Launch Meeting of the Risk Assessment Network

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ACKNOWLEDGEMENTS AND CITATIONS

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

The international research network on Risk Assessment is organised by IEA Greenhouse Gas R&D. The organisers acknowledge the financial support provided by EPRI for this meeting and the hospitality provided by the hosts TNO.

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

John Gale, IEA Greenhouse Gas R&D Programme (Chair)
Sevket Durucan, Imperial College London
Hans Aksel Haugen, Statoil
Wolf Heidug, Shell
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The report should be cited in literature as follows:

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LAUNCH MEETING
of the
RISK ASSESSMENT NETWORK

Date: 23 – 24 August 2005

Offices of TNO-NITG
Utrecht, Netherlands

Organised by IEA Greenhouse Gas R&D Programme and TNO-NITG
with the support of EPRI

Executive Summary

This report summarises the major outcomes of the launch meeting of the Risk Assessment Network which was jointly organised by IEA GHG and TNO with the support of EPRI. It was held at the TNO offices in Utrecht, Netherlands, 23-24 August 2005. This international meeting was attended by 40 delegates from industry and research institutes drawn from nine countries.

Prior to this meeting a proposal for a new international research network had been developed by IEA GHG and circulated to interested parties. The proposal aimed to explain the planned operation, tasks and structure of the network and the key tasks such a network could perform in developing an understanding of risk assessment activities underway worldwide and the results these assessments generate and how it could identify the gaps in understanding. The proposal formed the basis of the launch meeting.

The outcome of the launch meeting was the agreement of the creation of an International Risk Assessment Network under the terms stated in the draft proposal. It was also agreed that the research network should also aim to address what the regulators are expecting and whether risk assessment can provide the answers they require. The scope of the Risk Assessment Network can be divided into a number of smaller and more specific subject areas, Data Management and Risk Analysis, Regulatory Engagement and Environmental Impacts. To continue to promote the progress of the network, it was decided that subgroups should be created that focused on these more specific areas and could run alongside the operation of the network. The subgroups (referred to as working groups) would direct their own work, reporting back to the network at the annual meeting. The subgroups are diverse in topic but allow participants in the network with special interest to focus on specific areas. The working group sessions were an opportunity for participants to discuss the way forward.

The establishment of the working groups also helps to highlight interest groups such as Regulatory bodies, NGO's and scientific specialists that are missing from current Risk Assessment discussions and those who should be encouraged or approached to join in the future.

- The next meeting of the Risk Assessment Network should be in September/October 2006 and held in North America.

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1. Introduction

This report summarises the major outcomes of the launch meeting of the Risk Assessment Network, which was jointly organised by IEA GHG and TNO with the support of EPRI. It was held at the TNO offices in Utrecht, Netherlands, 23-24 August 2005. This international meeting was attended by 40 delegates from both industry and research institutes[1].

1.1 Workshop aims and objectives:

The launch meeting of the Risk Assessment Network followed two previous meetings on Risk Assessment held in London, UK[2], February 2004 and Vancouver, Canada, September 2005. The London meeting aimed to assess the status of risk assessment tool and technique development ,and what further development work was required. The Vancouver meeting brought together the key groups working on risk assessment for CO_2 storage from around the world to consider the need for an international network on this topic.

The key message from the initial meetings was that to gain public acceptance of CO_2 capture and storage, two key areas will need to be demonstrated: that the technology is safe and that its environmental impact is limited. Safety can be demonstrated to some extent through monitoring programmes at CO_2 injection operations that are currently underway. However, whilst early results from these injection operations indicate leakage is not occurring, such programmes do not necessarily engender confidence in the long term i.e. 1000's years after injection has ceased. Risk assessment (RA) studies can assist the development of monitoring programmes for injection sites, relying on predictions of the long term fate of the injected CO_2 and assessing the potential for leakage in both the short and long term. To gain public acceptance of CO_2 capture and storage (CCS) the regulators and public will also need to have confidence in the predictions made by the risk assessment studies. To gain such confidence it will be necessary to understand the different approaches being used and the assumptions underlying the results. The results should be produced in an open and transparent manner, so that the results are understood and the implications for ecosystems and human health can be fully appreciated.

[1] A full list of delegates is available at the back of this report in Appendix 1.
[2] IEA GHG Report PH4/31

Following the second risk assessment meeting held last year after GHGT-7 in Vancouver (September 2004), an outline proposal was developed to incorporate the needs and desires expressed by those who attended the meeting. The draft proposal was circulated to all who attended the meeting at the beginning of 2005 with a request for comments by end of March 2005. The final version of the proposal was circulated at the meeting. The proposal aimed to explain the operation, tasks and structure of the network and how it will operate the benchmarking process and identify the gaps in understanding. The proposal formed the basis of the launch meeting.

The aim of the meeting was to launch the Risk Assessment Network, review the recent developments in risk assessment and to establish the working groups on key topic areas. The meeting provided the first opportunity for the working groups to meet and to set their structure, agenda and technical scope.

The objective of the meeting was to formalise the operations of the Risk Assessment Network and develop the plan for future activities.

1.2 Workshop Outcomes:

1) Establishment of the risk assessment network

2) Establishment of key technical working groups and future network plans

3) Determine timeline for network

1.3 Workshop Programme

The 2 day workshop programme enabled the developments since the first Risk Assessment Meeting in November 2004 to be presented and allowed breakout groups time to discuss the development of the Risk Assessment Network. This was followed by open discussions and meeting close. The full agenda is shown in Table 1.

1.4 Network Aims and Objective

Objective:

- Develop an open and transparent process to allow different RA approaches and their results to be understood

Aims:

- Provide a forum to allow different RA approaches to be compared

- Determine what the results are telling us and how they differ
- Provide an umbrella group for international collaboration on RA
- Identify gaps in knowledge and make recommendations on how to close these gaps
- Act as an informed body on RA for dialogue with regulators and NGOs.

Timescale:

- 5 years starting in August 2005

Table 1. Agenda of the Launch Meeting of the Risk Assessment Network: 23-24 August 2005.

Day 1 – Tuesday 23 August 2005		
08.30 – 09.00	Registration	
09.00 - 09.15	Opening with introductions	
09.15 - 09.30	Plan for the two days	
Session 1. Developments since last meeting		
09.30 - 10.00	Well bore integrity workshop findings	BP
10.00 - 10.30	Break	
10.30 - 11.00	Modelling workshop report	US EPA
11.00 - 11.30	RA studies in the CO2STORE project	Statoil
11.30 - 12.00	Weyburn II – plans for new RA activities	PTRC
12.00 - 12.30	Remediating leakage	ARI
12.30 - 13.30	Lunch	
Session 2. Network Development		
13.30 - 14.00	Outline proposal for network and introduction to working groups	
14.00 - 17.00	5/6 - Breakout groups under a nominated chair to address issues: • What group will consider (technical scope) • Agree composition • How it will be structured • Future plans • Appointment of working group leader (s) Break included	

Day 2 – Wednesday 24 August 2005	
09.00 - 09.15	Recap of day 1
Session 2. Network Development Cont.	
09.15 - 10.30	Presentations by breakout groups on their proposals for each task area
10.30 - 11.00	Break
11.00 - 12.30	Continued...
12.30 - 13.30	Lunch
13.30 - 14.00	Review of proposed plans and network structure
14.00 to 15.00	Open discussion on network plans
15.00 -15.30	Break
15.30 - 16.30	Discussion on way forward
16.30 - 17.00	Wrap up and meeting close

2. Developments since the Risk Assessment Meeting in London, February 2004.

2.1 Well Bore Integrity Workshop Findings – BP

A report was presented on a workshop jointly organised by IEA GHG and BP on well bore integrity held in Houston, USA in April 2005[3]. The objective was to provide continuity between the risk assessment and other networks that are currently operating on related topics.

The aim of the Well Bore Integrity Workshop was to:

- Assess the current state of knowledge on well bore integrity,
- To determine future research needs,
- To identify how significant, if at all, the effect of CO_2 is on well bore cements,
- And to identify if there is significant risk of CO_2 leakage from well bores in the future.

A question that the workshop asked was what is the current state of knowledge?

It is acknowledged that CO_2 reacts rapidly with Portland cement. However, results from wells in the USA, where production of CO_2 from naturally reservoirs and its use in CO_2-EOR[4] has been in operation for 30 years, show that despite this period of contact with CO_2 there are signs of corrosion but the well construction materials have not dissolved rapidly. This is a result of the carbonic acid becoming neutralised by the cement and unless there is an influx of fresh acid, corrosion does not continue. The key factor then becomes contacting of the cement with fresh fluid that can lead to further degradation.

However, the industry only has 30 years of experience of well cements interaction with CO_2 and has not had to design a leak free well over long timescales. What would happen in 500 years is unknown and therefore it is not possible to promise a leak free well, although state of the art technology can be used to reduce risk. Portland cement does react with CO_2 and as a result there can be a loss in density and strength with an increase in porosity. Whilst laboratory experiments have simulated what reactions occur in the well, the degree of the reactions is not comparable to in-situ reactions.

[3] IEA GHG Report 2005/12
[4] CO_2 Enhanced Oil Recovery

The other option is to build new wells that do not contain the risk, i.e. do not use Portland cement. However, it is the existing and abandoned wells that remain the problem.

The discussions continued to designing an experiment to test reactions. These tests should answer some of the questions such as; how has it been attacked? What is the composition? And how often does it occur?

The BP production well at Sheep Mountain in Colorado, USA could provide some frequency information. It has been in contact with CO_2 for 30 years. However, it is always possible that the consequences of contact with CO_2 could vary in different locations.

Future research needs involve identifying:

- The frequency of well failure,
- The mechanisms of well failure,
- And the consequences of well failure.

The next meeting of this network is planned for spring 2006. The aims and objectives for this meeting are:

- To define well failure,
- Begin standardising testing procedures,
- Obtaining industrial and regulatory evidence for failure frequencies, although this information is likely to be sensitive,
- Design a R&D programme to gather information from existing CO_2 EOR operations,
- Design monitoring procedures.

In the following discussion, it was noted that laboratory experiments provide a far more corrosive environment due to the nature of the experiment. Also it was felt that there would be a negative reaction, by operators, to a regulation requiring the use of new CO_2 resistant cements that are more. If it was necessary to go back and replug old wells with CO_2 resistant cements then the cost could be prohibitive.

2.2 Modelling Workshop Report – US EPA

The results of a USEPA organised workshop held in April 2004 were presented. The US EPA described why, as an organisation, it is involved in Risk Assessment for CO_2 storage. Risk Management helps them to better understand the processes and potential impacts in order to safely permit and to determine effective and efficient risk management techniques for CO_2 storage. The US EPA has established a working group with representatives from several offices (including Waste, Air, Solid Waste, International Affairs and General Council) with a key goal to integrate the goals of their Climate Change and the Underground Injection Control (UIC) programmes. The UIC was created in 1980 as part of the Safe Drinking Water Act, to protect underground sources of drinking water from contamination by regulating the construction and operation of injection wells. Enhanced oil recovery (EOR) is covered by the UIC programme.

The US EPA currently uses models to ensure that permitting requirements are met, and to help bound the limits of the waste plume in terms of maximum pressure and horizontal and vertical extent of movement. The US EPA uses 4 classes of wells; I, II, III and V. Class I wells cover the most hazardous waste products and require that no migration from the "injection zone" can be demonstrated through modelling. The parameters set for the hazardous waste are strict and require confidence over significant timescales (10, 000 years). The US EPA has not yet classified CO_2 storage wells (other than EOR which are classified as Class II wells) and there has been no decision on timeframe or amount of acceptable movement. It is not easy to directly compare hazardous waste disposal with CO_2 storage; firstly CO_2 is not classed as a hazardous material, secondly, its nature and behaviour post-injection are more complicated or less well understood. This makes setting the parameters for the models more complicated for CO_2 storage. At the moment it is only best estimates for specific parameters are used, but better experimental data is required to constrain parameter values.

The US EPA arranged a workshop to look at the issue of modelling CO_2 injection. The objectives of the workshop were to see how the current models can be applied to CO_2 storage, to obtain state-of-the-art information on modelling CO_2 storage, and to begin the dialogue between researchers, industry and US EPA (regulators).

The outcome of the workshop was that the US EPA would like to be in a position to select the correct model(s) for CO_2 storage. Hopefully identifying the key parameters for CO_2 storage through thoughtful selection and then being able to complete uncertainty and sensitivity analyses will ensure they are modelled in the right way. The results of the model should then be compared to field observations.

It will also be important that there is successful communication with the public, ensuring that the risk related to CO_2 storage is shared in a way that will be understood. Modelling of CO_2 injection can provide confidence and assure the public that CO_2 is not a hazardous waste. For example, surface dispersion can reduce the risk of asphyxiation in certain circumstances. However, it is important that the risk from storage is put into context with doing nothing and the impacts that could result from climate change.

Although CO_2 storage will be covered under the UIC programme it has not been decided whether it will be included as an existing well class or as a new class. The UIC programme and other related experience will help in further developing and refining the Risk Assessment for CO_2 storage.

2.3 Risk Assessment studies in the CO2STORE project – Statoil

CO2STORE is a follow up and extension of the SACS project. The project is due to end in February 2006. One part of the project is assessing the feasibility of four new prospective storage formations. All four formations are deep saline aquifers. The case studies under investigation are: offshore Norway, offshore UK, on shore Germany and on/offshore Denmark. All four case studies are undertaking risk assessment studies [5] as part of the CO2STORE project. The risk assessment component of the project is still on-going and so the results presented were preliminary.

In the Norwegian case study, three prospective basins were identified but only one was considered as a realistic prospect for CO_2 storage. The preferred field was the Trøndelag platform off central Norway. The storage potential was estimated as 1000 Mt with the CO_2 being trapped in structural traps. Seismic data indicated no potential pathways for seepage. Simulation runs, where 100 Mt was injected did not result in leakage over 5000 years. The assessment of the basin was based upon seismic

[5] Each project is using a Feature, Events and Processes database to develop scenarios for possible leakage from the storage reservoirs being assessed.

surveying as no drilling has taken place. It was concluded that there was insufficient data currently available for a detailed risk assessment study.

The German case study was the most advanced in terms of its risk assessment work but the study was not fully complete. An evaluation of 26 prospective onshore formations had been undertaken and one site, Schweinrich selected as the most suitable. The site has a lot of geological data and geophysical survey already available from previous hydrocarbon/geothermal explorations and earlier assessments looking for nuclear waste repositories. A scenario-based risk assessment approach, using TNO's FEP database, has been undertaken, followed by reservoir modelling. Currently, there are no accepted criteria for safety/threshold levels for Risk Assessment, so the levels used were those above which no adverse effects have been detected. Simulation studies are on going.

In the UK case study, the Quintessa FEP database was used to assess the risks associated with CO_2 storage. There is a fault at the crest of the chosen storage structure but the permeability of the fault and the associated damage zone are uncertain. The uncertainties of the storage site are difficult to resolve without drilling, which would be expensive and would also introduce additional risks. The existing wells in the area have been plugged and abandoned to a high standard and there is no reason to consider that they might leak. It may be possible to plug them again if this was not the case. The reservoir cap rock consists of mudstones and lignite, the samples from the wells could not be used to test the permeability but it expected that it is adequate for storage. There is also no reason to expect that the cap rock integrity would be modified by any geochemical reactions. The basin has greater risks than a petroleum area because of the poor knowledge from very few wells. The simulations of the CO_2 once it has been injected into the reservoir all show that it ends up next to the fault at the crest of the structure. Proving the integrity of the storage site could be very costly.

The Danish case has not progressed to the risk assessment stage.

In the following discussion, it was noted that to effectively assess any formation there needs to be a lot of data, if that is not already available then gaining that data can take a lot of time and be expensive.

Also, both offshore and onshore sites need to take into account the future intrusion by man into a storage site. Inadvertent intrusion could result in leakage of the stored

CO_2 though current best practice often uses seismic data to identify shallow gas and other hazards ahead of drilling.

2.4 Geological Storage of Carbon Dioxide: Risk Assessment Activities and Plans at Weyburn - PTRC

Results from the Weyburn project showed that uncertainty increases with time and there are still gaps in the knowledge which require more work on existing data and the availability of new data. Phase 1 of the Weyburn project gathered baseline and injection data and ran two types of risk assessment studies (deterministic and a probabilistic approach). Risk assessment will continue to be a significant part of the Weyburn project and will be a major component of the final phase that will start in 2006. Goals for this project include the development of; new and better simulation models, transparent risk assessment tools, and effective screening and monitoring programmes.

Other projects that are planned include:

- Storage of 1300 ton/day of carbon dioxide from a refinery in Regina into a local saline aquifer
- Prospect of an integrated capture and storage project near Boundary Dam, Saskatchewan
- A collaborative project between PTRC, Sask Power, University of Regina, Federal and provincial government

In the following discussion it was noted that although it can be agreed that uncertainty increases over time for geological storage, the situation for the well bores could get worse. However, other aspects of storage, such as geochemical reactions could be a beneficial process. Risk assessments need to evaluate these beneficial and detrimental processes over the long term.

2.5 EnergyINet[6]

EnergyINet is developing an Integrated Geostorage Simulator (IGS) using a commercial multi-component reservoir simulator driven by geostatistical models. The reservoir simulator drives models that simulate the performance of advanced geophysical monitoring technologies. The integrated simulator will enable probabilistic predictions of CO_2 flow within reservoirs, co-optimized storage and EOR, and monitoring reservoir performance using geophysical methods.

As the plume ages and more of the CO_2 dissolves, the risk of leakage decreases as the amount of free phase CO_2 decreases, since the buoyancy decreases as the density of CO_2-saturated saline porewaters increase. Initial results show that it is possible to accelerate the dissolution of CO_2 in brines by pumping undersaturated brine to the top of the CO_2 plume. The rate of dissolution can be increased by more than a factor of ten at a cost that is less than 1% of the cost of capture and compression.

EnergyINet is also involved in the comparison of models used for risk assessment and is involved in a variety of activities within Canada. It is working towards integrating different models already used within industry to produce one that can look at risk assessment of the geological storage of CO_2. To date the models used in risk assessment are designed for other purposes and are chosen because they best fit the type of situation found for CO_2 injection and storage but they are not ideal.

2.6 Remediation of Leakage from CO_2 Storage Reservoirs - ARI

ARI presented their work on a study commissioned by IEA GHG[7]. The aim was to develop a reference manual on prevention, monitoring, & remediation of leakage at various types of CO_2 storage reservoirs. The study would have a diverse target audience of technologists and policy specialists.

The report reviewed 5 steps in assessing the risk of a site for the storage of CO_2:

1) Geological Leakage Pathways

2) Manmade Leakage Pathways

3) Screening Sites to Avoid Leakage

[6] Followed on the end of the PTRC presentation.
[7] IEA/CON/04/108 Remediation of Leakage from CO_2 Storage Reservoirs

4) Monitoring Technologies

5) Remediation Technologies

The study reconfirmed the 4 types of trapping within a storage site:

- Physical trapping by cap rock
- Solubility trapping in fluid phase
- Residual gas trapping in pore spaces
- Mineral trapping

Of the 4 methods of trapping identified, physical trapping is the most susceptible to leakage and was the focus of the study. However, it is acknowledged that overtime CO_2 becomes increasingly trapped by the other methods, reducing the amount in free phase.

The study identified the possible leakage pathways from a physical trap within a storage site, both geological and manmade, and looked at how these might be avoided or the possibilities for remediation. The risks from geological pathways can be avoided by completing a thorough geologic survey at the project outset. From manmade pathways the most hazardous and also most likely source of CO_2 leakage is from well bores. It should be emphasised that where transient releases from well bores have occurred, and these events are rare, remediation was quick.

Geological pathways include faults, the study of which is an active area of research in hydrocarbon exploration. However, fault-sealing mechanisms in relation to CO_2 are still relatively unknown. The study also identified case studies where old faults had been reactivated or new ones created following the fluid production or withdrawal. Once faulting has been induced, it may not be stopped by water injection or pressure maintenance programmes. Therefore the study concludes that reservoirs should be avoided where stress and pore pressure data indicate active faulting under original or depleted conditions.

An example of manmade leakage pathways reviewed in the study was Sheep Mountain in the USA. The natural CO_2 field (110 million t or 2 Tcf OGIP) is located in SE Colorado at 1km depth and supplies 3,000 t/day of CO_2 (54 MMcfd) (down from 15,000 t/day in 1987), which is used as an injectant for the Permian basin EOR operations. The CO_2 field is shallow, but has a complex topography and structure. A blowout occurred early in field life when pressure was still high and the structure poorly understood. The blowout lasted 18 days and the quantity released was comparable in size (but not duration) to the CO_2 release event at Lake Nyos. The well was eventually controlled using dynamic kill technology[8].

The study looked at the implications that this might have on CO_2 storage in the future. Fortunately there were no adverse environmental or health impacts, it is a sparsely populated area. However, the incident demonstrated that the well control techniques developed by industry can be applied successfully to CO_2 production and therefore, by analogy, to CO_2 injection. The location of the leak was identified, the cause of the leak was determined and a method to stop the leak was found. It is possible that there will be a lot of information available on the field chosen if it is a depleted oil/gas field but those that are identified as structurally complex should be avoided.

Another case assessed in the study was a natural gas storage site in Kansas, USA. The natural gas leaked from a salt cavern storage site and migrated updip until it reached a high permeability fractured dolomite and reached the surface through an abandoned brine well.

The study showed the success in detecting the leakage and how it can be remediated.

Insights into the geological storage of CO_2 can be also gathered from Natural Analogue[9] studies, underground injection sites[10] and CO_2-EOR[11].

In screening a site for geological storage there are a number of generalised criteria that can be selected, although it is acknowledged each site will potentially have unique geological features. Some suggestions on these general criteria are:

- **Proximity:** Urban areas will require more thorough vetting than remote areas.
- **Geologic/Reservoir Data:** Existing logs, core, well testing (fluid comp, stress), seismic, etc. augmented by new data collection.

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8 To stop a blowout, mud is injected to fill the well. However, this may not be successful if the density of the injected mud is being reduced by the CO_2 flowing into the bottom of the well. It simply may not possible to inject enough "clean" dense mud to shut off the CO_2 flowing in. Dynamic kill technology employs a friction reducer added to the mud to allow the mud to be pumped into the well fast enough to overcome the buoyancy of the CO_2 entering the well, thereby "killing" the blowout.

9 Natural storage sites of CO_2, some which have contained CO_2 for significant periods of geologic time

10 Short-term injection and withdrawal

11 Provides the most experience for CO_2 injection

- **Reservoir Simulation:** Where possible history match pre-CO_2 operations or CO_2-injection data to ground truth the model. Geochemical & reactive transport models.
- **Analysis:** Multiple cap rock traps with relevant natural or industrial analogs, injection experience and large data set preferred, but not always available.

Looking at the case of natural gas storage, it is recorded that there has been 10 migration events that have occurred, from a total of 600 operations, over a 90 year timescale. The specific monitoring technologies, the suites of techniques and the remediation methods applied from natural gas storage, EOR, and hazardous waste storage provide some relevant experience for the geological storage of CO_2.

Key conclusions:

1) Well bores most likely and most serious potential leakage path.
2) Site screening method emerging from analogue studies; prevention always preferable to remediation.
3) Well bore remediation technologies exist, but cap rock remediation remains difficult.

3. Working Groups

The network should be able to address what the regulators are expecting and whether risk assessment can provide the answers. The scope of the Risk Assessment Network can be divided into a number of smaller and more specific subject areas. To continue to promote the progress of the network, it was decided that subgroups should be created that focus on these more specific areas and could run alongside the operation of the network. The subgroups (referred to as working groups) would direct their own work, reporting back to the network at the annual meeting. The subgroups are diverse in topic but allow participants in the network to focus on specific areas. The working group sessions were an opportunity for participants to discuss the way forward.

The establishment of the working groups also helps to highlight interest groups that are missing from Risk Assessment discussions and those who should be encouraged or approached to join.

The meeting split into four working groups:

- Data Management and Risk Analysis (x2)
- Regulatory Engagement
- Environmental Impacts

The list of working group participants in given in Appendix 2. A summary from each of the groups is available below.

3.1 Data Management and Risk Analysis Working Group 1

Summary breakout session: Risk assessment and data management – Group 1

Launch meeting risk assessment Network, Utrecht, 23 August 2005

Chair: Ton Wildenborg

Reporter: Philip Stauffer

Participants: Charles Christopher, Gabriel Marquette, Scott Stevens, Steven Benbow, Wei Zhou, Ziqiu Xue, Philip Stauffer, Rickard Svensson, Richard Rhudy, Yann Le Gallo, Wim C. Turkenburg, Koorosh Asghari, Hiroshi Suenaga, Ji-Quan Shi, Elizabeth Scheehle, Ton Wildenborg

The questions defined for the working group on risk assessment and data management were used as a guide for the discussion in this breakout session (see Appendix 3). The first group of questions was directed to the inventory of current and planned activities related to risk assessment and data sets (Question 1-5). The next set of questions dealt with the goals and organisation of the network (Question 6-8). The last question (Q9) on data gaps was not tackled by the RA/data Working Group 1.

Inventory of RA activities/datasets/methods

A quick-scan of activities on risk assessment and data collection showed that a considerable level of activity already exists internationally both of generic and site-specific nature (Table 2).

Table 2

Current and planned RA activities

Site	***Country***	***Type of act.***	***Institute***
Generic		RA lit. review	UU
Generic		RA method dev.	UU/TNO
Generic		Prob. Well bore model	U. of Alberta
Generic		Well/caprock integrity models	Schlumberger (COSMOS-1/-2)
Generic		RA terminology and methodology	EU consortium (CO2GEONET)
Generic		Dev. Of RA model/decision tree	IFP
Generic		T-H-M-C code for PA model	Quintessa
Generic		Dev. Of RA model/decision tree	Quintessa
Generic		Dev. Integrated RA model	USEPA
Generic		Long-term cement degradation model	Mon. Sci
Generic		Acceptance/regulation/ra approach	EU Technology Platform (Schlumberger)
Generic/SACROC/Hobbs	USA	Dev. Integrated RA model	Los Alamos
Generic/Weyburn	Canada	Dev. Integrated RA model	PTRC/Mon. Sci
In Salah aq./gas field	Algeria	Integrated RA & benchmarking	BP/CO2ReMoVe
Lindach gas field	Austria	R.A.	EU consortium (CASTOR)
Apache Middale	Canada	R.A.	PTRC
Micropilot	Canada	RA for ECBM	Imperial
Weyburn	Canada	RA	PTRC
Weyburn	Canada	RA method dev.	U. of Calgary (GEOSTORE)
Ketzin	Germany	Integrated RA & benchmarking	CO2ReMoVe
Schweinrich	Germany	Integrated RA	Vattenfall/TNO (CO2STORE+)
Nagaoka	Japan	Def. of dataset	RITE/Quintessa
Ogachi	Japan	Geochemical process model/hot dry rock	RITE/CRIEPI
K12-B gas field	Netherlands	R.A.	EU consortium (CASTOR)
Sleipner	Norway	Integrated RA & benchmarking	Statoil/CO2reMoVe
Snohvit	Norway	Integrated RA & benchmarking	Statoil/CO2reMoVe
Miller field	Scotland	RA	BP/ind. cons.
Casablanca oil field	Spain	R.A.	EU consortium (CASTOR)
US fields & aq.	USA	RA	Regional partnerships
Various	USA	Datasets natural & industrial analogues	ARI

Several well-documented datasets[12] are already available, e.g. for the Weyburn and the Sleipner sites (see also Table 3). The use of these data is in some cases restricted due to data confidentiality and for all of them the completeness is still questioned.

Table 3 Overview of sites with risk assessment datasets

Site	***Storage medium***	***Country***	***Institute***	***Remark***
In Salah		Algeria	BP	planned
Gorgon		Australia	Chevron	confidential
Weyburn	oil field	Canada	PTRC	
Apache Middale	oil field	Canada	PTRC	planned
Pennwest		Canada (Alberta)		planned
Montmiral	CO2 field	France		
Ketzin	aquifer	Germany		planned
Schweinrich		Germany		
Nagaoka	aquifer	Japan	RITE	planned
K12-B	gas field	Netherlands (offshore)		
Sleipner	aquifer	Norway (offshore)	Statoil	
Forties	oil field	UK (offshore)	BP	
SACROC	oil field	USA		confidential
McElmo dome	CO2 field	USA		
Frio	aquifer	USA		
Mountaineer		USA (West-Virginia)		

To date limited benchmarking activity has been going on or is planned (Table 4).

Table 4 Overview of current and planned benchmarking activities

Current		
Weyburn	Monitoring Sci	Eclipse-GEM
Generic problems	LBNL	Injection performance

Planned		
Weyburn- final phase	PTRC	Planned
CO2ReMoVe - Various sites	EU consortium	Planned

Because of time constraints, little attention was directed to the risk assessment techniques, which have been or will be used. Only high-level definitions of existing techniques were given:

- Modelling technique

[12] One of the actions that came out of the launch meeting was to prepare a worldwide inventory of available datasets and their characteristics.

  - Deterministic
  - Probabilistic
  - Hybrid
- Expert elicitation (ESL: introducing Bayesian uncertainty and weighting on the basis of expert opinion)
- Scenario approach (FEP analysis)

The gaps question was not discussed in this Working Group.

Network issues

It was noted in the Working Group that the process in the network needs to be defined; this is still lacking. Neutral to positive terms should be used (evaluating instead of critiquing) in dealing with the comparison/benchmarking of methods and techniques for risk assessment.

Terminology

One of the items that the Network should deal with is the development of consistent and accepted terminology in the area of risk assessment, terms like dataset, risk assessment, performance assessment and benchmarking. Risk assessment calculates the risk, which is probability multiplied by consequence and compares this result to a risk metric.

Datasets

The Network provides standards for datasets both for results and input. Data can be divided in categories, e.g. site data, material properties, chemical data etc. The Network also compiles datasets for benchmarking. Preferably, it must be possible to start with small datasets, which can grow in time. The web-enabled Network Data Management must enable linking to site-specific databases.

The Network does not function as a data clearing house; quality assurance and formatting of datasets is not an obligation of the Network.

A risk assessment dataset will consist of generic data and site-specific data. A generally valid definition of the minimum dataset which is required cannot be provided because these requirements depend on conditions differing from site to site (discussed in plenary discussion after breakout).

Benchmarking

The Network tasks are in defining the benchmarking protocol and in evaluating the benchmarking results. The risk assessment modelling itself or the development of risk assessment tools are out of the scope of the Network.

Benchmarking contributes to confidence building, but in itself will not contribute to knowing the 'right answer'. In benchmarking it is of prime importance to have a clear definition of the objective, which cannot be manipulated by the modellers:

- A way forward in benchmarking is to use different codes and evaluate to what degree the outcomes differ (SPE style), e.g. comparison of dynamic response ($\partial X/\partial t$), starting from a pre-defined scenario.
- The benchmarking exercise could try to find consistent patterns in the RA results, and to share this experience without judgement.
- Alternatively, benchmarking could be focussed on the definition of the Conceptual Model.

Dissemination

The Network publishes results after approval by the members and provides means for internal communication (e.g. web site[13]).

3.2 Data Management and Risk Analysis Working Group 2

In its discussions addressing a number of questions raised at the meeting, the Breakout Group 2 on "Risk Assessment and Data Management" first focused on the terminology used and the scope of RA work currently applied/considered in CCS. It was viewed essential that we had the ability to communicate well with groups outside the CCS research community. There was consensus that the definition and scope of

[13] www.co2captureandstorage.info

"risk assessment" as applied to CO_2 Storage needed to be clarified and a common terminology be established. The initial discussion was extended to point out the need to emphasise and consider:

- The importance of main drivers in risk assessment, such as the environment, economics and regulatory needs, as well as the technological aspects covered by the Network.
- The timescale of storage, the concentration and duration of (acceptable) leakage.
- The processes, pathways and consequences principle of risk assessment methodology commonly used in other fields.

The general view was to include Environmental, Economic, Health and Social aspects of risk assessment in the methodological approach adopted. Such holistic approach would require the engagement of expertise from these fields within the Network.

In considering the current and/or planned RA activities the breakout group mainly referred to well established and publicised projects and sites such as Weyburn, CO2STORE (Sleipner), CASTOR (limited scope for RA), the US Regional Partnerships which plan to carry out RA in 14-15 planed projects, as well as CO2ReMoVe which is expected to start in January 2006. It was also highlighted that, through some of these projects, as well as their own internal research, a number of institutions such as Quintessa, TNO, Imperial College, Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBL) and Pacific Northwest National Laboratory (PNNL) are developing RA methodologies independent of site specific applications.

FEPs and Scenario Analysis, as well as some deterministic and probabilistic approaches have been widely used in RA applications so far. Current research emphasis is extended to include risk and uncertainty quantification. There are a number of well structured data sets which may be available to a certain group of researchers. These include Weyburn, Sleipner and others that are being developed in current and new projects. Cooperation between groups within the Network, and beyond the continental boundaries, is desirable, however, data availability to the wider Network community is likely to be subject to an agreement between the Network and the owners of the data.

The question of Benchmarking attracted lengthy discussion on the definition of the term benchmarking and concern was raised about lack of sufficient and long-term field data to conduct a benchmarking study. The consensus decision was to use the term Comparison of RA Methodologies rather than benchmarking. It was essential that the main requirements for such comparison studies be established. The Group was not sure that every institution involved in CCS RA was ready to meet the requirements of a full scale RA comparison study yet. An indication of the timing of such a study was not forthcoming.

The Network members attending the breakout group discussion were supportive of both Sharing of Data Sets and Results. It was felt that sharing of results could easily be achieved between the members. However, sharing of data owned primarily by the operators and/or a research consortium needed to be based on certain rules and agreement between the parties involved. It was felt that the request to access and share data in comparative RA activities would be most convincing if parties are able to demonstrate readiness and capability to utilise this data effectively and to the benefit of both the research and industrial communities. In this respect, the timing and funding for Network activities on comparison of RA methodologies was the main concern.

The breakout group discussed the current projects which may already have included Benchmarking/Comparison of RA methodologies in their research agenda. The EU Funded Project CO2ReMoVe, subject to successful negotiation and funding in 2006, and ZERT (Zero Emission Research & Technology) in the US were identified as having such objectives in their programme. It was proposed that IEA GHG could/should lead the Network activities in providing wider access to these data sets and seek/provide additional funding for RA methodology comparison studies should this be necessary.

The group discussed Gaps in Data for RA studies next. Relative lack of detailed knowledge and data on a number of areas were pointed out as follows:

- Data on structures between the reservoir and the surface
- Fault properties
- Well and caprock integrity
- Supercritical CO_2 behaviour
- Residual trapping
- Geochemical and geomechanical processes
- Environmental, health and safety impacts

At the end of the discussions, it was recommended that the Network could/should consider and:

1. Establish the certification requirements which may form the basis to RA studies,
2. Establish the nature of data to be used in the RA comparison studies (real; part real - part assumed),
3. Establish the minimum requirements for an organised data set (availability),
4. Decide on the RA terminology to be used (such as benchmarking or comparison of methodologies),
5. Decide on the timing of such studies (are the Network partners ready to utilise and make maximum use of available data sets?),
6. Explore and identify/set up mechanisms to raise additional funding for some additional work the Network may carry out, and
7. Decide on a procedure or a mechanism to approach groups/owners to request data (US DOE, Research Consortia, and Industry).

Finally, it was felt that there may be the need to set up Task Groups/Working Parties to address some of these questions in the first instance.

3.3 Regulatory Engagement Working Group

Introduction:

The policy/regulatory subgroup was tasked with looking at the interrelationships between the needs of the policy makers and regulators and the ability of the risk assessment community to deliver on these needs. In short, how would risk assessment be designed to meet the needs of regulators and how would these needs be determined?

Group composition:

The subgroup was comprised of:

Malcolm Wilson

Tony Espie

John Gale

Wolfgang Heidug

Tore Torp

Discussions:

The early part of the sub-group discussion was an identification of the questions risk assessment would be required to answer.

Risk can be broken out into two areas of interest – Global and Local:

Global risk refers to the impacts of CO2 re-entering the atmosphere and creating climate change problems – the issue to be resolved here is the monetizing of the risk (quantification in monetary terms).

Local risk refers to the local HSE issues and how these may be quantified in terms of potential damage to ecosystem health, risk of injury or death in humans, damage to potable water supplies etc.

There is also an issue of timing to be considered – the global risk is time constrained by the life-time of fossil fuels and the time required for greenhouse gas concentrations in the atmosphere to decline. The local HSE risk is constrained by the time it takes to reduce the risk of leakage to essentially zero, probably the time for CO_2 to be dissolved in fluids in the reservoir and for buoyancy to be eliminated.

The discussion then moved to messaging – it was recognized that there must be a consistency of messaging coming from the risk assessment community – this does not mean in any way a restriction in models, techniques, approaches etc, rather a way of describing the results that come from models in a consistent manner so that differences from the models can be adequately explained.

What are the criteria required to define a good regulatory framework? In other words, what are the informational requirements for an adequate risk assessment to be able to meet the needs of screening, performance assessment etc for regulatory purposes.

What is involved in Integrated Risk assessment when applied to the geological storage of CO_2? This will be key to industry requirements for geological storage.

What are the "levers" for changing the risk profile? Are these regulatory levers, development of mitigation plans, changing public perception?

What will regulations look like – prescriptive versus performance based standards or some combination of the two? How will the outputs of RA meet these regulatory needs?

How will RA help to determine the monitoring requirements? What will be the monitoring requirements based on different levels of risk assessed for the site for storage?

There will be a need for ongoing critiquing of RA work[14]. What kind of exercise will this be? How would an expert "panel" (used very loosely here to mean expert reviews) be created to look the creation of assumptions for risk assessment work in order to ensure comparability of outputs?

Outcomes/Recommendations:

1. The group saw the benefit of having an informed group to provide advice to regulators and to the "risk assessment community":

a. An informal peer review process

b. Consistency of messaging

c. Testing of messaging, not an advocacy group or exercise.

2. Commentary on the impacts of regulatory standards – not an attempt to get universal standards, rather a practical understanding of the consequences of different regulatory structures.

3. The RA focus should be on local HSE issues, local enforcement of regulations. In the case of climate and ocean impacts, there is likely to be regional or international enforcement of regulations and a different regulatory framework.

[14] "Critiquing" of RA work is likely to occur in the same way as any other part of the science – through peer-review literature, supported by discussions in conferences and workshops.

4. Assistance/advice in the creation of RA methodology:

a. What is the RA intended to do, what are the expected outcomes from the risk assessment work? This will help determine the appropriate methodology, approach etc.

b. Looking at short-term HSE issues – site license requirements, developing monitoring plans, site planning etc – what are appropriate risk assessment requirements to meet these needs?

c. Looking at long-term issues, particularly the reversion of the site and liability back to the public. What are the risk assessment requirements to assure confidence in the level of risk to make this happen in a timely and orderly fashion? How long is monitoring required?

5. There is a need to undertake a collection of regulations to determine what is currently out there and how the risk assessment might fit into this. The IEA GHG has a tender out for the collection of this information; the outcomes of the study could be passed through the regulatory sub-group to evaluate the implications of the current national frameworks from the perspective of risk assessment and the need for modification of regulations to meet storage needs. This would help the group develop an informed base to help provide advice on the development of regulatory frameworks/modification of existing frameworks.

6. How will the regulatory sub-group operate? There was no real consensus around this except that there was a need to develop a better interface between the risk assessment community and the regulatory community as regulations are being developed. The ultimate goal is the try to assist in the development of regulations that meet the needs of both the regulatory community and the industry that will be undertaking storage. The group agreed to try to set up a workshop or two to bring regulators together to allow for a discussion of their needs, the ability for risk assessment to respond and how the groups could work together. In short, the group saw the need for an interface between the regulator and the risk assessment community to be developed and for the group to act as "informed translators" between the two communities.

7. The other requirement was around timescales and the need to marshal arguments around different timescales for FEPs, model runs, monitoring etc. Explanations of why the RA timescales are chosen and for what purpose will be essential to a broad understanding of the results.

Miscellaneous comments:

There are a number of reports in the public domain that may be of value. These include the Canadian and US reports for 2004-05 to the UNFCCC and an understanding of how the reporting of emissions/injection occurs.

The sub-group would be proactive to the extent of inviting regulators to informal meetings to discuss risk assessment and the development of regulations. IEA GHG to look at opportunities on the backs of other meetings.

Work with other IEA groups such as WPFF or the use of IEA/CSLF forum.

There will be an attempt to initiate a meeting as early as February.

Specific tasks:

IEA GHG to look at opportunities to bring together regulators with the sub-group – perhaps one European and one North American meeting.

IEA GHG to move ahead with relevant studies that will be of value to the risk assessment group and the regulatory sub-group – underway.

3.4 Environmental Impacts Working Group

Group members:

Jonathan Pearce (chair)

Hans Aksel Haugen (reporter)

Sara Eriksson

Angela Manancourt

Joris Koornneef

Anna Korre

Chris Karman

Mike Stenhouse

Eight questions were given to the group for consideration. The questions are dealt with one by one below, and thereafter general comments and thoughts from the group discussions are presented.

Q 1: Should this group compile available data on leakage and environmental impacts for use in RA studies?

A 1: Group answered yes to this question, but terrestrial and marine ecosystems should be looked at separately. Within these ecosystems it was recognised that different environments will have different responses (e.g. soil, urban, agricultural etc). Human health responses were also considered important. Important to identify gaps in datasets.

Q 2: Should the group develop specific data sets for use in all RA studies or just advise which reference data to use?

A 2: Definitions of environmental impacts are needed. We need criteria for what makes up a good dataset. Datasets develop all the time. The group suggested an expert group should be given the task to review datasets. Experts in toxicology, ecotoxicology, marine biology, etc. should be engaged.

Q 3: Is there data available for all environmental impacts (human health, marine systems, land based ecosystems)?

A 3: The group was not able to give a definite answer to this question. There is some information, but the group simply does not have the full overview. Clearly, this question can be better answered once environmental data have been compiled per Q1.

The main differentiation should be between marine and land ecosystems, maybe with a further subdivision for specific ecosystems/habitats (such as wetlands). Indicator or key species need to be identified, but the group suspect that data may be lacking. However, it was also recognised that regulators need to protect the whole ecosystem, not just specific species.

Q 4: How extensive is the available data?

A 4: With reference to A 3, the group would say the amount of data is probably extensive for humans, there is for instance a report by Susan Rice. Otherwise data availability is variable.

