Risk Assessment Workshop

London, February 2004

Report Number PH4/31
July 2004

This document has been prepared for the Executive Committee of the Programme.
It is not a publication of the Operating Agent, International Energy Agency or its Secretariat.

REPORT ON

RISK ASSESSMENT WORKSHOP

Organised by IEA Greenhouse Gas R&D Programme and BP
with the support of EPRI and the UK DTI

Wednesday 11th to Thursday 12th February 2004

DTI Conference Centre, 1 Victoria Street, London, SW1H 0ET,
UK

RISK ASSESSMENT WORKSHOP

Executive Summary

A workshop has been held in London in February 2004 that examined the current status of research work on risk assessment for geological storage of CO_2. The workshop was organised by the IEA Greenhouse Gas R&D Programme and BP and was attended by some 48 delegates drawn from research organisations active in the risk assessment field from around the world.

The workshop identified that there are a number of risk assessment activities underway around the world. These activities involve the development of: risk scenario assessment methods, analytical and numerical risk assessment models and risk assessment processes based on expert review panels. All these processes are at an early stage of development and further refinement of their approaches and data sets is underway.

Detailed risk assessment case studies have now been completed at two oil fields: the Forties field in the North Sea and the Weyburn oil field in Saskatchewan, Canada. Initial results from these case studies indicate that the risks of leakage from the geological storage reservoir are negligible. In the case of Forties, the cap rock is not faulted and there is limited fluid flow within the field, which suggests that by careful selection of reservoirs the risks of leakage from geological storage formations can be minimised. However, well bore failure is an area of concern, particularly for mature onshore oil provinces like the Williston Basin and the Alberta basin in Canada. The well failures of most concern are the smaller long term leaks particularly in abandoned fields; in contrast large scale failures would be identified by monitoring systems and remediation actions set in place quickly.

Some deficiencies in the data currently used by the models under development was identified   Particular data deficiencies include issues pertaining to the flow through faults, well bore failure modes and leakage pathways and incorporation of data on geochemical reactions within the reservoirs which could possibly affect cap rock integrity.   A number of research activities are now underway that are studying well bore failure, faults in natural CO_2 reservoirs and geochemical reactions within reservoirs that should allow data on the processes that control well bore leakage to be modelled in the future.

The rate of leakage that will cause ecosystem damage onshore are well understood as are the physical impacts on the human population and which sectors of the population are most at risk. However there is only limited information currently available on the potential impacts of offshore leakage on sub sea ecosystems.

The engagement of stakeholders was seen as a key issue that needs to be addressed. The current inability to communicate with stakeholders on the risks of storing CO_2 underground, due to limited data availability, is seen as an area that needs to be addressed. Careful thought needs to be given to the limited information that is currently available on the risks of CO_2 leakage and its impacts to determine what positive messages can be drawn currently to begin a process of dialogue with key stakeholders on the risks associated with geological storage of CO_2.

The workshop identified a number of key further research needs which included:

- Identification of the potential causes of leakage through abandoned wells need determination of the processes controlling leakage,

- The processes controlling leakage through faults also needs to be researched in depth so that faults can be incorporated into the risk assessment models,

- Research work is needed to identify the potential effects on ecosystems of undersea leakage of CO_2.

A number of actions were agreed which included:

- IEA GHG will develop its www.Co2sequestration.info web site to include a web page that will facilitate general access by projects to the generic FEP database. During the development of the web site the TNO-NITG and Quintessa databases will be merged to produce a single generic data set for general application.

- The organisers will consider the establishment of an international network of research groups active in the field of risk assessment. Such a network would plan to meet annually and provide a forum for exchange of information and the latest results in this important research area and co-ordinate future benchmarking exercises.

RISK ASSESSMENT WORKSHOP

1.   BACKGROUND

CO_2 capture and storage in geological formations is now establishing itself as a technical option that has the potential, when used in conjunction with other mitigation options[1], to make deep reductions in atmospheric emissions of CO_2. There are now several commercial scale projects, either underway or in the planning stage, that capture CO_2 emitted from gas processing operations and store the CO_2 in geological formations. One such operation is the Sleipner project in the North Sea, which has now been injecting nearly 1 million tonnes of CO_2 into a deep saline aquifer above the Sleipner Vest gas field since 1996. The natural gas extracted from the Sleipner Vest gas field contains 8% CO_2 by volume which must be reduced to 2.5% before it can be pumped ashore.   The CO_2 produced is captured, rather than vented and injected back into a geological formation. In addition to the gas processing operations, CO_2 is routinely injected into geological formations in North America as part of enhanced oil recovery operations. Whilst these operations do not deliberately aim to store CO_2, some residual CO_2 will remain within the oil field trapped in the residual oil and dissolved in water.

Operations, such as those described above, however, are only storing a small proportion of the CO_2 emissions that will have to be avoided if the UNFCC[2] goal of 'stabilisation of atmospheric concentrations of greenhouse gases' is to be achieved. To achieve this goal substantial deployment of CO_2 capture and storage technology will be required across the globe. Such a widespread deployment of technology will mean that policy makers and the general public will need to be fully behind the technology.   Two key areas that will need to be demonstrated to gain public acceptance of CO_2 capture and storage are: that the technology is safe and that its environmental impact is limited.   The main feature that will define the safety and environmental impact will be if fugitive leakage occurs from the system and the impacts any leakage could have on ecosystems and human health.

The CO_2 capture and storage system can be divided into three component parts, which are:

- Capture of the CO_2 at a power plant or large industrial facility,
- Dehydration, compression and transmission of the CO_2 to the storage site,
- Injection and storage of the CO_2 underground in a geological formation.

If we consider each component, then it can be considered that: the capture plant is a standard piece of chemical industry equipment and the chemical, power and industrial facility operators will all have standard procedures to manage and minimise the risk of fugitive leakage during the construction and operational stages. The risk of fugitive

---

[1] Other mitigation options can include: energy efficiency improvements, fuel switching and use of renewable energy
[2] United Nations Framework Convention on Climate Change

emissions occurring from the capture component can therefore be considered to be negligible. Similarly, there are extensive pipeline networks across the world carrying hydrocarbons and a large pipeline network in North America carrying 40 Mt/y of CO_2. Once again it can be considered that the risk of fugitive leakage occurring from the pipeline networks should be negligible because of the extensive experience worldwide in the safe construction and operational management of pipeline networks. For the injection and storage component the potential for leakage cannot be readily estimated because there is only limited reference experience available. Hydrocarbon gases and CO_2 are routinely injected extensively as part of enhanced oil recovery operations in many parts of the world. In addition more hazardous compounds like H_2S are injected underground in North America as part of acid gas injection operations. Also in the USA there is a substantial programme of injecting hazardous fluids underground. In all these cases there is extensive design, operational and regulatory experience which again indicates that the injection operation should not pose a significant risk for leakage. The greatest uncertainty however relates to the storage sub-component principally due to the limited knowledge currently available on the fate of injected CO_2 in geological formations and the potential for CO_2 to migrate out of the formation and leak to the surface.

To assess the current state of knowledge on the potential for CO_2 migration out of a geological storage formation, and the risk such migration would pose, a workshop was held in London in February 2004. The workshop was organised by BP and IEA Greenhouse Gas R&D Programme (IEA GHG) with the support of UK DTI[3] and EPRI[4]. This report provides a summary of the workshop results and outlines future work that is needed to address the research gaps identified.

2.   RISK ASSESSMENT WORKSHOP

2.1   Workshop aims and objectives

The aim of the workshop was to bring together the main research groups currently active in the field of risk assessment of CO_2 geological storage worldwide in order to discuss and critique the work that is currently underway.

The first objective of the workshop was to assess the current state of progress on risk assessment activities relating to the geological storage of CO_2. Having assessed the status the next objective was to begin the development of a road map for necessary future activities. Future activities that could be considered include: identification of research gaps, prioritisation of additional work requirements, testing and validation of modelling tools and processes. In addition, it was considered necessary to assess when the process of engaging of stakeholders should begin and the way such engagement should occur in order to gain the confidence of policy makers and the general public.

---

[3] United Kingdom Department of Trade and Industry
[4] Electric Power Research Institute

2.2 Workshop attendees

Workshop attendees were invited by the organisers, in total some 48 delegates attended the workshop; these delegates were drawn from 32 different organisations and 10 different countries. The attendance list is given in Annex 1 for reference.

2.3 Workshop programme and structure

The two day workshop was structured to provide both technical presentations and time for open discussion. The presentations were focused into five topic groups covering the different aspects of risk assessment work currently underway. The topic groups were:

1. Risk Identification and Scenario Analyses
2. Assessing Long-Term Storage Performance
3. Impacts of CO_2 Leakage
4. Well bore Seepage and Risk Analyses
5. Regulation and Public Perception

The technical programme for the workshop is presented in Table 1 for reference.

After the presentations and to focus the discussions on research gaps and future research needs the assembled experts were then divided into groups. Each breakout group was given a set of questions to consider and was asked to report back on their deliberations to the main assembly, with time allowed for discussion.

3. SUMMARY OF WORKSHOP RESULTS

3.1 Review of Presentations

Risk identification and scenario analyses

Two organisations (Quintessa and TNO-NITG[5]) have been developing databases of Features Event and Processes (FEPs). An FEP is any feature, event or process, which directly or indirectly may affect the (long-term) safety of CO_2 storage. The development work by Quintessa was undertaken as part of a European Commission (EC) supported activity within the Weyburn Monitoring Project, whilst the work by TNO-NITG was supported by the CO_2 Capture Project. In both cases, the development of the individual databases is largely complete.

The FEP databases produced by the two groups are structurally different because they have been created to produce different outputs. The Quintessa database was aimed to

---

[5] Netherlands Institute of Applied Geosciences – National Geological Survey

Table 1.   Risk Assessment Workshop Programme

Day 1	Wednesday 11th February 2004
Opening Session	
09.00 to 09.15	Introduction to workshop aims and objectives. *John Gale, IEA GHG*
09.15 to 09.30	The risk assessment process and outline of the building blocks. *Tony Espie, BP*
Session 1 - Risk Identification & Scenario Analyses	
09.30 to 09.50	Safety assessment methodology: the scenario approach (SAMCARDS). *Ipo Ritsema - TNO-NITG*
09.50 to 10.10	The development of a generic FEP database for the geological storage of CO_2. *Philip Maul and Steve Benbow, Quintessa*
10.10 to 10.30	Facilitated panel/open discussion
10.30 to 11.00	Break
Session 2 – Assessing Long-Term Storage Performance	
11.00 to 11.30	GEODISC/CO2CRC approach and results. *Adrian Bowden, URS*
11.30 to 12.00	Assessment of the long-term fate of CO_2 in the Weyburn field. *Mike Stenhouse and Wei Zhou, Monitor Scientific*
12.00 to 12.30	NGCAS approach and results. *Roy Wikramaratna, ECL*
12.30 to 13.30	Break
13.30 to 13.50	1) a mathematical model for probabilistic risk assessment and 2) risk scenarios pertaining to CO_2 injection and storage in coal beds. *Shaochang Wo, INNEL*
13.50 to 14.10	Numerical simulation on storage and leakage behavior of injected CO_2. *Yukio Imaseki, RITE*
14.10 to 15.00	Facilitated panel/open discussion on approaches adopted.
15.00 to 15.30	Break
Session 3 – Impacts of CO_2 Leakage	
15.30 to 15.50	Assessment impacts of surface leakage of CO_2. *Prasad Saripalli, Battelle*
15.50 to 16.10	The use of SWIFT and QRA in determining risk of leakage from CO_2 capture, transport and storage systems. *Mark Vendrig, DNV*
16.10 to 16.30	What can we learn from studies on Natural Analogues? *Jonathan Pearce, BGS*
16.30 to 17.00	Health and ecological risk assessment *Susan A. Rice and Associates.*
17.00 to 17.15	Facilitated panel/open discussion on impacts of CO_2 leakage

Table 1   Risk Assessment Workshop Programme, cont'd

Day 2	Thursday 12th February 2004
Opening Session - Day 2	
08.45 to 09.15	Recap of Day 1 and plan for Day 2. *John Gale, IEA GHG*
Session 4 – Well bore Seepage and Risk analyses	
09.15 to 09.35	Well bore dynamic & leakage studies at the Weyburn project. *Rick Chalaturnyk, University of Alberta*
09.35 to 09.55	Leakage through existing wells: models, data analysis, and laboratory experiments. *Mike Celia, Princeton University*
09.55 to 10.15	The stability of hydrated cement under CO_2 sequestration conditions. *Mileva Radonjic, Princeton University*
10.15 to 10.45	Break
10.45 to 11.30	Facilitated panel/open discussion on well bore /cement failure analyses.
Session 5 – Benchmarking Performance and Risk Prediction Tools	
11.30 to 12.30	Breakout groups discussions
12.30 to 13.30	Break
13.30 to 14.00	Continuation of breakout group discussions
14.00 to 14.30	Break out group feedback
14.30 to 15.00	Facilitated panel/open discussion on Benchmarking of CO_2 storage performance and risk prediction tools, benefits, process, datasets, timescale, funding etc
15.00 to 15.30	Break
Session 6 – Regulation and Public Perception	
15.30 to 16.30	"Linking risk assessments to regulation" *David Keith, Carnegie Mellon* "Participatory planning for CCS: attempting rapprochement between divergent agendas and public risk perceptions" *Simon Shackley, UMIST*
Session 7 - Closing Session	
16.30 to 17.00	Wrap up discussion and close

be a generic data set that would be used as a reference source for the construction of more detailed project data sets[6]. It therefore contains some 200 FEPs. Quintessa considered that it was not possible currently to assign probabilities to the geological storage system and hence no effort was made to develop the FEP database further. The TNO-NITG data base contains significantly more detail (500 FEPs in total) because it was developed as a tool for assessing risk not merely as a reference source. The approach used allows the FEPs to be selected from the data base and then allows probabilities to be assigned to each of the FEPs (each FEP can be considered as a qualitative risk factor). This approach allows it to develop risk scenarios for a particular project. It is felt that this type of risk assessment tool could be used in the licensing and certification stages of project development.

As stated earlier the main development phase of these FEP databases has been completed. The next step in their development is refinement through use. To achieve this aim it is planned to develop a combined generic data set that will be posted on a publicly available web site for other groups to use in their risk assessment activities.

Assessing Long-Term Storage Performance

Results were presented from two projects that had undertaken detailed risk assessments of case studies, the Forties oil field in the North Sea and Weyburn oil field in Canada. In the Forties case, a simplistic risk assessment process was developed that used the generic FEP database developed by Quintessa to develop potential leakage scenarios. Analytical and numerical models were then applied to determine the bounds of risk acceptability. No attempt was made to assign probabilities because it was felt by the project team that a probabilistic analysis might not be needed and also there were doubts that probabilities could be assigned to geological events. It was concluded that the risk of leakage from the geological storage reservoir via pathways such as transmission through the overburden and via an underlying aquifer were negligible[7]. However, it was noted that the impact of CO_2 on the long term integrity of the cap rock needed to be resolved. Leakage through operating and abandoned wells[8] was identified as a potential issue, but a detailed assessment of the risk of leakage from wells that punctuate the reservoir had not been completed within the current project scope.

In the Weyburn case, both a qualititative and probabilistic risk analysis[9] had been undertaken. The detailed results of these analyses were not available at the meeting

---

[6] In fact this was exactly how the FEP database was applied within the Weyburn Monitoring project.

[7] Modelling indicated that less than 2% of the injected CO_2 would migrate into the underlying aquifer in 1000 years and that the fluid flow was so low that the dissolved CO_2 would not flow outside the boundary of the field.

[8] Some 190 wells punctuate the Forties field; 89 are abandoned whilst a further 29 are suspended. In addition in the next 10 years it is expected that a further 30 wells will be drilled and a number of existing wells (24) abandoned.

[9] As implied by the term qualitative, the process of assigning a risk to an event is primarily left to the judgment of experts and hence in this case potential leakage pathways are qualitatively risk-ranked based on a perceived consequence and likelihood. In a probabilistic assessment, a statistical approach is used to assign degrees of confidence for any leakage event that might occur.

but some general conclusions could be drawn. In the qualititative risk analysis case, the Quintessa FEP data base was used as the reference source to build a Weyburn specific FEP set[10], which identified the key leakage pathways. Eclipse 300, an industry standard model[11], was used to develop the geological system model for assessing the long term fate of the injected CO_2. It is accepted that this model has some deficiencies, for example: it cannot take into account geochemical interactions and does not handle well leakage easily. Nevertheless, at the time the project started there were no purpose designed risk assessment models available. Wells were again seen as having significant potential to leak. For the probabilistic risk analysis a different reservoir model was used, CQUESTRA. CQUESTRA is a spreadsheet code developed to model storage in oil fields and incorporates a simulation programme called CrystalBall that can be linked to the spreadsheet model to assess risk and uncertainty. Risk and uncertainty are assessed using a Monte Carlo simulation. The two different modelling approaches are now being compared by the project as a benchmarking exercise. At the time of the workshop the bench marking exercise was not complete and results could not be presented.

In addition new purpose designed models for probabilistic risk assessment (PRA) are being developed and one was described that has been developed by INEEL[12] as part of the CO_2 Capture Project activity. The model is designed to work for all geological storage options. However, the model has not yet been tested using data from a specific project case.

An alternative approach for qualititative risk assessment has been undertaken in Australia. The method is called RISQUE which uses expert panels to identify and evaluate the risk factors involved. The process is designed to be transparent to allow stakeholders to "buy into" the judgements made. In this case, risk is characterised in terms of the likelihood of a risk event occurring and the consequences of such an event are assessed. The process was applied to 4 potential geological storage sites (all deep saline aquifers) in Australia. The aim of the exercise was to rank their suitability as potential demonstration projects. The risk factors assigned were much broader than geological risk but considered project financing, wider community benefits and community amenity as well. For example, the risk factors assigned to the storage reservoir were:

o *Containment* i.e. 99% of the injected CO_2 should be retained over 1000 years.
  Risk events that could affect containment were listed and include for example: leakage via faults, or wells or as a result of over pressurisation during injection. In essence the list of risk events can be interpreted as a FEPs list.
o *Effectiveness* i.e. that there was sufficient storage capacity available to justify an injection project.

---

[10] 55 FEPs in total were selected as being relevant to the Weyburn case
[11] Eclipse 300 has been used by EnCana the Weyburn field operator for their field simulation work for both water and CO_2 flood design.
[12] Idaho National Engineering and Environmental Laboratory

The RISQUE method clearly diffentiated between the four reservoirs reviewed and therefore acted as a useful pre-screening tool for selecting potential demonstration sites that minimise the risk of leakage. It is noted that there was considerable discussion on the justification for selection of such a rigorous containment target. It was commented that this was a first stage exercise and the intention was to broaden the analysis by including more reservoirs and then confirm and justify the risk factors used initially.

A numerical simulation of leakage from an aquifer was presented by RITE. When CO_2 was injected it was found that the highest pressure in the reservoir occurred at the point that injection ended. The model then simulated the leakage rate from a fracture that could be induced at this point by tectonic activity. The simulation then assumed that a 25m wide fracture could be induced by an earthquake that acted as a transmissive pathway from the geological storage reservoir to the sea floor. (Note: The fracture width was considered by the experts present at the workshop to be an extreme example.) The possible range of CO_2 leakage rates were then examined based on assumed permeabilities within the induced fracture. If a fracture occurs at the point that injection ends (i.e. at the highest pressure within the reservoir), with a high permeability (10 mDarcy) leakage to the sea floor occurs 10 years after fracture inducement and then peaks after 35 years. The model indicated leakage would still be significant after 200 years. At a low permeability in the fracture (1 mDarcy) negligible leakage was modelled after 200 years. If fracture inducement occurred 100 years after injection was complete in the high permeability case leakage rates would be significantly lower and the peak rate would not occur until 75 years after inducement. Simulations such as this give useful guidance on potential leakage rates from geological storage reservoirs, but the results should be treated with some caution because the assumptions used in the model were not based on real data on fracture propagation and permeability within an induced fracture. Actual data is needed in both cases to allow accurate leakage rates to be calculated.

Impacts of CO_2 leakage

Det Norsk Veritas have undertaken a qualititative risk analysis assessment on the engineered system i.e. the surface pipeline and injection systems associated with a storage operation, and for the reservoir itself. The assessment used a Structured What if Technique (SWIFT) which involved the use of expert panels. For the engineered system it was found that data on the frequency of leakage occurrences from components of the system based on experience in the chemical, oil and gas industry was available in the public domain. This information could be referenced to assess the potential for leakage from the system. Extending this information to a conceptual CO_2 storage system indicated that the likely leakage rates from the engineered system were negligible (<0.03% of storage rate per year). Based on readily available standards for acute health effects from CO_2, and based on worst case scenarios, fatalities due to these leakage rates were unlikely and that the risks to individuals were typically within industry guidelines.

A simulation methodology for assessing the impacts of surface leakage of CO_2 has been developed by Battelle/PNNL[13]. The results of a case study were presented that modeled the release of CO_2 from a conceptual reservoir and attempted to calculate surface leakage rates. The case study was based on a cap rock with a continuous fracture to the surface with a permeability of 1 Darcy in the fracture. The estimated CO_2 leakage rates at the surface were in the range 0.1 to 80 gCO_2/m^2/day. As noted for the simulation study presented earlier, the results should be treated with some caution because the assumptions used in the model were not based on real data on fracture permeability. Actual data is needed in both cases to allow accurate leakage rates to be calculated. Such cases most probably represent a worst case scenario. Nevertheless, dispersion modeling results indicate that, at the surface, leakage rates calculated the CO_2 would quickly disperse into the atmosphere at moderate wind conditions[14]. It was then concluded that at these estimated leakage rates, CO_2 leakage would not represent a risk to surface vegetation or human health. It is planned that the developed methodology will be tested on actual data from the Mountaineer project in the Ohio valley in USA in the near future.

The European Commission supported NASCENT project has been studying a number of case studies of natural CO_2 accumulations throughout Europe. Some of these natural CO_2 accumulations leak and some do not - understanding why certain reservoirs seal and others leak is one of the key aims of the projects. Studies of fractures at these sites has shown that there are cases of carbonate inclusions in the fractures which indicates that leakage may have occurred through these fractures during the fields history but over time the fractures have self-healed. In areas where significant leakage occurs (700 gCO_2/m^2/day) there is evidence of crop death and CO_2 accumulation in the basements of buildings which can represent a hazard to human occupants. As far as water quality is concerned, in most sites there is evidence of contamination of borehole water in some producing CO_2 fields. The water contains raised Ca, Mg, HCO_3 and total hardness.

The impact of CO_2 leakage on the human population was reviewed by Susan Rice. Published exposure limits usually refer to the impact CO_2 exposure would have on a healthy adult. However we should consider that there are sections of the population that might be more sensitive such as individuals with heart disease or infants and children for example. To cover for these more susceptible sections of the population we ought to consider a lower exposure limit (e.g. 2% by volume CO_2) as the cut off point than the often quoted exposure values.

Well bore seepage and risk analysis

The Weyburn project has undertaken a detailed assessment of well bore integrity. Such an assessment is considered essential at an established oil field like Weyburn in an old oil province where numerous wells will have been drilled some potentially dating from before the 1900's. From State records the project has identified that some 2000 wells (both operational and abandoned) have been drilled across the

---

[13] Pacific Northwest National Laboratory
[14] Wind speeds of 10 to 20 miles per hour were assumed

Weyburn oil field. Therefore, it is not only important to determine the integrity of the cap rock or bounding seal but in this case probably more important to determine the impact that such a well density might have on the security of any injected CO_2. The time frame for well failure varies; operational well failures occur within the 25 year injection phase whereas abandoned wells must be sealed for periods much longer than the injection time, conceivably 100s or 1000s of years.

To assess the integrity of the injected CO_2 the project has developed a well bore integrity assessment model which was presented at the meeting.

Well leakage pathways include:

- Upward migration of liquid along the outside of the well casing,
- Escape of CO_2 into an overlying aquifer due to a well bore failure,
- Vertical migration through closed or abandoned wells.

Well known causes of leakage are corrosion of well casing and annulus cement failure. These pathways have been built into a well bore integrity model which is still currently being developed and refined.

The importance of wells as a potential source of leakage was re-emphasized in the next presentation. An analysis of the Alberta basin, a major target sedimentary basin in Canada indicated the presence of 350,000 wells. The Viking aquifer[15] alone in that basin is punctured by 195,000 wells. An analysis of these wells show that two types of well dominate the picture: abandoned wells (~92,000) and oil/gas production wells (~58,000). Another consideration is the clustering of these wells, an analysis of which has shown that the CO_2 plume from a typical injection well could impinge upon hundreds of other wells. Because of the importance of wells in the assessment of leakage from CO_2 storage reservoirs Princeton University are developing an analytical model that is focusing on the issue of well leakage in the Alberta basin. The models aims to: estimate the leakage rates from producing and abandoned wells and the potential environmental effects that any leakage might have. Estimating leakage over the Alberta basin reservoir requires modeling large numbers of wells simultaneously, which would be very time consuming with the more complex numerical models. The model is now being expanded to include an arbitrary number of leaking wells and the effect that intermediary aquifers layers will have on CO_2 leakage. The earlier simulation presented by Battelle which that CO_2 would flow directly to the surface, the intermediate layers will act to hold up leakage the extent of which needs to be assessed to determine the impact these layers might have on both the time that leakage might occur and the likely leakage rates.

A new laboratory activity has commenced at Princeton to model cement degradation (the scope of the programme was outlined in a separate presentation by Mileva Radonjic). Once this laboratory work is complete the data will be incorporated into the analytical model.

---

[15] The Viking aquifer is one of the higher aquifers in the sedimentary succession in the Alberta basin and is likely to be a prime candidate for CO_2 storage.

Regulation and Public Perception

Two presentations covered the issues of public perception and regulation. The first presentation reviewed the results of a survey on CO_2 capture and storage (CCS) in the UK undertaken by the Tyndall Centre[16]. The study indicated that CCS had limited support as a stand alone option. In contrast, support for renewable energy sources and energy efficiency was high, whilst support for nuclear power was limited. With regard to CCS, the survey indicated that it was not clear to the people involved what the benefits to the economy and public are from CCS. In this instance CO_2-EOR was viewed more favorably than straight storage because it was perceived that the CO_2 was being put to use. One major concern raised was the current inability of experts to answer questions concerning the risks associated with CCS. One of the key conclusions was that a process to engage the public in the UK on the potential impacts of climate change and the benefits of CCS are needed. Any engagement should include details on the risk associated with CO_2 storage.

David Keith felt that it is possible, in principle, to analyse the effectiveness of a specific storage project and to analyse the expected effectiveness of an ensemble of storage projects providing these sites adhere to specific design guidelines that specify site selection criteria and parameters such as capacity, seal integrity, injection depth and well closure technologies. Regulations for CCS are important to ensure that storage projects are selected that ensure that reservoir effectiveness is maximised. However he felt that setting a standard should not be attempted just because early work on risk assessment makes it seem attainable. He raised a concern that in probabilistic risk analysis is that it is hard to estimate the uncertainty in any uncertainty and even in the core physical sciences, experts generally underestimate uncertainty. He also cautioned that we should be wary of building a process that makes stakeholders expect a full PRA if it is not possible to deliver one. Transparency is vital as the first large-scale projects may well have enormous public visibility for two reasons: firstly concern about local risks and secondly concerns about the broader issues of fossil fuel use and climate change.

3.2 Review of Breakout group activities.

Four breakout groups were formed after the presentations to review the status of the topics covered. The four breakout groups were:

1 FEP databases,
2 Status of risk assessment studies,
3 Implications of seepage,
4 Engaging stakeholders.

Each breakout group were invited to consider a set of questions posed by the organisers. The questions posed are listed in Table 2.

---

[16] The purpose of the Tyndall Centre is to research, assess and communicate from a distinct trans-disciplinary perspective the options to mitigate, and the necessities to adapt to, climate change, and to integrate these into the global, national and local contexts of sustainable development.

Table 2   Questions Posed to Breakout Groups

Breakout Group 1 FEP Databases	Breakout Group 2 Status of risk assessment studies	Breakout Group 3 Implications of seepage	Breakout Group 4 Engaging stakeholders

Questions posed:
• What is the status of the generic database?
• What are the steps towards completion?
• How will it become an accepted auditable resource?
• Who are the stakeholders?
• When will it be available for publication on the IEA GHG web site?
• What maintenance may be required?
	Questions posed:
	• Technical gaps (Tools, scenarios, documentation etc) in the existing studies and how these can be addressed?
	• Options for taking risk assessment process forward?
	• How do we reconcile learning's from different studies?
	• Is benchmarking of tools the next step?
	• What are the components of a Benchmarking process?
	• What data is needed to benchmark tools?
	• What data do we have and what more is needed?
	• How do we bring in the lessons from analogue studies?
		Questions posed:
		• Do we understand all the leakage pathways?
		• Are their gaps in our knowledge and how do we address them?
		• Do we know the likely leakage rates?
		• If not what more needs to be done?
		• Do we understand the impacts of leakage?
		   o Onshore
		   o Shallow marine environment
		• Have we identified all the current studies in this area?
			Questions posed:
			• Who are the key stakeholders and what role does Risk Analysis have in engagement?
			• How are current stakeholder engagement activities working?
			• Should current activities be extended?
			• How much do they need to be extended?
			• What is the current level of confidence in the Risk Assessment results?
			• What needs to be done to increase confidence – do we need a standard?
			• How can the results of Risk Assessment studies be best passed on to the policy makers?
			• What results do policy makers wish to see?

Feedback by the breakout groups on the questions posed and others issues they considered important were then presented to the assembled experts.

The responses to the questions posed and other issues raised are summarised below:

Breakout Group 1 – FEP Databases

The development of the generic FEP database by the Weyburn project is now complete. This database will be hosted on the Quintessa home site and a link established through IEA GHG's www.co2sequestration.info web site for general use of the database. Alignment of the Quintessa and NITG-TNO data bases will begin in May 2004. It is planned that the composite generic FEP database will be available after GHGT-7 and will be linked from the www.co2sequestration.info web site. It is proposed to change the name from FEP's to Generic Performance Factors. The data base will remain on the Quintessa server and will be maintained by them. Funding for continued maintenance will be required. To make the database an accepted auditable resource Quintessa plan a peer review exercise that would be undertaken prior to the full generic data base being made public.

Breakout Group 2 - Status of risk assessment studies

The group considered that PRA is a good discussion tool within the technical community. However, it is not a transparent process and therefore may not hold up well to hostile questioning. As far as PRA is concerned the framework to do it is there but there is insufficient data on the geological system to allow risk to be framed with confidence.

The group themselves posed two questions:

1) Whether we currently have the knowledge and confidence to model a scenario for the time scales of interest (possibly 1,000's of years)?
2) Do not have a clear goal, are we looking to store for 99.99% of what has been injected for 1000 years?

Technical gaps identified include:

- A lack of knowledge on processes that could naturally mitigate leakage,
- A lack of well documented worst cases which could also leakage to be modelled as well as containment,
- We have a problem in understanding the physics of some release pathways (e.g. wells and faults) and currently a lack of data to close the gap.

It was noted that Faults have not been addressed in the numerical modelling work yet and were not discussed at this meeting.

To take the process forward it was considered that there are a range of options. Currently we have detailed numerical models but a lack of data to populate them.

Data on geochemistry faults and well failure analyses need to be incorporated into the numerical models to move forward. Alternately, we have analytical models that can model wells in simple ways. The issue then becomes which of these types of model should be focused on for further development. Whichever route is chosen, detailed simulations of well bore system leakage is urgently needed to develop an understanding of the physical processes that will occur and the range of variables that need to be considered.

As far as benchmarking is concerned, it is recognised that we need such a process but it was questioned whether the models we currently have are sufficiently developed to justify inclusion in a benchmarking exercise. A benchmarking activity was attempted by LBNL; they used a simplified test case to assess the capabilities of different models. Such an exercise will give some answers but the value of the results can be questioned. It was felt that benchmarking of whole models at this stage might be counter productive and restrict the development of the models. However benchmarking of problems like well bore leakage might be a way forward. To do such an exercise will need a common case but we do not have the data yet for wells. Weyburn has attempted a benchmarking exercise using simplified boundary conditions the exercise has served to highlight the problems and issues inherent in such an exercise.

Breakout Group 3 - Implications of seepage

The group concluded that the leakage pathways were understood but the processes that define leakage along these pathways were not clearly understood. It was acknowledged that there were gaps in our knowledge in this area and that as a first step it might be appropriate to do a gap analysis to determine which the key gaps that need to be addressed are. Such an exercise could be completed using an expert panel or by using process interaction diagrams/interaction matrices and possibly by PRA if we have an appropriate model to use.

Demonstration projects also provide useful ways to assess gaps providing such projects are fully accessible and have complete monitoring programmes and supporting laboratory programmes to assist in the evaluation of field data. Laboratory testing provides useful input to the models. The idea of a dedicated leakage test facility has been mooted and this could be a good idea. Such a facility would give the opportunity to force leakage and monitor the results.

As far as leakage rates were concerned these were considered to be likely to be site specific and there are a number of different styles of leakage – episodic, dispersed etc.

With regard to the issues of understanding the impact of leakage the group broke this into two features. First, the impacts of leakage on climate change and second the impacts of leakage on health and safety. In the former case, we understand the impact that leakage will have; and the impact is the same whether the leakage occurs onshore and offshore. However, in the latter case, onshore and offshore leakage will have different impacts. In the onshore case we have data on the impacts of leakage on humans and plants, whilst the effects on farm animals are less well known. Offshore

we have limited data on the effects of dispersed leakage on shallow marine ecosystems and industry such as commercial fishing.

It was felt that not all studies that could feed into this subject area had been identified.

Breakout Group 4   Engaging stakeholders

The group indicated that there are a range of stakeholders that need to be considered, ranging from protagonists to antagonists, all of which will need to be convinced of the safety of CCS. The way the different stakeholders are engaged will require different strategies. It was felt that a policy of engagement on the higher level issue of the strategic role of CCS with key stakeholders and policy makers should be actively underway now. A similar exercise should be considered with the general public but it is acknowledged that there are resource issues here for most organisations.

As CCS projects move closer to the market place, there will be more site specific risk assessments and local antagonists and the general public will no doubt become more closely involved. Again, it is felt that there is a need to begin this process but that this should proceed incrementally as information becomes available. To move forward one could consider setting up an advisory group with key stakeholders and specialists that could assist the dialogue process, by assessing the key public perception issues and how one could proceed to address them. In all cases there will be a need for transparency in the dialogue process.

3.3   Review of issues raised in general discussion

A number of additional issues were raised in the discussion periods that have been summarised below:

Terminology	- There was an extensive debate within the group on the definition of leakage, for the purposes of the meeting this was defined as the passage of gas to the surface from a storage reservoir. It was noted that seepage is often quoted in the literature and migration is a term often used to describe movement of CO_2 outside of the reservoir. There is a need to ensure that the terminology used is consistent so as not to confuse the stakeholders and public.
Which leaks are most important	- Large leaks such as fractures from a pipeline or a well failure are likely to be readily detected by monitoring systems or operators. Remediation procedures will be put in place quickly to shut such leaks down. Small dispersed leaks will not be noticed or detected as readily and it could be that these represent a greater risk because they involve a slow build

up of gas in a building or depression in the ground.

- The general public will be more worried about impacts (i.e. how it will affect them directly) than probabilities of a risk occurring. Probability is a scientific concept that they may not grasp or may be suspicious of.

Onshore versus offshore storage	- Offshore storage might be more acceptable in this respect because the risks to the human population are much lower, although the costs of remediating leakage offshore will be higher.
Well bore integrity	- The Underground Injection Control (UIC) programme in the USA requires operators to identify abandoned wells and go back in and plug them if there is considered to be a risk of leakage. The UIC programme could act as a regulatory analogue for CCS. It was also noted that the UIC programme only requires monitoring of injection wells not abandoned wells. In addition reference was made to a case study in Texas where only half the abandoned wells could be identified, but injection still went ahead because the operator had made best efforts to identify them.
	- The Alberta Energy and Utilities Board recognised the problem with abandoned wells and had set in motion a funded programme to rehabilitate old wells.
	- The question was raised, how far into the future will we need to consider abandoned wells to be an issue? The question is similar to one that was posed throughout the meeting namely how long do you need to monitor for?
	- Another question posed was, could we study a leaking well as a case study? However, it was noted that field operators in North America did not always acknowledge that wells leaked and were not always amenable to monitoring at sites for business reasons.
Natural analogues	- Studies on natural analogues can provide data on faults and impacts of leakage. How this data can best be incorporated into the models was questioned. Could a leaky field we used as a test case for a risk assessment model?
	- One opinion was that natural analogues could be used for consequence analysis but not in a PRA.

	- Concern was raised about comparing natural analogues with CO_2-EOR projects because the geochemistry could be different.
Liability	- The issue of who would be liable for the stored CO_2 in the future was raised on several occasions. It was mooted that the operator would be responsible until the abandonment then, after a period, the national Governments may take on the responsibility.
	- Procedures could be put in place for regular well work-overs after abandonment. The costs for such work-overs are considered to be small. A project developer could be required to take out an insurance policy or indemnity bond to cover the cost of monitoring the abandoned wells and future work-overs after abandonment. The question of the duration that monitoring was needed was again raised again and the length of time insurance would have to cover. Perhaps this only needed to be for 50 years after abandonment, after which liability reverts to national governments?
Industrial analogues	- What modelling tools are used for natural gas projects? Such have a commercial interest in assuring no leakage
	- The question was posed whether the well documented release form the Hutchison natural gas storage reservoir in Kansas could be modelled as an analogue for leakage?
Target setting	- We must be cautious about setting arbitrary targets like 1% leakage in 1000 years that might not be attainable. Targets must be well considered so that we do not become hostages to fortune in the future.
Message conveyance	- There is a need to consider the key messages that need to be conveyed and to whom. The development of the key messages might be best covered by specialist communicators rather than the technical community.
	- Messages should aim to convey confidence and not be alarmist. There is a danger that messages from some simulation work could be taken out of context by antagonistic elements. Also care must be exercised in using analogies to avoid giving the wrong message by accident.

4.   CONCLUSIONS

The following key conclusions can be drawn from the workshop:

Scenario and risk assessment model status.

1.   Work on risk identification and scenario analysis is now largely complete. The next stage in the process for the risk assessment activities is to put a generic data base on an open web site so that they can be used by project developers. Through its use the database of qualitative risk factors, or FEPs, can be further developed as a risk assessment tool.

2.   Two different risk assessment modelling approaches are being tested currently. The first approach uses a simpler analytical modelling approach whilst the second uses a numerical modelling approach. The simpler analytical approach allows for a more rapid analysis of leakage issues but in many cases initial results are based on assumptions rather than actual data. The assumptions drawn must therefore be treated with some caution until the models are populated with data on leakage pathway issues such as: fracture permeability and well bore permeability. Numerical models are more detailed in their approach but require extensive data sets on the geological formation; however they can be limited because they do not readily consider issues such as geochemical reactions within the reservoir and well bore leakage. The common factor to both approaches is that we currently do not have sufficient knowledge and data on all potential leakage pathways to populate these models to allow comprehensive assessments of the risk of leakage by all pathways from a geological reservoir to be undertaken.

3.   New models are being developed but these require testing against known data sets; however at present the number of data sets available is limited.

4.   Benchmarking of the various risk assessment models was considered to be desirable. It is felt that currently the models need further development and refinement before benchmarking can occur. Also, currently there are only a limited number of data sets that can be used in any benchmarking exercise and the accessibility of these data sets needs to be reviewed. An iterative process involving the testing of different models on specific issues such as well bore leakage could be considered once the leakage pathways and processes determining leakage by such routes are fully understood.

Qualititative or probabilistic modelling

5.   Currently most of the modelling activity undertaken has involved a qualititative assessment of the risks of leakage. There are concerns within the expert community that probabilities cannot currently be assigned to leakage events from a geological storage formation with any degree of certainty due to our limited understanding of the storage system. If probabilities are assigned based

on assumptions alone the uncertainties in the numbers generated could undermine the credibility of the risk assessment results.

The need for transparency in the modelling process

6.   There is general agreement that the risk assessment process needs to be as transparent as possible. Detailed modelling could be less transparent than other risk assessment approaches that use expert panels to assess risk factors and consider the likelihood of leakage occurring.

Long term storage assessments

7.   Only two detailed case studies have been undertaken to date, both on oil fields. The first was based on a conceptual case of CO_2 injection into the Forties oil field in the North Sea, whilst the second was based on the on-going CO_2-EOR project at the Weyburn oil field in Canada. Both studies have indicated that the risks of leakage occurring from the geological storage reservoir are negligible. The area of most concern with regard to leakage was identified as well bores.

8.   There is currently considerable uncertainty over the leakage potential from wells. For mature onshore oil fields like the Weyburn field and the Alberta basin there are thousands of wells that penetrate the bounding seals of potential storage reservoirs. Many of these wells have been abandoned and there are uncertainties concerning their abandonment status (e.g. how they have been abandoned and the status of their casing and packing materials). In the North Sea the number of wells drilled in a mature oil field like Forties is much less than onshore, numbering only hundreds. However any detailed assessment of risk for a storage system must include a thorough assessment of the status of wells and their potential to leak not only during the injection operation but also potentially for hundred to thousands of years after injection has ceased.

Impacts of leakage

9.   The main potential leakage pathways from geological storage reservoirs have been identified. However, the processes that control leakage along many of the key pathways (e.g. faults and well bores) are not yet fully understood.

10.   The impacts of leakage onshore are fairly well understood. The magnitude of leakage rates that cause ecosystem damage is known from studies of natural leakage (e.g. volcanoes and natural analogues). The impacts of leakage on the human population are understood and it is clear that some people will be more susceptible to raised CO_2 levels in the workplace and hence safety levels must be set to protect these more susceptible individuals.

11.   The impacts of leakage offshore are not understood.

Stakeholder engagement

12.   The current inability to communicate with stakeholders on the risks of storing CO_2 underground is seen as an area that needs to be addressed. Careful thought needs to be given to the limited information that is currently available on the risks of CO_2 leakage and its impacts to determine what positive messages can be drawn currently to begin a process of dialogue with key stakeholders on the risks associated with geological storage of CO_2.

5.   FURTHER RESEARCH NEEDS

A number of key further research needs were identified:

1.   The potential causes of leakage through abandoned wells need to be determined and the processes controlling leakage researched so that well bore leakage can be incorporated into the risk assessment models. It is noted that some research is underway in that area but an assessment needs to be made of the work underway to address any research gaps.

2.   The processes controlling leakage through faults also needs to be researched in depth so that faults can be incorporated into the risk assessment models. Again some work is underway on natural analogues where leakage is occurring and an analysis of this work is needed to identify whether the data obtained can be included within the models or there are further research needs.

3.   Currently information on the impacts of offshore leakage is limited. Research work is needed to identify the potential effects on ecosystems of undersea leakage of CO_2.

6.   NEXT STEPS

The following next steps are planned:

1. IEA GHG will develop its www.Co2sequestration.info web site to include a web page that will facilitate general access by projects to the generic FEP database. During the development of the web site the TNO-NITG and Quintessa databases will be merged to produce a single generic data set for general application.

2. IEA GHG web site will be expanded to host the presentations and the report from the workshop

3. The organisers will consider the need to develop a risk assessment road map to guide the development of research activities in this area.

4. The organisers will consider the establishment of an international network of research groups active in the field of risk assessment. Such a network would plan to meet annually and provide a forum for exchange of information and the latest results in this important research area and co-ordinate future benchmarking exercises.

RISK ASSESSMENT WORKSHOP

ANNEX 1

ATTENDANCE LIST

Table A1   Workshop Attendance List

Name	Affiliation	E-mail
Annika Andersson	Vattenfall Utveckling	annika.andersson@vattenfall.com
Koorosh Asghari	University of Regina	Koorosh.Asghari@uregina.ca
Steve Benbow	Quintessa	stevenbenbow@quintessa.org
Adrian Bowden	URS	adrian_bowden@urscorp.com
Michael Celia	Princeton University	celia@princeton.edu
Rick Chalaturnk	University of Alberta	rjchalaturnyk@ualberta.ca
Charles Christopher	BP	christca@bp.com
Tim Dixon	Future Energy Solutions	Tim.Dixon@dti.gsi.gov.uk
Lars Ingolf Eide	Norsk Hydro ASA	lars.ingolf.eide @hydro.com
Tony Espie	BP	espiet@bp.com
Todd Allyn Flach	Det Norske Veritas	Todd.Flach@dnv.com
John Gale	IEA GHG	johng@ieagreen.demon.co.uk
Neeraj Gupta	Battelle	gupta@battelle.org
Hans Aksel Haugen	Statoil	hakha@statoil.com
Wolf Heidug	Shell	Wolfgang.Heidug@shell.com
Yukio Imaseki	RITE	imaseki@rite.or.jp
Scott Imbus	ChevronTexaco	scott.imbus@chevrontexaco.com
Anhar Karimjee	US EPA	Karimjee.Anhar@epamail.epa.gov
David Keith	Carnegie Mellon Univ.	keith@cmu.edu
Mark Kelley	Battelle	Kelleym@battelle.org
Angela Manancourt	IEA GHG	angela@ieagreen.demon.co.uk
Philip Maul	Quintessa	philipmaul@quintessa.org
Brian Morris	UK DTI	Brian.Moris@dti.gsi.gov.uk
Denis O'Brien	European Commission	Denis.O'Brien@cec.eu.int
Curtis M. Oldenburg	LBNL	Cmoldenburg@lbl.gov
Takashi Ohsumi	RITE	ohsumi@rite.or.jp
Jonathan Pearce	British Geological Survey	jmpe@bgs.ac.uk
Mileva Radonjic	Princeton University	radonjic@princeton.edu
Susan A. Rice	Susan A. Rice and Assoc.	sarice@sara-tox.com
Ipo Ritsema	TNO-NITG	i.ritsema@nitg.tno.nl
Richard Rhudy	EPRI	rrhudy@epri.com
David Savage	Quintessa	davidsavage@quintessa.org
Prasad Saripalli	PNNL	Prasad.Saripalli@pnl.gov
Mike Saunders	BP	saundem@bp.com
Bill Senior	BP	Seniorb@bp.com
Simon Shackley	Tyndall Centre, UMIST	Simon.shackley@umist.ac.uk
Jeroen van der Sluijs	Copernicus Institute	j.p.vandersluijs@chem.uu.nl
Mike Stenhouse	Monitor Scientific	mstenhouse@monitorsci.com
Peter Stollwerk	NOVEM	p.stollwerk@novem.nl
Rickard Svensson	Vattenfall Utveckling AB	rickard.svensson@vattenfall.com
Jesse B. Uzzell	Det Norske Veritas	Jesse.Uzzell@dnv.com
Mark Vendrig	Det Norske Veritas	mark.vendrig@dnv.com
Roy Wikramaratna	ECL Technology Ltd	roy.wikramaratna@ecltechnology.com
Ton Wildenborg	TNO-NITG	a.wildenborg@nitg.tno.nl
Julia West	British Geological Survey	jmwes@bgs.ac.uk
Iain W. Wright	BP	wrightiw@bp.com
Wei Zhou	Monitor Scientific	wzhou@monitorsci.com

Workshop Programme

Programme - Day 1, Wednesday 11th February 2004

Opening Session – Day 1	
Welcome & Safety Briefings Introduction to workshop aims and objectives.	*John Gale, IEA GHG*
Introductory presentation: The risk assessment process and outline of the building blocks.	*Tony Espie, BP*
Session 1 - Risk Identification & Scenario Analyses	
Safety assessment methodology: the scenario approach (SAMCARDS).	*Ipo Ritsema - TNO-NITG*
The development of a generic FEP database for the geological storage of CO_2.	*Philip Maul and Steve Benbow, Quintessa*
Facilitated panel/open discussion on future research needs, agreement of future actions to establish, validate and maintain web based FEP database for future project reference	
Session 2 – Assessing Long-Term Storage Performance	
GEODISC/CO2CRC approach and results.	*Adrian Bowden, URS*
Assessment of the Long-term Fate of CO_2 in the Weyburn Field.	*Mike Stenhouse and Wei Zhou, Monitor Scientific LLC*
NGCAS approach and results.	*Roy Wikramaratna, ECL*
1) a mathematical model for probabilistic risk assessment and 2) risk scenarios pertaining to CO_2 injection and storage in coalbeds.	*Shaochang Wo, INNEL*
Numerical Simulation on Storage and Leakage Behavior of Injected CO_2.	*Yukio Imaseki, RITE*
Facilitated panel/open discussion on approaches adopted. Key issues to be addressed include: • Where are the existing shortfalls? • What additional information is needed and in what form? • What further work is needed to improve performance assessments?	
Session 3 – Impacts of CO_2 Leakage	
Assessment Impacts of Surface leakage of CO_2.	*Prasad Saripalli, Battelle*
The use of SWIFT and QRA in determining risk of leakage from CO2 capture, transport and storage systems.	*Mark Vendrig, DNV*
What can we learn from studies on Natural Analogues?	*Jonathan Pearce, BGS*
Health and Ecological Risk Assessment.	*Susan Rice, Susan A. Rice and Associates, Inc.*
Facilitated panel/open discussion on impacts of CO_2 leakage, where are the gaps in our knowledge and how do we fill them?	

Programme - Day 2, Thursday 12th February 2004

Opening Session - Day 2	
Recap of Day 1 and plan for Day 2.	*John Gale, IEA GHG*
Session 4 – Well bore Seepage and Risk analyses	
Well bore dynamic & leakage studies at the Weyburn project.	*Rick Chalaturnyk, University of Alberta*
Leakage through Existing Wells: Models, Data Analysis, and Laboratory Experiments.	*Mike Celia, Princeton University*
The stability of hydrated cement under CO_2 sequestration conditions	*Mileva Radonjic, Princeton University*
Facilitated panel/open discussion on well bore / cement failure analyses. Questions to address: • What are the shortcomings in the current analyses? e.g. status of theoretical models, input data for modelling, field data • What additional information is needed and in what form? • What further work is needed?	
Session 5 – Benchmarking Performance and Risk Prediction Tools	
Introduction to breakout group activities	
Breakout groups discussions	
Facilitated panel/open discussion on Benchmarking of CO_2 storage performance and risk prediction tools, benefits, process, datasets, timescale, funding etc	
Session 6 – Regulation and Public Perception	
Linking risk assessments to regulation	*David Keith, Carnegie Mellon*
Participatory Planning for CCS: Attempting Rapprochment between divergent agendas and public risk perceptions	*Simon Shackley, UMIST*

Risk Assessment Workshop

DTI Conference Centre, London

11th to 12th February 2004

Risk Assessment Workshop

Safety

- Wear security badges at all times
- Hand it when you leave each day
- Sign attendance list - one for both days

Fire alarm

- Bulletin over PA system
- Leave by Fire Exits – Not lifts
- Exit building and turn right
- Muster on green outside Westminster

Risk Assessment Workshop

Housekeeping

- Tea and coffee outside in foyer

- Buffet lunch outside in foyer

- Dinner this evening at Base One Restaurant
  - Instructions in your delegate pack
  - 7pm for 7.30 sit down

- Issues during meeting contact Angela
  - We will endeavour to help

Risk Assessment Workshop

Workshop aim

- To bring together key international research groups to discuss and critique work underway

Objectives

- Assess current state of progress on risk assessment

- Identify gaps and prioritise further work

- Begin to consider how we might test and validate the various tools

- Consider how best to engage stakeholders to build confidence in the technology

Risk Assessment Workshop

Technical programme

- Intensive programme of technical presentations grouped into key subject areas
    - Risk assessment and scenario analysis
    - Assessing long-term storage performance
    - Impacts of CO_2 leakage
    - Well bore seepage and risk analysis
- Break out groups
    - Benchmarking performance and risk prediction tools
- Panel discussion on engaging stakeholders

Risk Assessment Workshop

Day 1 activities

- Scene setting presentation by Tony Espie, BP
- Three sessions of technical presentations
  - ➤ Sessions 1 and 3 – 20 minute presentations
  - ➤ Session 2 – 30 minute presentations
- After each session we will have a discussion period
  - ➤ No questions during the presentations themselves
- Tight programme
  - ➤ Need speakers to keep to allotted times

Risk Assessment Workshop

Day 1 activities cont'd

- Additional presentation by Susan Rice at end of Session 3 – Impacts of CO_2 Leakage

Risk Assessment for Storage of CO$_2$ in Geologic Formations

Introduction

Context

- Capture and storage of CO_2 in geological formations can offer a material contribution to mitigation of GHG emissions

- IPCC special report on Capture & Storage of CO_2 due for delivery in 2005

- Technical, commercial, acceptance issues to be resolved prior to large scale implementation
  - Cost (primarily of capture and transportation)
  - Performance prediction (duration of storage and risk)
  - Public engagement

IPCC C&S Report

- Initial draft sub-section on Risk Assessment refers to structured process :

  - 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

Status of Risk Assessment

- Identifying key risks and scenarios
  - Good process, close to initial publicly available resource

- Quantifying risks
  - Substantial activity on tool development
  - Initial case studies now becoming available
  - Limited information on impacts e.g. shallow marine environment

- Evaluating risks
  - Limited activity so far
  - Limited interaction with stakeholders so consensus on criteria for acceptance of risk

- Monitoring and Intervention
  - Focus has been on testing technologies and 'over-acquisition' of data rather than long term monitoring strategies

The Challenge

- Performance prediction for sub-surface is inherently uncertain especially for long time frame

  - No direct experience base to calibrate expectations

  - Need to 'reality check' prediction tools

  - Need to compare and contrast tools to understand strengths and weaknesses

  - Need to identify gaps in data and modelling

- Challenge is to design process to validate / benchmark tools

  - Stakeholders

  - Scope

  - Datasets

Risk Assessment Workshop, London, 11 & 12 Feb 2004

Safety Assessment Methodology
- SAMCARDS Scenario Approach

Netherlands Institute of Applied Geoscience TNO
- National Geological Survey

t

Ipo L. Ritsema & Ton Wildenborg

Overview

- **CO$_2$ storage assessment base**

- **Qualitative probabilistic scenario assessment**

- **Quantitative probabilistic scenario assessment**

- **Risk management of geological CO$_2$ storage**

- **Conclusions and acknowledgements**

Major CO$_2$ storage site systems (Features) and risks to biosphere and anthroposphere

CO$_2$ Leakage and Seepage

Ground Tremors and Subsidence

Atmosphere

Hydrosphere

Soil

Fresh water

Water bottom

Overburden

Cap rock

Reservoir
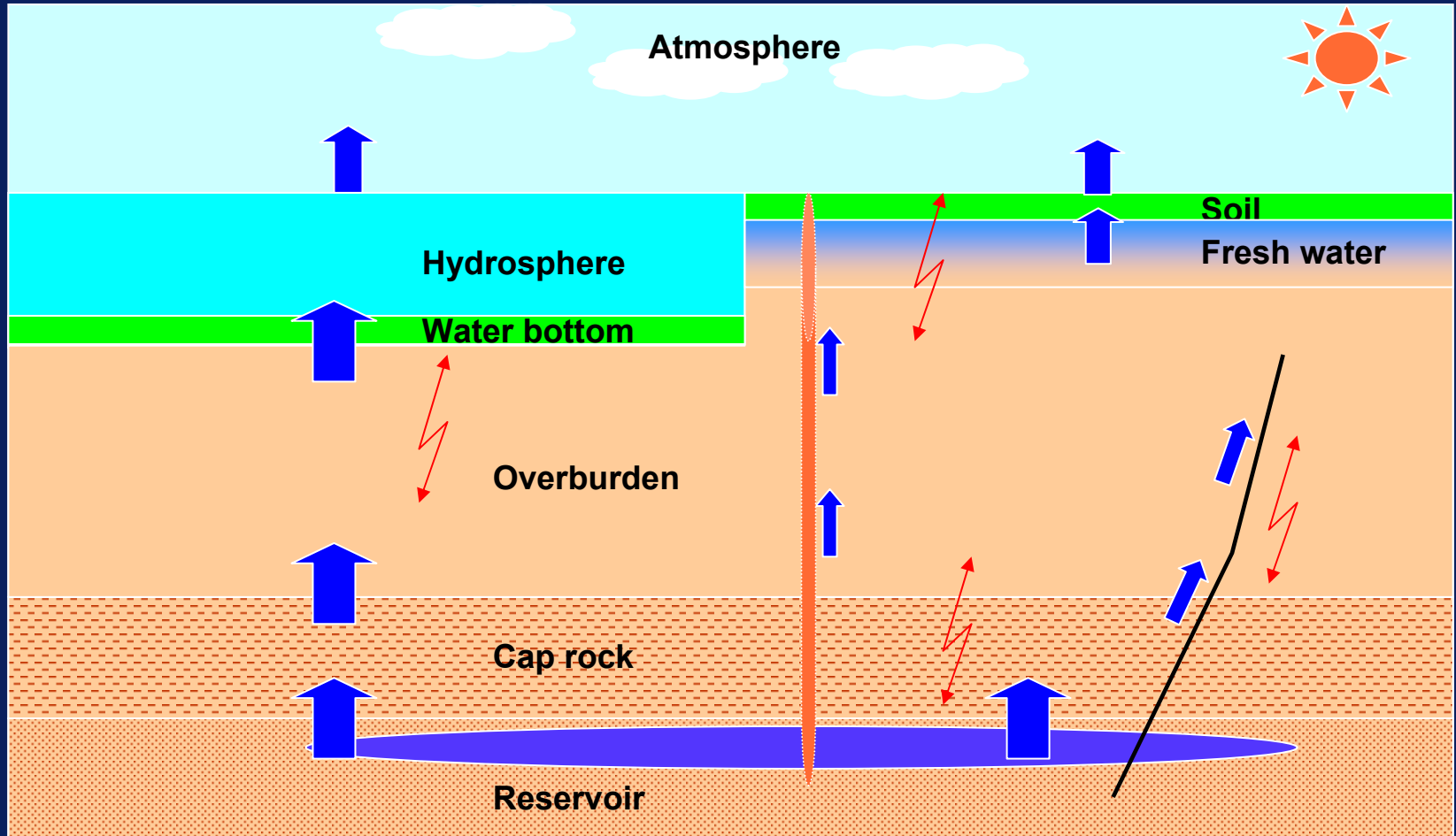
Major Events and Processes of CO_2 systems

- **Coupled F-M-T-C dynamic behaviour in each CO_2 storage system**

CO$_2$ Fluid dynamical processes (F)

CO$_2$ Mechanical processes (M)

CO$_2$ Therm(odynamic)al processes (T)

CO$_2$ Chemical processes (C)

CO$_2$ system
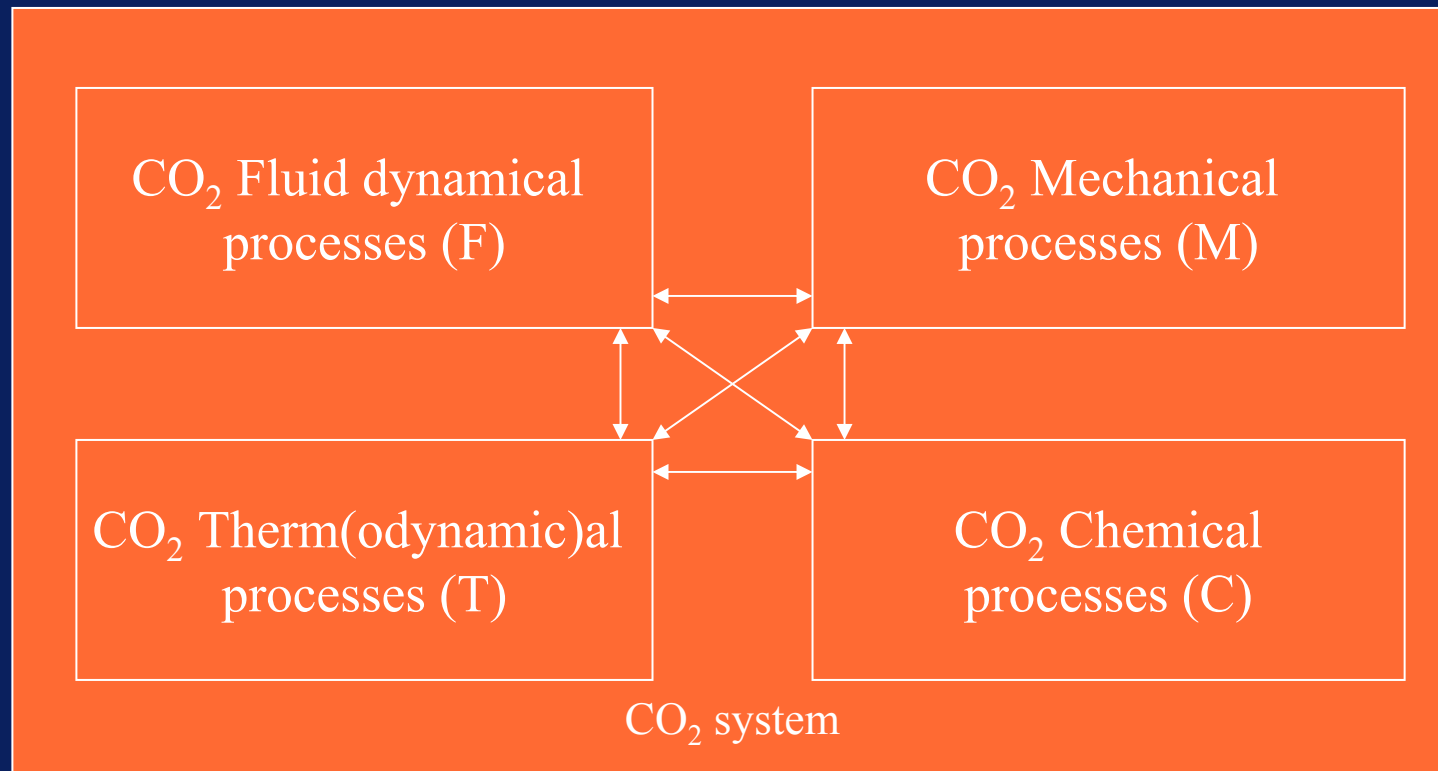
Workflow of scenario approach
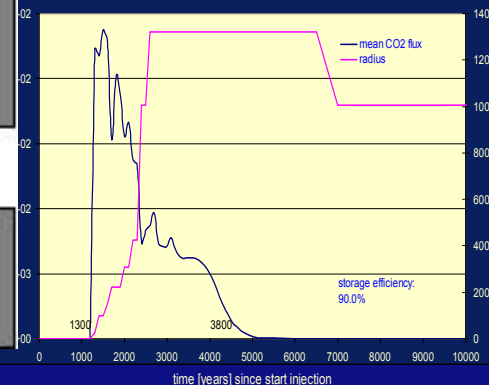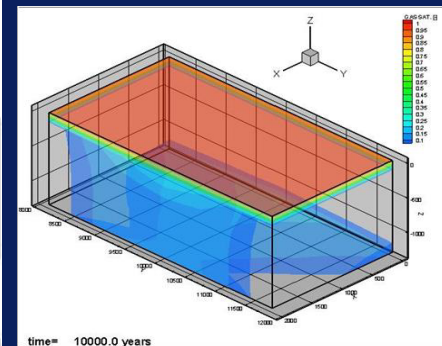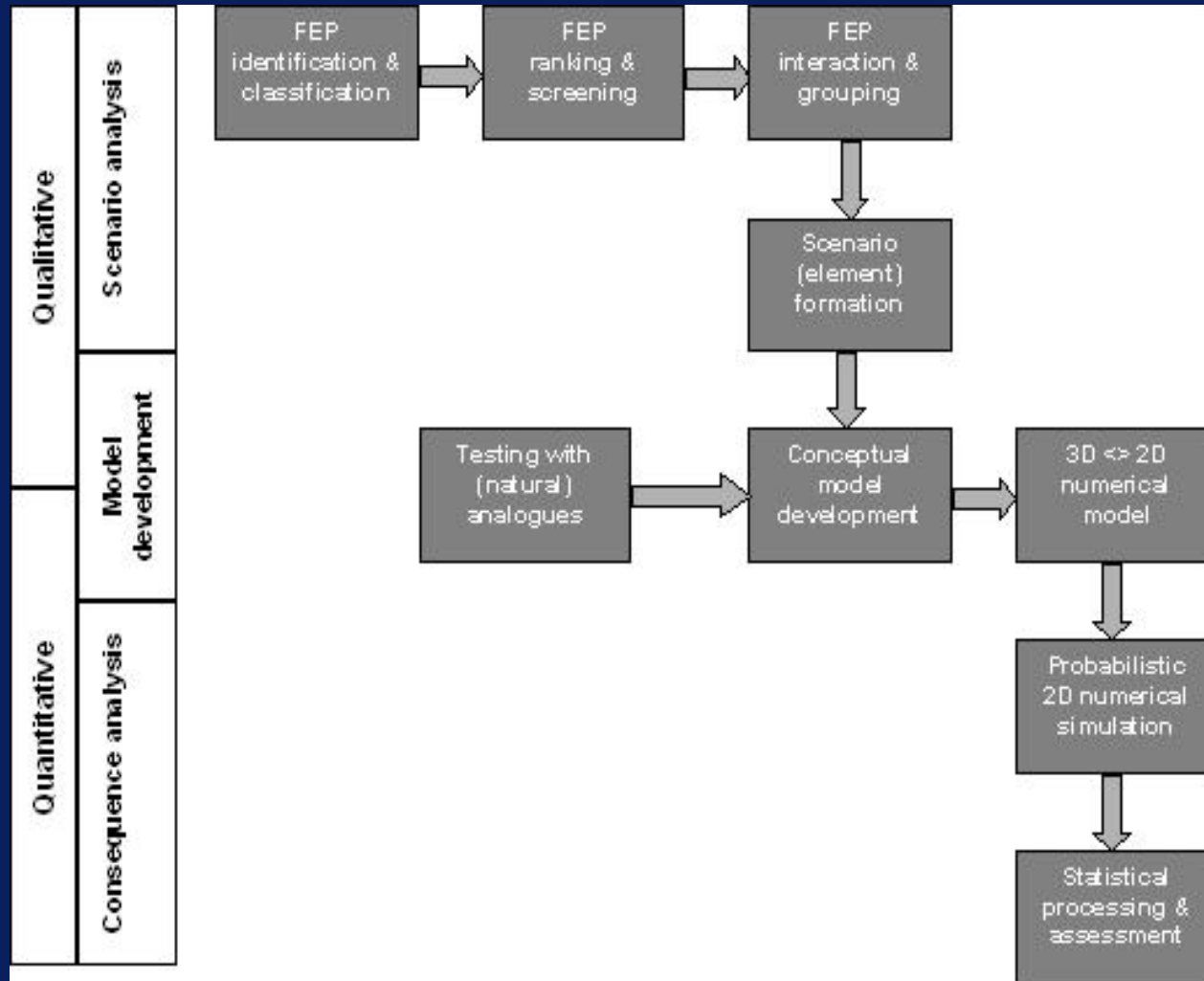
Long term risk assessment methodology

- **Qualitative risk factor identification and classification**
    - System Feature, Event, Process (FEP) database based on expert workshops
    - Structuring and classification based on expert workshops
- **Qualitative selection relevant FEP's and migration scenario's**
    - Ranking of specific FEP's using probabilities of occurrence and impact
    - Definition of migration path scenario's
- **Quantitative model development**
    - CO_2 migration processes models for all subsystems
    - Modelling for complete scenario's
    - Running models probabilistically
- **Quantitative sensitivity analysis**
    - CO_2 concentration and flux in systems and at system boundaries
    - Evaluation CO_2 concentrations and fluxes against norms or baseline CO_2

Qualitative probabilistic scenario approach

FEP identification

FEP classification

FEP selection

Scenario definition and selection

Model concept

Model building

Consequence analysis

PA of key factors

FEP Analysis

Qualitative Scenario Selection

Impact Model Development

Quantitative Impact Modeling
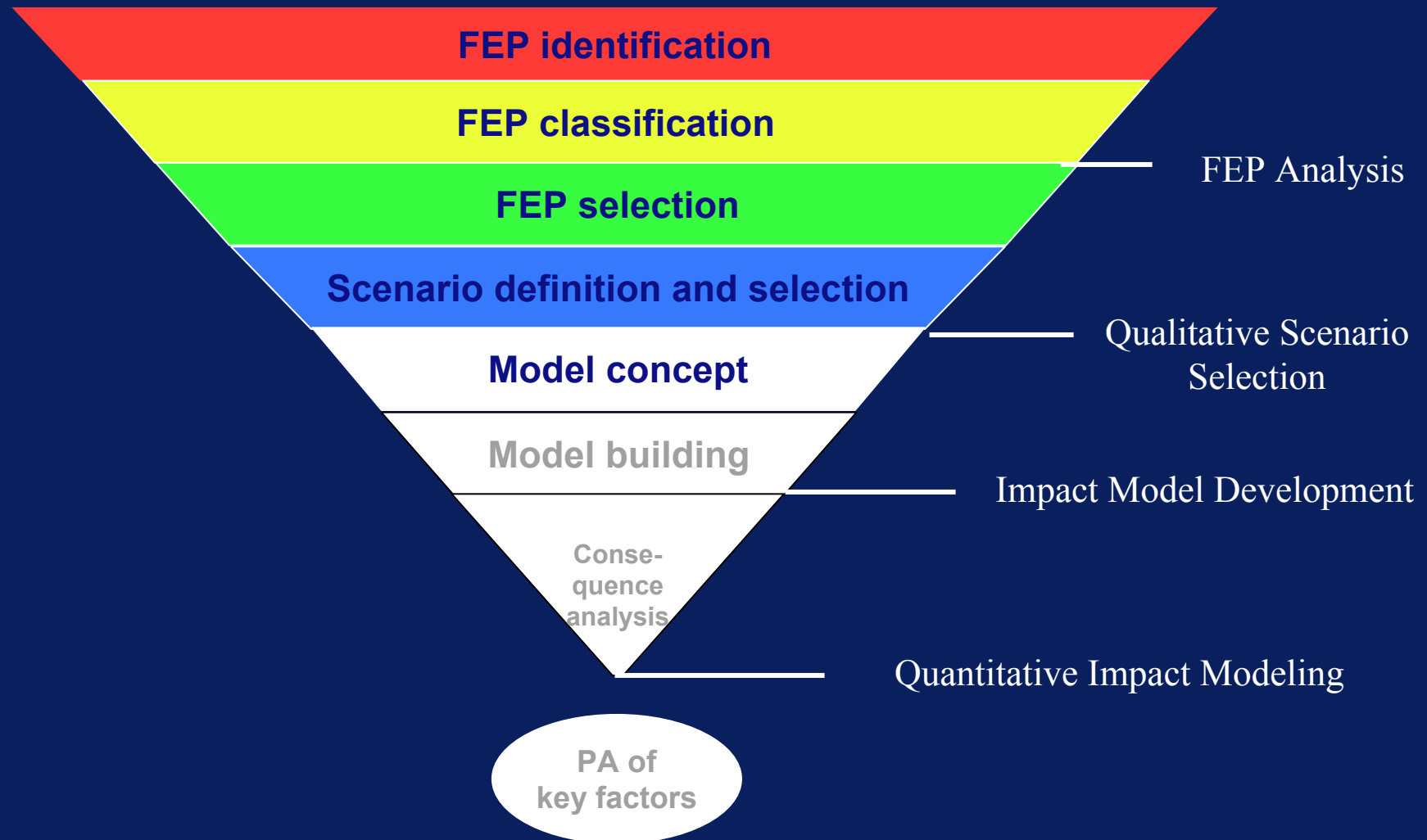
Qualitative probabilistic scenario approach

- **Assessment of all perceived subsurface risk factors for health, safety and environment**

- **Mapping of risk factors into features, events and process classes**

- **Qualitative probability assessment for feps (cause and effect relationship definition)**

- **Ranking and selection of migration scenario's with highest risk value = probability (frequency) * effect**

Risk factor identification in database and Feature, Event, Process (FEP) classification

Qualitative probability assignment to FEP's

FEP interaction identification

FEP interaction diagram

Tree diagram with selected, most probable, scenarios
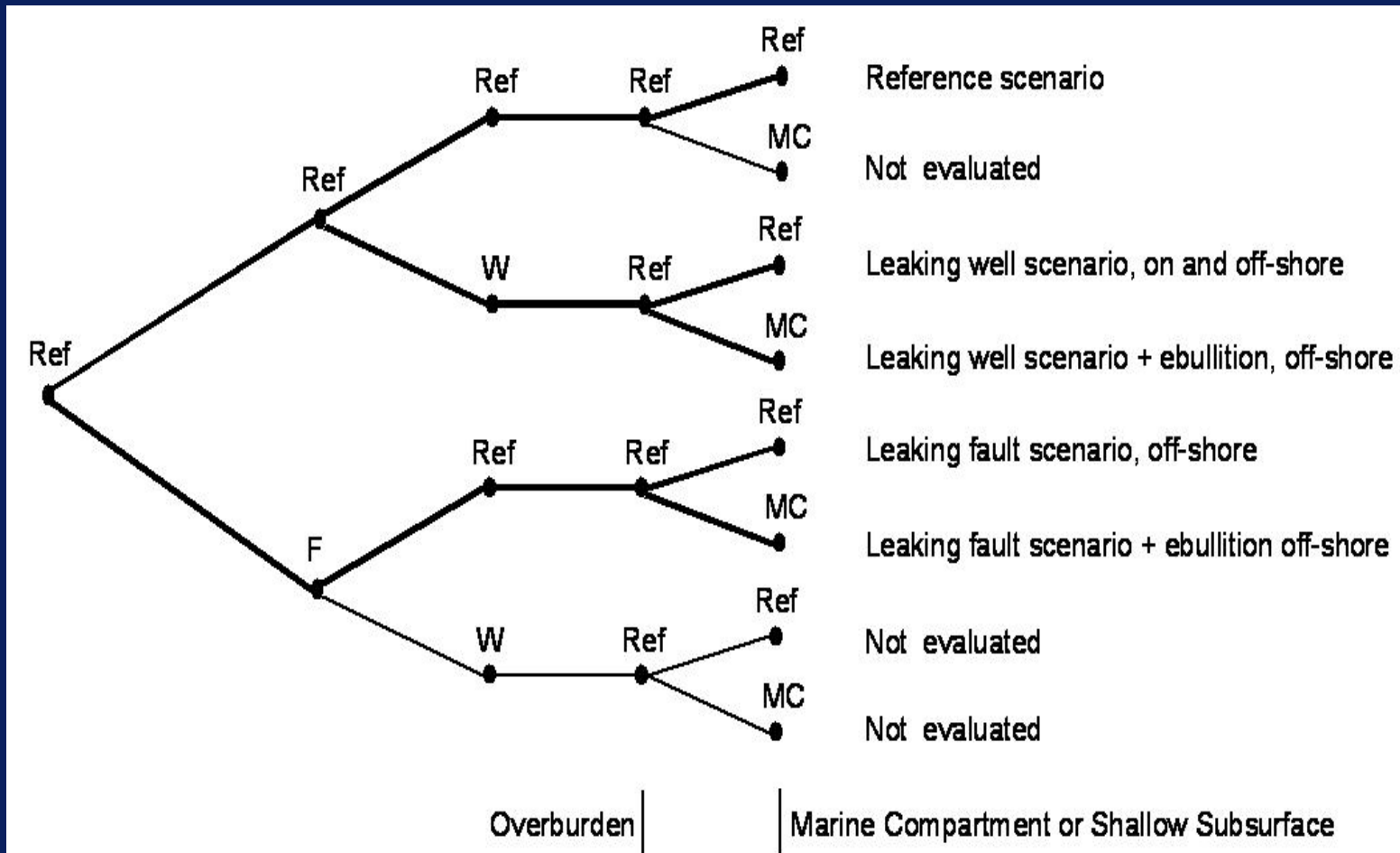
Quantitative probabilistic scenario approach
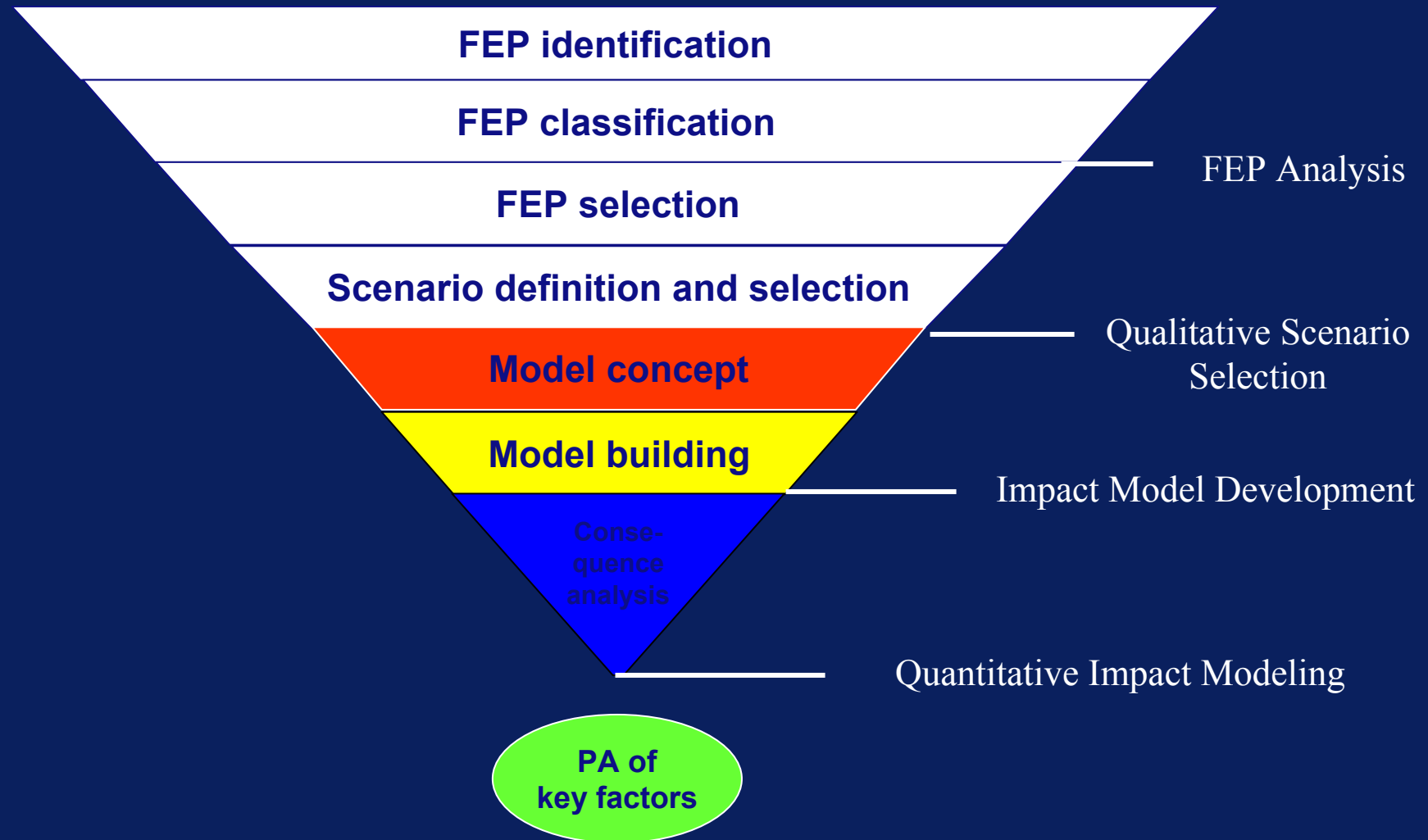
Quantitative probabilistic scenario approach

- **Schematisation of system - features**

- **Application of comprehensive geocientific
  event and process simulation software for calibration
  of impact transfer models**

- **Application of probabilistic transfer models to analyse
  consequences in geosphere, hydroshere, atmoshere
  potentially harming biosphere or anthroposphere**

