size of impact
- Maximize chance of realizing existence of open uncertainty
- Adopt "robust" design to minimize impact of open uncertainty

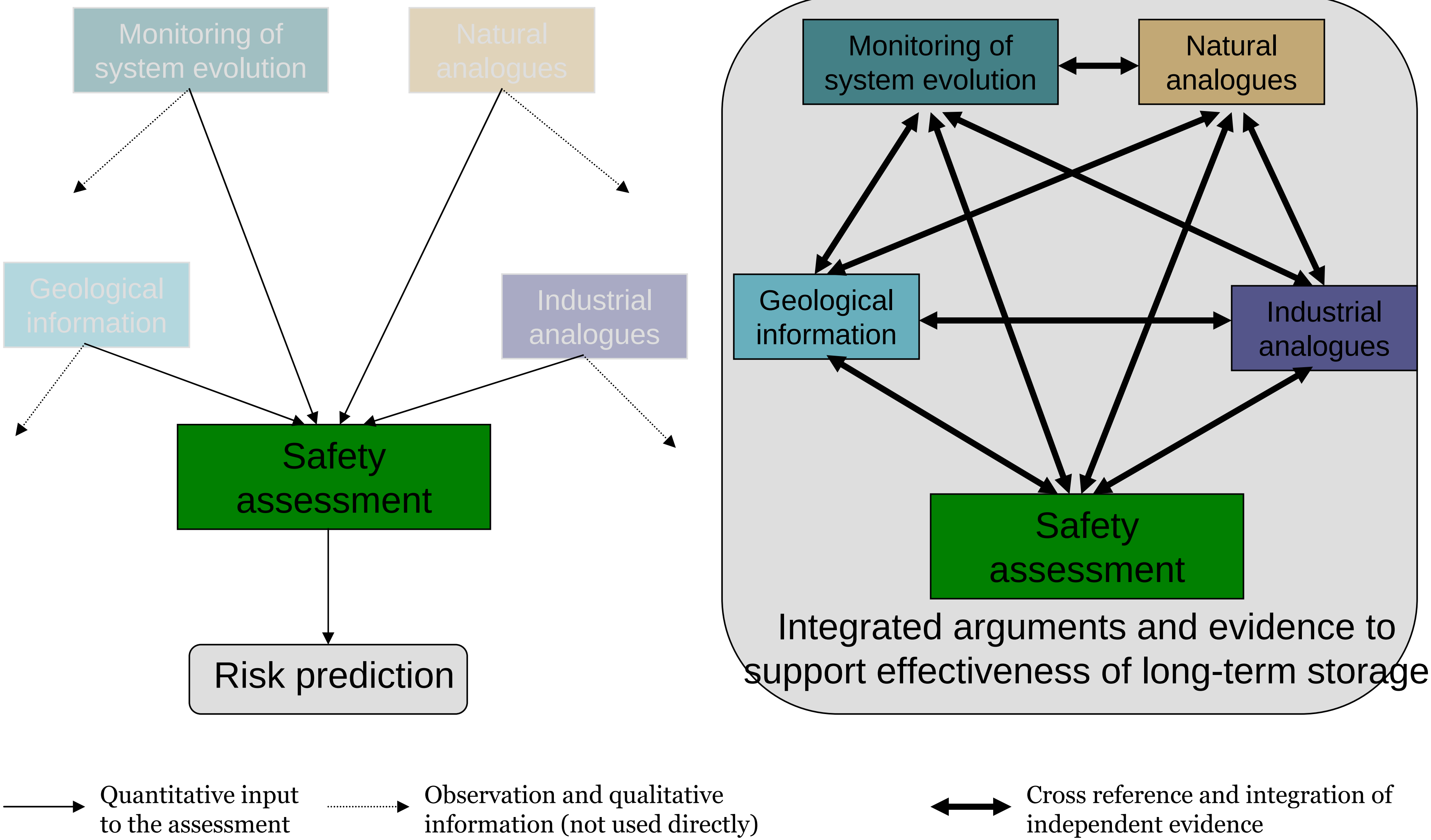
- Possibility theory, Fuzzy set theory, subjective probability
- Acquisition of new data / information
- Design change

- Verification / validation

Variety of imprecise and imperfect evidence



Advantage of using multiple lines of reasoning



Knowledge-base for confidence building

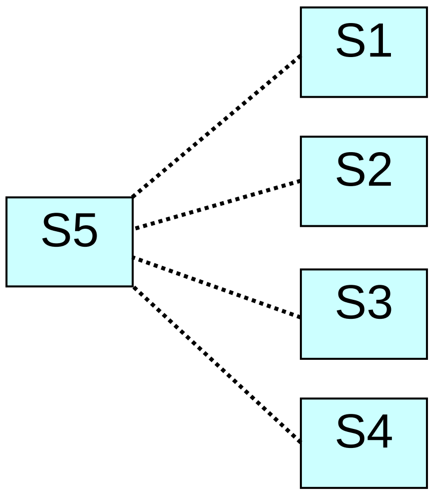
Benson (2007)

Argumentation model

Argumentation model

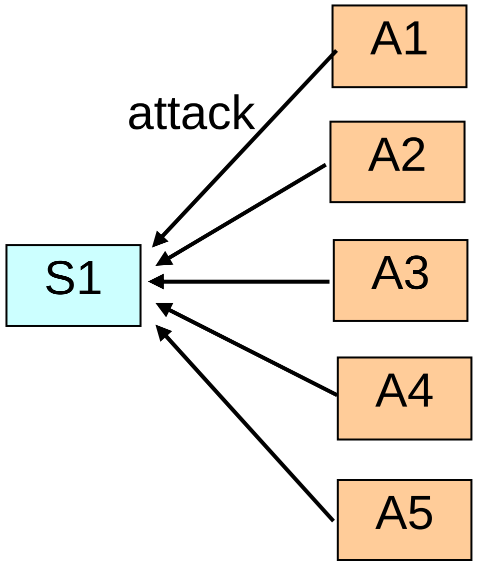
- Argumentation in a critical discussion can be used to arrive at intellectual consensus (De Groot, 1984).
- Arguments and evidence taken from the knowledge-base can be structured in order to convince a reasonable critic on specific standpoint, e.g., long-term effectiveness of CO_2 storage.
- Chain of arguments and counter-arguments is conceived as a dialogue between a proponent and an opponent of a thesis, who join to examine whether the thesis can be successfully defended against critical attack (dialectical model).
- Dialectical model enables to
  - Identify issues from various perspectives
  - Specify key uncertainties associated with the thesis
  - Assess relative strength of both sides

The confinement strategy put forward by the proponent



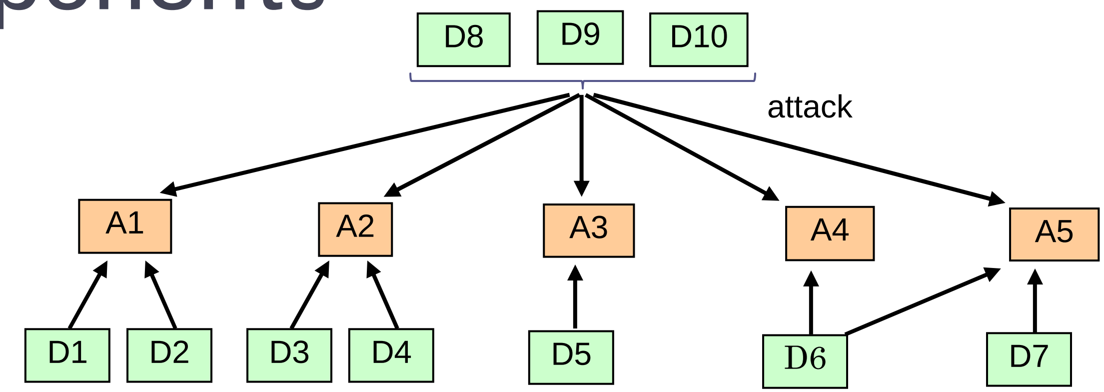
S1	CO_2 is trapped under an impermeable cap rock (Structural and stratigraphical trapping)
S2	CO_2 is trapped within fine pores of the reservoir rock by capillary force (Residual trapping)
S3	Groundwater retains dissolved CO_2 (Solubility trapping)
S4	CO_2 reacts with Ca and/or Mg in the aqueous phase to form carbonate minerals (Mineral trapping)
S5	Enhancement of stability of confinement over time

Possible attacks against the confinement strategy



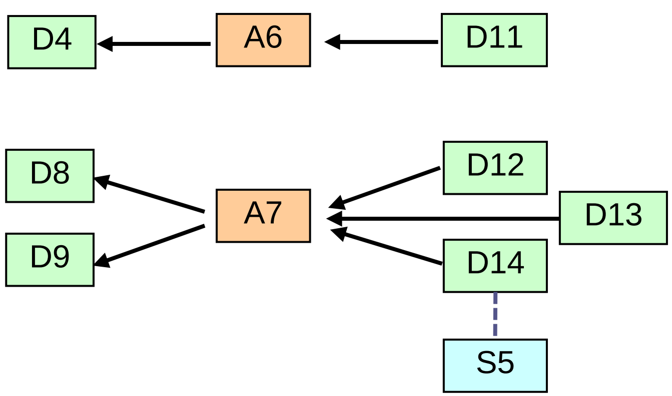
A1	Leakage of CO_2 might occur through fractures that are generated by overpressure in the cap rock during injection.
A2	There may be undetected permeable features such as sand and conglomerate layers intersecting the cap rock.
A3	Concrete seal degraded through reaction with dissolved CO_2 may serve as a migration path.
A4	Preferential migration of CO_2 through existing channels in the reservoir may reach the periphery.
A5	Dissolution of minerals in the carbonate reservoir may lead to "fingering" that provides preferential paths for CO_2.

Example of defense put forward by the proponents



D1	Fracturing of the cap rock can be avoided if injection pressure is controlled adequately.
D2	Injection pressure is to be monitored so that over pressure can be avoided.
D3	No such permeable features have been detected by comprehensive 3D seismic survey in the project area.
D4	The reservoir is a depleted natural gas field and long-term confinement by the cap rock has been validated.
D5	Precipitation of carbonate minerals on the surface of concrete provides dense protective layer and further chemical alteration of the concrete will be suppressed.
D6	Injection pressure of CO_2 is not high enough to migrate beyond the spill point.
D7	Amount of minerals to be dissolved through reaction with CO_2 is not significant.
D8	Unlikely event of CO_2 leakage, it can be detected by routine monitoring during and after the injection.
D9	Remedial action can be taken for CO_2 leakage in the future.
D10	CO_2 that had leaked from the reservoir dissipates rapidly and its impact on local environment is not significant.

Possible further argumentation between two parties



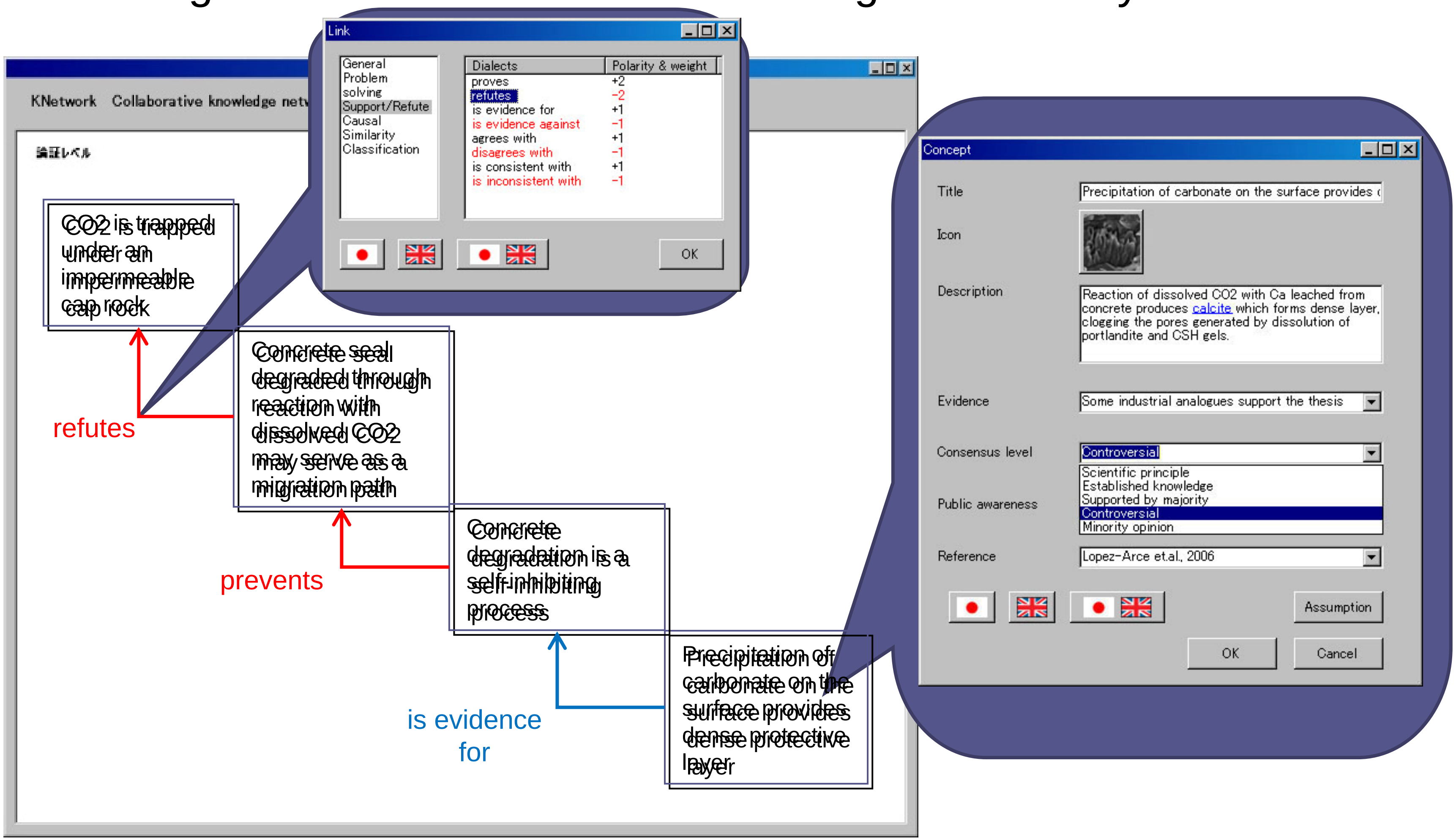
A6	CO_2 leakage might occur through abandoned well.
A7	No organization exists that takes legal responsibility of remedial activities against possible CO_2 leakage in the future.
D11	It can be confirmed from the record that all the abandoned wells were properly sealed and it is very unlikely for them to serve as migration paths.
D12	Organizations that can take financial responsibility for future remedial actions continue to exist as long as use of fossil fuels is continued.
D13	After termination of use of fossil fuels, it is unlikely for leakage of CO2 to contribute to global warming significantly.
D14	Since stability of confinement provided by geological storage is to be enhanced over time (S5), it is very unlikely for leakage to occur abruptly in the distant future.

Knowledge networking support tool for argumentation

KNetwork

Collaborative knowledge networking tool KNetwork

Network of arguments and associated knowledge with clearly defined “links”



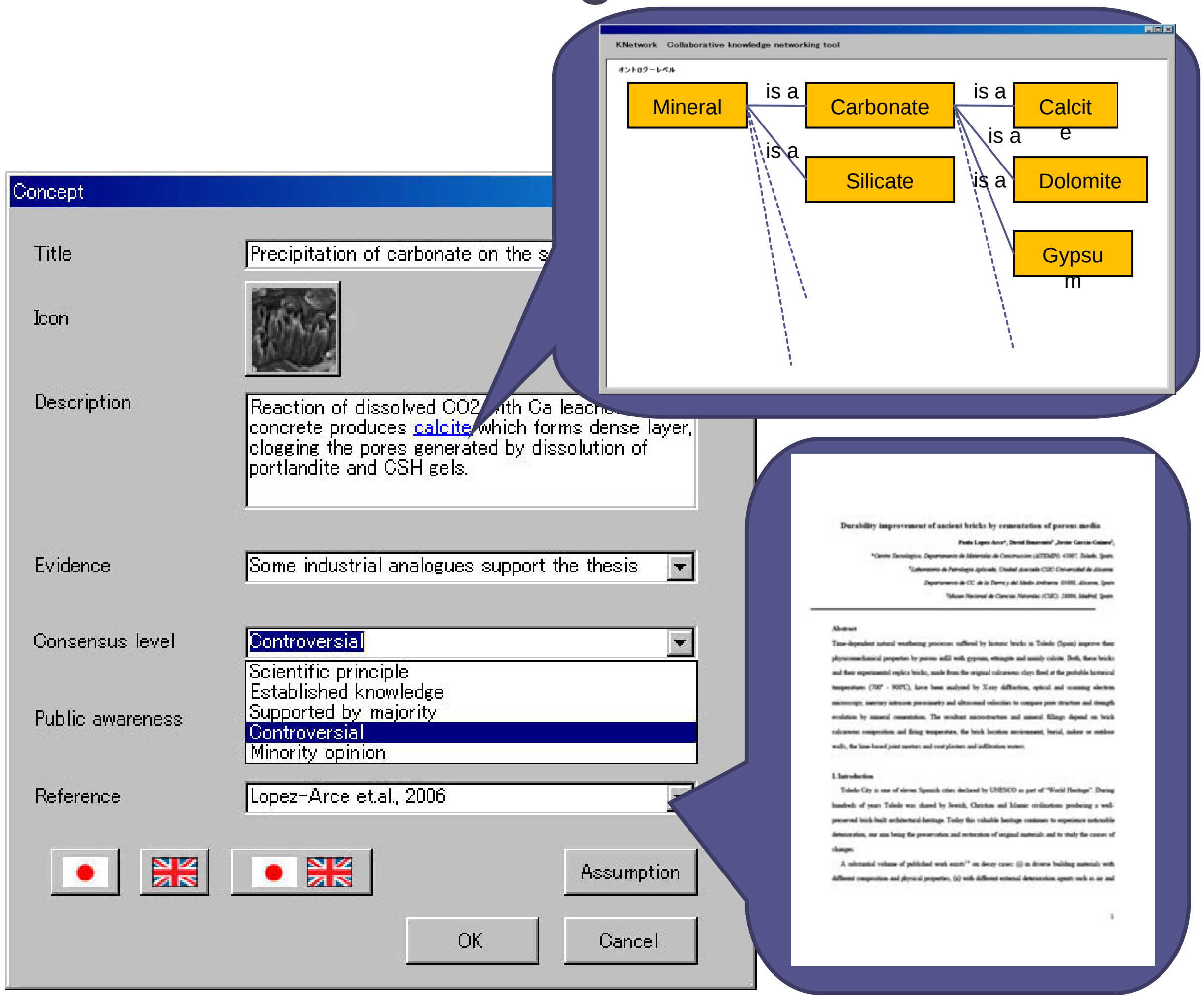
Class of "links" and their dialects

Class	Link	Polarity and weight
General	is about	+1
	uses/applies/is enabled by	+1
	improves on	+2
	impairs	-2
	other link	+1
Problem solving	addresses	+1
	solves	+2
Support/ refute	proves	+2
	refutes	-2
	is evidence for	+1
	is evidence against	-1
	agrees with	+1
	disagrees with	-1
	is consistent with	+1
	is inconsistent with	-1

Class	Link	Polarity and weight
Causal	predicts	+1
	envisages	+1
	causes	+2
	is capable of causing	+1
	is prerequisite for	+1
	prevents	-2
	is unlikely to affect	-1
Similarity	is identical to	+2
	is different to	-1
	is the opposite of	-2
	shares issues with	+1
	has nothing to do with	-1
	is analogous to	+1
	is not analogous to	-1
	part of	+1
Classification	examples of	+1
	subclass of	+1
	not part of	-1
	not example of	-1
	not subclass of	-1

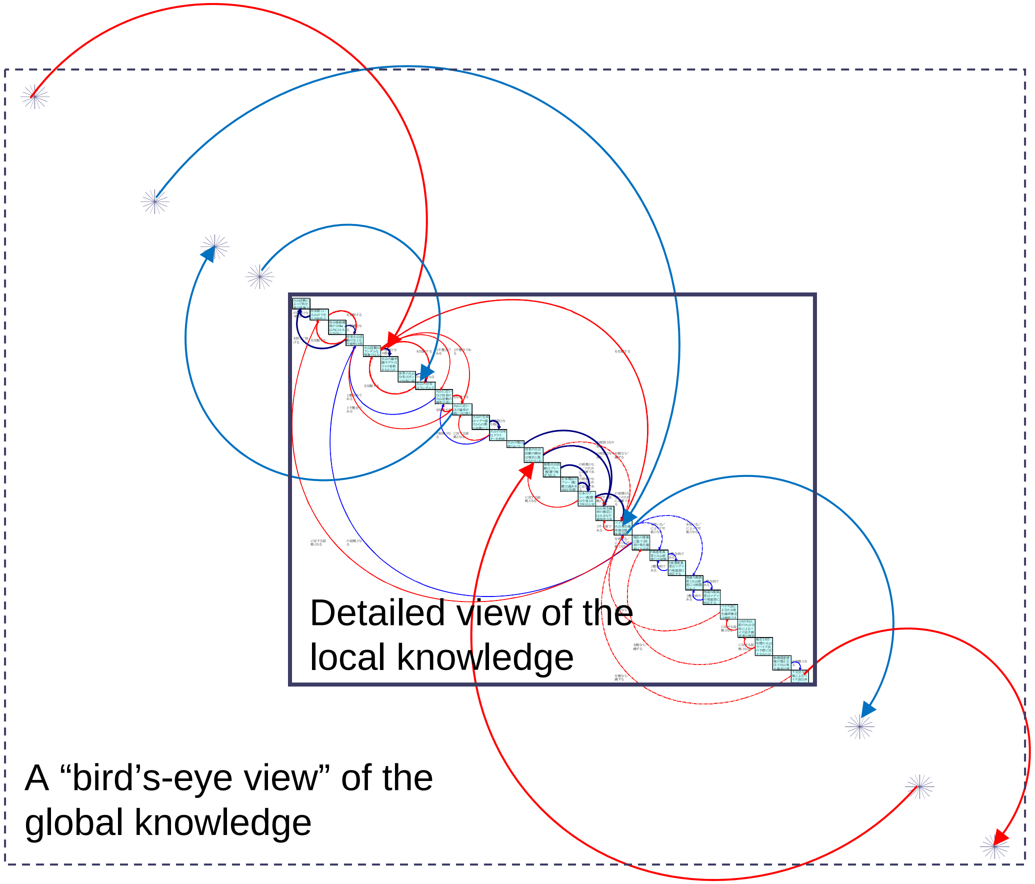
Hyperlink with other knowledge-bases

- Key concepts and terminology appearing in arguments are hyperlinked with the ontology base so that clear definition can be viewed when required
- Key scientific references are also hyperlinked with the relevant entry in KNetwork



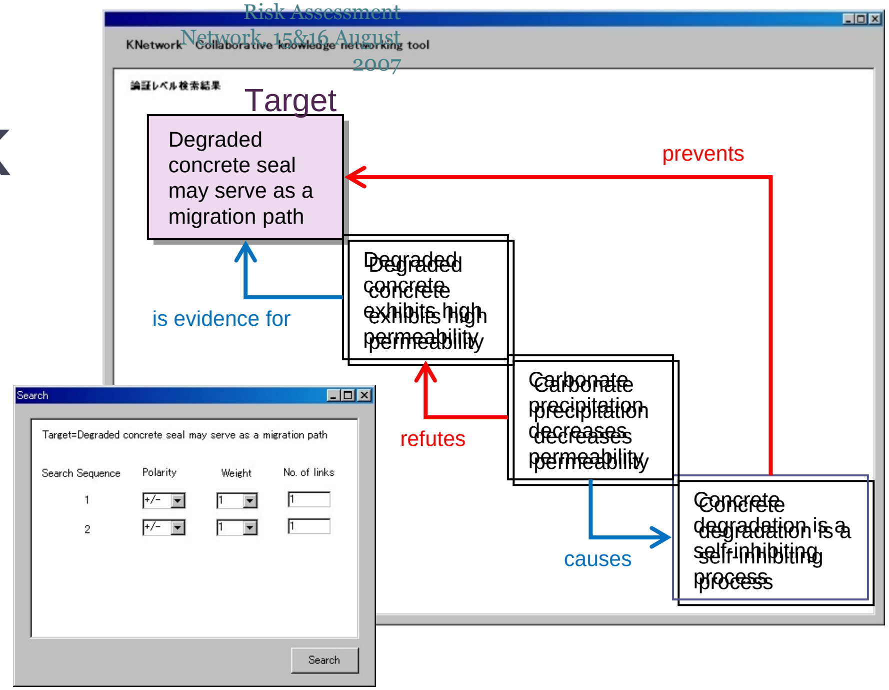
"Small network" concept to visualizing multi-disciplinary knowledge network

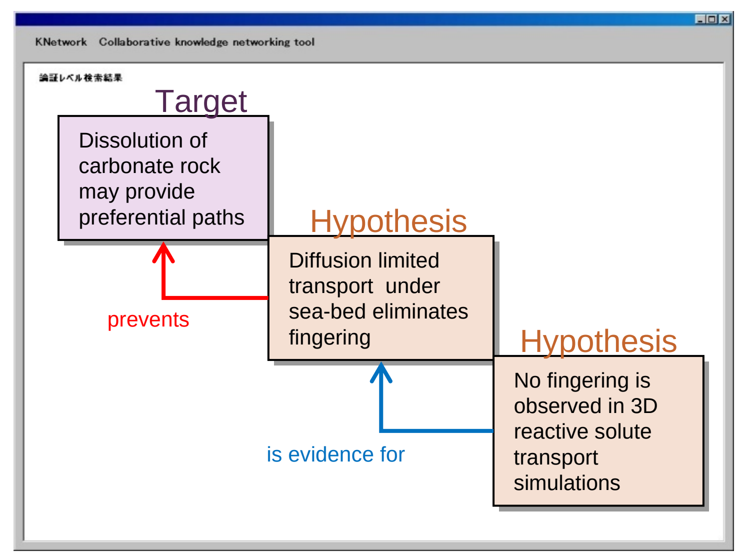
- Collaboration among experts on the web can result in a huge network.
- Each pair of knowledge from remote scientific backgrounds are connected with relatively small number of links via "hubs".
- Users can see both detailed network of their own research field and "hubs" in other fields when they search and define links.



Support to argument generation by KNetwork

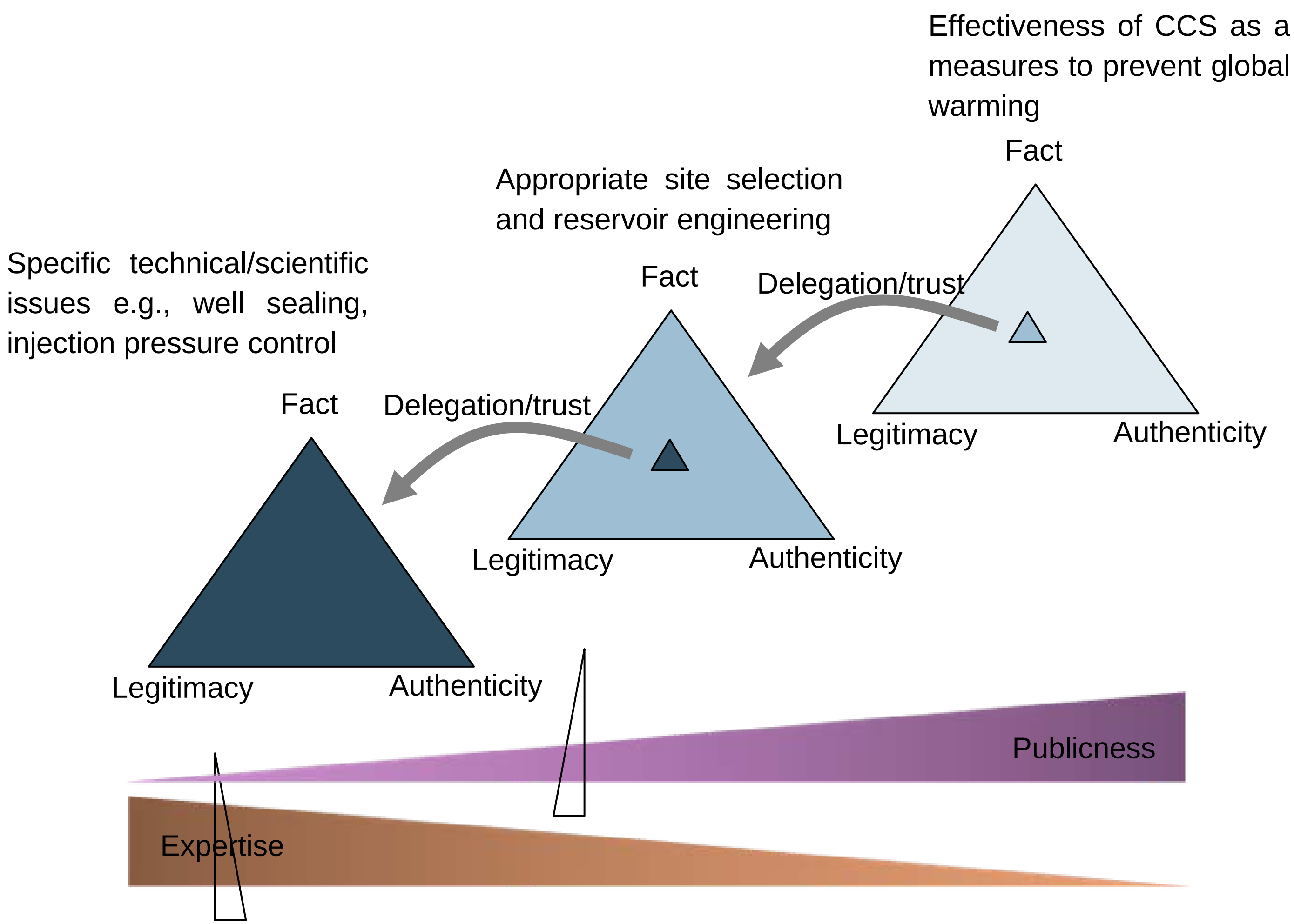
- Conditional search on the links can automatically pick up
  - Arguments that refute or are inconsistent with the target argument put forward by the opponents
  - Arguments that refute or are inconsistent with the argument supporting the target
- By including "working hypotheses" in addition to established knowledge, users can generate a tentative argument, highlighting R&D issues that are required for the tentative argument to become valid.





Concluding remarks

Towards construction of "chain of trust" through nested arguments



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Risk Assessment for CO_2 Storage in Geological Formations

Moving from Cottage Industry to Industrial Application

Tony Espie, Advisor CO_2 Storage

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Outline

- Context
- Where have we been
  - In Salah
- What are we doing now ?
  - DF1 - 6
- Where do we go from here ?

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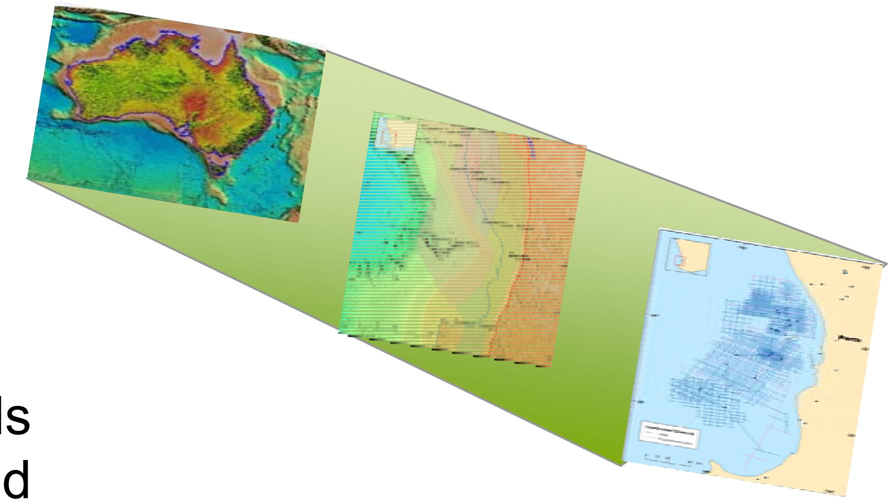
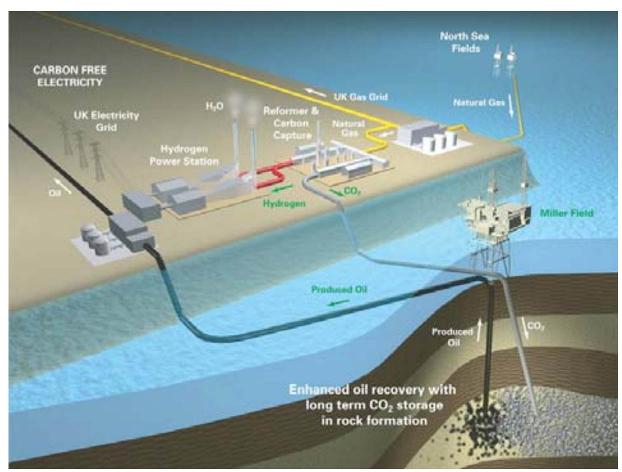
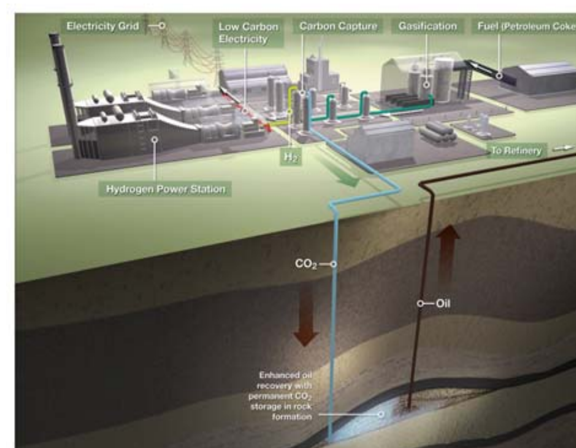
Context

- BP has one CCS project operational (In Salah) and six others other development (DF1 – 3 publicly announced)
- Need to streamline subsurface processes to focus on what needs to be done rather than what would be nice to have







Where Have We Been ?

Risk Assessment for In Salah

- Primary focus on :
  - Capacity
  - Impact on hydrocarbon operation
  - Injectivity
- Secondary focus on :
  - Seal capacity (thick regional seal)
  - Faulting (no faulting observed above reservoir)
  - Well integrity

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In Salah Gas Development

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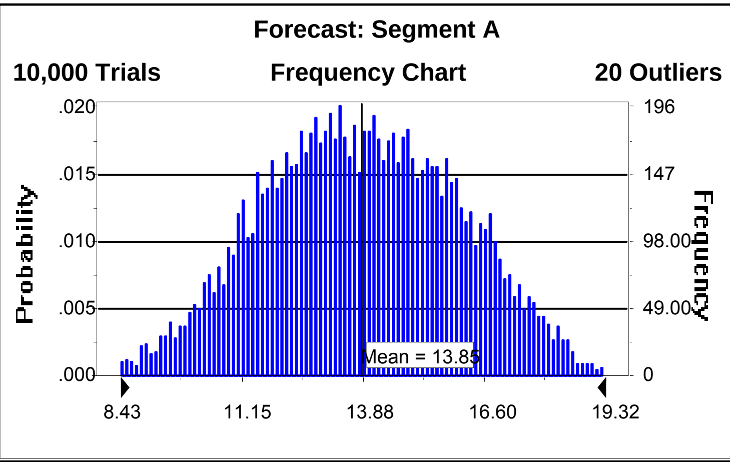
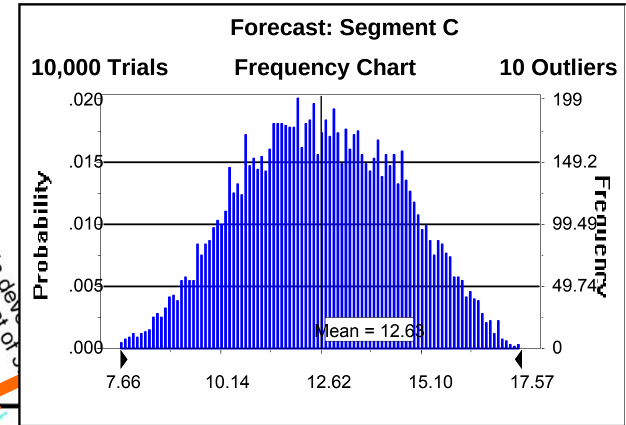
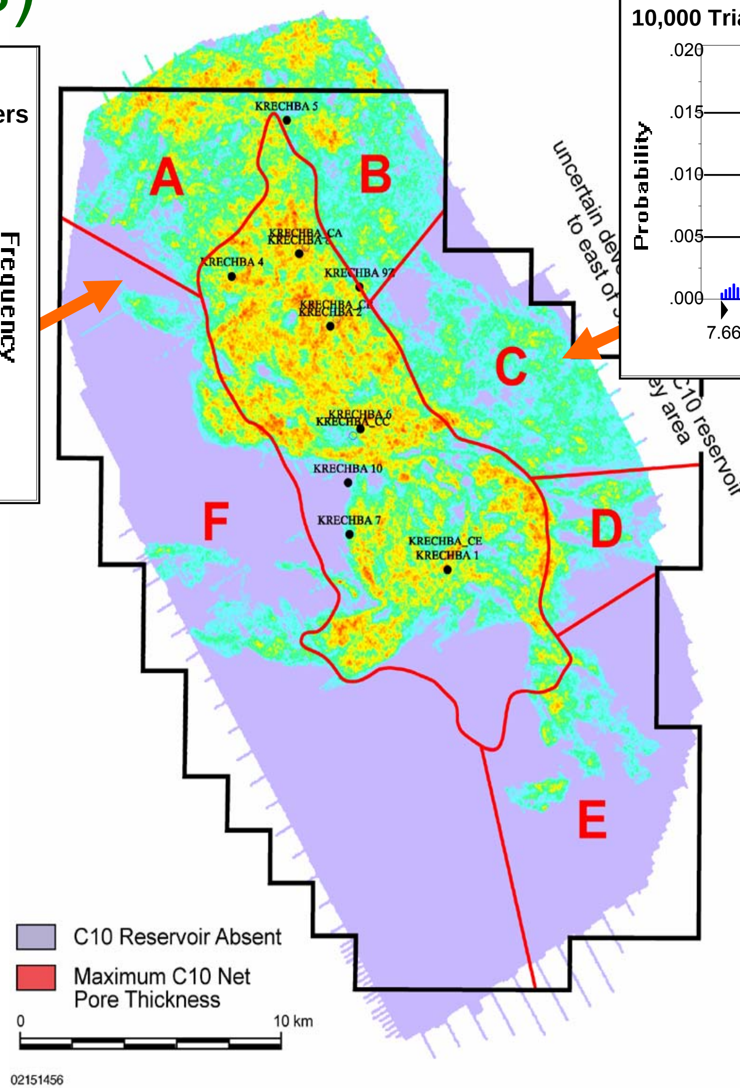
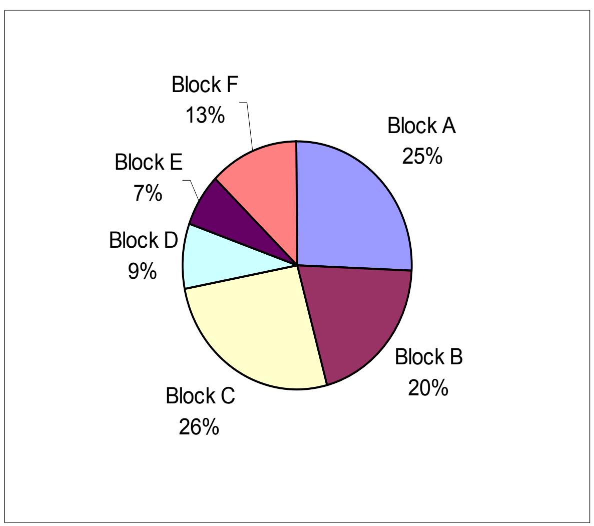
Forecast CO_2 Storage Capacity and Times (Years)









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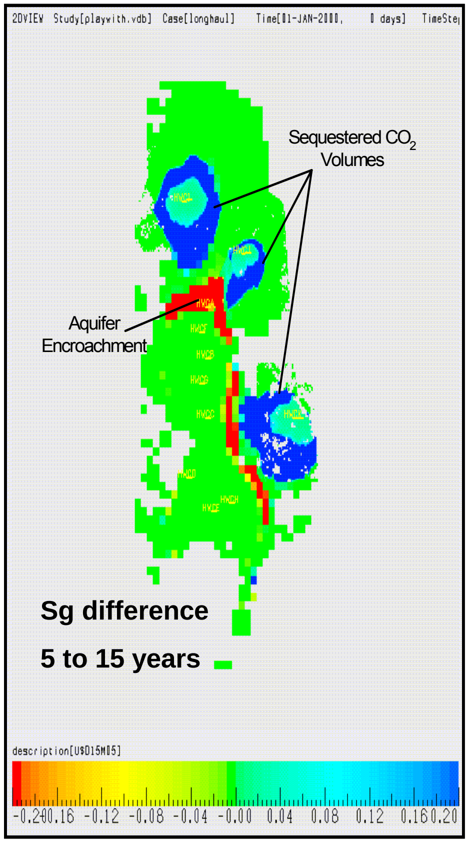

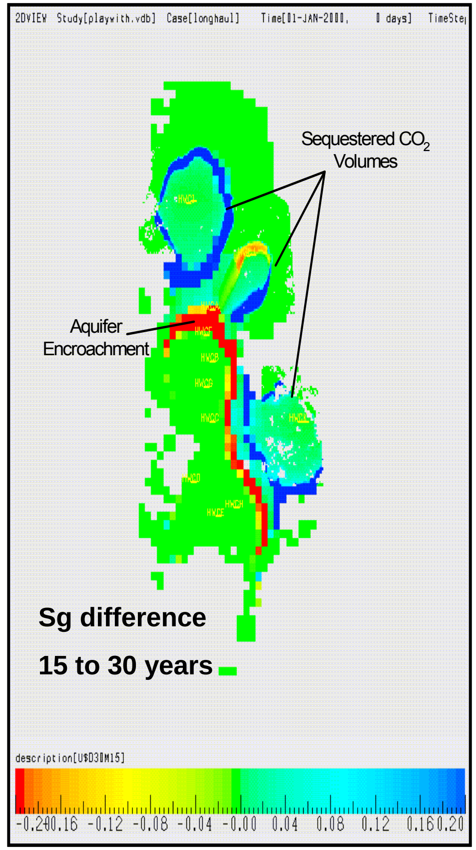

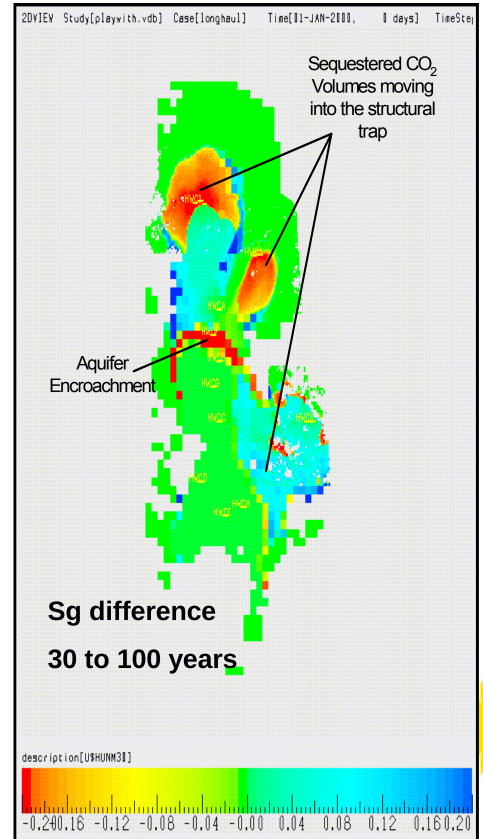

Change in gas saturations over time, resulting from CO2 injection at three locations

What Are We Doing Now ?

Structured process for Risk Assessment :
Australia-NZ Standard for Risk Assessment

- Identification of key risks and event scenarios
- Quantification of risks
- Evaluation of risks (with stakeholder input)
- Process modification to eliminate excess risk
- Monitoring and intervention strategy to manage remaining risk

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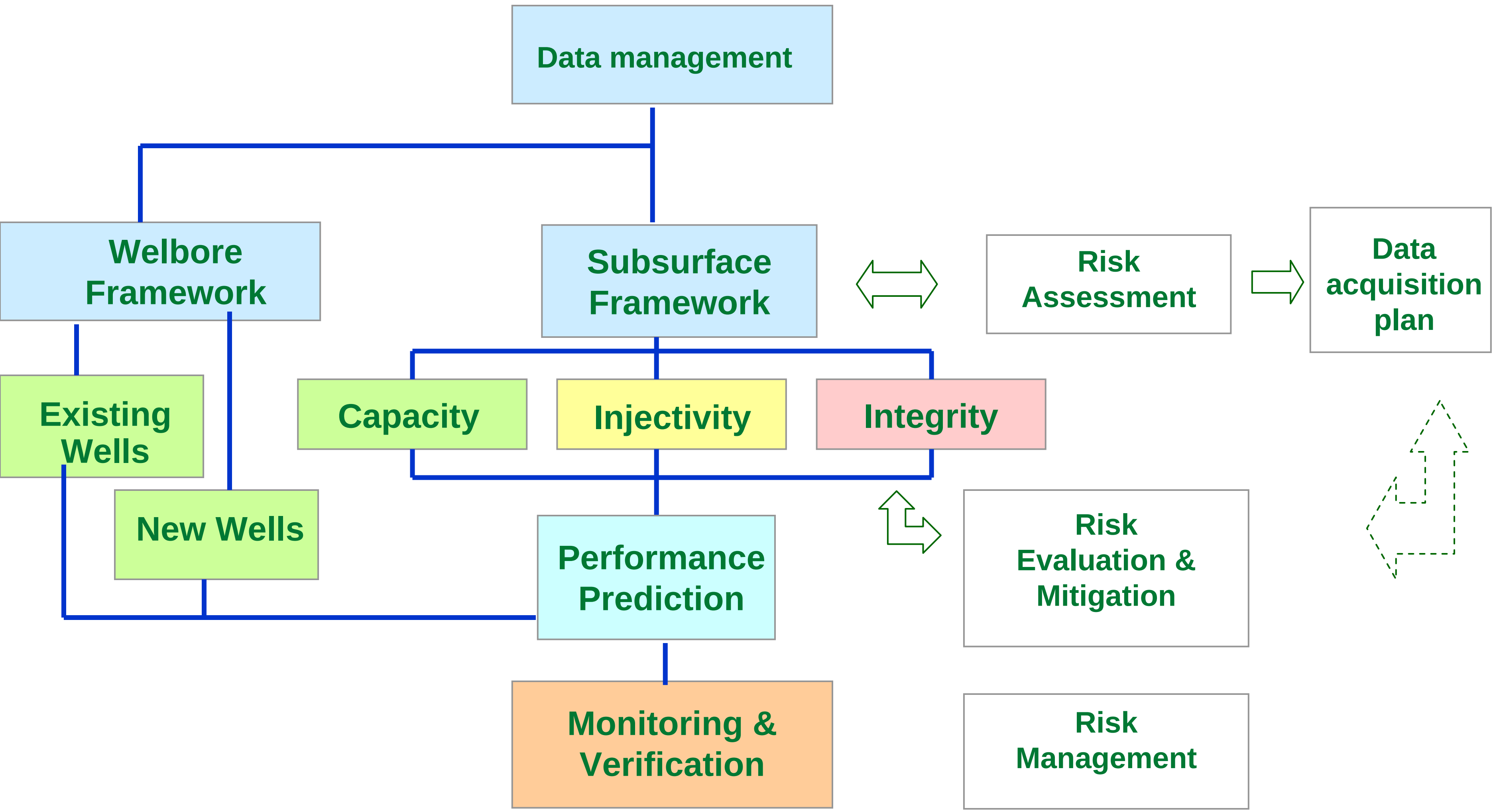
CO_2 Storage Workflow



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The Gaps

- Issue is not the workflow but rather the criteria that are used for evaluation
  - E.g. capacity
    - Bulk pore space vs Effective pore space vs seal capacity vs economic capacity ?
- Bust between capacity and rate
  - Utilisation of lower perm formations challenging
- Risk Assessment
  - Tools and processes for Quantitative Risk Assessment are not sufficiently robust for use in Regulatory processes
    - Look for unacceptable consequences as primary screening criterion in under-performing projects

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An Approach to Assessing CCS Projects

- Design to minimise risk
  - Site selection criteria
- Assess risks
  - Develop risk register
  - Model to understand controls on storage and potential downsides of injection rather than attempt to quantitatively predict performance over hundreds of years
  - Test – can we live with consequences ?
- Monitor to manage risks
  - Look for early indicators of problems
    - e.g. pressure-mass balance inconsistencies
    - Wellbore integrity

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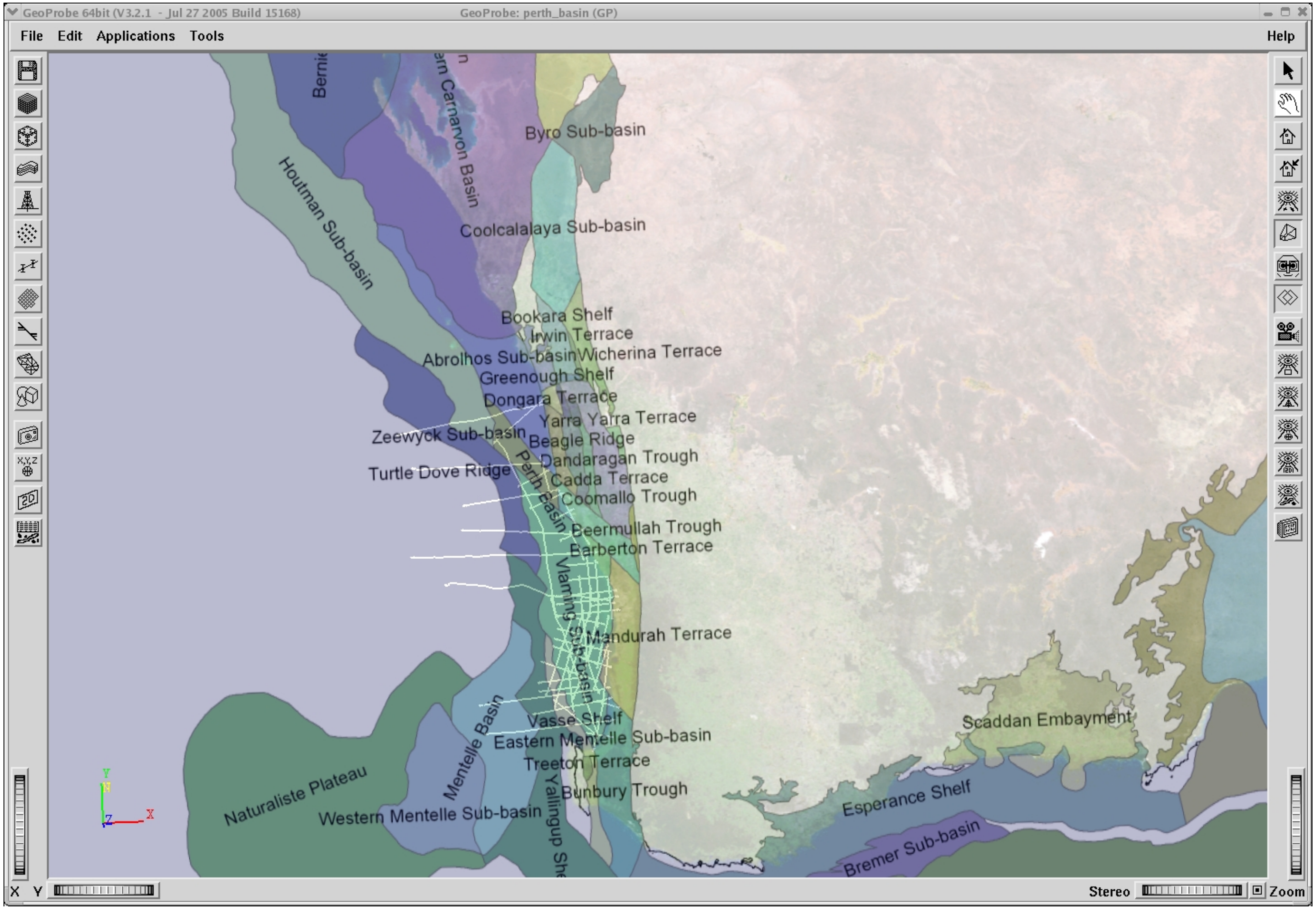
Regional setting: WA sedimentary basins



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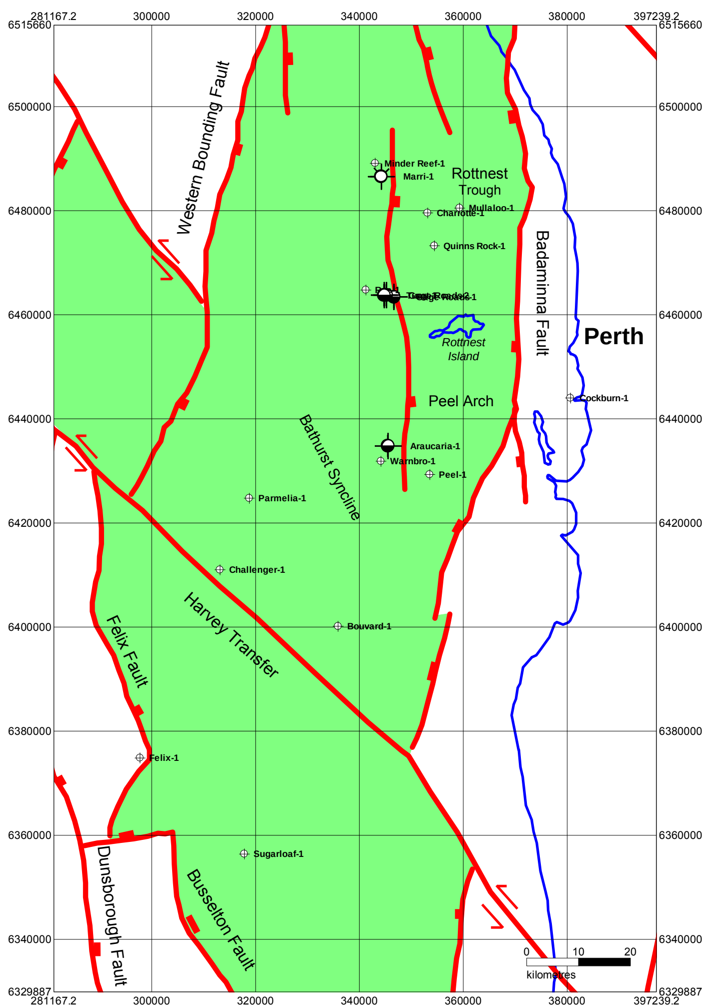
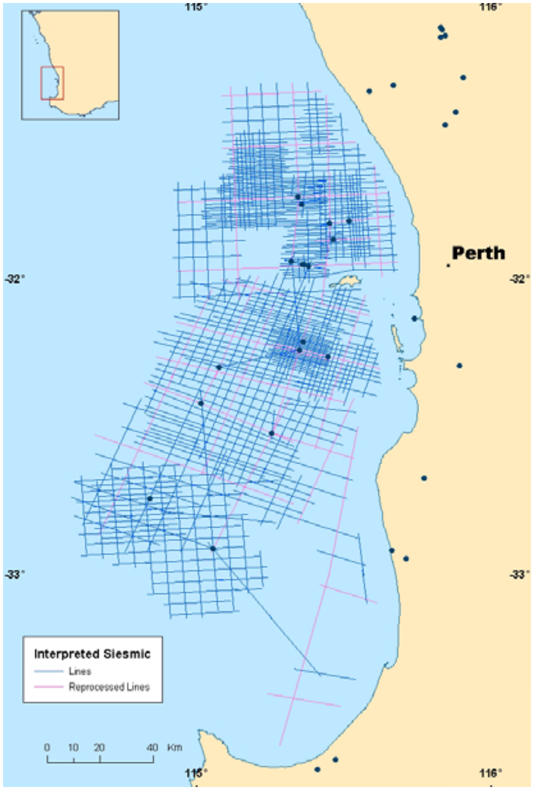
Structural Framework: Vlaming sub-basin



- Fault-bounded basin
- Shallow water (200m)
- Close proximity to Kwinana refinery
  - 20km offshore
- Thick sedimentary succession
  - >15km sediment
- Identified as a potential storage site by CO2CRC study