It was noted that Susan Rice Associates produced a comprehensive review for EPRI (US Electric Power Research Institute) on published data on CO_2 impacts on humans. Conclusions from this study were presented at the Risk Assessment meeting in London, 2004. Health Canada [1989], NIOSH [1997] and Snodgrass ([1992, cited in Rice [2003])(?) also produced some information on human responses to elevated CO_2.

Q 5: Do we know what leakage rates will cause local hazards, can this be generalised or is it site specific?

A 5: We do not know, but generic approaches and data may give us a concentration level for CO_2 on which local studies can be based. There are dose/response based guidelines (SSD: Species Sensitivity Distributions) in EU for protecting species from chemical exposure (the EU-TGD: Technical Guidance Document). It is suggested to follow these guidelines where possible. This means that, for instance, an exposure concentration could be derived at which 95% of the species would be protected.

The four previous questions and answers indicate that generic information can be extracted, but we still have to rely to a large extent on modelling and thus need to work very closely with risk assessment group.

There is also a need to remind ourselves of the hazard of doing nothing. What CCS actually implies with regard to risk assessment is the reduction of very likely global impacts but at the same time introducing possible local impacts. Finding the right balance of emphasis on either of these is a challenge.

Q 6: What information do we need to determine environmental impacts (footprint of leak, duration of leak, prevailing wind conditions etc.,)?

A 6: The question is much about modelling, for instance dispersion rates, pathway modelling, rate modelling. Leaking may be episodic, may depend on season (frost may reduce leaking) etc. Modelling should look at a worst case scenario; include fluxes, time (duration of leak), rates.

CO_2 and reduced pH may bring other contaminants with it; heavy metals, other gases, hydrocarbons. It is important to have good knowledge of the specific sites.

An open question is what about leakages that happen in 1000 years or more from now – we cannot for instance trust conditions are the same as they are now.

With respect to the amount of data needed it might be necessary to distinguish between environmental hazard assessment (a generic approach) and environmental risk assessment (a site specific approach, requiring detailed information).

At this point the group had a lengthy discussion. Our preliminary conclusion was to emphasize the need of a closure plan in order to avoid questions about monitoring forever.

Q 7: Are there any ongoing or planned relevant experimental activities addressing impacts on marine and/or land based ecosystems?

A 7: Norwegian University of Science and Technology is preparing to build a pressure tank to simulate marine bottom conditions at depths up to 300 meters.

CO_2Geonet have started experiments, both land based and marine.

TNO is working on an idea to do small to medium scale experiments.

Plymouth Marine Lab: Experiments on CO_2 and effects in the marine environment

In addition the research proposal for the PhD. of Joris Koornneef (Utrecht University) contains a plan for constructing a report on the environmental impact of CO_2. However, the full scope and approach are not established yet as this proposal is still under construction.

Q 8: Are safety criteria for local HSE needed and should/can this group define them?

A 8: The group could possibly advise regulators on how they can define criteria and on what information is needed to do this. The dose/response curve approach should be adopted. Monitoring will also be needed. Some criteria exist in many countries, e.g. indoor air CO_2 concentration or drinking water standards (trace metals), although some modelling needs to be done to derive numbers for comparison with such criteria.

It was commented that minimum requirements of datasets for regulators to give a permit, or minimum requirements of datasets to do benchmarking, are two different things.

General comments:

Group composition: Currently there is only one biologist in the group. More biologists, toxicologists and people who have done real work on CO_2 effects should be brought in.

Funding: Quite a lot of work is ahead of us. A very important task is to define what needs to be done in broad terms and bring up the need for funding. In addition the working group should help identify scientific groups working with these issues.

Suggestions: There is a need for two state of the art reports: one on terrestrial and one on marine environment. These reports should also identify knowledge gaps. People/groups who may produce these reports should be identified.

4. Discussions

This section provides the major points of discussion from the meeting.

- Identifying the missing groups in the network. Regulators are not well represented, neither are specialists or NGO's. The working group looking at Environmental Impacts would benefit from more biologists and toxicologists being involved. NGO's should be approached to join the network, it was suggested that the network provides them a more neutral contact to the subject rather than having to be linked to specific projects.
- Before any measure of comparing datasets, access to data by a wider audience needs to be facilitated. This could be a role for the network, specifically for IEA GHG.
- Terminology was a common point for discussion. Commonly referred to as benchmarking there was a consensus from the data management working group that a more suitable term could be 'Comparison of RA Methodologies'.
- In order to begin comparing the datasets, the first step should be to establish a protocol of what data is wanted. It needs to be clear and concise.
- Comparing RA models on a case that was rejected might be less sensitive than using the data available from operating projects.
- It could be a role for the network to show the reliability of predictive tools. If there are differences then it should be explained why.
- In the models that are available at the moment, the codes are not written with CO_2 injection in mind. Rather than cobble together existing codes, which were not designed for this purpose, could it be a role of the network to develop a model together writing a new code? It might not be the time yet but within 2-3 years of CO2ReMoVe an agreement could be achieved.
- Comparisons between the models and codes used for RA would be useful and problems could be developed that each model works on individually. The weaknesses in the code could be identified and improved through this type of collaboration.
- Comparing models could become a dominate part of the network but it should not dominate other important questions raised by the other groups (Regulatory Interactions and Environmental Impacts). Comparison will be very time consuming.

There could be a forum to discuss the comparisons, and others in the group go away and get external funding to do the code comparison.

- Risk assessment is not new. The regulator in the Netherlands has had to look at codes and came up with a list of codes/models that were accepted. The regulators will say which codes/models are allowed to undertake risk assessment. However, they could go to the model with gives the lowest risk.
- The regulators should be kept informed of the different techniques and the current status. It could be the networks role to communicate this.
- If you were to choose a dataset based on current models in what format should the data set be in? What size of dataset should be made? And where would it be stored?
- By stating what is in a dataset you are influencing risk assessment. But it is important to use what ever data is available. The amount of data will vary between different sites. There will be some generic data such as how CO_2 behaves but there will be a lot of information that is site specific.
- It could be possible to define a set of parameters for modelling; therefore, can we define what is needed for risk assessment.
- At this stage it is not possible to quantify the bare minimum requirements for data. Each model requires generalised data and specific data. Unless there is comparison between the models it will be difficult to increase confidence. One solution suggested was to have access to the most comprehensive dataset available and then test it with different models. Not all models will use all available data. The results will then show how close they compare. Until there has been this type of comparison it will not be possible to suggest a minimum. This type of comparison may still not provide us with a minimum but it is a start and may provide a direction for future developments.
- It was suggested that the current status of risk assessment allows a definition of a good dataset.
- All available models should be identified and an inventory should be produced.
- A question raised was when should the modelling stop and a more practical aspect start? Practical could be in the next few years but is everyone on the same timescale?

- Is it possible to use the tools currently available and compare how the various projects perform? This would certainly help to identify any gaps.
- Regulators can permit but at this time it is not possible to guarantee security of storage. However, the risk will decrease with time as the models improve.
- It was suggested that there were two steps that were important. The first is that it was important to identify the minimum codes that were required to provide information to the regulator in order to give sufficient confidence. The second step is to set the codes for the models themselves.
- The urgency could be underlined by Otway Basin Project. It was clear the progress of the project was decided by regulatory and liability issues. Authorities are afraid of setting an example that becomes binding for the future. There is an urgent need for progress in this area.
- IGCC plants with CO_2 capture technology are close to being finalised. There are a lot of projects ready to go ahead. Some are close to oil reservoirs where there is money to be made. Others are located close to saline aquifers were there is little known about the structures and information will be required, soon!

5. Progress to be made before next meeting

Tasks to progress before next meeting

- Inventory of RA models/tools and status
    - CO2GEONET on RA framework and terminology
- Inventory of data sets
    - Cross link to RA tool group on model needs
- State of Art on Environmental Impacts
    - IEA GHG study
- Regulatory interactions
    - IEA GHG study
    - Preliminary meeting in February 2006?

Next Meeting

- September/October 2006?
    - North America?
- Outline Agenda
    - Feedback from next step activities
    - Start discussion on data set requirements
        - Links modellers and data set providers
        - Working section of meeting
    - First RA methodology comparisons?
        - Weyburn, CO2STORE, CO2CRC??

Appendix 1

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Appendix 2

Working Groups

Data Management and Risk Analysis	**Risk Analysis**
Chair: Ton Wildenborg Reporter: TBC	Chair: Sevket Durucan Reporter: TBC
Charles Christopher	Dave Savage
Gabrielle? Marquette	Jitsopa Suebsiri (Noony)
Scott Stevens	Lars Ingolf Eide
Steven Benbow	Prasad Saripalli
Wei Zhou	*Hans Peter Rohner*
Ziqiu Xue	Arie Obdam
Philip Stauffer	Kaoru Koyama
Rickard Svensson	Rajesh Pawar
Richard Rhudy	Koji Yamamoto
Yann Le Gallo	Francois Kalaydjian
Wim C. Turkenburg	Jeroen P. van der Sluijs
Koorosh Asghari	Kay Damen
Hiroshi Suenaga	Irina Gaus
Ji-Quan Shi	Larry Myer
Elizabeth Scheehle	Rob Eijs
Regulatory Engagement	**Environmental Impacts**
Chair: Malcolm Wilson Reporter: Tony Espie	Chair: Jonathan Pearce Reporter: Hans Askel Haugen
Wolf Heidug	Sara Eriksson
Tore A TORP	Walther van Kesteren
John Gale	Joris Koornneef
	Anna Korre
	Angela Manancourt
	Chris Karman
	Mike Stenhouse

Appendix 3

Questions for Working Groups

Data management and risk assessment – 2 groups

1. What risk assessment activities are currently underway or planned?

2. What data sets are currently available for use in RA activities?

3. What data sets are being developed and when will these be available for review/benchmarking?

4. What RA techniques are currently being used and will be used in planned projects?

5. Do any current or planned projects include benchmarking activities?

6. How could groups undertaking RA activities be best organised to undertake a benchmarking activities and is it practical to do so?

7. Is it more effective to share data or results through these forums?

8. Should this network focus on presenting and reviewing results rather than establishing benchmarking procedures on its own?

9. What are the gaps in data needed for better RA?

Regulatory Interactions

1. What regulatory groups should be engaged?

2. What sort of messages should this RA network be looking to convey to the regulators?

3. How best to engage the regulatory groups?

4. Do we know what the regulatory groups expect from RA studies?

5. Do we know which countries plan to include RA studies within their regulatory processes and which don’t and why not?

6. Do we know what RA techniques they are considering?
7. Do we think they are aware of the strengths and weaknesses/limitations of different approaches?

8. How will they use the results of risk assessment studies?

Environmental Impacts

1. Should this group compile available data on leakage and environmental impacts for use in RA studies?

2. Should the group develop specific data sets for use in all RA studies or just advise which reference data to use?

3. Is there data available for all environmental impacts (human health, marine systems, land based ecosystems)?

4. How extensive is the available data?

5. Do we know what leakage rates will cause local hazards, can this be generalised or is it site specific?

6. What information do we need to determine environmental impacts (footprint of leak, duration of leak, prevailing wing conditions etc.,)

7. Are there any ongoing or planned relevant experimental activities addressing impacts on marine and/or land based ecosystems?

Are safety criteria for local HSE needed and should/can this group

Appendix 4

Presentations and Posters

Presentations

Day 1 – Tuesday 23 August 2005	
IEA GHG Opening and Plan for the two days	
TNO Introduction and welcome	
Session 1. Developments since last meeting	
Well bore integrity workshop findings	BP
Modelling workshop report	US EPA
RA studies in the CO2STORE project	Statoil
Weyburn II – plans for new RA activities	PTRC
Remediating leakage	ARI
Session 2. Network Development	
Outline proposal for network and introduction to working groups	IEA GHG

Day 2 – Wednesday 24 August 2005	
Session 2. Network Development Cont.	
Presentations by breakout groups on their proposals for each task area: • **Data Management and Risk Analysis 1** • **Data Management and Risk Analysis 2** • **Regulatory Interactions** • Environmental Impacts (none produced)	
Summary of Working Group Discussions	IEA GHG
Closure of Risk Assessment Meeting	IEA GHG

Posters

Quantitative risk assessment regarding CO2 storage - TNO's experience	TNO
A computational estimation of CO2 migration injected into a reservoir	CRIEPI
A Risk Screening Tool for Site Selection	LBL
A CO2 Sequestration Systems Model supporting Risk-Based Decisions	LANL

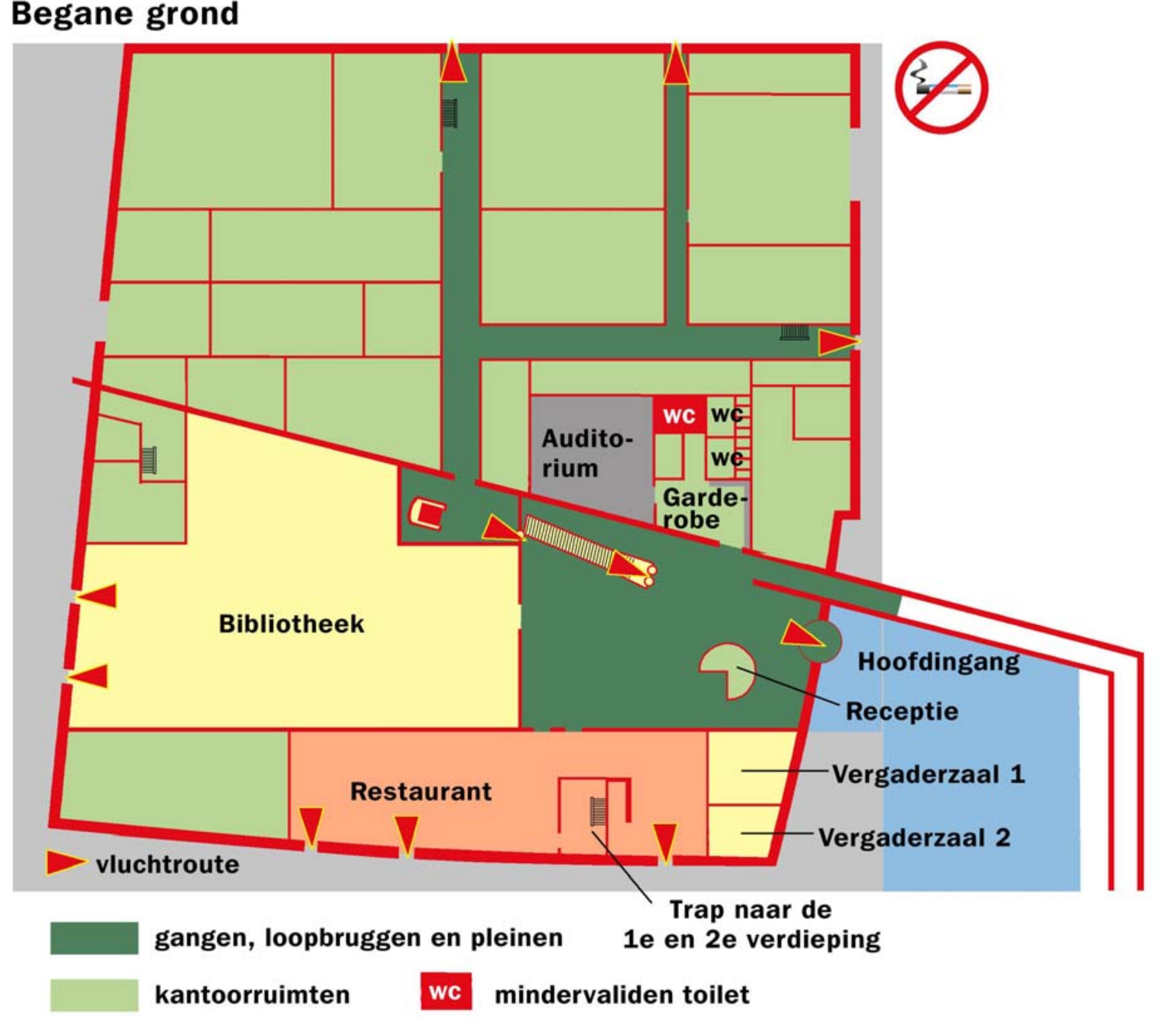
Launch Meeting
Risk Assessment Network

Utrecht, 22 & 23 August 2005

TNO | Knowledge for business

Safety measures

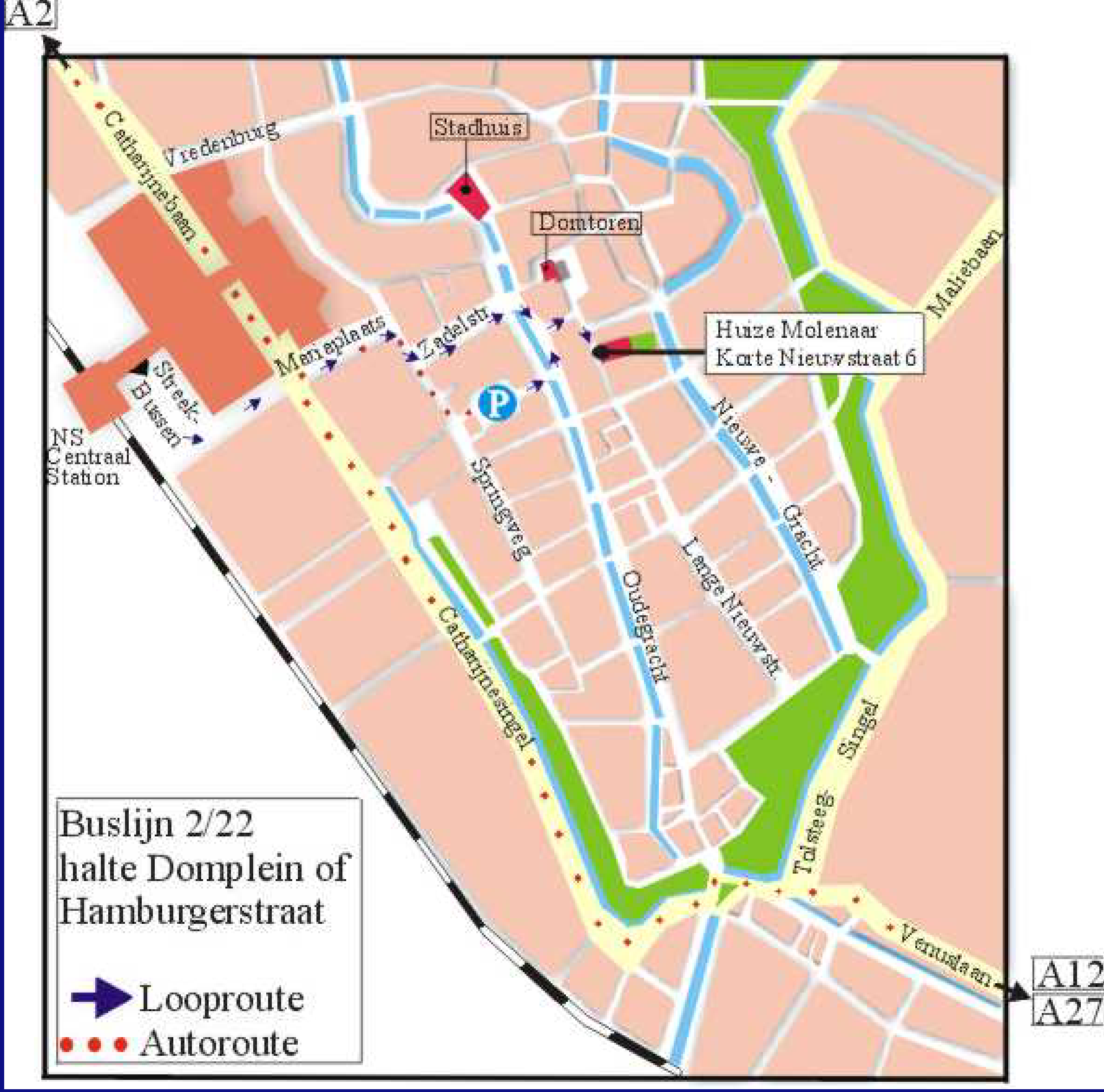
1. In case of emergency: slow whoop
2. Move to the (emergency) exits ▶
3. Gather at the outdoor area



Dinner this evening:
Huize Molenaar

Address:
Korte Nieuwstraat 6

You are welcome from: 19.30 hours



Break out sessions

• Group 1: Data management & Risk Analysis	Room 1
• Group 2: Risk Analysis	Auditorium
• Group 3: Regulatory Engagement	Auditorium
• Group 4: Environmental Impacts	Room 2

Well Bore Integrity Workshop

Charles Christopher, BP Houston

Marriott Woodlands Waterway Hotel and Convention Center, Houston, Texas, USA

Organised by IEA Greenhouse Gas R&D Programme and BP

with the support of EPRI

4-5 April 2005

Objectives

- Assess the current state of knowledge on the integrity of well bore cements exposed to CO2
- Address the key future research needs in this area.
- Develop a picture of how significant, if at all, the effect of CO2 on well bore cements will be post-storage and
- If well bores do pose a significant risk of CO2 leakage in the future.

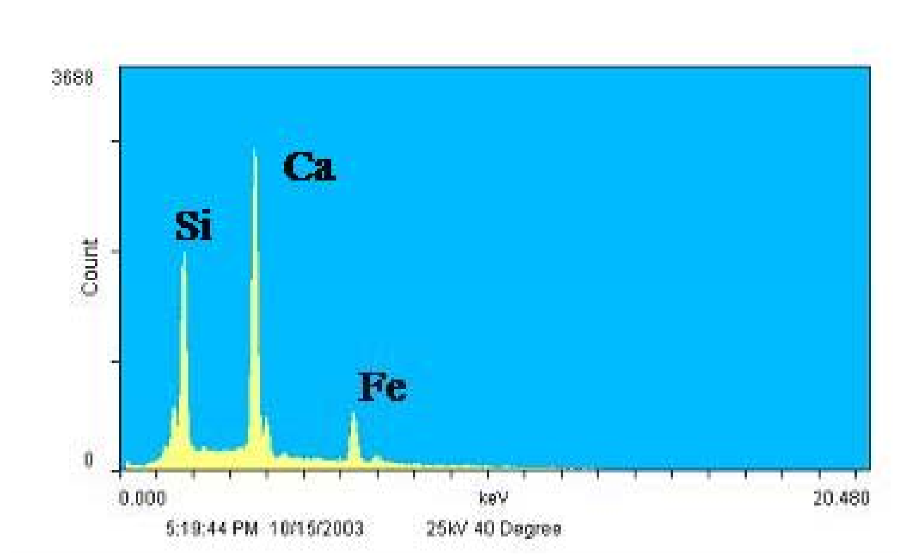
Expected Outcomes

- Lead to the establishment of a working group on well bore integrity that could feed into activities underway on risk assessment,
- Help to develop a list of research needs for assessing well bore integrity in CO2 rich environments,
- Provide a source of information for stakeholders.

Agenda

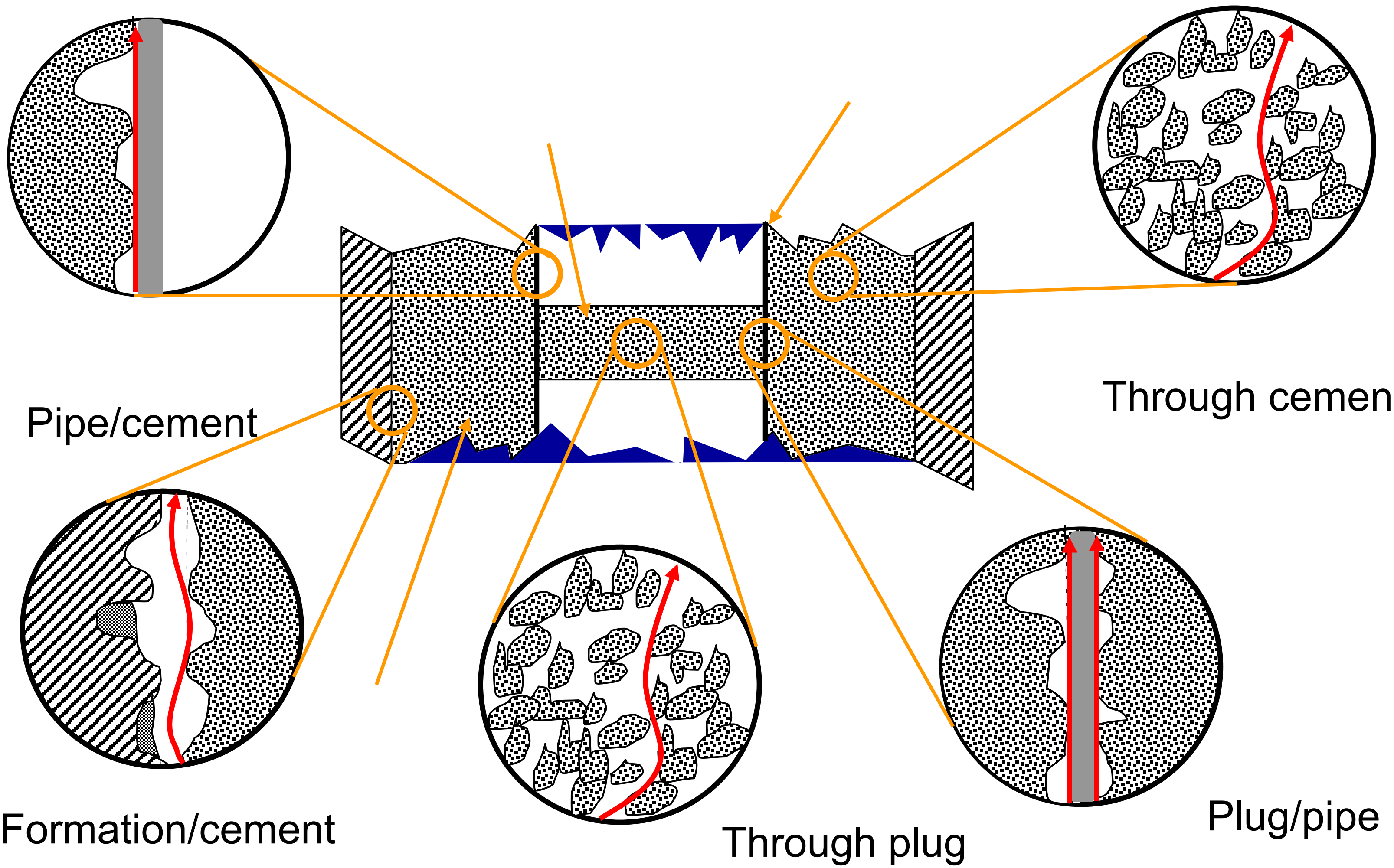
- What we know
  - CO_2 reacts with Portland cement rapidly
  - CO_2 does not dissolve well construction materials rapidly but 30 years of service do show increased corrosion

Scherer - Princeton

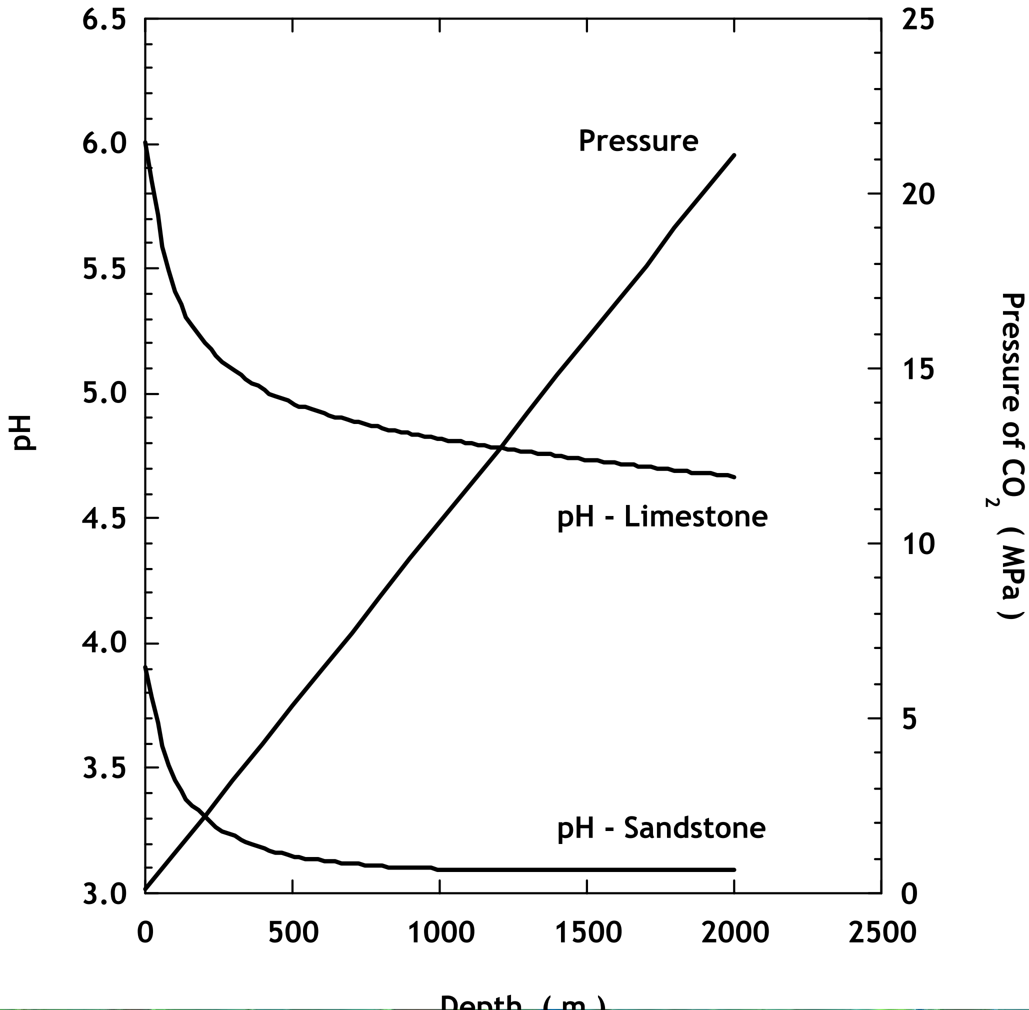


CO2 reaction with cement resulting in color change and evidence of calcium dissolution

Potential avenues for leakage



pH is Buffered in Limestone Systems



Conclusions

- Ensuring well integrity over long timescales has not been attempted before and represents a new challenge to the oil and gas industries.
- It will not be possible to promise a leak-free well, but rather we should emphasise that we can build wells employing state-of-the-art technologies which will reduce risks.
- Portland-based cements will react with CO2, leading to cement degradation. The main reactions involve carbonation of the major cement components – Portlandite and calcium silicate hydrates which are converted to carbonate minerals such as aragonite, calcite and vaterite.
- Degradation results in a loss of density and strength and an increase in porosity.
- Laboratory experiments of these reactions are able to simulate those observed in wells that have been exposed to CO2 in EOR injection and production wells. However, the degree of reaction (i.e. the rate of reaction) does not seem to be comparable between laboratory and field.

Conclusions cont.

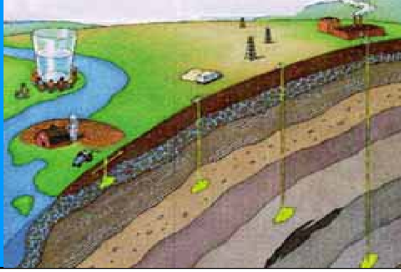
- Multidimensional models are now being developed to simulate processes observed both in the laboratory and in the field, at the small-scale of specific leakage mechanisms within a well and also over the larger scale examining broad leakage on the basin-scale.
- However, we are unable to use these models in a predictive sense due to a lack of detailed knowledge of mechanisms of attack.
- New cements have been developed and deployed that reduce the amount of alteration caused by acid attack. These cements either reduce the proportion of Portland-based cement in the mix, add inhibitors or use completely new calcium phosphate-based cements that do not contain any reactive portlandite.
- Studies of well completions from CO2 EOR operations were recognised as offering significant valuable data on real failure processes and consequences. Although these offer the longest "experiments" to date, timescales are still limited to a few decades.

Future Research Needs

- **The frequency of failure.** It was concluded that little data was available from oil and gas operations that enabled frequency estimates to be made. This was due to several reasons including commercial sensitivity and inconsistent definitions of failure.
- **The mechanism of failure.** Several mechanisms were suggested during the meeting but little is currently known about detailed processes on the small scale that lead ultimately to leakage.
- **The consequences of failure.** These could be very different depending on rate of CO2 loss, total amount lost, location of well (populated, onshore, offshore, agricultural land etc).

Next Wellbore Integrity Workshop
April 4-5, 2006 - Houston, Texas

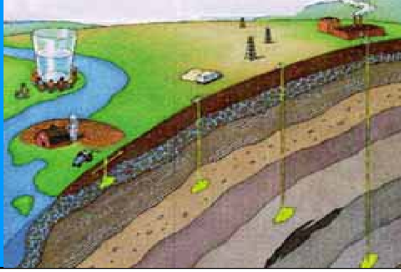
- Defining well failure.
- Standardising testing procedures.
- Industrial and regulatory evidence for failure frequencies.
- Designing a R&D programme to obtain evidence from existing CO2 EOR operations.
- Designing monitoring procedures.



USEPA Modeling Workshop (April 2005) Summary and Relevance for Risk Assessment

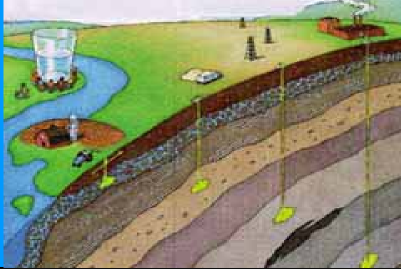
Elizabeth Scheehle
August 22, 2005

Overview



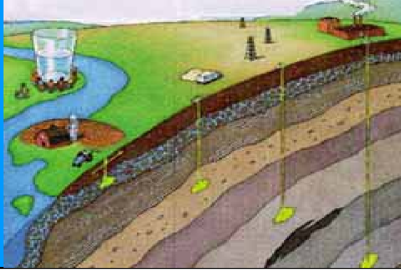
- Background on USEPA GS efforts
- Reservoir Modeling workshop objectives
- Reservoir Modeling workshop summary
- Modeling gaps & Research Needs
- USEPA Modeling related efforts
- Risk Assessment next steps

Why does USEPA do Risk Assessment?



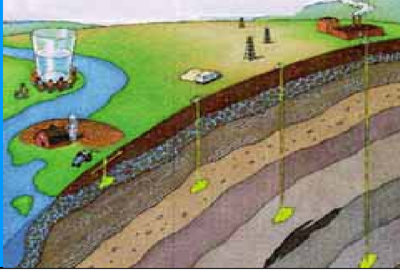
- Risk Management
  - to better understand the processes and potential impacts in order to safely permit
  - Determine effective and efficient risk management techniques
    - Focus on most risky failure pathways to minimize regulatory burden
      - Take into account potential for failure, effects of failure, and uncertainty
    - Practical and effective siting and monitoring requirements
    - Remediation options

Background



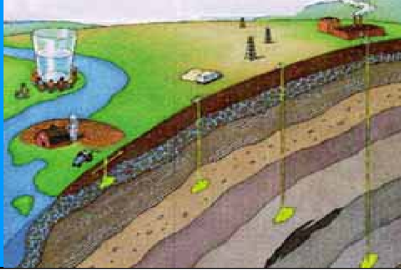
- EPA has a workgroup consisting of staff from various offices including: Water, Air, Solid Waste, International Affairs, and General Council.
- Major goal to integrate goals of Climate Change program and Underground Injection Control (UIC) program
- Safe Drinking Water Act created UIC in 1980
  - UIC Mission:
    - to protect underground sources of drinking water from contamination by regulating the construction and operation of injection wells
      - More than 400,000 injection wells are known to be in operation but only small percentage are Class 1 (strictest requirements)

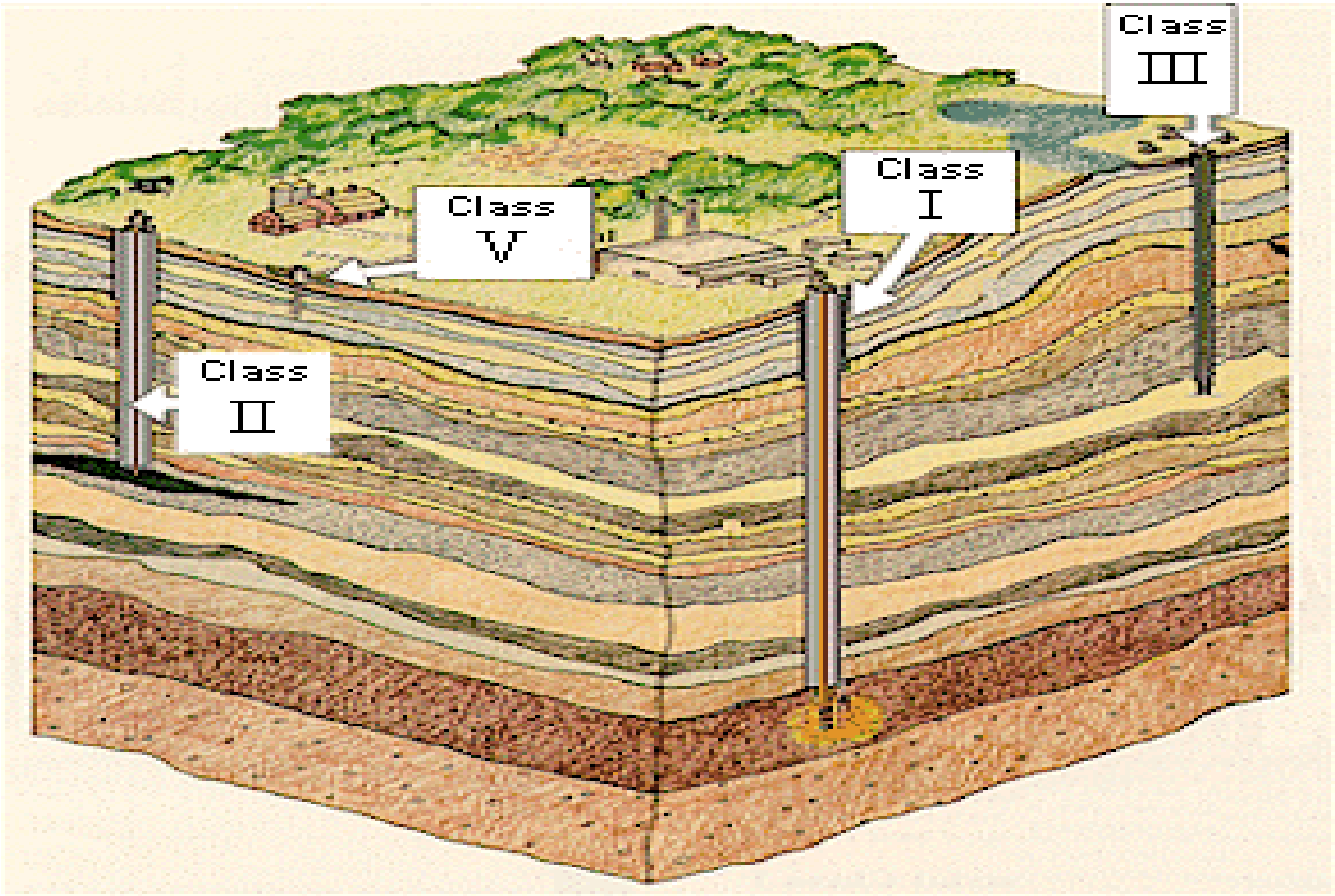
UIC Background



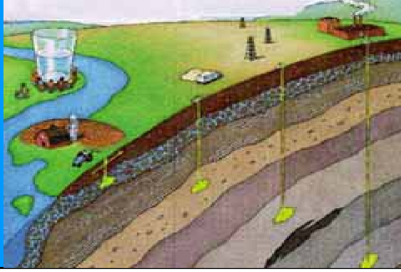
- EPA and states regulate wells according to the injection activity (i.e. injectate, depth, etc.)
  - UIC covers all injectate – liquid, gas, slurry
  - CO_2 for EOR is currently covered by UIC
  - UIC program has evaluated similar technical issues
    - Area of review
    - Bouyancy of injectate
    - Mechanical integrity of wells

UIC Well Classes



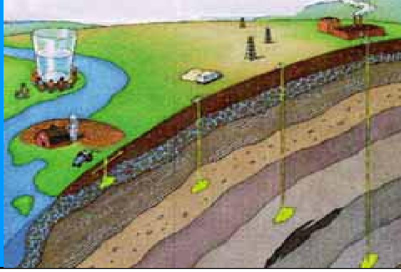


EPA and Modeling - UIC example



- To ensure permitting requirements met
- Models are used to bound the limits of the waste plume:
  - Maximum pressure buildup from disposal operations
  - Maximum horizontal and vertical extent of waste plume at the end of the 10,000 year containment period
- Types of Models Used
  - Numerical (Finite Difference)
  - Analytical
- Model complexity driven by the geology and "no migration petitions" for Class I hazardous wells

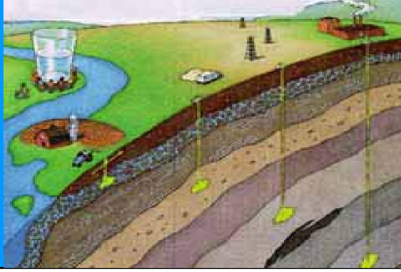
Petition Modeling vs. CO_2 Sequestration



- No Migration Petitions
  - Injectate is a restricted hazardous waste
  - UIC regs define the requirement for the no migration demonstration
    - Class I well classification
    - 10,000 yr timeframe
    - Waste cannot exit Injection Zone
  - Single phase liquid
  - Simple PVT behavior
  - Single layer horizontal plume model
    - No vertical leakage allowed
  - Plume defined by CRF

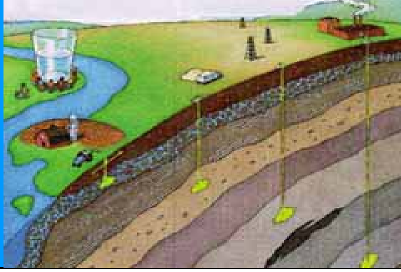
- CO_2 Sequestration
  - CO_2 is not a restricted hazardous waste
  - Well classification for (Non-EOR) sequestration well not defined
  - No defined requirements for sequestration demonstration
    - Timeframe
    - Maximum allowed vertical movement
  - Multiple phase fluids
  - Complex PVT behavior
  - Multilayer model to allow vertical movement
  - Delineation of horizontal CO_2 movement

Overall Modeling workshop objectives



- To assess potential role and application of reservoir models and simulation to geologic carbon storage
- Provide USEPA with information about the "state of the art" on development and applications of modeling approaches and numerical simulators for geologic CO_2 storage
- Encourage dialogue between EPA, researchers, and industry

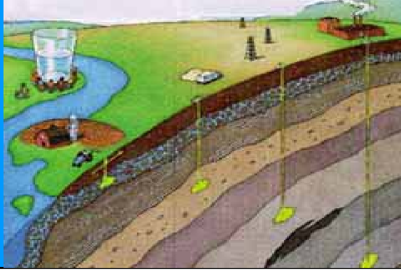
General Workshop Results



- CO_2 geologic sequestration should be based on:
  - careful selection of a geologic model and
  - reservoir simulation of the storage site,
    - supported by various geologic-petrophysical data.
  - Additional requirements include:
    - thoughtful selection of model input parameters,
    - uncertainty analysis and sensitivity analysis, and
    - calibration of model results with field observations.