Risk assessment modelling scheme
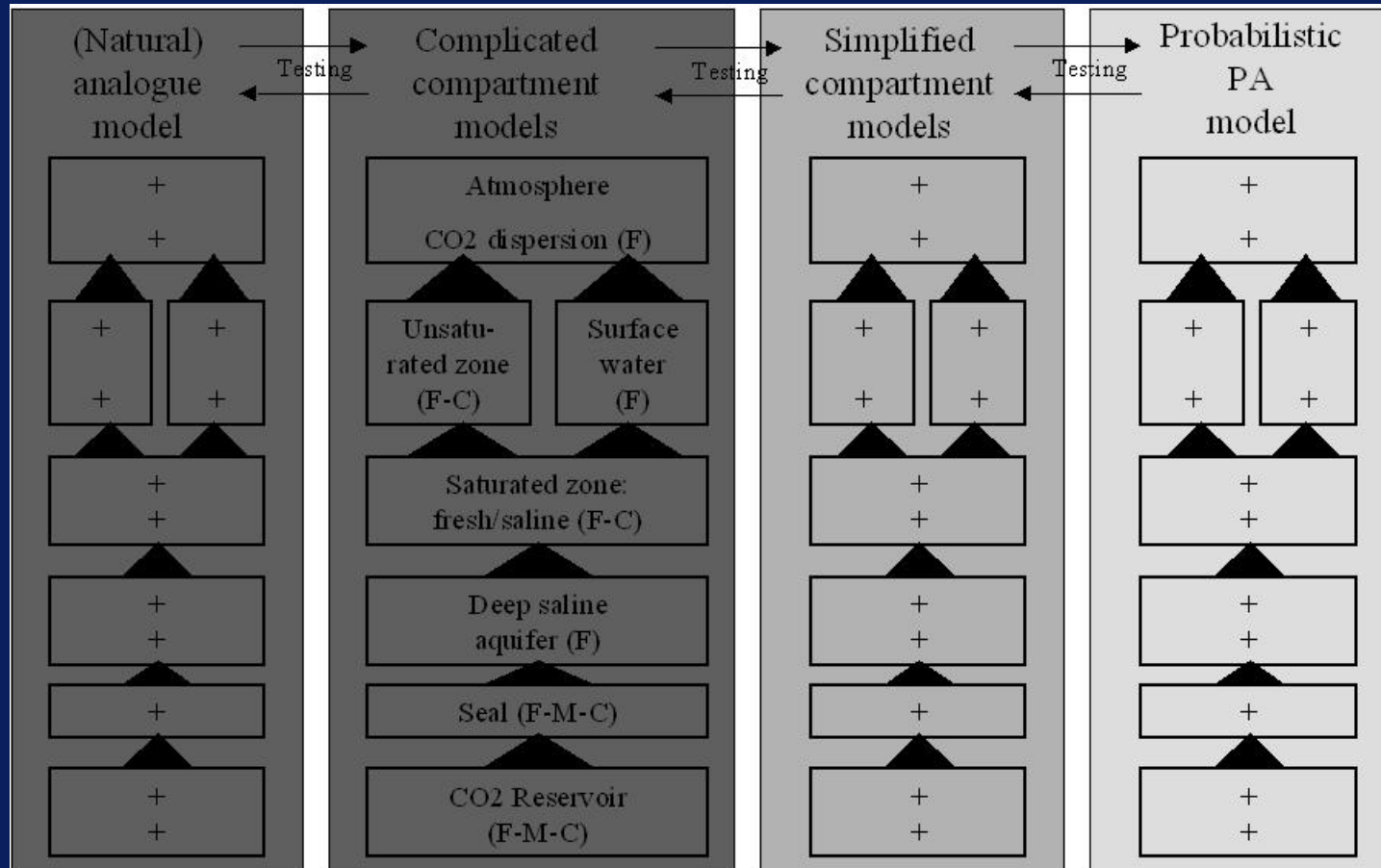
CO$_2$ storage system model codes

Compartment	Mechanical processes	Hydraulic processes	Physico-chemical processes	Marine hydraulic processes	Atmospheric physical processes
Storage reservoir	DIANA	SIMED DIANA	TAFFETAS/ MARTHE		
Cap rock					
Overburden					
Shallow aquifer/soil			STOMP		
Hydrosphere (sea)				DELFT3D	
Atmosphere					PLUME+/ LOTOS/UAM

Cap rock system modeling (TNO)

Finite element model for stress & deformation modeling, fed by reservoir simulator

Predictions
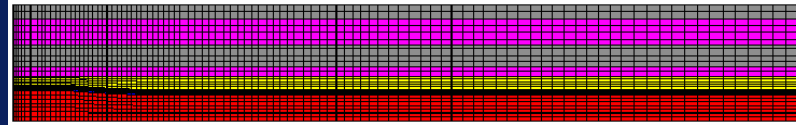
The stress path diagram

Changes in the mean effective stress due to CO2 injection

Seal

Reservoir

Deviatoric stress

Mohr-Coulomb failure lines

Start injection

End injection
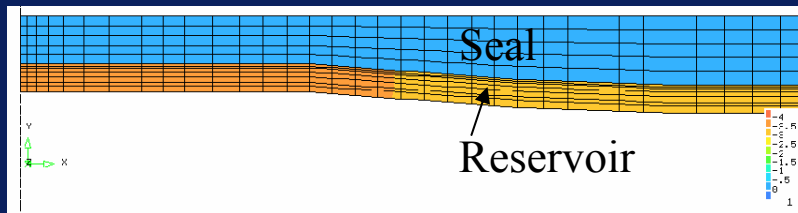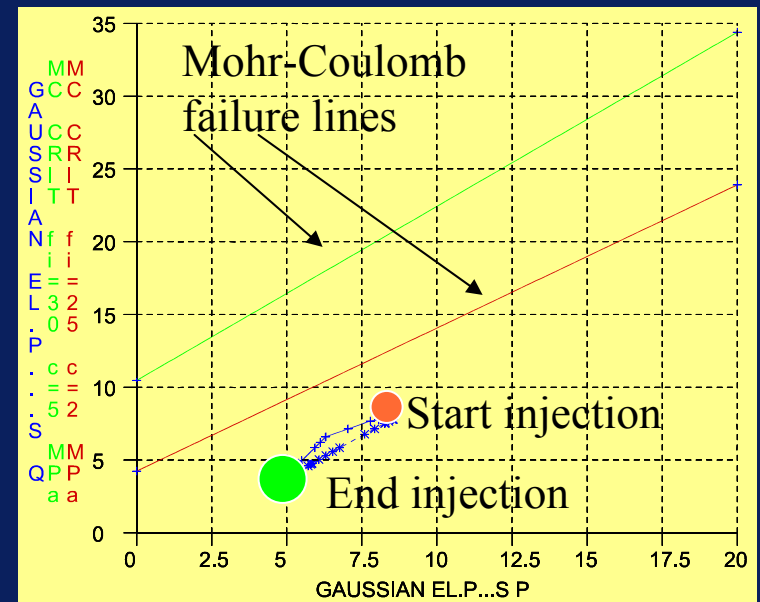
Normal effective stress

Geochemical aquifer system modeling (BRGM)
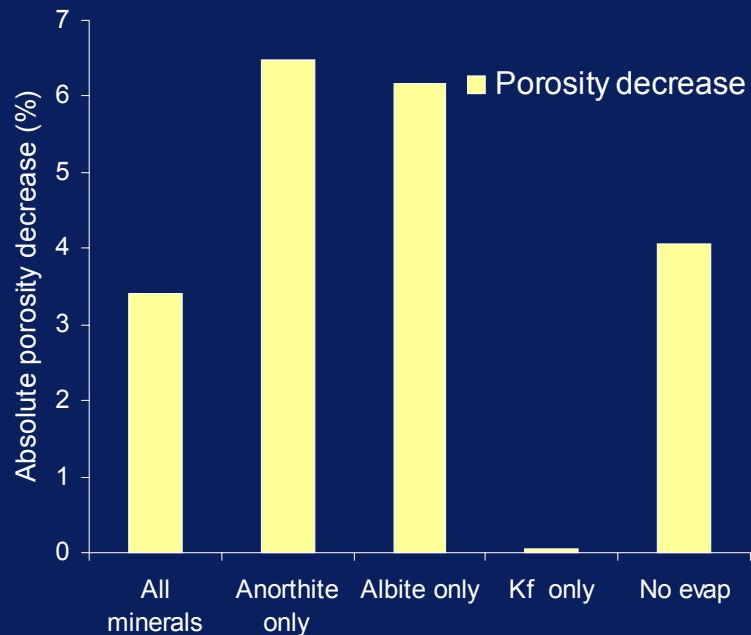
- **Porosity decrease at equilibrium for various feldspar mineralogies**
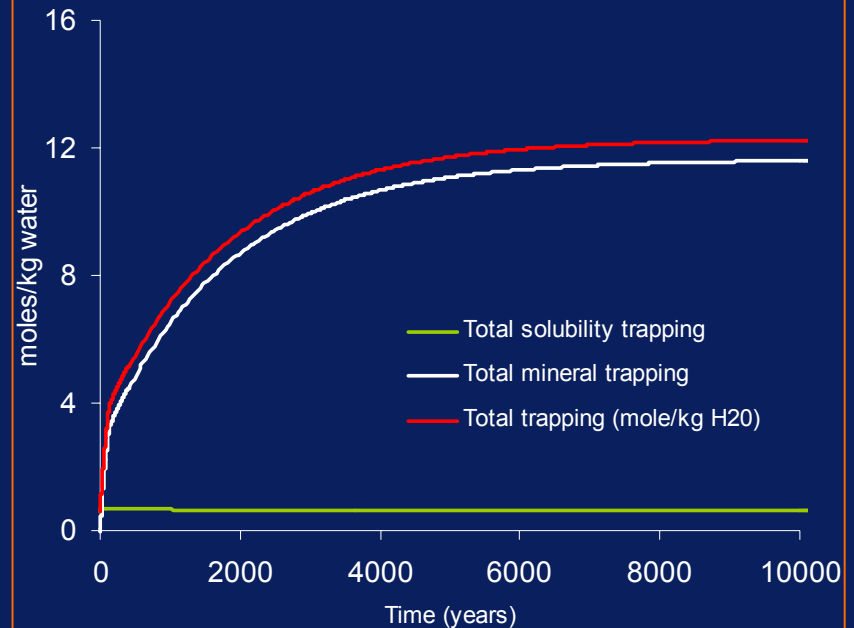
- **Mineral and solubility trapping of CO_2 versus time**

Chapter 4

Reference scenario: A realisation of CO_2 saturation after 10 000 yrs
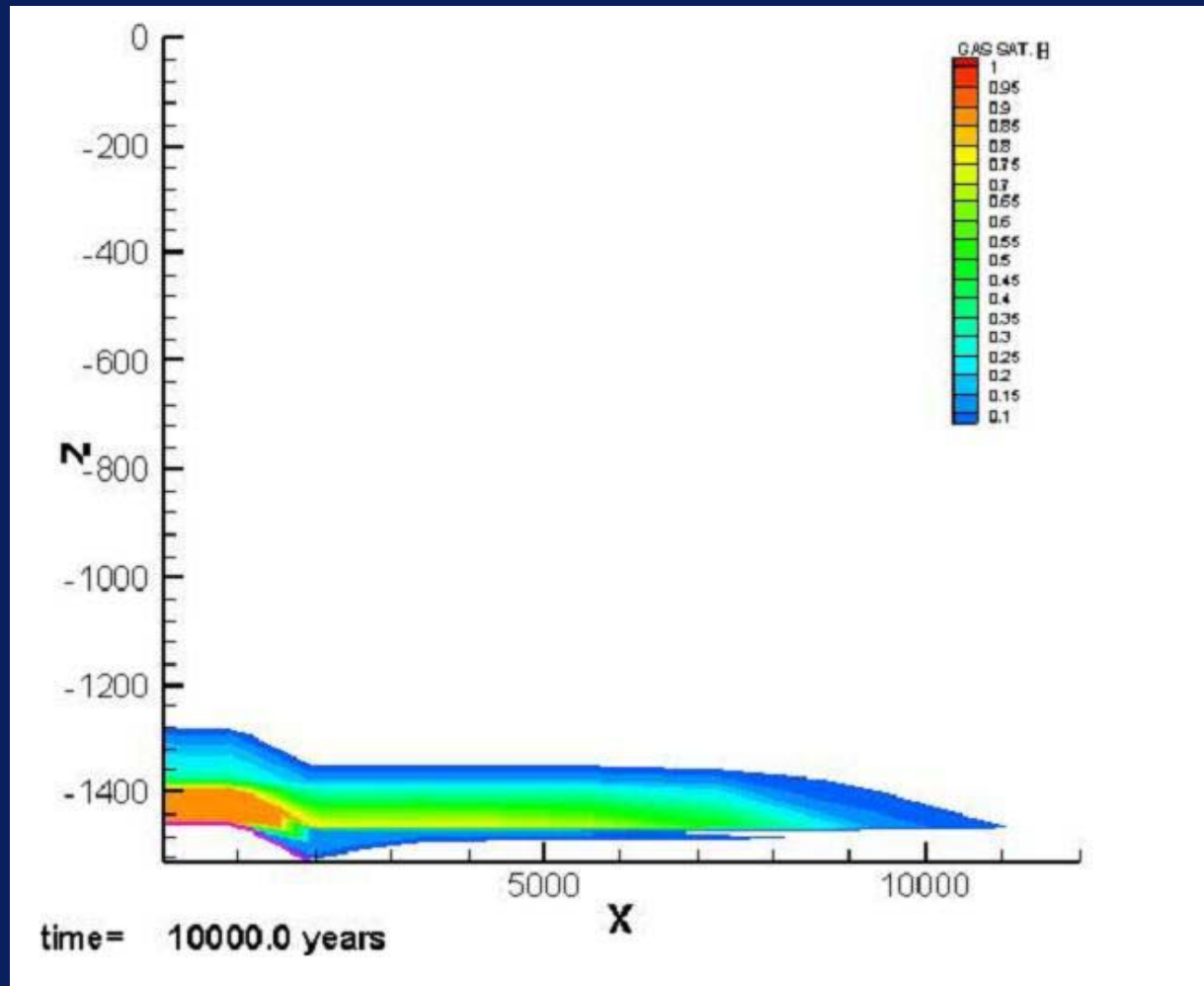
- **100% containment: no CO_2 above seal**

  Part of CO_2 penetrated seal

  No signficant mechanical and chemical effects on seal

  Limited increase of reservoir permeability

Well leakage scenario
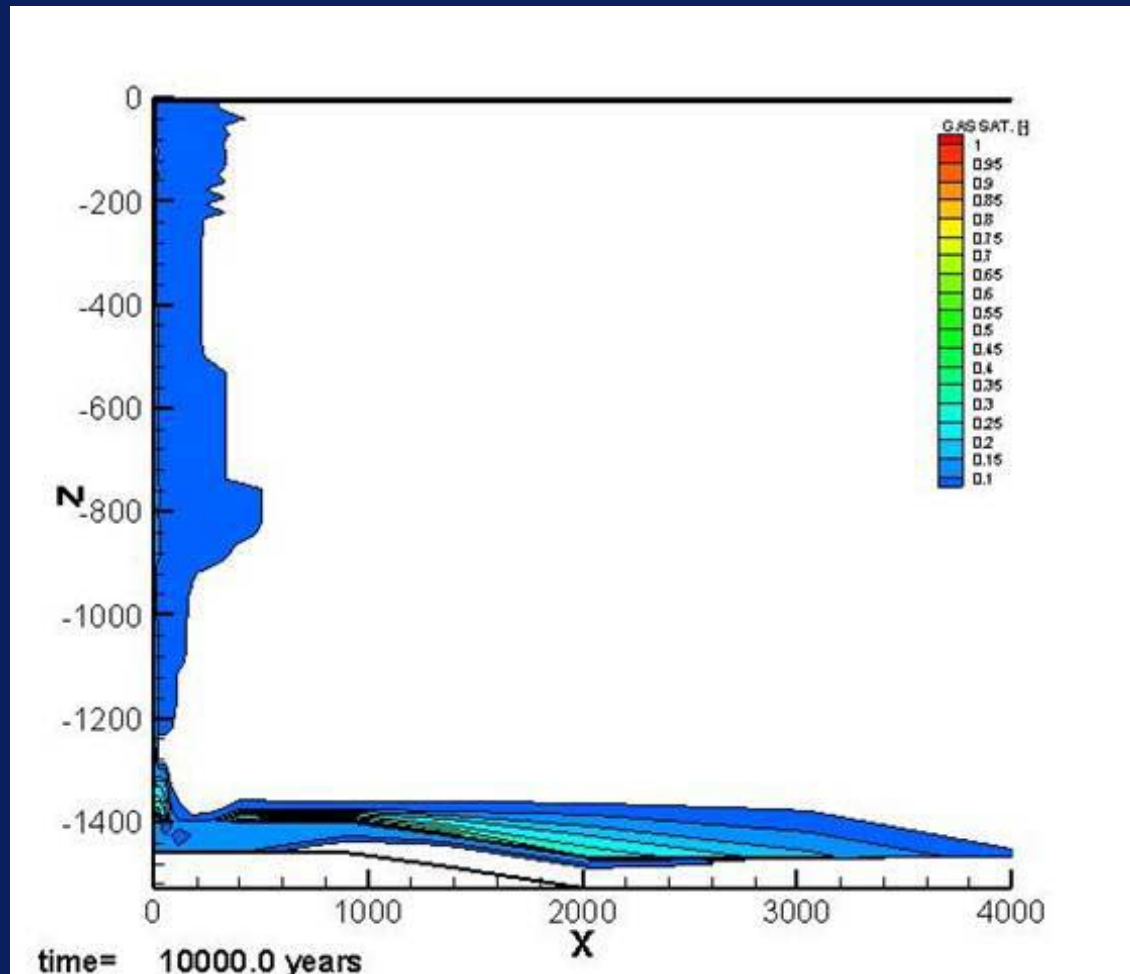
- **Average values at -300 m:**
  23% released from reservoir

  Maximum flux after 1500 years

  Affected area: 0.18 km²

CO$_2$ breakthrough modelling example: at –300 m depth, case: no seal (TNO)
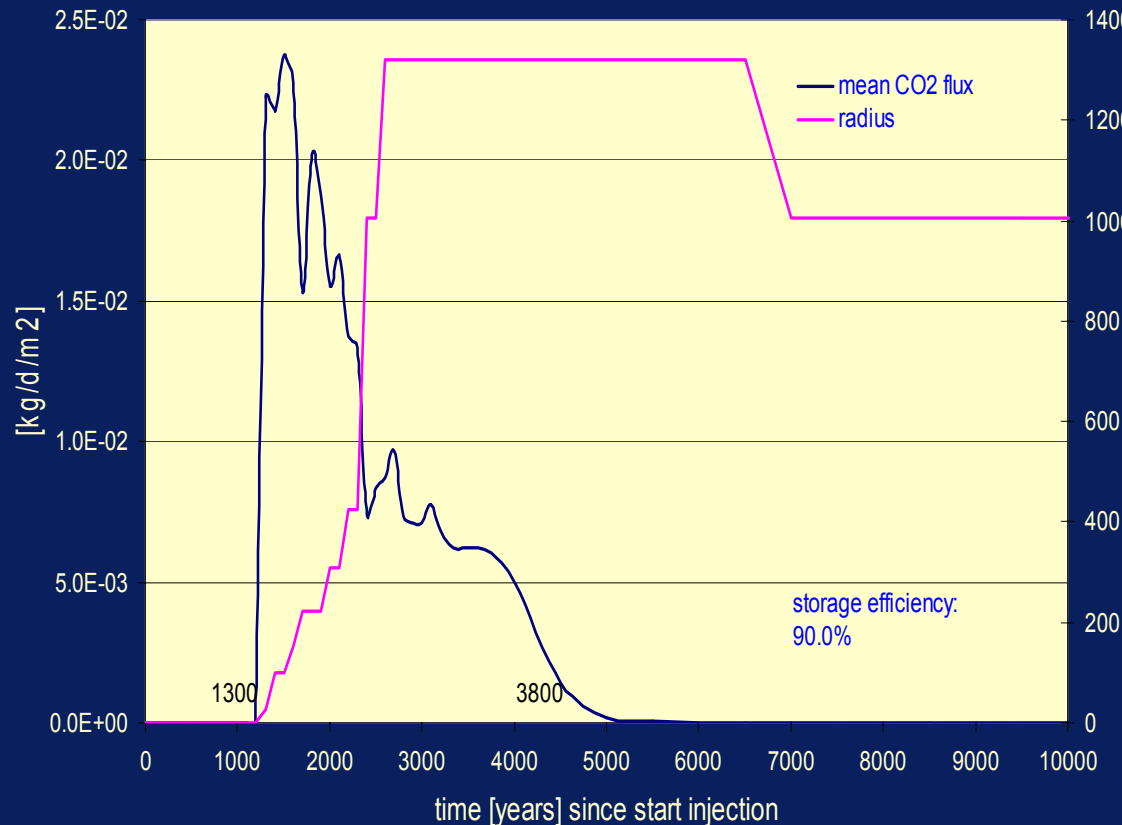
- Break-through concentrated at the injection well location
- Break-through starts after 1,300 years
- Maximum flux is 2.38 * 10^{-2} [kg/d/m2]
- End of break-through after ca. 3,800 years
- Maximum radius of flux area well is ca. 1,300 m
- Only 10 percent of the injected quantity escapes

Fault leakage scenario: CO_2 saturation after 10 000 yrs
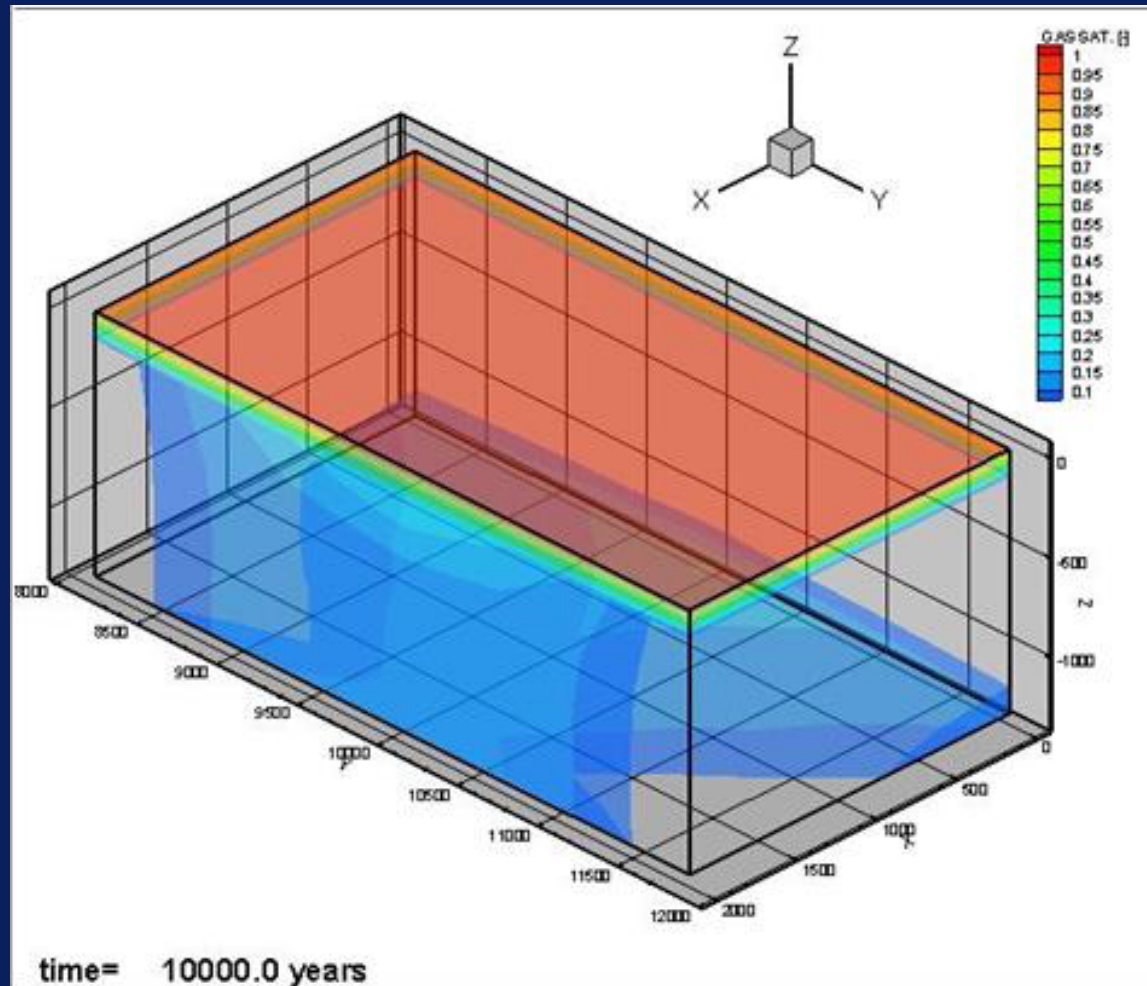
- **Average values at -300 m:**

  0.08% CO_2 released

  Maximum flux after 5500 years

  Affected area: 0.01 km²

Safety indicators as output from the transfer models

Fresh groundwater (LBNL & TNO)	Soil (LBNL & TNO)	Basement constructions (LBNL)	Earth's surface (TNO)	Atmosphere (LBNL)	Sub-seafloor (WL)	Marine hydrosphere (WL)
$[CO_{2gas}]$	$[CO_{2gas}]$	$[CO_{2gas}]$	Seismicity index	$[CO_{2gas}]$	$[CO_{2gas}]$	$[CO_{2gas}]$
$[CO_{2dissolved}]$	$[CO_{2dissolved}]$		Subsidence		$[CO_{2dissolved}]$	$[CO_{2dissolved}]$
Ph	Ph		Uplift		Ph	Ph
Mobility heavy metals						

Mobilisation of heavy metals by CO_2 in aquifer (BRGM)
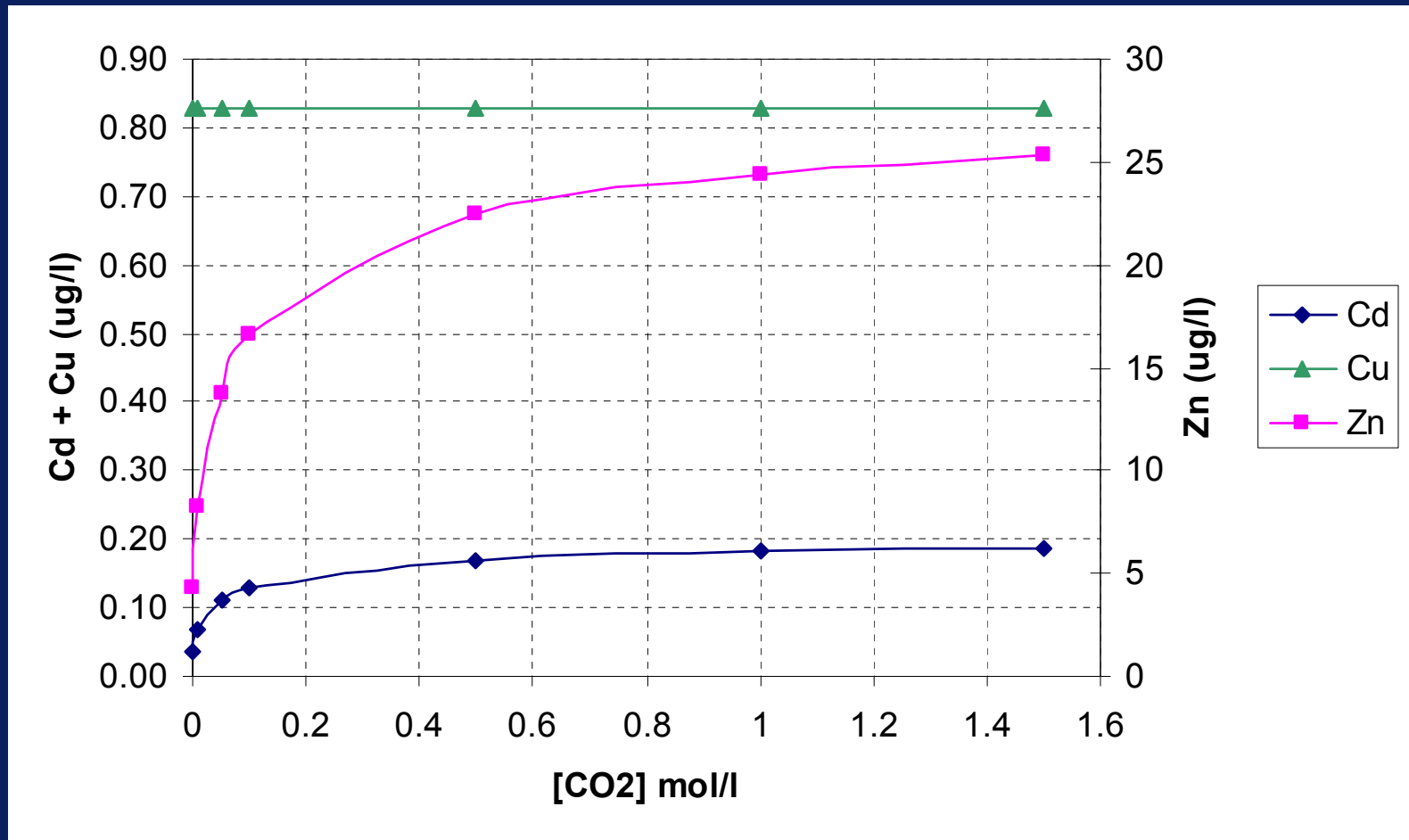
Well leakage scenario indicator distribu-tion: Continental environment (LBNL)

CO_2 molar fraction in gas phase in unsaturated zone at 1 m below surface
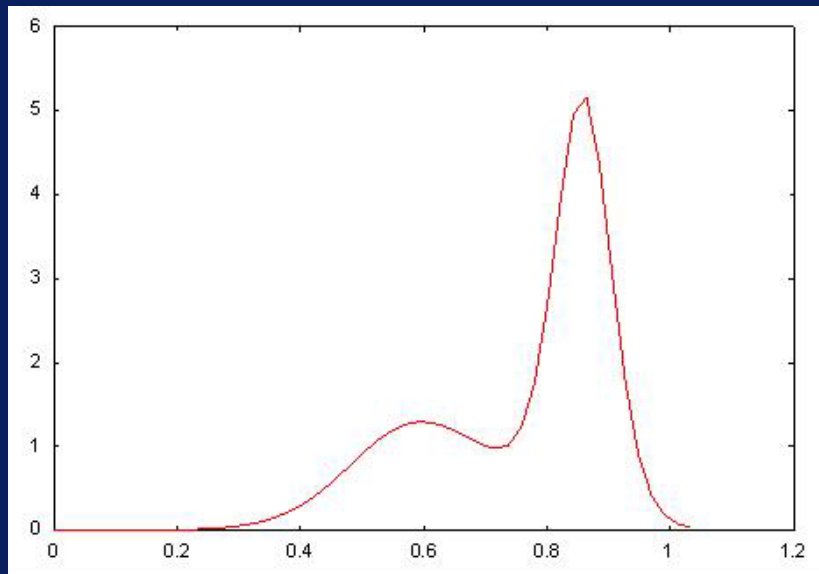
[10]log mass fraction CO_2 dissolved in water at 40 m below surface
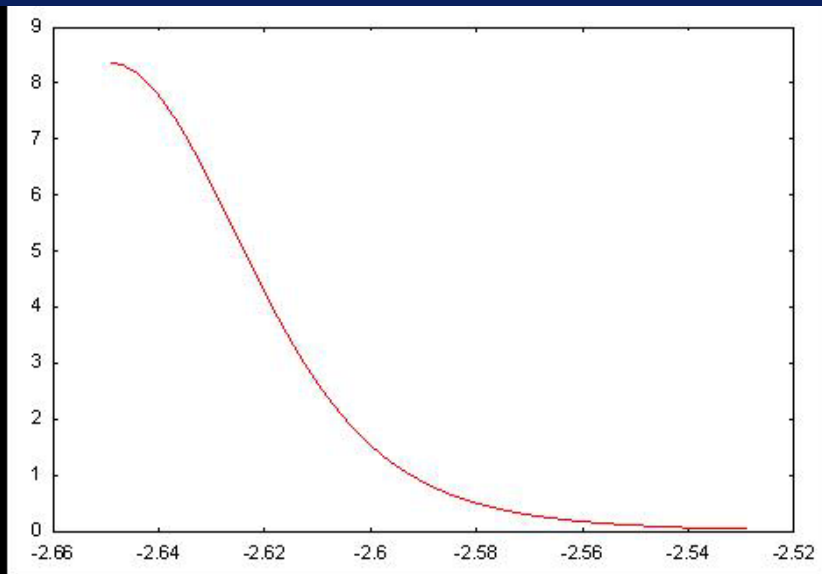
CO$_2$ concentration in hydrosphere (Delft Hydraulics)

- CO$_2$ dissolved in water
- CO$_2$ transported by tidal waves
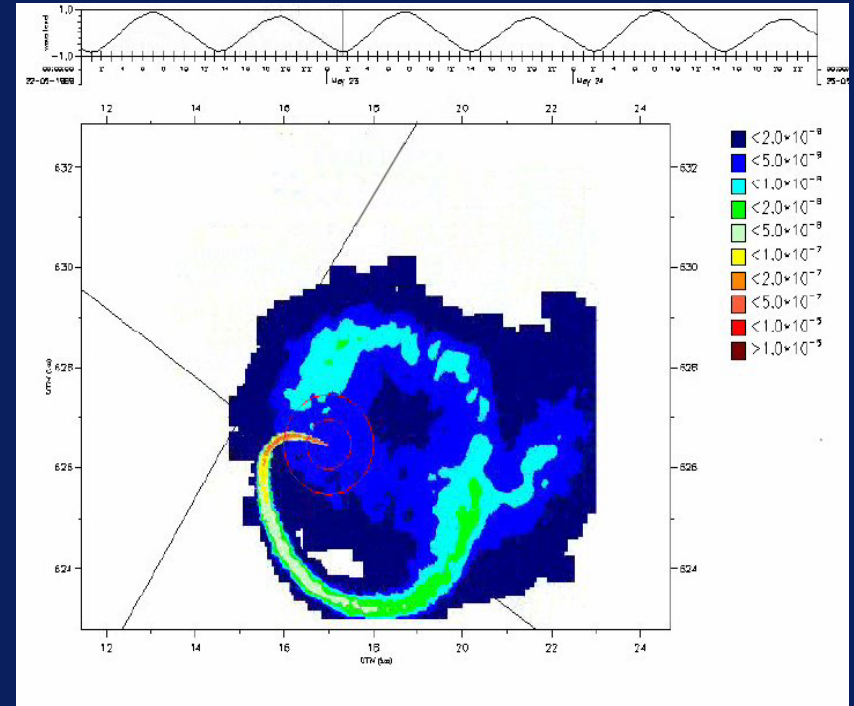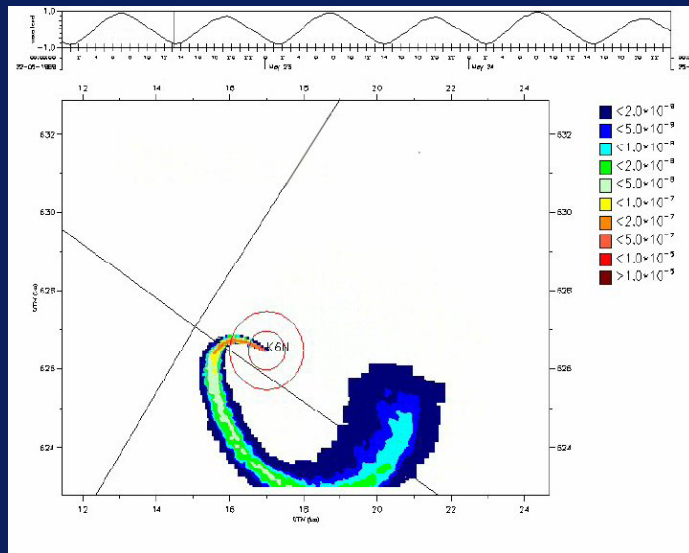
Well leakage scenario indicator distribu-tion: marine environment – seawater (WL)

CO_2 concentration in units of standard CO_2 concentration in seawater $* 10^{-5}$
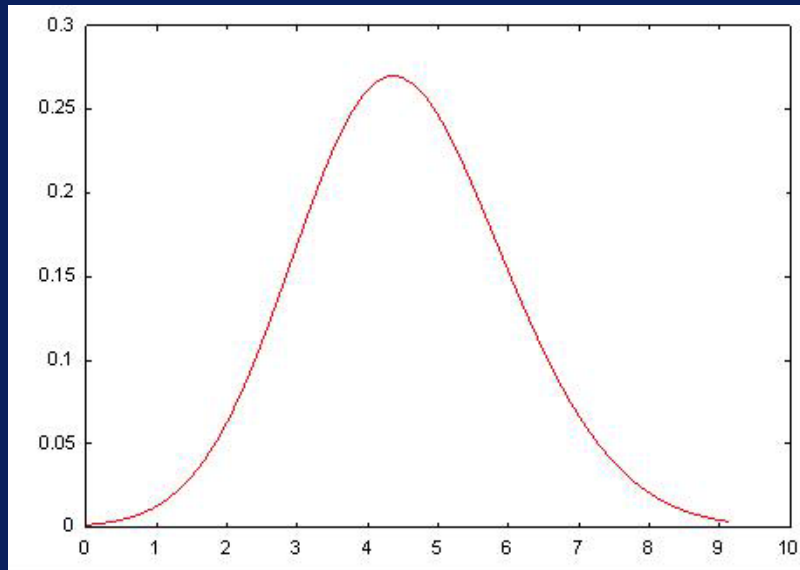
^{10}log CO_2 release (kg) to the atmosphere due to episodic release

Risk management of geological CO$_2$ storage

Life cycle CO$_2$ storage facility

- Site selection
- Site characterisation
- Design and construction of facility
- Testing facility
- Operation
- Abandonment
- Post-abandonment/liability with operator
- Post-abandonment/transfer of liability
- Post-abandonment/liability with authority

EIS · LIC · CER · CER

Risk management

- Baseline surveying & risk assessment
- Monitoring & verification
- Remediation planning & actions

Risk management for CO_2 storage

- **Risk management system**
  - Operational decision cycle (operator)
  - Long term, spatial planning decision cycle (authorities)

- **Monitoring and Evaluating**
  - Collecting and interpreting data (observation)
  - Comparison with predictions and expectations (signaling)

- **Deciding on mitigation options and acting**
  - Changing injection volumes and conditions (only operational cycle)
  - Changing monitoring tools and measurement configuration and frequency
  - Starting, adjusting, stopping mitigation measures

Natural & man-induced CH_4&CO_2 monitoring
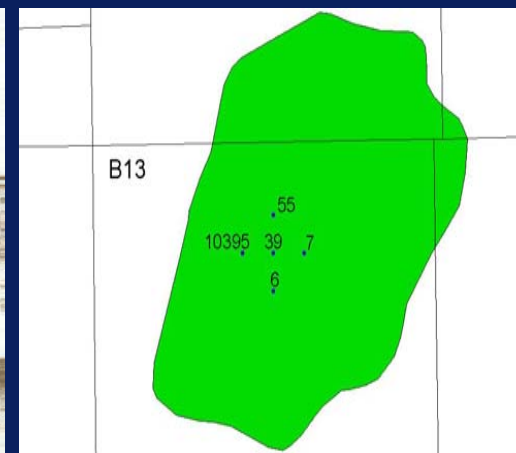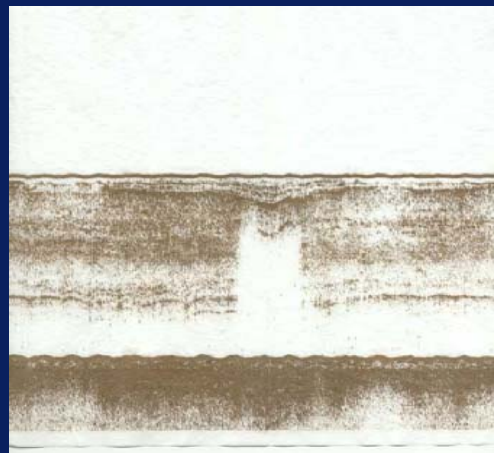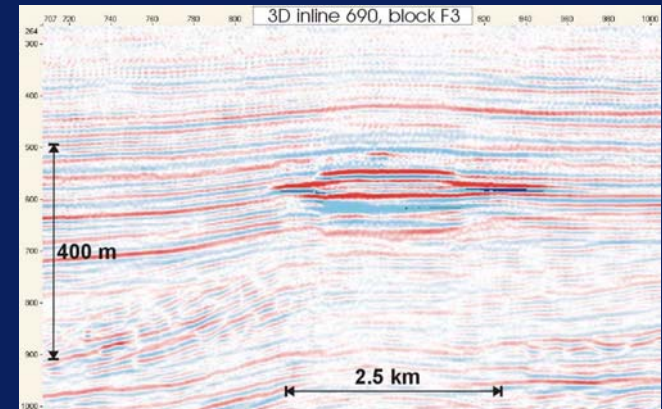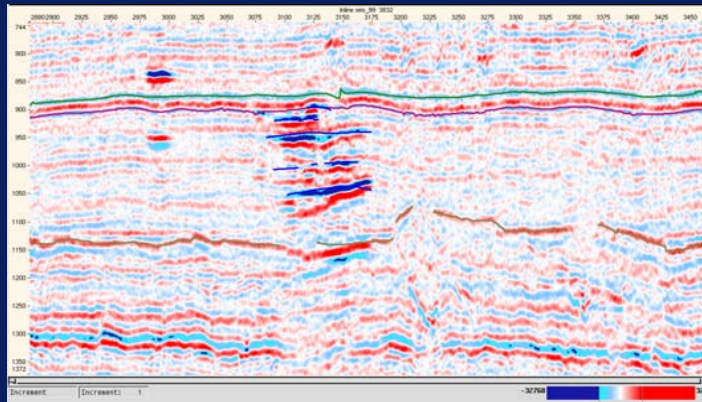
Natural seepage 50 -   10.395 ppm CH_4
Natural seepage   5 - >10.000 ppm CO_2

Conclusion and acknowledgements

- **Q&Q probabilistic scenario approach useful**
  - Transparent process ensures confidence
  - Total system performance assessment (TSPA) ensures completeness

- **Recommendations**
  - Consensus on methodology and tools to be expanded
  - Analysis and modelling tools to be improved
  - Input data and information to be be expanded

- **Acknowledgements**
  - CCP consortium, European Union, DoE, Statoil
  - SAMCARDS partners (TNO, BRGM (FR), Delft Hydraulics (NL), Wageningen University (NL), LBNL (US)

The Development of a Generic FEP Database for the Geological Storage of CO$_2$

Steven Benbow

Philip Maul

David Savage

11 February 2004

Quintessa

Structure of Presentation

- *The Development of the Generic FEP Database in the IEA Weyburn CO_2 Monitoring and Storage Project Project Steve Benbow)*

- *Demonstration (Steve Benbow)*

- *Potential Applications of the Database (Philip Maul)*

Quintessa

FEPs

"A key activity in the development of performance and safety analyses is the comprehensive identification of potentially relevant factors, often termed: Features, Events and Processes (FEPs)"

Quintessa

FEP Database Structure

Two parts:

- *Generic FEP list*
  - *Comprehensive (within defined bounds) master list of FEPs with descriptions*
  - *Organised into categories (eg. CO_2 storage, CO_2 properties, Geosphere, Impacts, …)*
  - *Metadata, links to generic documents, images, movies, …*

- *Project-specific FEP information*
  - *Collection of FEPs with descriptions*
  - *Each project FEP cross-referenced with (one or more) generic FEPs*
  - *Metadata, links to project documents, images, movies, …*

e.g. Nascent

FEP Database Links

Generic FEP list

GFEP 1

GFEP 2

GFEP 3

Project A

PFEP A1

PFEP A2

PFEP B1

PFEP B2

http://www
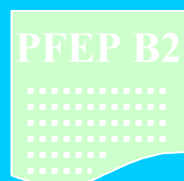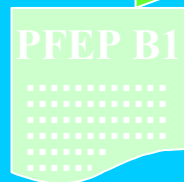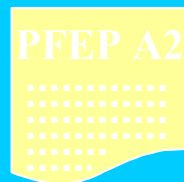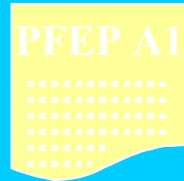
Scope of the Generic FEP Database

- *Contains FEPs associated with the geological sequestration of CO_2*

- *Not specific to any particular concept or location (underground, undersea, coal beds,…)*

- *FEPs relevant to long-term safety and performance of the sequestration system after injection of CO_2 has ceased*

Quintessa

Structure of the Generic FEP Database

- *FEPs are ordered hierarchically in FEP categories*

- *Within a category, FEPs are ordered in FEP classes*

- *Classes contain FEPs (and sub-FEPs)*

Quintessa

FEP Categories

- *Assessment Basis*
- *External Factors*
- *CO_2 Storage*
- *CO_2 Properties, interactions & transport*
- *Geosphere*
- *Boreholes*
- *Near-surface environment*
- *Impacts*

Quintessa

Demonstration of the FEP Database

Quintessa

Safety Assessment and Systems Analysis
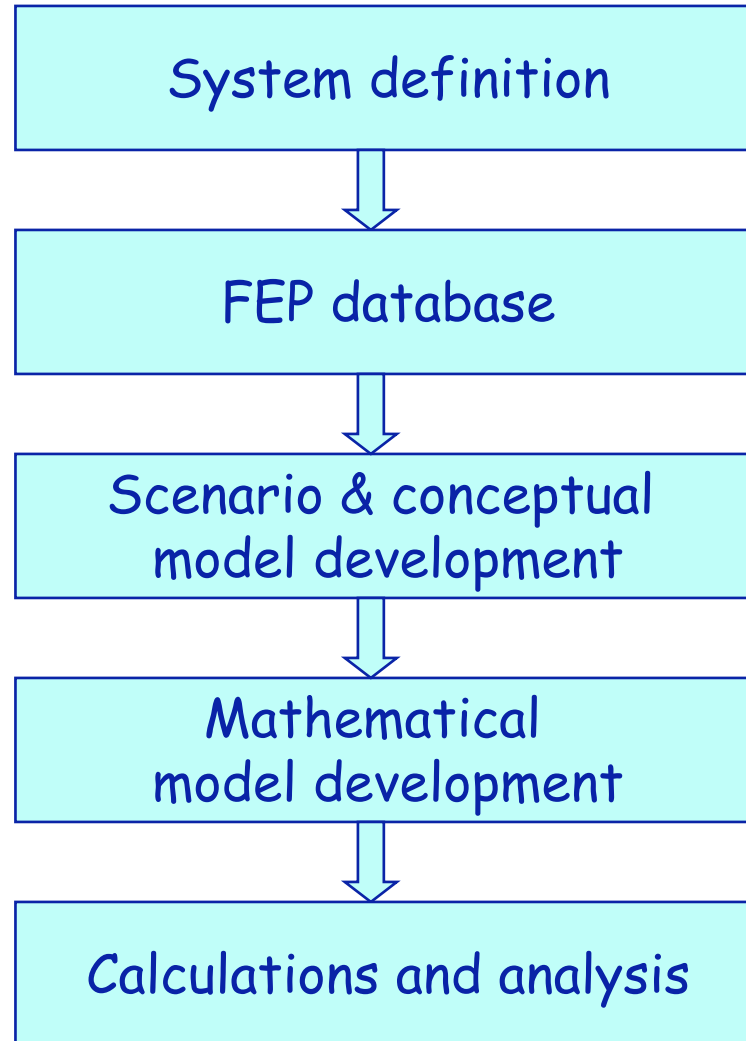
The Systems Approach
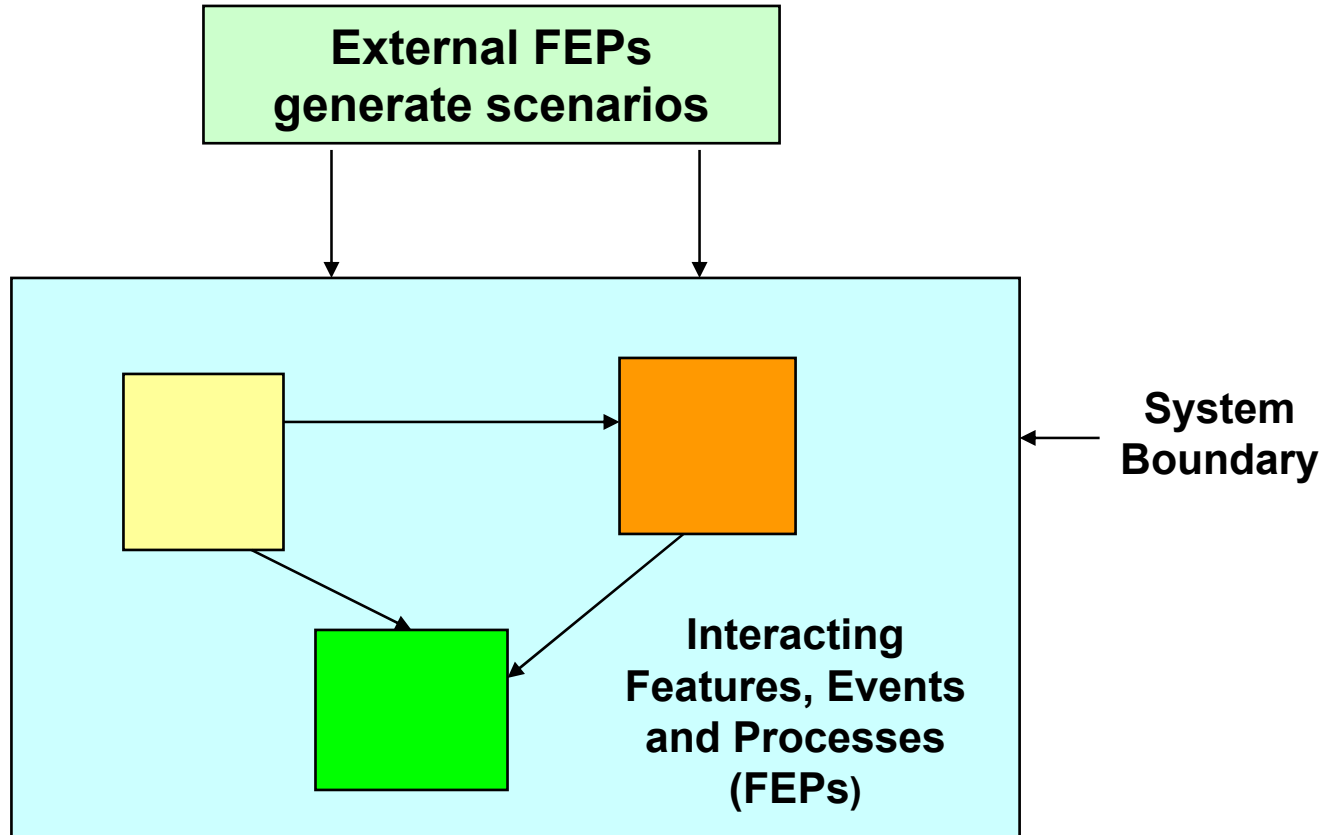
FEP Database Applications

- *As a knowledge base for CO_2 sequestration studies*

- *To aid the development of scenarios*

- *As an audit tool for Systems-Level Models*

  (all demonstrated in the IEA Weyburn CO_2 Monitoring and Storage Project project)

Quintessa

Currently Available Models

- *Models based on reservoir simulations*
  - *Represent the multi-phase nature of the transport*
  - *Simplified representation of impacts*

- *Models for impacts of CO_2 released to the accessible environment*
  - *Detailed consideration of potential impacts*
  - *Simplified representation of the 'source term'*

- *Models that include important FEPs for the whole system are at an early stage of development*

Quintessa

Systems Modelling in Other Fields

Lots of relevant experience in the field of radioactive waste disposal where relevant timescales are also very long (10 000 years+) but…

Radionuclides are trace contaminants that do not perturb the system.

CO_2 does perturb the system, and its properties vary dramatically between different parts of the system

Systems Modelling for CO_2 storage is much harder!

Quintessa

Quintessa Prototyping

- *Uses a 'compartmental' modelling approach*

- *Implemented in Matlab/Simulink*

- *Demonstrates FEP representation in systems level models*

- *Undertaken separately from the Weyburn CO_2 Monitoring and Storage Project project project*

Quintessa

A Model Compartment

Quintessa
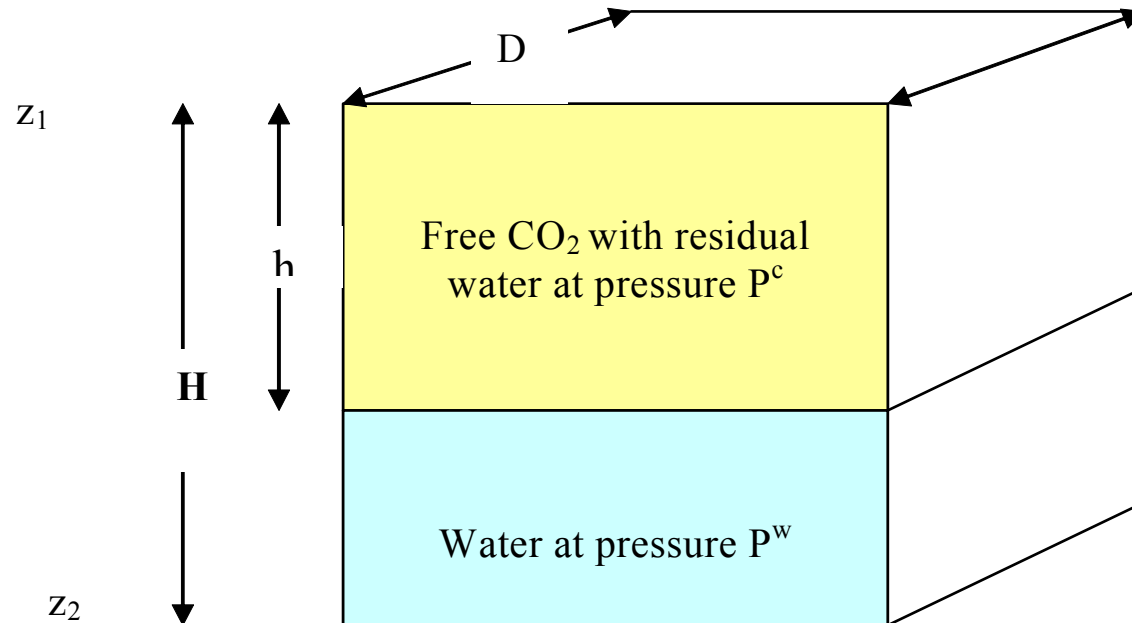
Pressure Calculation

- *From a knowledge of the amount of water, free CO_2, and dissolved CO_2 in a compartment representative pressures in the two phases can be calculated (using information on compressibilities)*

- *These pressures can then be used in the calculation of fluxes of water, free CO_2, and dissolved CO_2 between compartments*

Quintessa

Transport between Compartments

free CO_2:
vert. advection

free CO_2:
horiz. advection

dissolved CO_2:
horiz. advection
in groundwater

Quintessa
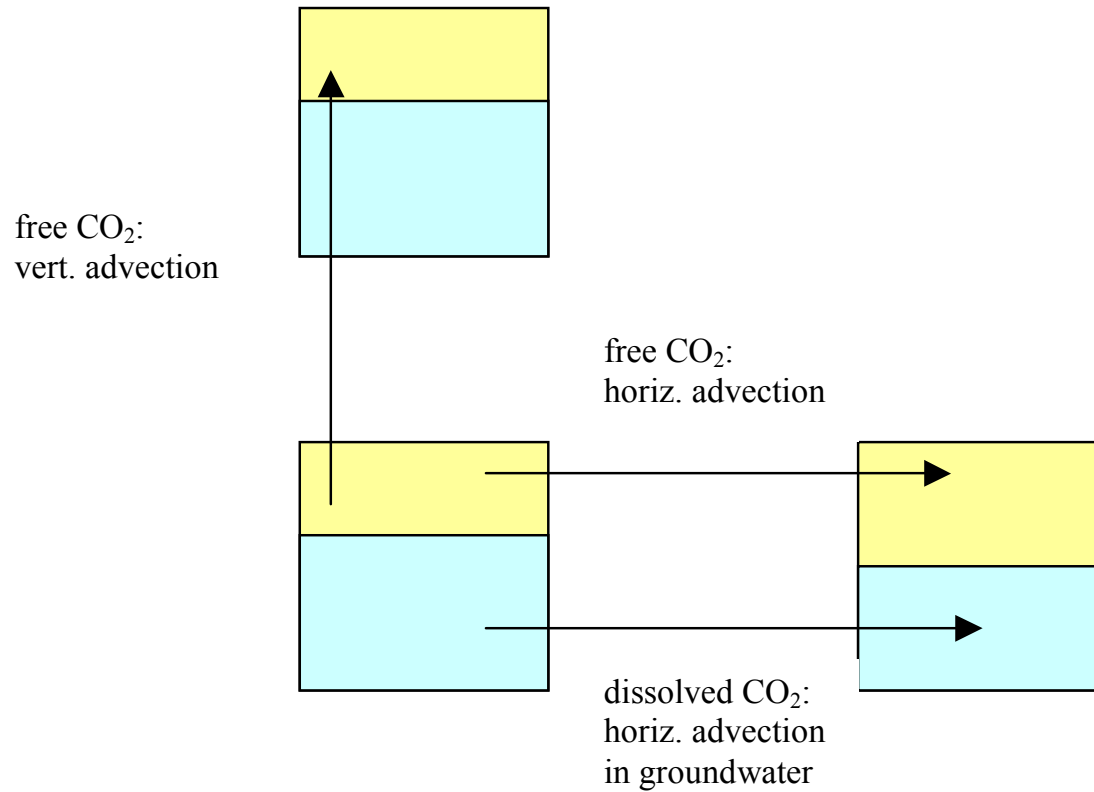
Prototyping Issues: Transport through the Cap Rock

- *This is likely to be key part of the system in determining overall performance*

- *Prototyping suggests transport could be episodic*

- *What are the key processes?*

- *Are they in the FEP database?*

- *Do we have sufficient information to parameterise the processes?*

Quintessa
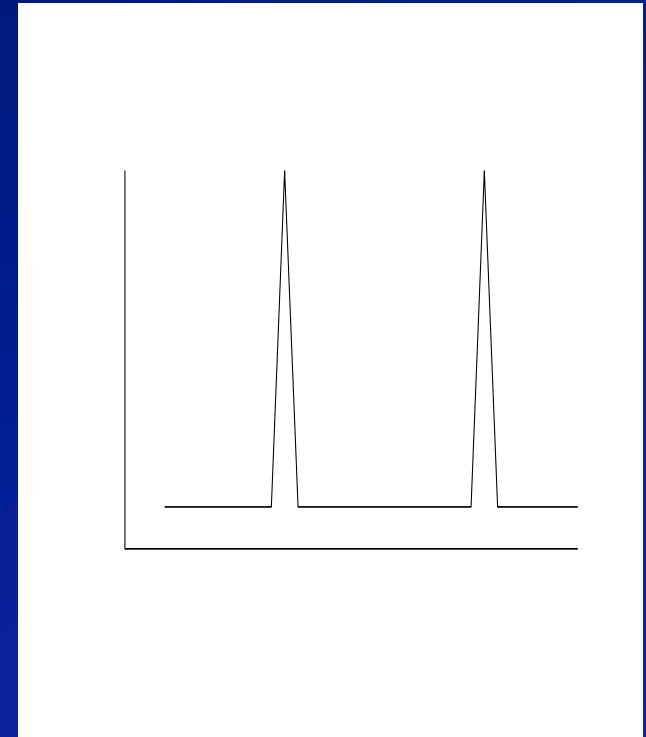
Prototyping Issues: Near Surface Releases of CO_2

- *If the pressure reduces, so does the CO_2 solubility and gaseous CO_2 can be produced*

- *What processes can result in such pressure reductions?*

- *Are there other important processes that can result in near surface releases?*

Quintessa

Main Conclusions

- *The generic FEP database is an important part of the safety assessment process, providing a potential 'knowledge base'. The database should be extended and maintained.*

- *Systems-level modelling for CO_2 storage is at an early stage. Such models need to use information from more detailed models (e.g., reservoir simulations and geochemical codes) and could usefully be applied to natural analogue sites.*

Quintessa

Risk Assessment of Suitability of Selected Australian ESSCIs for Geological Storage of Carbon Dioxide

Adrian Bowden
Andy Rigg

London

13th August, 2003

GEODISC Aims

- Assess and compare alternative CO_2 injection ESSCIs on the basis of:

  - risk of leakage

  - effectiveness of the intended reservoir

  - adverse consequences of CO_2 injection sites

  - Demonstrate the value and safety of geological disposal of CO_2

  - Include less tangible, community and environmental issues in any assessment

Overall Approach

- Needed:
  - transparent risk assessment process
  - to ultimately interface with the wider community
  - to allow stakeholders to assess whether the injection process is safe, measurable, verifiable and economically sound
- Used RISQUE method
  - quantitative technique
  - characterises risk in terms of the likelihood of risk events occurring and of their consequences
  - integrates current best practice risk assessment methods with best available information provided by an expert panel

Specific Approach (i)

■ Assess the risk posed by typical CO_2 injection projects in four selected ESSCIs (Dongara, Petrel, Gippsland and Carnarvon)
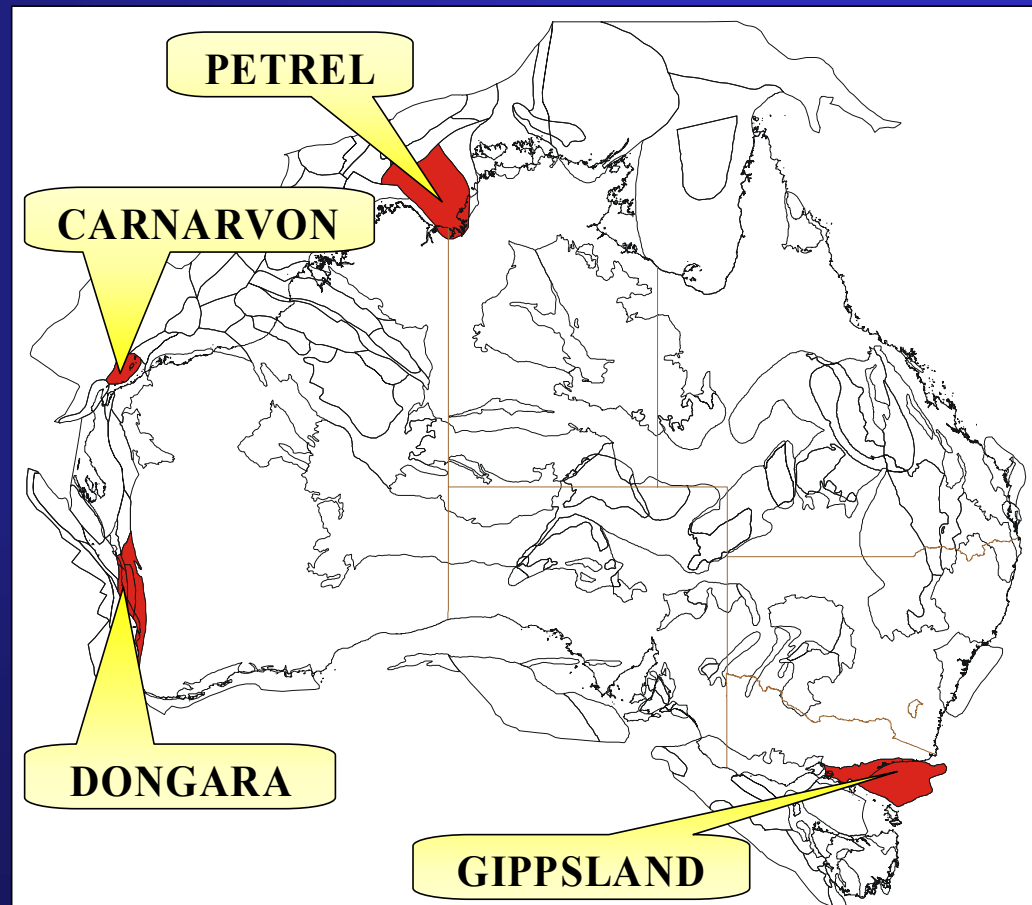
Specific Approach (ii)

- Address key performance indicators

- Form a basis to compare ESSCIs

- Include technical, economic and community risk events

- Assist communication of risk to stakeholders

- Incorporate results into risk management design of injection projects

- Help identify specific areas of future research

ESSCIs measured against 6 KPIs

- Containment (KPI 1) - CO_2 mass retained after 1,000 years at least 99% of the injected mass (over 20 years).

- Effectiveness (KPI 2) - Reduction of CO_2 mass stored should not lead to a zero or negative net project value.

- Self-funding potential (KPI 3) - Project financial benefit-cost ratio (including risk cost) greater than 1.0.

- Wider community benefits (KPI 4) - Wider benefit-cost ratio greater than 1.0.

- Community safety (KPI 5) - Within guideline societal risk values for the dams industry (ANCOLD target level 0.0001 fatalities per year).

- Community amenity (KPI 6) - Based on dams case study: community amenity risk quotient less than around $1,000 per year.

KPIs 1 and 2: Reservoir performance

■ The following risk events could potentially affect **containment**:

- Leakage via permeable zones in seal, leakage via faults, leakage via wells, regional scale over-pressurisation, local scale over-pressurisation, exceeding spillpoint, earthquake, misidentification of migration direction, well-head failure, pipeline failure, compressor failure, and platform failure.

■ The following risk events could reduce reservoir **effectiveness**:

- Lack of CO2 storage capacity, reduced injectivity, stakeholders reject or oppose project, poor public perception of other projects, inadequate CO_2 source, groundwater displacement, sub-surface biological concerns, regulatory change, licencing / ownership / liability issues, and facility environmental damage.

Reservoir performance

Summary of acceptability

	A. RESERVOIR PERFORMANCE		B. ECONOMIC BENEFITS		C. COMMUNITY IMPACTS	
	Containment KPI 1	Effectiveness KPI 2	Self Funding KPI 3	Wider Benefits KPI 4	Community Safety KPI 5	Community Amenity KPI 6
DONGARA	YES	NO	NO	Marginal	YES	Marginal
PETREL	YES	YES	YES	YES	YES	YES
GIPPSLAND	YES	YES	YES	YES	YES	Marginal
CARNARVON	YES	NO	YES	YES	YES	Marginal

Rank 1: Petrel- acceptable on all KPIs. Not be available for 25 years. Low NPV reflects late project timing.

Rank 2: Gippsland - acceptable for most KPIs. Modest benefit-cost ratio due to high capture costs and late (10 years) timing.

Rank 3: Carnarvon - would contain the CO_2 but despite potential reduction in financial return due to ineffectiveness, Carnarvon would derive substantial economic benefits and a high benefit to cost ratio. Community amenity risk marginally acceptable.

Rank 4: Dongara - not expected to be self-funding. Reservoir effectiveness would not meet the KPI. Also poses the greatest community amenity risk.

NOTE: If early timing was a key factor, the best option would be **Carnarvon**, which could most likely derive very good project economics and has good potential to meet all of the KPIs, provided community issues were adequately addressed and managed.

Recommendations

- If the opportunity arises, the risk assessment method and structure should be applied to other potential CO_2 injection sites in Australia to:

  - compare and rank their suitability

  - assist selection of the most appropriate ESSCI for a pilot injection project.

- Further research areas:

  - better define likelihoods and consequences within key technical areas

  - improve definition of wider community benefits

  - develop specific outputs to communicate benefits, costs and risk to stakeholders

  - confirm and justify KPI targets

IEA Weyburn CO_2 Monitoring and Storage Project

Assessment of Long-Term Fate of CO_2 in the Weyburn Field

M. Stenhouse[1], W. Zhou[1], D. Law[2], Steve Whittaker[3], R. Chalaturnyk[4] and W. Jazrawi[5]

with contributions from ECOMatters (Marsha Sheppard *et al.*)

[1]: *Monitor Scientific, LLC;* [2]: *ARC;* [3]: *SIR;* [4]: *University of Alberta;* [5]: *PTRC/EnCana*

The Weyburn EOR Project and CO$_2$ Monitoring Program

CO$_2$ pipeline

Weyburn EOR Unit

Well Path

Midale Evaporite

Midale Marly

Vuggy Shoal

Vuggy Intershoal

Midale Vuggy

Frobisher Marly

Frobisher Evaporite
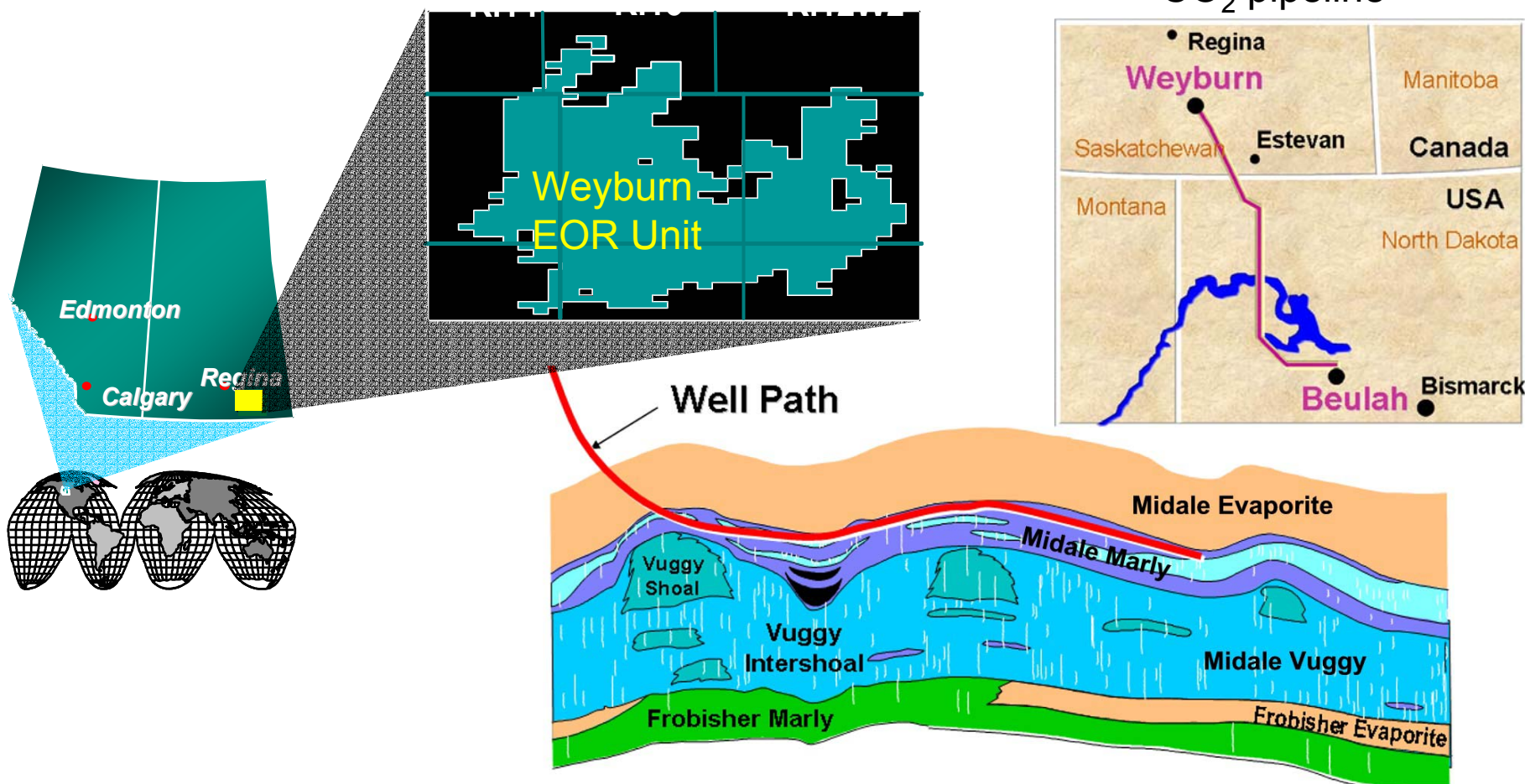
Objectives of Modeling Long-term Fate of CO$_2$

- **Performance assessment of the storage system in the Weyburn field**

- **Identify leakages, if any, and leakage pathways (natural and artificial)**

- **Provide input for environmental risk analysis**
  - Global environment
  - Local environment

Assessment - Phased Development
in response to phased data collection, research, and improved understanding over the course of the Project

- **2001 – 2002: Emphasize systematic methodology for performance assessment**
  - ❑ **Systems Analysis / Scenario Development framework**
  - ❑ **Understanding of basic processes of CO$_2$ migration**

- **2003: Development of System Model**
  - ❑ **Finalize "Base Scenario" and "Alternative Scenarios"**
  - ❑ **Integration among modeling groups**
  - ❑ **Preliminary system model simulations**
  - ❑ **Probabilistic Risk Assessment**

- **2004 plan: 75-pattern model + full geosphere**

Systems Analysis / Scenario Development Framework

- **Key components of methodology**
  - I.   Concept of the 'System' - describe/define
  - II. Identification and analysis of Features, Events and Processes
    - *What they are, how they interact with each other*
  - III. Scenario Development
    - *Base Scenario and "What if"scenarios*
  - IV. Identify information/data input and modeling / calculational needs and responsibilities

Concept of the "System" and FEPs for CO$_2$ Storage

Combination of Features, Events and Processes (FEPs) that can be used to describe or represent the System's overall behaviour (Internal FEPs)

***e.g.* geological, hydrogeological, chemical, geochemical, geomechanical, thermal, CO$_2$ properties and transport**

FEPs (Events) that are not part of the 'normal' System but can affect it (EFEPs)

***e.g.* earthquakes, future drilling**
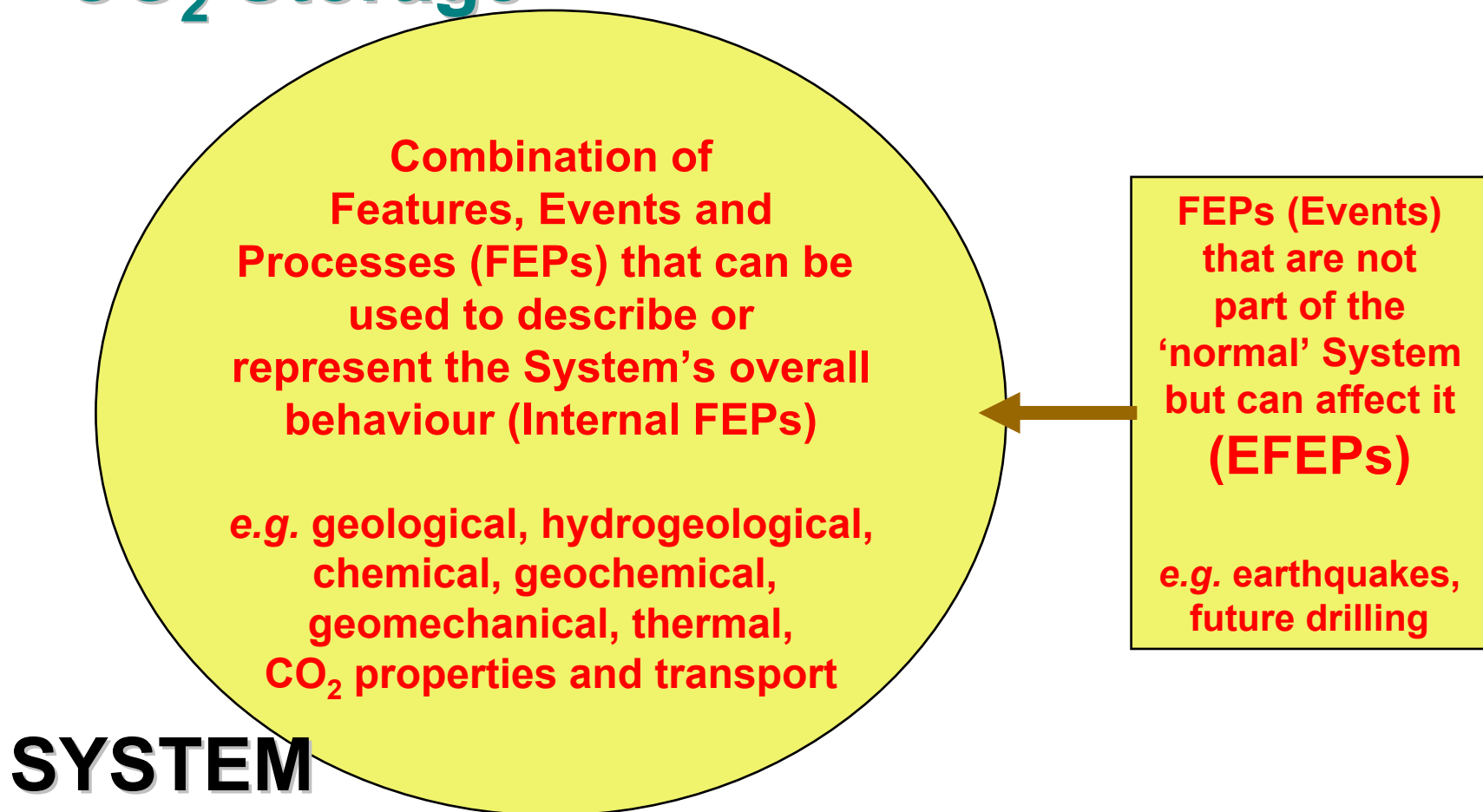
SYSTEM

Development of FEPs for the Weyburn System
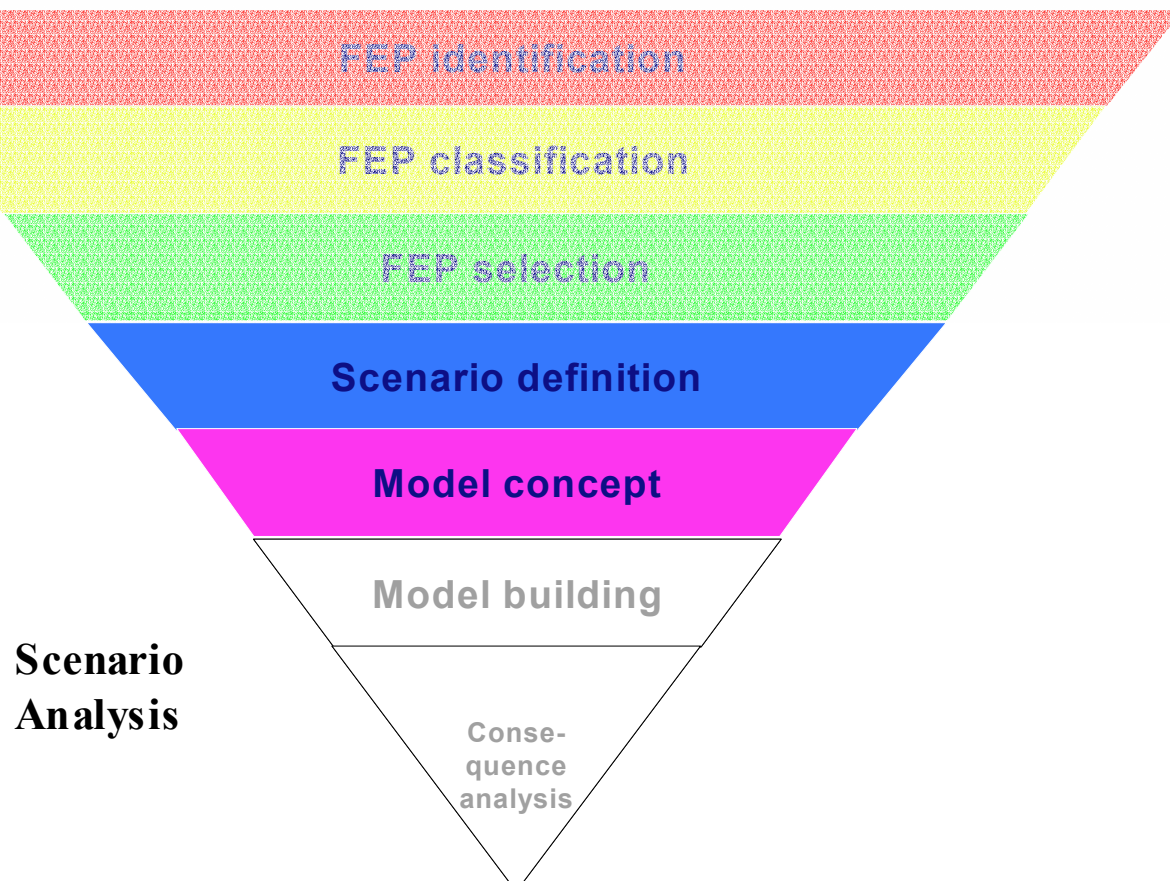
Weyburn Working List of FEPs

- ## Initial List of FEPs
  - Mapped to Quintessa's generic FEP list (2001)
  - Mapped to Rome FEP List (January 2002) (engineering/borehole; reservoir; cap rock; biosphere)
  - Calgary Workshop (June 2002)
- ## Working List (2002/2003)
  - Consists of ~ 55 System FEPs primarily for reservoir and geosphere

Base Scenario and System Model

- **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**
  - **Biosphere starts from the deepest possible potable aquifer**
  - **Assessment conducted over 5000 yrs or until 50% loss of CO$_2$**

The System Model
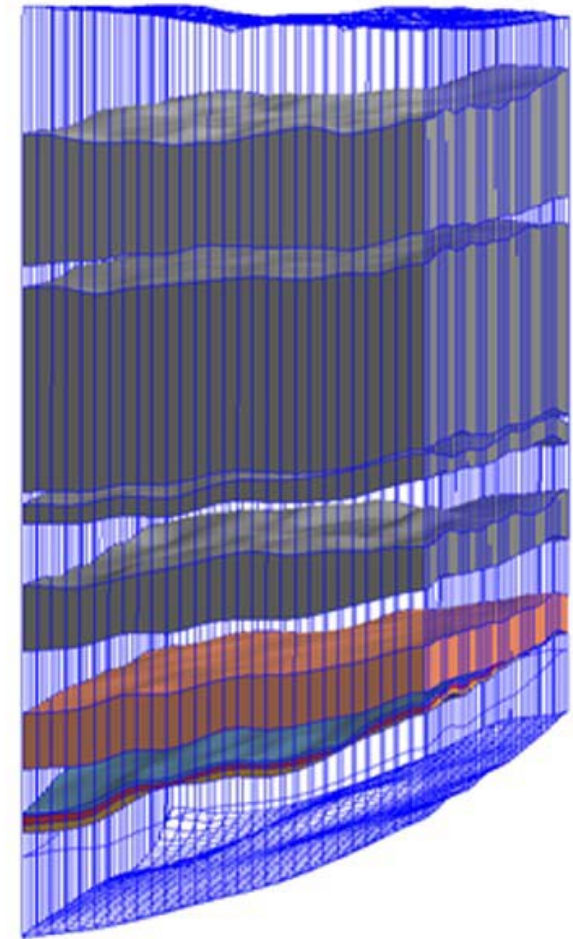
Alternative Scenarios

Alternative Scenario Name	Unique characteristics
Engineering options for EOR (a) Maximize CO$_2$ storage (b) Water flush at the end of EOR	Option (a) involves larger reservoir pressures; over-pressurisation and caprock fractures are possible problems. Option (b) would result in changes to CO$_2$ distributions in the reservoir and could also decrease CO$_2$ storage
Well abandonment options	Emphasis on improved long-term sealing capabilities
Salt dissolution of underlying formations	Dissolution and subsidence may lead to development of fractures
Leaking wells	Involves extreme failures only as the Base Scenario has 'normal' leakage
Fault movement or reactivation, including undetected faults	Could represent a new and fast CO$_2$ transport pathway; could affect several formations
Tectonic activity	Low probability but possible
Deliberate & accidental human intrusion (a) Destruction of surface casing (b) Resource extraction	Likely scenario involves intrusion into the reservoir in search for CO$_2$ or petroleum. Option (a) could affect the uppermost seal in one or more wells. Option (b) likely involves extraction of some shallower resource, but could lead to CO$_2$ blow-out from CO$_2$ trapped in formations above the reservoir