Database

- Open file subsurface database available
  - variable quality / density
- 2D seismic grid
  - 9100 line km
  - variable vintage/quality
- 18 exploration wells (1967-1998)
  - variable log suite / quality
  - no discoveries
  - 2 reported oil shows
  - trace gas through drilled section



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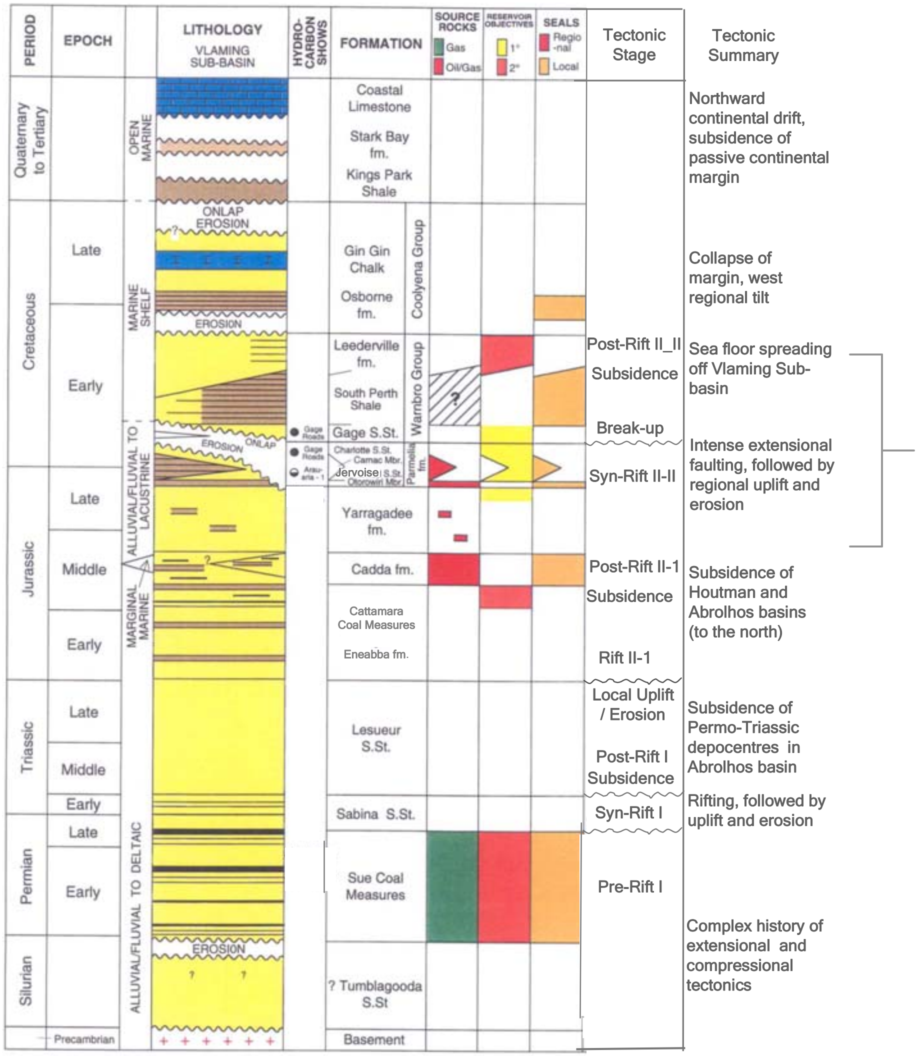
Stratigraphy



3 potential storage systems (reservoir/seal pair) being assessed:

Gage Sandstone / South Perth Shale

Parmelia Group sandstones / shales

Yarragadee Fm (sst) / Otorowiri Fm (shale)

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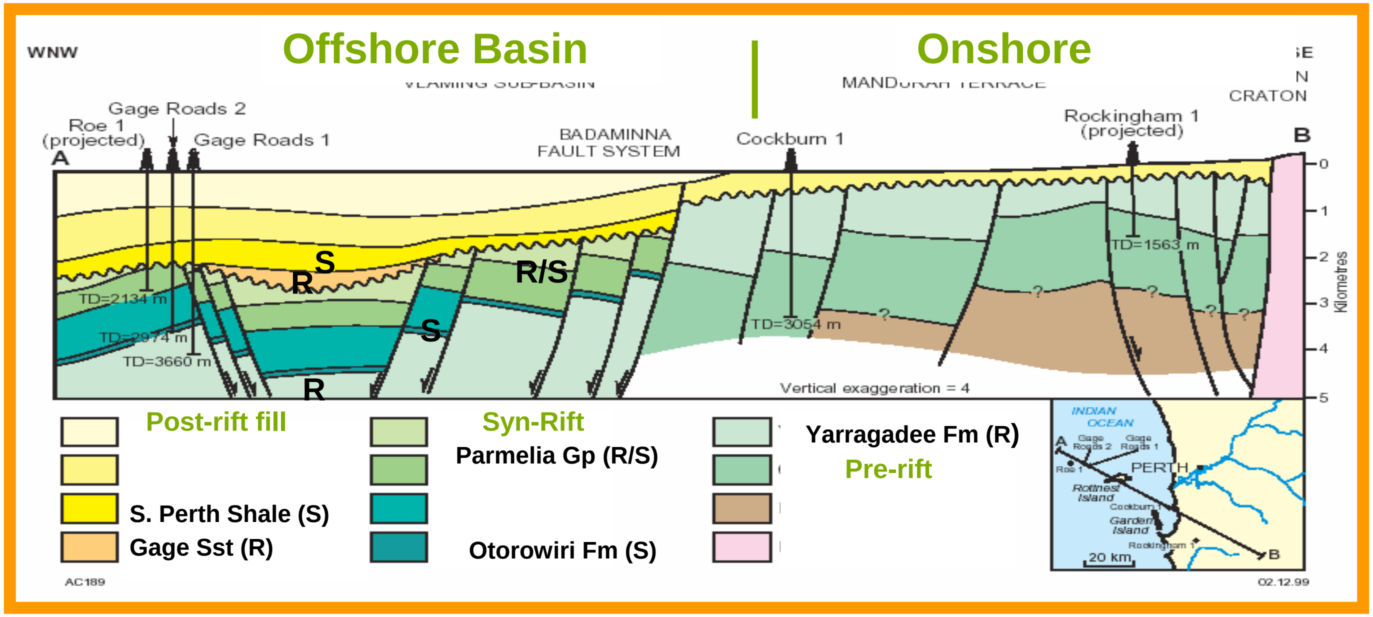
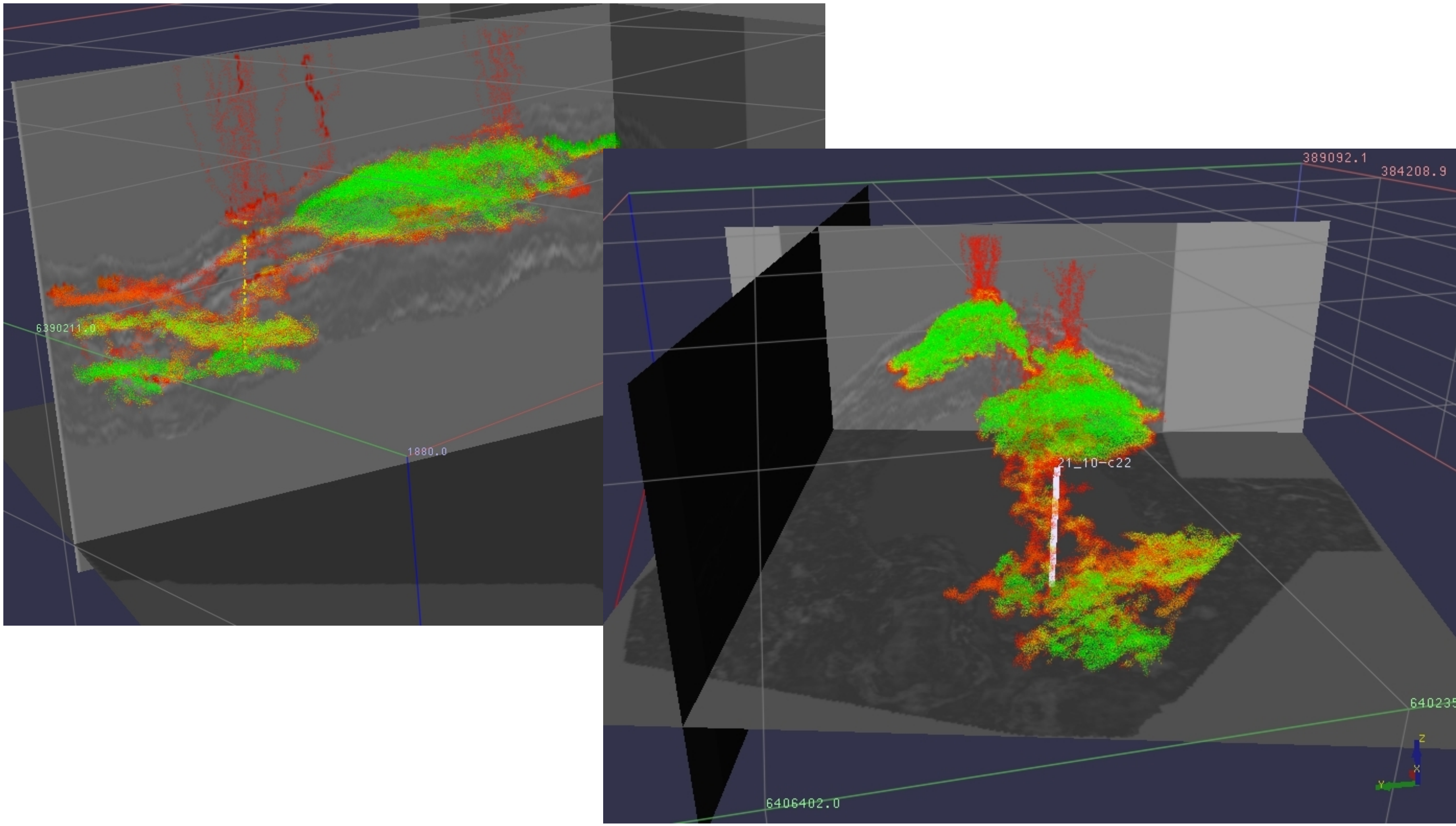
NW-SE cross-section across Vlaming sub-basin



Evaluating Seal Integrity



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Creating Risk Register

	Risk	Monitoring Data Needed	Mitigation	Remarks
Surface facilities				
	Facilities failure : flange leakage	**Leak detection Atmospheric concentration**	**Protect by minimising flanges on CO2 system, i) Automatic gas detection system and shutdown system ii) Integrity inspections / portable detection**	**Personal exposure limits in facilities**
	Facilities failure : Vessel / pipework failure	**Leak detection Atmospheric concentration**	**i) Automatic gas detection system and shutdown system ii) Integrity inspections / portable detection**	**Personal exposure limits in facilities**
	Compressor failure : seals failure	**Leak detection Atmospheric concentration**	**Instrument alarms**	**Personal exposure limits in facilities**
	Pipeline failure : corrosion through carbonic acid formation	**Line pressure Atmospheric concentration**	**Protect through : i) 4^{th} stage compressor operating conditions ii) Dehydration with glycol (malfunction alarms on plant) iii) Pipeline blowdown for long shutdown period iv) Integrity management Remote concentration monitoring**	**Release modelling required to evaluate implications**
	Wellhead failure : wellhead rupture and uncontrolled release	**Surface monitoring**	**i) Automatic wellhead shutdown system (low pressure trip) ii) Wellhead downhole check-valve**	
	Metering failure	**Calibration of meters**		

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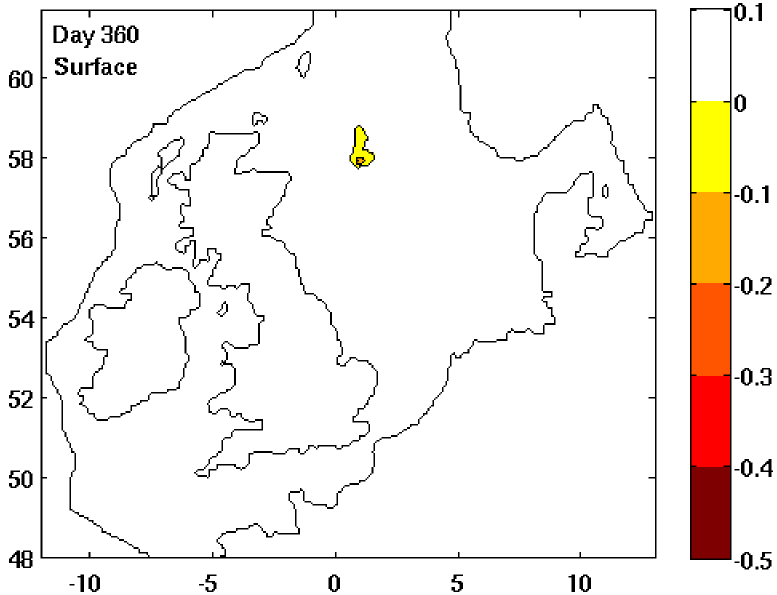
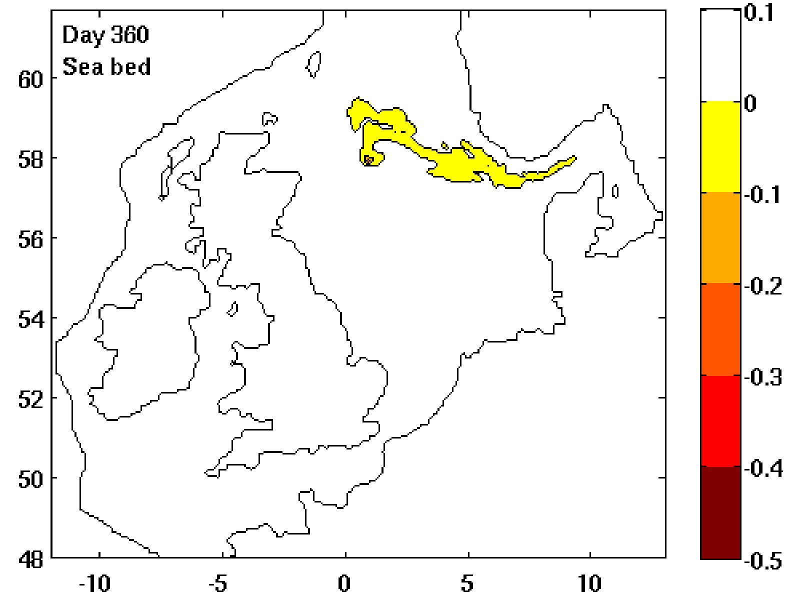
Modelling of Releases





Simulated Pipeline release into North Sea :
4 million tonnes/year for 1 year

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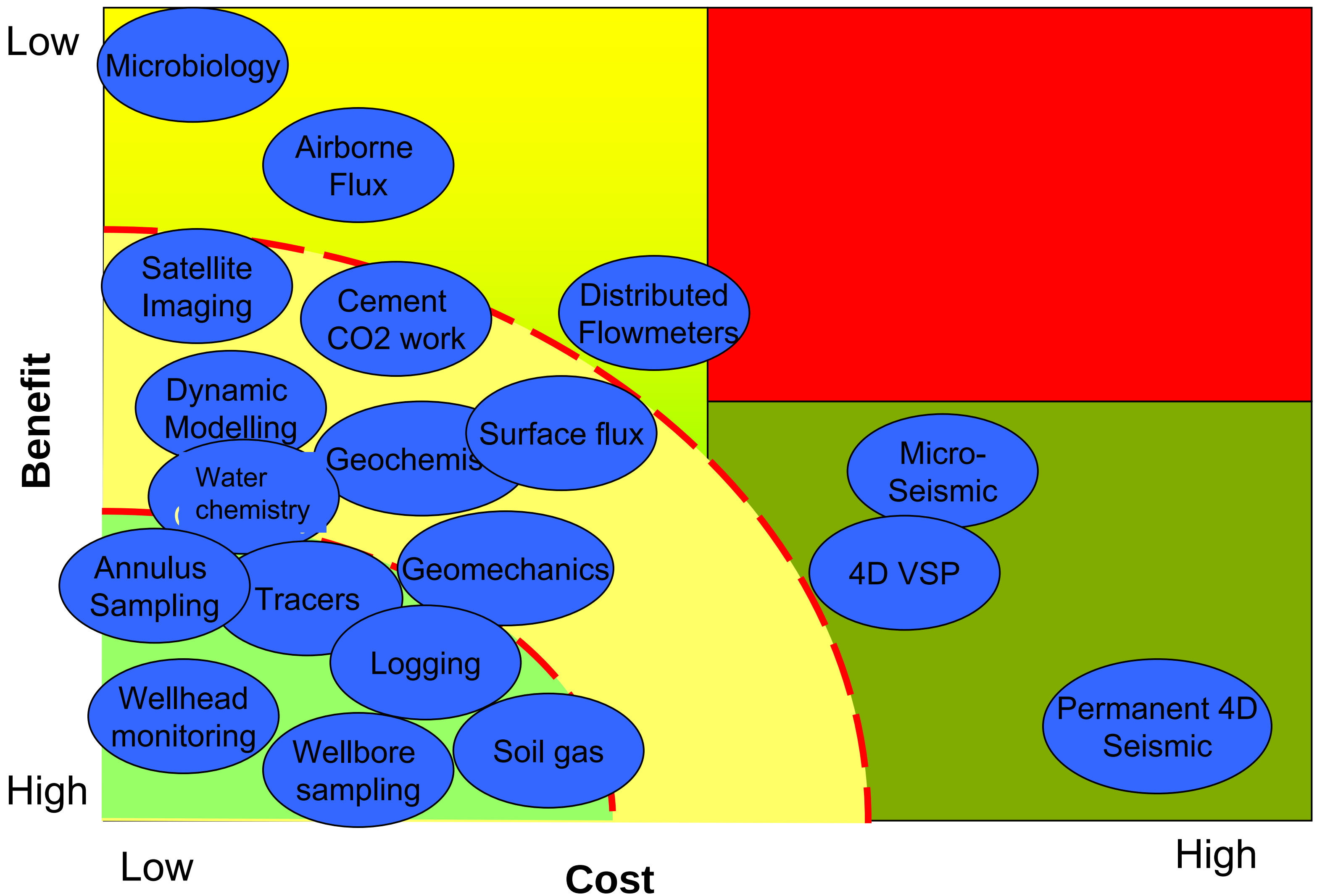
Focused Monitoring Deployment



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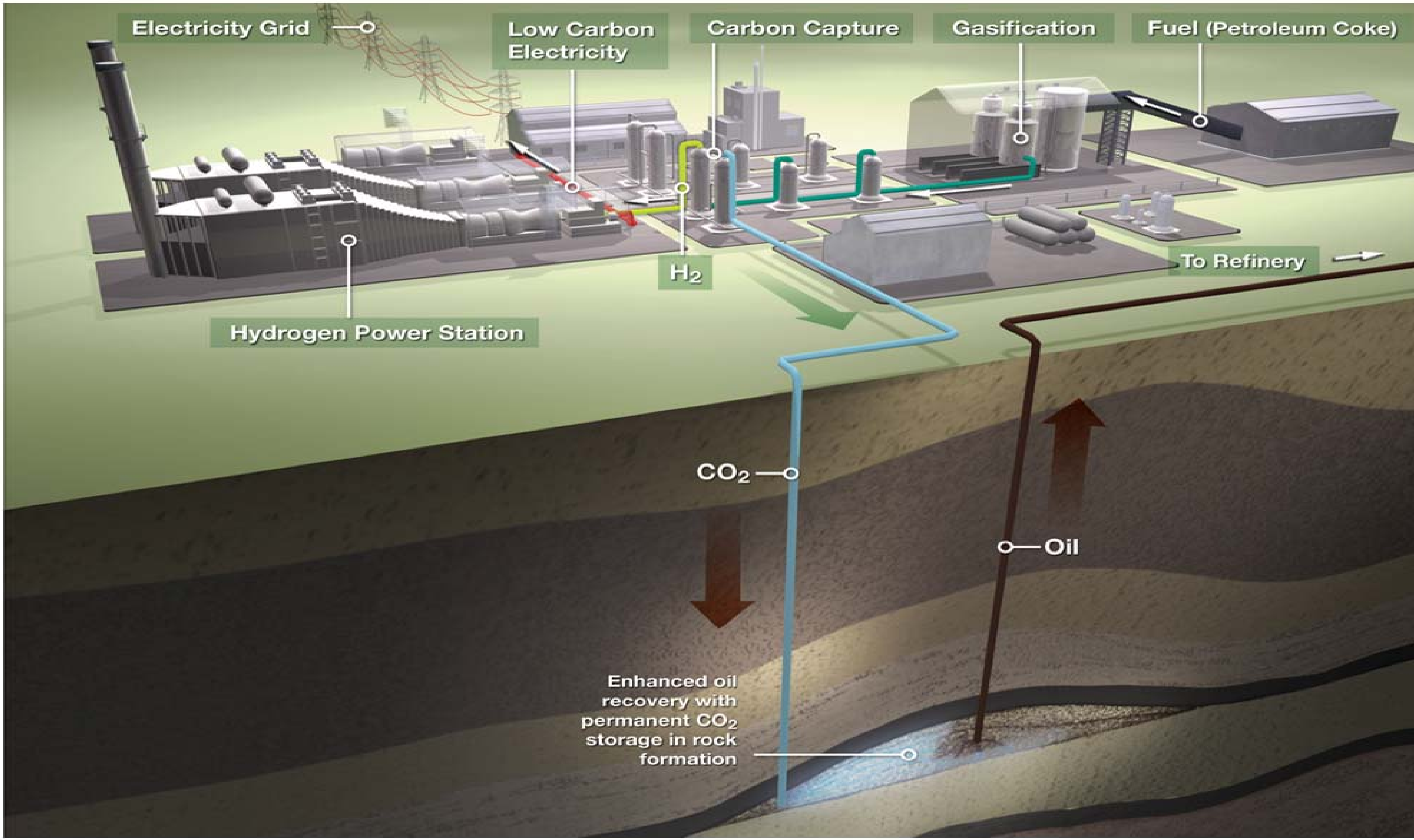
Questions ?



Risk assessment expectations

IEA GHG 3rd Risk Assessment Network Meeting
London, August 15th and 16th, 2007
Claudia VIVALDA – Schlumberger Carbon Services

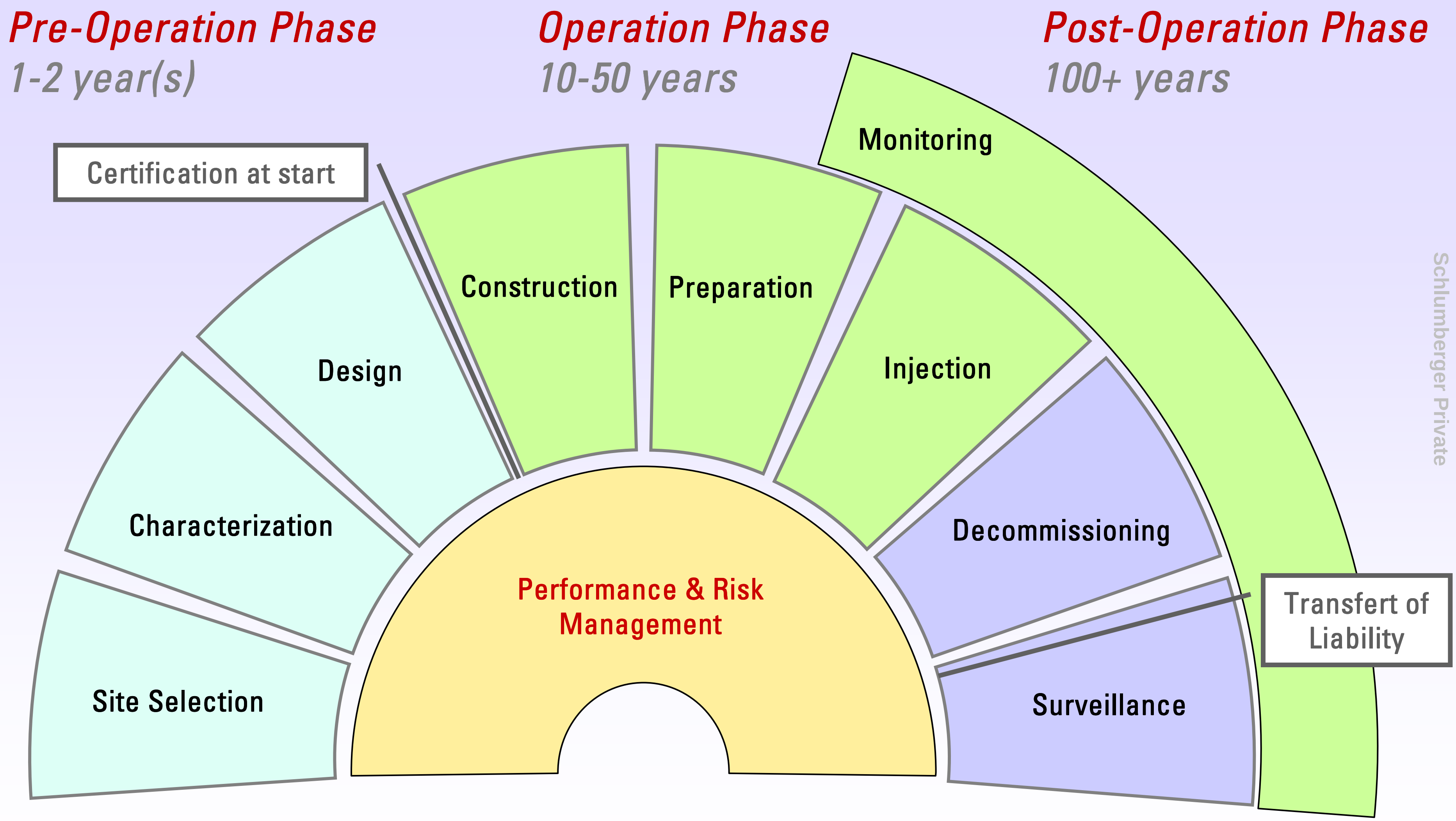
Content

- Introduction to CO2 storage Life-Cycle
- Risk Assessment versus CO2 storage Life-Cycle
- Quantitative Risk Assessment Steps
- CO2 Storage and Quantitative Risk Assessment
- Uncertainty Management
- Expert judgments in Risk Assessment
- Concluding remarks

Some definitions

- **Risk** is defined as the chance of something happening that will have a (generally adverse) impact on health&safety, environment, cost, image, ... It may be an event, action, or lack of action. It is measured in terms of consequences and likelihood/probability.
- **Qualitative risk assessment** is where the likelihood or the severity of the consequences are expressed in qualitative terms (i.e. not quantified).
- **Quantitative risk assessment** is risk assessment where the probability or frequency of the outcomes can be estimated and the severity of consequences is quantified so that risk is calculated in terms of probable extent of harm or damage over a given period. The estimation can be *subjective* (e.g. judgment) or *objective* (e.g. calculation).
- **Risk identification** is the process of determining what can happen, why and how. Identifying risks requires looking at all possible sources of risk and the elements at risk.
- **Pathway** is the mechanism of exposure of a receptor to a stressor, e.g. environment to CO2 leakage.
- **Uncertainty** is lack of knowledge about specific variables, parameters, models, or other factors.
- **Expert judgment** means judgments obtained from experts about their field of expertise that are explicitly stated and documented for review and appraisal by others.

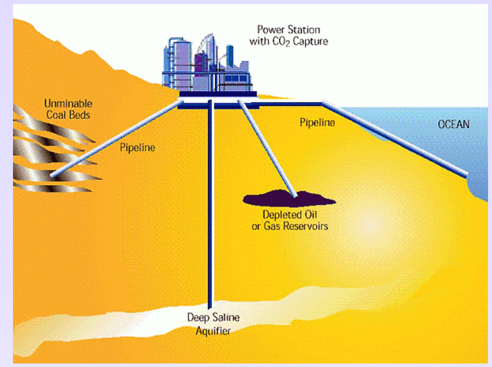
The CO2 Storage Life-Cycle



Risk assessment vs CO2 Storage Life-Cycle (I)

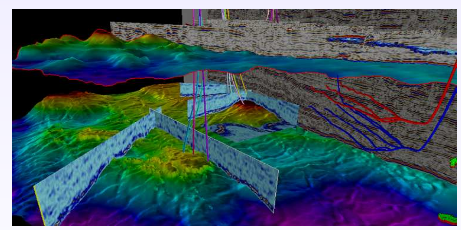
- **Site selection**:
  - *Objective*: maximize performance, minimize the risks. Qualitative Risk Assessment. Quantitative (subjective) Risk Assessment.

    Methods: e.g. risk register, what-if analysis, Analytical Hierarchy Process, experts' elicitation, FEP analysis, RISQUE method, …



- **Characterization**:
  - *Objective*: know what is important, to have the risks under control at the best performance. Iterative process. From Qualitative to Quantitative Risk Assessment.

    Methods:
    - Qualitative: see above + others (to be identified/developed)
    - Quantitative: to be identified/developed



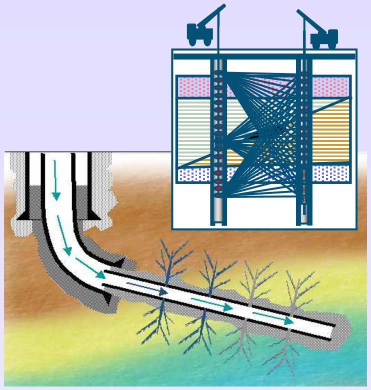
Approach: region/site specific.

No universal recipe at the current state of the art.

Risk assessment vs CO2 Storage Life-Cycle (II)

- **Design**:
  - *Objective*: assure a robust design vis-à-vis the performance requirements and risks avoidance. Qualitative and/or Quantitative Risk Assessment of the engineered system.

    Methods:
    - Qualitative: see above + FMECA, HAZID, HAZOP, etc
    - Quantitative: FT/ET, Petri Nets, Markov chains, etc. for the engineered system. To be identified/developed for the geological system.



- **Construction**:
  - *Objective*: build the system as designed, do not introduce additional risks or notify them if unavoidable, minimize operation risks. Qualitative/Quantitative Risk Assessment.

    Methods: e.g. risk register, HARC, what-if analysis, …

Approach: region/site specific.

No universal recipe at the current state of the art.

Risk assessment vs CO2 Storage Life-Cycle (III)

- **Preparation**:
  - *Objective*: no induced risks, proceed according to the procedures. Qualitative risk assessment.

    Methods:
    - Qualitative/Quantitative: risk register, risk avoidance procedures, HAZOP, ...

- **Injection**:
  - *Objective*: optimize operations to achieve the foreseen performance and to keep the risks under control. Update Qualitative and Quantitative Risk Assessment. Risk Management.

    Methods:
    - Qualitative/Quantitative: risk register update, RCM, …

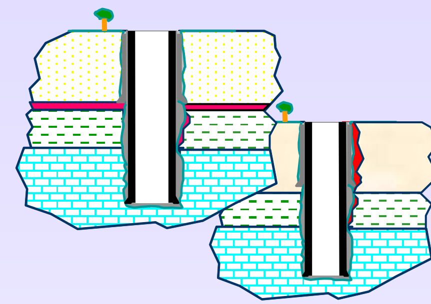
Approach: region/site specific.

No universal recipe at the current state of the art.

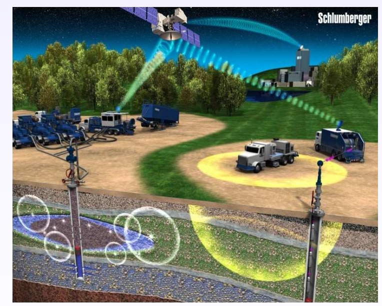
Risk assessment vs CO2 Storage Life-Cycle (IV)

- **Decommissioning**:
  - *Objective*: optimize plugging design to minimize long term risks, minimize operation risks, minimize geological system risks. Qualitative and Quantitative Risk Assessment.

    Methods:
    - Qualitative: risk register, what-if analysis, Analytical Hierarchy Process, experts' elicitation, FMECA, HAZID, HAZOP, etc
    - Quantitative: FT/ET, etc. for the engineered system. To be identified/developed for the geological system.



- **Surveillance**:
  - *Objective*: monitor/survey what is important, to have the risks under control. Update Qualitative and Quantitative Risk Assessments.



Approach: region/site specific.

No universal recipe at the current state of the art.

Quantitative Risk Assessment (QRA)

- QRA tries to answer the questions:
  1. **What** can go wrong?
  2. **How likely** is it to go wrong?
  3. **What** are the **consequences** of going wrong?
  4. **What** is the **confidence** in the answers to the above questions?

Formal answers to the questions

- **What**: relies on qualitative methods, e.g. FMECA, HAZID, HAZOP, Experts' elicitation. Initiating events are identified.

  Note: QRA pass through a qualitative phase

- **How likely**: is estimated using formal methods, e.g. fault trees, Markov chains, Petri nets, statistics. Likelihood are typically quantified using probability theory. Subjective judgment can also be employed.

- **Consequences**: are estimated using formal and simulation models, e.g. event trees, cloud or smoke dispersion models, fire propagation models, soil and near underground contamination models, oil/gas layer dispersion.

- **Confidence**: is assessed conducting e.g. uncertainty and sensitivity analysis, benchmarks.

Successfully applied to engineered systems

CO2 Storage risk

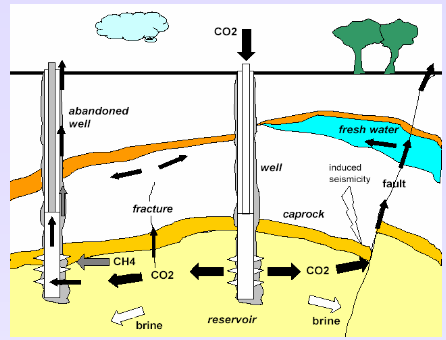
Definition

- CO_2 Storage risk is defined as loss of injectivity, capacity, containment (effectiveness)

CO2 Storage and QRA

- **What**: imaginative process to build risk pathways and scenarios, supported by e.g. risk register, what-if analysis, experts' elicitation, FEP analysis, RISQUE method,…
- **How likely**: expert judgment, natural analog(?), ??
- **Consequences**: natural analog, laboratory and field tests, dynamic simulation models, e.g. CO_2 plume migration, mechanical interactions, physical and chemical reactions, fault and fracture behavior, …
- **Confidence**: uncertainty and sensitivity analysis, benchmarks, …

Zoom on: what confidence



(from Damen et al, 2003)

-25 to -20	BLACK	NON-OPERABLE:	Evacuate the zone and or area/country
-16 to -10	RED	INTOLERABLE:	Do not take this risk
-9 to -5	YELLOW	UNDESIRABLE:	Demonstrate ALARP before proceeding
-4 to -2	GREEN	ACCEPTABLE:	Proceed carefully, with continuous improvement
-1	BLUE	NEGLIGIBLE:	Safe to proceed

MITIGATION / Control Measures / PREVENTION — LIKELIHOOD → ; SEVERITY ↓

SEVERITY \ LIKELIHOOD	Improbable 1	Unlikely 2	Possible 3	Likely 4	Probable 5
Light -1	-1 1L	-2 2L	-3 3L	-4 4L	-5 5L
Serious -2	-2 1S	-4 1S	-6 3S	-8 4S	-10 5S
Major -3	-3 1M	-6 2M	-9 3M	-12 4M	-15 5M
Catastrophic -4	-4 1C	-8 2C	-12 3C	-16 4C	-20 5C
Multi-Catastrophic -5	-5 1MC	-10 2MC	-15 3MC	-20 4MC	-25 5MC

White arrow indicates decreasing risk

What confidence?

Uncertainty analysis

Objective: determine *how the uncertainty* in the initial conditions affect the results.

- Two main types (definitions from SANDIA National Laboratory)
  - **Aleatory uncertainty**: inherent variation associated with the physical system or the environment. Also referred to as variability, irreducible, stochastic, random uncertainty. Example: wearing processes, atmospheric conditions, ….
  - **Epistemic uncertainty**: due to lack of knowledge of quantities and processes of the system or the environment. Also referred as subjective, reducible, model form uncertainty. Example: lack of experimental data, poor understanding of physics phenomena, ….

Why separate aleatory and epistemic uncertainty

- **Epistemic uncertainties** are reducible: if we identify them and rank them according to their impact on the risk figure, risk can then be significantly reduced by further data acquisition on the most contributing parameters

- **Aleatory uncertainties** are intrinsic: further data acquisition gives better knowledge about the shape of their probability distribution. The impact on the risk figure could be less significant

Where uncertainties are hidden?

- Measurements
- CO_2 physical/chemical/mechanical interactions with surrounding environment
- Models
- Numerical implementations / Simulations
- Pathway/Scenarios selection and representation

Even if we do not address the full range of uncertainties in risk assessment we cannot forget that they exist

Main challenges

- **Representation**, **aggregation**, **propagation**, and **interpretation** of uncertainties
  - Identification of *relevant parameters* to assess risk pathways
  - Identification of *uncertain parameters*
  - *Classification of uncertainties* among aleatory and epistemic
  - Uncertain parameters *aggregation*, *reduction*
  - Uncertainty *propagation* through models
  - *Representation* and *interpretation* of uncertain results

What confidence?

- **Sensitivity analysis**

  Objective: identify *what parameters* affect the results most.

- **Benchmark** with other models and results comparison

Expert judgment use

- **Setting priorities** for data collection
- **Designing site data-collection** activities
- Determining the **level of resources** for reducing uncertainties
- **Quantifying the uncertainty** in numerical values for key parameters
- **Developing pathways/scenarios** and assigning corresponding **probability of occurrence**
- Formulating **approaches for validating conceptual and mathematical models** as well as **verifying computer codes**, e.g.
  - *Screen* insignificant scenarios
  - Select methods for *propagating uncertainty* through models and codes
  - *Quantify uncertainty* in the predictions
  - *Interpret* results

Formalized expert judgment process

Four step process:

- **Identifying** the **elicitation issues** and **information needs**
- **Selecting** the experts
- **Training** the experts
- **Carrying out** the elicitation sessions

Selecting the experts

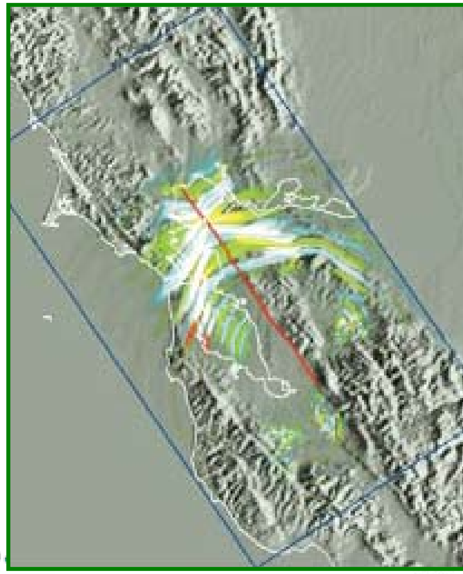
Three types of experts:

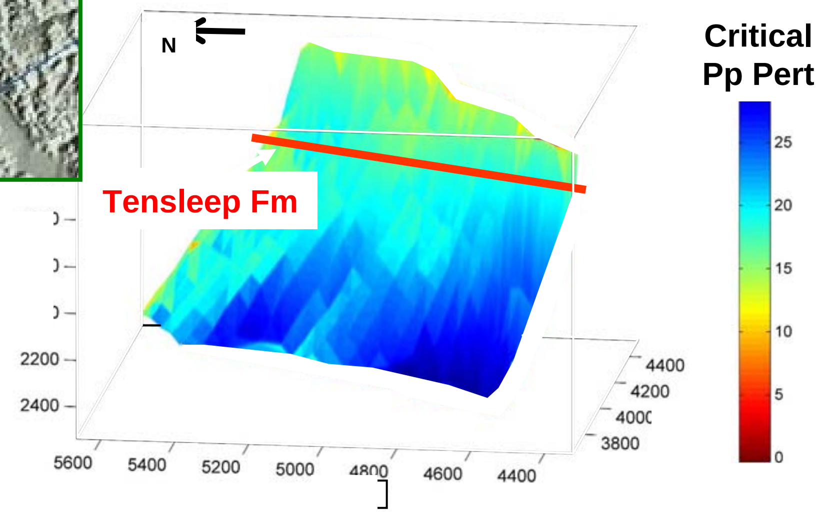
- **Generalists**: knowledgeable about various overall aspects of the storage site performance and risk assessment. Substantive knowledge in one discipline and general understanding of the technical aspects of the problem.
- **Specialists**: at the forefront of one specialty relevant to the performance of the storage site, but often do not have the generalist's knowledge about how their expertise contributes to the overall performance assessment.
- **Normative experts**: training in probability theory, psychology and decision analysis. Assist generalists and specialists with substantive knowledge in articulating their professional judgments.

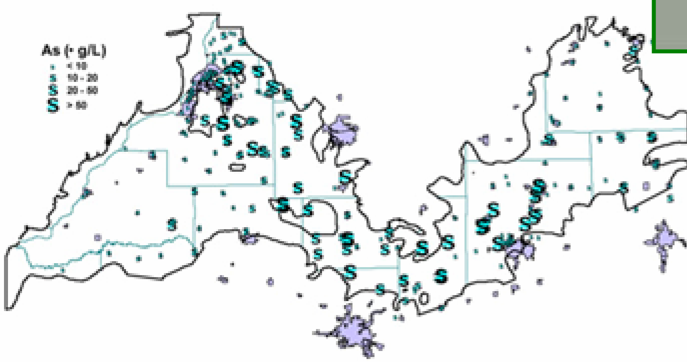
Concluding remarks

- For the first years, **site customized procedure** for risk assessment able to answer to the 4 questions initially raised, e.g. what wrong, how often, what consequences, what confidence. Combination of qualitative and quantitative methods
- Very **difficult to dissociate physical model from risk model**
  - Simulation models should be built taking into account quantitative risk assessment needs
  - Uncertainties should be considered
- Need of a **set of models** that combined together can be used to build the "risk model" of a specific site

Operational protocols for geological carbon storage and a new hazard characterization approach







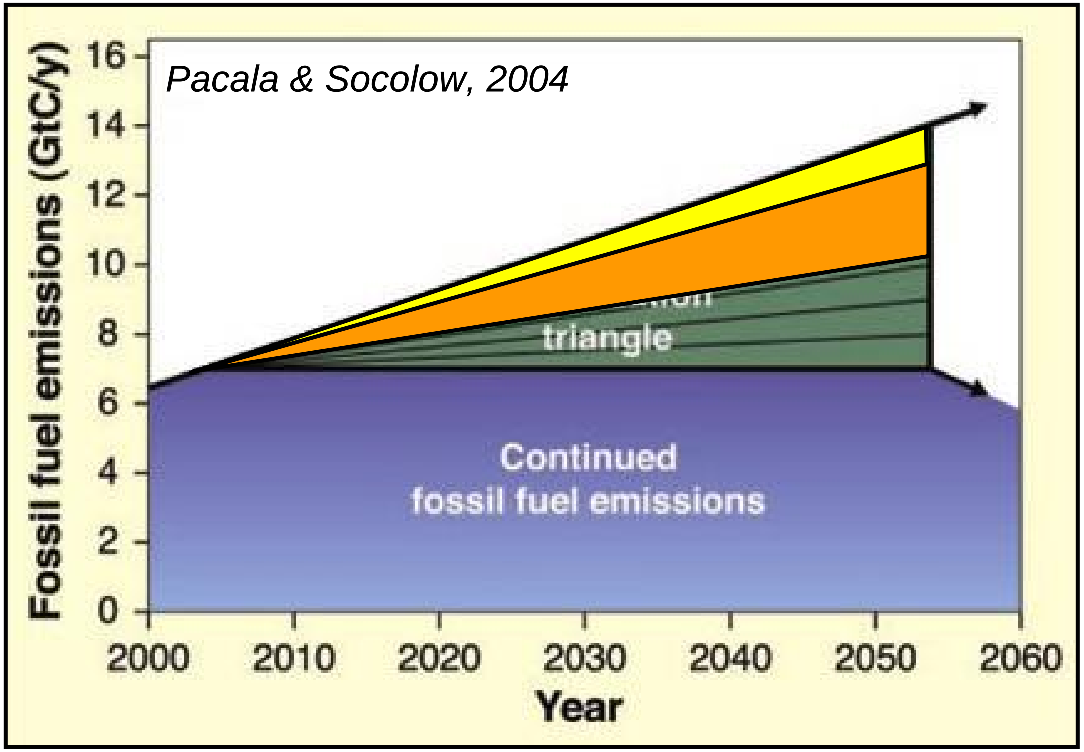
S. Julio Friedmann

Director, Carbon Management Program

Energy & Environment Directorate, LLNL

http://eed.llnl.gov/co2/

CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions



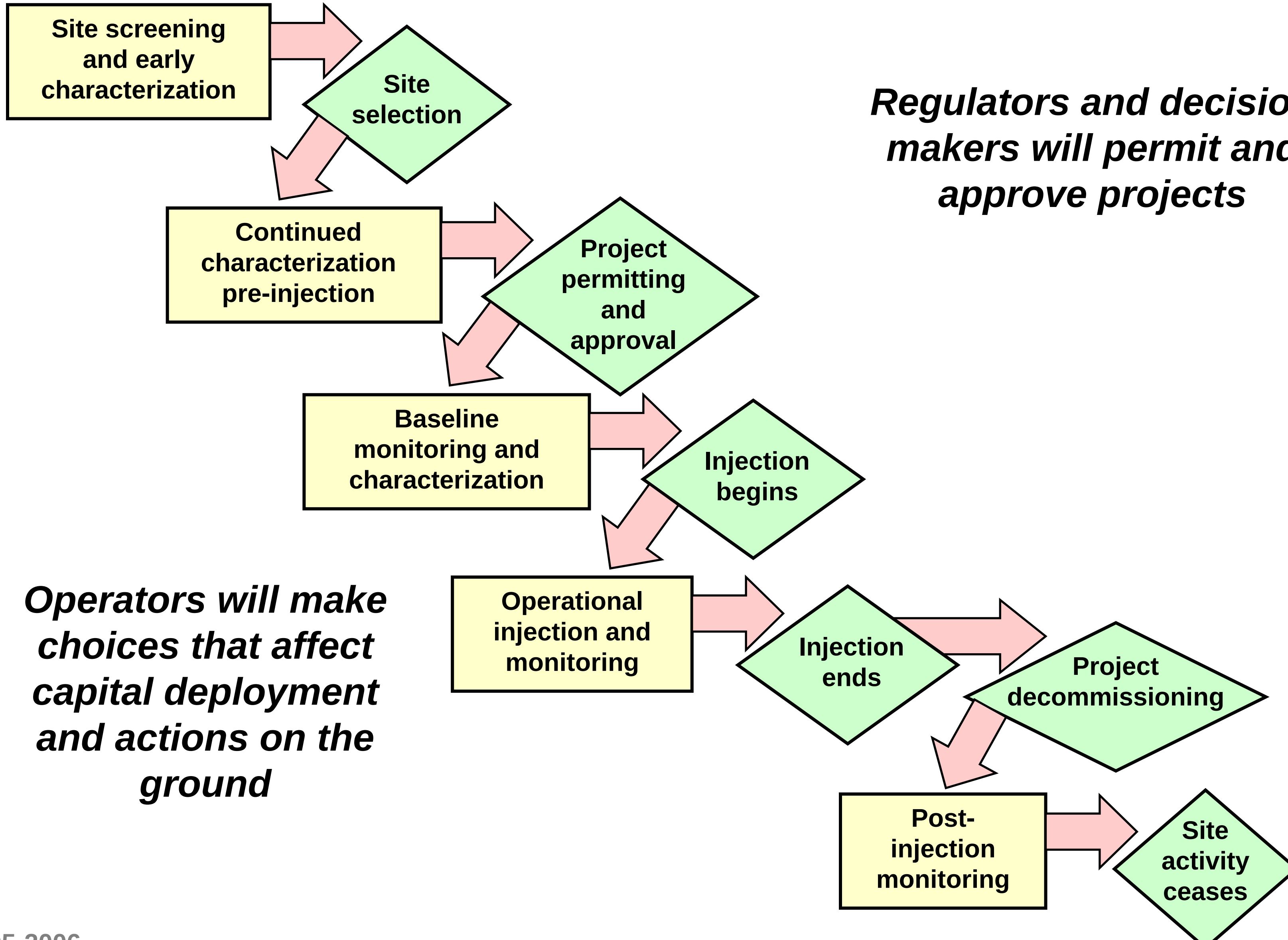
- A key portfolio component
- Cost competitive to other carbon-free options
- Uses proven technology
- Applies to existing and new plants
- Room for cost reductions (50-80%)

- ***ACTIONABLE***
- ***SCALEABLE***
- ***COST-EFFECTIVE***

This will require injection of very large CO_2 volumes a given site

- ***1 to 6 million tons/year***
- ***50 to 60 years***

Deployment of CCS is complex and will involve many tasks and decisions



Regulators and decision makers will permit and approve projects

Operators will make choices that affect capital deployment and actions on the ground

Why operational protocols?

CCS protocols help operators & regulators make decisions based on sound technical constraints across a range of geological circumstances

Protocols for CCS should help stimulate development of both commercial projects and evolving regulations

These protocols should also guide operators in terms of selecting and maintaining site effectiveness, esp. regarding key hazards and risks

Protocols should be FAST –
Flexible, Actionable, Simple, Transparent

The focus for operational protocols should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

RISK = Probability * consequence

RISKS are often difficult to determine

- **Hard to get probability or consequence from first principles**
- **Current dearth of large, well-studied projects prevents empirical constraint**

Earth and Atmospheric Hazards

The hazards are a set of possible features, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts.

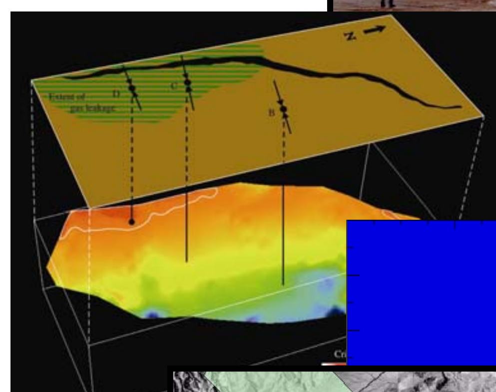
Atmospheric release	**Groundwater degradation**	**Crustal deformation**
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
		Induced seismicity
		Subsidence/tilt

Atmospheric release hazards could vent substantial CO_2 to the surface

Only under some atmospheric dispersion conditions, but require understanding of both likely cases and maximal tolerances

Well leakage

- Many possible processes, mechanisms
- Only a hazard if these processes lead to substantial venting

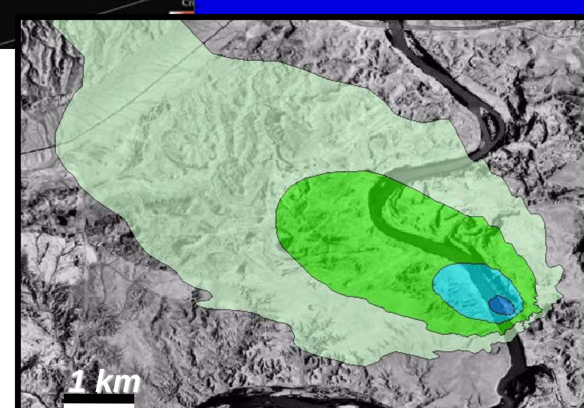


Fault leakage

- Likely to be slower flux and concentration than wells
- Focus first on extreme cases

Caprock leakage

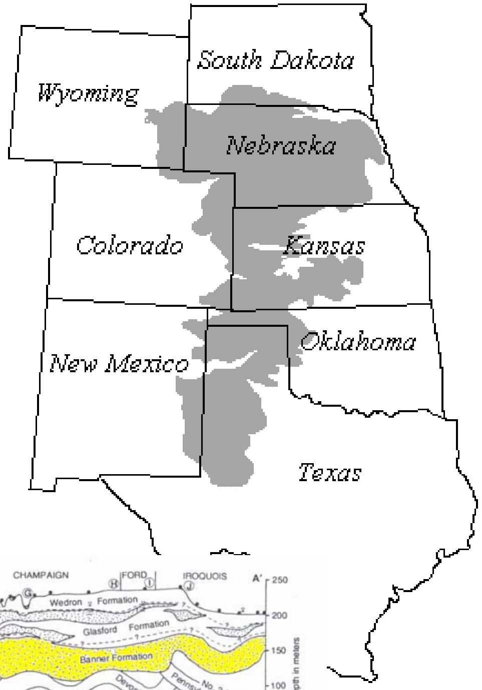
- Likely to be slower flux and concentration than faults or wells
- Focus first on self-reinforcing cases



Pipeline/operational failure

Groundwater release hazards could result from substantial CO_2 release to shallow subsurface

Only some releases and groundwater aquifers will produce hazards of substance that require understanding of both likely cases and maximal tolerances

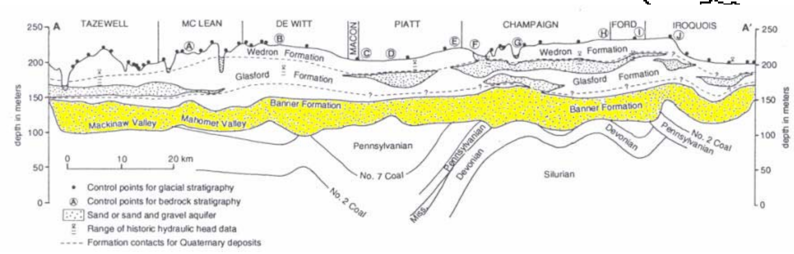


Well leakage

- Many possible processes, mechanisms
- Only a hazard if these it leads to substantial groundwater contamination

Fault leakage

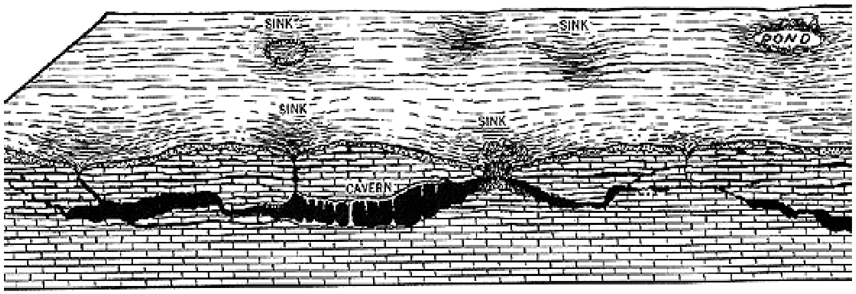
- Likely to be slower flux and concentration than wells
- Focus first on extreme cases



Caprock leakage

- Focus first on self-reinforcing cases

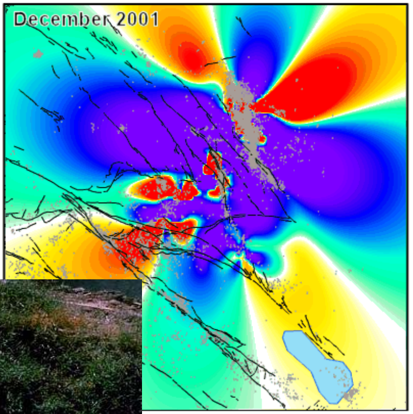
Karst development



Crustal deformation hazards result from geomech. responses to pressure transients and volume changes

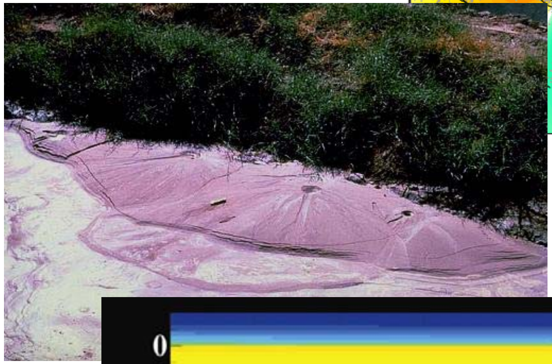
Induced well failure

- Mechanical failure leading to atmospheric/ GW hazards
- Potentially high cost element, EIS concern



Fault slip/leakage

- May concentrate, increase flux
- May lead to well failure

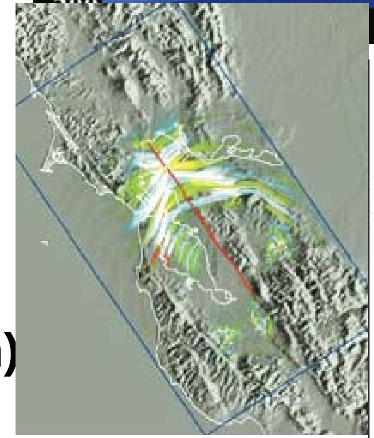


Caprock failure

- Focus first on self-reinforcing cases

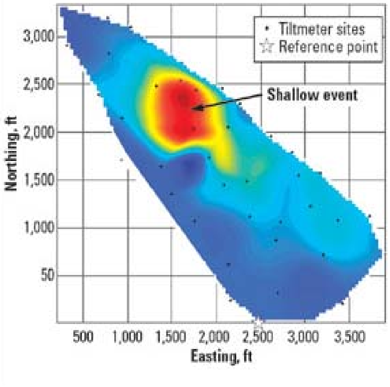
Induced seismicity

- Of great local concern (CA, CO)
- Highly sensitive to local conditions (in-situ stress, basin fill, fault size)

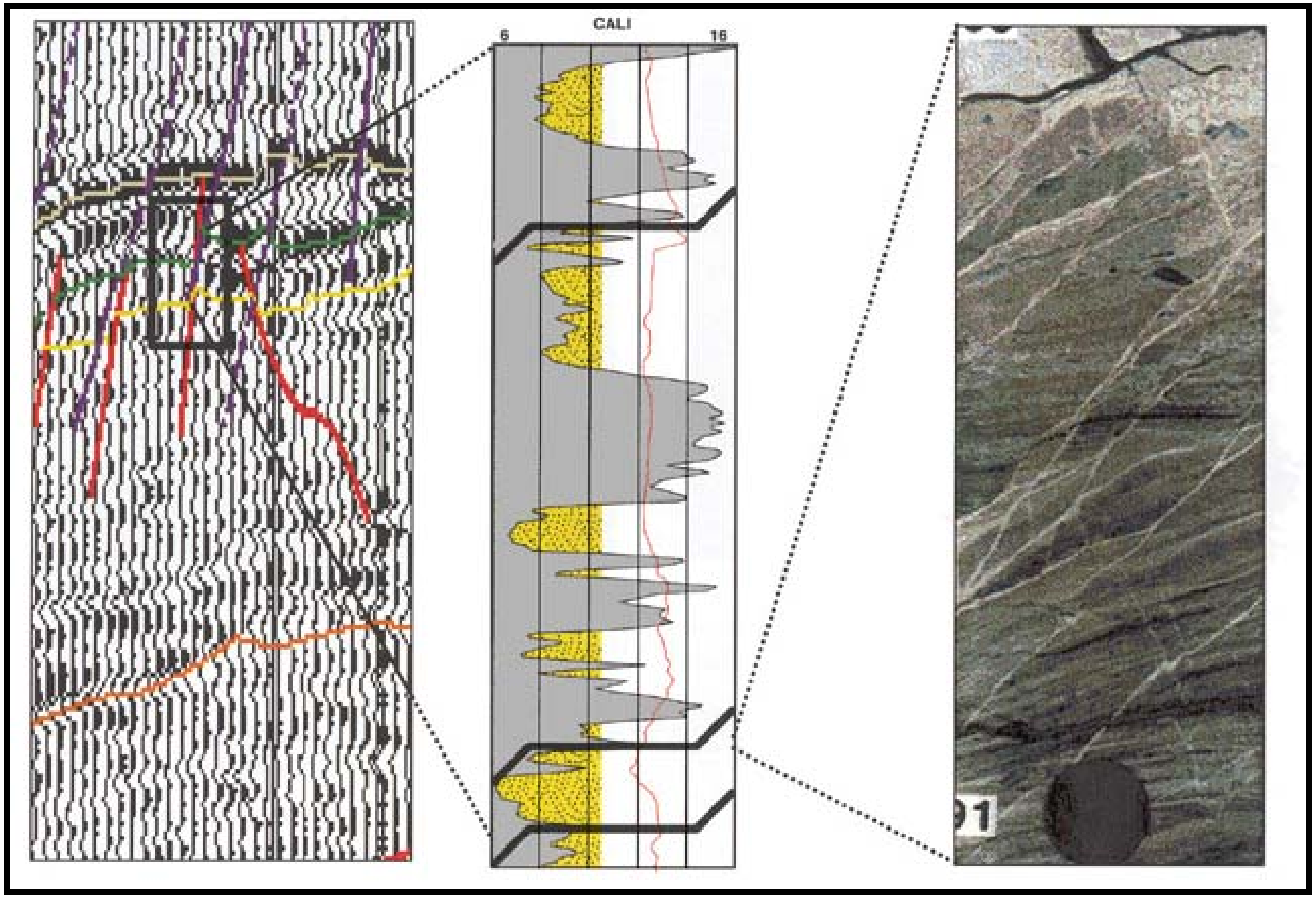


Subsidence and tilt

- Of great local concern (e.g., LB Aquarium)



Example of Hazards assessment: Fault-fluid transmission



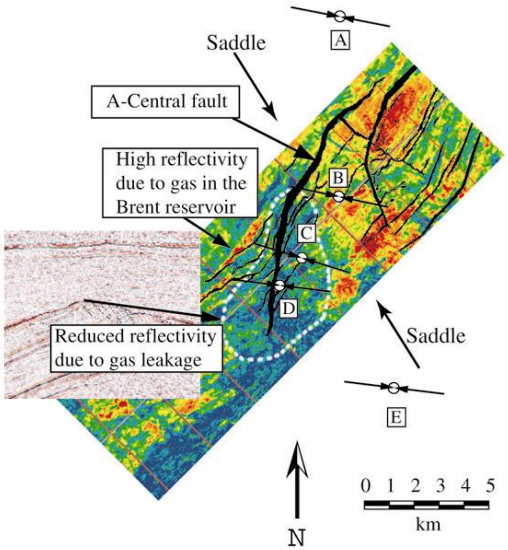
Leakage risk occurs at all scales; accurate characterization requires multiple data sets and detailed analysis.