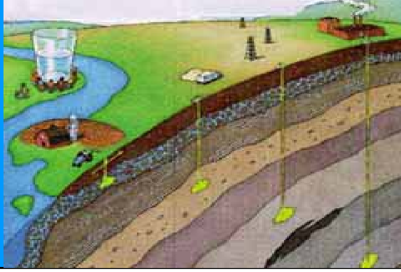
- Illustrated areas of new research and data needs to improve application of modeling and reservoir simulation
  - Need for simplification
  - Sensitivity analysis to provide major parameters

Workshop Results – Risk Assessment



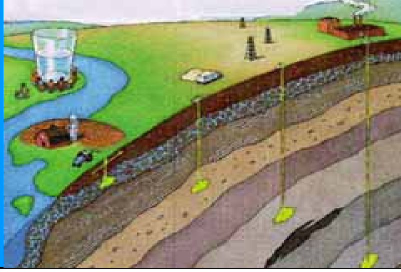
- Numerical modeling is important for risk characterization from three perspectives:
  - To make quantitative predictions of the features, events, and processes associated with CO_2 migration.
  - To quantify aspects of the injection site risk, including probabilistic renderings of site uncertainty and planning of monitoring strategies
  - To explore complex system response associated with CO_2 injection
- Site assessment matters the most. Risk models are flawed without a good site assessment
- Risk assessment requires quantitative inputs
  - Probabilistic approaches require calibrated probability density functions and require a large number of realizations
  - Deterministic approaches need precise quantification of features, events and processes.
- Modeling can perhaps counter the public perception that sequestered CO_2 is as hazardous as nuclear waste.
- Potential migration paths along annuli between formation rock, cement, and casing and must be integrated with large-scale models of plume movements.
- Subsurface CO_2 concentrations can be high even for small leak fluxes
  - Atmospheric dispersion (particularly wind) is effective in dispersing seeping gas and reducing human health risk.
- Perspective – Risk needs to be compared to risk of climate change.

Modeling Challenges



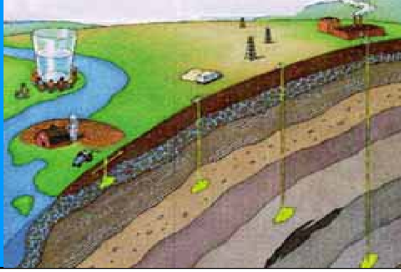
- Potential Impacts to Groundwater
  - Most models focus on leakage to surface
- Multiple projects and pathways
  - Abandoned well model focused on one well
    - In US projects will encounter numerous wells and potentially more than one leaking well
  - Impact of two sequestration projects
    - Pressure increase
    - Fluid Displacement

Modeling/Risk Assessment Efforts



- EPA UIC program &LBNL have a 20+ year working relationship. Currently working on:
  - Ruling out "catastrophic release"
  - Identify realistic scenarios and model CO_2 behavior
- Risk Assessment workshop in October
  - Connected with Ground Water Protection Council
  - Hope to gather on-the-ground input from experts in underground injection and groundwater protection

Risk Assessment Status and Next Steps



- Develop framework for national level risk assessment for geologic sequestration
  - Develop scenarios
  - Exposure, Effect, and Risk Characterization
  - Evaluation
- Modeling efforts will help:
  - Define scenarios varying only important siting parameters
  - Refine exposure pathways and potentially some effects
- UIC and other relevant experience will be used to further develop and refine the RA
  - Failures (number, type, circumstances)
  - Siting requirements needed to reduce risks
  - Groundwater impacts (displacement)
  - Data needs (UIC well locations, etc.)
- Will need to use expert elicitation, especially for effects

Risk assessment studies in the CO2STORE project

Launch meeting of the risk assessment network,

Utrecht 23/24 August 2005

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The Sleipner field – CO_2 Treatment and Injection

CO2STORE is a follow up and extension of the SACS Project (1998 – 2002)

CO2STORE participants

Statoil (coordinator)
BP Exploration
Energi E2
ExxonMobil
Hydro
Industrikraft MidtNorge
Progressive Energy
Schlumberger Research
Total
Vattenfall

BGR
BGS
BRGM
GEUS
IFP
NGU
NITG-TNO
SINTEF

IEA Greenhouse Gas R&D Programme

European Commission

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CO2STORE – the work packages (1)

Work Package 1 – Transfer

- Expected results: Conclude on the feasibility of four new prospective reservoirs for CO_2 storage and to transfer knowledge gained for Sleipner to these case studies
- WP leader: GEUS
  - Case: Kalundborg (GEUS)
  - Case: Midt Norge (NGU)
  - Case: Schwarze Pumpe (BGR)
  - Case: Valleys (BGS)

Work Package 2 – Long Term

Expected results : Models backed by observations for final-fate prediction of CO_2 in the Utsira reservoir (Sleipner)

- WP Leader: SINTEF
  - Team 1: Geochemistry (BRGM)
  - Team 2: Reservoir Simulation (SINTEF)

CO2STORE – the work packages (2)

Work Package 3 – Monitoring

- Expected results: Analyze two seismic surveys (2002 and 2005) and conclude on the feasibility of more cost-efficient gravimetric techniques
- WP Leader: NITG-TNO
  - Team 1: Seismic (NITG-TNO)
  - Team 2: Gravimetry (Statoil)

Work Package 4 – Management

- Expected results: Updated Best Practice Manual and other public documentation for dissemination of the technology
- WP leader: Statoil
  - Team 1: Reporting (Statoil)
  - Team 2: Best Practice Manual (BGS)

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Risk assessment work in CO2STORE

- According to Description of Work for CO2STORE, all 4 case studies in Work Package 1 shall produce ”Outline risk assessments (FEP and scenario analysis)”
- Case Studies have chosen somewhat different approaches based on local conditions
  - Risk assessment ←→ Potential risks
- Common activities for all work packages: One day seminar/technical meeting autumn 2004
- Risk assessment work is still ongoing and conclusions are therefore preliminary

CO2STORE – the case studies

CO2STORE – the case studies

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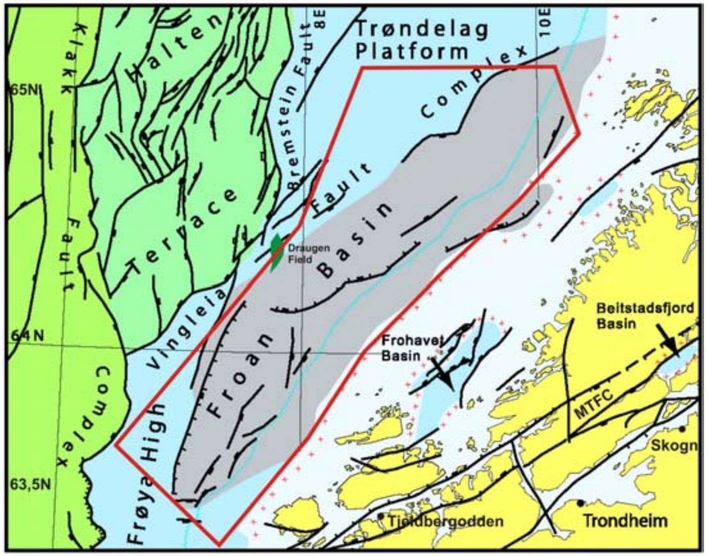
Froan Basin area of the Trøndelag Platform



None of the simulations with up to 100 Mt injected CO_2 resulted in any leakage over periods of 5000 years

Most of the CO_2 was trapped in subtle structural traps

Dissolution of CO_2 into formation water and trapping as residual gas will aid local fixation of the CO_2

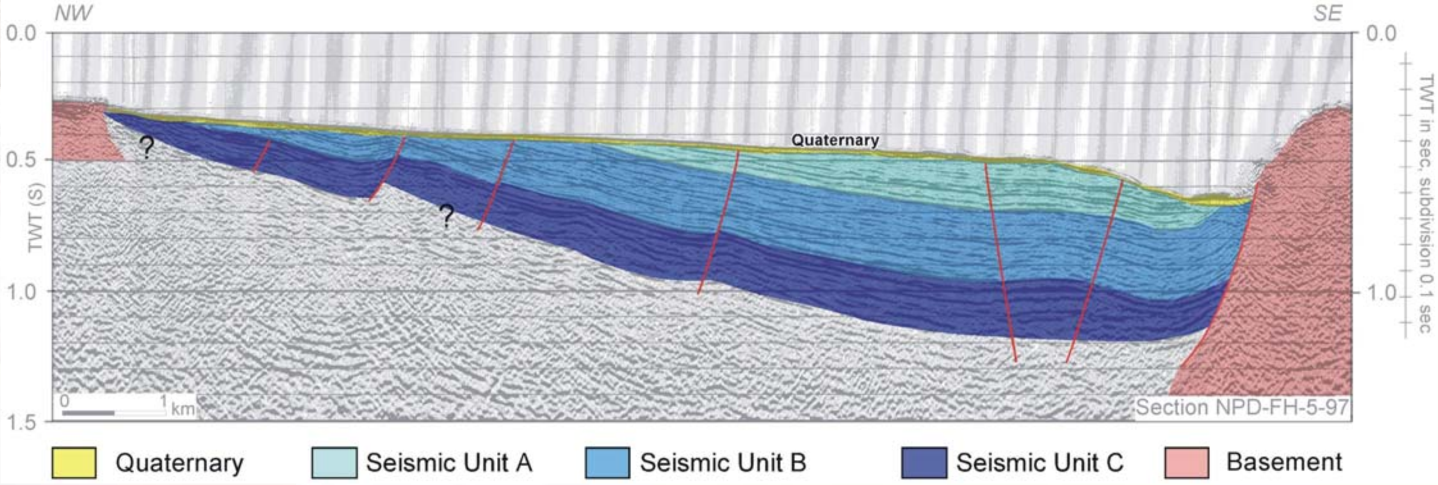
The overall storage potential of the Jurassic formations of the Trøndelag Platform is estimated to be several 1000 Mt

Seismic data indicate that there will be no CO_2 leakage to the seabed along faults

More data is needed for a detailed risk analysis

SINTEF

Frohavet Basin



CO_2 will start to leak after few years if reservoir permeability is high, if the k_v/k_h ratio is high, or if the relative perm. to gas is high.

If these parameters are low, no leakage may occur for several centruries, and thereafter leakage rates may be acceptable.

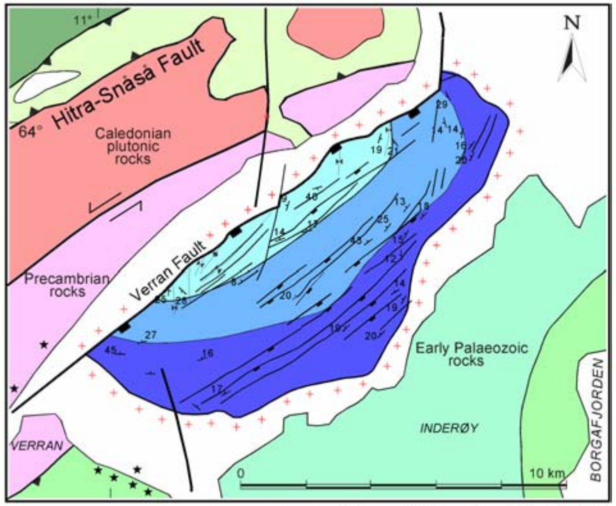
In the case of very good parameter combinations, no leakage at all may occur.

The Frohavet Basin may be an option for CO_2 storage.

SINTEF

Storage capacity needed for a gas-fired power plant at Skogn

50 million tonnes CO_2 over a period of 25 years, i.e. 2.9 millioner Sm^3 CO_2 per day



Structural data modified from Bøe & Bjerkli (1989)

Beitstadfjorden Basin

CO_2 will start to leak after few years of injection
If leakage starts after 4 or 40 years depends on permeability

A maximum of ca. 70 000 tonnes CO_2 can be stored in the Beitstadfjord Basin

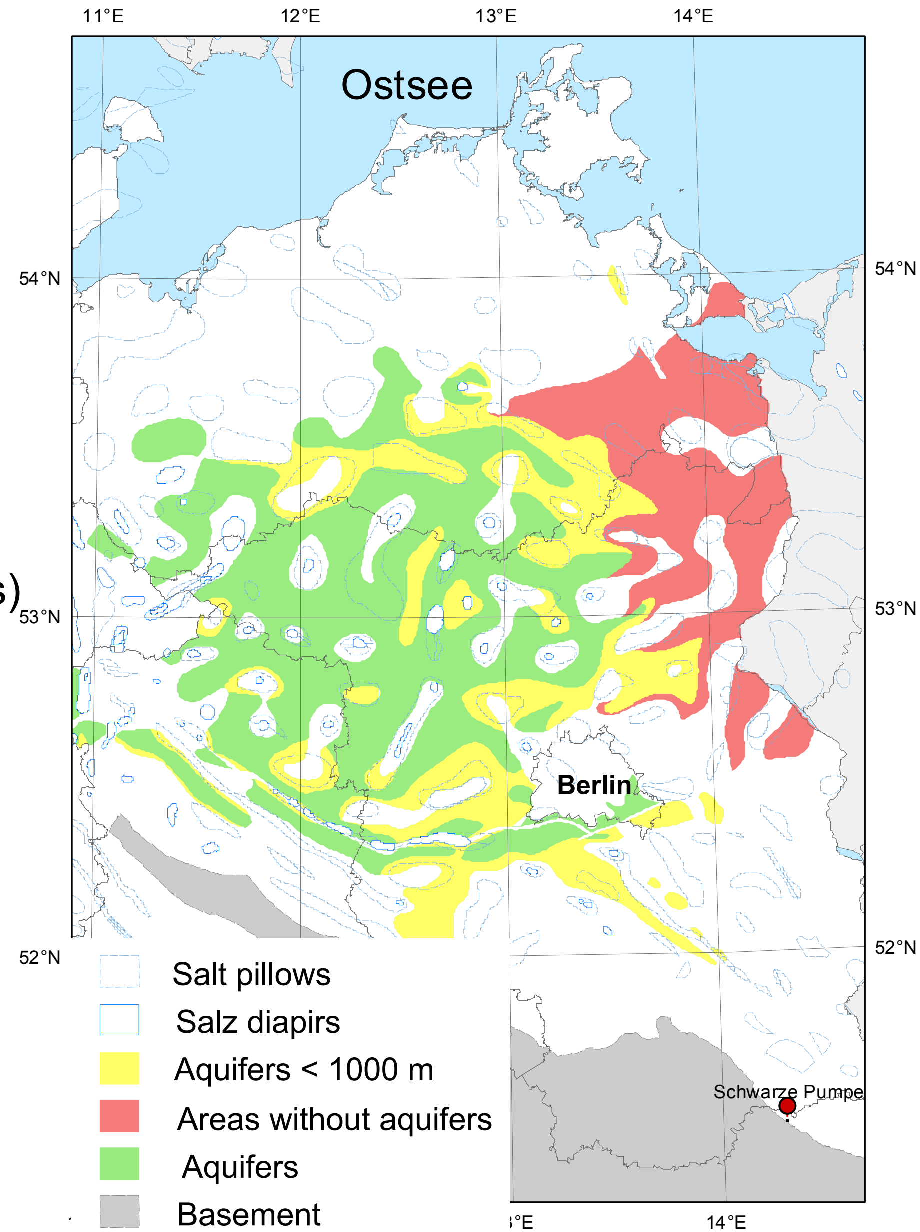
The Beitstadfjord Basin is not an option for CO_2 storage

CO2STORE – the case studies

STATOIL

Implementation of Site Selection

- Systematic, area-wide application of site selection criteria
- Focus on anticlines/structural traps
- Calculation of storage capacity
- Ranking (geology, data availabilty, others)
  - Selection criteria:
    Structural closure
    Suitable cap rock
    Depth: 900 to 4000 m
    Storage capacity 400 Mt
    Single site/layer
    Thickness of reservoir > 20 m
    Porosity > 20%



Available Data…

- Sound data set available from several surveys:
  - Exploration for hydrocarbons (60th – 80th)
  - Hydrothermal energy survey (80th)
  - Nuclear waste repository

- Well data (60th – 80th)
- Geophysical surveys (2D seismic, gravimetry, magnetotelluric (60th - 70th)

Summary:

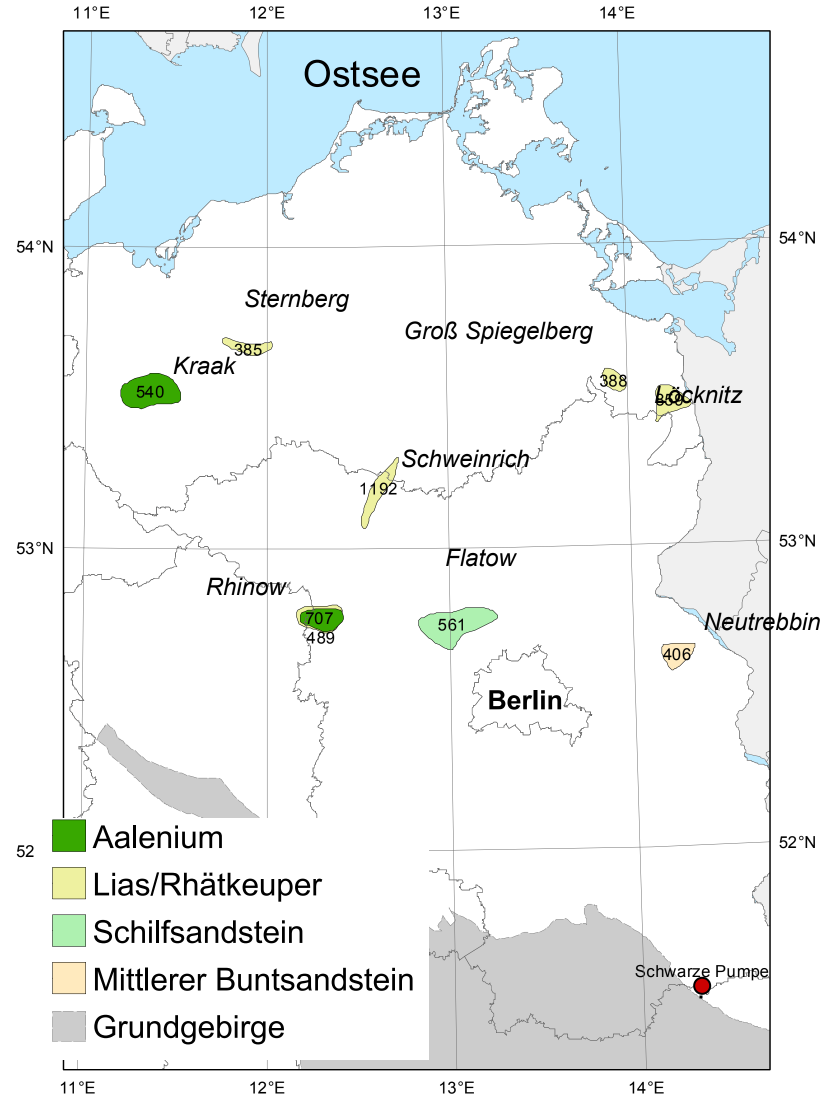
- area-wide sound knowledge of geological framework
- Data from former surveys: formation boundaries, lithotypes, facies, …
- no new seismic shot / no new wells drilled…

Findings from Site Selection

- 9 (26) potential storage sites

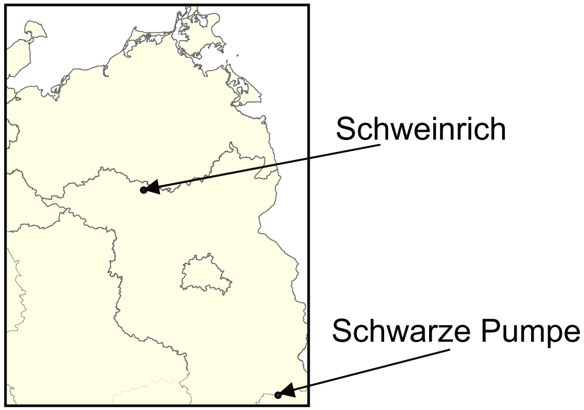
  ⇒ **Schweinrich**
- area-wide sound geological/geophysical dataset for site selection and site pre-evaluation
- data with variable quality standards dependent on state-of-the-art (60th/70th/80th)
- great number of structures "more or less" well explored (penetrated/unspoiled)

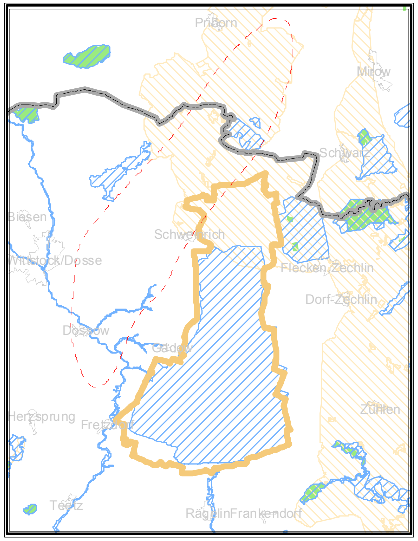
⇒ **no problems conducting the site selection**



Study area and method

- The Schweinrich site in NE Germany
- Method
  - a scenario approach using the TNO developed FEP database
  - Reservoir modelling of selected scenarios
  - Results compared to environmental effect levels





VATTENFALL

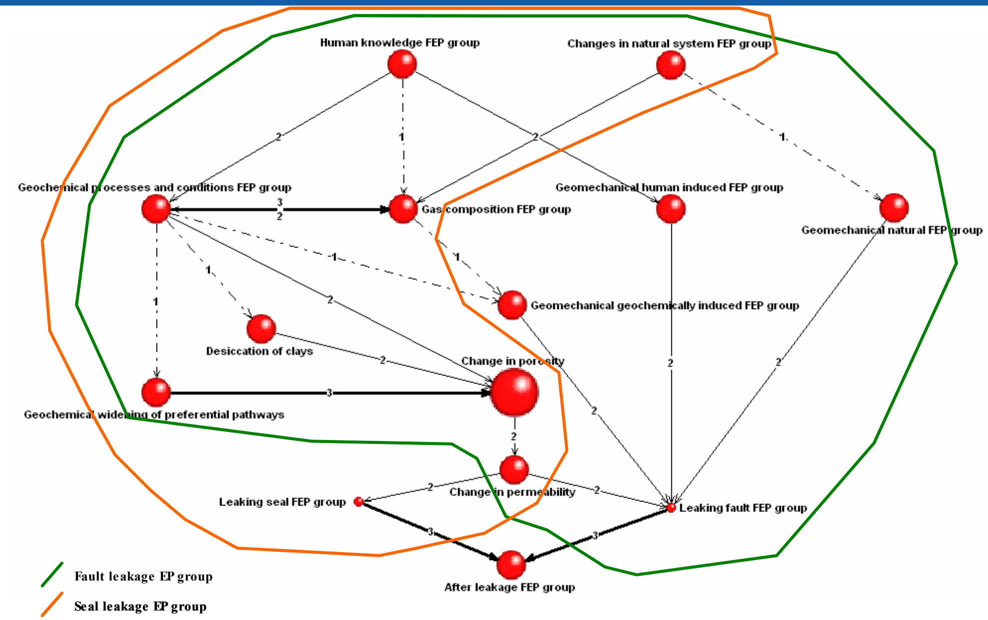
FEP analysis results and evaluated scenarios

FEP analysis

- No pre-existing wells
  - Leakage through drilled injection wells
- Two leakage possibilities
  - Leaking fault
  - Leaking seal

Evaluated scenarios

- Reference scenario
- Leaking fault
- Leaking seal
- Leaking well

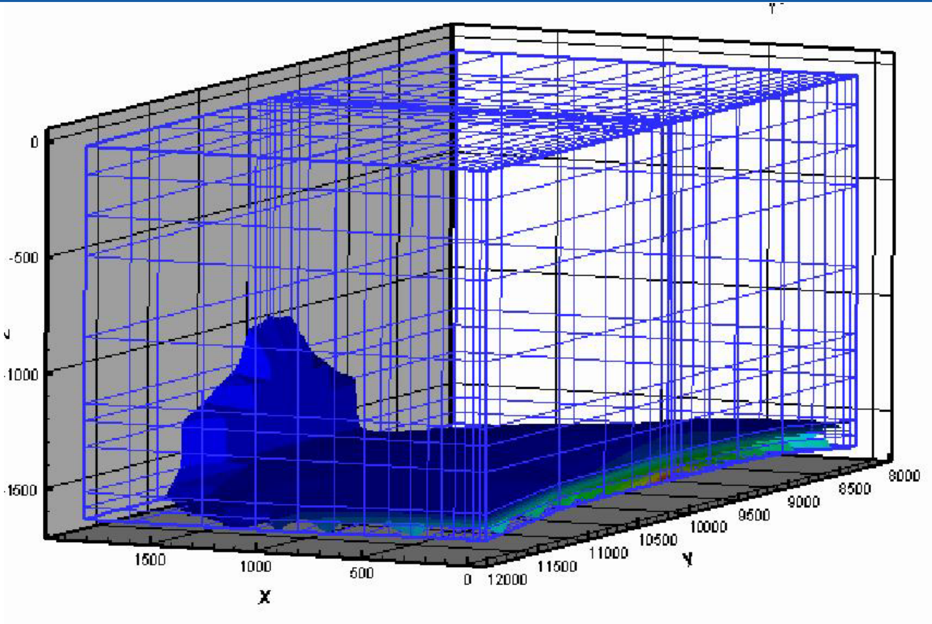


Influence diagram with scenario defining EP groups

VATTENFALL

Modelling example and results

- Models have been developed in SIMED II
- Modelling ongoing
- Shallow subsurface will be developed
- Commonly accepted criteria for risk assessment do not exist. In the mean time, levels above which no adverse effects have been detected are used.



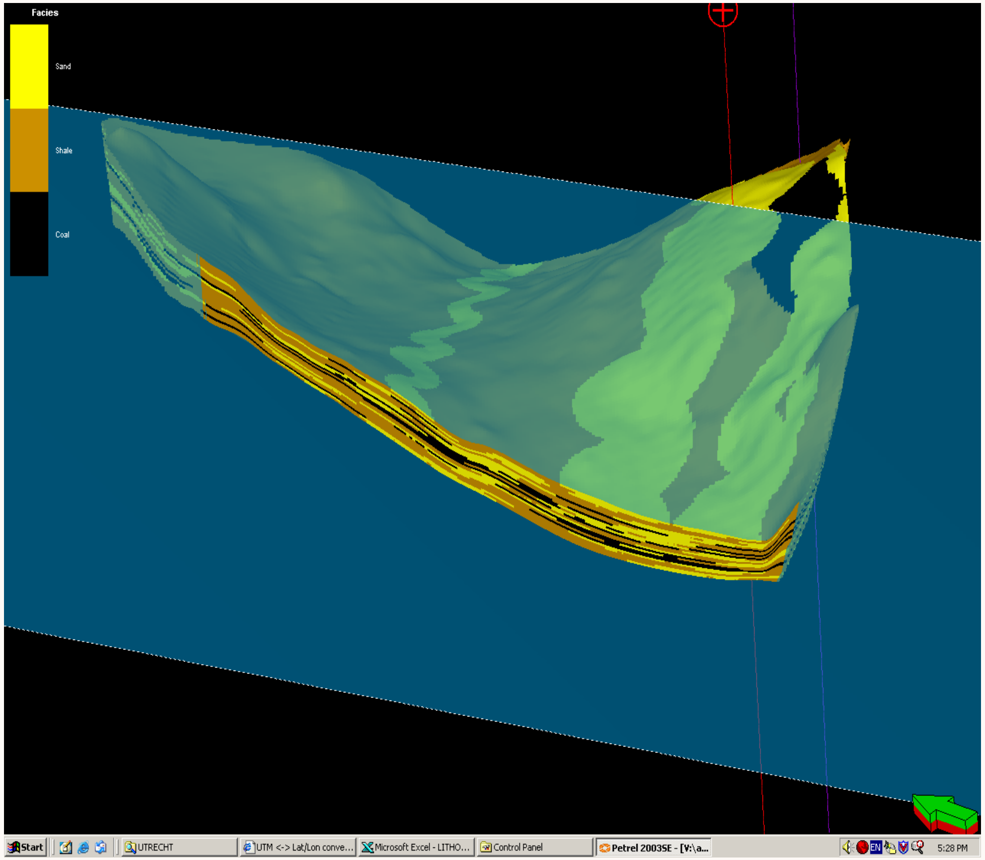
Leaking fault model

CO2STORE – the case studies

Valleys Case Study

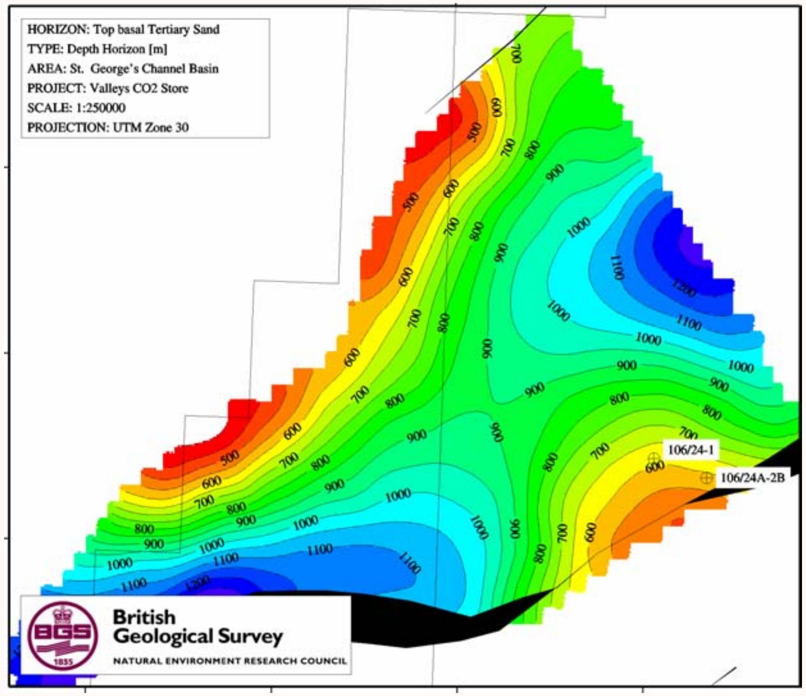
- Methodology:
    - Use FEP approach - Quintessa FEP database
- Main perceived risks:
    - Reservoir distribution
    - Fault seal at crest of storage structure
    - Existing wells
    - Top seal

Reservoir distribution



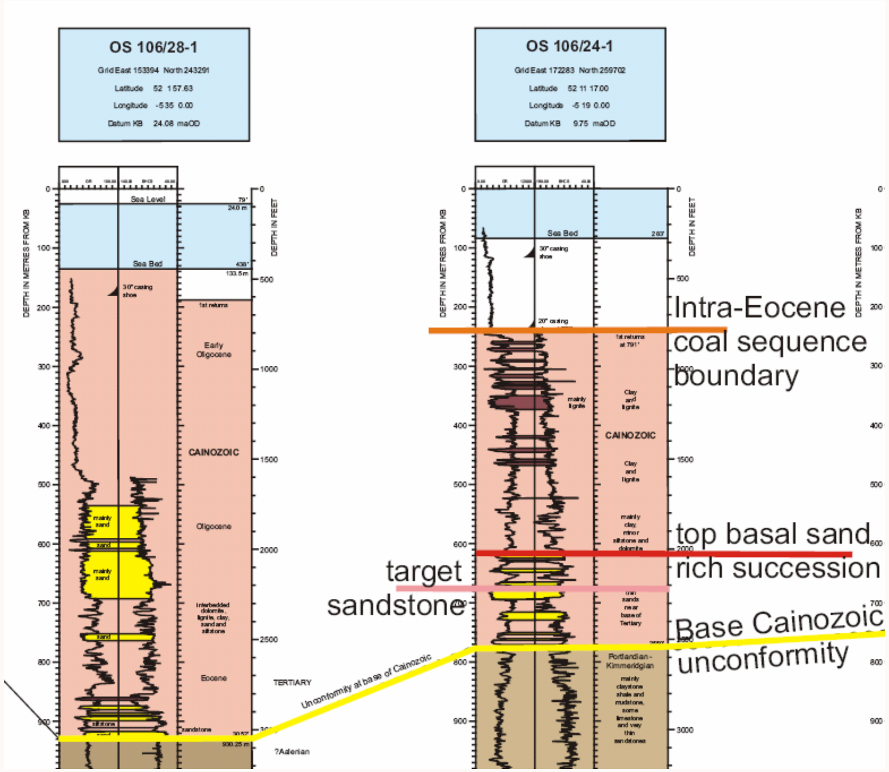
- Fluvial depositional environment
- Petrel model based on well data
- Uncertainty over sand distribution and continuity
- Difficult to resolve without drilling

Fault seal at crest of structure



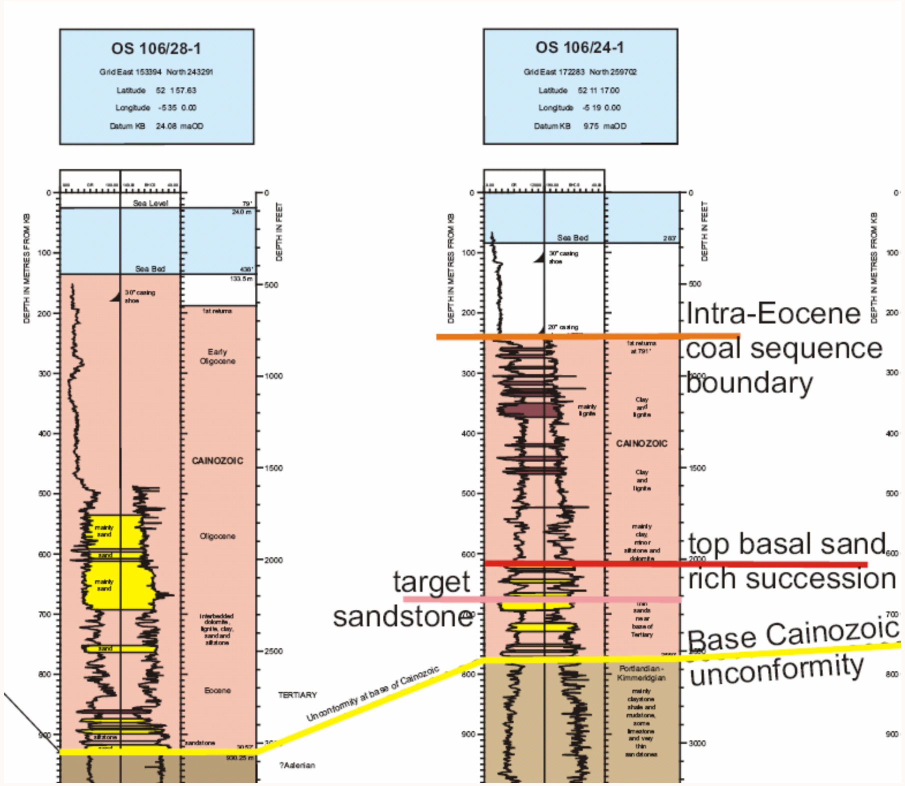
- Partially filled by salt wall
- Initial permeability of fault itself and associated damage zone highly uncertain
- Precipitation reactions predicted where fault is filled with salt
- Drilling and coring might be possible but very expensive

Existing wells



- Wells 106/24-1 and 106/24a-2B lie on migration path/ within storage site
- Plugged and abandoned to high standards, so no reason to assume they will leak
- May be possible to plug them if they do turn out to leak

Top seal



- Reservoir sands overlain by mudstones and lignite
- Permeability not known as could not be tested from cuttings material
- Expectation is of good seal
- Cap rock integrity not likely to be modified by geochemical interactions

Preliminary Conclusions Valleys

- Now in the process to go through FEP process to ensure the major risks have been identified
- Since St. George's Channel basin is poorly explored, with only a handful of wells, the geological risks are much higher than in petroleum-bearing basins
- Simulations show all CO_2 ends up next to the fault
- The cost of reaching robust conclusions about

  (1) whether the fault will leak or seal, and
  (2) whether there is sufficient reservoir sand,
  could be very high.

CO2STORE – the case studies

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The Sleipner CO_2 injection risk analysis

- Three subprojects to be started in 2006:
- **Impacts on Sleipner.** Supplement to regular operational risk assessment. Personnel, environmental and economic risk associated with the operation of the Sleipner licence in the close future.
- **Impacts to other licences.** Personnel, environmental and economic risk associated with the operation of other licences, operated by Statoil or other companies today and in the future. Economic risk related to potential negative impacts from the injection of CO_2 into Utsira to production and well operations in formation intersecting or communicating with Utsira is expected to be a main aspect.
- **Long term performance.** Long term risk related to subsurface deposition of CO_2

And then: What if something leaks…??