Modeling: Gradual Refinement Towards Comprehensive Assessment

- **2001 model:**
  - ❑ 2D vertical cross section
  - ❑ 3 components and 2 phases
  - ❑ Sensitivity study on diffusion, advection, permeability, and salinity
- **2002 model:**
  - ❑ 2D cross-section with simple geological features
  - ❑ 5 components and 3 phases
  - ❑ Sensitivity study on capillary pressure, flow rates of formation water in aquifer below the reservoir
- **2003 model:**
  - ❑ The System Model with all the digitized geological features
  - ❑ 7 components and 3 phases
  - ❑ CO$_2$ source: upscaled 75-pattern and detailed 1 pattern treatments
  - ❑ "Unit Cell" abandoned well modeling

Why Choose E300 as the Modeling Tool?
(E300 is *developed by GeoQuest/Schlumberger*)

- **Available to the modeler and also used by EnCana**
- **One of the existing tools that can provide the closest approximation to the system:**
  - *Advantages* include:
    - Previously field applied and tested for CO_2 flood EOR
    - Equations of state and CO_2 dissolution in water
    - Incorporating industry-standard geological data
  - *Disadvantages* include:
    - Unable to couple rock property changes due to geochemical reactions
    - Inaccurate density calculation for water with dissolved CO_2
    - Inconvenient in modeling well leakage
- **No specially-developed tools currently available**

Full Probabilistic Assessment - EcoMatters

- **Emphasize parameter uncertainties**
- **CrystalBall used as the probabilistic engine**
- **Assessment tool: CQUESTRA – compartment model**
  - Formation layers are treated as a series of mass balance boxes connected by fluxes
  - Simplified transport model
  - Single component (CO_2) in gas phase only with flowing water as a sink to remove dissolved CO_2
  - Modeling starts after pressure transient

Compartment Model in CQUESTRA

Biosphere

Aquitard & Aquifers

Wells

CO$_2$ Reservoir

Aquifer
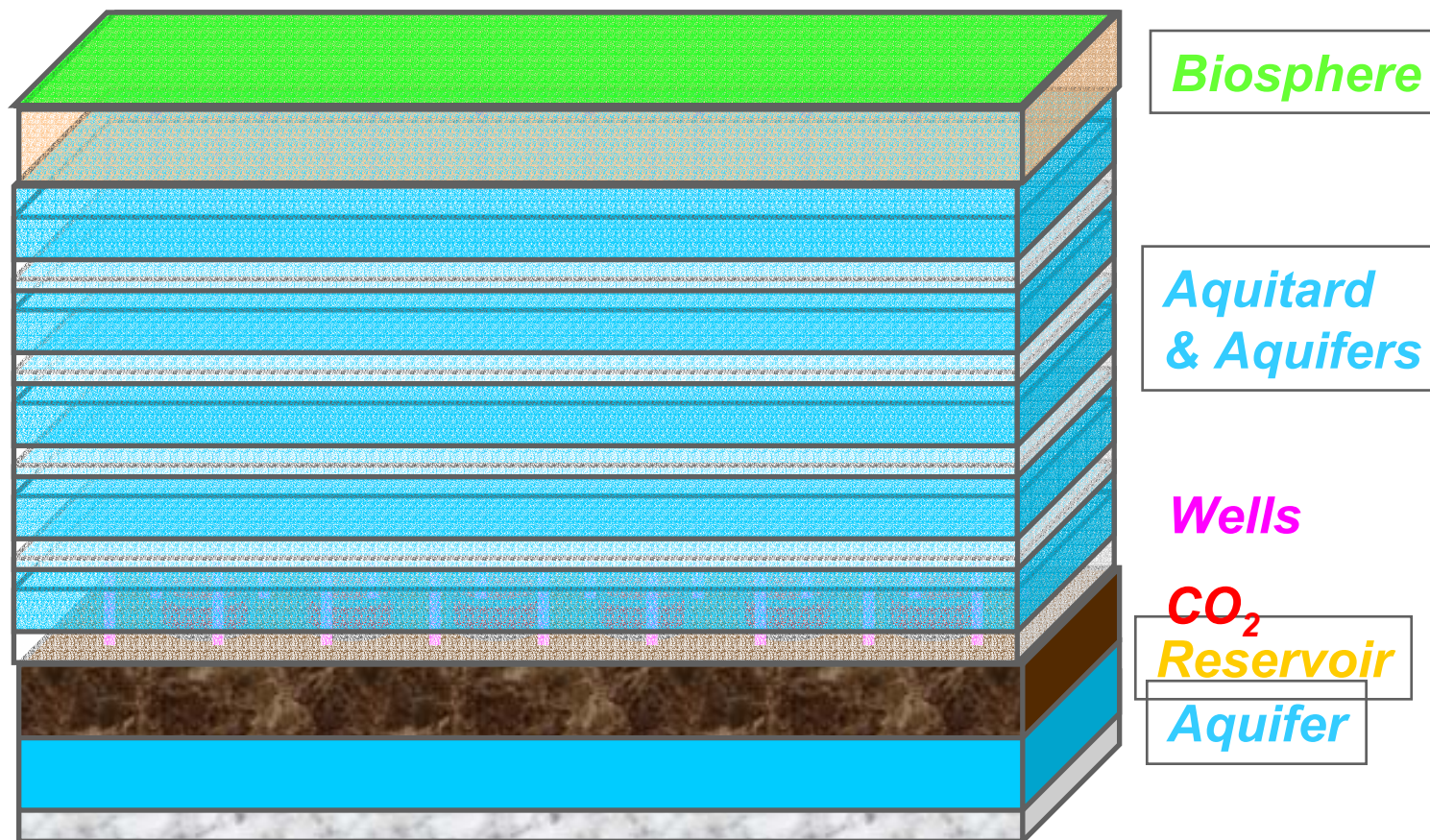
Integration of Modeling Approaches

System well known   **Time line**   **Uncertainty increasing**

2002
Start of
EOR

2034
End of
EOR

7000

Starting Conditions

Wellbore Studies (UofA)

Detailed reservoir simulation **(ARC)**

Compare results

Deterministic Assessment (detailed simulations)

Compare results

Probabilistic Assessment (parameter uncertainty)
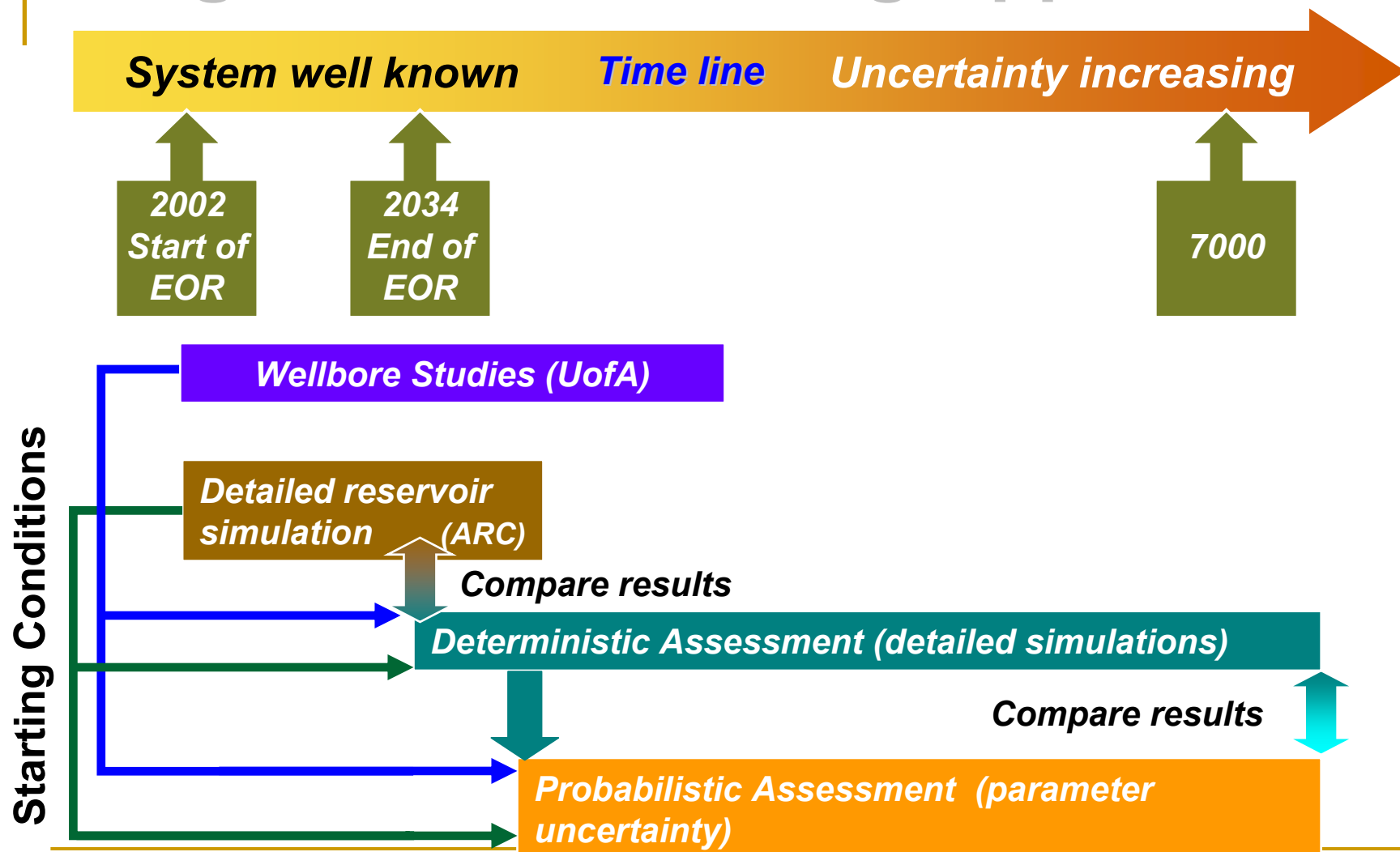
Detailed Studies Provide Key Input to Long-term CO$_2$ Migration Modeling
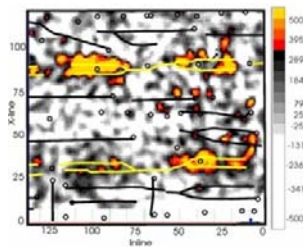
Seismic study

EnCana field data

Reservoir simulation
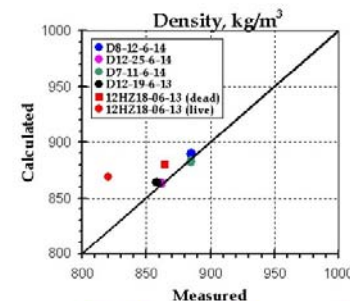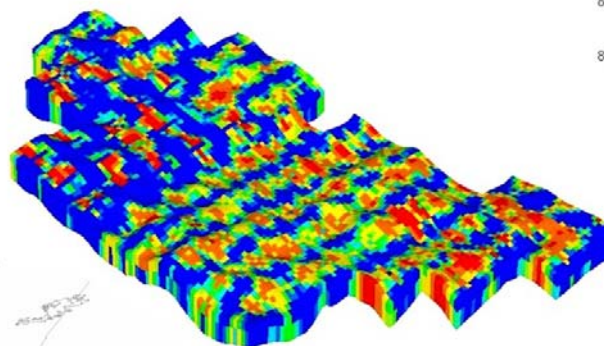
Fluid sampling and PVT study
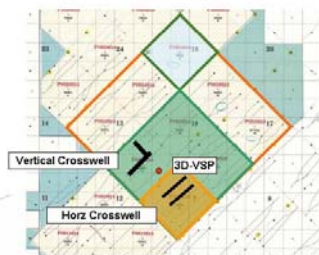
System Model

Regional study

Williston Basin

Regional geological and hydrogeological studies

Abandoned well sealing integrity study
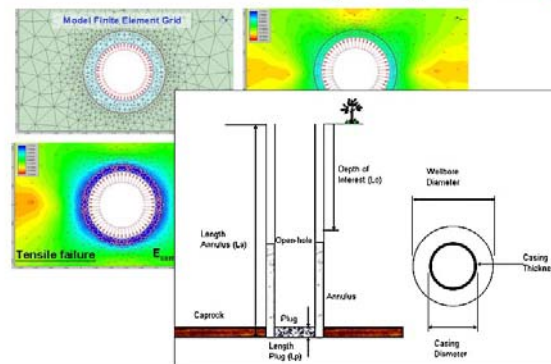
2003 Model: Benchmarking Study
designed to compare the E300 model results with CQUESTRA

- **Geosphere migration model**
  - Understanding basic processes without upscaling of EOR reservoir simulation results
  - Source: EOR Pattern 1 from detailed reservoir study (Alberta Research Council)
  - Fictitious geosphere based on the System Model geological profile
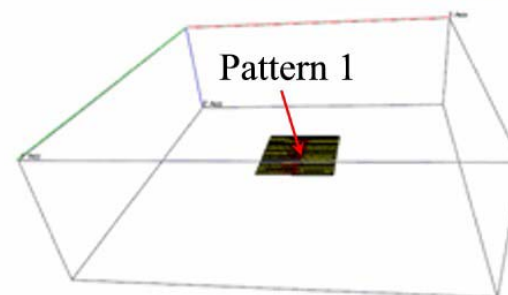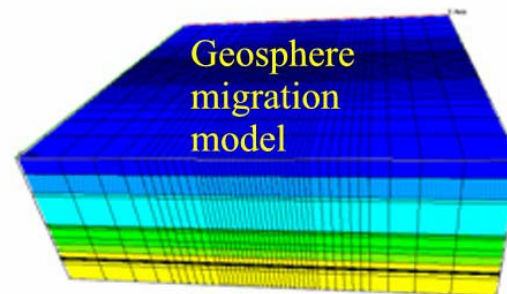
- **Well annulus leakage model**
  - Study processes leading to leakage via well annulus
  - One well in EOR Pattern 1
  - Fictitious geosphere in the Midale reservoir only
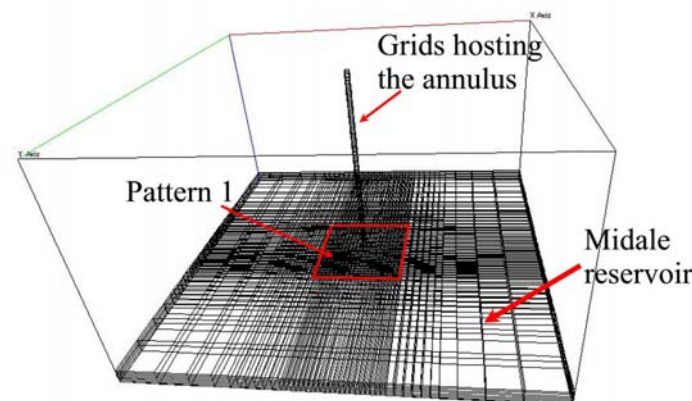
CAUTION!

■ **The results presented here are from the Benchmarking Study and are NOT relevant to the Base Scenario results that will be available in April, 2004. The benchmarking results do, however, provide some insight into processes occurring in the Weyburn reservoir.**

Examples of E300 Results (1): Gas Saturation Evolution in Pattern 1
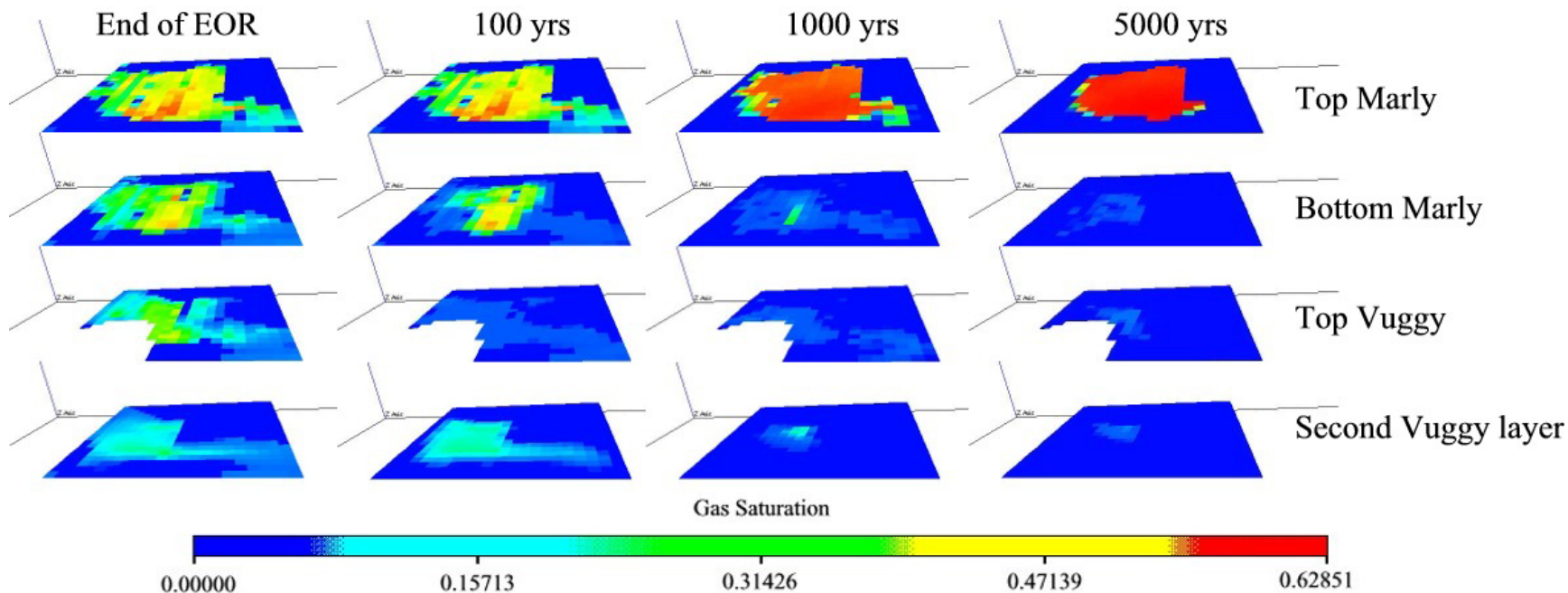
Geosphere Migration Results
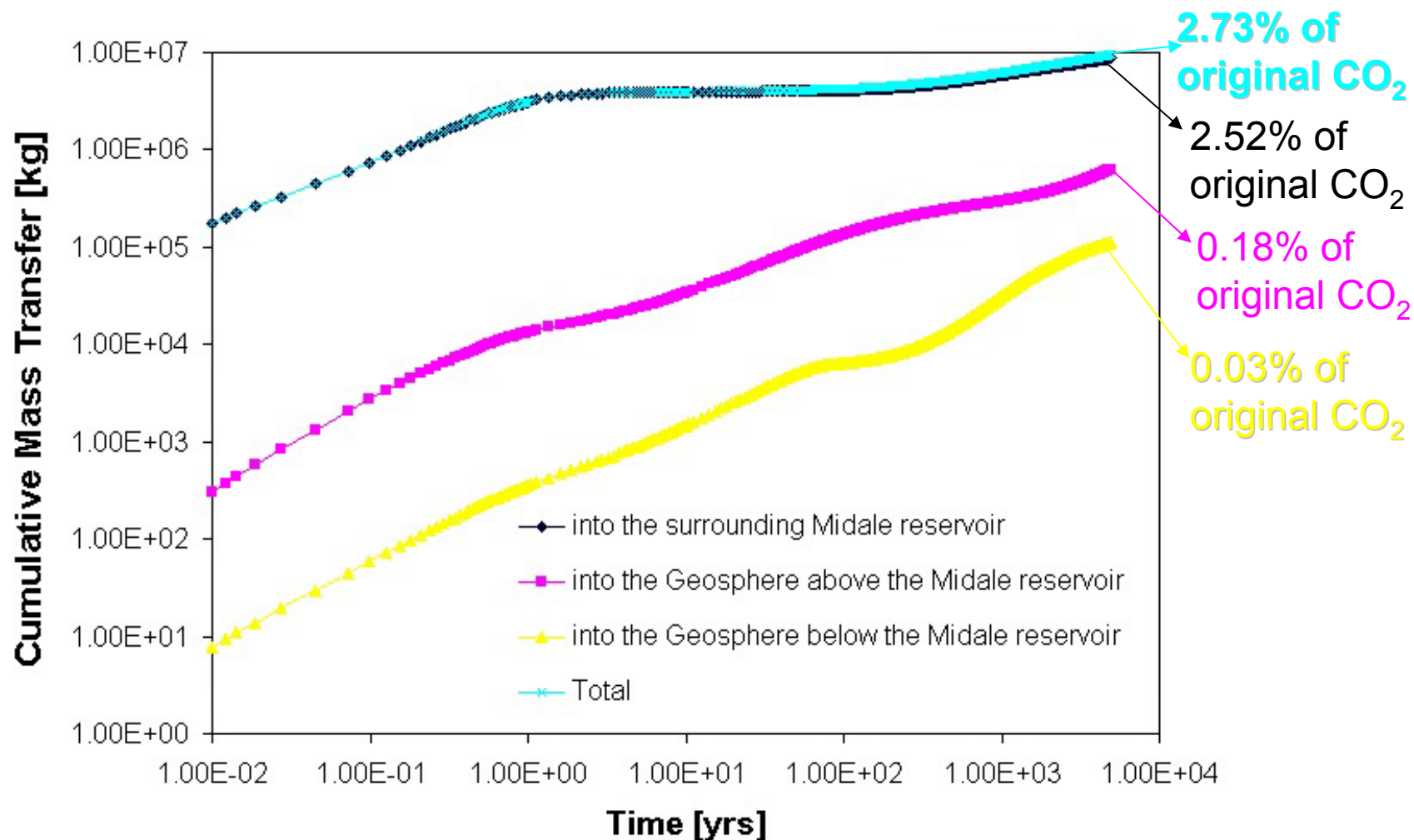
Phase Movement after EOR
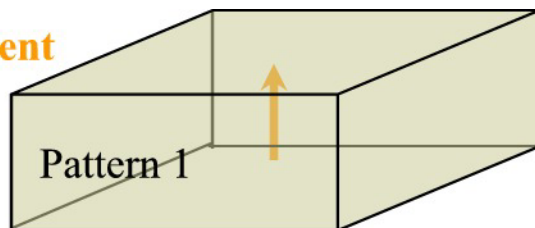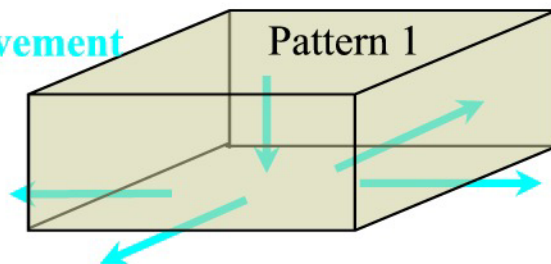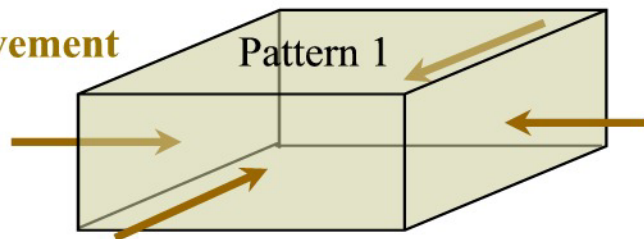
- CO$_2$-rich phase moves up and is trapped in the upper Marly below the caprock.

- Water injected during EOR moves downward and away from Pattern 1 at depth of lower Vuggy, carrying dissolved CO$_2$.

- Oil outside Pattern 1 with lower CO$_2$ concentration moves into the Pattern 1 region from lower Marly and upper Vuggy, picking up some CO$_2$ from gas and water. CO$_2$ dissolved in oil moves away from Pattern 1 via diffusion.

Mass Transfer Coupled with Fluid Flow and Mass Partitioning
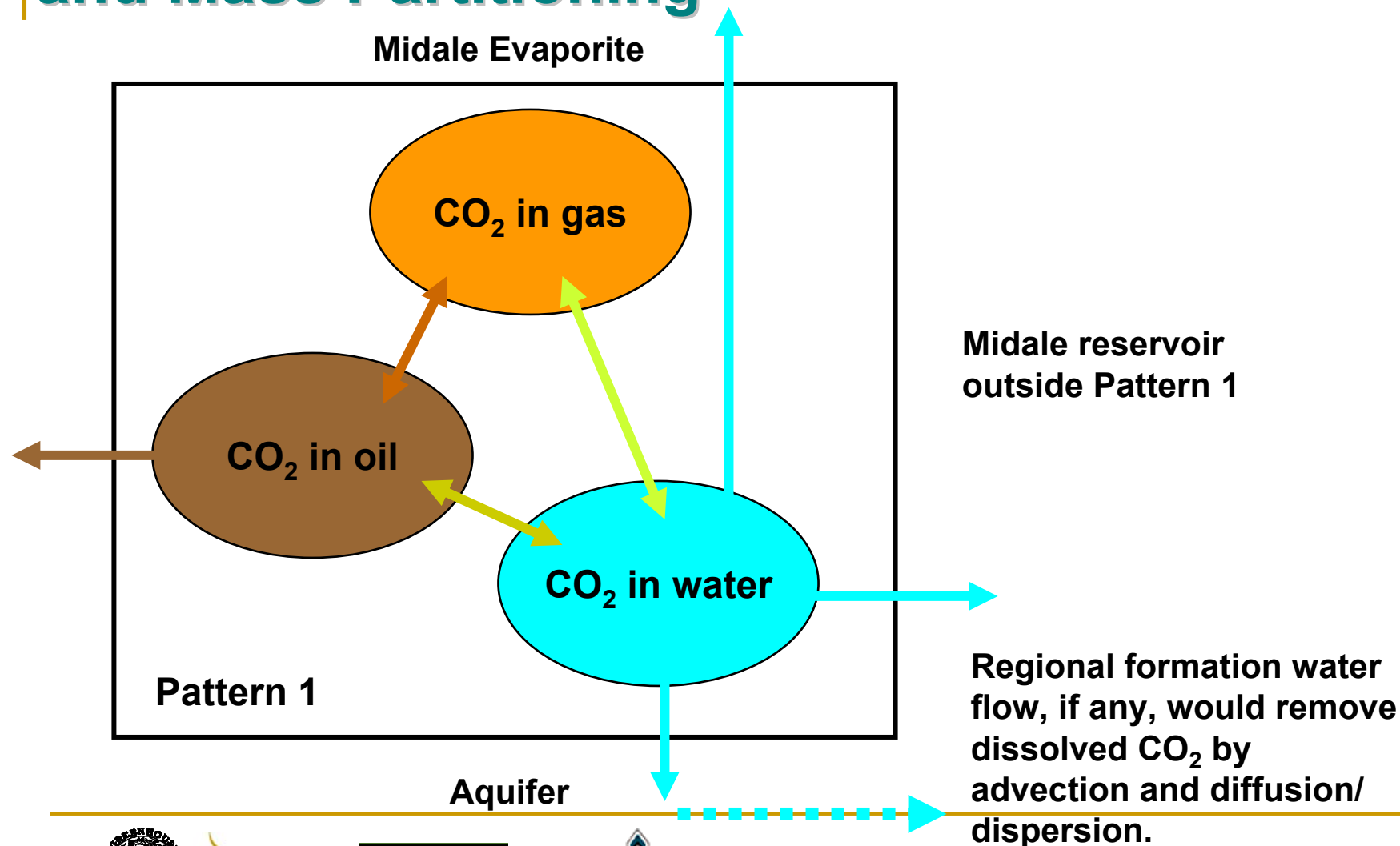
Example of Results (2): Saturation Histories in the Well Annulus
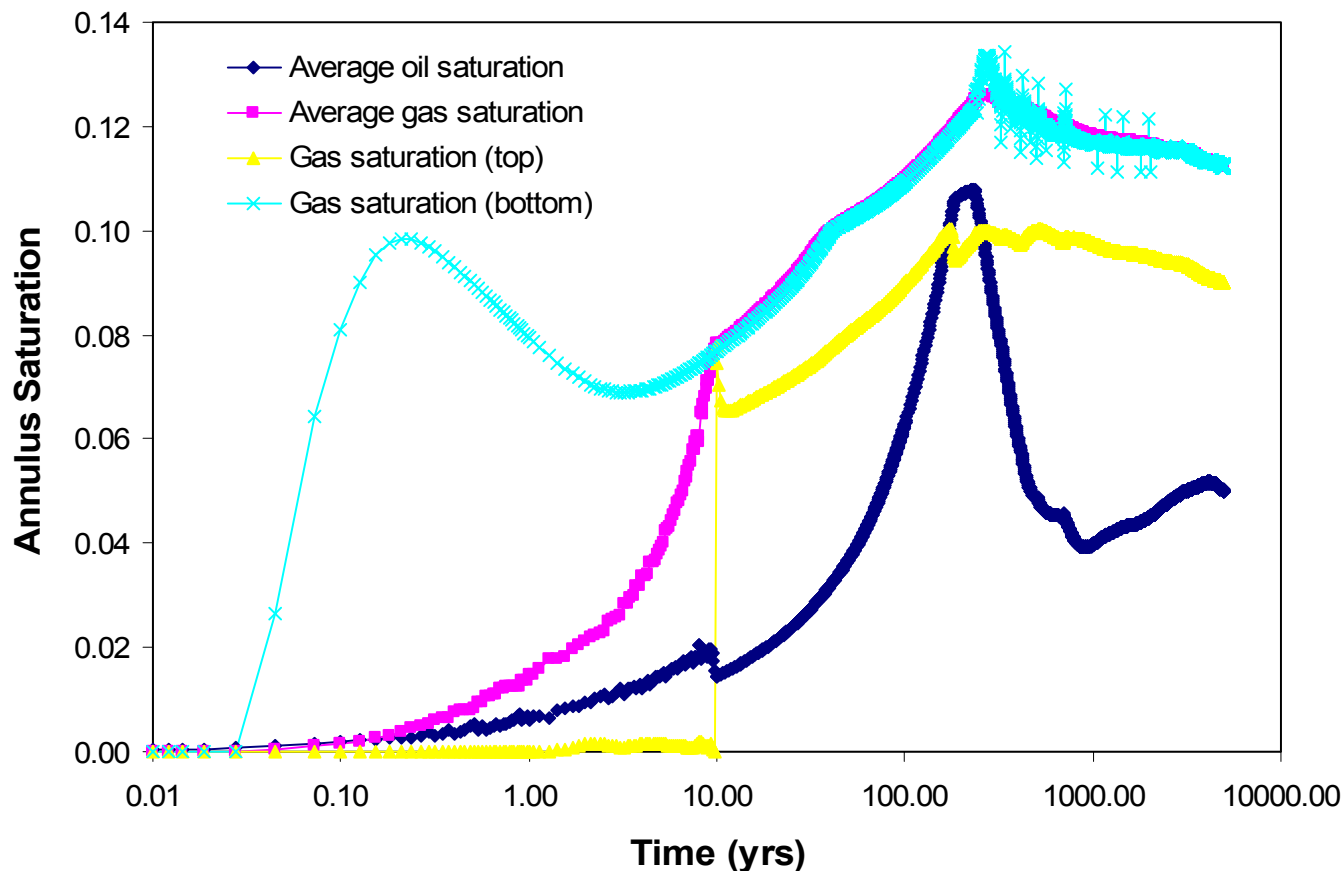
Well Annulus Leakage Results
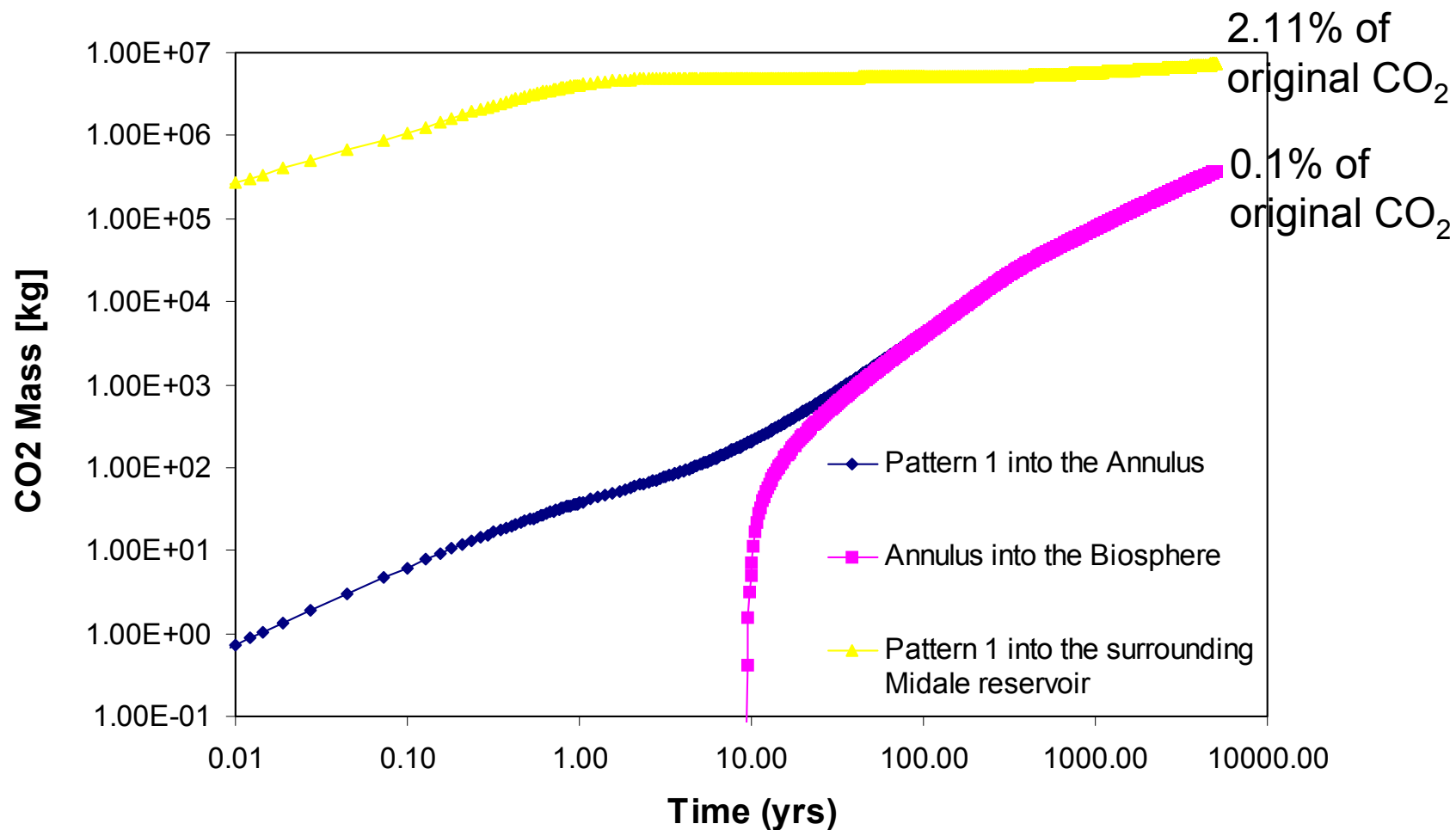
2004 Geosphere Migration Model

- **Based on 2003 Benchmarking modeling experience, but more comprehensive**

- **Use the refined geological System Model**
  - Align with 75 EOR patterns
  - Inside each pattern, use the same spatial discretization as the reservoir simulation model

- **Petrophysical properties and hydraulic heads are mapped into the model grids**

- **75-pattern reservoir simulation results at the end of EOR input as initial conditions**

Alignment between the System Model and the 75-Pattern Model
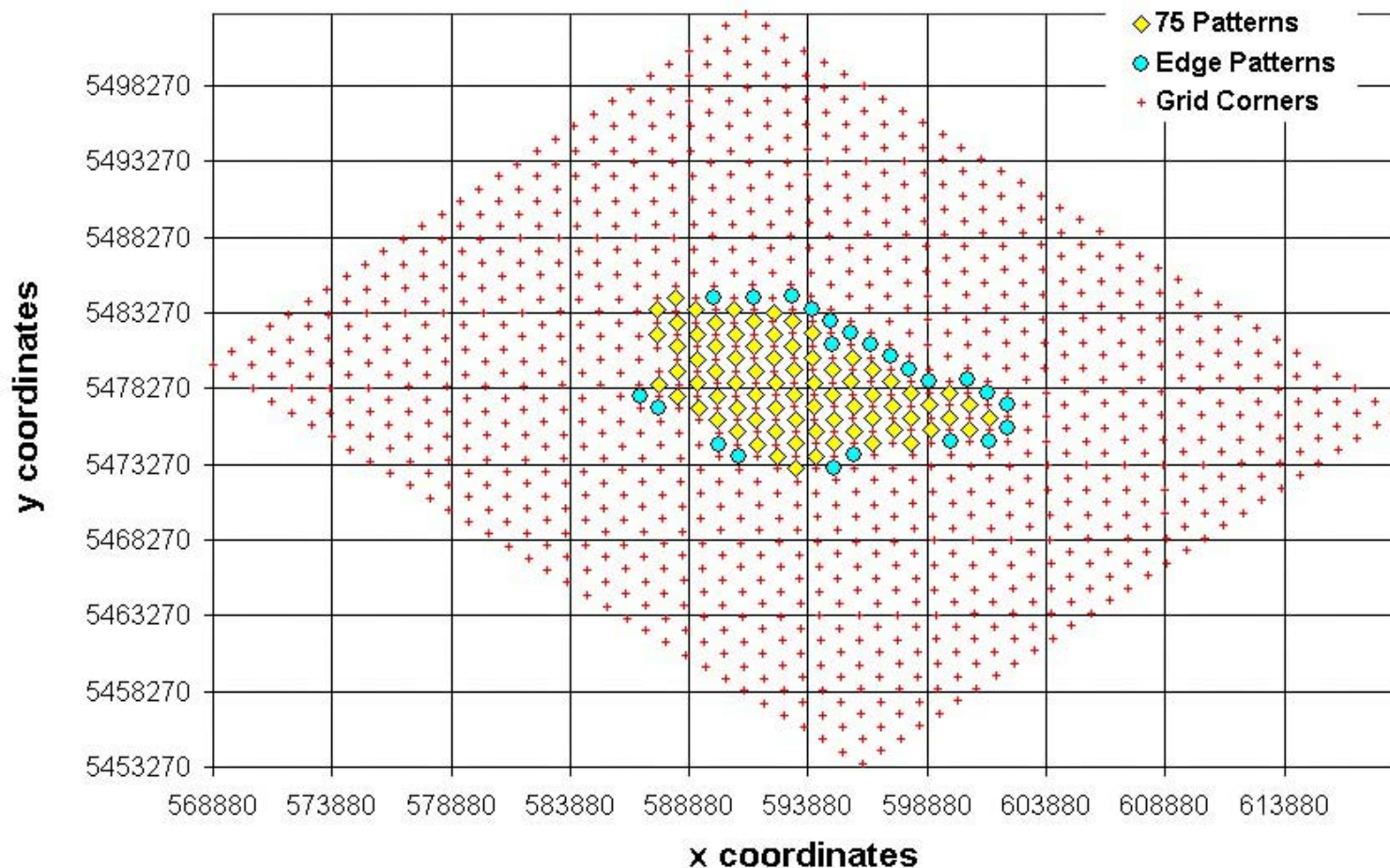
75-Pattern Simulation Model and Results

CO$_2$ Global Mol. Fr.

01 / 01 / 2034

End of EOR
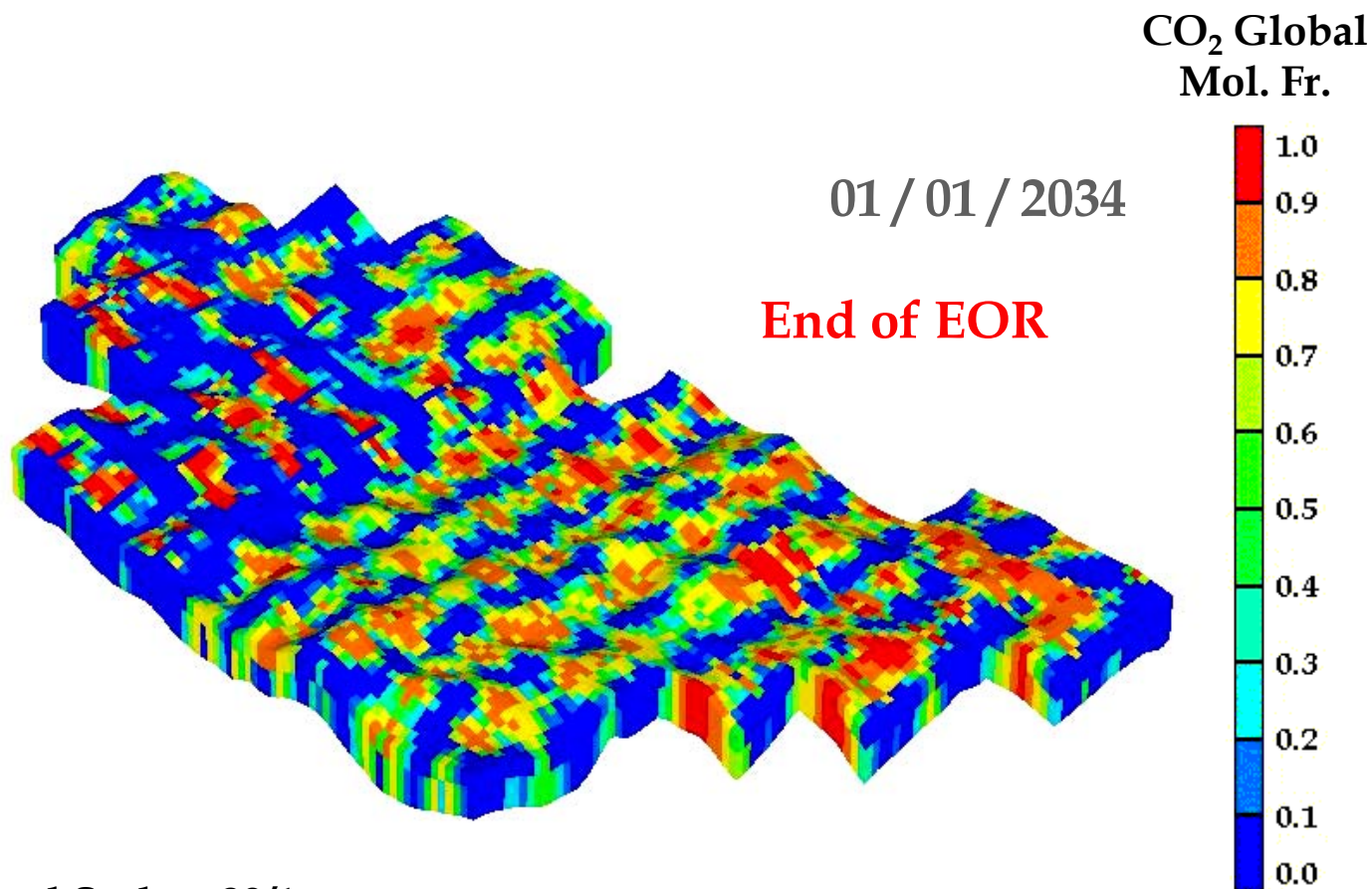
Vertical/Horizontal Scale = 30/1

Probabilistic Well Leakage Assessment

- **The 'Unit Cell' model**
- **Emphasize uncertainties in**
  - Seal properties and degradation
  - CO$_2$ source
  - Reservoir properties
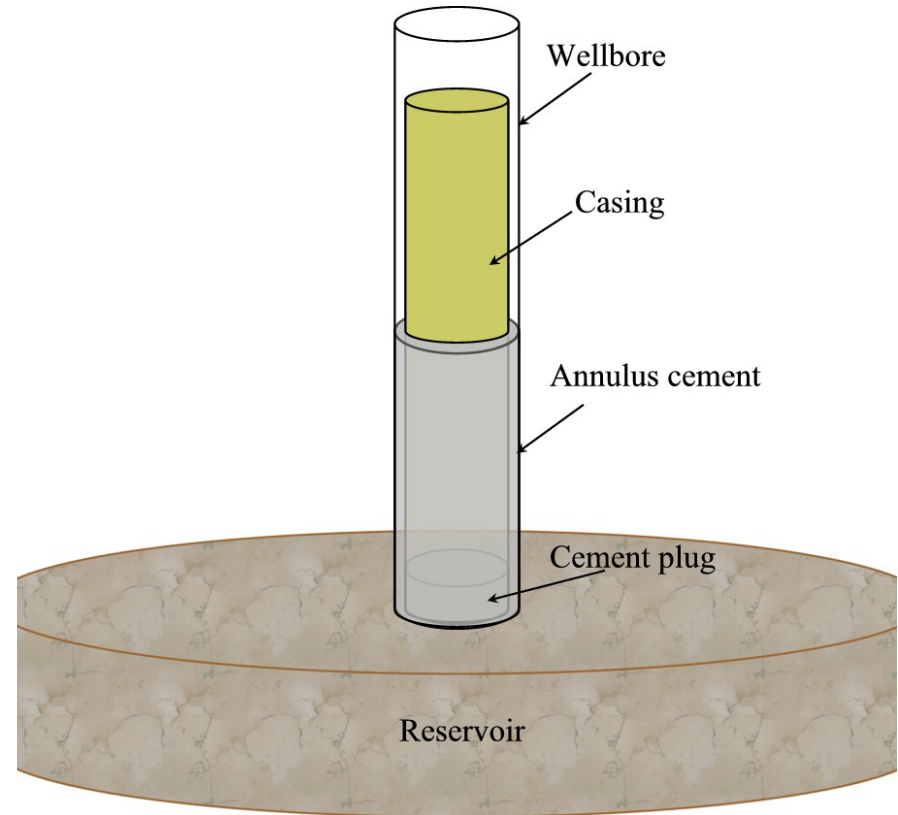
Conclusions

- **Gained experience and learnt lessons from the past three years.**

- **2004 work is technically challenging.**

- **Still have gaps: *e.g.***

  - ❑ Coupled geochemical reactions

  - ❑ Effects of large-scale modeling

  - ❑ Modeling of Alternative Scenarios

A field that is still developing!

Acknowledgement

- **We are grateful for the expertise and enthusiasm of those Research Providers who provided key information and data as input to the long-term assessment modeling.**

NGCAS Approach and Results

Long Term Performance Assessment of CO_2 Storage in Oil Reservoirs

Roy Wikramaratna

Laurence Wickens

ECL Technology Ltd

Risk Assessment Process

Key steps:

- Problem specification
- Identification of key hazards/risk factors
- Definition of risk assessment methodology
- Application to a specific example
- Evaluate acceptability of risk
- Identify areas requiring more detailed study and/or risks requiring mitigation

Problem Specification

Assessment of the risks associated with the long-term geological sequestration of CO_2 in a depleted oil reservoir

- In particular, risks associated with leakage of CO_2 from the reservoir back into the biosphere

Identification of Key Risk Scenarios

Key hazards/risk factors

- failure of long-term sequestration, leading to the return of significant amounts of CO_2 to the atmosphere

- risk to humans and/or environment due to localised release to the biosphere
  - level of hazard defined by nature of release and subsequent dispersion or concentration rather than simply the total amount released
  - need to look at potential pathways and assess risk for each pathway

Risk Assessment Methodology

Identify potential pathways for release

Analytical and/or numerical models to establish bounds on release rates for different pathways and potential release scenarios

Modelling philosophy

- Use simplest approach giving acceptable bound on the risk

- Approach selected may give acceptable bound for one situation; different case may require more sophisticated approach to give a tight enough bound

Possible Outcomes of Risk Assessment

(a) Conclude that the risk is acceptable for example considered

(b) Identify areas where existing models or level of understanding of issues inadequate to give an acceptable bound on the risks

- Such areas require further study

(c) Identify areas where existing models suggest risks may be unacceptable

- Actions to mitigate risk

… or …

- Unacceptable risks lead to rejection

Application to Example - Forties

Have applied approach to an example based on a North Sea reservoir (Forties)

Will outline main issues considered and main conclusions only

- Have discussed this example in more detail already (at yesterday's meeting)

CO2 Release Scenarios
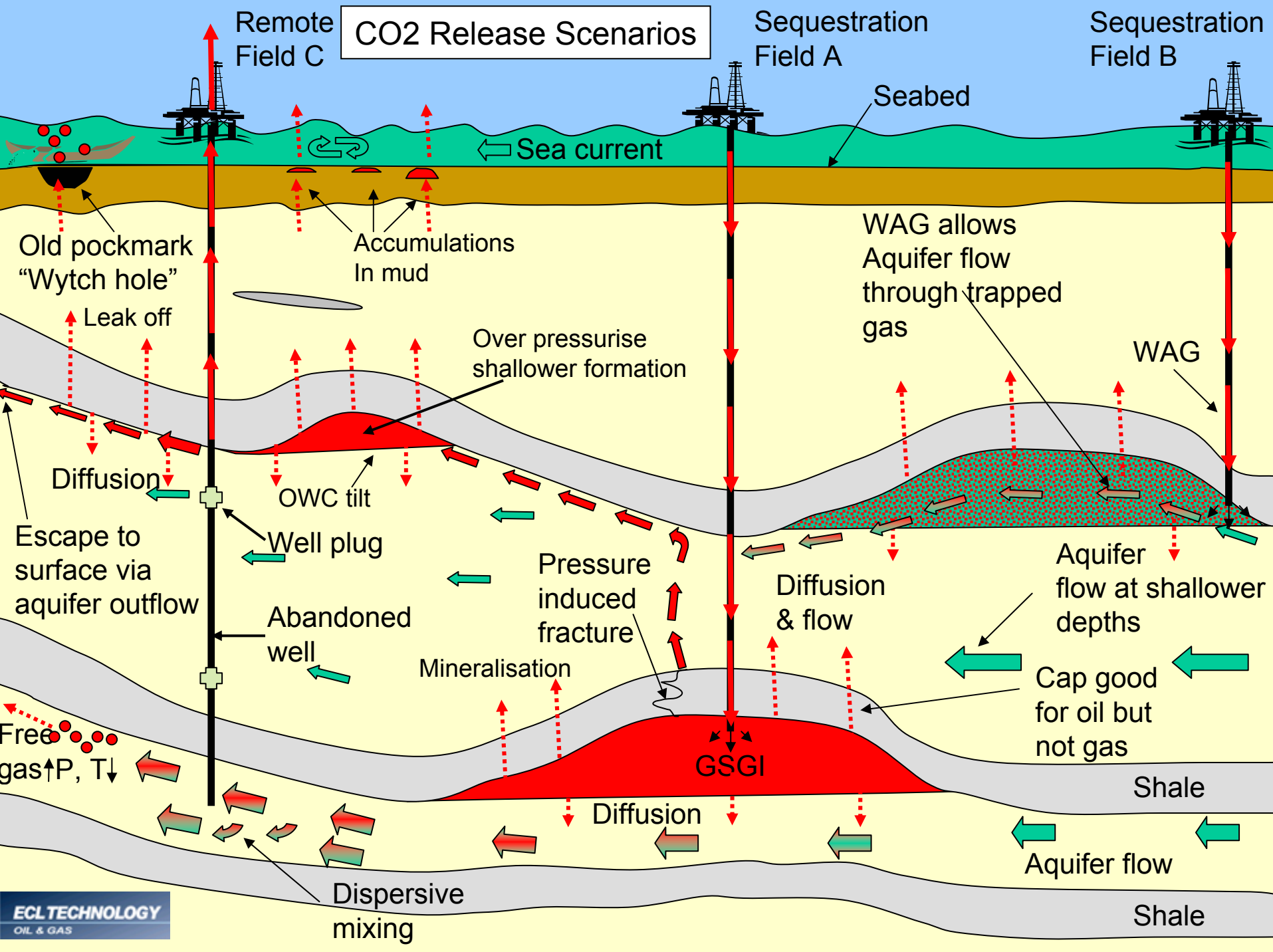
Example - Forties Reservoir

SEA LEVEL

SEA BED

Water Depth
~90-130m

Depth to OOWC
~2217m

Forties Diameter
~10km

Vertical Closure
~155m

OOWC

Nearest Land
~180km

BASE OF AQUIFER

Aquifer Thickness
~300m
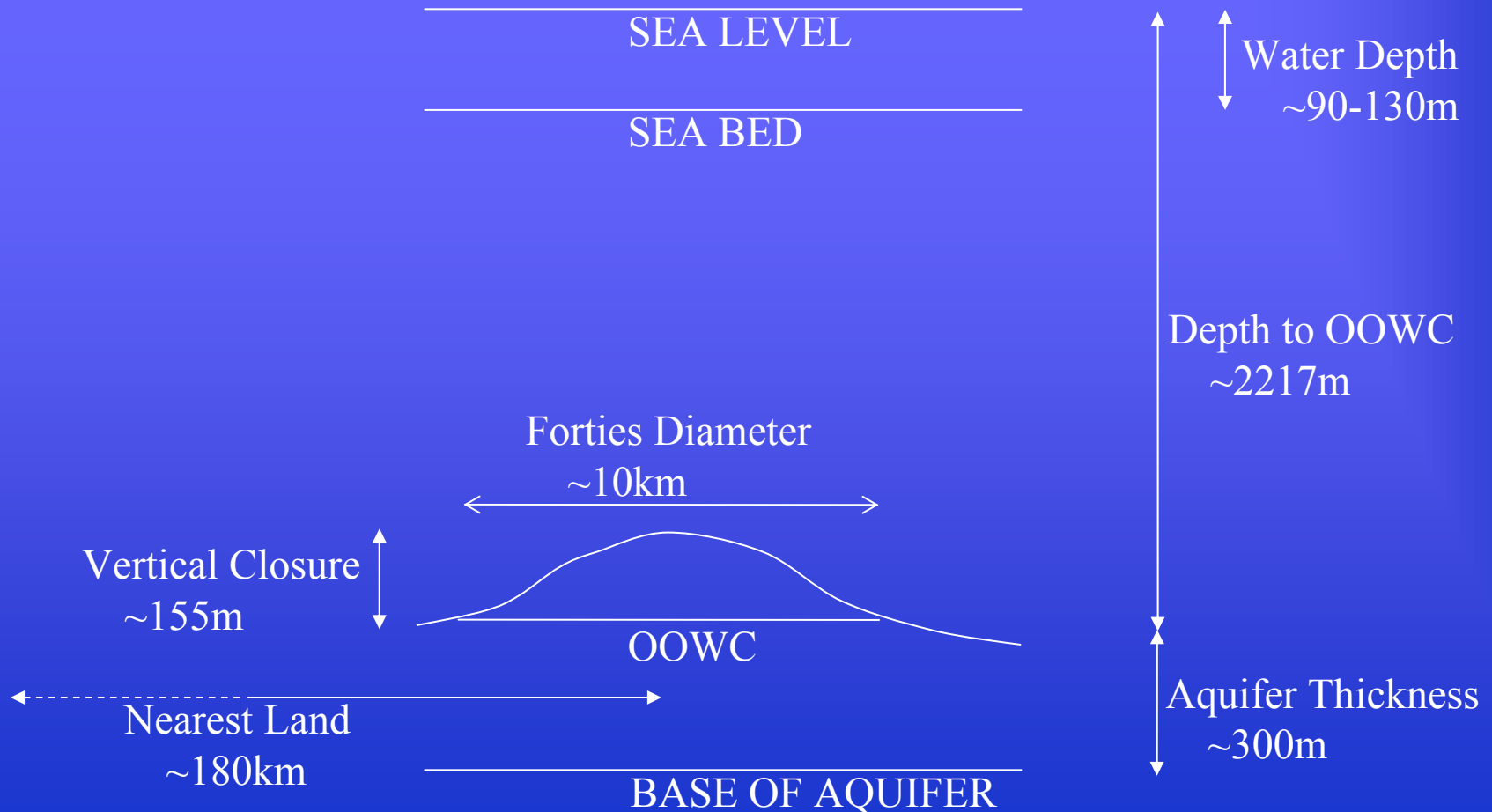
Fluid Densities - Forties

CO_2 (Surface Conditions) $2kg/m^3$

CO_2 (1000m, 120°F) $450kg/m^3$

CO_2 (Reservoir; 2200m, 205°F) $540kg/m^3$

Oil   (Reservoir; 2200m, 205°F) $750kg/m^3$

Brine (Reservoir; 2200m, 205°F) $1030kg/m^3$

Schematic - CO$_2$ release scenarios for Forties

NGCAS
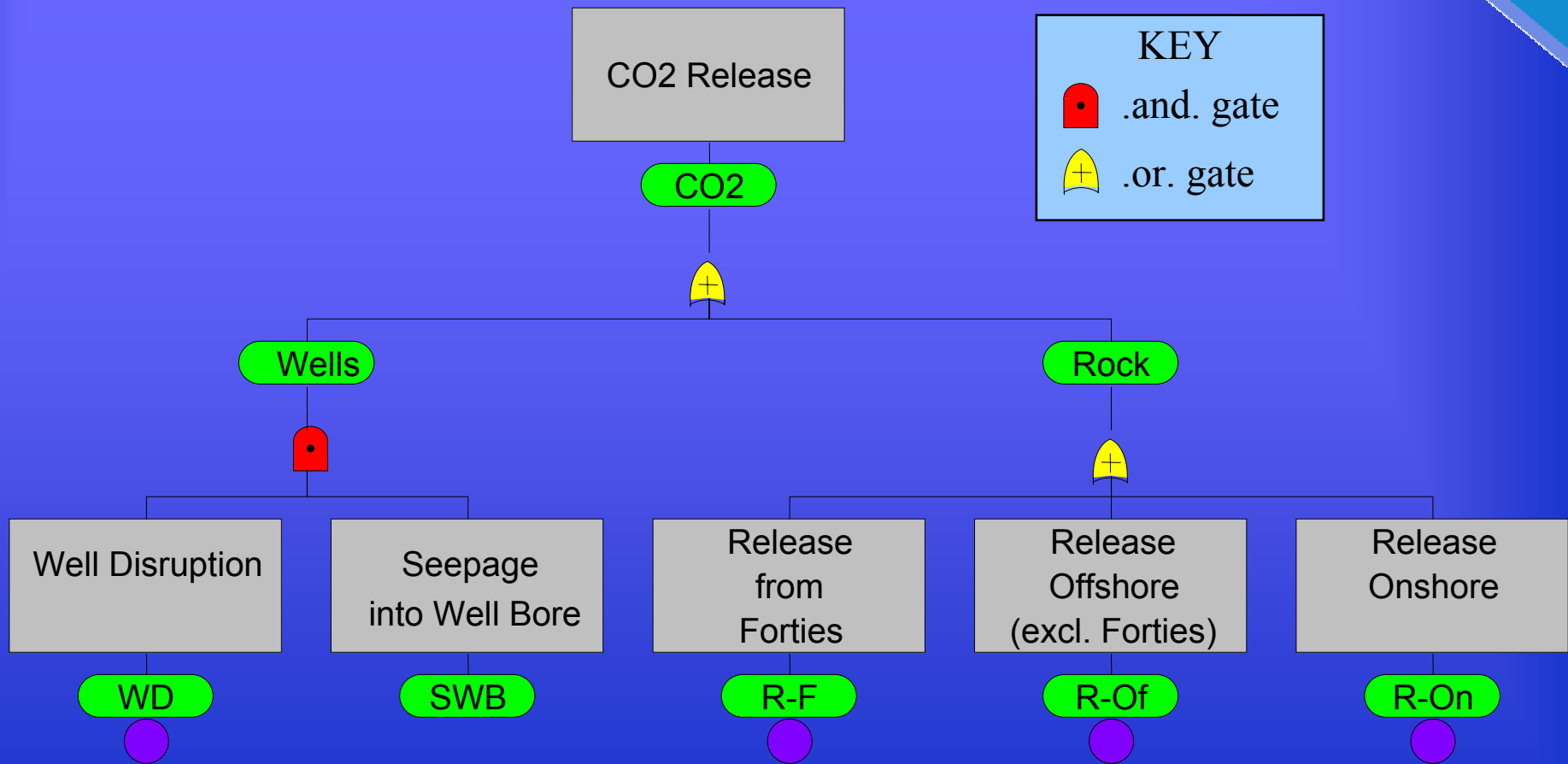
Escape Risk Scenarios

Key pathways for release

- Pathways through the underlying aquifer
  - ◆ Release offshore
  - ◆ Release onshore
- Pathways through caprock and overburden
- Well pathways

Escape Risk Scenarios

Key pathways for release

- Pathways through the underlying aquifer
  - Release offshore
  - Release onshore
- Pathways through caprock and overburden
- Well pathways

KEY

- .and.
- .or.

CO2 Release — CO2

Wells — Rock

Well Disruption (WD) — Seepage into Well (SWB) — Release from Forties (R-F) — Release Offshore (excl. Forties) (R-Of) — Release Onshore (R-On)
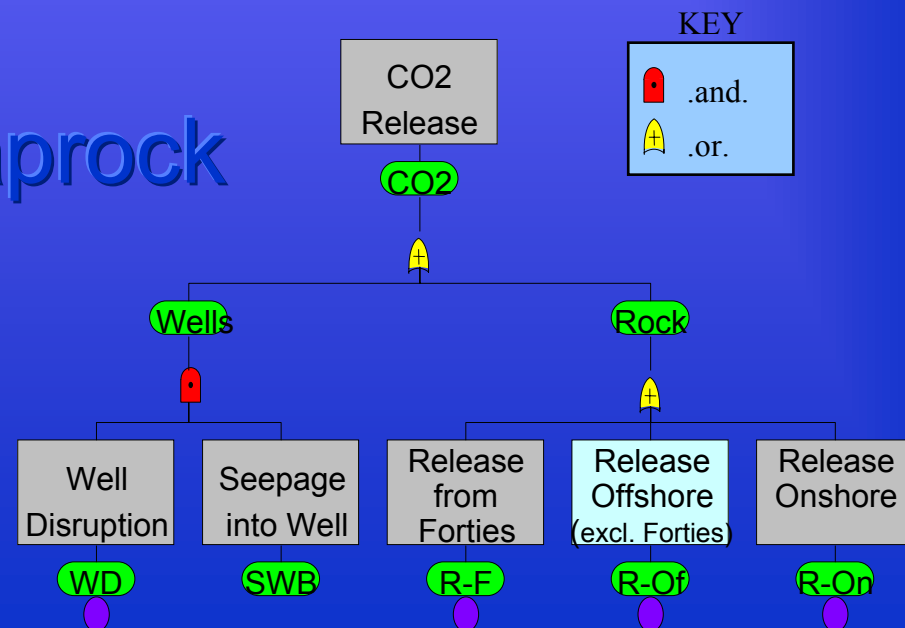
Pathways Through Underlying Aquifer

Dissolved CO_2

- Convection
- Diffusion

Liquid phase CO_2

- Entrainment in aquifer flow
- Effect of high injection pressures at wells, leading to downward flow and escape from trap
- Overfilling of trap

Conclusion on Pathways through Aquifer - Forties

Risks associated with transport pathways through the underlying aquifer, leading to offshore release, are negligible

Escape Risk Scenarios

Key pathways for release

- Pathways through the underlying aquifer
  - ◆ Release offshore
  - ◆ Release onshore
- Pathways through caprock and overburden
- Well pathways
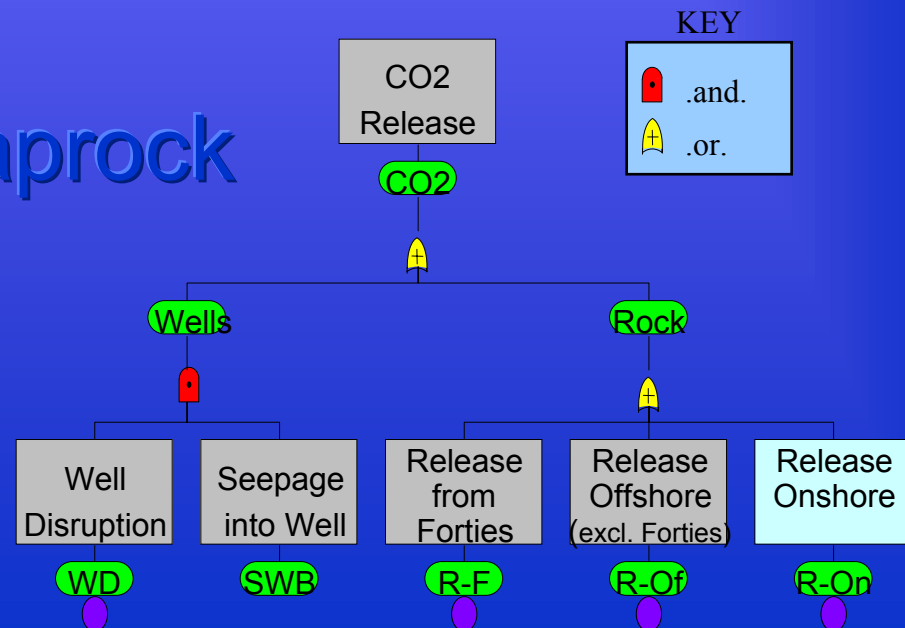
Conclusion Concerning Release Onshore - Forties

Have shown that magnitude of escape and speed of transport mean that release offshore is not an issue

Follows that release onshore is also not an issue (since magnitude would be reduced and timescale increased by comparison)

Escape Risk Scenarios

Key pathways for release

- Pathways through the underlying aquifer
  - ◆ Release offshore
  - ◆ Release onshore
- Pathways through caprock and overburden
- Well pathways
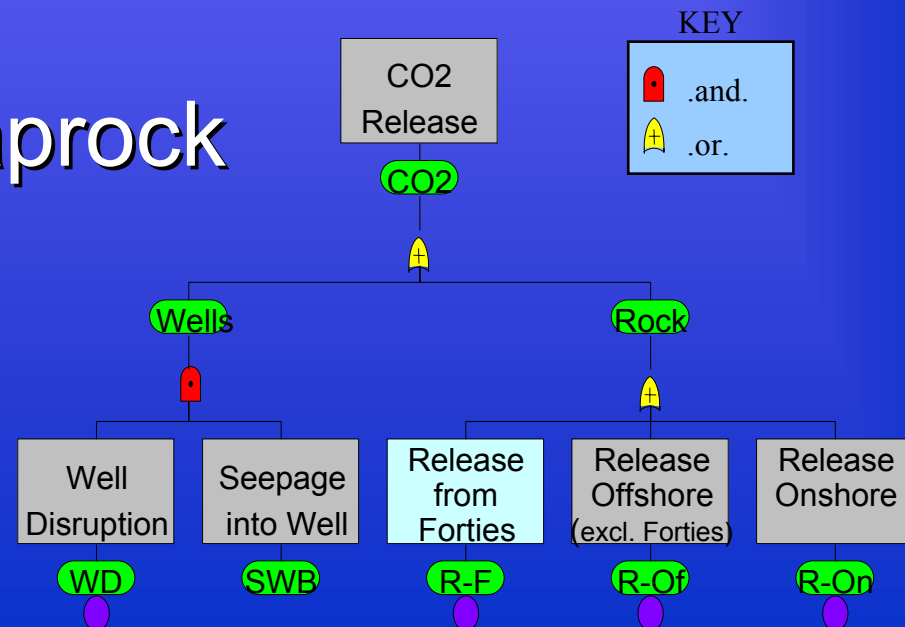
Pathways Through Caprock and Overburden

Consider effects of

- Overpressure
  - increased overpressure due to replacing oil with CO_2
  - local pressure increases at injectors
- Diffusive flux of dissolved CO_2 through caprock and overburden
- Seal damage due to
  - earthquakes/seismic activity
  - chemical reactions involving CO_2

Conclusion on Pathways through Caprock - Forties

Conclude that risks associated with transport pathways through the caprock and overburden are negligible

One potential area identified that may require further work

- Long-term effects of CO_2 on reservoir seal

Escape Risk Scenarios

Key pathways for release

- Pathways through the underlying aquifer
  - ◆ Release offshore
  - ◆ Release onshore
- Pathways through caprock and overburden
- Well pathways
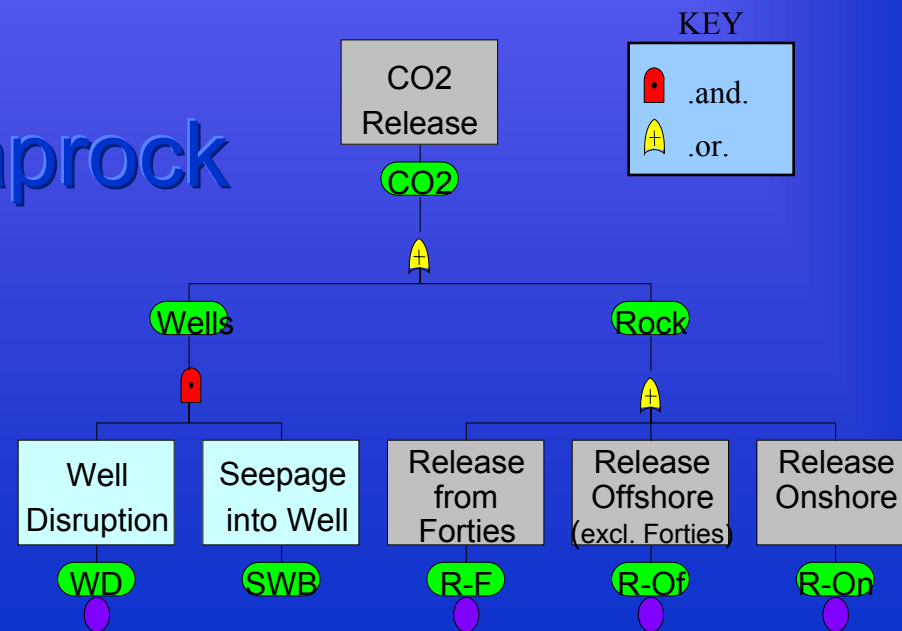
Number of Potential Well Pathways - Forties

Based on data provided by Apache North Sea (Forties operator), December 2003

Current well status

- 190 wells
- 89 abandoned, 27 suspended

Next 10 years

- 30 additional wells drilled
- 24 wells abandoned

Issues Relating to Well Pathways

CO_2 flow in reservoir

Entry to wellbore

Flow up wellbore

- Position of flow barriers; abandonment strategy
- Overpressure; fracture of flow barriers

Escape from well

- Overpressure; fracture of formation
- Leakage from well
  - Into formation or into sea
  - Back to platform

Conclusions on Well Pathways - Forties

Potentially provide route for escape of CO_2

Large number of potential pathways suggests more comprehensive assessment of associated risks may be desirable

Need to understand abandonment strategies adopted in wells already abandoned

- Would require a detailed audit of all wells
- Choice of appropriate strategy for future abandonment might mitigate long-term risks

CONCLUSIONS - 1

Oil reservoirs have potential for CO_2 sequestration

- Combine with EOR to increase benefits
  - Conventional EOR would regard CO2 injection as a cost rather a benefit
- Good characterisation available – helpful in risk assessment
  - Information on size, structure, geology
  - Sealing characteristics of caprock
  - Data from wells, logs
  - Production and injection history

CONCLUSIONS - 3

Have presented a risk assessment methodology, as used in NGCAS project

Illustrated with examples from a North Sea field (Forties)

In applying to a different field situation

- Relative importance of risk factors may change
- Approach to quantifying particular risk factors may need to be modified
- Conclusions will be case-specific

CONCLUSIONS – 4
Forties Risk Assessment

Risks associated with escape through the caprock and into overburden considered negligible (although long-term seal integrity may need further study)

Transport pathways through underlying aquifer considered to have no areas of concern in the long term

Further work required on well integrity and potential pathways through abandoned well bores in order to be able to demonstrate negligible risk

Idaho National Engineering and Environmental Laboratory

A Mathematical Model for Conducting Probabilistic Risk Assessment of CO_2 Storage in Geological Traps

Shaochang Wo

Fossil Energy Technologies Dept., INEEL

IEA/RA Workshop, London, UK, Feb. 11-12 2004
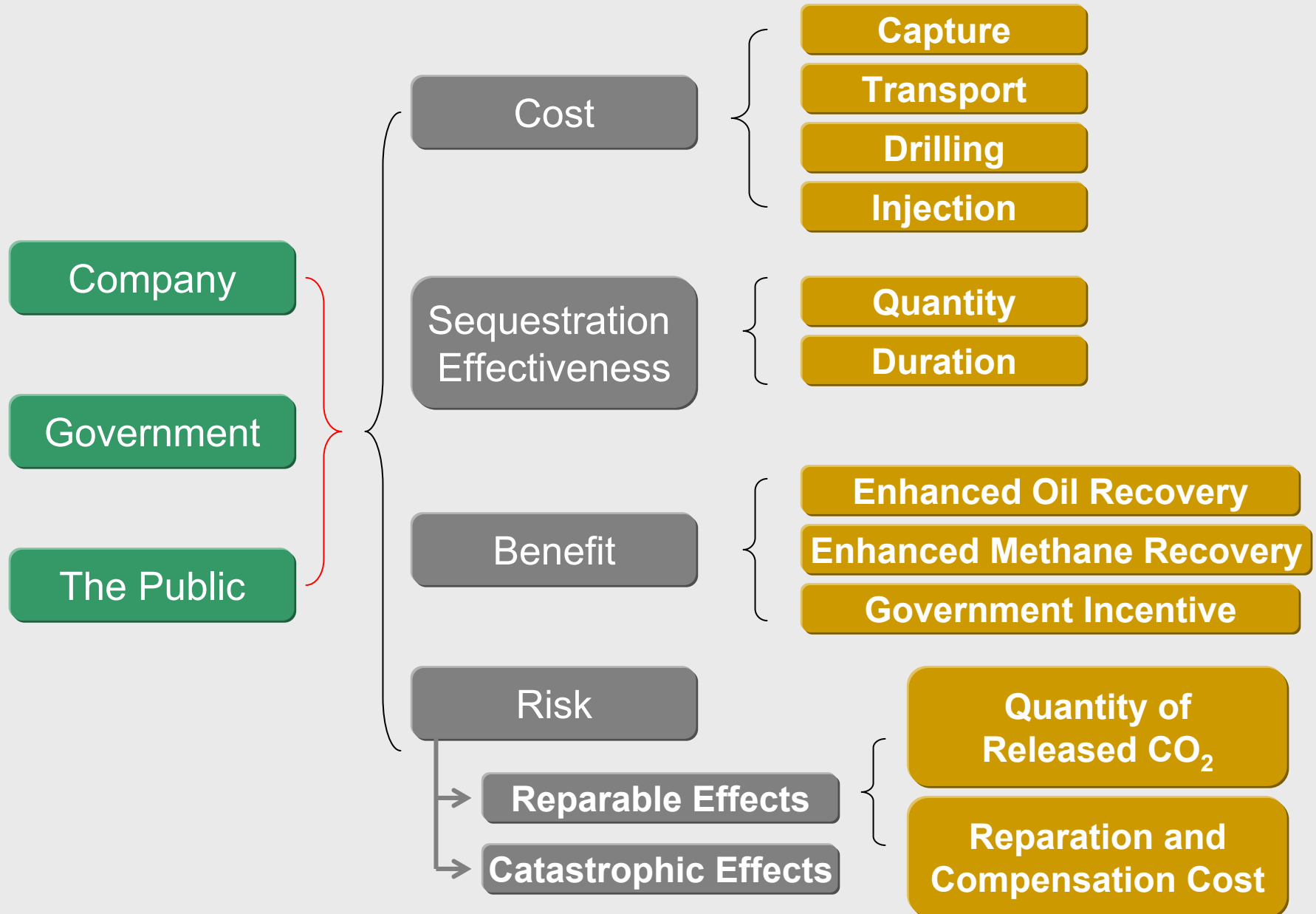
GUIDELINES IN MODEL DEVELOPMENT

- ❑ Generality and transparency
- ❑ Designed for implementation on a relational database
- ❑ Inference rules can be converted to and verified by set operations
- ❑ Quantified indicators as model outputs
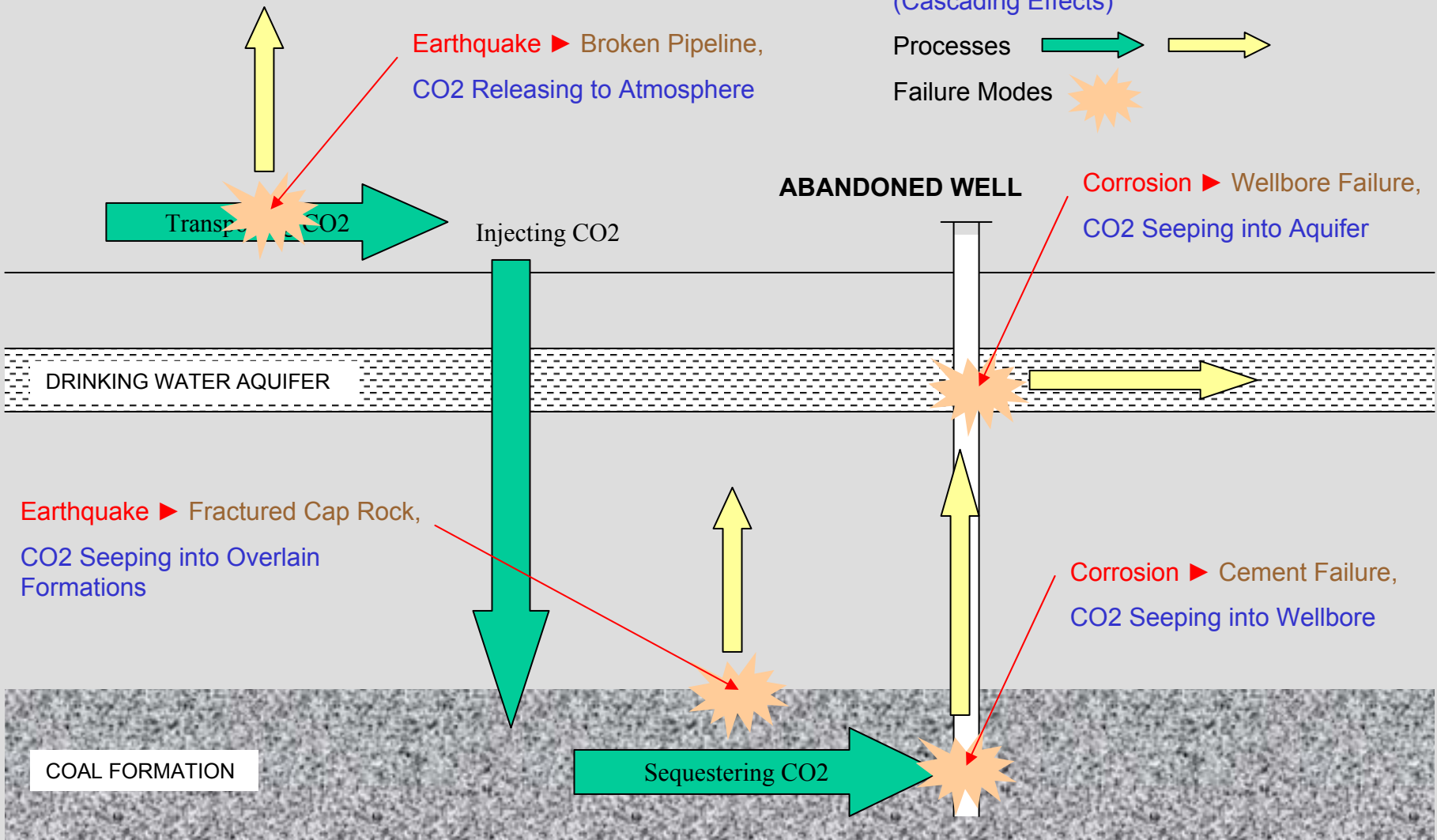
QUESTIONS FOR IDENTIFYING A FAILURE MODE

- ❑ What can go wrong?
- ❑ What causes the failure?
- ❑ What is the likelihood of the failure happening?
- ❑ How much CO_2 could release?
- ❑ What are the consequences?
- ❑ What is the remediation cost if the failure is reparable?

SIX CONSTITUENTS *(implemented by six database tables)*

(1) $I = \{i_1, i_2, i_3, \Lambda\}$, Initiators.

(2) $P = \{p_1, p_2, p_3, \Lambda\}$, Processes.

