4TH WELLBORE INTEGRITY WORKSHOP

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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

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

The fourth international research network on Wellbore Integrity was organised by IEA Greenhouse Gas R&D Programme in co-operation with Schlumberger. The organisers acknowledge the financial support provided by Oxand, Suez, Total and BRGM for this meeting and the hospitality provided by the hosts Hotel Concorde Montparnasse, Paris.

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

Bill Carey, LANL (Chairman)
John Gale, IEA Greenhouse Gas R&D Programme (Co-chair)
Veronique Barlet-Gouedard, Schlumberger
Idar Akervoll, SINTEF
Mike Celia, Princeton University
Rich Chalaturnyk, University of Alberta
Stefan Bachu, Energy Resources Conservation Board
Daryl Kellingray, BP
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The report should be cited in literature as follows:

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Summary Report of 4th Wellbore Integrity Network Meeting

Date: 18 – 19 March 2008

Hotel Concorde Montparnasse,

Paris, France.

Organised by IEA GHG and Schlumberger,

with the support of Oxand, Suez, Total and BRGM

FOURTH WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON WELLBORE INTEGRITY

Executive Summary

The fourth meeting of the Wellbore Integrity Research Network was held in Paris, France in March 2008. As with the previous meetings, there was a good attendance from industry, academia and regulators and the meeting included presentation of some new research results, some of which generated in depth discussion and interesting points that were discussed in greater detail in the facilitated discussion sessions.

The presentations were held over 2 days, and were split into four topics. These were: field investigations of wellbore integrity, experimental studies of wellbore integrity, numerical modelling, and monitoring, risk and development of best practices. Each session was followed by a facilitated discussion on the topics covered by the presentations, as this format has been tried and proven at previous meetings. The debates spurred by these discussions often carried over into the coffee breaks and beyond, such was the interest and variation in opinion generated.

The level of involvement and discussion highlighted both that the issue of wellbore integrity is still of very high importance to CO_2 geological storage projects, and that there is still much relevance and benefit in holding the network meetings. The insightfulness of the discussions showed the depth of knowledge and understanding involved in the network is industry leading, and indeed the affiliations of participants further illustrated this.

Discussions were equally weighted across the topics, with a wide range of inputs from all participants, demonstrating the value of the meetings and the level of interest felt by all who attend. There was debate over several contentious issues, and this illustrated the work still to be done which the network can contribute to; there is a variety of opinion on some issues, and the CCS community needs to work through these to achieve the appropriate consensus so as to address concerns of both the general public and regulatory bodies alike. The approval of these two stakeholder groups will be vital in achieving acceptance of the technologies used for CCS, and the material presented by groups working on complex dynamic modelling show that real progress is being made towards demonstrating a good level of certainty of long-term, safe and secure storage.

Discrepancies highlighted at previous meetings between laboratory and field experiences are still present, but the gap between them is narrowing, and there was a feeling of an increased understanding as to what generates these gaps. With constructive criticism, some of the techniques used to extrapolate long-term data from short-term accelerated laboratory based procedures were questioned and defended, illustrating that, despite progress being made, there is still a long way to go before laboratory results can be confidently applied to predictive models.

The need for the continued existence of the network was discussed and agreed. There is still new and innovative research being presented at the meetings, showing that there are still developments and breakthroughs to be made towards the long term goals of providing assurance to stakeholders that the mechanisms operating within the wellbore are understood, risks can be identified and minimised in advance, and should leaks occur, monitoring methods will allow rapid detection and mitigation.

Contents

1. Introduction

This fourth meeting of the wellbore integrity network was held in Paris, and hosted by Schlumberger. The President of Schlumberger Carbon Services, David White, gave an introduction to the meeting, introducing and giving a brief background to Schlumberger encompassing their background of CCS activities and related activities.

At the end of the 3rd meeting of the network, it was hoped that the future meetings would continue to provide a valuable insight into the activities and state of art on wellbore integrity issues, and David's presentation mirrored that hope stating that the issues associated with wellbore integrity were a global problem, and on that basis, they need a global solution which has lead to an ever expanding worldwide research and development budget.

David explained that although there is definitely a convergence of opinion taking place regarding CO_2 and climate change, there still exists a healthy scientific debate regarding some aspects of the science. This was born out in the discussion sessions, with numerous views expressed; this scientific debate is necessary in order to progress towards the ultimate goal of demonstrating safety and security of CCS, and of particular relevance to this network, the ability to accurately model a '1000 year well'[1]. The transition from the 1000 year well concept to that of accurate modelling to demonstrate safety over geologic periods has led to an increased focus on the modelling community, and this was also borne out by the focus on the modelling session being much more detailed than in previous meetings.

David went on to say that even if the global population takes into account the uncertainties to CO_2 and climate change, there are definable benefits to curbing CO_2 emissions and improving efficiency of power generation. In terms of CCS viability, it is therefore important for the scientific community to be well prepared to answer any and all questions likely to be raised by the general public, regulators and legislative bodies alike.

David discussed the viability of different mitigation options, and the potential difference each option can make, and also provided a useful summary of the issues which will need to be solved in order to obtain public acceptance of the technology, with particular attention to risks and regulations. He also commented that it was important to put risks and activities into perspective, and that one view was that currently, we have an effective leakage rate of 100%. Whilst this is obviously unjustifiable from a scientific view, as emissions to atmosphere from power stations cannot be considered as leaks as they are not intended to do anything else, it does add reason to the argument that any CO_2 that is stored and prevented from entering the atmosphere is a bonus over the current situation. In other words, doing something is better than doing nothing. David concluded with the quote that there is 'No such thing as a bad experiment, just an unexpected result.'

[1] The concept of a 1000 year well was one conceived before the start of the inaugural Wellbore Integrity Network meeting, and the network set out to determine the feasibility of such a well. Since then, the concept has adapted, and is now looked at as accurately predicting the behaviour of injected gasses and wellbore materials for a length of time equal to that in which the CO_2 would become permanently trapped and immobilised.

2. Aims & Objectives of the 4th Workshop

The network was, at the start of this meeting, entering into its fourth year of operation, and the network was originally established with 5-year tenure. Therefore, the results and conclusions of this meeting will form part of the discussion at the 5th meeting in 2009 as to the validity of continuing the network past the original 5 years as planned.

The broad aims of the network remain unchanged, and they are:

- To provide confidence to all stakeholders that the mechanisms involved with maintaining wellbores are understood.
- That the safety of storage, specifically in relation to wellbores, can be ensured because the risks can be identified and minimised.
- That wellbores can be monitored for early signs of leakage, and remediated as necessary.

The meeting also had some specific aims identified in the conclusions from the 3rd meeting, and these included:

- Investigating the contrast between field and lab results.
- Updating the advances in technologies and understanding, as was seen between the 2nd and 3rd meetings.
- Continued investigation of the advancements made in the modelling of wellbores and the reactions between CO_2 and wellbore materials.

3. Workshop Attendees

The meeting was attended by 73 delegates from 12 countries (Appendix 1). The delegates represented regulators, international industrial operators and geological researchers from Australia, Europe, North America and Asia.

4. Workshop Programme

The programme and agenda for the meeting are presented in Appendix 2. The meeting was divided into a series of sessions, which focussed on specific topics within the scope of the network, with discussion sessions held after each technical session.

5. Technical Presentations

The presentations were held in 4 sessions, each covering a different broad topic, and with a related facilitated discussion. The results from the presentations are summarised in sections 5.1 to 5.4 below, and details of the facilitated discussion sessions can be found in section 6.

5.1 Field Investigations of Wellbore Integrity

5.1.1 SINTEF Assessment of Sustained Well Integrity on the Norwegian Continental Shelf, Preben Randhol and Inge M Carlsen, SINTEF Petroleum Research

Preben gave a detailed, geographically specific presentation about the activities of SINTEF on the Norwegian Continental Shelf, and the presentation was well received. Regional reporting is becoming more important and relevant as variations in practices around the world must be understood to determine best practices in different situations.

Operations within the Scandinavian region are moving more towards sub-sea injection programmes and injection in arctic regions. These types of operations encounter specific problems, including those associated with access when working in the sea, and more precisely difficulties with arctic conditions and accessing sites that may become ice bound.

The development trend of projects in this area is to re-use the existing well infrastructure, and this leads to the need for thoroughly documented field integrity. All wells used in these operations, both oil and gas producers and injectors, and gas lift wells have to be designed with two barriers to prevent hydrocarbons reaching the surface.

The presentation then went on to the more focused area of wellbore integrity, and revealed that of all the wells in the scope of operations on the Norwegian continental shelf, between 20- 30% of wells have suffered at least one leak. This highlights the importance of wellbore integrity, and indeed the presentation listed 5 considerations as to why wellbore integrity is of such importance: safety, environment, production, reputation and asset value. These considerations are representative of the aims of the activities on wellbore integrity around the world, as they cover confidence, security, monitoring and environmental protection, the areas which will be influential in deeming a project publicly acceptable or not.

The SINTEF studies on wellbore integrity mapped leakage history from 1998 to the first quarter of 2007, and there is a notable rise in the percentage of wells that have suffered leaks, from 1.69% in 1998 to 25.5% in quarter 1 of 2007. On the surface, this looks like a worrying trend, but there may be mitigating factors in this, which are listed in the presentation to include the increasing age of the wells surveyed; as wells age, the degradation will increase, and this will increase the likelihood of a failure and leak. Another factor may be reporting procedures and awareness of the issues and processes involved; the data does not appear to be strictly age related, in so far as some older fields have lower leakage rates than some newer fields. There is also an interesting correlation between an apparent increase in well failure and the date that the company employed an individual to manage and investigate leaks. This further backs up the theory that the leaks are not a new phenomenon, but rather they were not understood and reported correctly before this point.

At this point, the presentation was opened to questions, and Ron Sweatman asked what were the main causes of leaks identified. Idar Akervoll answered that they were mainly internal failures, but with some seal and steel issues as well. At no point in the investigation was a cement failure noted, and Idar confirmed that if such a failure were present, it would have been identified. Although determining the leakage pathway is problematic in this case study, it is thought that monitoring detection should be able possible.

5.1.2 Charles Christopher, BP; A Comprehensive Wellbore Integrity Programme,

Charles Christopher gave a brief summary of the requirements of a CO_2 Wellbore Integrity Programme which included field data and references to an ongoing project, although no results or conclusions were presented from this project as it was in progress, the preliminary results therefore still require careful evaluation and confirmation before being disseminated.

Despite this, there were three main points presented as possible areas for future development and research:

- The kinetics tests carried out within the laboratory environment did not reciprocate and match the results gleaned from the field experiments. This suggests that more extensive field and laboratory work is required to determine the consequences and repercussions of this if the results are replicated in subsequent experiments.

- A cement core[2] taken from the well covering a depth to include both the cap rock and cemented section shows signs of very good bonding between the sections. It was also noted that the cement section appeared to be porous and is being analysed in more detail to determine this porosity.

- It can be concluded that a comprehensive wellbore integrity programme must include the regulators involved in a storage project, as well as the surrounding community and the project operators. As much information as is possible should be assimilated and disseminated at an early stage to minimise the need for repeated requests for information.

Charles finished by saying that there were some very interesting and promising results coming from the project, but until full evaluation of results have been carried out no figures and data will be published.

5.1.3 Theresa Watson, TL Watson & Associates, Review of Failures in Wells used for CO_2 and Acid Gas Injection

Theresa presented work undertaken by TL Watson and Stefan Bachu of the Energy Resources Conservation Board reviewing failures in wells used for CO_2 injection and acid gas disposal in the Alberta region of Canada. The data was newly acquired, and the report was yet to be completed, but the initial results were discussed by this presentation.

The work described how the acid gas / CO_2 wells in Alberta were assessed, along with the regulations that applied when the wells were drilled, and this in itself provided a good overview of the regulatory changes and procedures throughout the region. The report highlighted the fact that according to the regulations, there is no requirement to inspect the casing used in the wellbore to determine the presence of carbonation and its action on the

[2] In total, eight samples were retrieved from the well at different levels, showing a decrease of permeability and porosity from 1 – 2 orders of magnitude, however permeability and porosity increase and compressive strength decrease in the samples taken in front of the reservoir.

materials present in the wellbore. The regulations were noted to have had no effect on the occurrences of H_2S leakage, although this was thought to be due to the stringent practices followed by acid gas disposal operators as H_2S leaks are likely to be fatal due to the toxicity of the gas involved.

Unsurprisingly, the review showed that the failure rate was lowest in purpose built wells over those that have been converted from previous operations; this was more pronounced in acid gas injectors over CO_2 injectors.

Theresa went on to analyse the causes of failures observed, and it was clear that the primary cause for injection failure was tubing and packer failure. These types of failures are easy to detect, and annual testing requirements are designed to ensure continued integrity of these elements, with failures needing immediate repair. When the report looked at failures not linked with injection, the spread of causes was not dissimilar to that of the general well population in the region.

Members of the meeting queried the impact of the use of specialised cements on the failure rates, and it was confirmed that experience shows that failures still occur; even when the well concerned was completed using specialised, CO_2 resistant cement.

5.1.4 Matteo Loizzo, Schlumberger Carbon Services, Advances in Cement Interpretation: Results from MOVECBM (Poland), COSMOS-2 (France/Germany) and Otway Project (Australia).

This presentation dealt with advances in interpretation of the results from cement experiments, and as a starting point, worked from the conclusions drawn from the EPA CO_2 Geosequestration workshop in 2007. From this point, analysis from the CO2SINK and MOVECBM projects, amongst others, were taken and from this, the key advancements in the state of knowledge were highlighted.

It was explained that leaching relies on fluid flow transport, as the absence of this transport mechanism precludes the action of leaching through the cement. The presentation went on to provide a good explanation of the various pathways that can be present, and the mechanisms that can facilitate and assist leaching. Much discussion centres on the quality of cements used, but the presenter explained that the best possible cements will only be successful in resisting corrosion in the best circumstances and conditions. Even the strongest cement will crack if hit hard enough or subjected to sufficient stresses and forces, so the creation of pathways is always theoretically possible. To this end, the best designs should be used to minimise risks, and this should be coupled with effective monitoring to detect pathway formation as soon as possible.

The testing of cements was explained, and both sonic and ultra-sonic methods were described along with the combination of these methods with wire-line tools to maximise the ability to detect pathway formation and transport. The presentation went on to explain that these methods do still have limitations, and there are limits to what can be detected; an example being that when there is a fluid filled annulus, the testing is much less sensitive, and the attenuation of the tools becomes greatly reduced.

Analysis of the channel porosity in the projects used as examples illustrated the effectiveness of the well design, and indeed the time log results from the Ketzin project clearly showed when the cement turned from a slurry to a solid-set material. It was highlighted at this point that a good, solid cement can have certain drawbacks, in so far as if the well requires remediation in the future; repair by cement squeeze is much more difficult and less likely to be successful in a stronger, harder cement than a weaker cement that was made with a higher water content. However, cements with higher water contents are prone to higher porosity which is undesirable in CO_2 storage situations. For a detailed explanation of the differences in cement / water ratios, see the 2007 Wellbore Integrity Workshop report.

The presentation went on to highlight the types of cracks that can form and the problems associated with them. Specifically, it was explained that horizontal cracks on their own do not represent a great risk to storage integrity, but they can allow separate vertical cracks and defects to join up and potentially create pathways to subsurface areas above the caprock, thus causing integrity issues.

5.2 Experimental Studies of Wellbore Integrity

5.2.1 Brian Strazisar, NETL, Kinetics of Well Cement / CO_2 Reactions.

Brian drew from the presentation given at the previous meeting of the network, and gave an update on new results and completed aspects of the experiments. The focus of the experiments was on existing wells rather than new wells, and the potential impact of cement degradation in such wells on the integrity of CO_2 storage.

The experiments were able to simulate both hydrodynamic and solubility trapping of CO_2, and observed that the degradation rate commences high and drops off as the reaction continues. The penetration of the carbonation reaction on the cement sample was found to be in the region of a fraction of a millimetre, so on a well scale, very little.

The experimental procedure went on to project exposure into the future, over a scale of 20, 30, and 50 years, and these projections showed the carbonation penetration reaching depths of up to 1mm (the deepest penetration reached just over 1.15mm) depending on the critical state. The experiment looked at different cement blends as well, and the worst example was a 35:65 pozmix sample which, after a period of 9 days, had degraded right through, although the outside of the resultant calcite ring proved to be harder than the original cement. An opposite sample of 65:35 ratio also degraded right through over the 9 day timeframe, and also showed increased hardness of the calcite ring over the original cement. The porosity of this sample went from 1 to 19 microdarcy in the 9 day period.

- Q. If the porosity is measured, which zone is measured?
- A. The porosity stated is an average of the 3 identified zones.
- Q. How was the CO_2 pressure maintained as a constant over the 1 year period?
- A. A syringe pump was permanently attached to the apparatus, and although leakage did occur, the syringe pump maintained the pressure as a constant.

The key findings to date do show progress from the results presented at the 2007 meeting, and it is now understood that the fractures seen under the scanning electron microscope (SEM) are actually caused by the vacuum of the SEM.

There are no plans for future experiments to utilise higher temperatures, and it was clarified that the experimental procedure is using a 1% NaCl to maintain conformity with previous experiments. No other fluids have been used, but it is accepted that there will be differences in the results if different fluids were used. There are no current plans to use ‘typical values’, but there could be some benefit of this for the future.

5.2.2 Bogdan Orlic, TNO, Some Geomechanical Aspects of Well Integrity

This presentation covered the work of TNO staff, and follows from the work presented by Franz Mulders at the previous meeting of the network. Franz discussed the De Lier project, which has subsequently been cancelled due to high associated risks and excessive remediation costs predicted in the event of a leak. Although this site has been disregarded, a new feasibility study is being undertaken on an alternative site. Both projects, when dealing with best practice for abandonment of wells, recommend the ‘Pancake Plug’ method, a diagram of which can be seen in the presentation slides. The presentation went on to discuss the implications and requirements for practical research projects and CCS activities in the Netherlands, and the stringent conditions imposed by Dutch Mining Law. These conditions lead to extended laboratory modelling to demonstrate the minimisation of risks, and to this end, the projects involved look at all the stresses that are imposed on wellbore materials, and the effects of combining different stresses to create multiple stresses of wellbore cements and casings.

There was an explanation of why wellbores in areas of high rock salt abundance are considered to be risky due to the inability of salts to withstand changes in stresses. This was countered by Cal Cooper of ConocoPhillips by saying that the slides used in the presentation illustrate that a high presence of salts promote flow, and that the salts can ‘self seal’, effectively remediating any stress fractures as they occur, making areas of high salt abundance potentially secure sited for CCS. It was conceded that this may be a point worthy of investigation, however, the intention of the report was to identify the leakage pathways rather than suggesting ways round the problems or storage options.

5.2.3 Veronique Barlet-Gouedard, Schlumberger Well Services, Cementitious Material Behaviour under CO_2 Environment – A Laboratory Comparison

The objective of this presentation is to compare different cements, some of them have been previously described in publications or presentations. The cement which is presented in detail is Portland + fly ash type F. The comparison is with previous tested materials as Magnesium Potassium Phosphate, Calcium Aluminate Phosphate, Portland cement, Portland/Fly ash type C, CO_2 Resistant cement developed by Schlumberger (EverCRETE). All of these systems have been designed at 1.89 SG (specific gravity). All these cements have been tested under the same temperature, pressure, fluids with CO_2 (pure water with CO_2 has been used to simulate more severe conditions than brine with CO_2 to be able to show all the carbonation/dissolution process with shorter durations in the laboratory.)

The slides shown went through the basic set up of the experiments, and explained how previous research had determined the toxic levels of CO_2 for humans are at approximately 10% atmospheric concentrations, although effects are felt at anything over approximately 2-3%. This was explained as the background to the importance of wellbore integrity and its relevance to health and safety issues.

The experiments described used a Portland + Fly ash Type F cement under typical pressures and temperatures encountered in a CO_2 storage situation. The equipment used has the potential to operate and test at much higher pressures and temperatures, but for the purpose of this experiment, both parameters were kept at levels analogous of a storage reservoir scenario.

The experiments looked at the effects of wet supercritical CO_2 and CO_2 dissolved in water on cement samples over 3 weeks, 3 months and 6 months exposure. It was noted that after the 6 month period, all samples had been degraded, although the experimental conditions were regarded as more severe than conditions experienced in the field, in order to accelerate the results and allow extrapolation of the same effects under more average conditions.

Veronique concluded with a series of graphs illustrating the change in pore size and related changes in porosity obtained with Portland + fly ash type F system, and a good explanation of the criteria for durability of samples and a comparison of the performance of different cement types such as Magnesium Potassium Phosphate, Calcium Aluminate Phosphate, Portland cement, Portland/Fly ash type C or type F and CO_2 resistant cement developed by Schlumberger (EverCRETE).

Charles Christopher commented that some samples obtained from the field appeared more similar to the 3 month samples than the 6 month samples, suggesting that time may not be the correct variable to plot, and advised caution over use of the experimental data. It was also pointed out that the extent of degradation after 6 months can make extrapolation of results a complicated procedure.

5.2.4 B. Lecampion, Schlumberger Carbon Services, Evolution of Cement Mechanical Properties During Carbonation.

Brice Lecampion gave an informative presentation further covering the effects of carbonation and mechanical degradation of cements in the wellbore environment. The presentation described in detail the experimental procedure and the conditions under which the carbonation was measured.

The methodology used repeated scratch testing to expose the carbonation front by determining the strength of the cement at varying depths, and the depth of carbonation was extrapolated using the hypothesis that the carbonated area will have a higher strength that the un-reacted zone. The results from this can then be up-scaled to determine the long term processes and mechanical effects of the carbonation.

The results so far are promising, but as yet are incomplete, and further testing is required to conclude the experiment. With the preliminary results obtained so far, it should be possible to correlate the porosity of each zone and determine from this the mechanical properties of each zone. It was noted at this stage of the results, that the inner zones of all the samples retain similar properties to those of the initial sample material, suggesting that an un-reacted zone exists at the centre of the sample, but this was a speculative conclusion.

In the concluding remarks made regarding the early stages of carbonation that have been observed, it was stated that the mechanical performance of the cement sheath will be associated with the thickness of the dissolution zone in the early stage of CO_2 – cement interaction, also that up-scaling allows the operator to estimate the elastic properties of different zones found within the samples.

5.2.5 A. Schubenel, ENS/CNRS Paris, Hydro-Mechanical Properties of Carbonated Cements

This presentation described work on a new experimental procedure designed to determine the hydro-mechanical properties of carbonation at in situ reservoir conditions for temperature and pressure. The methodology involved gluing sensors to the samples in order to obtain accurate measurements for Vp and Vs.

The results show that a high crack density equates to high conductivity at effectively zero pressure, and that the permeability reduces with increased carbonation, but the additional shear stress induced by this drastically increases the formation of cracks throughout the samples. It is possible that this damage could be due to the re-pressurisation process, and there are plans to repeat the experiments under in situ conditions to rule out the possibility of influence from the de-pressurisation / re-pressurisation process.

A question was asked at this point as to whether samples should be created under in situ conditions as this could involve different stresses than creating samples under ex-situ conditions and then subjecting them to in situ conditions. The answer to this was that currently it is not possible to create samples in the suggested manner, however new equipment that is under development may make this a possibility and will be investigated in more detail when the equipment is ready for use. An additional comment suggested that dry samples are representative of the conditions near the wellbore perforations as the injected gasses would force any free fluid from the area, thereby drying the cement.

5.2.6 G. Rimmele, Schlumberger Well Services, How to Accelerate Cement Ageing in CO_2 Fluids: LIFTCO$_2$ and COSMOS-I

This next presentation dealt with experiments into accelerated ageing of experiments to extrapolate results of long term wellbore integrity and immersion in CO_2 fluids. The acceleration factor was used to illustrate the time frames anticipated to be involved in a CCS project, rather than a laboratory based experimental procedure.

Although there have been, and still are, many experiments being carried out on the subject and effects of mechanical properties of carbonation, this procedure differs in that it uses an electrical current flowing through the cement sample, and bubbling of CO_2 through an electrolyte to simulate the ageing of the materials and samples over the life of a CCS project.

The methodology called for core samples to be taken and the carbonation and degradation extent measured. The mineralogical analysis showed marked differences between the experiments using 0 volts and those using 10 volts; the alteration front is slightly thicker at the cathode in the 10 volt simulation. The alterations fronts varied from 0.3mm with a 0 volt current, 0.6mm at 10 volts, and 1mm at 30 volts. The presentation showed that this method allows acceleration of cement ageing in CO_2 environments.

Questions were asked as to the effects of higher still voltages, and it was explained that this was investigated, but there were increased enhancements, and indeed it can induce radial cracks in the cement samples. The main discussion from this presentation ran into the prolonged discussion session, and focussed on the theory that in a cement ageing test, it is extremely undesirable to alter the physics involved with the processes, and by inducing an electrical current, this is exactly what was being done to the situation. This was countered by stating that the results show the same reactions at different rates, so the experiment was judged to be accurate. This seemed to be a divisive issue, with some involved with the discussion agreeing that the changes made to the physics rendered the experiment unstable, and others siding with the theory that as the results show the same reactions at increased rates, it is a valid methodology.

5.3 Numerical Modelling

5.3.1 Rajesh Pawar, LANL, Numerical Modelling of Wellbore Leakage in Large-Scale CO_2 Injection Simulations Incorporating Wellbore Details and Complexities of Phase-Change

Following on from his presentations covering the CO_2PENS model from the 2007 meeting, this set of slides covered the motivation behind the research, and outlined the studies previously completed on the subject, before explaining the complex mechanisms involved in a wellbore release scenario. Briefly, the mechanisms include: flow in the wellbore and / or annulus, the presence of multi-phase fluid flow which in turn can induce phase change, and these effects are coupled with the possibility of heat and mass transfer reactions, stresses imposed, both geological and mechanical, and geochemical reactions that can be present as well. The interactions between these are vast and varied, and Rajesh referred to the study carried out by Lynch et al in July 1987, whereby it was stated that:

> *'To characterise CO_2 leak through wellbores and to develop effective mitigation strategies it is important to accurately capture wellbore flow physics and couple wellbore flow with reservoir flow.'*

The presentation then moved on to the ever-increasing number of models purporting to cover large scale fields, but described the associated problems with the models as well, and also the context of some models; some models describe the area modelled as the wellbore area, and some as the near-wellbore. In the context of modelling, the wellbore area is considered to extend a matter of inches from the wellbore, and the near wellbore environment is considered to surround the wellbore to a distance of up to 10's of metres.

The example used as a large scale injection operation was that of a large field, with known leaky wells, and modelled migration of injected CO_2 over a prolonged period of 400 years. Interestingly, in this scenario with wells known to be prone to leakage, the graphical interpretations show a maximum leakage of 10% of the total injected volume; in reality it is likely to be far reduced from this as the model does not incorporate mitigation and remediation of wells and leaks when they occur. This shows a much smaller quantity of leakage than some previous predictions have allowed for.

The model then moves on to cover and incorporate multiple layers and multiple wells in a much larger field, illustrating that the model is capable of large scale field predictions, and that significant advancements have been made in recent years in the ability of modellers to predict more accurately the long-term fate of CO_2 injected into geological storage reservoirs.

Q. Based on the example of a leak/flow rate of 3.5 kg/s, what is the distance travelled by this amount of CO_2 in a second?
A. It wasn't calculated, but would vary depending on the permeability of the geologic formation.
Q. Can preferential annular (micro) pathways be added to the model?
A. It can be specified, and the model allows for fluidity.
Q. How does the model handle phase changes?
A. there is a look-up table included in the model, and this allows for changes in thermodynamic properties.

5.3.2 Bruno Huet, Princeton University, Investigation with Dynaflow of the Effect of pH and CO_2 Content of the Brine on the Degradation Rate of Cement

The objective of the experiment described in this presentation was to better understand the mechanisms involved with the reactivity of cement and CO_2/brine water. The presentation also explained the various leakage pathways that could be present in a wellbore, and categorised them into 5 types:

1. Leakage between well cement and well casing,
2. Leakage between geologic formation and well cement,
3. Leakage through plug cement,
4. Leakage between well or plug cement and well casing,
5. Leakage through well cement.

The presentation included a short video clip demonstrating the concentration of mineral zoning which was very useful in describing the process that was discussed in the slides and the presentation. The images showed the thickening of the calcite layer from 3 days to 29 days, and the zoning of altered and original cement was clear to see.

Although complex to describe, the graphs showing the analysis of the changes and progression of the calcite layer were quite demonstrative, and helped to explain the experimental results. One of aims of the work was to compare the model to the results of Duguid et al, and it was found that in order to match the results of these experiments, it was necessary to increase the diffusivity by a factor of 4.

The presentation concluded by confirming that an equilibrium approach is sufficient to demonstrate transport in the wellbore, and that CO_2 uptake occurs during the formation of the $CaCO_3$ layer. Once the layer has formed, at a later stage, there is no CO_2 uptake, but rather a very slight release and only Ca leaks are present which demonstrates diffusion.

Following the conclusions, the research team laid out the challenges to be addressed in the future, and these included determining the pressure equation (density gradient), and the development of a model to illustrate multi-phase transport and the reactivity of cement exposed to wet or dry CO_2.

The presentation linked into the next, by Jean Prevost of Princeton.

5.3.3 Jean Prevost, Princeton University, Fully Coupled Geo-mechanics, Multi-Phase Flow, Thermal, and Equation of State Compositional Simulator

Jean Prevost introduced the model used by his team of researchers. He explained that the model is more complex than many models used, and that it takes into account all aspects of a CCS injection operation. This echoes the sentiment previously expressed by Stefan Bachu that a multi-element model is what will be needed in order to perform a complete simulation of a storage project, and this is what will be demanded by regulators to demonstrate a high level of certainty and confidence in a storage operation.

He went on to express that the Dynaflow model is currently the only model capable of showing the boiling of super-critical CO_2, however the results are still not perfect, and they are susceptible to errors, as shown on one of graphs by a large spike.

The model can demonstrate the interactions at the rock / wellbore interface, and the simulation can investigate the bending and shear stresses imposed on the caprock by the increase in pressure resulting from CO_2 injection and the deformation of the overburden as a result of this.

This is a particularly important factor as bending stresses can cause shear in the overburden which could potentially open new leakage pathways, threatening the structural integrity of the reservoir. As previously explained, there are still some areas susceptible to errors, and the future focus of work will look to correct these areas, and perfect the model.

5.3.4 Jeremy Saint-Marc, Total, An Innovative Approach to be Proactive when Designing Cement Sheath for Gas Storage

Total's presentation is not available on the IEA GHG website as permission was not received to us it as part of the report. The presentation described the Total well design, including cements and casings. The purpose of the design is to connect the surface to the subsurface in a model, and demonstrate the links between the two facilitating safe transit of fluids and suitable abandonment procedures to retain the fluids safely in the formation.

To ensure maximum security of storage, a minimum of 2 barriers are used, one of which is used as a backup of the primary barrier, and both barriers consist of cement and packer materials. The casing design is initially a geometric circular design, and then external conditions and stresses are introduced to determine the most suitable material to resist these external factors. Failure is defined as the point at which tolerances are exceeded resulting in a breach of confinement. A similar process is used to determine the most suitable cement, however as it is assumed that even the best cement may leak in the future, best practice includes designing better wellheads to confine and CO_2 that leaks through the cement and would otherwise manifest as Surface Casing Vent Flow (SCVF).

The design of the primary barrier of casing and a cement sheath will be dependant on the environment surrounding the well, i.e. pressure, temperature, porosity etc. The model scenario involves a 6 month period for installation and testing of the wells, followed by a production phase, and abandonment some 30-50 years later. Continued cycles of processes promote fatigue and stress to the materials, which would probably lead to failure of the wellbore system. Understanding the impacts of certain external factors means that continued testing can confirm a well as being safe, by determining the stresses that must not be exceeded.

The chemical interactions were initially unknown, so the development of a chemical model was undertaken. Into this was incorporated the cement design and in situ conditions to make a thermo-chemo-hydro-poro-mechanical model of wellbore integrity. Total developed the software necessary to model and bring together the well history, well integrity, cementing procedures and rock mechanics into a comprehensive system for wellbore environment modelling.

5.3.5 Rick Chalaturnyk, University of Alberta, Numerical Simulations for the Design of In-Well Verification Testing of Well Integrity

Rick described an approach to wellbore integrity that started with the notion that the ability to capture the exact state of all the wellbores in a given field is very difficult, and therefore the approach was taken to combine both real data gathered from the field, with analytical or numerical simulations to quantify the processes associated with hydraulic integrity of the wellbores.

The approach looked at a great range of background information, and used extensive data from the Weyburn project to build a database. The Weyburn project was ideal for the exercise as data was collected from 185 wells from day 1 of the project.

The model was used to determine various elements of the wellbore environment including degradation rates from sulphate attack and stress distributions inside the cement and the formation. The output of the model was a set of predictions for the long-term integrity of the wellbores, and the extent of degradation for 100 to 1000 years, but no-one believed the predictions that the model produced. The model also allowed adjustments to demonstrate the effect of variations in the number of perforations, and the effects this has on the pressure and the different reactions in the silt, sand and shales surrounding the wellbore.

5.3.6 Jonathan Ennis-King, CO2CRC, Reactive Transport Simulations of the Effect of Transport Parameters on the Breakthrough Time for Vertical Migration of CO_2 in a Micro-annulus of a Cement Ring

This presentation described a 2 part experiment, to simulate gas phase transportation, and a fracture-matrix theory to determine the vertical migration rate of CO_2 up a micro annulus in a cement plug in a conventionally completed, Portland cement well.

The geochemical model used encountered some challenges in relation to the C-S-H phase, and therefore the decision was made to follow the work by Carey and Lichtner (2007) representing CSH as a discrete set of solid phases spanning the composition range of the cement. Diffusive transport is recognised as a slow process when taken on its own, with movement of less than a metre over 1000 years, so the experiment references the SACROC study which suggested vertical transport through a high permeability ‘shale fragment zone’.

Once these parameters had been established, the challenge facing the research team was to estimate the transport parameters, including fracture size, permeability, and capillary pressure thresholds, to determine if the transport path is continuous or broken. The parameters that were used are shown in detail on the slides of the presentation.

The next stage was to establish the reservoir conditions and input these into the model before using the model to calculate the predicted flow in scenarios with and without reactions. The similarities and differences observed in these simulations allowed determination of the thresholds, flow rates and the effects of the reactions on the transport mechanisms.

The elements of the experiment relating to Fracture-Matrix theory used the results of Sudicky and Frind (1982) and Tang, Frind and Sudicky (1981), with adaptions to move from adsorption-diffusion to reaction-diffusion, from planar diffusion to cylindrical geometry (wellbore) and move from single-phase to two-phase.

These experiments led to the conclusions that a continual micro-annulus leak can be retarded due to consumption of CO_2 in the reactions with the cement, the cement element holds the key uncertainties and unknowns in the transport parameters, and that the fracture-matrix theory can predict the scale of retardation. The direction of future work in this area should concentrate on extended detailing of the geochemical model, increased characterisation of the transport parameters, and refinement / quantification of the fracture-matrix theory.

5.4 Monitoring, Risk and Development of Best Practice

5.4.1 Ron Sweatman, Halliburton, CO_2 Resistant Cements and Chemical Sealants

Ron started his presentation by addressing the question of whether class I or II wells have ever leaked into sources of drinking water. The evidence and testing supplied by the US EPA, State Regulators and the UIC Programme all confirmed that there have been no recorded leaks from either class of wells into Underground Sources of Drinking Water (USDW). The testing completed showed that 2% of class I wells surveyed showed signs of poor external MIT, compared to 11% of class II wells – the classification used for CO_2 injection.