- NASCENT: Impacts on communities and terrestrial ecosystems
- Impacts of CO_2 on marine ecosystems not well understood. Upcoming research project to study toxicological effects of CO_2 and low pH on various marine animals under real depth conditions

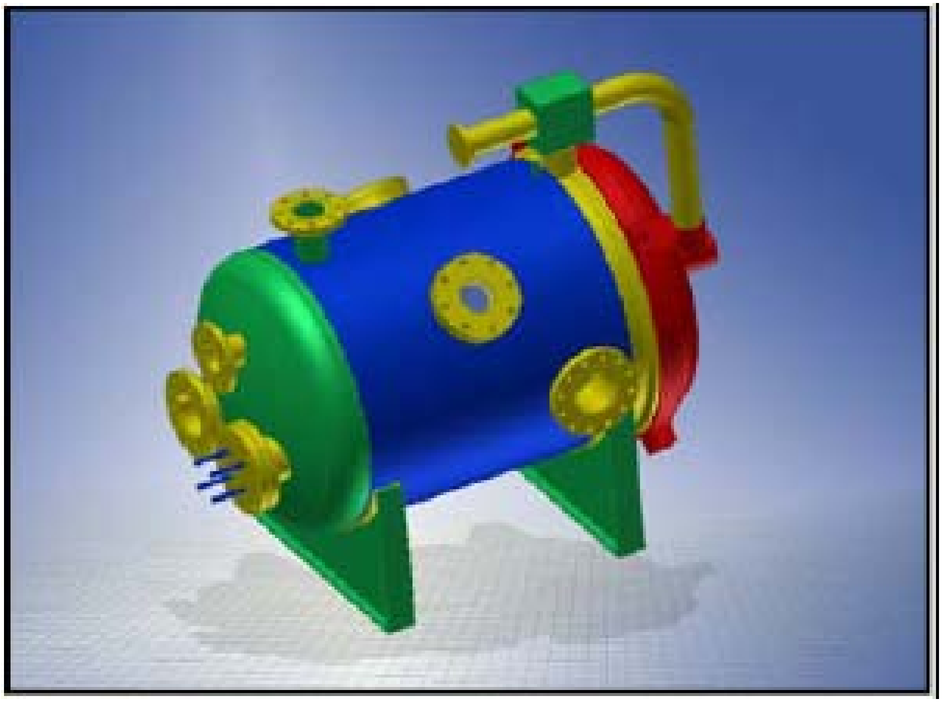
NTNU in cooperation with Statoil to build a titanium tank to simulate conditions on ca. 300 meter depth:

100 cm Ø

30 bar pressure

Sampling device

Various instrumentation



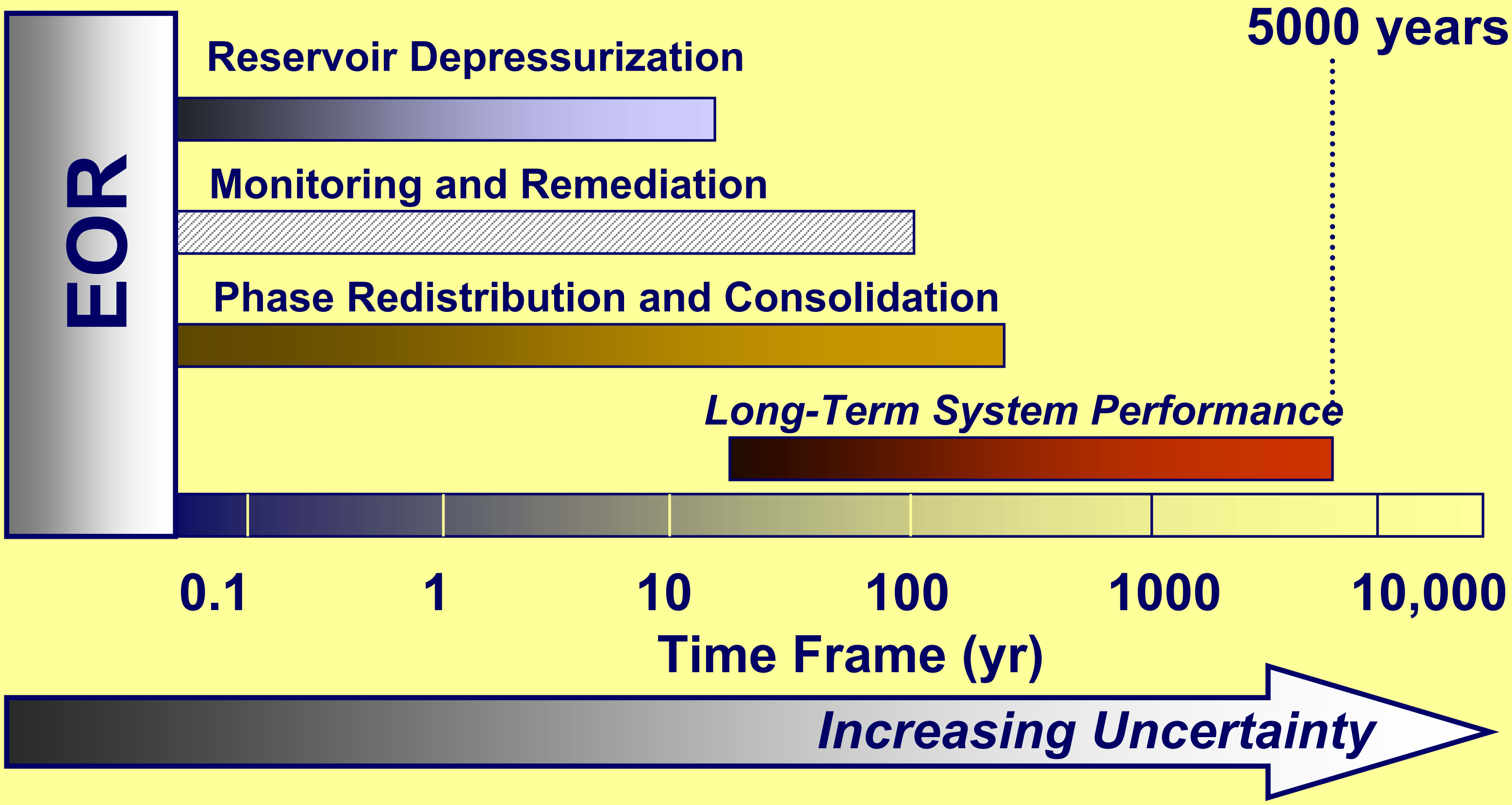
Geological Storage of Carbon Dioxide Risk Assessment Activities & Plans

Koorosh Asghari

CO_2 EOR/Sequestration Advisor

Petroleum Technology Research Center (PTRC), Regina, Canada

Uncertainty as Function of Time

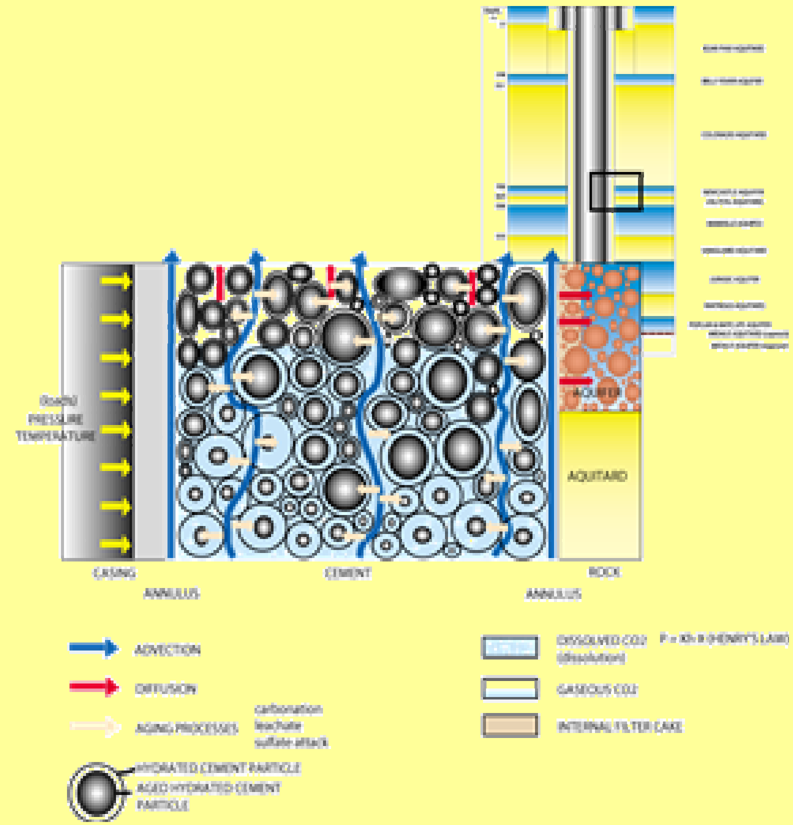


Petroleum Technology Research Centre

Courtesy: EcoMatters

Gaps

- Risk Assessment
- Understanding the wellbore
- Role of fractures
- Improved integration
- Further processing of existing data
- Continued data collection
- Conformance control technology in the field



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Risk Assessment: a major focus area for PTRC

- Early steps of RA were undertaken during the Phase One of Weyburn Project
- Two sets of RA studies were completed at the end of Phase One of Weyburn Project (one deterministic and one probabilistic)
- RA is a major component of the Final Phase of Weyburn Project
- Additionally, PTRC has identified RA as a main focus area that goes beyond Weyburn
- PTRC continues to participate in the various international RA networks

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PTRC’s RA Plans: Beyond Weyburn Phase One

- Weyburn Final Phase
- Apache Midale
- Saline Aquifer

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PTRC's RA Plans: Weyburn Related

- Modelling Issues
- New Tool Development and Evaluation
- Full Stochastic Treatment of CO_2 Storage
- Evaluation of Environmental Impacts
- Integrated Risk Assessment Techniques for Weyburn

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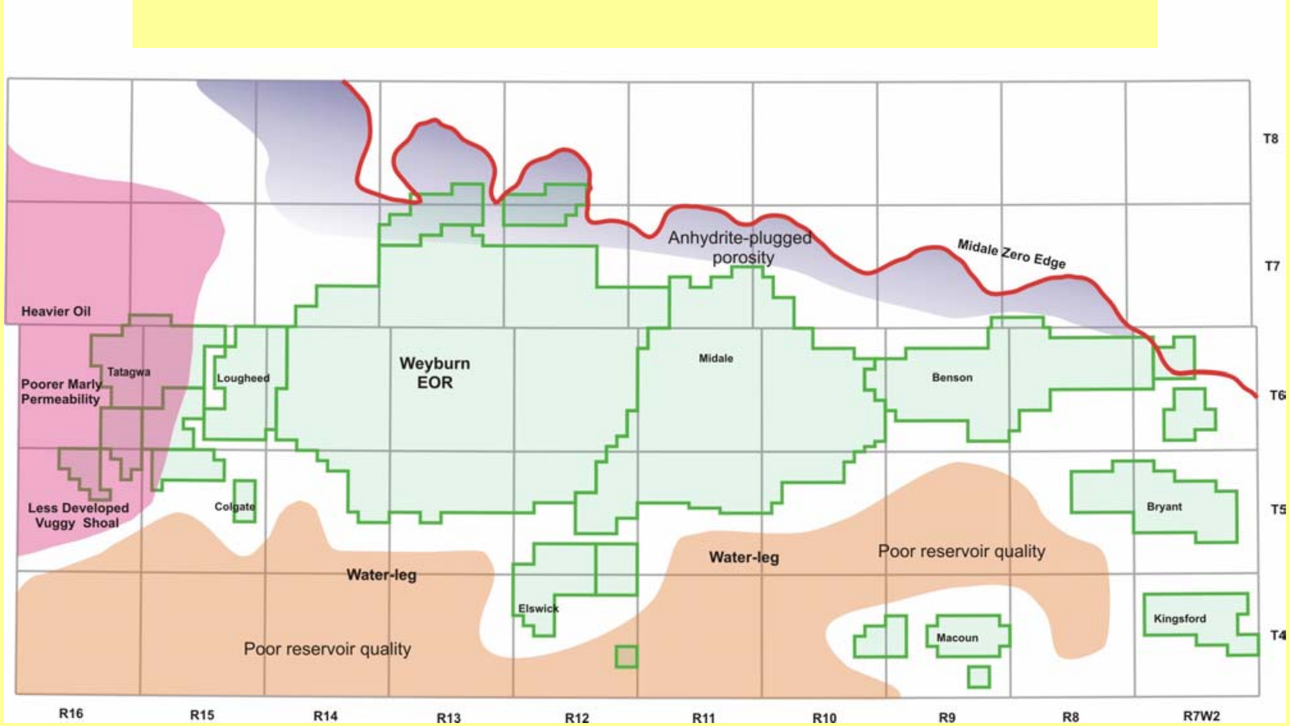
PTRC's RA Plans: Apache Midale



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PTRC's RA Plans: Saline Aquifer

- Storage of 1300 ton/day of carbon dioxide from a refinery in Regina into a local saline aquifer
- Prospect of an integrated capture and storage project near Boundary Dam, Saskatchewan
- A collaborative project between PTRC, Sask Power, University of Regina, Federal and provincial government

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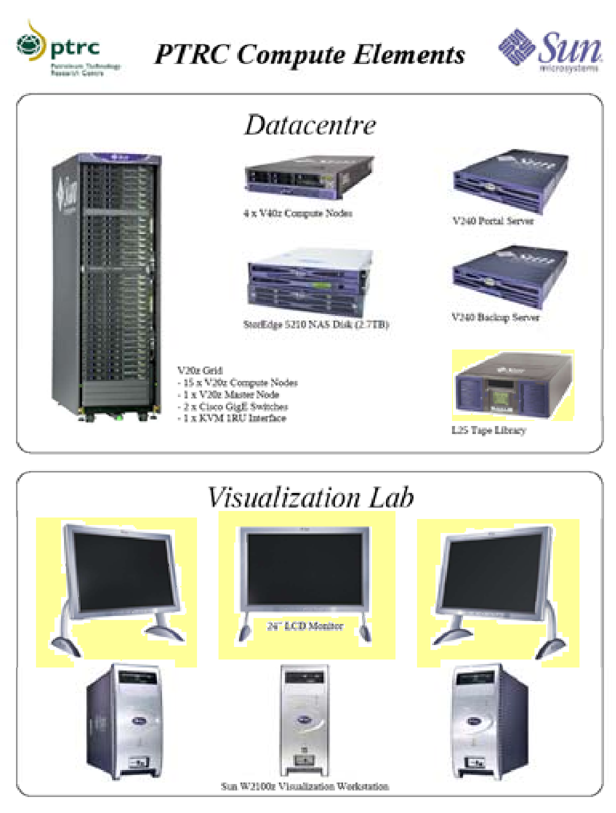
Data Storage and Management

- Data is the key input to the RA process
- Installation of the grid computing system has been Completed. Still needs to implement portal to facilitate easy access for external users
- The process of collecting and storing the data obtained during the Phase One of the Weyburn project has been started
- Requested by Energy Inet to house Pennwest project data



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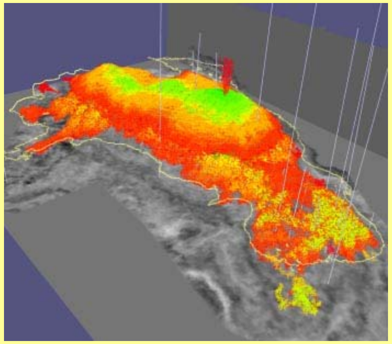
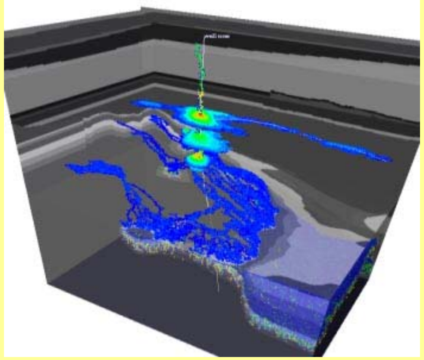
New Tools for Reservoir Simulation

- Permedia &Mpath
- Some of Permedia's sponsors:

  BP
  ConocoPhillips
  ExxonMobil URC
  Norsk Hydro
  Shell
  Statoil Research
  Total





- PTRC-Permedia MOU signed in June 2005

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Mid-Term Goal

- CO_2 Storage Procedures Manual
  - Understand monitoring techniques
  - Conformance techniques
  - Geological interpretation
  - Wellbore design

- Risk Assessment tools developed
  - New and better models
  - Transparent RA tools
  - Confidence in storage integrity
  - Regulators able to set policy
  - Effective screening and monitoring programs designed

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EnergyINet

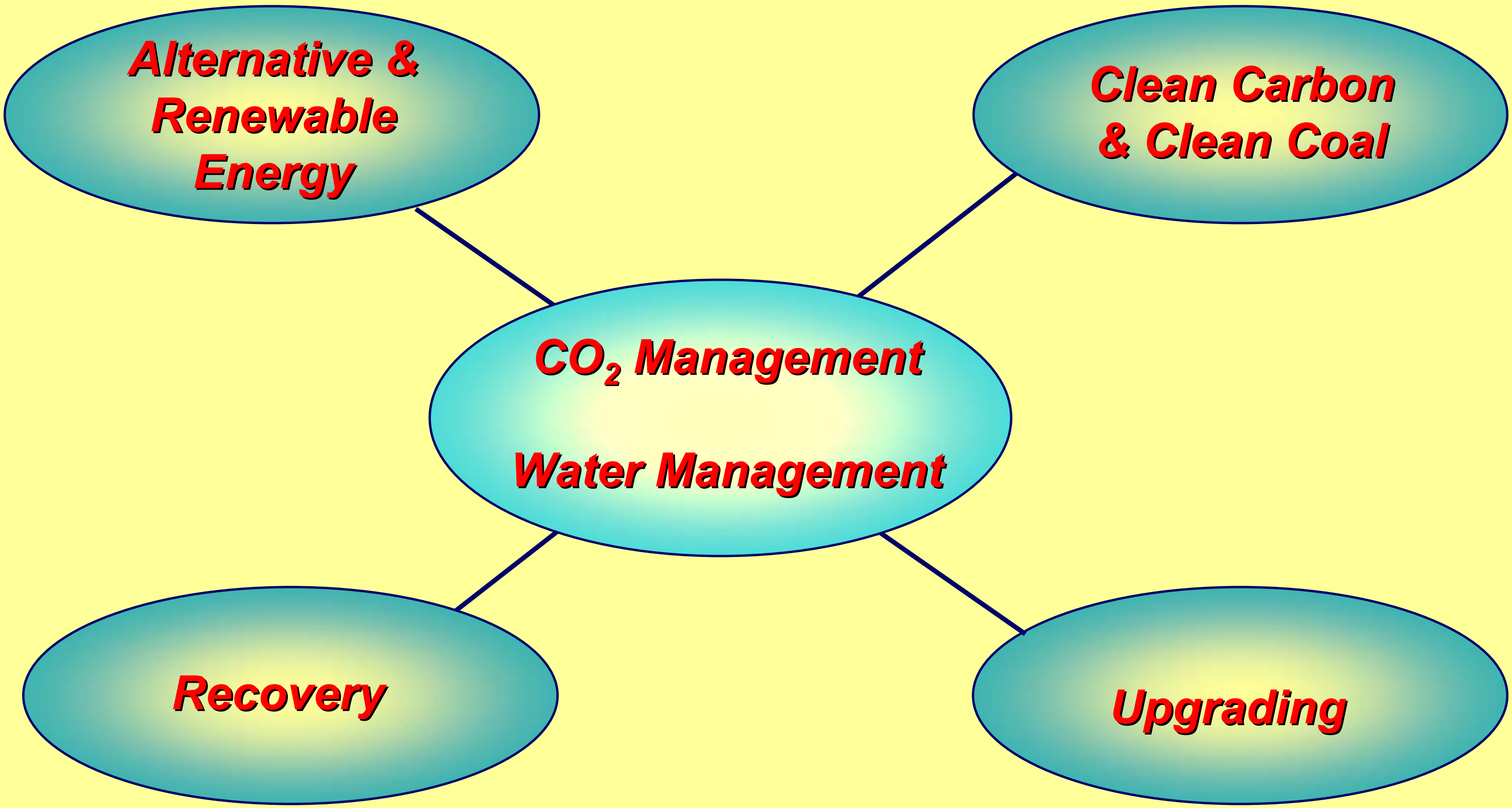
Unlocking Tomorrow's Energy

www.energyinet.com

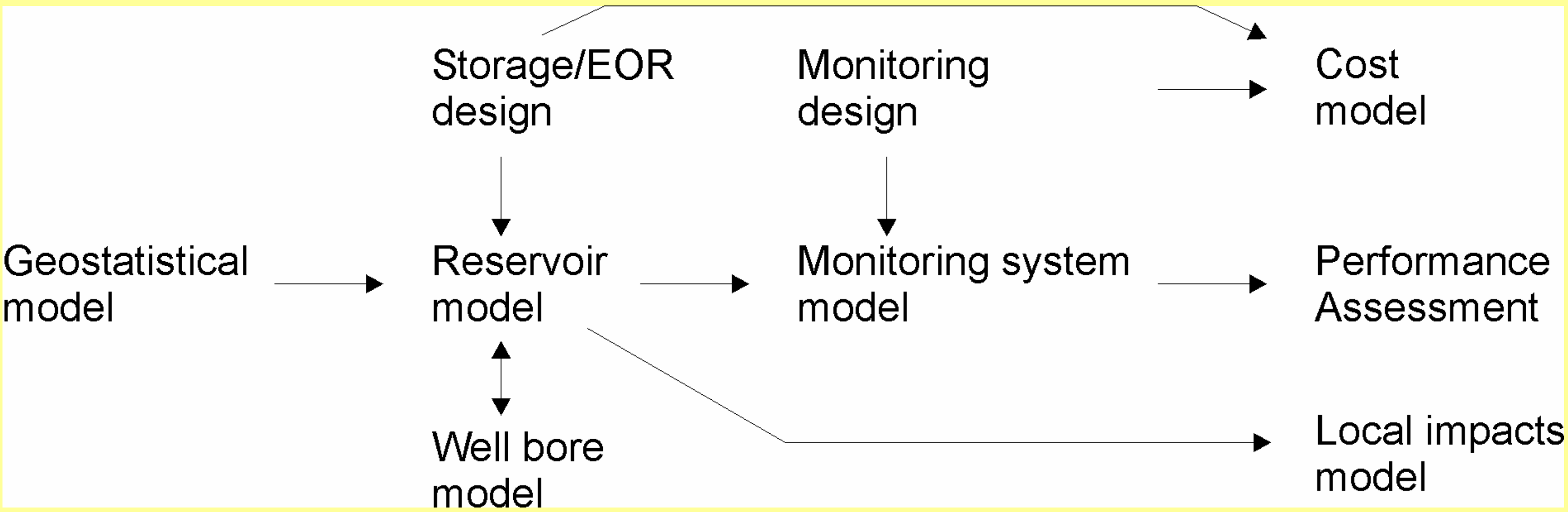
Energy Innovation Network

- Vision
  - An abundant supply of environmentally responsible energy, creating economic prosperity and social well-being for Canadians.
- Key Operating Principles
  - Integration – opportunities that emerge when the energy sector is viewed as an inter-connected whole
  - Collaboration – avoiding fragmentation and achieving shared goals

EnergyINet Innovation Programs



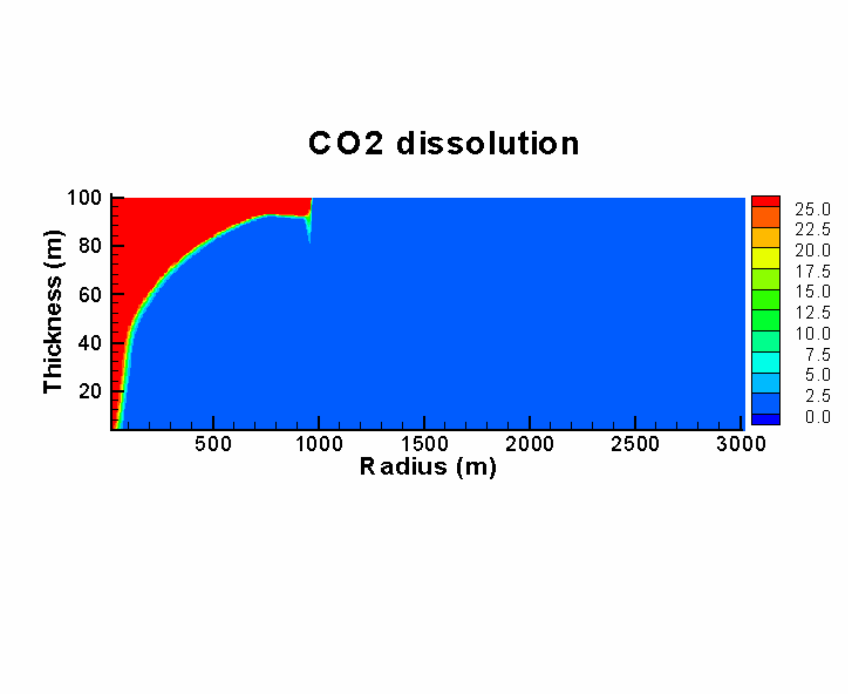
Integrated Geostorage Simulator



- We are developing an Integrated Geostorage Simulator (IGS) using a commercial multi-component reservoir simulator driven by geostatistical models. The reservoir simulator drive models that simulate the performance of advanced geophysical monitoring technologies. The integrated simulator will enable probabilistic predictions of CO_2 flow within reservoirs, co-optimized storage and EOR, and monitoring reservoir performance using geophysical methods

Some initial results: Reservoir Engineering to Accelerate Dissolution

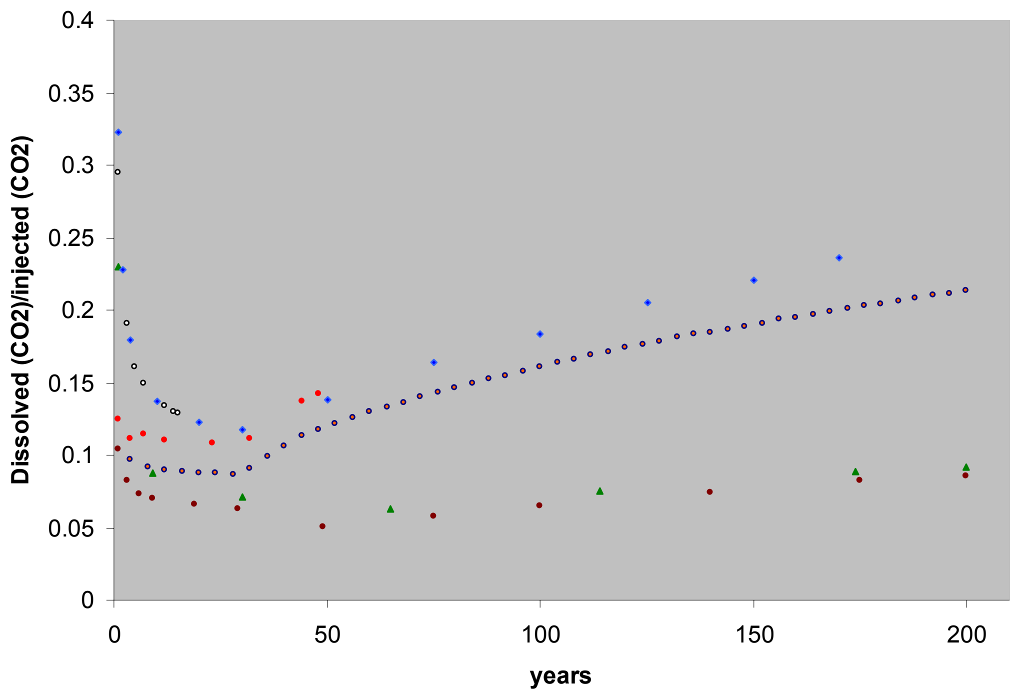
- It is possible to accelerate the dissolution of CO_2 in brines by pumping undersaturated brine to the top of the CO_2 plume. The rate of dissolution can be increased by more than a factor of ten at a cost that is less than 1% of the cost of capture and compression.



- Radial 2D simulation with
- CO_2 injected in center &
- water injection in circular
- horizontal well at 1000 m
- radius

Some initial results: Model intercomparison

- Comparison of Eclipse and GEM on water injection
- 2D Reservoir, infinite in R direction, 100m depth in Z direction.
- Reservoir Properties: T=50C; P=150 bar; K=200md; ϕ=0.25; Salinity=40,000ppm; compressibility=1.45X10^{-5} bar^{-1}



Water injection:
Eclipse shows less disolution than does GEM

No water injection:
Eclipse and GEM simulatoins are almost identical

Remediation of Leakage from CO_2 Storage Reservoirs

IEA/CON/04/108

Scott H. Stevens
Greg Bank
James Caballero

Advanced Resources International, Inc. (ARI)
Arlington, Virginia, USA

IEA Greenhouse Gas R&D Programme
Risk Assessment Network
TNO-NITG, Utrecht, The Netherlands

August 23-24, 2005

Study Objectives

1) **IEA GHG commissioned study.**

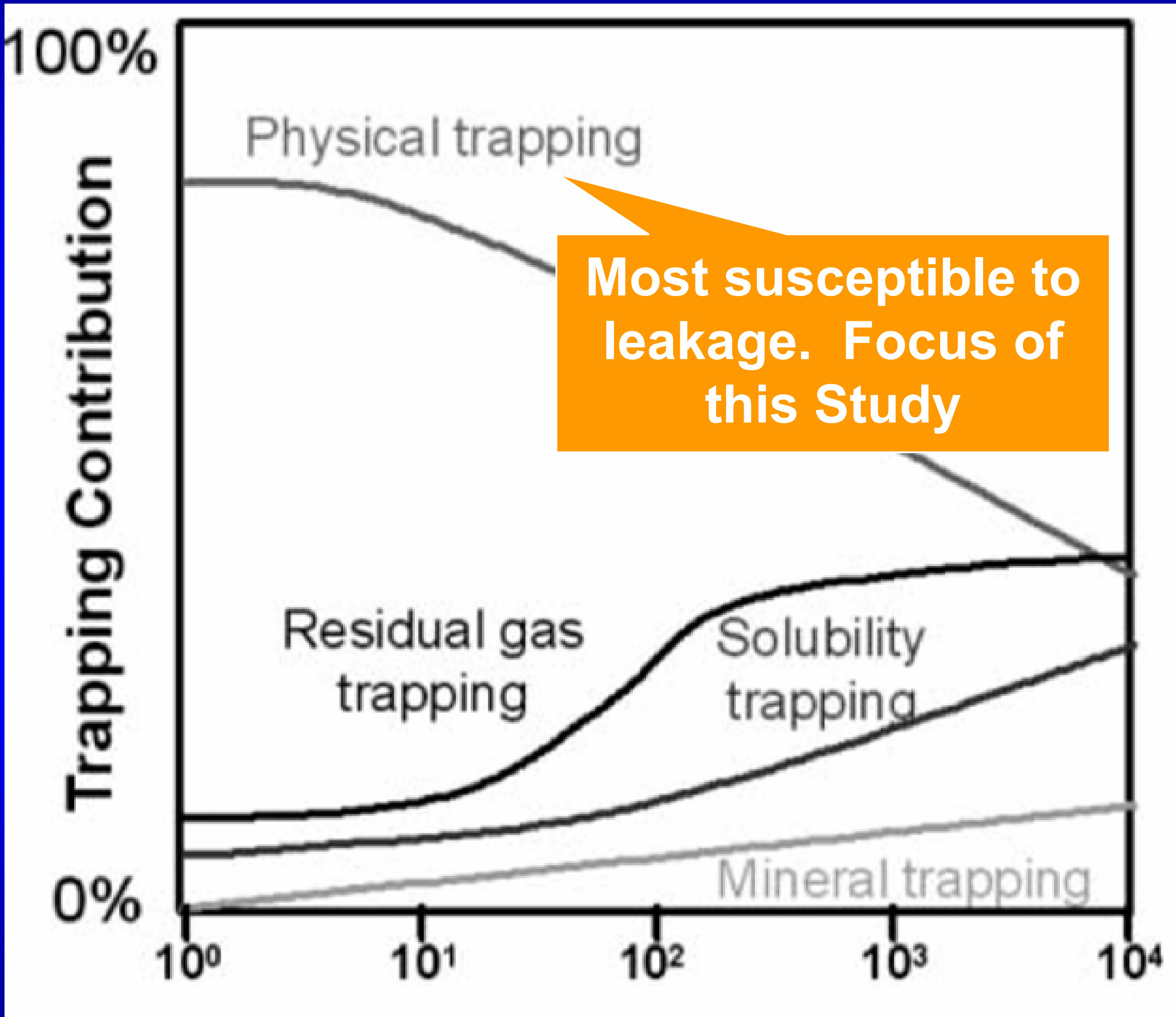
2) **Develop a reference manual on prevention, monitoring, & <u>remediation</u> of leakage at various types of CO_2 storage reservoirs.**

3) **Diverse target audience of technologists and policy specialists.**

CO_2 Storage Mechanisms

CO_2 Storage Mechanisms

1) Physical trap by cap rock (most susceptible)
2) Solubility trap in fluid phase
3) Residual gas trap in pore spaces
4) Mineral trap

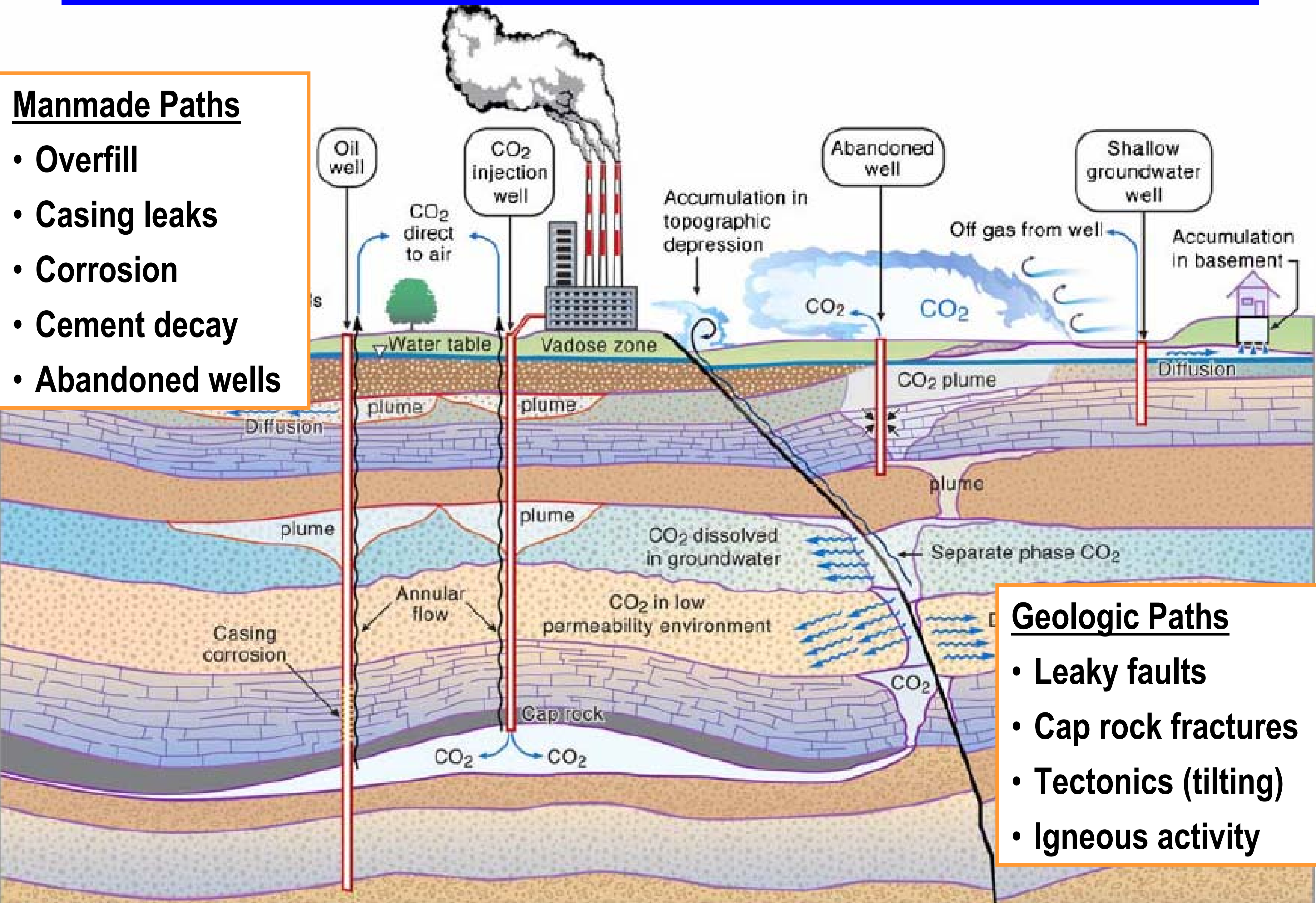


Benson, 2005

Potential CO_2 Leakage Paths : Geologic & Manmade

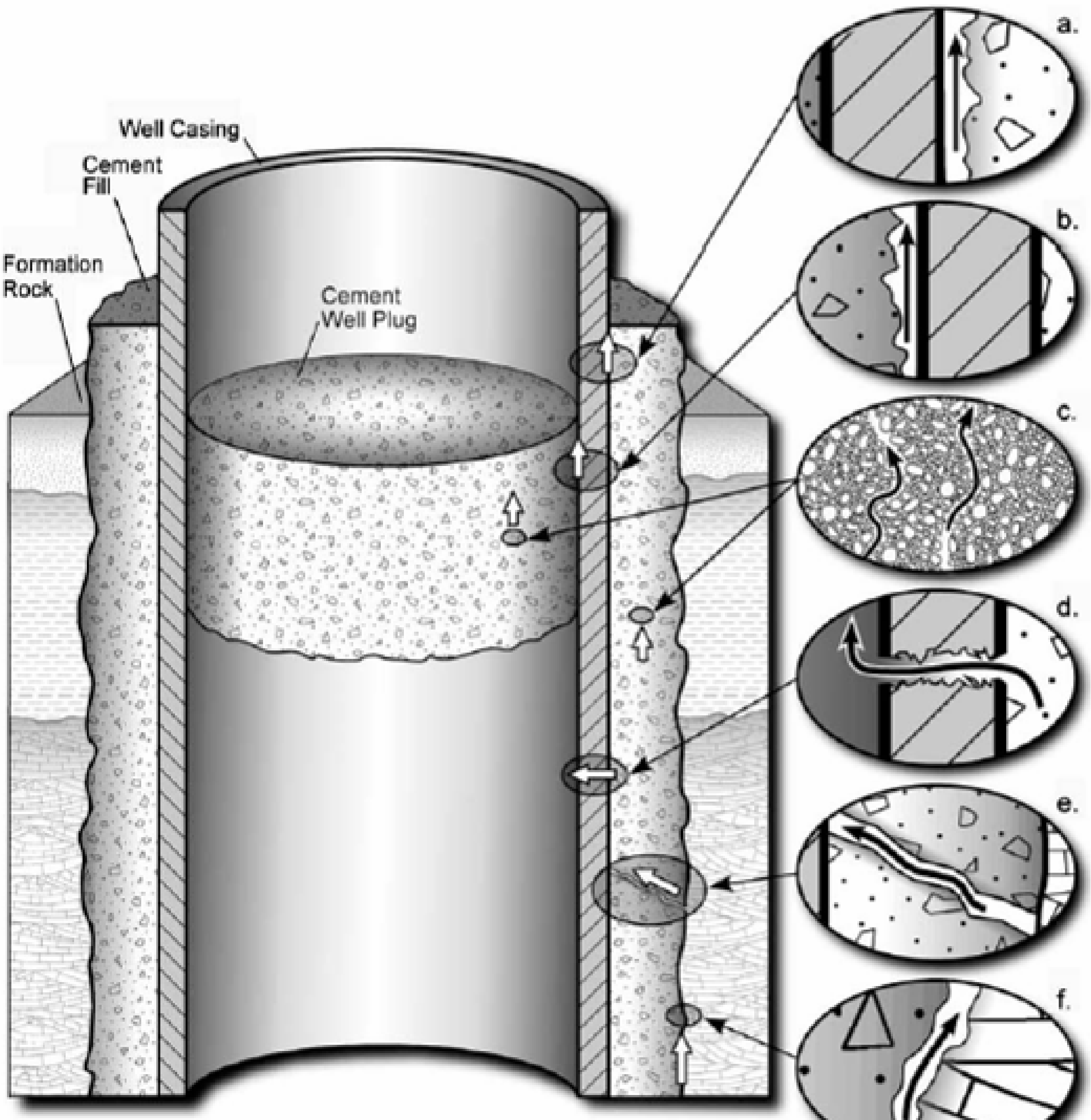
Manmade Paths

- Overfill
- Casing leaks
- Corrosion
- Cement decay
- Abandoned wells



Geologic Paths

- Leaky faults
- Cap rock fractures
- Tectonics (tilting)
- Igneous activity



Scherer et al., 2005

Wellbore Leakage

- *Most hazardous and most likely source of CO_2 leakage.*

Remediation of CO_2 Leakage

1) **Geologic Leakage Pathways**

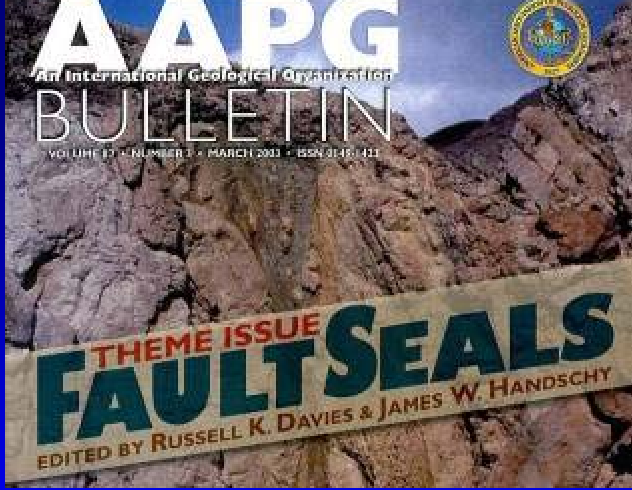
2) Manmade Leakage Pathways

3) Screening Sites to Avoid Leakage

4) Monitoring Technologies

5) Remediation Technologies

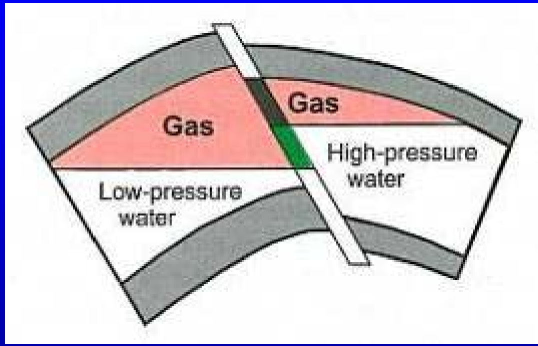
Faults : Seal or Leak ?



Active area of research for hydrocarbon exploration but still not predictive. Even less known about CO_2 movement/trapping across faults.

Fault Sealing Mechanisms

1) Shale gouge in the fault plane.
2) Juxtaposition of reservoir (e.g., ss) against non-reservoir lithologies (e.g., shale) across the fault plane.
3) Seal is function of both rock and fluid properties.
4) Capillary pressure ($P_{CO2} – P_w$).
5) Relative permeability (f of fluid composition).
6) Heterogeneity of fault fill also key.
7) Safeguard: Even if leakage occurs, membrane sealing “snap-off” (K_{rCO2}) resumes at ¼ to ½ of original membrane sealing capacity.



Production- and Withdrawal-Induced Faulting

Case studies show that fluid production or withdrawal has induced faulting in oil & gas reservoirs

Risks

- Sheared injection wells & casing: CO_2 & well capital loss.
- Hole instability during injection well drilling.
- CO_2 leakage along new or reactivated fault planes.
- Earthquakes and ground uplift/subsidence.

Key Studies

- Classic study of injection-induced earthquakes, Rangely oil field, Colorado (Raleigh, 1972)
- Review (Grasso, 1992)
- Definition of conditions causing fault movement or lock (Zoback, 2002a, b)

Production- and Withdrawal-Induced Faulting

2 Fields With Opposite Results

Example 1 : (North Sea)

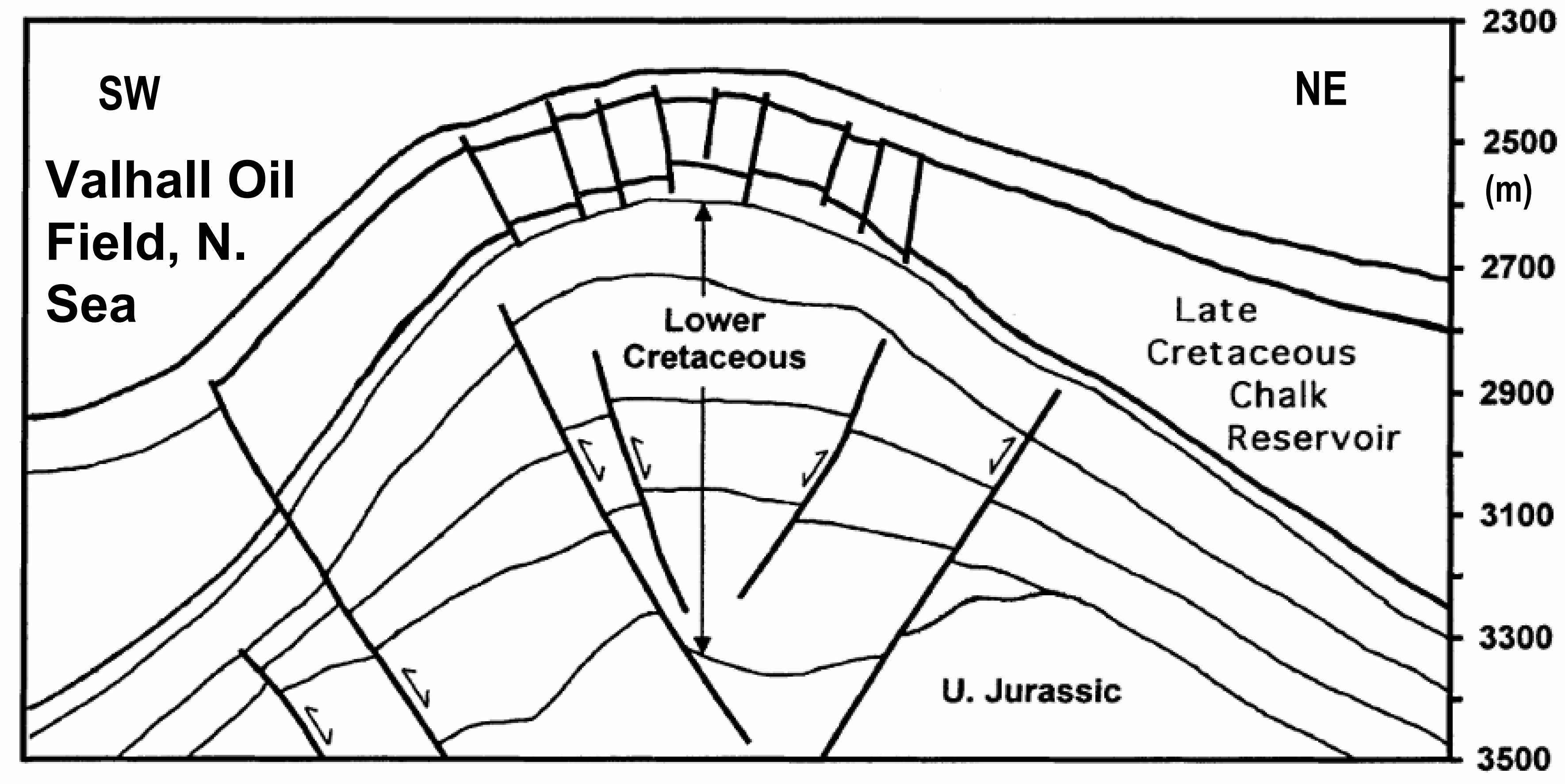
- Production (depletion) exacerbated normal faulting already cutting the crest of the cap rock.
- New faults induced on the flank & micro-earthquakes.