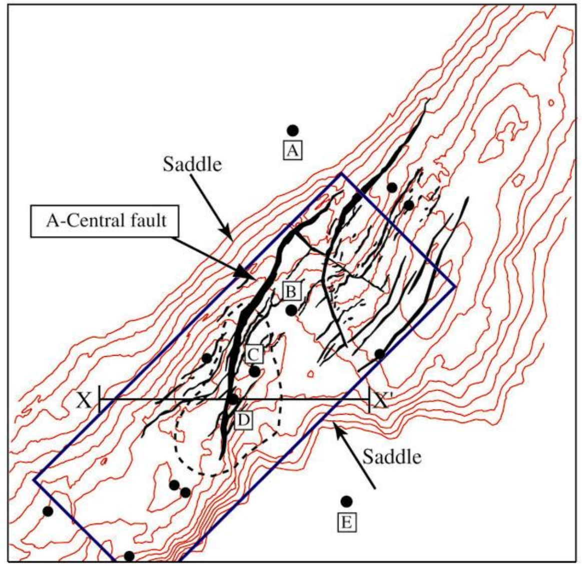
Seismic, well-log (esp. FMI), core, and production data (e.g. flow rates, pressure variations) are key to accurate risking of fault seal.

Given this complexity, hazard assessment must focus on large-volume fluid migration, flux determination & prediction, and induced slip

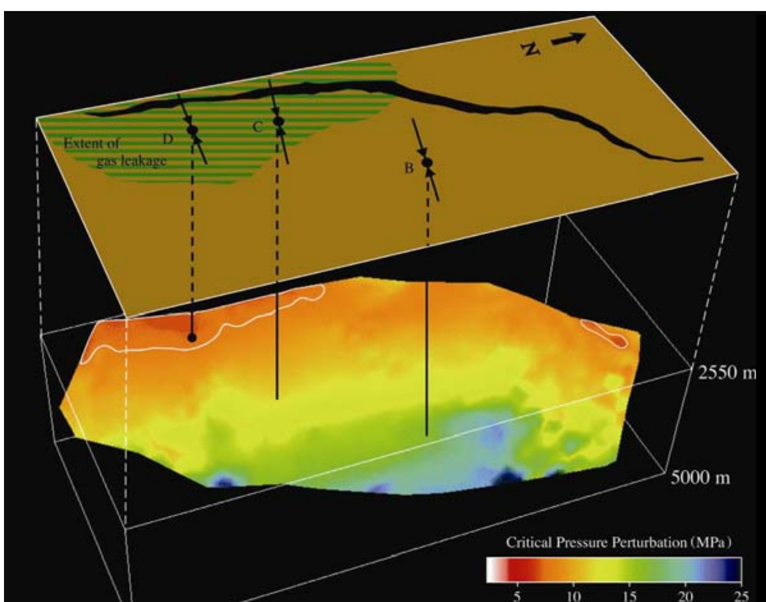
Wehr et al., 2000

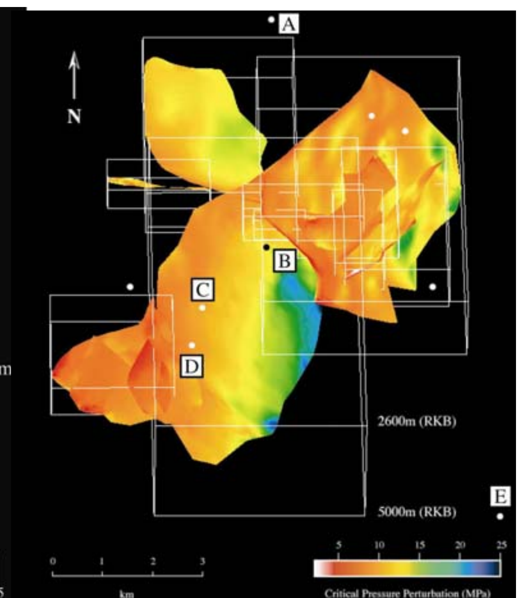
Fault reactivation & leakage hazards can be identified and managed w/ conventional tools





Fluid migration occurs with a high likelihood of fault reactivation. Zoback (Stanford) & his students use this method to predict reactivation pressure for individual faults and networks



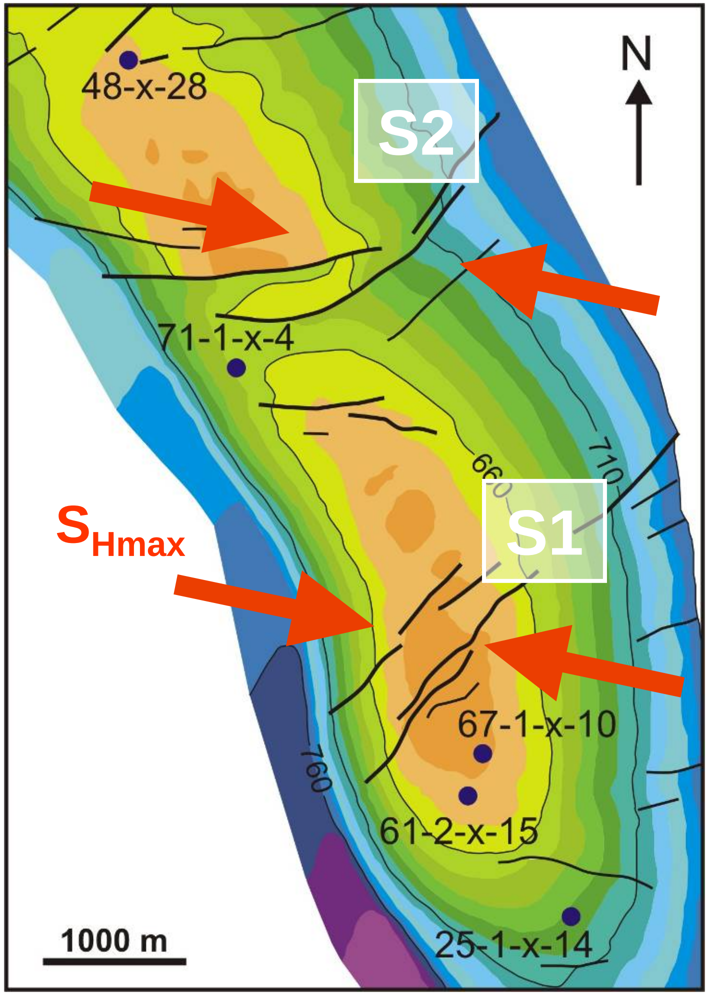


Function of geometry, orientation, pressure

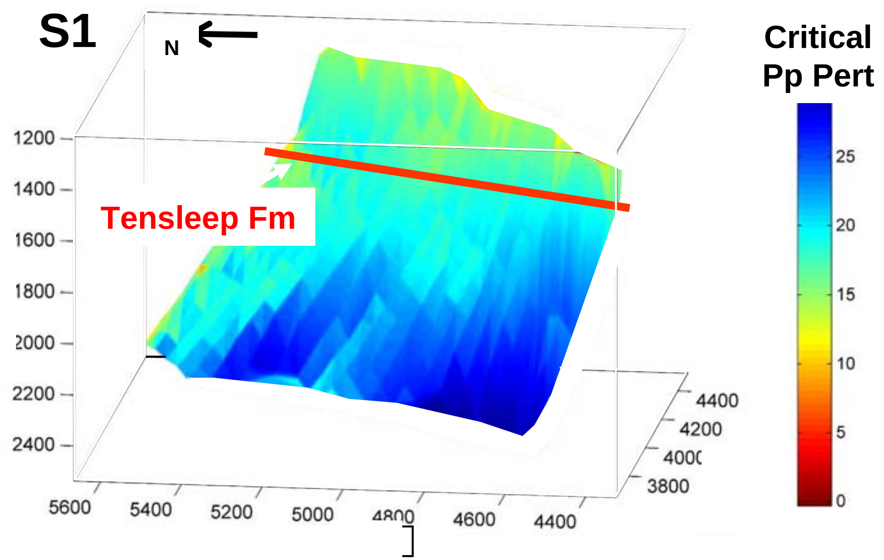
- ***Good fault map (3D-seismic)***
- ***In-situ stress tensor (leak-off test)***

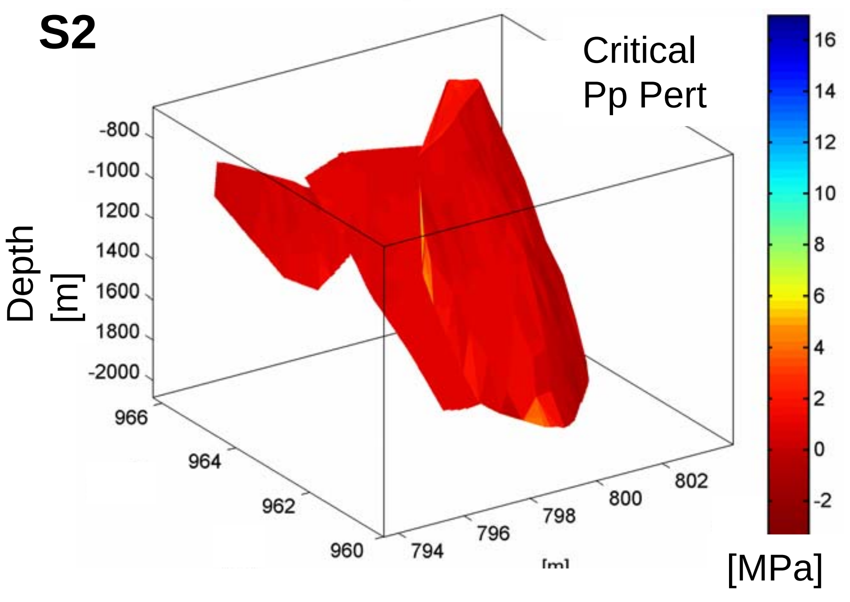
Easily calculated, Easily prevented

Teapot Dome case illustrates sensitivity to geometry and stress (L. Chiaramonte, Stanford)



Time structure map 2nd Wall Creek Fm
(after McCutcheon, 2003)

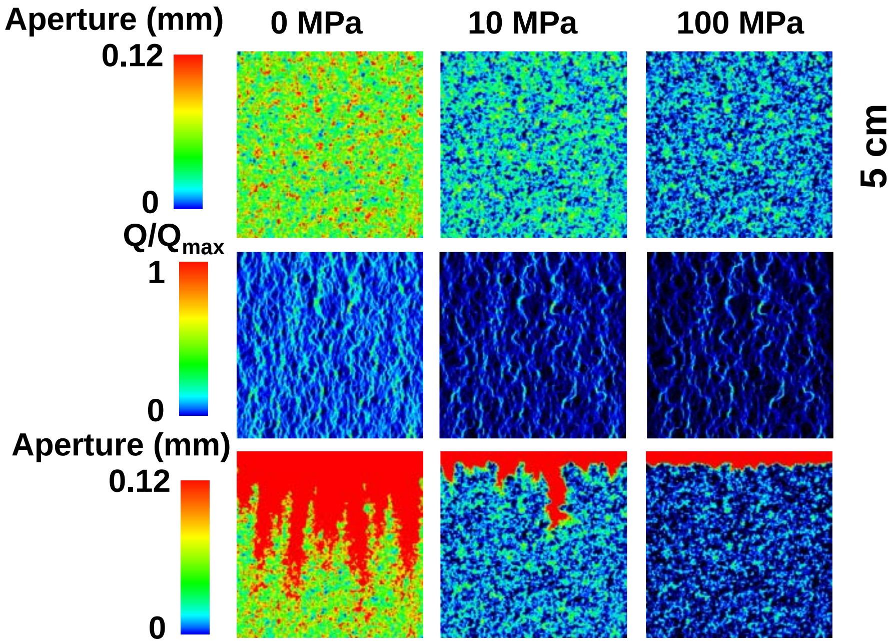


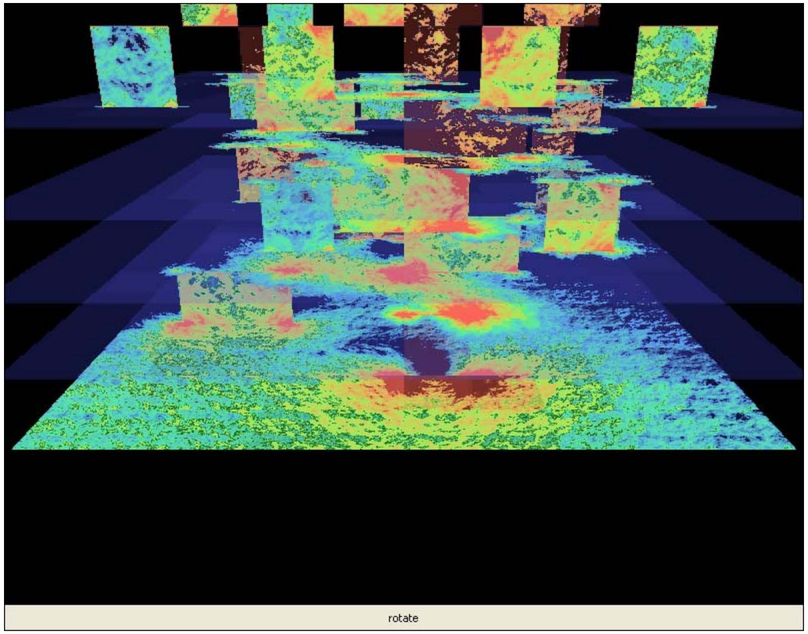


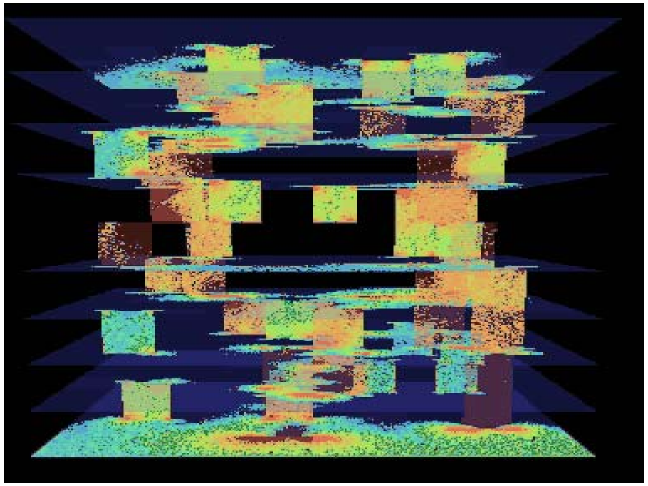
Fluid migration can be estimated with discrete fracture models and reactive transport

Coupled fluid-migration/ reactive transport in changing stress field can be simulated accurately

- ***Representative apertures for bounding analysis***
- ***Dynamic permeability field***
- ***Flux term calculated for pressure regime***





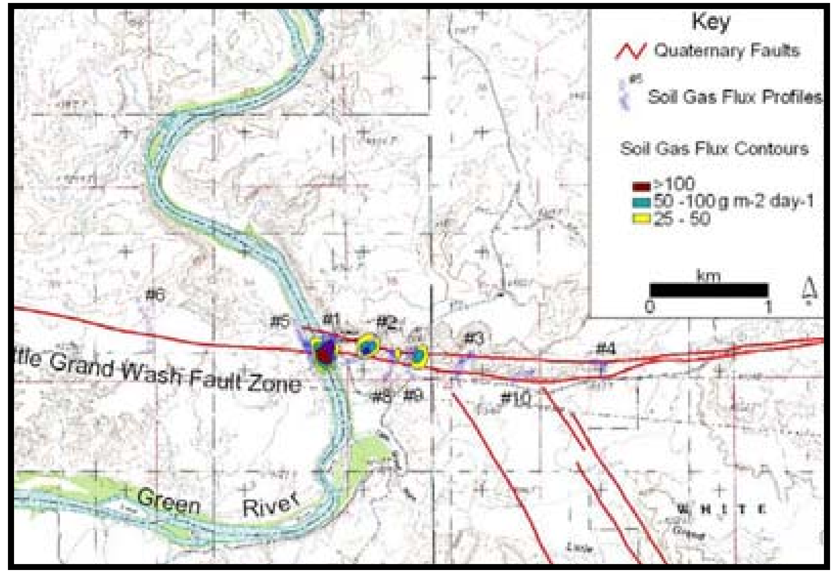


Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

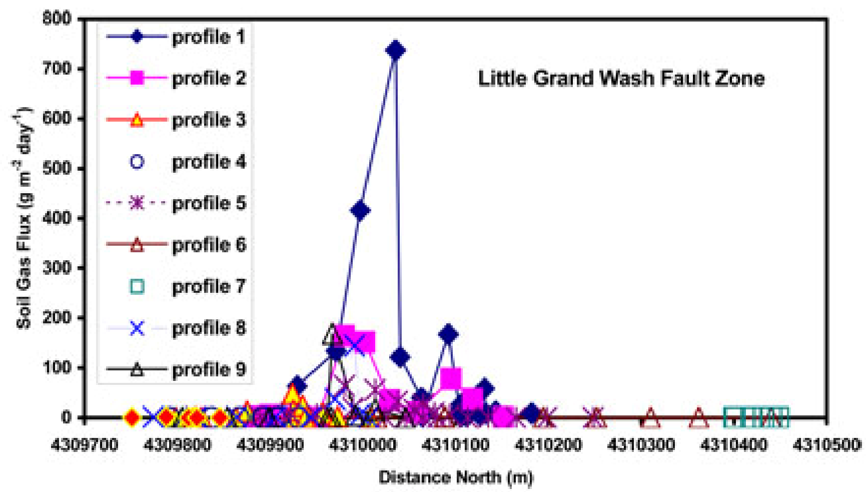
Allis et al. (2005) measured soil flux along the LGW fault zone.

Overall, concentrations were <0.1 kg/m²/d.

Integrated over the fault length and area, this is unlikely approach 1 ton/day.



At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. At the very least, this creates a challenge for MMV arrays

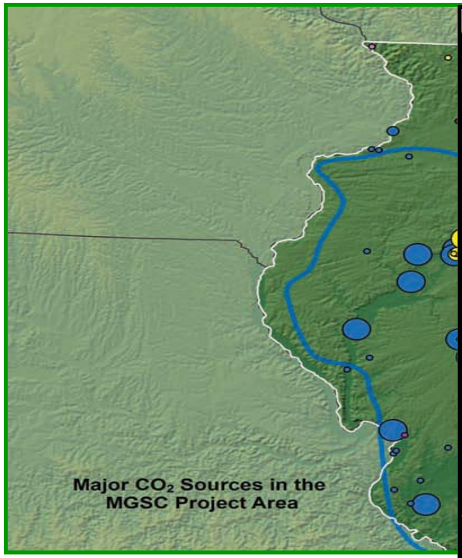


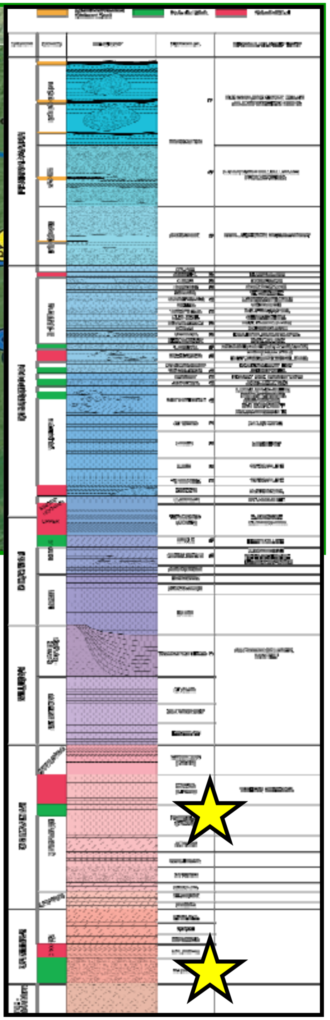
Allis et al., 2005

Case I: Central Illinois Basin

General

- Many large point sources, some pure
- Large-capacity targets (29-115 Gt in SF)
- Solid geological knowledge



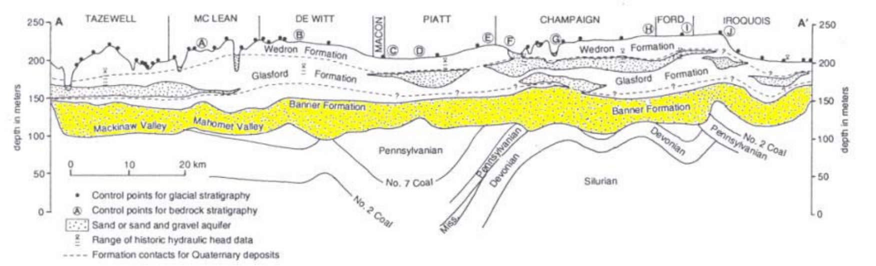


ICE components

- Two main saline formations studied
  (Mt. Simon, St. Peters)
- O.K. injectivity, high capacity
- Evidence of effectiveness

Central hazards

- Deep wells
- Unmapped faults
- Groundwater risks



Risk coefficients – mostly decrease

- Low population density
- Faults don't reach surface
- Very few wells into deep targets
- Effectively aseismic

Special thanks to the MGCS & Illinois State Geological Survey

Because of local nature of hazards, prioritization (triage) is possible for any case

Case 1: Illinois basin

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

A protocol for central Illinois should focus on groundwater hazards from wells

Due diligence could be met through aggressive site characterization, targeted monitoring, and simple mitigation strategies

Atmospheric release hazards	Groundwater degradation hazards	Crustal Deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/ leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

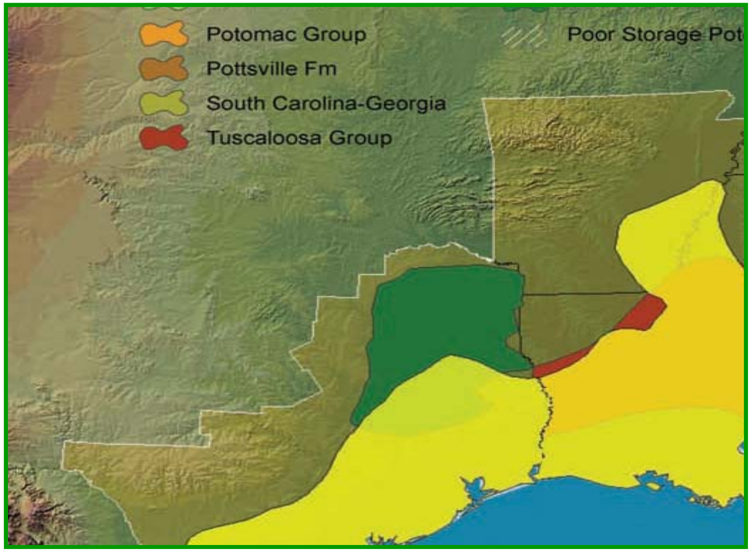
Groundwater degradation
- Additional analyses needed?
- Mitigation strategy needed?

Well leakage and failure
- Maximum rates, under what circumstances?
- Maximum injection pressures?
- Deep wells intersecting sensitive groundwater areas?

Pipeline leakage
- How large to present a threat; where; how?

Induced seismicity/faults
- Maximum sustainable reservoir pressures?
- Faults posing greatest risks?

Case II: TX-LA Gulf Coast

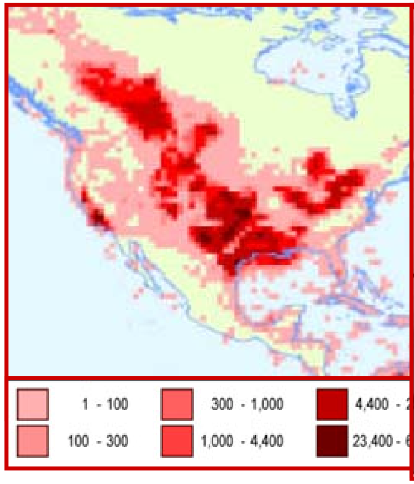


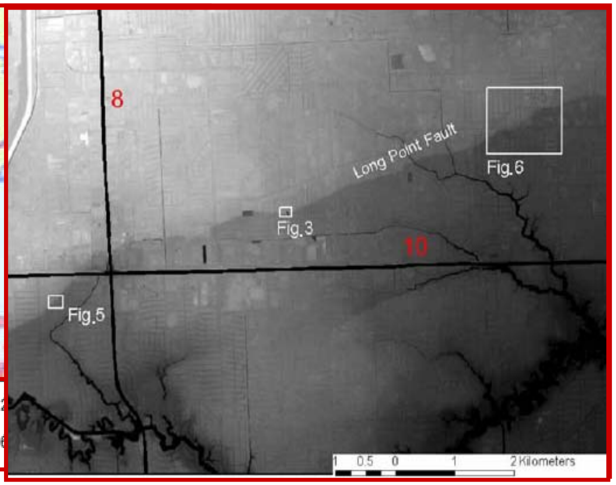
General

- Many large point sources, some pure
- Very large capacity (177-710 Gt for SF)
- World-class geological knowledge

ICE components

- Many potential reservoirs and seals
- High injectivity, high capacity
- Evidence of geological effectiveness





Central hazards

- V. high density of deep wells
- Mapped faults
- Groundwater risks

Risk coefficients – varies spatially

- Low - high population density
- Some faults reach the surface
- Many wells into deep targets
- Effectively aseismic, but mechanical risks

Special thanks to the SECARB & The Bureau of Economic Geology

An alternative prioritization could be proposed for other cases (e.g., Texas GOM)

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Prioritization uses expert knowledge and can be advised by science and experience

A protocol for the Gulf coast should focus on wells, wells, and wells

Due diligence could be met through aggressive site characterization, targeted monitoring, and simple mitigation strategies

Atmospheric release hazards	**Groundwater degradation hazards**	**Crustal Deformation hazards**
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/ leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Atmospheric release
- Pipeline leakage maxima?
- Location of unmapped/abandoned wells?

Well leakage and failure
- Maximum rates, under what circumstances?
- Maximum injection pressures?
- Deep wells intersecting sensitive groundwater areas?

Pipeline leakage
- How large to present a threat; where; how?

Fault slip and leakage
- Maximum sustainable reservoir pressures?
- Faults posing greatest risks?

The monitoring suite design and integration should focus on the hazards

Some approaches are obvious – others may have limited value in understanding hazards

Well configured to hazards

Geomechanical/Seismic
- Microseismic arrays
- Down-hole tilt
- Strain/pressure gauges

Well leakage and failure
- Aeromagnetic surveys
- Well-head sniffers/sensors
- Overlying unit pressure sensors

Not so obvious

Deep arrays
- Cross-well tomography
- VSP

Surface arrays
- LiDAR/FTIRS
- Soil gas flux chambers
- Atmospheric eddy towers

In all cases, real-time integration will provide clear understandings with the smallest M&V suite

A two-phase technical program can help provide insight needed to develop CCS protocols

First, simulations should provide constraints on CCS operating conditions

Second, a field program must substantiate these constraints

The program should focus on EARTH & ATMOSPHERIC HAZARDS of greatest relevance and provide:

- **If CO_2 leaks, what's the groundwater impact?**
- **Will large earthquakes occur due to CO_2 injection?**
- **Can our pipeline be routed in a way to minimize risk?**

Bounding analyses and simulations are necessary but not sufficient to create broad protocols

Conclusions

Operational protocols will help CCS deployment

- Help guide regulations, standards
- Help gain public acceptance
- Help operators make decisions

Hazards are the key

- Provide decision-making framework
- Flexible to local geology
- Guide planning monitoring
- First step in risk quantification

The map is not the territory

Alfred Korzbyski

The E&A hazards and need for protocols leads to a few important questions

•What is the technical basis for developing a risk hierarchy? How can that basis be improved?

•If wells represent the greatest risk, how can that risk be quickly characterized, quantified, and managed?

•If geomechanics represent substantial risks, what are the minimal data necessary to properly characterize those risks

•What science is necessary to understand the potential risks to fresh groundwater?

•What is the least monitoring necessary to serve the needs of all stakeholders?

The full list of E&A hazards suggests a need to rank, quantify, and respond to risk elements

This suggests the need for PROTOCOLS to inform operators and regulators on what actions to take for preparing a site. Given the lack of empirical data, other approaches are needed.

Use of analogs
- **Industrial analogs (NG storage)**
- **Natural analogs (HC systems, CO_2 domes)**

Simulation
- **Key features & processes**
- **Must be accurate, but not unduly complex**

Lab experimentation
- **Focus on most relevant problem**
- **Experimental design is key**

Scenario development
- **Max/min cases can be defined and tested**

Risk assessment methodology
- **Requires integration of results**
- **Some probabilistic methods as approp.**

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- Some probabilistic methods as approp.

Iteration

Integration

“Useless arithmetic” or “the best of our knowledge”?

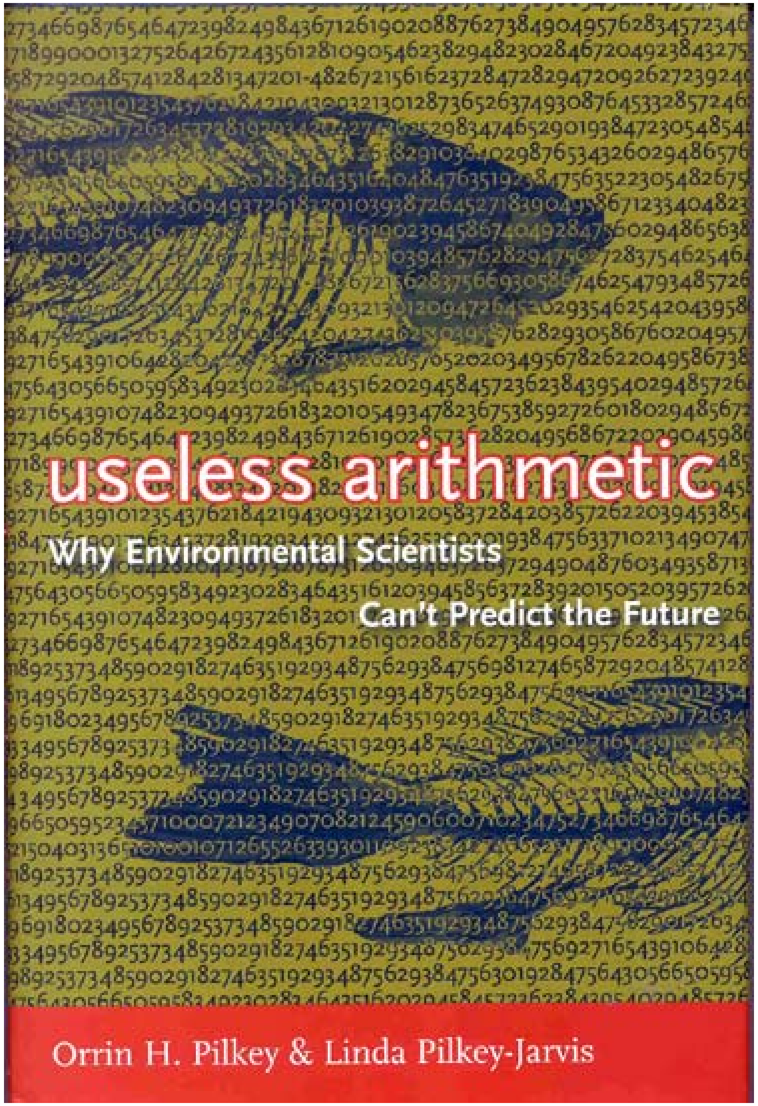
Does probabilistic risk assessment of long-term geological storage of CO_2 make sense?

Dr. Jeroen van der Sluijs, Ferhat Yavuz MSc, Joris Koorneef MSc, and Prof Dr. Wim Turkenburg

Presentation at the 3rd Risk Assessment Network Meeting, organised by IEA Greenhouse Gas R&D Programme, London 15-16 August 2007

Copernicus Institute for Sustainable Development and Innovation
Utrecht University

Pilkey & Pilkey, 2007 book



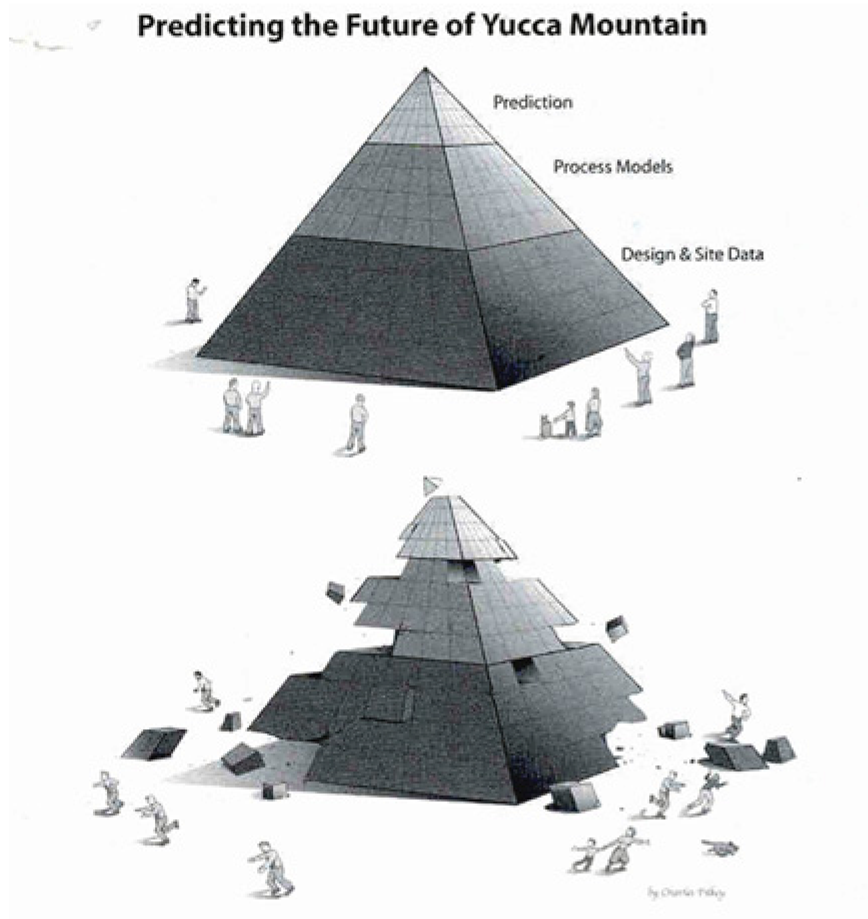


Figure 3.5 The Department of Energy views the modeling effort at Yucca Mountain as a pyramid. At the bottom are field observations. In the second layer are the hundreds of mathematical models that predict how natural processes will work over very long periods of time. At the top are the models that put it all together to predict the behavior of the repository over a long period of time. But a pyramid founded on limited data and faulty models projecting far into the future can never survive! Drawing by Charles Pilkey.

Yucca Mountain: bizarre mismatch

Regulatory standard implied need for scientific certainty for up to one million years

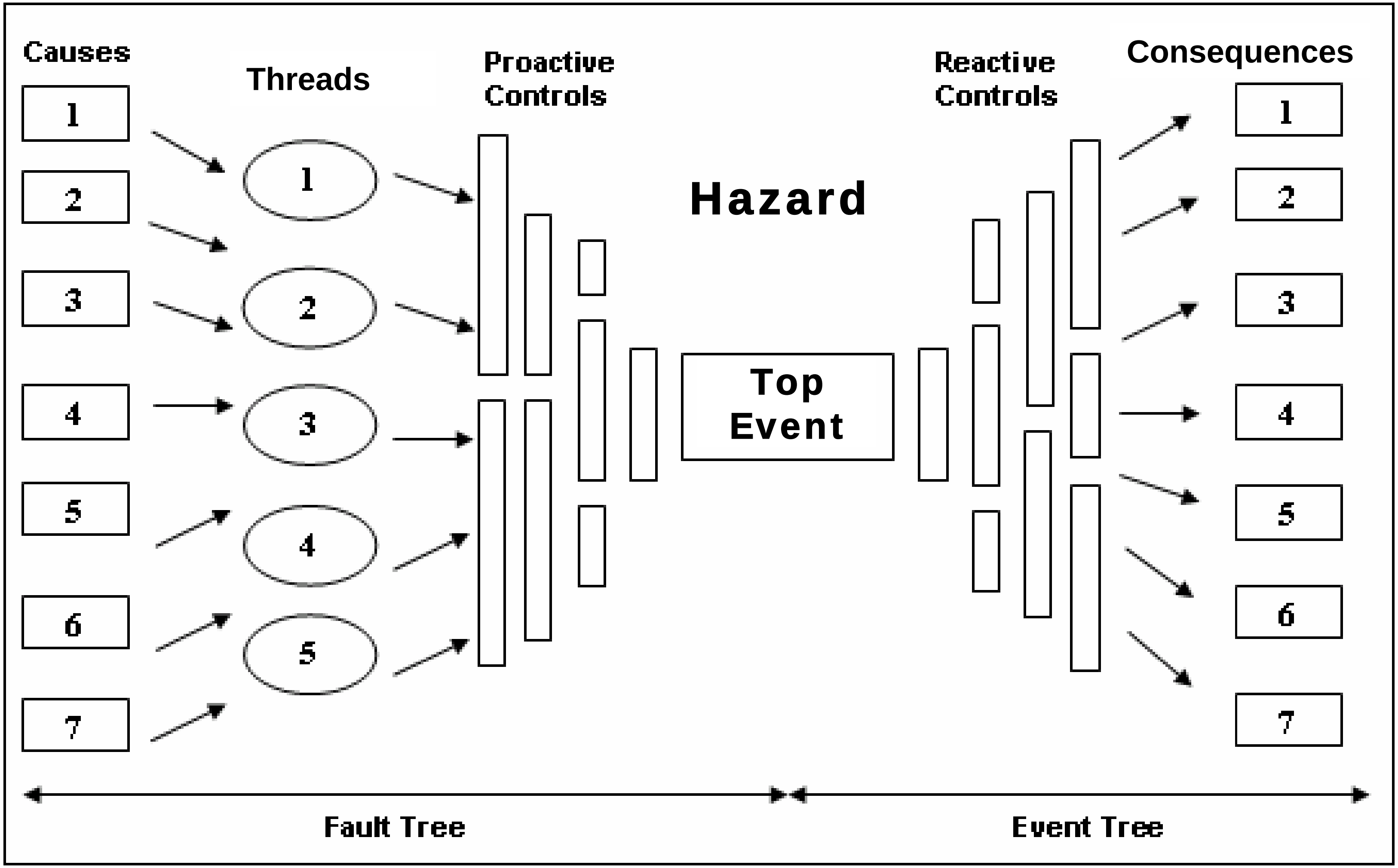
- **State of knowledge**
  - limitations of a quantitative modeling approach *(US-DOE's Total System Performance Assessment, TSPA)*
  - radical uncertainty and ignorance
  - uncontrolled conditions of very long term unknown and indeterminate future.

Ignorance:

Percolation flux: TSPA model assumed 0.5 mm per year (expert guess)

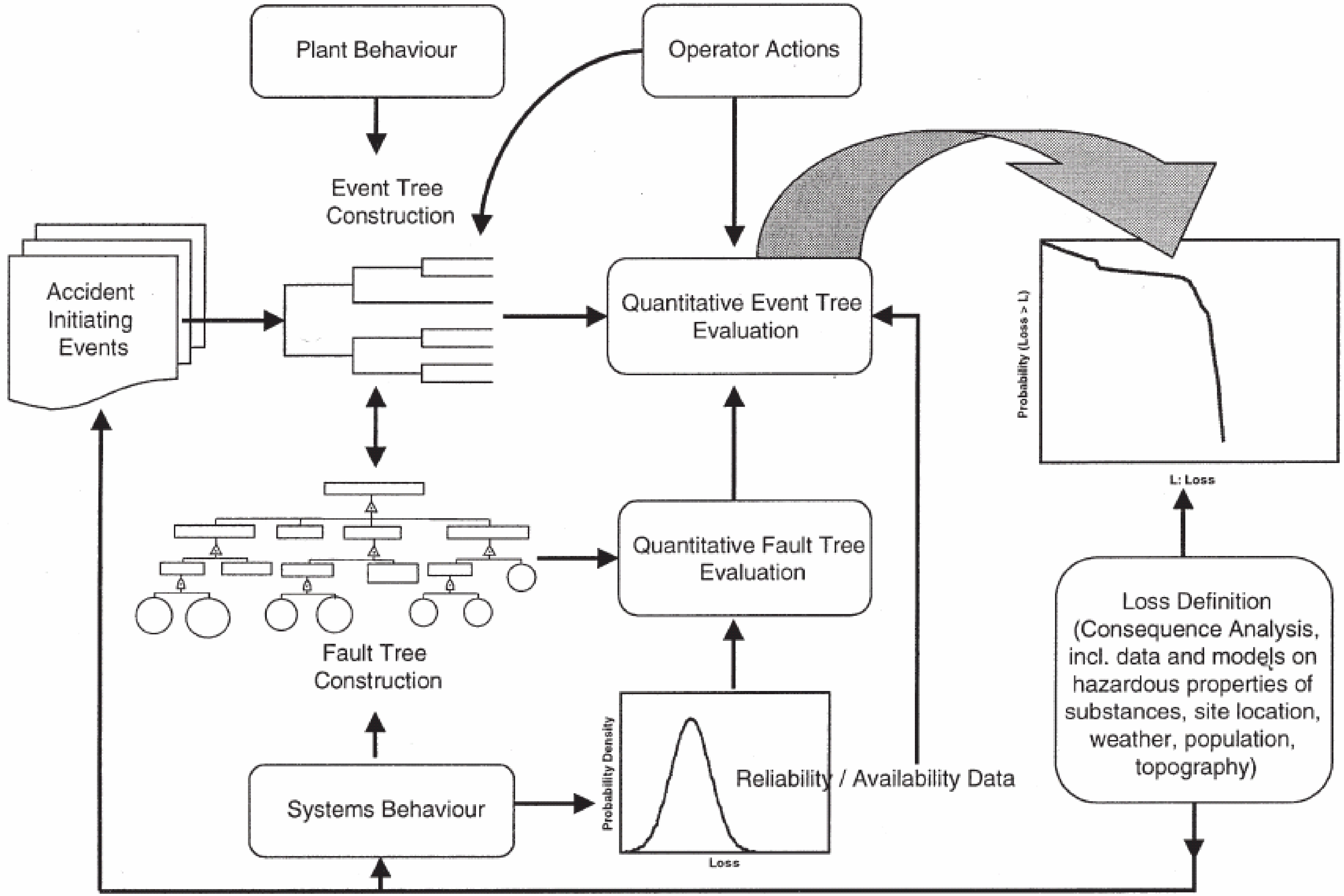
Elevated levels of Chlorine-36 isotope in faults uncovered by tunnel boring: percolation flux > 3000 mm per year over the past 50 yr…

Bow Tie approach



modified from http://nmishrag.mishc.uq.edu.au/NMISHRAG_Chapter4_4.1.5.asp

Probabilistic risk analysis—sequence of analysis steps



Source: Kirchsteiger, 1999

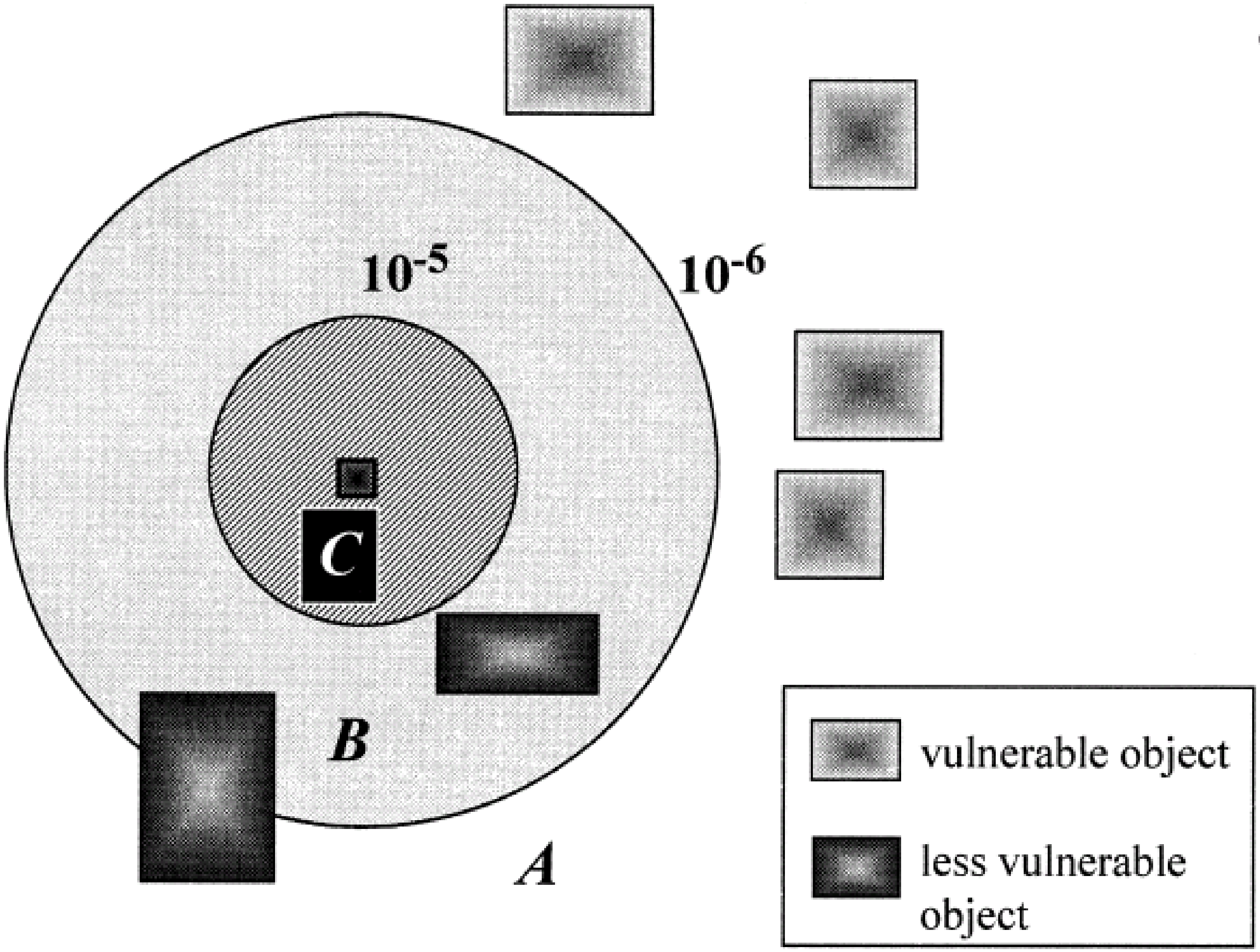
NL External Safety

The ***individual risk*** for a point-location around a hazardous activity:

probability that an average unprotected person permanently present at that point location, would get killed due to an accident at the hazardous activity.

Bottelberghs 2000, *Journal of Hazardous Materials* **71**, 59–84.

NL Acceptability criteria for individual risk



Vulnerable objects (housing, schools, hospitals, etc) <10^{-6} per year (area A)
Less vulnerable objects < 10^{-5} per year (area B)

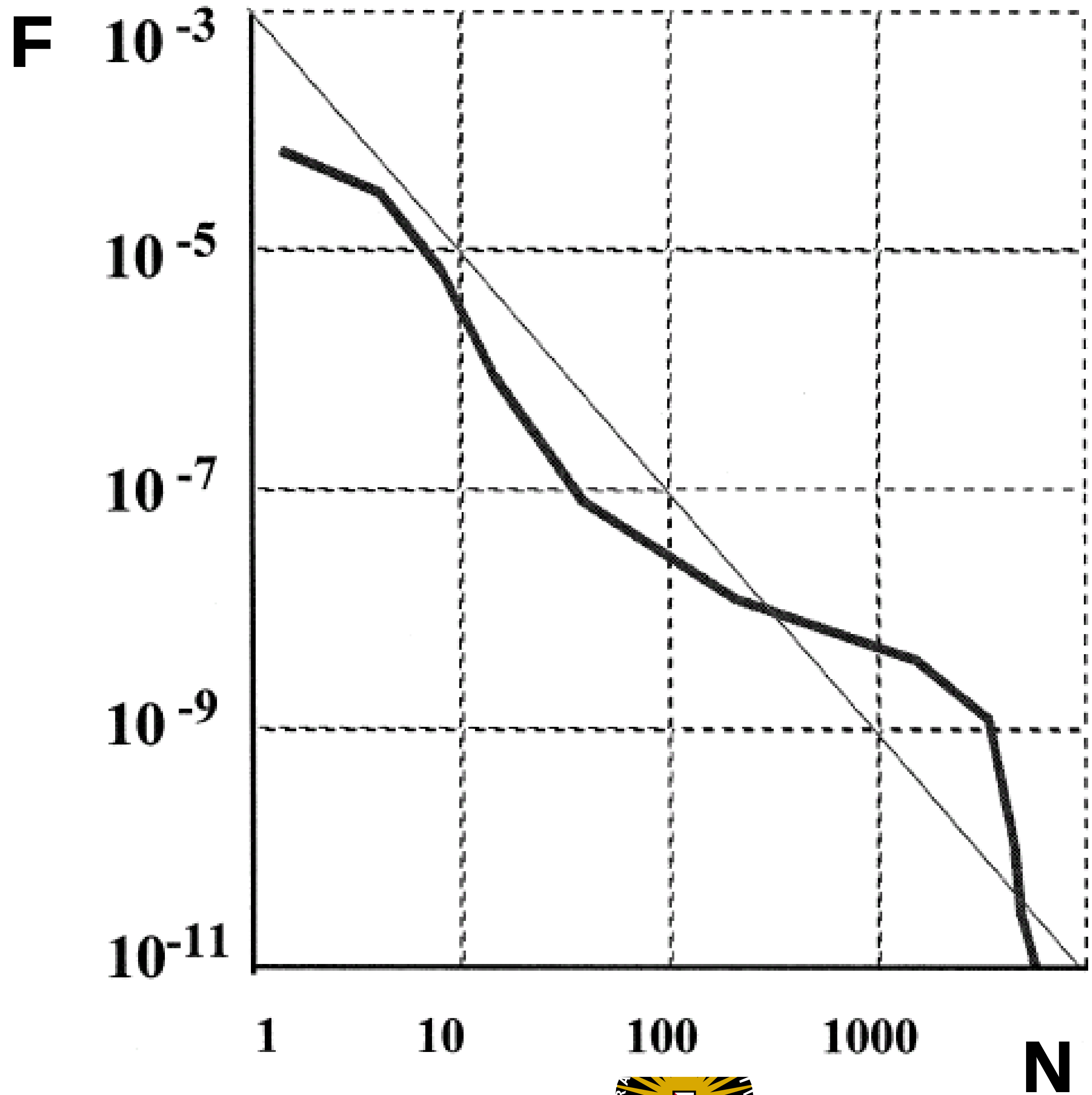
Example of a societal risk curve plot (*F*,*N* plot)

societal risk:

Probability that a group of more than N persons would get killed due to an accident at the hazardous activity

N = number of lethal victims;

F = probability per year for an accident at the hazardous activity that would cause >*N* victims.