(3) $M = \{m_1, m_2, m_3, \Lambda\}$, Failure Modes.

(4) $C = \{c_1, c_2, c_3, \Lambda\}$, Consequences (Effects).

(5) $D = \{d_1, d_2, d_3, \Lambda\}$, Indicators.

(6) $Q = \{q_1, q_2, q_3, \Lambda\}$, Inference Queries.

SEVEN TYPES OF IDENTIFIED INFERENCE RULES
(implemented by seven database tables)

(1) $P \Leftarrow \overset{\varpi}{F}_P(I),$ identify processes affected by each initiator.

(2) $M \Leftarrow \overset{\varpi}{F}_M(P),$ define failure modes associated with each process.

(3) $C \Leftarrow \overset{\varpi}{F}_C(P,M),$ identify consequences if a failure mode occurs.

(4) $I \Leftarrow \overset{\varpi}{F}_I(C),$ identify cascading effects.

(5) $D \Leftarrow \overset{\varpi}{F}_D(I,P,M,C),$ dynamically calculate and reevaluate indicators.

(6) $I \Leftarrow \overset{\varpi}{F}_I(Q),$ indirectly identify initiators.

(7) $C \Leftarrow \overset{\varpi}{F}_C(Q),$ indirectly identify consequences.

Effect of Corrosion on Casing & Tubing Failure
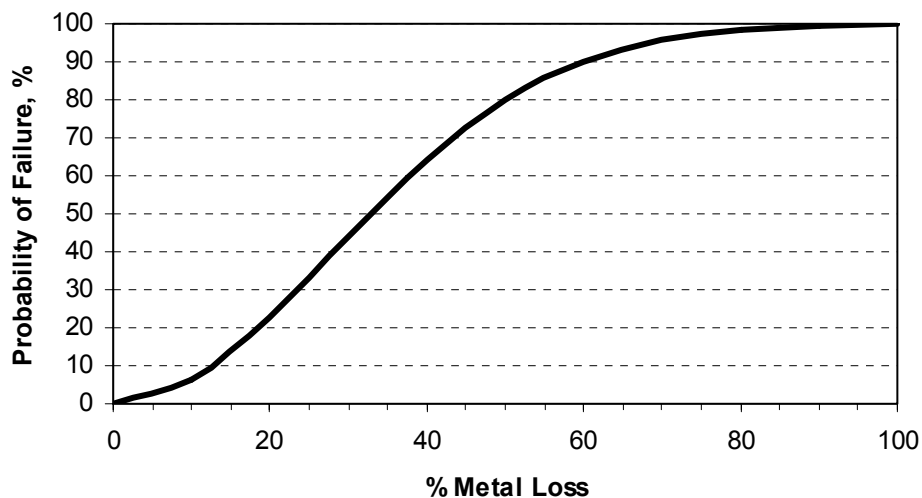
Bradenhead (Casing) Pressure and Gas Leakage
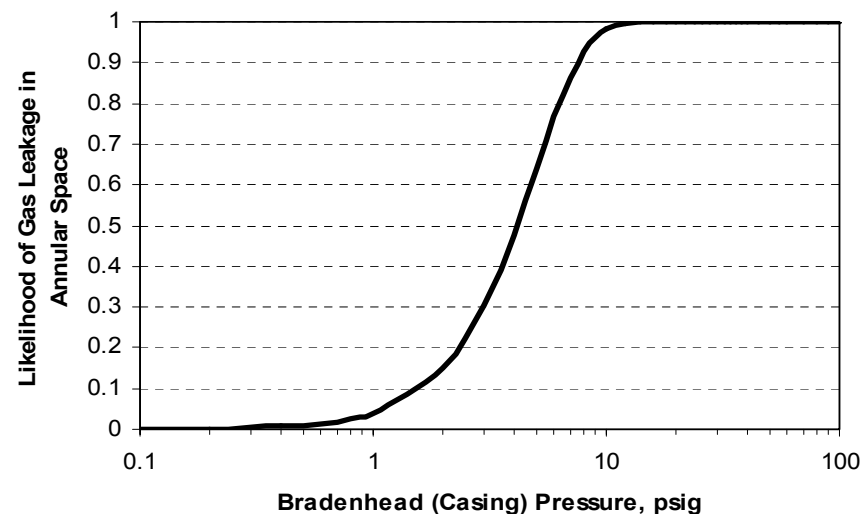
Distance Effect of Point Source CO_2 Release into Atmosphere on Severity of Human Safety & Health Hazard
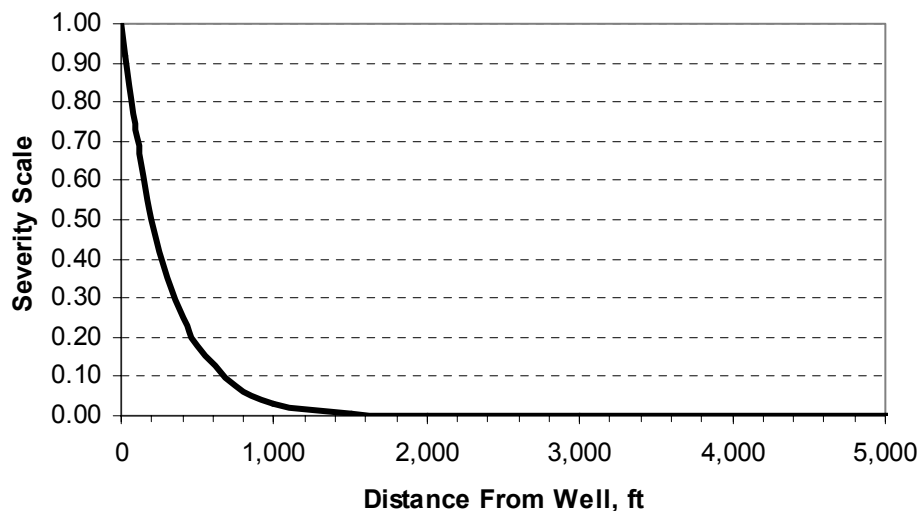
Rate Effect of Point Source CO_2 Release into Atmosphere on Severity of Human Safety & Health Hazard
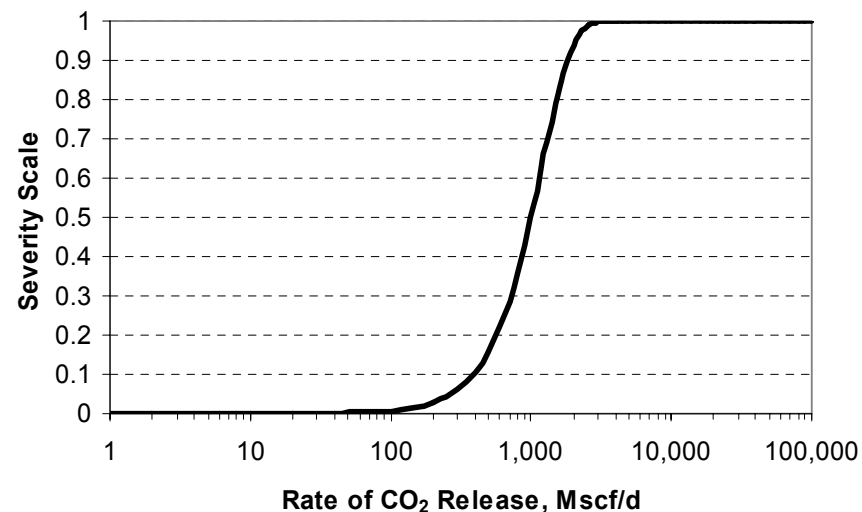
EXAMPLES OF CRITERIA FOR RANKING THE SEVERITY SCALE OF CONSEQUENCES

Criterion	Severity Scale (0~1)
Adverse Effect to Human Health	S_1
Adverse Effect to Animals	S_2
Potentiality of Violating Regulations	S_3
Duration	S_4
Cascading Effect	S_5
Undetectability	S_6
Uncontrollability	S_7
Irreversibility	S_8

$$Combined\ Severity\ Scale = \frac{\sum_i w_i S_i}{Number\ of\ Criteria} \qquad where\ w_i\ are\ weighting\ factors$$

Quantifying the risk of a failure mode

A failure mode: *M*

Occurred in a process: *P*

Caused by *n* initiators: *I$_i$* with *LIKELIHOOD(I$_i$), i=1~n*

CO_2 releasing rate at 100% failure: Rate*

Reparable cost at 100% failure: Cost*

The likelihood of CO2 existence in process *P*

$$LIKELIHOOD(P) = \begin{cases} 1, & \text{if } P \text{ is a planned } CO_2 \text{ path} \\ \prod_k LIKELIHOOD(M_k), & \text{otherwise} \end{cases}$$

where *LIKELIHOOD(M$_k$)* are the likelihood values of the preceding failures in the cascading CO_2 releasing path.

The combined likelihood of *n* initiators

$$LIKELIHOOD(\{I_1, I_2, \Lambda, I_i\}) = LIKELIHOOD(I_i) + LIKELIHOOD(\{I_1, I_2, \Lambda, I_{i-1}\})$$

$$- LIKELIHOOD(I_i) * LIKELIHOOD(\{I_1, I_2, \Lambda, I_{i-1}\}), \ i = 2 \sim n.$$

The effective likelihood of the failure mode

$$LIKELIHOOD(M) = LIKELIHOOD(P) * LIKELIHOOD(\{I_1, I_2, \Lambda, I_n\})$$

The effective CO_2 releasing rate of the failure mode

$$Rate = Rate^* * LIKELIHOOD(M)$$

The effective reparable cost of the failure mode

$$Cost = Cost^* * LIKELIHOOD(M)$$

The effective severity scale of consequence *i*

$$\sqrt{(Severity\ Scale\ of\ Consequence\ i) * LIKELIHOOD(M)}$$

SCENARIO SIMULATION

1) Activate selected initiators;

2) Identify affected processes;

3) Calculate the failure likelihood of each failure mode;

4) Identify the consequences;

5) Estimate the CO_2 releasing rate, reparable cost, and severity scale;

6) Repeat step (1)~(5) if new initiators are invoked by resulting consequences (cascading effects);

7) Calculate and reevaluate indicators.

CONVERT A DECISION TREE TO SET OPERATIONS
(often used in indirectly detecting initiators or consequences)
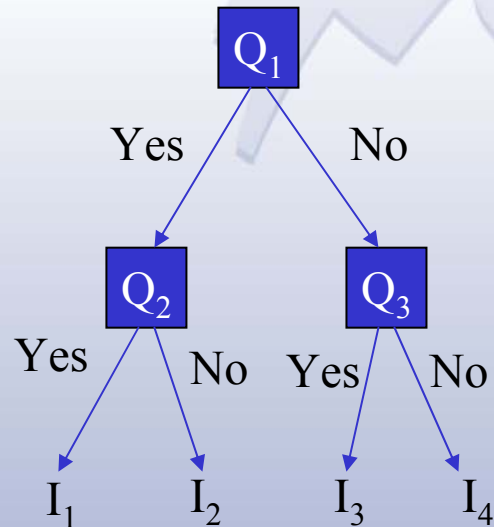
	I_1	I_2	I_3	I_4
Q_1	Yes	Yes	No	No
Q_2	Yes	No	NA	NA
Q_3	NA	NA	Yes	No

Two Sets of Inference Rules:
Forward (Starting from Queries) and
Backward (Starting from Initiators)

Example (forward)

$$Decision\ Tree : If\ Q_1\ true\ and\ Q_2\ false\ then\ I_2$$
$$Set\ Operation : \{I_1, I_2\} \cap \{I_2\} = I_2$$

File Edit View Insert Format Records Tools Window Help

MS Sans Serif   8   **B** *I* <u>U</u>

Main Page

PROJECTS

Project Name	Company Name	Perfomed By	Description

Risk Assessment Project of the Tiffany Unit, San Juan Basin

◄ View Existing Projects ►

Create A New Project

PROCESS IDENTIFICATION

CO2 Fate and Transport

INITIATOR AND EFFECT TABLES

Initiators   Failure Modes   Effects

RISK SEVERITY MATRICES

Activate Initiators   Define Severity Scales

REPORTS AND ANALYSIS TOOLS

Redo Evaluation

Reports   Graphs   Maps

Record: |◄ ◄   1   ► ►| ►*   of 2

New_Project

Create A New Project

Project ID   (AutoNumber)

Initiators

Initiator Table

Initiator ID   3   Initiator Name   Corrosion-Sulfide/(

Classification ID   102   Variable Type   1

☑ Spatial Scale Applicable

Effects

Effect Table

Effect ID   4

Effect Name   Increased Bradenhead Pressure

Hazard Scale   10

Defined Processes

Process Relationship

Processes

Process ID	Process Name	Node #	Up Node #	Down Node #	Description
1	P1_Surface_Trans	1	0	2	Surface CO2 Transportation
2	P2_Injection	2	1	3	CO2 Injection Process
3	P3_In_Formation	3	2	4	CO2 in the Fruitland Coal Bed
4	P4_Outcrop_Seep	4	3	99	CO2 Seepage from Outcrop
6	P5_Caprock_Seep	5	3	99	CO2 migrates into the caprock (Kirt

Form View   NUM

Start   ...   3:57 PM

File Edit View Insert Format Records Tools Window Help

Tahoma | 9 | **B** *I* U
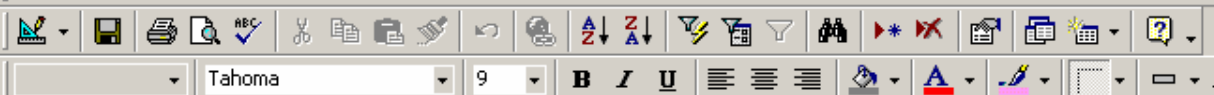
FailureMode

Selecte A Failure Mode
Production Tubing Failure

Failure Mode ID 1

Max Rate 12.50 Mcf/Day
Effective Rate 2.90 Mcf/Day

Max Cost $68,000.00 $
Effective Cost $15,756.12 $

Failure Mode Description
Production Tubing Failure - Carbon Steel Piplines within Five-Year Production

Monte Carlo Simulation   Update

Effective Likelihood 0.2317
Effective Severity Index 0.3759

Number of Runs 200

Activate Initiators

	Activation	FailureModeID	InitiatorID	InitiatorName	Likelihood
▶	☑	1	2	Corrosion-CO2	0.22
	☑	1	3	Corrosion-Sulfid	0.015
	☑	1	4	Earthquake	0.00001
*	▨				

Record: |◀ ◀| 1 |▶ ▶| ▶* of 3

Define Consequences Severities

	Activation	FailureModeID	EffectID	EffectName	SeverityScale
▶	☑	1	1	Adverse Effec	0.0001
	☑	1	2	Adverse Effec	0.05
	☑	1	3	Potentiality o	0.01
	☑	1	4	Increased Bra	0.2
*	▨				

Record: |◀ ◀| 1 |▶ ▶| ▶* of 4

Severity Matrix

Probability: [0, 0.01] (0.01, 0.05] (0.05, 0.1] (0.1, 0.5] (0.5, 0.9] (0.9, 1]

Likelihood Caused by the Initiators

FailureModeID	InitiatorName	Unlikely	Seldom	Occasional	Likely	Frequent	Inevitable
1	Corrosion-CO2				0.22		
1	Corrosion-Sulfid		0.015				
1	Earthquake	0.00001					

Record: |◀ ◀| 1 |▶ ▶| ▶* of 3

The Combined Likelihood of the Failure Mode

FailureModeID	FailurModeName	Unlikely	Seldom	Occasional	Likely	Frequent	Inevitable
1	Production Tubing				0.23171		

Effective Severity Scales of the Consequences

FailureModeID	EffectName	Unlikely	Seldom	Occasional	Likely	Frequent	Inevitable
1	Adverse Effect on				0.10764		
1	Adverse Effect on				0.00481		
1	Increased Braden				0.21527		

Record: |◀ ◀| 1 |▶ ▶| ▶* of 4

Form View

NUM

Start | C:\BP\R... | Docume... | Untitled... | Shaoch... | IEA_RA... | Tiffany... | Failure... | 5:44 PM

ONE-TIME SCENARIO SIMULATION vs. MONTE CARLO SIMULATION

Effect of Corrosion on Casing & Tubing Failure
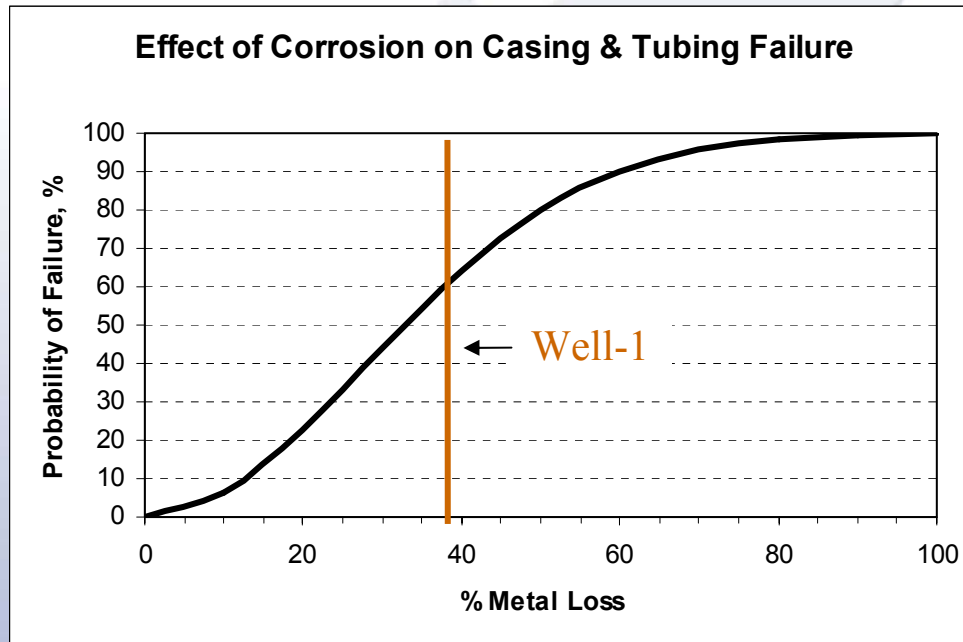
Initiator: Corrosion-Metal Loss

Process: Well-1 Production Tubing

Failure Mode: Tubing Failure

Likelihood: 60%

One-Time Simulation

LIKELIHOOD	0.6

Monte Carlo Simulation

LIKELIHOOD	1
LIKELIHOOD	0
LIKELIHOOD	1
LIKELIHOOD	1
LIKELIHOOD	0

$y = Random(\ )$

$$LIKELIHOOD = \begin{cases} 0, & \text{if } y > 0.6 \\ 1, & \text{if } y \leq 0.6 \end{cases}$$
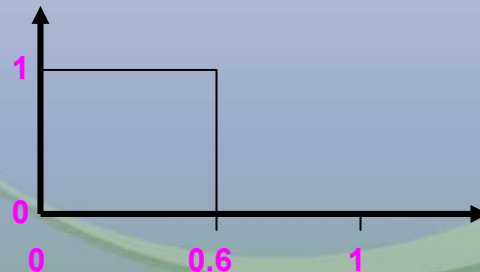
Example of Monte Carlo Simulation of a Failure Mode
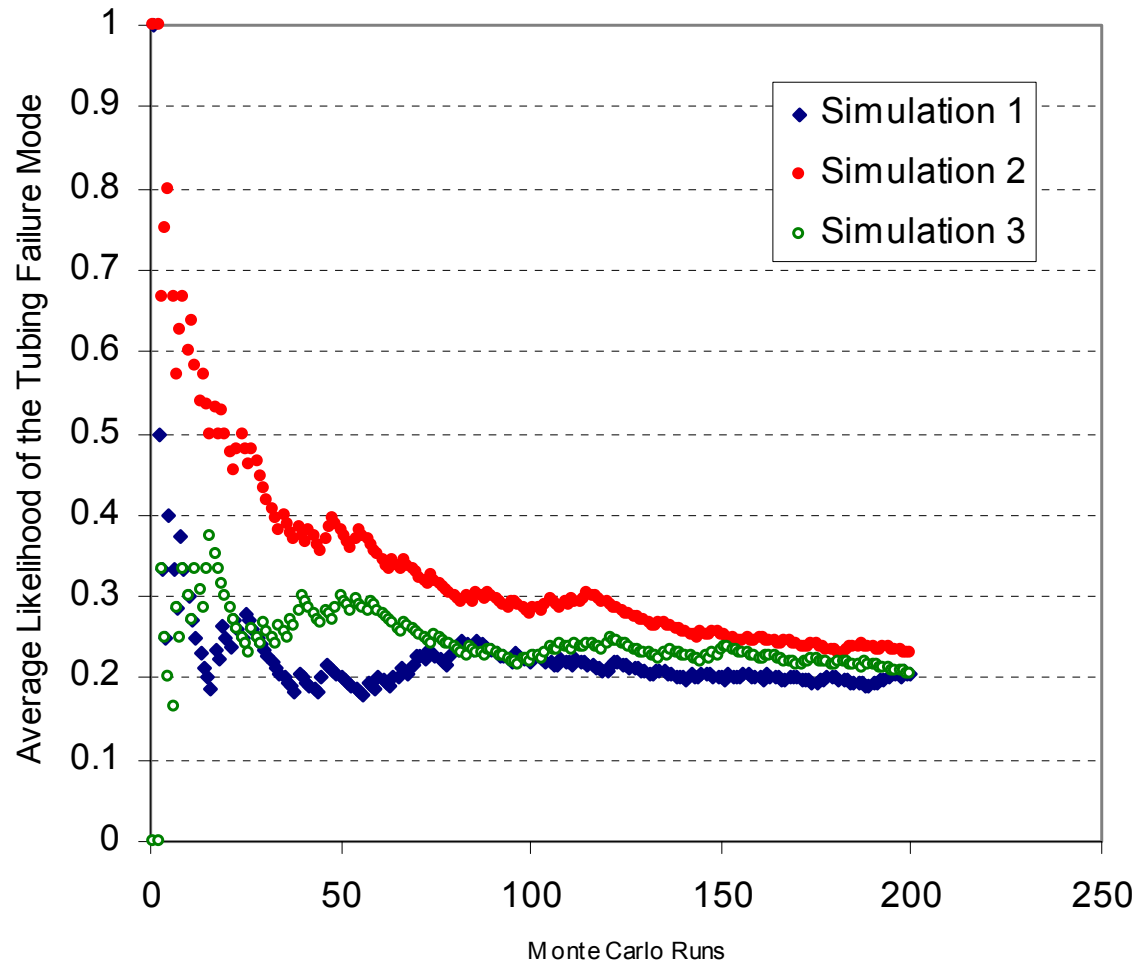
In general, if there are *N* Initiators.

For one-time Scenario Simulation run, use

$$I_i \text{ with } LIKELIHOOD(I_i), i = 1 \sim N.$$

For a series of Monte Carlo Simulation runs, use

$$I_i \text{ with } LIKELIHOOD_{MC}(I_i), i = 1 \sim N,$$

$$\text{where } LIKELIHOOD_{MC}(I_i) = \begin{cases} 0 & \text{if } LIKELIHOOD(I_i) < Random() \leq 1 \\ 1 & \text{if } 0 \leq Random() \leq LIKELIHOOD(I_i) \end{cases}$$

THREE-STEP APPROACH OF A DYNAMIC SYSTEM

Information/Data Acquisition	Representation & Implementation	System Analysis
Project Plan	Processes	Inference Logic Based on Set Theory
Potential CO2 Releasing Paths	Failure Modes	Scenario Testing
Hazard Identification	Initiators	Consistency of Risk Scales
Expert Knowledge	Consequences (effects)	
Regulations & Policies	Risk Quantification	
Simulation Forecast	Indicators	

INDICATORS USED IN RISK ANALYSIS

- Activated Initiators

- Affected Processes (Failure Modes)

- Possible Consequences and Their Severity Scales

- Process Tree (CO_2 Fate and Transport)

- Initiator-Process-Consequence Diagram (One to Many)

- Consequence-Process-Initiator Diagram (One to Many)

- Initiator-Consequence Diagram (Many to Many)

- Overall Risk Index

- Sensitivity of Initiators to the Overall Risk

- Sensitivity of Consequences to the Overall Risk

Recommendations

❑ A risk assessment system for CO_2 sequestration should be viewed as a dynamic information system. The capability of being easily updated with new data is essential.

❑ Need standardized criteria and severity scale ranking method for evaluating consequences.

❑ Need well defined quantitative risk indicators that can be used by decision makers.

Acknowledgments

Numerical Simulation of Storage and Leakage Behavior of Injected CO_2

YUKIO IMASEKI,   **TAKASHI OHSUMI**

Research Institute of Innovative Technology for the Earth

(RITE)

Japan

11 February, 2004

Outline of My Presentation

1. Background and Purpose

2. Simulation of CO_2 Injection

   When is the risk highest?

3. Simulation of CO_2 Leakage

   What would happen if CO_2 leaks?

4. Conclusions

Background / Purpose

■ Target：

   Aquifers of Offshore Japan

      (Potential capacity :73.5 billion tons
of CO_2)

■ Technical concept：

   Supercritical CO_2 injection through wells
                              similar to that of
Sleipner case

   BUT

     Complex geological strata and
                         frequent earthquakes

■ Purpose：

   Assess the risk of CO_2 injection into
Aquifers

3

Outline of My Presentation

1. Background and Purpose

2. Simulation of CO_2 Injection

3. Simulation of CO_2 Leakage

4. Conclusions

Input Data of Simulation

Sea

Top :
1,000m

Spill Point: 1,900m

Injection site
Domal & Anticlinal Aquifer

Area : 70km^2

Thickness : 100m
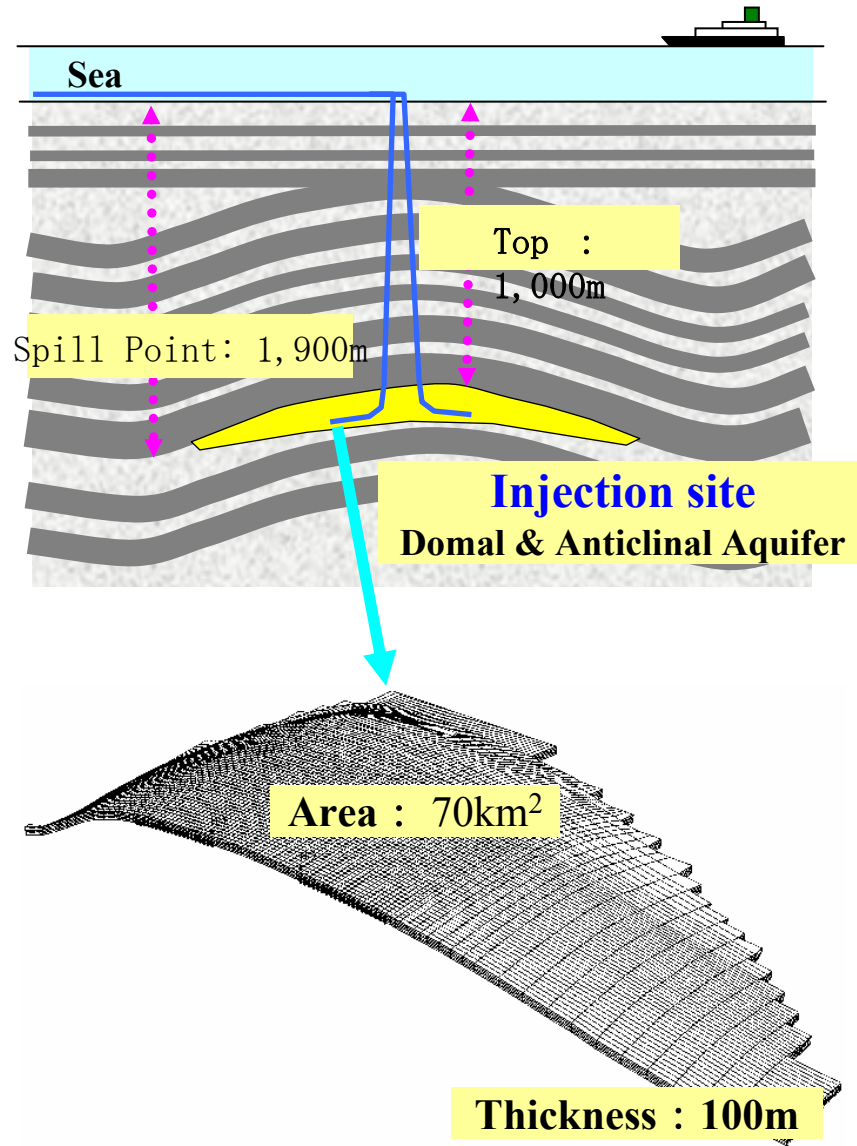
Operation

Injection Rate	:	10,000tons／day
Injection Period	:	20years
Total amount	:	73million tons
Injection Wells	:	Horizontal×2

Aquifer

Volume	: 1620million m^3
Temperature	: 50℃
Pressure	: 110kg/cm^2 at 1,000m
Horizontal Permeability	: 200md
Vertical Permeability	: 20md
Porosity	: 23%

RIT

5

Modeling Structure of Aquifer

Plane View

Injection Well

12km

9km

Cross View
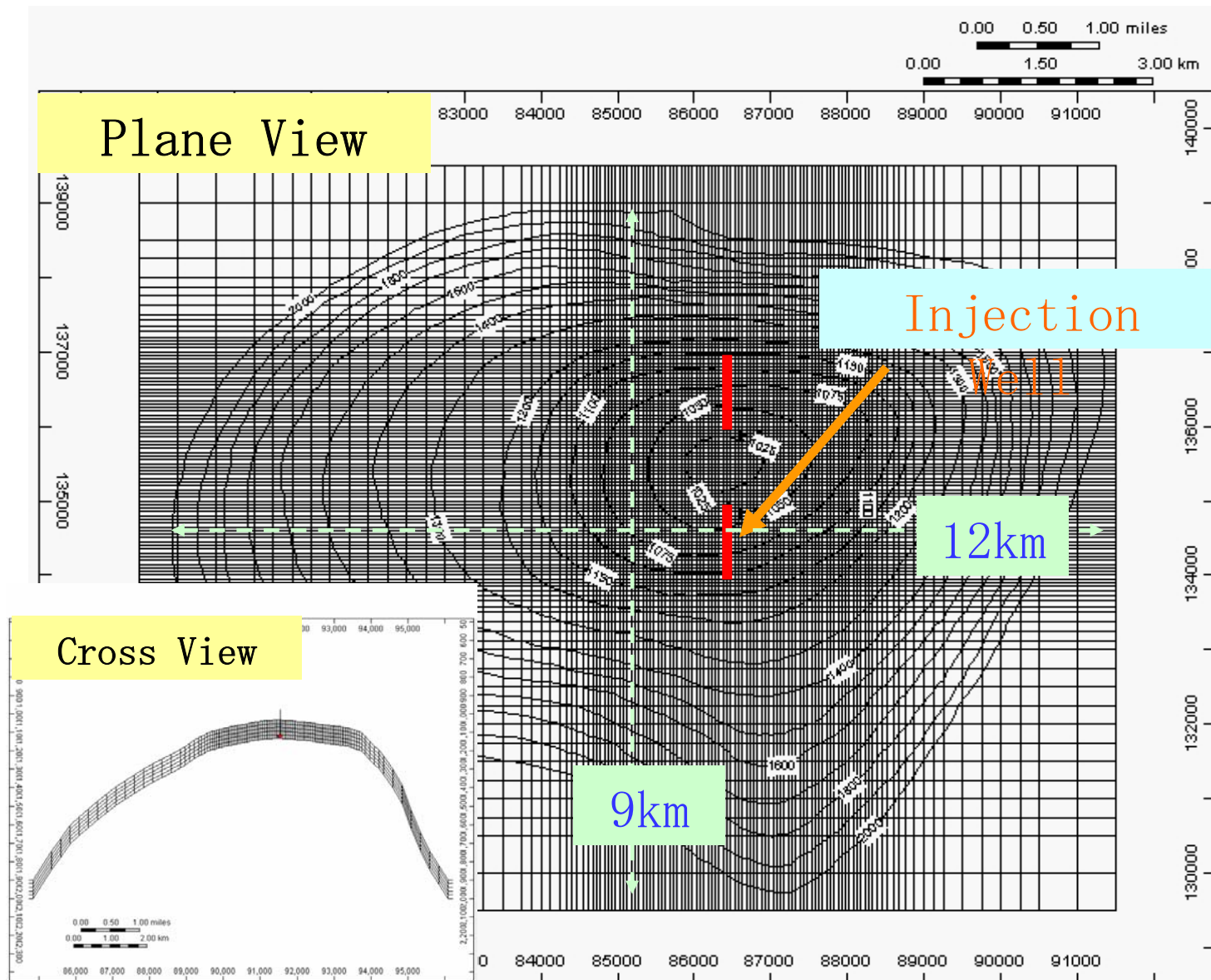
CO₂ Distribution at Completion of Injection
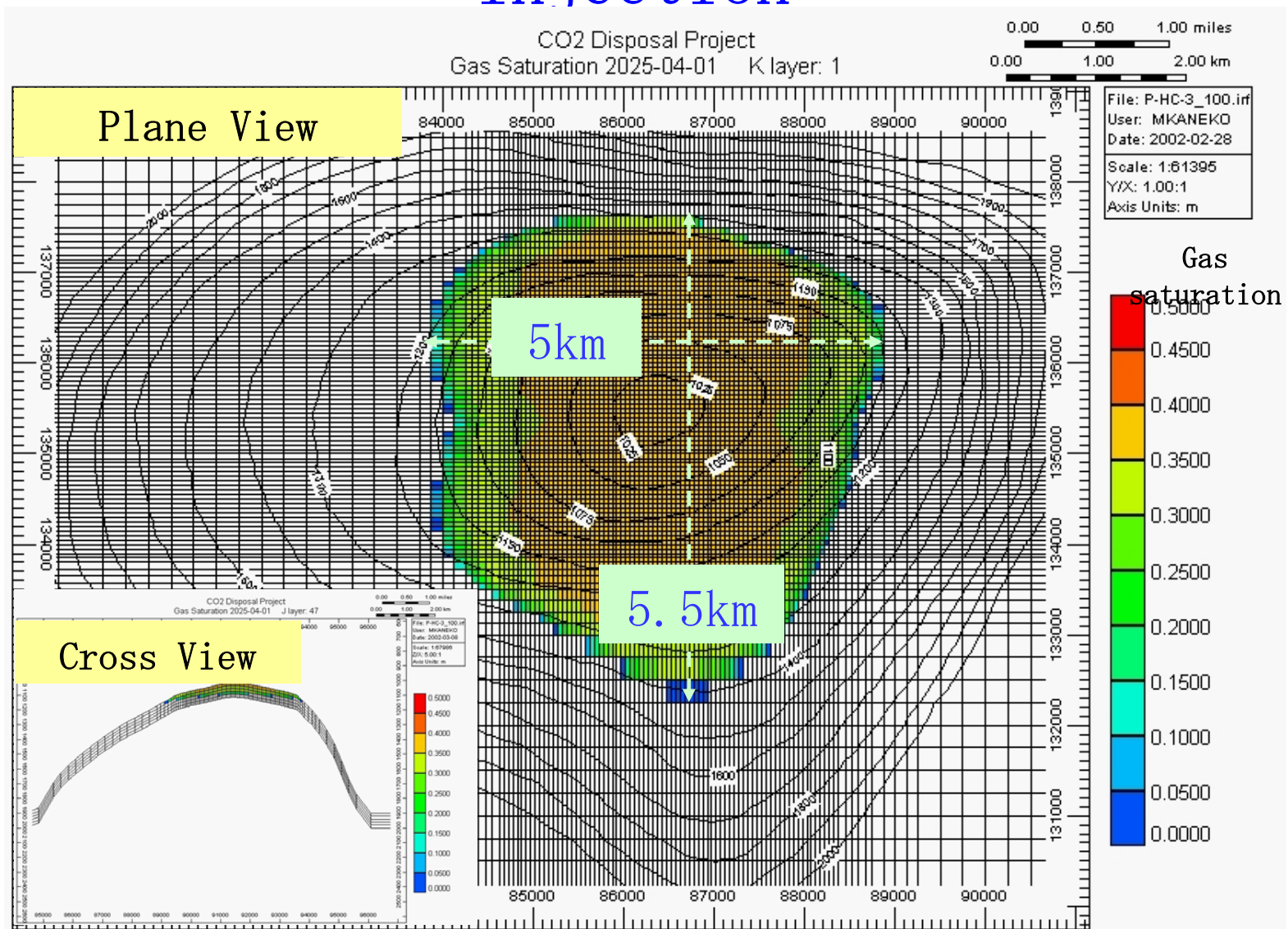
Profile of Pressure Increase

At Completion of Injection

Profile of Pressure Increase (2)

CO2_DP 2050-04-01   K layer: 1

25 years After Completion of Injection

File: F-0.0b.irf
User: SZHANG
Date: 2003-02-22

Scale: 1:59444
Y/X: 1.00:1
Axis Units: m

kg/cm^2

Profile of Pressure Increase (3)

100 years After Completion of Injection

CO2_DP 2125-04-01   K layer: 1

kg/cm²
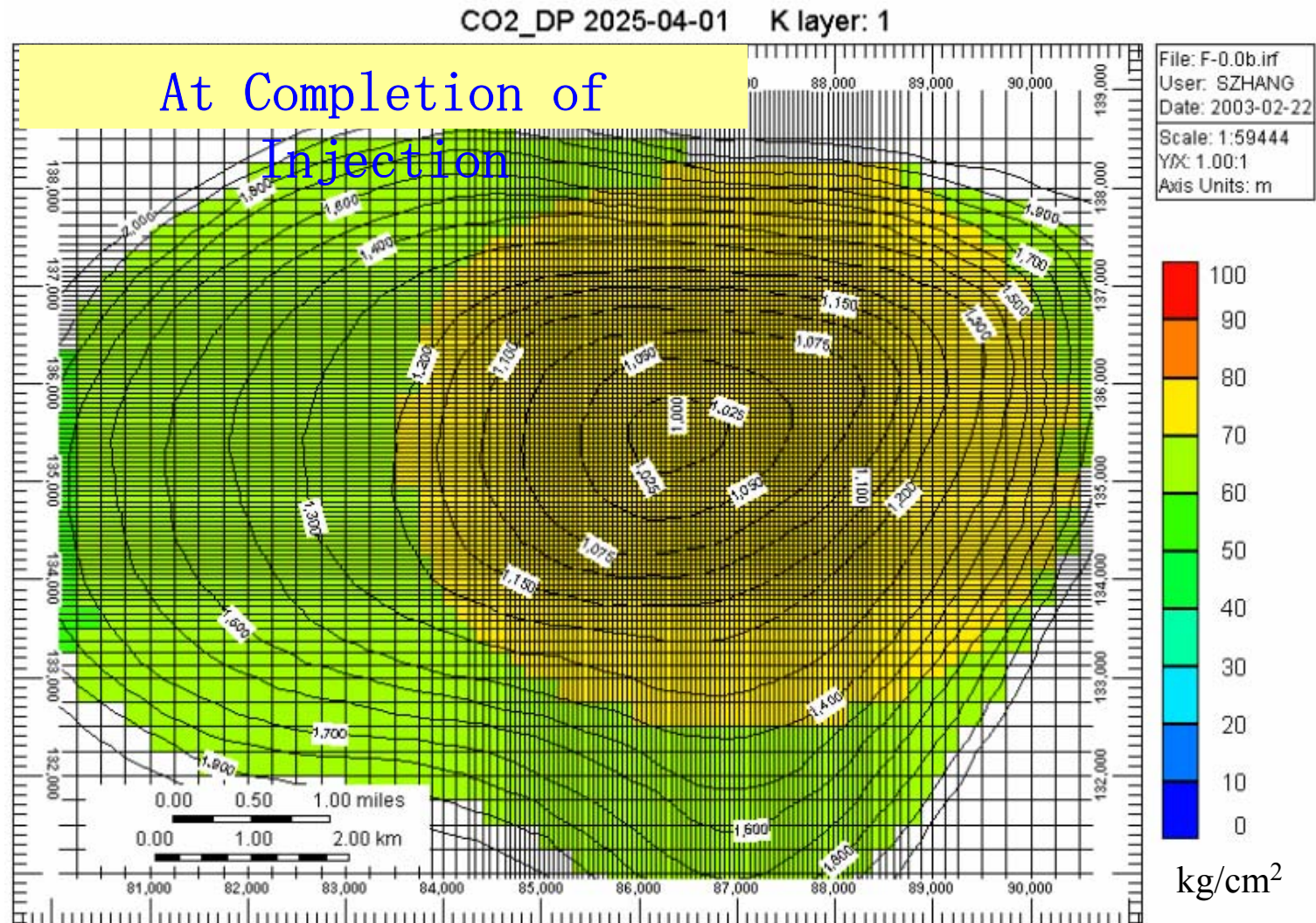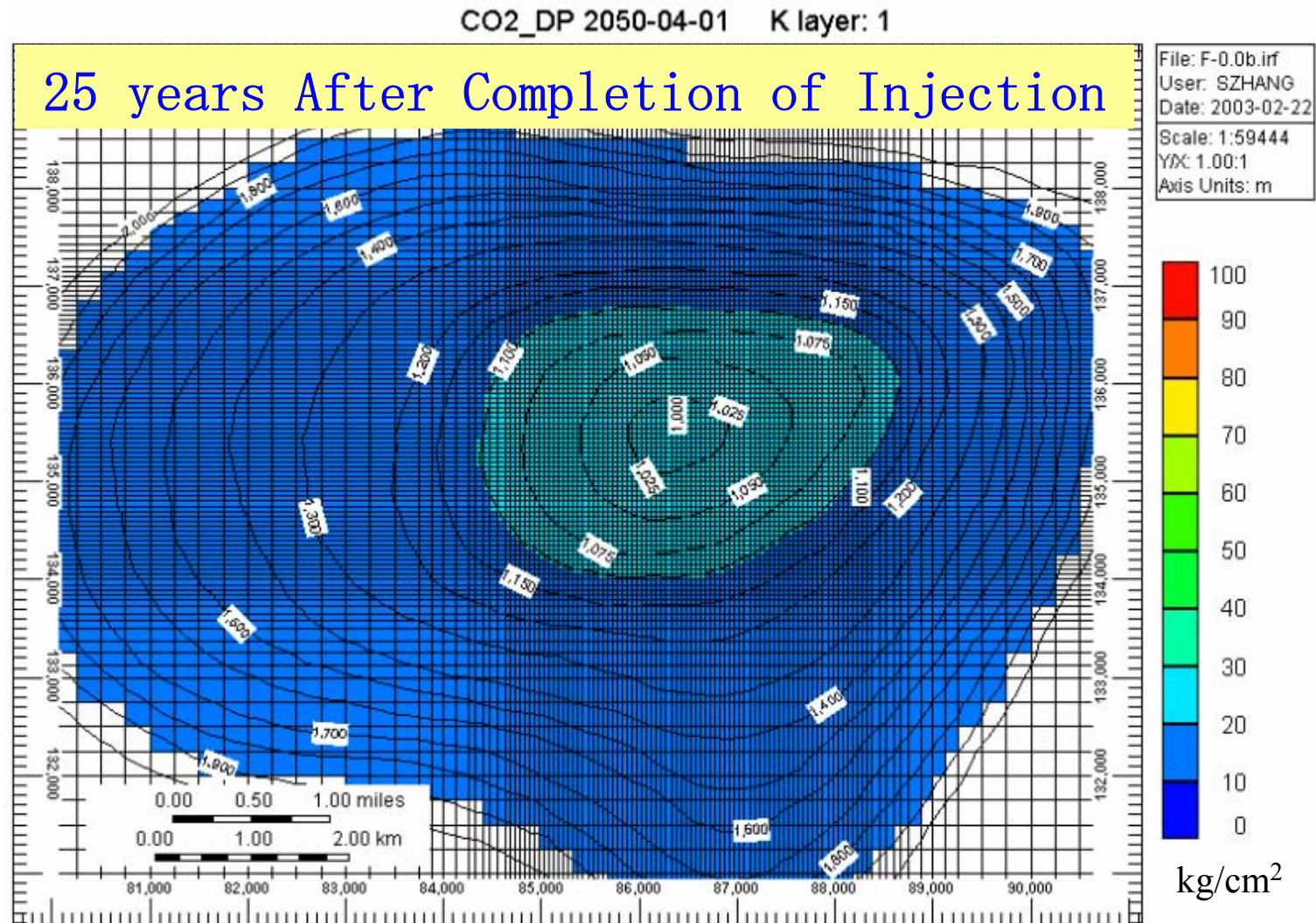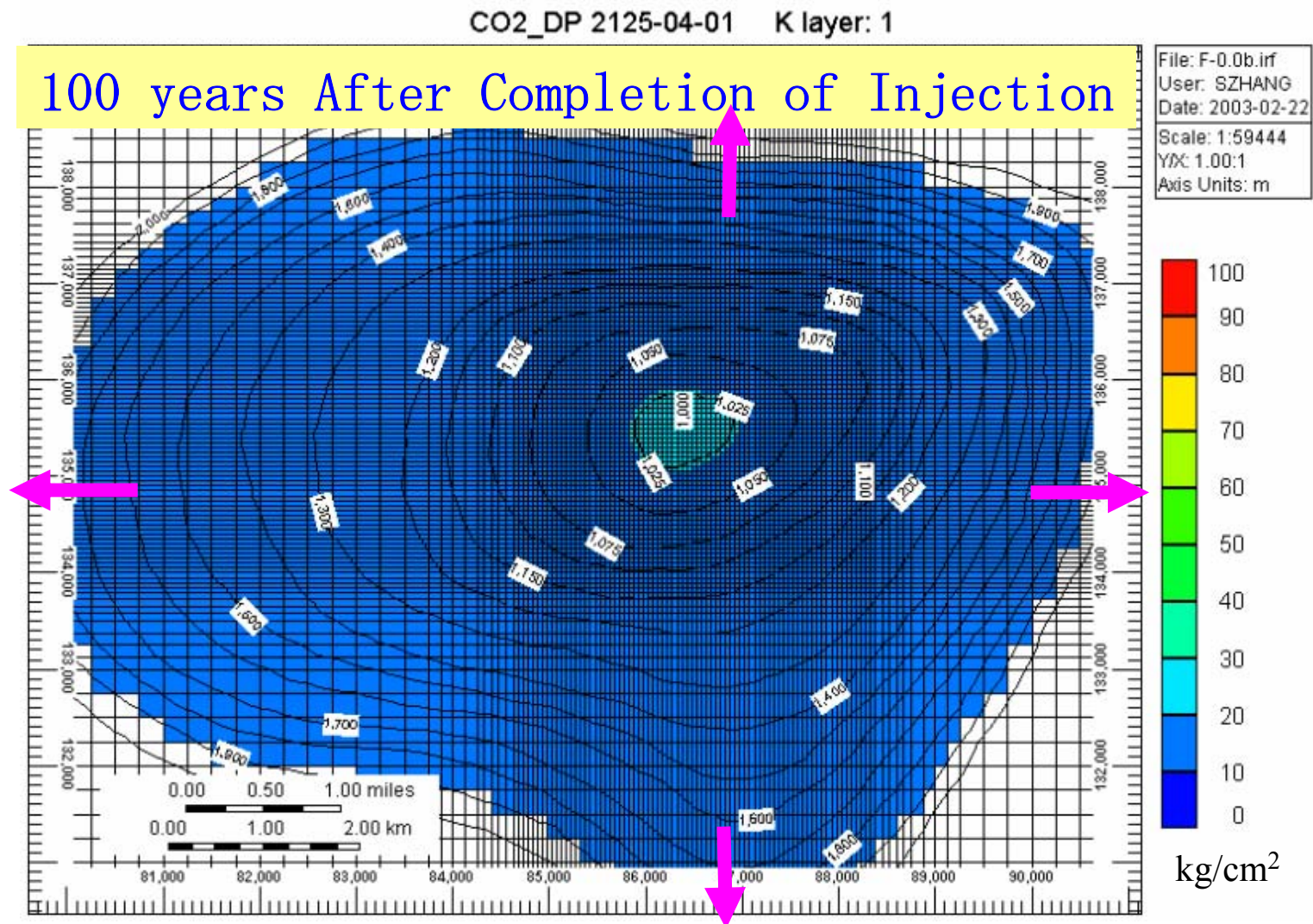
When is the Risk Highest?

Pressure of Aquifer Before Injection
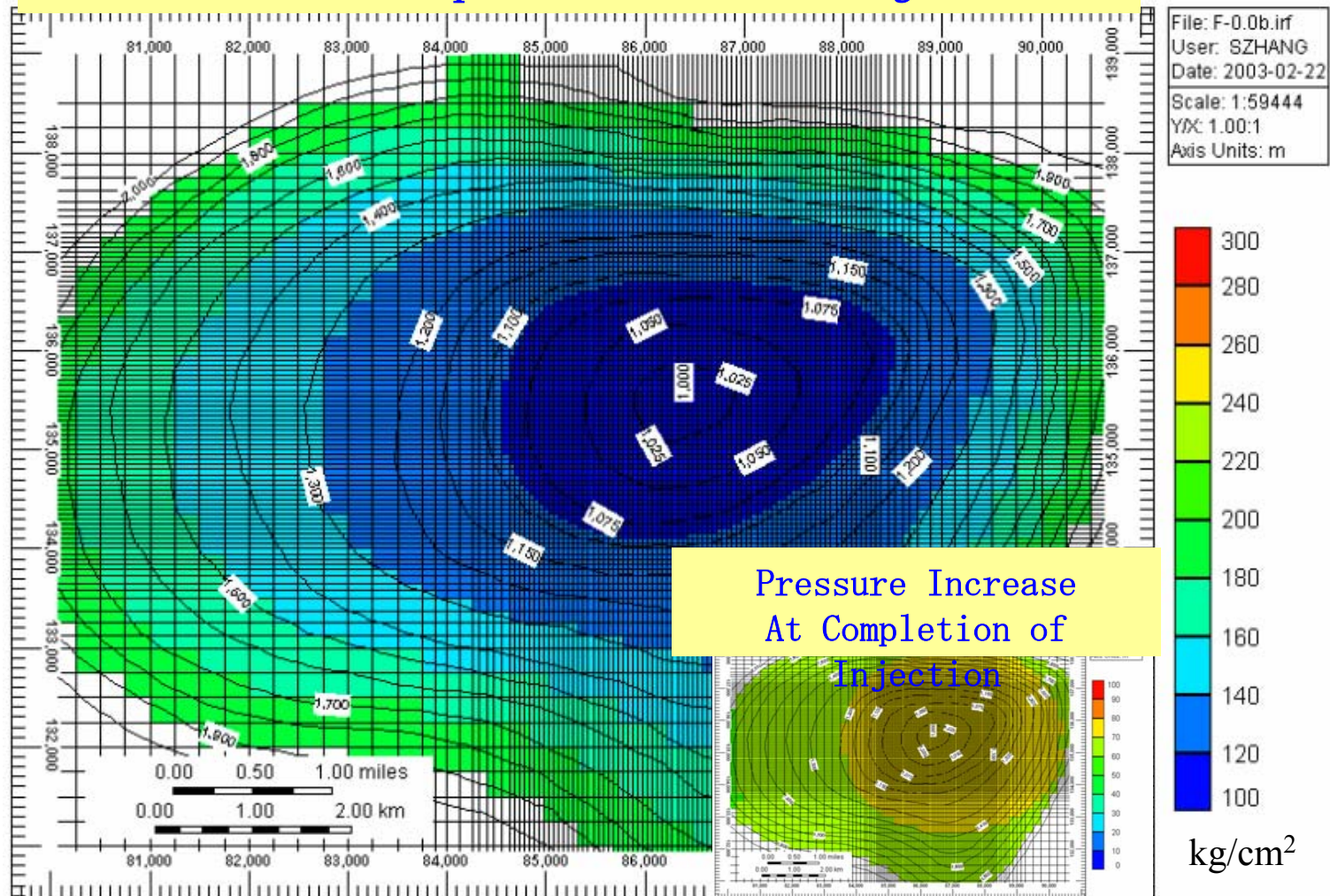
Pressure Increase At Completion of Injection

kg/cm²

Outline of My Presentation

1. Background and Purpose

2. Simulation of CO_2 Injection

3. Simulation of CO_2 Leakage

4. Conclusions

Modeling of Leakage Pathway
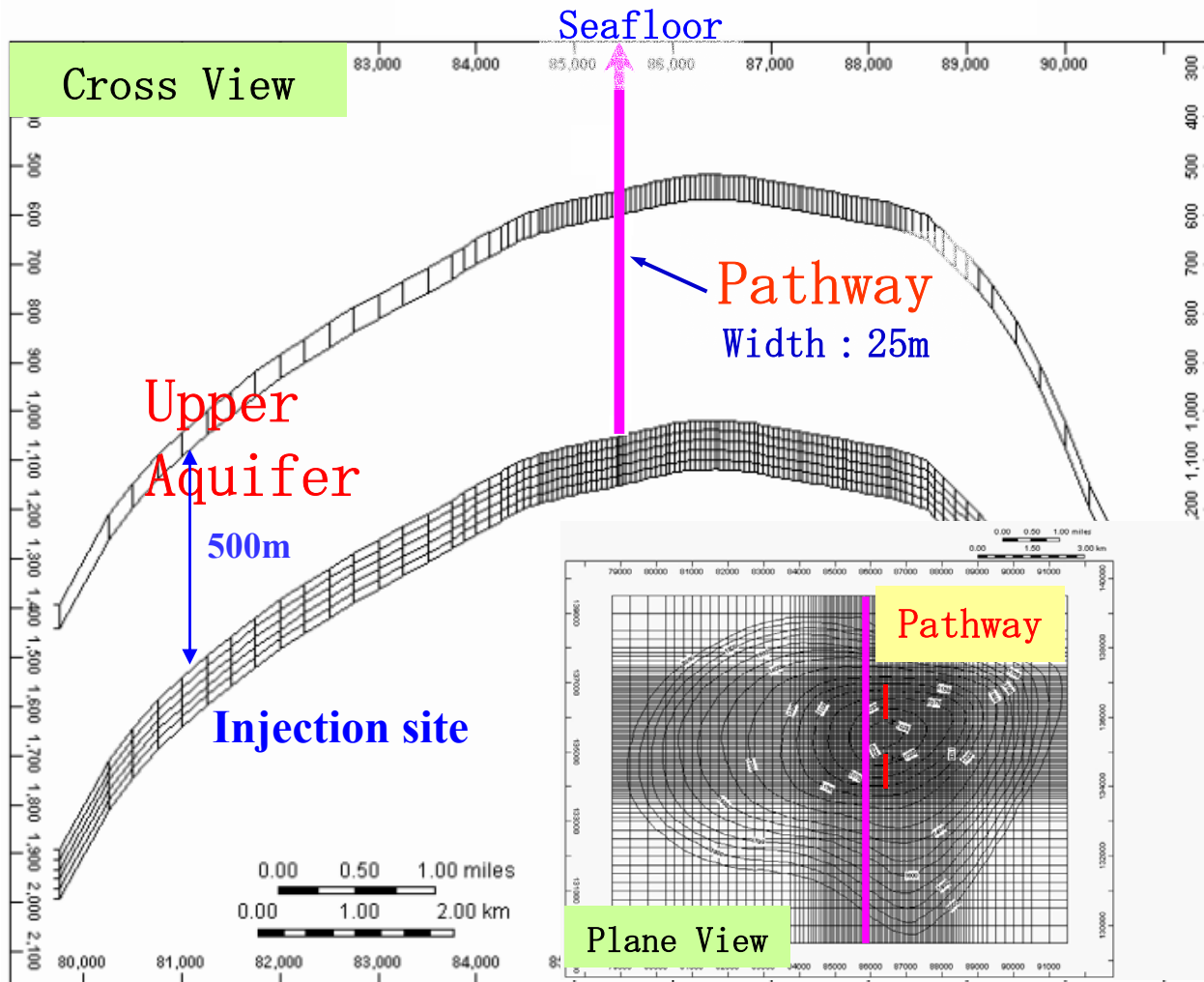
Permeability of Pathway

1、10md

14

25 years After Occurrence of Leakage

CO$_2$ Gas Reaches to the Upper Aquifer

File: LC-kv-1.irf
User: SZHANG
Date: 2003-02-25

Scale: 1:59391
Y/X: 1.00:1
Axis Units: m

Simulation

Permeability : 1md
Occurrence of pathway
        : Right after completion of injection

Gas saturation

0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

15

25 years After Occurrence of Leakage

Gas Saturation 2050-04-01   J layer: 42

Cross View

Plane View

Simulation

Permeability ：1md
Occurrence of pathway
　　　 ：Right after completion of injection

Gas saturation

200 years After Occurrence of Leakage

Gas Saturation 2225-04-01   J layer: 42

File: LC-kv-1.irf
User: SZHANG
Date: 2003-02-25
Scale: 1:62143
Z/X: 5.00:1
Axis Units: m

Simulation

Permeability : 1md
Occurrence of pathway
    :Right after completion of injection

Gas saturation

Slow CO₂ Migration at Initial Stages

25 years After Occurrence of Leakage

Upper Aquifer

Cross View

Injection Site

Permeability : 1md

Gas speed

(m/year)

File: LC-kv-1.irf
User: SZHANG
Date: 2003-03-02
Scale: 1:34701
Z/Y: 5.00:1
Axis Units: m

15.0
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0

Speed Becomes Faster

200 years After Occurrence of Leakage

Upper Aquifer

Injection Site

Cross View

File: LC-kv-1.irf
User: SZHANG
Date: 2003-03-02
Scale: 1:34701
Z/Y: 5.00:1
Axis Units: m

Gas speed

(m/year)

Permeability : 1md

15.0
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0

CO_2 Leakage Detection at Early Stages

Pressure Increase Inside of Upper Aquifer

At 10 years After Occurrence of Leakage

CO_2 Gas

kg/cm^2
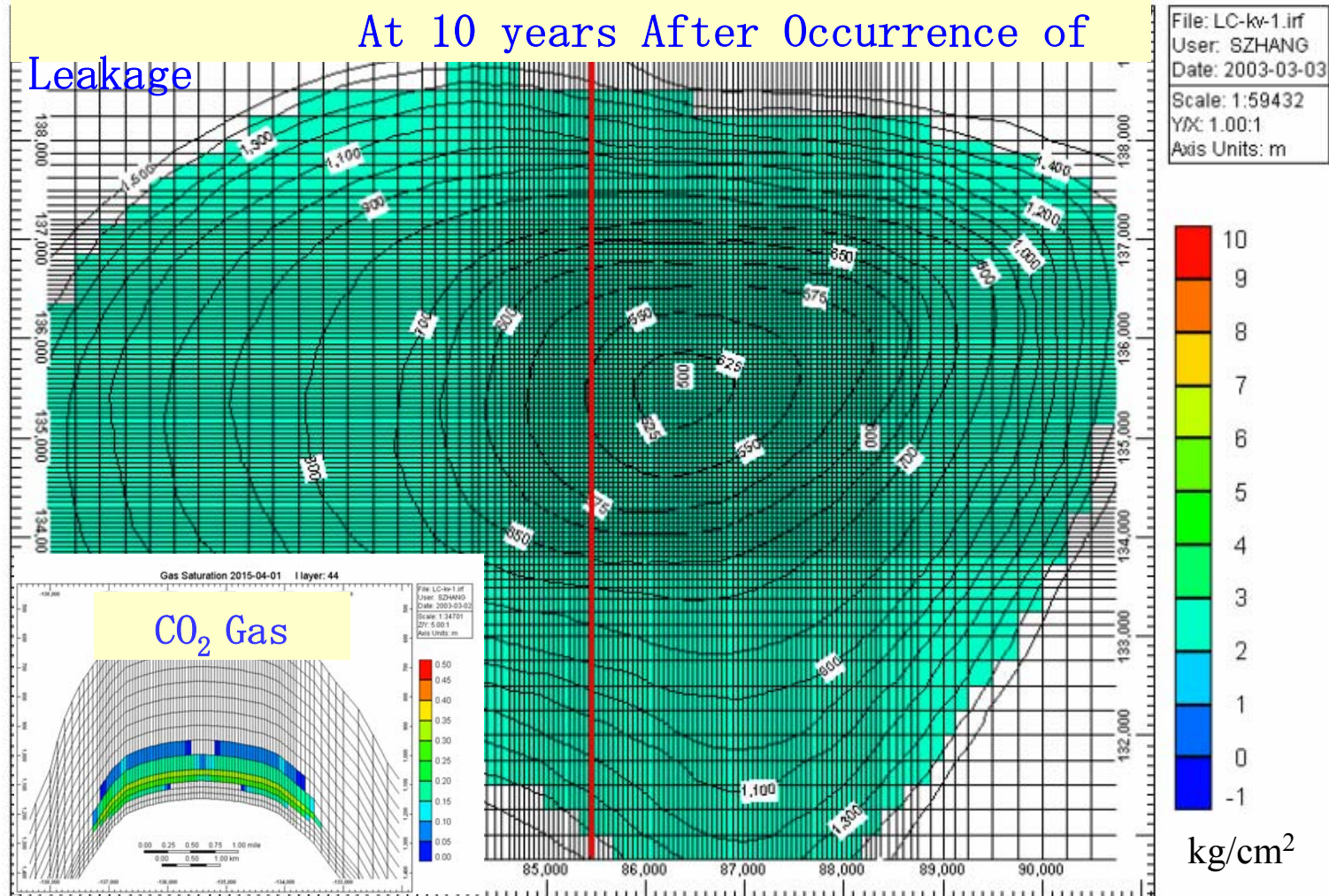
Leakage Continues for a Long Period
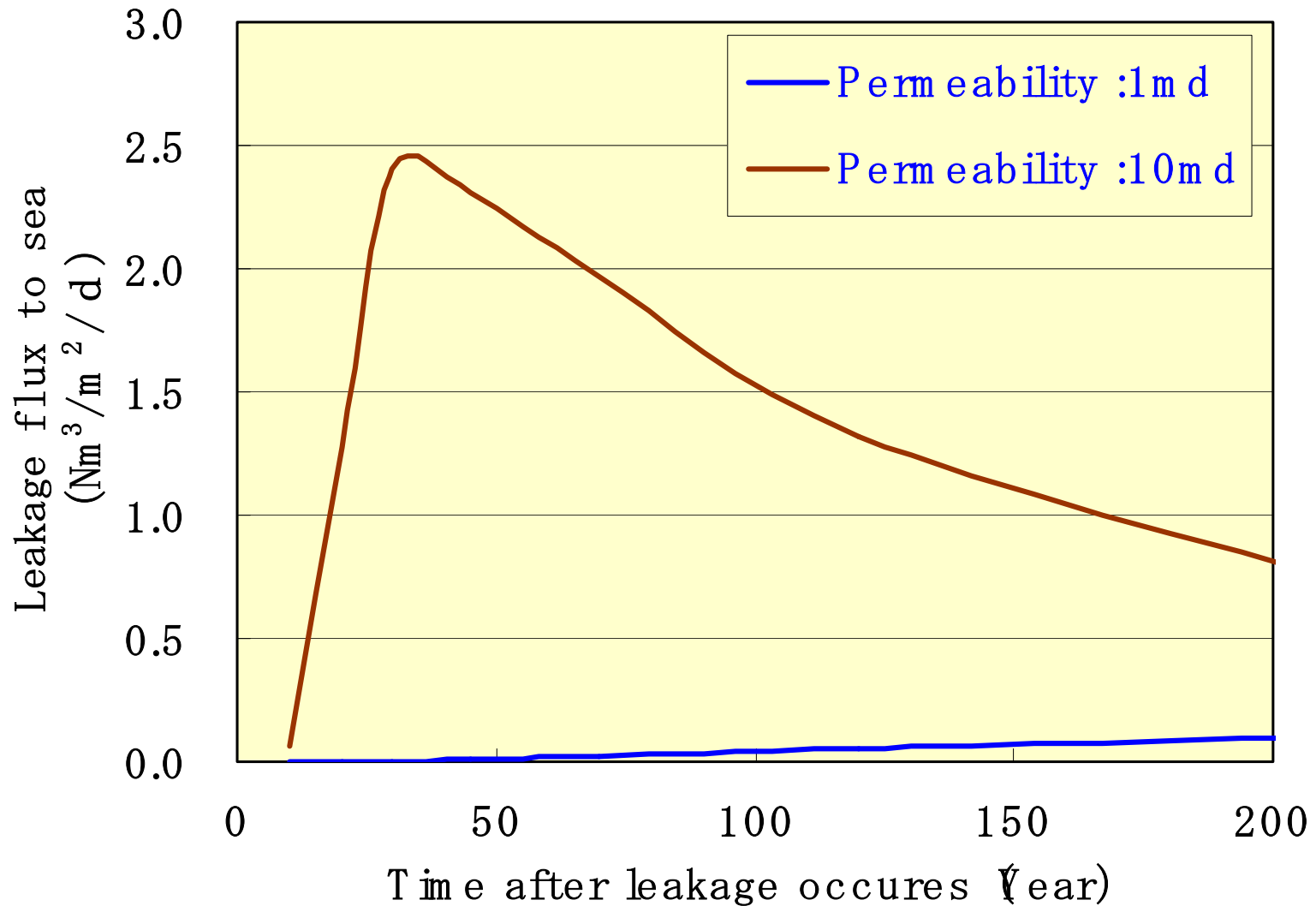
Occurrence of Leakage

At Completion of Injection

100 years After

RIT🌐

22

Flux Gets Smaller as Leakage Delays to Occur

23
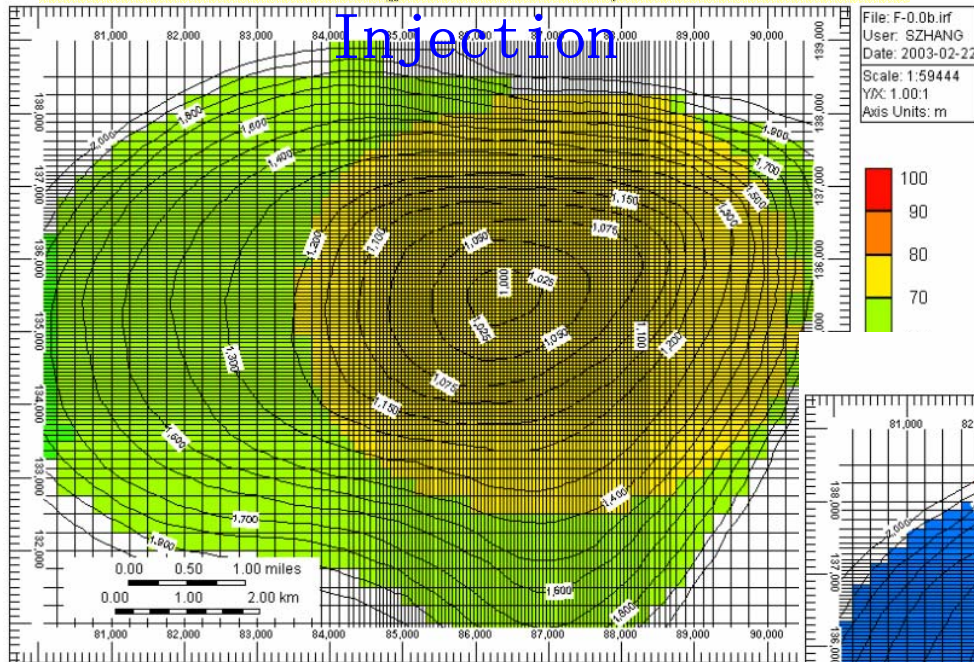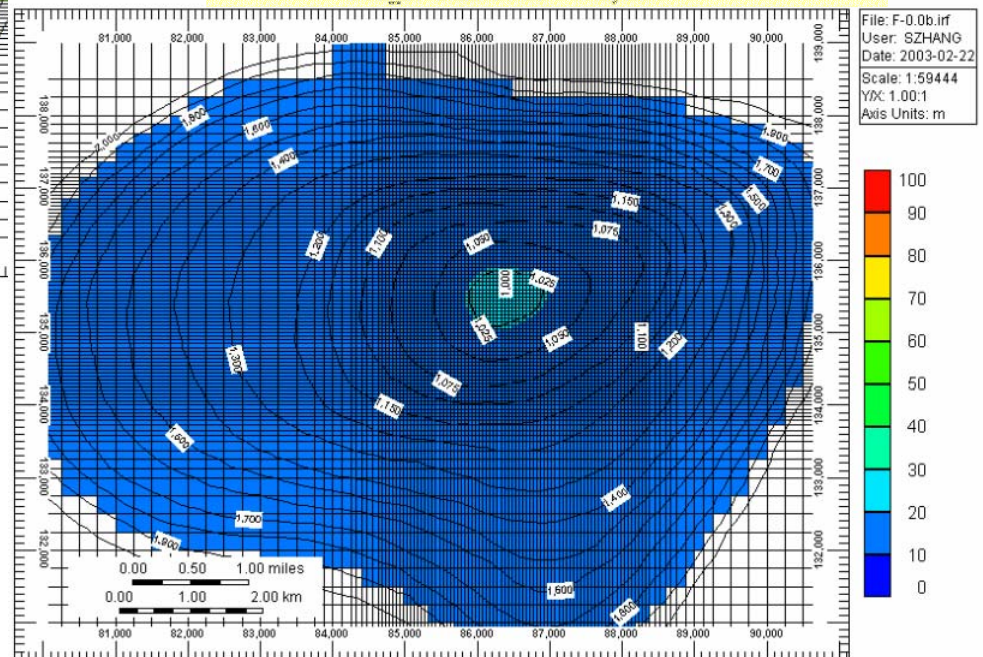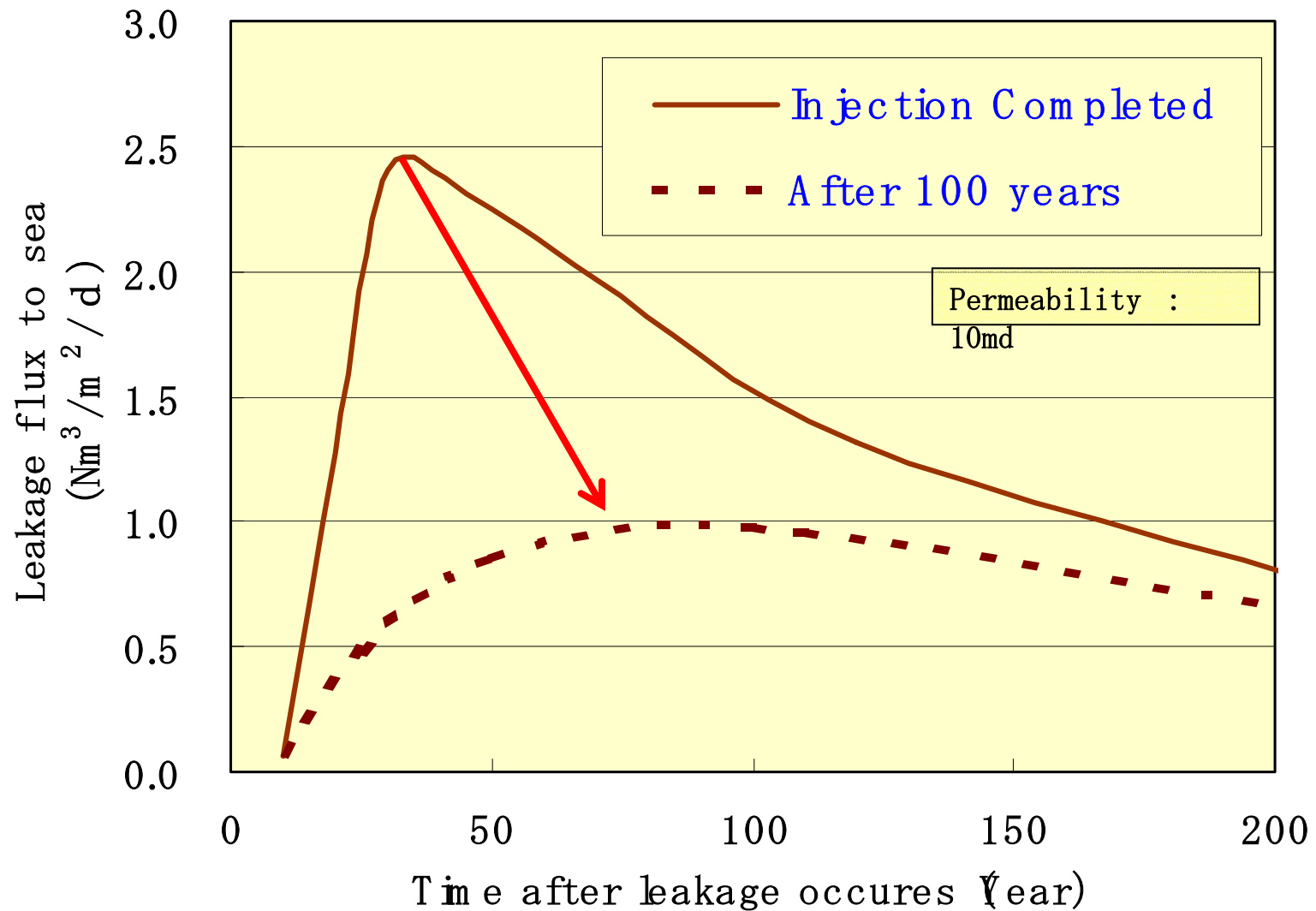
Conclusions

1. The risk of inducement of fractures is the highest at the completion of CO_2 injection.

2. If leakage occurs, it continues for a long period.

3. However, leakage flux gets smaller as leakage delays to occur.

4. Even if leakage occurs, we have enough time to make up a counterplan.

Assessment of Impacts of Surface Leakage of CO_2

Prasad Saripalli, Neeraj Gupta and Mark Kelley

Battelle Memorial Institute
Pacific Northwest National Laboratory
USA

Presented at:
Risk Assessment Workshop
IEA Greenhouse Gas R&D Programme
February 11-12, 2004

Surface Leakage: Definition

Migration of sequestered CO_2 via leaks in the well cementing, casing, fractured or relatively high permeability zones in an otherwise impermeable cap rock.

Assumptions:

Acute, accidental releases of large volumes not included.

Leakage data from natural analogs of leakage do not pertain to sequestration fields, which are designed, monitored and operated for safety. They are useful for consequence assessment, but not hazard. Instead, focus on leakage rates from engineered analogs for hazard data.

Gas Migration Mechanisms

. <u>Diffusion</u> (10^{-4} – 10^{-2} m/d)

• <u>Advection</u> with moving waters

• <u>Bubble ascent</u>: Discontinuous flow assoc. with slow velocities

• <u>Effusion</u>: Flow of immiscible fluid through pores, fractures

(Price, 1986; Saunders, 1999; Etiope and Martinelli, 2002; Klusman, 2003)
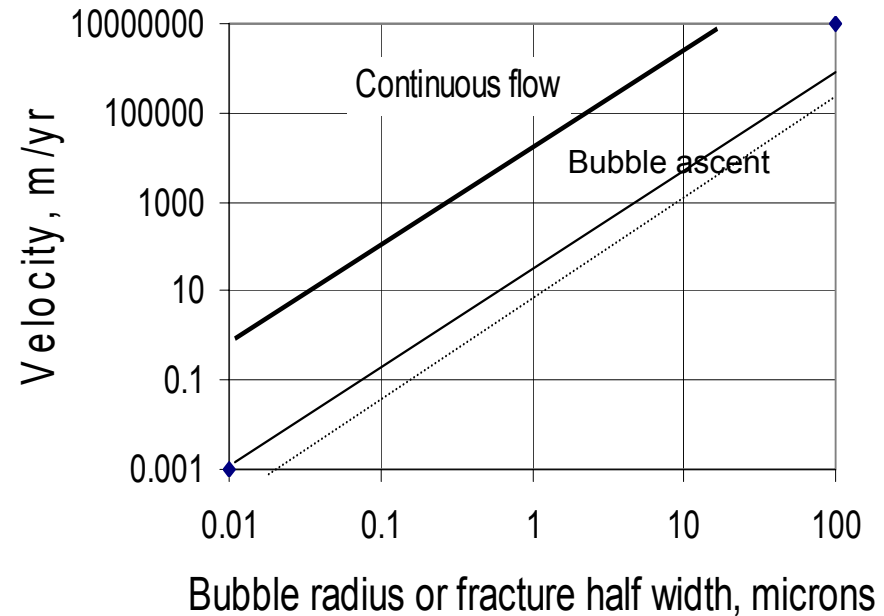
Effusion (gas phase advection) through fracture networks is the dominant surface leakage mechanism (Etiope & Martinelli, 2002)

Battelle

Surface Leakage: Conditions
(Volckaert et al., 1993)

$$P_g < P_w + P_c$$ CO$_2$ enters the caprock only by diffusion

$$P_g > P_w + P_c$$ Buoyant advection of CO$_2$ displacing water

$$P_g = P_{fr} >> P_w + P_c$$ CO$_2$ fractures and enters the caprock

$$P_c = \frac{2\sigma}{r}$$ Capillary pressure $\qquad P_g$ CO$_2$ phase pressure

$$P_w = \rho g H_w$$ Hydrostatic pressure

Battelle

Field Observations of Gas Flux &Concentrations

Flux/Conc. (gm/m^2/d)(ppmv)	Reference
0.7 – 20(2000-4000)	CO_2 EOR Flood, Rangely, CO. (Klusman, 2003)
0.2-48 (0.5-5%)	Encana CO_2 EOR, Weyburn, Ca (Strutt, 2003)
0.29 – 0.95 0.02 0.72	CH_4 Denver-Julesburg basin (Klusman, 1998) CH_4 Railroad Valley (Klusman, 2003) CH_4 Powder River (Klusman, 2003)
700 gm/d/well	Well leakage avg. over several gas wells (Schmitz, 1996; Husky Oil, Canada)

Typical CH_4 emissions from landfills are 140 gm/day/person and from a cow is 280 gm/day (Schmitz, 1993; 1996).

Battelle

Base case Simulation: An Idealized Field Case

Base Case Injection and Formation Parameters

Well radius = 1 ft

Drainage radius = 30000 ft

Porosity = 12%

Injection rate (constant) = 3914 cum/day

Far-field boundary pressure, P_e = 3300 psi

Injection pressure, P_i = 3350 psi

Depth to top of host formation = 7800 ft.

CO_2 density = 0.68 gm/cc

Formation thickness = 50-100 ft

Permeability = 1-50 mD

Caprock permeability = 0.0001 – 0.001 mD

Viscosity of CO_2 phase, μ_g = 0.000043 Pa.s

Viscosity of water, μ_w = 0.00043 Pa.S

Thickness of cap rock = 6300 ft.