Ron then asked the delegates whether any of them had heard of a CO_2 leak from a class II well, and none of those present had, which led to the question of what makes these wells so effective? The presentation went on to list the extensive repository of best practices and procedures for the design and installation of wells. Also, tests performed by researchers at Yale and Harvard Universities have shown that less than 1% of injected CO_2 converts to Carbonic Acid (H_2CO_3), and most of this is formed at some distance from the wellbore due to high initial flow rates.

Additionally, it has been noted that cement exposure to CO_2 can be reduced by a substantial amount by the interactions of various brine fluids with drilling fluids or cement filtrate near the wellbore. This interaction can form a barrier by reducing the permeability in the near wellbore formation. Ron went on to discuss the already-presented issues associated with the carbonation and degradation of Portland cements, but with the additional aspect of the possibility of the reaction acting as a self-sealing mechanism, and this was backed up to some degree by a series of chemical equations describing the reactions. Although this has been discussed before, the extent to which it occurs is not fully understood.

Ron then discussed alternative sealing methods, an area given comparatively little thought and discussion at previous network meetings, despite the fact that there are examples of where Pozanite has been used as a sealing mechanism, and has been operating as such for up to 36 years in situ conditions.

The presentation concluded by outlining some suggested next steps, which start by getting all the delegates and contributors to the wellbore integrity network ‘on the same page’, agreeing on the same preferred methods and practices, before then providing an informed, consensus opinion to regulatory and legal bodies, and using documented successful case studies develop new API/ISO standards and address the issues raised by regulators with hard facts and knowledge.

5.4.2 Theresa Watson & Stefan Bachu, TL Watson & Associates & Energy Resources Conservation Board, Field Scale Analysis of Risk Wellbore Leakage

Theresa presented a review of previous work and an update from the presentation at the 2007 meeting of the Wellbore Integrity Network. She discussed the price implications on wellbore construction (which developed from a subject covered on her poster presentation). The issue faced is one of speed versus efficiency. The theory is that at times of high demand, wellbore are created and completed at as fast a rate as possible to maximise profits, but the possibility is that these wellbores will not be as high a standard of completion as those completed at times of low demand, when time is not as much of a critical value, and therefore completion standards are likely to be higher.

In conjunction with the ERCB, TL Watson have created a database that can be interrogated by the user to predict which wells in a field are most likely to leak, and also compares this with environmental and demographic information to categorise the risks associated with those leakages. This tool is likely to be increasingly useful, as it is predicted that within the province of Alberta, there will be approximately 1 million wells by 2056, compared with 343,000 in 2006.

5.4.3 Rick Chalaturnyk, University of Alberta, Monitoring of Wellbore Performance at Penn West CO_2EOR

Rick gave an overview of the monitoring project underway at the Penn West CO_2EOR project, and outlined the instruments used in the observation well. The project is a collaborative project, running over a period of several years, and the aims of the project are to develop an increased understanding of the eventual fate of CO_2 injected into hydrocarbon reservoirs as well as further developing the understanding of the role of geological storage of CO_2 can play in mitigating the long-term effects of climate change.

While demonstrating the suitability of the reservoir and others like it for EOR and CCS, the aims are also to develop and demonstrate a comprehensive monitoring programme, showing that it is possible to detect and quantify the long-term fate of injected CO_2. The project will also develop post-closure monitoring programmes, and evaluate the different tools available for monitoring.

The monitoring tools used cover the expected range of survey methods including 3-d seismic surveys to determine the extent of the CO_2 plume migration, downhole sensors for pressure and temperature, and the installation of geophones in the wellbore. The combined effect of the using these monitoring techniques allowed an accurate picture of formation response to the injection process, and accurate logging of pressure and temperature within the well. These were plotted on a graph against time which was referenced to the activity of injection and cementing to demonstrate the effect surface activities have on the reservoir below.

It is hoped that this monitoring project will help develop understanding and break down gaps in knowledge which will then be transferable to other operations around the world. The costs involved with the array of monitoring equipment and technology led to comments from the project engineers that they were “sticking my house down this hole!” The results however showed the effect of the CO_2 on the reservoir temperature as the front passes, and also highlighted the pressure fluctuations resulting from opening the valves at the wellhead. The accurate monitoring has greatly helped understanding of these processes, and will be hugely beneficial in providing confidence and assurance of the eventual fate of CO_2 and its effect on the reservoir, thus helping development of CCS as a commercial proposition.

5.4.4 Jerome Le Gouevec, Oxand S.A., Well Integrity Performance Management: A Risk-Based Approach – Application to a Carbon Capture and Storage Project in Algeria

This presentation centred on a case study in Algeria, where an oil and gas company was interested in investigating the possibilities held by injecting supercritical CO_2 and the associated enhanced recovery of natural gas (EGR). The company had a specific field in mind which had 9 existing wells, 3 of which they wished to convert into injectors, and Oxand and Schlumberger worked in partnership to determine the suitability of these wells for the proposed scheme. They developed a trademark assessment called 'Performance and Risk Assessment' (P&R^{TM}) which was used to assess well integrity over the injection phase.

There was a good amount of existing available data, and on the basis of this, the goals were set to include proposals for a risk mapping exercise for the 9 wells, prioritisation of mitigation options including a cost/benefit analysis, and determination and justification of the 5 most suitable wells for conversion to injectors. The data and goals were incorporated into a work flow involving static and dynamic modelling, assessment of probability and severity of leaks, and a mapping exercise leading to a series of recommendations.

The static model was conceived by combining aspects of the surrounding geology and parameters of the wellbore itself; while the dynamic model integrated degradation mechanisms and fluid transport to determine probability and magnitude of leakage. Once these models were developed, certain scenarios were simulated using a programme called SIMEO-STOR^{TM}. Once the risks were identified and assessed, the recommended actions were developed to allow the operators to make informed selections and choices for the operation of the proposed project.

The activities performed allowed the use of a risk-based approach to set the criteria for supporting the decisions made for well selection, proposals for 5 of the existing wells to be converted, and a risk management strategy was developed accordingly. The operators were satisfied with the assessments carried out, and the process allowed informed and more importantly justifiable decisions to be made regarding the operation of the site.

Questions were taken from the floor as follows:

> Q. The approach to some of the work appears to be deterministic, how was this approach determined?
> A. There was a model used for the entire project, and this dictated the approach used.
> Q. How was the level of knowledge in the consequence grid normalised?
> A. This was an issue faced in conjunction with the operator, it was discussed jointly, and the decision involved opinion from the operator, therefore it could subjective to some degree, but it is difficult to avoid this.
> Q. What degree of cement permeability was considered as a risk?
> A. Risks were not necessarily associated with cement permeability; risks were defined by a range of information, not just single aspects of wellbore integrity and performance.

5.4.5 Craig Gardner and Bob Carpenter, Chevron, CO_2 Cementing – Where Are We Now?

Craig Gardner presented some review work carried out by Chevron, and the presentation stated that although there is some very good laboratory based work underway and completed, and also some excellent field results available, they must be looked at in conjunction with each other to provide a worthy analysis of the current state of cementing technologies. He echoed Ron Sweatman's question of how many wells are known to have leaked, and suggested that a leakage event must be associated with a specific time frame within the life cycle of a project to bare relevance and hold value as reference information.

Many presentations look at methods of abandonment and their relative merits, and this presentation also touched on the concept that often zonal isolation will depend on the ability of the cement sheath to withstand externally imposed stresses. Craig also pointed out that very little, if any, laboratory work has been done on the mechanical property evaluation of resistant and normal cements following long-term CO_2 exposure.

The presentation also looked at various limiting factors and leakage pathways before opening the talk up to questions from the group.

> Q. As more CCS projects come on line, will there be a reduction in the costs associated with CO_2 resistant cements?
> A. It is a possibility, but sources are limited as most of the resistant cements are only available from 1 country.
> Q. Are new cements working towards solving stress cracking and mechanical integrity issues?
> A. Not really, development is currently focussing on resisting CO_2 degradation rather than mechanical stresses.

At this point, a general query was made regarding the use of alternative materials other than cement, and Craig stated that they are not given a great deal of research as they have generally proven to be less effective as cement.

> Q. What percentage purity is considered acceptable for CCS purposes – is there a need for new laboratory work to investigate the effect of different purities?
> A. Craig opened this question up to the group as it wasn't something covered by the presentation or the work of Chevron.

There may be pressure to move towards the acceptance of dirtier streams of CO_2 which if likely to have impacts on many aspects of storage. It was suggested that acid gas injection can be considered as CO_2 injection with impurities, and more countries are taking up acid gas disposal options, as well as considering on-shore injection. The London Convention (dealing with off-shore injection) states that the CO_2 stream must be 'overwhelmingly CO_2', but doesn't give a definitive answer. Comments were made that we must consider 2 streams – that from coal power generation that will likely contain SO_x, NO_x, and particulates, and that from gas power generation that will contain H_2S.

6. Discussion Sessions

As in the previous meeting of the network, it was decided that open, facilitated discussions were of more worth than closed break-out groups. The meeting included
4 of these sessions, and the salient points from these are described below.

6.1 Field Investigations of Wellbore Integrity

The discussion began with some questions asked to those who conducted laboratory based experiments, and dealt with how porosity was determined and measured. It was stated that good laboratory procedures allow the researchers to create cement samples with consistent porosity values. The discussion moved to the potential effect of stimulation on cement quality as opposed to straight forward carbonation, this reflected some of the work presented by Bill Carey and Walter Crow and they confirmed that their work had not yet investigated this aspect, but history tracking has taken place and stimulation experiments will hopefully be identified and carried out in the future.

The next topic discussed, queried whether existing analytical techniques can identify changes occurring in the cement as it sets and segregate those effects from the changes that take place over periods of years in the field? In the examples described in the presentations, the cement was installed through a high water/CO_2 environment so distinguishing the changes can be difficult and there may be ambiguities in the measurements which are difficult to rationalise.

Bill Carey's presentation raised another question, that of whether it is possible to determine if the cement – shale interfaces are intact in the samples. Bill confirmed that in some instances they were intact, but generally they were separated. The experimental procedure did not look at changes in the geology of the shales.

Much discussion also debated what can be expected from future experiments and hypothesising from what has been found in other samples. It was noted that there is a trend developing towards uniformity of samples from each location, and a suggestion was made to make an effort to bring together the samples that are well-referenced by many publications and presentations to allow first hand comparison and analysis.

Debate also covered definitions of strengths of cements as the term strength can be used in several different contexts. The general consensus was that the term strength should refer to the compressive strength of a sample, although Rick Chalaturnyk suggested that measurements of tensile strengths may prove more interesting and beneficial. Additionally, Rick pointed out that measurements of cement stiffness can also be valuable information for developing knowledge and understanding of the behaviours of cements in the wellbore environment.

Going back to the presentation of Bill Carey and Walter Crow, it was noted that the perforations in the samples were largely isolated from each other, and the absence of extensive cracking prevented them forming channels which might be found in the field environment. It was accepted that this was a limitation of the experimental procedure, and the methodology attempted to eliminate the potential for statistical error wherever possible, but limitations still exist in the procedure.

Veronique Barlet-Gouedard stated that the field results collected by Schlumberger correlate with the their laboratory work, which is a great benefit, and that many people associate porosity with carbonation, but the laboratory results show the deposition of calcite can be associated with changes of porosity, often reduced porosity as the pores can become blocked with the calcite deposits. This is the first time that the field and laboratory results have confirmed each other to such a strong degree. Bill Carey suggested that it was still too difficult to understand the interactions in cement and they depend greatly on the type and blend of cements used, sometimes showing uniform carbonation, but at others showing fairly disparate carbonation. The response observed in the cement cannot be solely due to carbonation, this is an important fact as it shows that carbonation is not the single impact-baring factor on porosity of cement.

At this point the discussion was steered with a pair of questions; what is the best recommendation for cement at the current time, and what is the end state that we are most concerned about?

Representatives from Chevron stated that they may choose a low permeability cement that may not allow good measurements. Many delegates commented that these questions may be better answered by some of the presentations scheduled over the remainder of the meeting.

Theresa Watson commented that in many situations you do not have all the data you would like to determine quantity of water, densities and other properties, and that cement quality, good or bad, can be irrelevant if channels exist in the cement for transport, and that most issues are likely to occur from uncemented areas, rather than the cemented areas.

Stefan Bachu summarised many points by stating that so far, almost everything we can measure is qualitative, but when it comes down to regulation of CCS, regulators will want quantitative figures, and at this stage this will pose a problem as this information may be unavailable. This should be a research area highlighted for the future. Bill Carey stated that there is a lot of data on sustained casing pressure and surface casing vent flow (SCP & SCVF) that could be used to determine quantitative figures, but this does not allow for post abandonment situations.

Ron Sweatman stated that the existence of SCP reports do not automatically mean that this will be a problem; SCP can be caused by gas from the reservoir, not necessarily gas from the injection process. Correct abandonment procedures can overcome or work around problems as and when they occur.

Veronique Barlet-Gouedard commented that flexibility for cement depends on the injection scenario, and questioned whether flexibility is always required if the temperature can be changed – sometimes expansion properties can replace flexibility properties. This point was generally conceded, although this option is highly dependant on surveys to accurately determine individual requirements together with reservoir properties and conditions.

6.2 Experimental Studies of Wellbore Integrity

The second discussion session was initiated with the provocative question of why are we conducting experiments to simulate cement ageing when carbonation is not considered a major problem in existing wells in the field?

This sparked a large debate, and the main reason that was agreed by the majority of the delegates was that we are looking to attempt a demonstration of security of storage for 100-

1000 years, and there is no historic data from wells in the field for a comparable scale. The experiments show that we have the ability to speed up reactions that occur naturally, but how can we justify the assertion that performing a test in an electrical field of 30 volts is equivalent to several hundred years of 'normal' wellbore activity in the field? The general opinion was that by maintaining a control sample in 'normal' conditions, we can measure the enhanced effects and extrapolate against the control sample to determine the acceleration rate according to the scale. There are plans to adapt the LIFTCO2 protocol for high pressure high temperature (HPHT) conditions to generate more realistic conditions for CCS application.

If we can prove the physics are the same and that 3 weeks of accelerated experimental conditions is equal to 1 year of normal field conditions, then we have a very good model which is suitable to use now, but this is highly dependant on the ability to prove that the physics used in the base calculations are correct. If we compare the 3 week 30 volts sample with the 6 month sample shown in some of the presentations from Schlumberger we can correlate them to demonstrate distinct similarities although they are not close enough to be classed as being subjected to the same effects. In order to utilise this experiment as a model, would require accurate measurements and adjustments to align the samples, nevertheless it is a good analogue and the method can be developed into something more beneficial and very interesting.

The next question that was asked was what type of experiment or testing procedure do we need to develop in order to generate the data required to model activity in the wellbore environment. It was agreed that the experiments presented at this meeting show that progress has been made, and that the network meetings are still providing a platform for knowledge dissemination; however it was again pointed out that discussions are still focussing heavily on cementitious and Portland materials, and not enough time was being given to the alternative sealants and sealing agents such as elastomers. It was suggested that if there is a move towards deviated or horizontal wells, we will need alternatives to current cement, however this was countered by representatives of Schlumberger who suggested that price is still a prime concern, even with cements that perform very well, and elastomers are comparably more expensive than the best performing cements and will therefore be considered as a less attractive option to a commercial application. Additionally, if the requirements for an operation include the re-use of existing wells (which is likely) then we will need to gain a comprehensive understanding of the cements that are likely to be present in the wellbore already.

At this point, the suggestion was echoed from before whereby the samples referred to are brought together to allow analysis and a move towards a definitive method for sampling. Walter Crow commented that some samples had been subjected to complete degradation, with no compressive strength remaining, and questioned whether this can be reconciled to field experiences of cements from much older wells still remaining intact. Bill Carey used this to reiterate the need to compare samples first hand.

Representatives of Chevron queried that given the scenario that everything at the injection well appears to be perfect in terms of permeability, porosity, and resistant cement, what does the supercritical CO_2 look like at a distance of 500 yards from the well where it may interact with an existing 'bad' well? Brian Strazisar postulated that it would initially form a supercritical plume, and that long term it would dissolve into the reservoir fluids, but this depends on the flow rate and duration of injection etc.

6.3 Numerical Modelling

In this third session discussion, there was a great deal of debate regarding permeability modelling, and the relative merits of establishing an experimental procedure that would return to a similar permeability as the initial condition. There was consensus that in order to facilitate the measurement of migration, it would be necessary to simulate a reservoir's return to initial permeability, or as close as possible. A note of caution was sounded however, that an incorrect permeability can give a distorted figure for the velocity of the CO_2 plume front, so steps must be taken to ensure that the initial data is accurate to maintain validity to the model.

There is also a strong relationship between permeability and resistance, so there is a high level of benefit to be gained from working with multiple parameters to maximise the accuracy of the results. Assessment of permeability can assist in determining a picture of reservoir properties, although if measuring the permeability of the cement sheath, it is only possible to measure the average permeability. It was stressed at this point that permeability may not account for the total flow present as other variables can have an impact on flow, so a thorough range of measurements in addition to permeability are required to measure flow.

There are also issues regarding the interpretation of data gathered, for example if the first data log is imperfect, it will push the following results out of line and result in inaccurate readings.

Stefan Bachu informed the group that during the previous week, the Federal Government of Canada stated that all new power plants must be CCS ready, and this fact combined with the trend of many oil companies that have started looking for suitable storage sites leads to the important question that government, opposition to CCS and ENGO's will all ask, which is:

> How much, when and where will leaks happen?

Stefan suggested that this approach would lead to the decision to play on the safe side and not conduct CCS operations, so what is needed is to bound the problem by explaining that we have the ability and technology to detect and quantify leaks, as well as having the means to mitigate leaks if they occur.

Another key question that needs answering is what happens 50+ years after injection ceases? Does liability still lie with the operator, or does it transfer to the state? Regulators do not have answers to these questions, and oil companies in the Alberta region are targeting the deepest possible reservoirs in the least penetrated areas in order to minimise the risks associated with storage.

Cal Cooper of ConocoPhillips asked whether the wellbore is the greatest risk, as the chance of a blow out is more likely than a wellbore failure when dealing with deeper wells as the pressure will build more quickly if things go wrong. Stefan answered this by stating that the operational aspect is relatively less important as the activities are understood and regulated – these issues affect other analogous operations, and there is a proven method for dealing with them. Problems will arise when unexpected leaks occur and are unexplained.

Matteo Loizzo from Schlumberger questioned whether Stefan was suggesting requirements for the safest possible option, or for a limited leak scenario. Stefan qualified his comments by stating that no regulator will specify an allowed amount of leakage as it is publicly unacceptable – there is enough opposition to CCS already, without effectively endorsing leaks from storage reservoirs, which leaves the solution as a risk based limitation approach to ensuring safety of CCS operations.

Cal Cooper agreed with Charles Christopher who reiterated the need for bounds to be placed on criteria, as it is close to impossible to generate a leak capable of posing a risk to human health – risks and leaks must therefore be quantified and explained. Jean Prevost then suggested that there has been evidence of reactions within the cement plugging leakage pathways, so maybe we should work towards developing a testing procedure to discover the possibilities of using these reactions to our advantage.

The next point raised was that erosion of the well casing is more likely to pose a risk to wellbore integrity than micro-annulus in the cement, and erosion of the cement will happen to some degree due to the corrosive environment of the near-wellbore. Researchers must generate a quantifiable identification of risks, and an analogy was given that planes should not fall out of the sky, but sometimes they do; well should not leak CO_2, but sometimes they will – the question is how much will they leak, not if they will leak.

Public acceptance is a key factor in any CCS operation, and talking to the public about limited levels of leakage may not be accepted, and could result in project cancellation. It must be explained that leaks can be detected at an early stage, and mitigation procedures realised to minimise or prevent risks and exposure. Bill Carey suggested we could compare CCS to EOR operations as the process is similar, but Stefan Bachu reasoned that the increased injection quantities involved in CCS would not allow direct comparison. Theresa Watson concluded by saying that of all known leaking wells, none leak at a rate of greater than $^{1}/_{10}{}^{th}$ of a cubic metre a day, and in comparison with David White’s comment in the introduction, currently we have “100% leakage”. ‘High level’ regulators may approve CCS, but the regulator responsible for the site may have a different view – the research community need to talk to both types of regulators, address the issues and forge a way forward.

6.4 Monitoring, Risk and Development of Best Practices

The fourth and final discussion session focussed around the result of a questionnaire that was circulated by Jorg Aarnes of DNV, the results of which are summarised below.

Based on the information and knowledge gathered, it is concluded that, in terms of well integrity for CO_2 storage operations, the main risk is leakage through abandoned wells. The risk associated with leakage through abandoned wells is of course site dependent, but guidelines for managing this risk will nevertheless be needed at many storage sites. Indeed, the survey revealed that there is almost a consensus that the integrity of every abandoned well in the associated storage region needs to be assessed based on the well-specific data in order to evaluate storage feasibility of a particular storage formation. The main concern is related to material degradation of the cement and steel casing, but lack of adequate abandonment practices is also a general concern.

Apart from concerns about the long term integrity of abandoned wells, there is awareness that current well construction standards and operating practices should be revisited and modified to serve as guidance for safe operation of CO_2 injection wells. This includes requirements to well materials and linings, as well as mechanical integrity and leak detection testing.
The conducted survey also gives grounds to conclude that well integrity related knowledge gaps still exist. In particular, we lack sufficient knowledge about long term material properties,

and we do not yet have adequate predictive modelling tools, i.e., computer simulation software capable of predicting long term material degradation, while accounting for the main chemical, mechanical, thermal, and possibly hydrological conditions that a well will be exposed to over its life time. This implies that at sites where the risk of leakage through abandoned wells is relevant, operators will have to address and manage this risk by implementing proper monitoring programs and devising mitigation and remediation plans to handle potential leakage events.

Individual well assessments are not realistically possible, and the example used to illustrate this point is that the North Sea, an area likely to be subjected to CCS, has approximately 17,000 wells, whereas Alberta are drilling 60,000 new wells every year, and Texas has approximately 1.5 million existing wells. The more viable approach is to look at the scale of pilot and demonstration projects, which is likely to be a good deal smaller than commercial operations, and therefore there are likely to be only a few wells coming into contact with the CO_2 plume. These wells can be subjected to individual assessments, and from this we can learn and extrapolate to a larger scale, such as might be involved with a commercial scale operation, with fewer well assessments.

It was suggested at this point that wells drilled before c. 1940 were often installed without any casing material, and therefore the wellbores will be very different to current ones, and indeed many may not exist anymore. This was contradicted by Theresa Watson who said that in over 50 wells, each over 50 years of age, each one of them was located and re-enterred. It was suggested that there may be influencing factors in terms of differing geology having different impacts on old wells.

The discussion then moved to provision of direction for regulators. Should regulators consider all wells as potentially involved in CCS operations or not? They will require some input from the network in order to avoid huge financial penalties on industry that render CCS unfeasible.

The final issue addressed was that of reservoir pressures. The question was asked as to whether injection should be scheduled to cease when the original reservoir pressure was reached. The consensus was that formation fracture must be avoided, so injection would need to stop when the reservoir pressure is reached, but then should this pressure be set as the original pressure before extraction of oil or gas? It was suggested that the most likely limit to be imposed is a percentage of the fracture pressure, not higher than the original pressure of the reservoir. The additional benefit of not exceeding the reservoir pressure is the removal of a driving force for leakage. The issue with setting a percentage of fracture pressure was pointed out to be that the fracture pressure of a reservoir can be subject to change, highlighting this as an area for future consideration.

7. Summary

Bill Carey affirmed that it was still intended to continue the meetings of the Wellbore Integrity Network as they were still generating interesting and in some places contentious debate, and that there is still a tangible benefit, with new material being presented. There is frustration that knowledge is not developing faster, but there is a general move towards a consensus, with the challenge for the group to move towards a mentality and consensus of perspective for the next meeting.

There was a notable input from geomechanical experts, which will hopefully grow in the future, possibly addressing the question of what scale of micro-annulus, if any, can be sustained by the wellbore. Wellbore imaging is also of great importance, and there is anticipation of what to expect in the future in this area, it is looking very interesting, but also more problematic than first thought.

The ultimate measurement to strive for is an in situ test; models cannot fulfil the requirements on their own and our knowledge base comes from collaborative field and laboratory work, which puts us in a very fortunate position. EOR activities can be viewed as an analogue in terms of reservoir pressures, which could be a beneficial argument used to convince the public into acceptance of the technology and operations.

8. Conclusions

The key conclusions that can be drawn from the meeting are:

1. The contrast between field and laboratory based experiments noted at last years meeting is still present, but results are moving together, demonstrating a greater understanding of the interactions and reactions in the wellbore and near-wellbore environments. Laboratory experiments designed to simulate long-term exposure to CO_2 are showing results more in-line with experience gained in the field. There is however still some question of the methods used to accelerate the ageing process, and this is an area for further consideration and development.

2. The models that have been developed to simulate long-term, large-scale CCS operations have improved greatly, and will be required to play a major role in addressing the concerns of both public and regulatory bodies alike. The models have been developed to allow feedback from real-life experience to improve and streamline the simulations, meaning that each subsequent simulation will be more accurate and reliable than the previous.

3. There remain a great variety of sampling techniques, and there would be a great benefit in rationalising these into a consensus methodology. This will also prove beneficial in presenting a unified approach when justifying actions and proposals to the general public and regulators.

4. The network organisers will attempt to facilitate at the next meeting the opportunity to bring samples together to allow comparison and contrast activities. It is envisaged that his may run alongside the poster presentation at the next meeting, but it is also accepted that transport of samples may not be possible.

4th Well Bore Integrity Network Meeting,18th-19th March 2008, Paris, France

Jonathan Ennis-King	CSIRO	Nevio Moroni	ENI DIV E&P
George Scherer	Princeton University	Saeko mito-Adachi	RITE
Stefan Bachu	Alberta Energy & Utlities Board	Roelien Fisher-Dorenbos	Shell
Theresa Watson	T.L. Watson & Associates Inc.	Michael de Vos	State Supervision of Mines
Rick Chalaturnyk	University of Alberta	Bogdan Orlic	TNO
Thibaut Dornoy	BJ Services Company	Tjirk Benedictus	TNO
Mohamed Azaroual	BRGM - Water Division	Todd Flach	Det Norske Veritas
Axel-Pierre Bois	Curistec	Jorg Aarnes	DNV
Dominique Fourmaintraux	Dfringenirie	Ingrid Anne Munz	Institute for Technology
Fabrice Brunet	ENS-CNRS	Fabrice Cuisiat	Norwegian Geotechnical Insitute
Remi dreux	Gaz de France	Idar Akervoll	SINTEF
Jerome Corvisier	ENS/CNRS	Arne Singelstad	StatoilHydro
Alexandre Schubnel	ENS/CNRS	Charles Christopher	CO2 Store/BP
Eric Lécolier	IFP	Toby Aiken	IEA GHG
Rabih Chammas	OXAND	Tim dixon	IEA GHG
Jerome le Gouevec	OXAND	Dan Mueller	BJ Services
Yvi le Guen	OXAND	Walter Crow	BP Alternative Energy
Laure Deremble	Schlumberger	Craig Gardner	Chevron
Jean Desroches	Schlumberger	Robert Carpenter	Chevron
Gabriel Marquette	Schlumberger	Cal Cooper	ConocoPhillips
Olivier Porcherie	Schlumberger	Harry Limb	ConocoPhillips
Natalia Quisel	Schlumberger	Glen Benge	ExxonMobil
Claudia Vivalda	Schlumberger	Michael Parker	ExxonMobil
Véronique Bartlet-Gouédard	Schlumberger	Lance Brothers	Halliburton
Bruno Huet	Schlumberger Carbon Services	Kris Ravi	Halliburton
Brice Lecampion	Schlumberger Carbon Services	Ron Sweatman	Halliburton
Matteo Loizzo	Schlumberger Carbon Services	Bill Cary	Los Alamos National Laboratory
David White	Schlumberger Carbon Services	Rajesh Pawar	Los Alamos National Laboratory
Gaetan Rimmele	Schlumberger Well Services	Jean Prevost	Princeton University
Nicolas Aimard	Total E&P	George Scherer	Princeton University
Jérémie Saint-Marc	Total E&P	Erick Cunningham	Schlumberger
André Garnier	Total E&P	Jonathan Koplos	The Cadmus Group
Peter Sauer	RWE	Brian Strazisar	US DOE/NETL
Marcus Habighorst	RWE	Roland Sieber	TU Munich
Trach Tran-Viet	State Authority for Mining, Energy & Geology	Nicolas Jacquement	BRGM - Water Division
Laurant Jammes	Schlumberger	Jose Salazar	Schlumberger
Preben Randhol	SINTEF		

Notre Dame de Paris

4th Wellbore Integrity Network Meeting

18th-19th March 2008

Hotel Concorde Montparnasse,

Paris, France

Organised by

IEA Greenhouse Gas R&D
Programme and Schlumberger

Hosted by

Schlumberger

Sponsored by

Suez
Oxand
Total
BRGM

IEA GREENHOUSE GAS R&D PROGRAMME

18th March 2008 Day 1

08.30 to 09.00 Registration

Session 1 – Introduction

09.00 to 09.30 Welcome/ Safety/ Context; David White – Carbon Services Schlumberger President

Session 2 - Field Investigations of Wellbore Integrity.

09.30 to 09.55 SINTEF Assessment of Sustained Well Integrity on the Norwegian Continental Shelf; Preben Randhol and Inge M. Carlsen, SINTEF Petroleum Research

09.55 to 10.20 The CO_2 Capture Project Field study of wellbore Integrity; Walter Crow and Bill Carey- BP-LANL

10.20 to 10.45 Well Characteristics at Acid Gas Disposal and CO_2-EOR Projects in Alberta; Theresa Watson, TL Watson and Associates, Stefan Bachu, Energy Resources Conservation Board

10.45 to 11.00

11.00 to 11.25 Advances in Cement Interpretation: Results from MOVECBM (Poland), COSMOS-2 (France/ Germany) and Otway Project (Australia); M. Loizzo, Carbon Services, Schlumberger

11.25 to 12.25 **Facilitated Discussion**

12.30 to 13.30 Lunch

Session 3 - Experimental Studies of Wellbore Integrity

13.40 to 14.05 Kinetics of Well Cement/CO_2 Reactions; Barbara Kutchko and Brian Strazisar, NETL

14.05 to 14.30 Some Geomechanical Aspects of Well Integrity; Bogdan Orlic, TNO

14.30 to 14.55 Cementitious Material Behavior Under CO_2 Environment – A Comparison with Portland Cement; V.Barlet-Gouédard, Well Services, Schlumberger

14.55 to 15.20 Break

15.20 to 15.45 Evolution of Cement Mechanical Properties During Carbonation; B. Lecampion - Carbon Services-Schlumberger

15.45 to 16.10 Hydro-Mechanical Properties of Carbonated Cements; A. Schubenel - ENS/CNRS Paris)

16.10 to 16.35 How to Accelerate Cement Ageing in CO_2 Fluids: the LIFTCO_2 (Leaching Induced by Forced Transport in CO_2 fluids), in the Frame of the COSMOS-I (CO_2 Storage, Monitoring and Safety Technology) EU Transnational Project; G. Rimmele - Well services - Schlumberger

16.35 to 17.30 **Facilitated Discussion**

18.00 to 19.00 **Poster Session**

Close Day 1

19.00 Dinner sponsored by Schlumberger: Hotel Concorde Montparnasse

19th March 2008 Day 2

Session 4 - Numerical Modelling

08.30 to 08.55	Numerical Modeling of Wellbore Leakage in Large-Scale CO_2 Injection Simulations Incorporating Wellbore Details and Complexities of Phase-Change; Rajesh Pawar, LANL
08.55 to 09.20	Investigation with Dynaflow of the Effect of pH and CO_2 Content of the Brine on the Degradation Rate of Cement; Bruno Huet, Jean Prevost, George Scherer, Princeton University
09.20 to 09.45	Fully Coupled Geomechanics, Multi-Phase Flow, Thermal, and Equation of State Compositional Simulator; J.H. Prevost, Princeton University, L.Y. Chin, ConocoPhillips Company, and Z.H. Wang,

09.45 to 10.15 Break

10.15 to 10.40	An Innovative Approach to be Proactive when Designing Cement Sheath for Gas Storage; Jeremy Saint Marc, Total
10.40 to 11.05	Numerical Simulations for the Design of In-well Verification Testing of Well Integrity; Rick Chalaturnyk, University of Alberta
11.05 to 11.30	Reactive Transport Simulations of the Effect of Transport Parameters on the Breakthrough Time for Vertical Migration of CO_2 in a Microannulus of a Cement Plug; Jonathan Ennis-King, CO2CRC, Australia
11.30 to 12.30	Facilitated Discussion

12.30 to 13.30 Lunch

Session 5– Monitoring, Risk, and Development of Best Practices

13.40 to 14.05	CO_2 Resistant Cements & Chemical Sealants; Ron Sweatman, Halliburton
14.05 to 14.30	Field-Scale Analysis of Risk Wellbore Leakage; Theresa Watson TL Watson and Associates, Stefan Bachu, Energy Resources Conservation Board
14.30 to 14.55	Monitoring of Wellbore Performance at Penn West CO_2-EOR; Rick Chalaturnyk, University of Alberta

14.55 to 15.10 Break

15.10 to 15.35	Well Integrity Performance Management: a Risk-Based Approach - Application to a Carbon Capture and Storage Project in Algeria; Yvi le Guen, Oxand S.A
15.35 to 16.00	CO_2 Cementing - Where are we now?; Craig Gardner and Bob Carpenter, Chevron
16.00 to 17.00	Facilitated Discussion

Session 6– Summary, Discussion and Close

17.00 to 17.30	Chair: Bill Carey

Close Day 2

Posters

1. DNV and Todd Flach

2. Comparison Between Distinct Experimental Approaches to Simulate Cement Degradation under CO_2 Geological Storage Conditions; O. Porcherie, Well Services, Schlumberger.

3. Best Practices; J. Desroches -Well Services, Schlumberger.

4. Corrosion Analysis of a CO_2-ECBM Injection and Production Well; Tjirk Benedictus, TNO.

5. The Effect of a CO_2+SO_2 Brine on a Well Cement - Reactive Transport Modelling; Nicholas Jaquemet, BRGM, France.

6. Numerical Model for CO_2 Wells Ageing Through Water/Supercritical CO_2; F. Brunet and J. Corvisier, ENS, France.

7. Approaches to Risk Analysis of Well Bore Integrity; Natalia Quisel, Schlumberger.

8. Gas Transport in Well Annuli: Field Cases and Experimental Test Program of a Norwegian Research Project; Ingrid Anne Munz, IFE, Norway.