Strengths of PRA

- Integrative and quantitative approach
- Allows ranking of issues and results, explicit treatment of uncertainties, and optimisation
- Can be used to both enhance safety and manage operability.
- Results and decisions can be communicated on a clearly defined basis
- Its use is beneficial even if the models generated are not (fully) quantified
- Lack of accuracy of the data does not hamper the use of probabilistic approaches as comparative tools to rank alternatives

Weaknesses of PRA

- complex, time consuming, data-intensive
- unavoidably requires mixtures of ‘subjective’ (expert judgement) and ‘objective’ data (observations, measurements)
  - limits scientific rigor of result
  - feels uncomfortable
- large potential for misunderstanding of scientific status of the outcomes
  – undue sense of certainty
  – pitfall of “quasi precision”
- models of open (uncontrolled) systems can never be validated, only ‘confirmed’ by non-contradiction between observation and prediction (Oreskes et al. 1994)
- dangers of too early standardization & benchmarking (anchoring bias)

PRA of geological CO_2 storage versus PRA of industrial installations:

- Natural reservoir much less defined and way more heterogeneous
- Reservoir is not an engineered system
- >> time horizon
- The longer the time horizon, the more open the system is
- >> stored volume of substance
- << past experience
- >> dependency on expert judgement

in specific case of CO_2 storage all general weaknesses of PRA are amplified…

3 paradigms of uncertain risks

'deficit view'

- Uncertainty is provisional
- Reduce uncertainty, make ever more complex models
- *Tools:* quantification, Monte Carlo, Bayesian belief networks

'evidence evaluation view'

- Comparative evaluations of research results
- *Tools:* Scientific consensus building; multi disciplinary expert panels
- focus on robust findings

'complex systems view / *post-normal* view'

- Uncertainty is intrinsic to complex systems
- Uncertainty can be result of production of knowledge
- Acknowledge that not all uncertainties can be quantified
- Openly deal with deeper dimensions of uncertainty (problem framing indeterminacy, ignorance, assumptions, value loadings, institutional dimensions)
- *Tools:* Knowledge Quality Assessment
- Working deliberatively within imperfections

Dimensions of uncertainty

- Technical (inexactness)
- Methodological (unreliability)
- Epistemological (ignorance)

- Societal (limited social robustness)

*Qualified Quantities: NUS**AP**:*

Numeral, Unit, Spread, **Assessment, Pedigree**

Assessment expresses expert judgement on the unreliability

Pedigree evaluates the strength of a number by looking at:

- Background history by which the number was produced
- Underpinning and scientific status of the number

Example pedigree matrix for model parameters

Code	Proxy	Empirical	Theoretical basis	Method	Validation
4	Exact measure	Large sample direct mmts	Well established theory	Best available practice	Compared with indep. mmts of same variable
3	Good fit or measure	Small sample direct mmts	Accepted theory partial in nature	Reliable method commonly accepted	Compared with indep. mmts of closely related variable
2	Well correlated	Modeled/derived data	Partial theory limited consensus on reliability	Acceptable method limited consensus on reliability	Compared with mmts not independent
1	Weak correlation	Educated guesses / rule of thumb est	Preliminary theory	Preliminary methods unknown reliability	Weak / indirect validation
0	Not clearly related	Crude speculation	Crude speculation	No discernible rigour	No validation

Model Quality Assessment

- Models are **tools**, not truths
- **A model is not *good* or *bad* but** there are **'better' and 'worse' forms of modelling practice**
- Models are 'more' or 'less' useful when applied to a particular problem.

Model Quality Assessment can provide:

- insurance against pitfalls in process
- insurance against irrelevance in application

refs: www.mnp.nl/guidance
Risbey, J., J. van der Sluijs, et al. (2005): Application of a Checklist for Quality Assistance in Environmental Modelling to an Energy Model. *Environmental Modeling & Assessment* **10** (1), 63-79.

Valid uses of PRA of geological CO_2 storage:

- Comparative assessment of different reservoirs and storage options
- “Validation” of simpler methods
- Gain insight in key-characteristics that determine reservoir safety
- Gain insight in what factors should be monitored for early detection of leakage risks
- Improvement of operational practices
- Support of safer designs
- Informed debate with regulators and society (but it is essential to make pedigree of results explicit!)

Tricky and invalid uses of PRA of geological CO_2 storage

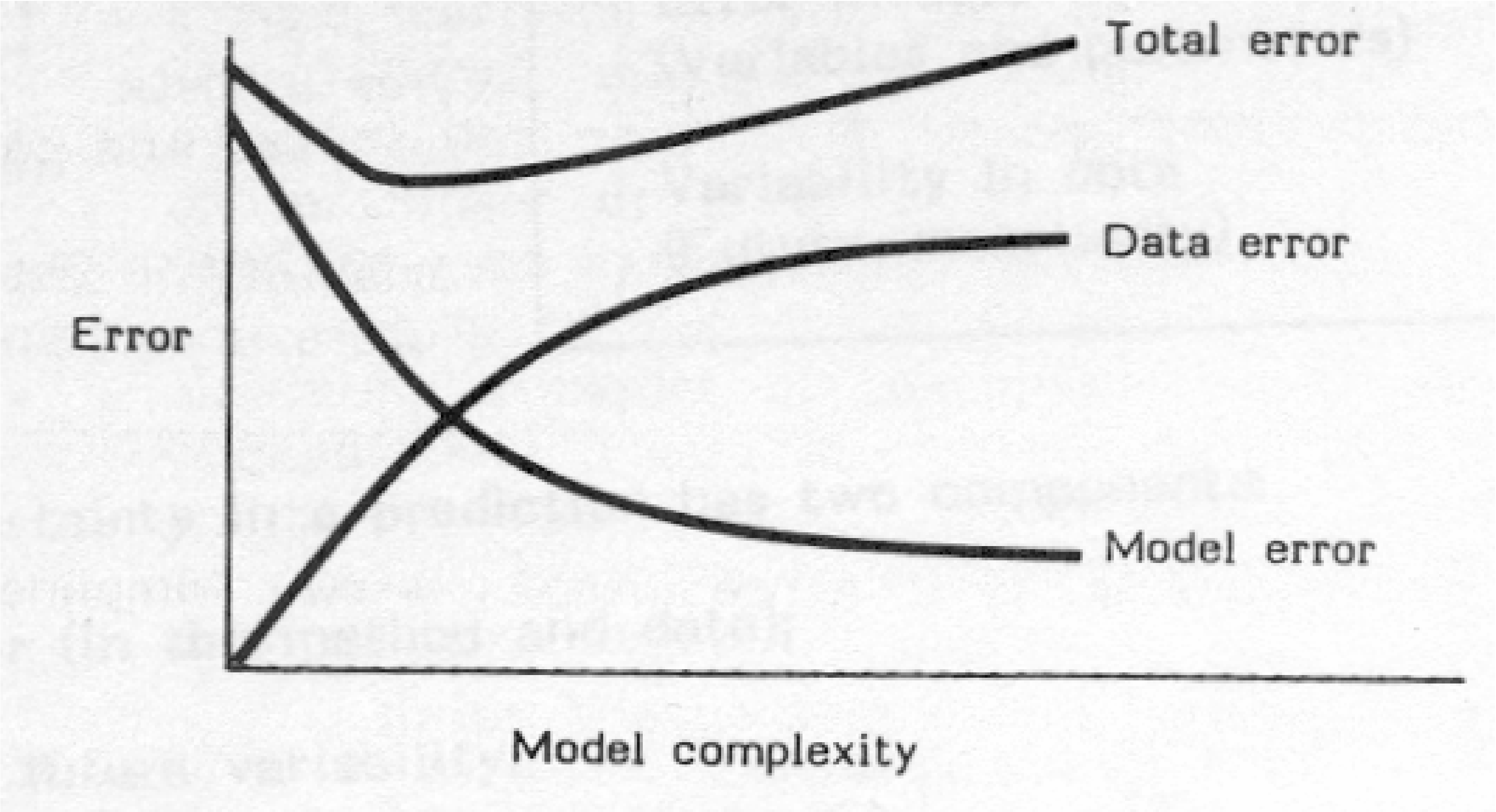
Invalid:

- Demonstration of safety
- Interpreting outcomes as absolute

Tricky:

- Demonstration of compliance to a quantified safety requirement
- Comparison to other (e.g. industrial) risks

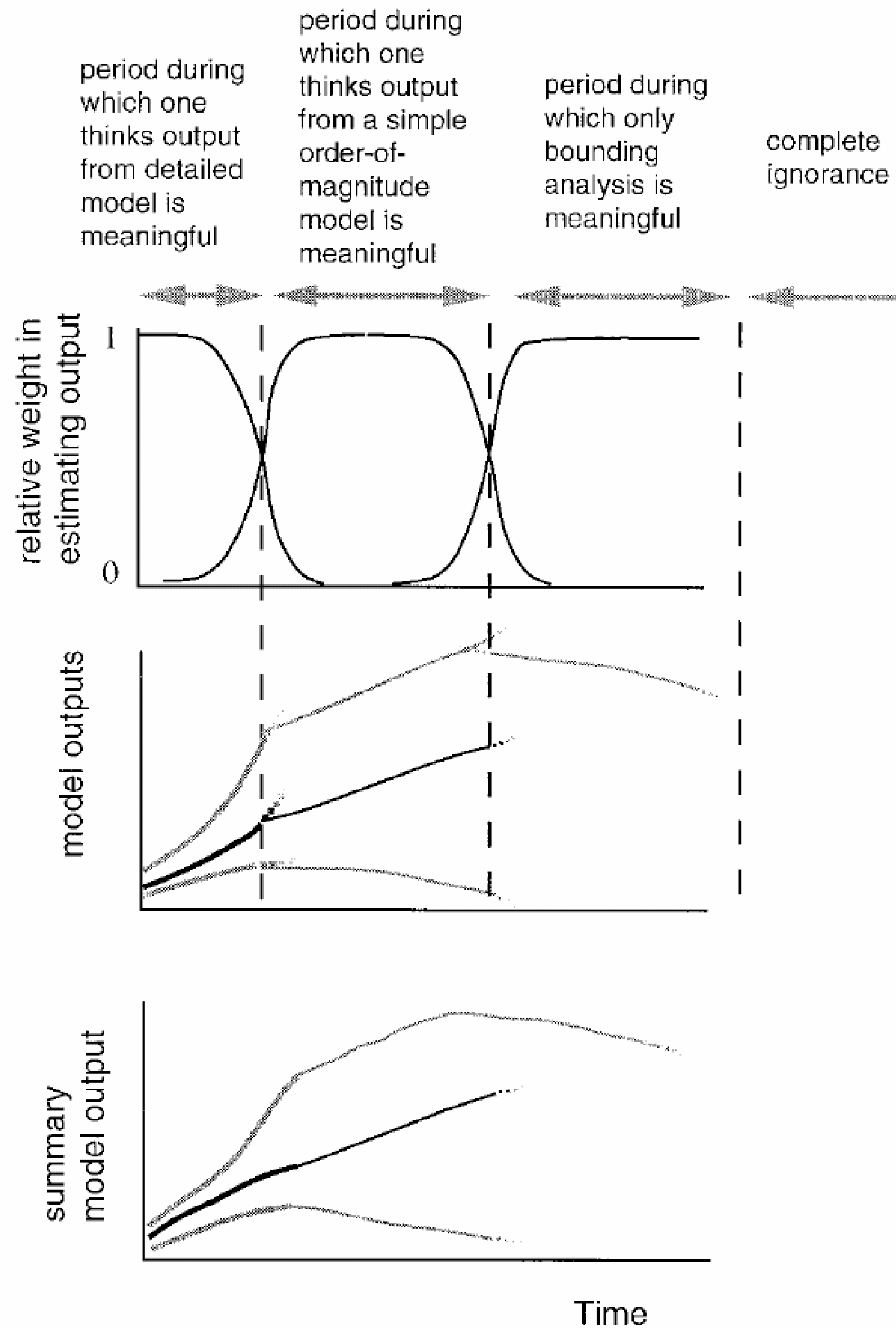
Uncertainty and model complexity



Casman et al. 1999:

Mixed levels of uncertainty

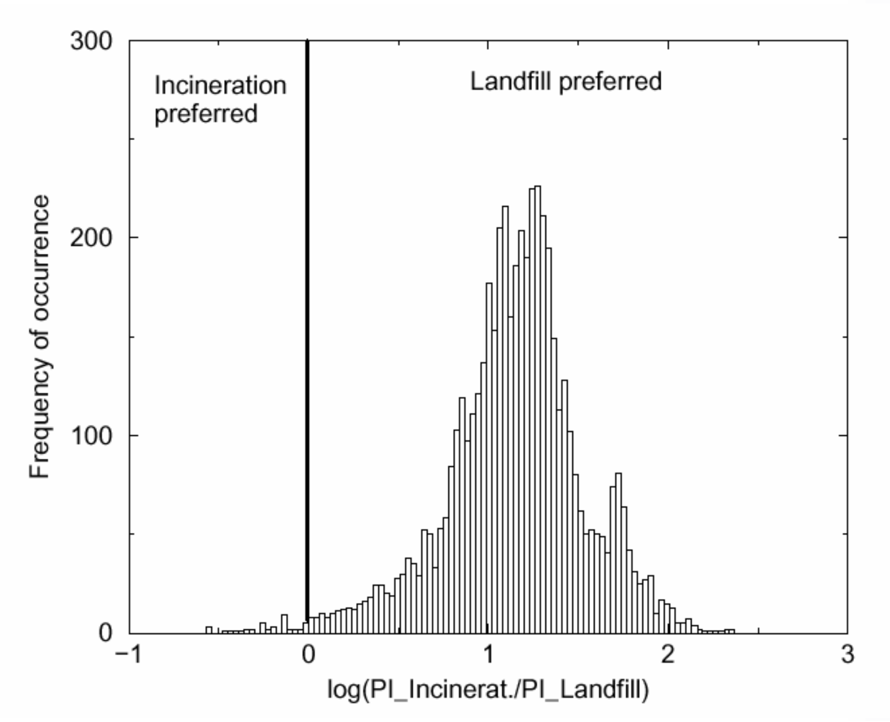
Fig. 3. Schematic illustration of the strategy of switching to progressively simpler models as one moves into less well understood regions of the problem phase space, in this case, over time. One starts with a detailed model that is likely to only be reliable for a few years. Gradually one moves over to a much simpler model based on order of magnitude considerations. Finally, in the long term, one can only bound the result, without giving best estimates.

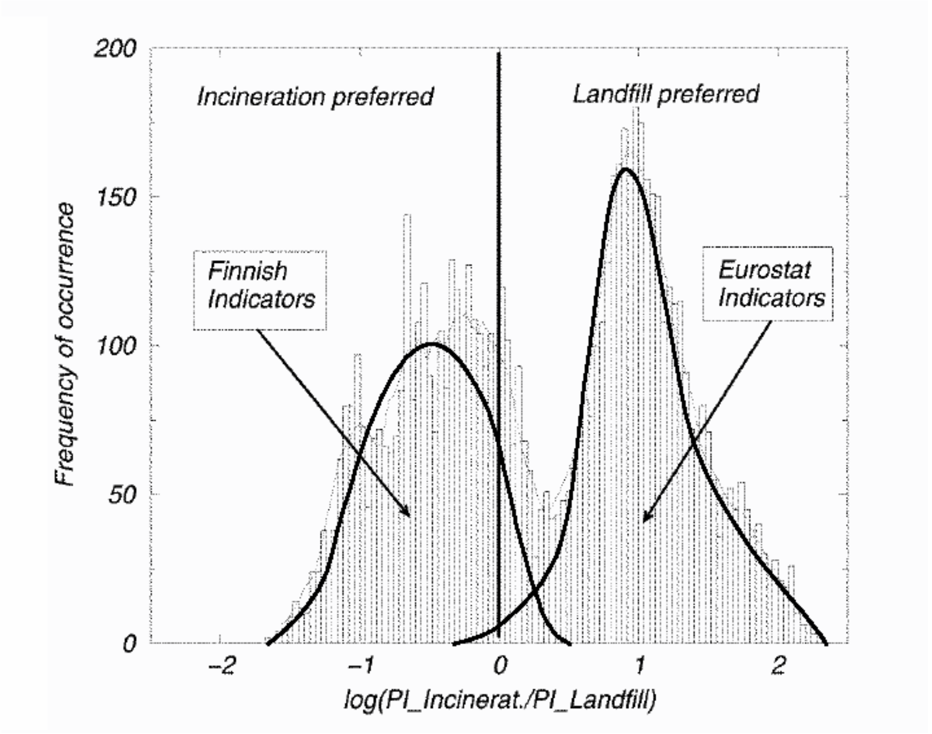


Risk Analysis, 1999, **19** (1), 33-42

High uncertainty is not the same as low quality,

but..... methodological uncertainty of choice of (risk) indicator can be dominant





(Example taken from Saltelli et al., 2000 book “Sensitivity Analysis”)

Conclusions (1)

- Specific characteristics of CO_2 storage amplify all generic weaknesses of PRA
- Strong dependence on expert judgement
- Need for systematic reflection on knowledge quality
- Need for systematic elicitation and documentation of ARGUMENTS behind each judgment by each expert
- Be very open and very transparent about uncertainty and pedigree of results
- Be explicit about all assumptions on which outcomes are conditioned
- Avoid mismatch between regulatory requirements and the limited level of rigor that state-of-the-art science can realistically achieve

Alternatives for regulation

- Precautionary Principle
  (1) measures that constrain the possibility of the harm to occur
  (2) measures that contain the harm (c.q. increase the controllability of the harm) when it would occur
  - Flexible standards: Step by step, case by case approach
  - First decades off-shore only?
  - Availability of control measures/remediation
  - Reversibility?
- Maximum Credible Accident approach?

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Keep it simple!
- Performance Assessment applied to Geological Carbon Dioxide Capture and Storage

Lars Olof Höglund and Bertil Grundfelt
Kemakta Consultants Co.

loh@kemakta.se
+46-8-617 67 17

www.kemakta.se

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Outline of presentation

- Carbon dioxide capture and storage in context
  - Capture and storage principles
  - Size of the problem and risks
- Outlook – Radioactive waste management
- Performance assessment methodology
- Issues of potential importance for GCS
- Concluding remarks

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Storage of CO_2 in Geological media

- CO_2 stored under high pressure and increased temperature – Liquid or supercritical state – to increase storage efficiency
- Three major types of geological formations:
  - Saline formations
  - Depleted oil and gas fields (CO_2 injection used today to increase recovery)
  - Deep coal deposits

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Capture mechanisms

- Physical barriers against CO_2 migration
  - Often an overlying impermeable structure
    - Shale
    - Salt etc
- Capillary retention
  - Residual gas phase
- Dissolution /dissipation of CO_2 in groundwater
- Reaction with rock minerals – carbonate precipitation
- Adsorption to coal etc.

- Studies of natural analogues suggest safe capture over geological time scale would be possible
- IPCC(2005) estimates show a likely 99,9% capture of injected CO_2 during 100 years, and 99% capture during 1000 years

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What capacity is needed?

- Present emissions about 25 Gtonnes/year
- Estimates show a necessary reservoir capacity over next century of 1000 – 2000 tonnes CO_2
- Oil and gas reservoirs is not sufficient
- Deep saline aquifers would offer required capacity

- For comparison:
  - Capture and storage from 600 coal power plants, each 1000 MW equals 3,6 Gtonnes/year of CO_2
  - Equivalent to 3600 times the Sleipner (1 Mtonnes/year during 10 years)

(Friedman, 2007)

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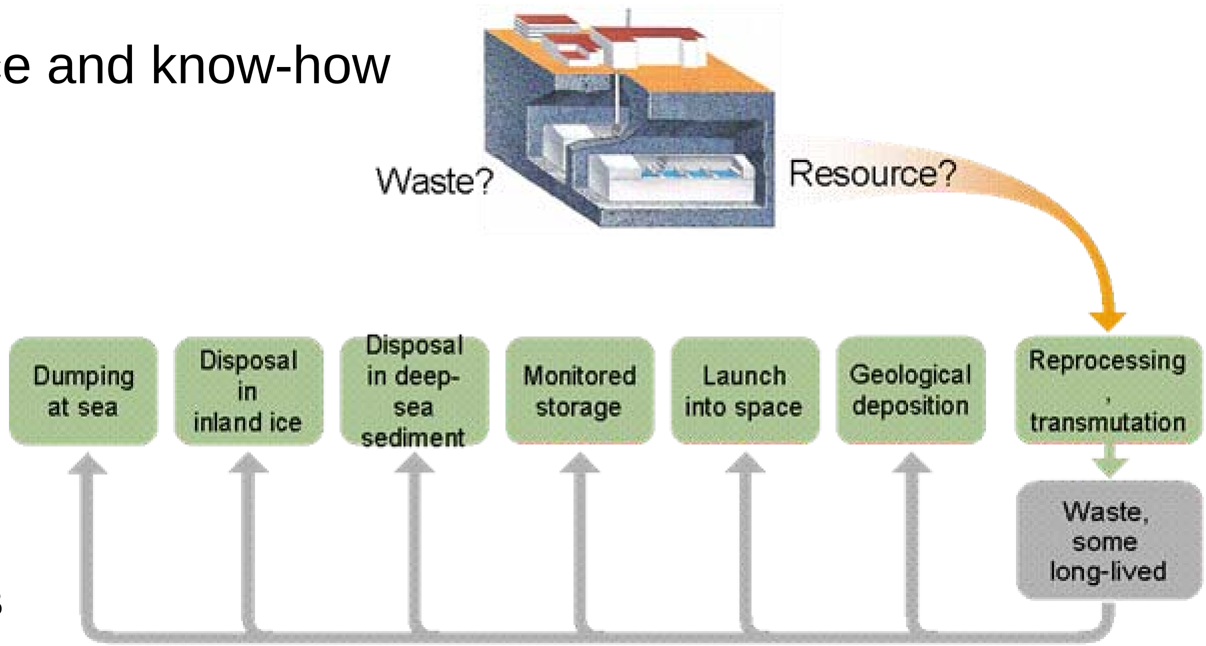
Risk factors

- Low density
  - Tends to migrate upwards
  - Mechanical stress on the rock
- High injection pressure causes pressure gradients
  - Large forces may occur in large storage reservoirs
  - Fracture opening due to pressure disturbance
- Hydrolysis causes acidic attack on surrounding rock
  - Porosity increase due to rapidly dissolving alkaline minerals
  - Self-healing due to mineral transformation processes
- A certain likelihood for leakage exists
  - Question is then – Is it a major problem or is it manageable?

Radioactive waste management – A brief outlook

- Similar questions have been addressed for disposal of radioactive and toxic waste
- Geological disposal a commonly accepted strategy
- Methodologies for performance assessment of storage facilities are available
- Significant experience and know-how



Source: SKB

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Incremental process of developing a final storage facility (NEA, 1999) – An example from Sweden

CO_2 today

Nuclear today

Step in the process	Role of PA/SA
1. Selection of disposal principles and repository concept	Demonstration of feasibility
2. Development of design (evaluation of alternative barrier materials, designs, and rock types)	Provides basis for selection of reference design
3. Definition of system design, and safety strategy for the selected barriers	Provides basis for system definition and EIS
4. Site characterisation (surface based), site comparison, system adaptation to site, design optimization	Supports request/decision for undertaking detailed site investigations
5. Detailed site investigations, shaft/tunnel construction, adaptation of layout and barriers to site, design of encapsulation facility	Supports request/decision for permission to site encapsulation facility
6. System design and site utilisation	Supports request/decision for final construction and depositing minor part of the waste
7. Re-evaluation of experience	Supports request/decision for complete repository construction and disposing of the waste
8. Design for repository closure/sealing, “as built” system description	Supports request/decision for sealing of the repository

Safety assessment in waste management

- Tries to answer questions about future radiation doses to the population and the environment due to leakage of radionuclides from a repository
- Normally follows the following systematics:

1.Broad identification of the future evolution of the selected disposal system (scenario development)

2. Development and application of appropriate models

3. Evaluation of potential radiological consequences in an integrated assessment

4. Uncertainty and sensitivity assessment

5. Validation and review of all components of the assessment

6. Comparison of results with criteria

7. Documentation of the assessment

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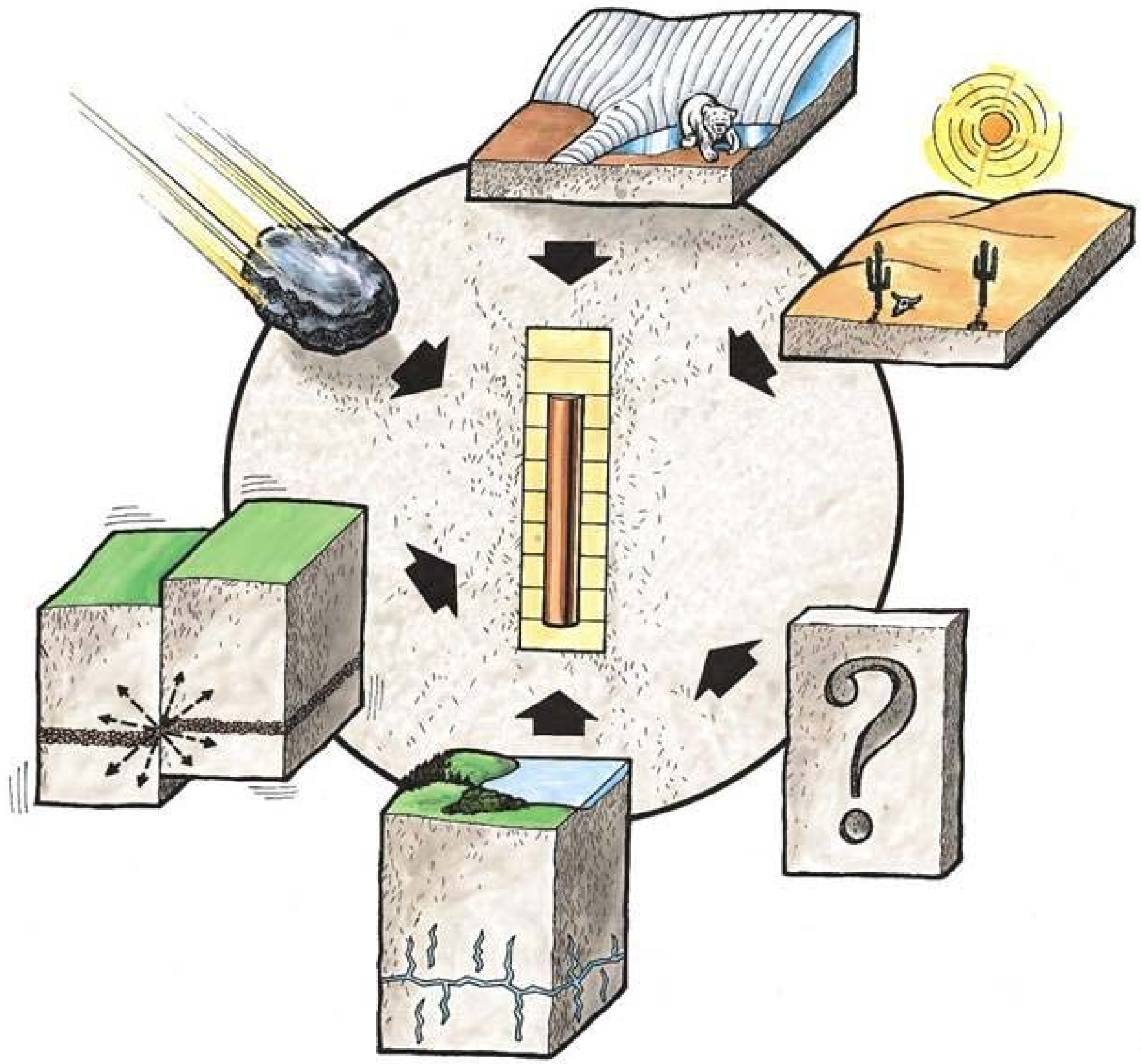
Safety assessments – scenarios due to changes in external conditions



Source: SKB

Selection of scenarios

- Applicable regulations mention three types of scenarios:
  - the main scenario which includes the expected evolution of the repository system;
  - less probable scenarios, which include alternative sequences of events to the main scenario and also the effects of additional events;
  - residual scenarios, which evaluate specific events and conditions to illustrate the function of individual barriers.

Source: SKB

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Performance Assessment Methodology

- A simple but robust methodology – based on fundamental and well-established scientific principles, e.g.:
  - Mass-balances
  - Thermodynamics
- Only fundamental mechanistic approaches allow reliable extrapolation in time
- Compare results with field and laboratory observations
  - Use deviations for improving the understanding
  - Observations of natural analogues to address long-term and/or large scale processes
- Feedback to the design work
  - Improvements
  - Optimisation

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Performance Assessment

- Keep it simple!
- Define what is really important
- Make simple estimates
  - Use reliable tools
  - Be quantitative
- Try to keep the overall picture in focus
  – Simple and Transparent
  - Set up a conceptual model of the system to be studied
- Use an iterative approach
  - Avoid unnecessary detail in the first rounds
  - Go in depth with issues judged to have potential global impact
- Discard processes/features/scenarios that are obviously irrelevant or can be discarded based on simple estimates

Performance assessment cont.

- Work through the system in a systematic way
  – use available tools such as FEPs and structured scenario analysis
- Thoroughly document what has been done!
  - What has been studied (purpose and scope of investigation, the studied site and storage system etc)
  - Which assumptions that were made
  - Quantitative parameterisation
  - Judgments made based on the quantitative results
  - Sensitivity of results to parameter uncertainty
    - Is the uncertainty expected to be of importance?
  - Who made the judgments

- Storage options must be robust and credible in order to become a significant part of the solution and in order to gain acceptance.

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Need for Performance Assessment Methodology

- The large scale of implementation and the long-term perspective is the real challenge
- A firm scientific basis is necessary
  - extrapolations only possible on a mechanistic basis
  - in-depth knowledge and comprehension required
- Acceptance by society demands highest credibility
- The burden of proof is on You!

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Issues of potential importance

- Scale-effects may be important
  - What is not observed in small scale experiments/ applications may well occur in large scale applications
    - Ex. Rock heterogeneity at different scales, Rock mechanical impacts of CO_2 pressure or buoyancy effect
- Impact on groundwater systems
  - Effects due to dissolution and hydrolysis of CO_2
    - pH impact
    - Dissolution/precipitation of minerals
    - Mobilisation of heavy metals
  - Displacement of saline groundwater
    - Huge volumes displaced by injected CO_2
    - High pressure gradients created
    - Impact on fresh groundwater aquifers
- Risk assessments should be used to address possible effects
  - Which processes/features may be critical?
  - What are the potential consequences?
  - Would the consequences be acceptable?
  - What would be required for this to happen? Reasonable?
  - Can they be avoided/minimised?

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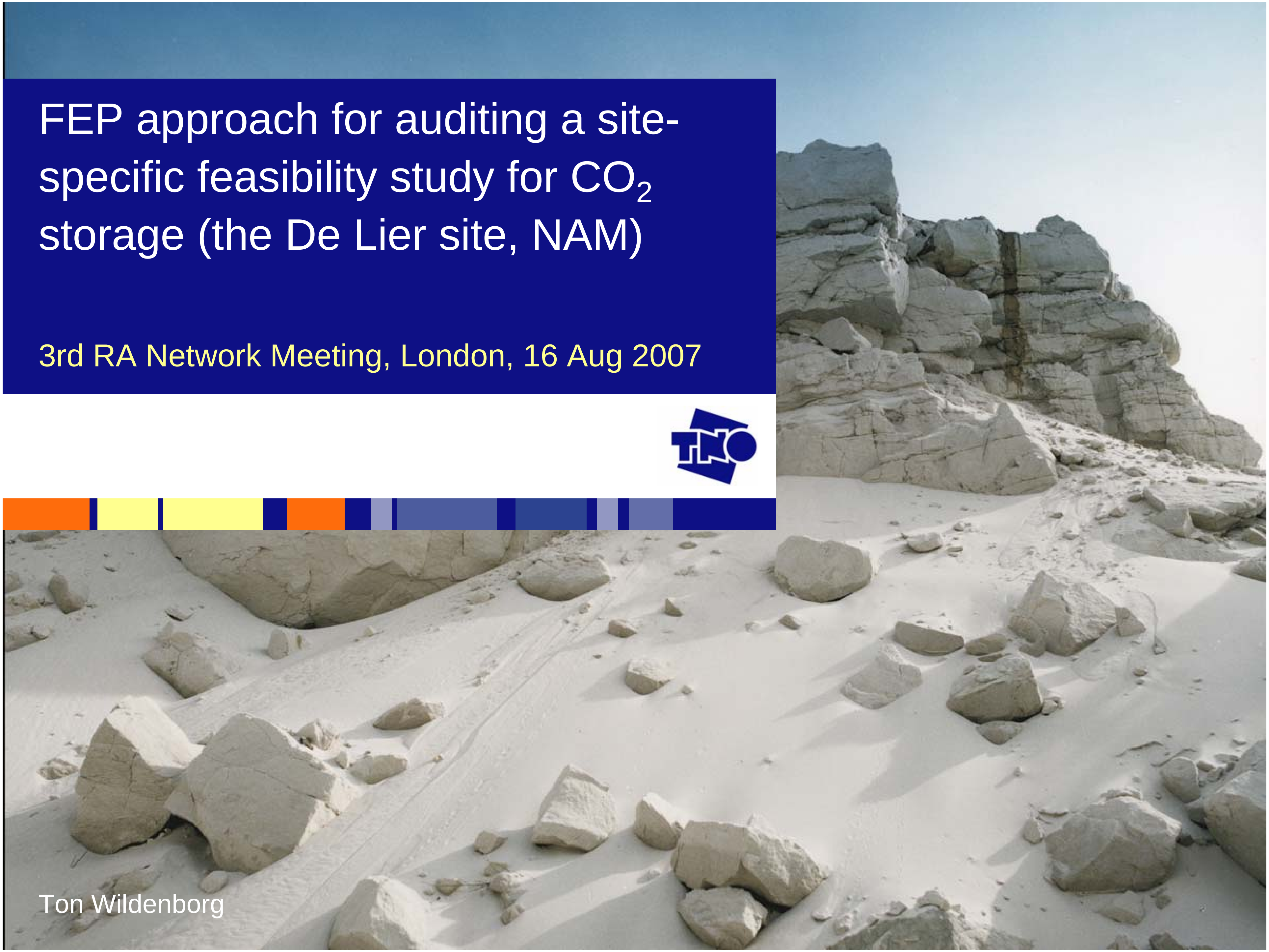
Concluding remarks

- Many facts point to the need for large scale mitigation of the CO_2 emissions
- The necessary scale of GCS application is far beyond present day application – although the technology can be applied
- The time factor seems to be important – it is not getting better!
  - We should not wait for the perfect solution and complete knowledge of all details
  - There must be a preparedness for certain surprises
- Performance assessment methodology can be applied to address and foresee (possibly avoid) some difficulties
- To balance atmospheric CO_2 levels over the next centuries, using GCS combined with other measures, is likely to be society's largest challange

Thank you for you attention!

FEP approach for auditing a site-specific feasibility study for CO_2 storage (the De Lier site, NAM)

3rd RA Network Meeting, London, 16 Aug 2007



Ton Wildenborg

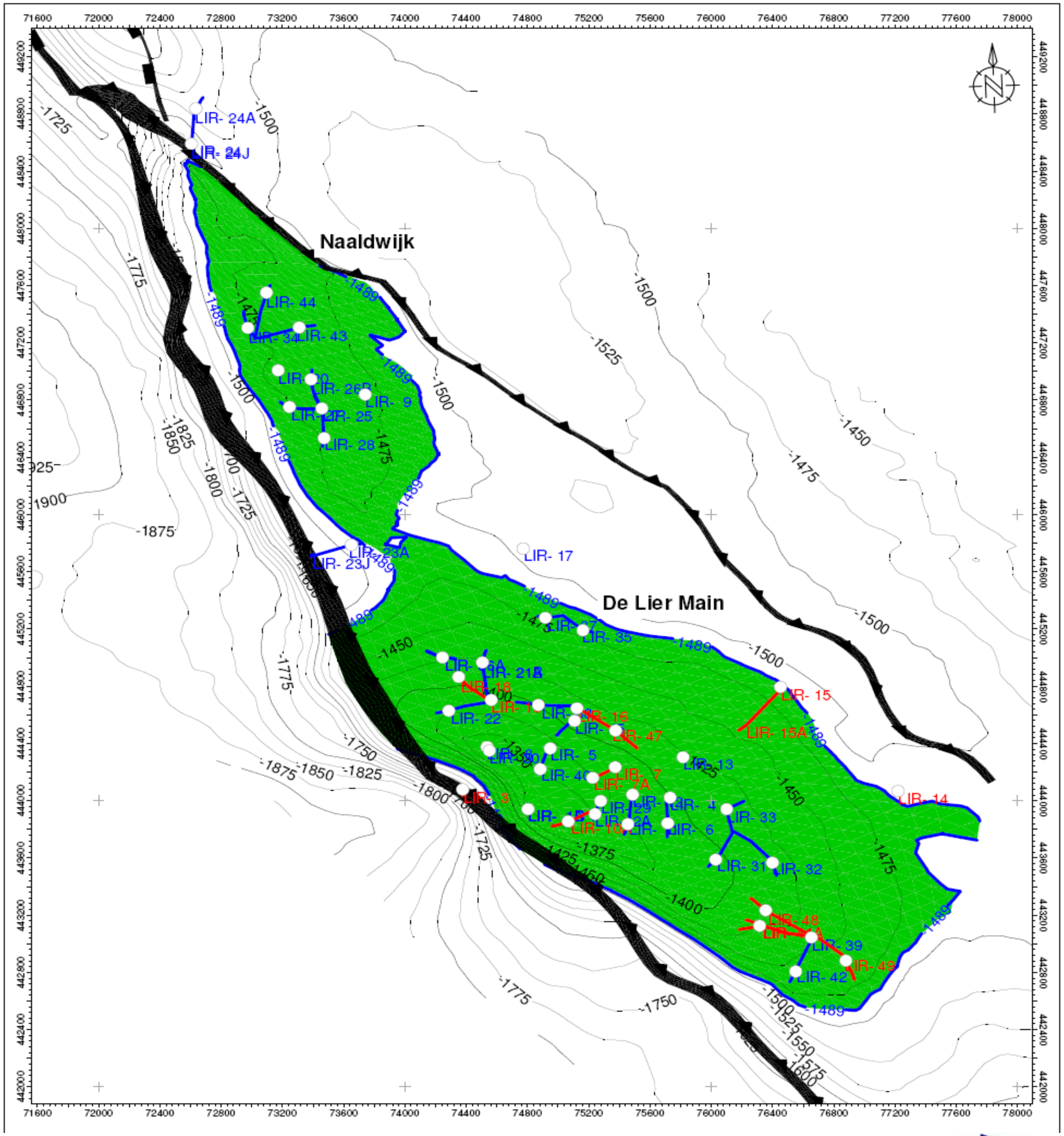
What is specific for assessment of CCS? Long-term component of storage (post-injection)

- No monitoring possible over a very long time period
  - Emphasis on preventive measures
  - Sound scientific basis
- No performance data (yet)
  - Use analogues
- More external factors
  - Comprehensive hazard/risk identification
- Very high uncertainty in properties
  - Conservative approach
  - Probabilistic approach

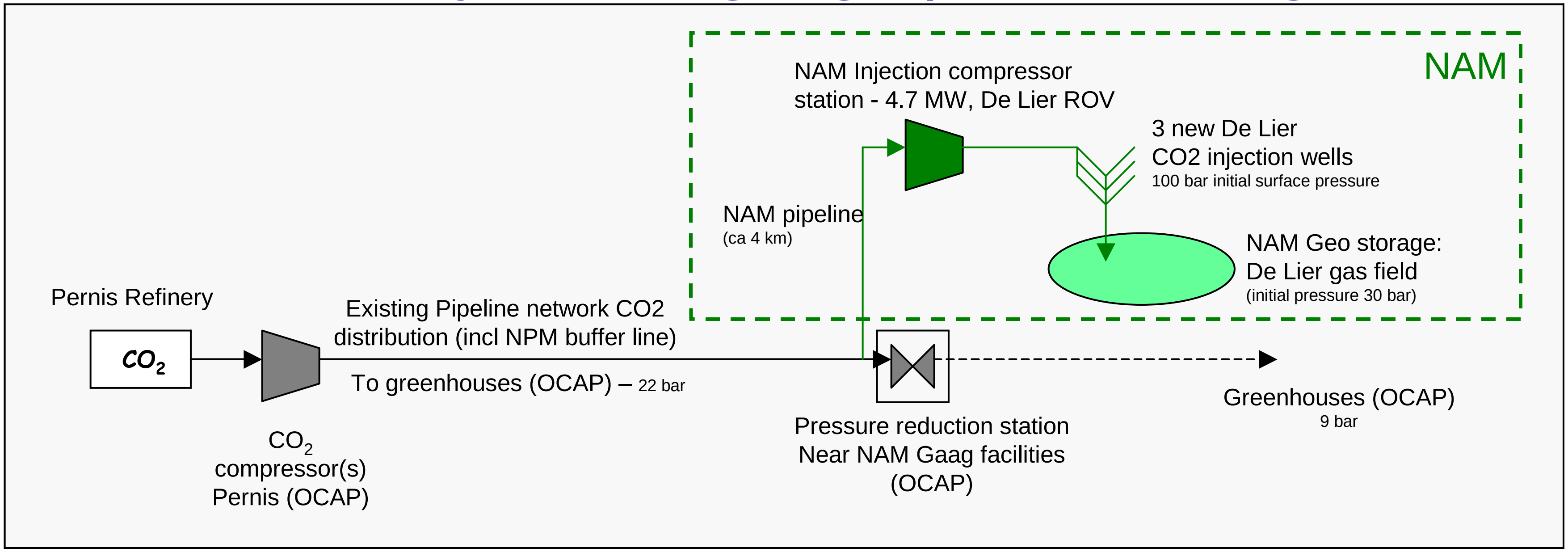
Contents

- The De Lier setting
- Objective and study programme
- Qualitative hazard assessment
  - Objective
  - Bowtie concept
- Scenario-based assessment methodology
- Approach for the De Lier case
- Results qualitative hazard assessment
- Conclusion

Depth reservoir



CCS system & geographical setting



Objective of feasibility study

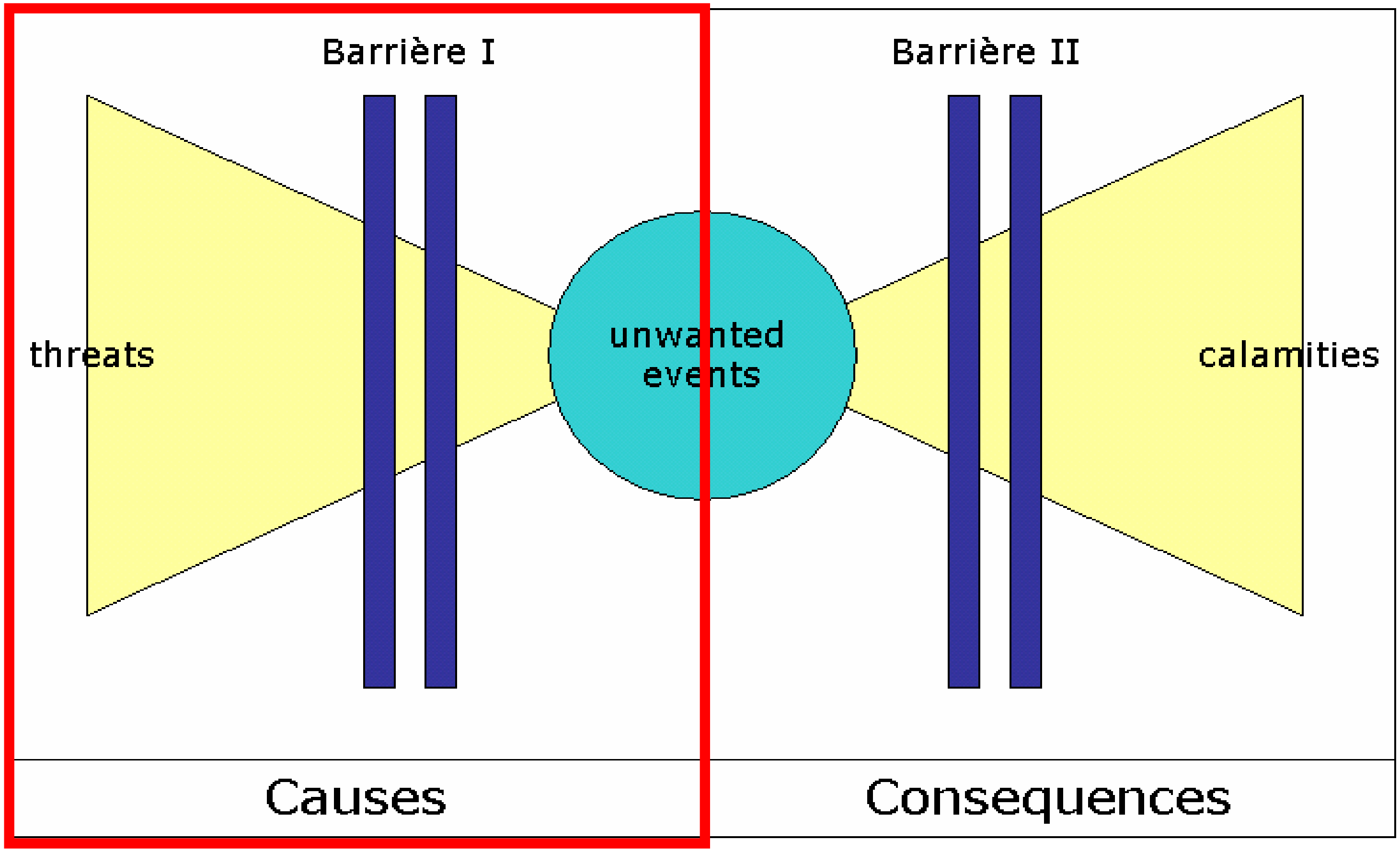
- Evaluating the feasibility of safe and effective storage of CO_2 in the depleted De Lier gas field (NAM)
- At this stage emphasis on integrity of containment (hazards)

No	Study name
1	Well Integrity
2	Subsurface Field model
3	Cap rock / Fault Integrity
4	Spill risk
5	Reservoir compatibility
6	Monitoring programme
7	Surface design incl. risks and mitigation
8	Qualitative hazard assessment

Objective of qualitative hazard assessment (study 8)

- Qualitative consensus on possible leakage scenarios of CO_2 (and residual gas) out of the containment
- Evaluate the **comprehensiveness** of the initial programme of technical studies

Hazards & risks – bowtie concept

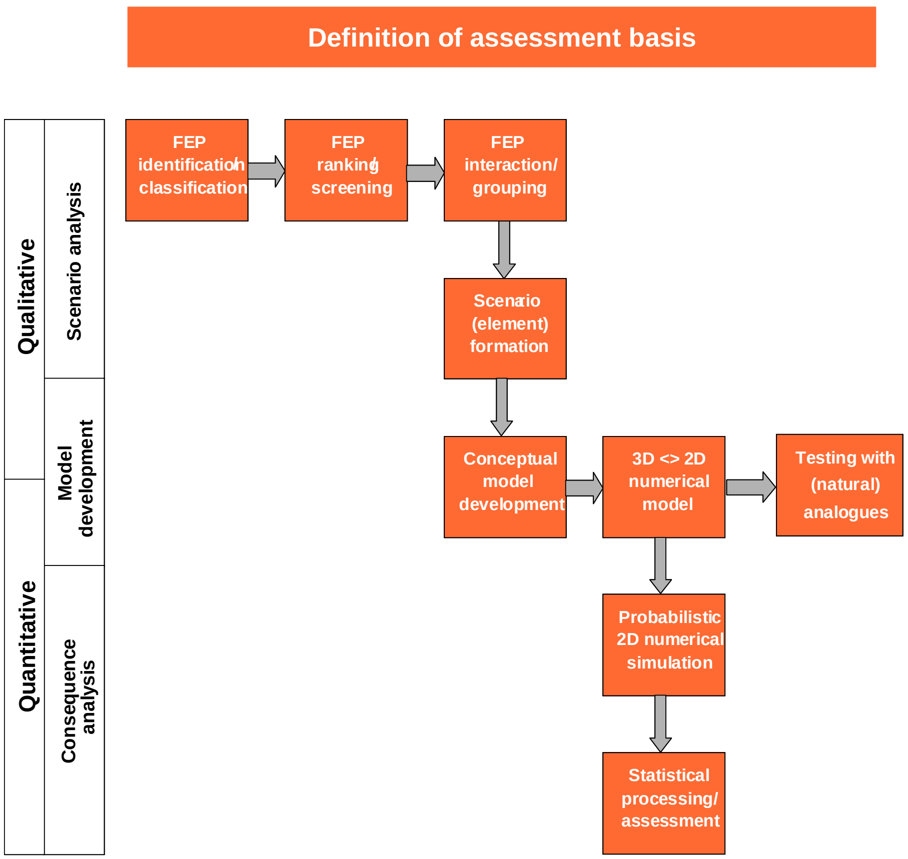


Hazards

Risks

Scenario-based assessment method

- Definition of the assessment basis (de Lier reservoir and surrounding)
- FEP analysis (Features, Events and Processes)
  - Identification
  - Ranking
- Scenario formation
- Development of dedicated models for simulation of safety scenarios
- Risk evaluation against HSE effects

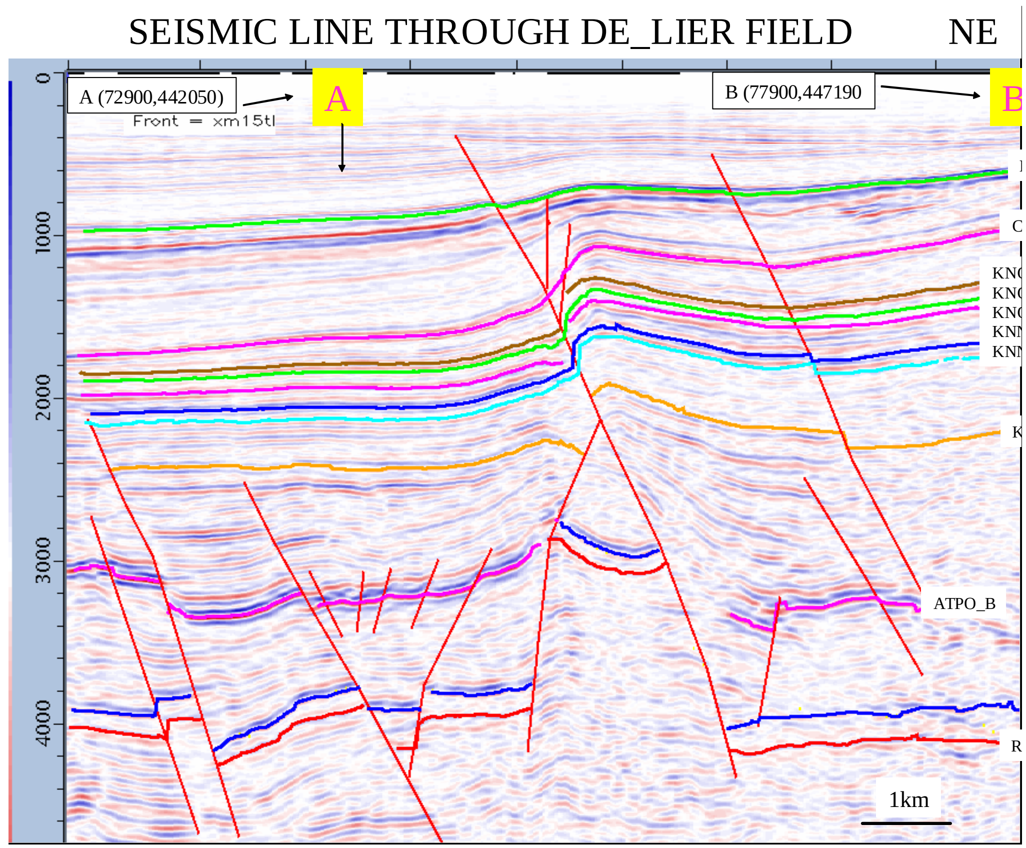


Approach qualitative hazard assessment (0)

Defining the assessment basis:

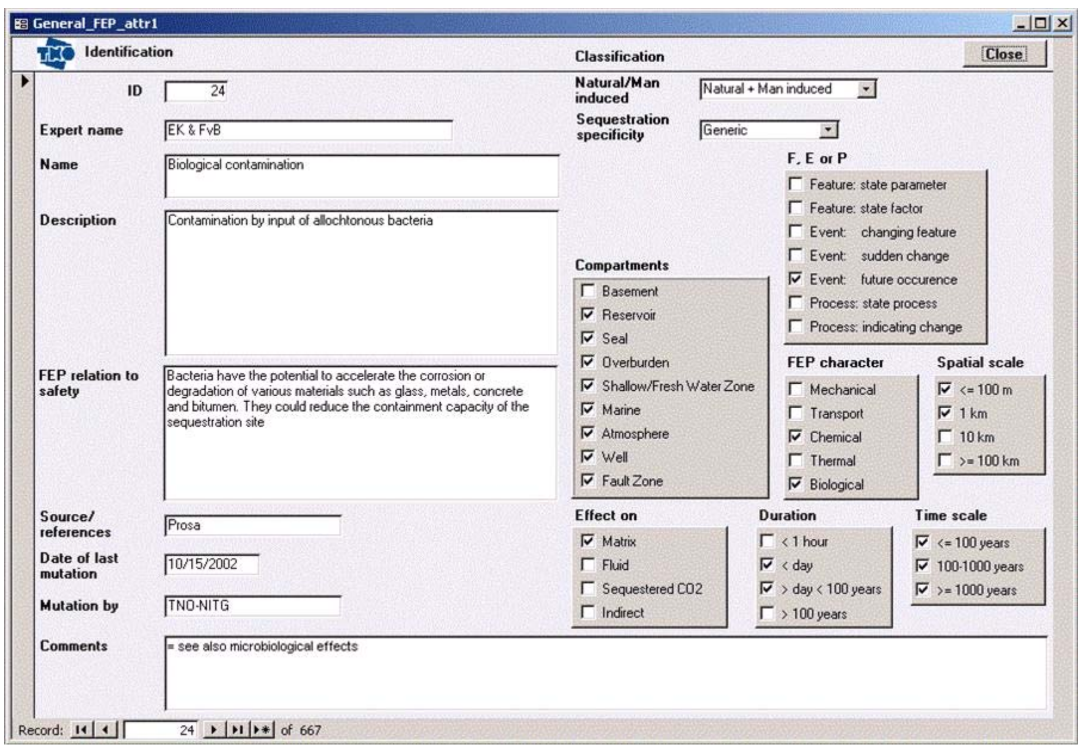
- Geographical and geological setting
- Containment concept
- Assessment target (criteria)

- Temporal and spatial scale
- Assessment procedure



Approach qualitative hazard assessment (I)

- Identification, pre-selection and grouping
  - FEP database of 657 FEPs
  - Pre-selected by TNO on redundancy and relevance to containment (reservoir and seal)
  - Resulting 200 FEPs were grouped



FEP grouping

- **Chemical reactions**
- **CO_2 behaviour**
- **Faults and fractures**
- **Fluid flow**
- **Human flaws**
- **Injection**
- **Mineral dissolution and precipitation**
- **Natural changes of the system**
- **Petrophysics**
- **Anthropogenic activities**
- **Rock mechanics**
- **Seal integrity**
- **Thermal processes**
- **Well integrity**

Approach qualitative hazard assessment (II)