Battelle

Base case: Pressure and Free phase Bubble Profiles
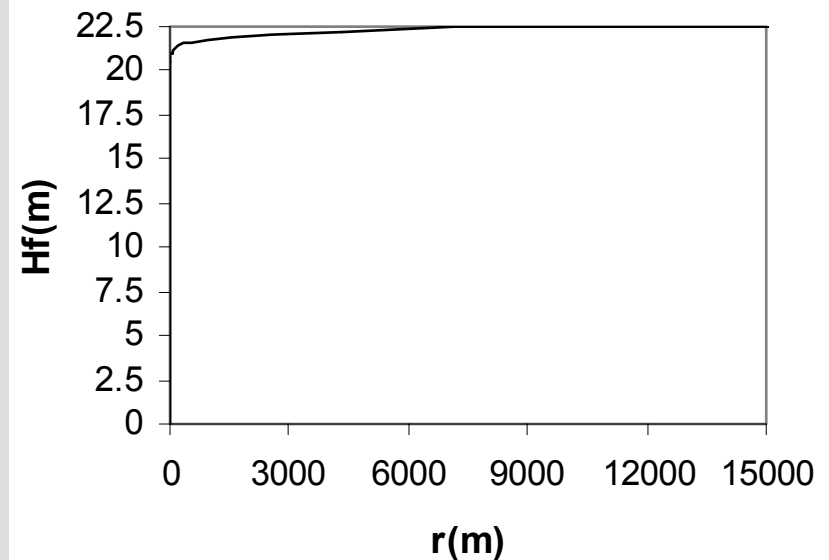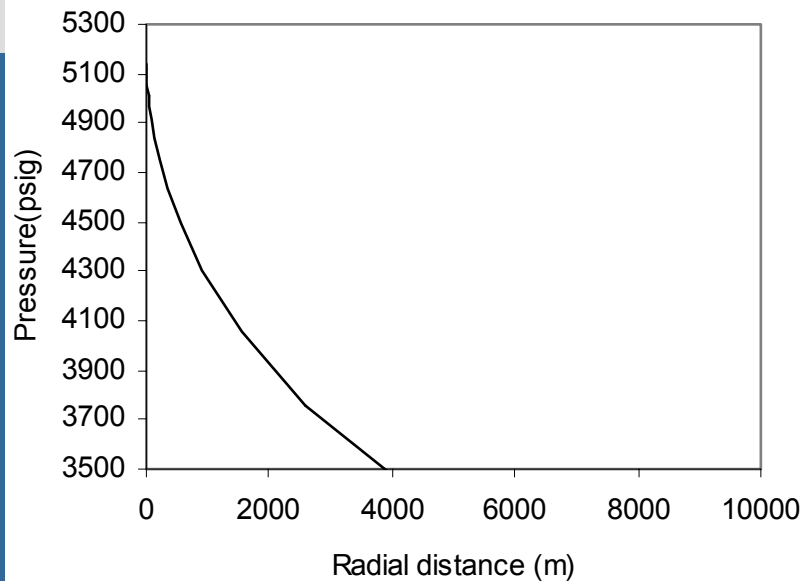
Base case Leakage Conditions Evaluation

State	P_g psi	P_w	P_c	Evaluation
Over-pressured during injection, near-wellbore	5000	3333	21-201	$P_g > P_w + P_c < P_{fr}$ No induction of new fractures; but effusion through existing fractures likely
Equilibrium formation pressure, after injection	3500	3333	21-201	$P_g \approx P_w + P_c$ No induction of fractures; Effusion unlikely; Micro-seepage likely

🔔 P_c ✪ Fracture aperture

P_w ✪ Caprock Thickness

Battelle

Migration via Fractures

For CO_2 to enter a fracture of size $2d$, the buoyant pressure exerted on the cap rock by CO_2 must satisfy

$$h_b \geq \frac{2\sigma}{\Delta\rho g d}$$

$$q_f = \frac{\Delta\rho g w d^3}{12\mu}\left(\frac{h_c}{h_c + l_f}\right)$$

Safety Target

Influence of fracture aperture on leakage (w = 10 m; over-burden 1890 m thick)
Assuming 1 continuous fracture in 1000 m²

Leakage (gm/m 2/day) vs. Fracture half-aperture, d (microns)

Battelle
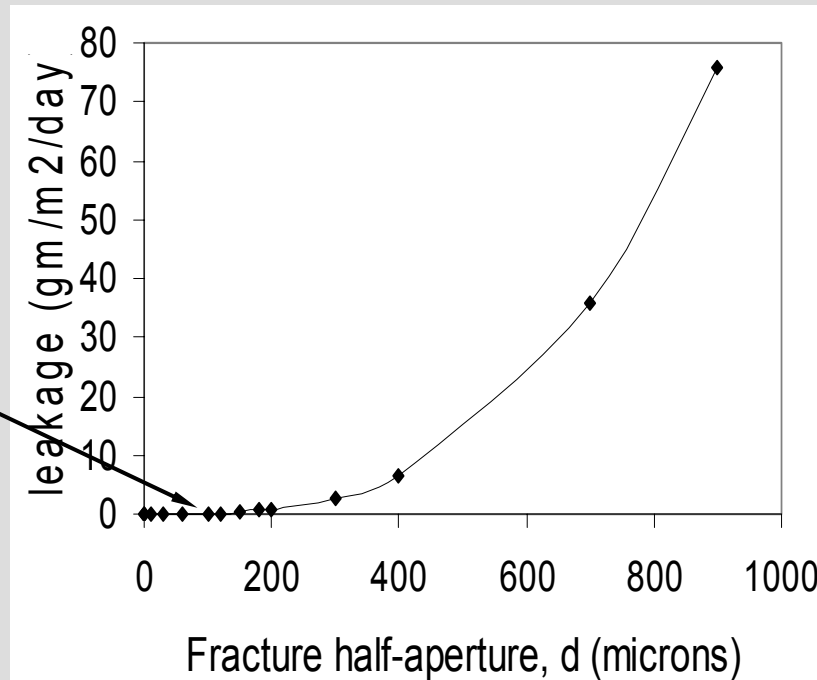
Migration through permeable cap rock

Assuming strong buoyancy within a 100 m zone around the well, leakage rates as a function of permeability (K) of cap rock are shown when $K>1$ Darcy, fine sands.
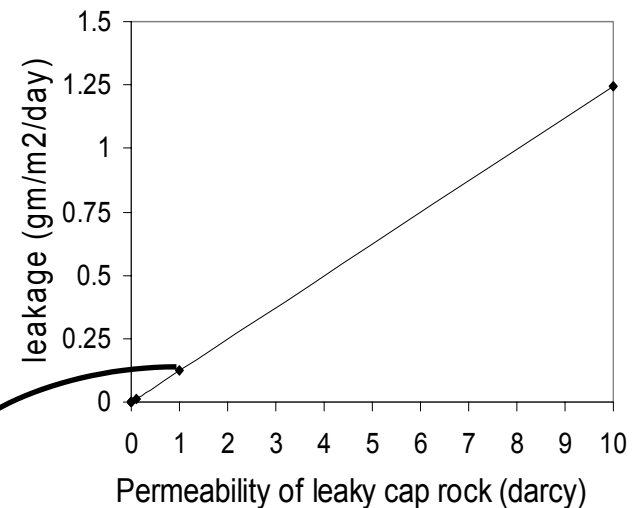
Leakage through permeable zones is within 0.1 – 1 gm/m^2/d

Influence of cap-rock permeability on leakage

Battelle

Atmospheric Dispersion Modeling

Methods were developed for transition of a negatively buoyant CO_2 plume to passive plume

$$\overline{CU} = \left[\frac{\Delta\rho gh}{\rho_a}\right]^{\frac{1}{2}}$$

Small, isolated releases (cloud height of <1 m) will quickly disperse under typical wind velocities (of 10-20 miles/hour).   The microseepage fluxes estimated (0.1 – 100 gm/m^2/d) fall in this range.

The resulting increase in CO_2 concentration is plotted as a function of % leaky caprock area. A tolerable cutoff may be 0.1% of total caprock area, corresponding to an increase of 50 ppmv.

Battelle
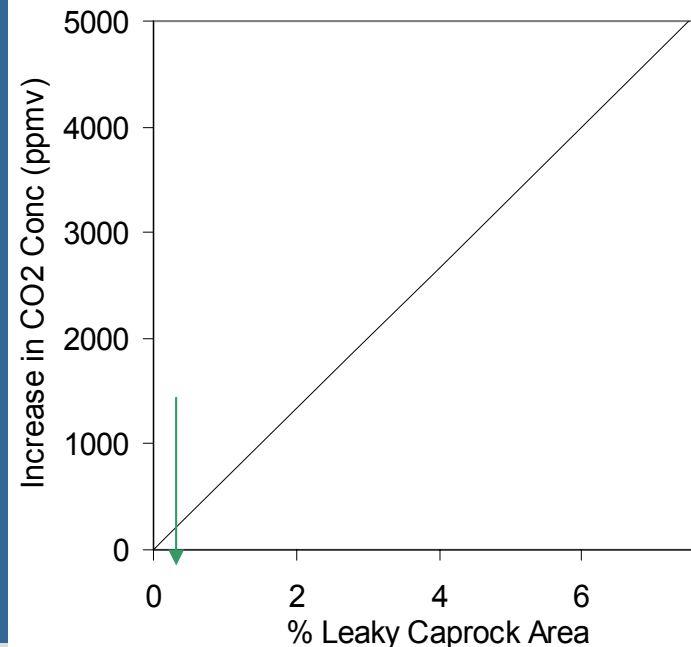
Consequences(↓indicates tolerable level)

Consequence Value Table for hazards
((x) is concentrations of CO_2 ; [x] is magnitude of consequence)

Media*	Consequences		
	Severe [1]	Moderate [0.5]	Low [0.1]
Air (3200 ppm)	Habitat loss (>10%)	Injuries (> 5%)	Discomfort (> 1%)
Bldgs (320ppm)	Injury, evacuation (> 5%)	Irritation, discomfort (> 2%)	Noticeable, no harm (> 1%)
Groundwater (10^{-4} M / 0.2%)	Acidity, well corrosion, irrigation loss (> 6%)	Mild acidity and corrosion (> 2%)	Elevated, low acidity without significant impacts (> 0.2%)
Surface water (10^{-5} M; .022%)	Acidity, CO_2 explosion, fish kills (> 2%)	Higher acidity, mild toxicity Effect on irrigation (> 1%)	Elevated, low acidity with no significant impacts (> 0.022%)
Soils (1-2%)	Low pH, tree kills, animal deaths (> 8%)	Moderate acidity, tree/ crop/soil cover loss (> 3%)	Mild suppression in pH with no significant impacts (> 2%)
Biota (10^{-5} M)	O_2 depletion, lethal (>4%)	Injure life functions (> 2%)	Mild toxicity (> 0.5%)

Battelle

Summary

- Modeling results from base case injection scenario indicate that, under a moderately worse cap rock integrity (1 continuous fracture in 1000 m^2 area; 1 Darcy permeable zones), the effusive leakage fluxes could be in 0.1 – 80 g/m^2//day range.

- These values compare well with fluxes reported at engineered gas/CO_2 flooding/storage sites.

- Well leakage could be in the range of 100 -1000 gm/d range.

- These leakage rates correspond to tolerable consequences.

- Caprock thickness, fracture/perm. zone extent, CO_2 bubble thickness, pressure and time are critical variables that influence these flux and consequence calculations. Results shown here are for a conservative site with relatively low total volumes.

Battelle

Research Needs

- Caprock thickness, fracture/perm. zone extent, CO_2 bubble thickness, pressure and time are <u>critical variables</u> that influence these flux and consequence calculations. Determine their ranges.

- <u>Overpressurizing</u> during injection is the most critical phase for leakage & consequence assessment. Its influence must be understood.

- <u>Dissipation of leakage fluxes with time</u>, due to dissolution of free-phase CO_2 bubble and dissipation of pressure should be assessed.

- Assessment of <u>hazard probabilities</u> and spatial frequencies based on historic records and geologic characterization.

- Leakage flux <u>tolerances</u> from climate policy view point should be assessed and combined with environmental consequence assessment.

Future Direction

- The methodology presented here is being applied to evaluate injection scenarios for the Ohio River Valley CO_2 Storage Project at the Mountaineer Power Plant

- Available data include detailed characterization using wireline, core analysis, and reservoir testing in a 3,000-m deep well

- A 2-D seismic survey, and

- An assessment of regional geologic features

- In addition to the semi-analytical models used here, more detailed numerical modeling will be used where feasible

difference that counts:
DNV CONSULTING

Safeguarding life, property

and the environment

The use of SWIFT and QRA in determining risk of leakage from CO_2 capture, transport and storage systems

Mark Vendrig
DNV Consulting

MANAGING RISK

introduction

The first risk study undertaken for the Dti relating to carbon capture and storage

However

> Not all risk techniques worked equally well despite good results on similar novel studies in the past

So

> We looked at the project to identify the reasons why only some techniques provided good results and ways in which to overcome the communication issues based on variable audience understanding

The material is presented in three sections:

1. Some basic risk concepts to aid communication
2. Risk analysis of the engineered system
3. Risk analysis of the storage system

MANAGING RISK   DNV

how risk is calculated

- Determine the frequency of the scenario
- Determine the consequence of a scenario
- Calculate the product of frequency and consequence – "the risk" - The likelihood that a particular outcome will occur

RISK = | **Frequency** | **x** | **Consequence** |
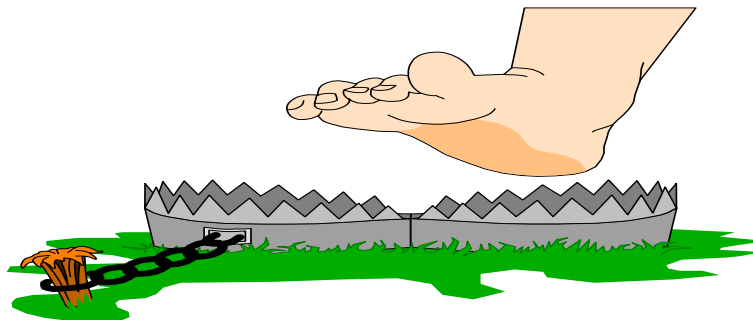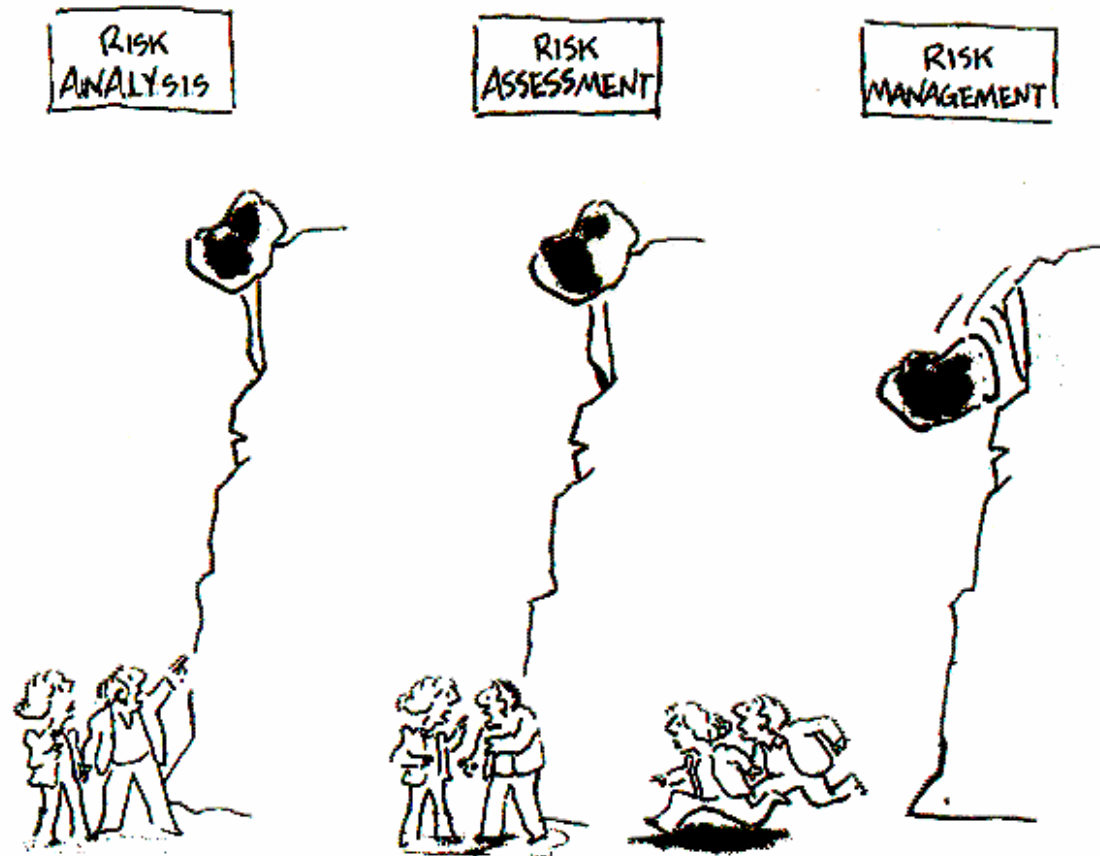
risk

From a cartoon by Sydney Harris

MANAGING RISK

risk and decision making
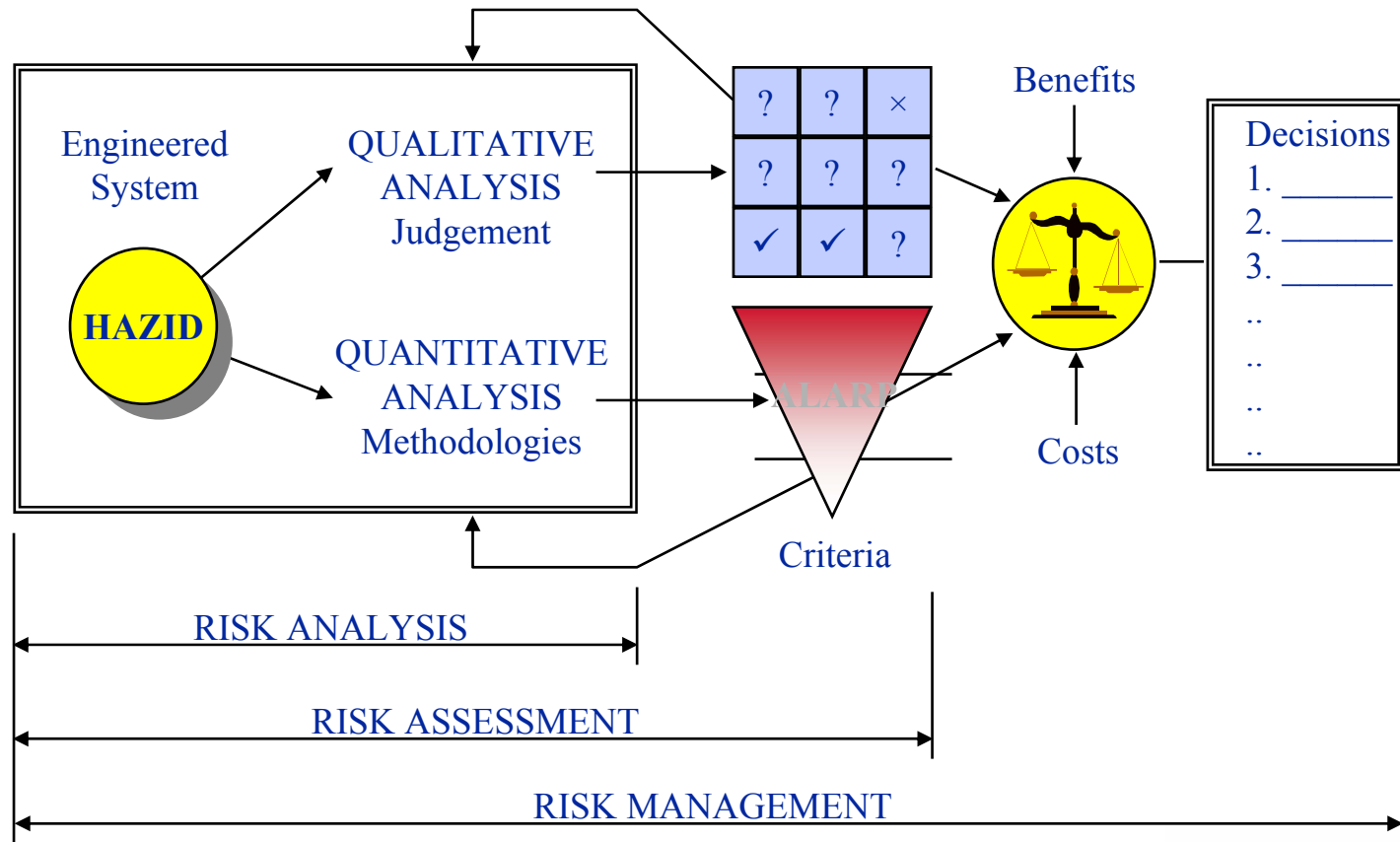
QRA of the engineered system (2002/2003)

MANAGING RISK DNV

main findings

- Multiple fatality risks from the engineered system are very unlikely

- The risk of fatality for individuals may exceed typical risk criteria for industrial facilities for some modules

- There is significant scope for the individual risks to fall within acceptable limits

MANAGING RISK

the engineered system

- Modular generic pipeline sections defined

- Industry failure frequencies used for all pipeline components

- Consequences of failures for all pipeline components based on industry records

MANAGING RISK DNV

engineered modular system

Modular system identification

Module no.	Module Description	Module Pipe Length
1	CO_2 recovery at source	500m
2	Converging pipelines	100m
3	Booster station	100m
4	Pipelines	10km
5	Injection plant.	500m
6	CO_2 riser to offshore platform from submerged pipeline	N/A
7	Line down to containment region	N/A
8	Tanker transport	N/A

generic modular pipeline system

Booster Module (3)
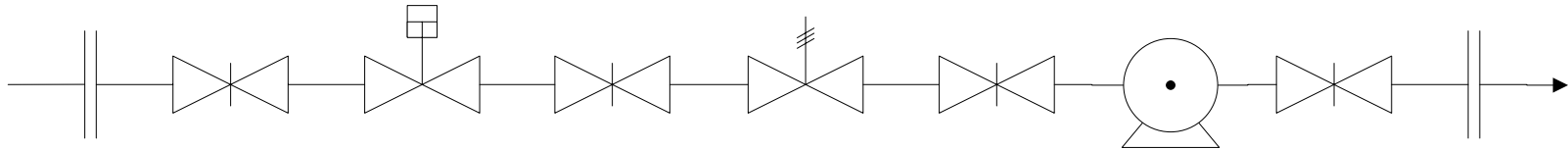
Component inventory for Module 3

Component	Number
Flange	16
Valve	6
Pump	1

Use pipeline data with fittings incorporated additio

failure rate summary

Failure Rate Summary for Each Module

Module		Failure Rate (per module year)	Leak every x years
1	CO_2 recovery at source	1.5E-01	7
2	Converging pipelines	4.6E-03	217
3	Booster station	4.0E-02	25
4	Pipeline	3.4E-04	2941
5	Injection plant	1.8E-01	6
6	CO_2 riser to offshore platform	2.6E-03	385
7	Line down to containment region	2.1E-04	4762
8	Tanker transport	Tonnes of cargo lost per journey $= 0.38 + 1.6 \times 10^{-4} x$; where x is the journey distance in nautical miles	

acute health effects of high concentrations of carbon dioxide

CO$_2$ Concentration		Time	Effects
Percent	ppm		
17 – 30	170 000 - 300 000	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
>10 – 15	100 000 - 150 000	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7 – 10	70 000 – 100 000	Few minutes 1.5 minutes to 1 hour	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
6	60 000	1 – 2 minutes < 16 minutes Several hours	Hearing and visual disturbances Headache, dyspnoea Tremors
4 – 5	40 000 - 50 000	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnoea
3	30 000	1 hour	Mild headache, sweating, and dyspnoea at rest
2	20 000	Several hours	Headache, dyspnoea upon mild exertion

Key range: 7-10%
The concentration where people may no longer be able to remove themselves from danger with very short term exposure.

1.5% or 15000ppm
The EH40 occupational exposure limit

Current atmospheric concentration
0.00370 % or 370ppm

MANAGING RISK   DNV

the Saripalli findings

Summary of consequences and concentrations in various environments (after Saripalli *et al,* 2002)

Media*	Consequences		
	Severe [1]	**Moderate [0.5]**	**Low [0.1]**
Air (280 ppm)	Lethal, habitat loss (>10%)	Injuries (> 5%)	Discomfort (> 1%)
Buildings (280 ppm)	Injury, evacuation (> 5%)	Irritation, discomfort (> 2%)	Noticeable, no harm (> 1%)
Ground water (10^{-4} M or 0.2%)	Acidity, well corrosion, irrigation loss (> 6%)	Mild acidity and corrosion (> 2%)	Elevated, low acidity without significant impacts (> 0.2%)
Surface water (10^{-5} M; .022%)	Acidity, CO_2 explosion, fish kills (> 2%)	Higher acidity, mild toxicity Effect on irrigation (> 1%)	Elevated, low acidity with no significant impacts (> 0.022%)
Soils (1-2%)	Low pH, tree kills, animal deaths (> 8%)	Moderate acidity, tree/ crop/soil cover loss (> 3%)	Mild suppression in pH with no significant impacts (> 2%)
Biota (10^{-5} M)	O_2 depletion, lethal (>4%)	Injure life functions (> 2%)	Mild toxicity (> 0.5%)

the engineered system

- Key CO_2 risk concentrations
    - 2000ppm for environment
    - 15000ppm for people

- Based on these, 30m to 5km zones will be impacted by CO_2 leaks depending on where the leak occurs in the system

risk transects for individual being exposed to a concentration of 2000ppm
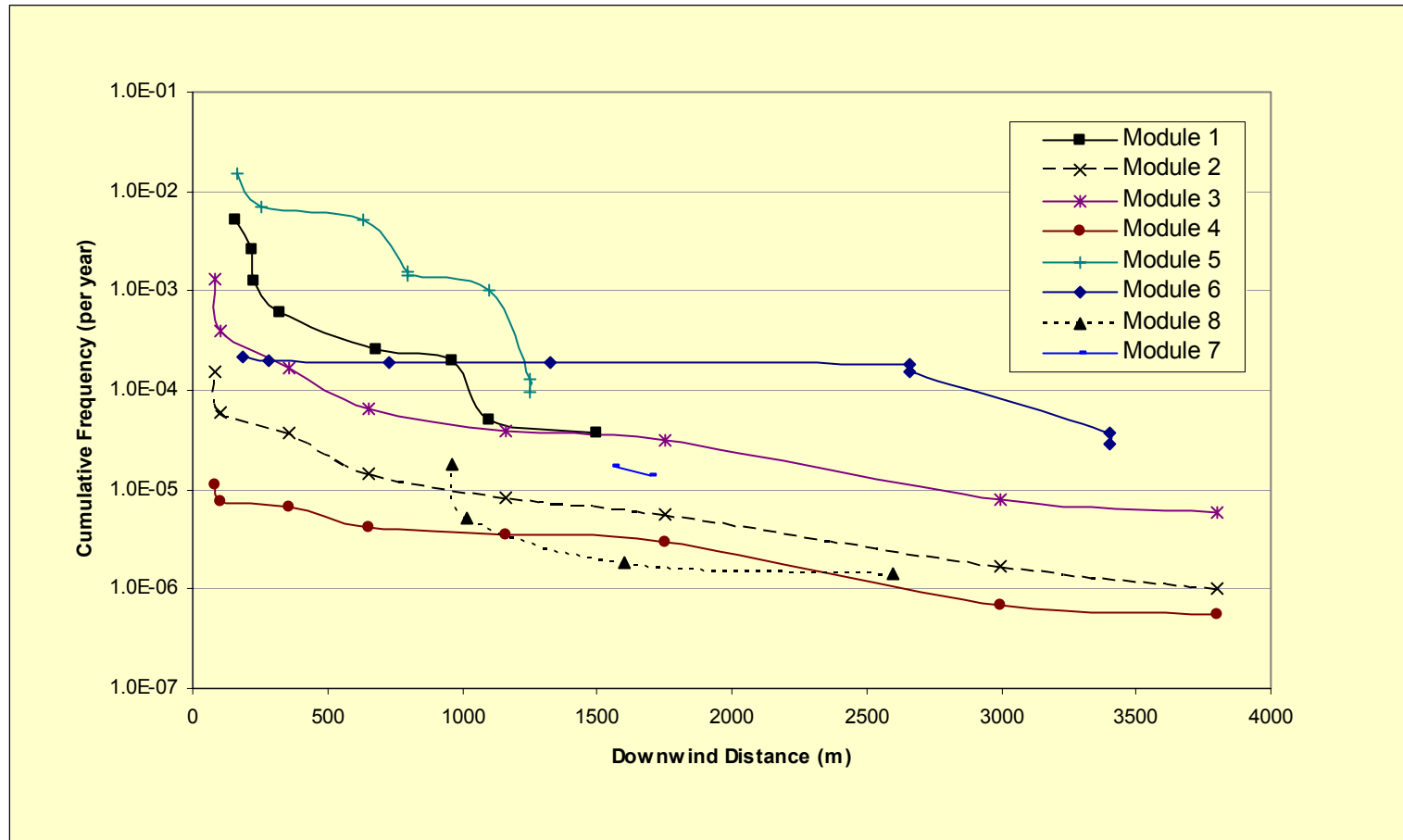
HSE risk criteria for individual fatality

Maximum tolerable risk for workers 10^{-3} per year
Maximum tolerable risk for the public 10^{-4} per year
Broadly acceptable risk 10^{-6} per year

Unacceptable region

Risk cannot be justified
save in extraordinary
circumstances

10^{-3} per year
10^{-4} per year

The ALARP or Tolerability
region
*(Risk is undertaken only if
a benefit is desired)*

Tolerable only if risk reduction is
impracticable or if it cost is grossly
disproportionate to the improvement
gained
Tolerable if cost of reduction would
exceed the improvement

10^{-6} per year

Broadly acceptable region
*(No need for detailed working to
demonstrate ALARP)*

Necessary to maintain assurance
that risk remains at this level

Negligible risk

MANAGING RISK DNV

module 3 fatality risk (booster stations)
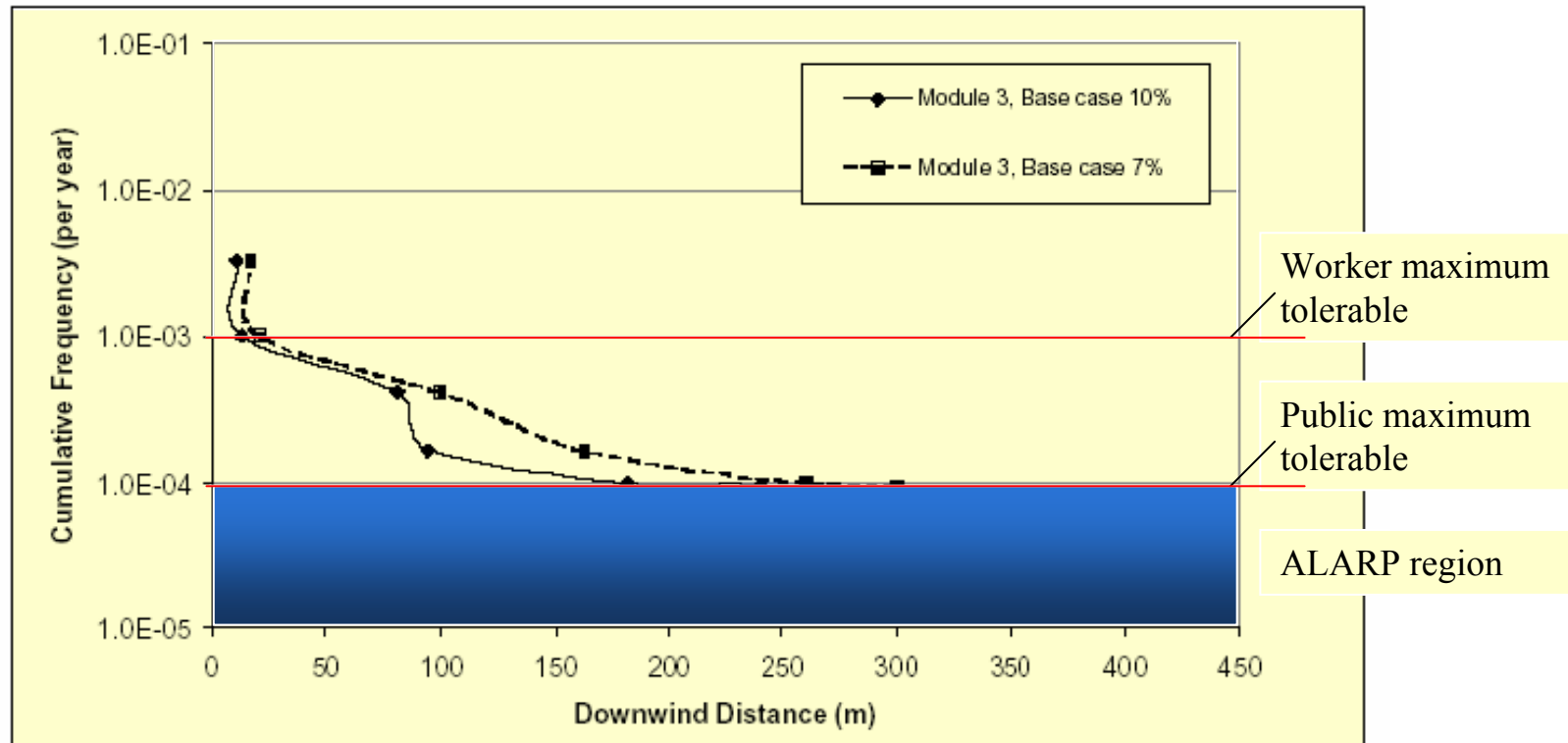
Individual Risk (Fatality) Transect Associated with Module 3

implication (module 3)

- The individual risk levels would be unacceptable for distances of:
  - 250m using 10% concentration as the fatality criterion
  - up to 450m with 7% concentration as the fatality criterion
- the results presented are considered to represent an upper bound because of the various conservative assumptions

limiting the risk (module 3)

- **Occupancy:** 100% occupancy assumed. If hazard ranges are non-residential, the frequency would be reduced by at least a factor of 4

- **Mitigation:** Containment, monitoring and additional detection could reduce risk

- **Isolation:** 50km of pipeline inventory assumed available for release (after isolation), which may be reduced with more isolation

- **Flow rate:** 20 million t/y assumed but may vary in practice

possible carbon dioxide losses

	Module	Release Inventory (tonnes per year)	Storage Rate (tonnes per year)	Release Inventory as % of Storage Rate		
				Base Case % Loss	With 3 months down-time per release	With no limit on un-isolated releases
1	CO_2 Recovery	836	3×10^6	0.0279	0.029	0.34
2	Converging Pipelines	124	20×10^6	0.0006	0.0006	0.007
3	Booster Station	695	20×10^6	0.0035	0.0035	0.041
4	Pipeline	12	20×10^6	0.0001	0.0001	0.0007
5	Injection Plant	871	3×10^6	0.029	0.030	0.35
6	CO_2 Riser	17	35×10^6	<0.0001	<0.0001	0.0005
7	Line to Containment	11	30×10^6	0.0004	0.0004	0.0044

SWIFT review of the storage systems

Figure derived from GESTCO
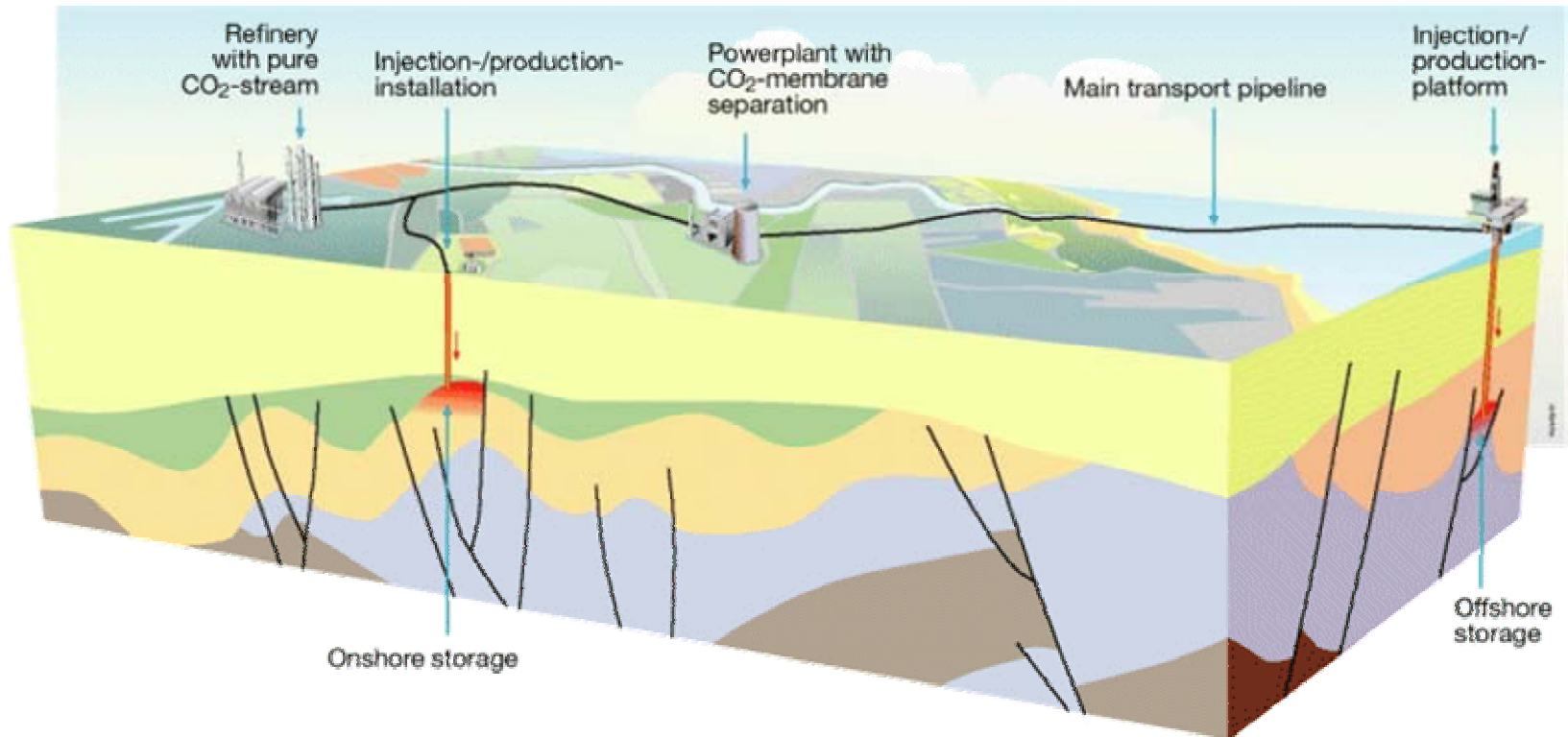
MANAGING RISK

top hazards

- Well bore failure
- Chemical interaction at the well bore
- Physical interaction at the well bore
- Geomechanical effects
  - Micro seismicity
  - Stress and micro fractures due to:
    - Injection rate/volume
    - Injection pressure (pressure changes and stress)
    - Injection fluid temperature (thermal stress)
  - Fault lubrication by CO_2 (causes slipping)
  - Fluid-CO_2 interface stress
  - Tectonic activities
  - Extraction of oil changes reservoir shape and stresses
  - Corrosion cracking (rock dissolution)
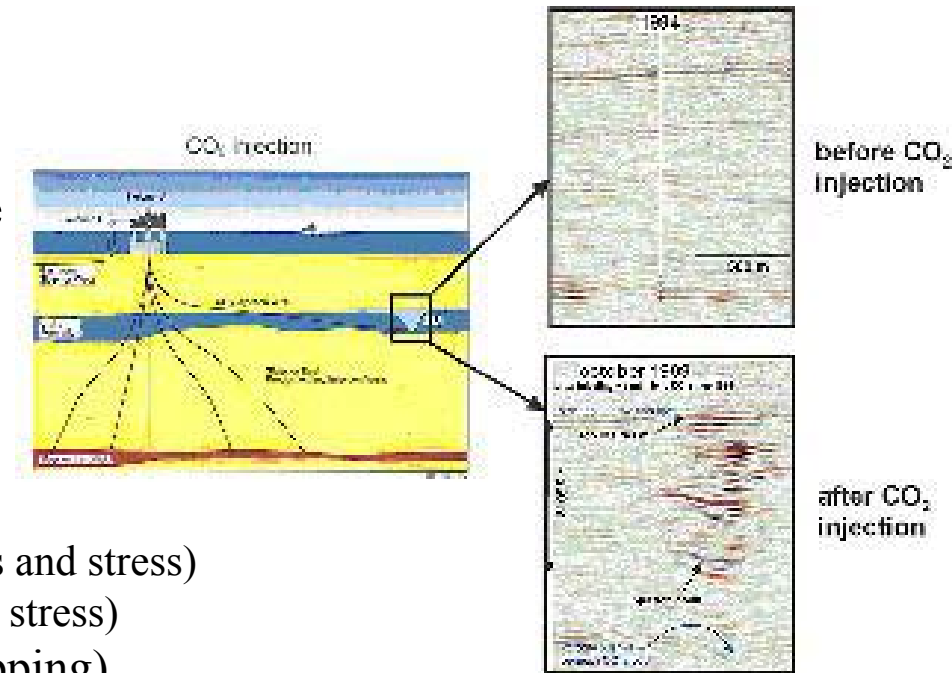
Picture from Changingclimate.com of Statoil operation

MANAGING RISK DNV

- **The frequency of significant leaks (>10 t/d):**
    - during operation is estimated as 10^{-3} per reservoir year (CI: 5×10^{-4} to 2.5×10^{-3})
    - after reservoir sealing, the uncertainty range rises to 4 orders of magnitude
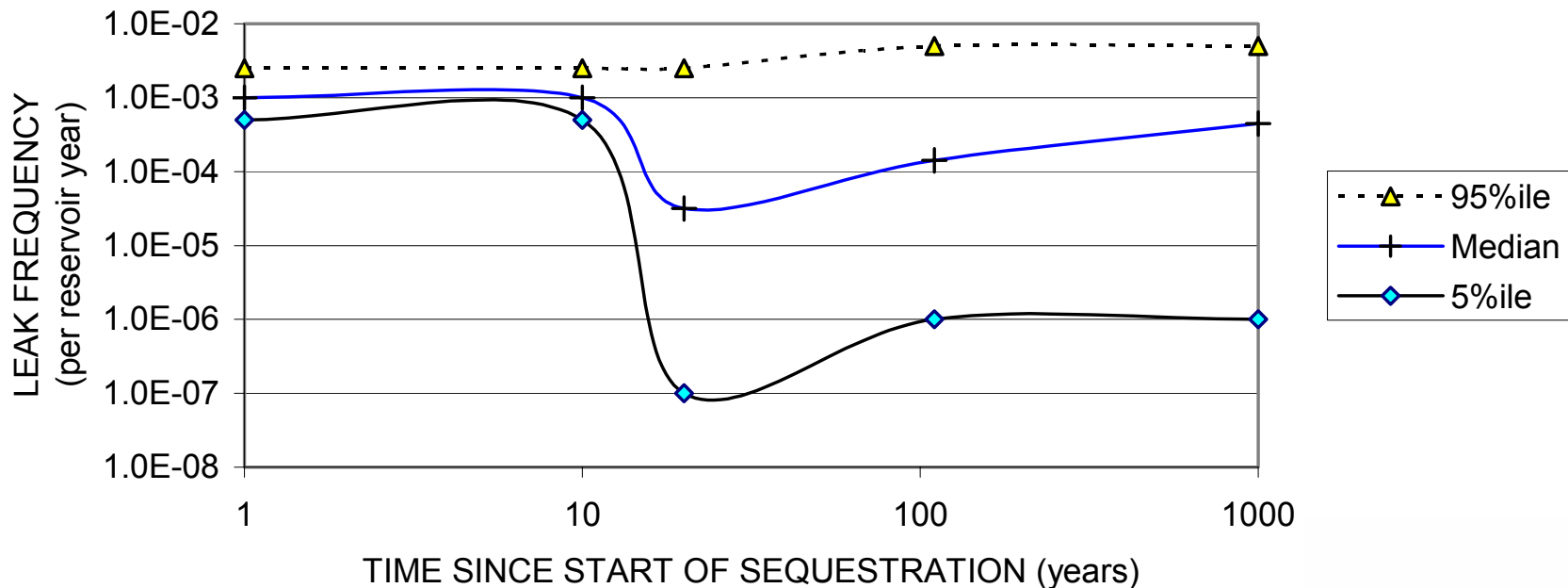
cumulative leak probabilities

- **The cumulative probability of significant leaks during the 1000 year reservoir design life:** is estimated as **0.34** (CI: 0.006 to 0.99).

MANAGING RISK
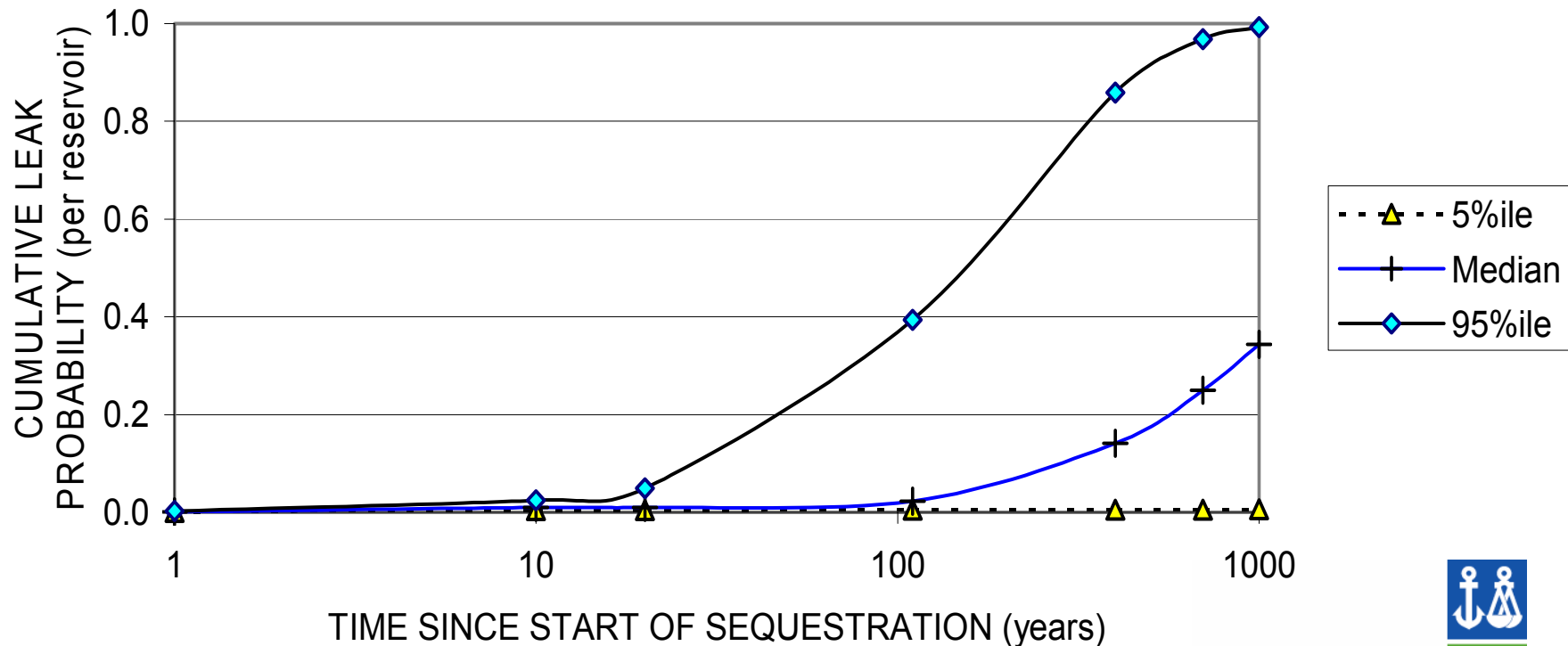
summary

- The probability distribution estimate of **initial release rates:**
  - median of 4500 t/d (90% range 500 to 10,000 t/d)

- The **mean release quantity**:
  - is estimated as 270,000 t (CI: 27,000 to 2.7 million)
  - represents 0.7% of the amount stored (CI: 0.07 to 7%)

- The estimated **probability-weighted release quantity:**
  - 92,000 t (CI: 1600 to 960,000) during the reservoir lifetime
  - 0.2% of the amount stored (CI: 0.004 to 2.4%)

implications

- It is currently difficult to quantify with any confidence the likelihood of accidental releases from CO_2 storage reservoirs because of:
  - the lack of detailed research and field trials
  - the difficulty of assigning generic risks to what in reality would be extremely site-specific risks

- Further research, combined with consideration of specific reservoirs, could eventually permit quantitative estimates of the risks

some learning points to aid future projects

- QRA was robust and used data from the oil and gas industry where a long track record was established

- SWIFT produced focussed and good results and stimulated in-depth discussion and brought diverse parties to a common understanding

- DELPHI is a good technique, but in the face of a lack of real historical data and site specific reservoir information the technique produced results with wide confidence intervals

- Risk communication must allow for audiences at all levels of understanding, from the no risk to extreme levels of risk perception

MANAGING RISK

What can we learn from studies on Natural Analogues?

The NASCENT project

Jonathan Pearce
Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG
Tel 0115 936 3222
jmpe@bgs.ac.uk

British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

NATURAL ENVIRONMENT RESEARCH COUNCIL

Acknowledgements

- EC FP5 Energy Environment and Sustainable development Programme
  - Contract ENK5-CT-2000-00303.
- Nascent partners:
  - BGS: Tom Shepherd
  - BRGM: Yves-Michel le Nindre
  - IGME: George Hatziyannis, Antonis Metaxas
  - URS: Salvatore Lombardi, Stan Beaubien
  - RWTHA: Bernd Krooss, Sandra Hildenbrand

Objectives

- Natural CO_2 occurrences are analogues for geological CO_2 sequestration and leakage

- Key issues
  - How will CO_2 affect the reservoir?
  - Under what conditions could CO_2 leak?
  - What are the potential effects of leakage?

- Rigorously answering these questions requires a risk analysis approach
  - Nascent will provide the data for this subsequent risk analysis

Approach

- **How could injected CO_2 change reservoir properties?**
    - CO_2-pore water-reservoir interactions
    - Geomechanical changes – fault reactivation, ground movement

- **What makes a good seal for CO_2?**
    - Caprock sealing capacity

- **Under what circumstances might CO_2 leak through a seal?**

- **How could we monitor leakage at or near the surface?**
    - Shallow gas case histories
    - Automatic monitoring stations
    - Soil gas surveys

- **What would be the effects of leakage?**
    - aquifers
    - people

Onshore Sites

Talk outline

- Use examples to illustrate potential processes of relevance to risk assessment
  - Effects on reservoir and leakage at Montmiral, France
  - Caprock sealing studies, and effective permeabilites for CO_2.
  - Effects of leakage on groundwaters at Florina, Greece.
  - Case histories (extreme?) in Italy and Florina

Structure of Bassin du SE

The Bassin du Sud-Est is bounded by features
which exhibit contrasted tectonic styles.

Structure of Bassin du SE

The Bassin du Sud-Est is bounded by features which exhibit contrasted tectonic styles.

1. Tabular Palaeozoic shield of the Massif Central

   - Rejuvenated by Pyrenean and Alpine orogenic phases.

2. Alpine thrust belt

   - folded during the Miocene following a west-east compression

   - uplifted the Mesozoic sedimentary strata of the basin to the outcrop.

3. East-west ridges due to the Late Cretaceous-Eocene Pyrenean compression

Legend:
- Pliocene volcanics
- Neogene-Oligocene
- Mesozoic sedimentary cover - autochthon
- Mesozoic sedimentary cover - inverted Alpine foreland
- Far travelled allochthonous Mesozoic units
- Basement
- Normal fault
- Reverse fault
- CO_2-rich springs
- CO_2 accumulations

Schematic NW-SE section

NW

SE

CO_2

CL1   TE101   DP108   Mo1   VMo2   SLF1   VAF1

F12 F13

F4

S1

Miocene

Oligocene

F8/F11

F

S4

Pre-Tertiary unc.

S2

Lower Cretaceous

Oligocene Salt

S7

S3

Terres Noires

S8

Upper Jurassic

S5

S9

S6

1000 m

CO₂ reservoir

10 Km

Dogger

Lias
Triassic
Basement

Tersanne area

Montmiral area

Fiancey area
(>> South)

Typical sandstone
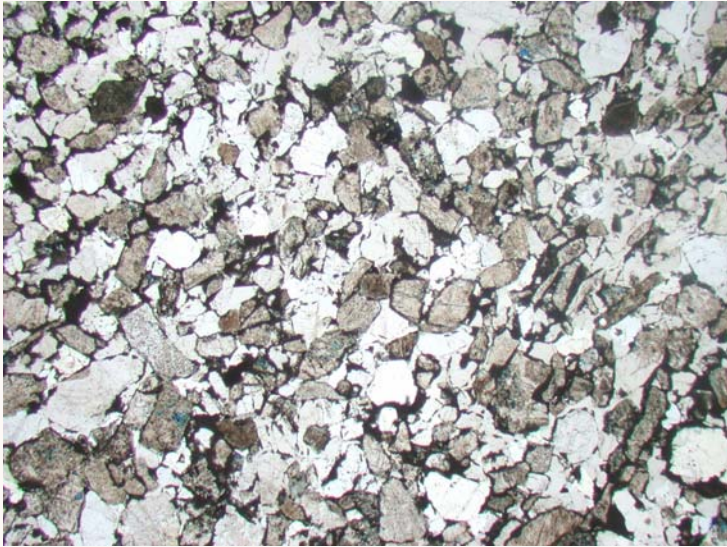
SL01-06
No CO_2
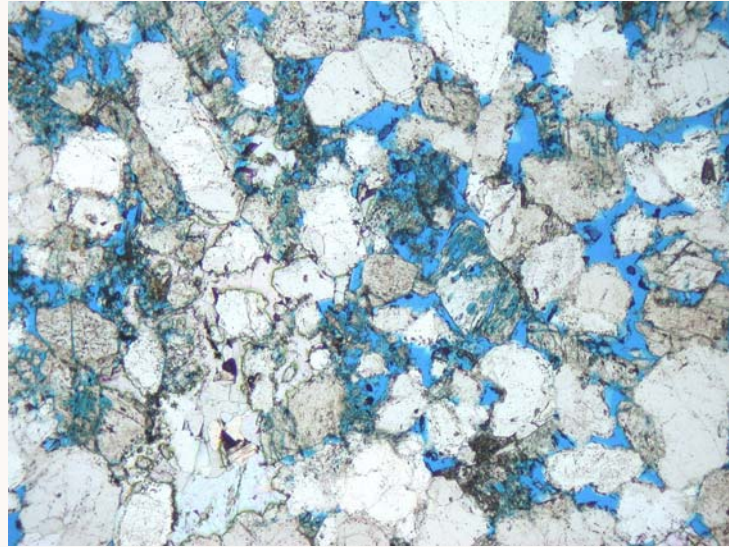
VM02-10
CO_2 production well

Porosities
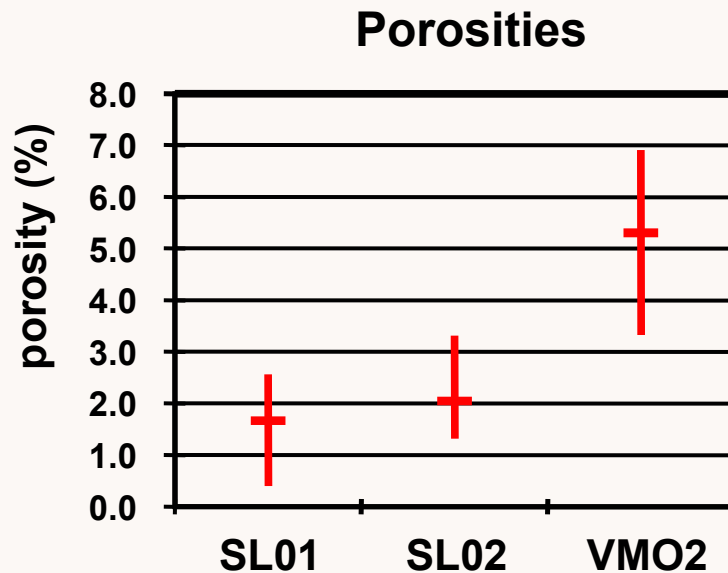
CO$_2$ migration along fractures
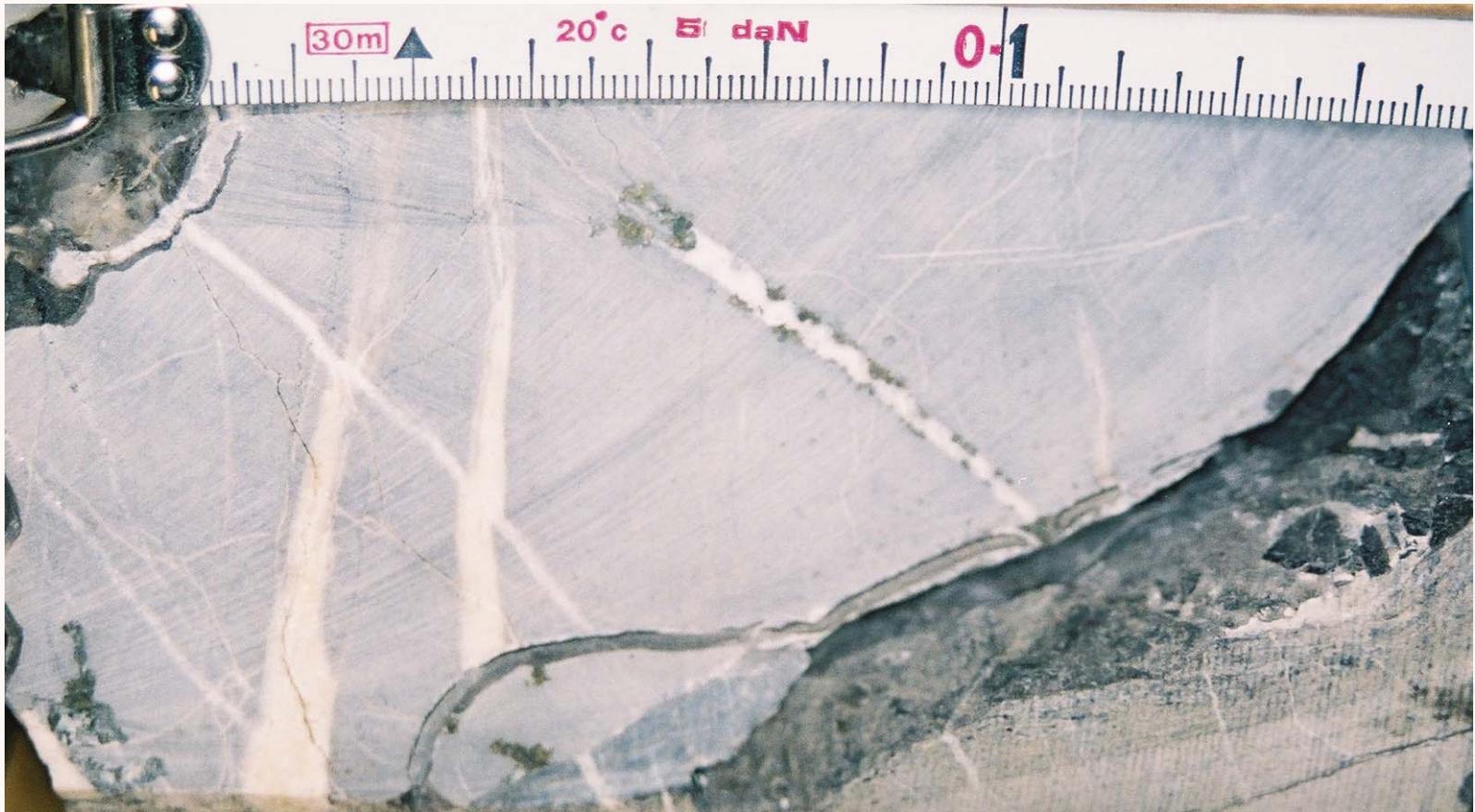
CO$_2$ migration along fractures
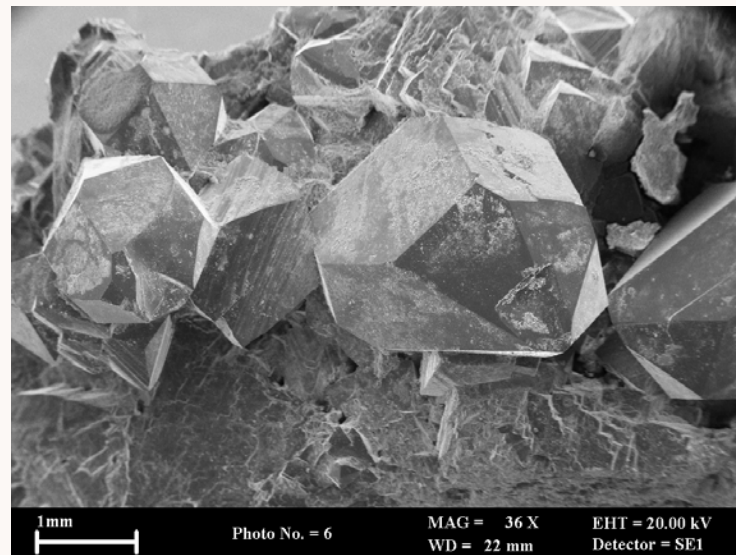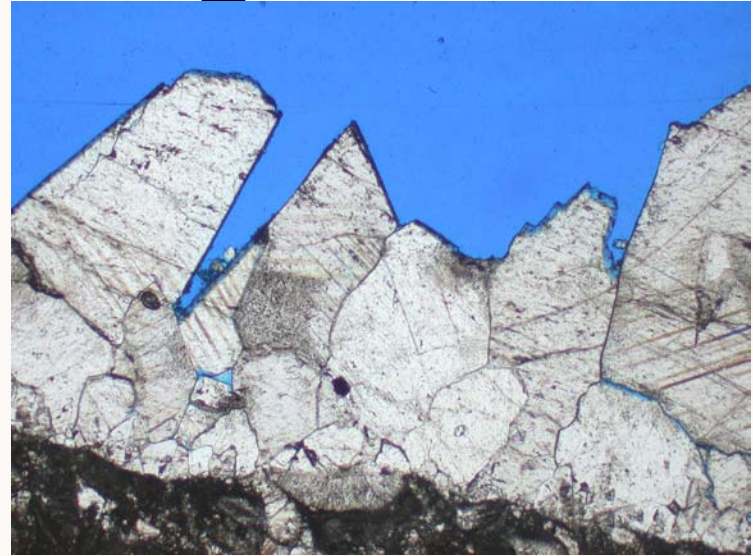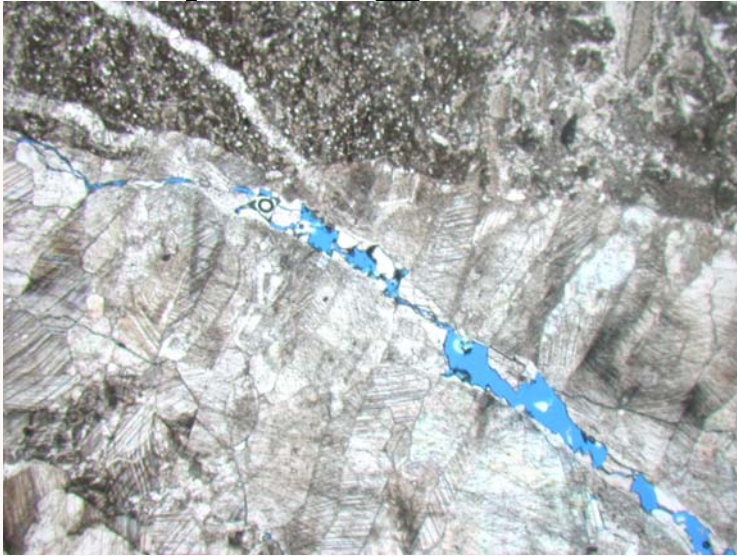
Fluid Inclusion Assemblages

Fluid Inclusion Types at room temp.

1. Aqueous (aqueous liquid+vapour)
2. Supercritical CO_2 or CO_2 liquid+CO_2 gas
3. Aqueous-carbonic (water+CO_2 liquid+CO_2 gas)
4. Hydrocarbon (liquid hydrocarbon+gas)
5. Mixed CO_2-liquid hydrocarbon

100 microns
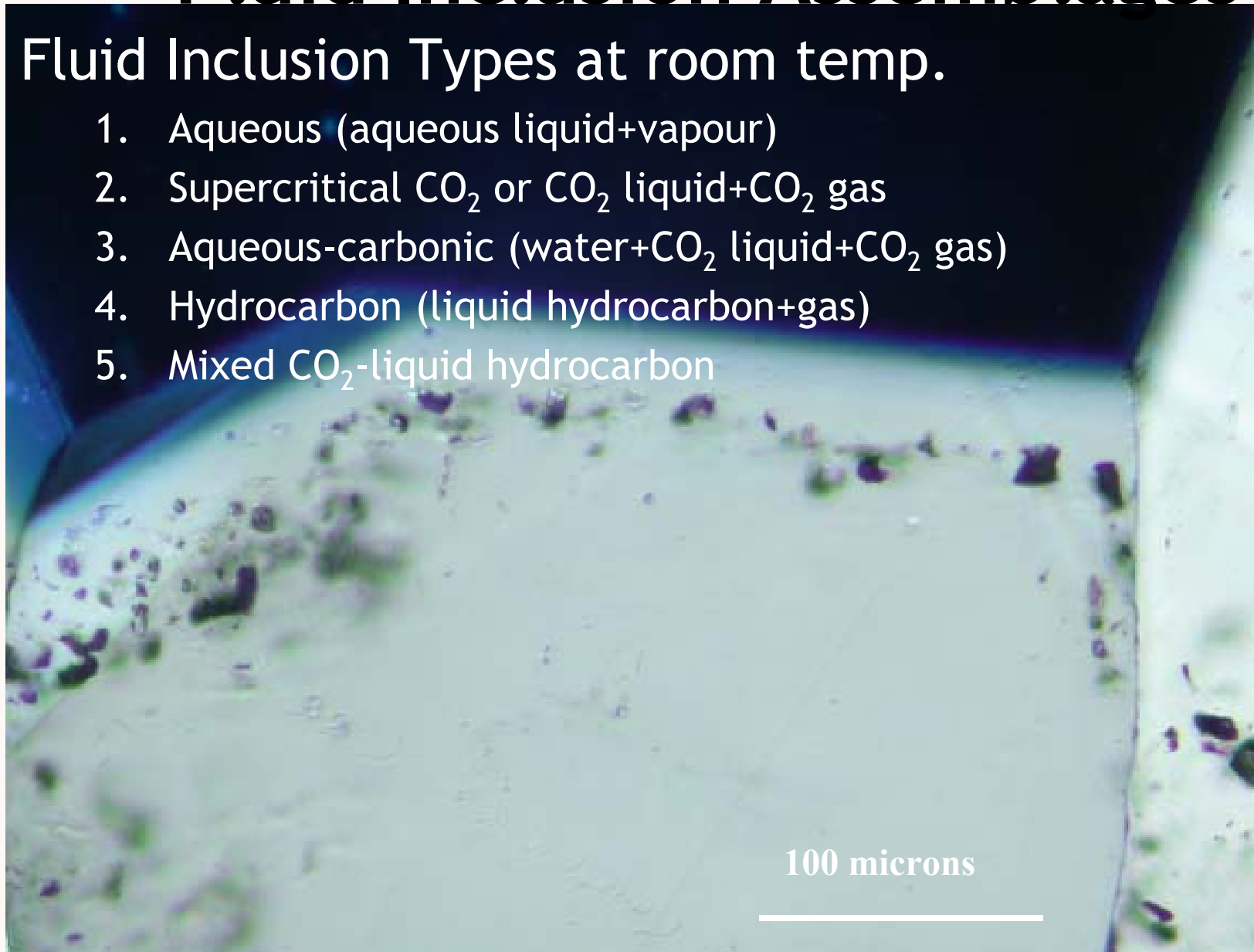
Simplified fluid evolution model

- ## Cementation of Triassic reservoir
  - fracturing and anhydrite veining

- ## Burial & Hydrocarbon generation in cover rocks at ~115 °C

- ## Uplift, fracturing and carbonate veining

- ## Introduction of CO_2 from basement & reservoir filling
  - cement dissolution, secondary porosity
  - (pure CO_2 inclusions in basement)

- ## Fracture reactivation
  - CO_2 migration through caprock
  - Hydrocarbon remobilisation by supercritical CO_2 at 45-65 °C

- ## Carbonate veining in cover rocks
  - primary CO_2 and HC inclusion
  - CO_2 inclusions with high content, light hydrocarbon gases

Migration through sealing rocks

- **Fracture systems**
  - sealing or non-sealing faults
  - tectonic events
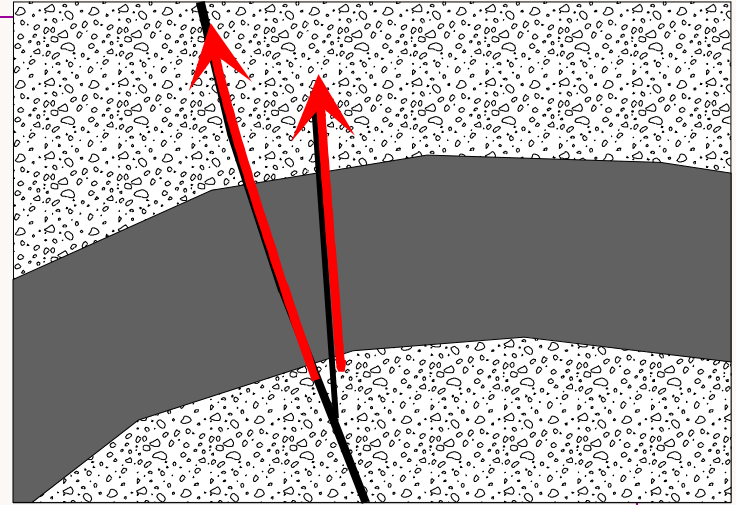
- **Undisturbed rocks (matrix)**
  - **pressure-driven volume flow**
    - o single-phase flow (water)
    - o two-phase flow (N_2, $CO_2 \rightarrow$ water) (episodic, "dynamic leakage")
  - **diffusion (CO_2)** (ubiquitous, pervasive, permanent)

Gas breakthrough

P_{water}

Δx

$k_{gas}(P_d)$

$k_{gas(max)}$

P_{gas}

P_d

$>> P_d$

$\Delta P = P_c$

$S_{gas,max}$
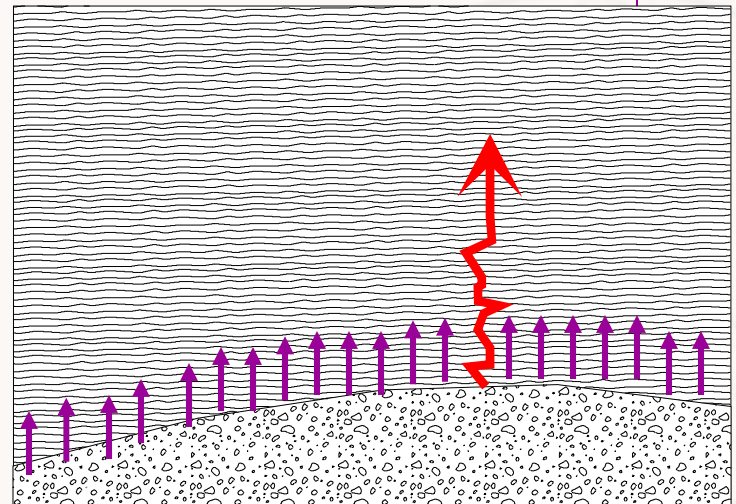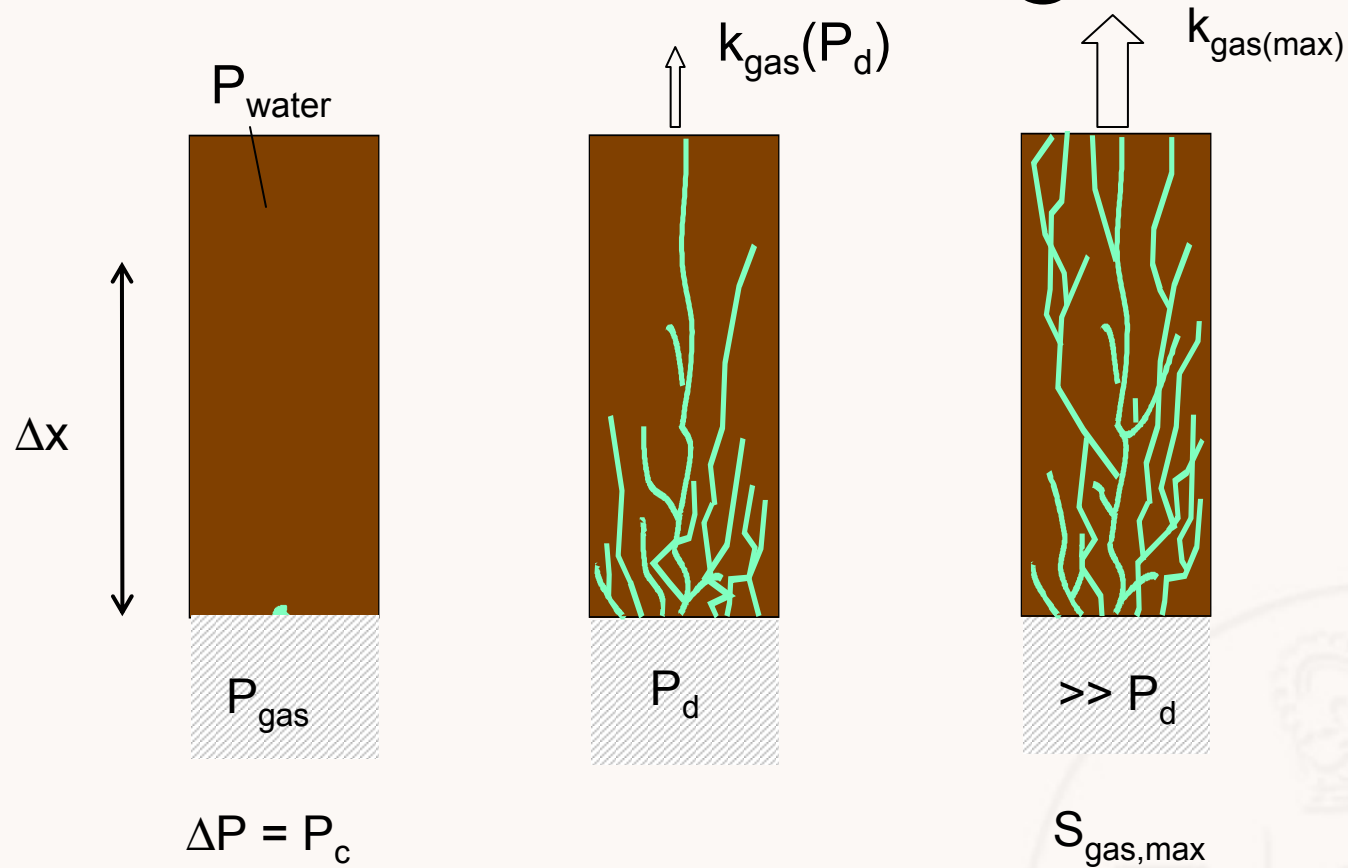
Gas breakthrough experiments

- $k_{eff} < k_{abs}$

- $k_{eff} < 10^{-24}$ m² → diffusion

$y = -0.3487x - 7.1433$
$R^2 = 0.663$

$y = -0.3478x - 7.5075$
$R^2 = 0.7679$

$y = -0.3571x - 7.563$
$R^2 = 0.9072$

Legend:
- N2 (n=25)
- CO2 (n = 17)
- CH4 (n = 17)
- regression N2
- regression CO2
- regression CH4

Axis labels: log(Pd(MPa)) vs log(keff/m²)
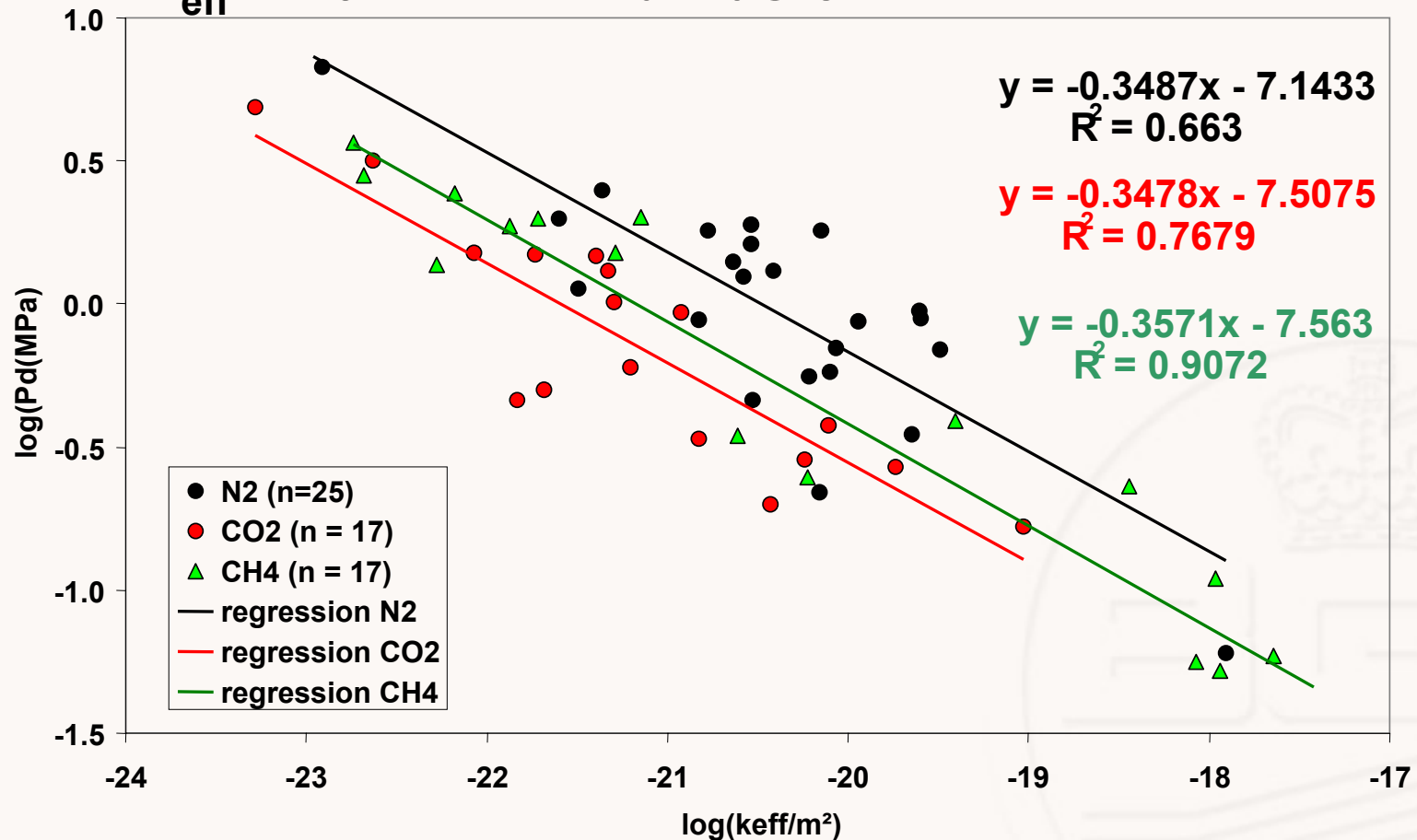
Conclusions

- Gas breakthrough experiments:
  - Data represent the maximum gas sealing efficiency (undisturbed, water-saturated rocks)
    - o minimum capillary displacement pressure (P_d)
    - o after breakthrough: effective permeability to the gas phase as a function of capillary pressure ($k_{gas}(P_c)$)

- Different gas breakthrough behaviour of N_2, CO_2 & CH_4
  - difference in wettability and interfacial tension

- Demonstration by a simple accumulation-leakage model:
  - lower leakage rates with $k_{gas}(P_c)$ than with constant k_{gas}
  - max. k_{gas} may not be reached (dependent on P_c, thus h)

LOCATION of STUDY AREA

- Florina site is located in N. Greece close to border with FYROM.

- There is a production plant there (~20,000 tn of CO_2 annual output).

- It is a low pressure CO_2 field,with pure gas (>99,5% of CO_2).

- Production is done by simple physical gas – water separation

Location of the study area
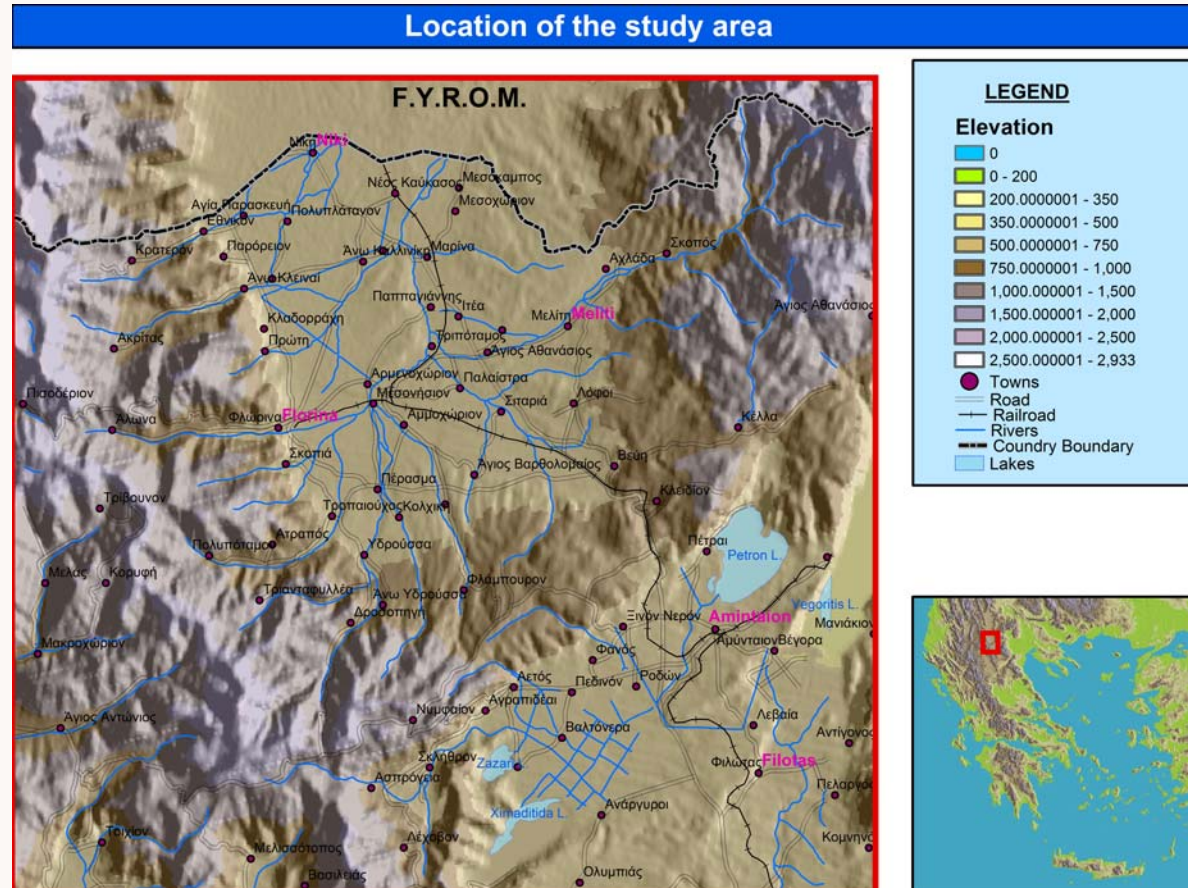
Borehole results

- 14 CO_2-rich zones have been detected and core sampling has been done around these zones.