Example 2 : (Gulf of Mexico)

- Initial stress and poroelastic state also promoted active normal faulting.
- But opposite result where depletion actually stabilized the reservoir and curtailed faulting.

Production- and Withdrawal-Induced Faulting

- *Example #1 of production-related induced faulting in North Sea.*
- *Problem of sheared well casings, subsidence, and gas leakage through the cap rock during development at Valhall and Ekofisk fields.*
- *Interpreted to be active faulting at crest of structure that spread onto flanks of structure.*

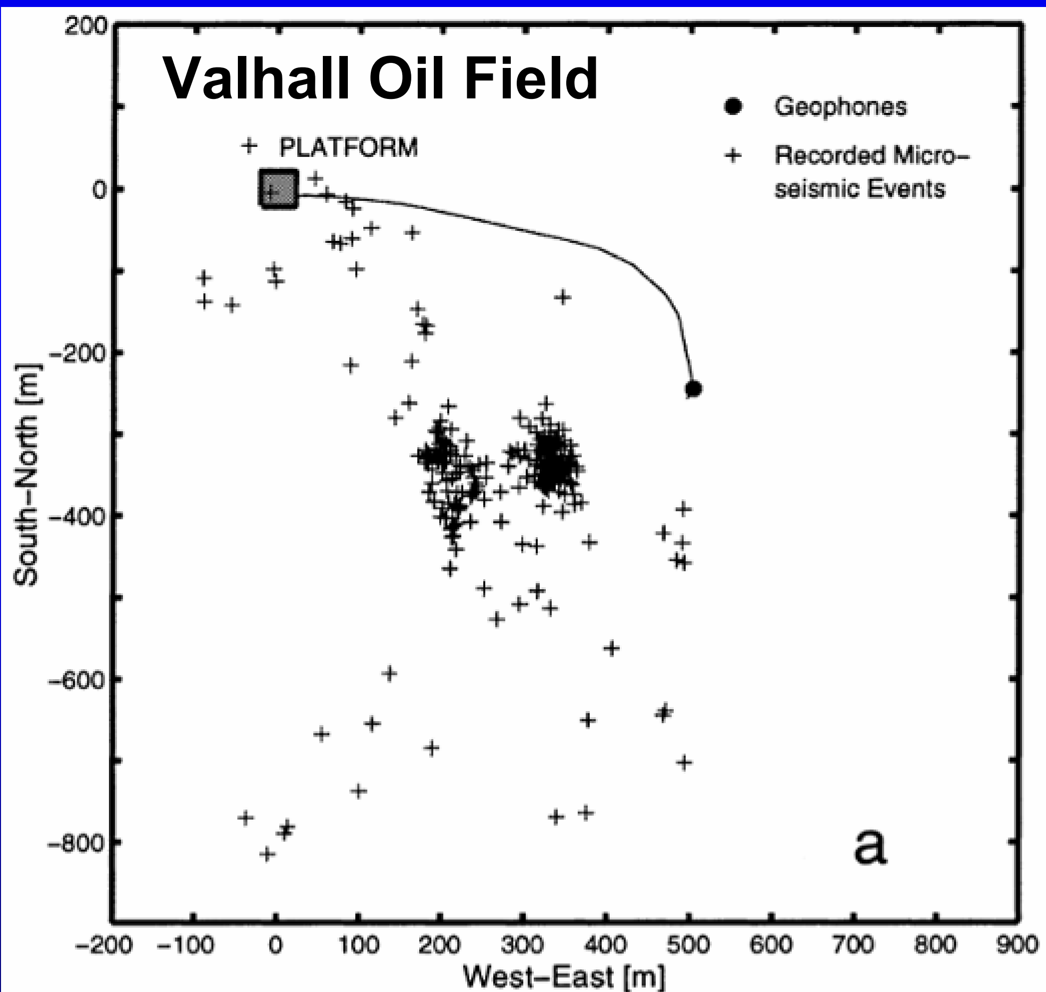


Zoback & Zinke, 2002

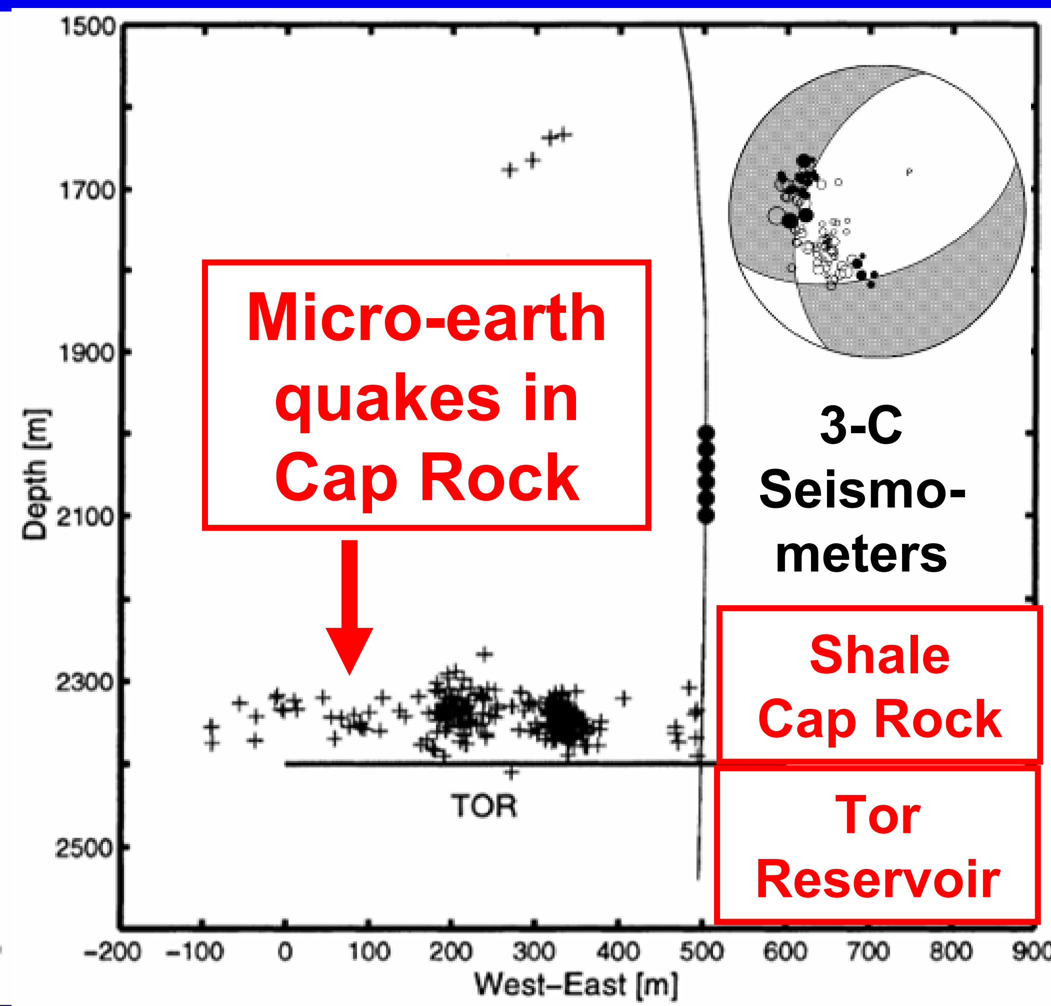
Production- and Withdrawal-Induced Faulting

- *Downhole seismometers detected 327 quakes in 1 month.*
- *Most quakes located 200 m W of monitoring well, in the shale cap rock above the Tor reservoir. Normal fault plane solutions.*

Map View

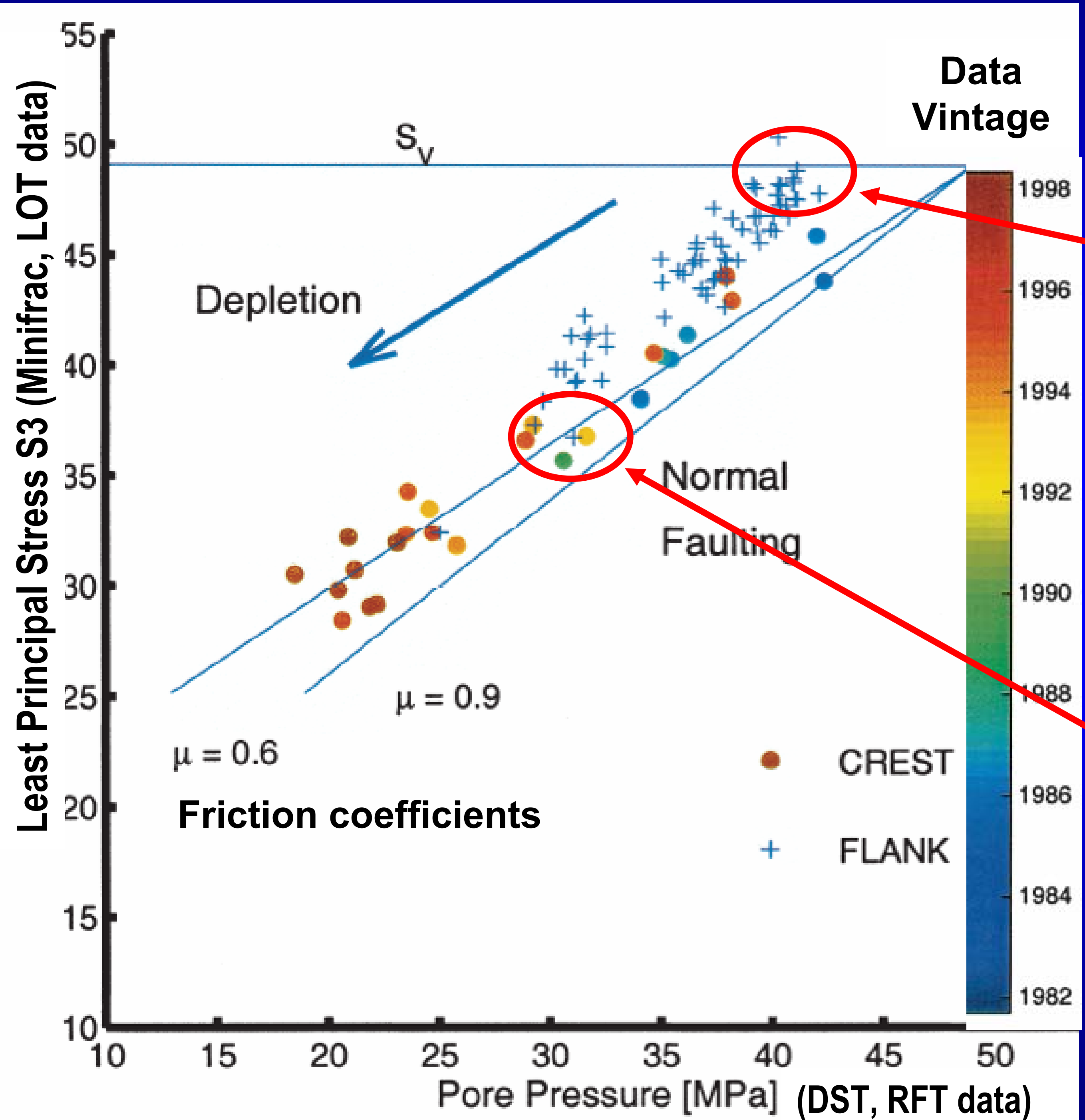


Cross-Section View



Zoback & Zinke, 2002

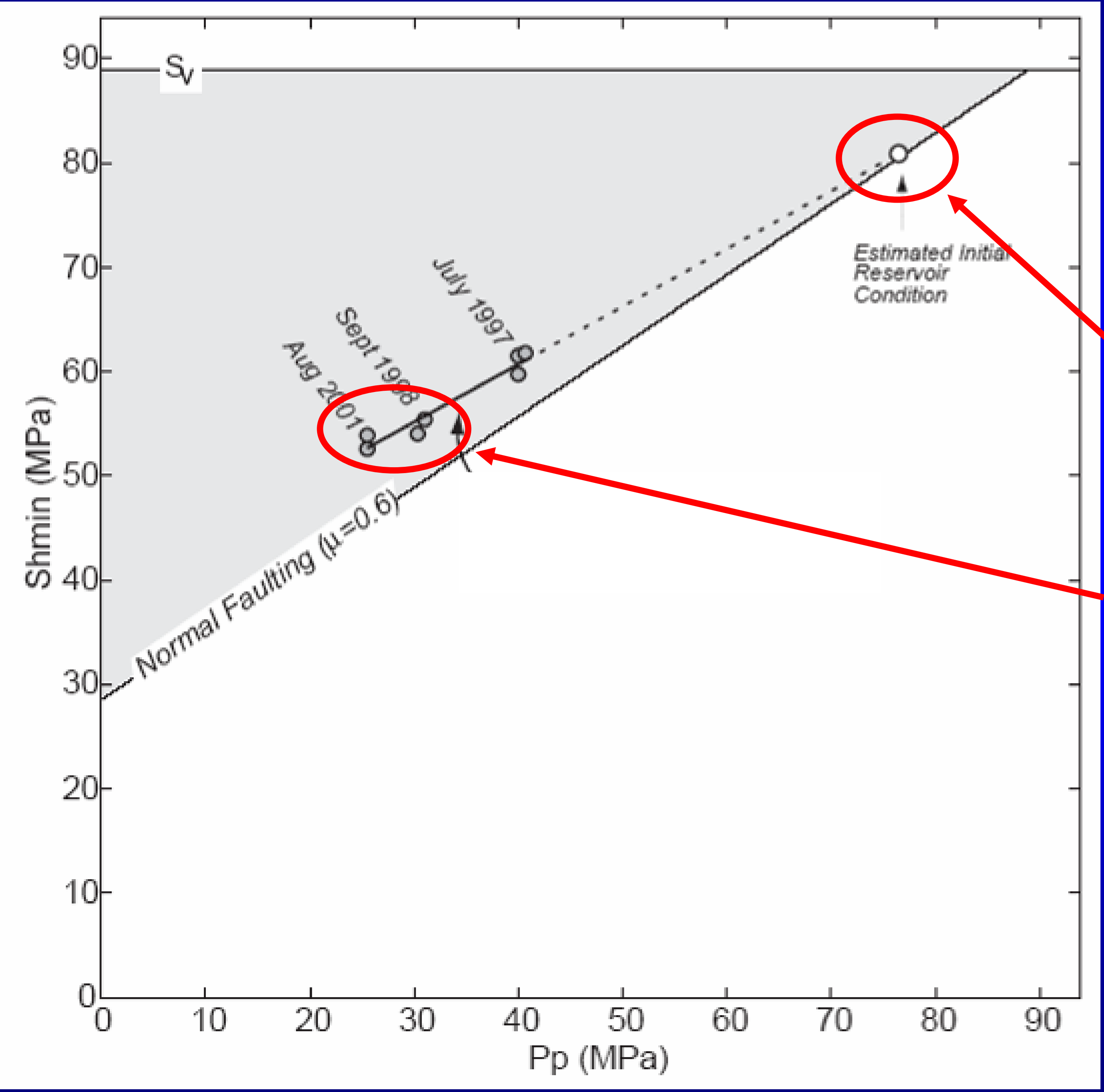
Production- and Withdrawal-Induced Faulting



- Over 15 years time, depletion reduces pore pressure & S-3 (color).
- Initially, stress on crest & flanks was close to overburden stress Sv, although flank had higher stress.
- Crestal measurements already in active normal faulting.
- Flank readings cross into normal faulting regime as depletion occurs <30 MPa.
- (No water flooding at Valhall, unlike Ekofisk)

Zoback & Zinke, 2002

Production- and Withdrawal-Induced Faulting



- *Example #2 (GOM) where depletion stabilized reservoir and curtailed normal faulting.*
- *Initial stress and poroelastic condition favored active normal faulting.*
- *Depletion stress path moved away from the active faulting envelope.*
- *Converse: injection (e.g., of CO_2) back to original state would promote faulting.*

Chan & Zoback, 2002

Production- and Withdrawal-Induced Faulting

Implications for CO_2 Remediation

- *Once faulting has been induced, water injection or pressure maintenance programs may NOT cause faulting to stop.*
- *38-cm/yr subsidence at nearby Ekofisk field was not quelled, nor even slowed, by water injection. Injection, in this case, merely exacerbates fault plan slippage and subsidence.*
- *Need to conduct stress and poroelastic analysis to screen candidate storage reservoirs prior to CO_2 injection.*
- *Avoid reservoirs where stress and pore pressure data indicate active faulting under original or depleted conditions, e.g., as indicated by well casing shear during development.*

Production- and Withdrawal-Induced Faulting

How to Screen Stress & Poroelastic Conditions

1. *Laboratory measurements of porosity and permeability reduction with effective confining pressure (sidewall core).*
2. *Model (e.g., Cam-Clay) to extrapolate lab data up to reservoir scale.*
3. *Initial stress state of reservoir must be measured or estimated.*

    - Initial pore pressure usually known.
    - Sv determined from integration of density logs
    - Shmin determined from leak-off tests (LOT) or mini-fracs.

4. *Continuous reservoir stress path measurements. Poro-elastic theory also may be used.*

Remediation of CO_2 Leakage

1) Geologic Leakage Pathways

2) **Manmade Leakage Pathways**

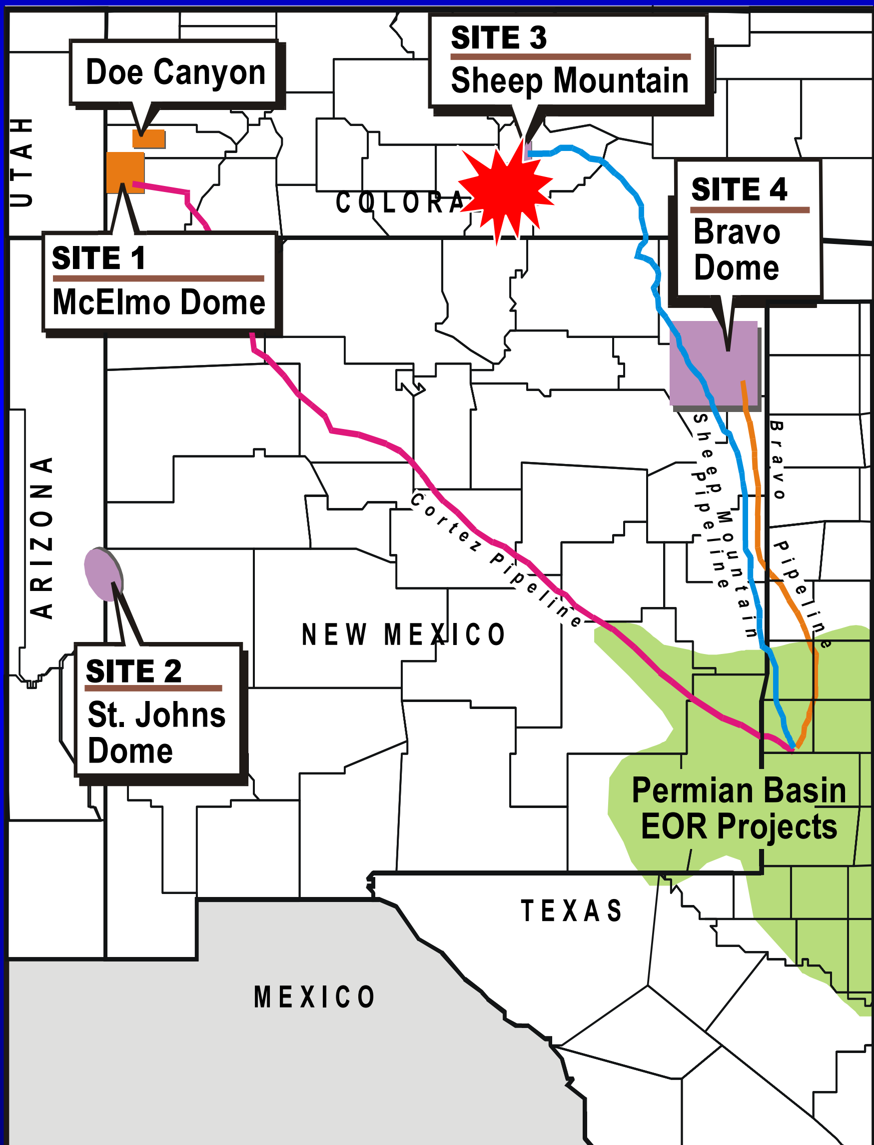
- CO_2 Wells (blowout, cement stability)
- Field Management (gas storage leak)

3) Screening Sites to Avoid Leakage

4) Monitoring Technologies

5) Remediation Technologies

Sheep Mtn CO_2 Well Blowout & Kill (1982)



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Field Characteristics

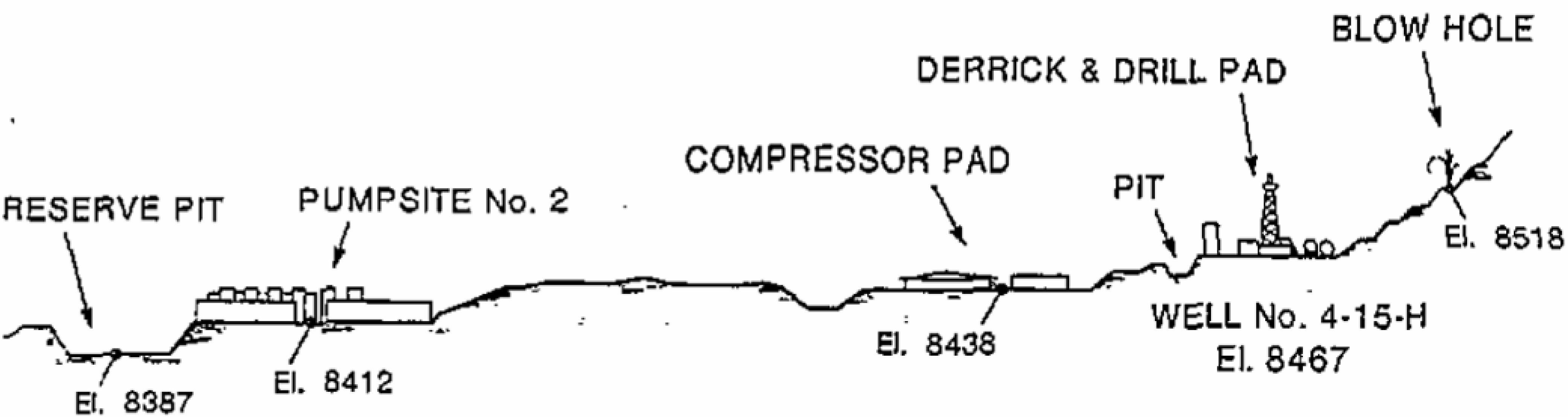
- *CO_2 field (110 million t or 2 Tcf OGIP) in SE Colorado. K Dakota sandstone reservoir @ 1km depth*
- *Supplies 3,000 t/day (54 MMcfd) (down from 15,000 t/day in 1987) injectant for Permian basin EOR.*
- *Shallow, but complex topo & structure; wells directionally drilled from central pad.*
- *Blowout occurred early in field life when pressure was still high and structure poorly understood.*

Stevens et al., 2000

Sheep Mtn CO_2 Well Blowout & Kill (1982)

CO_2 Leakage Event

- *On 3-17-82, directional CO_2 production well 4-15-H blew out during coring operations.*
- *18 days flowed est 11,000 t/day (200 MMcfd).*
- *Total emission 190,000 t (3.6 Bcf) of CO_2.*
- *Comparable in size (but not duration) to Lake Nyos event.*
- *CO_2 vented out of surface rock fractures on the slope of hill directly above the drill site.*



Lynch et al., 1985

Sheep Mtn CO_2 Well Blowout & Kill (1982)

Remediation

- *The underground blowout apparently occurred at base of surface casing (84 m), connecting with offset wells and surface fissures.*
- *Blowout induced by reduction in mud wt -- to 1.1 from safe 1.38 g/cc design -- via centrifuge to remove solids for improved coring.*
- *Operator initially unable to kill the well by injecting overbalanced kill fluids (simplest solution), because the small tubing size (11.4-cm or 4.5-in) caused excessive frictional pressure losses.*
- *Instead, the well was finally controlled by use of dynamic kill technology: the flowing frictional pressure was reduced by adding friction reducers to the $CaCl_2$-brine (1.26 g/cc) kill fluid (1500 bbls).*
- *This mixture was injected through a snubbing unit at a rate of 570 m^3/hour down the production tubing. Well was then P&A'd.*
- *A batch of hematite-based mud was prepared and stored as a backup, very heavy (2.64 g/cc) kill fluid.*

Lynch et al., 1985

Sheep Mtn CO_2 Well Blowout & Kill (1982)

Implications for CO_2 Storage

- *Fortunately, no adverse environmental or health impacts occurred in this sparsely populated area.*
- *Incident demonstrated that industry well control techniques can be successfully applied to CO_2 production and (by analogy) injection.*
- *Unlike over-pressured Sheep Mtn field, future sequestration sites are likely to be depleted oil and gas fields with low risk of blowout during injection.*
- *Storage sites, if depleted oil & gas fields, will have extensive data control.*
- *Structurally complex fields, such as Sheep Mtn, should not be selected as a storage site.*

Lynch et al., 1985

Wellbore Integrity

- ***Sheep Mtn CO_2 Field*** *(BP). Plastic-coated carbon steel tubing (PK99) and WH still corrodes, especially in last few years; stainless recommended (like at McElmo Dome). Casing annulus P closely monitored.*
- ***Cement Integrity*** *(Halliburton). Although few Permian B. CO_2-EOR wells have failed (LS), Portland cements corrode rapidly in CO_2-charged SS reservoirs. A solution is Ca-Ph based cement (ThermaLock) used in geothermal fields (pH = 2). But 6X more costly: $50 to $400k for onshore P&A, even more offshore.*
- ***1000-Year Well*** *(BP). Is standard needed? Workable? Numerous existing abandoned wellbores present greater danger than the better engineered CO_2 injection wells.*

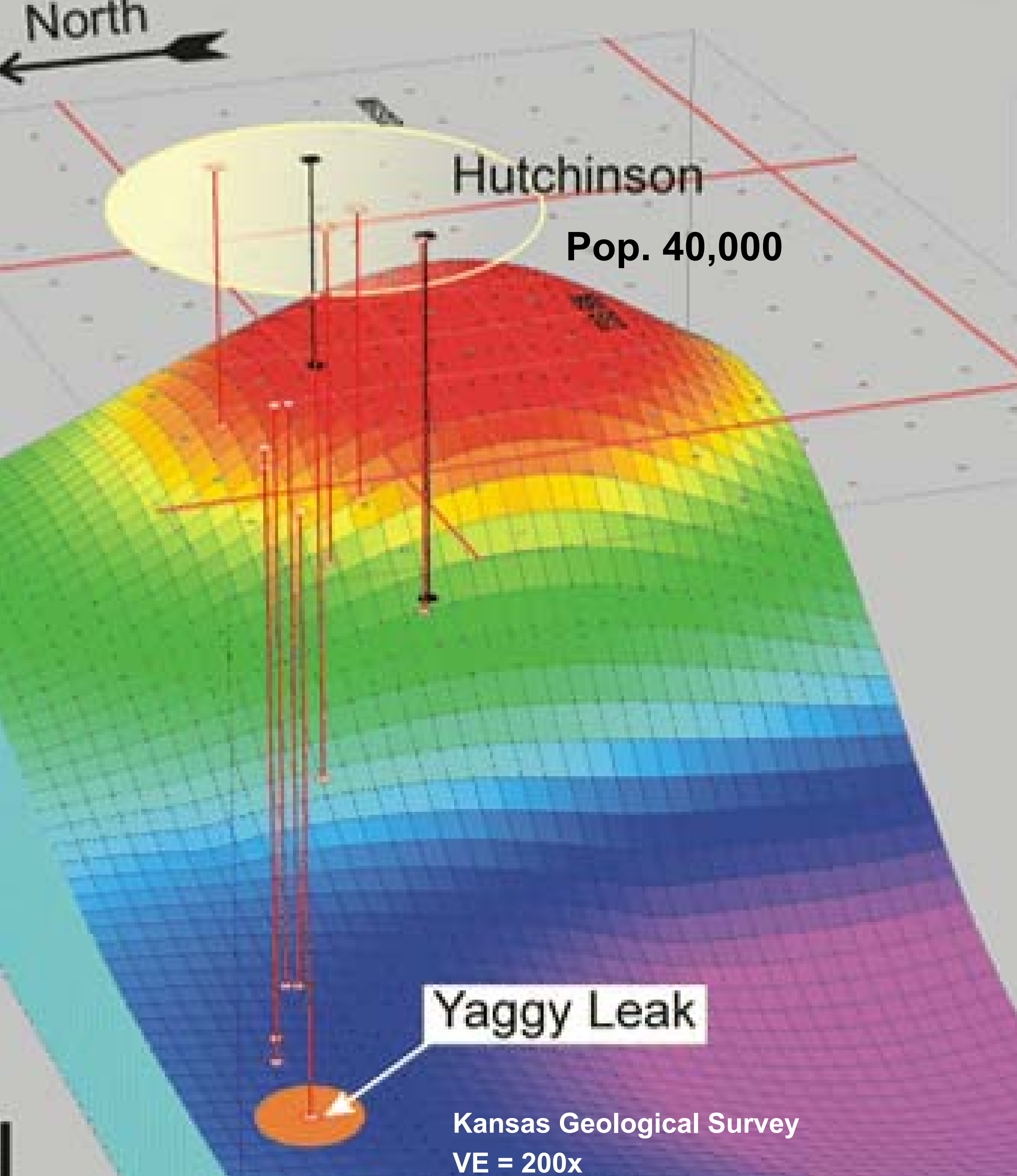
Lynch et al., 1985

Yaggy (Kansas) Gas Storage Field Leak

Hutchinson, KS Fire Dept

AAPG Explorer, July, 2002

- *1-17-2001 natural gas leak & explosion destroyed 2 buildings in the town of Hutchinson, Kansas, C-USA.*
- *The next day, another explosion 5 km away at mobile home park killed 2 people.*
- *Numerous gas geysers.*
- *An estimated 4 million m^3 of natural gas leaked from an injection/ withdrawal well at Yaggy underground gas storage field, 10 km away. Timing of leak uncertain.*

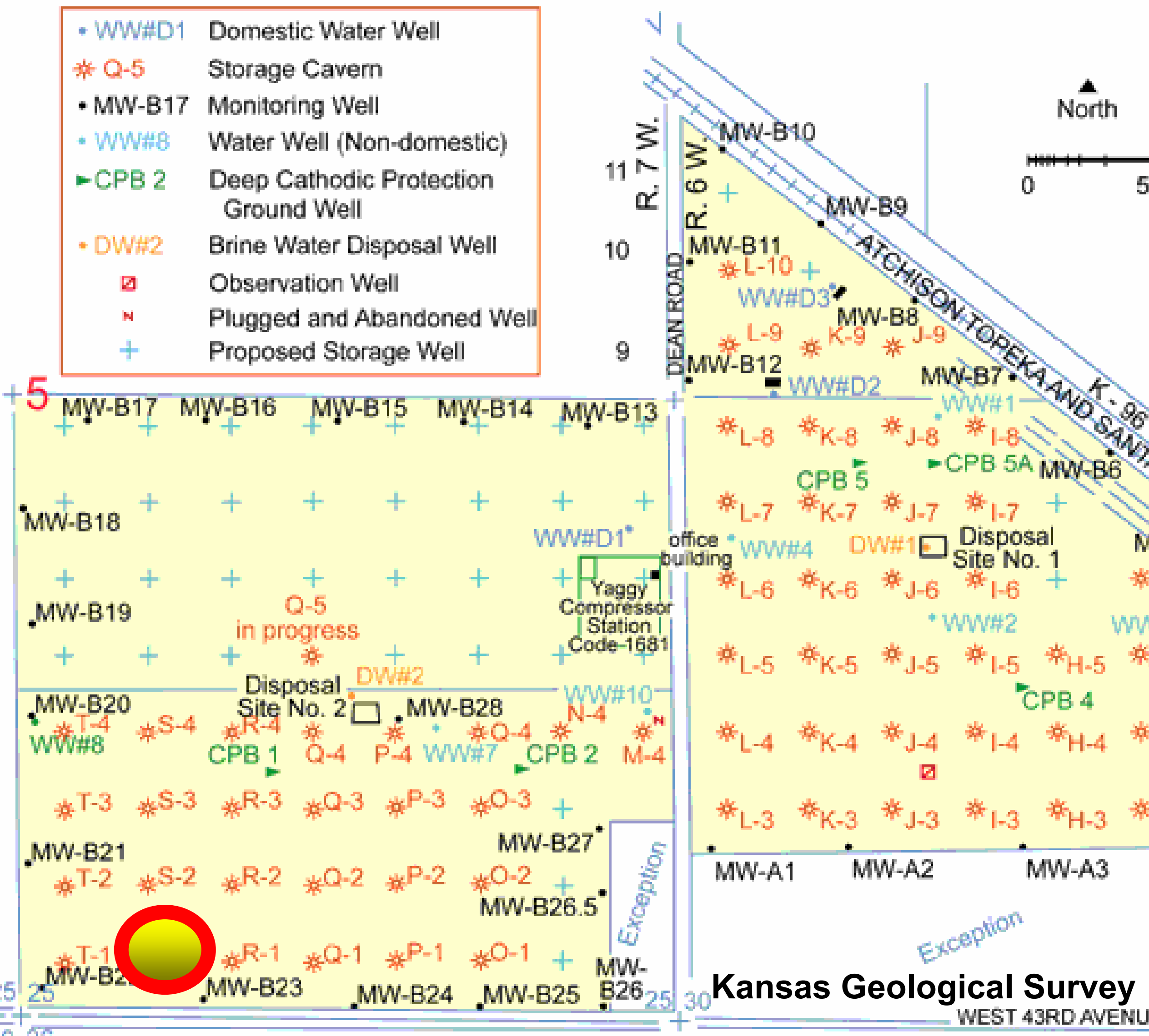


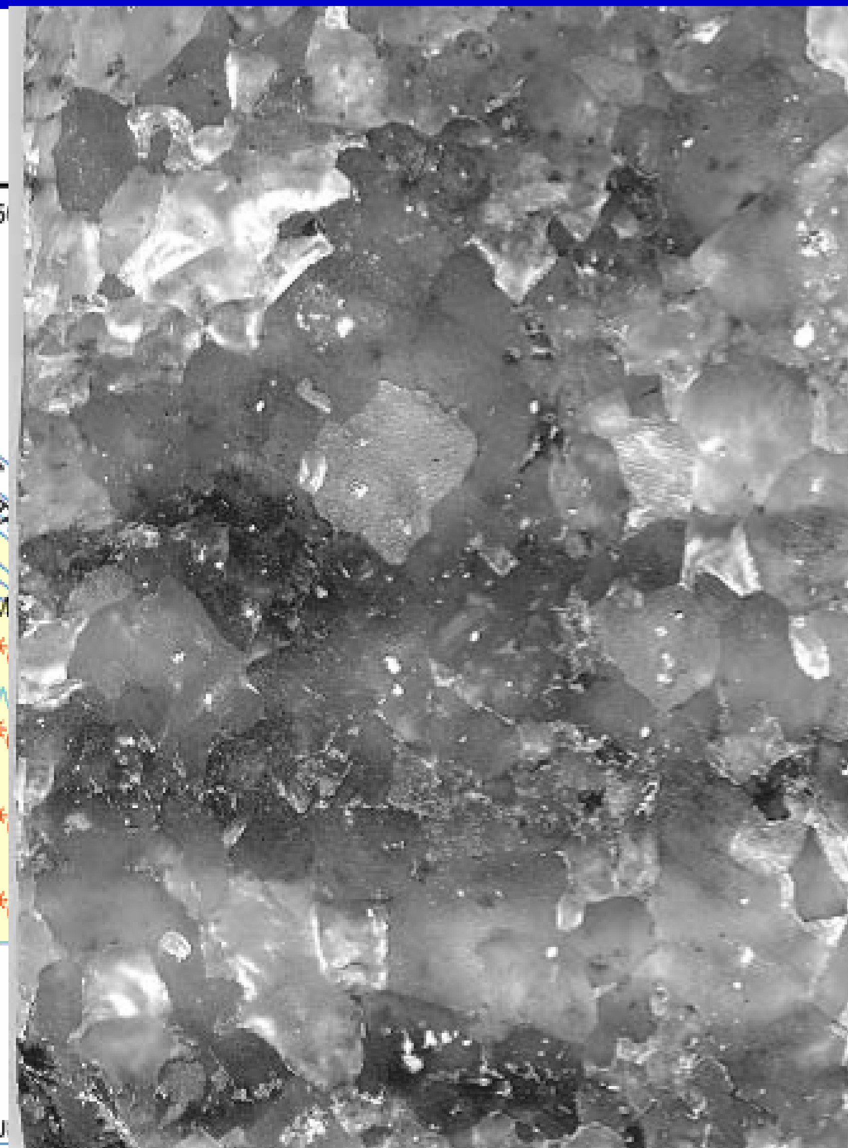
Yaggy (Kansas) Gas Storage Field

- *Gas leaked from underground salt cavern storage field.*
- *Flowed updip to Hutchinson, KS.*
- *Reached surface via high-perm fractured dolomite, then to surface through aband'd brine wells.*

Yaggy (Kansas) Gas Storage Field Leak (2001)

- *98 solution-mined storage caverns in Permian salt at depth of 200 m. Storage capacity totals 82 million m^3 (2.9 Bcf), making it a small field.*
- *Casing leak in S-1 storage well, @ 4 MPa pressure, just below top salt and 56 m above the top of the salt cavern, 3 days before 1st explosion.*





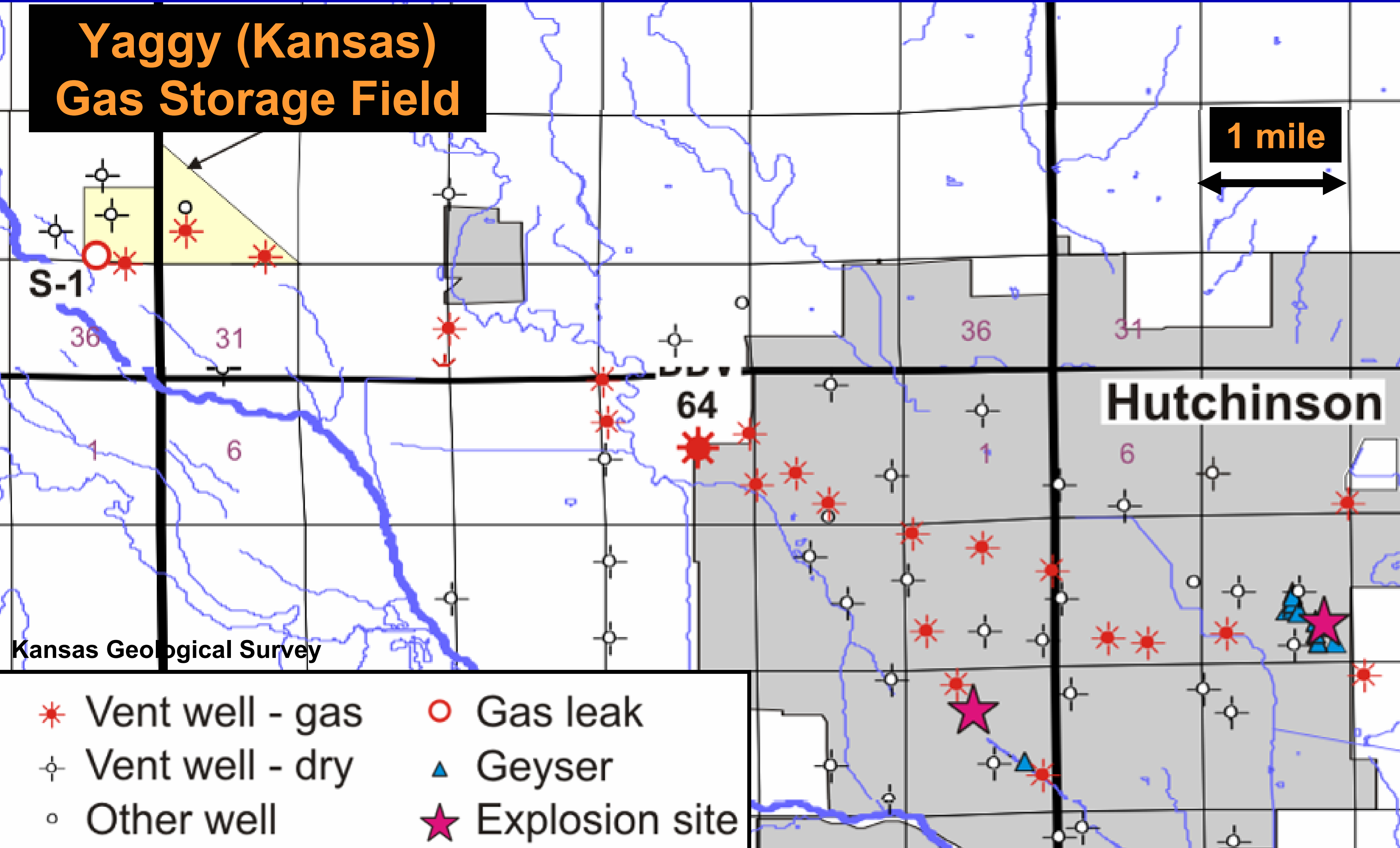
Yaggy (Kansas) Gas Storage Field Leak (2001)