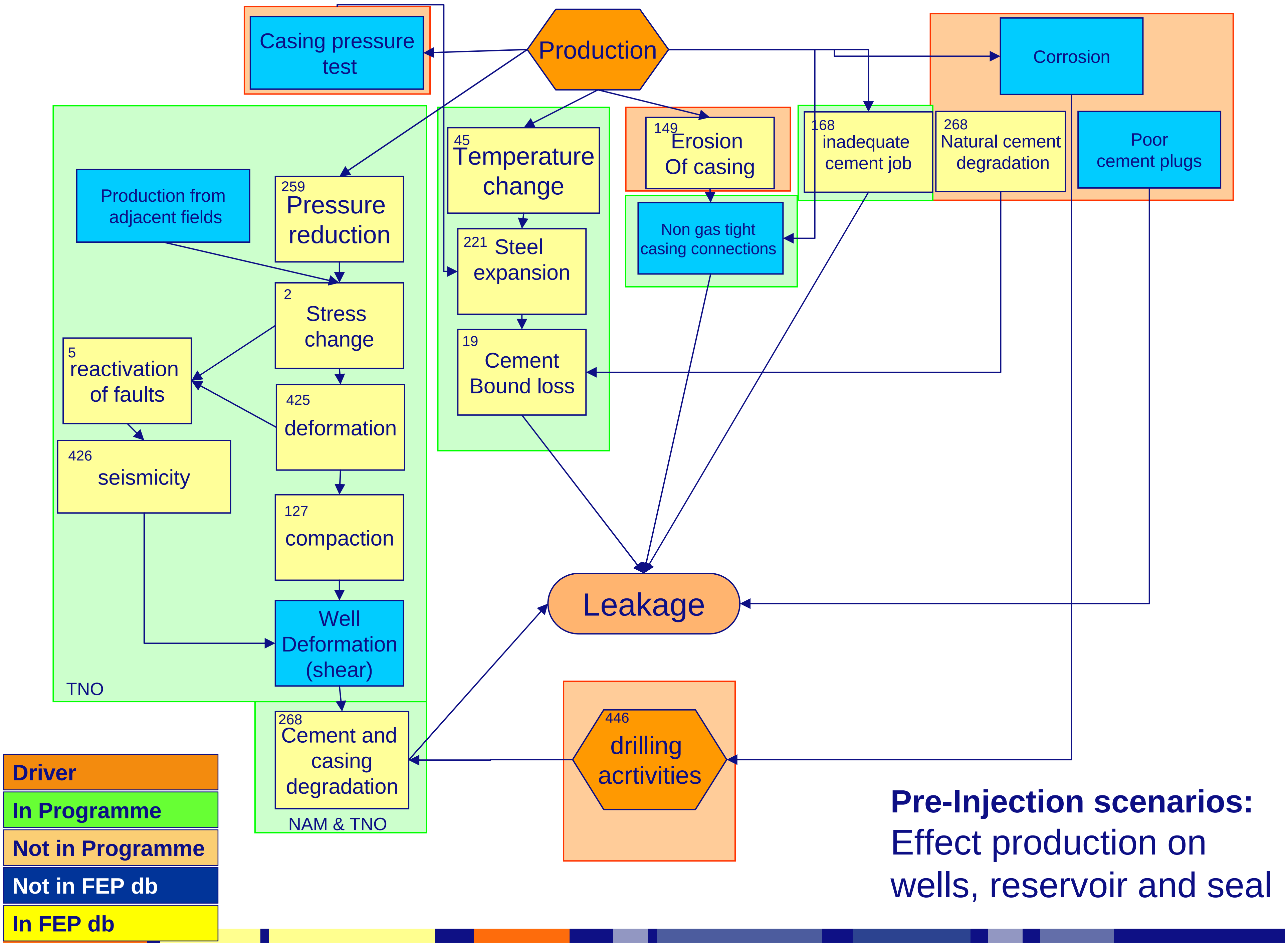
- Screening (13 experts consulted by e-mail)
  - Pre-selected FEPs ranked by experts (top-20 FEPs per expert)
  - 67 FEPs left after screening

Swelling/shrinkage due to chemical transition	Chemical swelling and shrinkage	5
Redox change	Chemical redox reactions	4
Change pH	Change in the pH of the solution, either decrease (acidification) or increase. The dissolution of CO_2 will cause a pH-drop which will be maintained for some time depending on the carbonate and silicate buffering capacities of the sediment	4
Mineralogical change	Change in mineralogy due to chemical reactions	4
Kinetics of chemical reactions	The theory of the thermodynamic behavior of matter (in chemical reactions) based in its simplest form on the identification of heat with the kinetic energy of a substance's rapid, randomly moving molecules and on a classical dynamic analysis of molecular	3
Geochemical widening of preferential pathways	Relatively fast dissolution of minerals, as is the case for carbonate dissolution, will quantitatively become more important when the carbonate saturated solution is transported away from the location where dissolution occurred. This is likely to be the c	3
Sorption/desorption of CO_2	Uptake/release of CO_2 molecules to/from the surface of solid bodies and/or liquids	2
Chemical barriers (Eh-pH)	Natural or induced 'fronts' of Eh and/or pH in porefluids can act as barriers to CO_2 migration. The forcification(?) of CO_2-bearing solids may result from such interactions.	2

Approach qualitative hazard assessment (III)

- Scenario formation (workshop)
  - Consensus building on selected FEPs
  - Combining selected FEPs using cause-consequence relations
  - Reviewing completeness of the De Lier feasibility study

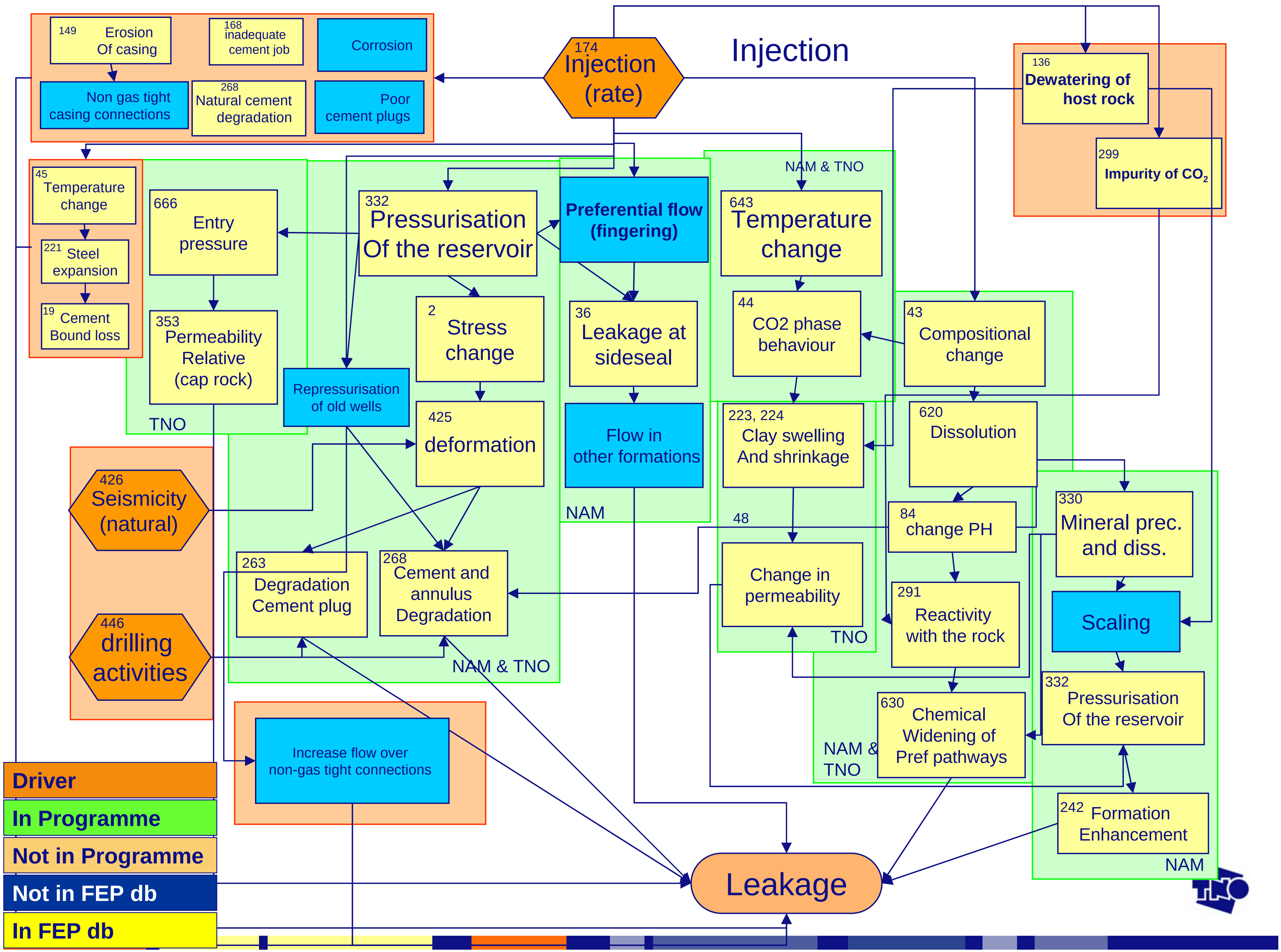
  - 42 FEPs remained for further (quantitative) assessment
  - Scenarios defined for three stages:
    - Pre-injection
    - Injection
    - Post-injection



Pre-Injection scenarios:
Effect production on
wells, reservoir and seal

Injection scenarios

- Pressure
- Temperature
- Compositional change

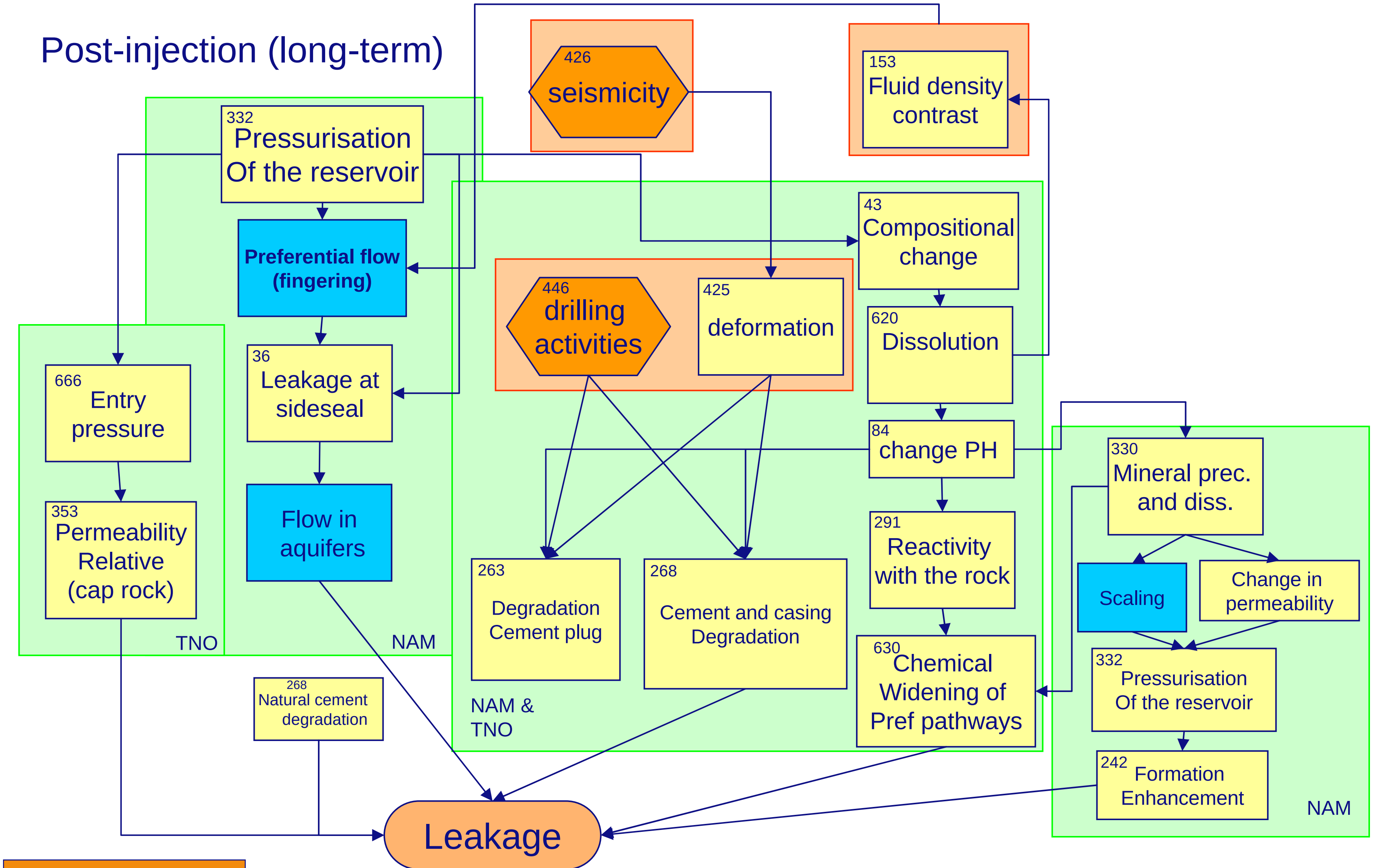


Injection
174 Injection (rate)
149 Erosion Of casing
168 inadequate cement job
Corrosion
Non gas tight casing connections
268 Natural cement degradation
Poor cement plugs
136 Dewatering of host rock
299 Impurity of CO_2
45 Temperature change
221 Steel expansion
19 Cement Bound loss
666 Entry pressure
353 Permeability Relative (cap rock)
TNO
332 Pressurisation Of the reservoir
2 Stress change
Repressurisation of old wells
425 deformation
Preferential flow (fingering)
36 Leakage at sideseal
Flow in other formations
NAM
NAM & TNO
643 Temperature change
44 CO2 phase behaviour
43 Compositional change
223, 224 Clay swelling And shrinkage
620 Dissolution
48
84 change PH
Change in permeability
TNO
291 Reactivity with the rock
330 Mineral prec. and diss.
Scaling
332 Pressurisation Of the reservoir
630 Chemical Widening of Pref pathways
NAM & TNO
242 Formation Enhancement
NAM
426 Seismicity (natural)
446 drilling activities
263 Degradation Cement plug
268 Cement and annulus Degradation
NAM & TNO
Increase flow over non-gas tight connections
Leakage
Driver
In Programme
Not in Programme
Not in FEP db
In FEP db

Post-injection

- Pressurized reservoir
- Buoyancy
- Reactions

Post-injection (long-term)



Driver

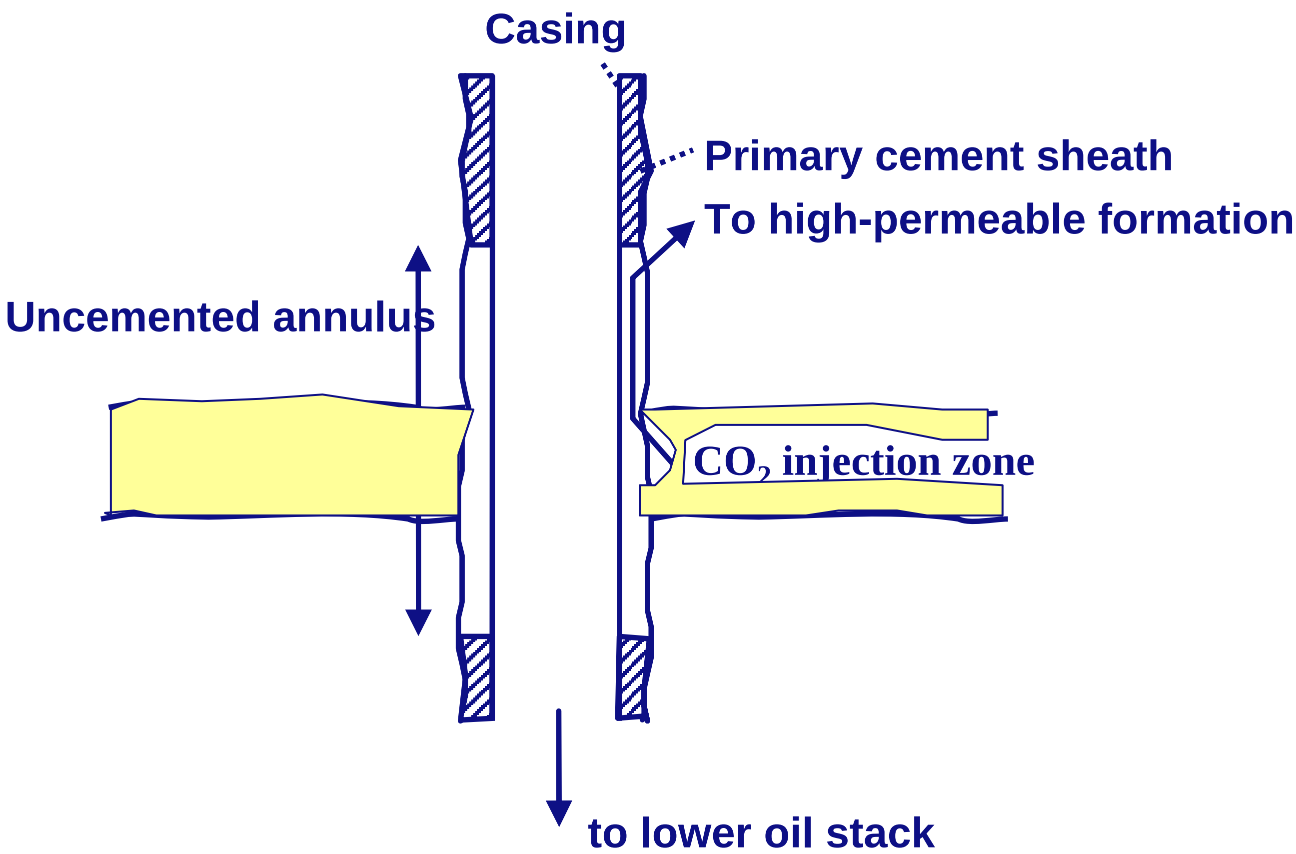
In Programme

Not in Programme

Not in FEP db

In FEP db

Well integrity: concern



Conclusion

- FEP approach provides a structured way of how to define possible leakage scenarios within limited time
- Splitting the time domain made scenario definition less complicated
- Most of the selected FEPs were included in the initial programme
- Recommended to include in study programme:
  - Degradation of casing and cement (testing, temperature change, poor cement job, casing erosion etc.)
  - Dewatering of host rock
  - CO_2 impurities
  - Interfering drilling activities
  - Seismicity

Using (not abusing) FEPs

Steve Benbow

Philip Maul, Richard Metcalfe, David Savage

Quintessa Ltd

Overview

Background

- FEPs and FEP databases

Possible usage

- Top-Down and Bottom-Up approaches

Application to natural analogue systems

- System-Level modelling

Summary

Definition of FEPs

- Many slightly different formal definitions (e.g. IAEA, 1997, 2004; Savage et al. 2004), but basically:
  - "Feature", a physical component of a system or a physical entity that influences a system
  - "Event", a process influencing system evolution over a short time period compared to the time frame being considered
  - "Process", a dynamic interaction between "Features", which may operate over any particular time interval of interest.
- Definitions of "Events" and "Processes" overlap
  - Different timescales
- No need to get bogged down in classification of phenomena!

FEP Databases

FEP Databases are just collections of FEPs, not a modelling tool

Uses of FEPs / FEP databases:

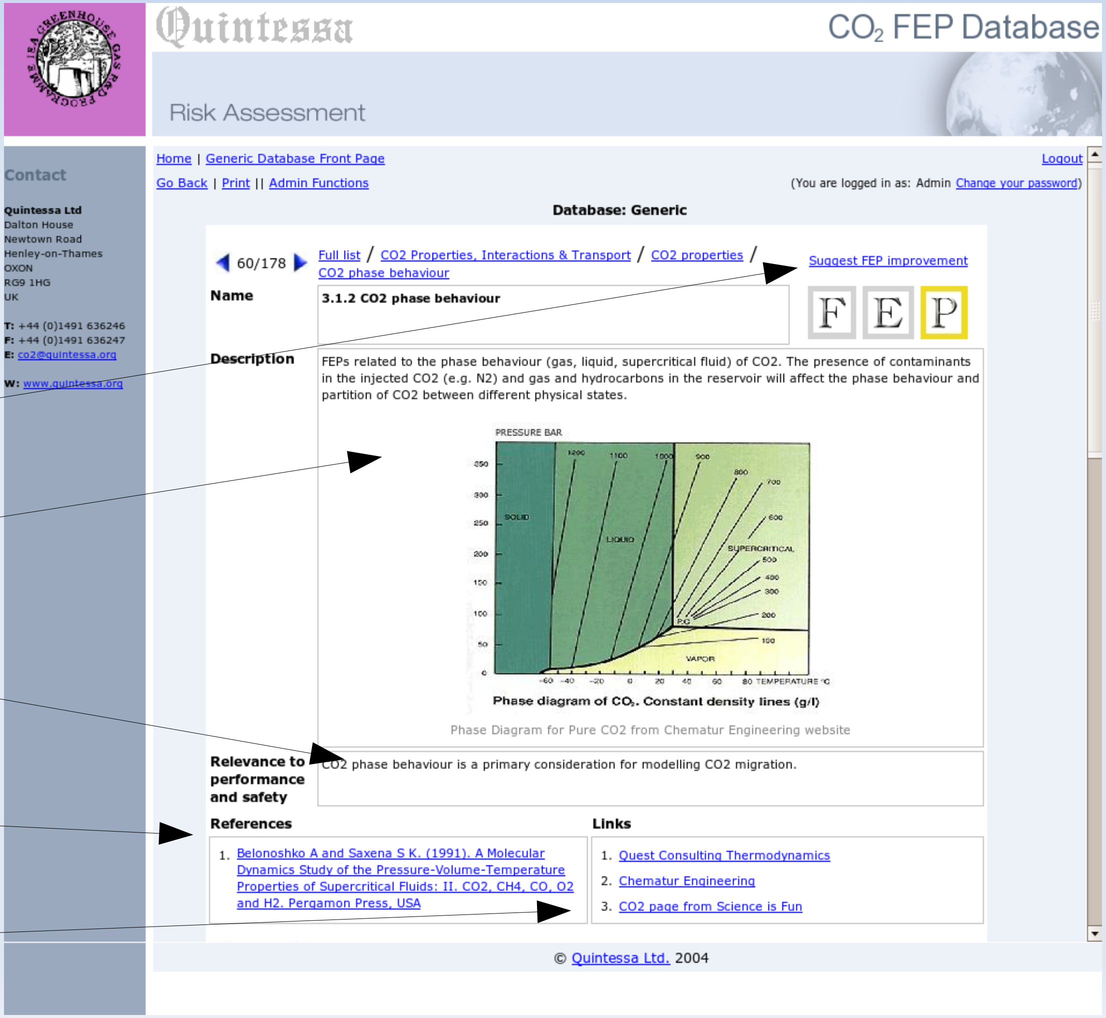
- Aid model and scenario development
  - Describe key scenarios - give us a language (terminology) to use
- Audit tool for system-level models
- Knowledge base for storage studies
- Stimulate discussions among experts
- Project FEP databases:
  - indicate range of phenomena that have been considered
  - build confidence in thoroughness and logic of a safety assessment

Quintessa's CO_2 FEP database

- Developed initially during the Weyburn project (2001-2004)
- Freely accessible – IEA Greenhouse Gas R+D Programme web page
  http://www.co2captureandstorage.info/riskscenarios/riskscenarios.htm

A knowledge base

- Suggest improvements
- FEP description
- Relevance to safety
- References
- Links



Possible Usage

FEP databases can be used in two ways:

"**Bottom-up**" approach

- Database is used directly in the development of assessment models, e.g.
  - Process influence diagrams
  - Interaction matrices

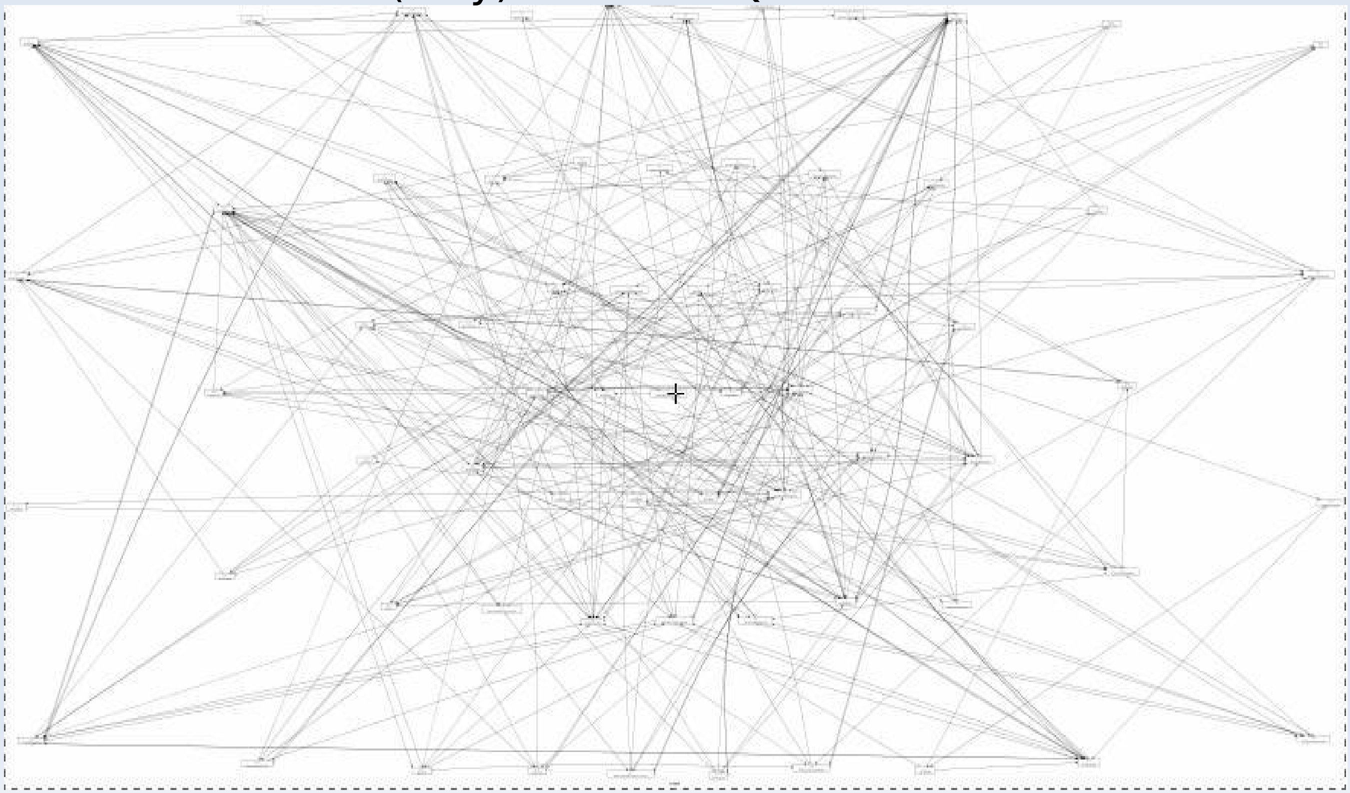
"**Top-down**" approach

- Database is used as an audit tool and modelling aid:
  - To ensure all relevant FEPs are in the model
  - To document why other FEPs are screened-out

Bottom-up

- If the database is used as a starting point, all possible FEPs and relationships must initially be considered.
- Potential for complexity is huge ...
- Where to begin ... ??

PID for (only) 69 FEPs. Quintessa database has ~ 150



Probabilistic RA

If the bottom-up approach is used, there is a tendency to reach for probabilistic tools in order to cope with the complexity.

This is fine if good PDFs are available for all likely FEPs and interactions.

- If they are not, there is a danger of “**risk dilution**”

Risk dilution: “*a situation where an increase in the uncertainty in the values of input parameters to a model leads to a decrease in calculated risk*”

(Generally involves the risk being spread out in time or space)

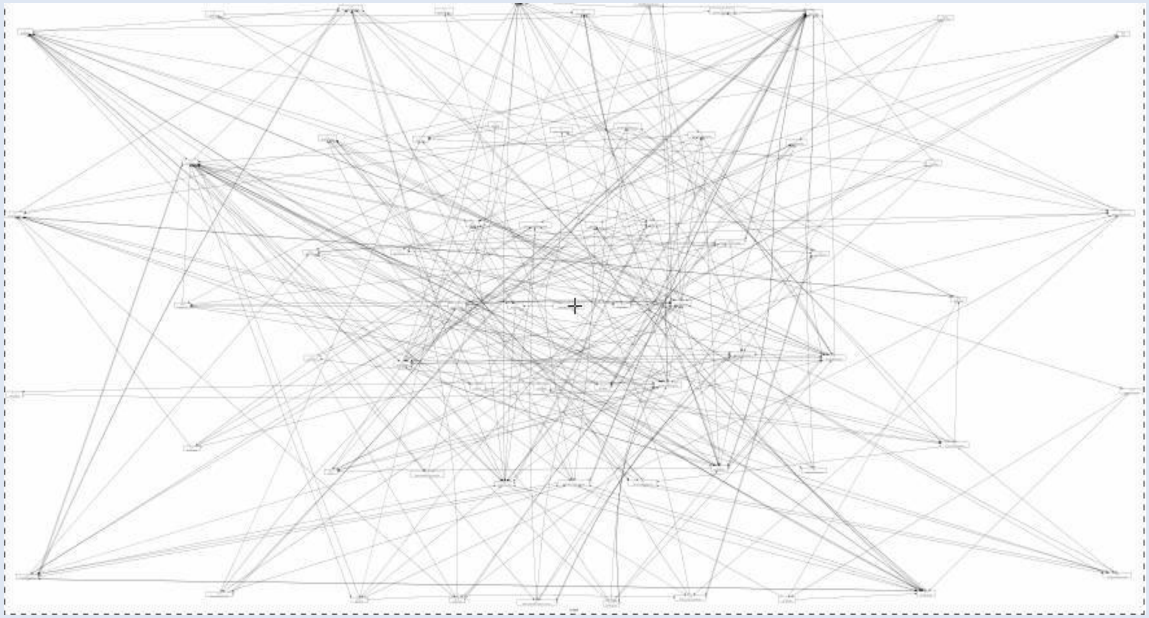
Examples:

- Ignoring parameter correlations – inadmissible parameter combinations contribute to lower calculation of an average
- When PDF is inappropriately wide or biased to low consequence outcomes

Sampling

How many runs do we need to convince ourselves that we've covered all relevant possibilities?

We must not only choose which relationships to include, but also how to include them.



(Only 69 FEPs ...)

It might seem as if FEPs are a bad idea ...

Top-down

Motivate with a real example: Latera analogue study

(CO2GeoNET, Maul et al., 2007
Quintessa, BGS, URS)

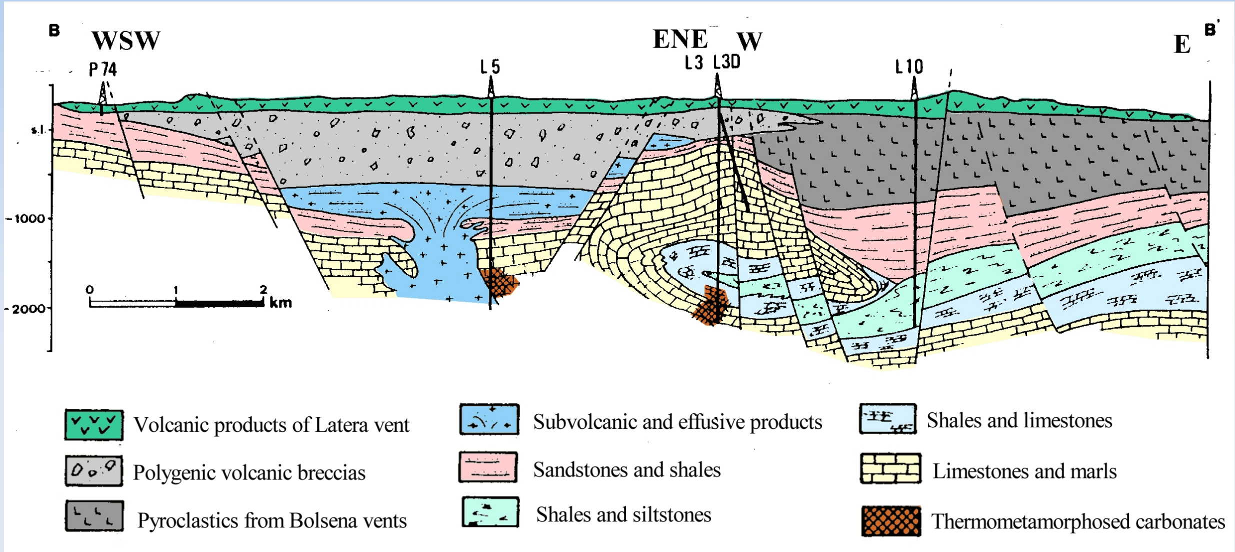
Not a performance assessment – just a modelling study, but approach to modelling the system is similar to PA

To appear – GHG Control & Technology

Latera

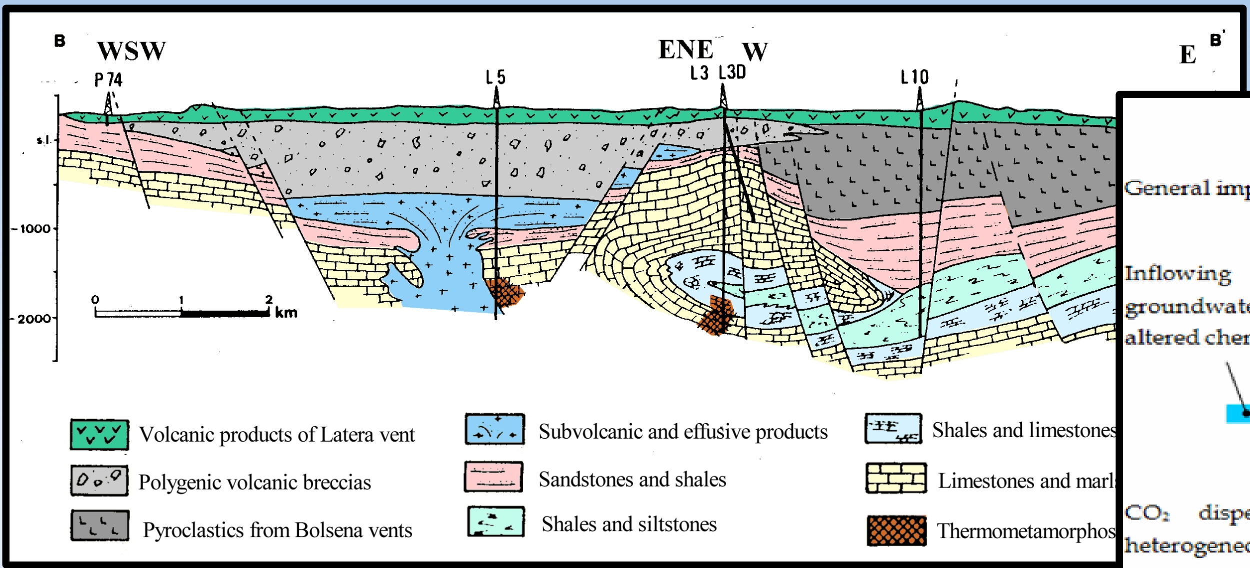
Objective: To simulate the following:

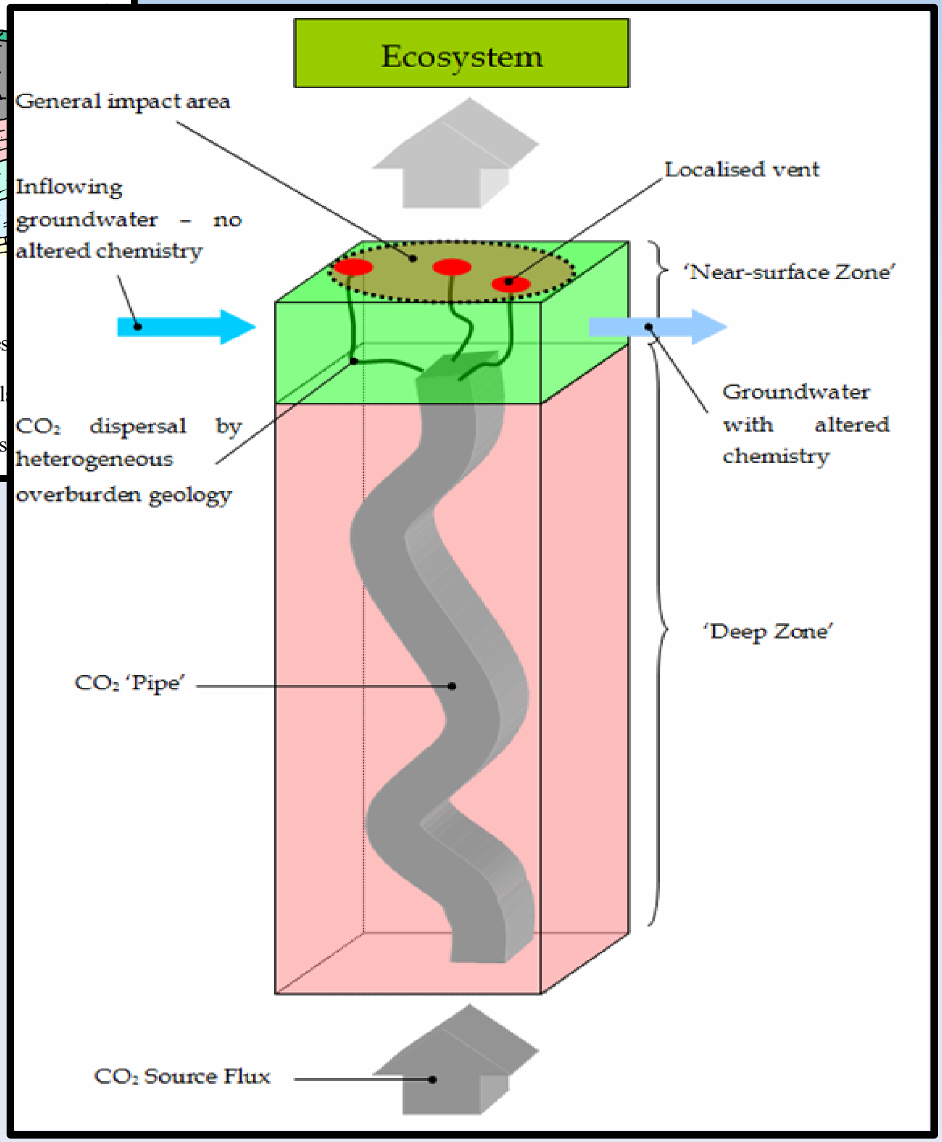
- **CO2 fluxes to the surface and near-surface aquifers**
- **Overall mass balance for the near surface part of the system**



- *The effect of CO2 fluxes on groundwater acidity*
- **Soil gas concentrations**
- Above-canopy atmospheric concentrations close to and away from venting regions
- **Potential impacts to flora** / *fauna and humans*

System-level model



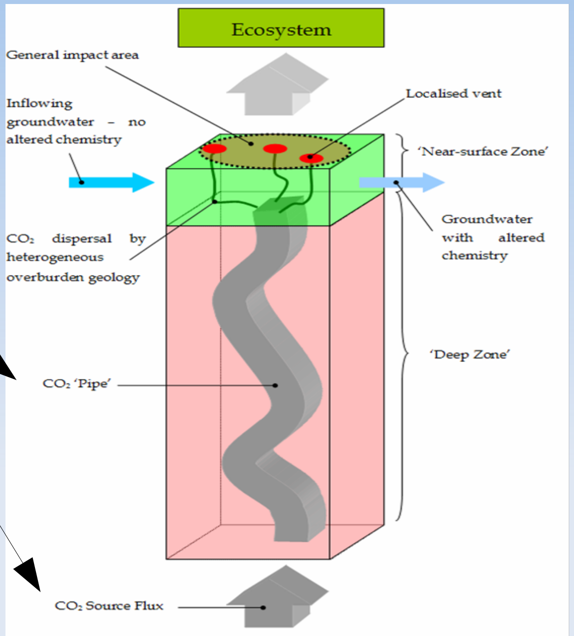


Top-down approach

Top-down approach:

- Identify the key **subsystems** and "**project FEPs**"
  - Using information from detailed site characterisation
- **Audit** the project FEPs using the FEP database to ...
  - Document "project-specific" details for **relevant** FEPs
  - Give reasons for all **screened-out** FEPs
  - Ensure that we've not **missed** anything

(Implies comprehensiveness)



- Identify the "**base case**" and the **scenarios** that we want to model
  - Aim to cover the range of "interesting" possibilities (central and worst cases)

- We develop a **model** (the "knowledge" in the database can help us).

The database is only ever used to assist in developing models/scenarios and as an audit tool – not as a "model generator"

Model development

We need to decide on an **appropriate level of detail** when modelling :

- It may be suitable to model some aspects of the system in "less detail" than others (e.g. the ecosystem)
  - *"Less detail" means less detailed representation of* ***processes and/or geometry***

- Other aspects may need to be modelled in more detail (e.g. the multiphase flow of CO_2 and water)

There is a balance to be struck:

- Less detail => less accuracy but faster runs / more scenarios are possible
- More detail => greater accuracy but slower runs / less scenarios are possible

If the accuracy is sufficient, less detail is "best"

Choice of code

Our choice of “level of detail” will be limited by what is possible in our code of choice.

- Latera example is implemented using QPAC-CO2 (prototype)
- **Q**uintessa **P**erformance **A**ssessment **C**ode – CO2
- A multiphysics code that enables representation of coupled nonlinear processes, e.g.
  - (T) Thermal, (H) Hydraulic, (C) Chemical, (M) Mechanical, (B) Biological
  - Also allows **user-defined** complicated nonlinear processes
    - e.g. the ecosystem

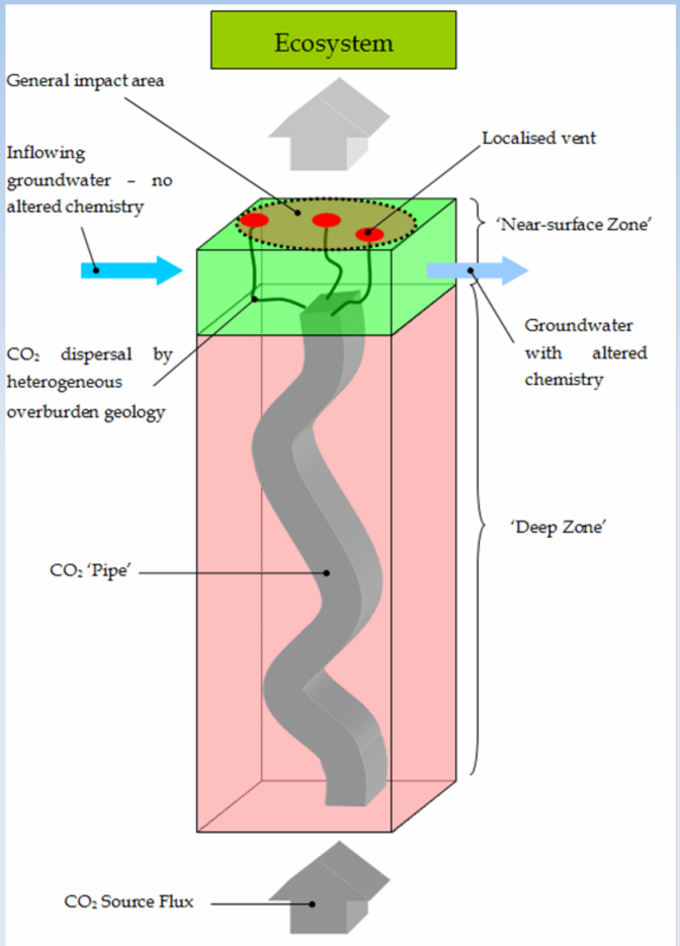
CO_2 transport from depth

Key features for CO_2 transport

- The **source zone** for CO2 is large, originating from thermo-metamorphosed carbonates at depth.

- **Elevated CO_2 fluxes** with consequent impacts on ecosystems occur in relatively small patches (observed in the region of 5-50 m in diameter). These patches tend to cluster into larger zones (~250m in diameter).
  - *Larger zones of elevated CO_2 fluxes have been correlated with sub-vertical **fault zones**. There is some evidence to suggest that they may occur at the intersection of faults.*

- **CO_2 migration pathways** appear to be restricted at depth to a relatively narrow vertical zones ('pipes' or 'chimneys') probably associated with faults and/or intersections of faults

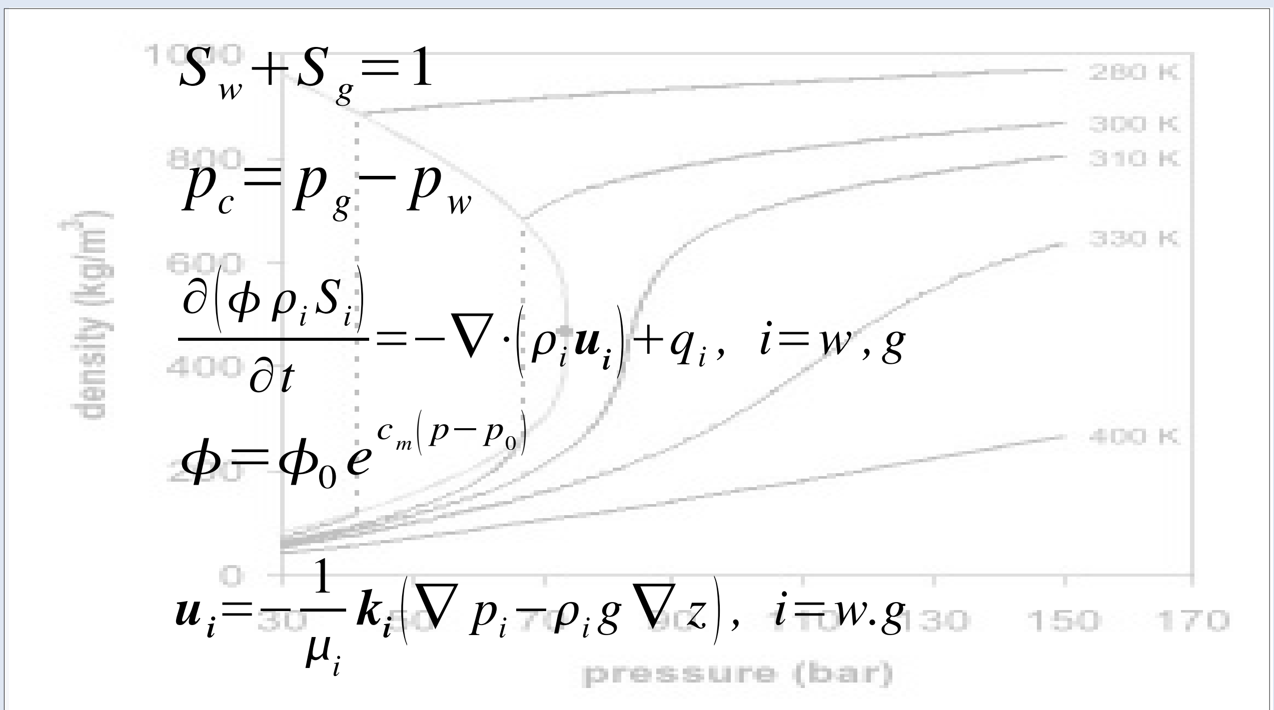


Near surface zone properties are very heterogeneous.

CO_2 transport model

We assume multiphase flow of CO2 from depth to the surface and solve for

- Saturation (n phases)
- Pressure (n phases)
- Density (n phases)
- Porosity



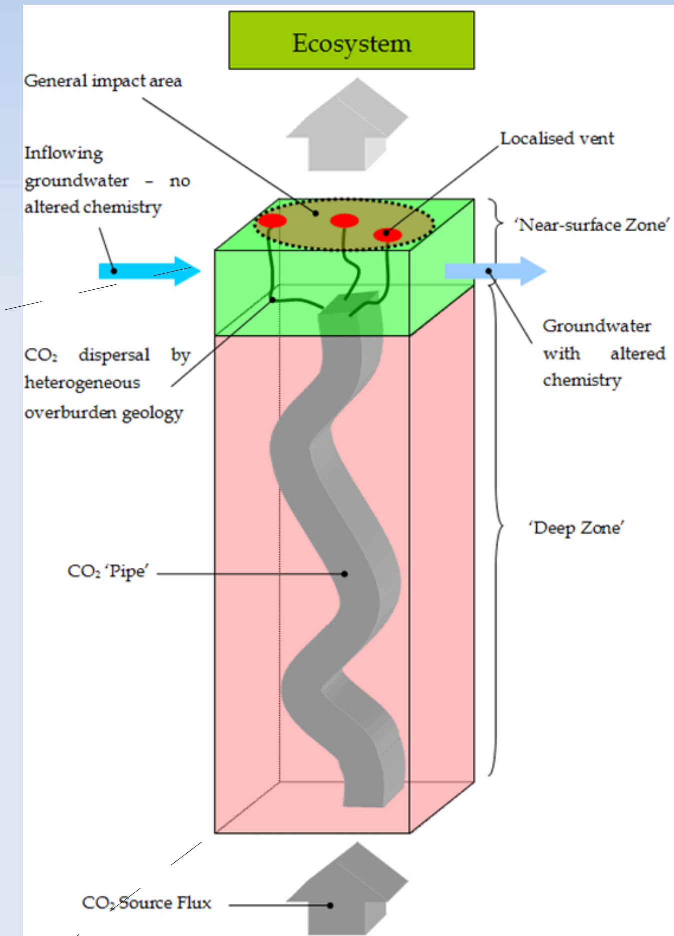
$$S_w + S_g = 1$$

$$p_c = p_g - p_w$$

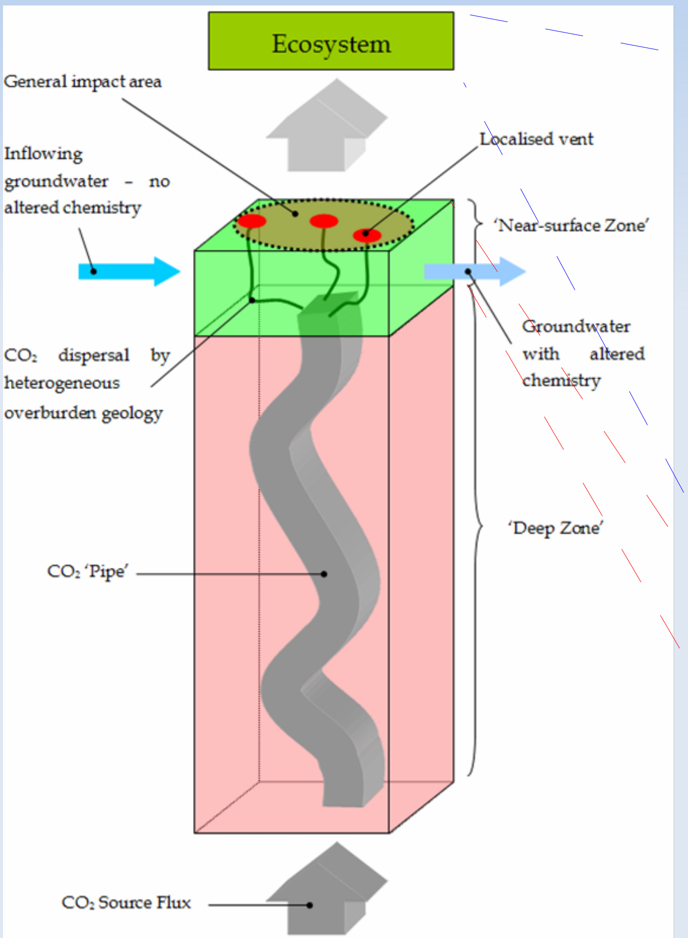
$$\frac{\partial(\phi \rho_i S_i)}{\partial t} = -\nabla \cdot (\rho_i \boldsymbol{u}_i) + q_i, \quad i = w, g$$

$$\phi = \phi_0 e^{c_m (p - p_0)}$$

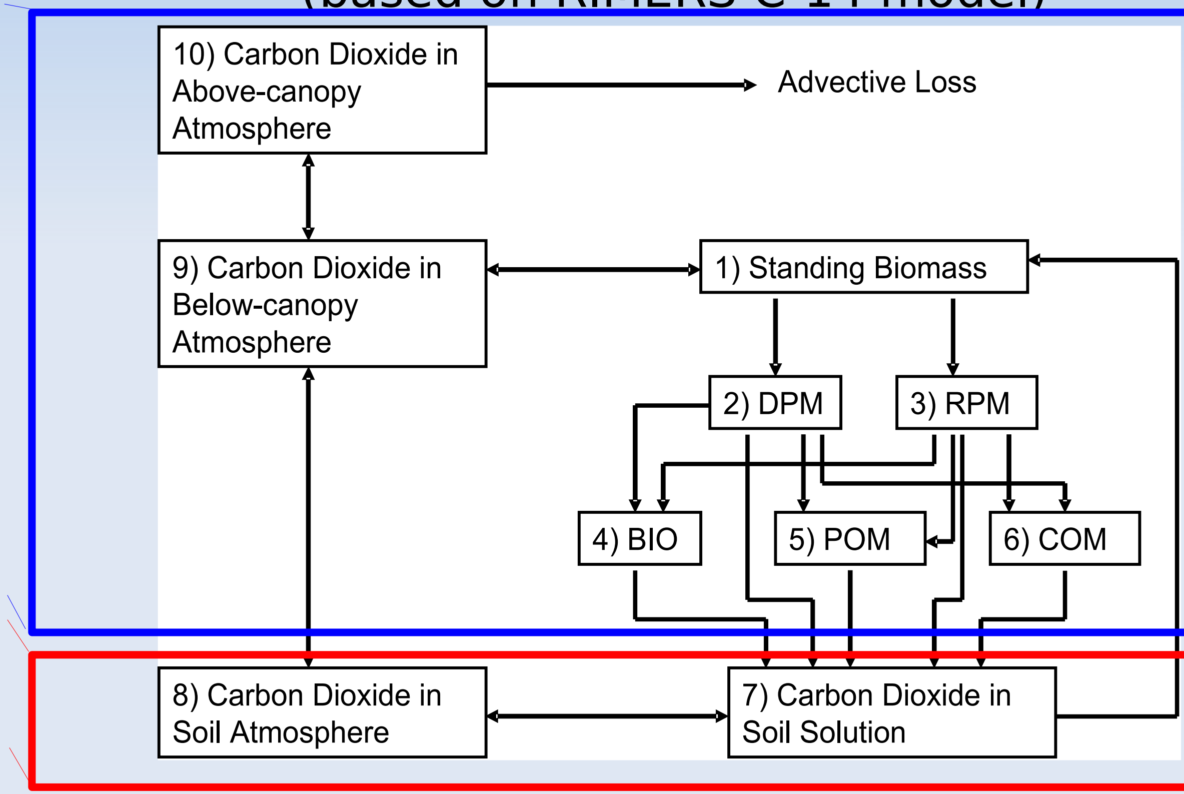
$$\boldsymbol{u}_i = -\frac{1}{\mu_i} \boldsymbol{k}_i (\nabla p_i - \rho_i g \nabla z), \quad i = w.g$$



Ecosystem model



Ecosystem model
(based on RIMERS C-14 model)



Ecosystem compartments:

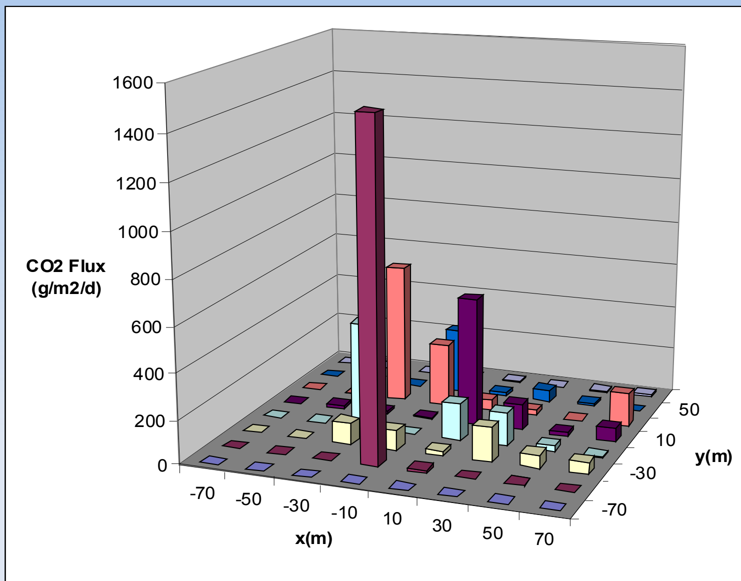
1. Standing biomass
2. Decomposable plant material (DPM)
3. Resistant plant material (RPM)
4. Microbial biomass in soil (BIO)
5. Physically stabilised organic matter (POM)
6. Chemically stabilised organic matter (COM)
7. Carbon dioxide in soil solution
8. Soil atmosphere
9. Below-canopy atmosphere
10. Atmosphere

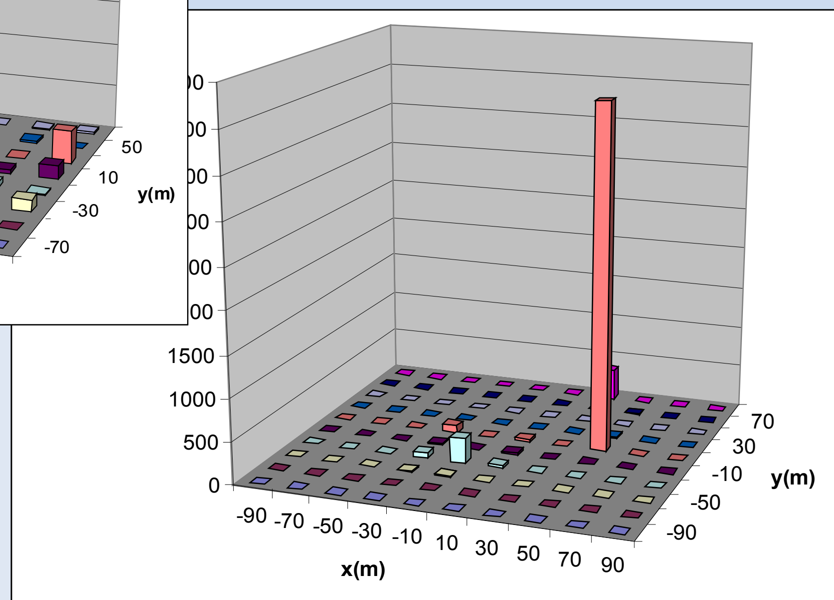
Ecosystem model - notes

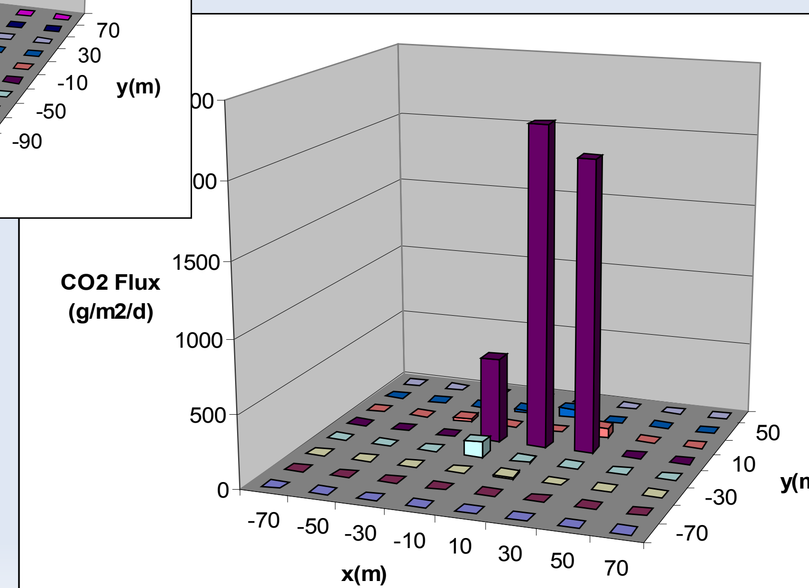
- The ecosystem model is intentionally fairly simple
  - Based on existing models for C-14, aimed at calculating long-term effects.