- Cyclical alternation of coarse and fine – grained sediments.

- High energy fluvial regime alternating with periods of reduced supply.

Conceptual Model of CO_2 migration.
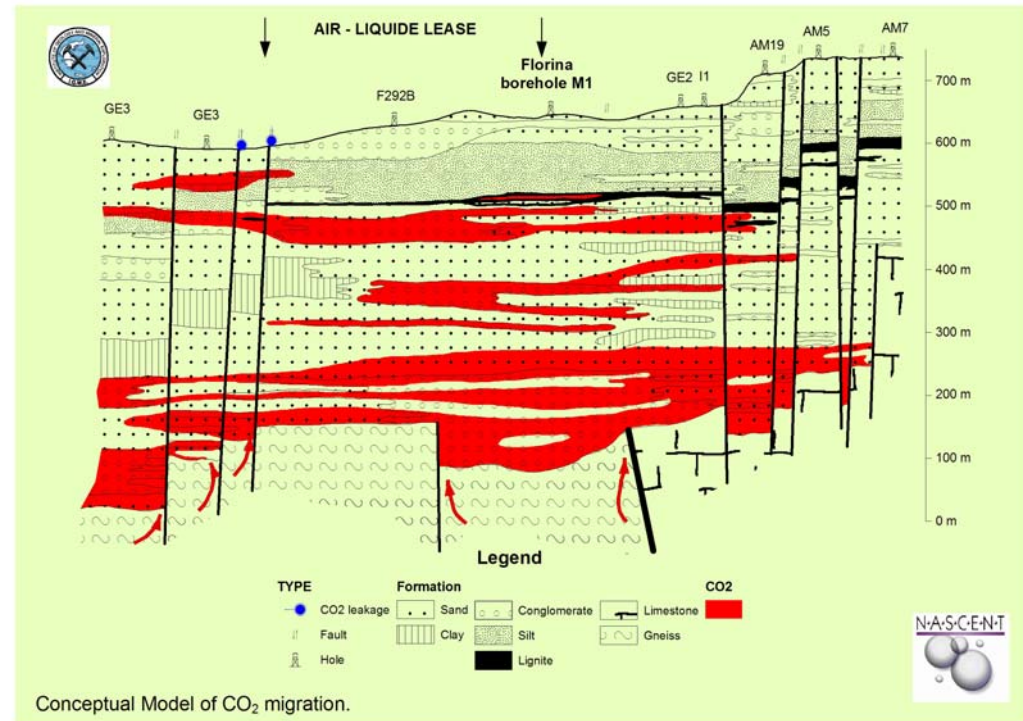
Mesokampos, Florina Basin, Greece
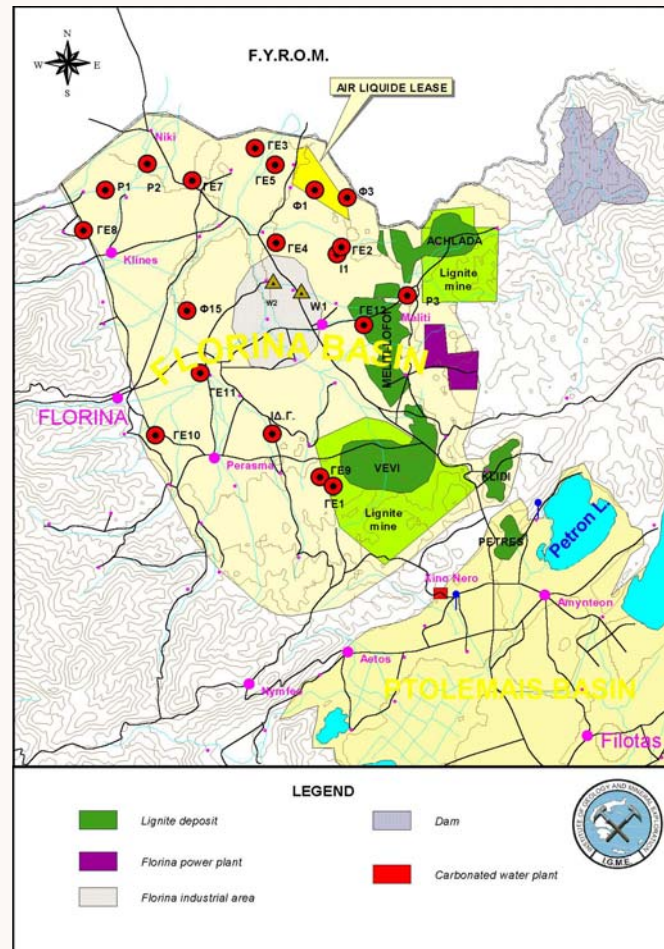
Mesokampos, Florina Basin, Greece
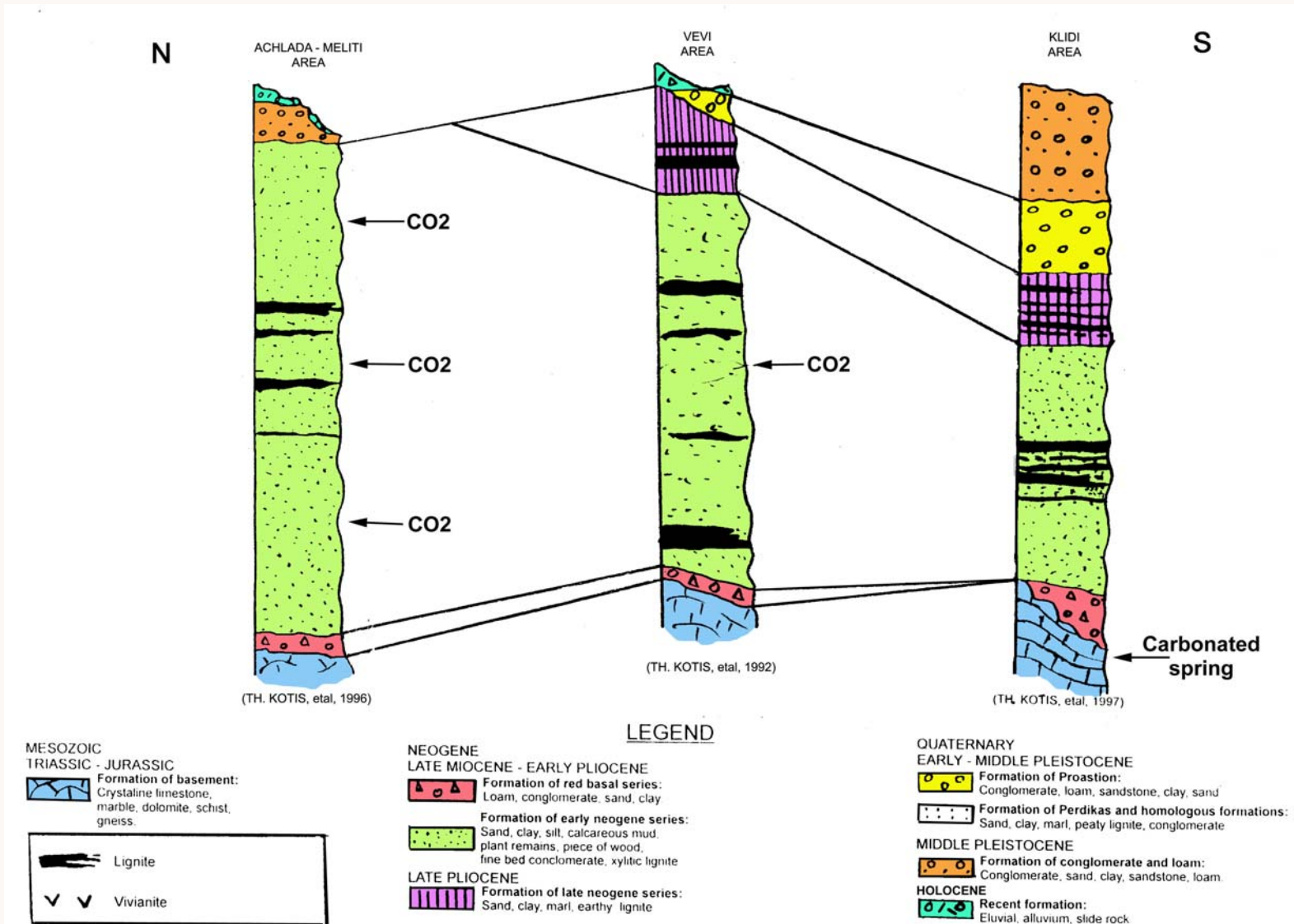
Diagenesis
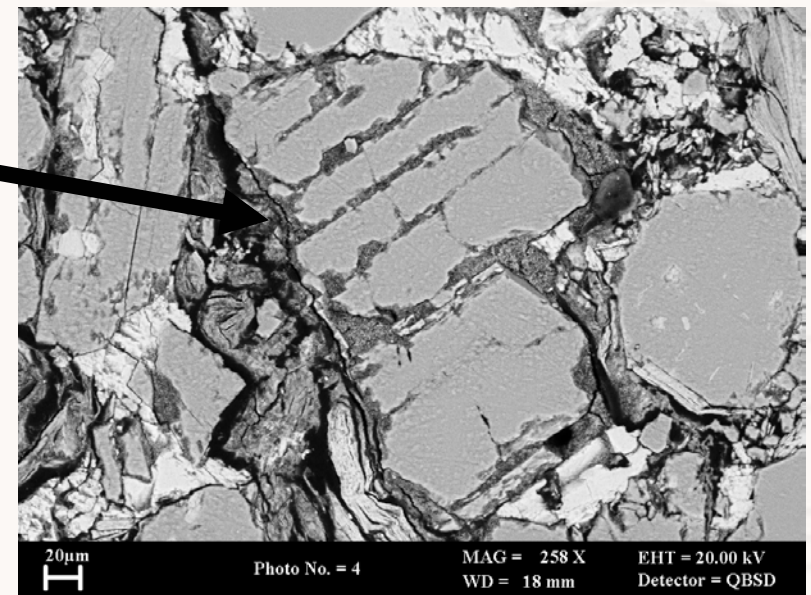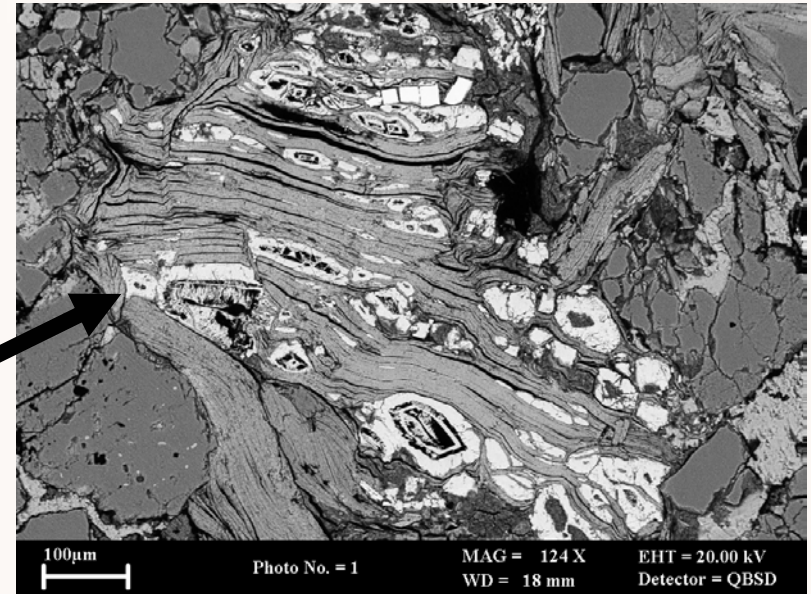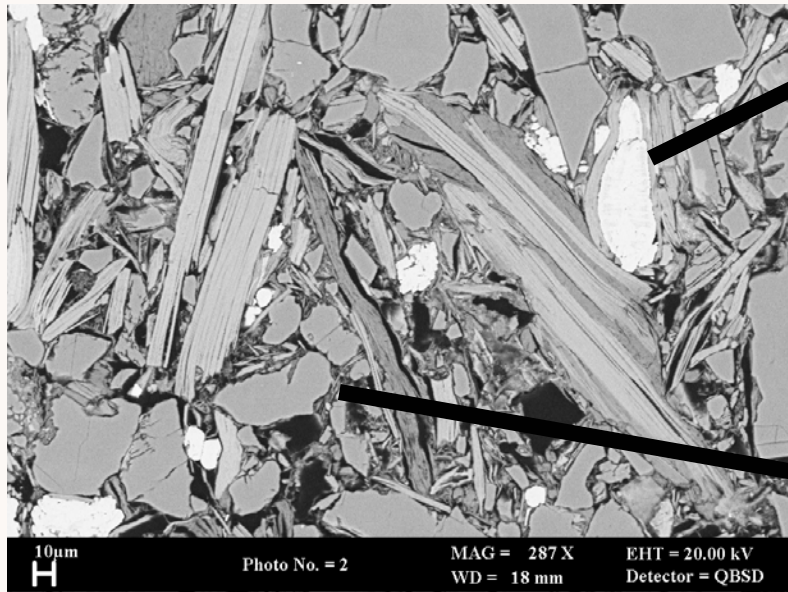
Case history:
Florina exploration well

- Summer 1990, a mineral water exploration well was drilled to a depth of 595 m

- CO_2 shows were identified from a depth of 97 m to bottom
  - pressure at wellhead was 3 MPa and water flow rate was 30 m^3 per hour.
  - Calculated pressure at well bottom was 5 MPa

- After completion, and while the wellhead valve was closed, CO_2 leaks were observed ~100 m from the well.

- A hole developed around the well head of more than 25 m^2, and a depth of 50 m

- The hole was filled by ~900 m2 of loose rock

- Local authority then created a concrete pool for local bathing, until one man swam in the pool and was asphyxiated

- In 2002, after 12 years CO2 and water flow finally ceased – possibly through self-sealing?

Florina Basin- Water quality

- Most of the water in the Florina basin is of very good quality for drinking, i.e. it is not affected by CO_2. e.g. Flambouro and Aetos spring.

CO$_2$ field

- Only the samples close to the CO_2 producing field are of bad drinking quality due to increased values of Ca, Mg, HCO_3 and total hardness (sample D1).
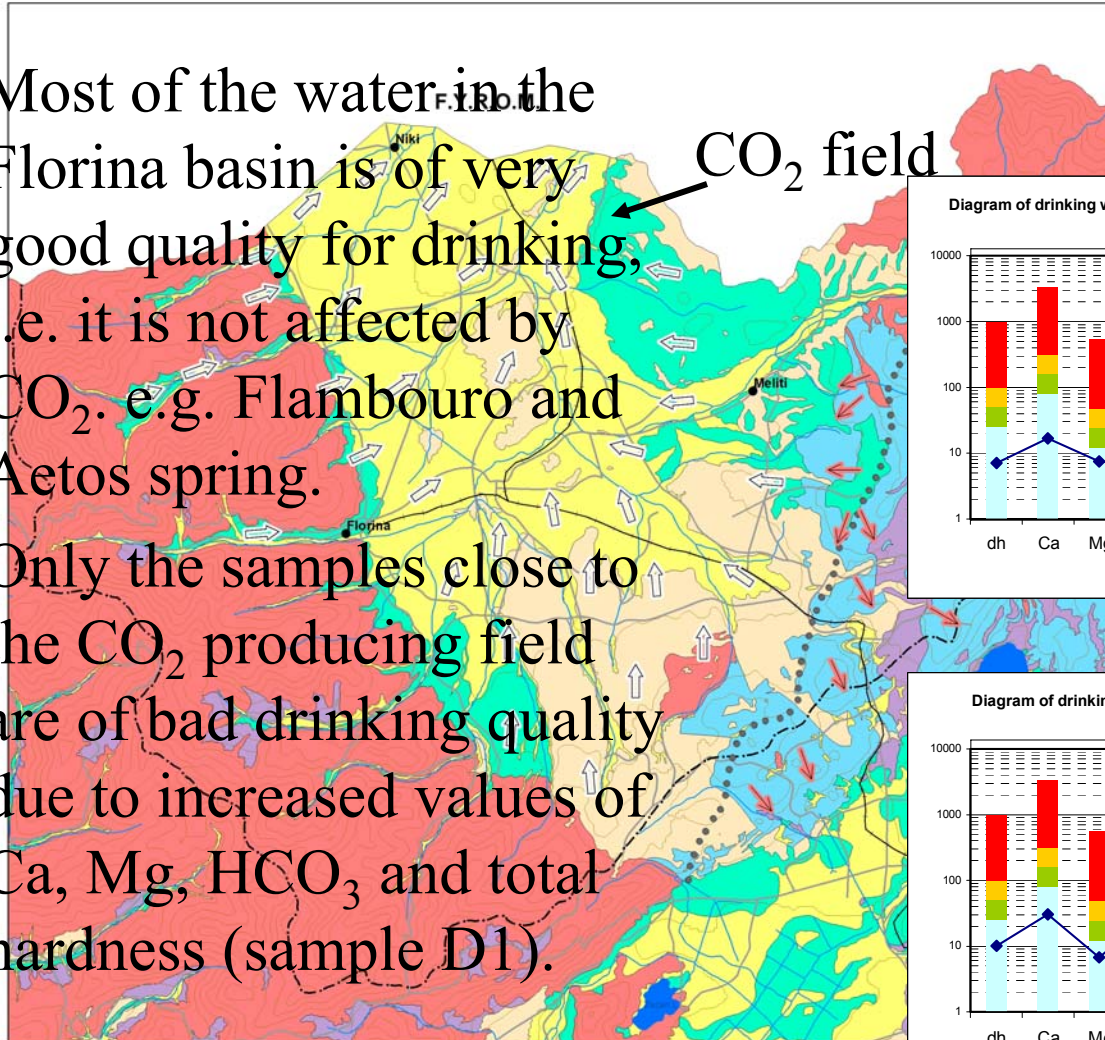
Diagram of drinking water quality acc to C. Waterlot

Δ17 Πηγή Φλάμπουρο

- bad quality
- medium quality
- satisfactory quality
- good quality

dh   Ca   Mg   Na   Cl   SO4   CO3

Permeability moderate
Permeability low
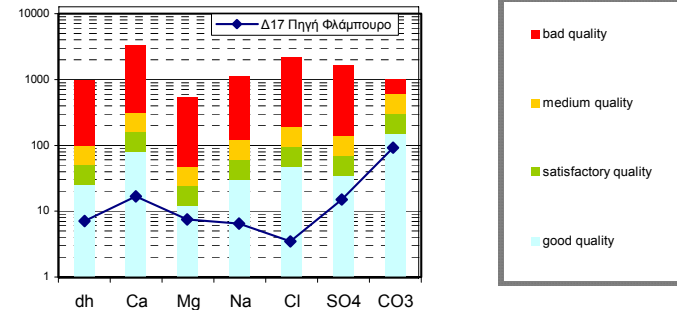
Diagram of drinking quality acc to C. Waterlot

Δ5 Πηγή Αετός

- bad quality
- medium quality
- satisfactory quality
- good quality

dh   Ca   Mg   Na   Cl   SO4   CO3
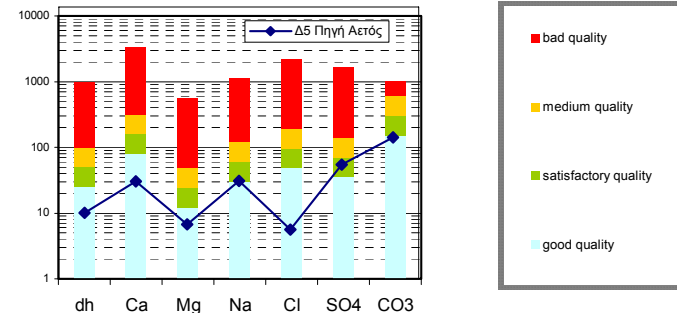
S. Vittorino
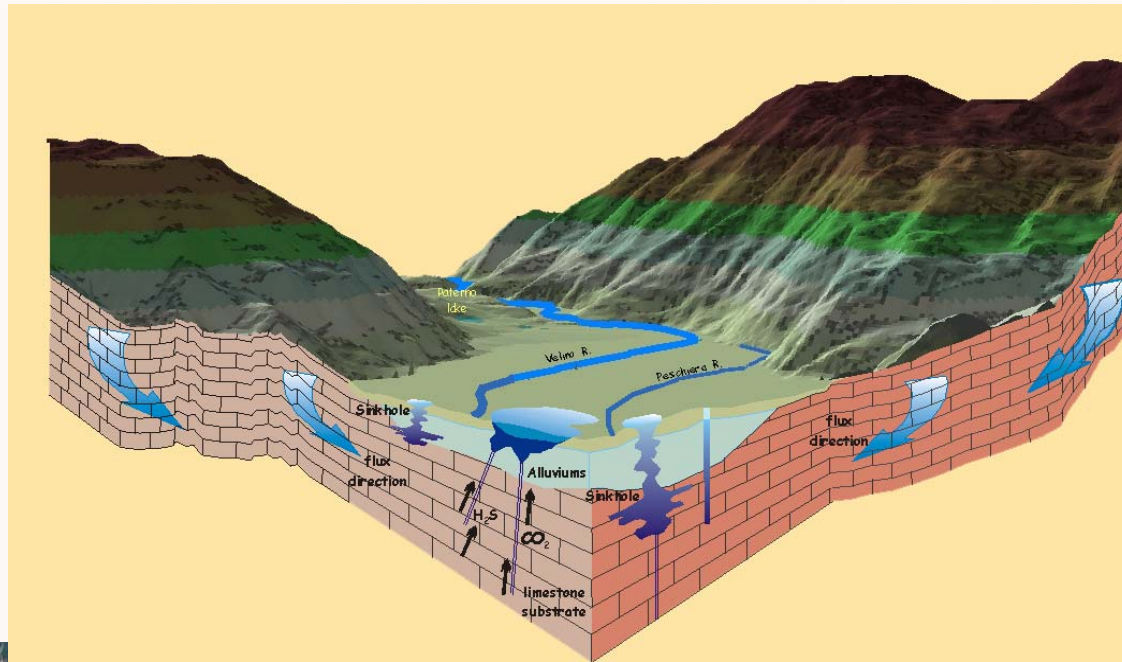
Contour map of carbon dioxide

CO₂ log % v/v legend:
1.38 (24)
1.30
1.20
1.13
1.05
0.98 (10)
0.90
0.83
0.75
0.67
0.60 (4)
0.56
0.42
0.21
0.10
-0.20 (0.6)
-0.50
-0.80
-1.10
-1.40

● Gas Vent
X Sinkhole

Fault
Micciani fault
Inferred fault

Fluid Chemistry Lab
Earth Science Department – University of Rome "La Sapienza"

Ciampino

Ciampino - Marino Districts, Rome
Detailed Soil Gas Survey

Dipartimento di Scienze della Terra
Università di Roma "La Sapienza"
P.le A. Moro, 5
00185 - Roma

CO2
(log %, v/v)

1.8 (63.10%)
1.6
1.4 (25.12%)
1.2
1
0.8
0.6
0.45
0.3

Ciampino - Marino Districts, Rome
Detailed Soil Gas Survey
Carbon Dioxide Hazardous Areas
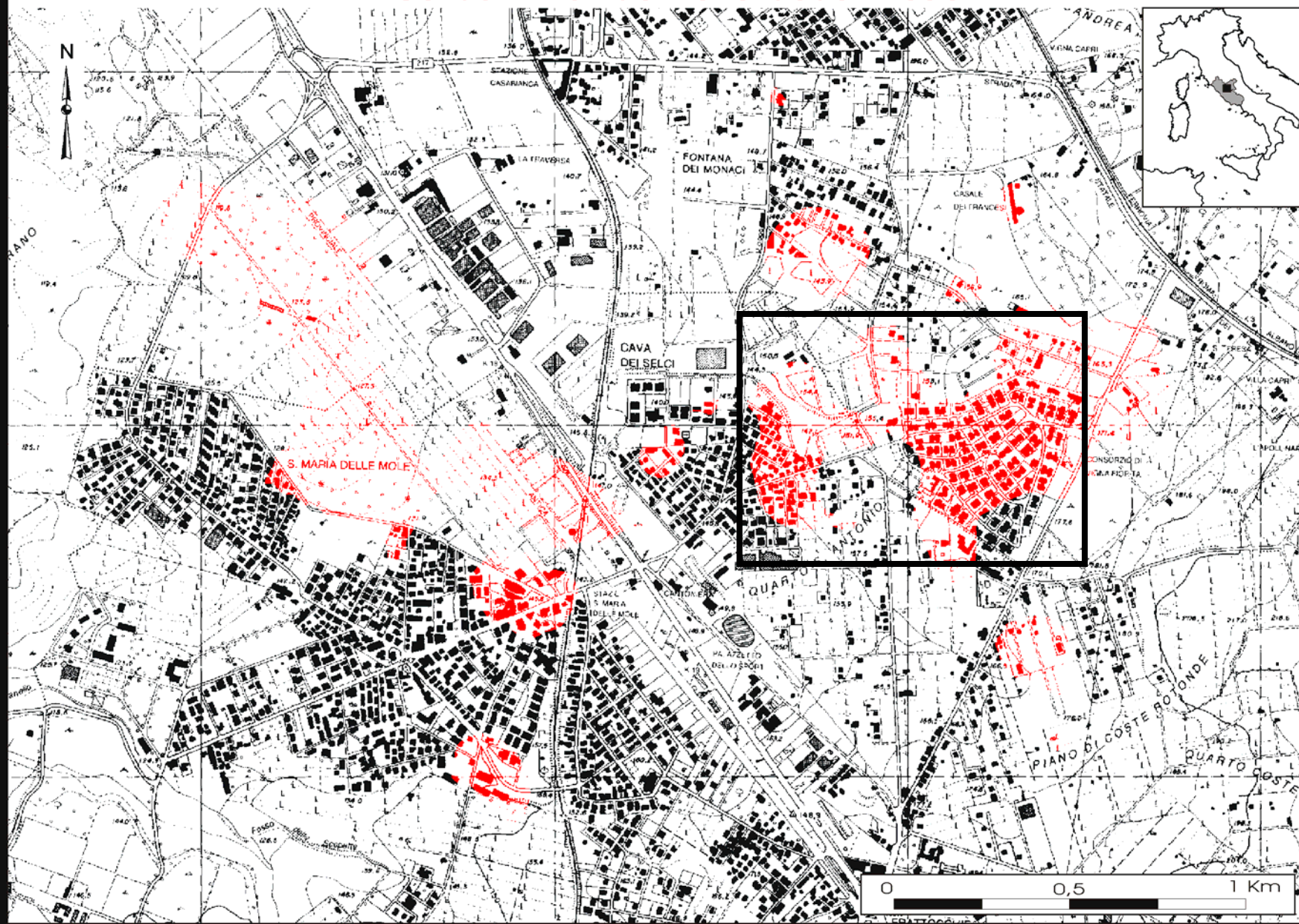
Dipartimento di Scienze della Terra
Università di Roma "La Sapienza"
P.le A. Moro, 5
00185 - Roma

Ciampino - Marino Districts, Rome
Detailed Soil Gas Survey
Sample Location at Vigna Fiorita Village

CO2 > 10%

CO2 < 10%

Ciampino - Marino Districts, Rome
Detailed Soil Gas Survey
Sample Location at Vigna Fiorita Village

Dipartimento di Scienze della Terra
Università di Roma "La Sapienza"
P.le A. Moro, 5
00185 - Roma
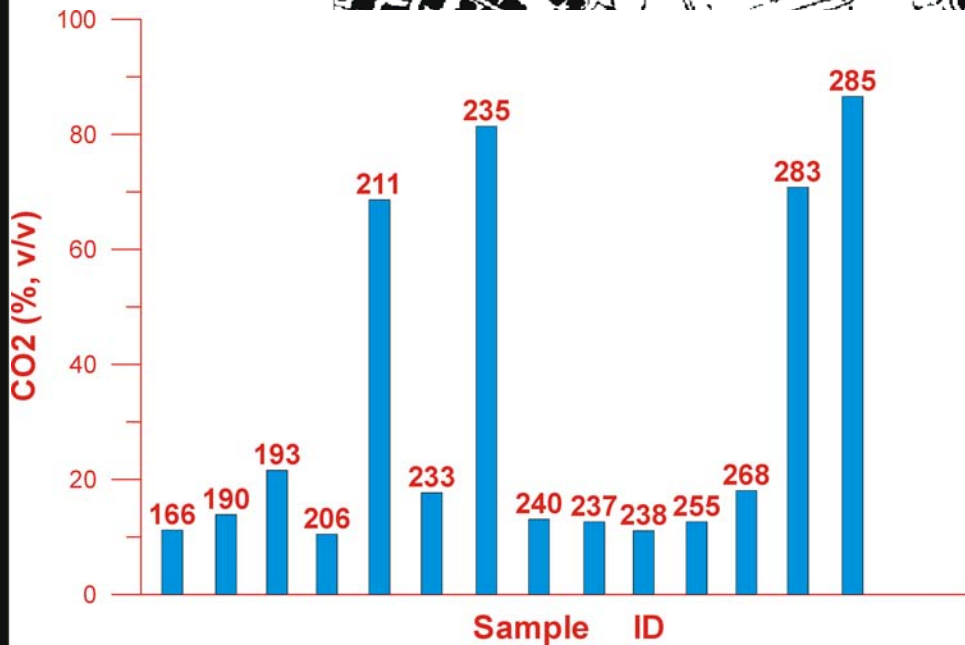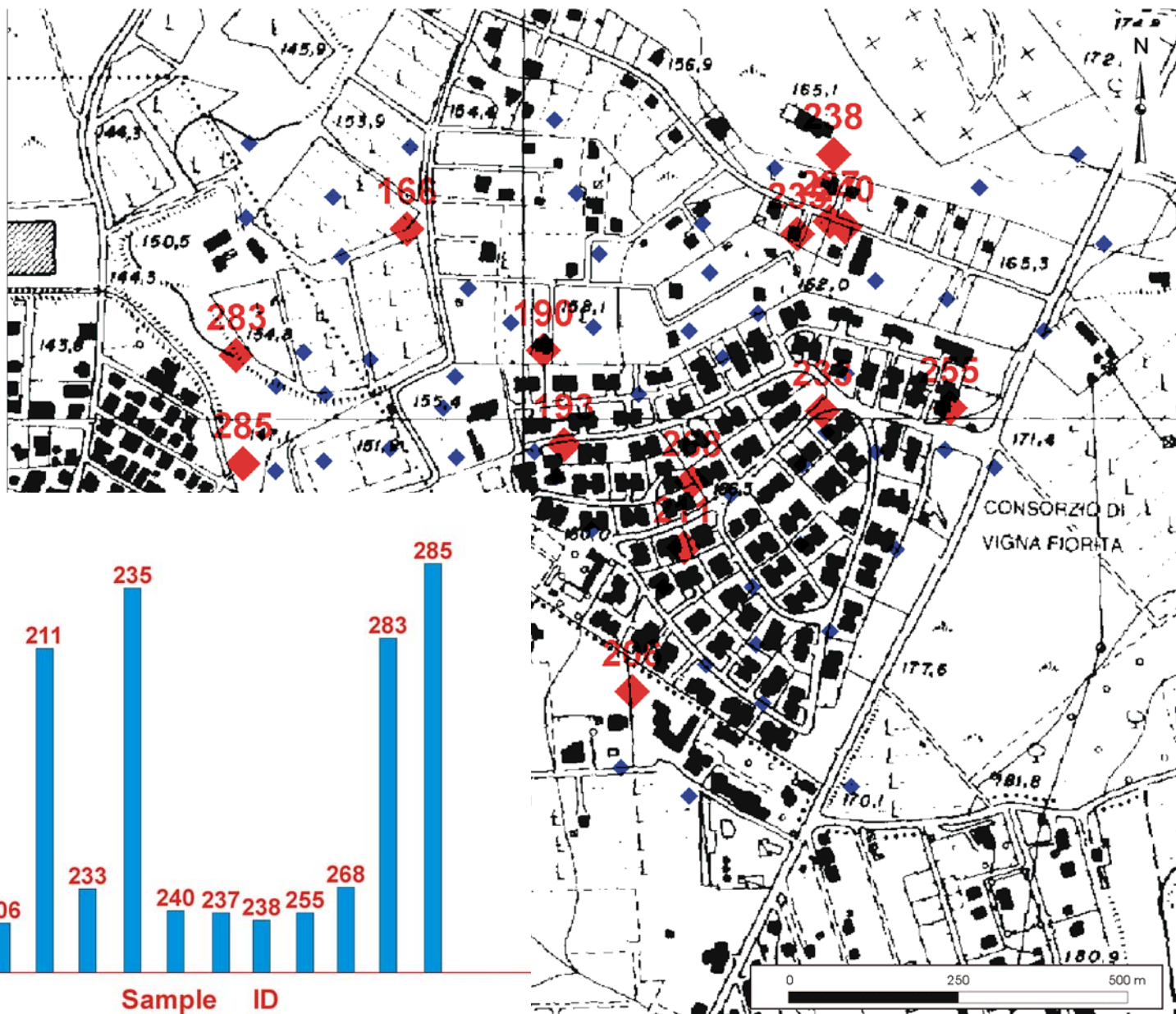
Ciampino f_{CO_2} = 0.7 kgm^{-2}day^{-1}

Conclusions

- Effects on reservoir
  - Increased porosity
  - Fracture self-sealing

- Migration through seals – rates & fluxes

- Effects of CO_2 migration on overlying aquifers – transport of hydrocarbons

- Validation of predictive modelling – both geochemical and geomechanical

- Case histories - effects on aquifers and people

Future work

- Bridge the gap between leakage from reservoir and appearance at ground surface
  - What is the role of fractures in controlling CO_2 migration
  - Why do some fractures act as pathways and others barriers
  - How quickly can CO2 migrate?
  - How much is trapped in overlying aquifers?
  - …

- What are the impacts of a leak on different ecosystems…?
  - Terrestrial: plants, microbes, humans
  - Marine: microbes, sediment-dwellers, fish
  - Likely to be very local and negligible compared to business-as-usual

Health & Ecological Risk Assessment

Susan Rice
   Susan A. Rice and Associates, Inc.

Richard Rhudy
   EPRI

Risk Assessment Workshop
February 11-12, 2004
London, UK

EPRI

Health Risk
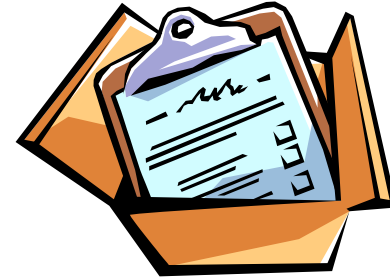
- **What do you need to understand**

- **What are the health consequences of environmental exposures to CO_2**
  - Slow leaks
  - Catastrophic releases
  - Aquifer contamination
  - Induced seismic activity

- **Dealing with environmental exposure requires development of a Health Risk Assessment Paradigm**

EPRI

Health Risk Assessment Paradigm
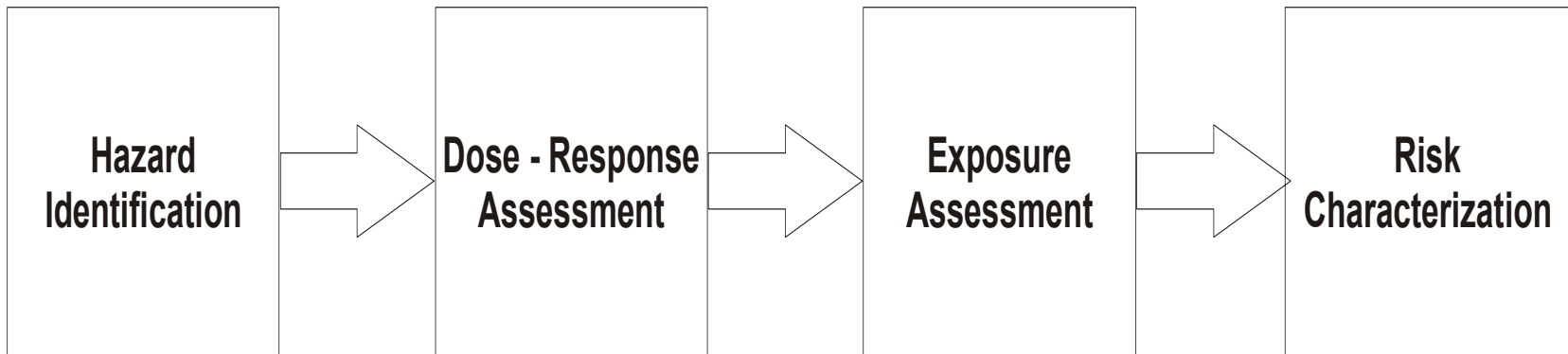
Project Aim

- **Define the toxic effects of CO_2**

- **Establish exposure-duration response profile**
  - Acute exposure
  - Chronic continuous or intermittent exposure

- **Identify sensitive human, animal and plant populations**

- **Initial work concentrated on human exposure**

- **Limited effort on animal and plant interactions**

EPRI

Hazard Identification

- **CO_2 is the 4th most abundant gas in the Earth's atmosphere (mean concentration = 370 ppm)**

- **Cameroon: 2 catastrophic releases in**
  - Lake Monoun 1984 -- killed 37 people
  - Lake Nyos 1986 -- killed more than 1,700 people in an area up to 15 miles from the lake

- **Mammoth Mountain in US**
  - 1990 tree-kill zone approximately 100 acres in size due to high CO_2 concentrations in the soil (20-90% vs the normal 1%) following a series of small earthquakes

- **Other gases used in the capture process or entrained gases also of concern**

EPRI

Mechanisms of Action

- Asphyxiant (displaces oxygen)

- Stimulates the sympathetic nervous system (impact on the cardiovascular and other systems)

- Causes the release of catecholamines (e.g., adrenaline)

- Causes respiratory acidosis (blood pH drop)

Interactions

- **Individual factors**
  - Age
  - State of health
    - Diseases
    - Medications
- **Environment**
  - O_2 concentration
  - Pollutants
  - Temperature
  - Chemicals
- **The CO_2 concentration and the O_2 concentration can interact to alter responses to CO_2**

Populations Sensitive to CO_2

- **Infants and children**
  - Infants and children breathe more air than adults relative to their body size and thus they tend to be more susceptible to respiratory exposures

- **Individuals performing complex tasks**
  - CO_2 can significantly diminish performance on tasks requiring psychomotor coordination, visual perception, attention, and rapid response

EPRI

Populations Sensitive to CO_2 (cont.)

- **Individuals with pulmonary and coronary disease**
  - CO_2 exposure can increase pulmonary as well as systemic blood pressure and should be avoided in individuals with systemic or pulmonary hypertension

- **Individuals on certain medications**
  - Respiratory center stimulation by CO_2 is depressed by lack of O_2 and by various drugs such as alcohol, anesthetics, morphine, barbiturates, etc.
  - Symptoms do not alert the individual to the presence of high CO_2 levels

EPRI

Populations Sensitive to CO_2 (cont.)

- **Other, including:**
  - Panic disorder patients
    - Increased frequency of panic attacks at 5% CO_2
    - Anxiety and somatic symptoms also are significantly increased (similar to those experienced by healthy subjects exposed to 7.5% CO_2)
  - Individuals with cerebral disease or suffering from cerebral (brain) trauma (CO_2 is a very potent cerebrovascular dilator)

EPRI

Cardiovascular System
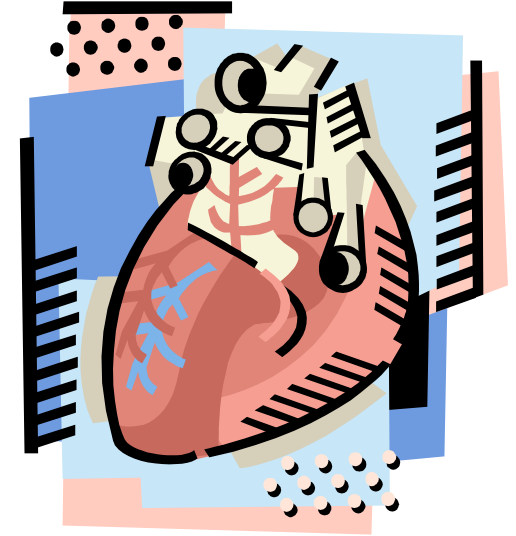
- **Effects are:**
  - Concentration dependent
  - Balance of direct and sympathetic effects

- **Direct effects on the heart**
  - Potent coronary vasodilator
  - Diminishes coronary contractility

- **Cardiac rhythm affected**
  - Rare nodal or ventricular extrasystoles: $\geq 6\%$ CO_2
  - PVCs in monkeys: as low as 3% CO_2
  - Prolongation of the QT interval

EPRI

Brain & Spinal Column

- **Increases cerebral blood flow (CBF): 1-2 mL/(100 g brain/min)/mmHg P_aCO_2**

- **Increases vascular permeability and hemorrhage in animals: 10% CO_2**

- **Increases cerebral spinal fluid pressure (CSF) in humans: 10% CO_2**

- **May increase intracranial pressure**

- **Convulsant in humans: ~30% CO_2**

EPRI

Visual System

- **Subtle effects for certain tasks may have significant adverse outcome: 2.5-5% CO_2**
  - Decreased detection of coherent motion
  - Reduced stereoacuity

- **Blurred vision: $\geq$6% CO_2**

- **Diplopia (double vision)**

- **Disturbed night vision: $\leq$3% CO_2 in presence of low O_2**

EPRI

Reproductive System

- **Maternal system in mice:
  20% CO_2 for 8 hr during the embryonic period**
  - Prevention of pregnancy or embryo death
  - Limb malformations

- **Paternal system in rats:
  2.5% CO_2 for 4 hr & 5% for 1 hr**
  - Degenerative changes in testes
  - Lack of mature sperm

EPRI

Metabolic State with Physical Exertion

- **2.8% CO_2 and 45 min strenuous exercise**
  - Well tolerated

- **~5% CO_2 and 45 min strenuous exercise**
  - 900% increase in arterial lactic acid
  - Mental confusion
  - Impaired vision (central and peripheral)
  - Collapse of 3 of 9 test subjects

EPRI

Project Accomplishments

- **Obtained an exposure-duration effect profile for humans**

- **Identified several susceptible human populations**

- **Obtained a preliminary exposure-duration effect profile for several mammalian species**

  - Primarily laboratory animals

- **Cursorily examined literature availability for birds, fish, and plants**

EPRI

Future Work

- **Fill in gaps for information on sensitive human populations and for target organs**
  – In-depth analysis of physiological literature
  – Define specific predisposing states and conditions within the sensitive populations

- **Expand and refine animal information**
  – Include other domesticated animals, especially those of economic importance
  – Define conditions of greatest risk

EPRI

Future Work (cont.)

- **Expand animal species to include wildlife, especially "endangered" species**

- **Examine the extensive plant literature for information on high-level CO_2 exposure**
  - Primary emphasis on crops and trees of economic importance
  - Secondary emphasis on potential impact of high-level CO_2 exposure to ecosystems, not individual species

EPRI

Risk Assessment Workshop

DTI Conference Centre, London

Day 2

12ᵗʰ February 2004

Risk Assessment Workshop

Recap of Day 1

- Covered the agenda

- Thank presenters for keeping to time

- Discussion sessions were lively
  - ➢ A lot of interesting points raised

- Hope you relaxed and enjoyed the dinner

Risk Assessment Workshop

Day 2 programme

- Last presentation session this morning
  - ➢ 1 presentation missing – Sintef
  - ➢ Previous presentation by Princeton Univ. now split into two
    - ◆ Mike Celia will open
    - ◆ Followed by Mileva Radonjic who will deal with issues of cement stability

- Breakout sessions
  - ➢ Discuss these in more detail later

- Related presentations on Regulation and Public perception of CCS

- Close around 17.00

IEA Weyburn CO$_2$ Monitoring and Storage Project

Wellbore Integrity Assessment
Weyburn CO$_2$ Monitoring and Storage Project

Rick Chalaturnyk, PhD, PEng.

Geological Storage Research Group

(Nathan Deisman (MSc), Jaime Jimenez (PhD), Francisco Moreno(PhD), Dr. Stephen Talman, Gilbert Wong ,PEng.)

Department of Civil and Environmental Engineering
University of Alberta, Edmonton, Canada

Leakage/Migration Issues

- Inadequate confining beds.

- Unplanned hydraulic fracturing.

- Preferential dissolution & creation of channels through confining layers

- Displacement of saline groundwater into a potable aquifer.

- Migration of injected liquid into potable water zone w/in same aquifer.

- Injection into an aquifer that is eventually reclassified as a potable water source.

- Upward migration of waste liquid from the confining zone along the outside of the well casing.

- Escape into potable aquifer due to wellbore failure.

- Vertical migration and leakage through abandoned or closed wells in the vicinity.

Geological Storage

- **Volume, rates and duration of injection are orders of magnitude larger than any other similar injection project**

- **Residence times of 10 or 100, or 1000 yrs?**

- **CO_2 plume will cover a very large area**

- **Geomechanical, geochemical and hydrogeological changes**

- **Abandoned wells must remain sealed for very large periods of time**
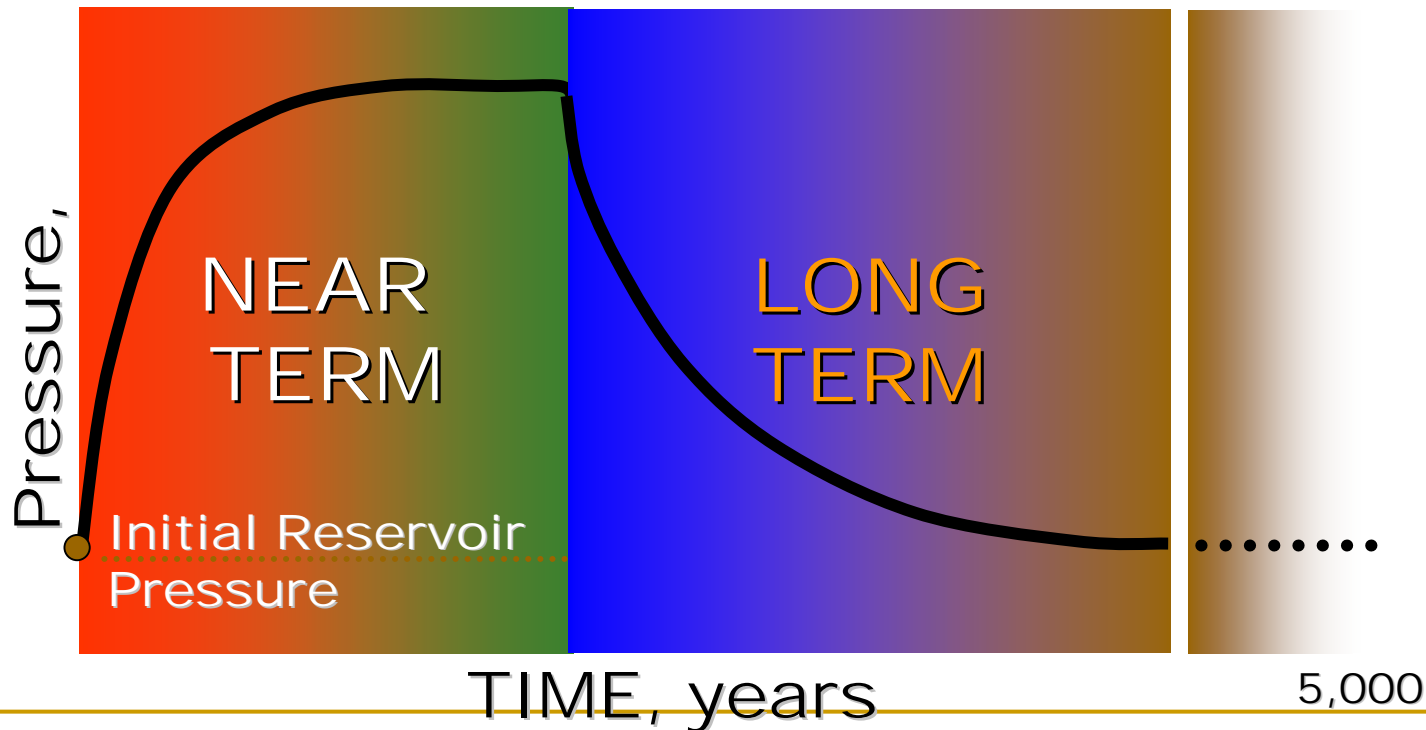
The Performance Assessment Challenge – Lots of Wells!!!

IEA Weyburn CO_2 Monitoring and Storage Project

Wellbore Integrity Assessment

Elements of Well Integrity

Mechanical…..

- **Mechanical Integrity**
  - Borehole stability
    - Increasingly conventional practice
  - Casing collapse
    - Conventional practice (tensile, burst and collapse strengths)
  - Casing connections
    - Conventional practice (stochastic treatment of leaks)
  - Casing corrosion
    - Conventional practice (stochastic treatment of rates)

Elements of Well Integrity Hydraulic….

- **Primary focus for Geological Storage**

- **Operational (Injection Pressures, etc.)**

- **Long-Term (Buoyancy Forces, etc.)**

  - Gas Migration

  - Corrosion

    - The most common failure mechanisms (corrosion, deterioration, and malfunction) cause mainly small leaks. Corrosion is historically known to cause 85% to 90% of small leaks.

Elements of Well History Impacting Hydraulic Integrity

Drilling
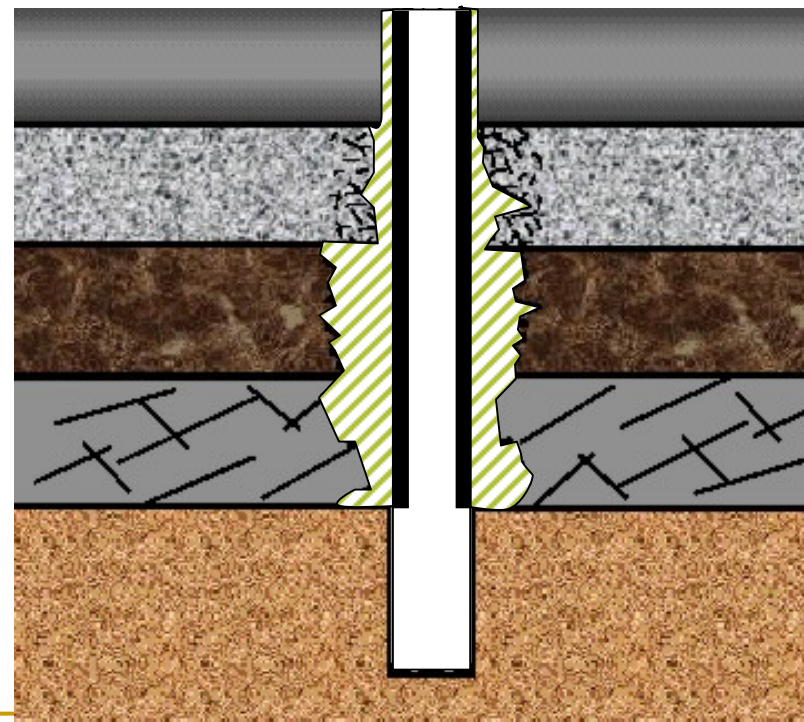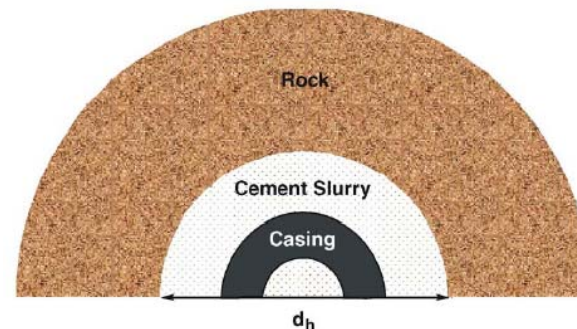
Elements of Well History Impacting Hydraulic Integrity

TIME

Drilling

Completion

Elements of Well History Impacting Hydraulic Integrity

Wellbore Integrity Assessment

TIME

Drilling

Completion

Production & Injection

Pressure & Temperature & Fluids
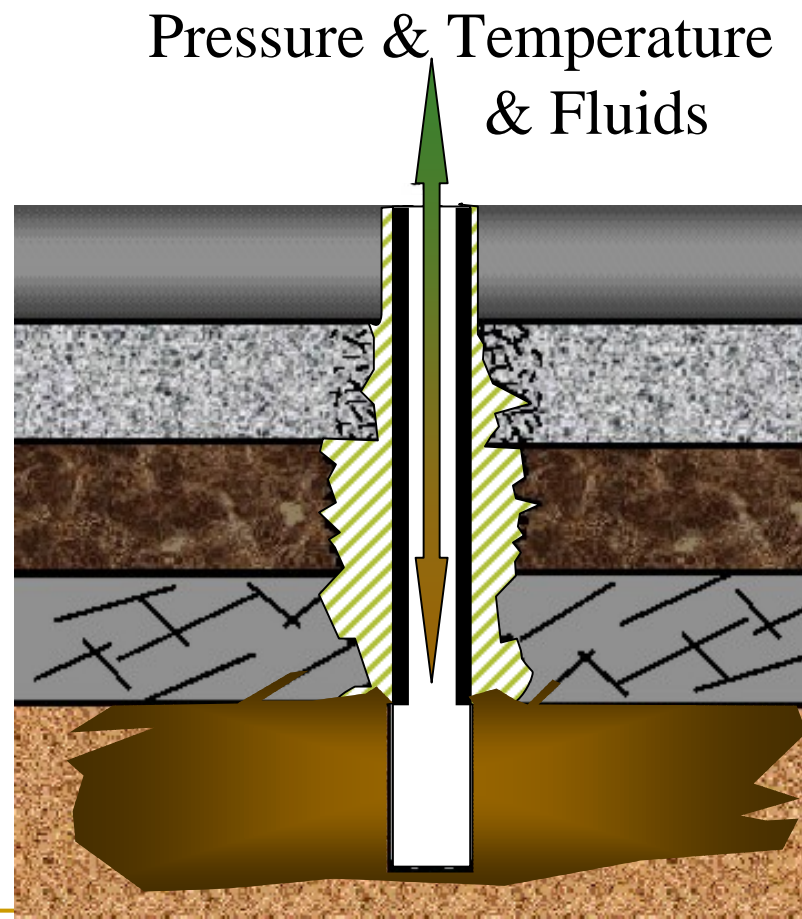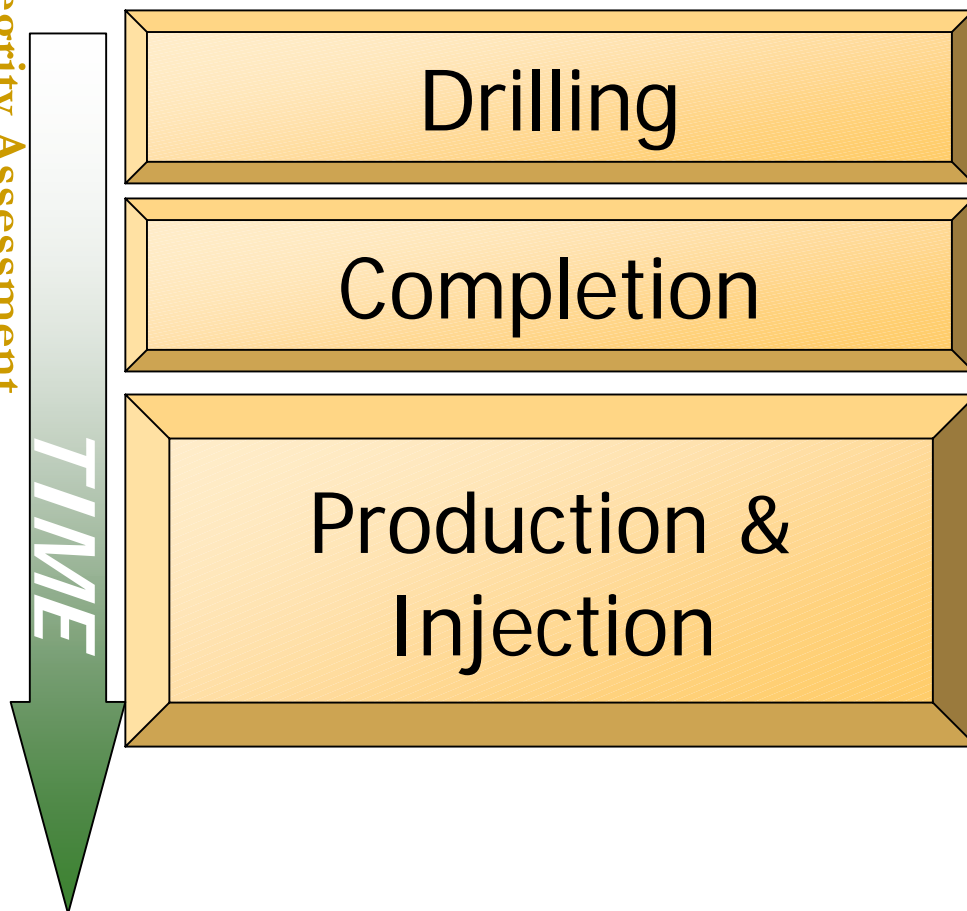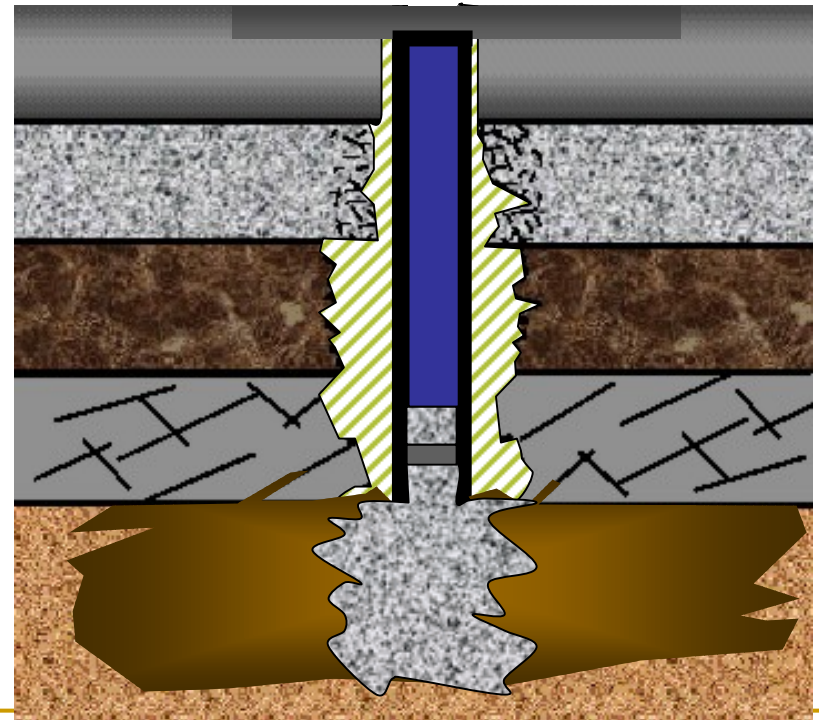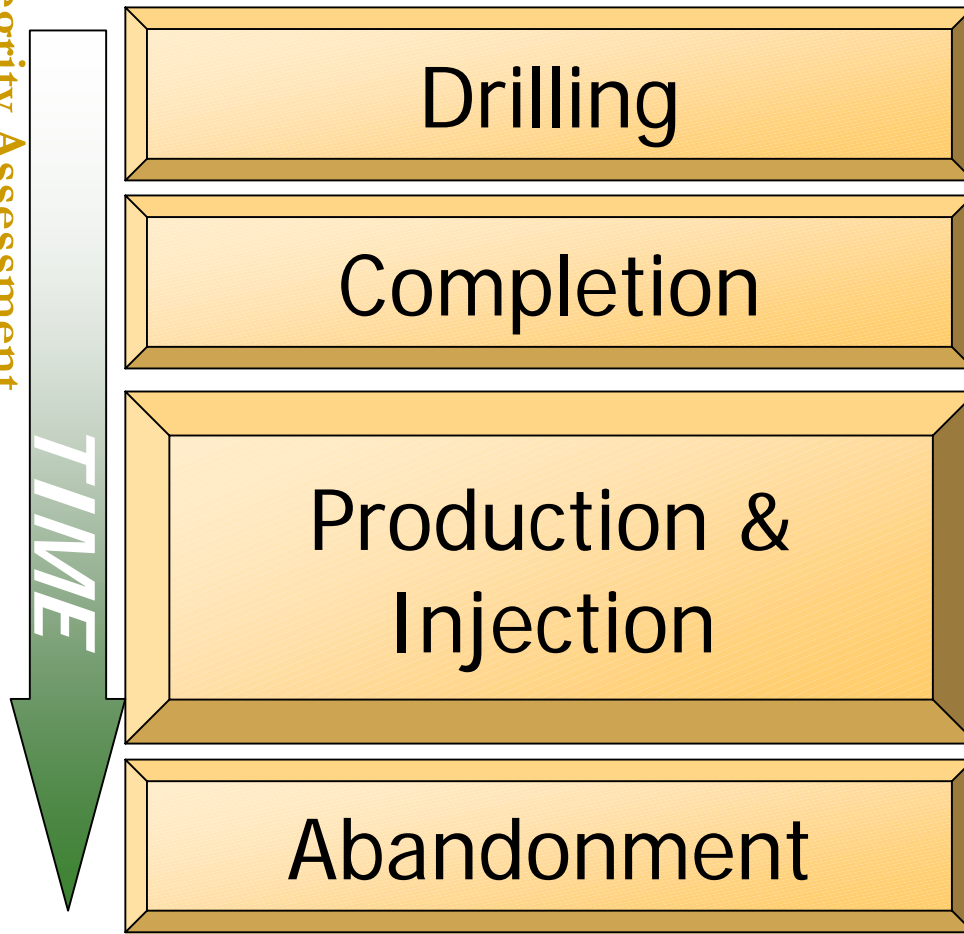
Weyburn Assessment Phases

- **Separate performance assessment process into two phases:**
  - Pre-Weyburn CO_2 Injection (in 2002)
  - Post-Weyburn CO_2 Injection (in 2003)
- **The pre- and post- phases of the performance assessment are a necessity. If we are unable to ascertain the state of the seal system (caprock and wells) prior to the injection of CO_2, it will be next to impossible to defend the integrity of the seals under the ensuing CO_2 injection and storage conditions**
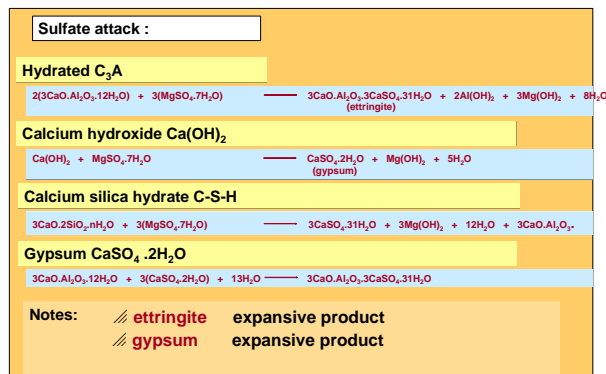
Well Integrity Assessment Methodology

Geomechanical Damage
- Drilling effects
- Completion effects

Hydrochemical Damage
- Drilling effects
- Completion effects

Mud Circulation
- Completion effects

...anical Damage
- Operational Effects
- Stress changes (p... temperature)
- Cracking

Geochemical Damage
- Aging

Detailed Examination!

Well Integrity Assessment Methodology

Fluid Filled Casing

Casing

Consolidated Mud Filled Annulus

Formations

Casing – Cement Annulus

Annular Cement Column

Cement – Formation Annulus

Abandonment Cement

Abandonment Cement – Casing Annulus

Abandonment Plug

CO_2

Cement plug

cement

Damaged caprock

caprock

Examples of Sulfate/Carbonation

Sulfate attack :

Hydrated C$_3$A

$2(3CaO.Al_2O_3.12H_2O) + 3(MgSO_4.7H_2O)$ ⟶ $3CaO.Al_2O_3.3CaSO_4.31H_2O + 2Al(OH)_3 + 3Mg(OH)_2 + 8H_2O$
(ettringite)

Calcium hydroxide Ca(OH)$_2$

$Ca(OH)_2 + MgSO_4.7H_2O$ ⟶ $CaSO_4.2H_2O + Mg(OH)_2 + 5H_2O$
(gypsum)

Calcium silica hydrate C-S-H

$3CaO.2SiO_2.nH_2O + 3(MgSO_4.7H_2O)$ ⟶ $3CaSO_4.31H_2O + 3Mg(OH)_2 + 12H_2O + 3CaO.Al_2O_3.$

Gypsum CaSO$_4$ .2H$_2$O

$3CaO.Al_2O_3.12H_2O + 3(CaSO_4.2H_2O) + 13H_2O$ ⟶ $3CaO.Al_2O_3.3CaSO_4.31H_2O$

Notes: ⫽ **ettringite** expansive product
⫽ **gypsum** expansive product

Carbonation :

Carbon dioxide CO$_2$

$CO_2 + H_2O$ ⟶ $H^+ + HCO_3^-$
(bicarbonate)

Calcium hydroxide Ca(OH)$_2$

$Ca(OH)_2 + H + HCO_3$ ⟶ $CaCO_3 + 2H_2O$
(calcite)

Calcium silica hydrate C-S-H

$3CaO.2SiO_2.nH_2O + H + HCO_3$ ⟶ $CaCO_3 + SiO_2.nH_2O$
(calcite)   (amorphous silica)

Calcite CaCO$_3$

$CaCO_3 + CO_2 + H_2O$ ⟶ $Ca(HCO_3)_2 + H_2O$
(calcium bicarbonate)

Notes: ⫽ **calcium bicarbonate** **water-soluble**

Carbonation (%) vs Depth, mm — legend: 0.6 years, 2.9 years, 6.6 years, 10.2 years

Poplar — Permeability, m^2 vs Time, years — legend: Empirical eq., Mechanistical eq.

Advection using Soeve cubic law

CARBONATION(AQUITARD-MICROANNULUS): Cycle=110 Time= Integral= 0.331713

Microannulus

Advection using Soeve cubic law

11:48:52 12/6/03
FlexPDE 3.10a

ro
zoom(0.0, 0.0.1)

420.
390.
360.
330.
300.
270.
240.
210.
180.
150.
120.
90.0
60.0
30.0
0.00
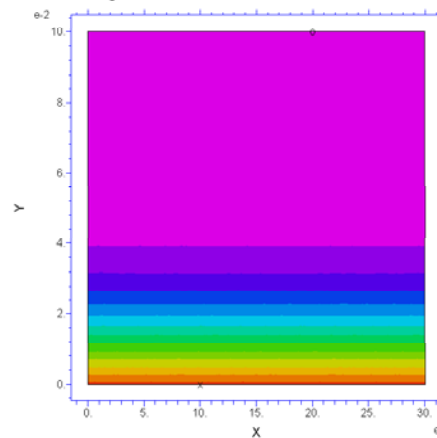
CARBONATION(AQUITARD-SIN-MICROANNULUS): Cycle=102 Time= 5000.0 dt= 99.093 p2 Node
Integral= 0.210525

No Microannulus

ptrc
Petroleum Technology
Research Centre

EnCana

Influences on Hydraulic Integrity

Geomechanical damage	Hydrochemical damage

Effects on hydraulic integrity due to

DRILLING

COMPLETION

WELL HISTORY

(excerpt from BP's "Beneath by Feet" video

Stress Analysis of Casing/Cement/Formation

Formation

Cement

Casing

P

Internal Wellbore Pressure

Formation Stiffness < Cement Stiffness

Stress Analysis of Casing/Cement/Formation

Cement Sheath COMPLETELY Yielded and Cracked
* High k!

Internal Casing Pressure
Cement Stiffness > Rock Stiffness

IEA WEYBURN CO$_2$ MONITORING AND STORAGE PROJECT
Risk Assessment Workshop, London, UK
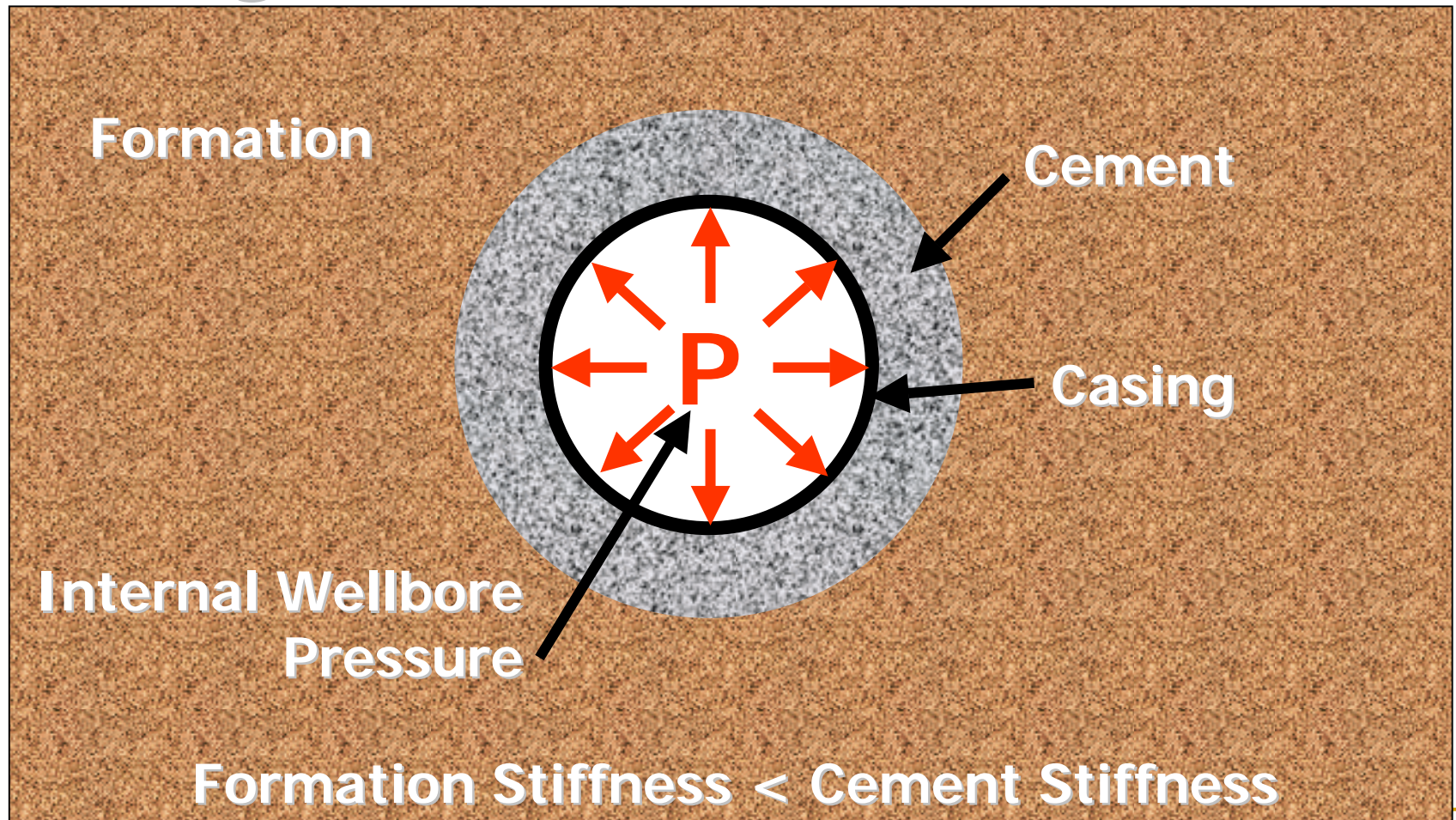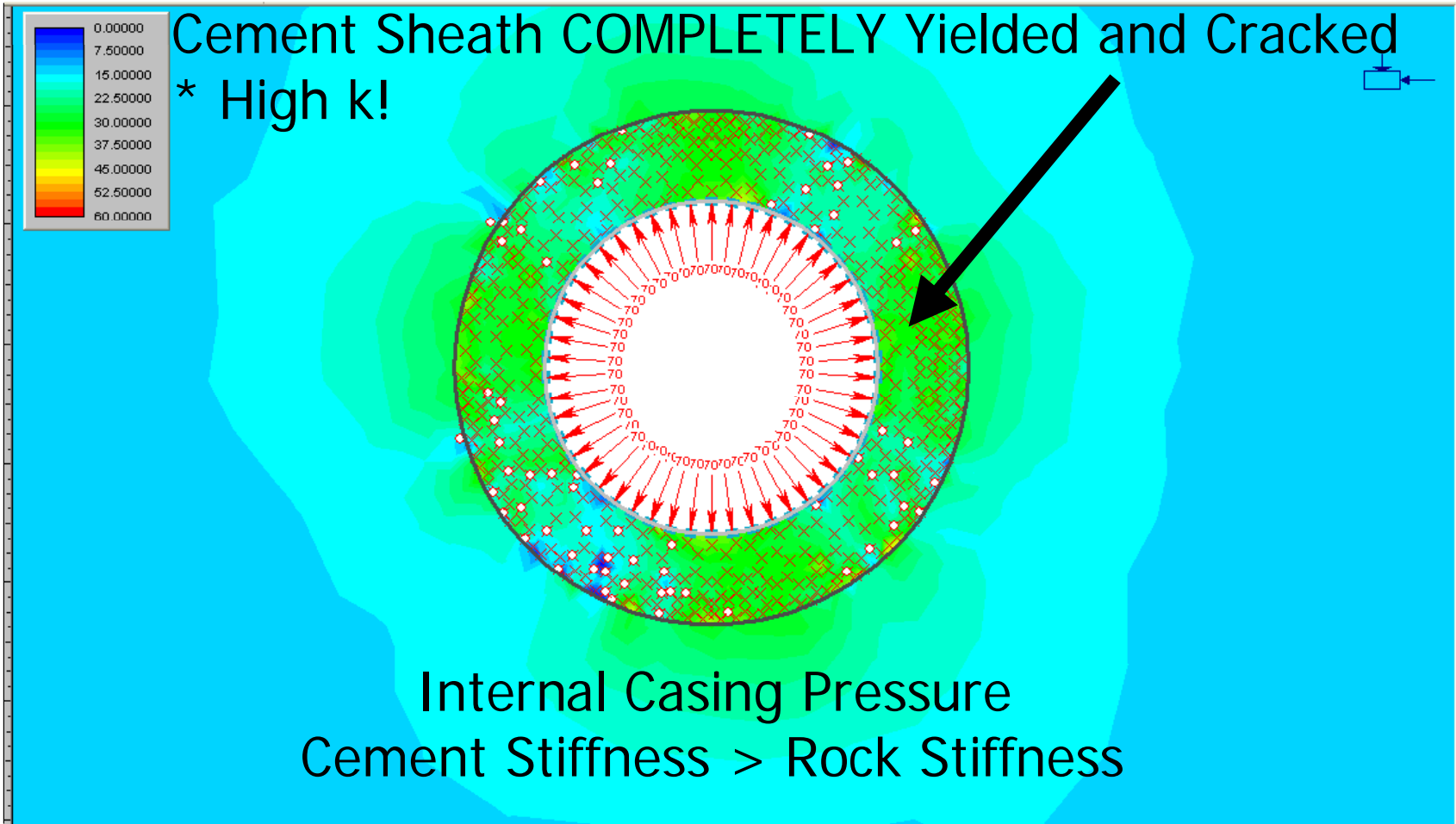
Stress Analysis of Casing/Cement/Formation

Failure Mode	Probability
Packer leak	$2.0\ 10^{-17}$
Major packer failure	$1.5\ 10^{-15}$
Injection tubing leak	$2.7\ 10^{-17}$
Major injection tubing failure	$2.1\ 10^{-8}$
Cement micro-annulus leak	$2.1\ 10^{-6}$
Confining zone(s) breach	$8.8\ 10^{-10}$
Inadvertent injection zone extraction	$6.6\ 10^{-7}$

from Clark, J.E., An overview of injection well history in the United States, American Institute of Hydrology, 4th USA/CIS Joint Conference, Cathedral Hill Hotel, San Francisco, California, November 9, 1999.

IEA WEYBURN CO_2 MONITORING AND STORAGE PROJECT
Risk Assessment Workshop, London, UK

Wellbore Integrity Assessment

Flux (Q) Assessment of Integrity -based on Transport Properties

Conceptual model

Cement plug

cement

Damaged caprock

caprock

Microannulus
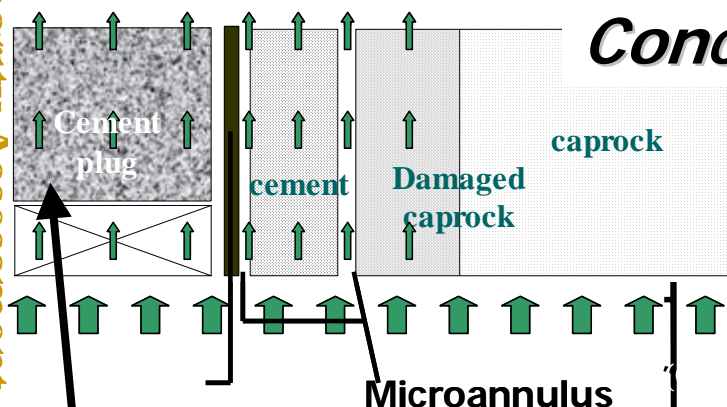
Includes Abandonment Strategy

Results format

t=50 yrs

Hydraulic Integrity Degradation

Q_{50}

Q_{15}

Q_0

t=15 yrs

t=0 yrs

Flow (Q)

Pressure (P_{CO2})
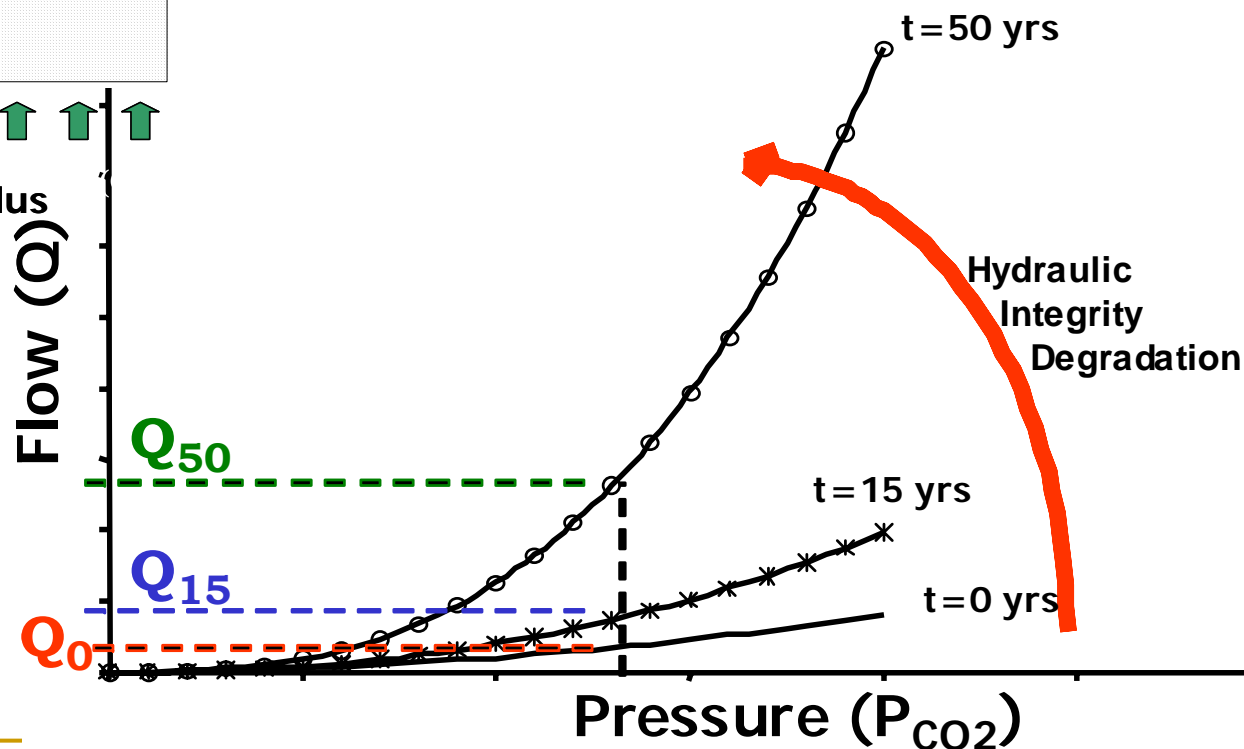
Wellbore System Integrity
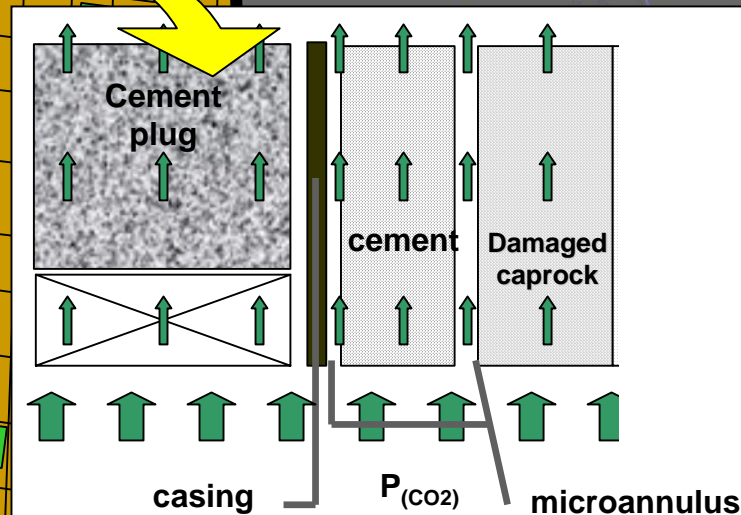
Cement plug

cement | Damaged caprock

casing | P(CO2) | microannulus

Caprock Sys Integrity

$Q = P^{(n)}$ Indicator (I_w)

t=50 yrs

Well deterioration

Flow (Q)

Q_{50}

Q_{15}

Q

t=15 yrs

t=0 yrs

Pressure (P)

Leakage vs. Pressure

Q (m³/sec/10000m²)

1.00E+09
1.00E+07
1.00E+05
1.00E+03
1.00E+01
1.00E-01
1.00E-03
1.00E-05
1.00E-07
1.00E-09
1.00E-11

FRACTURE DOMAIN PERMEABILITY

MATRIX DOMAIN PERMEABILITY

Grad (i) & P/σ'₃

k (m²)

CT
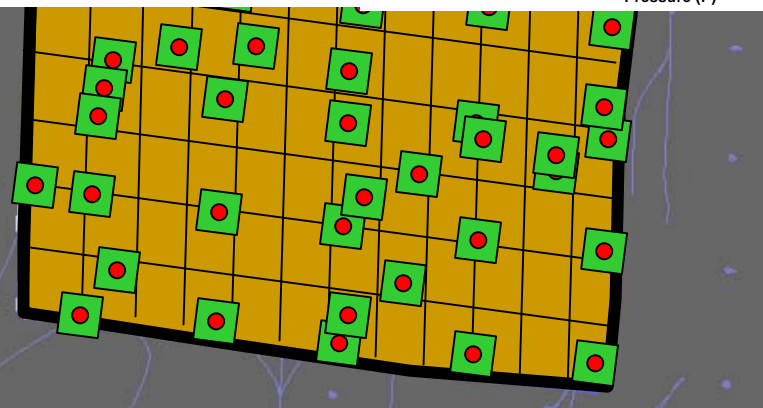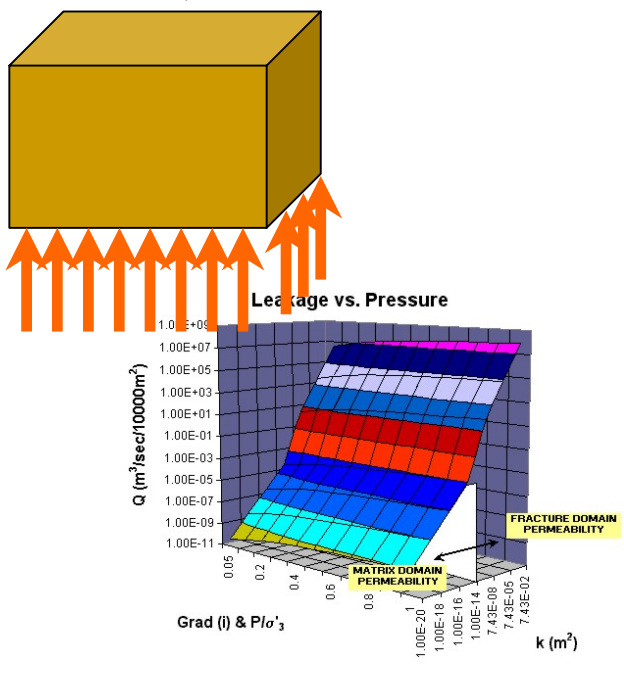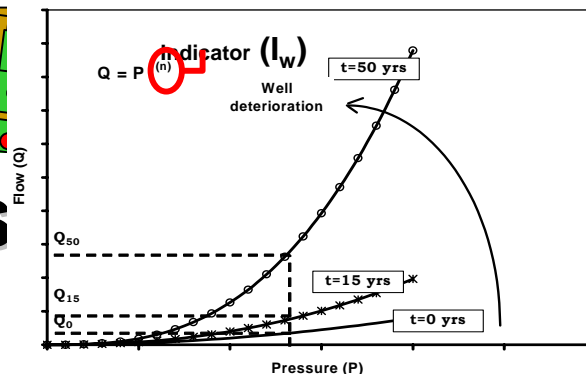
Wellbore Integrity Assessment
Weyburn CO_2 Monitoring and Storage Project

Geological Storage Research Group

Department of Civil and Environmental Engineering
University of Alberta, Edmonton, Canada

Leakage through Existing Wells: Models, Data Analysis, and Lab Experiments

Michael A. Celia and Mileva Radonjic

Department of Civil and Environmental Engineering
Princeton University

George Scherer	Rob Bruant	Stefan Bachu (AGS)
Peter Jaffe	Andrew Altevogt	Jan Nordbotten (UiB)
Satish Myneni	Sarah Gasda	Helge Dahle (UiB)
Catherine Peters	Andrew Duguid	
Jean Prevost	Li Li	

Princeton University

Outline

◆ Overview of recent activities
- – Leakage potential, existing wells, environmental effects.
- – Refocus effort toward detailed studies of well cements.