9. Residual Gases Management: An approach to Well Integrity; Jeremie Saint Marc, Total

Fourth Wellbore Integrity Network
- CO_2 Capture & Storage

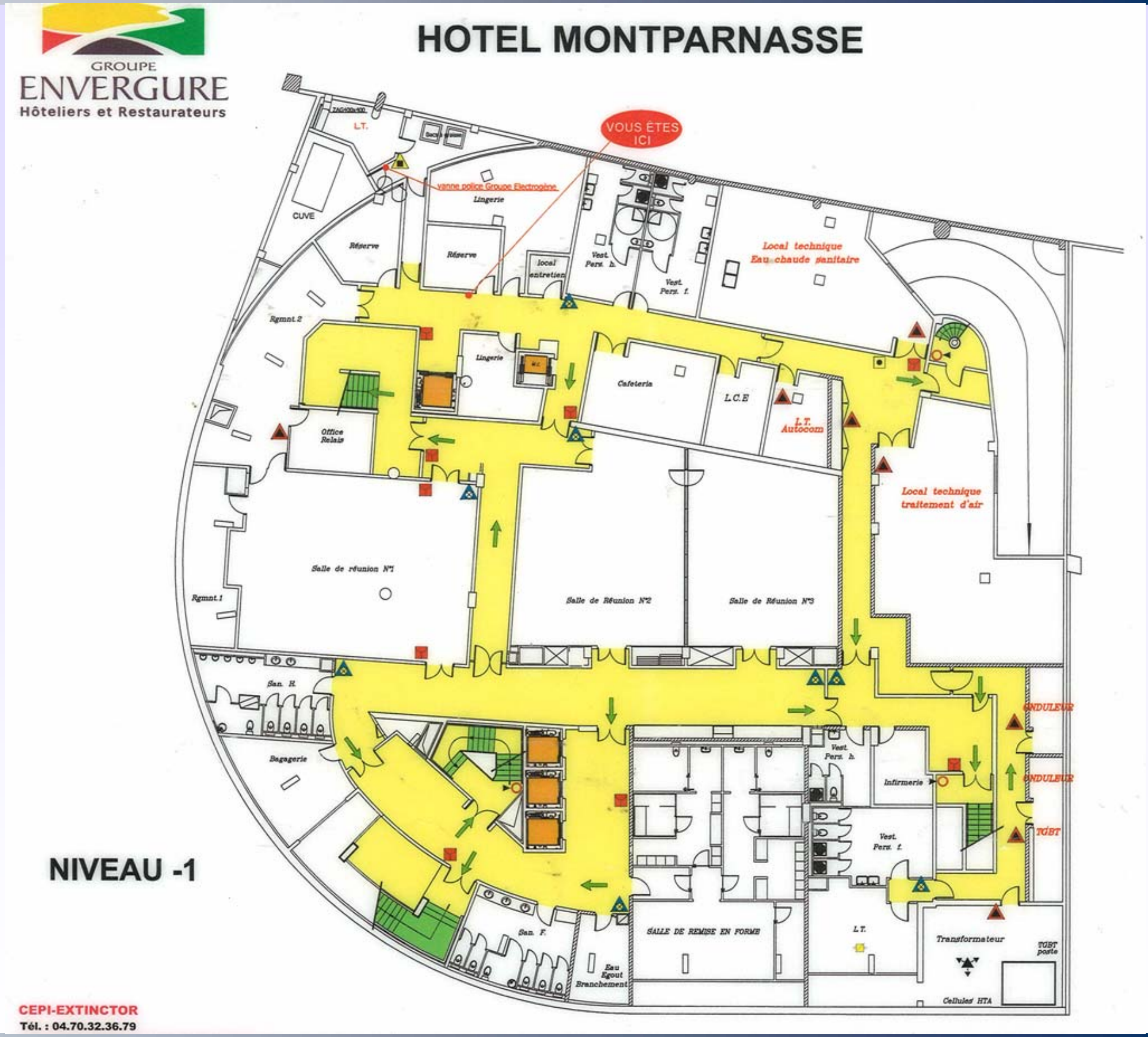
February 18th - 19th, 2008
Paris

David White
President - Schlumberger Carbon Services

Sponsored By

Safety Notice

- Please take note of the Emergency Exits
- No Fire Alarm Tests planned
- Muster Point

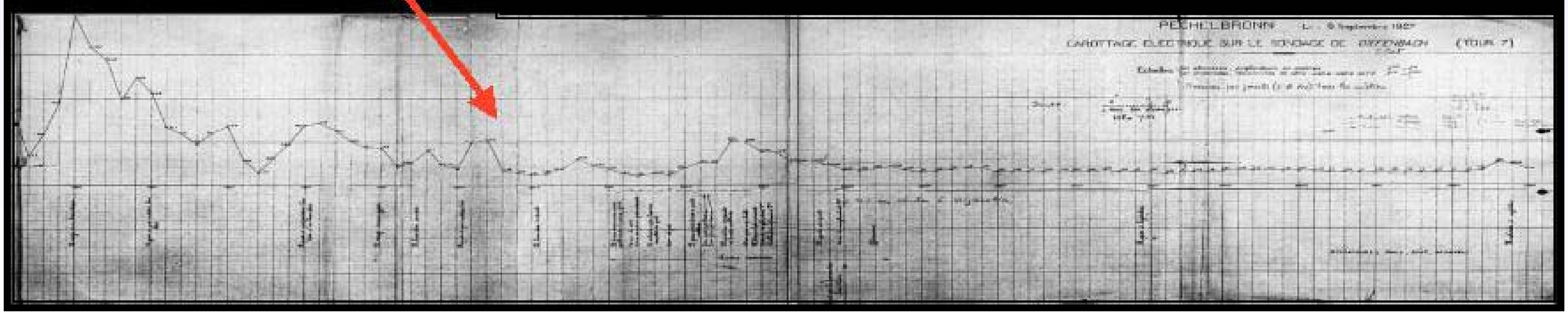


Schlumberger Profile

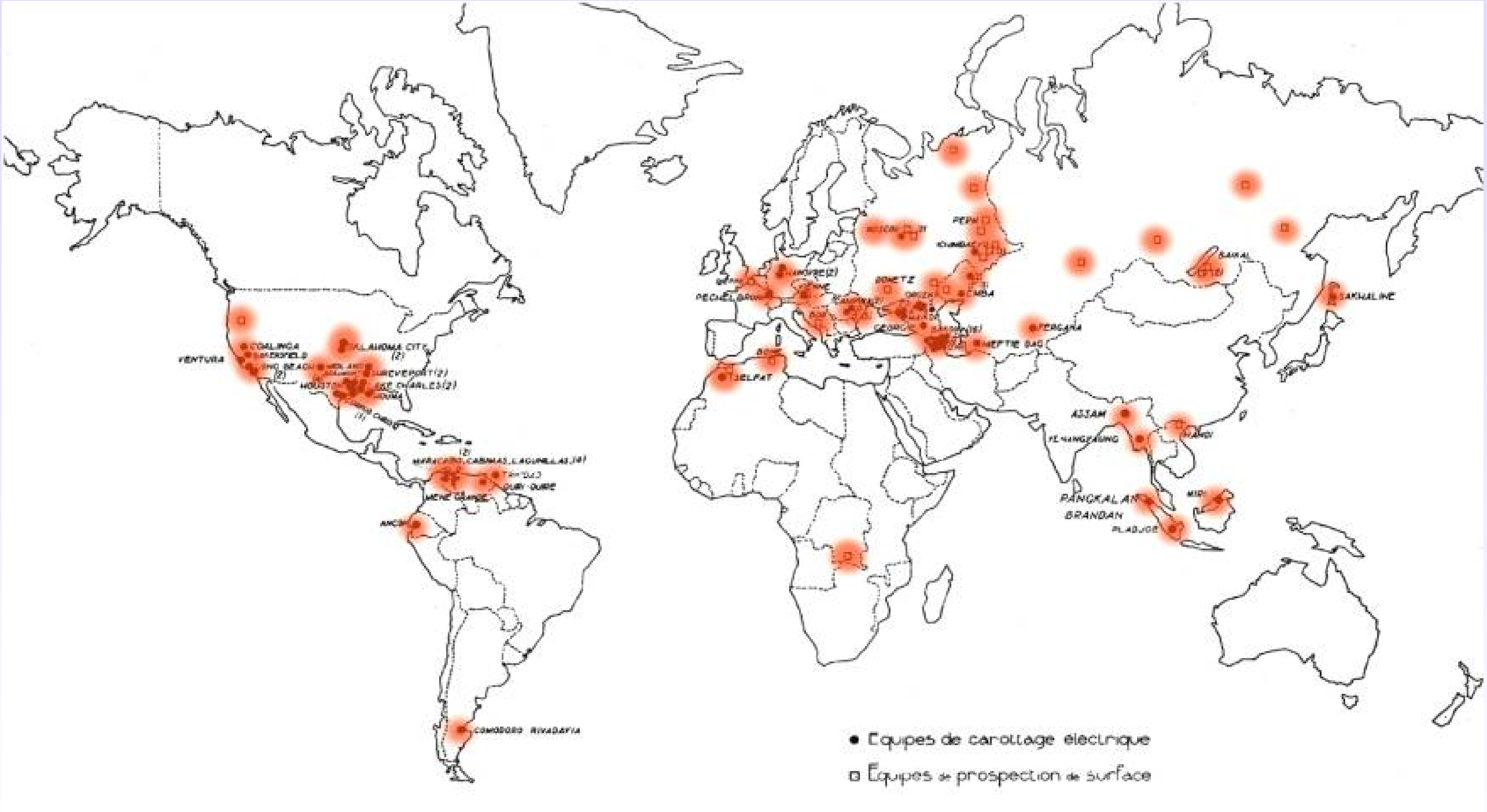
- 2007 Revenue $23B
- Jan 2008 Market Cap: $95B
- 2007 R&D > $700M
- Headcount: 70,000
- Countries > 80
- Founded 1926

- *Integrated Project Management*
- *Seismic Services*
- *Oilfield Services*
- *Carbon Services*
- *Water Services*

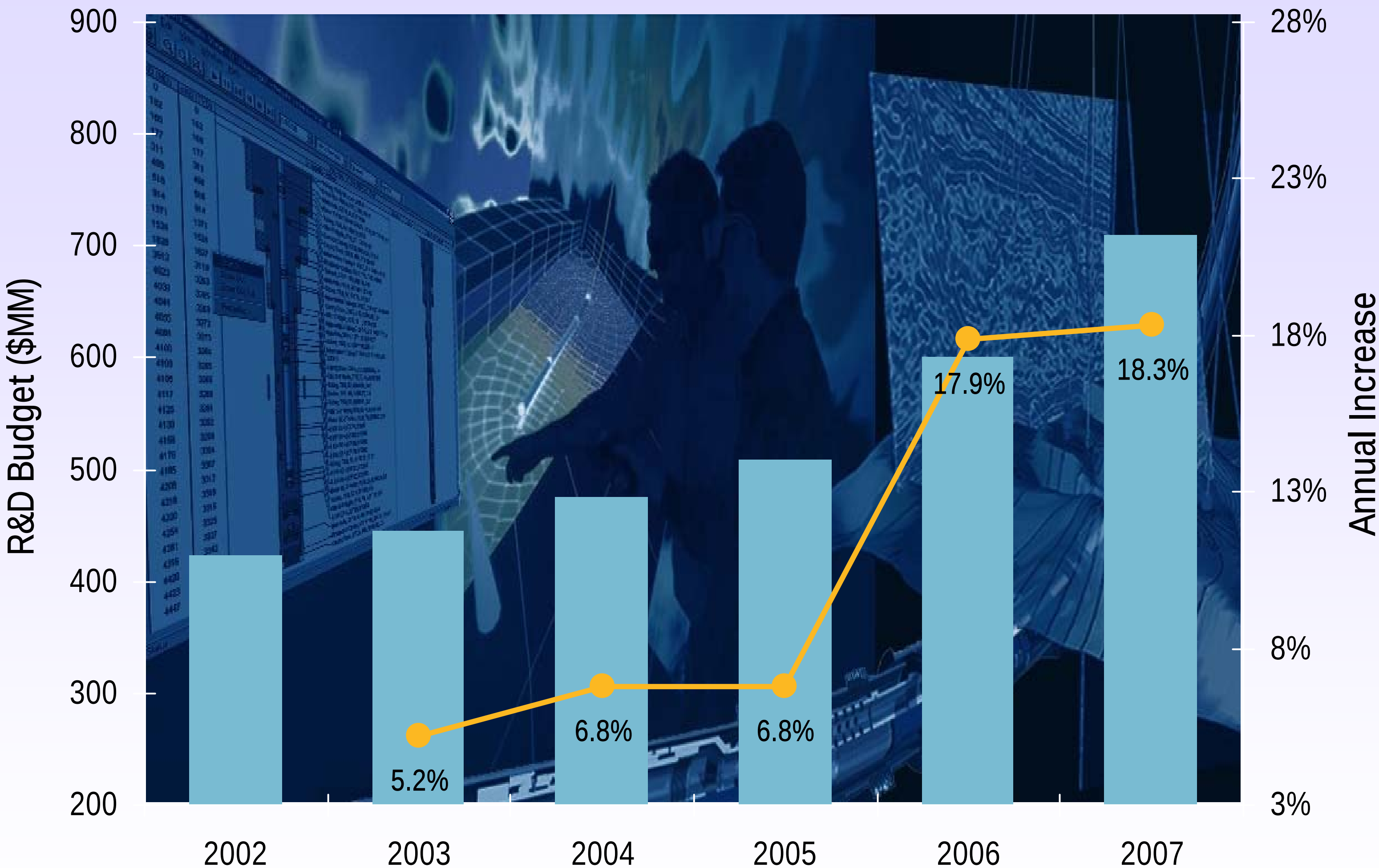
•1927: First electrical log in Pechelbronn, France



Schlumberger Worldwide Teams - 1935



Commitment to R&D

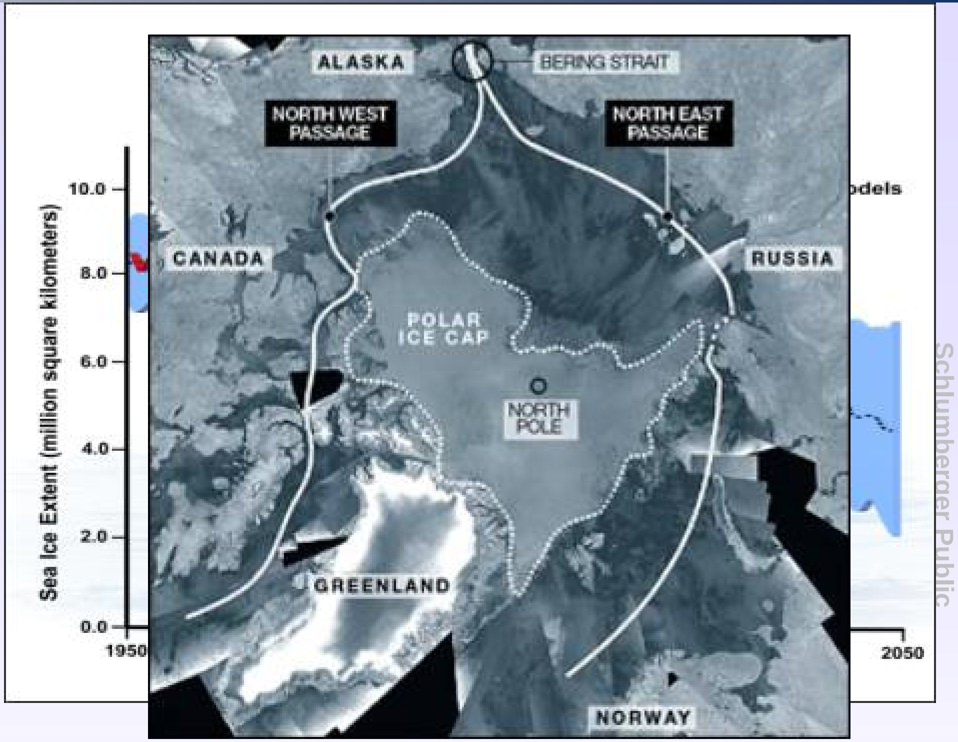


Climate Change: Opinions are Converging

There is **more and more a Consensus:**
Anthropogenic CO_2 is driving substantially climate change

There is still **uncertainties** on the impact of Clouds, on the acceleration of the ice melting, on the natural release of methane

Models have difficulty to assess
The hydrologic cycle, Clouds effects, Local extreme weather
There is huge local divergence between models
Models do not match distant past

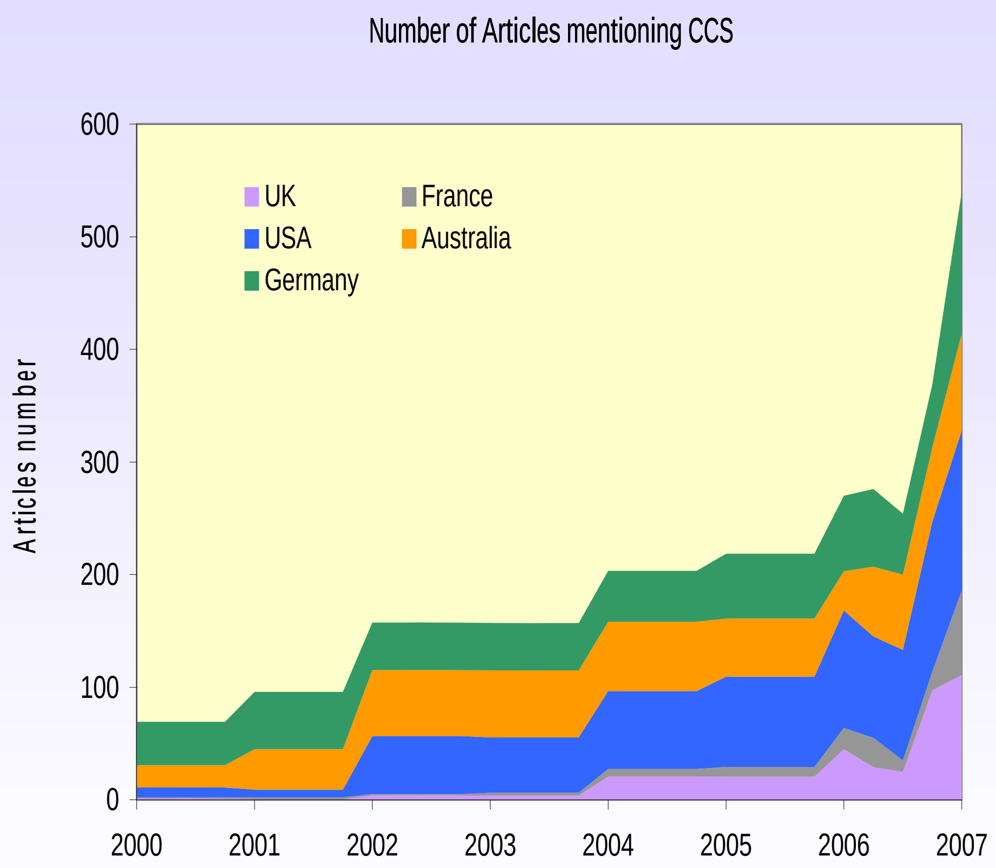


Current Observation are concerning:
Opening of the Northwest passage, Ice melting, ocean elevation…..
They **match the first model from 1988**

'No Regrets' Strategy

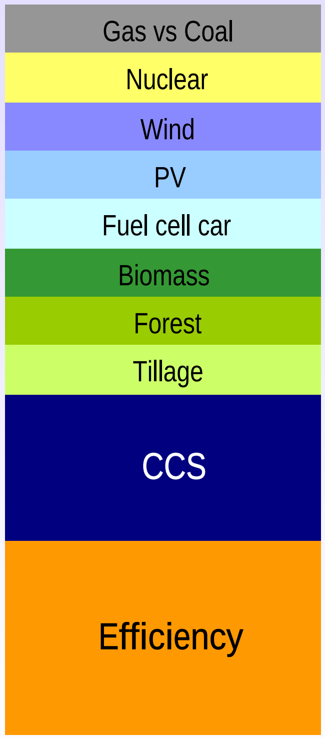
- We should curb CO_2 emissions
- We should improve energy efficiency
- We should seek alternatives to fossil fuels
- So long as fossil fuels (oil, coal, gas) continue to provide the lion's share of the world's total energy, we need to capture and sequester CO_2

CCS: Increasing Visibility



CO2 Reduction Potential

Comparison with other technologies



Sources: Socolov Wedges, 2004

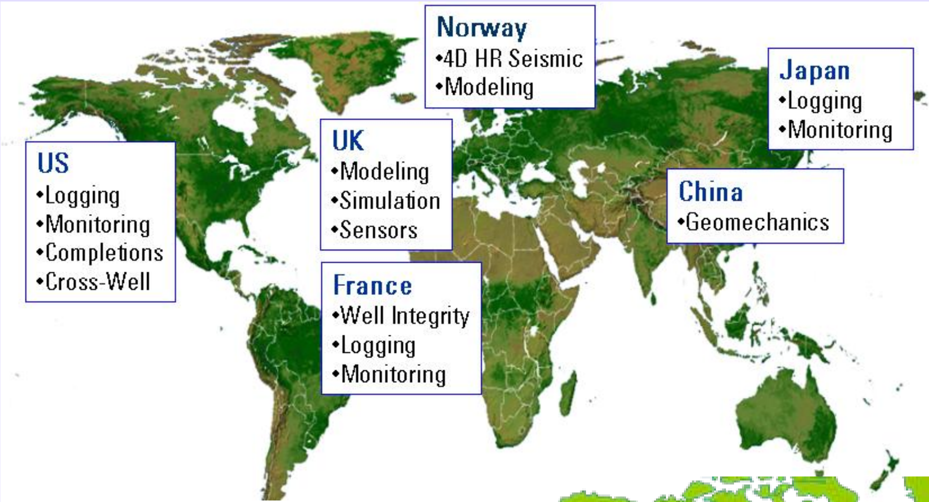
Schlumberger Public

Source Factiva

Enabling Issues to be solved

1. Cost & sustained market based economic incentives - Carbon Pricing
2. Long term liability
3. Public Perception – key concerns are leaks
4. Permitting & Site Certification
5. Monitoring and Verification requirements
6. Ownership of storage resources and of CO_2
7. Jurisdictional clarity of emerging policies and regulations
   - CO_2 as a waste, treatment of other stream gases?
8. Facilitation of initial infrastructure development

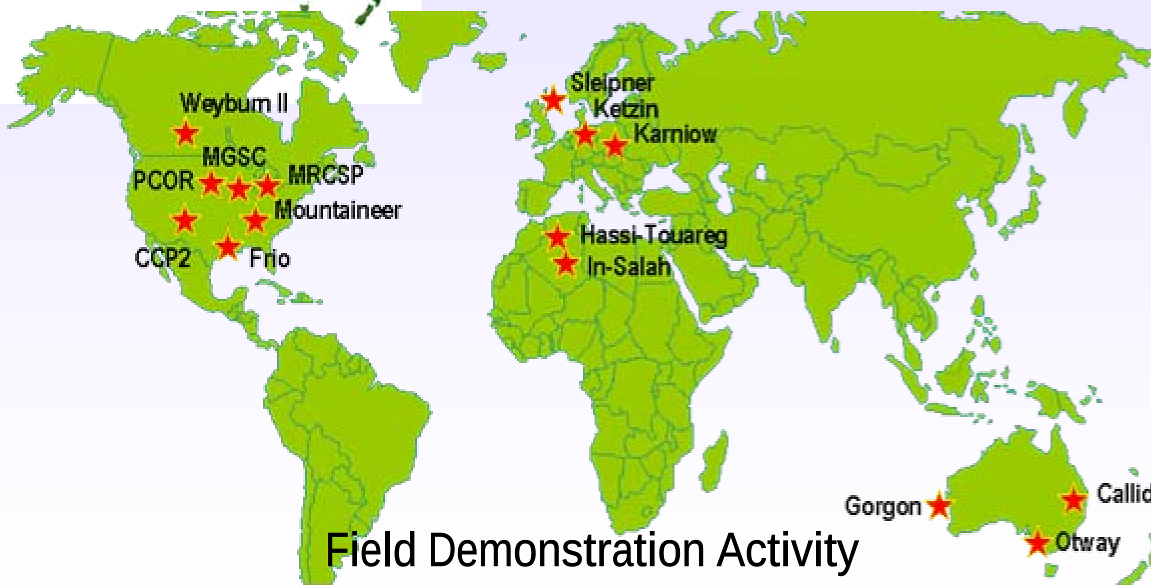
Schlumberger Involvement in CO_2 Storage



Internal CO_2 Research

Consortiums

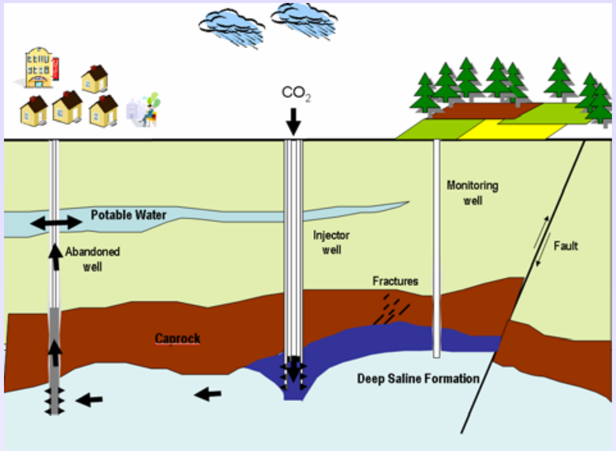
DOE RPP (US)	Weyburn II (Canada)
NACCSA (US)	CO2ReMoVe (EU)
Stanford GCEP (US)	DYNAMIS (EU)
MIT CSI (US)	MovEcbm (EU)
GCCC (US)	CO2SINK (EU)
CoalSeq (US)	CO2CRC (Australia)



Field Demonstration Activity

Managing CO_2 Storage Containment

Main objective is **safety**, second is accounting

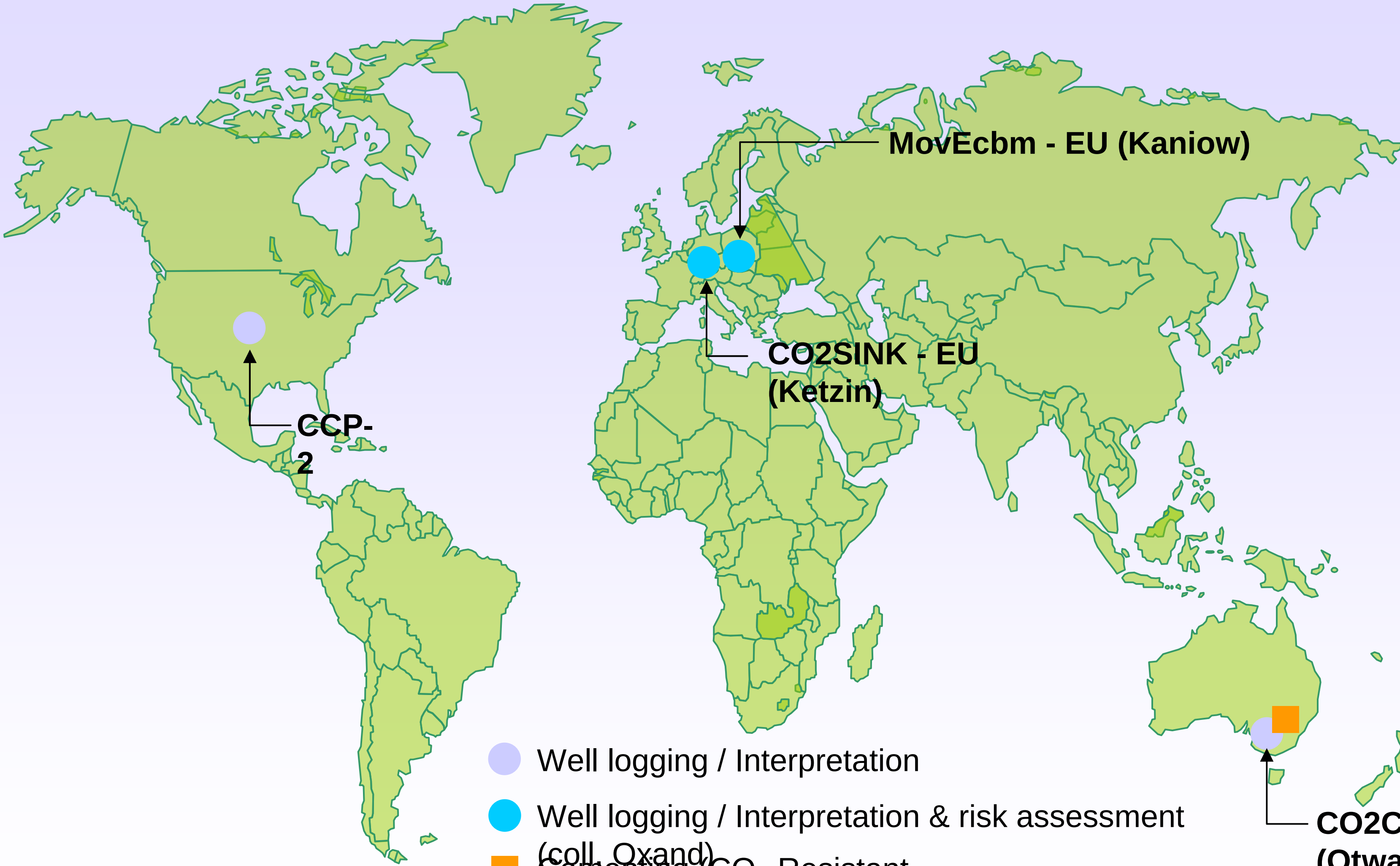


- **Risk Management** Methodology
- **Geological** containment: Faults, Caprock
  - Characterization & Monitoring (reservoir geomechanics)
  - Modeling
  - Remediation?
- **Well containment**
  - Characterization & Monitoring (near wellbore and completion integrity)
  - Modeling
  - Materials (for construction and repair)
  - Remediation techniques
- Seepage
  - Detection & Modeling
  - Impact

Well Integrity Challenges

- Well integrity has three zones: near wellbore formation, cement and casing
- Measurements (Characterization & Monitoring)
  – Characterization of the state of each material and their interfaces?
  – Detection, quantification and monitoring of degradation?
  – How to spot leaks? in real time?
- Prediction
  – Reliable modeling of the transport-reaction degradation in the three zones?
  – Prediction of risks associated with a loss of containment centuries into the future?
  – Estimation of the risk of leakage for old wells?
- Actions
  – Building wells that won't leak
  – Fixing leaks - for old wells?
  – Safely close fields after 50 years of injection?

Well Integrity – SCS involvement in R&D projects



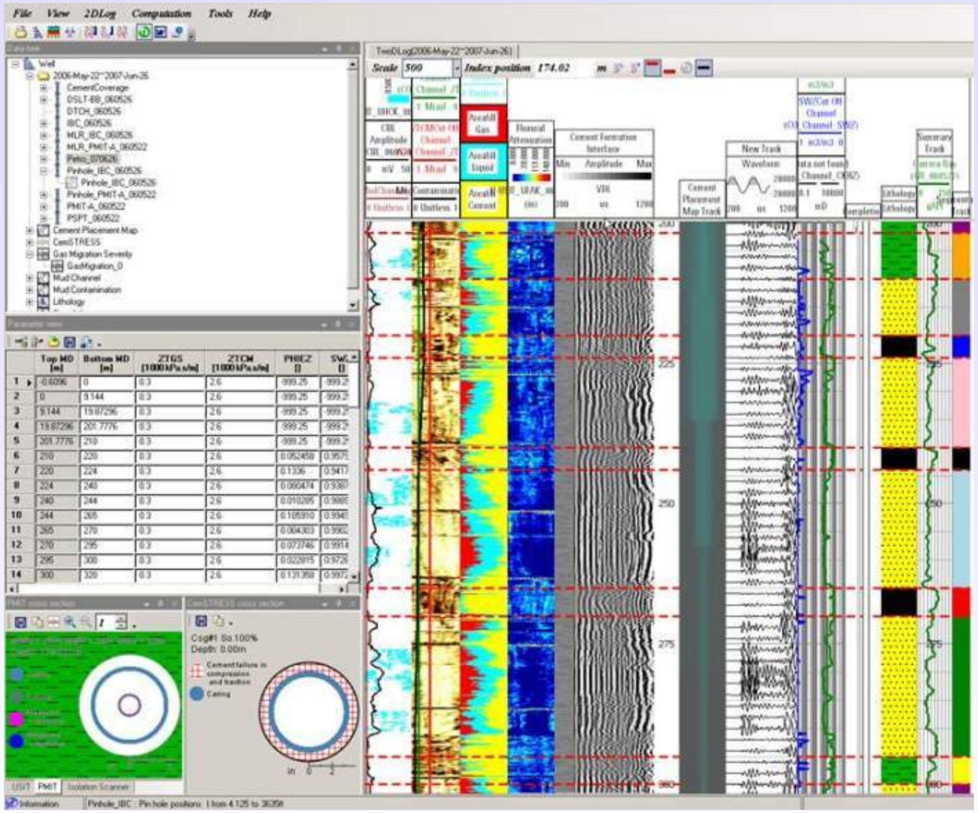
- Well logging / Interpretation
- Well logging / Interpretation & risk assessment (coll. Oxand)
- Cementing (CO_2-Resistant Cement)

Advanced Integrity Evaluation

An example of on-going SCS development:

Well Integrity Assessment and Monitoring software platform (WIAM)

- Display and analysis of **single** run and **time-lapse** wellbore **integrity logs** (characterization & Monitoring)
- Integration of **well cementing job design** information (mud removal, mechanical integrity analysis)
- Basis for **advanced computations** and **integrity risk assessment**



Example displaying integrity analysis for CO_2 injection well (MoveCBM project)

Meeting Agenda

Tuesday

- Field Studies and Approaches to Wellbore Integrity
- Experimental Studies of Wellbore Integrity

Wednesday

- Numerical Modeling
- Monitoring, Risk, and Development of Best Practices
- Summary, Discussion and Close

Thank you

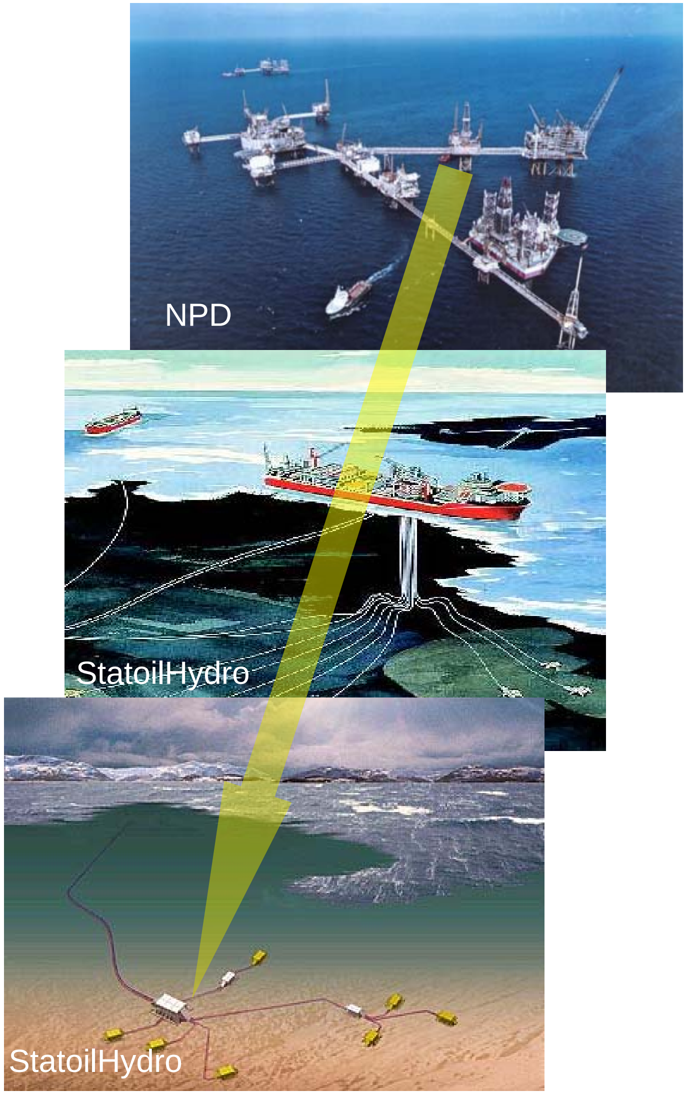
Assessment of Sustained Well Integrity on the Norwegian Continental Shelf

Preben Randhol and Inge Manfred Carlsen
SINTEF Petroleum Research

Norwegian Continental Shelf Development Trends

- The industry goes **subsea** and **towards the artic**
- Remote operations and control
- Integrated operations
- **HPHT** (Kristin, Victoria, ...)
- **IOR** and extended field life cycle
- **Re-use of well infrastructure** for low cost drainage points