- The carbon fluxes between the compartments depend in a **non-linear** way on the carbon contents of the compartments
  - i.e. differs fundamentally from a conventional compartment models.

Results

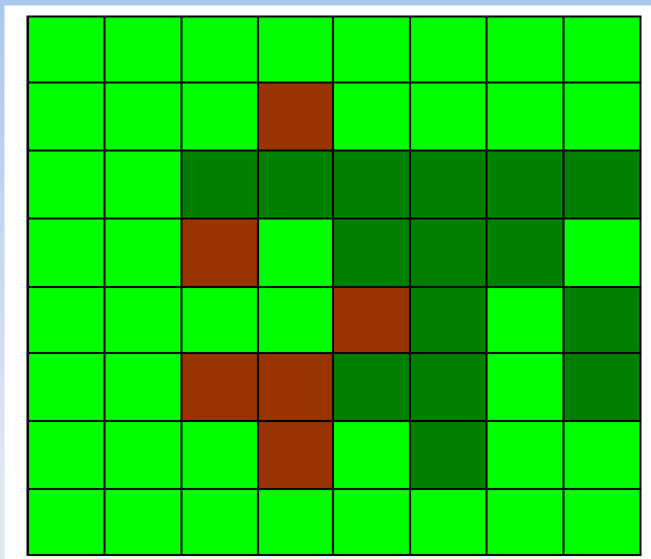




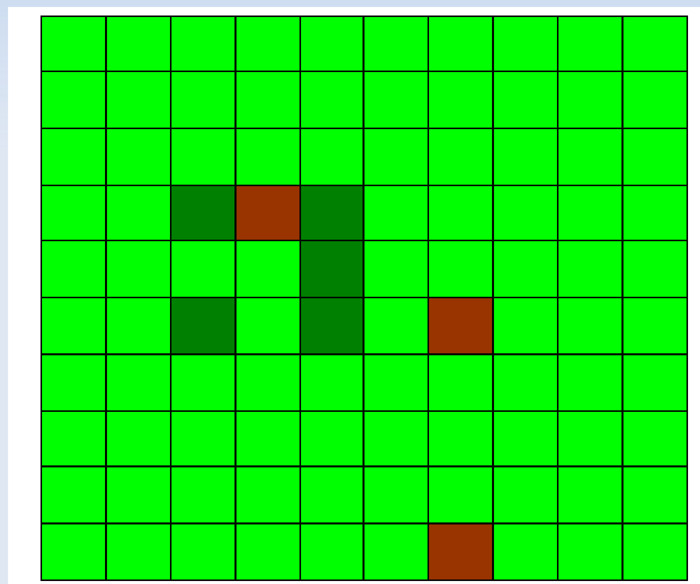


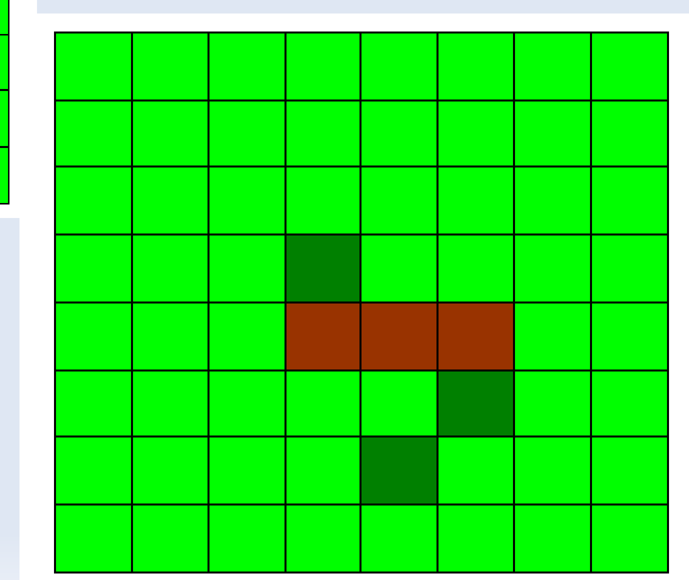
CO_2 fluxes at the surface

Results



Light green = 'normal' growth
Dark green = fertilisation
Brown = reduced growth or plant death





Effects on vegetation

FEP audit

An **FEP audit** was carried out against the Quintessa/IEA generic FEP database.

This is a useful exercise in order to **document** how the various FEPs have been dealt with in the current models, to **check** that no important details have been omitted and to **help identify further work** that would be beneficial.

FEP audit details

Database FEP Number	Description	Comments	
2.1.2	CO_2 quantities, injection rate	The General Model needs to be able to provide realistic simulations for the range of injection rates that may be considered in practice. For Latera the source term is natural and is estimated from information on surface fluxes and other data.	
2.1.3	CO_2 composition	For Latera H_2S is known to be important, but calculations for this gas have not been undertaken to date	IM
Carbon Dioxide Properties, Interactions and Transport			
3.1.1	Physical Properties of CO_2	The pressure and temperature dependence of properties such as viscosity need to be specified. Default values are available in QPAC-CO2.	DOC
3.1.2	CO_2 phase behaviour	A suitable equation of state is employed in QPAC-CO2.	
3.1.3	CO_2 solubility and speciation	The current version of QPAC-CO2 allows instantaneous dissolution to be represented according to Henry's law.	
Carbon Dioxide Interactions			
3.2.9	Water Chemistry	See 3.1.3	
3.2.11	Sorption and Desorption of CO_2	This will need to be considered in the General Model but is not available in the current version of QPAC-CO2.	IM
3.2.15	Gas Stripping	See 2.1.3 on H_2S	
3.2.19	Biomass uptake of CO_2	This is modelled explicitly in the ecosystem model.	DOC
Carbon Dioxide Transport			
3.3.1	Advection of free CO_2	The multi-phase flow equations are included in QPAC-CO2.	DOC
3.3.2	Buoyancy-driven -flow	“” “”	

Conclusions

We have demonstrated our approach to using FEPs and FEP databases in the system-level modelling approach ...

- Example QPAC systems-level model was discussed
- System was broken down in to “subsystems” corresponding to key project FEPs
- Processes relevant to each subsystem are modelled in appropriate detail
- Subsystems are joined by common CO_2 fluxes at the surface
- FEP audit reveals comprehensiveness of the model and identifies areas for consideration in future modelling studies.

The “FEP approach” is not “fancy” - it just gives us a logical way to structure our modelling study.

Summary

FEPs / FEP databases are a useful source of information and invaluable QA tools

They are **not** a modelling tool per-se

Databases need to be kept up-to-date if they are to provide a useful knowledge base

ptrc
Petroleum Technology Research Centre

University of Alberta

IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project *Risk Assessment*

Rick Chalaturnyk
Geological Storage Research Group

Department of Civil and Environmental Engineering
University of Alberta

3rd Risk Assessment Network Meeting
15th - 16th August, 2007
Imperial College, London, UK

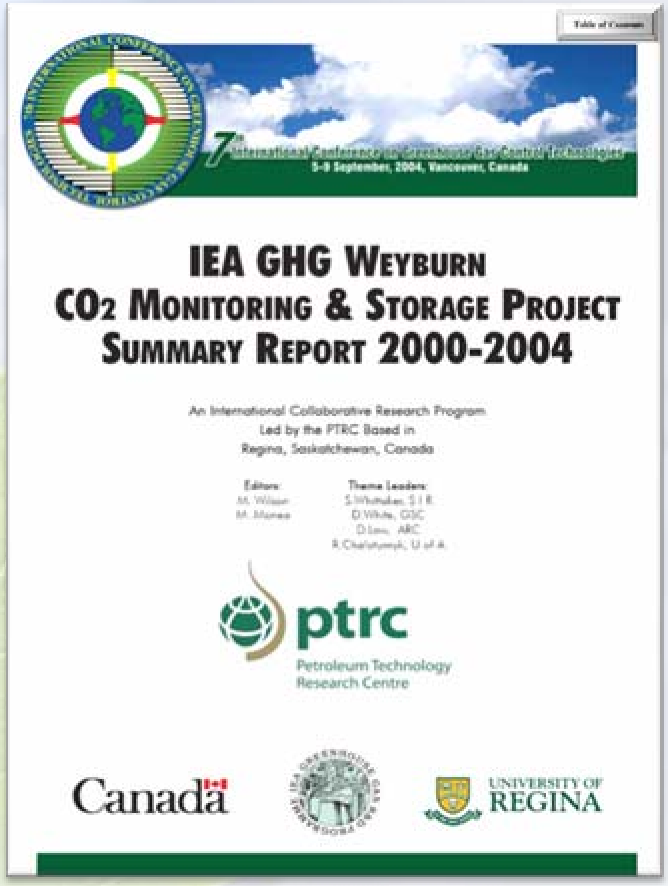
True Quantitative Risk Assessment!

Outline of Presentation

- Phase I Project Summary
  - Geoscience Characterization
  - Geophysics
  - Geochemistry
  - Reservoir Simulation
  - Risk (Performance) Assessment
- Final Phase Technical Research Program
  - Research Themes
- Summary

Phase I Project Overview

- Launched in July 2000 by *PTRC in collaboration with EnCana*
- Assess *technical and economic feasibility of CO2 geological storage*
- The *CO2* is pipelined from Dakota Gasification Co. plant in Beulah, N. Dakota, USA and injected into the Weyburn oil field at an initial average rate of *5000 tons/day, for a total of approx. 20 million tones over the 20-year life of the project*
- Funded by *15 industry and government sponsors* (Canada, USA, Japan, European Union)
- Employed *22 technology organizations and some eighty specialists in six countries*


7th International Conference on Greenhouse Gas Control Technologies
5-9 September, 2004, Vancouver, Canada

IEA GHG WEYBURN
CO_2 MONITORING & STORAGE PROJECT
SUMMARY REPORT 2000-2004

An International Collaborative Research Program
Led by the PTRC Based in
Regina, Saskatchewan, Canada

Editors:
M. Wilson
M. Monea

Theme Leaders:
S. Whittaker, S I R
D. White, GSC
D. Law, ARC
R. Chalaturnyk, U of A

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Final Phase of IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project

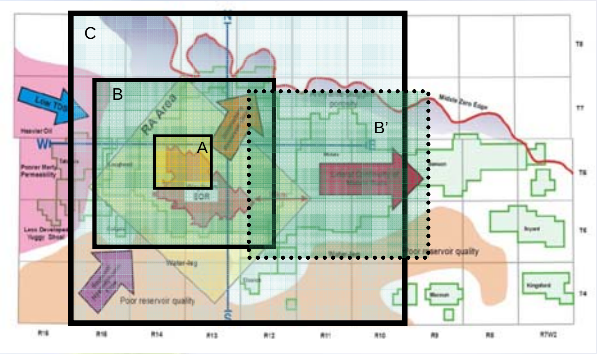
- **Non-Technical Component**
  - REGULATORY
    - Clear, Workable and Science-based Regulations for CO_2 Geologic Storage
  - PUBLIC COMMUNICATIONS
    - Public Awareness
    - Driven by the need for better public awareness of CO2 geological storage, especially on the issue of safety.
  - FISCAL POLICY
- **Technical Components**
  - GEOLOGICAL INTEGRITY
  - WELLBORE INTEGRITY
  - STORAGE MONITORING METHODS (Geophysics & Geochemistry)
  - RISK ASSESSMENT; Storage and Trapping Mechanisms; Remediation Measures; Environment, Health and Safety

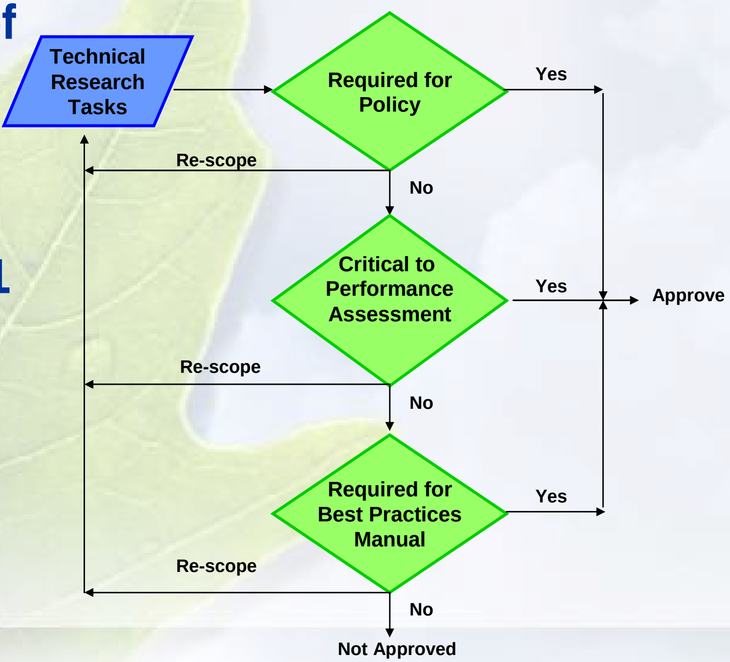
Final Phase Technical Work Program

- Program Principles
- Theme 1: Geological Integrity
- THEME 2: Wellbore Integrity
- THEME 3: Storage Monitoring Methods (Geophysics & Geochemistry)
- THEME 4: Risk Assessment; Storage and Trapping Mechanisms; Remediation Measures; Environment, Health and Safety
- THEME 5: Shared-Data Environment (SHADE)

Principles for Design of Final Phase TWP

- Integrated Focus on Phase 1A Area
- Midale Field to serve as further validation of a “storage and monitoring practice”
- Phase 1A data:
  - Reprocessing and extended analysis of seismic data;
  - Re-analyze geochemical data/mapping;
  - Data validation, peer review of Phase 1 information; and
  - Integration of all Phase 1 data onto common platform for efficient sharing among research providers (RPs).
- Common Software Platforms





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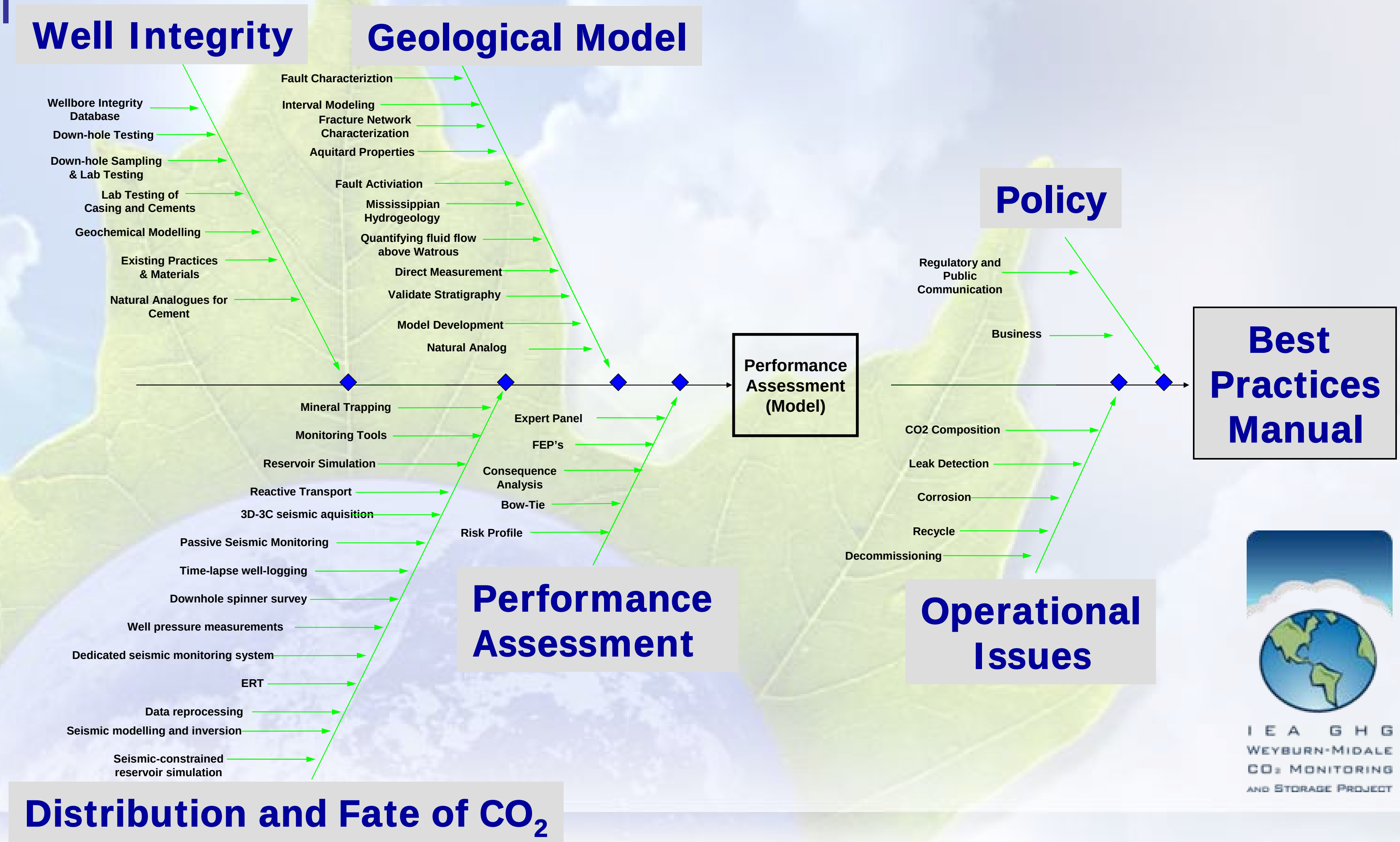
Final Phase of IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project

FINAL PHASE



IEA GHG Weyburn-Midale CO₂ Monitoring and Storage Project

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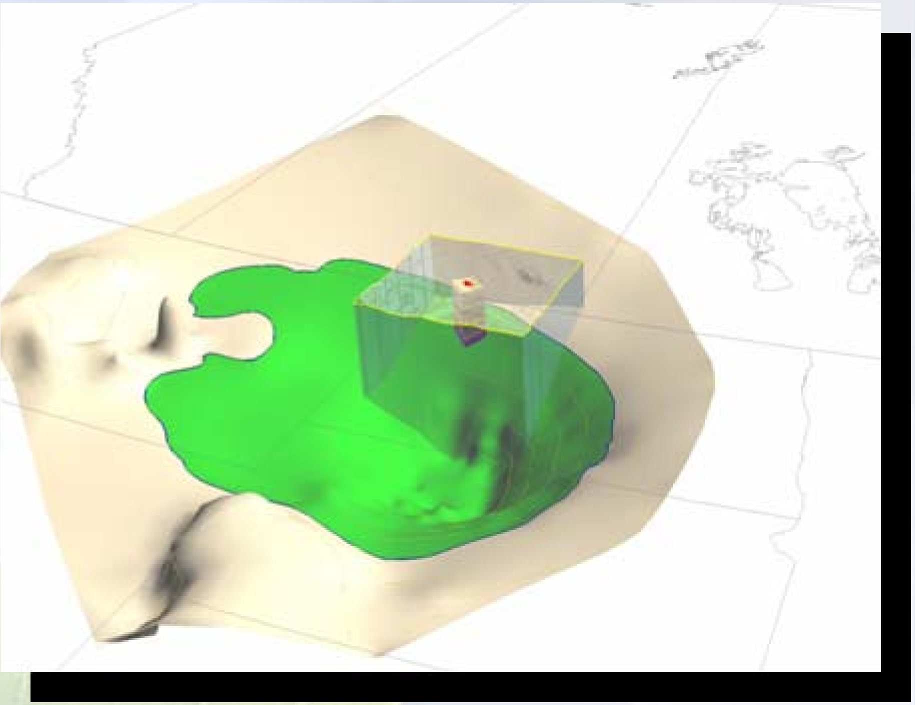
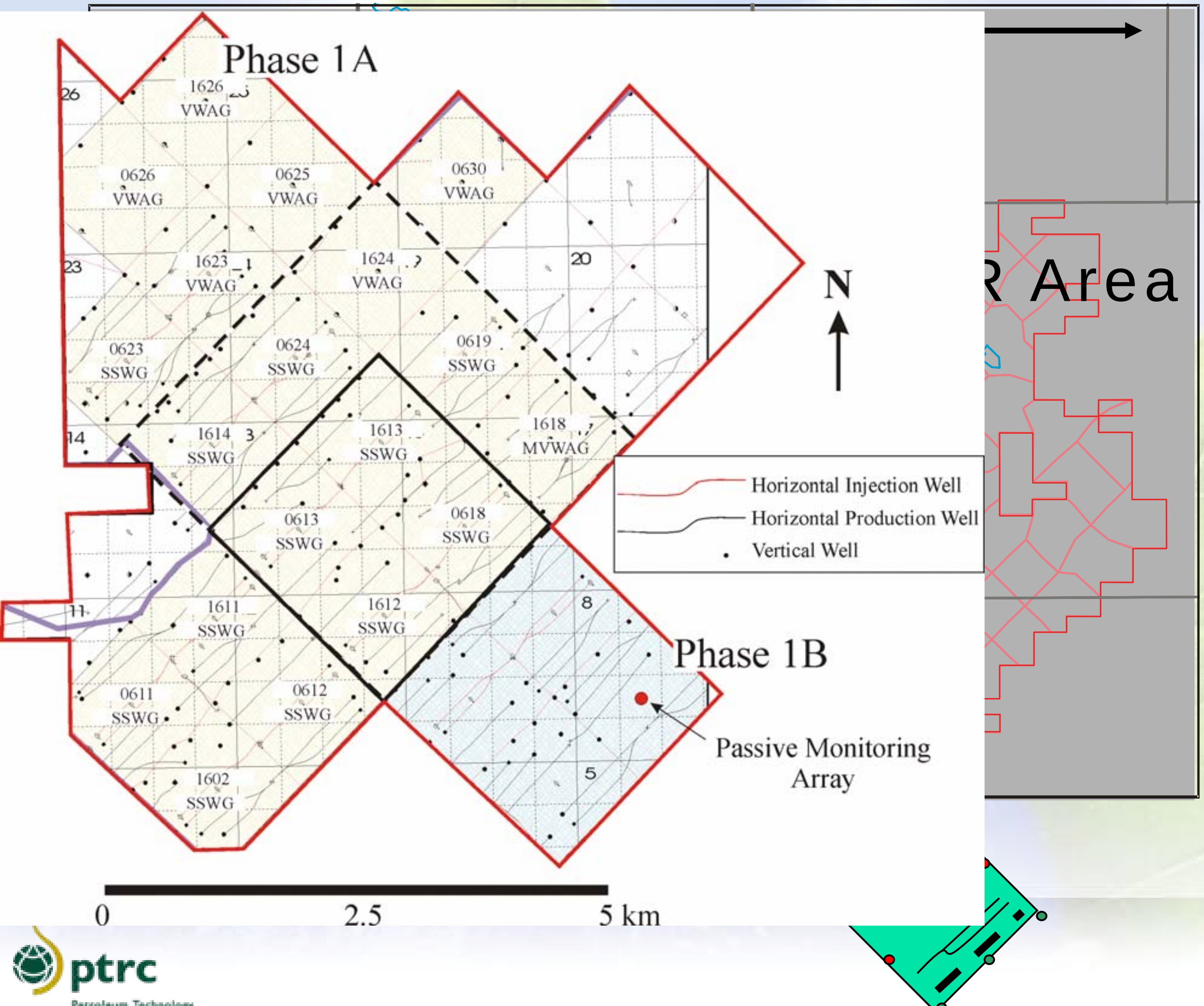
Geoscience Characterization

Objectives:

- **Assess integrity of geological container for storage of CO_2**
- **Provide input for performance and risk assessment and also scenario analysis of the long-term fate of CO_2 in the subsurface (Geological Model)**

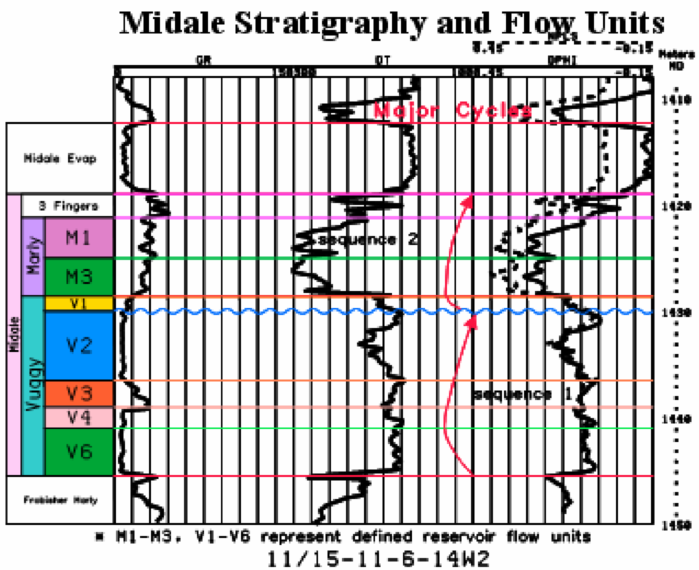


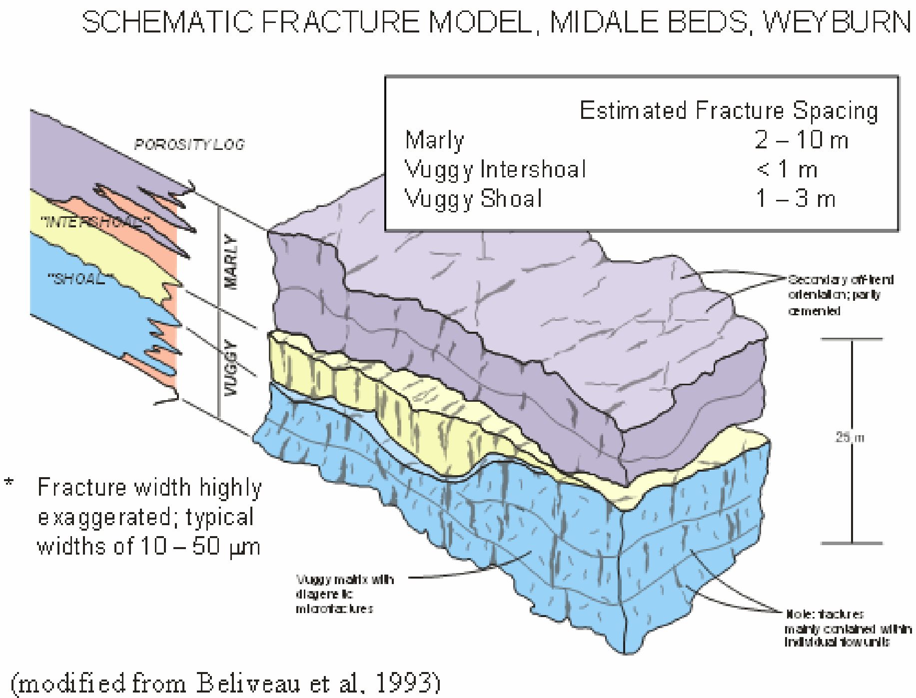
Weyburn Field: Phase 1A EOR Area

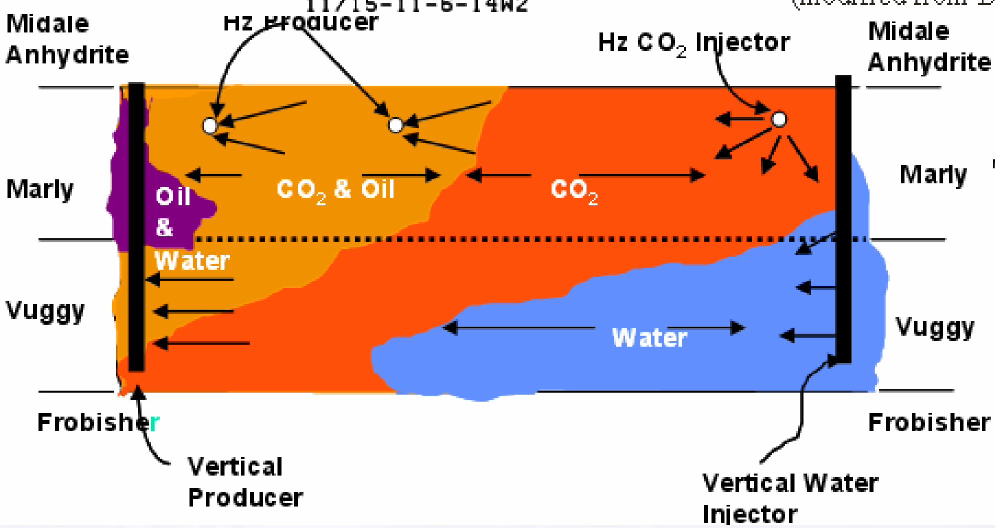


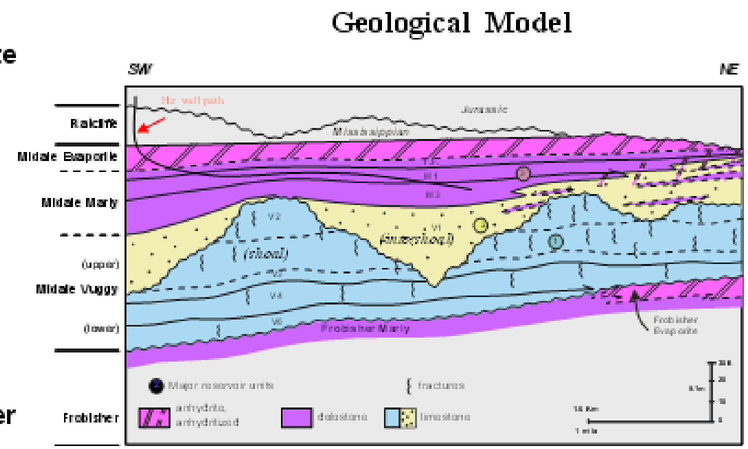
- Discovery: 1954
- ECA WI: 62.1%
- OOIP: 1,400 MMbbls
- Formation: Miss. Midale
- Depth: 1460 m
- Area: 45,000 acres
- Active Prod: 648 total, 278 hz.
- Sour crude: 25 - 34 API
- Cum. Prod.: 398 MMbbl (28%)
- YTD Avg.: 29,800 bbls/d
- EOR patterns in place: 44

Reservoir Structure

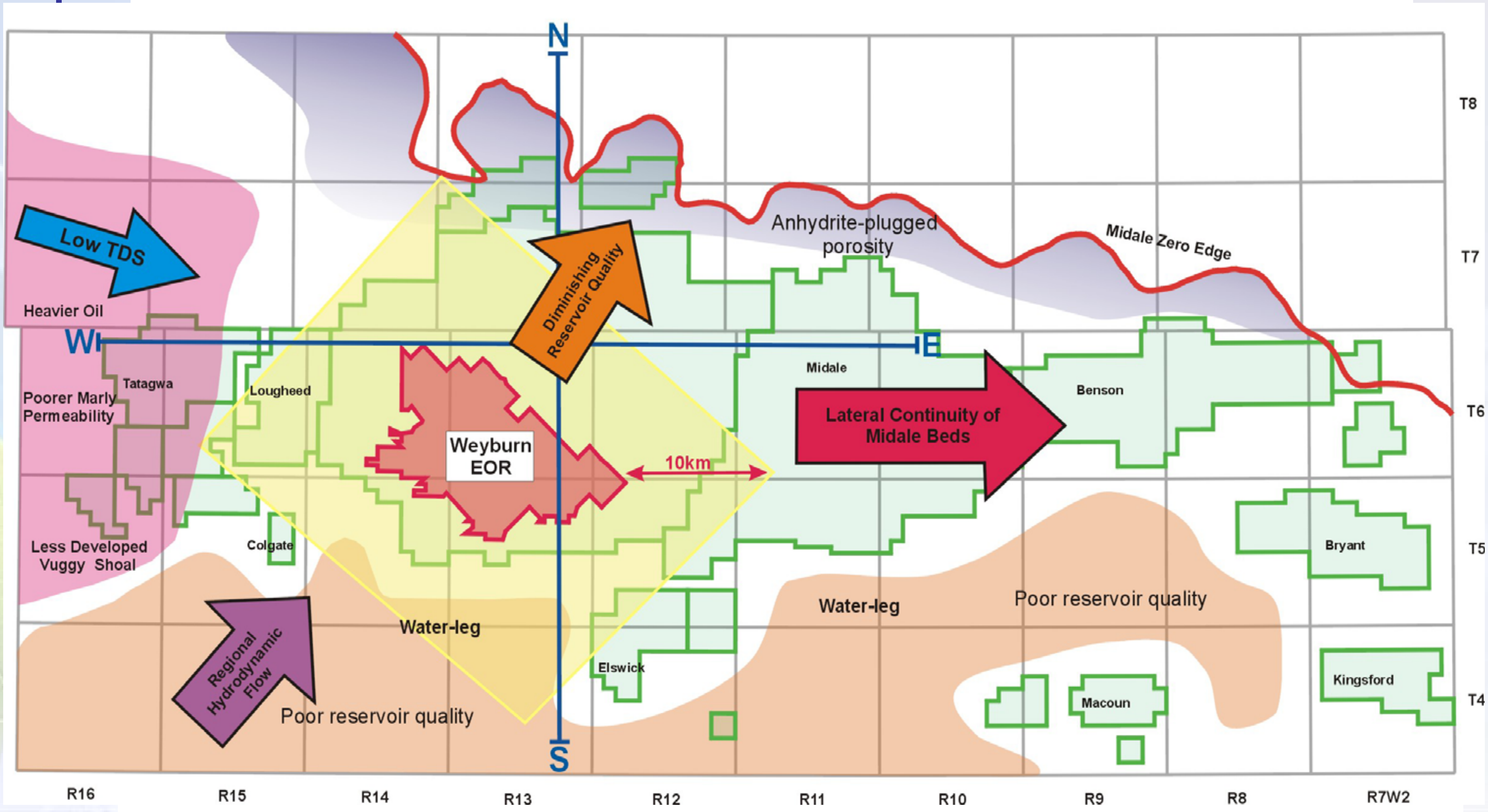








Weyburn CO_2 Storage System



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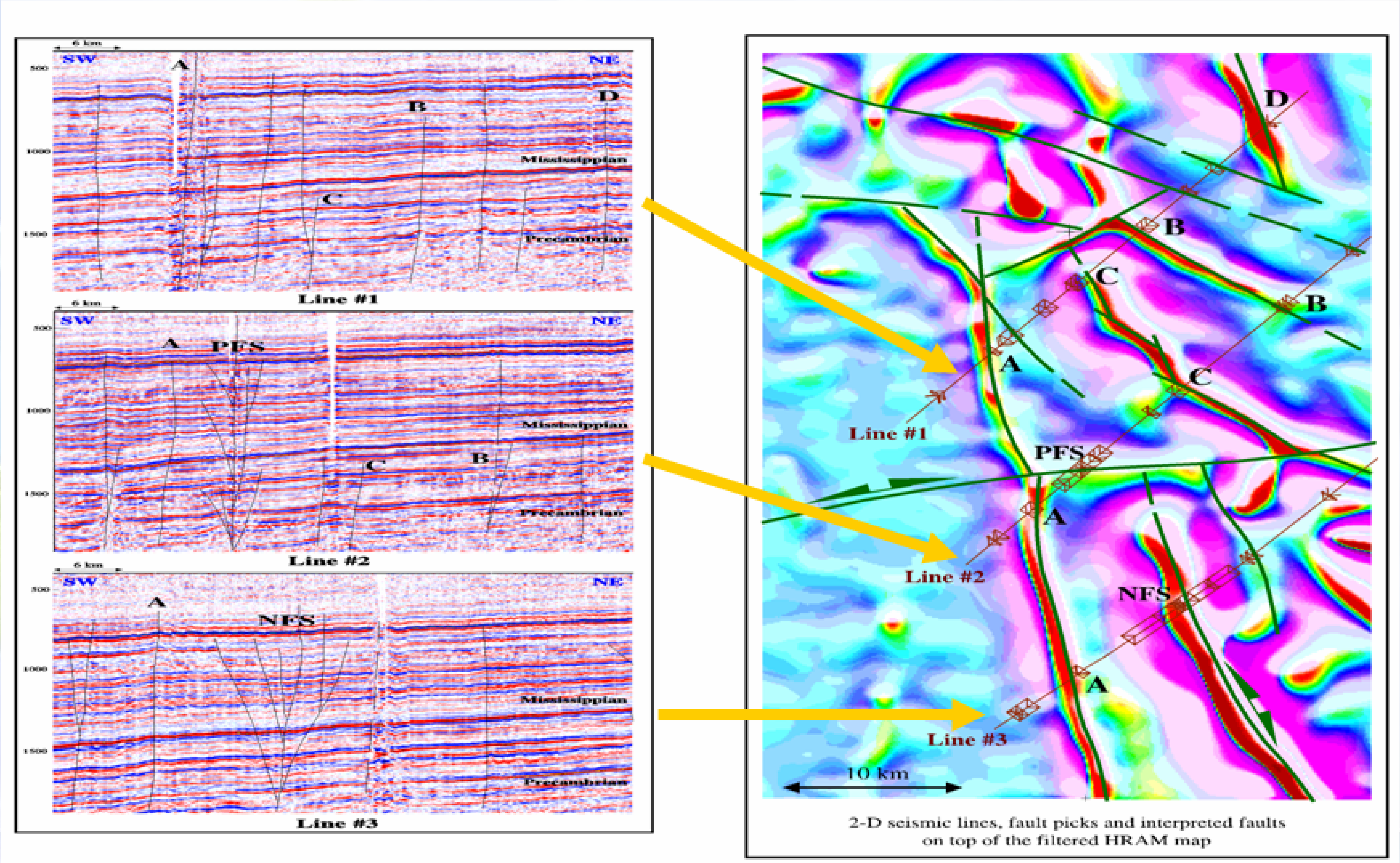
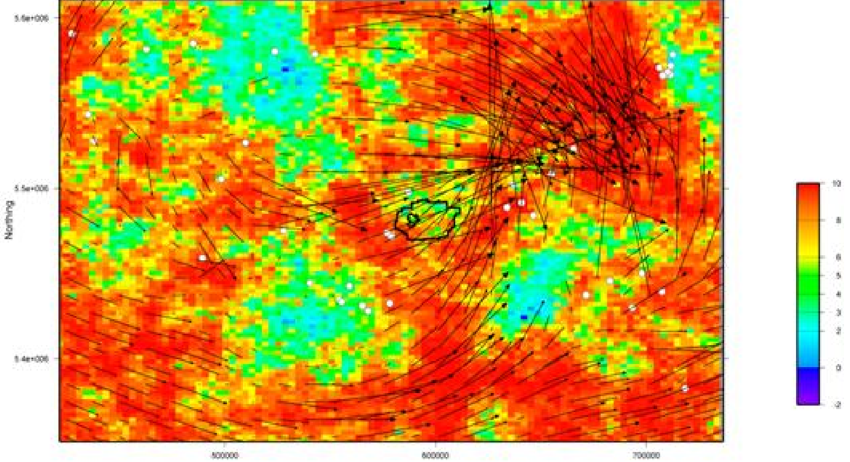
Seismic and Aeromagnetic Integration



2-D seismic lines, fault picks and interpreted faults on top of the filtered HRAM map

Property Characterization

Mannville Aquifer Simulated Permeability Field
Conditional Stochastic Simulation (SGS)



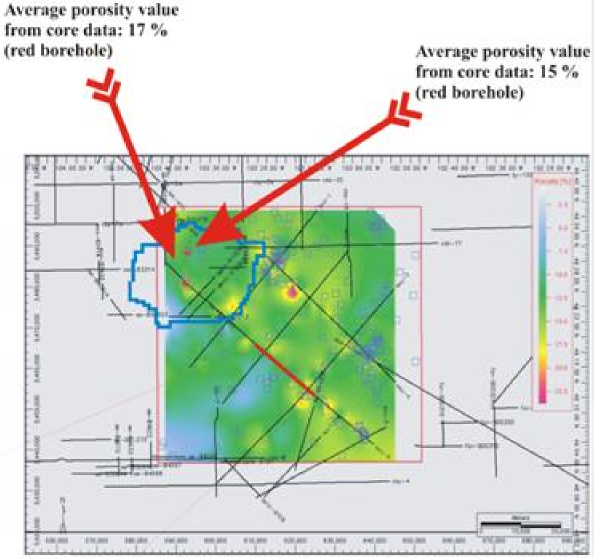
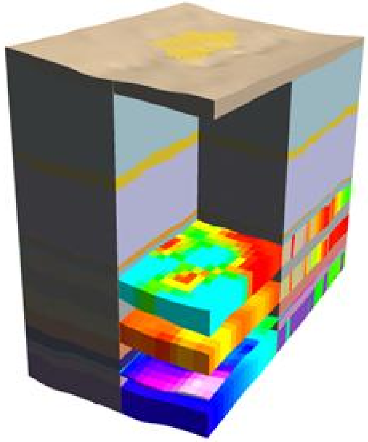
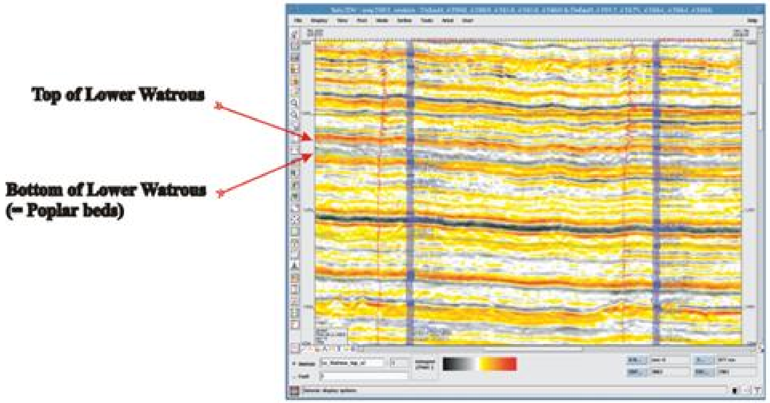


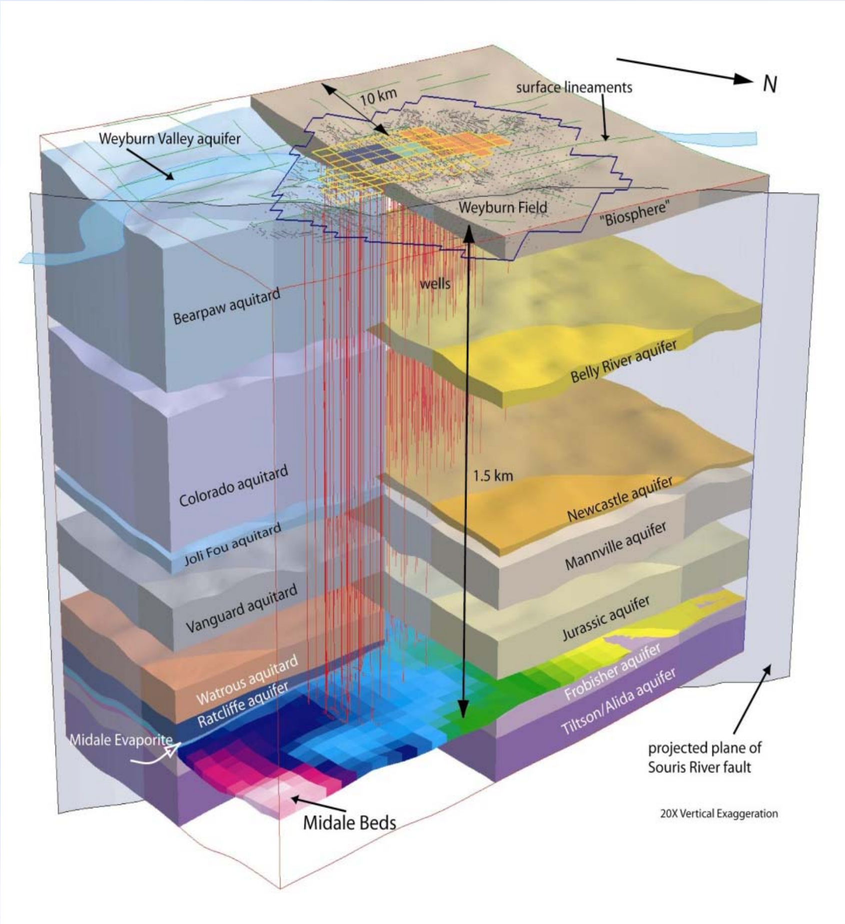
Fig. 14





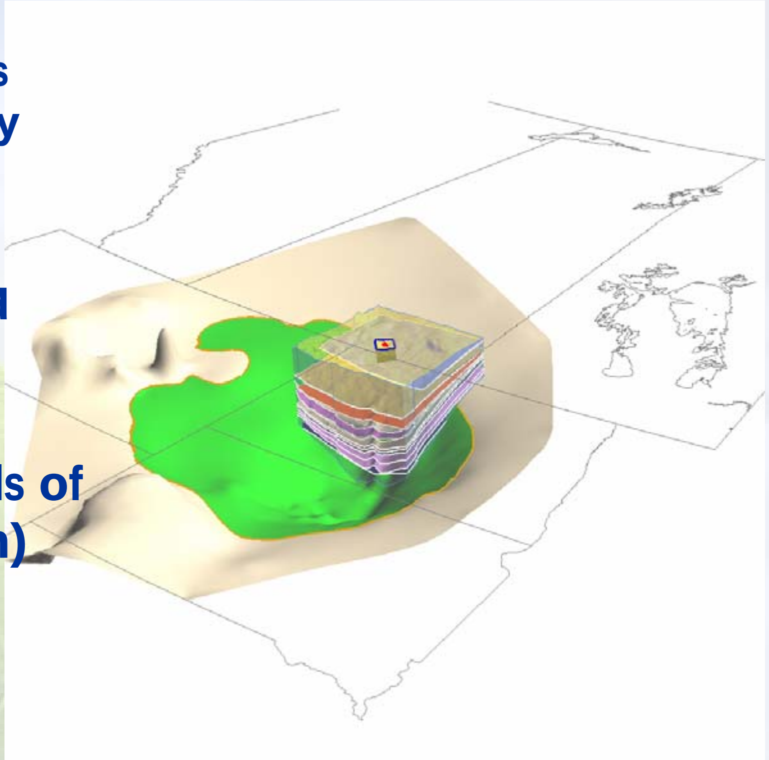
Geological Model

- Areal extent 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system
  - lithology
  - hydrogeological characteristics
  - faults
- Can be tailored for different RA methods and scenario analyses



Geological Container at Weyburn Suitable for long-term storage of CO_2

- Effective trapping setting
  - Primary seals are highly competent
  - Thick shale units above the reservoir serve as significant barriers to vertical flow (secondary seals)
- Basin Hydrogeology
  - hydraulic separation between Paleozoic and Mesozoic aquifers
  - sluggish flow in Midale Beds
- Tectonic elements have influenced all levels of stratigraphy (deposition, erosion, dissolution)
  - No hydraulic evidence of fluid movement



THEME 4: Risk Assessment; Storage & Trapping Mechanisms; Remediation Measures; HSE

FINAL PHASE

Knowledge Gap Drivers:

- A need to find consensus on risk/performance methodologies suitable for site approval for operations and for earning (storage) credits;
- A need for appropriate risk assessment methods and risk mitigation measures for confirming the safety and reliability of geological storage of CO_2;
- A strong need to rationalize the selection of cost and time-effective methodologies for risk assessment of the long-term fate of stored CO_2; and
- A recognition that risk/performance assessment is critical for the development of future regulations and/or identifying and addressing gaps that may exits in existing regulatory frameworks

Risk Assessment Program

Phase 1

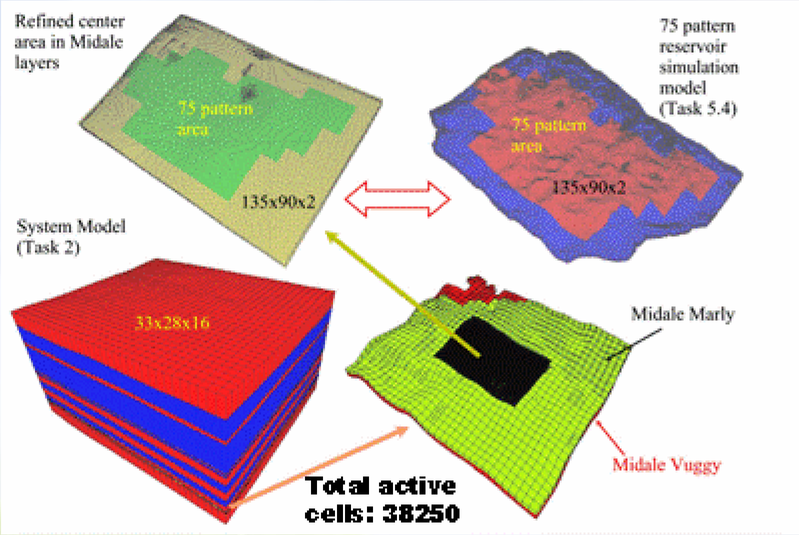
OBJECTIVES

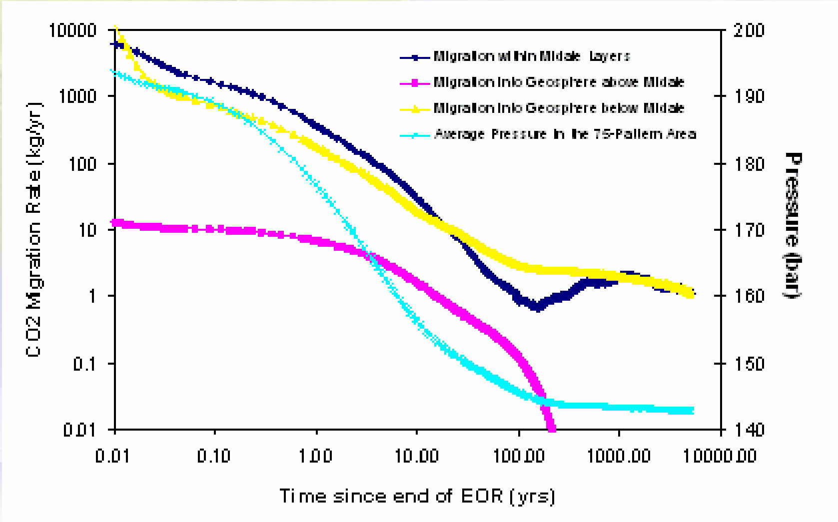
- Apply risk assessment techniques to predict the long-term fate of CO_2 within the storage system
    - Identify risks associated with geologic storage
    - Assess ability of oil reservoirs to securely store CO_2 (where CO_2 migrates to and what are the fluxes)
- Derive how much CO_2 is stored in the Weyburn reservoir as a function of time
- Explore consequences (HSE) of any leakage
- Provide assessment results primarily in terms of flux of CO_2 from the geosphere as function of time

Assessment Methodology

Phase 1

- FEP's (Features, Events and Processes)
- Systems Analysis
- Scenario Development
  - Base Scenario
  - Alternative Scenario's
- Deterministic Risk Assessment
- Probabilistic Risk Assessment





Features, Events and Processes

Quintessa CO2 FEP Database - Microsoft Internet Explorer

Main Index
Go Back | Print

Logout
(You are logged in as: P R Maul Change your password)

Database: Generic

20/202 Full list / External Factors / Climatic factors / Climate change, global

Suggest FEP improvement

F E P

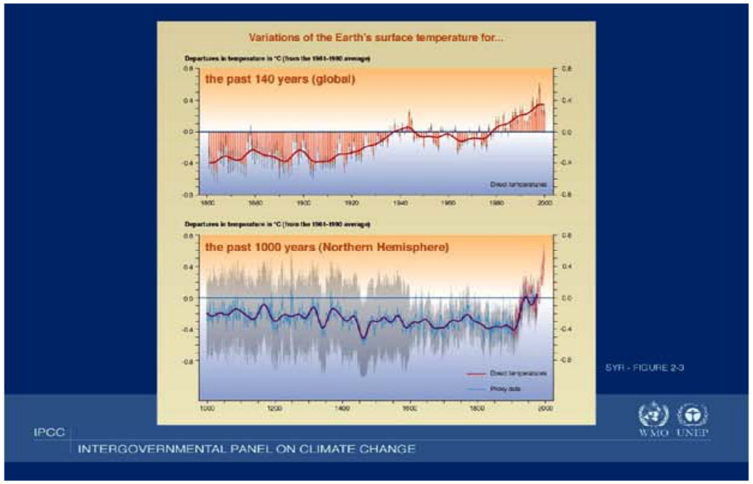
Name

1.2.1 Climate change, global

Description

The process of global climate change due to natural and/or anthropogenic causes. The last two million years of the Quaternary have been characterised by glacial/interglacial cycling. According to the Milankovitch Theory, the Quaternary glacial/interglacial cycles are caused by long-term changes in seasonal and latitudinal distribution of incoming solar radiation which are due to the periodic variations of the Earth's orbit about the Sun (Milankovitch cycles).

Evidence suggests that the Earth is presently in a period of global warming (see the figure below). The anthropogenic release of gases into the atmosphere may be increasing the rate of global warming by enhancing the natural 'greenhouse effect', a process by which longwave radiation emitted from the Earth is trapped in the atmosphere by 'greenhouse gases' such as CO2.



Original image: IPCC website

Relevance to performance and safety

Changes in the global climate are likely to impact the CO2 sequestration system in a number of ways. For example, through it's affect on sea levels and the local and regional climate.