◆ Brief presentation of selected results
- – Analysis of existing wells: Spatial statistics.
- – Quasi-analytical solutions for leakage estimation.

◆ Cement studies (presented by M. Radonjic)
- – New laboratory for cement experiments.
- – Design of experiments and preliminary results.

Location of the Alberta Basin

Princeton University

Position of the Viking Formation in the Sedimentary Succession, Alberta Basin
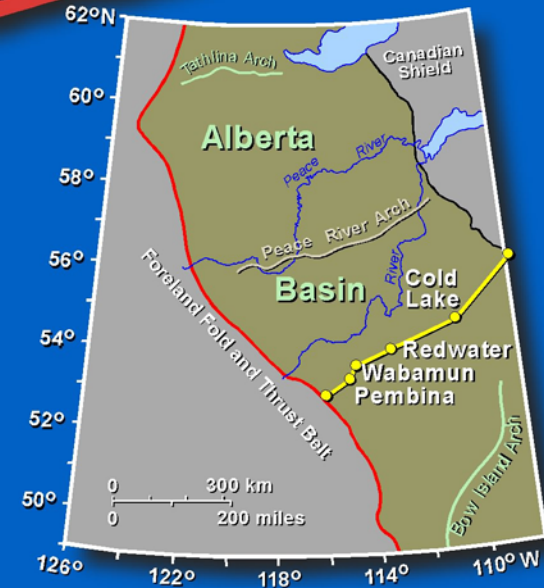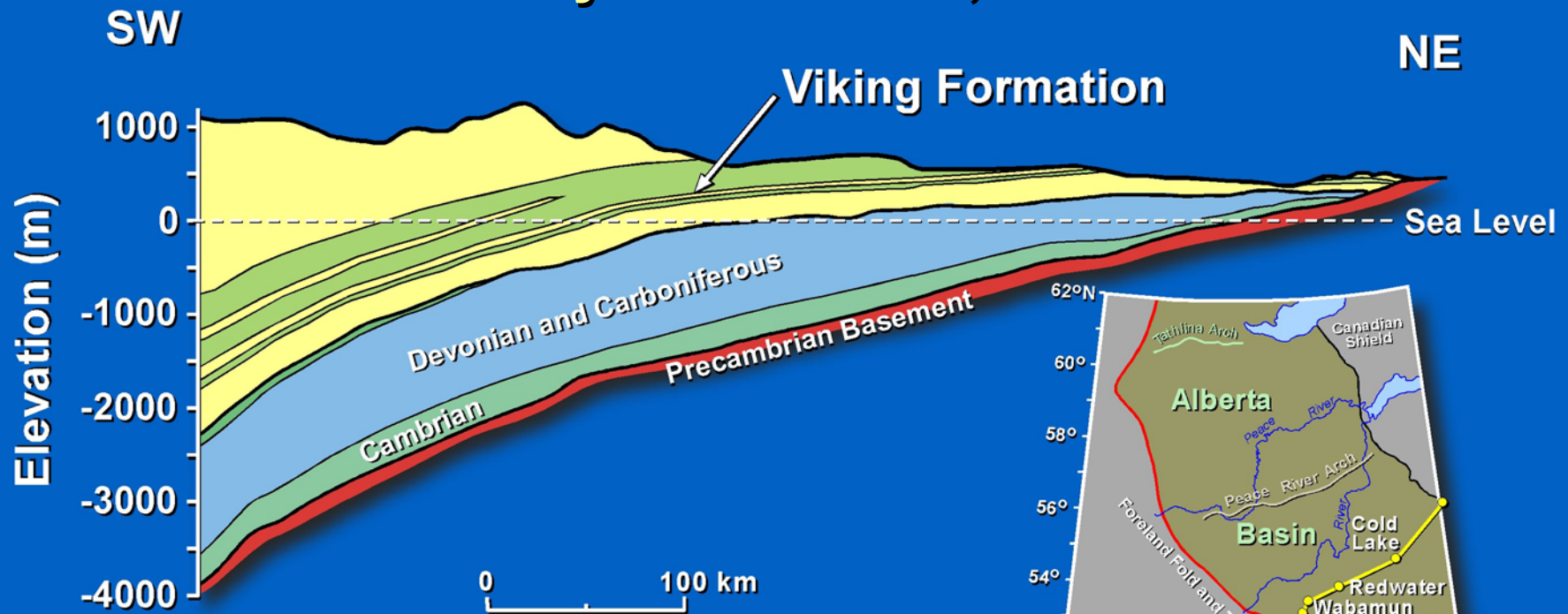
Mature Sedimentary Basins: Analysis of Wells

Viking Formation: 195,000 Wells

Alberta Basin: 350,000 Wells
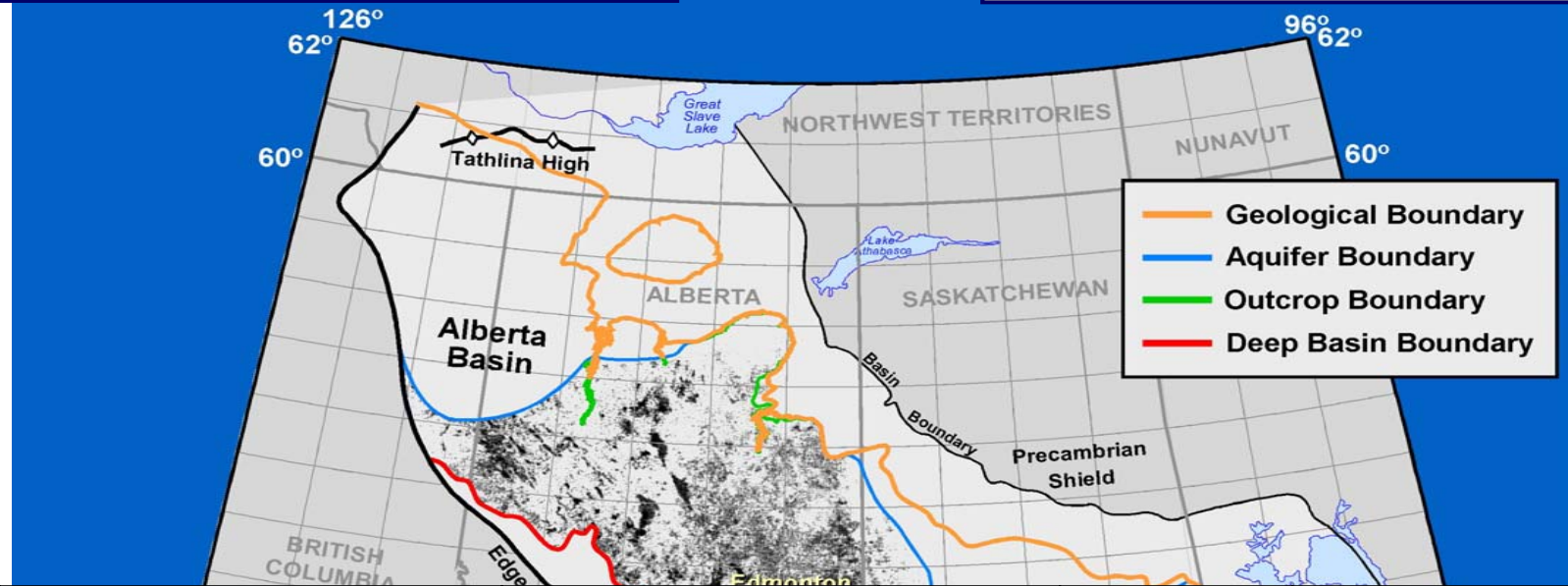
	Very High-Density (Heavy-oil)	High-Density	Medium-Density	Low-Density (Background)
Number of clusters	**32**	**268**	**963**	--
Number of wells [% total]	5.2	28.0	28.6	38.2
Area [% total]	0.1	2.7	10	87.2
Mean intrinsic density [wells/km²]	**17.1**	**3.75**	**1.13**	**0.15**

Number of Wells Impacted by 'typical' Injection
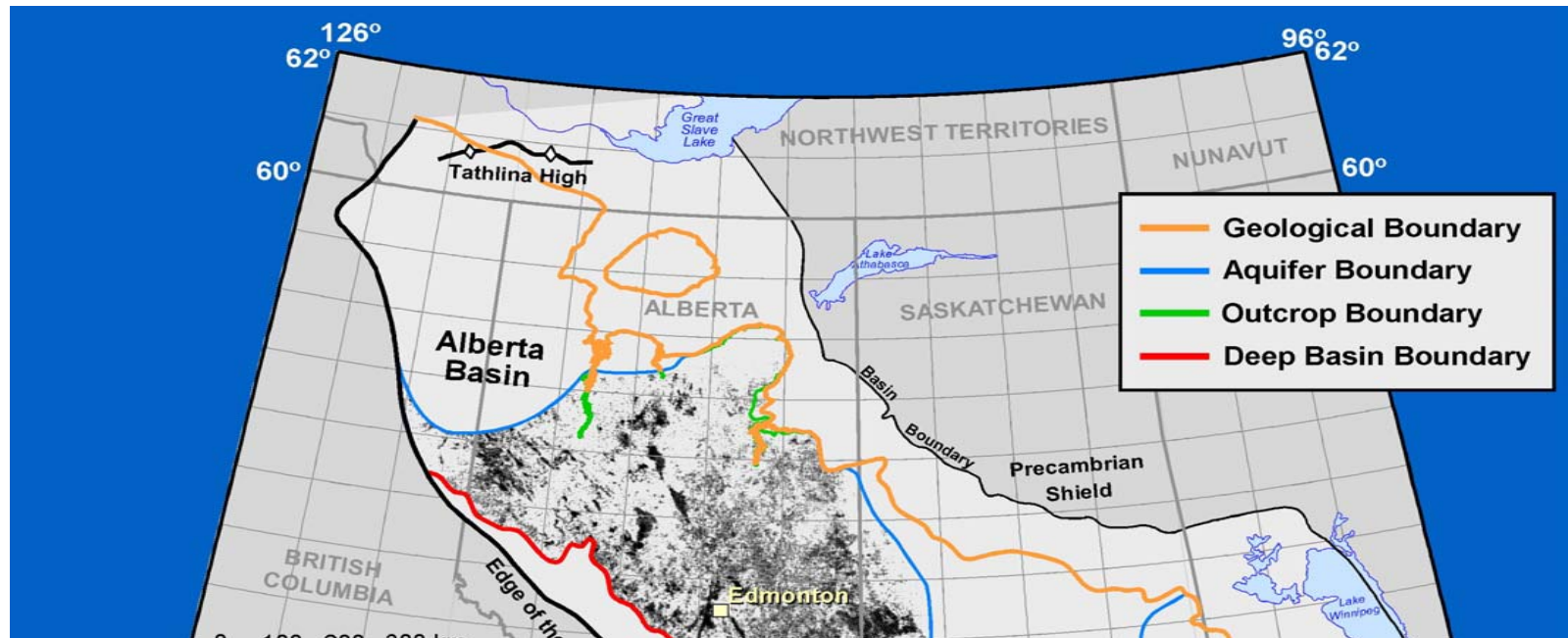
	Mean	Median	Range
High-density clusters	241.5	216	45-721
Medium-density clusters	62.6	61	8-144
Low-density Background	17.8	11	0-130

(Numbers from Gasda et al., 2003)

Status of Wells Penetrating the Viking Aquifer, Alberta Basin
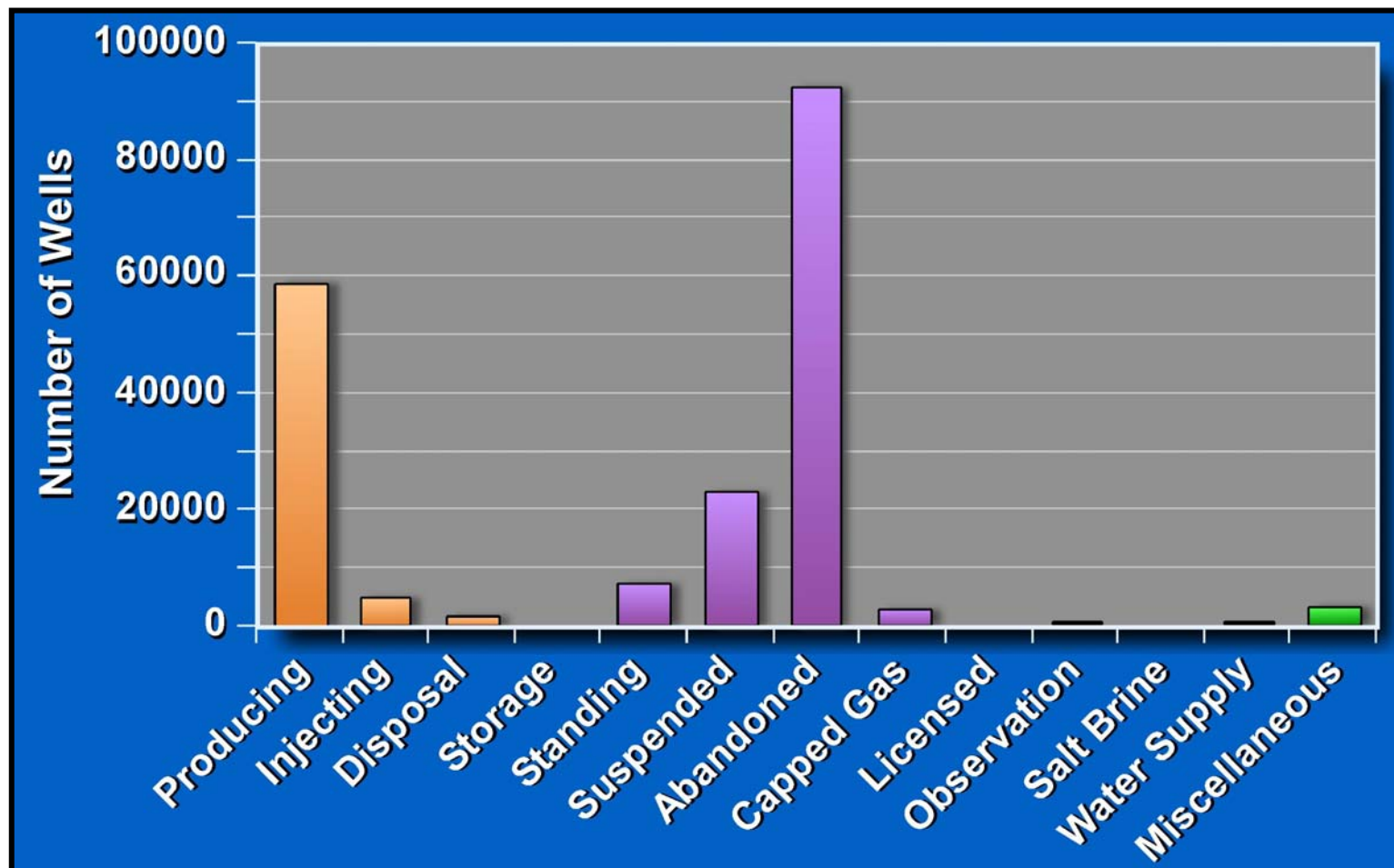
CO_2 Injection and Leakage Pathways
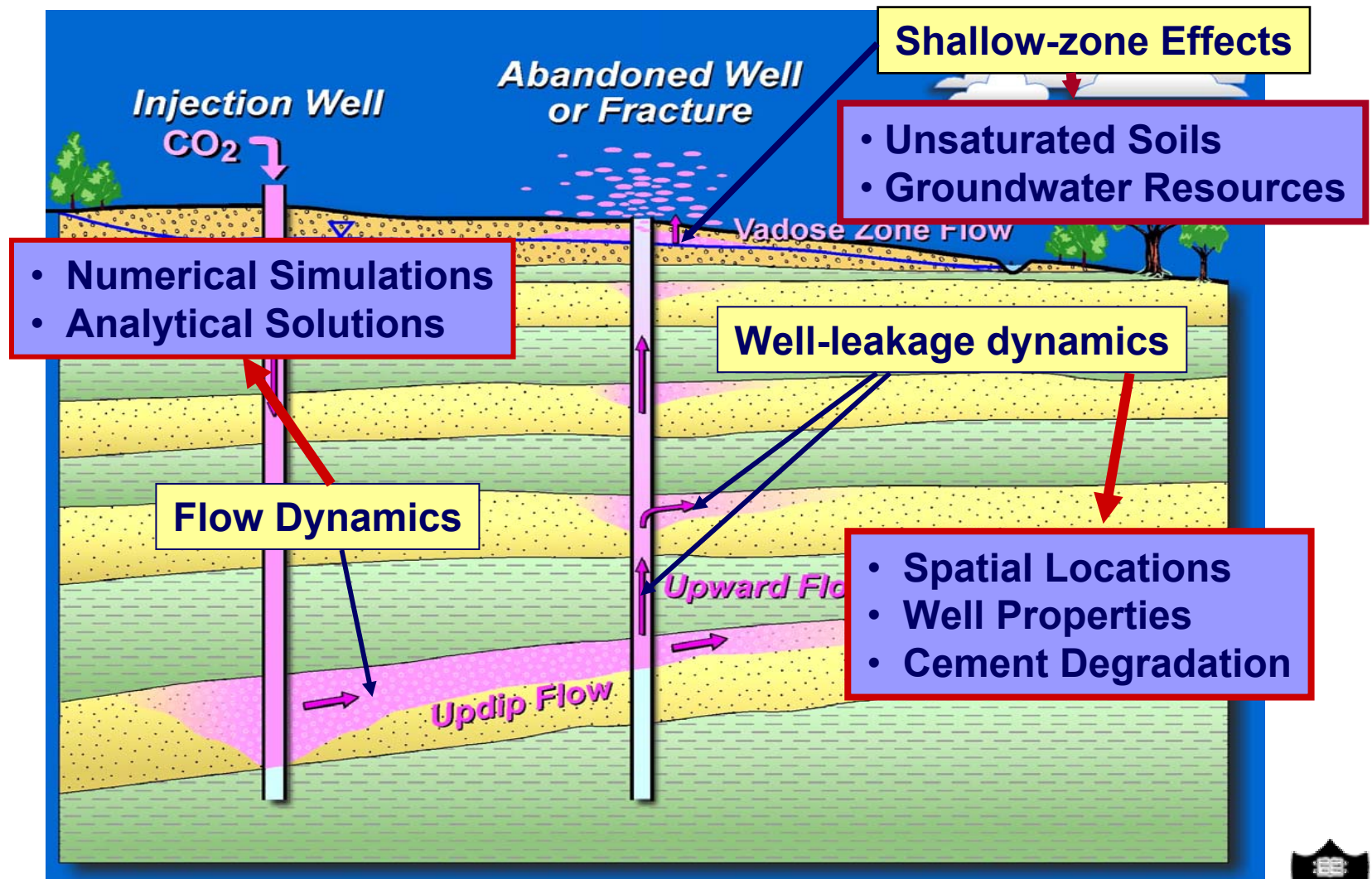
Overview of Selected Recent Results

◆ Simplified Solutions for CO_2 Transport and Leakage Estimation (3 Papers):

– Analytical solutions to accommodate many potentially leaky wells and multiple geological layers.

– Framework for linear equations (eg, hazardous waste injection), showing importance of caprock thickness and storage in layers above injection.

– Energy minimization arguments yield simple equations for evolution of CO_2 plume and pressure field; solution applies to all practical ranges of densities and viscosities (P,T,S) for CO_2 injection in aquifers.

– Bounding calculations for leakage of brine and CO_2 through leaky well.

– Comparisons to Eclipse show excellent match of results.

– Ongoing extensions: Intersecting CO_2 plumes, variable density along the well, redistribution of CO_2 after cessation of injection.

◆ Unsaturated Zone Studies (2 Papers)

– Modeling studies for CO_2 transport: dominant transport mechanisms.

– Modeling studies of geochemical response to elevated CO_2 concentrations: evolving redox profiles.

– Laboratory column study for geochemical tests.

Princeton University

New Analytical Solutions
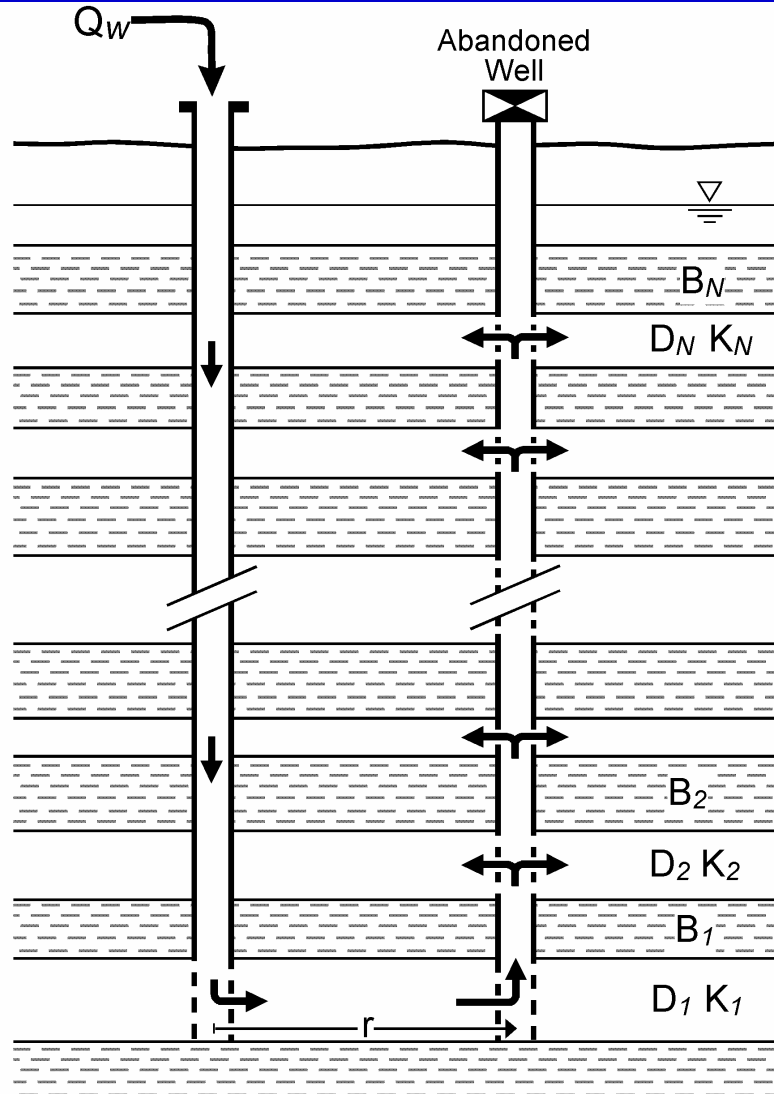
- ◆ Multiple aquifers/aquitards.
- ◆ Multiple active and passive wells.
- ◆ Superposition of approximate well functions.
- ◆ Dirac delta approximation for convolution integrals
- ◆ Vertical variability within passive wells.
- ◆ Multi-phase Flow:
  - – Vertical averaging of pressure
  - – Viscous and Gravity Effects.

Simplified Solutions for Injection and Leakage
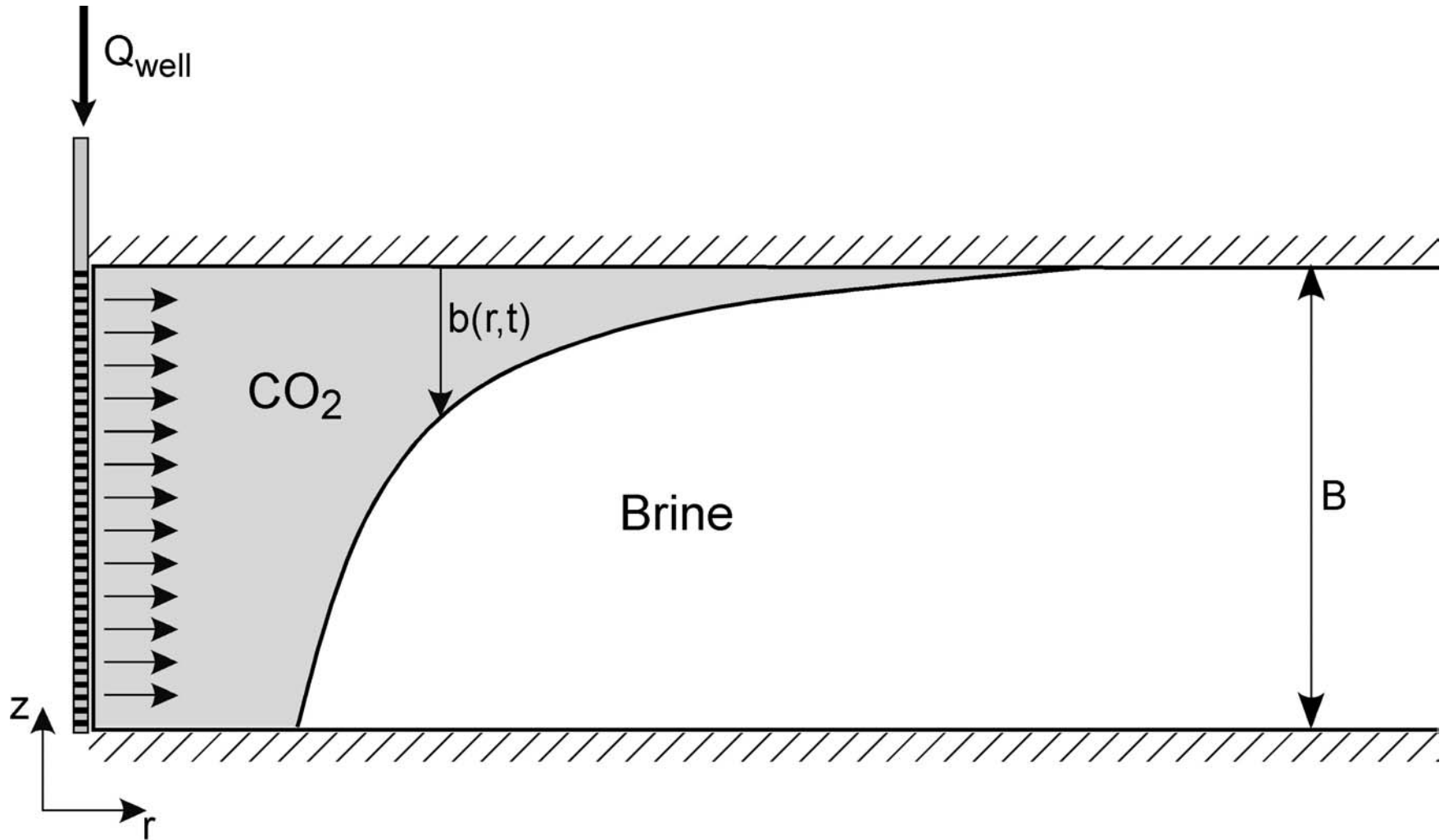
New Analytical Solution: Two-Phase Flow

Analytical solution (sharp interface) versus Effective Saturation from *Eclipse*

Full Numerical Solution (from *Eclipse*)

Analytical Solution

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

Solution includes unfavorable mobility ratio and gravity override
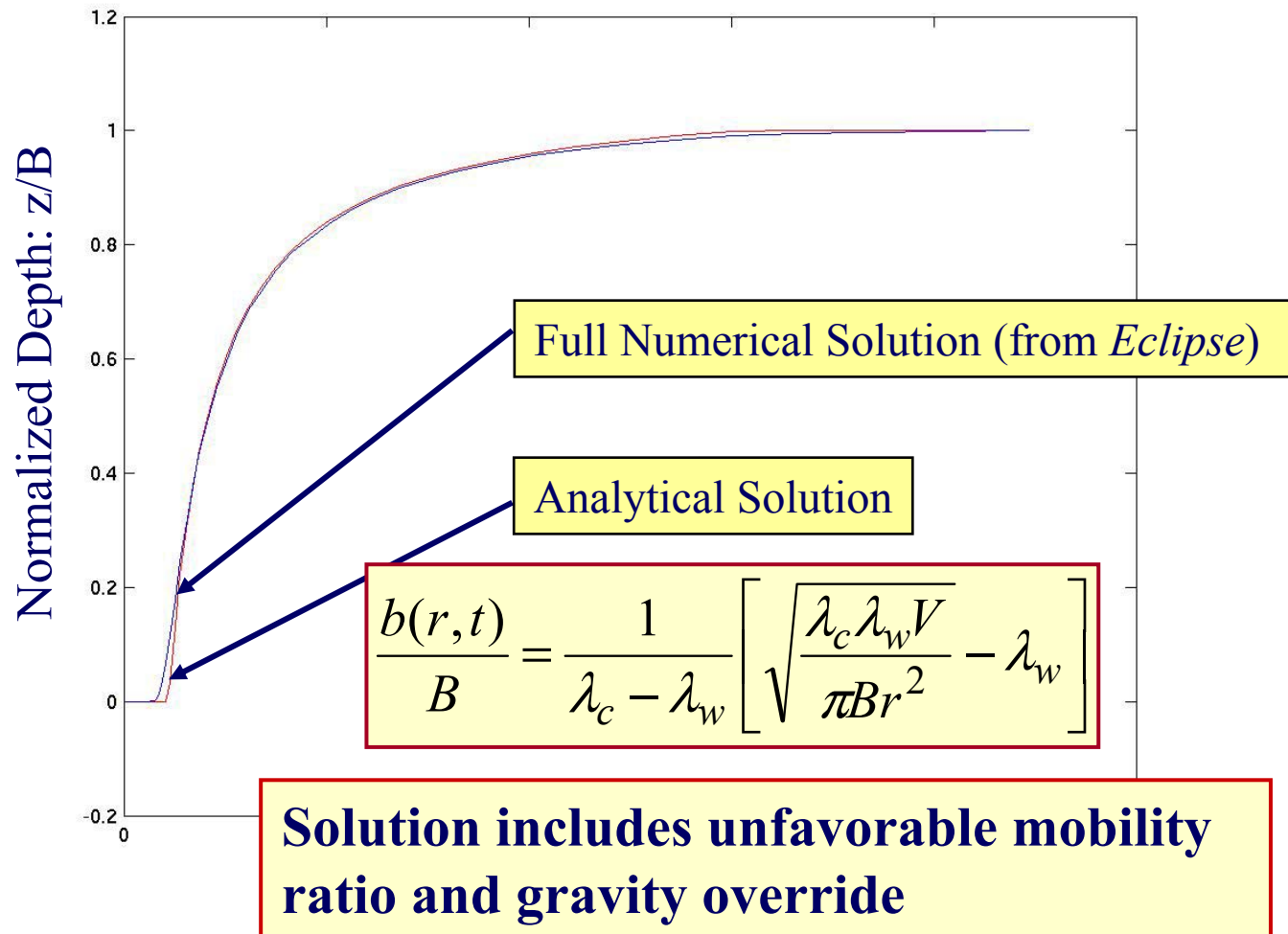
Table 1: Density Values for CO_2 and Brine

	Cold Basin	Warm Basin
Shallow Formation	$\rho_c = 714 \, kg/m^3$ $\rho_w = 1012 \text{ to } 1230 \, kg/m^3$	$\rho_c = 266 \, kg/m^3$ $\rho_w = 998 \text{ to } 1210 \, kg/m^3$
Deep Formation	$\rho_c = 733 \, kg/m^3$ $\rho_w = 995 \text{ to } 1202 \, kg/m^3$	$\rho_c = 479 \, kg/m^3$ $\rho_w = 945 \text{ to } 1145 \, kg/m^3$

Table 2: Viscosity Values for CO_2 and Brine

	Cold Basin	Warm Basin
Shallow Formation	$\mu_c = 0.0577 \, mPa \cdot s$ $\mu_w = 0.795 \text{ to } 1.58 \, mPa \cdot s$	$\mu_c = 0.023 \, mPa \cdot s$ $\mu_w = 0.491 \text{ to } 0.883 \, mPa \cdot s$
Deep Formation	$\mu_c = 0.0611 \, mPa \cdot s$ $\mu_w = 0.378 \text{ to } 0.644 \, mPa \cdot s$	$\mu_c = 0.0395 \, mPa \cdot s$ $\mu_w = 0.195 \text{ to } 0.312 \, mPa \cdot s$

New Analytical Solution: Two-Phase Flow

Cold, Shallow Case

Cold, Deep Case

Warm, Shallow Case

Warm, Deep Case
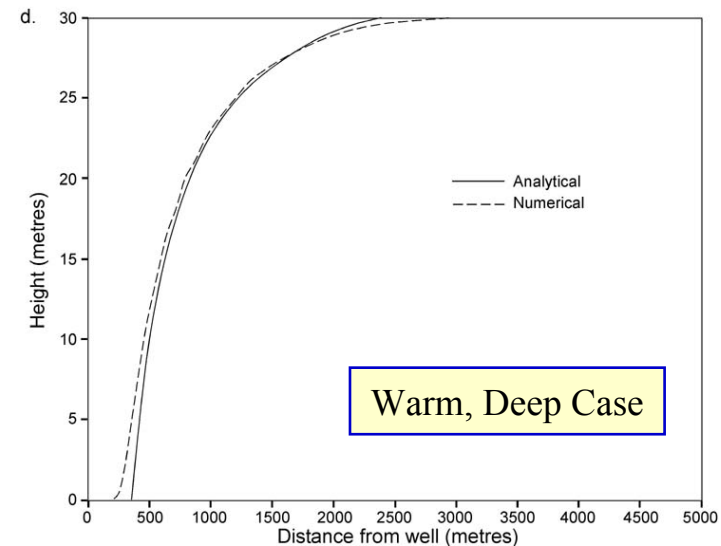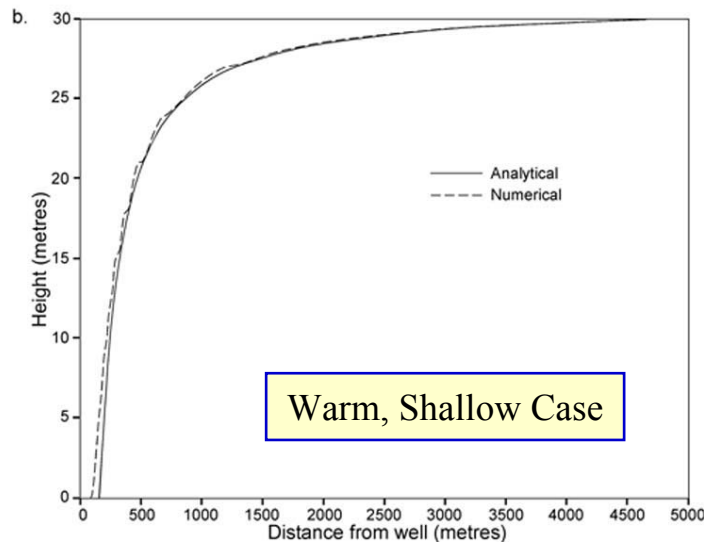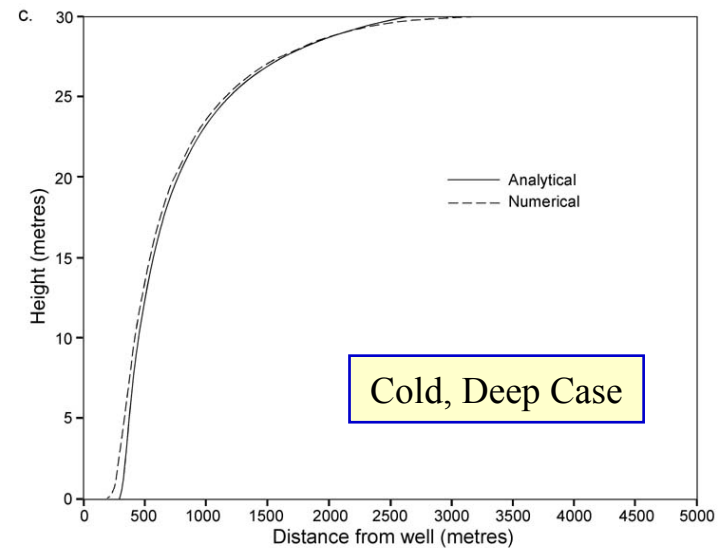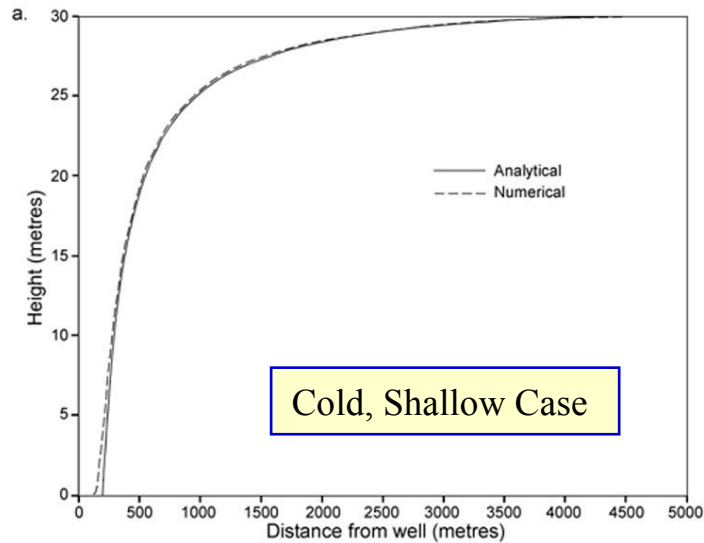
Leakage of CO$_2$: Test Problem

$p = p_{init}$

1 km

Leaky Well

Injection Well

10 km

10 km

Q_{inj}
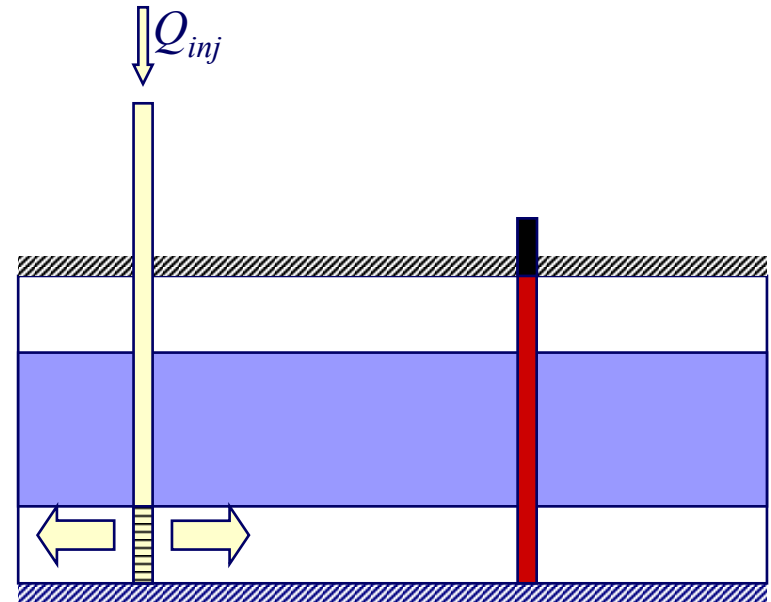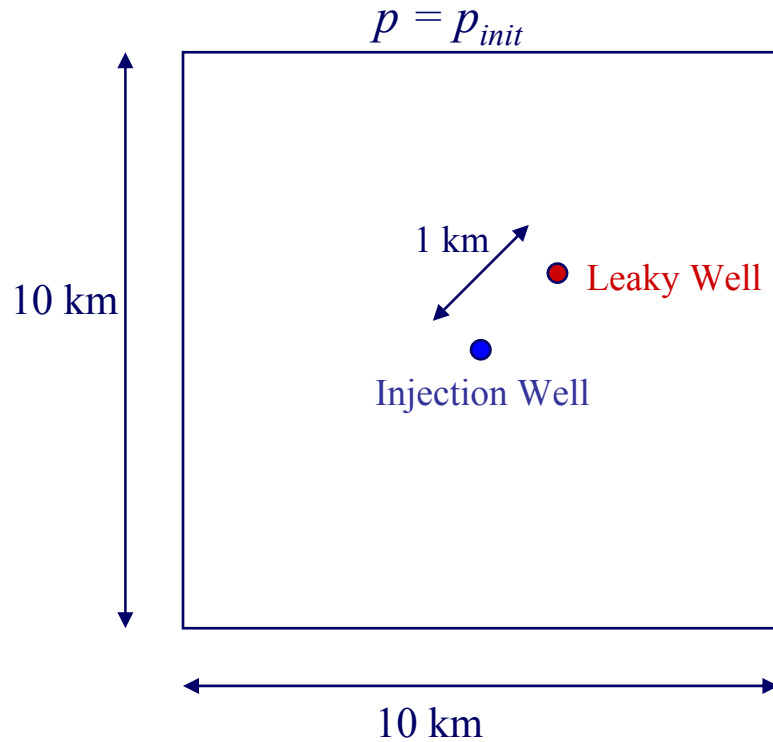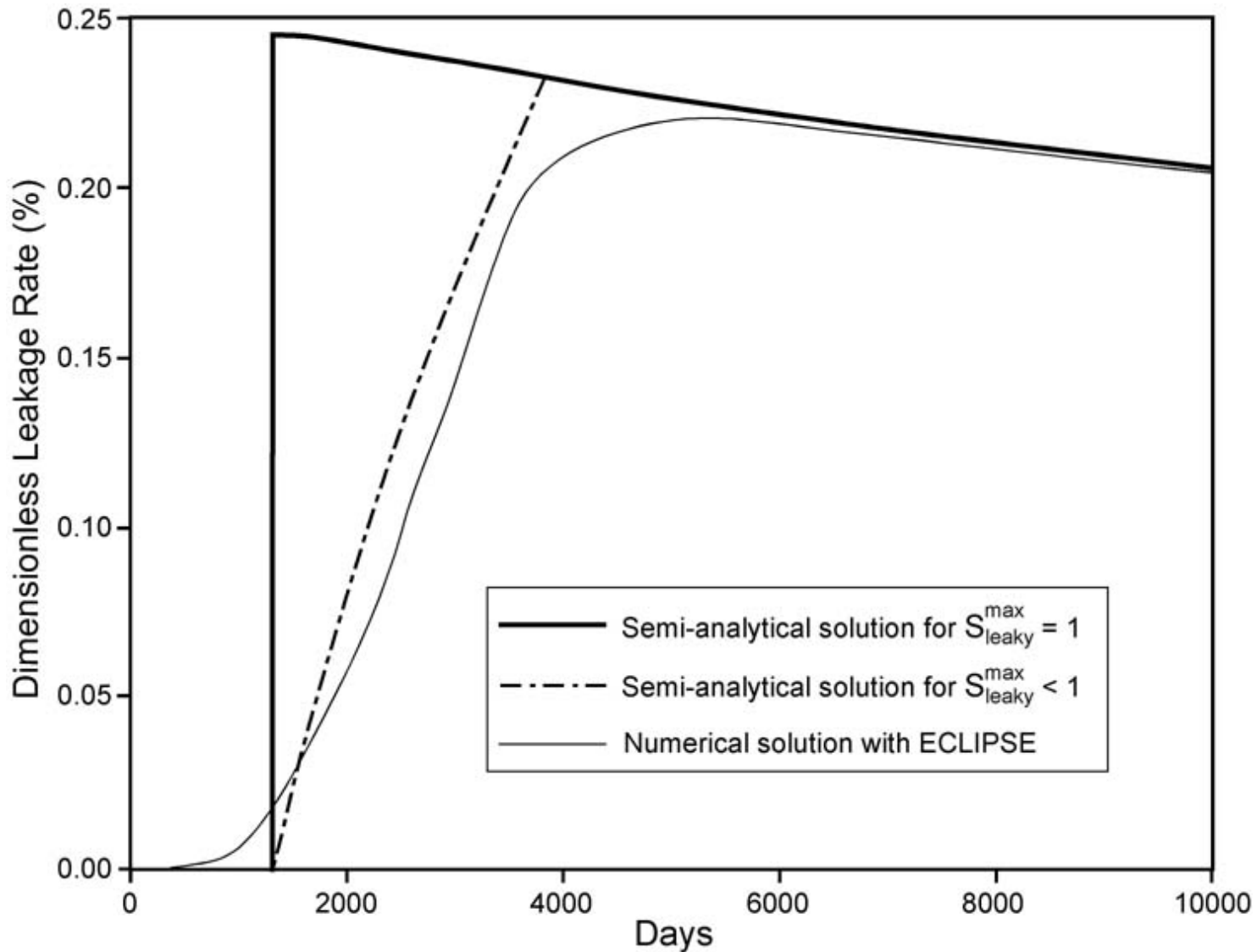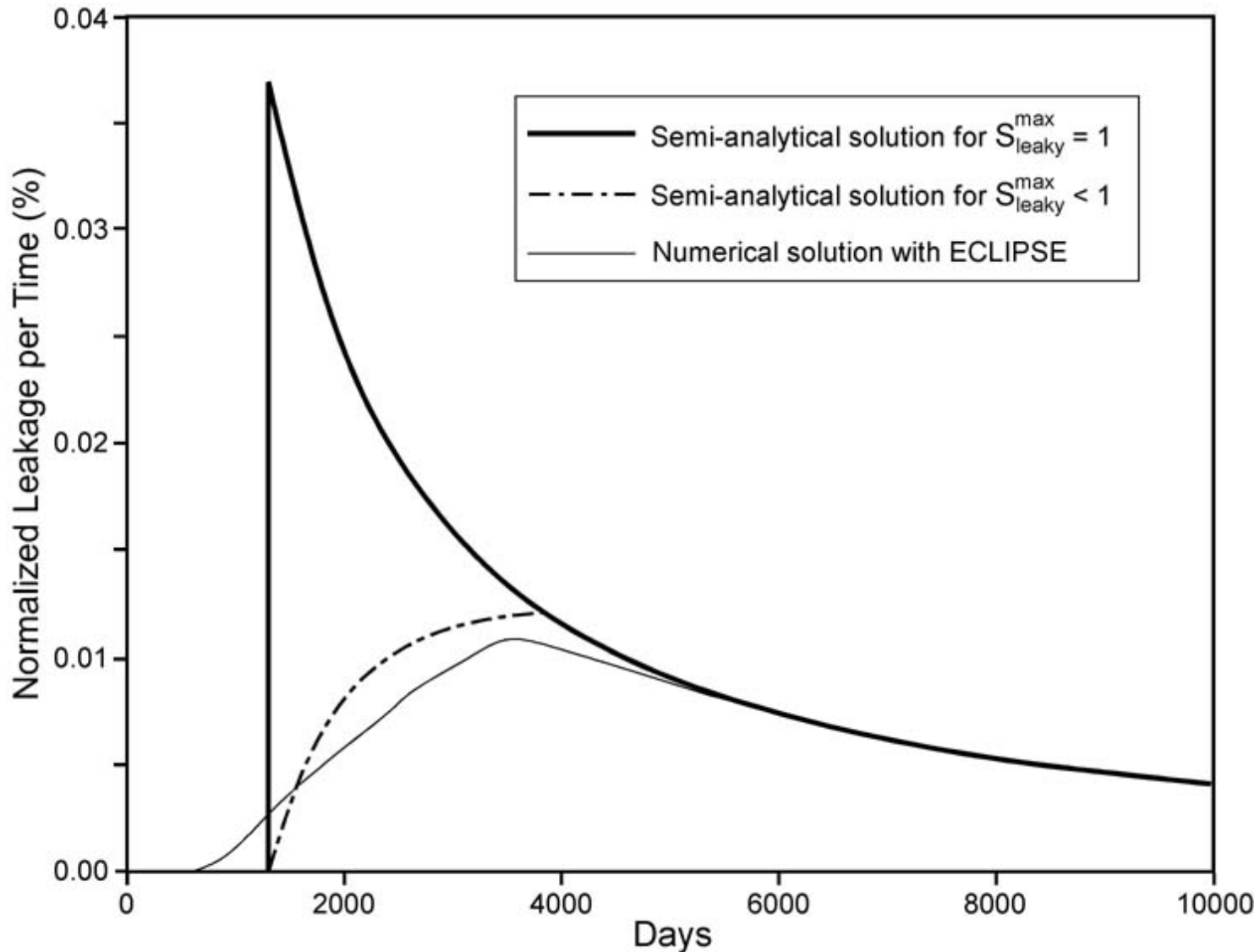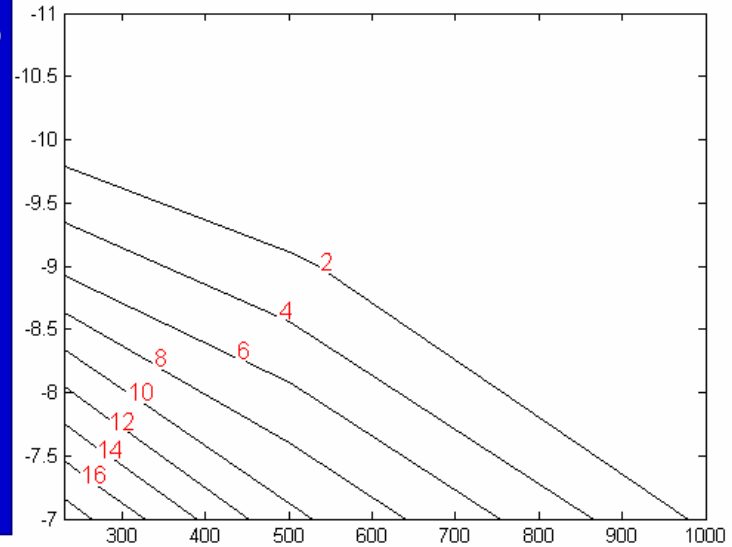
Leakage Solutions

Leakage Solutions

Expanded Parameter Space

**Status of Wells
Type of Cement
Location of Cement
Cement Degradation
with time**

Effective Permeability

Distance

**Cluster Analysis
Multiple Wells
Bulk Effects**

Ongoing Efforts

◆ Leakage Modeling for specific field site:

  – Apply numerical and analytical models to estimate leakage, coupled with well statistics for spatial locations.

  – Determine threshold statistics for well parameters associated with target leakage amounts.

  – Incorporate transient well parameters based on cement degradation estimates.

◆ Unsaturated Zone Studies:

  – Continue with laboratory column study.

  – Test models against laboratory data.

◆ Well-cement experiments and analysis will be the major effort for 2004.

Princeton University

Papers written in 2003

Analysis of Well Statistics in Viking Formation, Alberta Basin:

- Gasda, S.E., S. Bachu, and M.A. Celia, "The Potential for CO2 Leakage from Storage Sites in Geological Media: Analysis of Well Distribution in Mature Sedimentary Basins", submitted to *Environmental Geology*, December 2003.

Simplified Solutions for CO_2 Transport and Leakage Estimates:

- Nordbotten, J.M., M.A. Celia, and S. Bachu, "Analytical Solutions for Leakage Rates through Abandoned Wells", to appear, *Water Resources Research*, 2004.
- Nordbotten, J., M.A. Celia, and S. Bachu, "Injection and Storage of CO2 in Deep Saline Aquifers: Analytical Solution for CO2 Plume Evolution during Injection", submitted to *Transport in Porous Media*, October 2003.
- Nordbotten, J., M.A. Celia, S. Bachu, and H.K. Dahle, "Analytical Solution for CO2 Leakage between Two Aquifers through an Abandoned Well", submitted to *Environmental Science and Technology*, December 2003.

Large-scale Compositional Simulations:

- Prevost, J.H., R. Fuller, A.S. Altevogt, R. Bruant, and G. Scherer, "Numerical Modeling of Carbon Dioxide Transport in Deep Saline Aquifers: Equation Development", under review, *SPEJ*, 2003.

Princeton University

Papers written in 2003

## Shallow-zone Transport and Geochemisttry:

- Altevogt, A. and M.A. Celia, "Modeling Carbon Dioxide Transport in Unsaturated Soils", to appear, *Water Resources Research*, 2004.
- Altevogt, A.S. and P.R. Jaffe, "Modeling the Effects of Gas-phase CO_2 Intrusion on the Biogeochemistry of Variably Saturated Soils", to appear, *Proc. CMWR 2004 Conference*, June 2004.
- Wang, S. and P.R. Jaffe, "Dissolution of Trace Metals in Potable Aquifers due to CO_2 Release from Deep Formations", to appear, *Energy Conversion and Management*, 2004.
- Giammar, D.E., R.G. Bruant, and C.A. Peters, "Forsterite Dissolution and Magnesite Precipitation at Conditions relevant for Deep Saline Aquifer Storage and Sequestration of Carbon Dioxide, Submitted to *Chemical Geology*, 2003.
- White SJO., Hay MJ., Marcus M., Lanzirotti A., Myneni SCB. (Submitted) Consequence of elevated soil-CO2 on plant growth: A constraint for geological sequestration of CO2.

Upscaling Studies:

- Gasda, S.E. and M.A. Celia, "Upscaling Relative Permeabilities in a Structured Porous Medium", to appear, *Proc. CMWR 2004 Conference*, June 2004.
- Li, L., C.A. Peters, and M.A. Celia, "Examination of Upscaling Considerations for Geochemical Reaction Rates using Network Model Simulations of Calcite Dissolution", to appear, *Proc. 11th Int. Sym. Rock-Water Interactions*, June 2004.

Princeton University

Effect of CO$_2$ Leakage on the Redox Profile in the Vadose Zone
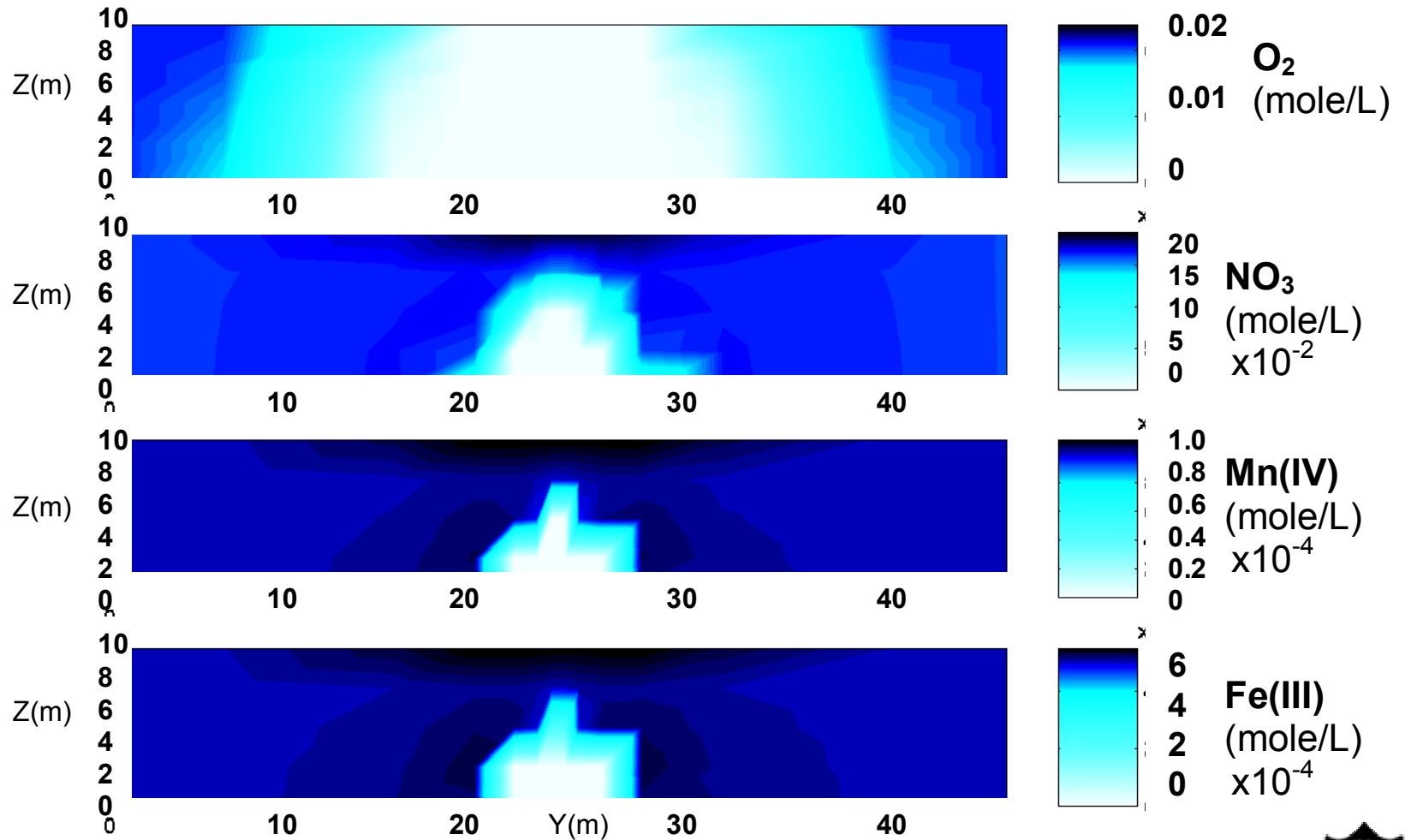
The stability of hydrated cement under CO_2 sequestration conditions

Andrew Duguid, Robert Bruant, George Scherer,

Sarah Gasda, Michael Celia, Mileva Radonjic

Princeton University

February, 2004

Outline

- CO_2 sequestration conditions/implications on cement
- Cement based systems
  - Chemical and physical properties of cements
  - Hydrated cements
  - Well cements
  - Cement degradation (CH-dissolution,
    CH and CSH carbonation, acid-attack)
- Experimental Program
  - Ambient pressure experiments
  - High pressure experiments
  - Field cement samples
  - Characterisation of the above materials and mechanisms

Possible Sequestration-Leakage Scenario
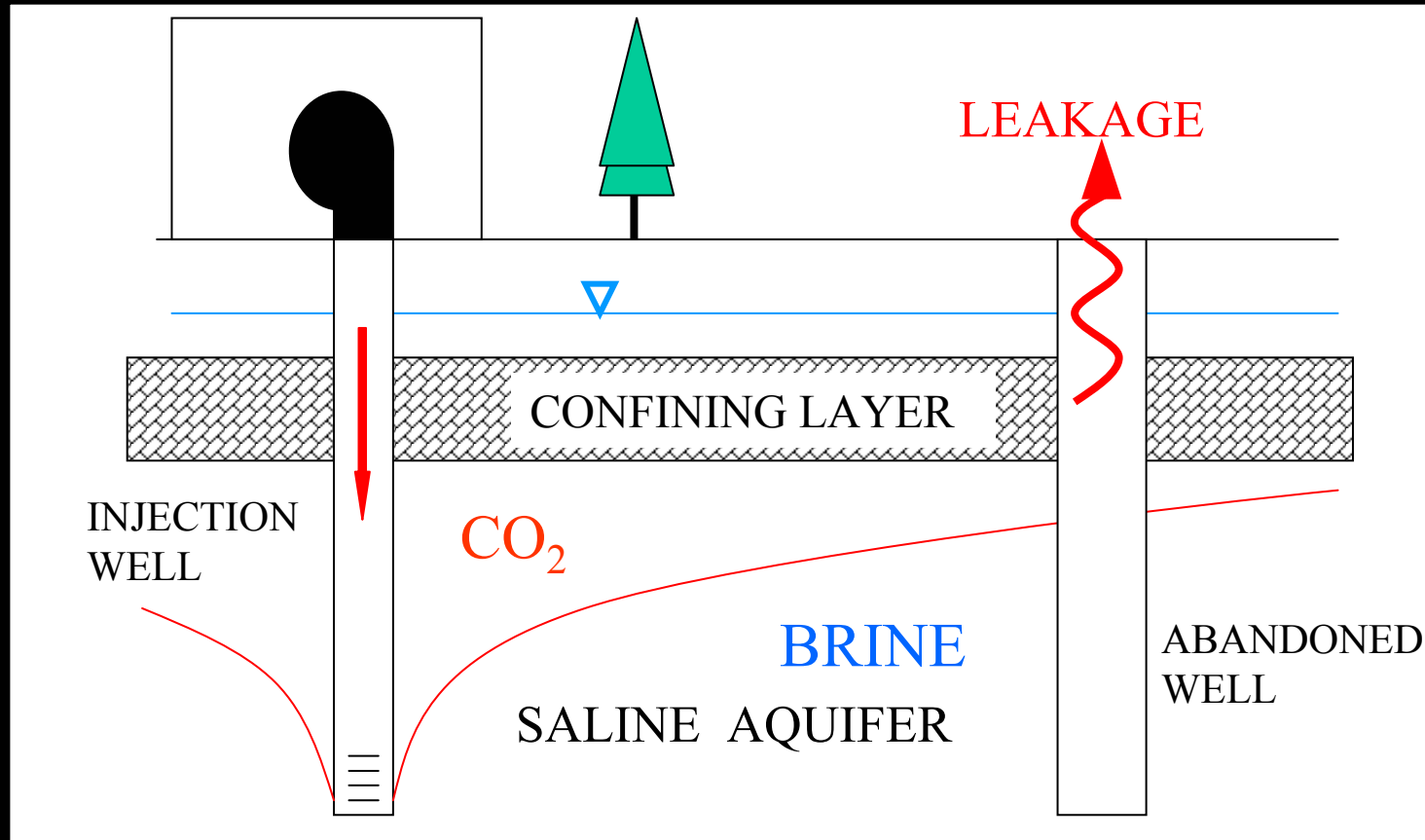
Well Cementing

- Wells are cemented to protect the well casing, to stop fluid exchange between formations (contamination) and to close the well when it is abandoned

- Eight American Petroleum Institute (API) types of well cement.
  - Class A through H
  - Different types for different applications (depths and temperatures)
  - Many additives to further adjust the cement to fit the particular application. An example is bentonite which is used to reduce slurry (cement) density

Typical Abandoned Oil Well

Surface casing

Primary cement

Cement plug

Secondary casing

Secondary cement

Mud

Production casing

Production cement

Cement plug
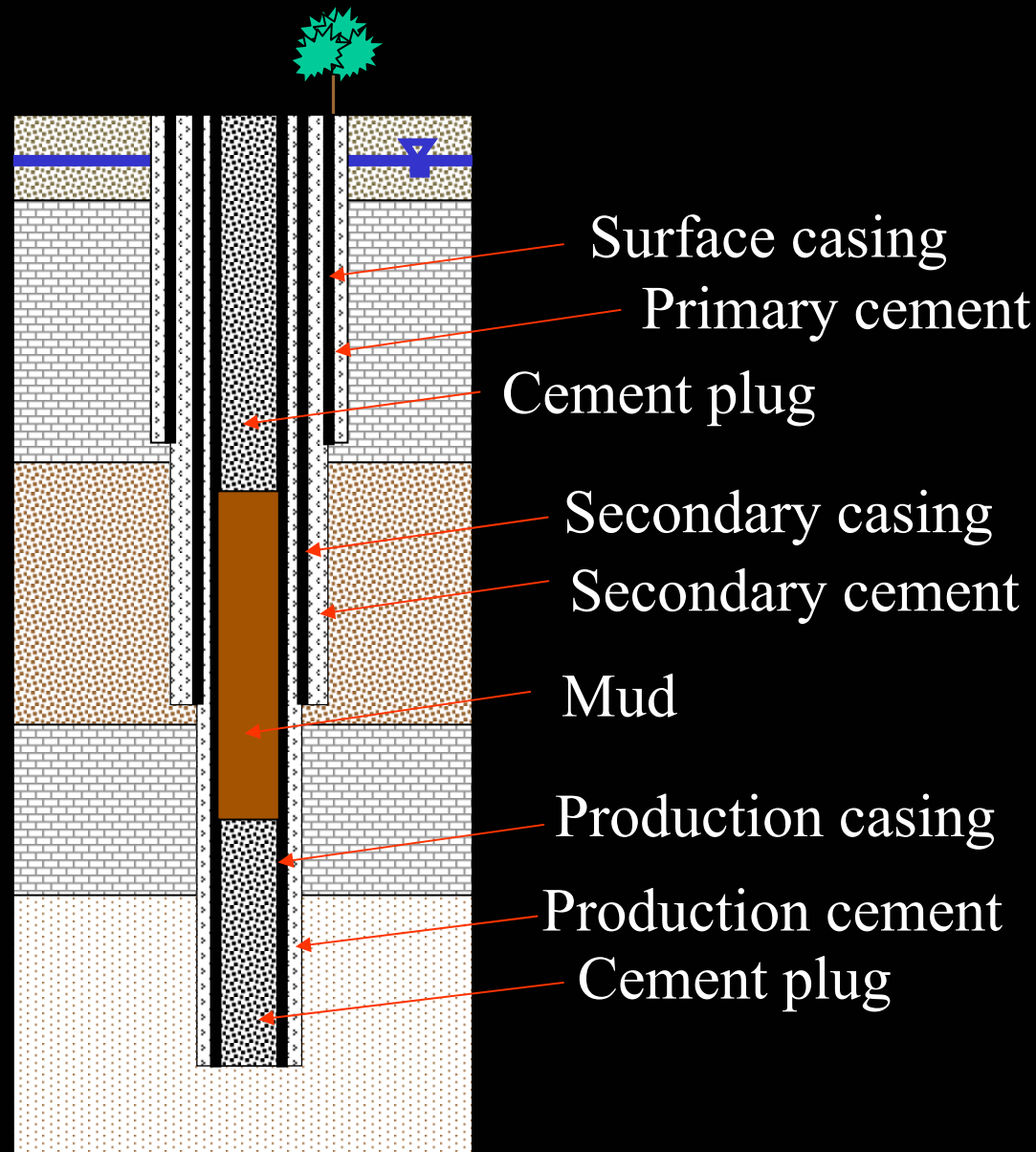
Avenues for leakage

- ## Pores
  - Hydration products (morphology, type of CSH)

- ## Annuli
  - Thermo-mechanical stresses from pumping oil
  - Shrinkage of cement
  - Rock-cement paste interface and
  - Cement paste-casing interface

- ## Microcracks
  - Expansive ineralogical transformations

Avenues for Leakage

Well plug

Well casing

Rock formation

Well cement
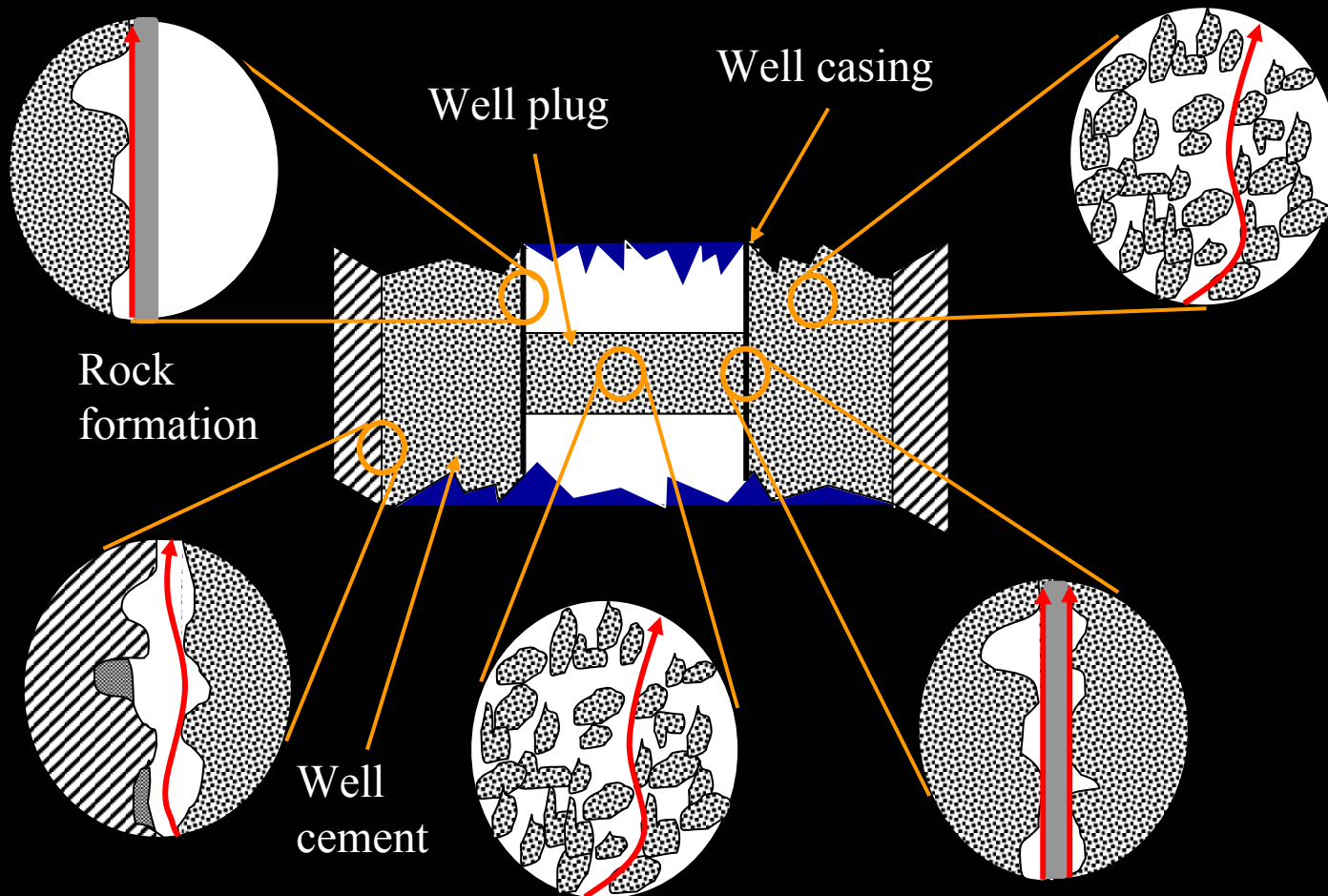
Chemical and physical properties of cement clinker

- Main constituents of portland cement clinker:
    - **50-70%** Alite - $3CaO\ SiO_4$
    - **15-30%** Belite - $2CaO\ SiO_4$
    - **5-10%** Aluminate - $3CaO\ Al_2O_3$
    - **5-15%** Ferrite - $4CaO\ Al_2O_3\ Fe_2O_3$

67% CaO, 22% SiO_2, 5% Al_2O_3, 3% Fe_2O_3, 3% rest

Particle size, specific surface area

OPC CLINKER
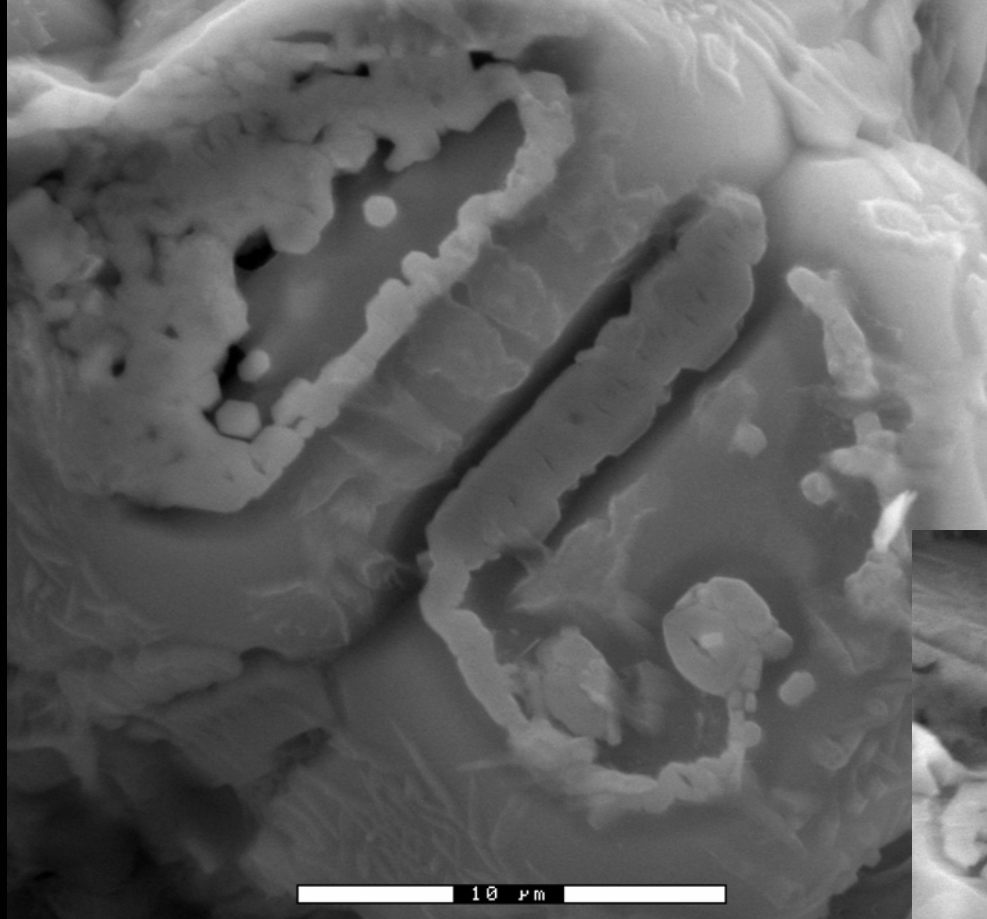
20.kV 3850x   GSED
IMERYS Central Research   ESF00236.TIF   00/08/16

10 μm

25 μm
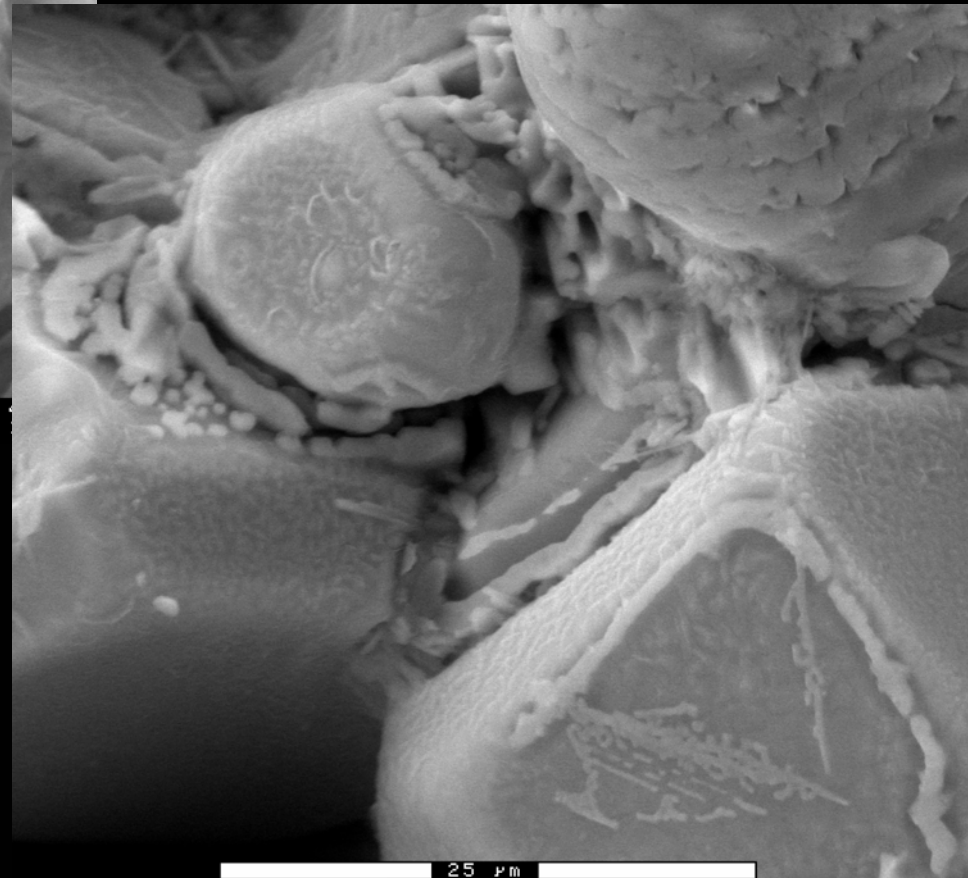
Hydration of individual cement components

Silicate Hydration

$$2C_3S + 10.6H \rightarrow C_{3.4}\text{-}S_2\text{-}H_8 + 2.6CH$$

$$2C_2S + 8.6H \rightarrow C_{3.4}\text{-}S_2\text{-}H_8 + 0.6CH$$

Aluminate Hydration

Monosulfate

$$2C_3A + 27H \rightarrow C_4AH_{19} + C_2AH_8$$

$$2C_3A + 21H \rightarrow C_4AH_{13} + C_2AH_8$$

$$C_3A + CH + 12H \rightarrow C_4AH_{13}$$

Ettringite

$$C_3A + 3C\underline{S}H_2 + 26H \rightarrow C_6A\underline{S}_3H_{32}$$

Ettringite to monosulfate

$$2C_3A + C_6A\underline{S}_3H_{32} + 4H \rightarrow 3C_4A\underline{S}_3H_{12}$$
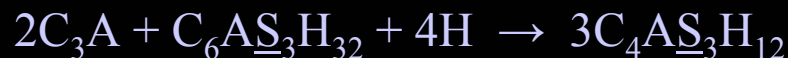
Aluminoferrite Hydration

$$C_4AF + 2CH + 12H \rightarrow C_4AH_{13}$$

Adapted from Nelson, 1990
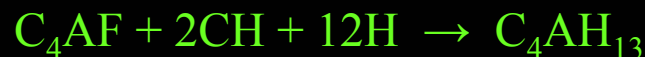
Hydration of alite (3CaOSiO$_4$)
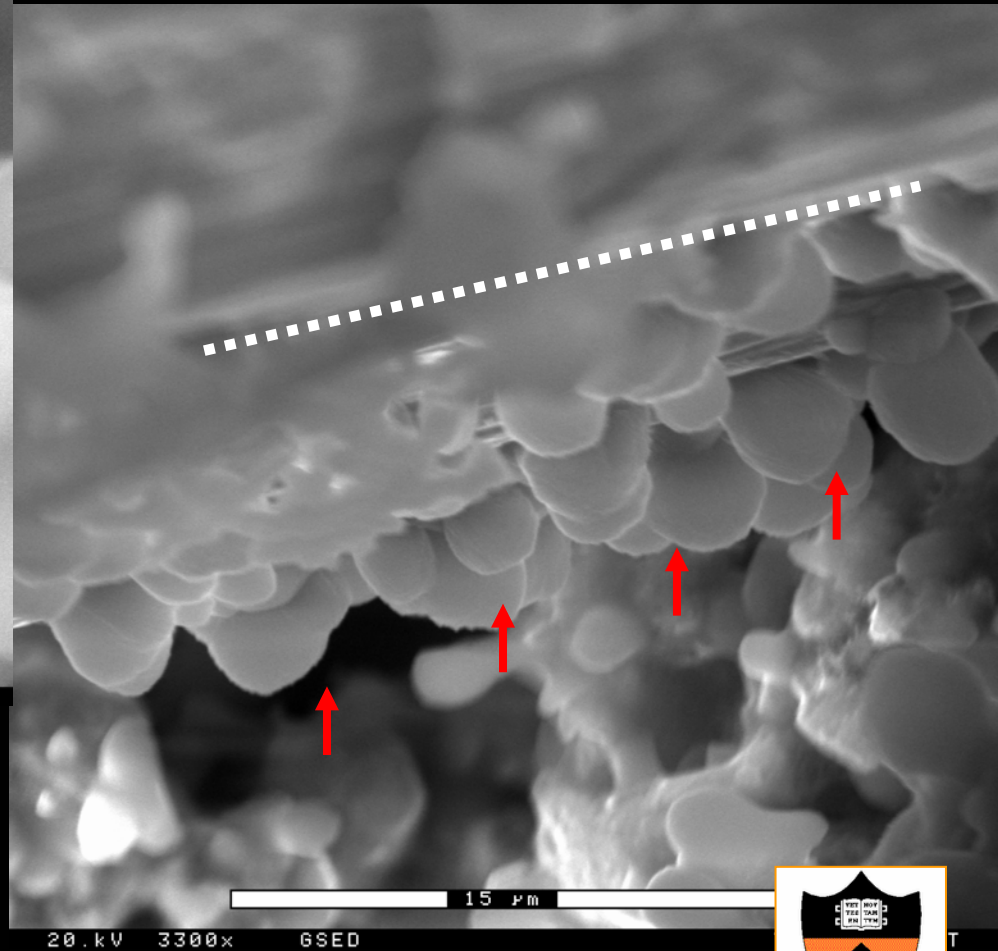
Oriented Portlandite growth

Rock / Hydrated cement-paste interface

PORTLANDITE

ROCK

ETTRINGITE

CALCIUM-
SILICATE-
HYDRATE
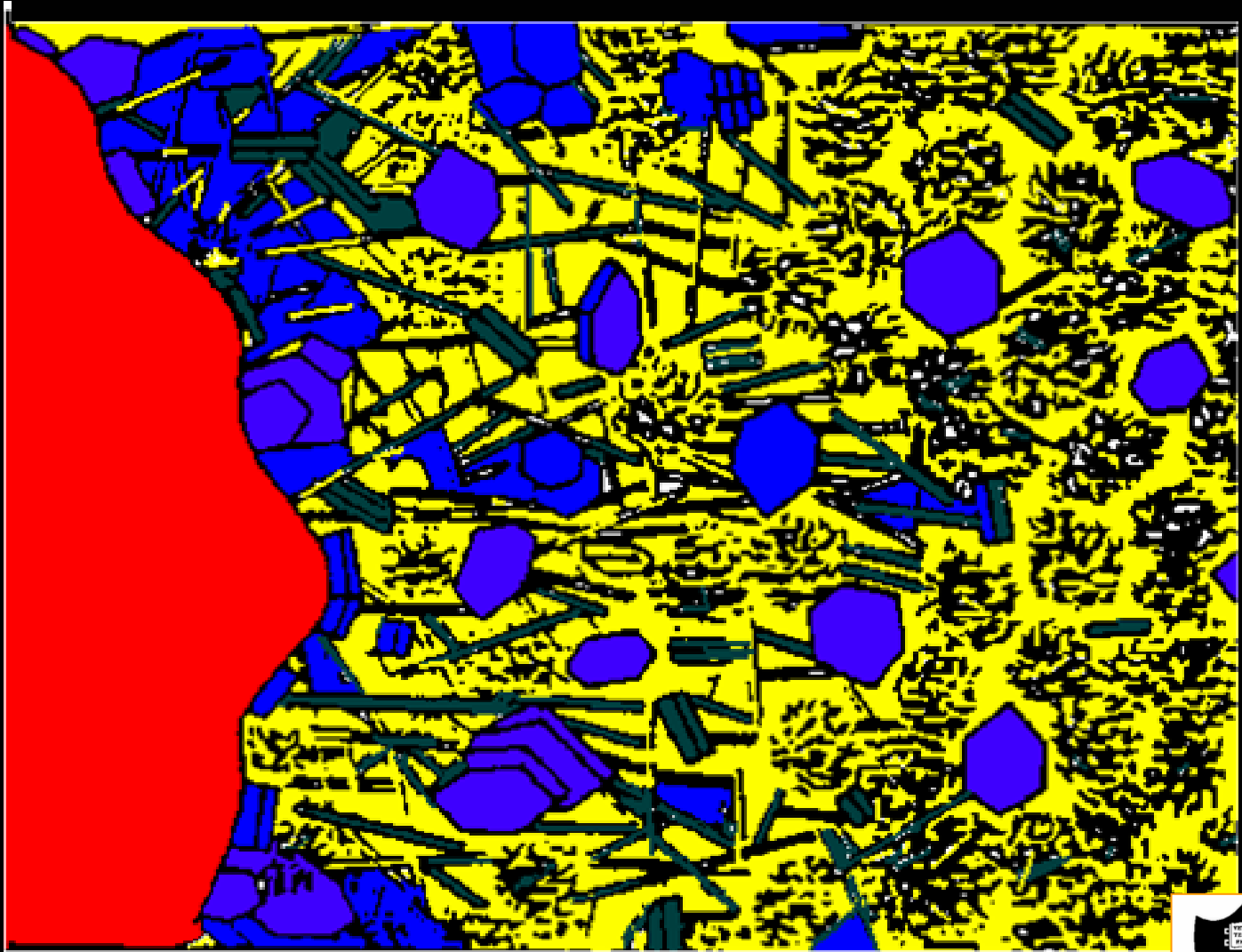
The impact of mix design and curing conditions on the durability of cements

Temperature

C_2S hydration is complete in: 1day at 80C, 3days at 60C, 14days at 40C and 27days at 25C.