- *Yaggy is a relatively small salt cavern gas storage field.*

MAJOR SALT CAVERN STORAGE CAVERNS
(Billion Cubit Feet)

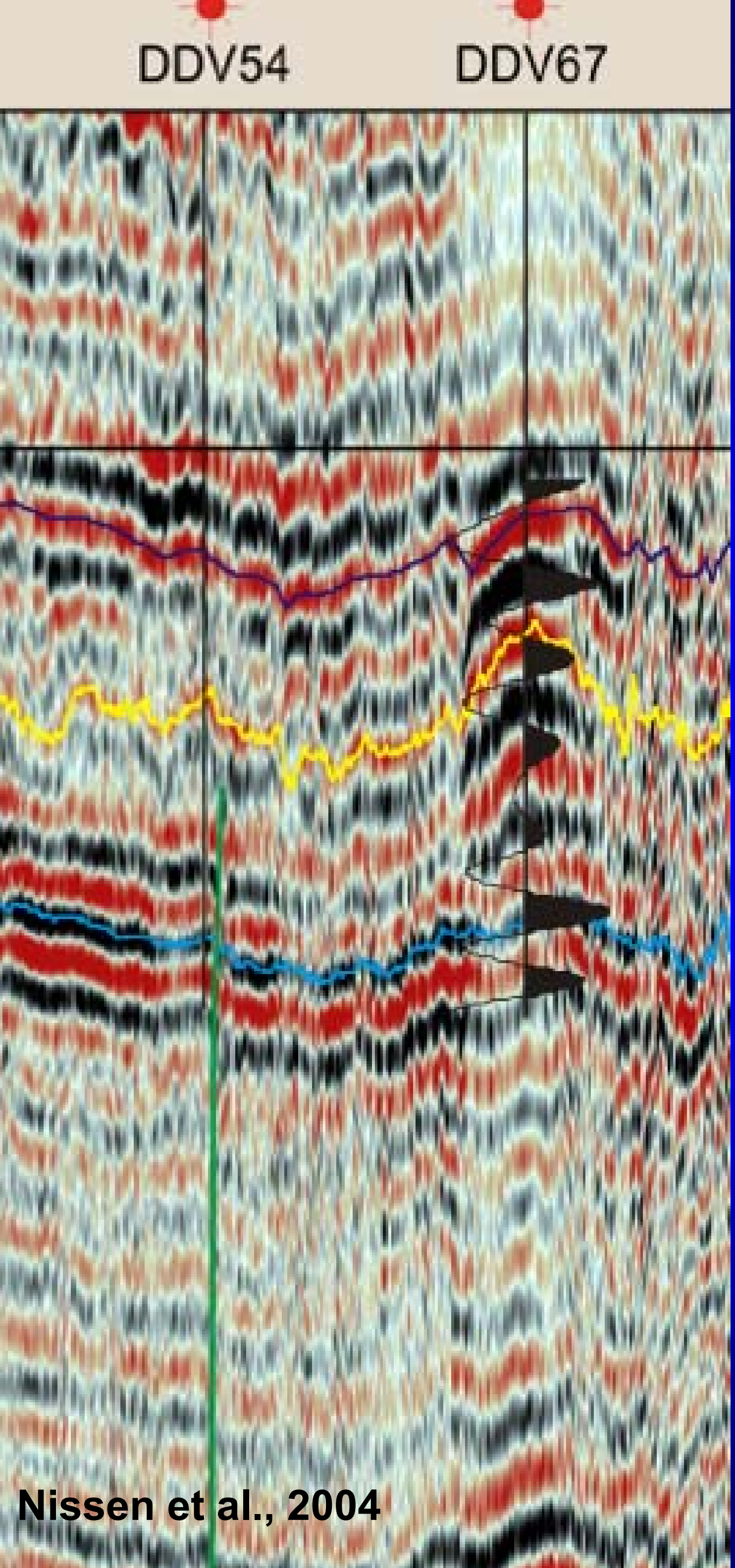
Facility	State	MMcfd Max Injection	MMcfd Max Withdraw	Bcf Capacity
Hattiesburg Hattiesburg	**Mississippi**	175	350	5.5
Moss Bluff Tejas	**Texas**	450	900	11.4
North Dayton HNG Storage	**Texas**	250	500	6.3
Petal Crystal Gas Storage Inc.	**Mississippi**	160	320	3.2
Stratton Ridge Tejas Ship Channel LLC	**Texas**	80	250	2.0
Stratton Ridge KN Energy	**Texas**	50	100	6.8
Wilson Storage Valero	**Texas**	360	800	7.2
Total:	**Natural Gas Week**	1,715	3,410	45.3

- *Following explosions, 57 vent wells & 5 observation wells were drilled.*
- *Gas channeled between field and town within thin (30-m) dolomite.*



Yaggy (Kansas) Gas Storage Field

Monitoring

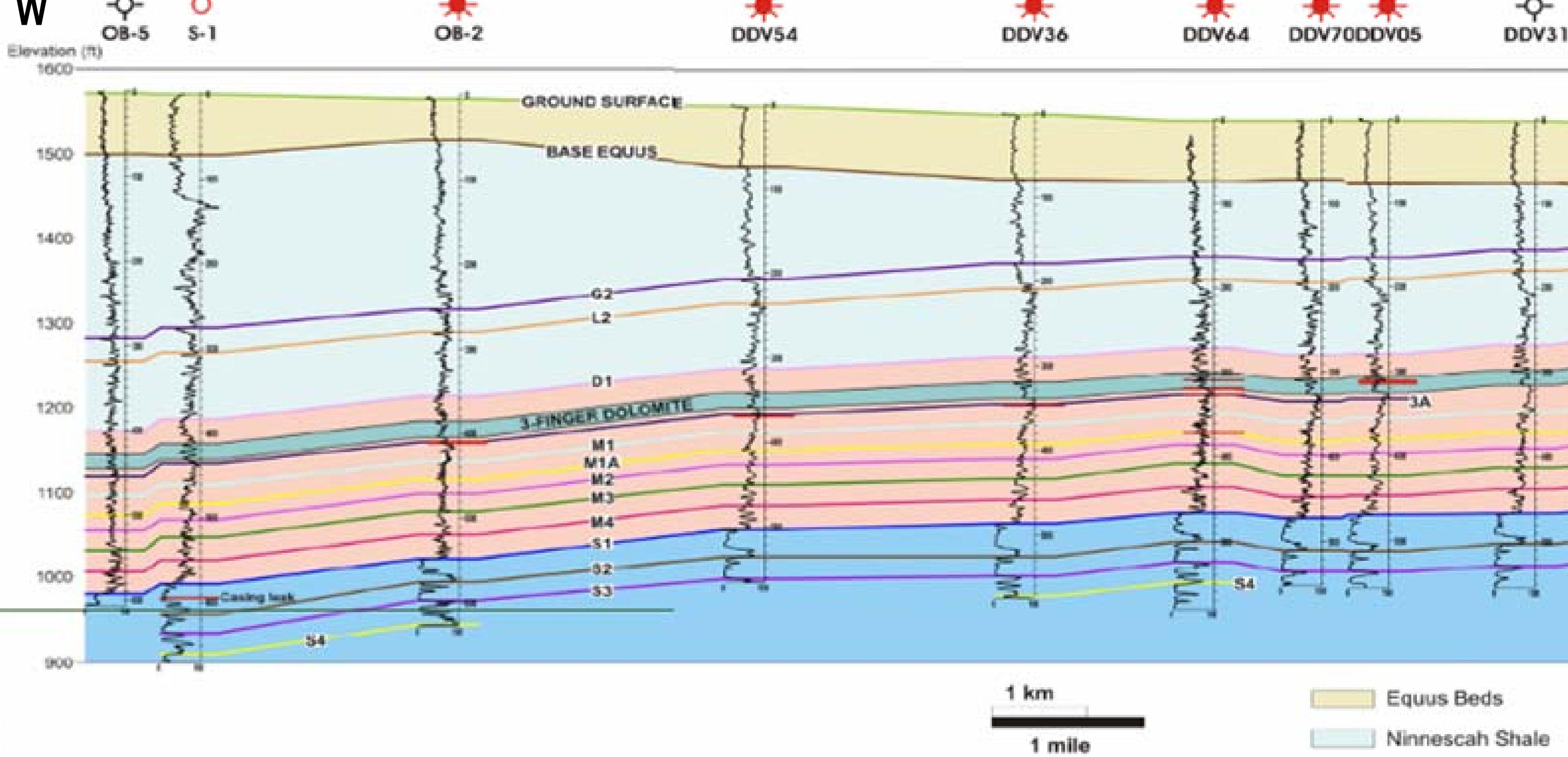


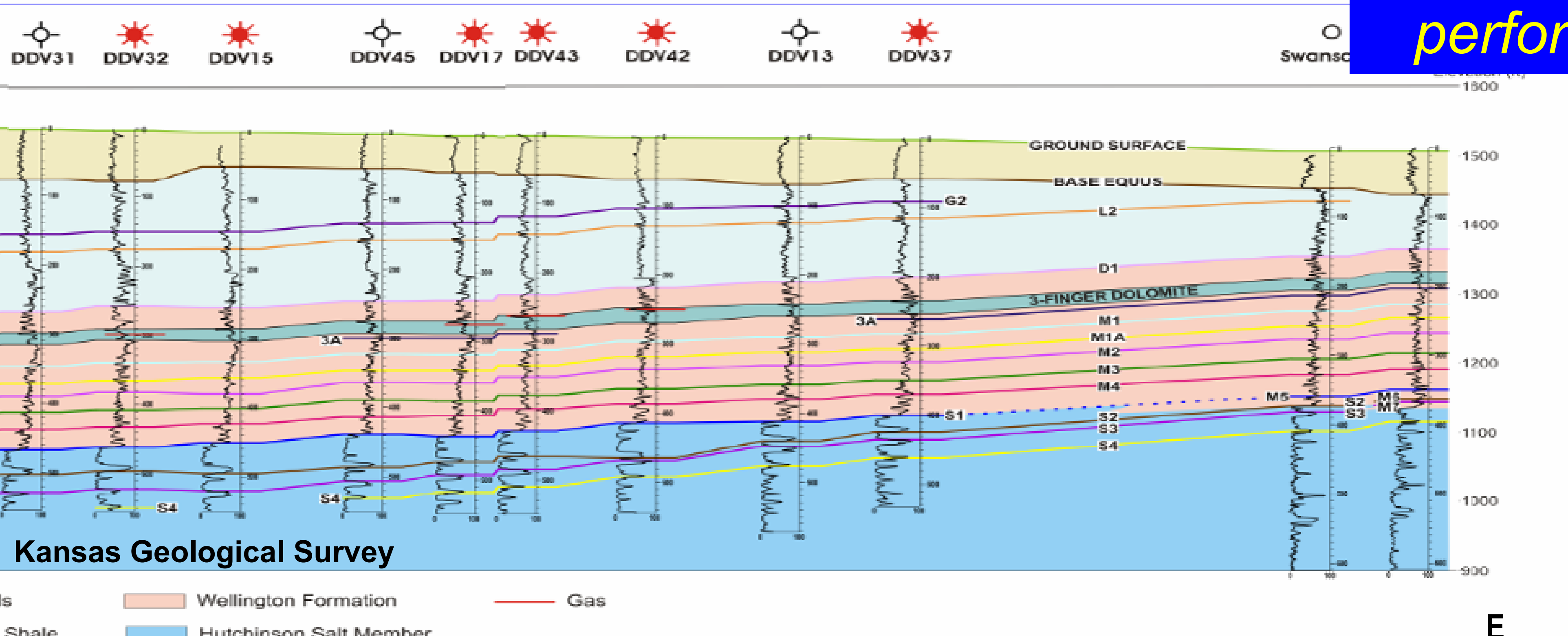
- *High-resolution shallow seismic used to directly detect gas pockets.*
- *Old-fashioned geologic detective work using logs, core & seismic explained leak.*
- *2 high-altitude instruments failed to detect CH_4 anomalies: NASA high-res spectral imaging spectrometer and 10-day survey using JPL's Airborne Emissions Spectrometer.*

Yaggy Gas Storage Field

Analysis

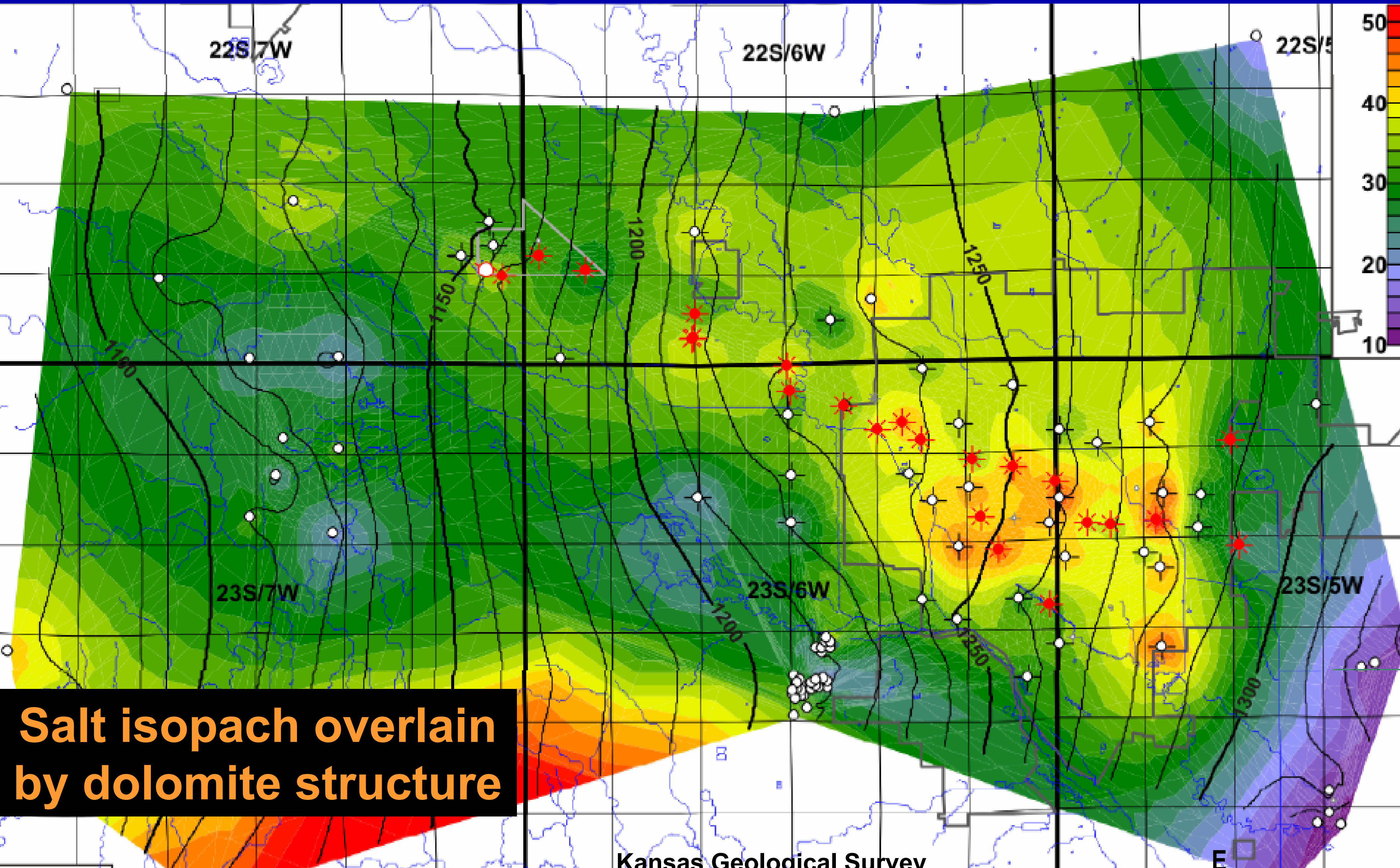
- *Detailed geologic mapping & correlation work was performed.*



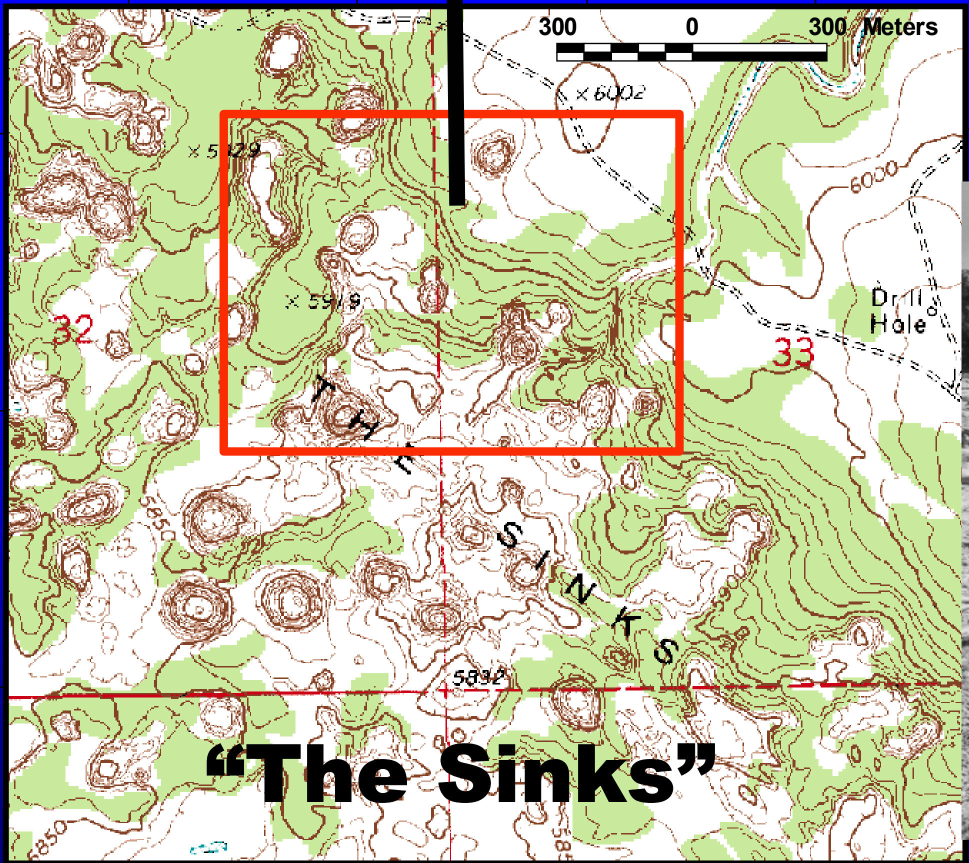


Yaggy (Kansas) Gas Storage Field : Interpretation

- *WNW-trending salt dissolution, itself controlled by deep-seated faults, caused fracturing and >perm of dolomite. Gas then flowed up dip.*



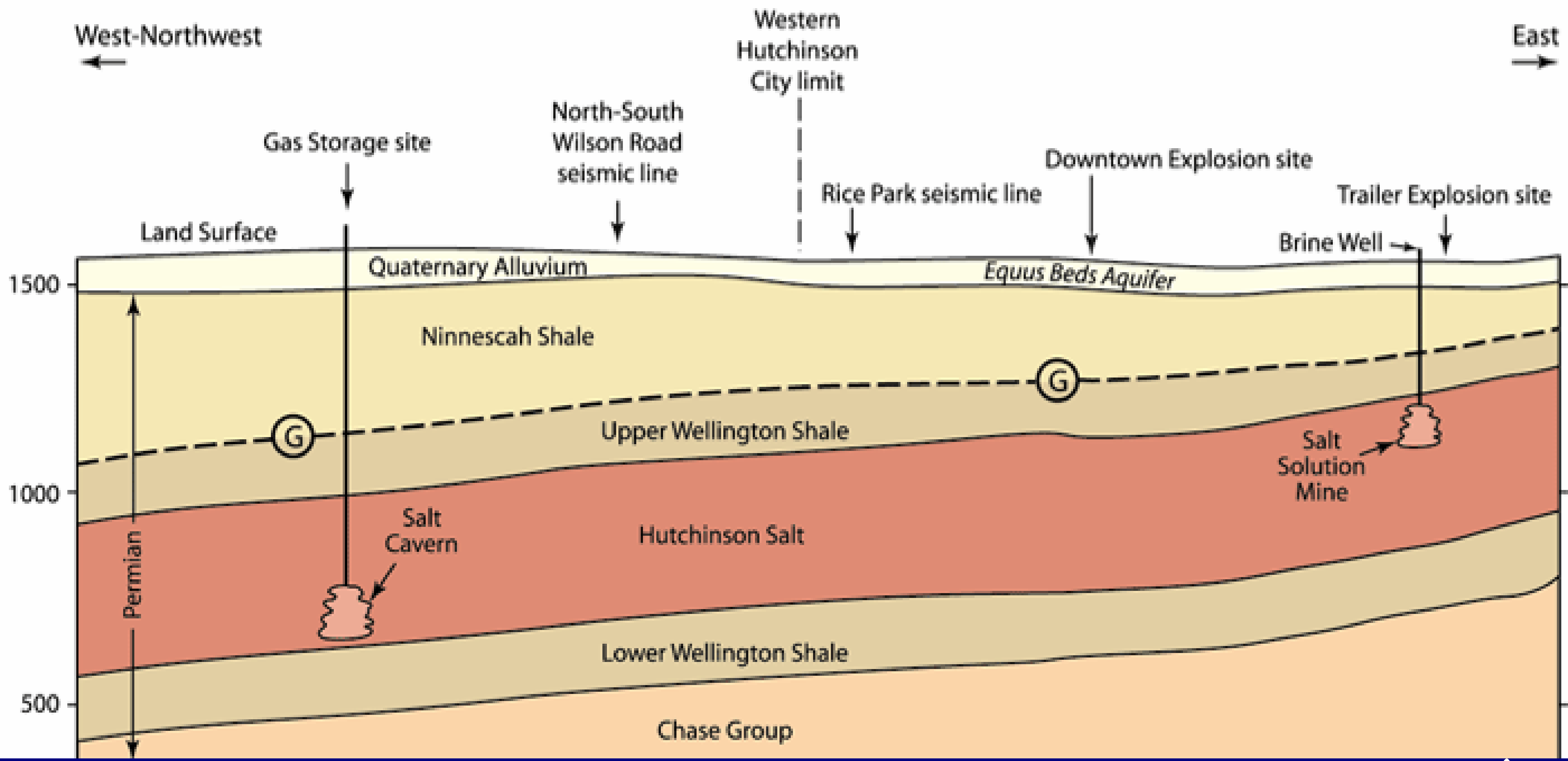
Salt Dissolution Tectonics - Arizona



Stevens et al., 2005

Yaggy (Kansas) Gas Storage Field

- *Salt dissolution caused flexure and fracturing in overlying 8-m thick dolomite, allowing pathway for gas.*
- *Fracture apertures opened by high-pressure gas injection.*

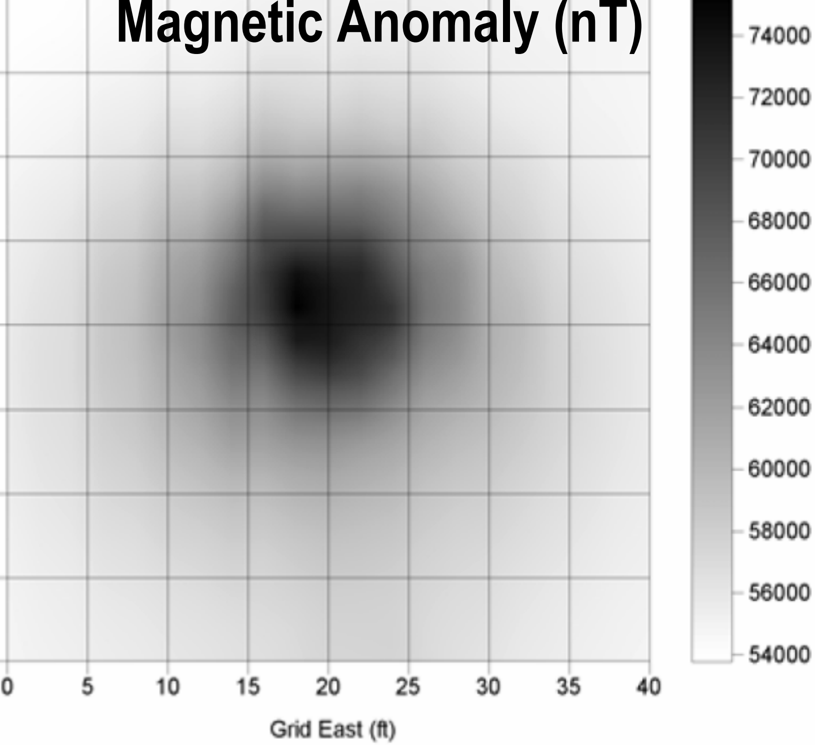


Yaggy (Kansas) Gas Storage Field

Remediation

Nissen et al., 2004

- *Leaking well S-1 P&A'd.*
- *Theory that casing failed due to mill work conducted down hole in 1993 at depth of leak, weakening the pipe.*
- *+/- 160 abandoned shallow brine wells plugged at cost of $10 MM.*
- *Vent wells drilled to drain and flare gas.*



Remediation

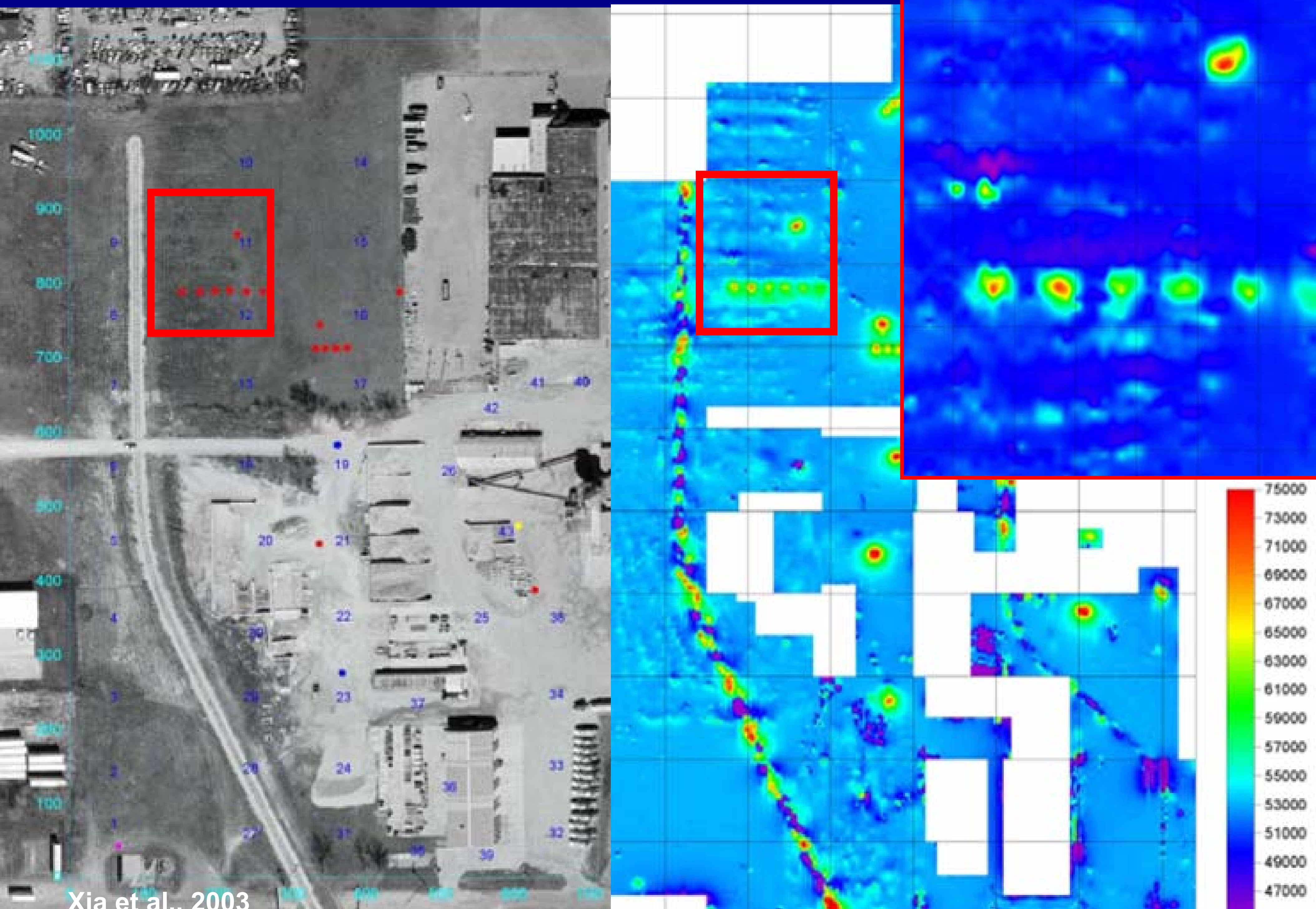
Magnetics Locate Abandoned Wells

- *Magnetometer located aband'd brine wells buried 0.7 to 1.2 m deep*
- *20-cm (8") casing near surface generates large anomaly 7000 - 28,000 nT (+50%) over background.*
- *Many false alarms from buried steel bars & pipes.*
- *Small test area (0.1 km^2). Estim \$300,000 / km^2.*

Xia et al., 2004

Remediation Mag Survey Located Aband'd Wells

- *(Gravity, EM, GP radar also considered but resolution too low.)*



Yaggy (Kansas) Gas Storage Field : Legal/Regulatory

- *Kansas didn't use IOGCC guidelines, e.g. emergency shutdown valves at WH or cavern spacing reg's. A report stated Kansas Dpt Health & Environment inspected site only once since opened in 1993. One P/T person equiv staff oversaw 632 CNG storage wells in the state.*
- *July 23, 2002 (18 months after leak) : KDHE assessed a $180,000 civil penalty against ONEOK's Kansas Gas Service division.*
- *Order requires ONEOK to monitor existing unplugged vent wells, drill additional observation/monitoring/vent wells, abandon brine wells, and prepare a geoengineering plan.*
- *ONEOK has appealed order. No date set for follow up conference.*
- *Two separate class-action lawsuits filed against ONEOK. 1) Property owners in Reno County who allegedly suffered loss awarded $5 million plus $2.6 MM fees, all of which is covered by ONEOK's liability insurance. No punitive damages assessed.*
- *ONEOK has appealed this verdict to the Kansas Supreme Court.*
- *2) Businesses in Reno County who allegedly lost income lost jury trial.*

ONEOK 10-Q Report, August 3, 2005

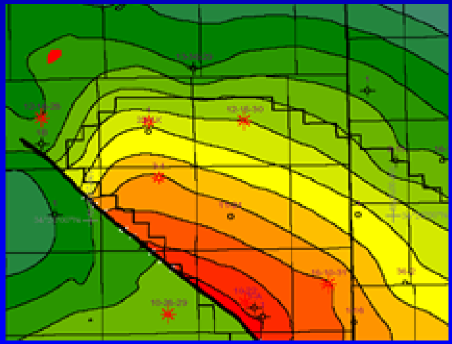
Remediation of CO_2 Leakage

1) Geologic Leakage Pathways
2) Manmade Leakage Pathways
3) **Screening Sites to Avoid Leakage**
4) Monitoring Technologies
5) Remediation Technologies

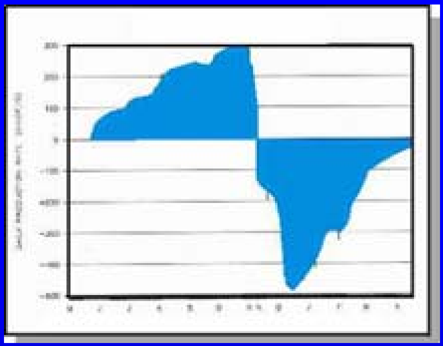
Screening CO_2 Storage Candidates

Insights from Ongoing Industry Injection/Storage Sites Provides Foundation for Selecting Successful Sites

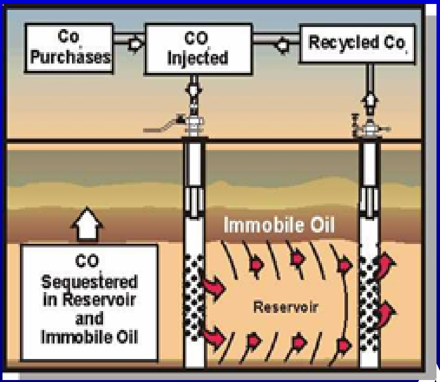
- ***Natural CO_2 Field Analogs:*** *Documented spectrum of natural sites and geologic processes, from CO_2 leaking to surface (avoid), to stored over millions of years (to be duplicated).*



- ***Underground Injection (UGS & aquifers):*** *Short-term injection and withdrawal. Insights on field selection, well design, hysteresis effects, remediation. All reservoir types, including saline aquifers. Abd'd well issues.*



- ***CO_2-EOR:*** *Most experience with CO_2 injection. However, cap rock integrity is less of an issue in selecting a field, since most CO_2 floods are miscible in oil and residence time is short. Abn'd well & corrosion issues*

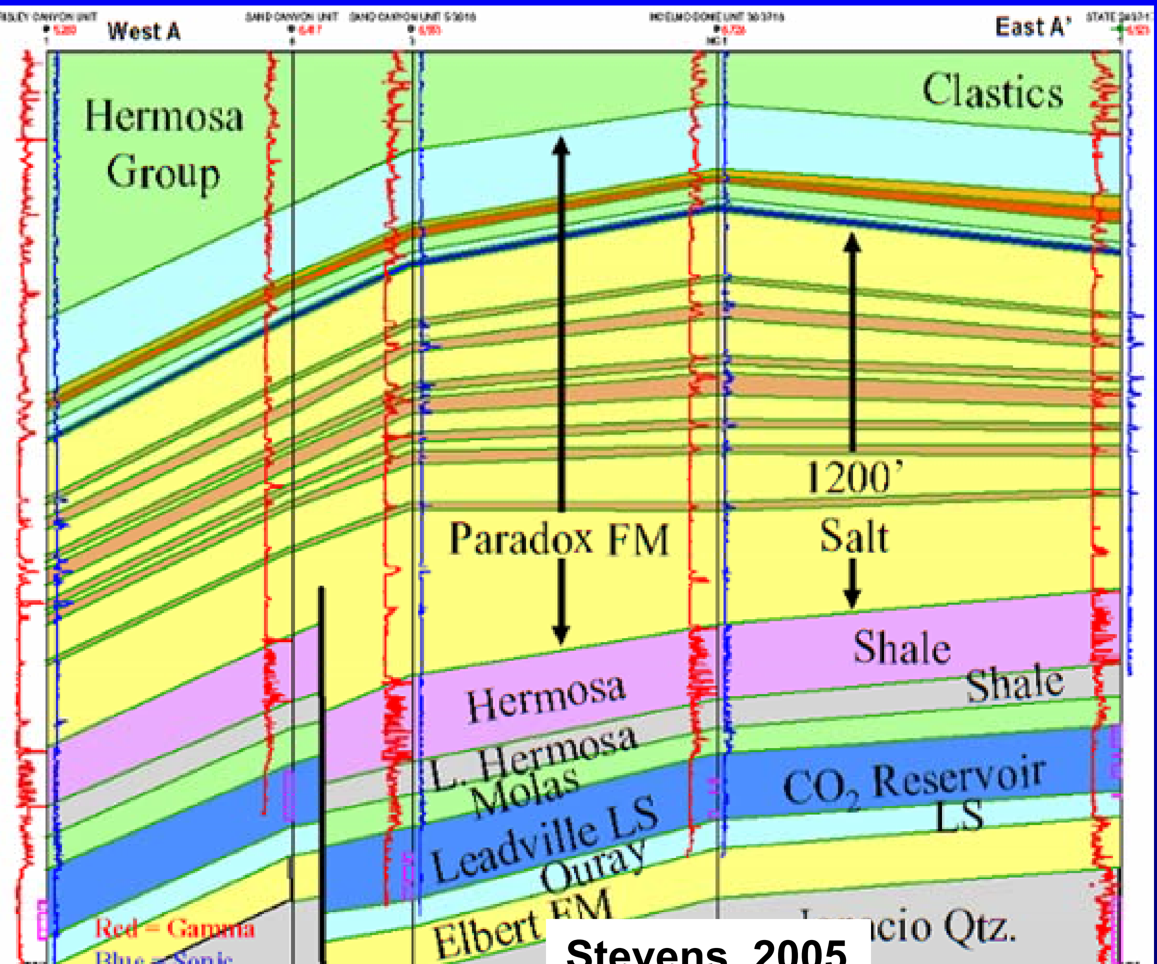


Secure Natural Analog McElmo Dome

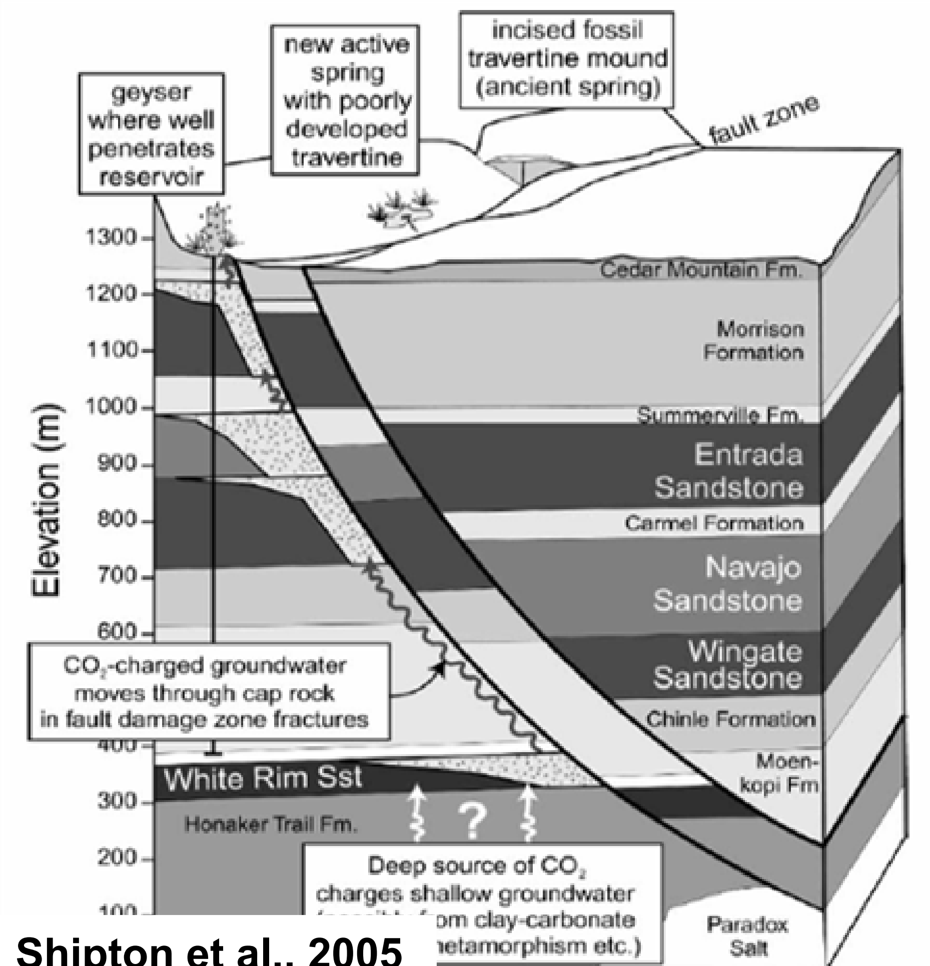
- *400 m thick halite cap rock.*
- *Faults die out in self-annealing salt.*
- *CO_2 emplacement estimated 70 Ma.*
- *Overpressured Jackson Dome.*

Leaky Analog Colorado Plateau

- *CO_2 leaks to surface.*
- *Similar stratigraphy to McElmo.*
- *Faults provide conduit for CO_2*



Stevens, 2005

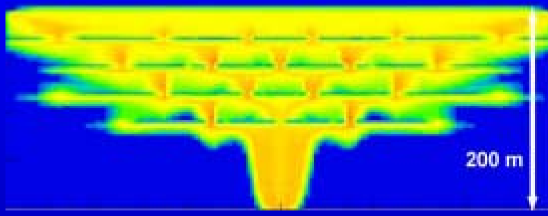


Shipton et al., 2005

Screening CO_2 Storage Candidates

"Good Practices" methodology will be site specific

- ***Proximity:*** *Urban areas will require more thorough vetting than remote areas.*
- ***Geologic/Reservoir Data:*** *Existing logs, core, well testing (fluid comp, stress), seismic, etc. augmented by new data collection.*
- ***Reservoir Simulation:*** *History match pre-CO_2 operations ground truths the model. Geochemical & reactive transport models.*
- ***Analysis:*** *Multiple cap rock traps with relevant natural or industrial analogs, injection experience and large data set preferred, but not always available.*



- *Very challenging to develop "Cookbook" procedures for screening great diversity of candidate sites, both surface and subsurface.*

Remediation of CO_2 Leakage

1) Geologic Leakage Pathways
2) Manmade Leakage Pathways
3) Screening Sites to Avoid Leakage
4) **Monitoring Technologies**
5) Remediation Technologies

Monitoring Technologies from Gas Storage

- ***Industry Record:*** *10 gas migration events recorded from 600 facilities over a 90-year period.*
- ***Inventory Verification:*** *P-V methods, reservoir simulation, volumetrics.*
- ***Monitoring:*** *Surface vegetation, shallow water wells, gas storage observation wells, logging, seismic, gas metering, gas sampling & analysis, tracer surveys, production testing, remote sensing.*
- ***Caprock Integrity:*** *Threshold pressure, well testing, air injection.*

After Perry, 2005

Monitoring Technologies from EOR Industry

- ***Gas Composition Tracking:*** *most common EOR technique.*
- ***Seismic Methods:*** *Not yet widely used. 3- and 4-D seismic, cross-well tomography, microseismicity under experimentation. Expensive and logistically difficult long term.*

After Grigg, 2005

Advanced Monitoring Technologies

- ***Remote Imagery:*** *hyperspectral geobotanical monitoring.*
- ***Gravity:*** *(surface and borehole) Useful more in thick aquifers than thin oil & gas reservoirs.*
- ***Electrical Resistivity (EM):*** *detect changes in water saturation, hence CO_2 flow. Low-cost and well suited to aquifer storage with no hydrocarbons.*
- ***Streaming Potential (SP):*** *Low-cost method measures fluid flow. Used to measure leaks in dams and waste pits. Modeling indicates measureable response in CO_2 storage.*
- ***Ground Deformation:*** *Tilt meters indirectly map CO_2 flow. By mapping high-perm regions have ability to predict future flow.*
- ***Gas Tracers:*** *Inert stable noble gas isotopes (Xe) mixed w/ injected CO_2. Questions about partitioning across phases.*