- **Sustained field integrity needs to be documented**

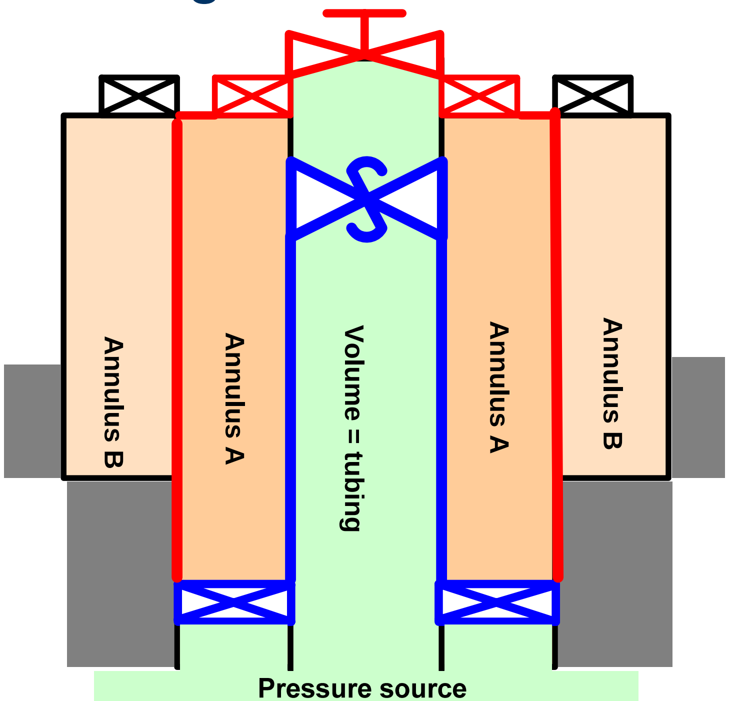


Barrier Requirement

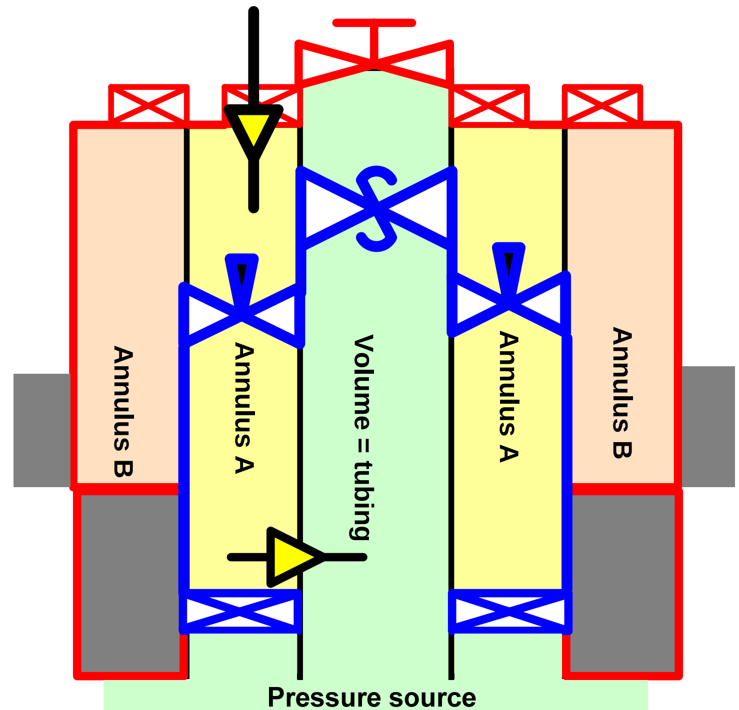
Well Integrity

"The application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of a well" (NORSOK)

- Two barriers are required to **prevent** hydrocarbons reaching surface



Oil/Gas producer / injector

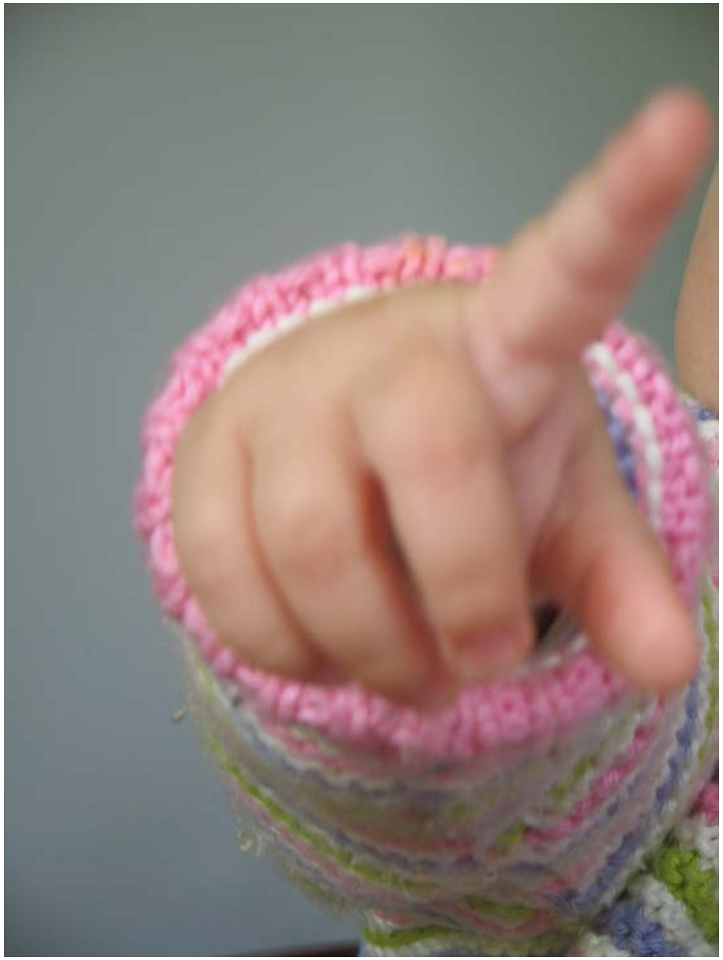


Gas lift well

Primary barrier **Secondary barrier**

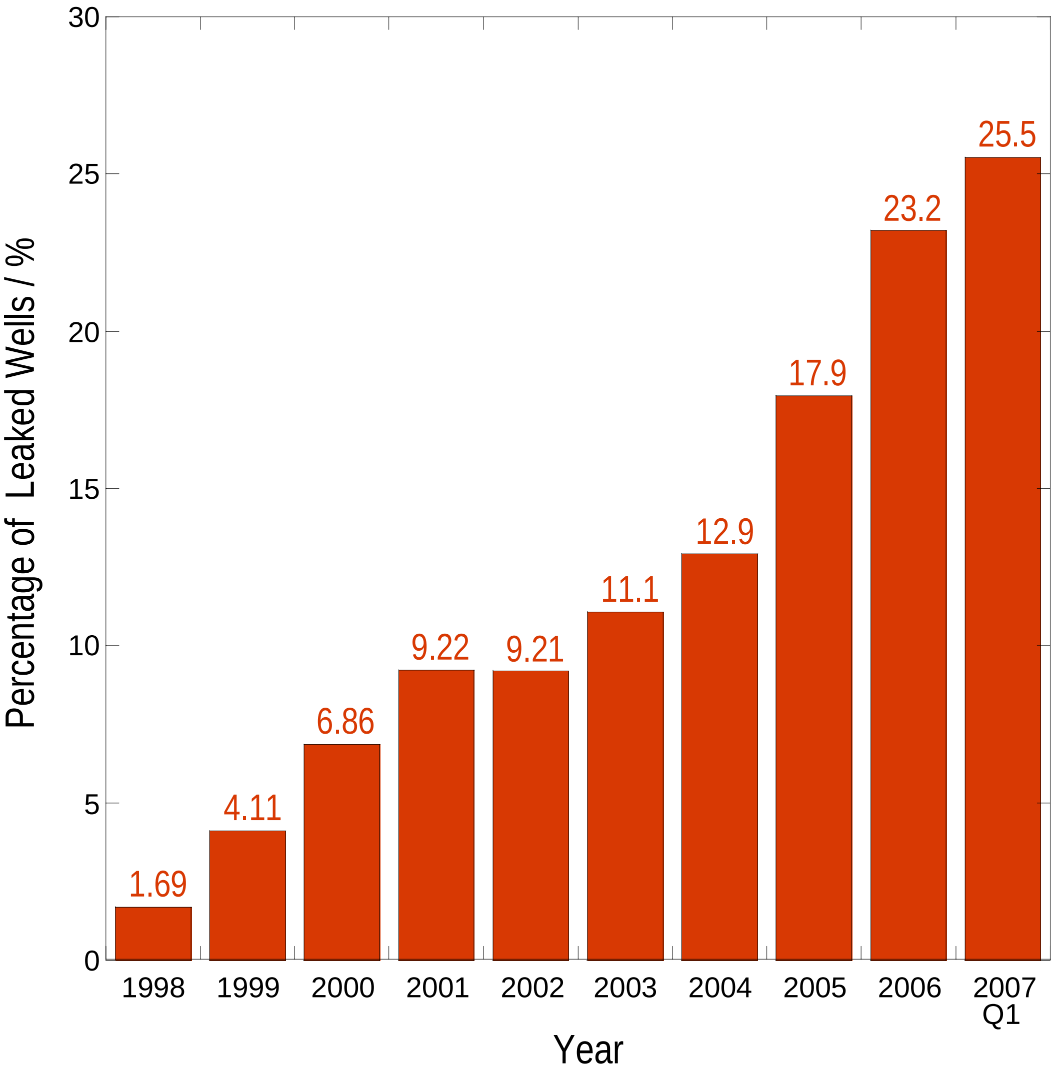
Well Integrity

- **What percentage of the wells have had at least one leak?**
  - ~20-30%
- **Why is Well Integrity important?**
  - Safety
  - Environment
  - Production
  - Reputation
  - Asset Value



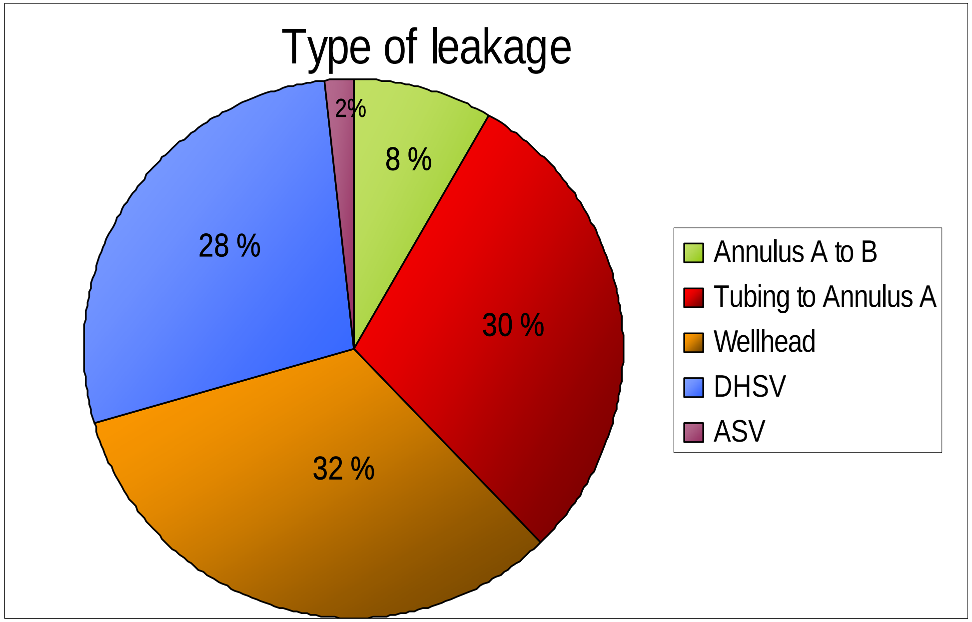
SINTEF Well Integrity Study on NCS

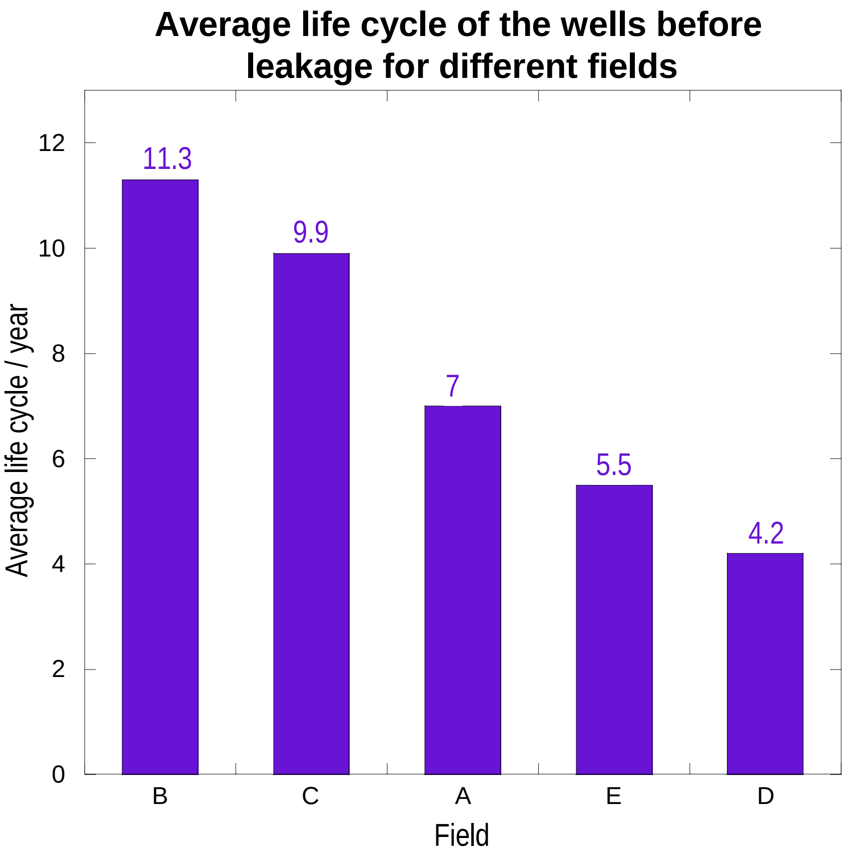
- Two SINTEF studies on well integrity for one operator's 8 fields with a total of 217 wells
- Leak history from 1998 to first quarter 2007 has been mapped and studied
- **The number of leaks can be due to:**
  - **Aging of the wells**
  - **Number of wells**
  - **Improved reporting/awareness**
  - **Operating outside the design envelope**



Well Life and Type of Leaks

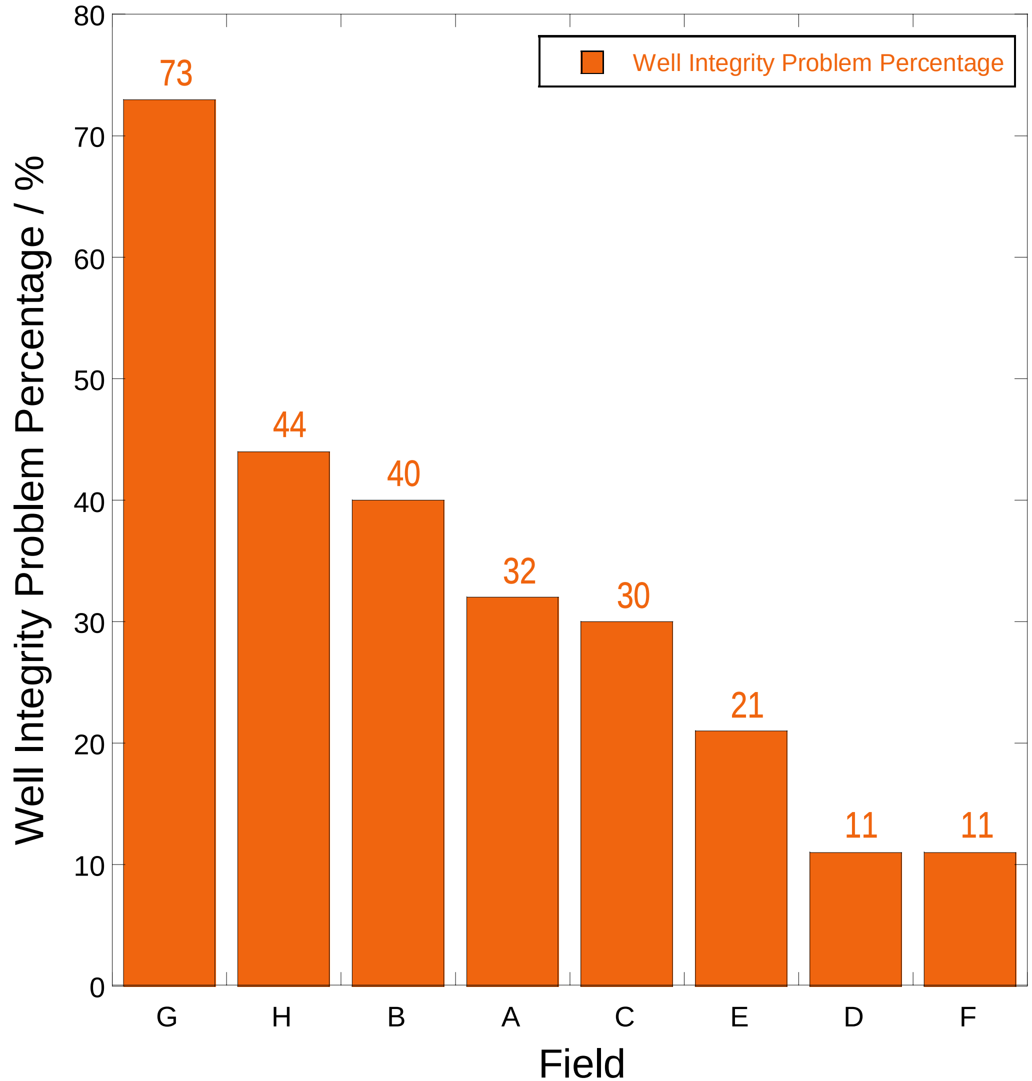
- There were three main types of leakages
- The Well Life Cycle varied for the different fields





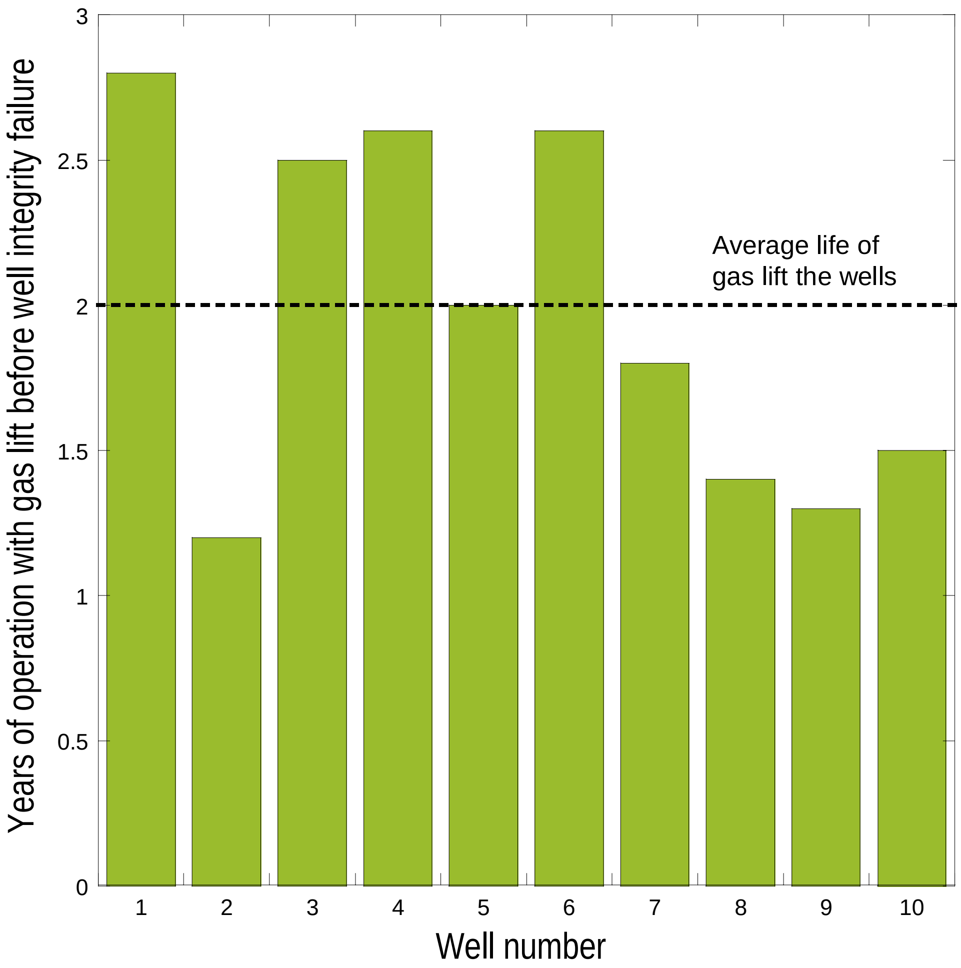
Well Integrity Field situation

- Variations from field to field
- Important differences such as:
  - Gas lift wells
  - Platform vs Subsea
  - Material choice
  - Etc...
- Cannot assume that each field will have same type/amount of problems
- Finding the root causes is a complex problem due to lack of exact data
- Data scattered between difference disciplines



Gas Lift Wells

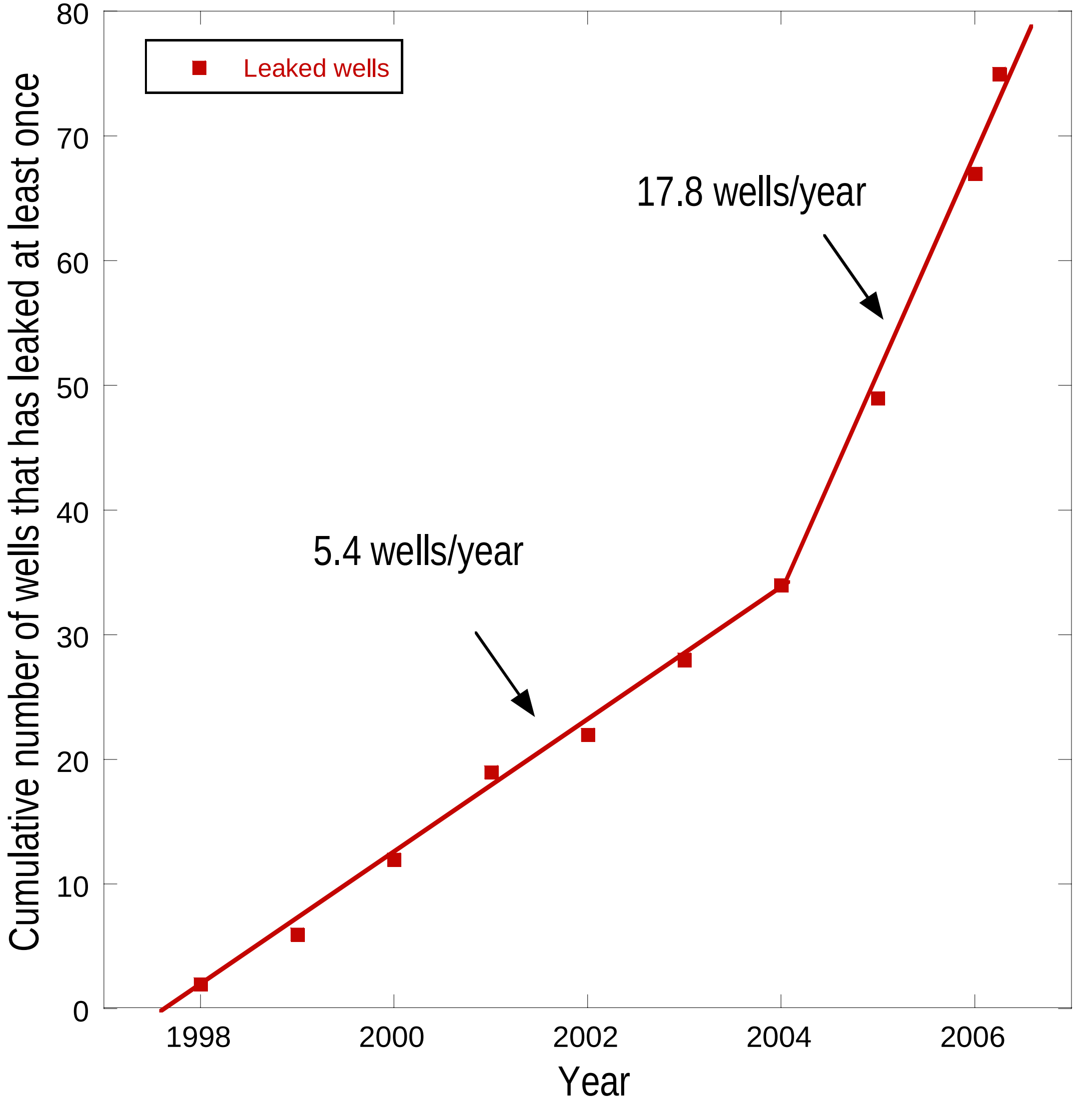
- Wells completed with low grade steel casing and 13 Cr tubing
- Depletion made it necessary to use gas lift
- Wells were designed for dry gas
- Operational conditions with wet gas and more corrosive CO_2 than design criteria
- **Operating outside the design envelope lead to very short lived wells**
- Average of 2 year operations before leakage occurred after gas lift was introduced



Look and you shall find

- Up to 2004 the trend was 5.4 wells per year with well integrity problem
- After 2004 the number was 17.8
- In 2004 personnel was hired to look at well integrity situation
- Plausible reason:

  Increased awareness and focus on reporting!



Norwegian Petroleum Safety Authority Well Integrity Study on NCS

- The Norwegian Petroleum Safety Authority (PSA) did a study in 2006
- Study involved
  - 7 operators on NCS.
  - 406 wells out of 2682

- **18%** of the wells showed to have had some form of well integrity weaknesses & uncertainties

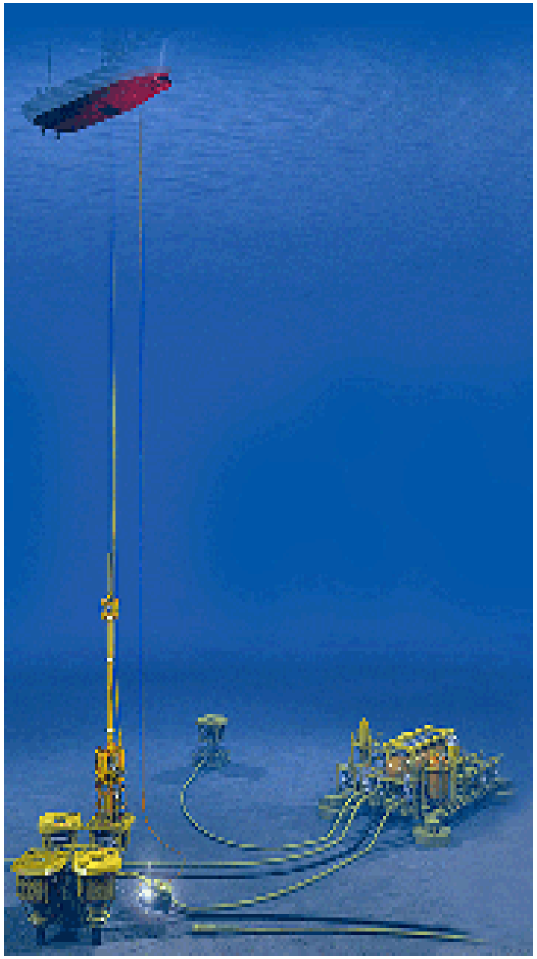
- **7 % of the wells completely shut in due to integrity issues**

(ref: http://www.ptil.no/.../nettPSAWellintegritysurveyphase1reportrevision3006.pdf)

Costs of production loss due to well integrity problems

- The NCS produce **1.5 billion barrel** per year
- That amounts to **$120 billion** (assuming $80/barrel)
- **A 7% loss in production equals**
  - **$8.4 billion**

  or
  - **The cost of constructing 200 wells** (@ $42 million/well)



The Problem Wells of the 90's (PSA Study)

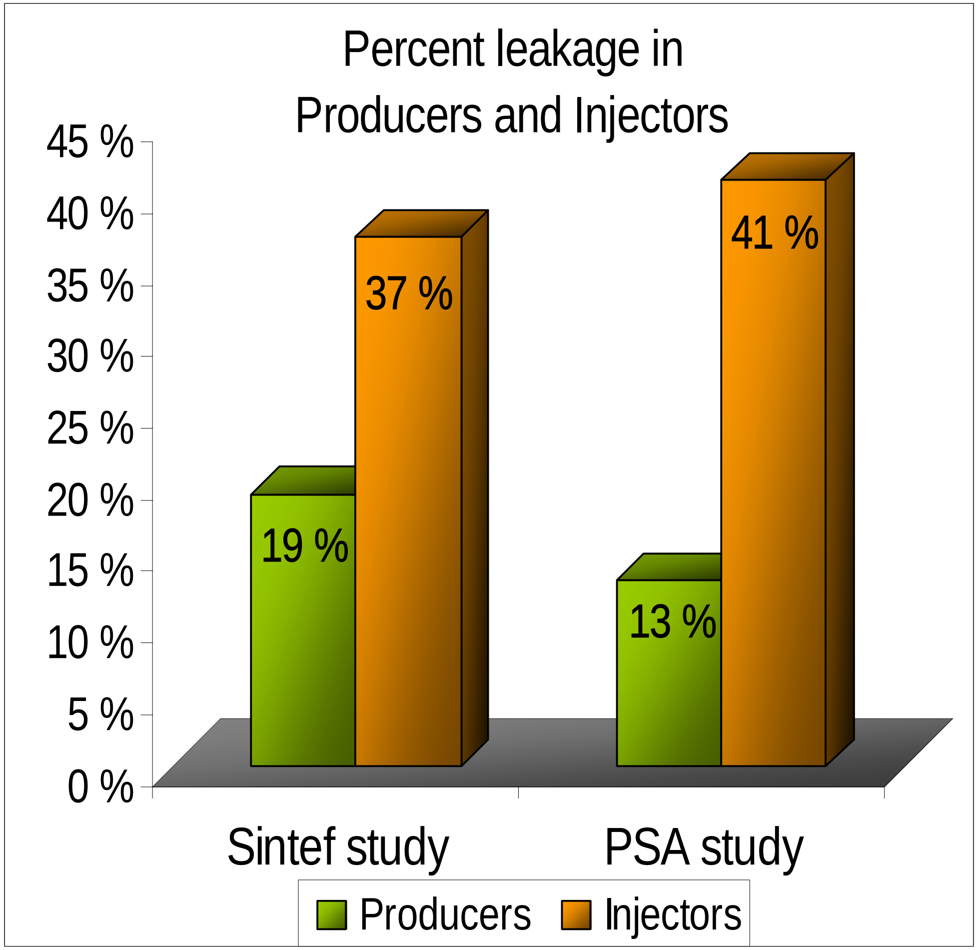
- According to the PSA study:
  - Wells drilled in the 1990s are over-represented regarding well integrity problems

- Possible reasons
  - High level of activity during this period, in combination with cutbacks and focus on costs
  - More technological advanced wells

(ref: http://www.ptil.no/.../nettPSAWellintegritysurveyphase1reportrevision3006.pdf)

Producers vs Injectors

- Injectors were found to be much more prone to well integrity failures
- **Injectors 2 to 3 times more likely to leak than producer wells**
- The two studies were conducted on different fields with only limited overlap
- The assessment of the Well Integrity situation in NCS seems therefore confirmed by the two studies



Well Integrity and CO_2

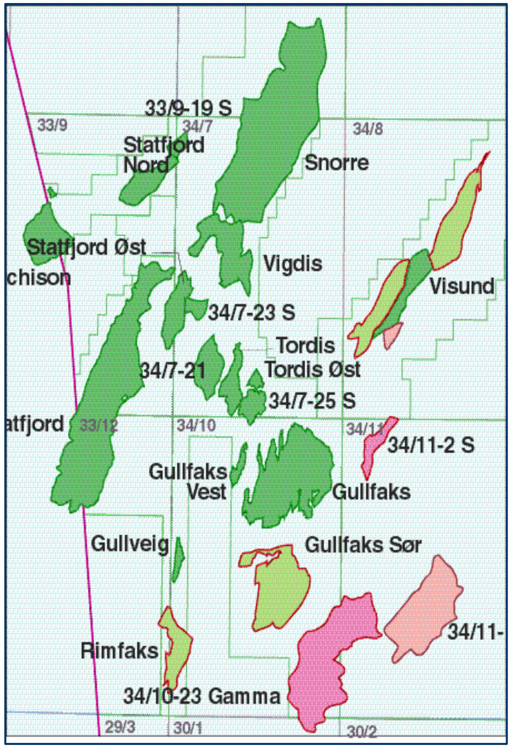
- Why is well integrity important in connection to CO_2?
  - Injection wells are more prone to leak
  - Gas lift wells more prone to leak due to CO_2 and H_2O

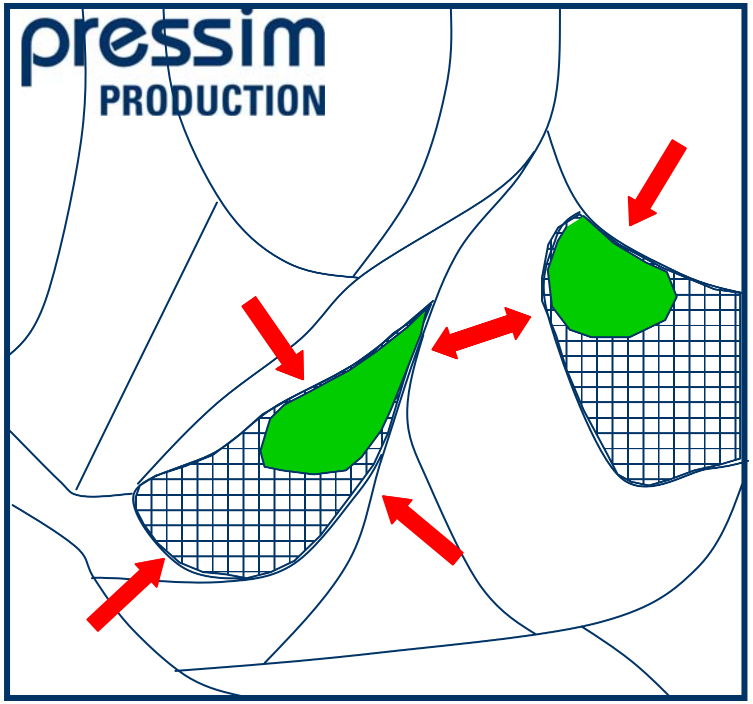
- IOR/EOR CO_2 wells
  - Risk of CO_2 blow out
  - Producer wells needs to handle possible large amount of CO_2
  - Control CO_2 migration path in the reservoir and assure safe storage

- Long term
  - Abandoned wells need to withstand CO_2 degradation
  - Need to map carefully all well trajectories and perforations

Field communication

- Need to quantify the regional lateral flow pattern and resulting pressure support
- Injected CO_2 should not end up in a neighbouring field