References

1. Houghton J T, Ding Y, Griggs D J, Noguer M, van der Linden P J and Xiaosu D (Eds.). (2001). Climate Change 2001: The Scientific Basis. Cambridge University Press

Links

1. Intergovernmental Panel on Climate Change (IPCC)
2. The Hadley Centre
3. Graph of global temperature change, 1861-2000 and 1000-2000

start | Inbox - Outlook E... | RE: ECHO Meetin... | 8 Microsoft Wor... | Microsoft Excel - ... | CEC1060AWeyburn | ClimChng | BBC NEWS | Busin... | FEP Database Re... | Quintessa CO2 FE... | Desktop | 13:37

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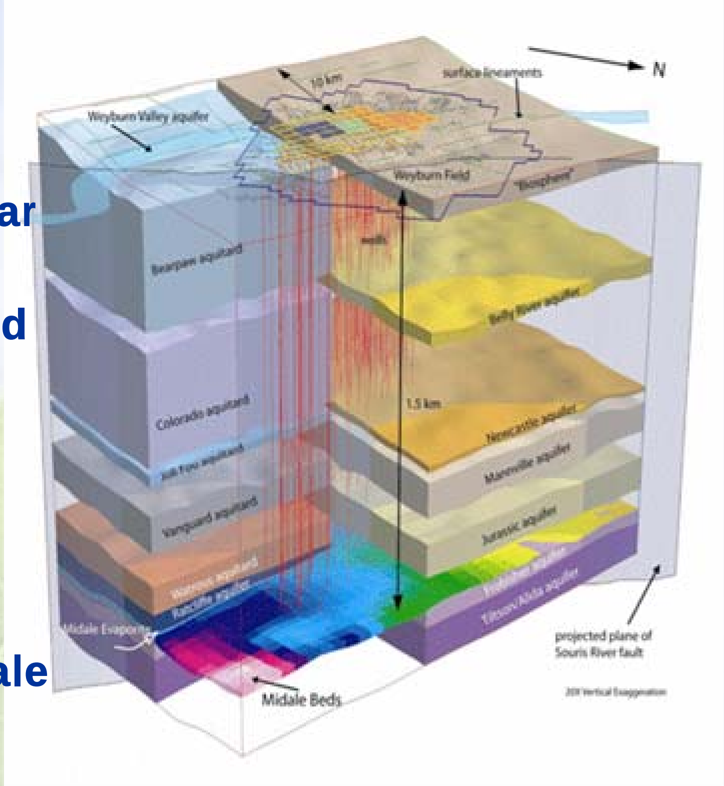
Base Scenario and System Model
Phase 1

- Base Scenario: expected evolution
  - Include FEPs relevant to long-term CO_2 migration
  - Caprock intact and no geological structure failure, but consider natural or man-made (near wellbores) fractures, if any exist
  - All wells are abandoned at the end of EOR, and sealed according to current practice procedures
- System Model for assessment
  - 75 patterns plus 10-km surrounding Midale formations
  - Aquifers and aquitards above and below Midale reservoir
  - All wells within the model domain are considered
  - Time scale: 5000 yrs or 50% loss of CO_2
  - Biosphere: start from the deepest possible potable aquifer



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Alternative Scenarios

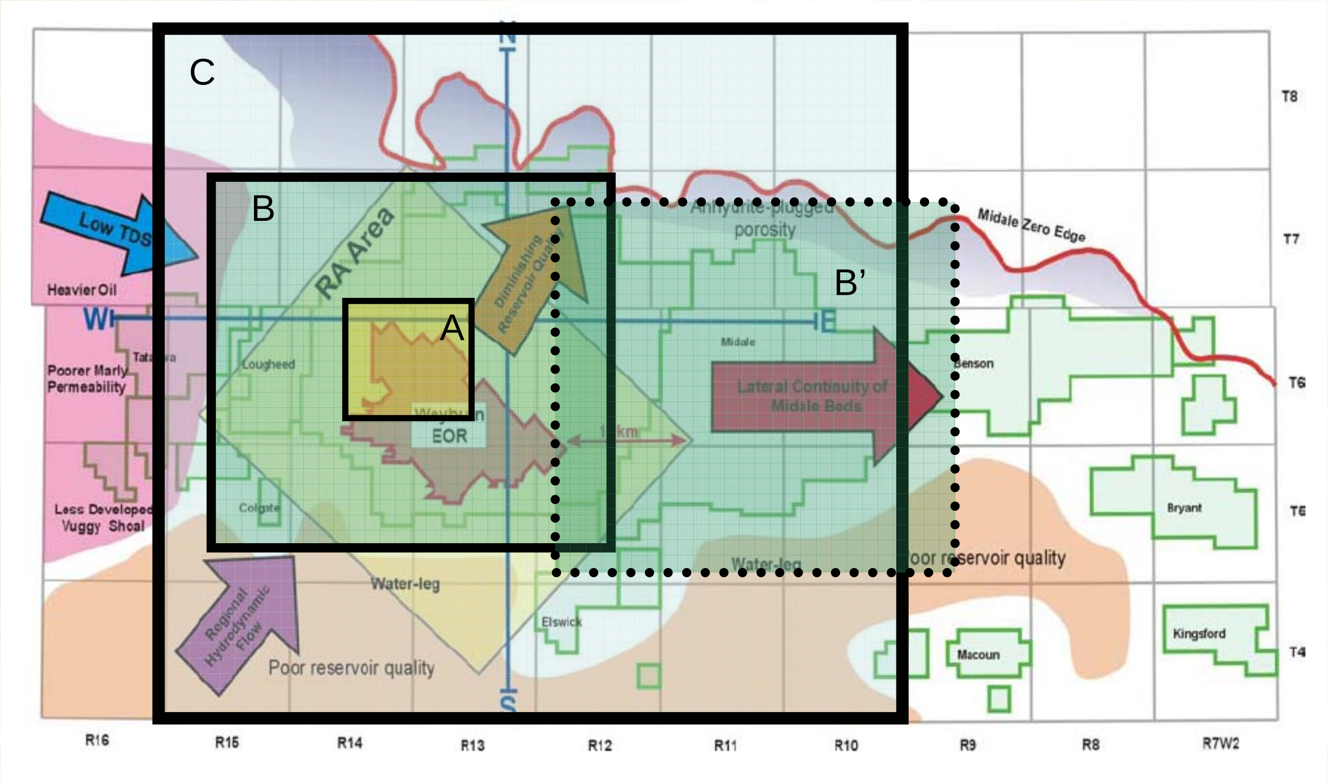
- Engineering options for EOR
- Reservoir operation options
- Well abandonment options
- Impact of salt dissolution
- Fault activation/re-activation
- Tectonic activity
- Human intrusion

THEME 4: Risk Assessment; Storage & Trapping Mechanisms; Remediation Measures; HSE

OBJECTIVE

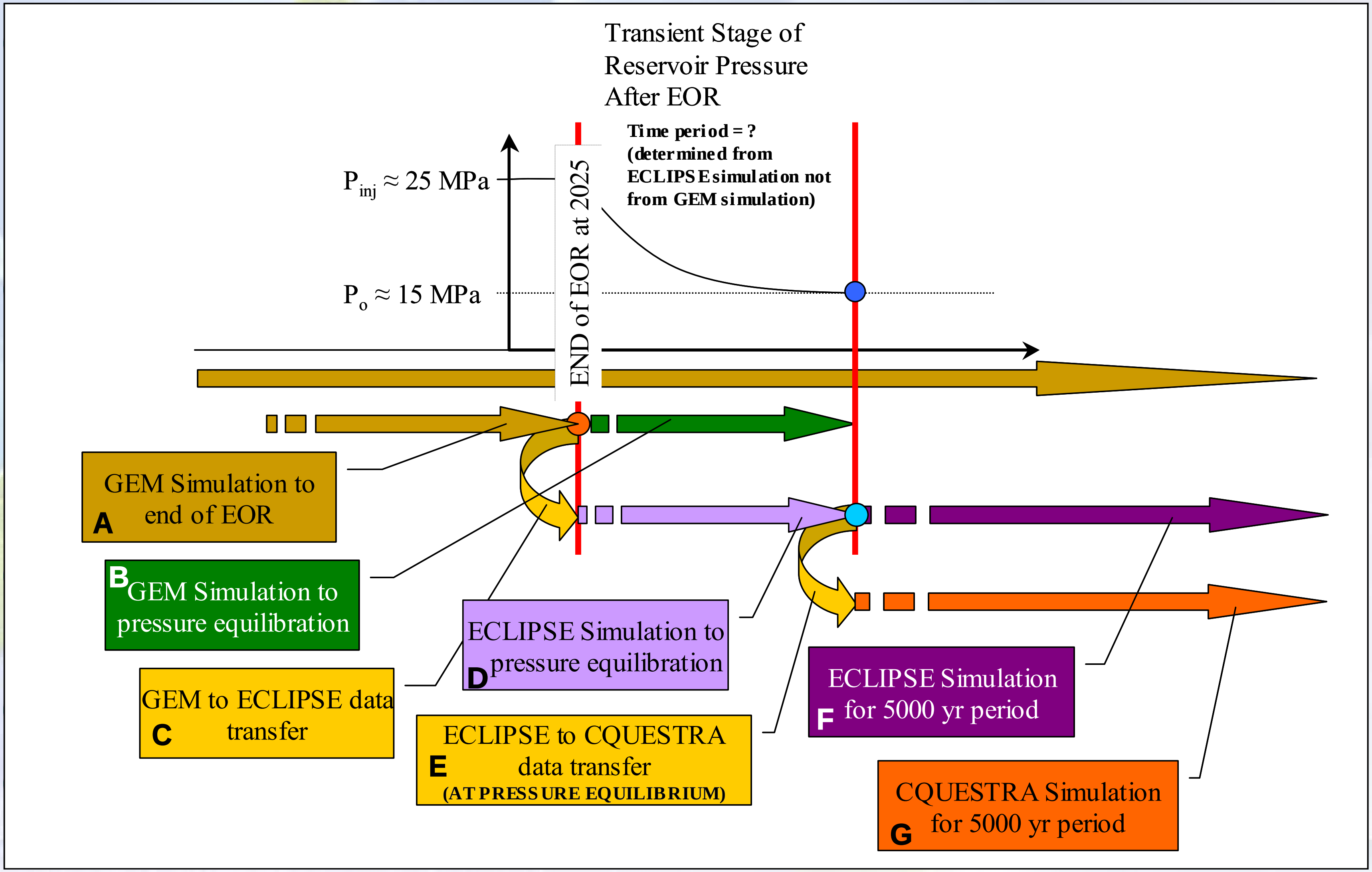
- **Complete a full field risk assessment of the Weyburn Storage site, Region B**

FINAL PHASE



THEME 4: Risk Assessment TWP

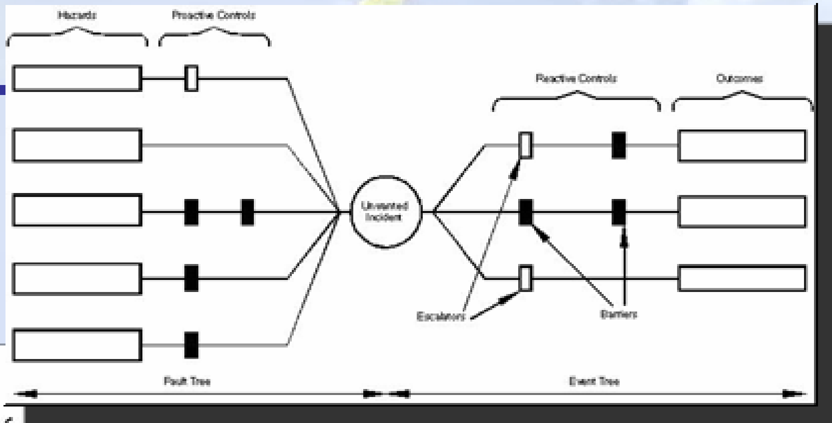
FINAL PHASE

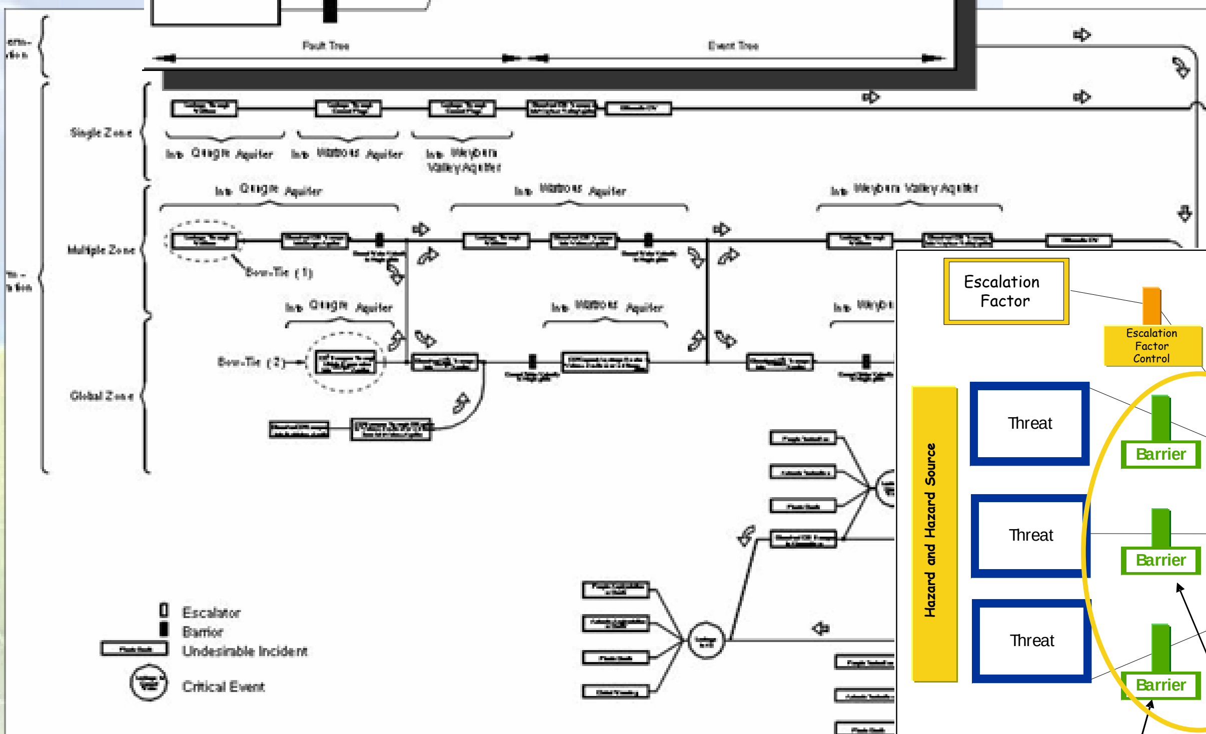


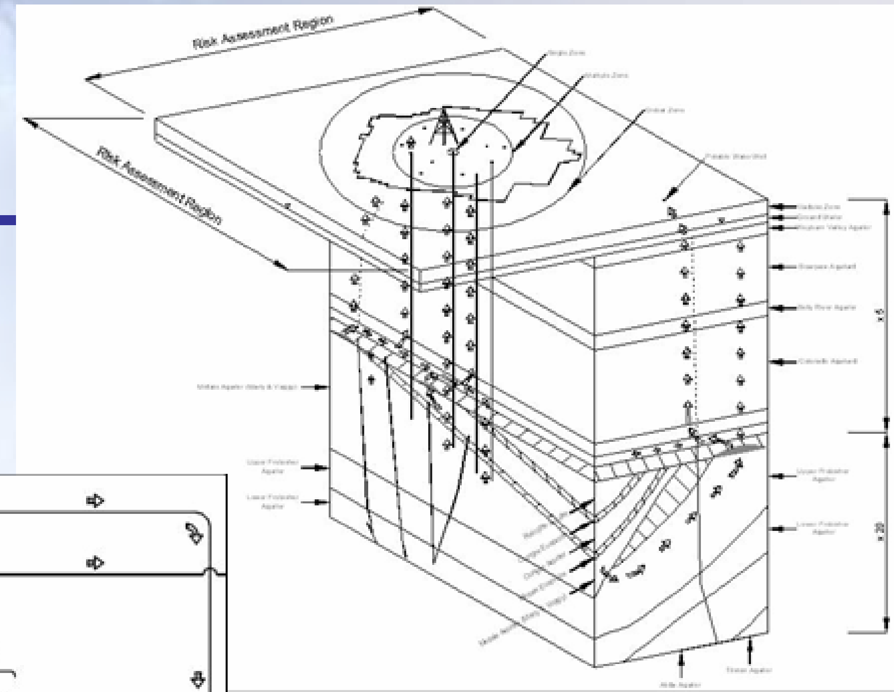
THEME 4: Risk Assessment TWP
Qualitative Risk Assessment

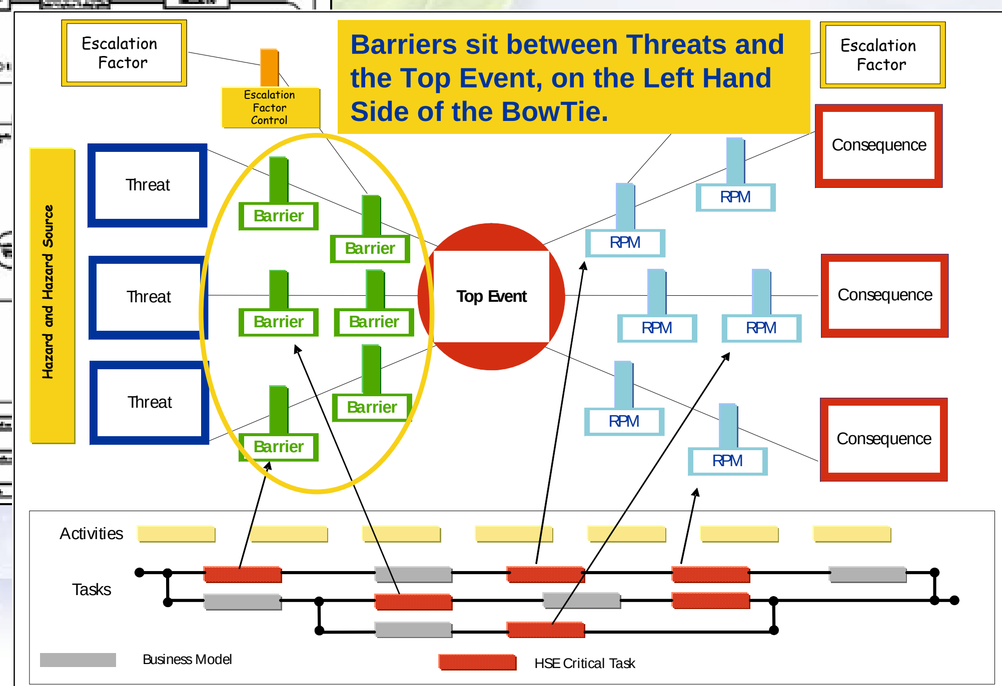
- Conduct a semi-quantitative RA utilizing experts and Phase I work in order to frame the entire risk assessment process.
  - This will engage a multidisciplinary panel of experts and stakeholders for input ranging from reservoir mechanics to hydrogeology to air quality/human health, public policy and regulations.
  - The goal is to complete even a qualitative risk assessment that identifies the major issues that include both likelihood and consequence and provide a framework for configuring the more detailed and comprehensive analysis tasks required for completion of a quantitative risk assessment.
- Bow-Tie Method
- URS Method (Australia)

Bow-Tie Method









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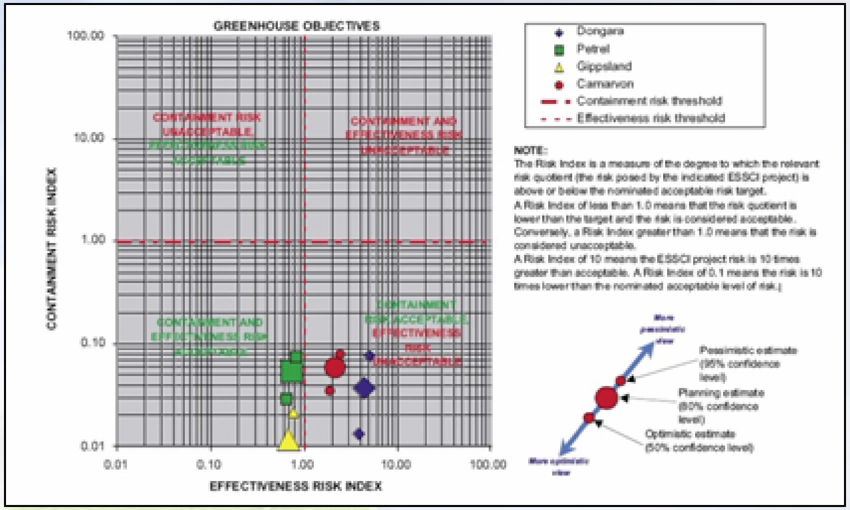
Assessing Risk in CO_2 Storage Projects – RISQUE Method (Bowden and Riggs, APPEA Journal, 2004)

- The expert panel is a critical resource in the RISQUE method. The quality of information used in the assessment is dependent on the level of skill and knowledge of the expert panel and to a lesser extent, on the ability of the risk analyst to effectively guide the panel through the process.



Quantification of Likelihood

Qualitative Description	Order of Magnitude Likelihood (Annual Frequency or Probability Over a Set Period)	Basis
A. Certain	1 (or 0.999, 99.9%)	Certain, or as near to as makes no difference
B. Almost certain	0.2-0.9	One or more incidents of a similar nature has occurred here
C. Highly probable	0.1	A previous incident of a similar nature has occurred here
D. Possible	0.01	Could have occurred already without intervention
E. Unlikely	0.001	Recorded recently elsewhere
F. Very unlikely	1×10^{-4}	It has happened elsewhere
G. Highly improbable	1×10^{-5}	Published information exists, but in a slightly different context
H. Almost impossible	1×10^{-6}	No published information on a similar case

Bowden, A R, Lane, M R and Martin, J H, 2001. Triple Bottom Line Risk Management – Enhancing Profit, Environmental Performance and Community Benefit, Wiley and Sons, New York.

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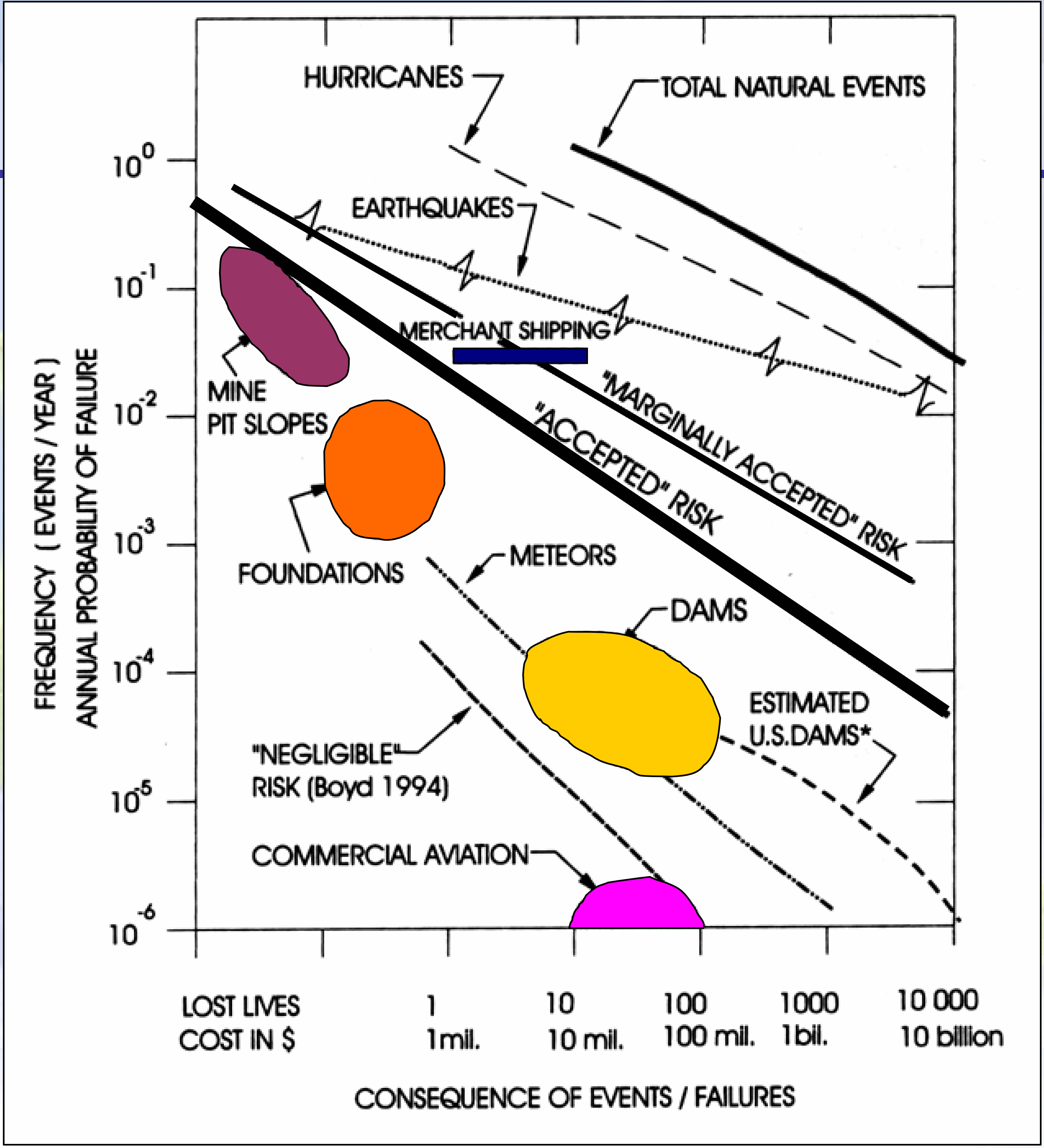
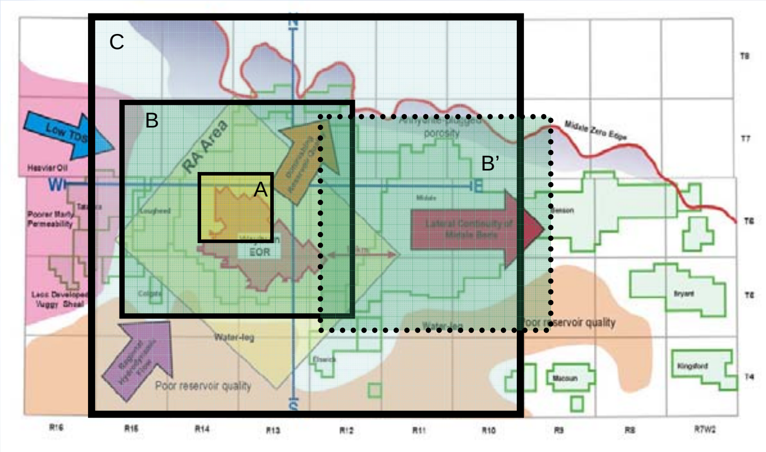

HURRICANES
TOTAL NATURAL EVENTS
EARTHQUAKES
MERCHANT SHIPPING
MINE
PIT SLOPES
"MARGINALLY ACCEPTED" RISK
"ACCEPTED" RISK
FOUNDATIONS
METEORS
DAMS
ESTIMATED
U.S.DAMS*
"NEGLIGIBLE"
RISK (Boyd 1994)
COMMERCIAL AVIATION
FREQUENCY (EVENTS / YEAR)
ANNUAL PROBABILITY OF FAILURE
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
LOST LIVES
COST IN $
1
1mil.
10
10 mil.
100
100 mil.
1000
1bil.
10 000
10 billion
CONSEQUENCE OF EVENTS / FAILURES

Final Phase of IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project



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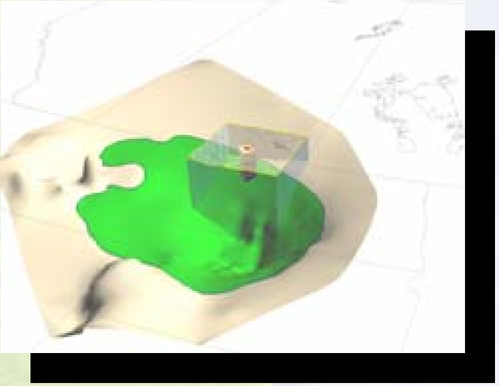

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IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project

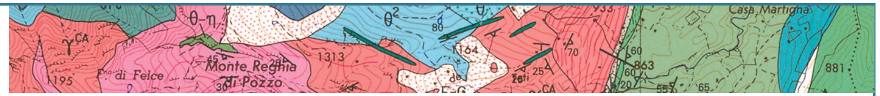
Rick Chalaturnyk

Geological Storage Research Group

Department of Civil and Environmental Engineering
University of Alberta

Schlumberger-MIT Conference

April 23-24, 2007



Methodological developments to define safety criteria

Olivier BOUC

Geoscience for a sustainable Earth

brgm

3rd IEA GHG Risk Assessment Network Meeting - London

Friday, 17 August 2007

Frame of our research

> **BRGM research about safety criteria for CO_2 geological storage**

- Internal research project
- 3 years project funded by the National Resarch Agency, with TOTAL, Armines, University Paul Sabatier (Toulouse), University of Neuchâtel

  "Safety criteria for CO_2 geological storage: qualitative/quantitative approach of risk scenarios"

> **Aim: contribute to demonstrating safety of CO_2 geological storage**

> **Safety criteria ≠ performance objectives**

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brgm

Safety criteria

> **Requirements to ensure near-zero local impacts on health, safety and the environment in the short, middle and long term**

- Qualitative / generic
- Quantitative / site specific

Purpose

> **Provide a simple workflow to evaluate safety in a licensing process**

- Build long-term evolution scenarios
- Evaluate potential targets exposure using simple models
- Determine safety criteria

> **Not a risk assessment**

- Rather keys to control a risk assessment

> **First choose a method to build scenarios**

- Methodological exercise to try the use of FEPs

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Context of the assessment

> **Hypothetical storage site**

> **In the East of the Paris Basin**

- Strategic aquifer at -800m

> **In the Dogger aquifer**

- -1700m, thickness 25m
- Nearly flat reservoir, very slow natural flow (1m/yr)
- Near hydrostatic stress state
- Φ ~ 16% ; K ~ 1 D ; T ~ 55-75°C ; P ~ 173 bars

Geoscience for a sustainable Earth
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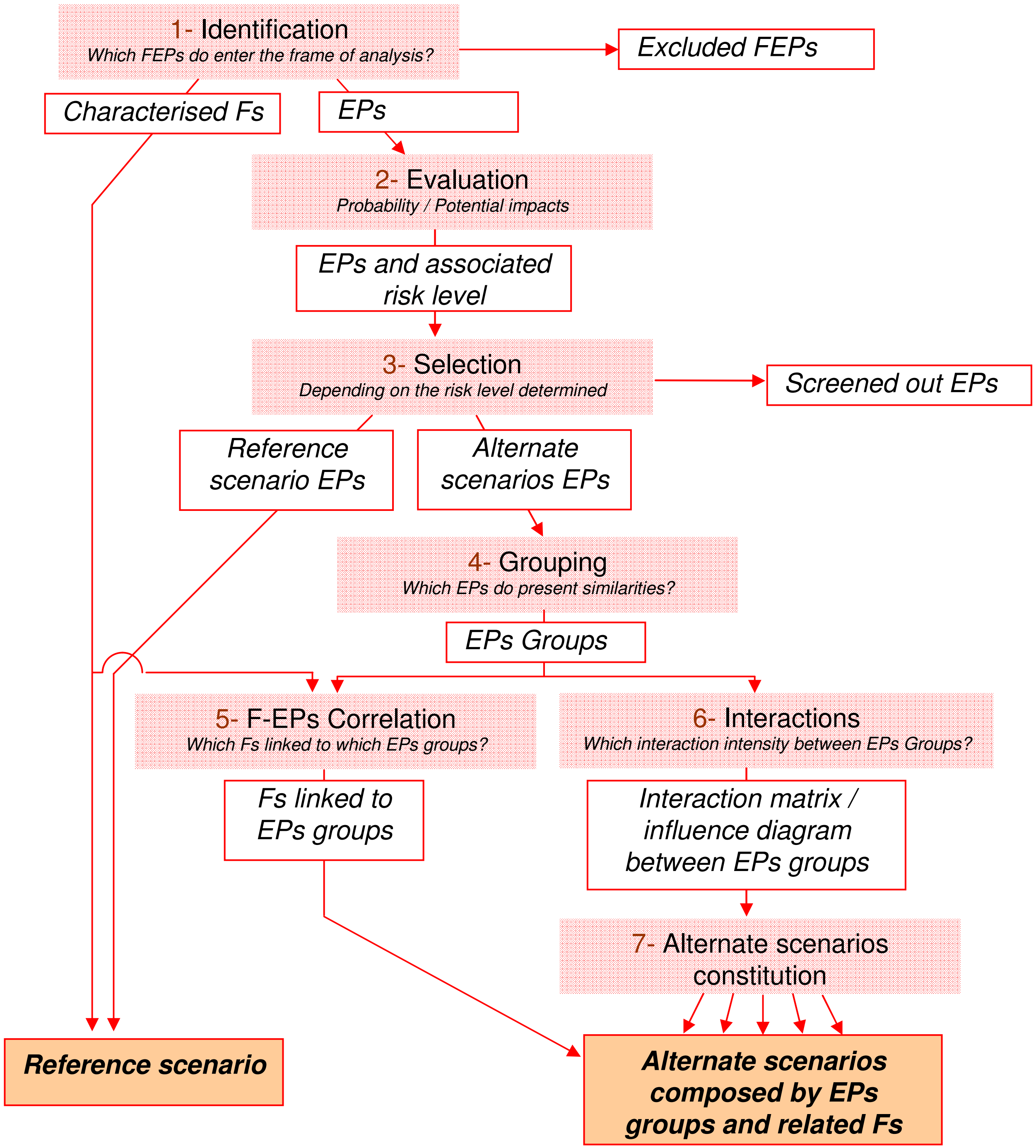
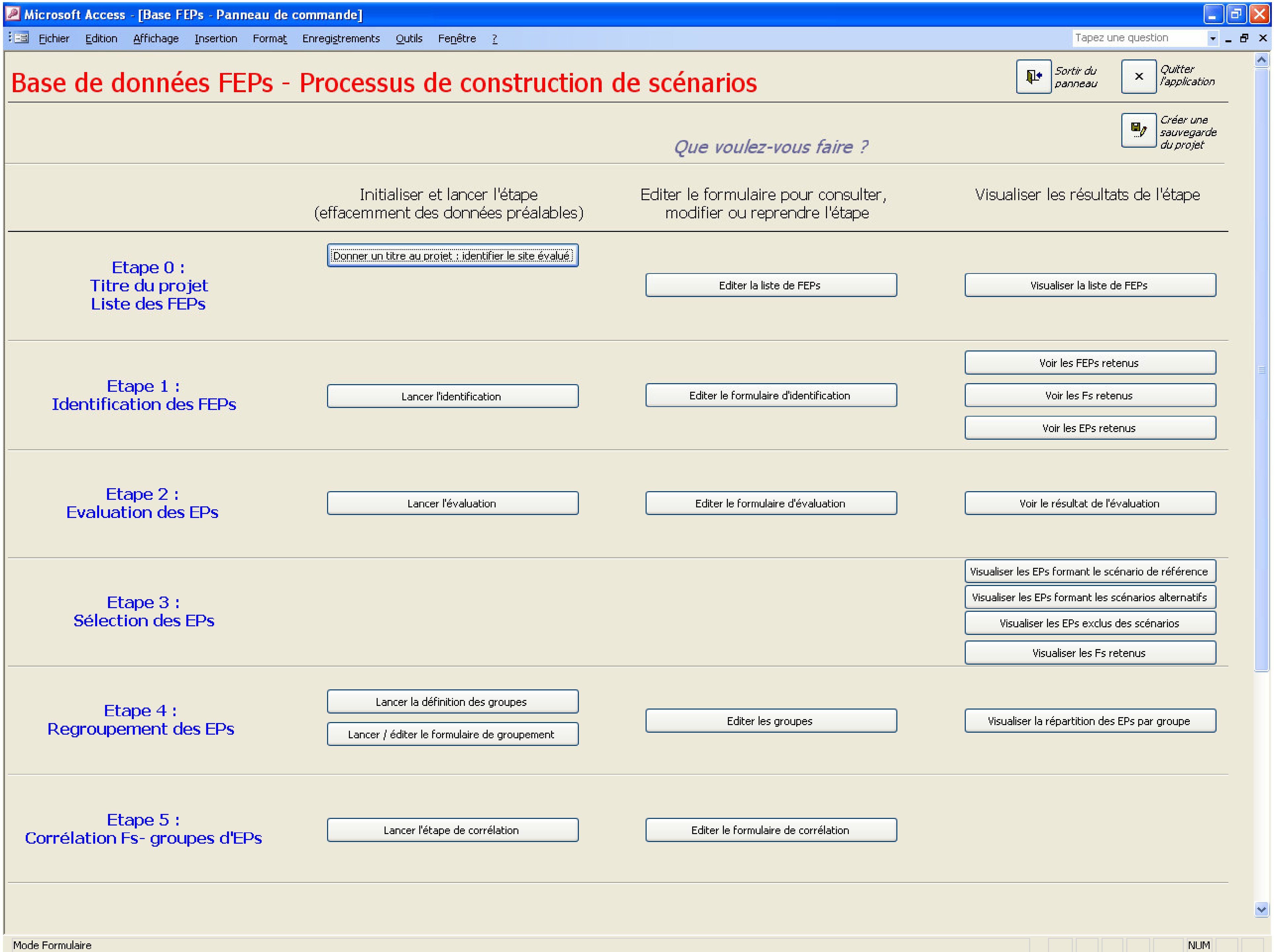
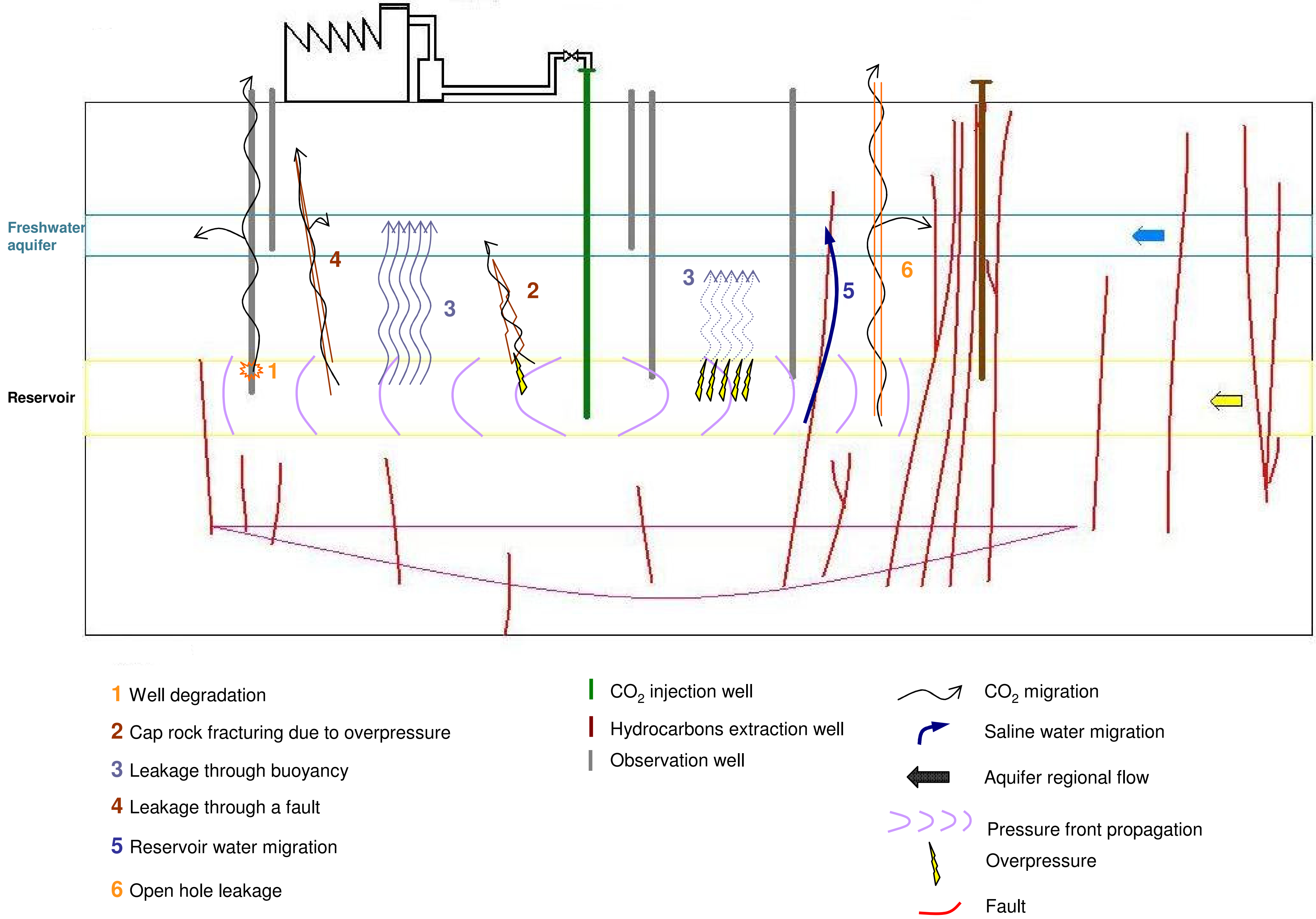
FEPs database workflow used

- Quintessa online FEPs database
- Workflow closely inspired by Vattenfall & TNO « Safety assessment of structure Schweinrich » in CO2STORE




Microsoft Access - [Base FEPs - Panneau de commande]
Fichier Edition Affichage Insertion Format Enregistrements Outils Fenêtre ?
Tapez une question
Base de données FEPs - Processus de construction de scénarios
Sortir du panneau
Quitter l'application
Créer une sauvegarde du projet
Que voulez-vous faire ?
Initialiser et lancer l'étape (effacemment des données préalables)
Editer le formulaire pour consulter, modifier ou reprendre l'étape
Visualiser les résultats de l'étape
Etape 0 : Titre du projet Liste des FEPs
Donner un titre au projet : identifier le site évalué
Editer la liste de FEPs
Visualiser la liste de FEPs
Etape 1 : Identification des FEPs
Lancer l'identification
Editer le formulaire d'identification
Voir les FEPs retenus
Voir les Fs retenus
Voir les EPs retenus
Etape 2 : Evaluation des EPs
Lancer l'évaluation
Editer le formulaire d'évaluation
Voir le résultat de l'évaluation
Etape 3 : Sélection des EPs
Visualiser les EPs formant le scénario de référence
Visualiser les EPs formant les scénarios alternatifs
Visualiser les EPs exclus des scénarios
Visualiser les Fs retenus
Etape 4 : Regroupement des EPs
Lancer la définition des groupes
Lancer / éditer le formulaire de groupement
Editer les groupes
Visualiser la répartition des EPs par groupe
Etape 5 : Corrélation Fs- groupes d'EPs
Lancer l'étape de corrélation
Editer le formulaire de corrélation
Mode Formulaire
NUM

Results: six leakage scenarios identified



Freshwater aquifer
Reservoir
1
2
3
4
5
6
1 Well degradation
2 Cap rock fracturing due to overpressure
3 Leakage through buoyancy
4 Leakage through a fault
5 Reservoir water migration
6 Open hole leakage
CO_2 injection well
Hydrocarbons extraction well
Observation well
CO_2 migration
Saline water migration
Aquifer regional flow
Pressure front propagation
Overpressure
Fault

Feedback from our attempt

> Method not optimal

- Tedious and time-consuming
- Result: very little surprise compared to the investment!
- Very close to the results of the CO2STORE study

> Some steps arguable

- OK for steps 1-3 (Identification – Evaluation – Selection)
- Step 4 (Grouping) determining and questionable: seems very subjective
- Idem for step 7 (Deducing scenarios from influence diagram)

> Results achieved by giving up steps 4-7

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Restrictions

> **Only a test – first use of the tool**

> **Hypothetical site → lack of real data**

> **Not an expert panel**

> **Difference TNO – Quintessa database**

- TNO maybe more suitable for this method
- But would it really be more time-efficient ?

> **Schweinrich case study hypotheses close to ours**

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brgm

Feedback (2)

> **Main advantages of the FEPs**
- Comprehensiveness
- Systematic documentation of the evaluation

> **Is this really appropriate in our approach?**

> **Maybe not a scenario-building tool?**

> **Rather an audit tool**
- "Top-down" use
- Cf. Quintessa document (Savage *et al.*[2004], A generic FEP database for the assessment of long-term performance and safety of the geological storage of CO_2)

Possible scenario construction methods

> **Non-FEPs approaches:**
- GEODISC (Australia): an expert panel reviews a limited number of risk events (probability/impacts)

> **FEPs approaches**
- Battelle, Mountaineer (USA): more qualitative and quick screening of the FEPs DB. Decision oriented for risk management.

> **Mixed approach:**
- Identification of simple scenarios by an expert panel
- Audit with the generic FEPs database

Further work and perspectives

> **Base safety criteria on potential targets**

> **Develop a site model representing the potentially exposed elements**

> **Link risk scenarios to targets exposure**

> **Build simple models to evaluate CO_2 fluxes between compartments**

- Analytical, semi-analytical, 1D
- How to ensure they are representative?
- Address uncertainties

> **Infer safety criteria**

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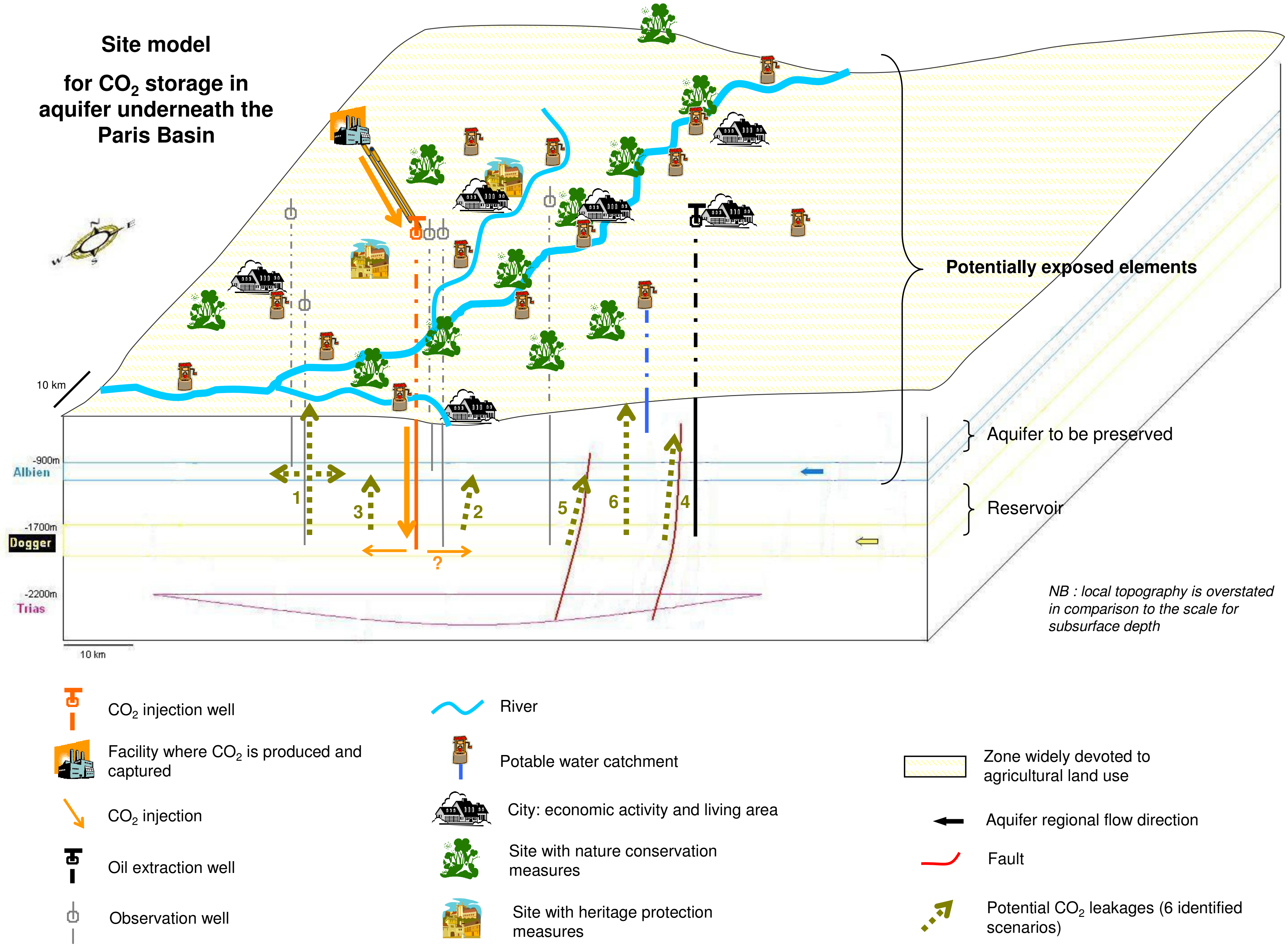

Site model
for CO_2 storage in aquifer underneath the Paris Basin
10 km
-900m
Albien
-1700m
Dogger
-2200m
Trias
10 km
1
2
3
4
5
6
?
Potentially exposed elements
Aquifer to be preserved
Reservoir
NB : local topography is overstated in comparison to the scale for subsurface depth
CO_2 injection well
Facility where CO_2 is produced and captured
CO_2 injection
Oil extraction well
Observation well
River
Potable water catchment
City: economic activity and living area
Site with nature conservation measures
Site with heritage protection measures
Zone widely devoted to agricultural land use
Aquifer regional flow direction
Fault
Potential CO_2 leakages (6 identified scenarios)

Geological CO_2 Storage
Certification Framework

- **Principal Investigators (PIs):**
  Curtis Oldenburg (LBNL)

  Steven Bryant (UT Austin)

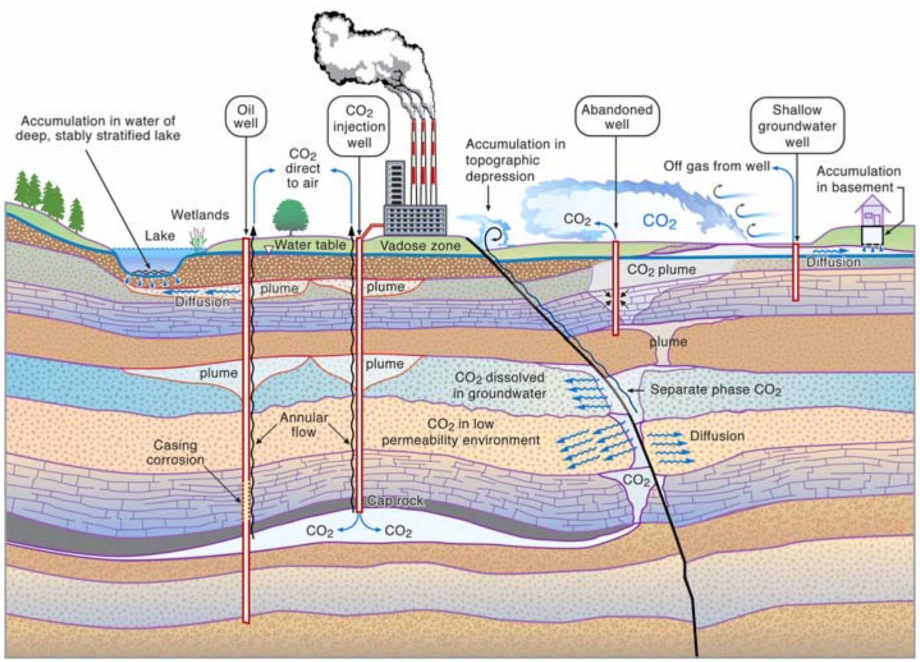
- **Overall Objectives:**
  Develop simple framework for evaluating leakage risk for certifying operation and decommissioning of geological CO_2 storage systems.

- **Impact:**
  Critical to the large scale deployment of CCS is a simple, transparent, and accepted basis for regulators and stakeholders to certify that the risks of geologic CCS projects to HSE and resources are acceptable.

- **Funding by:**
  CCP2

- **Duration:**

  Jan. 2006-Jan. 2008



Outline

- Overview of philosophy and approach of the CF
- Effective Trapping Requirement
- CO_2 Leakage Risk
- Methods of CO_2 Leakage Risk calculation
    - Compartments
    - Conduits
    - Impacts
    - Intersection of CO_2/conduits/compartments
- Elements of the CF project
- Summary

Certification Framework Overview

- Theory and Philosophy of Certification Framework
  - Effective Trapping requirement
  - CF is based on CO_2 Leakage Risk
  - Compartment concept
  - Broad classes of features
  - Catalog of model results
  - Model results are from sophisticated modeling of simplified systems
  - CF is probabilistic in existence of flow pathway, deterministic in flow along pathway
- Inputs are properties and definitions of the injection system
- Outputs are CO_2 Leakage Risk numbers for impacts to various compartments

Underground Injection Control (UIC)

- Class 1H are wells used to inject hazardous liquid waste.
- Requirement for certification is projection that no migration will occur from the injection zone while the waste remains hazardous (or for 10^4 years).
- USDW (Underground Source of Drinking Water) is primary concern.
- Class I well injection is deeper than (below) USDW.
- Injected fluids are nearly always denser than native fluids.

Under these conditions, the non-migration requirement is relatively easy to meet.