After Pickles, 2005; Hoversten, 2005; Nimz & Hudson, 2005

Remediation of CO_2 Leakage

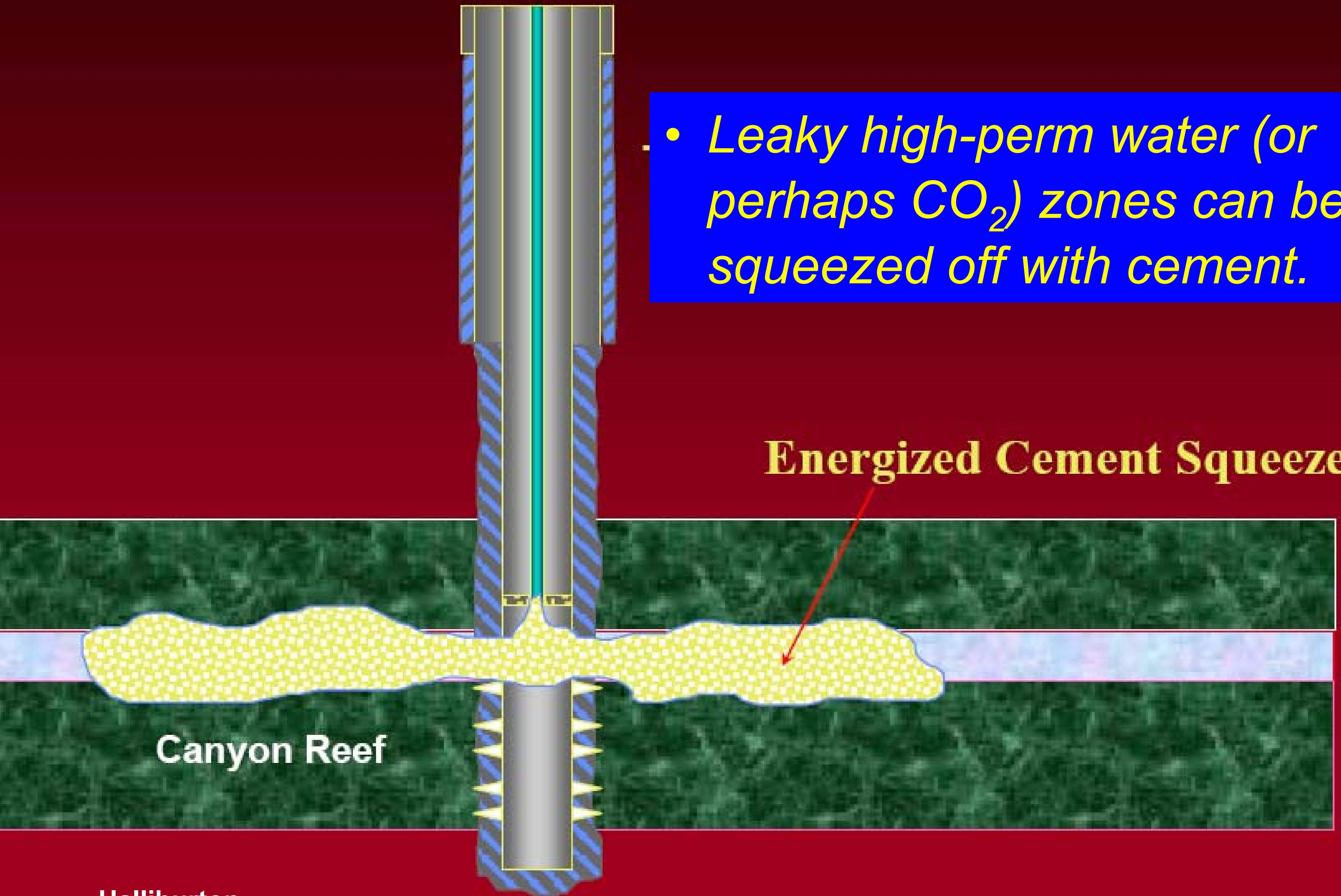
1) Geologic Leakage Pathways
2) Manmade Leakage Pathways
3) Screening Sites to Avoid Leakage
4) Monitoring Technologies
5) **Remediation Technologies**

Remediation of CO_2 Leakage

1) Wellbore remediation (mature)
2) Cap rock remediation (immature)
3) Field operating strategies (emerging)

CO_2 Leakage Remediation

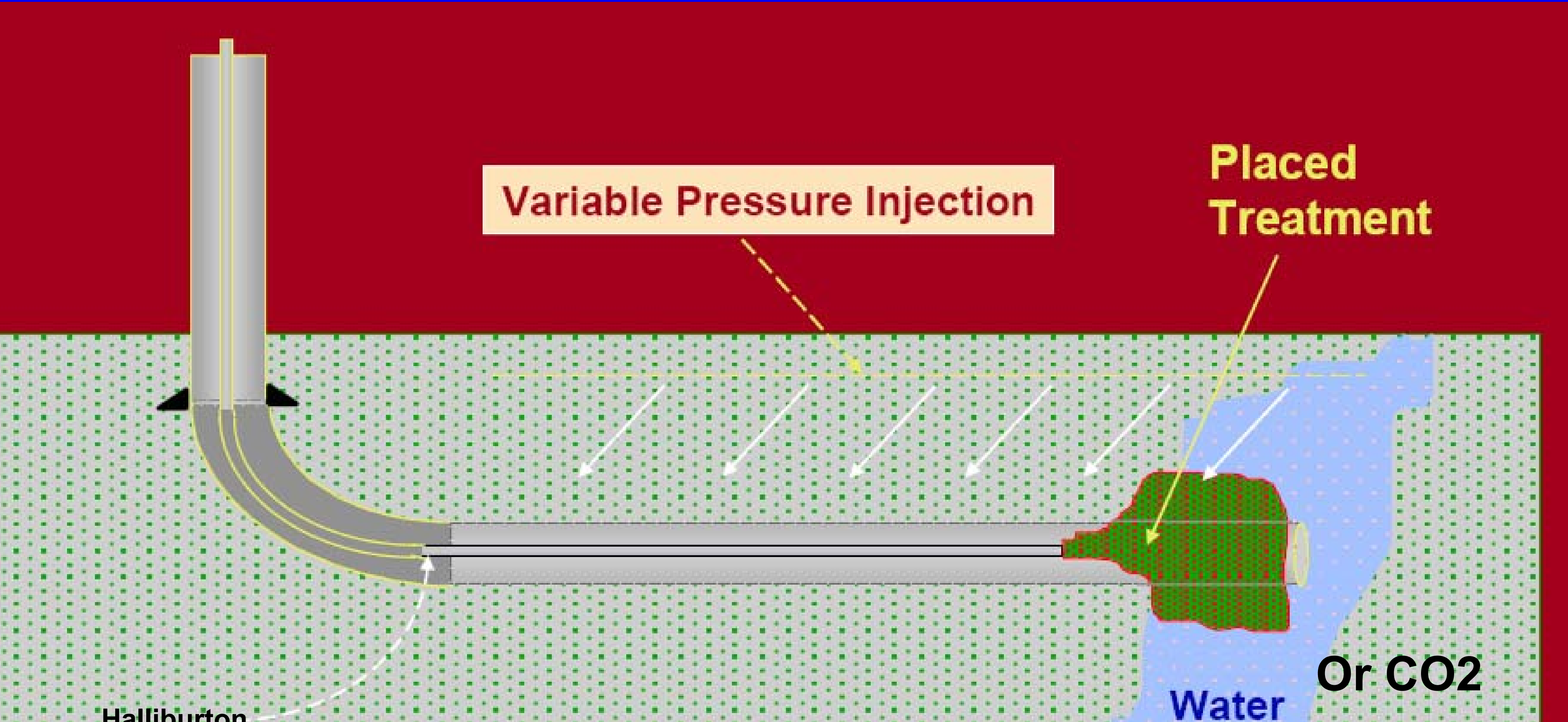
- *Leaky high-perm water (or perhaps CO_2) zones can be squeezed off with cement.*



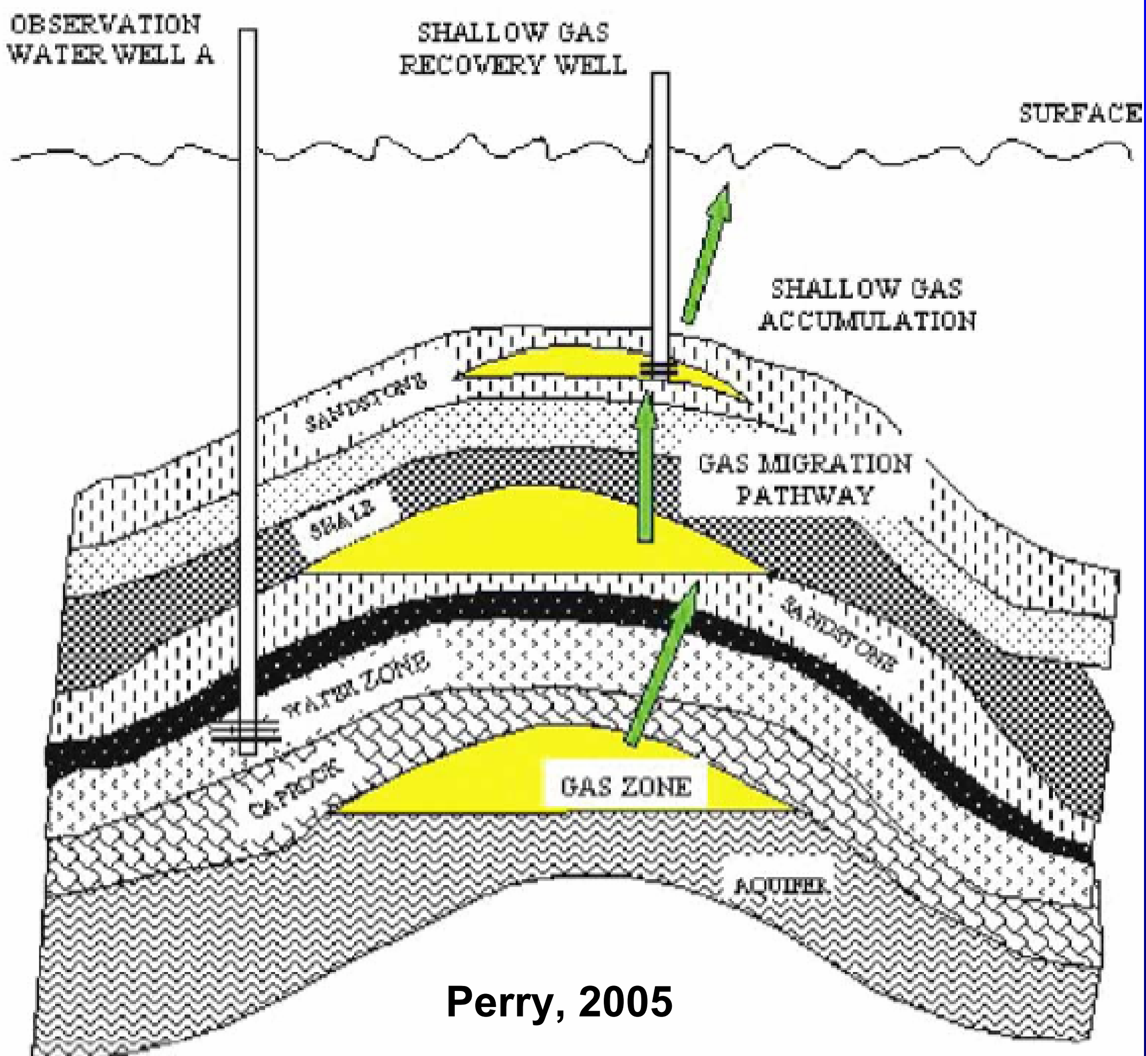
Halliburton

CO_2 Leakage Remediation

- *Horizontal wells are used to squeeze off leaky high-perm water (or perhaps CO_2) zones.*
- *Hugely expensive to remediate a 3-D leaking CO_2 storage field this way.*



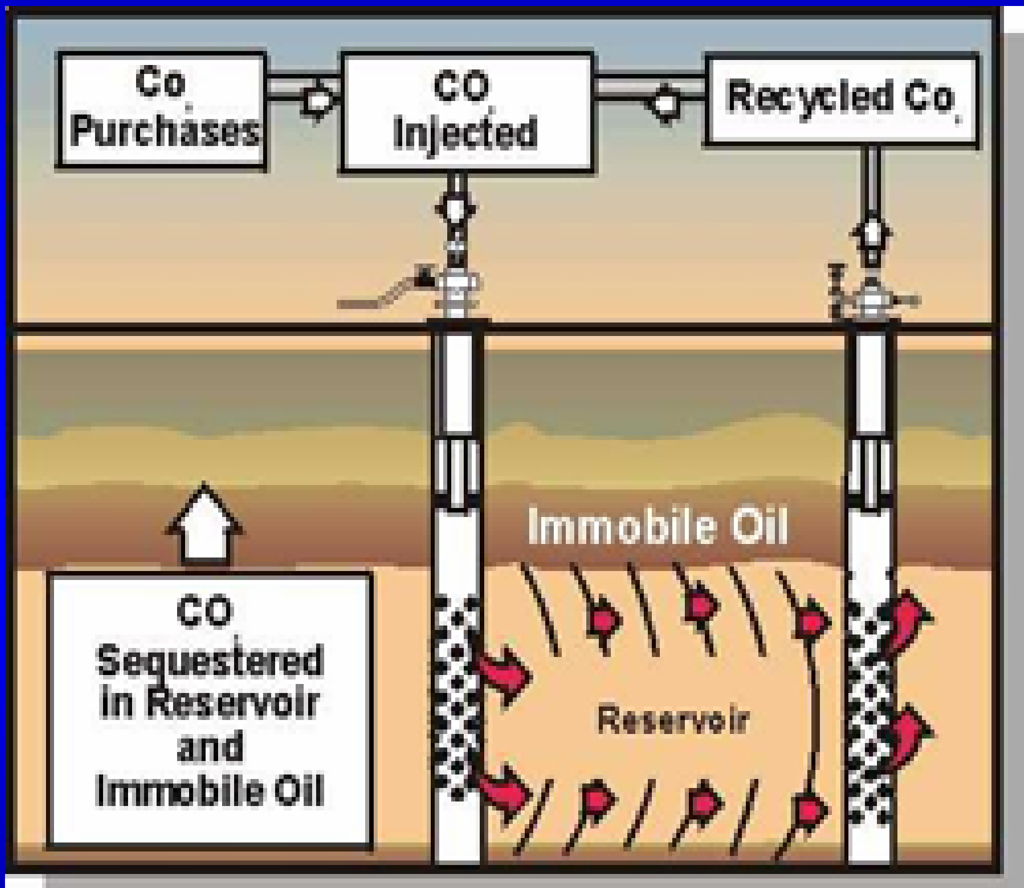
Remediation Technologies – from Gas Storage



Perry, 2005

- ***Aquifer Leakage:*** *Continuous removal of water from underneath the gas storage bubble lowers P. Has been used at a Midwestern USA gas storage field.*
- ***Gas Recycle:*** *Continuous production and re-injection of leaked gas.*
- *These are temporary measures not well suited to long-term storage.*

Remediation Technologies – from EOR

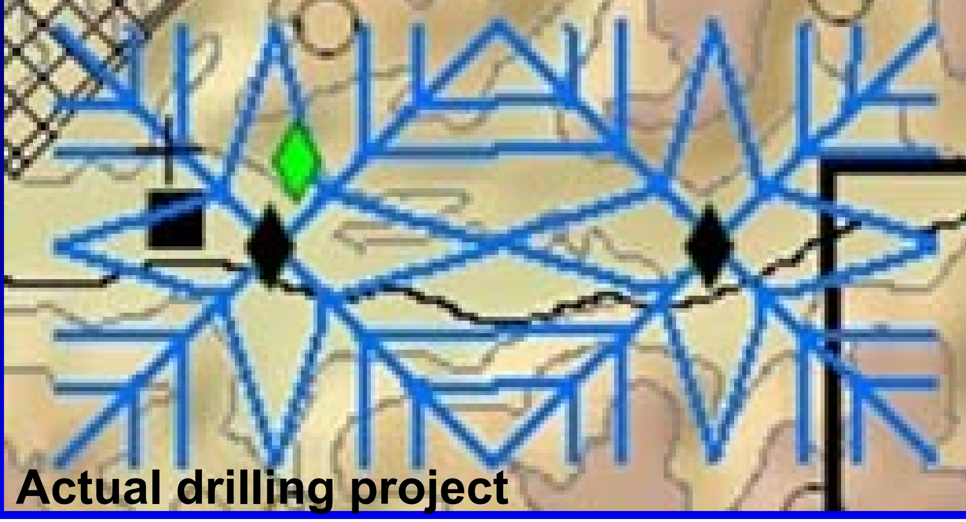


- ***Conformance:*** *Foams, gels have some success at controlling CO_2 movement, but costly.*

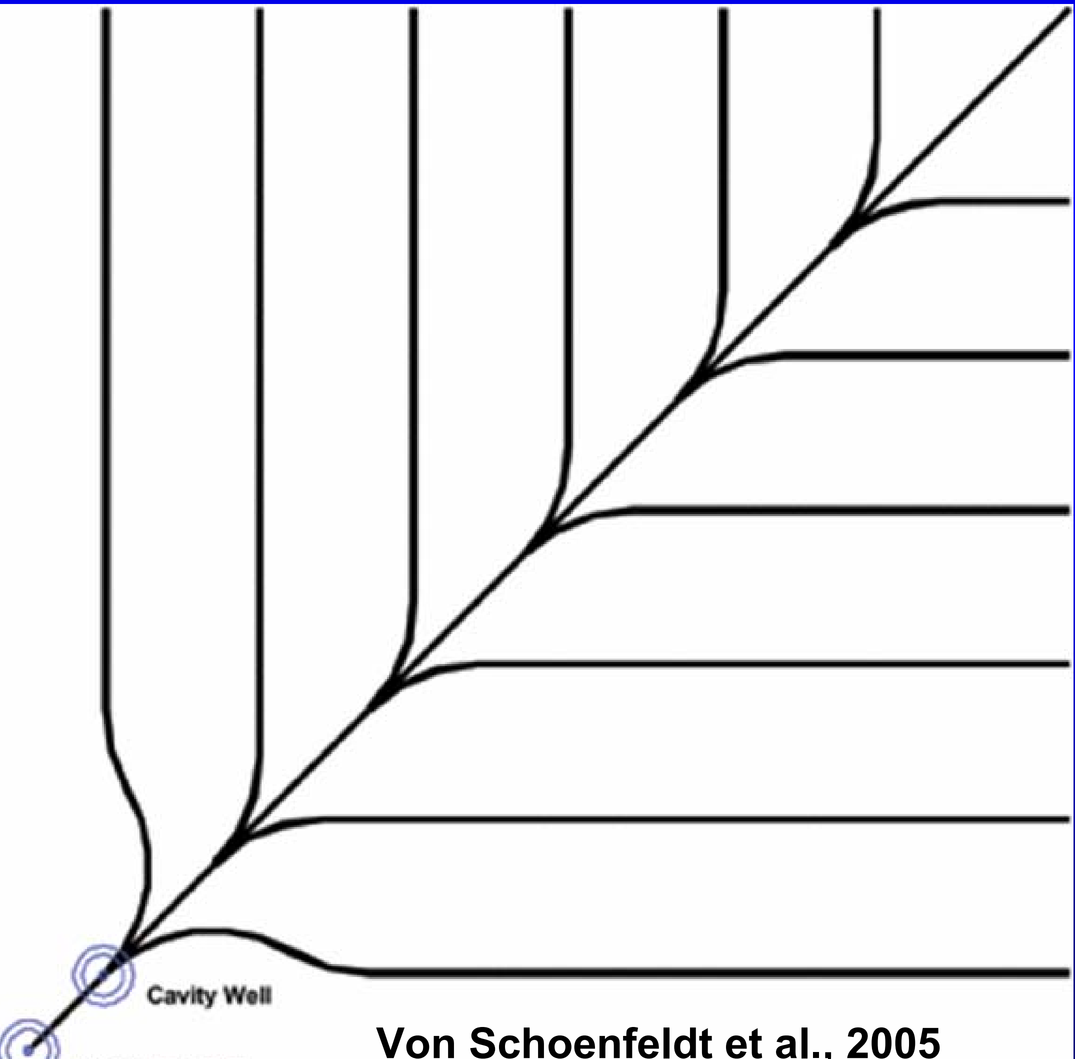
Grigg, 2005

Remediation Technologies – Advanced "Pinnate" Drilling

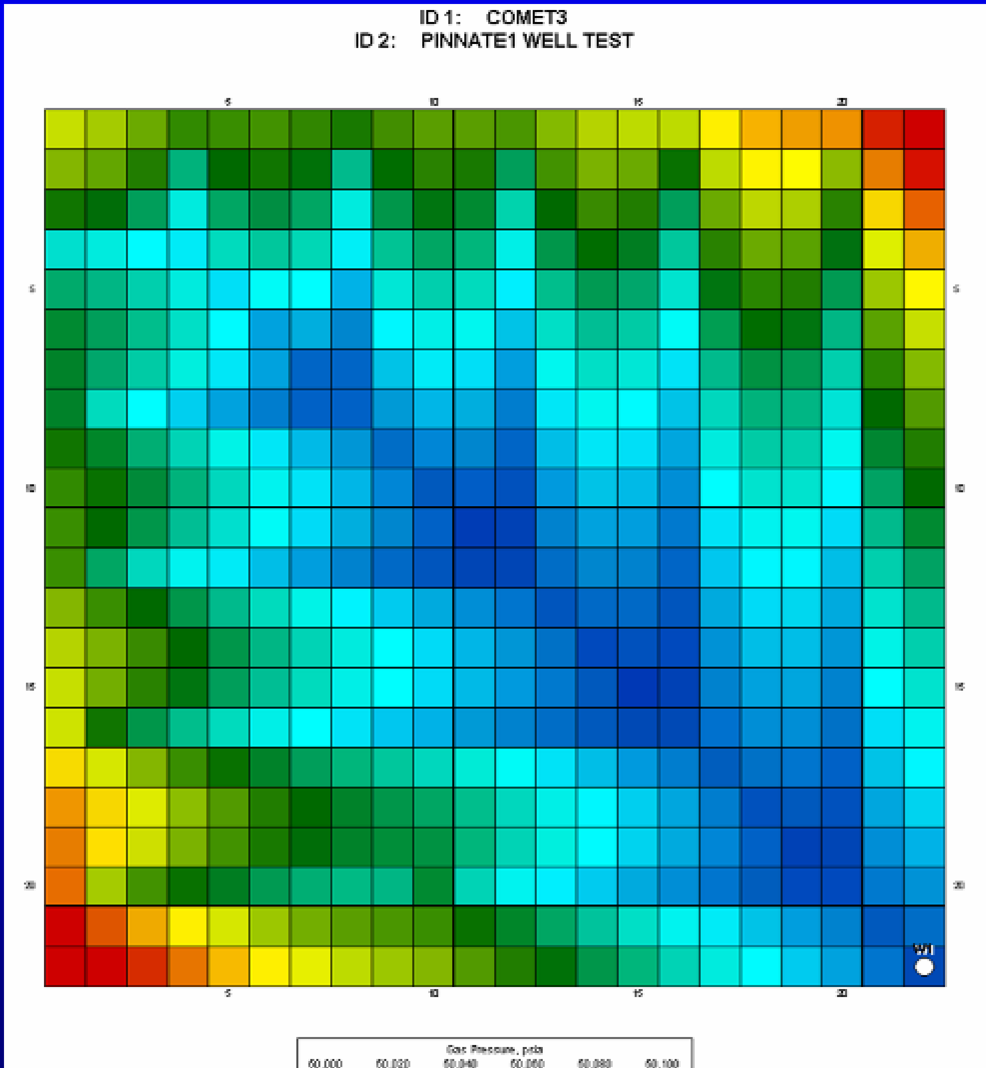
- *Multi-branched horizontal drilling gives greater reservoir contact; >200 wells to date; costs falling.*



Actual drilling project



Von Schoenfeldt et al., 2005

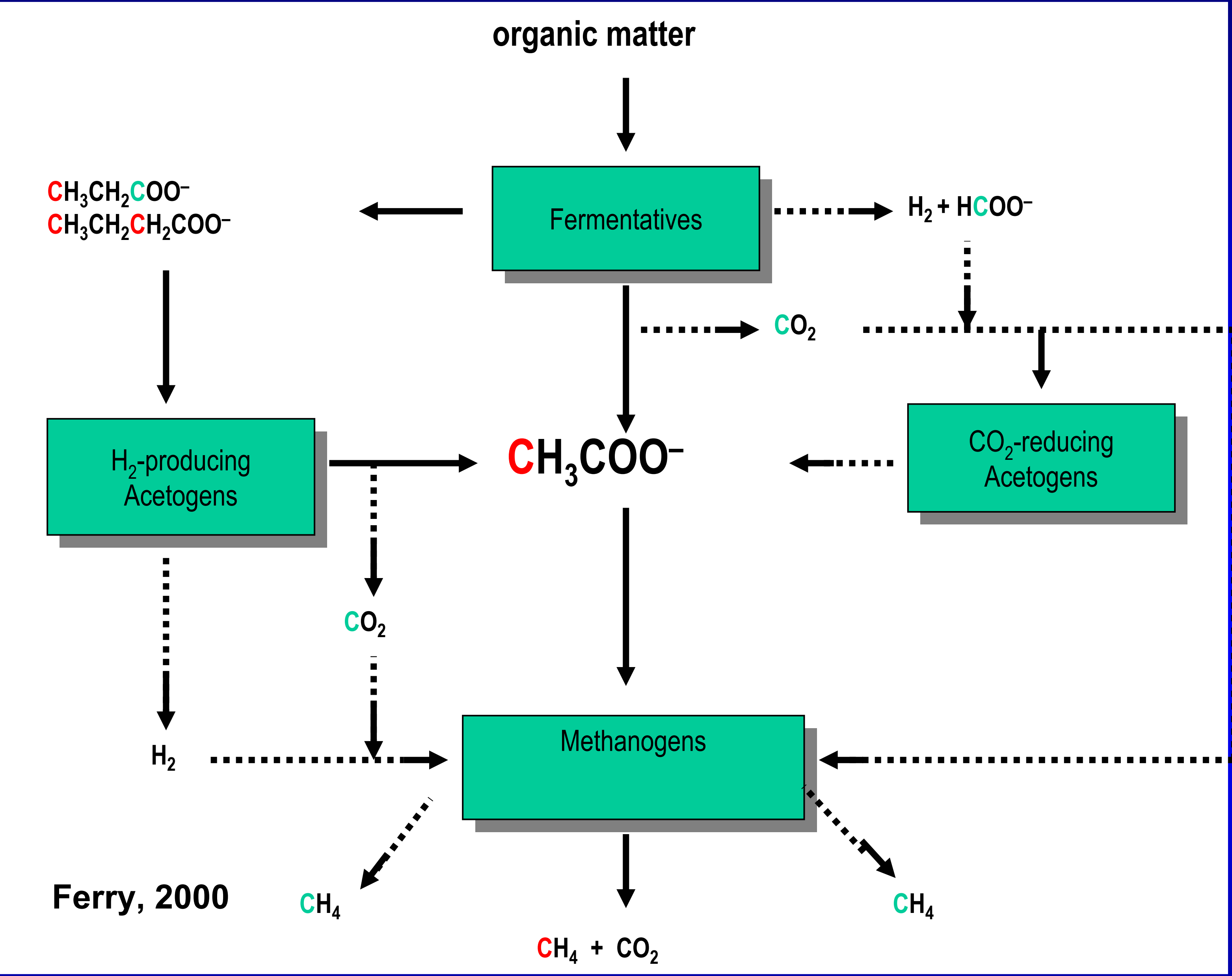


Remediation Technologies – Hazardous Waste Cleanup

Sandia Lab

- *Shallow, low-cost (US $75-225/m) drilling and remediation technologies from hazardous waste industry.*
- *Most hazardous clean up takes place in very shallow settings (<100 m depth).*

EOR Remediation Technologies : Methanogenic Bacteria



- *Methanogens convert CO_2 into CH_4 (solid lines).*
- *Need energy source (H^+, acetate, formate) from anaerobic consortia -- "interspecies electron transfer."*
- *Initial lab work underway.*
- *Long-term remediation of CO_2 sites.*

$CH3COO^- + H+ \rightarrow CH4 + CO2$ [1] - Acetate

$CO2 + 4H2 \rightarrow CH4 + 2H2O$ [2a] - Hydrogen

$4HCO2H \rightarrow 3CO2 + CH4 + 2H2O$ [2b] - Formate

Conclusions

1) Wellbores most likely and most serious potential leakage path.

2) Site screening method emerging from analog studies; prevention always preferable to remediation.

3) Wellbore remediation technologies exist, but cap rock remediation remains difficult.

IEA Greenhouse Gas R&D Programme

OUTLINE PROPOSAL FOR RISK ASSESSMENT NETWORK

Prepared by:

bp

Imperial College London

TNO Knowledge for business

ptrc Petroleum Technology Research Centre

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

IEA GREENHOUSE GAS R&D PROGRAMME

STATOIL

UNIVERSITY OF REGINA

Introduction

- Risk assessment workshop held in London 2003
  - Well attended
  - RA work at early stage
  - Highlighted need for benchmarking
- Vancouver 2004
  - Proposal for benchmarking activity presented
- After consultation led to revised proposal that is being put forward today

Outline Proposal

- Developed based on:
  - Feedback from the Vancouver meeting
  - Personal contact since the Vancouver meeting
  - Fourth draft which was modified following comments received
- Not a final document
- Brought back for discussion
- Aim at this meeting is to agree a route forward for a Risk Assessment network

Programme

- To discuss outline proposal and delegates views on way forward in break out groups
- Bring these views back to the full meeting
- Take those views on board in developing a route forward
- Proceed to develop a Risk Assessment network along the lines agreed at this meeting

Network Aims

Objective:

- Develop an open and transparent process to allow different RA approaches and their results to be understood

Aims:

- Provide a structured approach to allow different RA approaches to be compared
- Determine what the results are telling us and how they differ
- Provide an umbrella group for international collaboration on RA
- Identify gaps in knowledge and make recommendations on how to close these gaps

Timescale:

- 5 years starting in 2005

Basic Principles

- Participation
  - Open to all
  - Participants to be as actively involved as they like
- Open and transparent
  - Participants to be open and share results
  - Any processes documented for reference
- Data sets
  - Owned by technical groups
  - Onus on owner to set data sharing requirements
  - Allow results to be shared, commented on etc.,

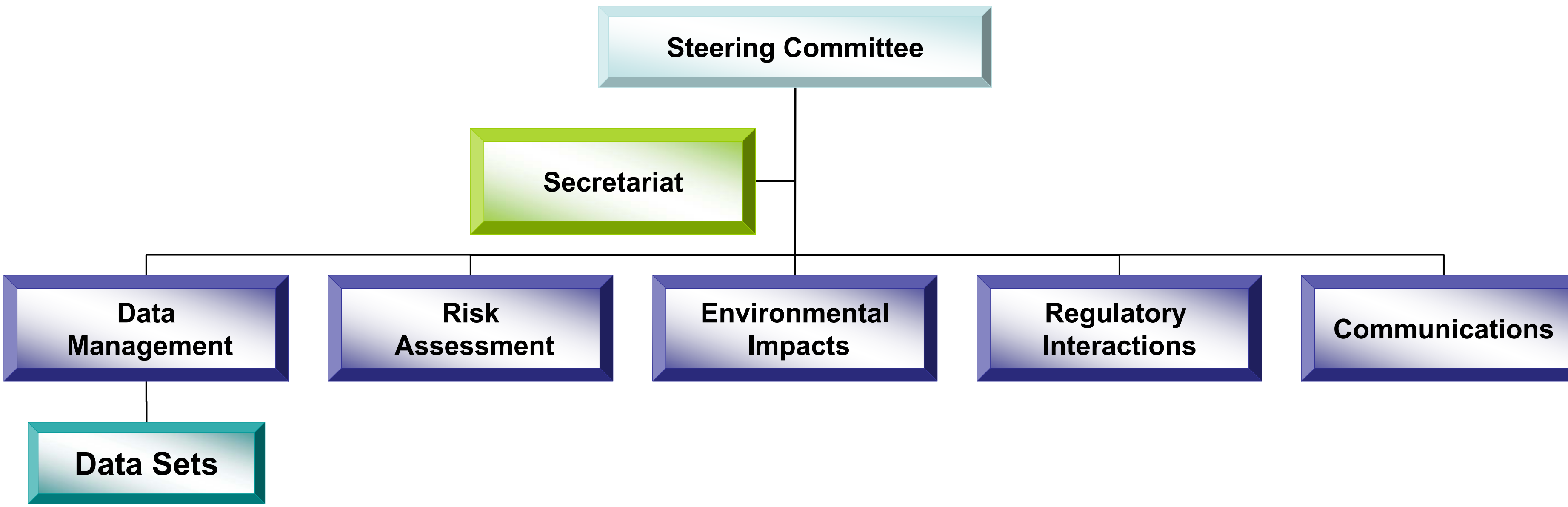
Basic Principles

- Techniques and models
  - Network will not develop techniques or models
  - No sharing of codes only assumptions
- Presentation of results
  - Network will not present results of RA work
  - Network can publish results of its activities
    - Agreed by participants/approved by Steering Committee
- Annual workshop – rotate: EU, NA, J/Aus?
- Web site – open and “members area”
  - www.co2captureandstorage.info

Network Operation

- IEA GHG to provide secretariat function
- Steering Committee to oversee activities/direction
  - Comprised of representative group of participants
  - International spread
- Activities organised under 5 working groups
  - Data management
  - Risk assessment
  - Environmental impacts
  - Regulatory interactions
  - Communications activities

Network Structure



Data Management Group

- Focal points for activities relating to data sets and their use as test cases
- Activities could include:
  - Guidelines on data set requirements
    - Setting minimum data set requirements
  - Inventory of data sets and contents
    - Proforma prepared by data set owner
  - Critiquing of data sets
    - Strengths/weaknesses
  - New data sets
- Comprised of data set owners

Data sets

- Offered at last meeting:
  - Weyburn
  - Sleipner
- Other potential data sets
  - In-salah?
  - Snohvit?
  - K-12B?
  - Gorgon, Etc.,
  - Natural analogues?

Risk Assessment Group

- Activities could include:
  - Inventory of approaches/models etc.,
    - Guidelines for benchmarking
  - Guidelines on assumptions to be used
  - Critique results
  - Guidelines on terminology to be used
  - Identify gaps
- Key output of group is to put results in context
- Comprised of RA approach developers and independents

Environmental Impacts Group

- Main activities could include:
  - Collate existing information on effects of seepage/leakage on human health and ecosystems
  - Provide reference impacts data for RA groups
    - Impacts considered on a common basis
- Comprised of research groups active in field

Regulatory Interactions Group

- Main activities could include:
  - Appraise network on regulatory developments in countries involved and RA requirements.
  - Assess regulators perceptions on needs for RA
  - Guidelines on what RA can provide for regulators
  - Timescales for RA needs/availability
- Comprised of individuals involved in groups like CSLF, CCP etc., active in regulatory development

Communications Group

- Assist in development of summary reports on network activities for general dissemination
- IEA GHG + other interested parties

Participation

- Open to all
- Chair elected for each group
- Chair to sit on SC

Funding

- Task shared agreement
  - Funding from existing projects
  - IEA GHG to provide support funds from own budget
  - Specific activities could be funded

Next Steps

- Work in breakout groups to agree network structure and how it will operate
- 4 groups
  - Data management & RA
  - Risk assessment
  - Regulatory interactions
  - Environmental impacts
- Feedback tomorrow
- Collate and discuss consensus on way forward at end of second day.

Some Thoughts

- Is it sufficient to just have a forum to share/discuss and compare results
- Several projects considering benchmarking activities
  - Provide the opportunity to compare experiences and results
- Could we set ourselves the task to explore how far we can go in terms of simplification
  - Minimum data sets - Battelle
  - Simplify models - USEPA

Breakout session
Data management & risk assessment

Report summary

23 August 2005

Terminology

- Dataset
- Risk assessment
- Performance assessment
- Benchmarking

Risk assessment activities: considerable level of activity internationally

Current and planned RA activities

Site	***Country***	***Type of act.***	***Institute***
Generic		RA lit. review	UU
Generic		RA method dev.	UU/TNO
Generic		Prob. Well bore model	U. of Alberta
Generic		Well/caprock integrity models	Schlumberger (COSMOS-1/-2)
Generic		RA terminology and methodology	EU consortium (CO2GEONET)
Generic		Dev. Of RA model/decision tree	IFP
Generic		T-H-M-C code for PA model	Quintessa
Generic		Dev. Of RA model/decision tree	Quintessa
Generic		Dev. Integrated RA model	USEPA
Generic		Long-term cement degradation model	Mon. Sci
Generic		Acceptance/regulation/ra approach	EU Technology Platform (Schlumberger)
Generic/SACROC/Hobbs	USA	Dev. Integrated RA model	Los Alamos
Generic/Weyburn	Canada	Dev. Integrated RA model	PTRC/Mon. Sci
In Salah aq./gas field	Algeria	Integrated RA & benchmarking	BP/CO2ReMoVe
Lindach gas field	Austria	R.A.	EU consortium (CASTOR)
Apache Middale	Canada	R.A.	PTRC
Micropilot	Canada	RA for ECBM	Imperial
Weyburn	Canada	RA	PTRC
Weyburn	Canada	RA method dev.	U. of Calgary (GEOSTORE)
Ketzin	Germany	Integrated RA & benchmarking	CO2ReMoVe
Schweinrich	Germany	Integrated RA	Vattenfall/TNO (CO2STORE+)
Nagaoka	Japan	Def. of dataset	RITE/Quintessa
Ogachi	Japan	Geochemical process model/hot dry rock	Quintessa
K12-B gas field	Netherlands	R.A.	EU consortium (CASTOR)
Sleipner	Norway	Integrated RA & benchmarking	Statoil/CO2reMoVe
Snohvit	Norway	Integrated RA & benchmarking	Statoil/CO2reMoVe
Miller field	Scotland	RA	BP/ind. cons.
Casablanca oil field	Spain	R.A.	EU consortium (CASTOR)
US fields & aq.	USA	RA	Regional partnerships
Various	USA	Datasets natural & industrial analogues	ARI

Datasets:

- Several well documented (Weyburn & Sleipner)
- Confidentiality issue
- Completeness

Site	***Storage medium***	***Country***	***Institute***	***Remark***
In Salah		Algeria	BP	planned
Gorgon		Australia	Chevron	confidential
Weyburn	oil field	Canada	PTRC	
Apache Middale	oil field	Canada	PTRC	planned
Pennwest		Canada (Alberta)		planned
Montmiral	CO2 field	France		
Ketzin	aquifer	Germany		planned
Schweinrich		Germany		
Nagaoka		Japan		
K12-B	gas field	Netherlands (offshore)		
Sleipner	aquifer	Norway (offshore)	Statoil	
Forties	oil field	UK (offshore)	BP	
SACROC	oil field	USA		confidential
McElmo dome	CO2 field	USA		
Frio	aquifer	USA		
Mountaineer		USA (West-Virginia)		

Use of RA techniques:
- Little attention because of time constraints
- High level definitions only

- Modelling technique
  - Deterministic
  - Probabilistic
  - Hybrid

- Expert elicitation

- Scenario approach

Benchmarking: limited activity

Current		
Weyburn	Monitoring Sci	Eclipse-GEM
Generic problems	LBNL	Injection performance

Planned		
Weyburn- final phase	PTRC	Planned
CO2ReMoVe - Various sites	EU consortium	Planned

Scope of network

- Develop common terminology
- Provide standards for datasets
- Compile datasets (for benchmarking)
- Define benchmarking protocol
- Evaluate benchmarking results
- Publish results after approval by members
- Provide means for internal communication (e.g web site)

Out of scope

- Modelling proper
- Function of data clearing house
- Tool development
- Quality assurance and formatting

General remarks

- Use more neutral/positive terms in critiquing (critiquing = evaluating)
- Network process should be defined

Data Management and Risk Assessment
(Breakout Group 2)

23 August 2005, Utrecht

Risk Assessment Terminology

- Discussion on the definition and scope of "Risk Assessment".
  - The use of common terminology.
  - Ability to communicate with groups outside the CCS research community.
  - The importance of drivers: environment, economics, regulatory.
  - Timescale, concentration and duration of leakage.
  - Indicators to quantify risk.
  - Emphasis on the processes, pathway, RA methodology and consequence assessment.

Consider Environmental, Economic, Health and Social aspects

Encourage and include expertise in these fields within the Network

Current and/or planned RA activities

- Weyburn
- CO2STORE
- CASTOR (limited scope)
- Regional Partnerships in the US (14-15 projects expected to carry out RA)

.....

- CO2ReMoVe – expected start Jan 2006, 3-4 industrial sites
- LANL, LBL, PNNL, Quintessa, TNO, Imperial, ... continue developing RA methodology independent of site specific applications

Data sets and availability, RA techniques used, benchmarking activities, cooperation between different groups?

- FEPs and Scenario Analysis; Deterministic and Probabilistic models
- Current research emphasis on risk and uncertainty quantification

- Weyburn
- Sleipner
- A significant number of data sets being developed in current projects, availability to the Network must be subject to agreement.

- Benchmarking or Comparison of RA Methodologies?
    - Requirements of benchmarking?
    - Timing/readiness for benchmarking?
    - Can we meet these requirements?

Data sets and availability, RA techniques used, benchmarking activities, cooperation between different groups?

- EU Funded Project CO2ReMoVe (Subject to successful negotiation) considers *Benchmarking/Comparison* of RA methodologies
- ZERT (Zero Emission Research & Technology) in the US has similar objectives

- Timing and Funding for Network activities on *Benchmarking/Comparison of RA methodologies* is the main concern
- Could IEA lead activities to facilitate additional funding should this be necessary?

Sharing of Data Sets and/or Results?

- Both
- Sharing results can be easily achieved
- Sharing data would be most effective if parties are ready to utilise this data effectively and to the benefit of both the research and industrial community.

Gaps in Data?