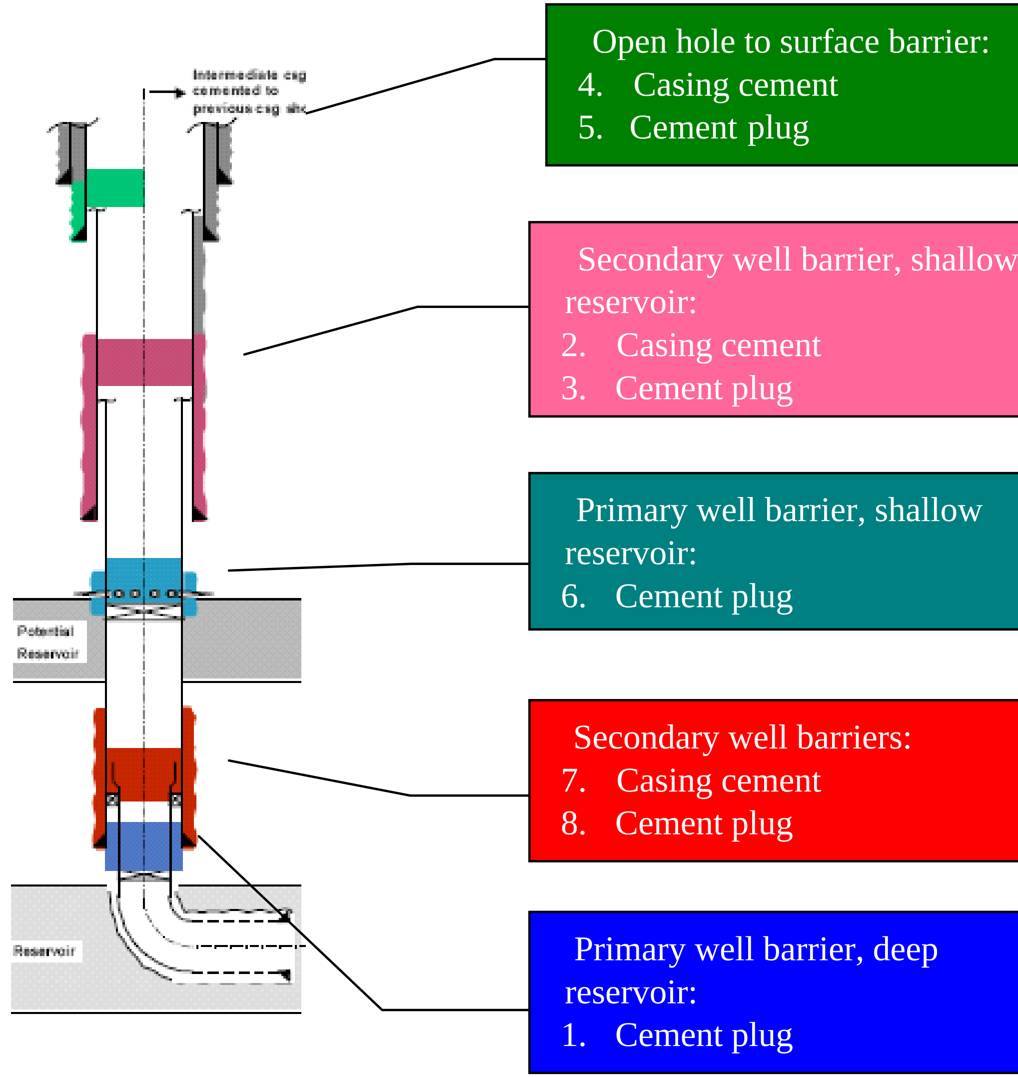




Abandonment Regulations NORSOK

- No specific methodologies to evaluate well integrity after permanent well abandonment

- Existing guidelines on permanent well abandonment intended for typical oil and gas wells and **not for CO_2-brine environment**



NORSOK

Current Status

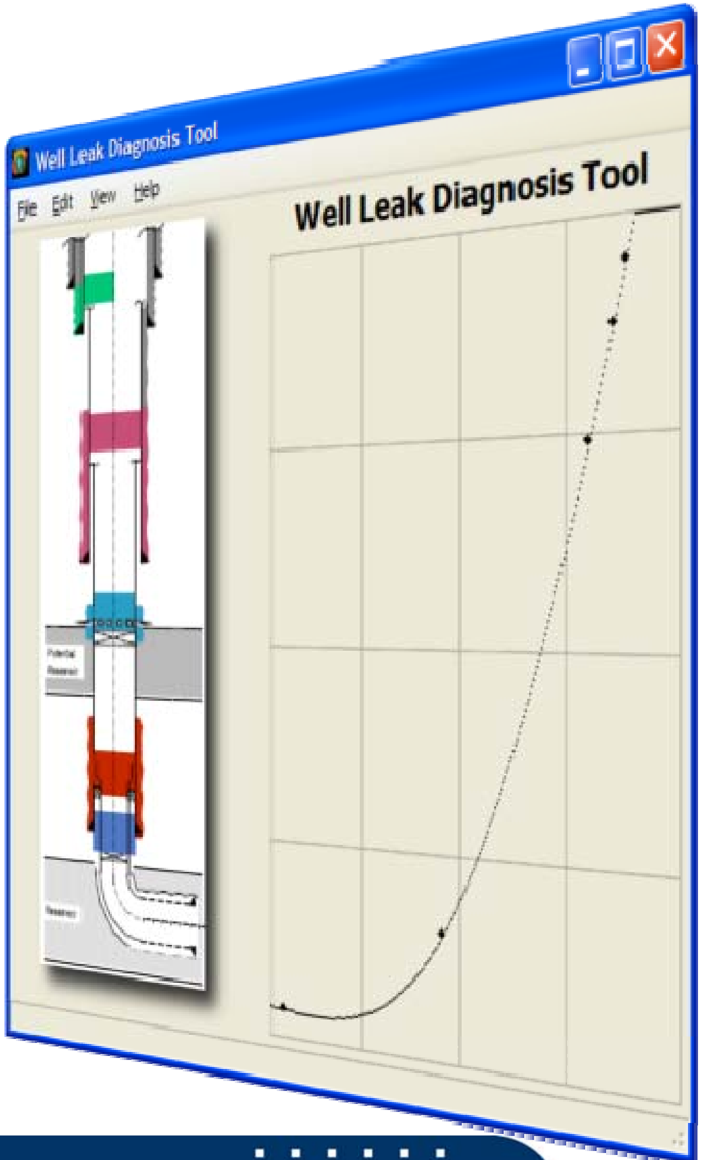
- ☑ Petroleum Safety Authorities follows the situation carefully
- ☑ Operators are focused on the well integrity issue
- ☑ Management tool for Mapping the Well Integrity are being used/rolled out (different *WIMS* systems)
  - ☑ Major improvement for operator to ***know*** the status and risk of the wells
  - ☑ Makes analysis and data mining much easier
  - ☑ A platform to build on

Focus for the future

- Areas with improvement potential
  - Audit the losses due to well integrity
  - Localisation of the leakages
  - Inspection of pulled equipment
  - Hand-over of well information between different field life phases
  - Essential well information that is *user-friendly* and *up-to-date*
  - Analyse the data to find root causes and corrective actions
  - Cross-disciplinary and cross-field experience exchange
  - Regular well condition monitoring
  - Improve design and best practise based on operational experience
  - CO_2 well integrity
  - Competence & training

Well Integrity - R&D focus

- An R&D project has been started at SINTEF to study
  - Leakage mechanisms
  - Develop models and software to analyse/localize leakages
  - Risk assessment of passing design life
  - Influence of CO_2, Arctic and HPHT on well integrity
  - Well Integrity and new technology or advanced wells
  - Subsea well integrity
- Project funded by Norwegian Research Council
- The project will also facilitate Workshops
  - First Workshop probably in September 2008



Thank you for your attention!

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CCP2 Wellbore Integrity Field Study

Objectives
- Establish the extent of alteration in CO_2 experienced wells
- Model the impact of documented alteration on long-term performance of the well barrier system.
- Develop appropriate engineering solutions to improve well integrity

Methodology
- Sample and analyze well materials
- History match well materials alteration to well life
- Forward simulate long-term well alteration in CO_2 charged environments

Deliverables
- 2 to 3 well studies with analyses of obtained fluid and solid samples
- Past and forward alteration scenarios
- Outline of engineering solutions

This is 1 part of a larger $35MM program
Capture / Storage / Policy / Communication

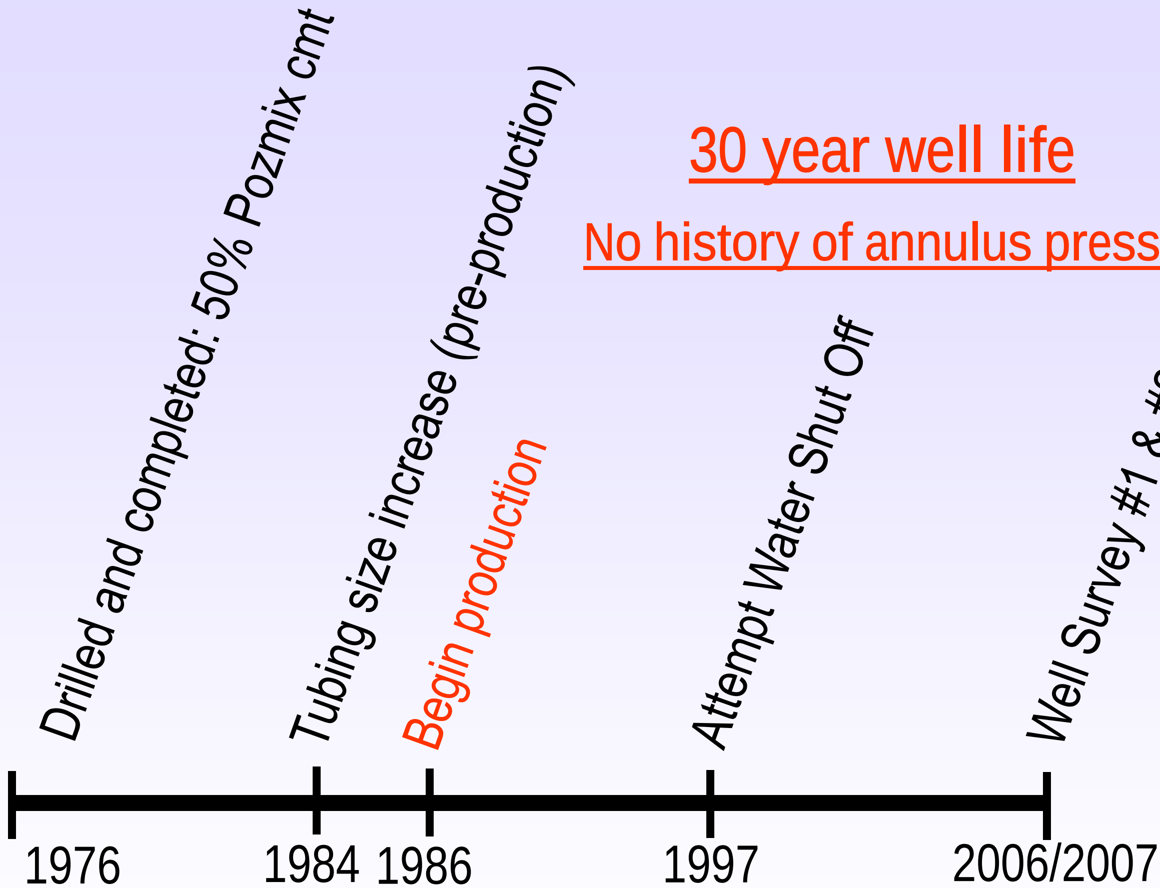
Well Selection Criteria for Integrity Survey

- Clastic reservoir
- At least 10 years CO_2 exposure
- Casing integrity largely intact
- 7” casing required for survey tool deployment
- Geologic, production and well construction data to complete analysis

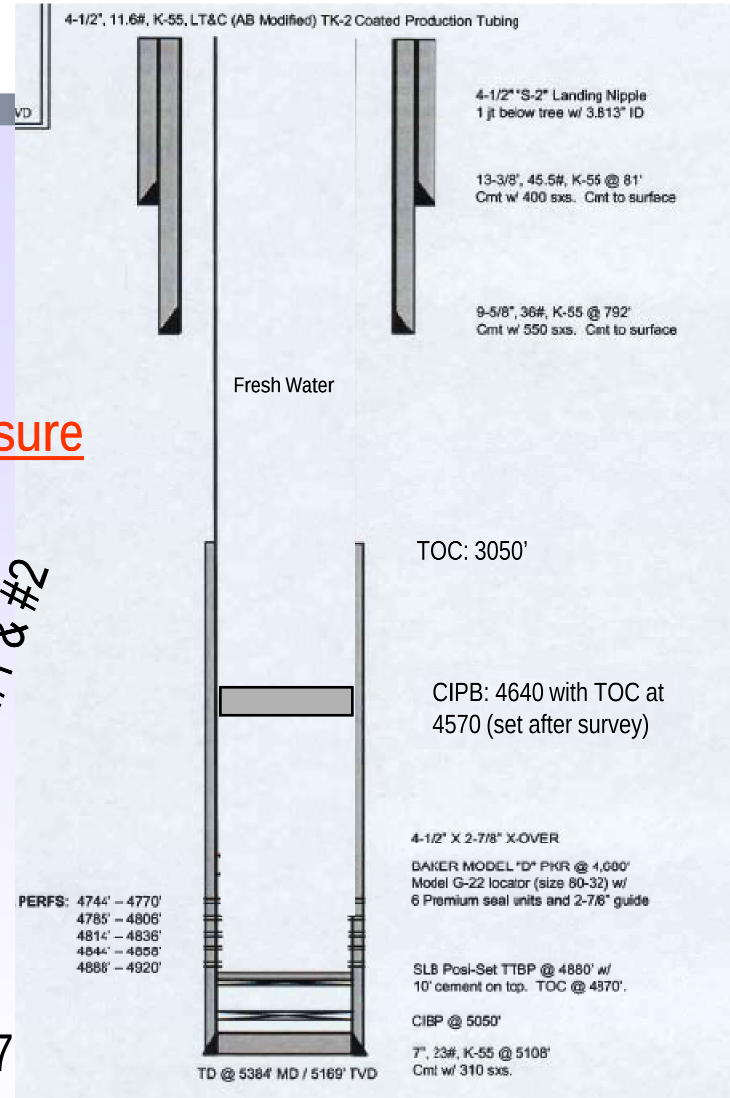
CO_2 Production Well Timeline

30 year well life

No history of annulus pressure



Actual Well History



bp Chevron ConocoPhillips Eni StatoilHydro BR PETROBRAS Shell SUNCOR ENERGY

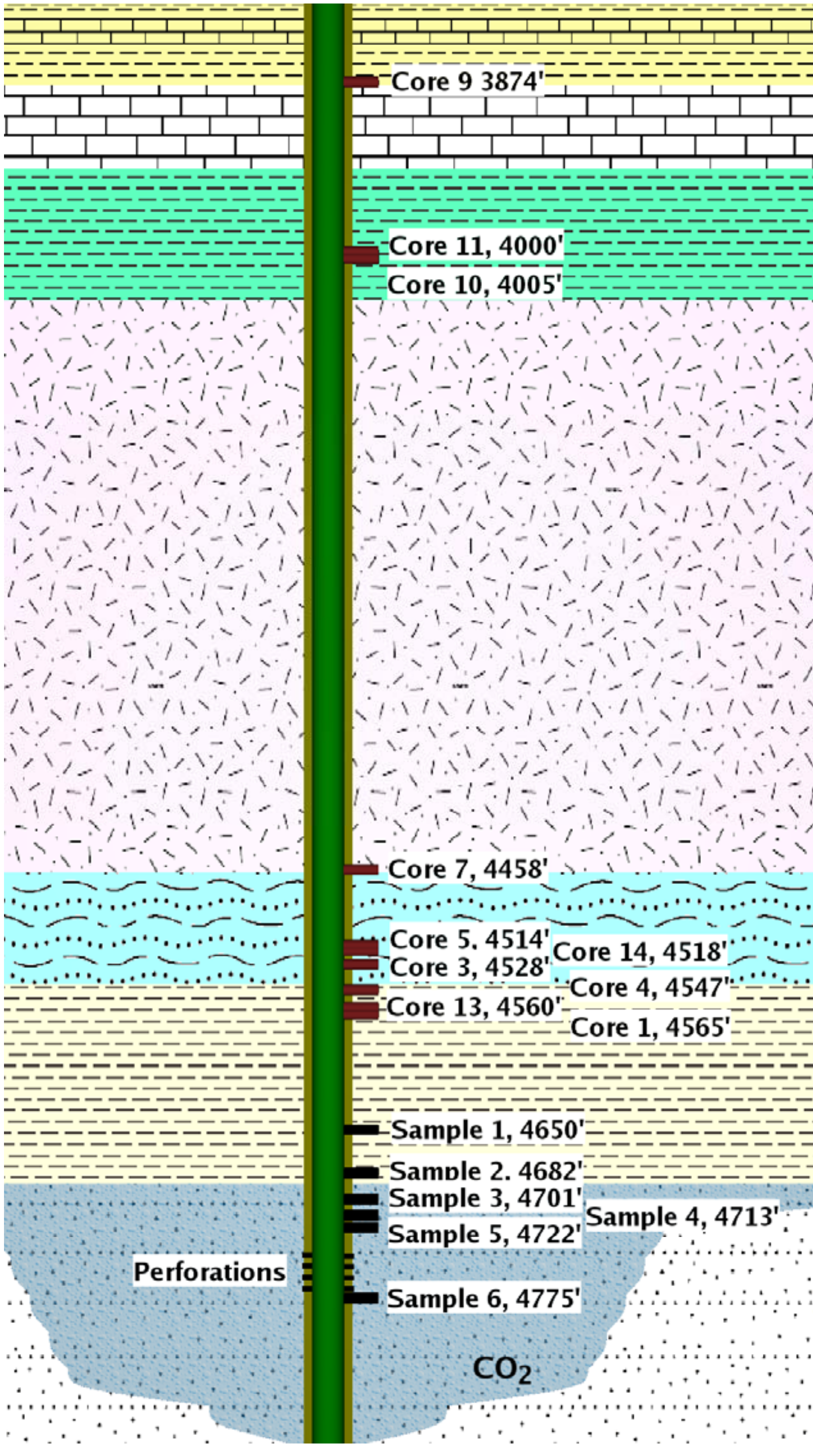
European Union
Norges Forskningsråd
U. S. Department of Energy

EPRI ELECTRIC POWER RESEARCH INSTITUTE
REPSOL YPF

Well Integrity Survey

Survey Components	Analytical Purpose
• Mechanical integrity – caliper survey • Cement condition cement bond log ultrasonic/scanner tools • Pulse test of cement sheath (in-situ perm)	Barrier assessment
• Gas saturation / spectroscopy - behind casing • Fluid/gas samples and pressure survey • Sidewall cores through casing	Signs and effect of CO_2 migration

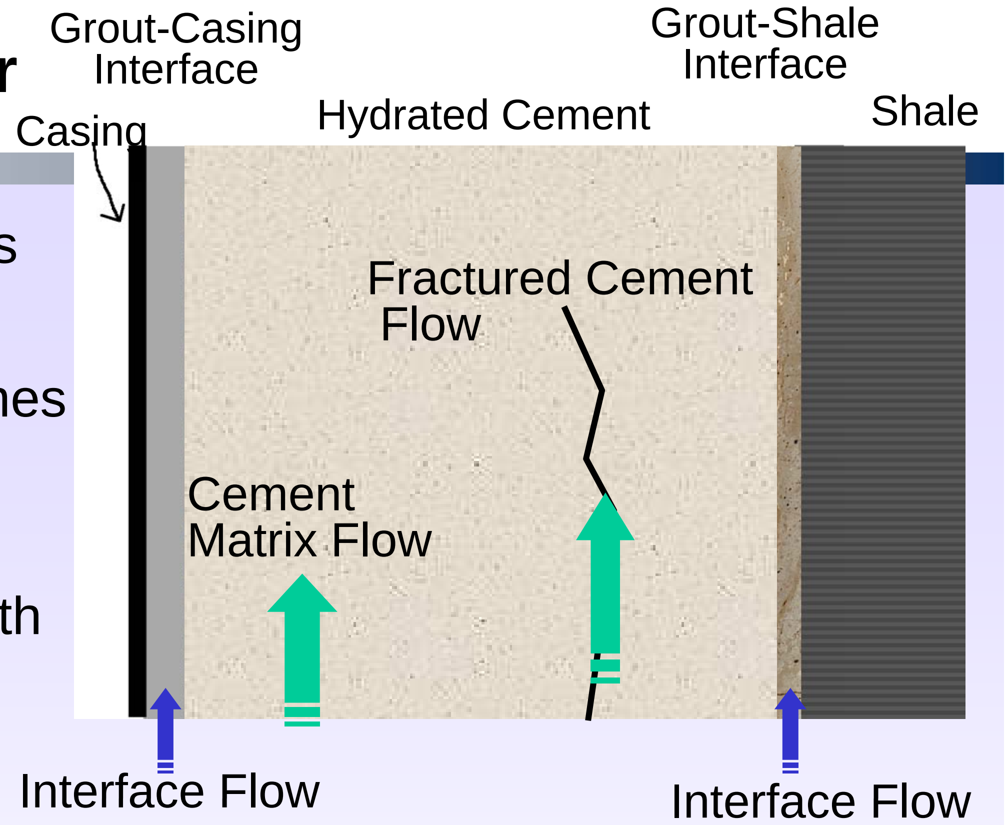
Stratigraphy and Location of Core Samples



10 sidewall cores taken in Survey #2

6 sidewall cores taken in Survey #1

CO_2 and the Wellbore Barrier



Migration Pathways and Mechanisms Along Cement Barrier

- Pressure differential between zones
- Matrix flow limited by capillary properties
- CO_2 diffusion along cement sheath

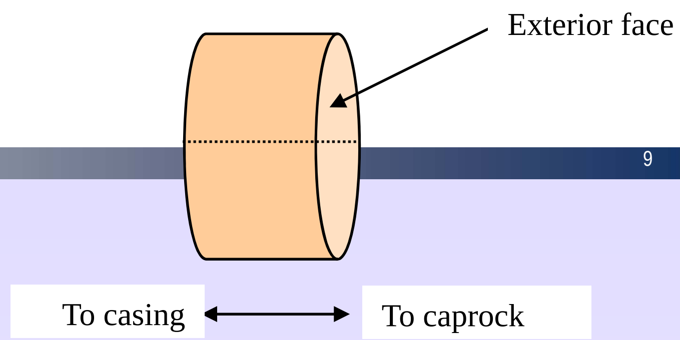
Potential Effects of Carbonation

- Beneficial:
  Decrease in porosity, decrease in permeability, and increase in strength
- Harmful:
  Reduction of pH of pore fluid leading to corrosion of casing
  Carbonation-induced shrinkage leading to cracks
  Reduction of casing/cement and/or cement/caprock interface integrity
  Loss of structural integrity at ultimate carbonation state
  Important factors controlling rates of carbonation
    Water/cement ratio, age of cement, capillary properties

Study Design

- Assess wellbore condition
  - Cement evaluation logs (sonic / ultrasonic), caliper
  - Effective permeability of wellbore outside of the casing
- Look for evidence of CO_2 migration
  - Cement mineralogy
  - Fluid sample chemistry
- Determine any consequences of CO_2 migration
  - Corrosion in casing
  - Hydrologic and mechanical properties of cement

Analytical Approach

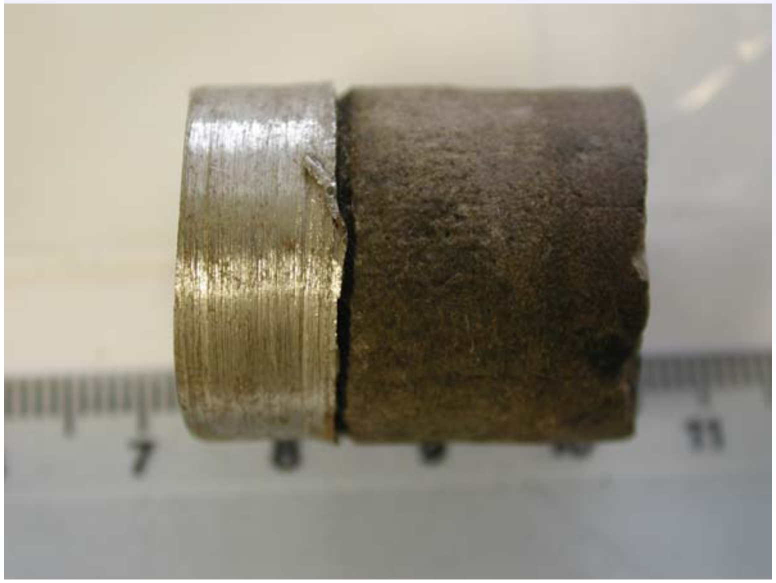


- X-ray diffraction, optical microscopy, and scanning electron microscopy of cement to assess presence of carbonates
- X-ray tomography
- Mechanical properties (moduli, acoustic velocity)
- Permeability, porosity, capillary pressure, and formation factor
- Compare with fresh cement laboratory samples
- Compare with cement sheath pulse test

Sample Recovery

- Cement recovery uneven with complete casing-cement-rock samples rare
- Samples generally separate from casing when recovered
- Interfaces (at separation) can be re-assembled, suggesting tight bonds
- Recovered cement is physically intact and spans the casing-rock annulus

Core from Bottom of caprock



Core from Top of caprock

Preliminary Observations

- Casing (and tubulars) in excellent condition
- Cement and interface condition indicate annular space intact and capable of limiting fluid movement
- Cement shows evidence of reaction with CO_2 to form calcium carbonate
- The extent of carbonation appears to decrease up the wellbore but has not yet been fully quantified
- Cement permeability decreases by 1-2 orders of magnitude from the bottom of the caprock to the top of the caprock

CCP2 Well Integrity Study

Key Messages

- Core samples have varying degrees of alteration but are intact
- Existing logging technology is capable of assessing well integrity

Way Forward

- Complete the sample / data analysis and report the results
- Create model to history match well conditions
- Forward-project barrier life and condition
- Engineer solutions that are fit-for-purpose to maintain barrier integrity

Acknowledgements:

CO2 Capture Project Member Companies & Associates

Review of Failures in Wells used for CO2 and Acid Gas Injection

Fourth Wellbore Integrity Network Meeting
Paris, France
March 19, 2008

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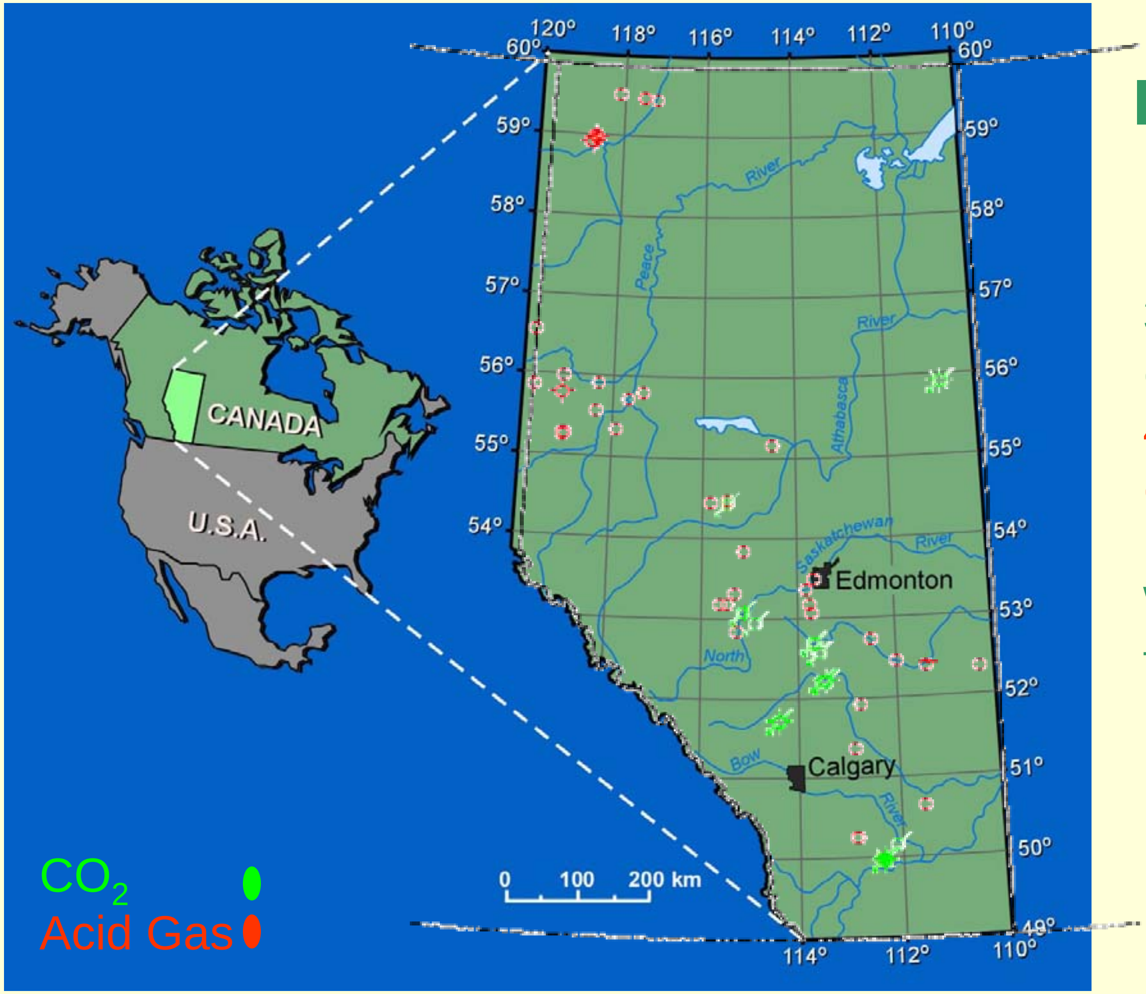
Introduction

- General Information
- Regulation
- Failure
- Risk
- Future Considerations
- Conclusions

General Overview

- Review of all wells that are, or have injected acid gas or CO_2
  - Tour report review
  - Cement, casing inspection and zonal isolation log review
  - Electronic data review
  - Regulation review
- Acid gas may be a mixture of H_2S and CO_2 as a waste stream from natural gas/oil production.
- Particular attention to the failures experienced by each well, causes and remedies.

Injector Location in Alberta

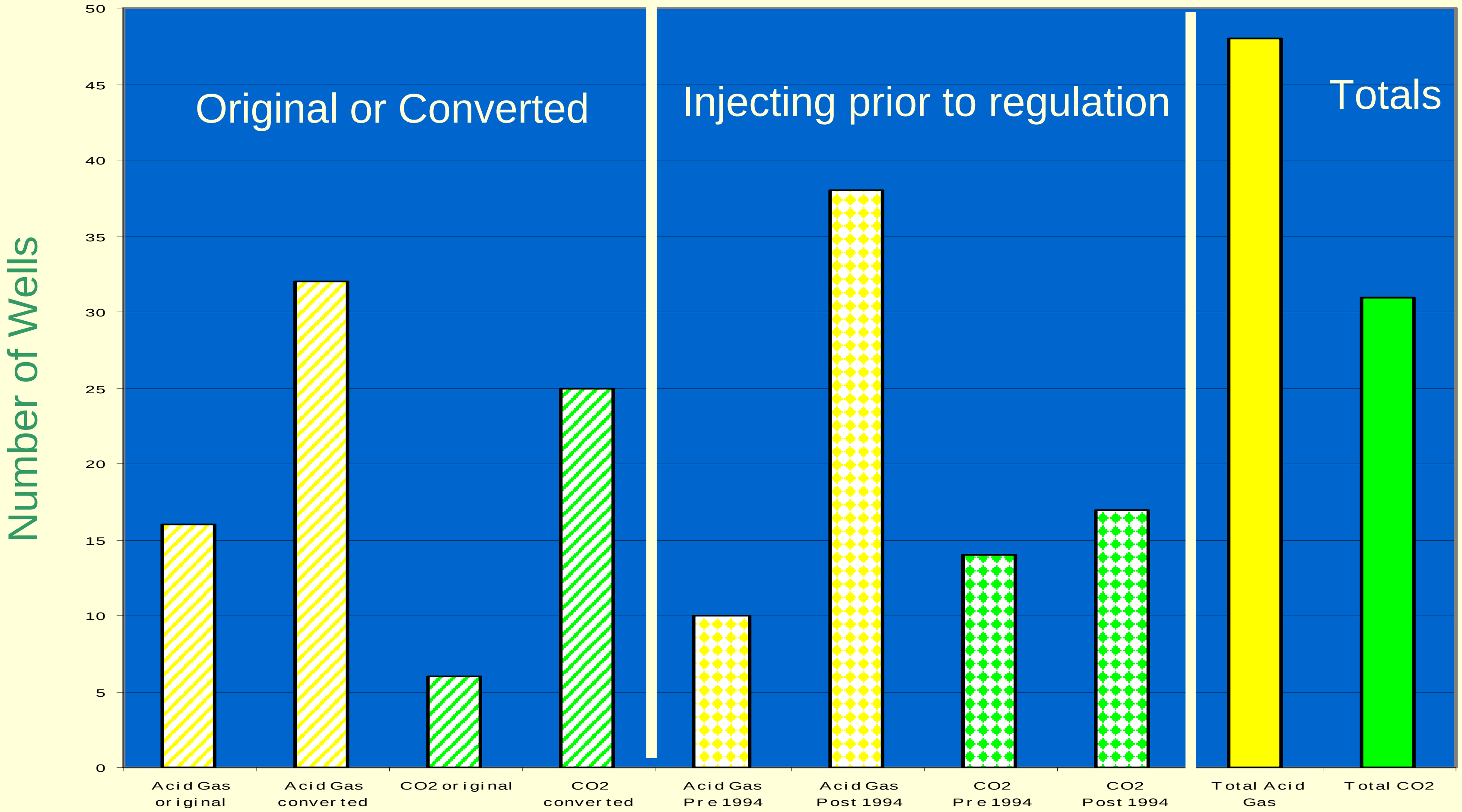


31 CO_2 Injectors
(5 abandoned)
48 Acid Gas Injectors
(3 abandoned)

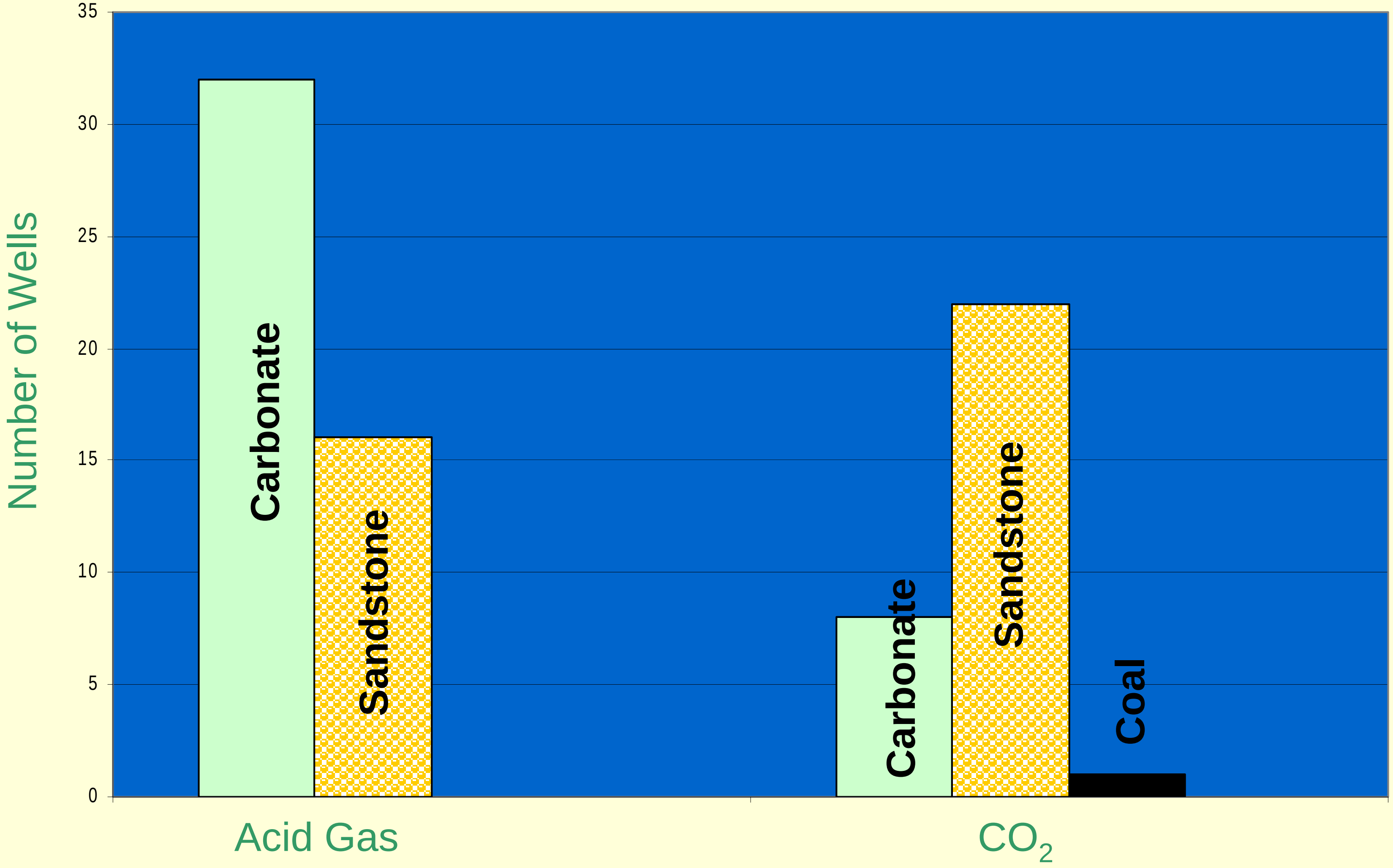
Widely distributed around the province

Area: 664,332 km^2
(256,610 sq.mi)

Number of Wells by Category



Injection Reservoir Type



Regulation

- Injection and Disposal Well Guide issued March 1994 (Guide 51).
- Prior to 1994 wells were approved for injection on an individual basis.
- Groundwater concerns were addressed in the regulations, but had not been specifically addressed prior to 1986.
- Classified injection wells in 1994.