C/S ratio of C-S-H increases above 75C

Water / cement ratio, increased porosity

Admixtures

Non-uniform distribution of hydration products

Solubility of CH decreases with increasing temperature

Texture of the hydrated cement more open at high T

Implications of curing temperatures on durability of cementitious systems

- Modifications of the microstructures:
  - Composition of hydrated products
  - Structure of hydrated products
  - Ionic concentration of pore solution
  - Pore size distribution
  - Microcracking

  - The consequence is a potentially favoured ingress of aggressive agents.

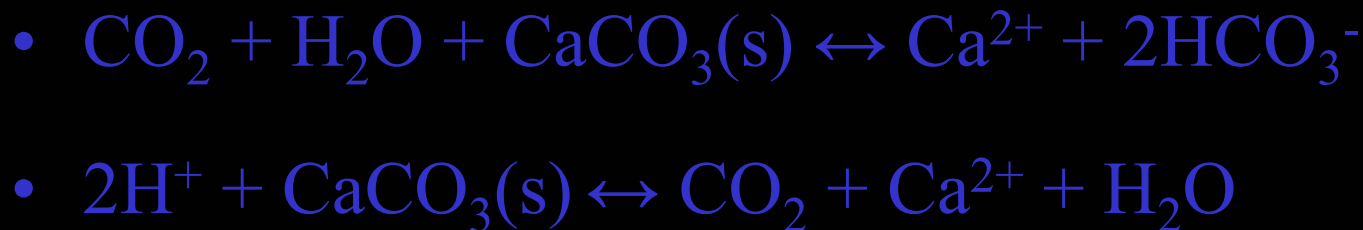# Dissolution / precipitation chemistry of carbonation reaction in cementitious systems

CO_2 dissociation

- $CO_2 + H_2O \leftrightarrow H_2CO_3{}^* \leftrightarrow H^+ + HCO_3{}^- \leftrightarrow 2H^+ + CO_3{}^{2-}$

Cement alterations

- $Ca(OH)_2(s) + 2H^+ + CO_3{}^{2-} \rightarrow CaCO_3(s) + 2H_2O$
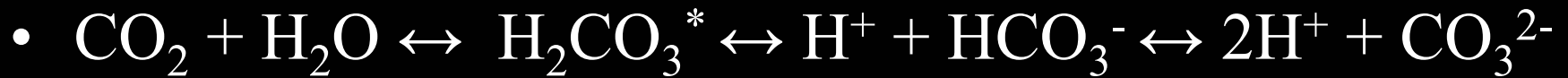
- $C\text{-}S\text{-}H(s) + 2H^+ + CO_3{}^{2-} \rightarrow CaCO_3(s) + S\text{-}H(s)$
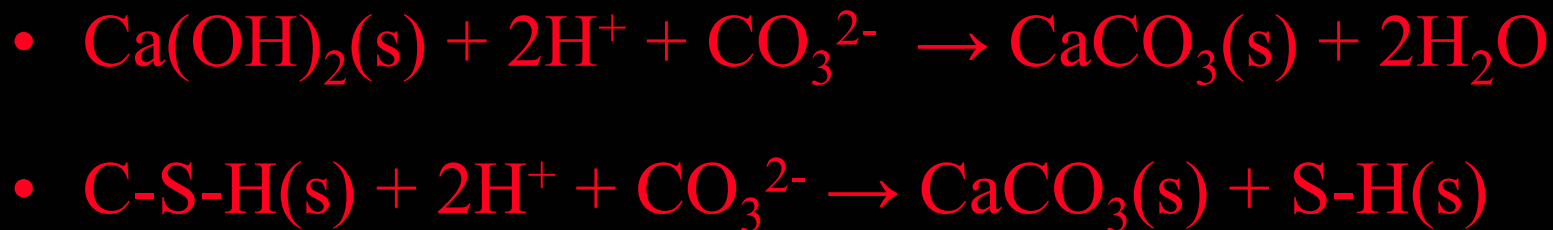
Calcium carbonate dissolution

- $CO_2 + H_2O + CaCO_3(s) \leftrightarrow Ca^{2+} + 2HCO_3{}^-$

- $2H^+ + CaCO_3(s) \leftrightarrow CO_2 + Ca^{2+} + H_2O$

The effect of acid attack on cementitious systems

- All phases in cementitious systems react with acid solutions by consumption of H ions.

- Congruent dissolution of CH
    This creates increased porosity and permeability

- Incongruent dissolution of CSH
    - There is a Si-rich deposited residual layer on the surface

- The growth of a protective layer forces a change from a reaction-controlled to a diffusion controlled process.

Carbonation as a surface reaction
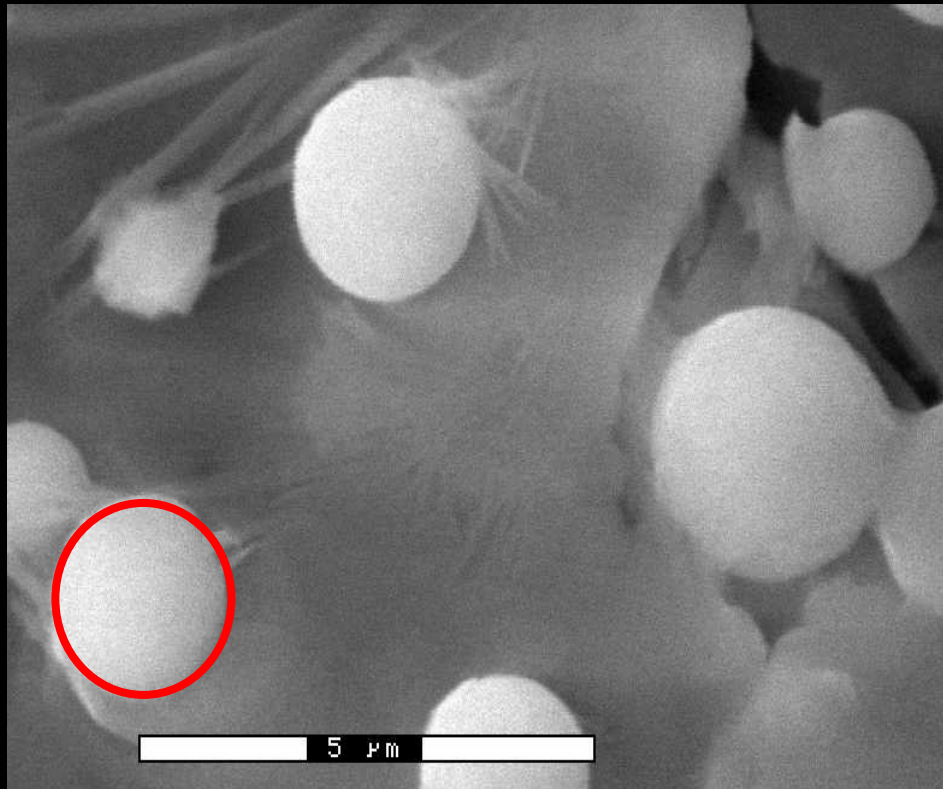
Lime - CO2 interaction and formation of submicron particles

The main aims of experimental program

- Quantitative data
  - Permeability, dissolution rates.
  - Quantitative data needed for use in transport models to simulate a potential leakage from sequestration sites.

  Qualitative data
  - Microscopic characterization techniques will provide an understanding of the mechanisms involved in cement deteriorations

Low-Pressure Experiments

- Cement and rock samples
  - Examine the degradation of cement, rock, and cement-rock interface
  - Class-H cement, Salem limestone, and Berea sandstone
- Degradation / dissolution governed by diffusion
- Atmospheric pressure
- Brine--0.5 m NaCl solution
- Examine the effect of temperature (21, 50, and 85°C)
- Look at the effect of pH (~4, 5.5, and 7)
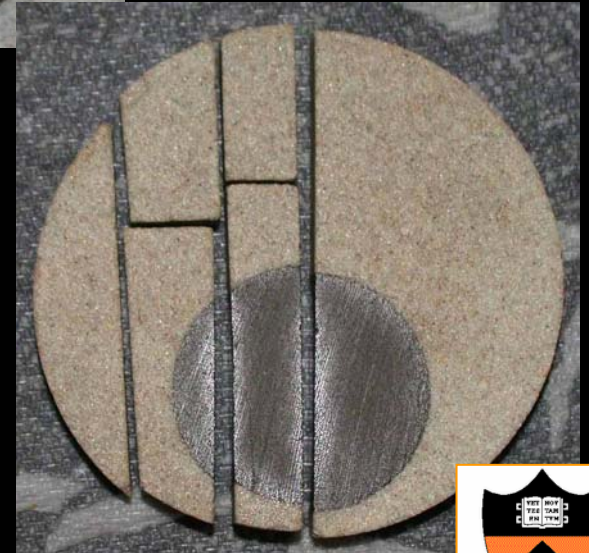- Examine the effect of bicarbonate concentration (P_{CO2} = 1.01 and 0.032 bar)

Slices of the Sample

0-month

1-month

2-month

3-month

6-month

12-months
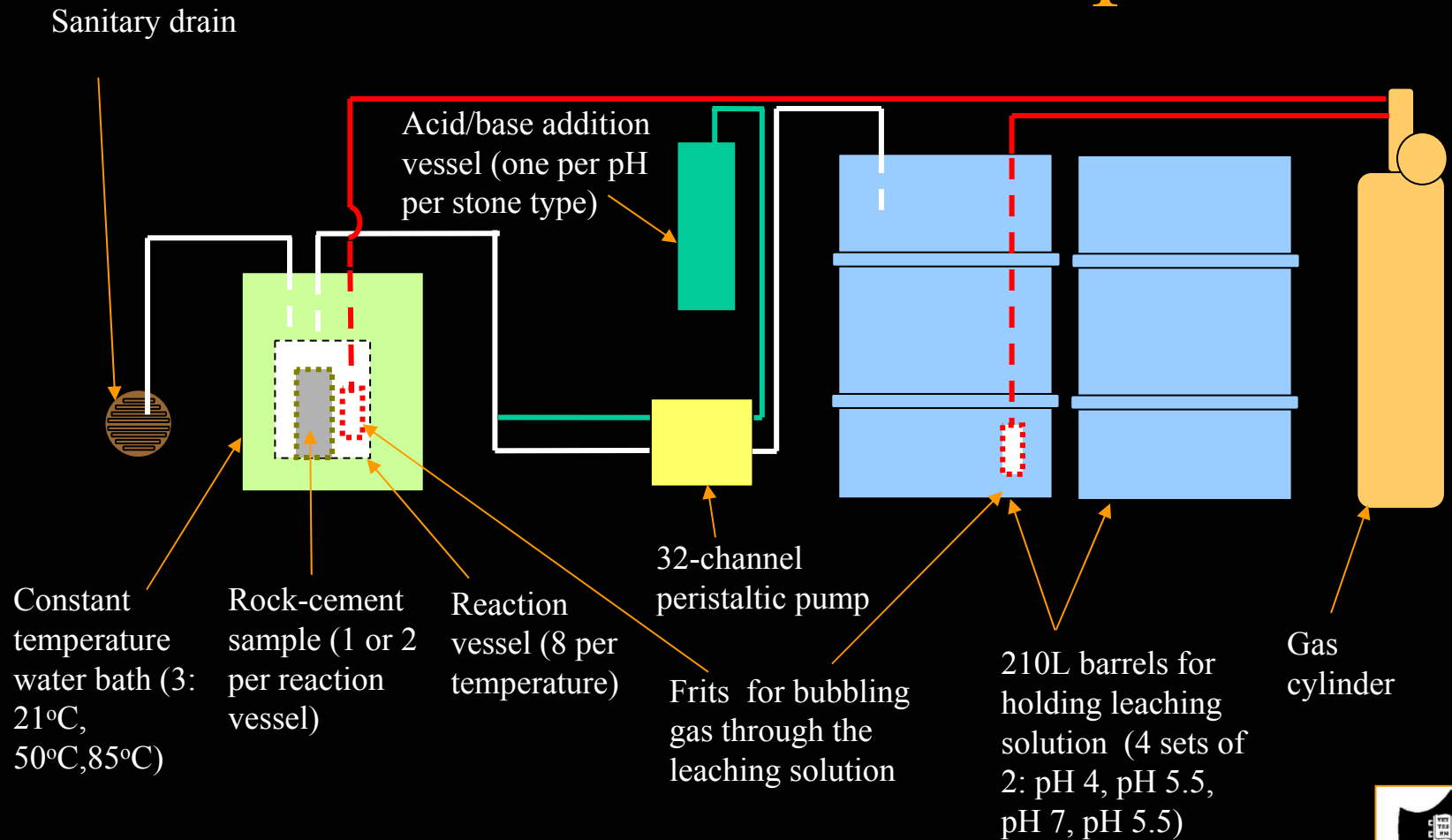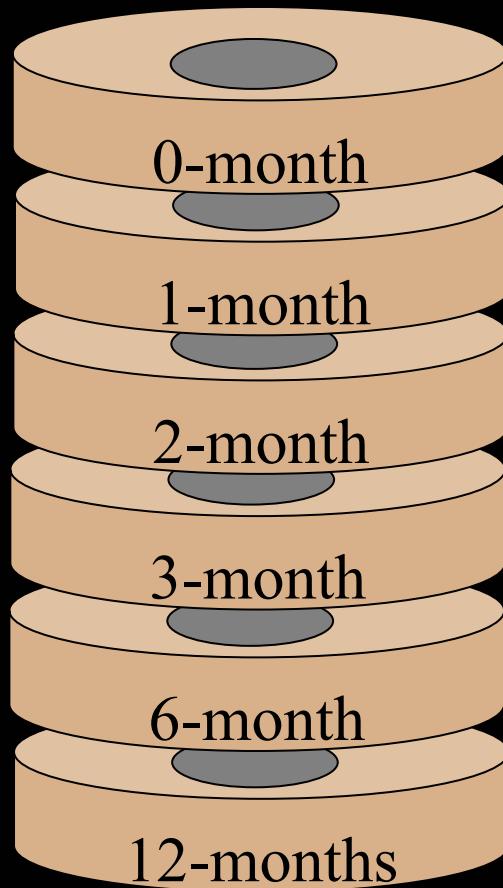
Permeability

ESEM

0-month results (21°C)

Interface
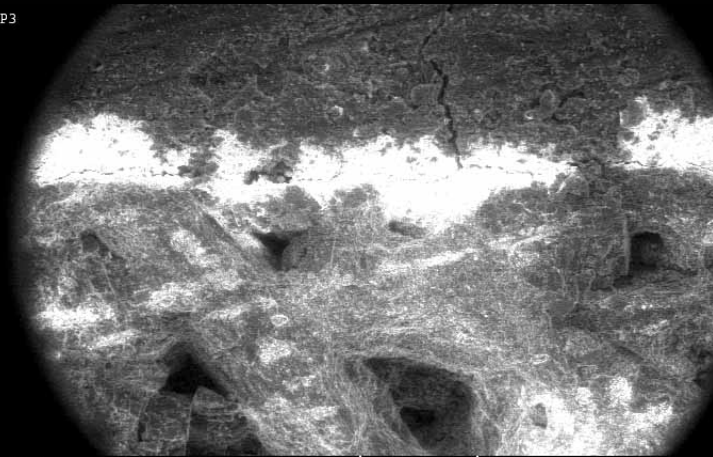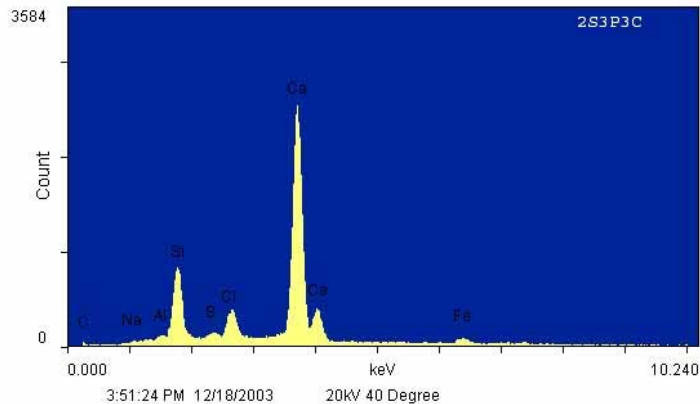
Center of Cement
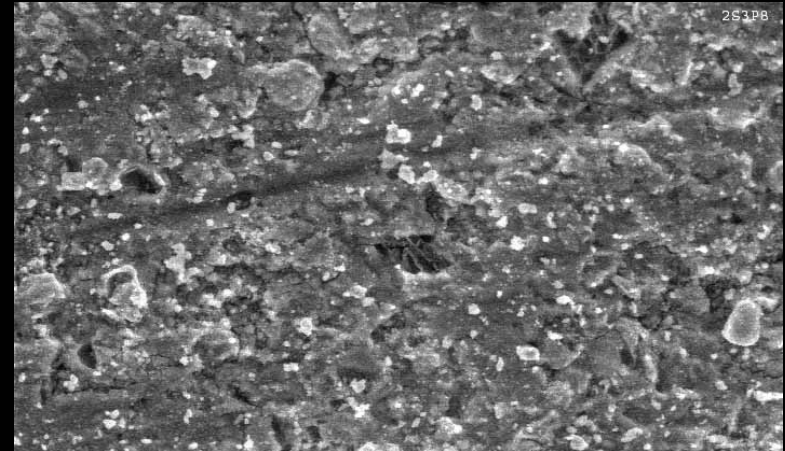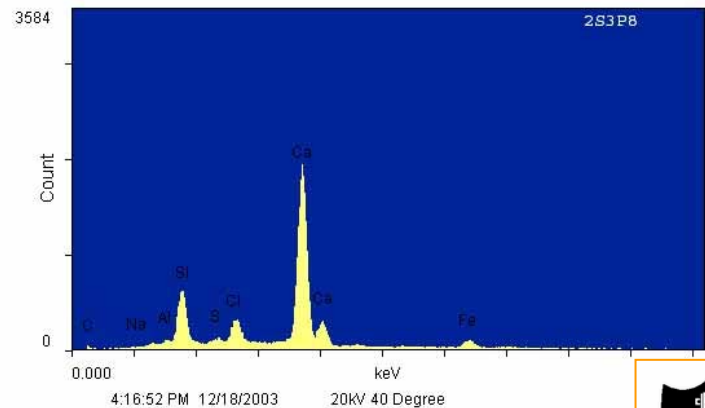
0-Month Results (21ºC)

Berea Sandstone Interfaces
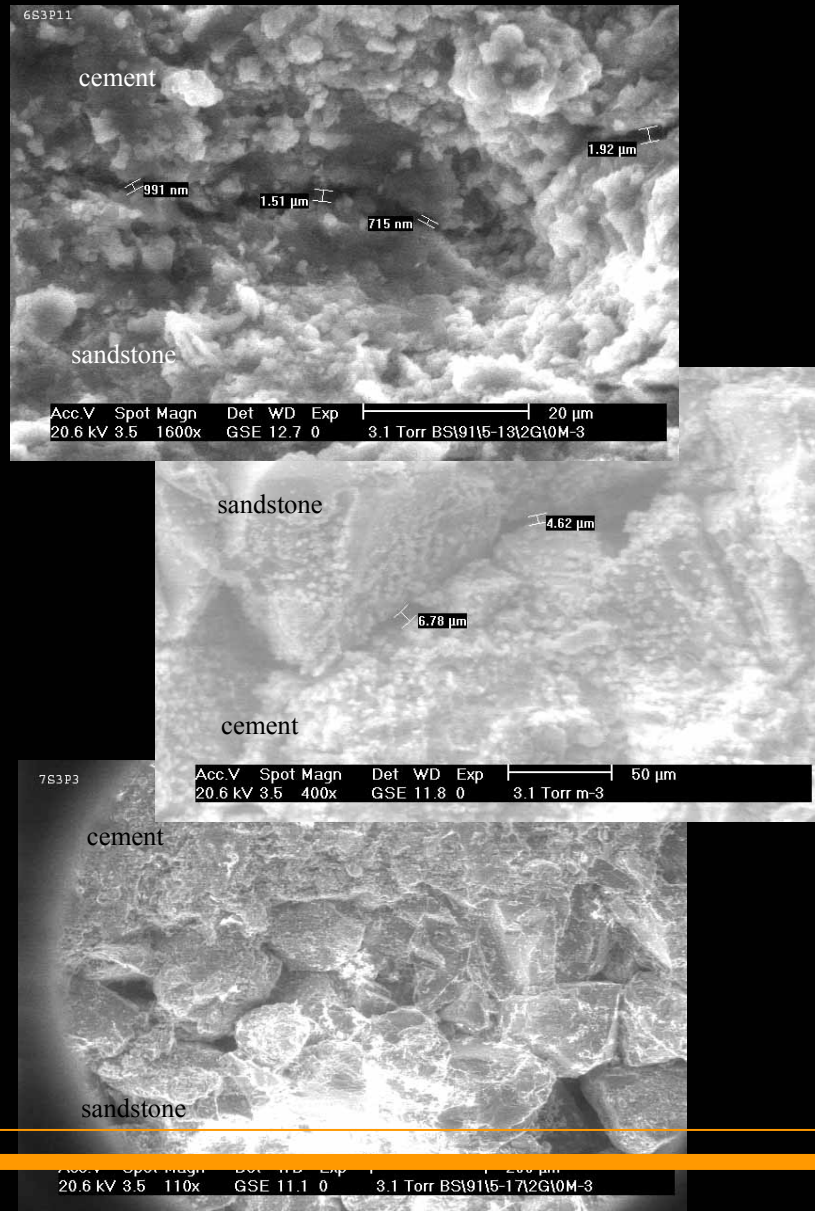
Salem Limestone Interfaces

Low-Pressure Measurements

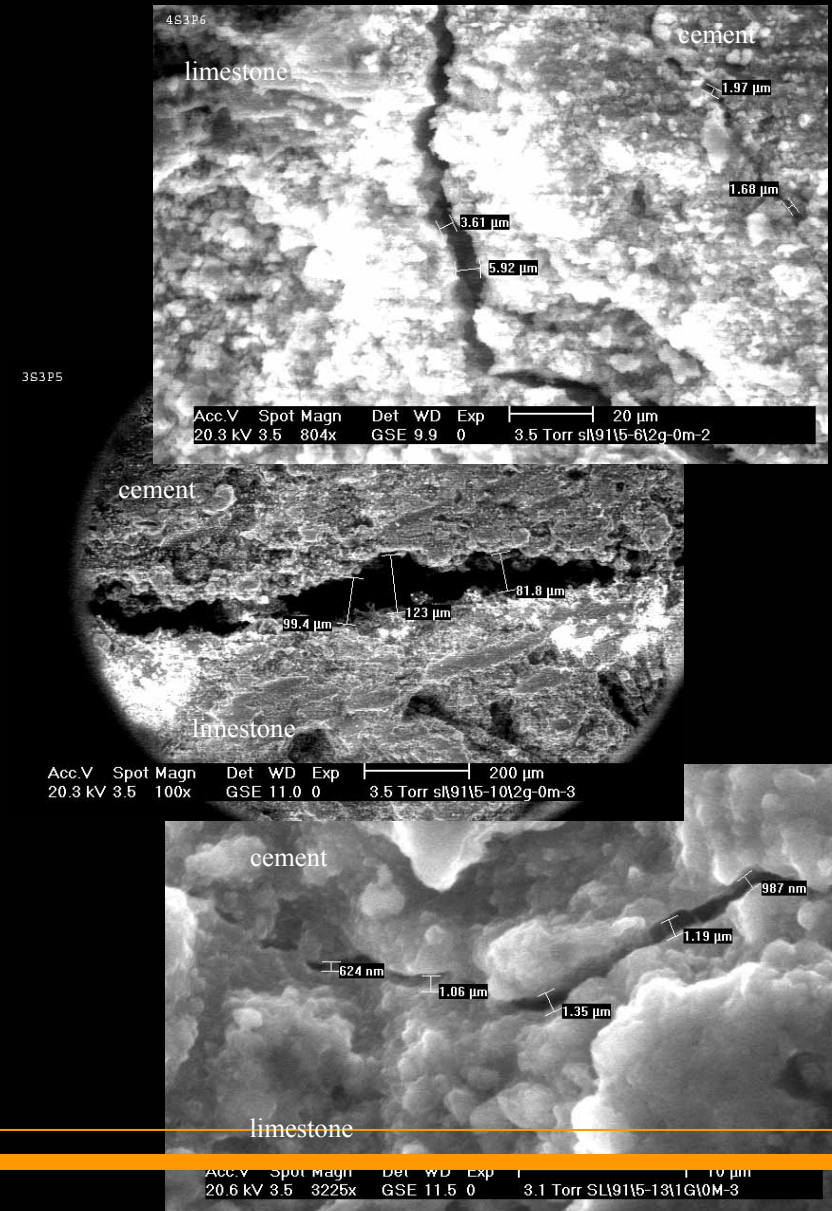- Average permeability of the sample
- Rate of reaction--Depth of reaction with time
- Identification of phase and property changes
  - Environmental scanning electron microscope (ESEM) with energy dispersive X-ray (EDX)
  - X-ray powder diffraction (XRD)
  - Nuclear magnetic resonance (NMR)

High-Pressure Experiments

- Look at the degradation of well cements under sequestration conditions

- Cement samples
  - 8.5 and 12.5mm cylindrical Class-H cement paste samples (with and without bentonite)

- Sequestration conditions
  - 10 MPa
  - 0.5 m NaCl solution with a CO_2 atmosphere
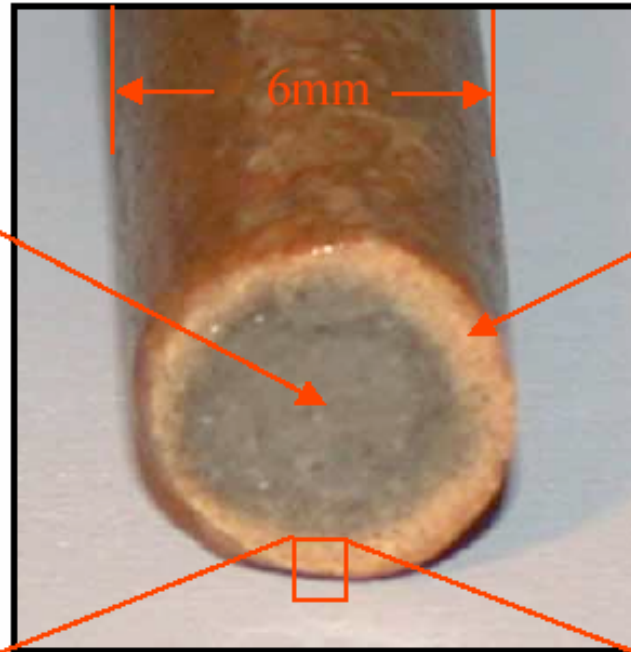 - Examine the effect of temperature (21, 50, and 85°C)

High-Pressure Preliminary Results

Reacted cement sample (50°C)
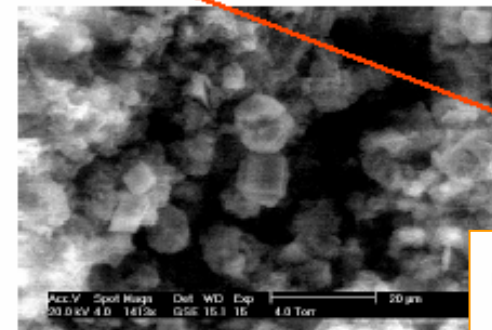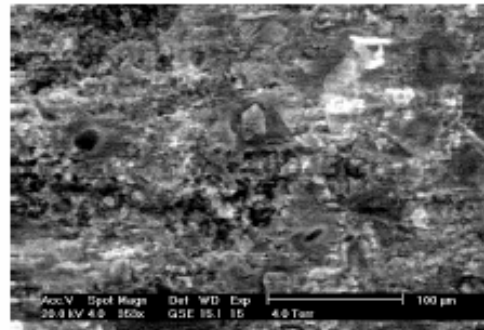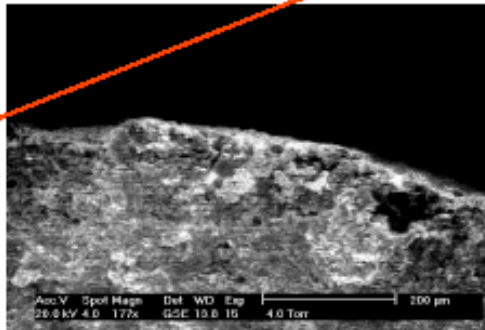
High-Pressure Preliminary Results

5°C   21°C   50°C

- Reaction depth increases with increasing curing temperature

High-Pressure Measurements

- Rate of reaction--Depth of reaction with time

- Types of reactions that occur
  - ESEM with EDX and XRD

- Permeability change with exposure to sequestration conditions using beam-bending permeametry

High-Pressure Results
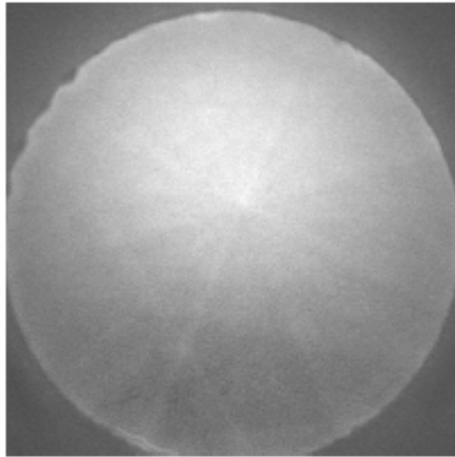
EBSD pattern for precipitated calcite
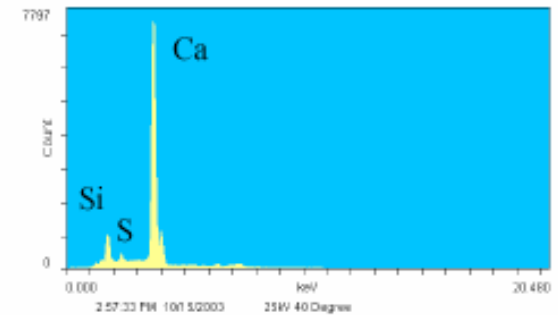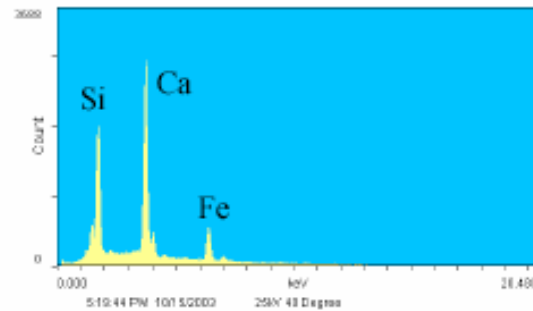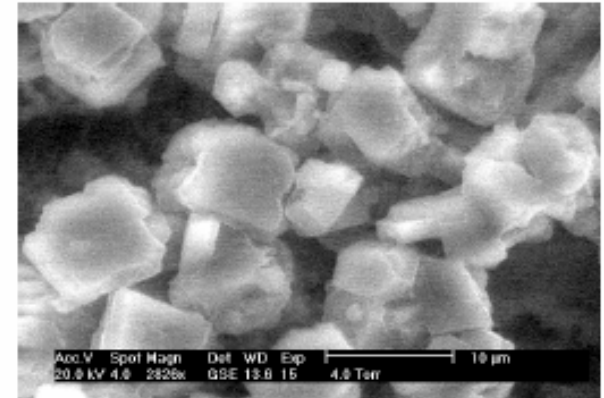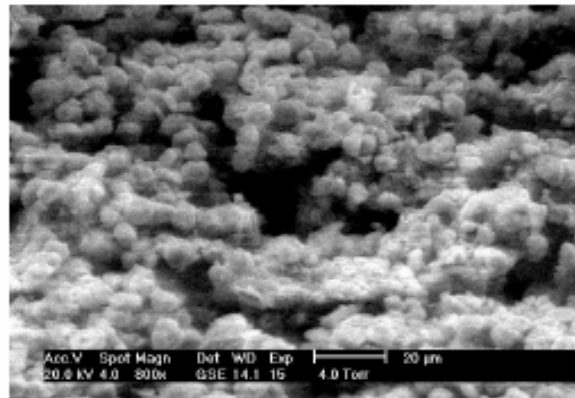
High-Pressure Results

Undegraded 50°C Sample
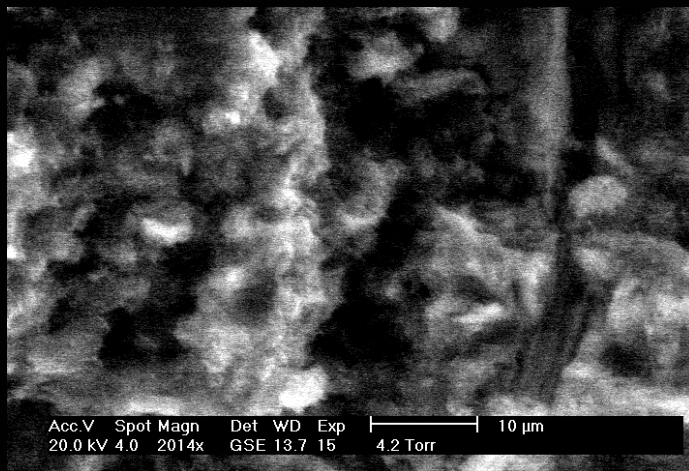
Degraded 50°C Sample
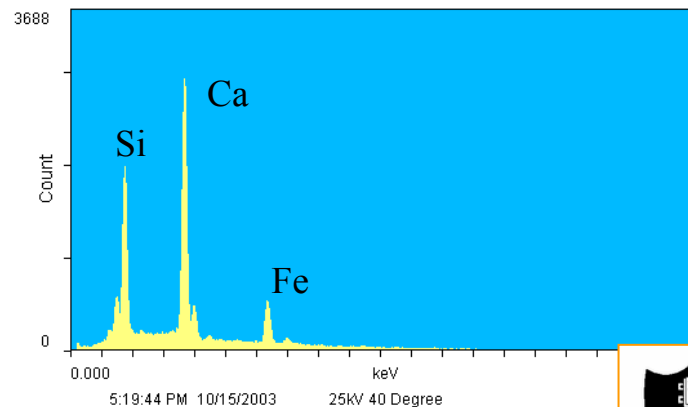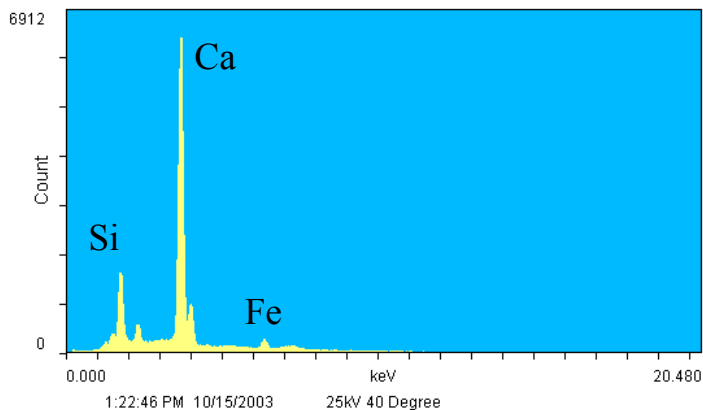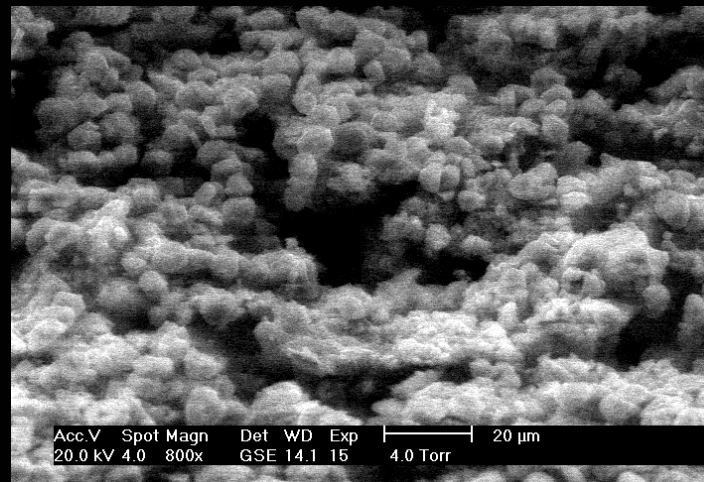
Summary

- The effect of sequestration on potential leakage pathways within an abandoned well

- Temperature, pH, bicarbonate concentration, and bentonite

- High- and low-pressure experiments
  - The high- and low-pressure experiments will examine changes in the transport properties of well cements
  - The low-pressure experiments will study changes at the cement-rock interface
  - The low-pressure experiments will yield information on variation undegraded cement properties with curing temperature

Thank you!
BP and Ford

Risk Assessment Workshop

Breakout groups

- Elected four breakout groups
  - ➢ Group 1   FEP Database
  - ➢ Group 2   Status of Risk Assessment Studies
  - ➢ Group 3   Implications of seepage
  - ➢ Group 4   Engaging Stakeholders

- Each group has been given a list of questions to consider
  - ➢ Question listed in the delegate pack
  - ➢ Ask groups to address questions and any other key issues they consider

Risk Assessment Workshop

Breakout group process

- Delegates placed into each group based on your disciplines/expertise
  - ➢ Want to keep group balance
  - ➢ If you want to move try and swap
- Elected a chairman to each group to ensure we get closure on the discussion
- Ask for a 10 minute summary of key points addressing the questions when we reconvene

Risk Assessment Workshop

Breakout group process

- 4 groups in 3 rooms
  - Groups 1 and 4 meet in the main room
  - Group 2 to meet in room 19
  - Group 3 to meet in room 21
- Time is split before and after lunch
- Ready to report back in here by 14.00
- Report back and questions until 15.00

Risk Assessment Workshop Breakout Groups

Thursday 12th February 2004

Breakout Group 1

FEP Database

Questions for Breakout Group 1
FEP Database

- What is the status of the generic database?

- What are the steps towards completion?

- How will it become an accepted auditable resource?
  - Who are the stakeholders?

- When will it be available for publication on the IEA GHG web site?

- What maintenance may be required?

Breakout Group 1
Status of generic database (1)

- ## Structure of web site
  - IEA GHG web page providing overview on risk assessment
  - Generic Performance Factors (lose FEP name)
    - Hierarchical structure
      - Spatio-temporal system angle
      - Process-event angle
  - Project or site specific database
    - More detailed
    - Documentation of the elimination of particular FEP's

Breakout Group 1
Status of generic database (2)

- Usage in Risk Assessment
  - Web site
  - Download/stand alone application

    - Use generic database to plan risk assessment or complete risk assessment and check with generic database

Breakout Group 1
What are the steps towards completion?

- Qunitessa Report to IEA GHG in March 2004
- Alignment of the Qunitessa and TNO-NITG FEP databases beginning May 2004
- Stakeholder group before it goes onto website September 2004 at GHGT7
- Post GHGT7 on IEA GHG website

Breakout Group 1
How will it become an accepted auditable resource?

- Peer review (Public, regulators and experts)
  - AEUB
  - USEPA
  - DG Environ
  - Climate Action Network Europe (CAN Europe)

Breakout Group 1
What maintenance may be required?

- Maintenance (Kept at Quintessa?)
  - Content
  - Software/hardware work

- Funding (to be determined?)
  - Agreement with previous investors
  - Development phase
  - Operational phase

Breakout Group 2

Status of Risk Assessment Studies

Questions for Breakout Group 2
Status of Risk Assessment Studies

- Discuss and summarise:
  - Technical gaps in the existing studies and how these can be addressed?
    - Tools, scenarios, documentation etc.
  - Options for taking risk assessment process forward
    - How do we reconcile learning's from different studies?
    - Is benchmarking of tools the next step?
    - What are the components of a Benchmarking process?
    - What data is needed to benchmark tools?
    - What data do we have and what more is needed?
    - How do we bring in the lessons from analogue studies?

Breakout Group 2
Technical gaps (1)

- PRA may be well & good for technical discussions but will/may not hold up to hostile discussion

- We have a framework for PRA but insufficient data to frame risk

- Lacking reasonably documented worst cases

- Better understanding of processes that could naturally mitigate leakage

- Do we have the ability/confidence to model a scenario for the time period of interest?

Breakout Group 2
Technical Gaps (2)

- Is the problem the understanding of the physics, availability of data?

- What is the goal? What is an acceptable leakage rate?

- Must be divided into local HSE & Global Climate Change

Breakout Group 2
Options for taking risk assessment process forward

- Types of models include detailed models to understand physics but have insufficient good data to run and simple models that can evaluate many wells in simple ways

- Need to do detailed simulation of well bore system to understand physics and ranges of variables

Breakout Group 2
Benchmarking

- Benchmarking is needed to evaluate models and understand differences

- What do we need to know about faults?

- Benchmarking:
  - Is it needed?
  - Is it the way to do comparison?
  - Do we have models that are sufficiently suitable to the purpose to justify benchmarking?

- What can natural analogues contribute?

Breakout Group 3

Implications of Seepage

Questions for Breakout Group 3
Implications of Seepage

- Leakage Pathways
- Knowledge Gaps gaps
- Leakage Rates
- Impacts of Leakage (climate & HSE)
  - Onshore
  - Shallow marine environment
- Current Studies Identified?

bp

EPRI

dti
Department of Trade and Industry

Breakout Group 3
Are leakage pathways understood?

- Identification of the pathways
  - Yes

- Detailed processes along the pathways
  - no

- Two levels
  - Scenarios for leakage….

Breakout Group 3
Are there gaps in our knowledge and how do we address them? (1)

- Gaps in knowledge
  - Yes and there will always be gaps in our knowledge

- Addressing them??????
  - expert(?) input to gap ranking…
  - Process interaction diagrams or interaction matrices may help identify key gaps and to rank gaps
  - PRA might be useful in ranking of the level of effort to be applied in "closing" a gap
    - If the PRA model is appropriate…
  - Demonstration project is the most likely method for the identification of the gaps

Breakout Group3
Are there gaps in our knowledge and how do we address them? (2)

- Very careful monitoring of existing projects
  - Full access and complete monitoring
  - Supported by laboratory programs to assist in evaluation of field monitoring data
- Establishment of dedicated, focused experimental test center (e.g. Teapot Dome)
- Laboratory testing provides fundamental inputs to models
- Natural Analogue key to long term processes

Breakout Group 3
Do we know likely leakage rates?
If not what more needs to be done?

- We do know the number starts with zero…

- Very site specific issue!!

- Uncertainty in "style" of leakage (episodic, dispersed, etc.)

- Issue with terminology: leakage vs migration

- Leakage rates from where?

- Assumed that leakage rates refers to leakage leading to "ecosystem" impacts

- Conduct field experiments to "force" leakage and monitor rates

- Possibility for lab experiments to provide inputs to mechanisms

Breakout Group 3
Do we understand the climate change impacts of leakage?

- Onshore and offshore are equivalent

- Only by analogy (volcanoes, industry)

- Leakage rates could be relatively large in comparison to HSE

- At what level(rate, time) is leakage not affecting climate change (e.g. 500-600 yrs)

Breakout Group 3
Do we understand the HSE impacts of leakage?

• Not well known although multidisciplinary areas may exist which may provide some valuable insight to effect of elevated CO_2 on plants

• Reasonable database of human health effects

Onshore	Shallow Marine
• Farm animals	• Ecosystem • Commercial fishery

Breakout Group 3
Have we identified all the current studies in this area ?

• No

Breakout Group 4

Engaging Stakeholders

bp

EPRI

dti
Department of Trade and Industry

Questions for Breakout Group 4
Engaging Stakeholders

- Questions (1)
  - Who are the key Stakeholders and what role does Risk Analysis have in engagement?
  - How are current stakeholder engagement activities working? Should current activities be extended? How much do they need to extend?
  - What is the current level of confidence in Risk Assessment results?
  - What needs to be done to increase confidence – do we need a standard?

bp

EPRI

dti
Department of Trade and Industry

Questions for Breakout Group 4
Engaging Stakeholders

- ## Questions (2)
  - – How can the results of Risk Assessment studies be best passed on to the policy makers?
  - – What results do policy makers wish to see?

Breakout Group 4

- Who are the Stakeholders?
  - Proponents
  - "Facilitators"/Assessors
  - Critical Reviewers
  - "General Public" – heterogeneous!

Breakout Group 4

- Different Strategies required
  - Role of 'Risk Analysis' vis-à-vis
  - Each group varies
  - EXEMPLARS
    - Participative Planning e.g. Hazardous waste storage USA

- Other Dialogues/Initiatives
  - e.g. WBCSD, USEPA, NRDC

Breakout Group 4

SEQUENCING Wider Sustainable Energy Agenda	Stakeholders with "professional/local interest"	Lay public
Higher level strategic view of role of CCS (e.g. climate change)	Need to do now	?
Site – Specific Assessment – Detailed Risk Assessment	Need to begin Proceed incrementally	Advisory group To advise on public perceptions

TRANSPARENCY

How was advice used?

bp

EPRI

dti
Department of Trade and Industry

Breakout Group 4

- Communication to wider public would proceed slowly though required for specific sites.

- International Co-ordination?

Linking risk assessments to regulation

Geo-storage risk assessment workshop, DTI conference center, London

12 February 2004

David Keith

(keith@ucalgary.edu)

Department of Engineering and Public Policy
Carnegie Mellon University

Center for Integrated Study of the Human
Dimensions of Global Change

CIS o*f* HDGC
Carnegie Mellon

UNIVERSITY OF
CALGARY

Carnegie Mellon

1

Risks: A taxonomy

Risks of Geologic Storage

Local

Global

Surface Release
- Suffocation
- Ecosystem impacts (tree roots, ground animals)

CO_2 in Subsurface
- Metals mobilization
- Other contaminant mobilization
- Effects on potable water

Quantity-based
- Ground heave
- Induced seismicity
- Displacement of groundwater resources
- Damage to hydrocarbon production
- Damage to other mineral resources (mining)

Surface Release
- CO_2 back to atmosphere

2

Storage system performance is contingent on design

Abstract statements about storage effectiveness are virtually meaningless without reference specific design characteristics because effectiveness is so strongly contingent on system design.

It **is** possible, in principle,

(1) to analyze the effectiveness of a specific storage project; and

(2) to analyze the expected effectiveness of an ensemble of storage projects adhering to specific design guidelines that specify site selection criteria and parameters such as capacity, seal integrity, injection depth and well closure technologies.

It is **not** possible, however, to produce a robust scientific judgment about storage effectiveness absent assumptions about storage system design and operation.

3

What would a full PRA look like?

Injection Scenarios

Data	Probabilistic model of subsurface	Model	Results
Cores, seismic, logs, in situ permeability, etc. Measurements uncertainties quantified.	*Gridded probabilistic values of porosity, permeability, etc; probabilistic estimates of relevant well properties.*	*Transport, geomechanics, geochemistry, etc; Model domain from injection site through overburden, vadose zone, and finally to near-surface atmosphere.*	*CO_2 transport and gas saturation expressed probabilistically.*

Local impacts
Impacts in local environment, health, groundwater, expressed probabilistically.

4

Some caution about probabilistic risk analysis

'Even tree' PRA

Fault tree PRA made famous by with Rasmussen (WASH 1400) Report on nuclear reactor safety published in 1975.

- Core melt frequency: 10^4 to 10^5 yr.
- TMI partial core melt/thermal-failure in 1979.

The Cassini Environmental Impact Study (EIS) published in 1993.

- Buried in the event tree I found the following assumption: The chance of earth impact due to an erroneous ground-based navigation command is estimated as 6.94×10^{-10}.
- The root cause of the Mars Climate Orbiter loss was a unit-conversion error in ground-based navigation software. The record of planetary encounters performed by JPL now stands at one serious navigation failure out of ~30 encounters.

Its hard to estimate the uncertainty in the uncertainty

Even in the core physical sciences, experts generally underestimate uncertainty.

Henrion & Fischoff, 1986. Updated in Kammen & Hassenzahl, 'Shall we risk it?', 1999. Fig 4-1.
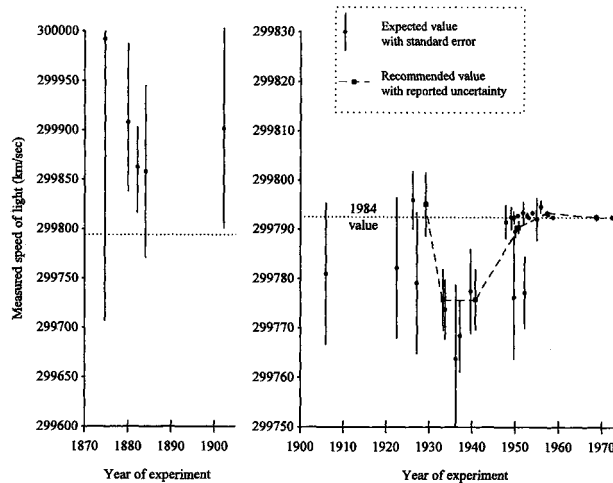
7

What goes wrong?

- Drive to assign probabilities in the absence of real data encourages guestimates based on simple heuristics that 'amplify' limited initial data.
  - 'Anchoring' and 'adjustment'

- Convergence on design specification (e.g., Cassini)

- Risks that cannot be quantified tend to be dropped. (Looking for the keys under the lamp).

8

What else is there?

No magic answer. In some circumstances PRA like Churchill's quip about democracy: Worst system in the world except for all the others.

Supplementary/alternative methods
- Expert elicitation
- Delphi
- 'Red team' assessments
- Bounding analysis

Aim at an easier target

We do not need to do a risk assessment for the gigaton scale today. This is a step-by-step process. Current risk assessment may enable a suite of power-plant scale 10 Mt/yr projects that will start over the next decade or two. The results of these will provide our children with data that will allow them to make choices about the gigaton scale.

9

Towards a regulatory structure

10

Structure of Regulations

Performance-Based Example for CO_2 :
1. The leakage rate shall not exceed 0.1% per year for 1000 years.
2. Risk to maximally exposed group shall not exceed 10^{-6} per year.

Examples: Structural & fire codes for large buildings, nuclear waste…

Prescriptive/Command & control/Design

An cap-rock must have thickness greater than 5m over a radius of X as determined by…

The injection pressure shall not exceed 85% of the reservoir fracture pressure as determined by the following test procedure…

The injection well shall completed as follows…

Examples: Operation of disposal and injection wells, structural & fire codes for small buildings…

11

Structure of Regulations (2)

Performance *vs* prescriptive: Differ in where they lay the responsibility for inferring performance from design:

– In a performance-based process the responsibility falls to the private operator, whereas,

– in a prescriptive system the responsibility of the operator is generally limited to following the rules, the regulator must ensure that rules ➜ performance goals.

Trade-offs: A performance system has the advantage of flexibility at the project level, but closure may be hard.

A prescriptive system could simplify permitting at the project level while—in principle—still allowing public debate about the effectiveness of the prescriptive rules in producing the desired performance goal.

12

Structure of Regulations (3)

A public permitting process must balance two competing kinds objectives: it should be objective, transparent, and open to public input; yet it also needs to be able to deliver 'closure' in the form of definitive answers in a reasonable period of time.

Trade-offs

A performance based system has the advantage of flexibility at the project level, but closure may be hard.

A prescriptive system could simplify permitting at the project level while—in principle—still allowing public debate about the effectiveness of the prescriptive rules in producing the desired performance goal.

Adaptability

The active phase of storage projects will often span several decades, so we can be certain that there will be significant improvements in our knowledge over a single project lifetime.

➔ A protocol should effectively incorporate knew knowledge as it emerges

Trade-offs

Adaptability to new knowledge ➔ Frequent changes to protocol
- ➔ Uncertainty for operators, regulators and NGOs➔
    - – Higher costs.
    - – Reduced ability to learn how to make protocol work by experience (*institutional* learning harder even if *technological* learning easier)
    - – Harder for regulators & NGOs to monitor compliance.

Transparency

The first large-scale CO_2 storage projects may well have enormous public visibility.

Two reasons: Concern about local risks & concerns about the wisdom of using CO_2 storage as a means to continue the use of fossil fuels while avoiding atmospheric emissions.

Both are legitimate. It's in public interest to disentangle them.

Want a process that is highly transparent, yet is able to focus debate on the safety & security of geologic storage.

If there is a public interest in getting some large early projects—building knowledge that will put our kids in the position to make good decisions—then we want to ensure that some projects go forward—assuming acceptable local safety—while discussion about the overall merits of CO_2 capture and sequestration continue elsewhere.

15

Lifetime: How long must we keep CO_2 underground?

Among the most important assumptions or parameters that drive the answer are the following:

1. The acceptable concentration of CO_2 in the atmosphere.
2. The amount of CO_2 that will ultimately be placed underground.
3. The existence of technologies that can remove CO_2 either by enhancing natural carbon sinks or by engineering new kinds of sinks.
4. The weight given to small increases in CO_2 concentrations on millennial timescales.

Personal opinion: 100 to 10,000 years are reasonable bounds. But, economists aside, I don't think anyone will accept less than about 1000.

Some relevant papers:
- Hepple & Benson, 2003
- Ha-Duong & Keith, 2003
- Herzog, Caldeira & Reilly, 2003
- Pacala, 2003

16

Summary

Avoid settling on standard simply because early work on risk assessment makes it seem attainable.

– Remember Yucca mountain.

Be wary of building a process that makes stakeholders expect a full PRA if it is not possible to deliver one.

Consider alternate framings for risk timescale. Do we have to evaluate on a 10,000 year times scale. Temporary storage & risk transfer.

New problems may demand new tools.

17

Selected Publications on CO_2 Capture and Storage

See www.andrew.cmu.edu/user/dk3p

Ha-Duong, M. and D. W. Keith (2003). "Carbon storage: the economic efficiency of storing CO2 in leaky reservoirs." *Clean Technology and Environmental Policy* **5**: 181-189.

Wilson, E. J., T. L. Johnson, and D.W. Keith. (2003) "Regulating the Ultimate Sink: Managing the risks of geologic CO_2 sequestration." *Environmental Science and Technology*, **37**: 3476-3483.

Keith, D.W. (2002). *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada*. Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario. ISBN: 0-662-31755-6.

Keith, D. W. and J. S. Rhodes (2002). "Bury, burn or both: A two-for-one deal on biomass carbon and energy." *Climatic Change* **54**: 375-377.

Keith, D. and M. Wilson (2002). *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada*. Regina, SK, University of Regina: 39.

Keith, D. W. (2001). Industrial Carbon Management: An Overview. *Carbon Management: Implications for R&D in the Chemical Sciences and Technology*. A. T. Bell and T. J. Marks. Washington, DC, National Academies Press: 127-146.

Keith, D. W. and E. A. Parson (2000). "A Breakthrough in Climate Change Policy?" *Scientific American* Febuary: 78-79.

Parson, E.A. and D.W. Keith (1998). Fossil fuels without CO_2 emissions. *Science* **282**: 1053-1054.

Keith, D. W. and H. Dowlatabadi (1992). "A Serious Look at Geoengineering." *Eos, Transactions American Geophysical Union* **73**: 289-293.

19

Tyndall°Centre
for Climate Change Research

Public and Stakeholder Participation in Carbon Capture and Storage Initiatives

Simon Shackley

Carly McLachlan

Clair Gough

Why is participation important?

Social mandate increasingly required

Corporate Social Responsibility / SD

Environmental groups & movement

Deliberative democracy

Government commitment to transparency and participation

Tyndall°Centre
for Climate Change Research

What is meant by 'participation'?

Four dimensions:

- *Communications*: Awareness raising / information provision

- *Understanding perceptions*: identifying the range of views held regarding a technology or option (initial perception and after information)

- *Including perceptions in decision-making*: using information on perceptions to inform decisions

- *Formal involvement in decision-making*: public sample have 'voting rights' or make the decision

Tyndall°Centre
for Climate Change Research

Methodology of the Tyndall / DTI Study

- 'Citizen Panels': 5 x 2 hour meetings held in 2002 & 2003

- Distinct socio-economic and demographic characteristics:

- One group all male, mainly professionals, held in York

- One female, mainly retail, admin. & secretarial, held in Manchester

Tyndall°Centre
for Climate Change Research

Survey Design

- Based on outputs from focus groups
- Administered over 2 days at an airport
- Over 200 responses
- Wide range of respondents though not statistically representative

Tyndall°Centre
for Climate Change Research

Main Findings of Citizen Panels

- General acceptance of CCS as a legitimate option to consider but not enthusiastic support by the majority

- Furthermore, acceptance of CCS was dependent upon awareness of four things:

- a) climate change being a problem,

- b) severity of the problem,

- c) extent of the CO_2 reductions required (I.e. minus 60%);

- d) CCS as part and parcel of a wider sustainable energy strategy
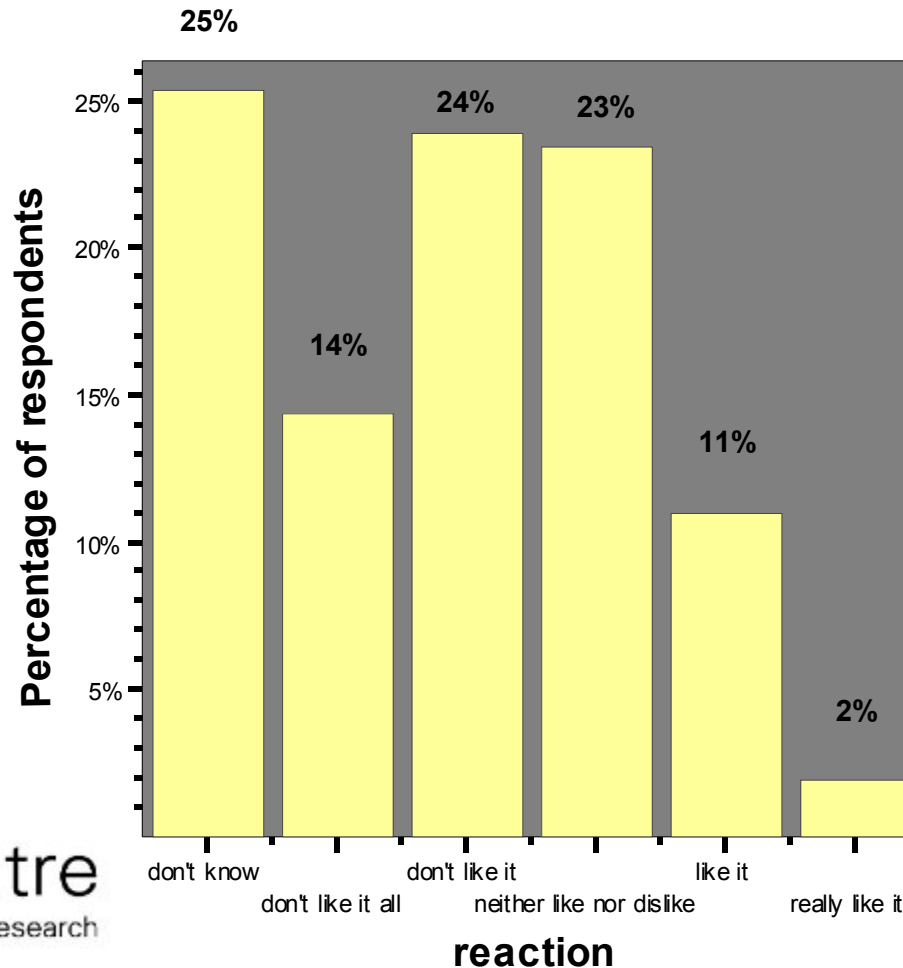
CCS as part of a 'sustainable energy strategy'

- There was very limited support for CCS as a 'stand alone' option (I.e. not part of a wider sustainable energy strategy) for the usual reasons cited (e.g. would deter investment in renewables & energy efficiency, morally suspect, too risky and uncertain to rely on).

- CCS also has to develop with a focus on 'benefits' to the economy, employment and wealth creation to the locality, region and UK. In this sense, EOR is viewed rather favourably - putting CO_2 to 'good use'.

Concern over risks ….

- Potential risks were of concern to panel members: e.g. leakage. In particular, the difficulty at present of answering risk assessment questions in detail led to concern in the group.

- Evidence of perhaps unrealistic expectations vis-à-vis levels of certainty which can be provided on the risks and their assessment.

- Desire for a "encyclopedia of facts" to bring about a common baseline of information which could be trusted and agreed upon by all.
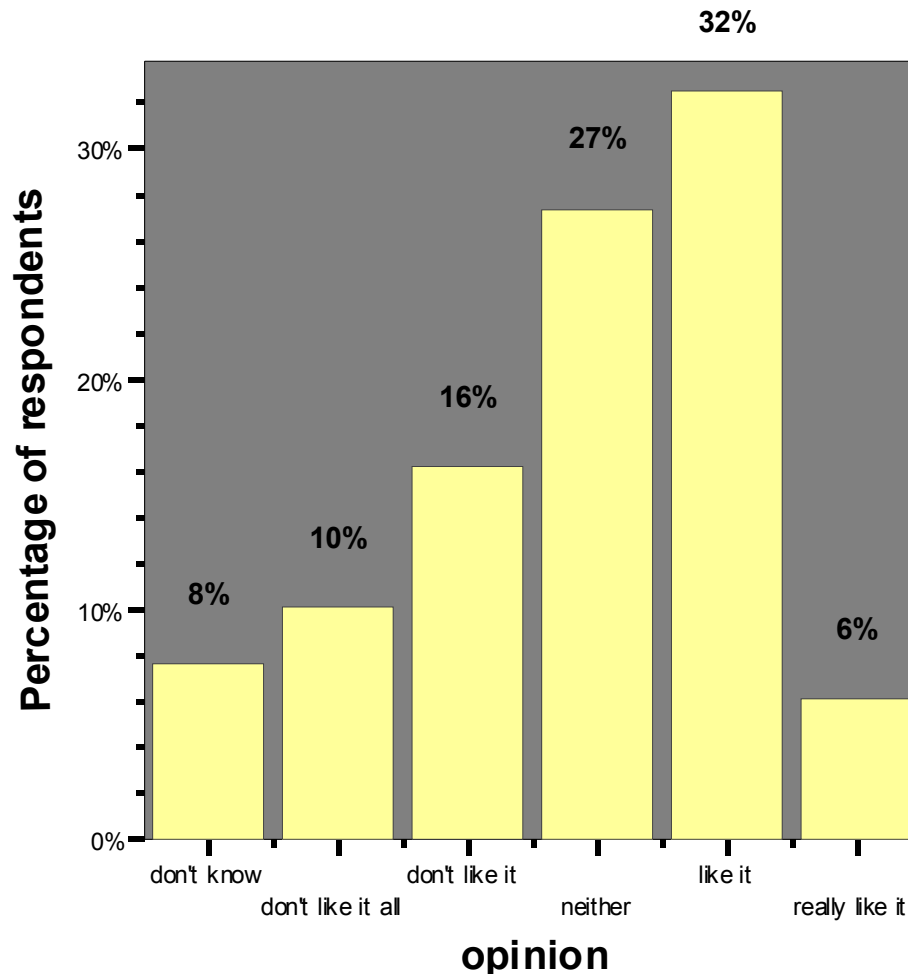
Main Findings of Survey

Negative attributes of CCS
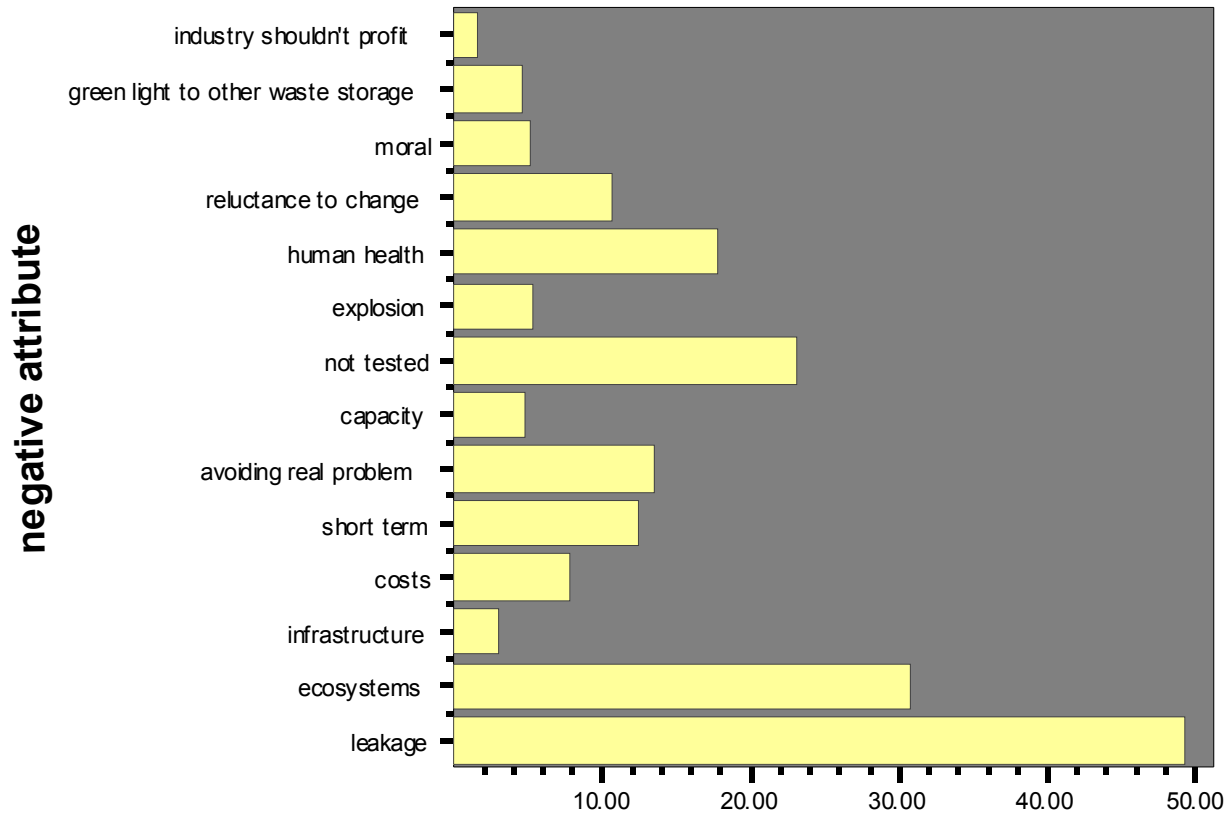
Support for Energy Efficiency

Percentage of respondents (y-axis): 0% to 100%
level of support (x-axis): don't know, strongly against, neutral, slightly support, strongly support
Values: 2%, 1%, 5%, 12%, 81%

Support for Nuclear Power

Percentage of respondents (y-axis): 0% to 100%
level of support (x-axis): don't know, strongly against, slightly against, neutral, slightly support, strongly support
Values: 7%, 39%, 17%, 14%, 16%, 9%

Support for higher energy bills

Percentage of respondents (y-axis): 0% to 100%
level of support (x-axis): don't know, strongly against, slightly against, neutral, slightly support, strongly support
Values: 1%, 55%, 14%, 7%, 17%, 7%

Tyndall°Centre
for Climate Change Research

Further understanding and research required….

Requires further work on understanding perceptions and how these may be affected by uncertainty and special interest groups

Survey work: needs repeating on a larger scale.

Public opinion on the institutional and policy processes which may be desirable as a way of including public perceptions and greater participation is worth gathering and considering.

e.g. suggestion of a joint meeting between citizen's panel, civil servants, ministers, industry, ENGOs ..

Implications for Specific CCS Proposals ….

Transparency in the process and in the information provided to the public / stakeholders will be critical

Communication and understanding perceptions is an important first step using techniques described

Citizens panels stressed the lack of awareness of climate change, its impacts and the need for CO_2 reductions: people need to know 'why' CCS is being proposed.
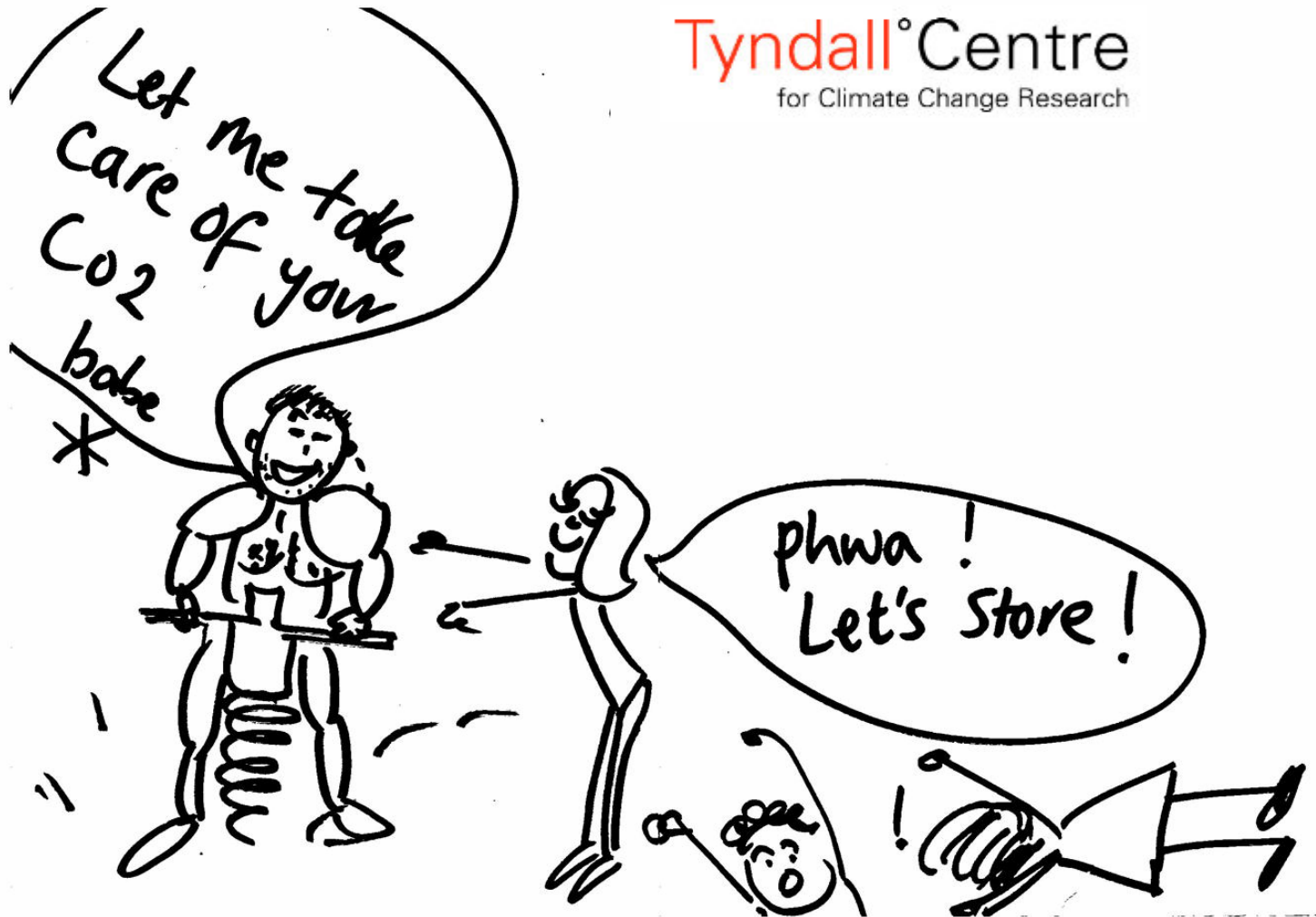
Communication efforts need to be re-focused.

The public • Keep up with the Jones's

Electric Bill Saving

Tyndall°Centre
for Climate Change Research
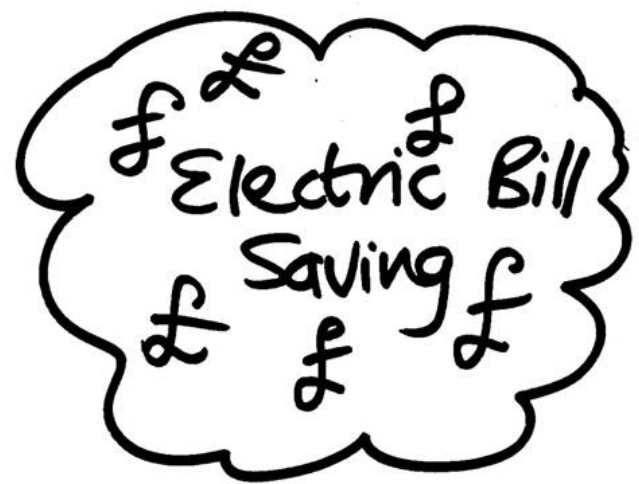
Participative Planning ….

Actual participation from stakeholders and/or public in decision-making from an early stage may help to secure wider consensus

This will assist in building-up and maintaining trust between developers and public / stakeholders which will help when project is underway and / or things happen unexpectedly

Developers have to think about what benefits arise for local populations potentially affected.

Can government and regional development agencies be persuaded to include CCS as a component of a sustainable energy strategy and agenda?

Uncertainty and Precaution ….

Scientific uncertainty in this area is high - it will not simply 'go away'. Uncertainty and differences in expert judgement should be acknowledged and accepted in an open fashion.

We should be clear about where 'the benefit of doubt' is being given.

Multi-criteria decision methods might help in allowing the public / stakeholders to identify the trade-off of different criteria which they are prepared to accept.

Some problematic intangibles: how will environmental groups respond?

More radical suggestions….

Provide resources for public representatives to review, hence participative meaningfully, in the planning and review process.

Set up a Citizen's Jury to review different CCS proposals and to decide which one is preferred.

But ….. We shouldn't raise expectations too much if there is no institutional or policy process to back it up and implement the outcomes of deliberative processes.

Tyndall°Centre
for Climate Change Research

Further information

- Tyndall Centre Report available at:

www.tyndall.ac.uk/publications/working_papers/

and on the DTI website

Other survey work on CCS see the MIT website (www.mit.edu)

On participative methods and case-studies:

www.the-environment-council.org.uk