- Data on structures between the reservoir and the surface
- Fault properties
- Well and caprock integrity
- Supercritical CO2 behaviour
- Residual trapping
- Geochemical and geomechanical processes

Summary and Recommendations?

- The Network could/should consider and decide upon:

  - A procedure/mechanism to approach groups/owners to request data
    US DOE, Research Consortia, Industry
  - The nature of data (real; part real - part assumed)
  - Minimum requirements for an organised data set (availability)
  - Benchmarking or comparison of methodologies
  - Timing of such studies? Are the Network partners ready to utilise and make maximum use of available data sets?
  - Mechanism to raise additional funding for some additional work
  - Certification requirements

- There may be the need to sep up Task Groups/Working Parties to address these questions in the first instance

Regulatory subgroup

Tore Torp
John Gale
Wolf Heidug
David Savage
Tony Espie
Malcolm Wilson

Regulatory subgroup

- What the regulator needs
  - Simple and transparent framework
- What the public needs
  - Confidence in safe storage
- What industry needs
  - Clarity and practicality

Regulatory subgroup

- Benefits to having informed group provide input to regulators
  - Informal peer review process for RA work
  - Providing consistent messages
  - Not an advocacy group, but can test messages/outputs from RA
  - Levers to change risk profile
  - Monitoring to meet risk profile
- Evaluate consequences of different regulatory structures
  - Not suggesting a universal standard, but consistent outcomes

Regulatory subgroup (cont)

- HSE – local stewardship
- Ocean and Climate response – international stewardship
- Development of RA methodology
  - Short-term – HSE – project permitting
  - Longer-term – return of site to public – length of time for monitoring
- Collection of regulations that are currently relevant or may be relevant
- Informed base for modification of existing regs to meet storage needs

Regulatory subgroup (cont)

- Subgroup operating:
  - "informed translators"
  - Collect some major UNFCC reports for views on geological storage reporting
  - Proactive – will invite regulators through IEA (WPFF) and CSLF to:
    - Note that informed body on risk assessment available
    - Ability to fill some of gaps seen in IPCC report
    - Provide discussion on what the RA group can do
    - Ultimate goal regulations acceptable to regulator and industry
    - Informal approach
    - Prescriptive versus performance based regulation

Questions

- Timescales – marshal arguments for appropriate timescales for monitoring, performance assessment etc
- Process for taking this forward – licensing and regulatory framework development

RISK ASSESSMENT NETWORK

Breakout Summary

Added Value/Focus

- What does the network offer
  - Technical community/researchers
  - Regulators
- Are we happy that a key activity is to act as an informed body?
  - Communication focus on regulators?
- Terminology
  - Issues came up throughout
  - Need to clarify

Fundamental Issues

- Do we want to:
  - Understand results that are available?
  - Compare results?
  - Critique results?
    - Critical critique?
    - Antagonistic/contentious
  - Benchmark
    - Can we/should we?
    - Other groups doing it – share expertise/compare

Timing

- We need a projects inventory to know when data is available
  - If we want to compare/understand
- Are the techniques ready to benchmark
  - Not all?

What should we develop

- RA Data sets – no
- Techniques – no
- Guidelines?
- Supporting data sets
  - Environmental impact data
- Do we need sub groups/meetings to develop these
  - As well as larger meetings

Other issues

- Facilitate or organise data exchange
  - Confidentiality issues
    - Set out to avoid this
- Funding for small tasks
  - Environmental impacts data
  - If needed when – now?
- Do we have the right composition?
  - No but we need to
  - Whole group/sub meetings?

RISK ASSESSMENT NETWORK

MEETING CONSENSUS

AND

NEXT STEPS

Network Aims

Objective:

- Develop an open and transparent process to allow different RA approaches and their results to be understood

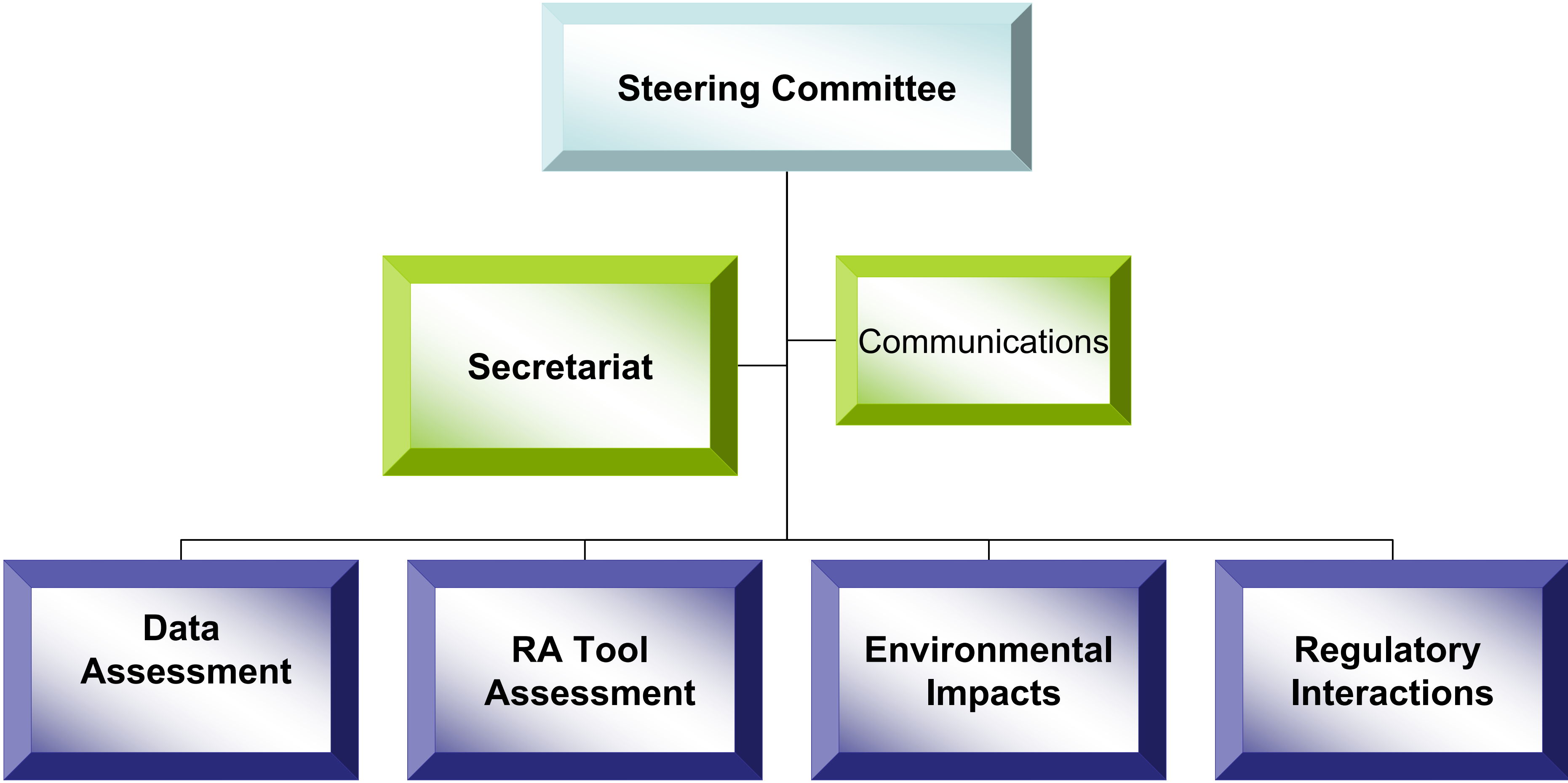
Aims:

- Provide a forum to allow different RA approaches to be compared
- Determine what the results are telling us and how they differ
- Provide an umbrella group for international collaboration on RA
- Identify gaps in knowledge and make recommendations on how to close these gaps
- Act as an informed body on RA for dialogue with regulators and NGOs.

Timescale:

- 5 years starting in August 2005

Network Structure



Next Steps Prior to Next Meeting

- Tasks to progress before next meeting
  - Inventory of RA models/tools and status
    - CO2GEONET on RA framework and terminology
  - Inventory of data sets
    - Cross link to RA tool group on model needs
  - State of Art on Environmental Impacts
    - IEA GHG study
  - Regulatory interactions
    - IEA GHG study
    - Preliminary meeting in February 2006?

Next Meeting

- September/October 2006?
  - North America?
- Outline Agenda
  - Feedback from next step activities
  - Start discussion on data set requirements
    - Links modellers and data set providers
    - Working section of meeting
  - First RA methodology comparisons?
    - Weyburn, CO2STORE, CO2CRC??

Meeting Notes/Presentations

- All presentations on www.co2captureandstorage.info
- Early next week
  - Protected site
- Participant contact list
- Reports from breakout groups within two weeks
- Report and next steps on web site

Geo-energy

TNO | Knowledge for business

TNO Built Environment and Geosciences
– *Geological Survey of the Netherlands*
PO box 80015
3508 TA Utrecht

Rob van Eijs
Ton Wildenborg
Chris Karman
Mark Spruijt

Quantitative risk assessment regarding CO_2 storage – TNO's experience

Identification of relevant features, events and processes (FEPs)

FEP analysis starts with the systematic identification of all FEPs that could affect the (long-term) safety of the storage system by experts from different but relevant areas of expertise. The FEPs are subsequently stored in the FEP database (Figure 1). The FEP database is used to support the subsequent steps in the FEP analysis process. In the analysis a distinction is made between features (F) as static factors, and events (E) and processes (P) as dynamic factors. Only the events and processes (EPs) are evaluated in safety assessment. The EPs that are likely or very likely to occur and at the same time are characterized by a medium to high risk will be included in the scenario elements (ranking).

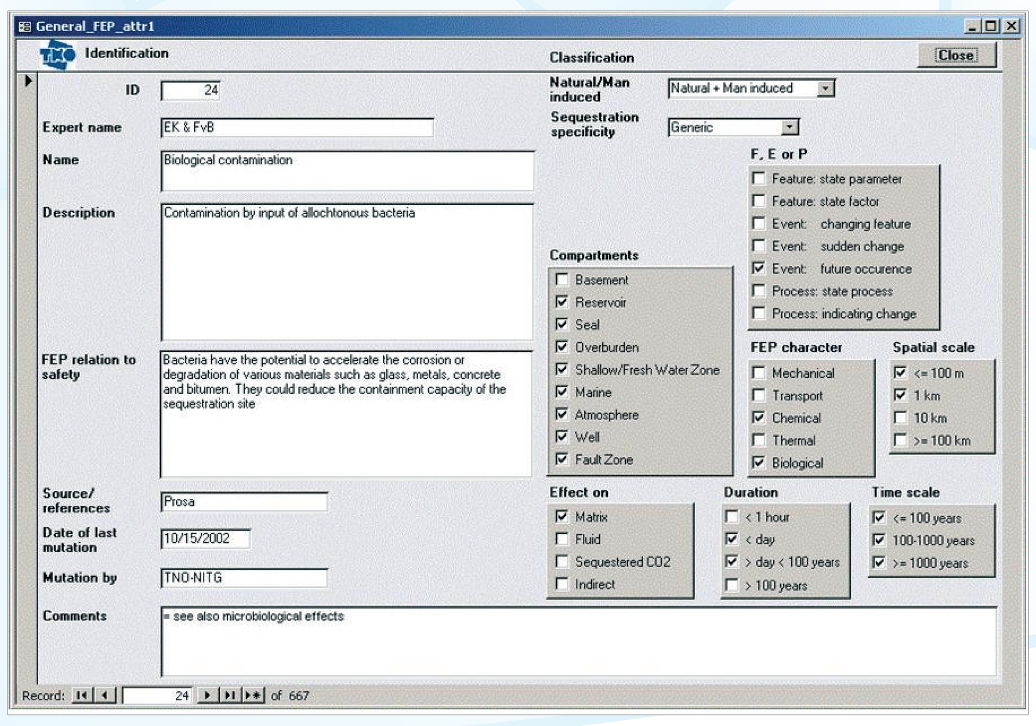
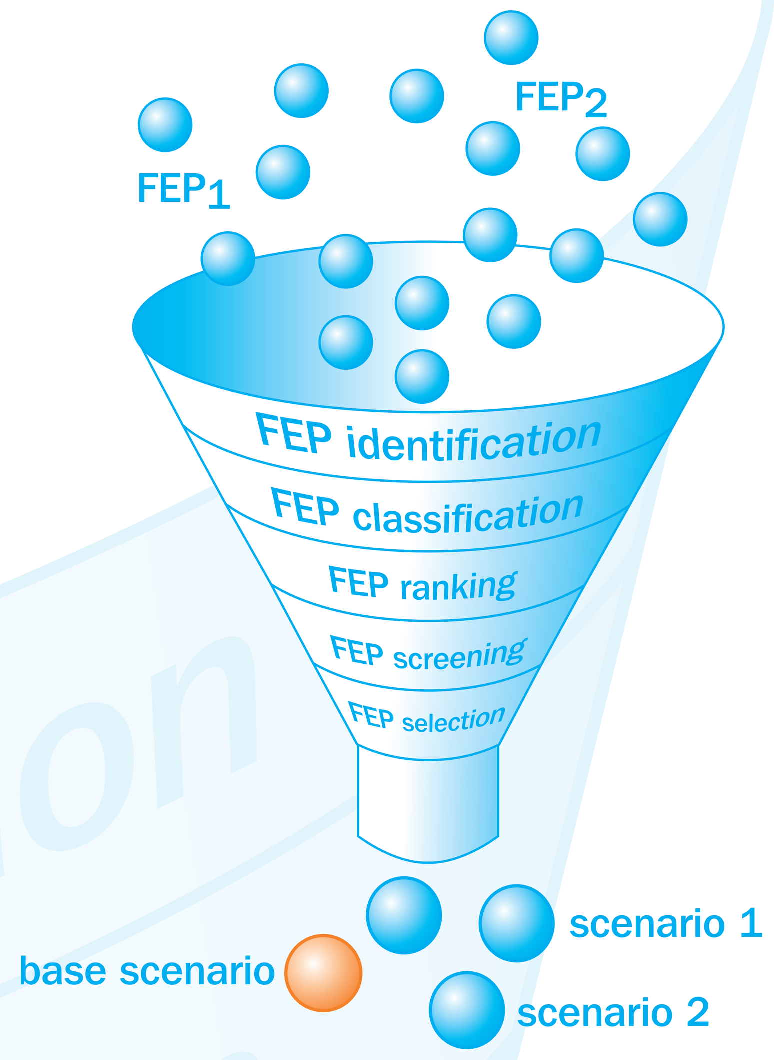


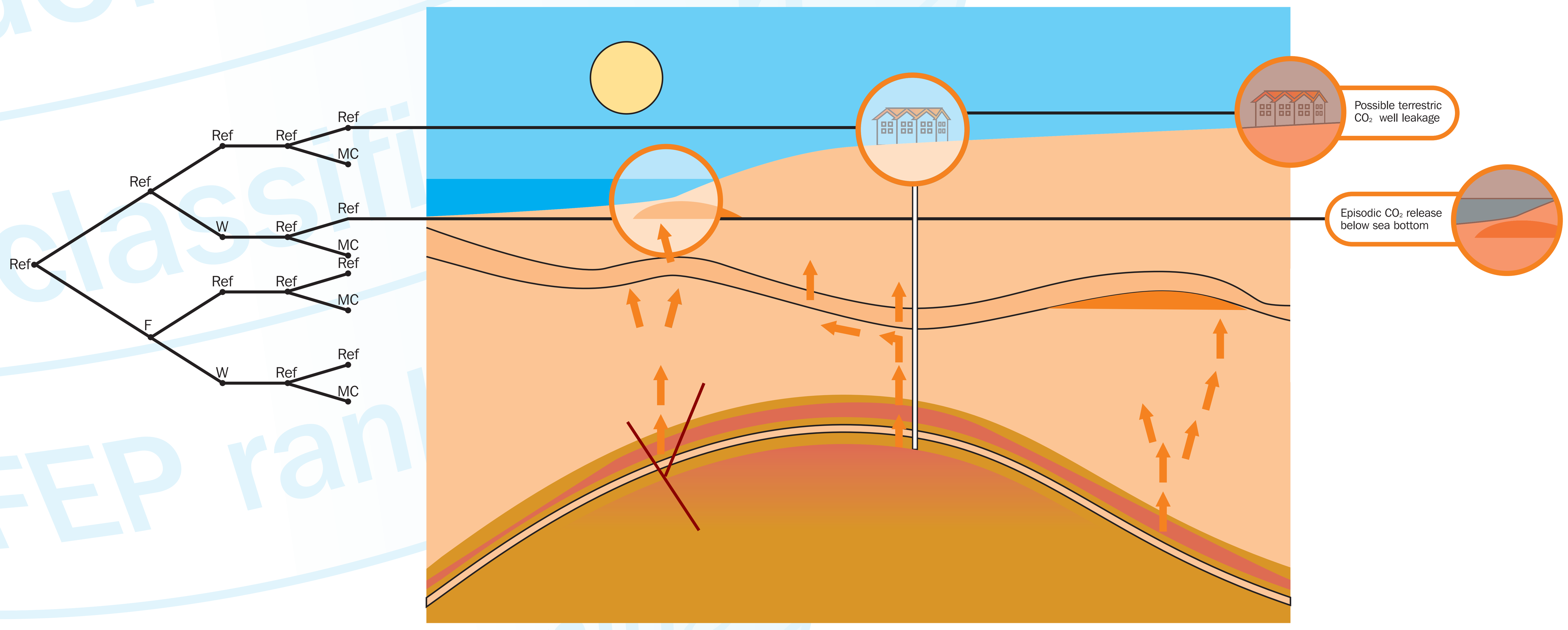
Figure 1



Defining scenarios

A scenario is formed by grouping of the identified scenario elements, which will result in a complete description of a potential future state or evolution of the storage facility. Temporal and spatial consistency of the assembled scenario elements must be checked. The aim here is to assure that the most critical scenarios for health, safety and environment have been included in the analysis.

As an example two scenario's are presented here
Possible terrestric CO_2 well leakage
Episodic CO_2 release below sea bottom.



Consequence analysis

Consequences for human health and environment, based on different scenarios, can be calculated on a deterministic and/or probabilistic way using computer or analogue simulations. TNO has been involved for many years in the field of hazardous materials, undertaking both experimental and theoretical research into modelling the effects of accidental releases.

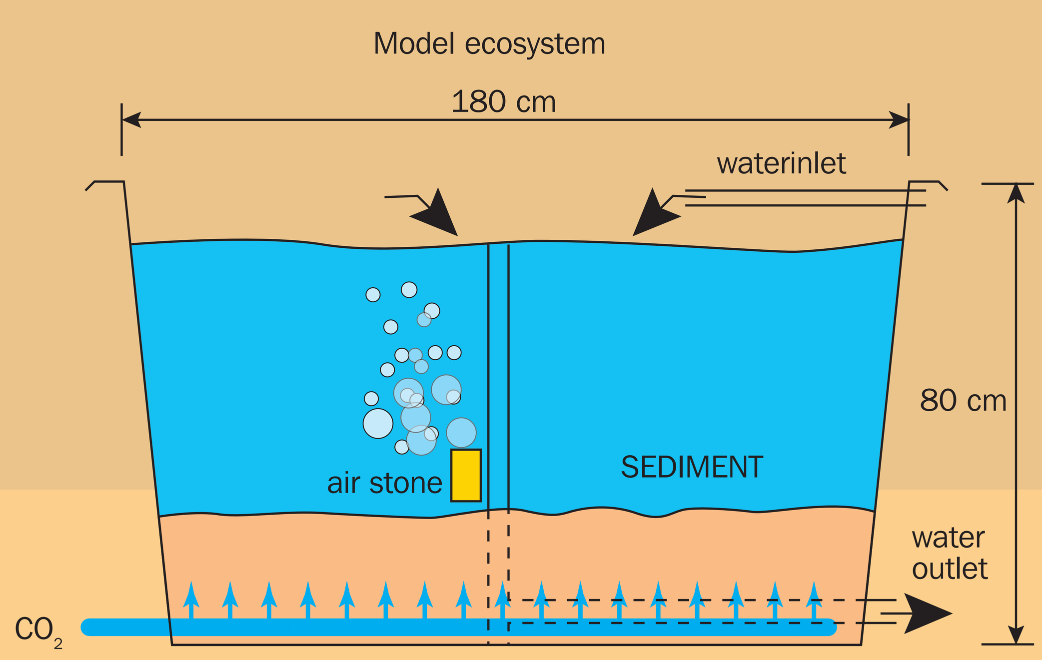
Episodic CO_2 release below sea bottom

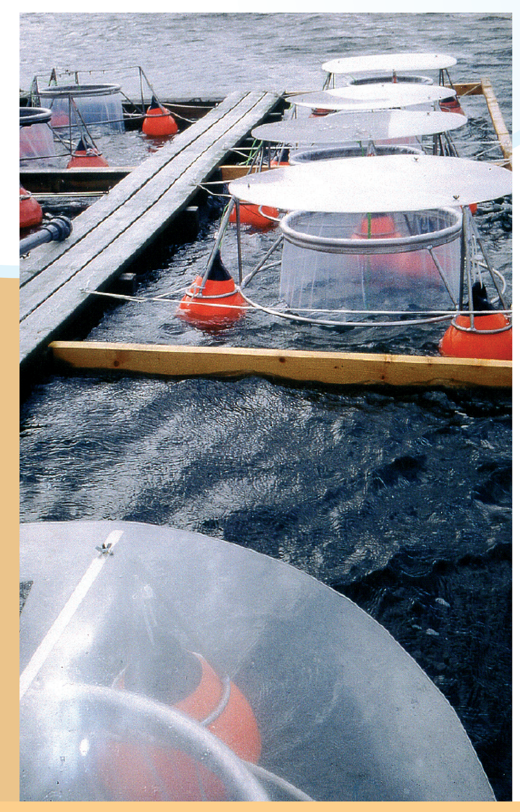
Environmental impact most relevant

CO_2 dispersion in the seabed and the overlaying water may lead to oxygen displacement. Furthermore, the pH change (CO_2 will react into HCO3- ; CO32- and H+) alters metal nutrient availability with possible consequences for the composition of the phytoplankton community and higher trophic levels up in the foodchain. However, few data are available that demonstrate these effectes.

CO_2 dose-response studies are proposed

- Determine relative increase of CO_2 concentrations in seabed and overlaying water
- Study the impact of increased CO_2 concentrations
    - sediment bound algae/diatoms (primary producers)
    - crustacean, mollusks, echinodermata (primary and secondary consumers)
    - focus on both sediment- and waterbound organisms



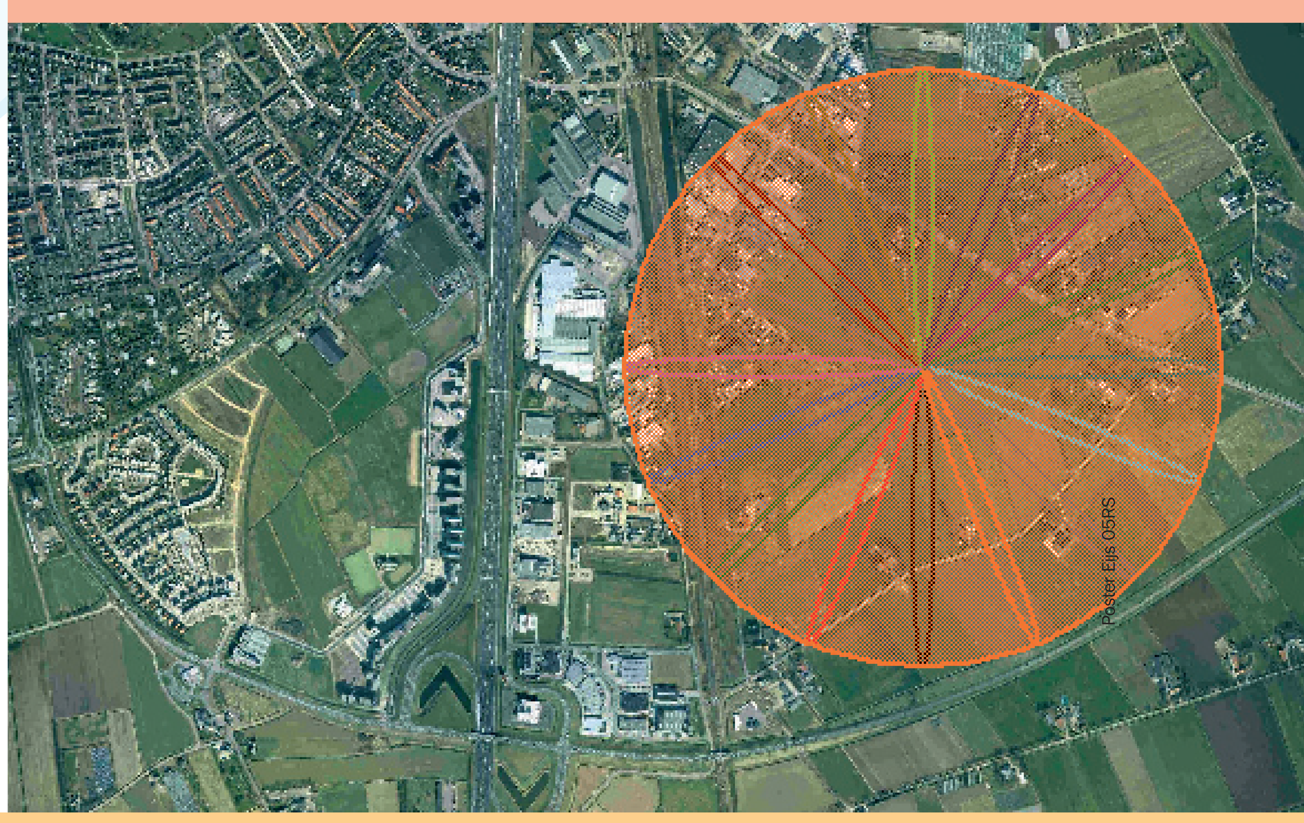


Possible terrestric CO_2 well leakage

Human health impact most relevant

Below is an example presented of a lethal CO_2 contour (=100000 mg/m^3) in a hypothetical case with the following boundary conditions:

- Wind speed is 1,5 m/s from all directions
- CO_2 flux at well head is 1.5E+6 m^3/day
- Pressure at well head is 5 bar
- 7" tubing



Policy support

At the end, it is needed to compare CO_2 leakage risks with other risks like storage of chemicals, flooding etc. (10^{-6} contour). Hence, policy can debate objectively on the acceptability of risks concerning CO_2 storage.

A computational estimation of CO_2 migration injected into a reservoir

Hiroshi SUENAGA (Central Research Institute of Electric Power Industry, JAPAN)

1.Introduction

When considering CO_2 geological sequestration in long-term period, it is necessary that an environmental impact for groundwater use with CO_2 migration is evaluated by using numerical simulation. We are conducting a modification of 2phase flow simulation code (TOUGH2) to achieve accurate expression of CO_2 dissolution to water. An estimation of CO_2 migration was performed using geological and hydrological model determined by results of logging in a borehole and core testing based on the Appalachian Basin geology in the Midwestern USA.

2. Models

(1)Geological and Hydrological Model (Fig.1, 2)

+ Area and depth of analysis are 20km * 10km and 2.4km, respectively
+ Structure is dipping slightly (~20m/km) to southeast
+ Depth of CO_2 injection is 2.4km in a sigle vertical well without any stimulation
+ Permeability and porosity data are acquired from logging in a borehole (0 ~ 800m) and laboratory measurement (800 ~ 2400m)

(2)Two Phase Flow Model (Fig.3)

+ Made by curve fitting to van Genuchten equation using laboratory measurements

(3)CO_2 Dissolution Model (Fig.4, 5)

+ Using accurate data

CO_2 dissolution phenomenon to water are conventionally expressed using Henry's law that dissolved CO_2 mass fraction is in proportion to water pressure. A relationship between dissolved mass fraction of CO_2 and water pressure might not be linear when the water pressure is higher and higher temperature(Spychar et al., 2003).We input accurate dissolution data. However, salinity is not considered in this calculation. This may cause a conservative results for dissolved CO_2 mass fraction.

+ Delayed dissolution phenomenon

When considering one dimensional and long distance migration of CO_2, dissolution phenomenon may NOT be completed instantaneously. For the larger grid scale of numerical analysis, dissolution phenomenon will be delayed.We developed a model that dissolved mass fraction of CO_2 to water in a grid is determined by a length of grid scale (L) and elapsed time from the beginning of dissolution.

(4) CO_2 Properties (Fig.6) are derived from Span and Wagner(1996)

3. Outlines of Calculation

(1) Initial Condition: thermal gradient is constant and pore pressure is hydrostatic

Temperature = 12.8 + 18.2*Depth(km)

(2) Boundary Condition: non- permeable

(3) 100 years CO_2 migration were calculated to evaluate a distribution of dissolved CO_2 with assuming CO_2 injection at the depth of around 2400m during 25years with a pressure of 35MPa, even though higher injection pressure is likely to be feasible in the region.

4. Case Studies

[Case1] Using representative permeability data derived from core measurement or logging data

[Case2] 10 to 10000 times larger permeability used at the depth of 800 to 2400m than that of Case1(essentially assuming that there is almost no caprock)

[I-D] Assumed instantaneous dissolution phenomenon (according to Henry's law)

[D-D] Using delayed dissolution model

5. Results (Fig.8, 9, 10)

- In case1 (realistic case), there is almost no migration of CO_2 from the reservoir zone even into the immediate caprock in 100 years
- In case2 (all sandstone case), CO_2 will yet go upward to the depth of 1500m in 100 years. Even in this greatly exaggerated scenario, there is not CO_2 movement into the freshwater zones that are typically present in top ~ 30 meters.
- Considering delayed dissolution phenomenon is needed to estimate an accurate CO_2 injection rate and migration area.

Acknowledgements: The work presented here is being conducted under funding from METI in collaboration with Battelle Memorial Institute, Columbus Ohio. Other participants in the project include Kameichiro Nakagawa, Takumi Shidahara, Takashi Ohsumi (CRIEPI), Neeraj Gupta, Phil Jagucki, and Joel Sminchak (Battelle).

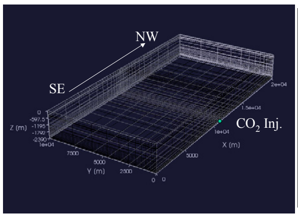


Fig.1 Calculated Area

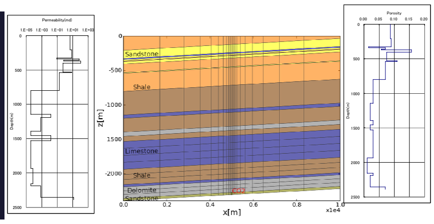
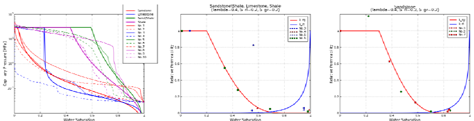


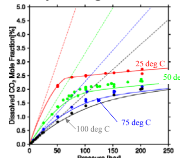
Fig.2 Geological and Hydrological Model



Capillary

Relative Permeability

Fig.3 Two Phase Flow Model by the Fitting of van Genuchten Equation



solid line: this model
dashed line: conventional Henry's law
dot: experimental data

Fig.4 CO_2 Dissolution to Water

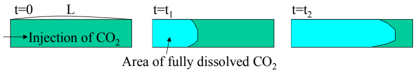
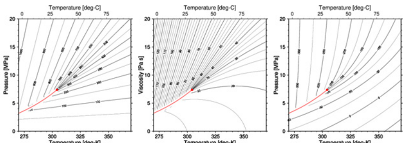


Fig.5 Schematic Diagram of Delayed CO_2 Dissolution Phenomenon



Density of CO_2 Viscosity of CO_2 Enthalpy of CO_2

Fig.6 CO_2 Properties

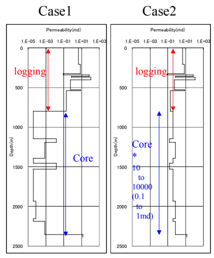


Fig.7 Difference of Permeability Distributions between Case 1 and 2

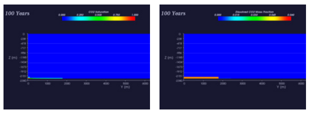


Fig.9 Distributions of CO_2-phase Saturation and Dissolved CO_2 Mass Fraction (CASE1, I-D, Y-Z Cross Section)

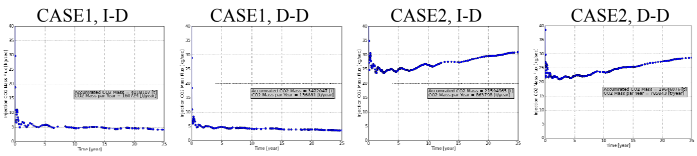
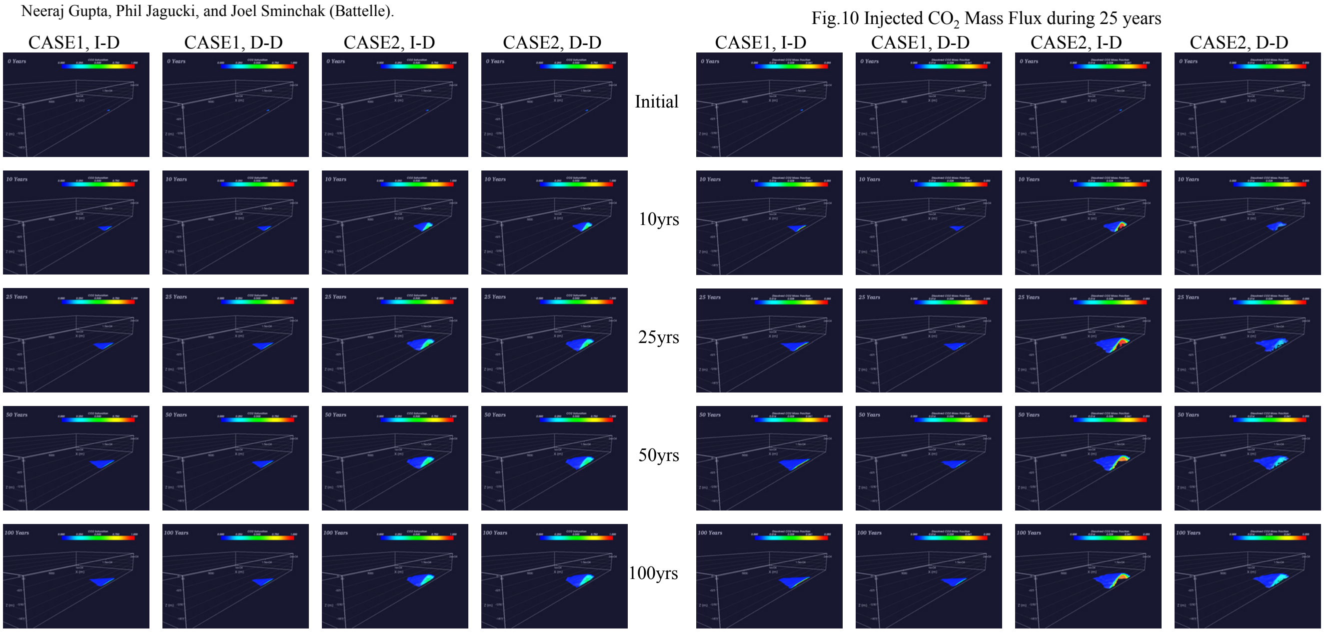


Fig.10 Injected CO_2 Mass Flux during 25 years



(a) CO_2-phase Saturation (b) Dissolved CO_2 Mass Fraction

Fig.8 Distributions of CO_2-phase Saturation and Dissolved CO_2 Mass Fraction to Elapsed Time

A CO_2 Sequestration Systems Model Supporting Risk-Based Decisions

Philip H. Stauffer, Hari S. Viswanathan, George D. Guthrie, Rajesh J. Pawar , John P. Kaszuba, James W. Carey, Peter C. Lichtner, Hans J. Ziock, Manvendra K. Dubey, Seth C. Olsen , Steve J. Chipera, Julianna E. Fessenden

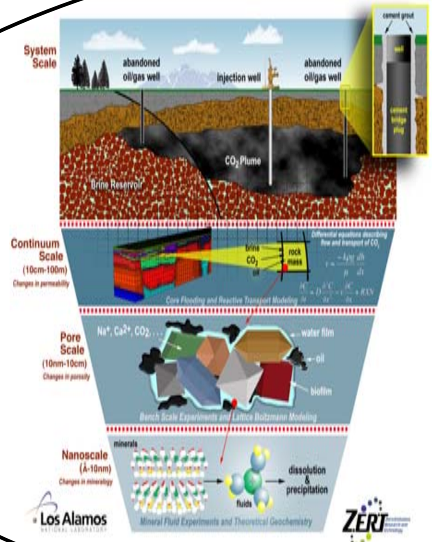
Unclassified

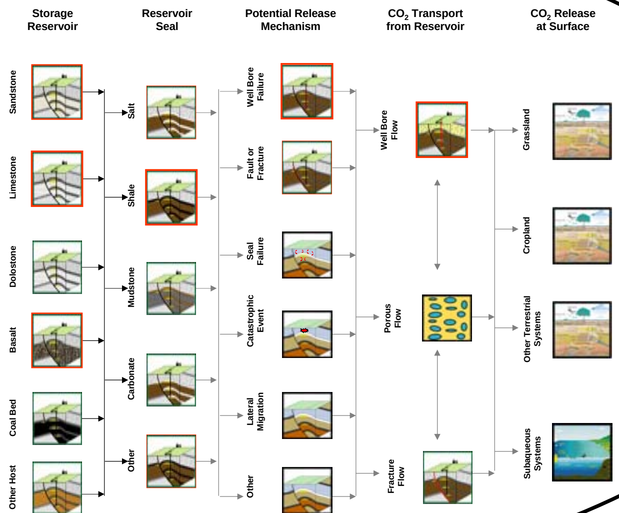
LAUR 05-6262

Abstract

As part of the Zero Emissions Research and Technology (ZERT) project Los Alamos National Laboratory is studying the injection of CO_2 into geologic repositories. We are formulating the problem as science based decision framework that can address issues of risk, cost, and technical requirements at all stages of the sequestration process including strategic monitoring. The framework is implemented in a system model that is capable of performing stochastic simulations to address uncertainty. Processes level laboratory experiments, field experiments, modeling, economic data, and risk theory are used to support the system level model that will be the basis for decision making . The current system model is already proving to be useful in showing complex interactions between the different components of the framework. The system model also provides a consistent platform to document decisions made during the site selection, implementation, and closure periods.

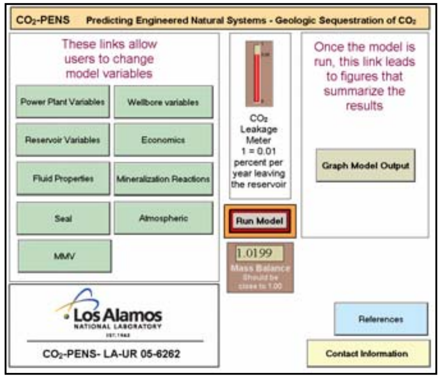
1) A Science-Based Decision Framework for Engineered Natural (Geologic) Systems



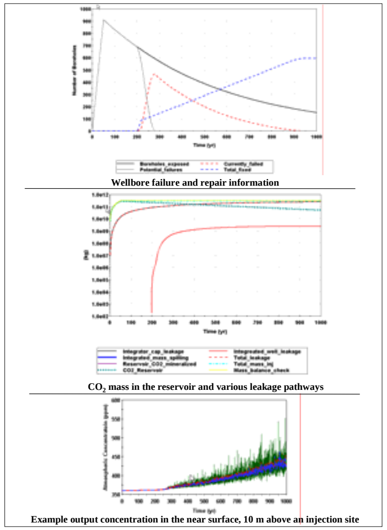


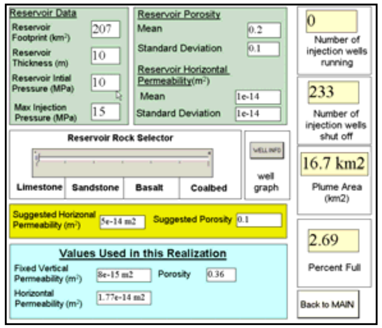
2) CO_2-PENS System Level Model used to explore complex interactions between Risk, Cost, and Technical Requirements

Main Simulation Control



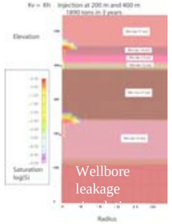
CO2-PENS Model Root





Reservoir Property Input | **Example Output**

3) Process Level Investigations used to Support System Level Calculations

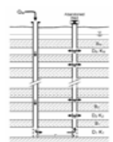


Numerical Modeling FEHM

Multiphase flow
Fractured porous media
Reactive chemistry

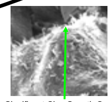
Analytical Solutions for Wellbore Failure

Obtain leakage rates using Semi-analytical solution by Celia et al. (collaboration with Princeton)



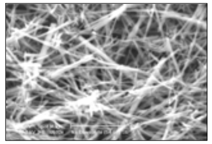
Nordbotten, J, M. Celia, S. Bachu, Water Resources Research, 2004.

Reservoir Processes >> CO_2 Fate and Transport

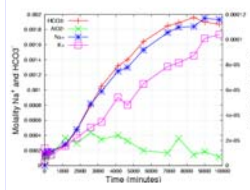



Significant Clay Growth Occurs

Hobbs Injection Site
Field injection
Lab experiments
Numerical simulations



CO2 Mineralization:
Dawsonite Synthesis Experiments

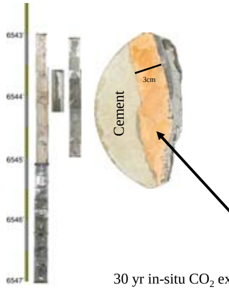


Core Flood Experiment
Calcite dissolution
Wormhole formation
Numerical simulations

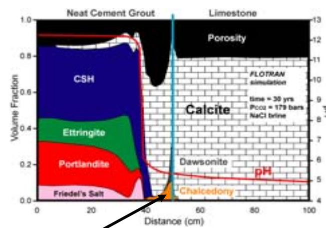
Cement Degradation >> Wellbore failure

CO2 Cement Brine Experiment
pH sensitive dye
Ca(OH)2 (high pH) -> CaCO3 (low pH)
PCO2 = 13.8 MPa

SACROC Core Analysis



FLOTRAN reactive chemistry simulations



30 yr in-situ CO_2 exposure history retrieved from core near the reservoir/caprock interface.
SACROC, Texas