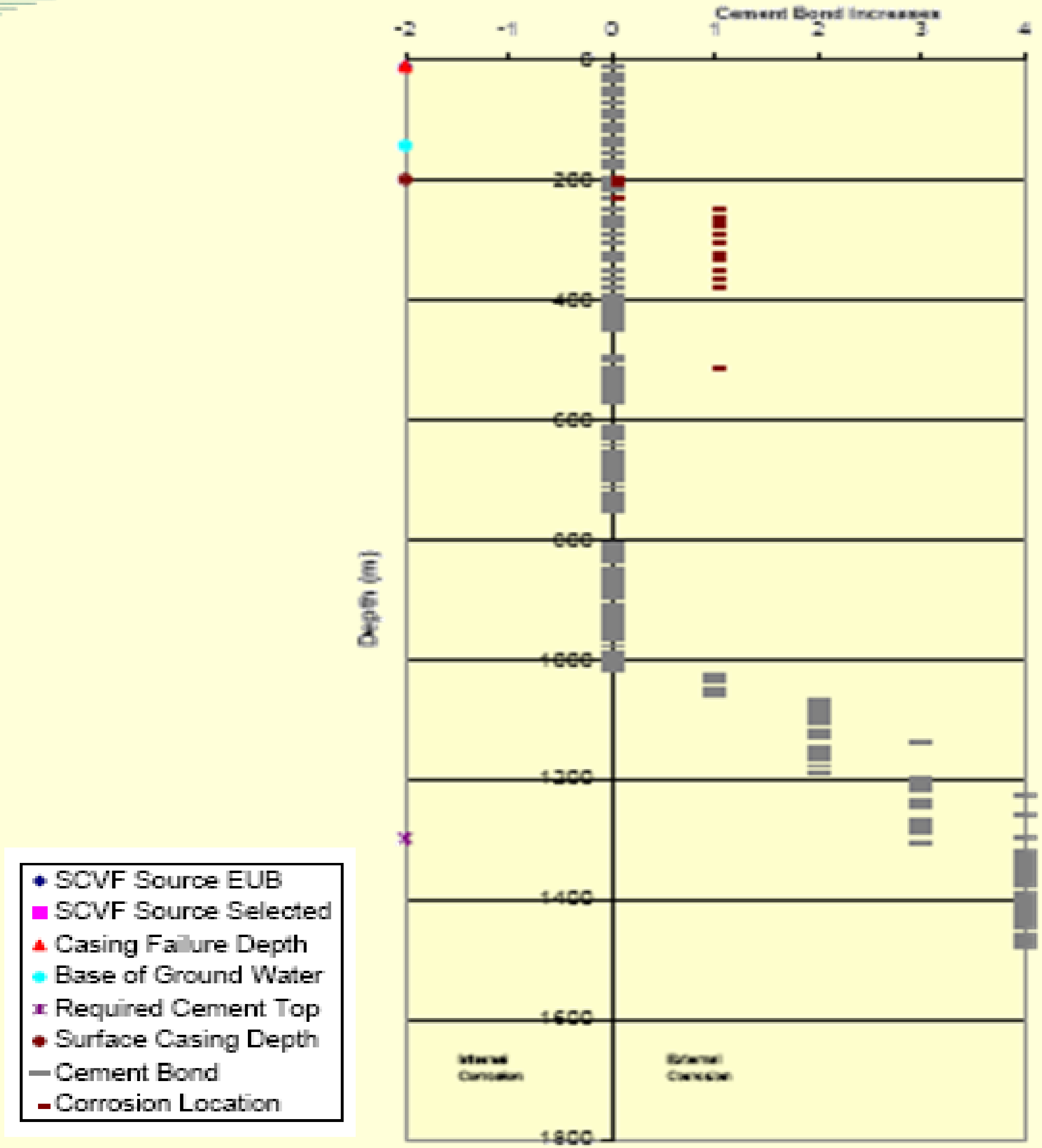
Well Classifications and Requirement Summary

SECTION	CLASS 1a	CLASS 1b	CLASS II	CLASS III	CLASS IV
2.0 WELL CLASSIFICATIONS					
* oilfield/industrial wastes	X				
* produced water/specified wastes		X			
* produced water/brine equivalent			X		
* hydrocarbon/inert/sour gases				X	
* steam/potable water					X
4.0 CEMENTING/CASING REQUIREMENTS					
* hydraulic isolation of host zone	X	X	X	X	X
* cement across useable groundwaters	X	X	X	X	X
* surface casing below useable groundwaters	X				
5.0 LOGGING REQUIREMENTS — INITIAL					
* cement top locator (when no returns)	X	X	X	X	X
* hydraulic isolation	X	X	X	X	X
* casing inspection — conversion	X	X	X	X	X
7.0 OTHER TESTS AND SUBMISSIONS					
* annulus pressure test — initial	X	X	X	X	
* daily annular monitoring	X				
* daily injectivity monitoring	X				
* hydraulic isolation logging — every 5 years	X				
* annual formation pressure survey	X				
* annual packer isolation test	X	X	X	X	
* well summary/completion schematic	X	X	X	X	X
* area of review (1.6 km radius)	X	X			
8.0 OPERATING PARAMETERS					
* wellhead pressure limitation	X	X	X	X	
* positive annular pressure	X				

Requirements

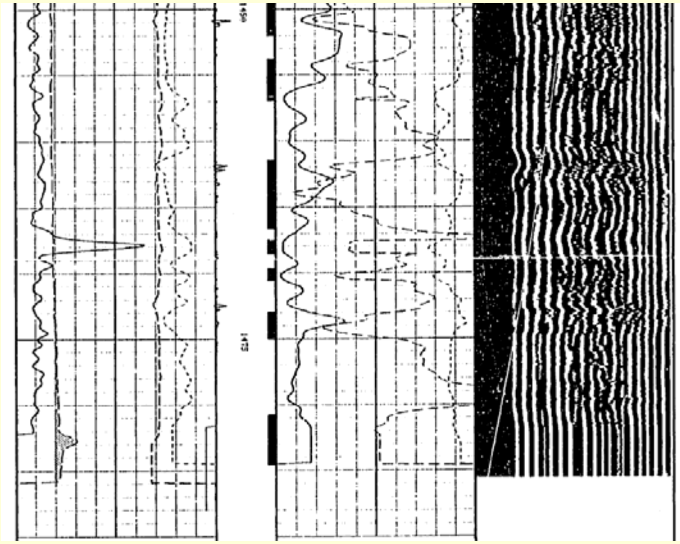
- Hydraulic isolation
  - Cement evaluation
  - Temperature survey
  - Radioactive log
- Groundwater protection
  - Cement top location
- Casing condition
  - Casing inspection
- Monitoring
  - Annual packer isolation testing

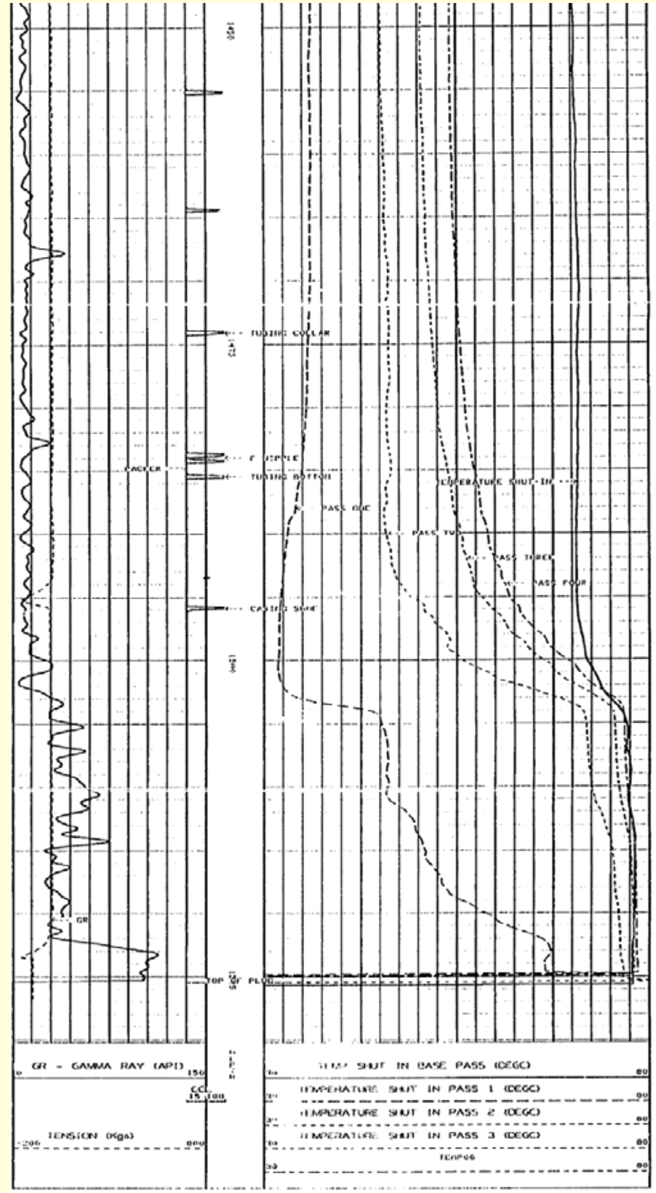
00/05-34-115-06W6/0



Acid Gas Injector Wellbore Condition

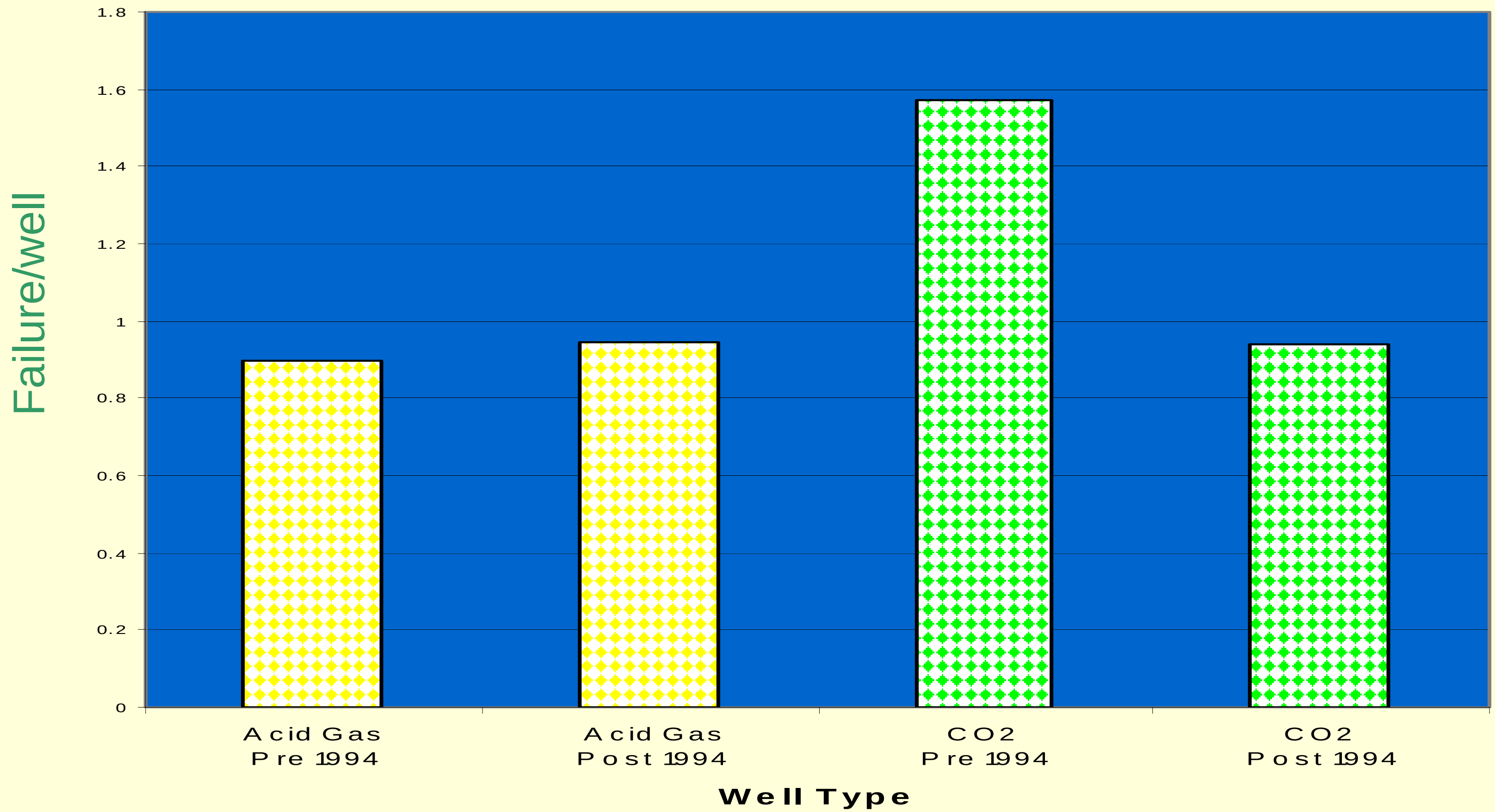
Spud in 1969
Converted in 1997
SCVF exists
Well cemented with 200 sacks 1-1-2
Casing grade K55





Log information for
00/05-34-115-06 W6

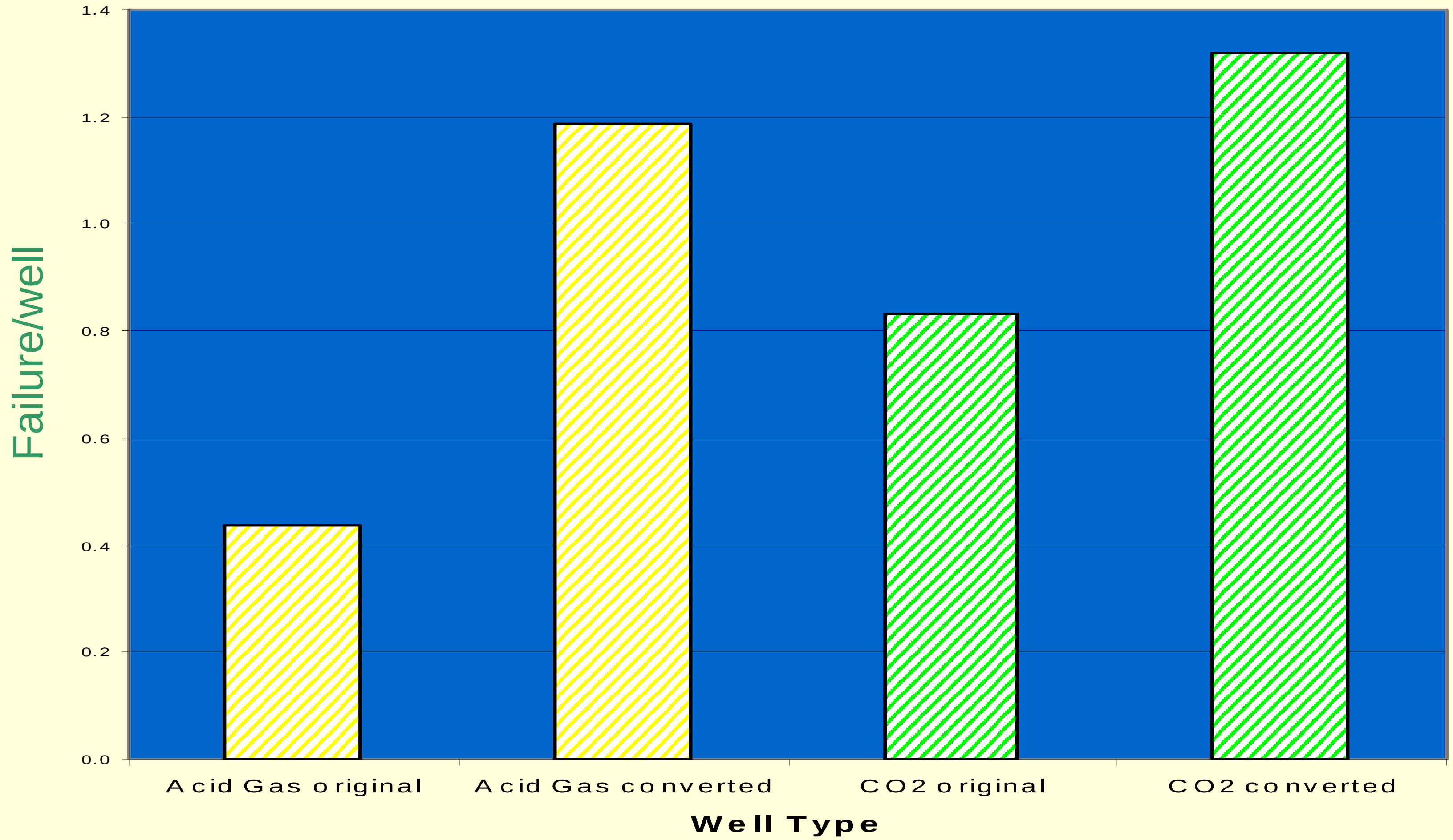
Failure per Well
Regulation Impact



Built for Purpose

- It was expected that wells drilled, cemented and originally completed as injectors would indicate fewer failures of all types.
- This hypothesis was confirmed, with acid gas injectors showing a stronger indication.

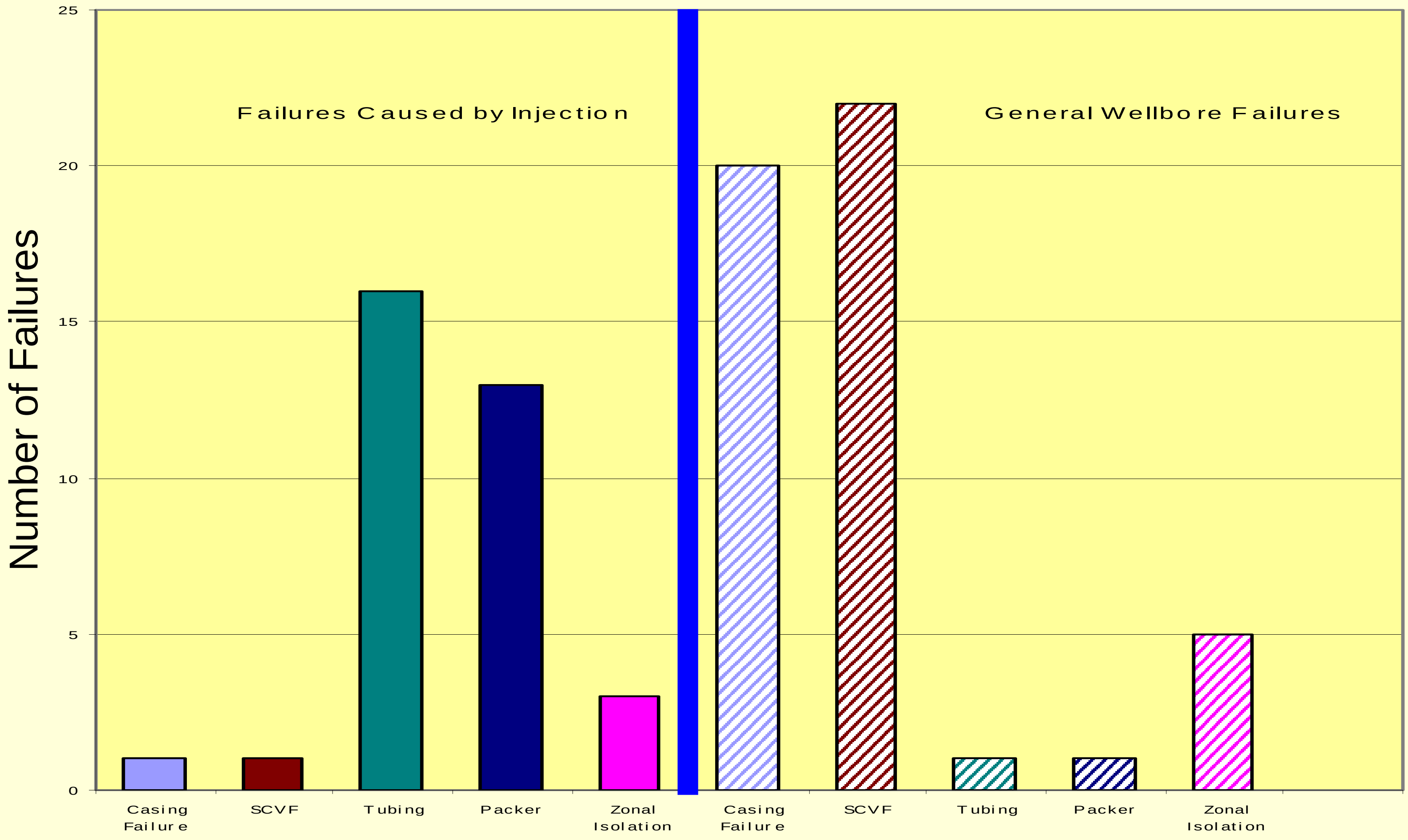
Failure per Well
Original Use and Converted



Failure Modes

- The majority of failures caused by injection were tubing and packer failures.
- These failures are easy to detect and there are annual testing requirements to ensure integrity of tubing, packer and casing above the packer.
- Failures must be repaired immediately.
- Failures not associated with injection are comparable to the general well population.

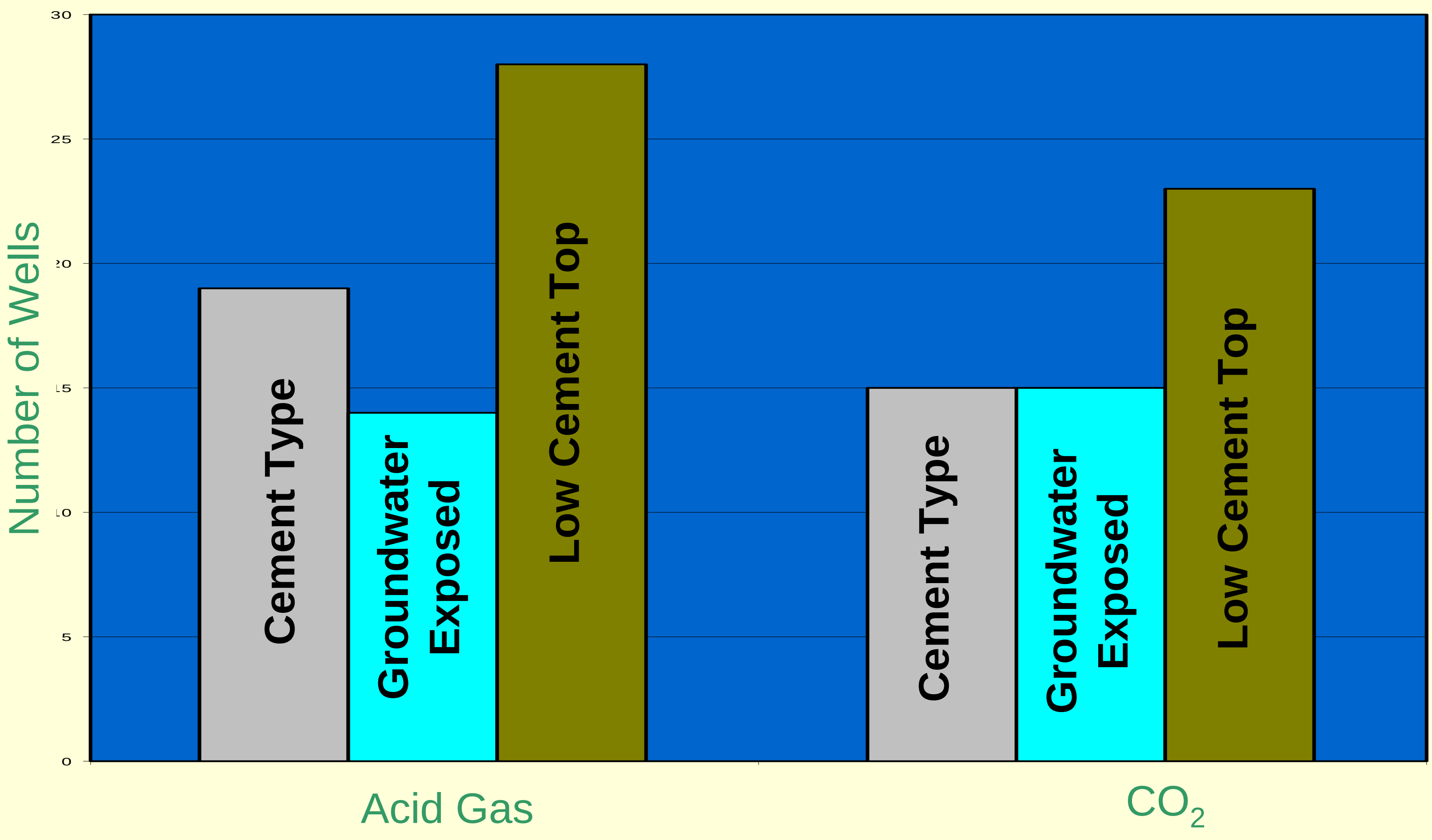
Failures by Mode



Identification of Potential Risk

- From prior work cement blends which contain extenders such as bentonite have been indicated as a potential for zonal isolation failure due to cement reaction with acidic fluids.
  - 3 of 16 acid gas injectors built for purpose had specialized cement to combat the affect of acidic environment.
- Groundwater protection is an important focus in Alberta.

Risk Factors for Failure



Future Regulation Changes

- Daily monitoring of annular pressure
- Hydraulic isolation testing every 5 years
- Cement across all groundwater
- Surface casing set and cemented below groundwater depth for acid gas injectors
  - Groundwater defined as <4000 mg/l TDS
- Acid gas injectors will be classified as 1a injectors and require additional safe gaurds.

Conclusions

- Wells built for purpose have fewer failures than wells converted.
- Wells placed on injection after the advent of regulatory controls in 1994 have fewer failures.
- Injectors have comparable failures, which are not caused by injection, to the general well population
- Updated regulations should have a positive impact on injector integrity.

Advances in cement interpretation Results from CO2SINK and CO2CRC

IEAGHG 4th Well Bore Integrity Network Meeting

Paris, 2008 Mar 18

We wish to thank CO2CRC and CO2SINK for their support and the permission to publish the data and analysis in this presentation

Matteo Loizzo

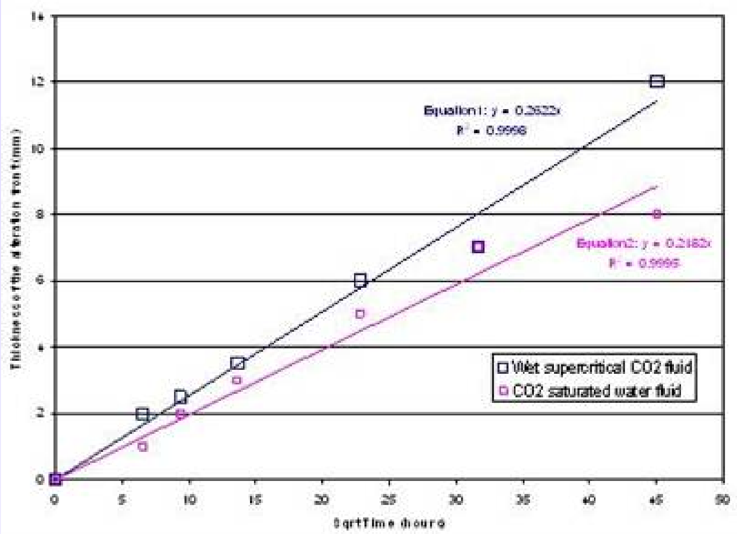
Schlumberger Carbon Services engineering manager

Outline of the presentation

- Where were we: some conclusions from the EPA CO_2 Geosequestration workshop in 2007
- Well integrity and CO_2: is it really so special?
- Pathways through cement
- Introduction to cement evaluation logs (sonic and ultrasonic)
    - Comparison of wireline tools capacity to characterize pathways
- Introduction to Ketzin and Otway
- Solid-in-solid channeling and contamination fronts
    - Consideration on the durability of contaminated cement
- Other interesting defects – horizontal cracks
- Analog to embedded chimneys – detecting a cable in Ketzin
- Conclusions

Loizzo & Duguid, EPA CO_2 Workshop – Mar 2007

- If cement leaching were a diffusion-driven process
  - CO2-saturated water
    - Time to react to 25 mm – 1.3 years
    - *Time to react to 1000 mm - 2100 years*
  - Wet supercritical CO2
    - Time to react to 25 mm – 1.4 years
    - *Time to react to 1000 mm - 2200 years*



Portland cement alteration in wet supercritical CO_2 fluid and in CO_2-saturated water, from V. Barlet-Gouedard et al., SPE 98924, 2006

- Leaching may become a concern when effective transport (fluid flow) is present. Fluid flow is in turn caused by **cement sheath defects**. Experiments are needed to substantiate this positive feedback hypothesis
- Sound cement design is required, both for the placement and post-placement phases
- Use of cement that minimizes leaching potential adds a risk mitigation layer to better ensure medium-term well integrity

Well integrity and CO_2: is it really so special?

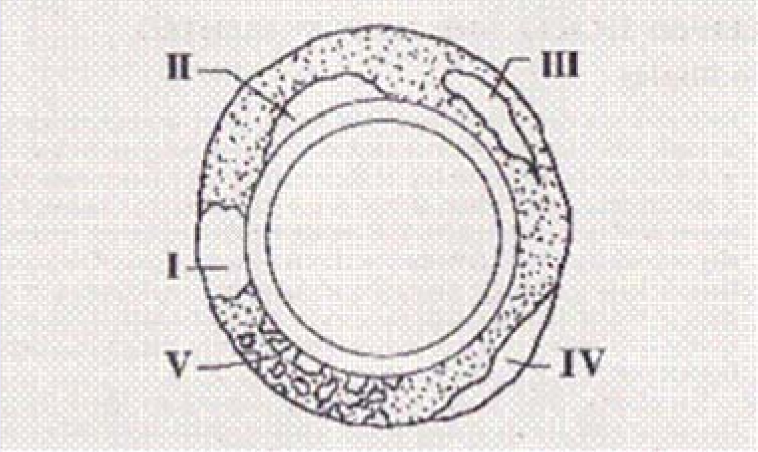
- Current containment: is the storage interval isolated right now?
  - Are there any pathways to a formation fluid leak? Are shallow permeable intervals isolated (as opposed to a leak to surface)?
  - If there's a leak, can it be fixed (squeeze/no squeeze)?
    - If it cannot be fixed, can it be avoided next time?

  1. **Identify and characterize vertically-connected pathways: channels, cracks, chimneys**
- Future containment: what's the chance of a CO_2 leak n years into the future?
  - Will CO2 attack degrade cement matrix, formation, casing or interface bonding and create a pathway?
  - Will CO2 degrade existing pathways, increasing leaks?