Main Differences Between Liquid Disposal and CO_2 Storage

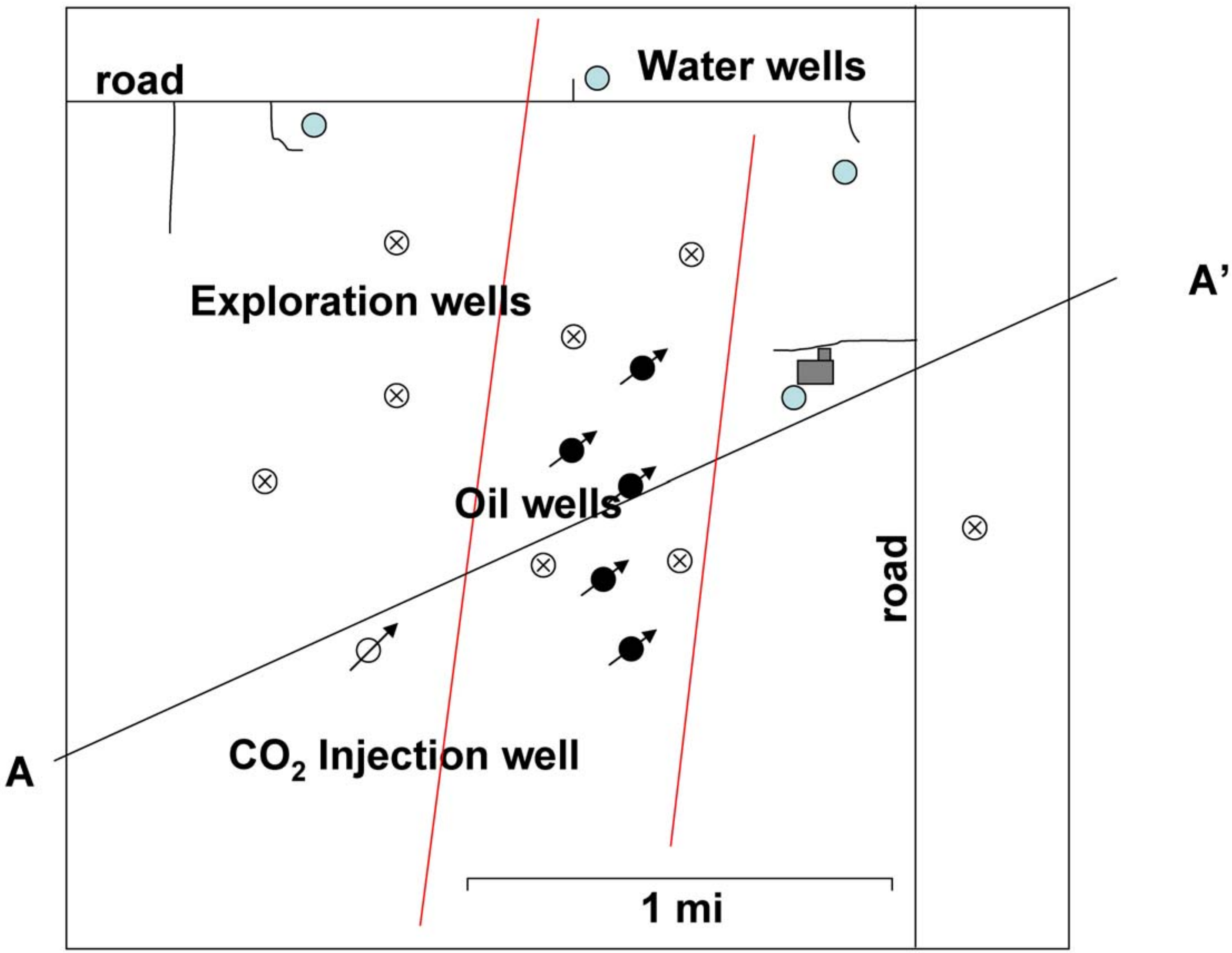
Liquid Disposal	CO_2 Storage
Liquid phase injectate	Supercritical fluid, gas-like viscosity
Density often greater than brine	Density always less than brine
Single-phase flow	Multiphase flow
Small volumes, low injection rates	Large volumes, injection rates

Implications for CO_2 Storage

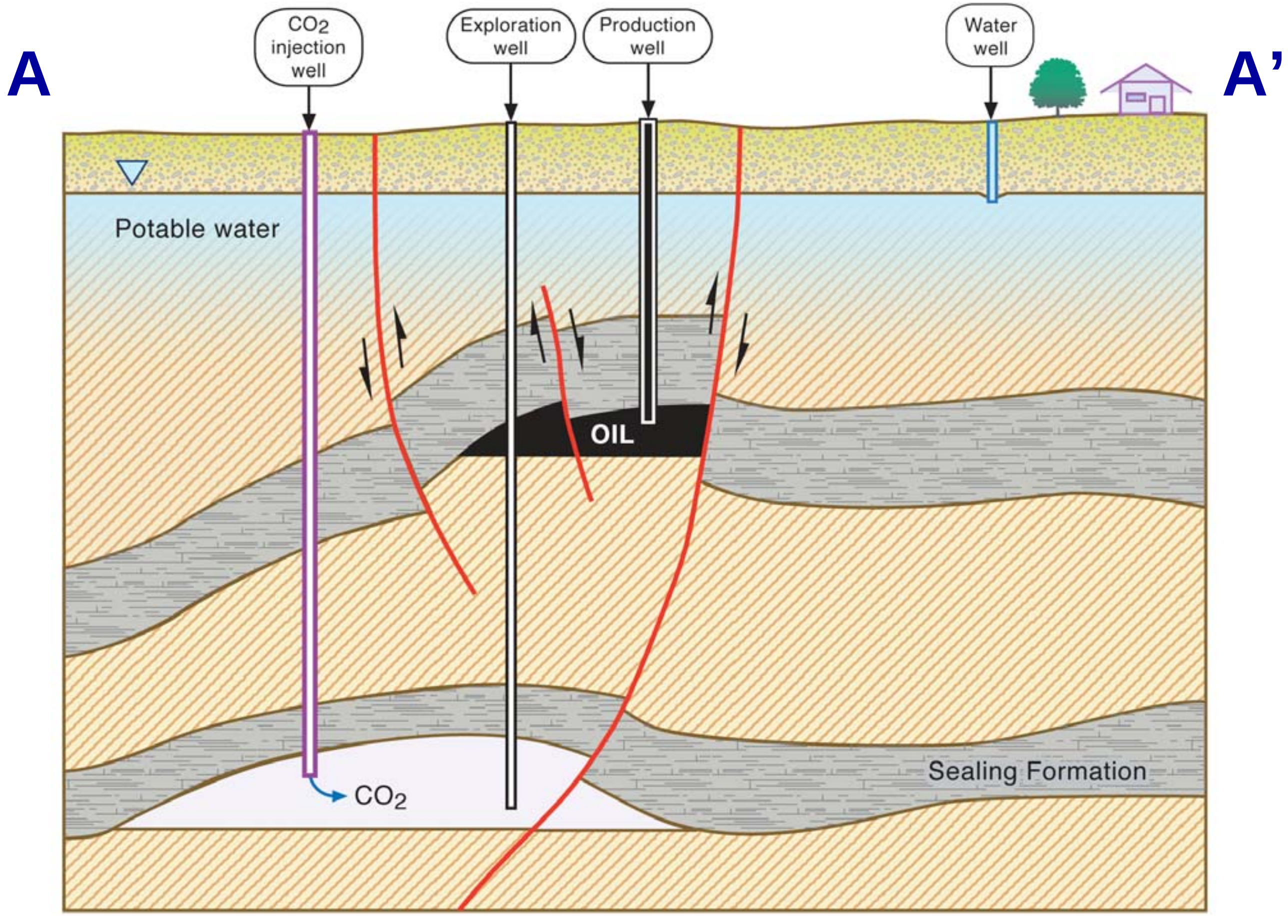
CO_2 immiscible with native fluids, highly mobile
CO_2 has tendency to migrate upwards
CO_2 may finger/bypass native fluids
CO_2 Area of Review may be very large

Key Definitions and Concepts

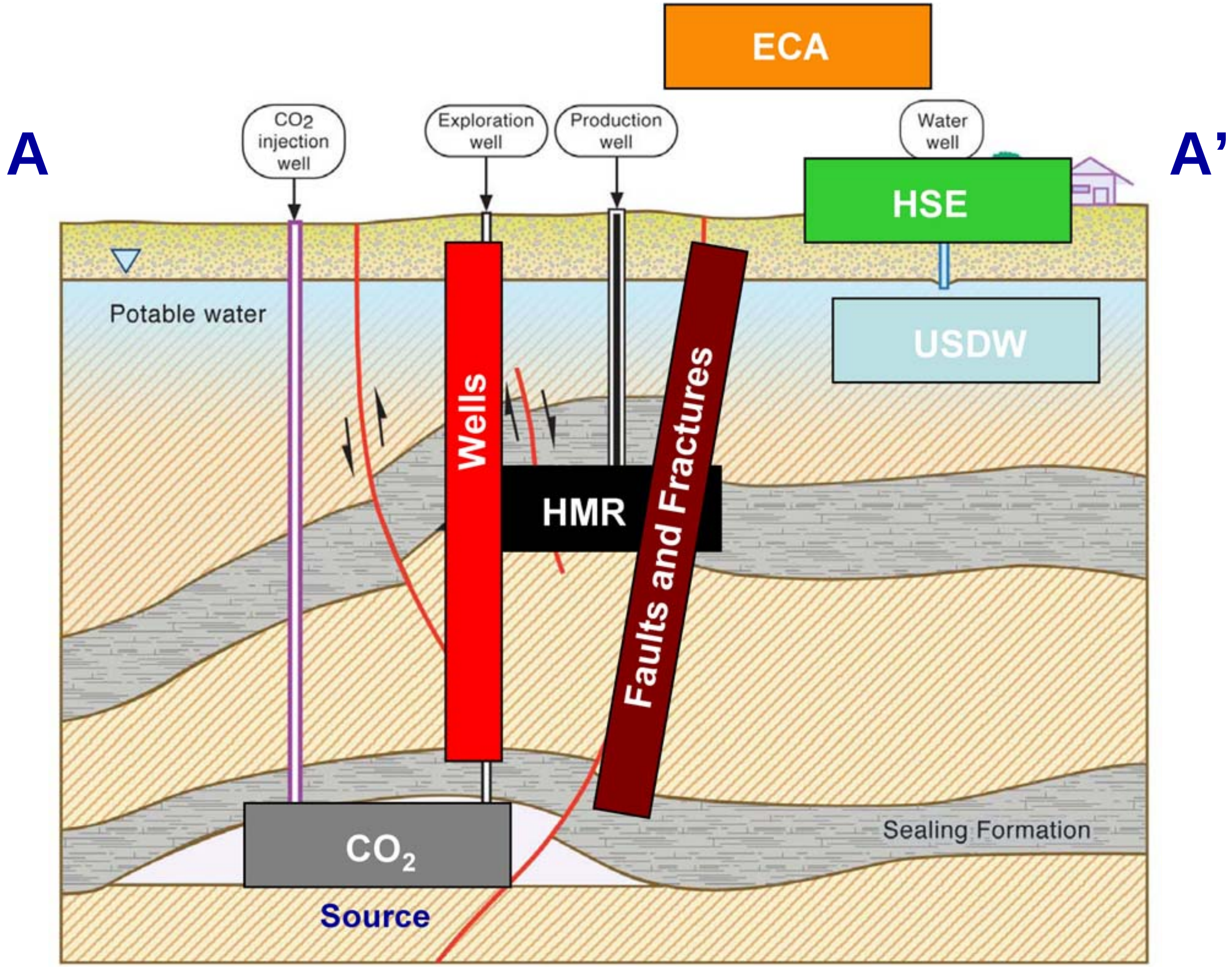
- **Effective Trapping** is the proposed overarching requirement for safety and effectiveness.
  - — Effective Trapping implies that CO_2 Leakage Risk is below agreed-upon thresholds.
- **Storage Region** is the three-dimensional area of the subsurface intended to contain injected CO_2.
- **Leakage** is migration across the boundary of the Storage Region.
- **Compartment** is a region containing vulnerable entities (e.g., environment and resources).
- **Impact** is a consequence to a compartment, evaluated by proxy concentrations or fluxes.
- **Risk** is the product of probability and consequence (impact).
- **CO_2 Leakage Risk** is the probability that negative impacts will occur to compartments due to CO_2 migration.


road
Water wells
Exploration wells
A'
Oil wells
road
A
CO_2 Injection well
1 mi

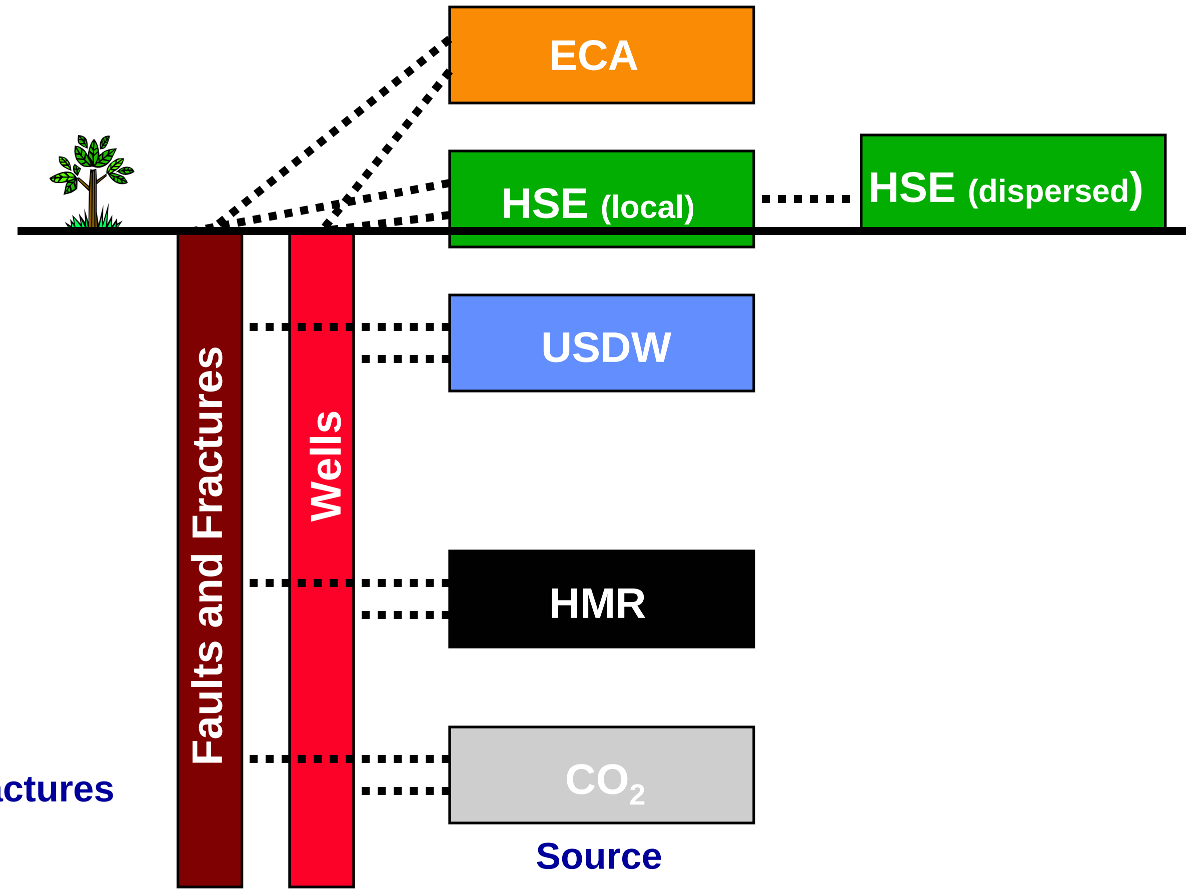
Example Cross-Section



Example Cross-Section



Compartments and Conduits



Two Conduits:
- Wells
- Faults and Fractures

Four Compartments:

ECA = Emission Credits and Atmosphere
HSE = Health, Safety, and Environment
USDW = Underground Sources of Drinking Water
HMR = Hydrocarbon and Mineral Resources

Factors in CLR (CO_2 Leakage Risk)

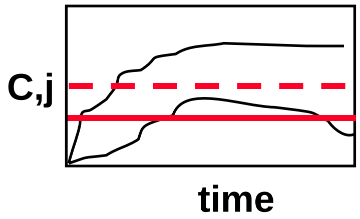
Impact X Probability

Receptors reside within compartments

(HSE, USDW, HMR, ECA)

Exposure to compartments leads to potential impact (CO_2 conc. (C) and flux (j) over time)

Limits are defined



Fault or well intersecting CO_2

Fault or well being conductive

Fault or well intersecting compartment

(Total probability is the product of the individual probabilities)

Exceeding limits = Impact [=] conc.-time, or flux-time

Impact X Total Probability = CLR

e.g., CLR [=] no. of conc.-time events/time

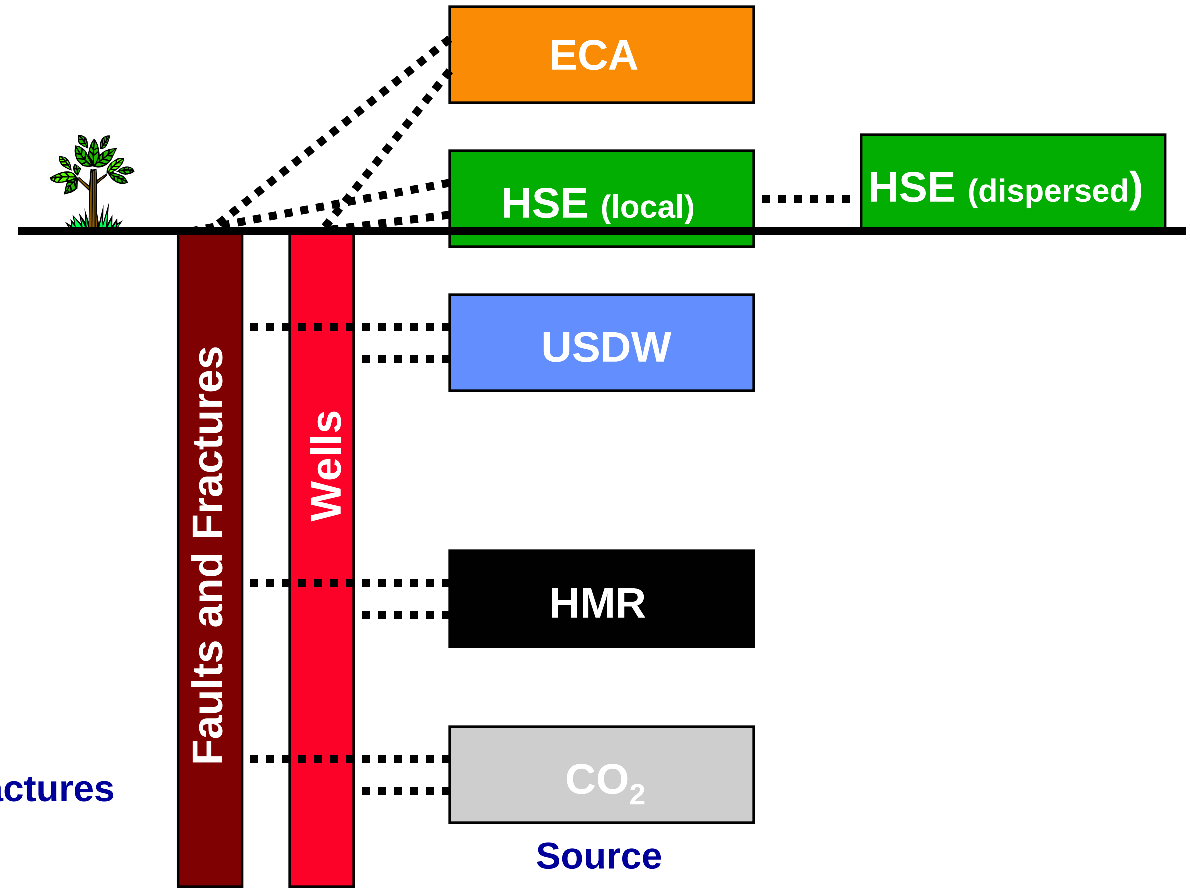
Examples of Impacts

- **Exceeding concentration limit at a receptor**
  - **—E.g., 0.4% CO_2 in air in an HSE compartment (indoors, local)**
- **Exceeding flux limit at a receptor**
  - **—E.g., CO_2 flux greater than 100 times background to the USDW compartment.**
- **Exceeding time-integrated conc. or flux at a receptor**
  - **—E.g., Concentration of CO_2 exceeds ten days of greater than 0.1% CO_2 in an HSE compartment (outdoors, local).**

Limits and Thresholds

- (1) Limits of flux, concentration, and their time-averaged forms need to be set for the compartments
  - Pertains to impacts that can occur due to exposure of compartments to CO_2.
- (2) Thresholds of CLR in compartments need to be set
  - Pertains to probability of occurrence of exceeding limits of concentrations, fluxes, and durations in compartments.
- In short, certification of a storage system will be allowed only if the CLR is below thresholds established for the probability that a limit will be exceeded for concentrations or fluxes at all compartments.
- When the CLR is below all thresholds, the effective trapping requirement will be met.

Compartments and Conduits

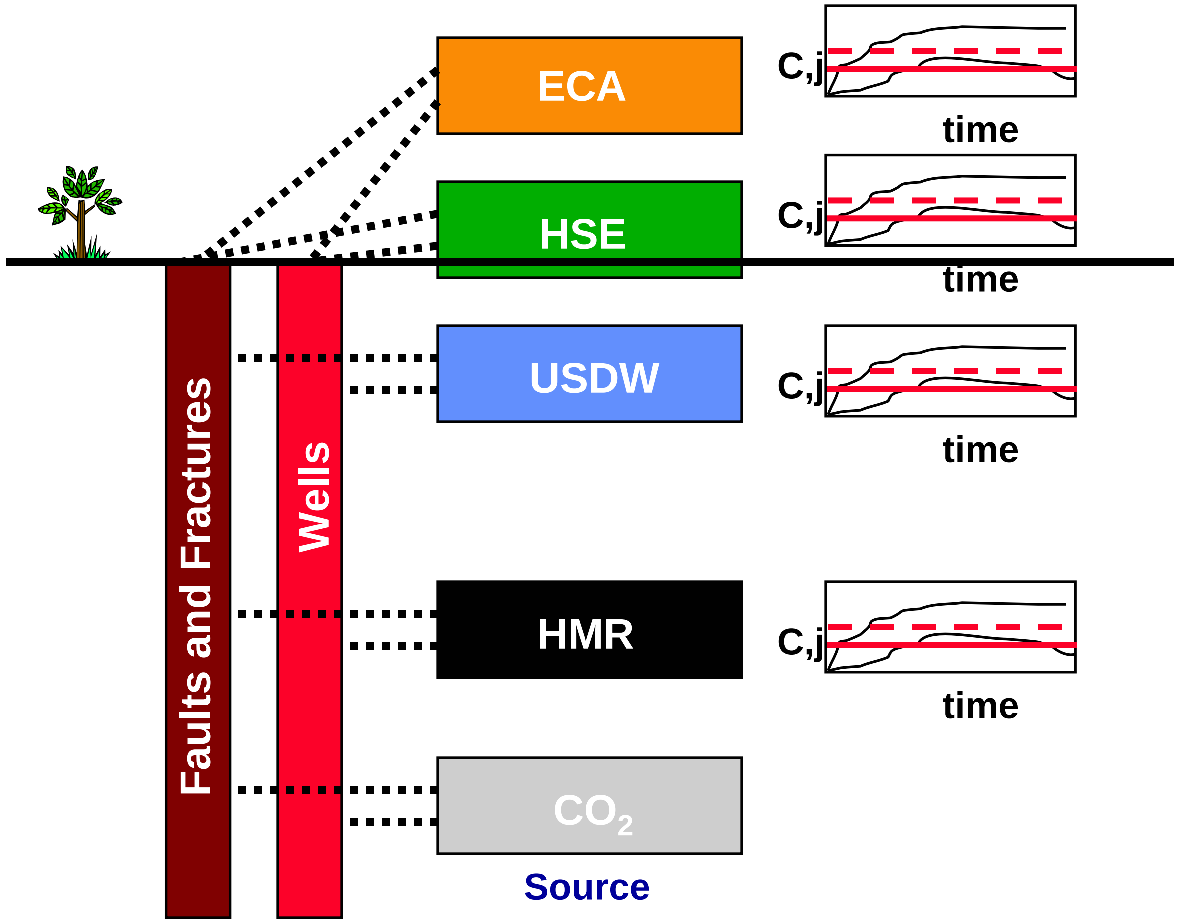


Two Conduits:
- **Wells**
- **Faults and Fractures**

Four Compartments:

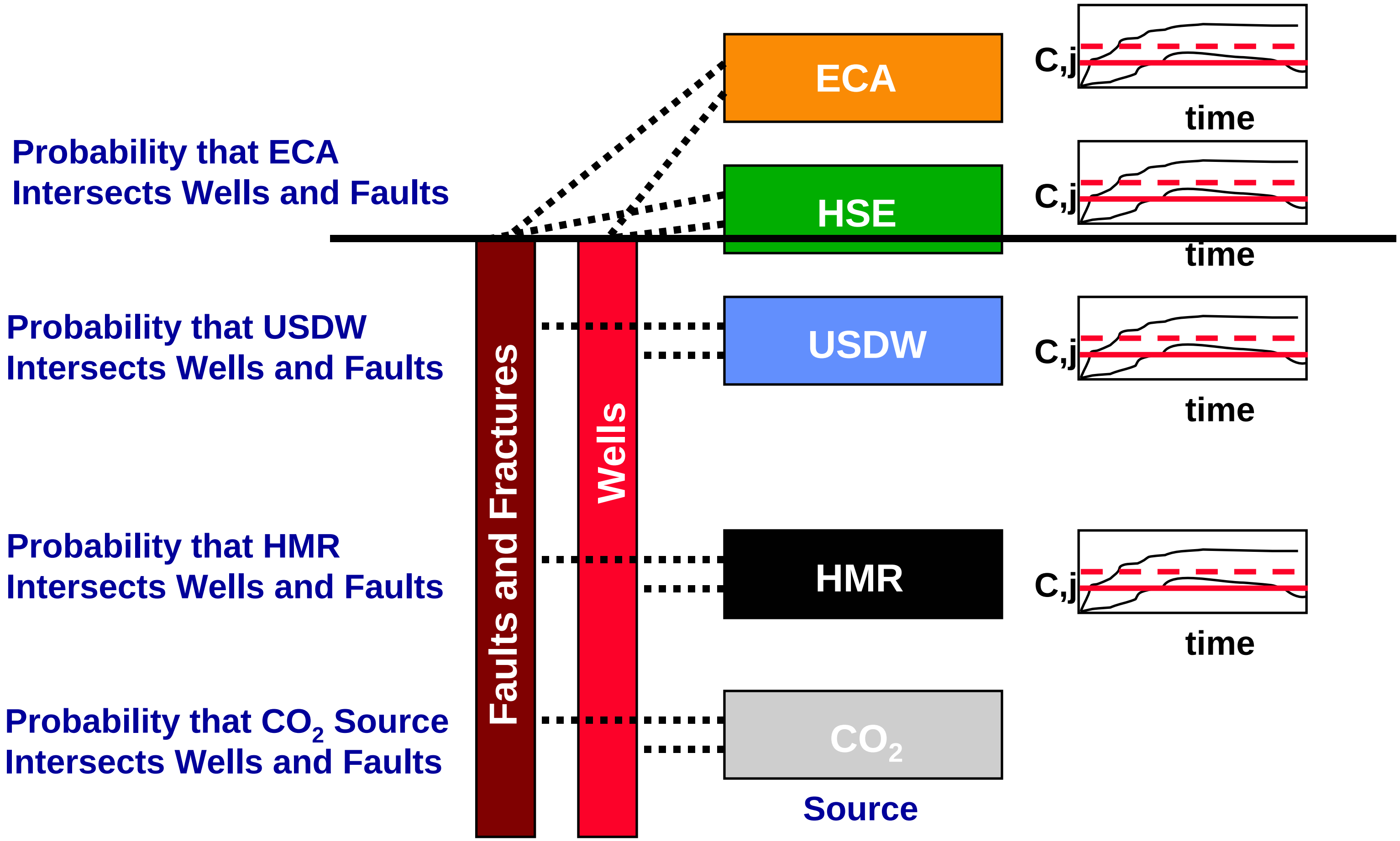
ECA = Emission Credits and Atmosphere
HSE = Health, Safety, and Environment
USDW = Underground Sources of Drinking Water
HMR = Hydrocarbon and Mineral Resources

Impacts



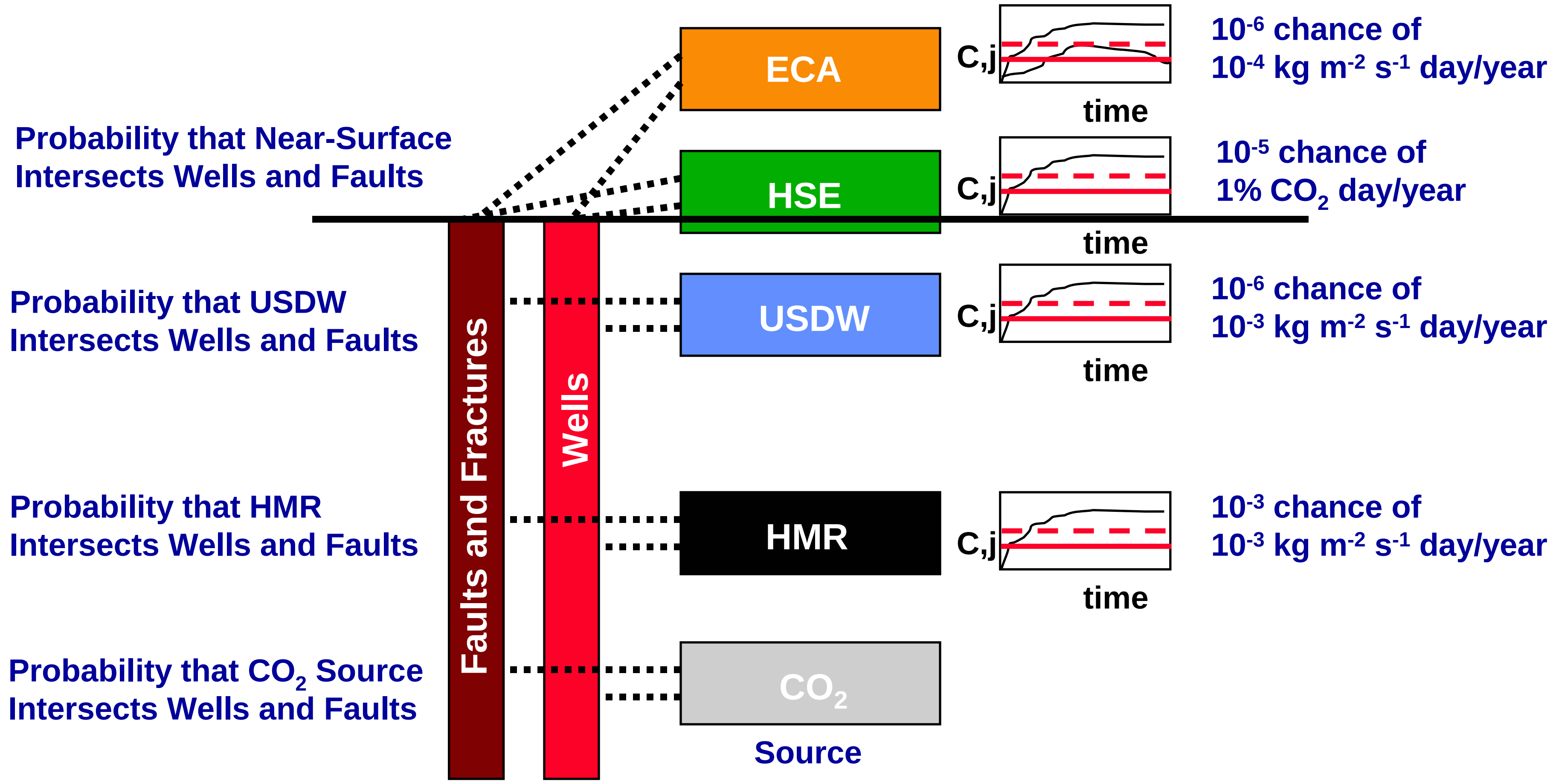
Impacts occur when the concentration or flux exceed limits defined a priori by regulators and industry. Impacts are concentration-time or flux-time events (e.g., 1% CO_2 days, or 10^{-4} kg CO_2 m^{-2} s^{-1} days).

Probabilities



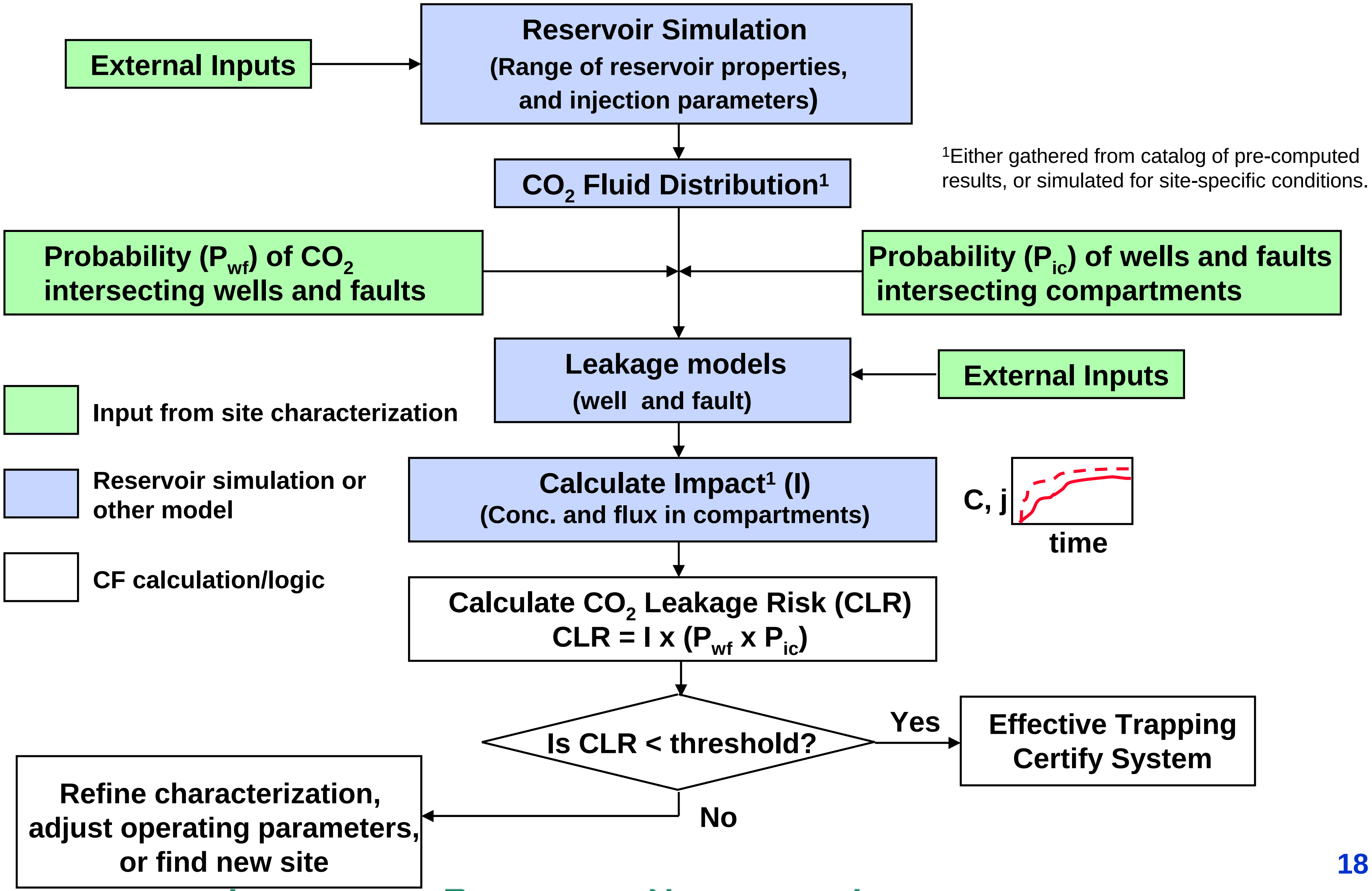
The probabilities considered by the CF are the probabilities of conduits intersecting the CO_2 source and the compartments.

CO_2 Leakage Risk



CLR to any compartment is the product of the probabilities that CO_2 will intersect source and compartment times the impact as calculated by concentration- or flux-time events. If CLRs are below thresholds, the storage system can be certified.

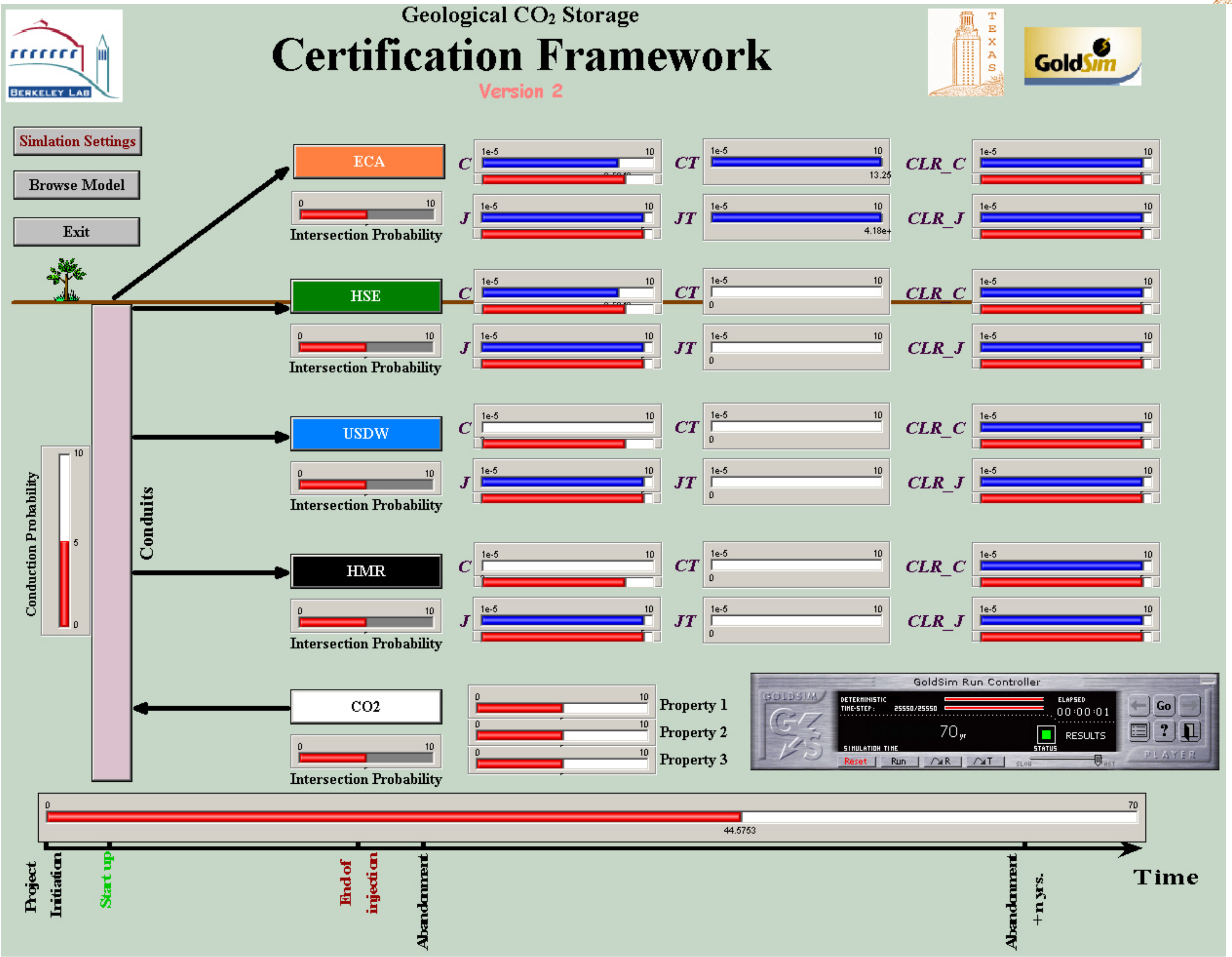
CF Flow Chart



Ongoing Efforts for CF

- Reservoir simulation catalog (Kumar (UT))
- Case studies (Nicot, (Texas BEG))
- Fault and well flow model (Minkoff (Univ. Maryland))
- Fault intersection and characterization (Jordan (LBNL))
- Above-ground CO_2 migration (Chow, Granvold (UCB))
- Interaction with regulators, guidance on impact thresholds and risk limits (McKone, Sohn, Price (LBNL))
- Uncertainty by fuzzy membership models (Zhang (LBNL))
- Rapid Prototype in GoldSim (Zhang (LBNL))

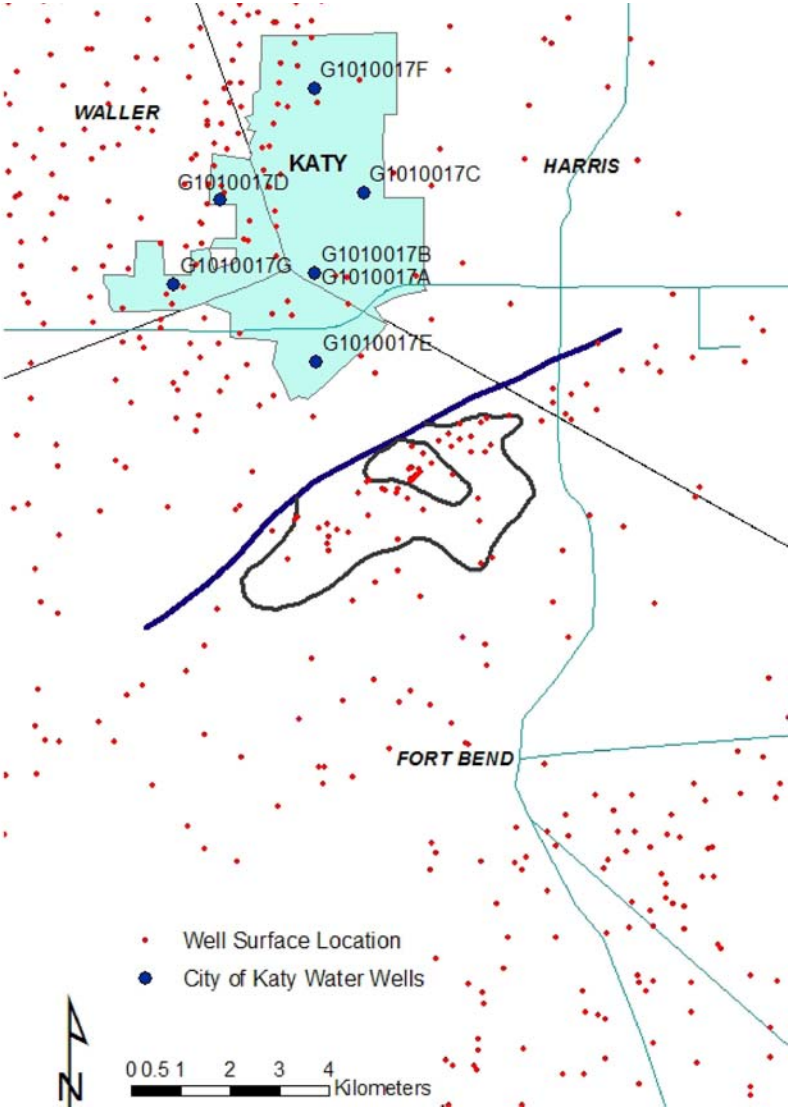
Rapid Prototype in GoldSim

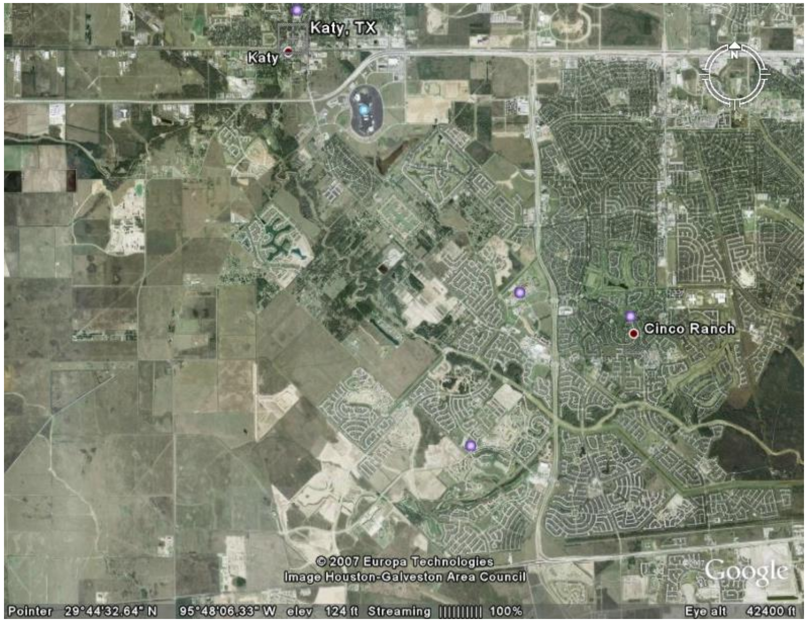


Case Studies

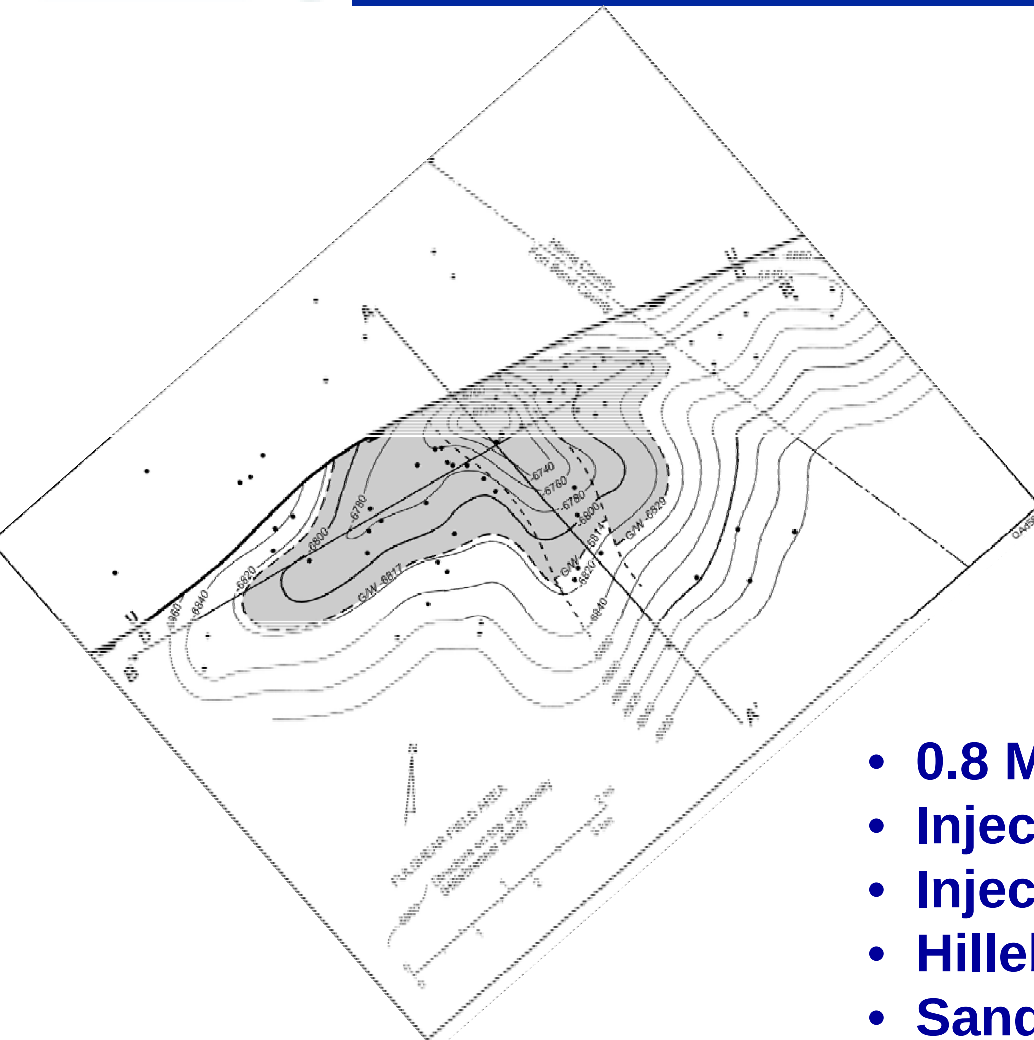
- Fulshear gas storage, Katy TX
- Mt. Simon formation in IL
- San Joaquin Valley, CA

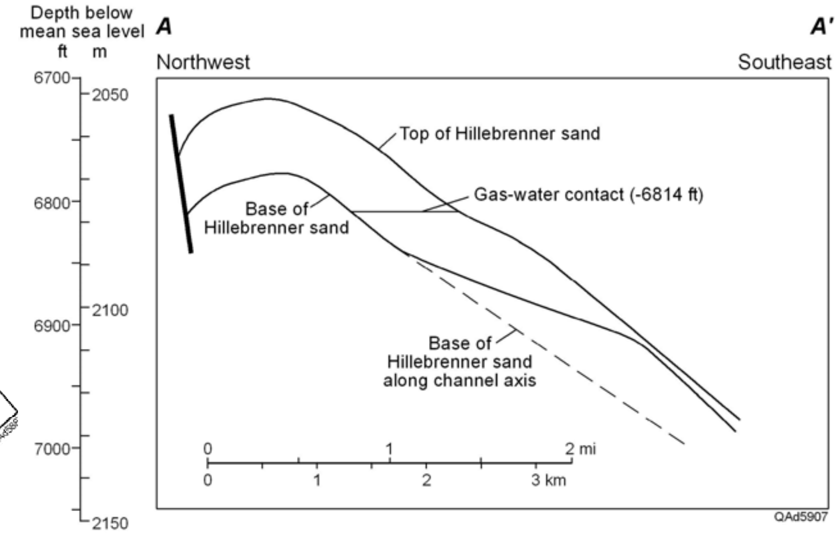
Case Study: Fulshear Gas, Katy, TX





Case Study: Fulshear Gas ca. Katy, TX

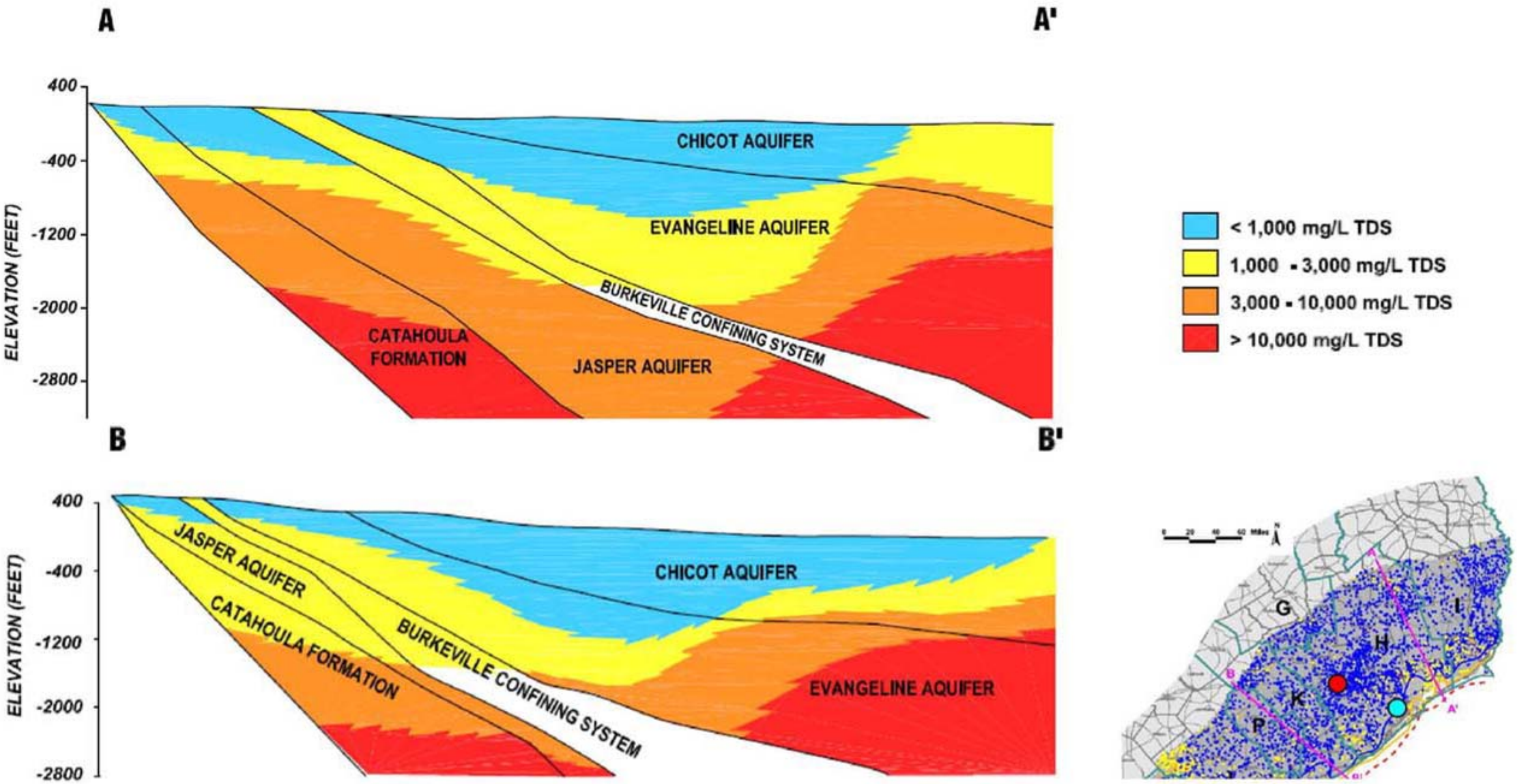




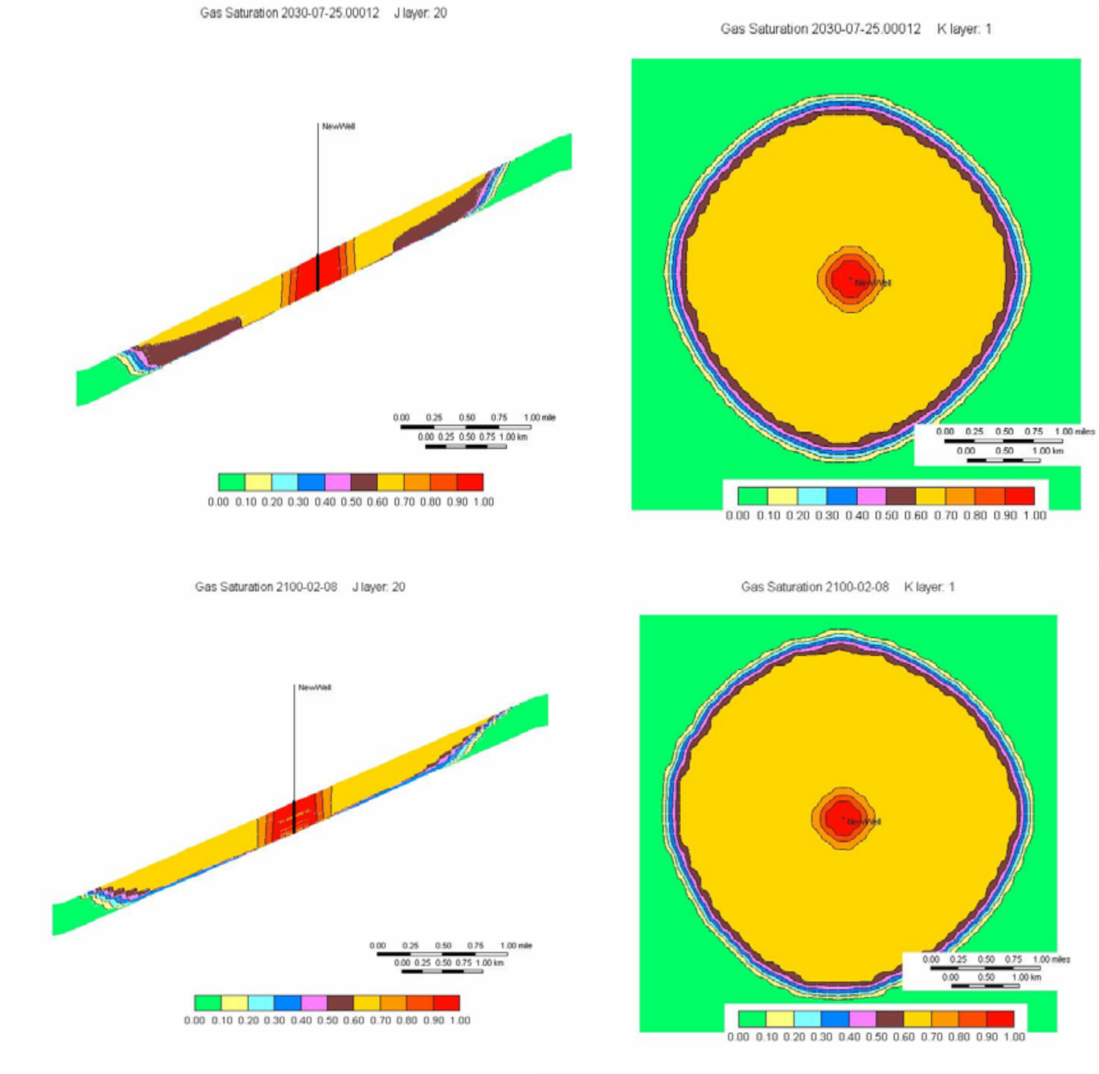
Injection Plan

- 0.8 Mt CO_2/yr into water leg of gas res.
- Injection at 7000 ft (2100 m) depth
- Injection ~ 2 mi downdip (to the SE)
- Hillebrenner sand dips ~ 1^{o} SE
- Sand is 10-50 ft thick
- Multiple claystone seals

Aquifers Above Fulshear Reservoir



Simulation of CO_2 Injection



CO_2 Migration

- **After 30 years, CO_2 plume extends ~1.5 mi (2.4 km) up dip**
- **Encounters well in ~25 yrs at 0.85 mi (1.4 km)**
- **Overpressure is 45 psi (3.1 bar)**
- **Only 10% of CO_2 is mobile after 100 yrs.**
- **Overpressure is fed to well flow model to calculate CO_2 flux into aquifers.**

Certification Framework Summary

- CF project is developing a simple, transparent, and accepted approach to geologic storage system certification.

Simplification
  - Certification based on Effective Trapping Requirement
  - CO_2 Leakage Risk
  - Compartment concept
  - Broad classes of features
  - Catalog of model results--but site-specific can be used also
  - CF is probabilistic in existence of flow pathway, deterministic in flow along pathway
- Transparency
  - Model results are from sophisticated modeling of simplified systems
  - Process and I/O can be visualized in GoldSim application
- Acceptance
  - Effective Trapping Requirement analogous to UIC non-migration
  - Working with Advisory Board and regulators

Advisory Board

- Regulatory
- NGO
- Industry
- Risk Assessment
- Research
- Integrator

- Vello Kuuskraa (ARI)
- Jason Anderson (IEEP)
- Stefan Bachu (Alberta EUB)
- Mike Celia (Princeton)
- Niels Peter Christenson (GEUS)
- David Hawkins (NRDC)
- Susan Hovorka (Texas BEG)
- Scott Imbus (Chevron)
- Anhar Karimjee (EPA)
- Mitch Small (Carnegie Mellon)

Acknowledgments

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