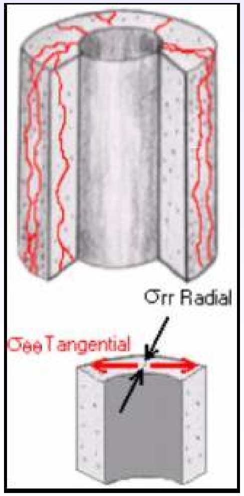
  2. **Characterize cement matrix – geometry and properties**
     - Input to transport-reaction models to predict behavior in 10's-100's of years
  3. **Use time-lapse logging to assess actual evolution and degradation**
     - 4D logging, compare to models

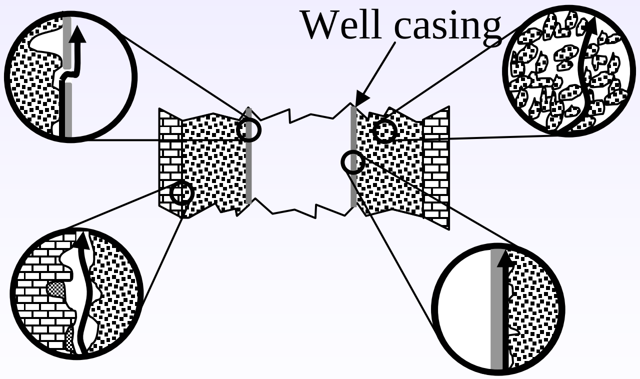
Pathways through cement – a journey into the unknown

- Vertically connected pathways can be caused by
  - Fluid-fluid displacement (fluid dynamics)
    - “Channels” are long, connected pocket of a fluid bypassed and left behind during cement placement – I, II and IV in the drawing to the right
  - Cement curing and degradation (transport-reaction)
  - Gas migration
    - “Chimneys” are connected path generated by coalescing gas bubbles escaping during cement curing – II (and maybe III, IV, V) in the drawing
  - Thermal and mechanical stresses (mechanics)
- Uncertainty and some disagreement in the O&G industry about which cement defects can exist and which can provide a pathway for fluid migration
  - For instance: is debonding at the formation face important? Do chimneys within the cement sheath exist? Is cement permeability an issue?
- Pathways signatures on 1- and 2-D cement evaluation logs are questionable, and lab experiment may not be adequate given the scales and coupled phenomena involved



J. Smolen, “Cased Hole and Production Log Evaluation”, Penn Well 2004

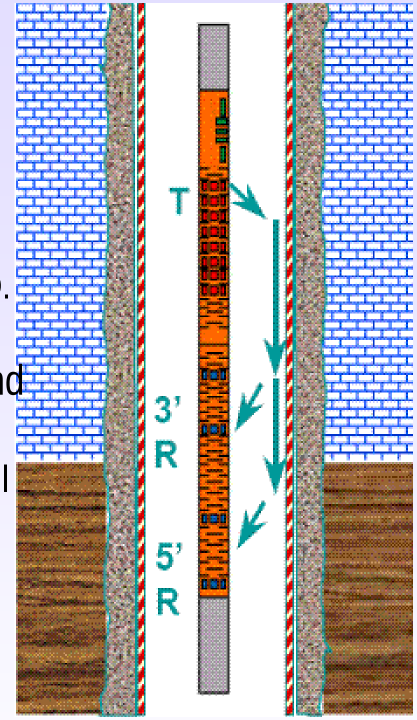




Adapted from A. Duguid et al., 2006

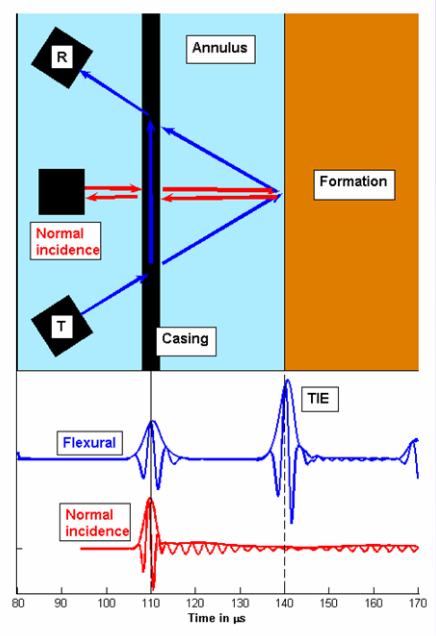
Well integrity evaluation – sonic (CBL)

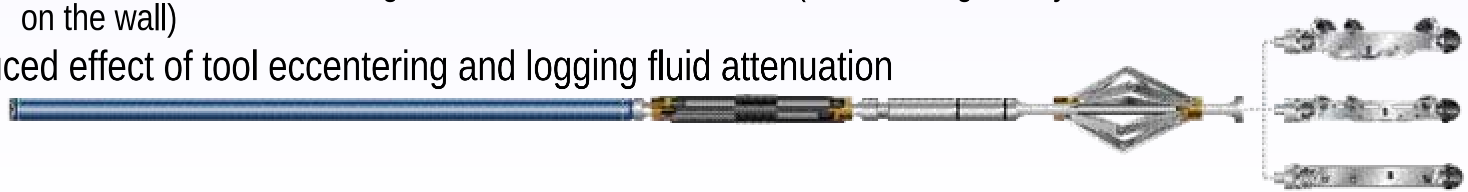
- Implemented on a wide range of tools
  - SCMT, DSLT, QSLT/SSLT, Sonic Scanner, CBT
- Concept from the 50's
  - Very empirical: first <u>detectable</u> peak, calibrated in water
- Measures amplitude or attenuation of casing arrival and VDL
  - Variable Density Log provides qualitative indication of cement-formation bond
    - *"The cement-to-formation bond is only seen on the VDL but cannot be quantified"* D. Rouillac, 1994
  - Amplitude (attenuation better) depends on leakage of extensional waves around 20 kHz
    - Depends on shear coupling between casing and annular material → must have well bonded (i.e. shear bond) solid (i.e. something with shear waves) in the annulus
- Rule of thumb: 80% BI over given distance (5-18 ft)
  - BI ~ log(amplitude) → 100% BI ~ 2 mV, 80% BI ~5 mV
  - CBL very useful only if amplitude 2-3 mV. Otherwise prone to false positives
    - Good CBL means good cement, bad CBL does <u>not</u> mean bad cement
- Strongly affected by tool eccentering and fast formation
  - Sonic Scanner less affected by eccentering, but more by fast formations



Well integrity evaluation – ultrasonic (USIT/IS)

- USIT→ pulse-echo measurement from ~1994
  - Skin-deep (casing-cement interface) measure, like the CBL
  - High precision – sometimes low accuracy
- Isolation Scanner → pitch-catch propagation measurement from 2006
  - Integrates USIT
- Ultrasonic measurements (higher resolution, lower depth of penetration) around 250 kHz
  - $\lambda \cong 4.5$ mm in logging fluid, beam width $\cong 1/2$ in, receiver separation (IS) = 10 cm
- The Isolation Scanner delivers 3 independent measures
  - Z (acoustic impedance): inverted from a normal incidence, pulse-echo measurement – same as the USIT
  - α (flexural attenuation): measured from the arrival amplitude at two transducer of a flexural wave propagating along the casing
  - v (annular velocity): “migrated” from the arrival time of the cement-formation interface echo, knowing the caliper
    - Analogy with seismics
    - Can be either compressional reflection (pp), shear reflection (ss), or mixed mode (ps/sp)
- Compressional and flexural waves not very sensitive to shear bonding between casing and cement
  - Less sensitive to debonding and fluid-filled microannulus (slick coating, oil layer, mud on the wall)
- Reduced effect of tool eccentering and logging fluid attenuation





Schlumberger

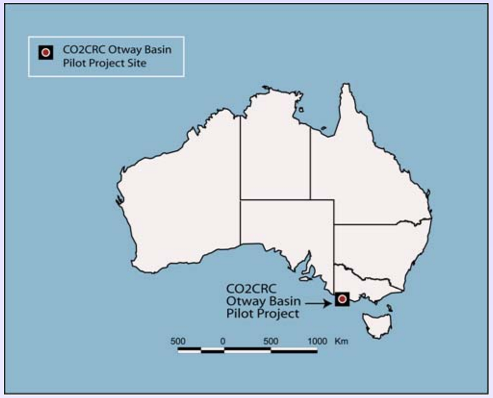
Characterizing pathways – wireline tool comparison

		CBL	*USIT*	*Isolation Scanner*
Good, well bonded cement		☺ 0.5 measures	☺ 1 measure	☺ 2+ measures
Mud channel	Good cement	☹	☺	☺☺
	Weak cement	☹	☹	☺☺
Solid-solid channel		☹	☹	☺☺
Vertical cracks	Thin (~10 μm)	☹ ☹	☹ ☹	☹ ☹
	Thick (~10 mm)	☹ ☹	☹	☺
Gas chimney	At casing	☹	☺	☺☺
	In cement	☹ ☹	☹ ☹	☺
Debonding	At casing (wet)	☹	😐	☺
	At casing (dry)	😐	☹	☹
	At formation	😐	☹ ☹	🕓
Cement radial variations		☹ ☹	☹ ☹	☺

☺ Unambiguous measure
😐 Some measure
☹ Affected, ambiguous
☹☹ No effect

Ketzin and Otway – introduction

- CO2CRC Otway, well CRC-1
  - 4½" casing
  - Injection in depleted sandstone gas reservoir at ~2100 m
  - CO_2 injection: 0.1 Mton over 2 years, starting in 2008
  - Cementing objective: long-term isolation across 2000-2053 m



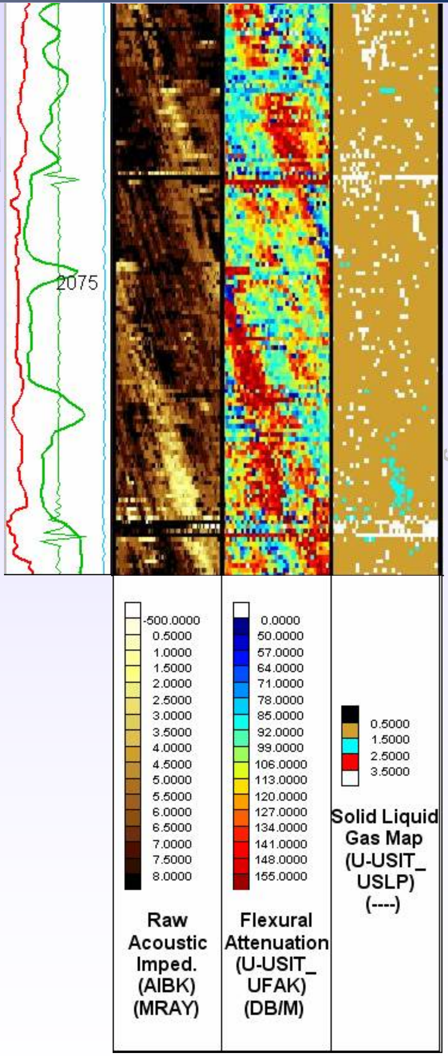
Source: CO2CRC

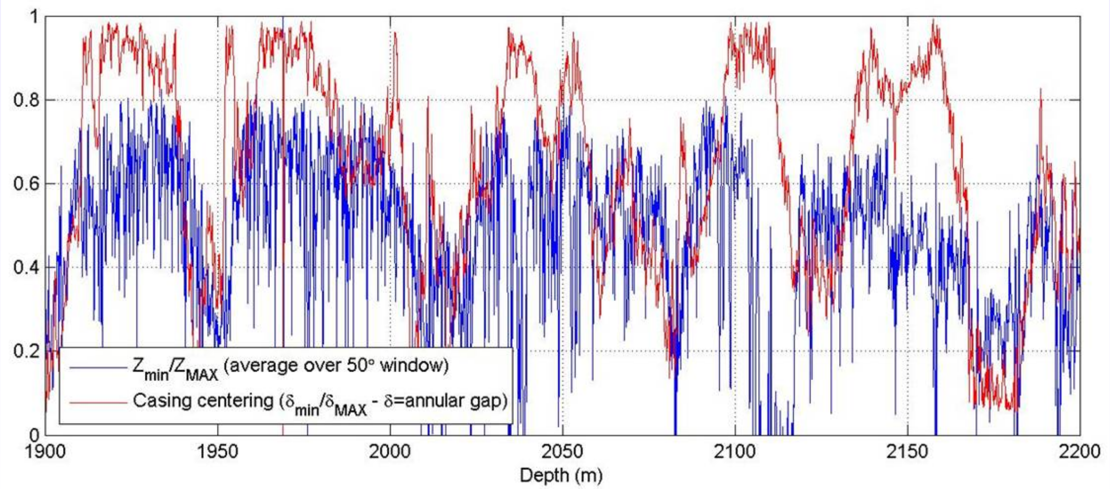
- CO2SINK Ketzin, well Ktzi 200
  - 5½" casing
  - Injection in sandstone saline formation at ~700 m
  - CO_2 injection: 0.06 MT over 2 years, starting in 2008
  - Cementing objective: long-term isolation between 5½" and 9 5/8" casing

Source: CO2SINK

Otway – solid-in-solid channeling

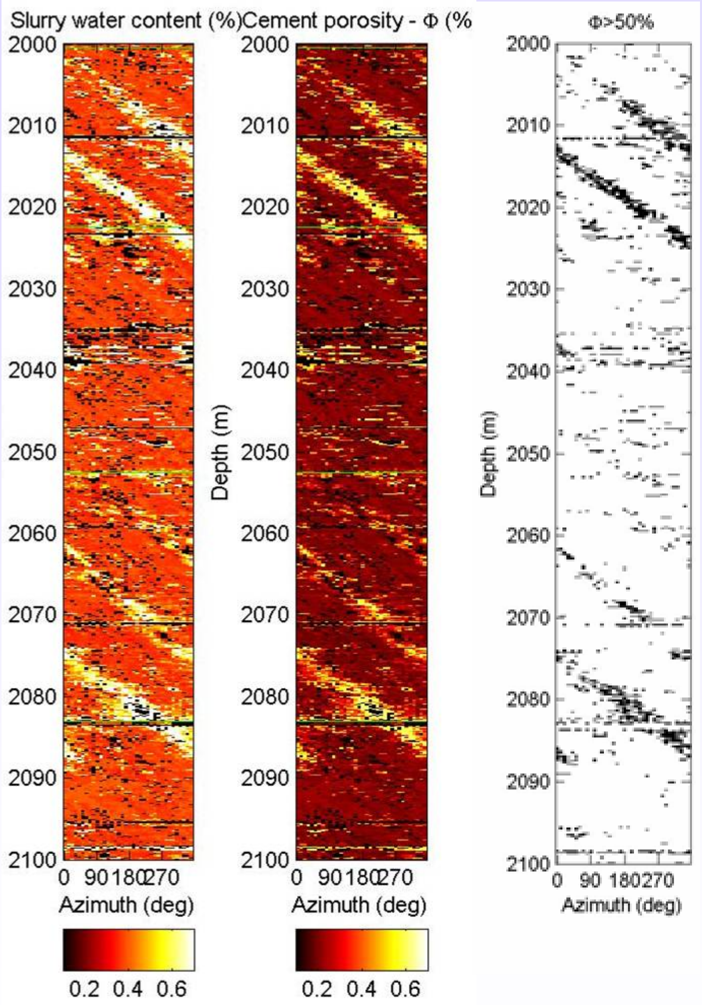
- Low acoustic impedance (Z) and high flexural attenuation (α) streaks spiraling SE-NW around the well
  - Aligned with the narrow side of the annulus, spiraling motion caused by tool rotation while pulling out of hole
- Solid/Liquid/Gas map (rightmost) shows unambiguously that streaks are solid
  - Z/α consistent with almost pure lead slurry
- Streaks correlated with lower casing centering
  - Lead slurry displaced mud, tail slurry didn't displace lead during placement $\rightarrow$ solid-in-solid channeling





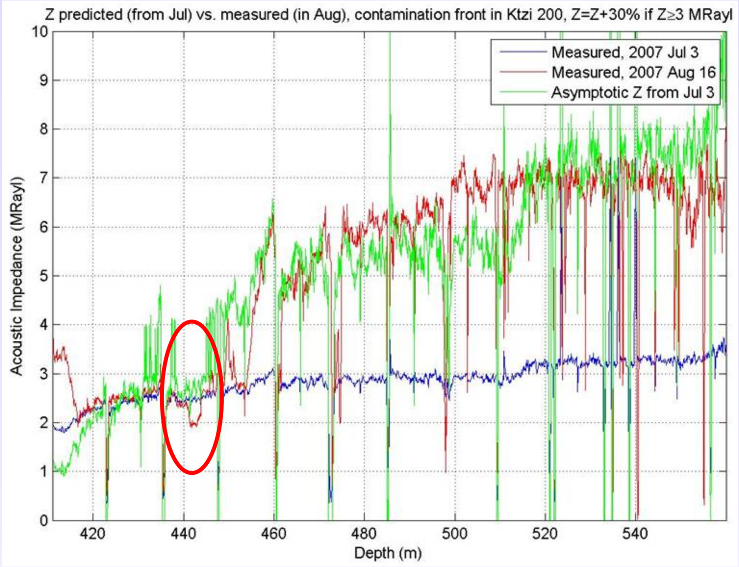
Otway – solid-in-solid channel porosity

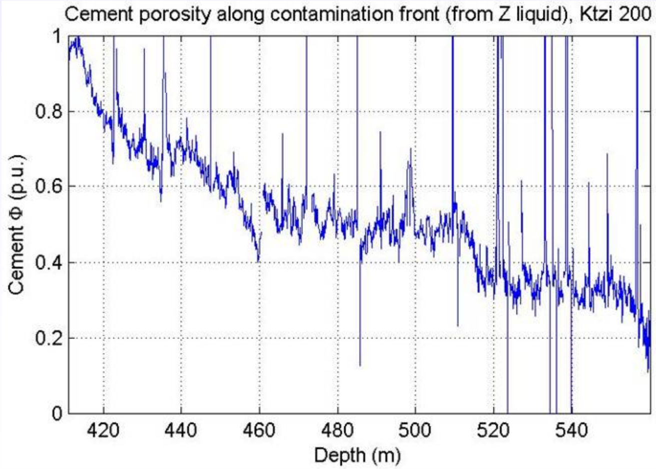
- Tail cement contaminated by lead shows higher water/cement ratio and cement porosity
  - Joint inversion of Φ from α and Z limited to “solid” areas of the SLG map
- Two intervals of good cement: 2028-2034 m and 2040-2052 m
- CRC-1 top-tier well
  - Excellent design and execution, no losses
  - Very good centralization design for a sub-vertical well $\rightarrow$ 1 centralizer every 2 joints for 1°-2° deviation
  - Engineered slurry expansion properties
  - Every prevention measure has been deployed successfully
- Use of CO_2-Resistant Cement helps provide long-term durability
  - Robust design incorporating mitigation measures

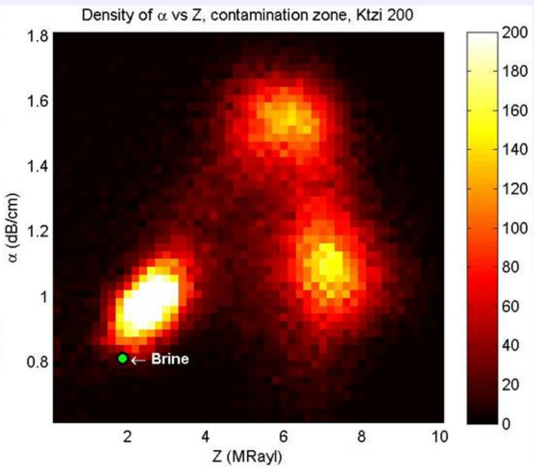


Ketzin – second stage cement contamination front

- Time-lapse log
    - 2007 Jul 3 $\rightarrow$ most of 2nd stage still liquid
    - 2007 Aug 16 $\rightarrow$ cement set
        - Density map below shows clear poles for weak and strong solid, as well as some residual brine and highly diluted slurry (lower left blob)
- Brine-cement mixing ratio from first log used to estimate asymptotic set cement acoustic impedance
    - Good match
- Average cement porosity shows ~100 m of solid with Φ>50%

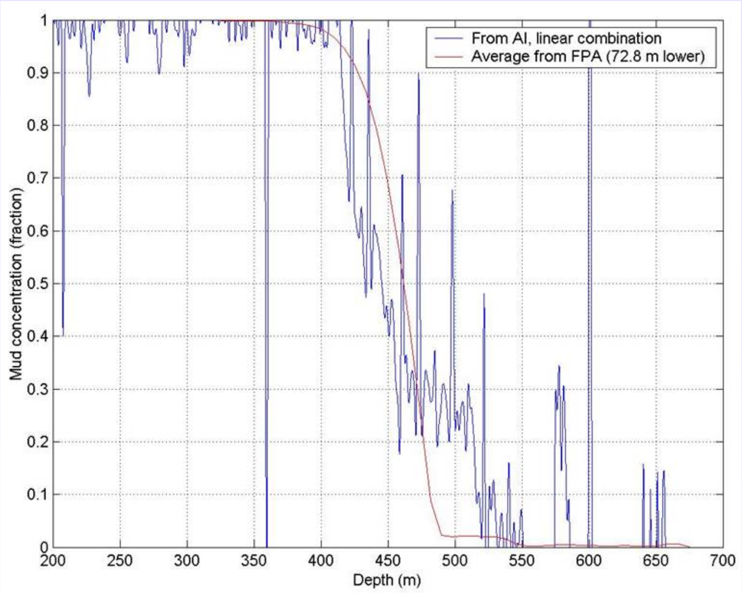






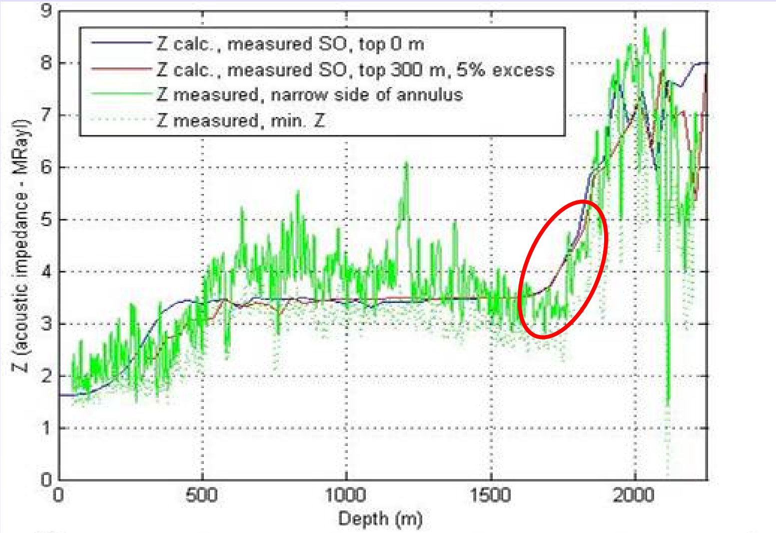
Ketzin – contamination front simulation

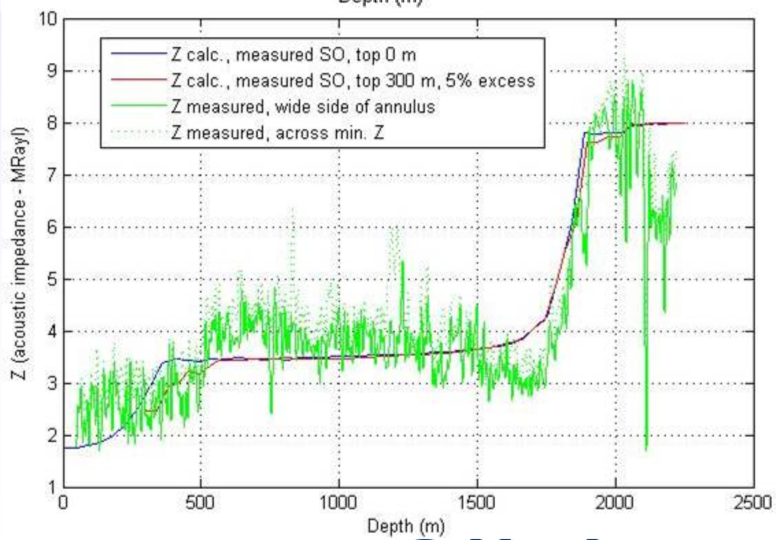
- Contamination of 1940 kg/m^3 slurry by 1140 kg/m^3 brine $\rightarrow$ binary system (no spacer or plug)
- Contamination front reasonably well simulated
    - Contamination profile "S"-shaped with flat tail
    - Central 10% to 90% contamination zone $\rightarrow$ 53 m
        - Including low contamination tails $\rightarrow$ ~130 m
        - It affects >1/3 of the cement annular coverage originally designed
    - Difference at the leading edge possibly due to instability of over-diluted cement slurry
        - Cement settling and brine separation
- The contamination observed happened while pumping down the casing
    - Adverse density gradient
    - Contaminated zone is stable in the annulus



Otway – lead-tail slurry contamination front

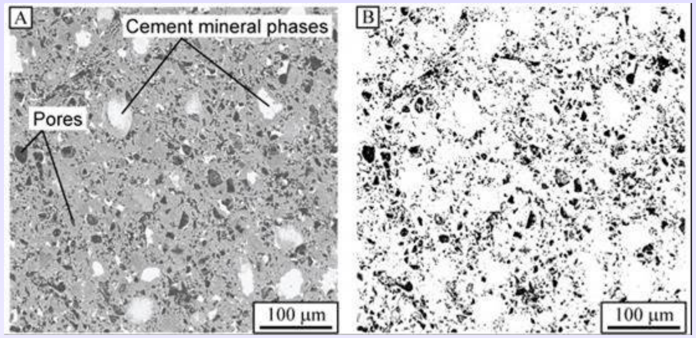
- Contamination of 1900 kg/m^3 tail by 1500 kg/m^3 lead slurry
- Very good match for start of tail contamination and initial slope, especially for the narrow side of the annulus
    - End of contamination front longer than measured $\rightarrow$ numerical diffusion while pumping down the pipe (red circle)
    - Good match for lead-spacer-mud contamination front
- Lead-tail contamination again happened while pumping down the pipe
    - Density difference actually beneficial $\rightarrow$ heavier fluid will increase hydrostatic head on the wide side of the annulus and push the tail into the narrow side





Contaminated cement – implications for long-term durability

- High water/cement ratio → high set-cement porosity → decreased durability when exposed to CO_2
- Cement displays bimodal porosity, similar to clay
  - ~1/4 of the cement mass in water goes into hydration (~nm scale), the rest forms capillary porosity (~μm scale)
- Higher porosity leads to…
  - Higher permeability → more formation fluid flows through cement
  - Higher water/cement ratio → more water to carbonate and leach cement
  - Larger pores → less permeability plugging from carbonation
- Streaks and intervals of lead-contaminated tail slurry could provide a preferential path for CO_2 migration
  - More research would be welcome to establish the connection between porosity/permeability and cement degradation kinetics

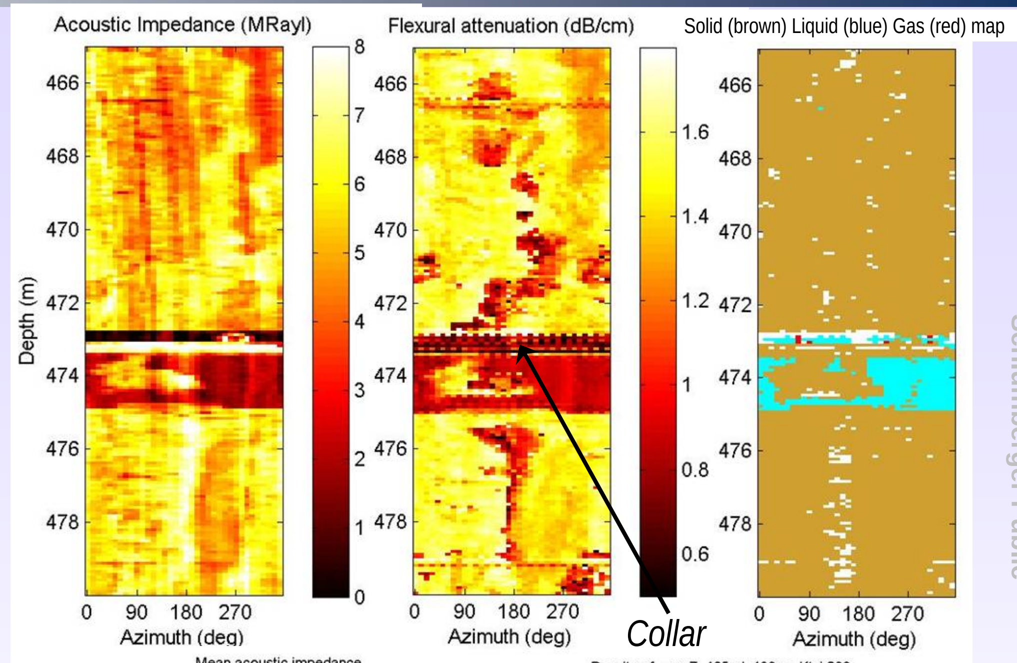


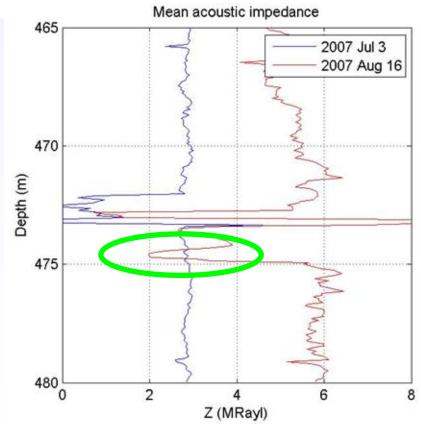
Local porosity of 15.8 ppg class G cement, from V. Barlet-Gouedard et al., unpublished internal report

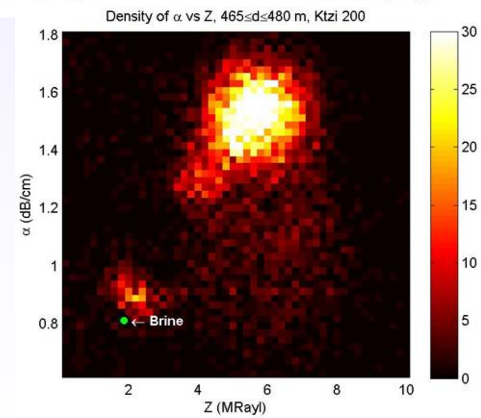
Sources: SPE 15176; N. Thaulow presentation to IEA-GHG meeting in Santa Fe (2007)

Other interesting defects – horizontal crack in Ketzin

- Short (two-meter long) gap around 474 m, just below a casing joint and a centralizer
  - See also red circle on slide 12
- (Mostly) brine-filled
  - Note the drop in acoustic impedance from the original slurry (green circle) and the clear brine pole on the density map to the right
- Possibly horizontal water-filled crack due to the cement vertical contraction across an impermeable zone
  - In this case the 9 5/8” casing
  - Links inner and outer casing interfaces
- Horizontal cracks do not affect vertical pathways but provide frequent connections between possible defects at the cement interfaces

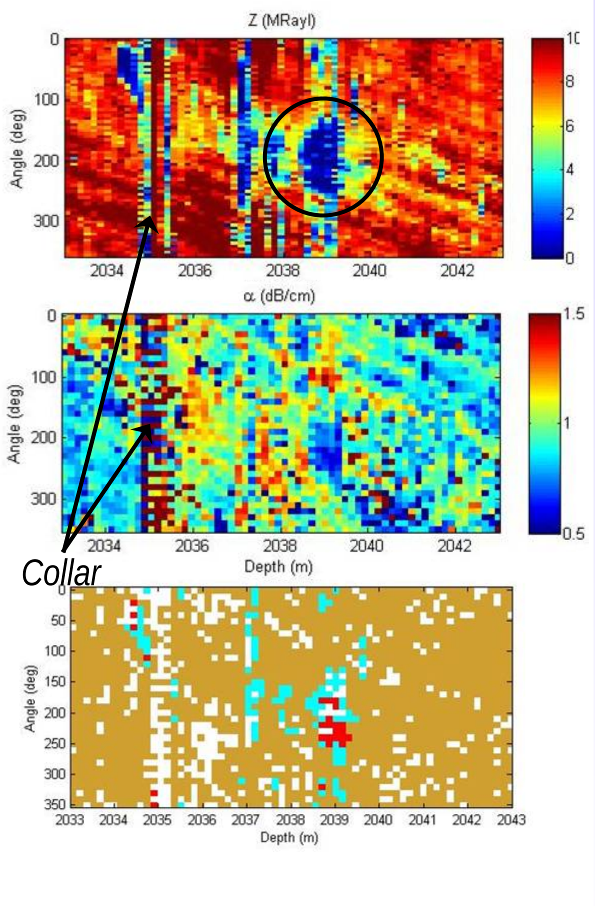


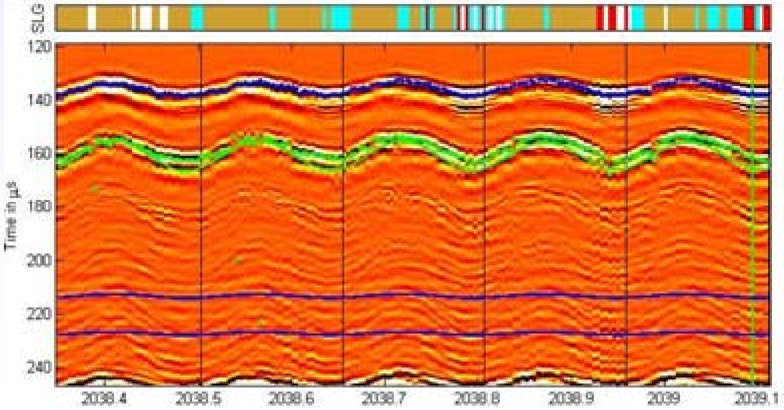




Otway – horizontal cracks

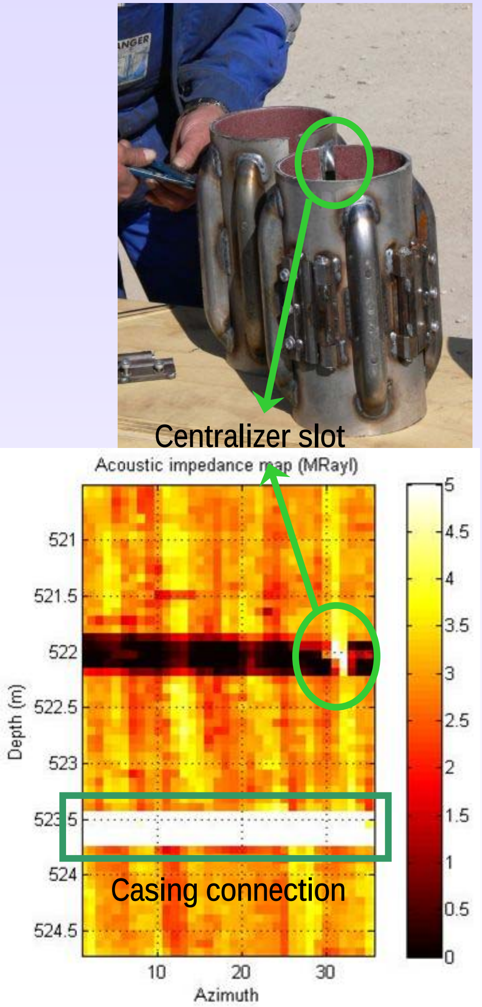
- Two horizontal narrow lines around 15 cm thick, at 2037 and 2039 m
  - Just below the collar at 2035 m
  - Very well-centered casing → SO>90%
- Acoustic impedance indicative of water
  - Too thin to get a clear water-like reading on flexural attenuation (T-R spacing of ~12 in), but partial blue flags on the SLG map
  - Water pocket (black circle) visible on α and SLG maps
- Red flags possibly caused by the narrow width of the feature → formation echoes are visible through it
- Cracks possibly caused by cement contraction along a shale section





Ketzin – detection of an embedded chimney analog

- Two sets of cables in the annulus, ~1/2 in diameter
  - Distributed Temperature Sensor (twin thin tubes)
  - Vertical Electrical Resistivity Array cable (power and data)
  - Clamped at centralizer $\rightarrow$ slot on centralizer visible on the acoustic impedance map
  - No cable signature visible on cement (interface) Z/α maps
- Analog of a very thin chimney embedded in the cement sheath
- Cable signature visible on the Isolation Scanner full waveform
  - Signature on ultrasonic waveforms can be isolated and tracked
  - Analysis indicated that DTS twin tubes are more easily detected

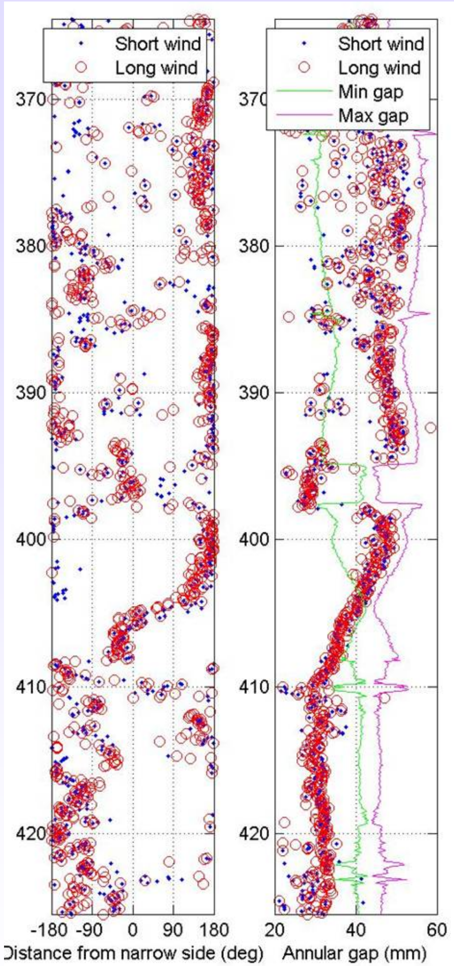


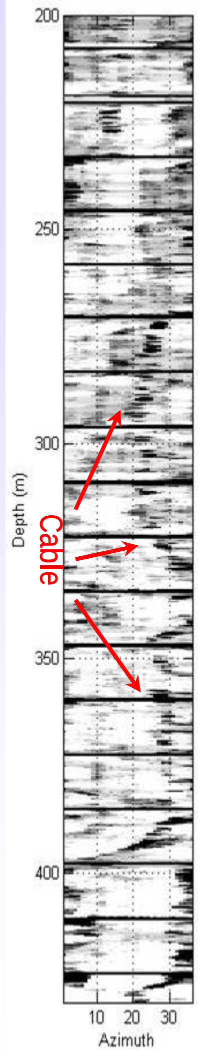
Schlumberger Public

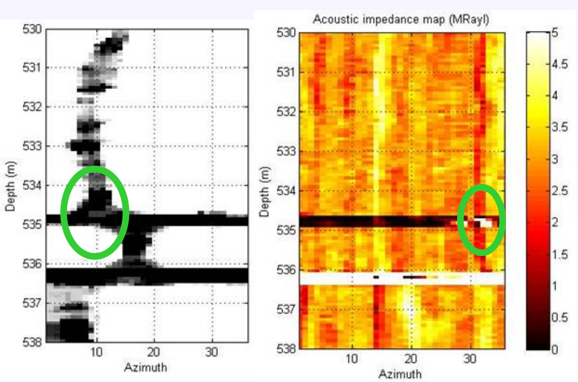
Schlumberger

Ketzin – detection of an embedded chimney analog

- Cable signature matches centralizer slot relative position (see below)
- Cable signatures can be positioned with respect to the formation echo (left maps to the right)
    - Cable across the wide side of the annulus over most of the interval







Conclusions

- Cement degradation may become a containment risk when effective transport pathways are present
- Current/future pathways and the cement matrix should be properly characterized to estimate the containment risk over 100's to 1000's of years
  - Logging tools that can identify and characterize defects and pathways should be preferred
  - Time lapse logging can be used to validate and update degradation models
- There is currently debate about the possible occurrence and importance of cement defects that can lead to pathways
- Examples from research projects show that cement contamination – leading to high-porosity cement across containment barriers – is a common occurrence
  - Contamination might be caused by fluid mixing at the interfaces or by improper displacement
  - Contaminated cement could degrade quickly and yet cannot be repaired
- Fluid contamination risk should be addressed through prevention (proper design) as well as mitigation measures (CO_2-resistant cement)

Degradation Rate of Well Cement and Effect of Additives

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Wellbore Integrity Meeting
March, 2008

Wellbore Integrity and CO_2 Storage

Carbon Sequestration will require unprecedented concern over leaking CO_2

– Well bores represent the most likely route for leakage of CO_2 from geologic carbon sequestration
– Research goal: to determine the potential impact of cement degradation in *existing wells* on CO_2 storage integrity

Research Questions

- Can we understand dynamics of CO_2 attack on well cement?
- What is the rate of penetration?
- How is cement affected by additives commonly used in the field?

Sample Preparation

Class H Neat Cement

- Prepared according to API Recommended Practice 10B
- Cured for 28 days submerged in 1%NaCl solution
- 4400 psi, 50°C

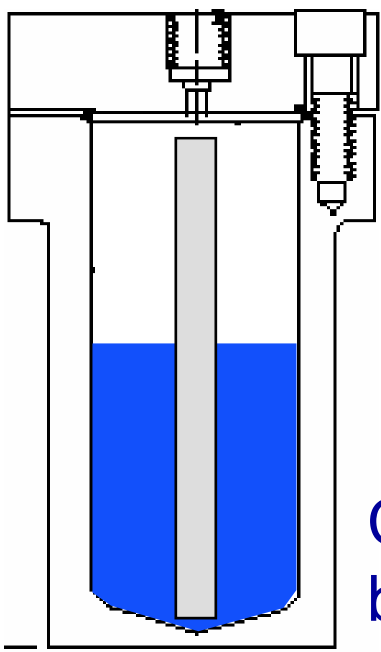
Analytical Techniques

- **1 cm slices, cut and polished**
- **Pre- and post-exposure analyses of cements**
  - SEM-EDS
    - X-Ray Mapping
  - XRD
  - Vickers Microhardness Testing

CO_2 Exposure

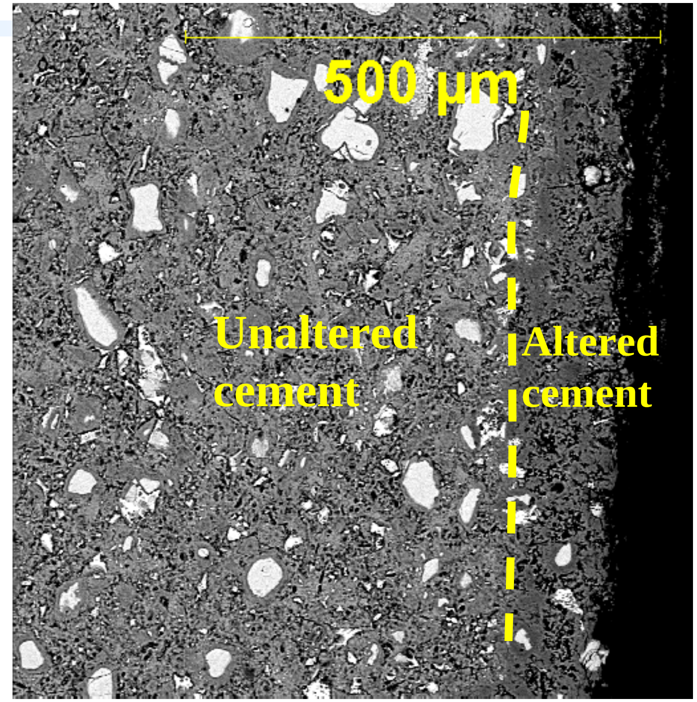
Simulate injected CO_2

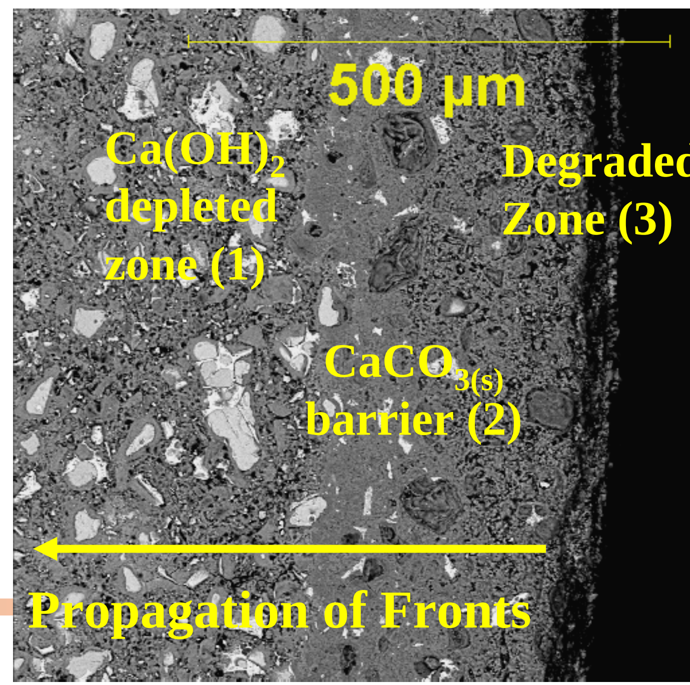
- Hydrodynamic trapping
- Solubility trapping



Supercritical CO_2

CO_2 saturated brine





CO_2-Saturated Brine Exposure

1. **Dissolution of $Ca(OH)_{2(s)}$ (zone 1) and precipitation of $CaCO_{3(s)}$ (zone 2)**

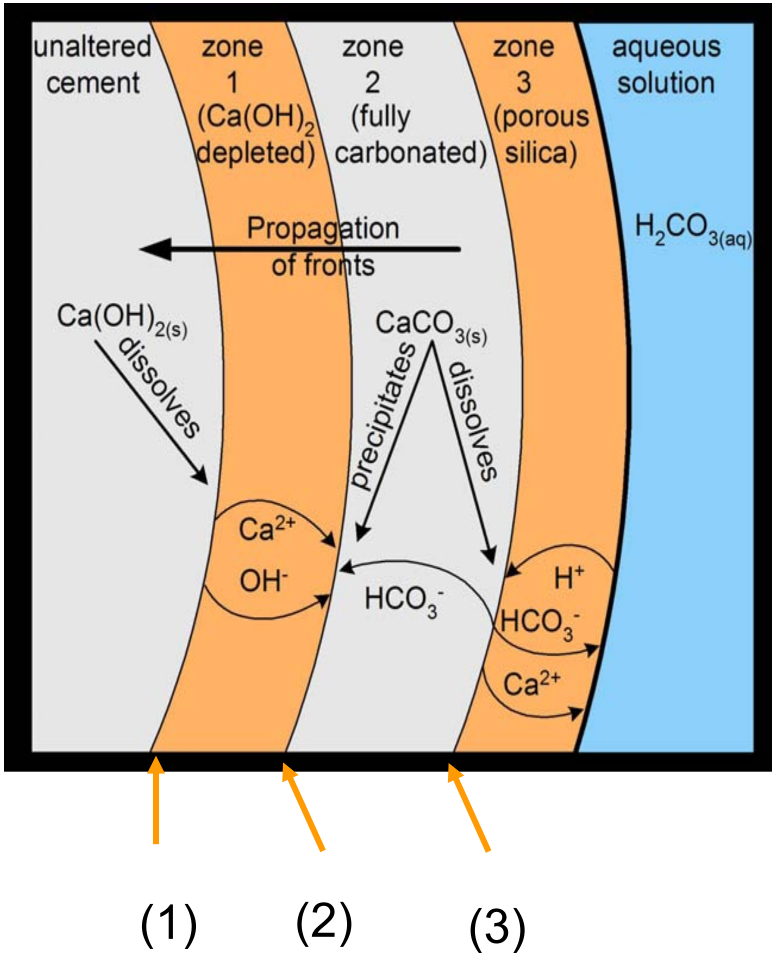
(1) $Ca(OH)_{2(s)} \rightarrow Ca^{2+}_{(aq)} + 2OH^{-}_{(aq)}$

(2) $Ca^{2+}_{(aq)} + HCO^{3-}_{(aq)} + OH^{-}_{(aq)} \rightarrow CaCO_{3(s)} + H_2O$

2. **Dissolution of $CaCO_{3(s)}$ and leaching of Calcium ions from the cement matrix (zone 3)**

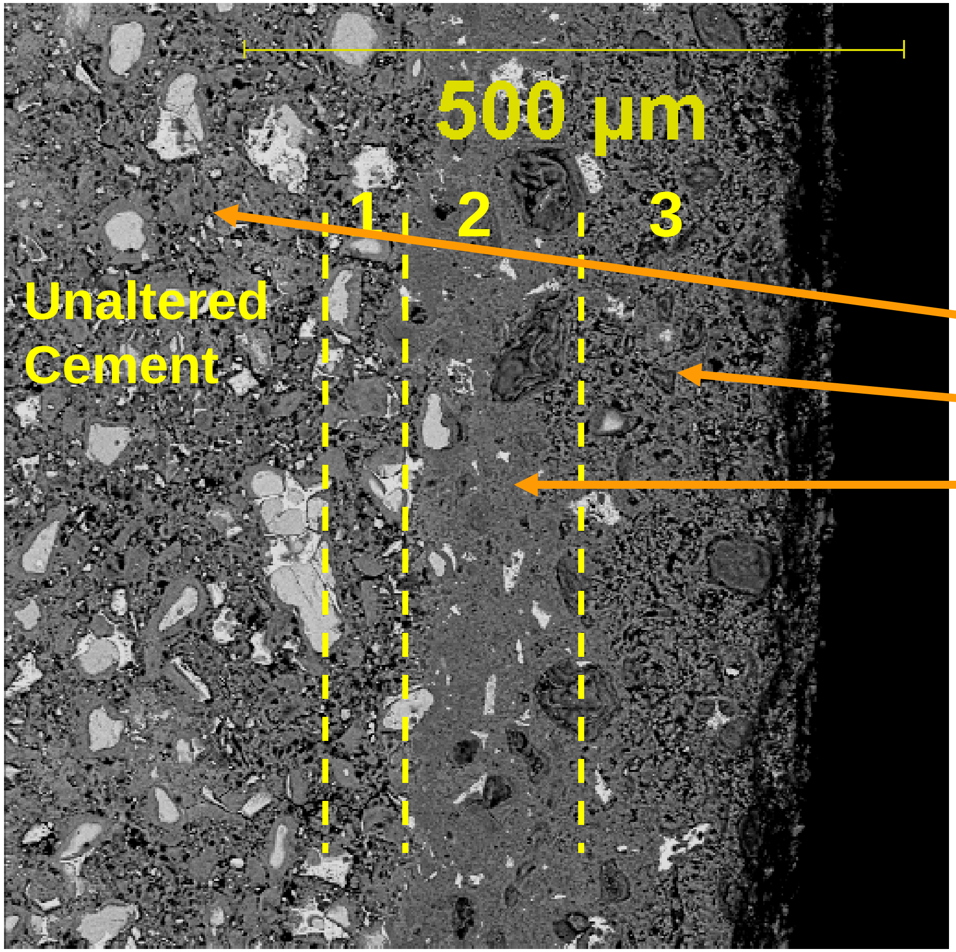
(3) $H^{+}_{(aq)} + CaCO_{3(s)} \rightarrow Ca^{2+}_{(aq)} + HCO^{3-}_{(aq)}$

(4) $C\text{-}S\text{-}H_{(s)} \rightarrow Ca^{2+}_{(aq)} + OH^{-}_{(aq)} + am\text{-}SiO_{2(s)}$



Cement Degradation Kutchko 2008

CO_2-Saturated Brine Exposure

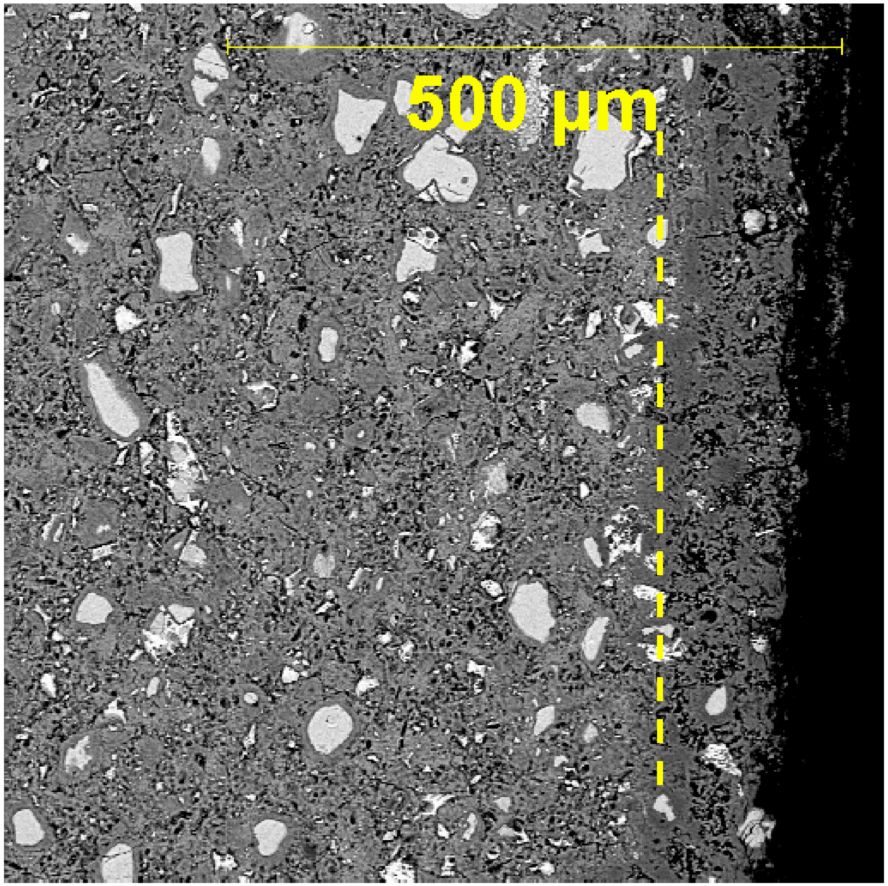


- **Mechanical Changes**
  - Microhardness (100 g):
    - Unreacted cement **64 HV***
    - Zone 3 **25 HV**
    - Zone 2 **127 HV**
- **Penetration Rate**
  - Initial rapid rate of alteration followed by a decrease in rate

*9 days exposure

***higher HV number = harder**

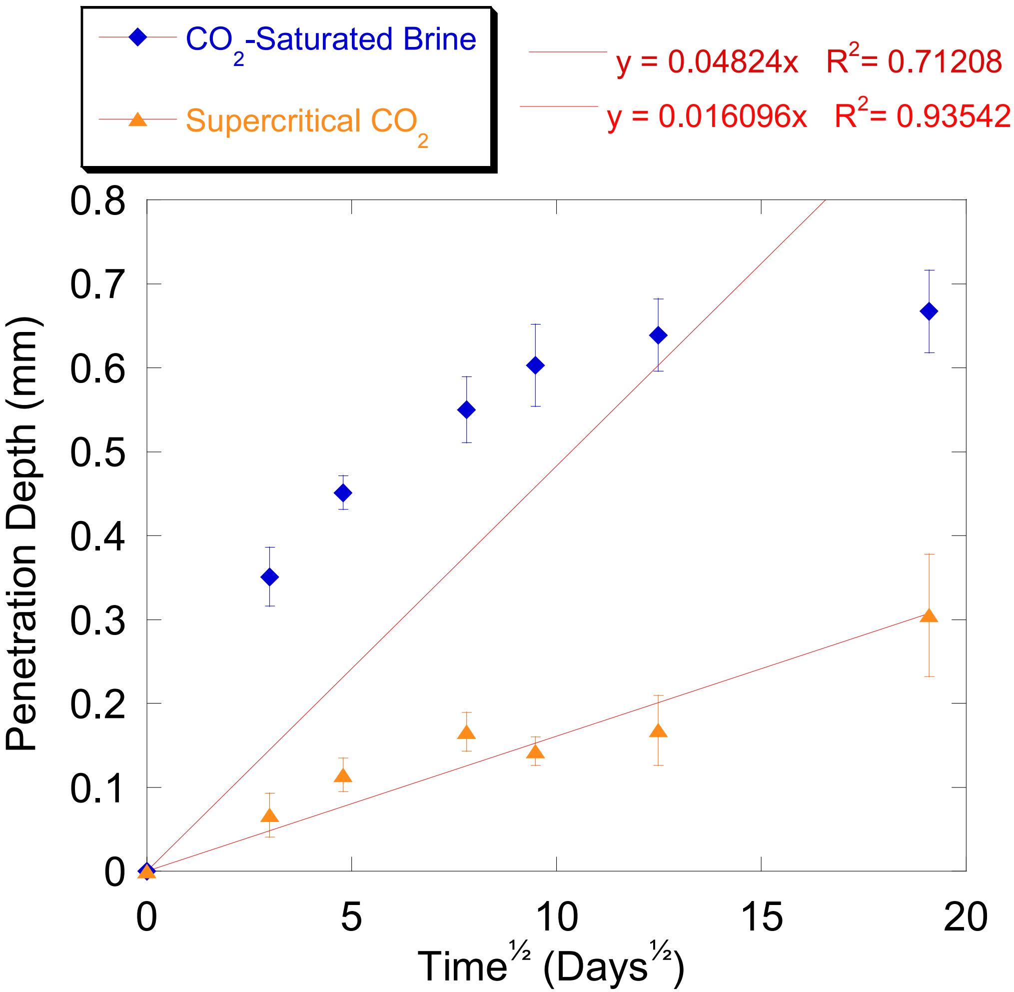
Supercritical CO_2 Exposure



*61 days exposure

- **Single reaction front**
  - multiple zones not observed
  - $CaCO_{3(s)}$ distributed throughout reacted portion rather than ppt in dense band
- **Penetration Rate**
  - More uniform progression of penetration

Rates of Penetration



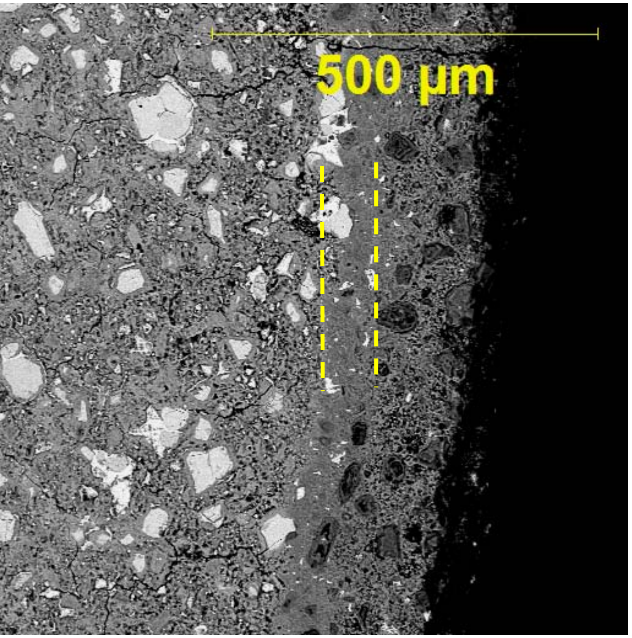
Ficks 2nd law of diffusion often used to estimate carbonation depth:

- $D = \alpha t^{½}$
- Where α is dependant on cement properties.

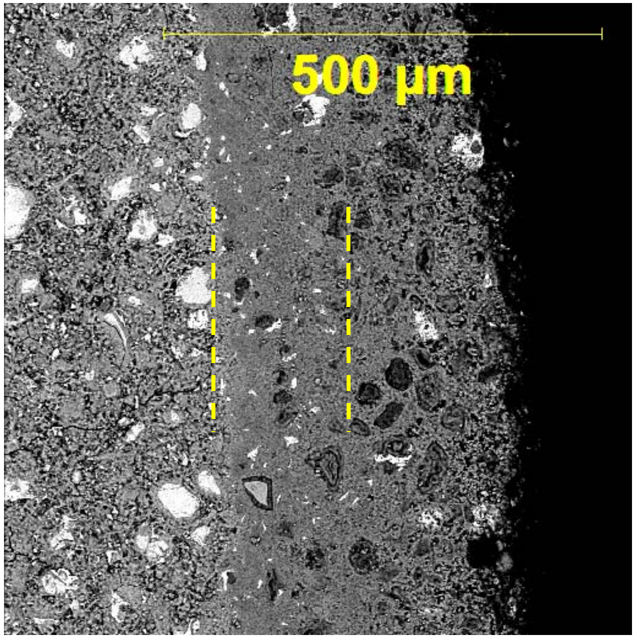
Formation of $CaCO_3$-rich layer (zone 2) creates new, dense phase

- As this phase grows, slower diffusion rates are observed and α decreases with time.

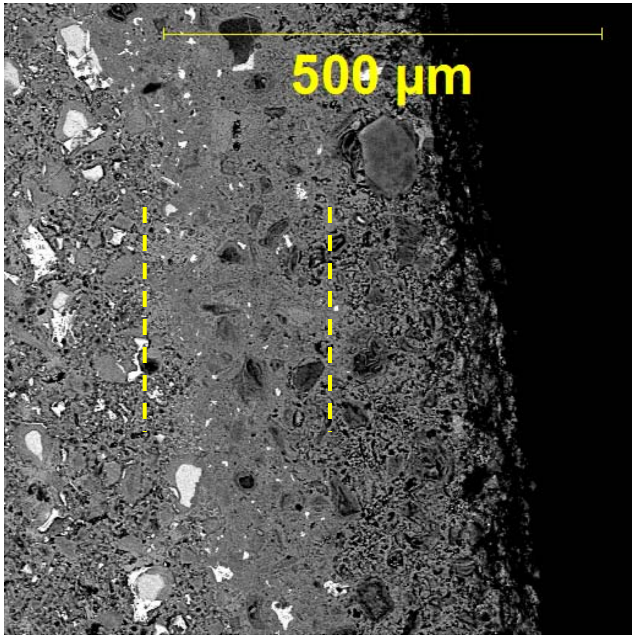
CO_2-Saturated Brine Exposure



9 days



90 days



365 days

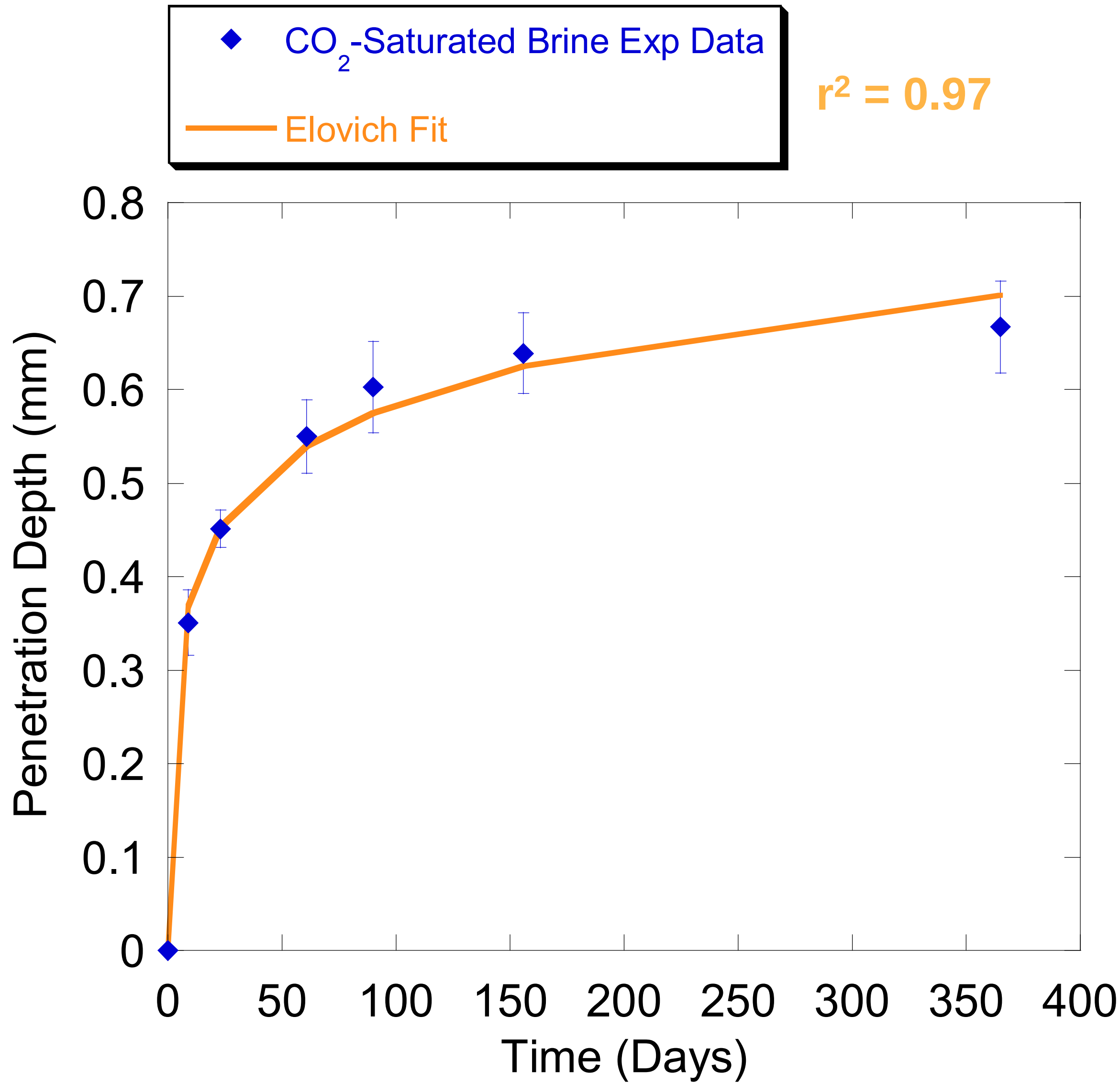
NETL

CO_2-Saturated Brine Exposure

Elovich Equation

$$\frac{dq}{dt} = a\exp(-bq)$$

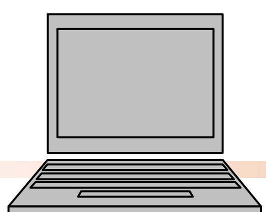
- Describes uptake or release kinetics involving rapid initial step followed by a decay of reaction rate
- Log-linear form of equation used to fit experimental CO_2 penetration data which relate to rate of CO_2 uptake:
- **$q = (1/b)\ln t + (1/b)\ln(ab)$**



- Where *q* = penetration depth (mm) at time t (day) of exposure
- *a* and *b* are constants determined from the experimental data

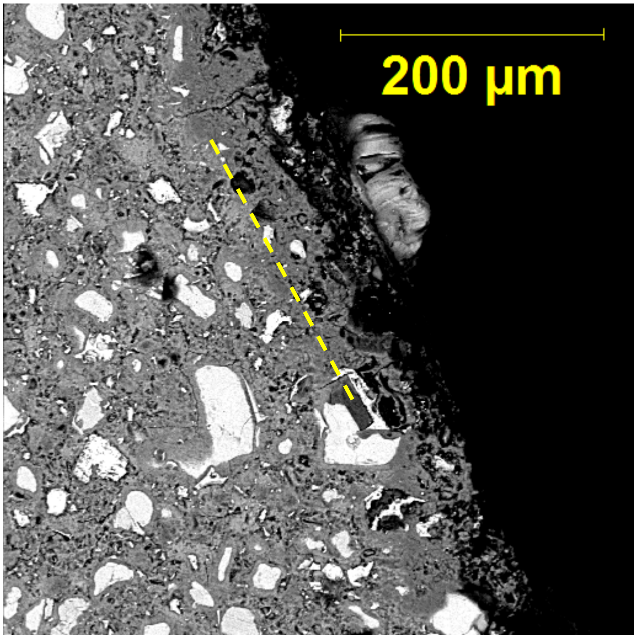
Extrapolation of Elovich Equation

- **Series of Monte Carlo simulations run**
  - To determine range of extrapolated penetration depths associated with the uncertainty in the Elovich parameters fitted to the data
- **Computer code to randomly generate a value for each variable**
  - Selected for each data point within one standard deviation of the mean measured value
  - Repeated 2000 times
- **Resulting synthetic data set then fitted with Elovich equation**
  - least squares best-fit values of *a* and *b* were determined for each 2000 simulation
- **Each set of *a* and *b* parameters substituted back into Elovich equation to estimate penetration depth at 20, 30, and 50 years of exposure**

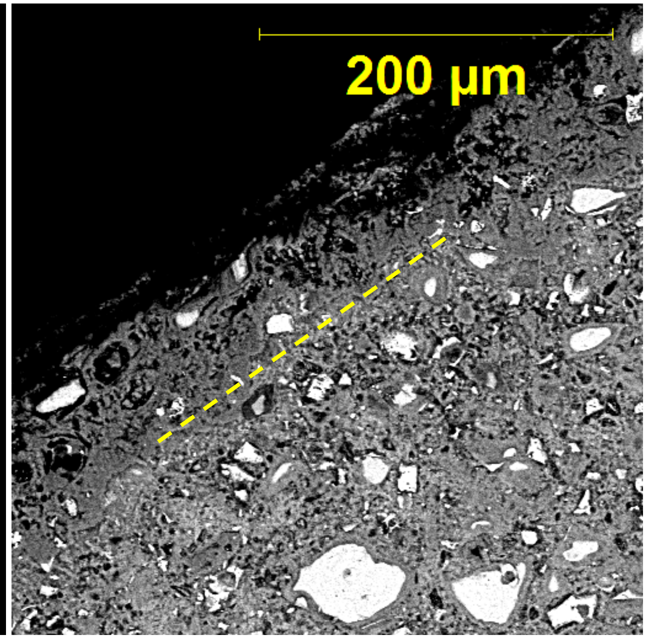


NETL

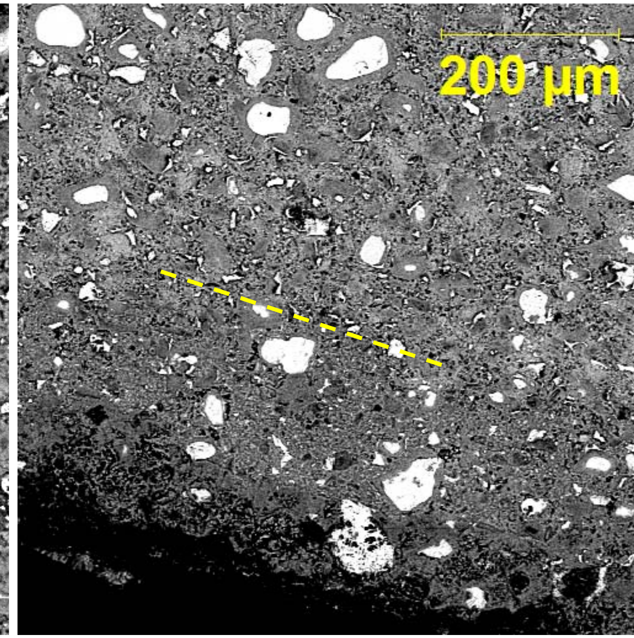
Supercritical CO_2 Exposure



9 days



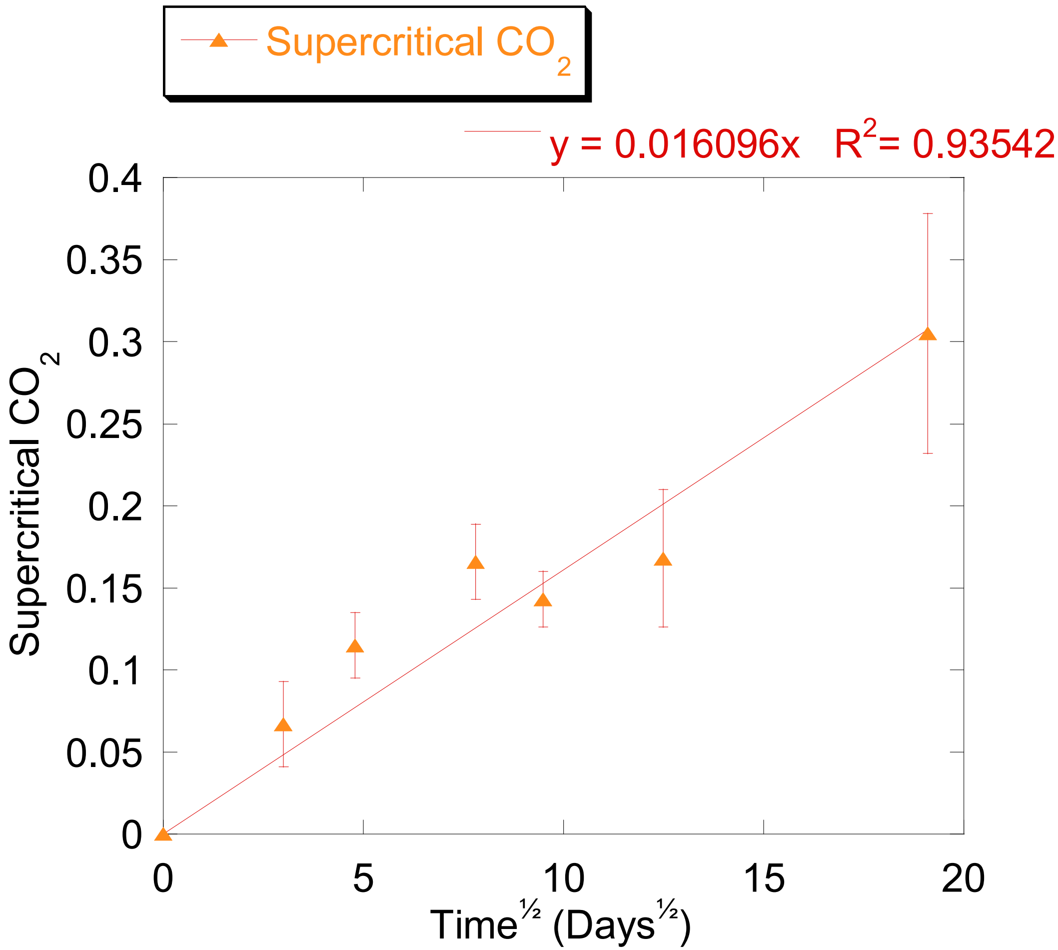
90 days



365 days

Supercritical CO_2 Exposure

- **Ordinary Carbonation**
- Ficks 2nd law of diffusion used to predict penetration
  - ❖ $D = \alpha t^{1/2}$
    - Lack of dense barrier
- **Series of Monte Carlo simulations run**
  - – 1000



*Projected Penetration Depths

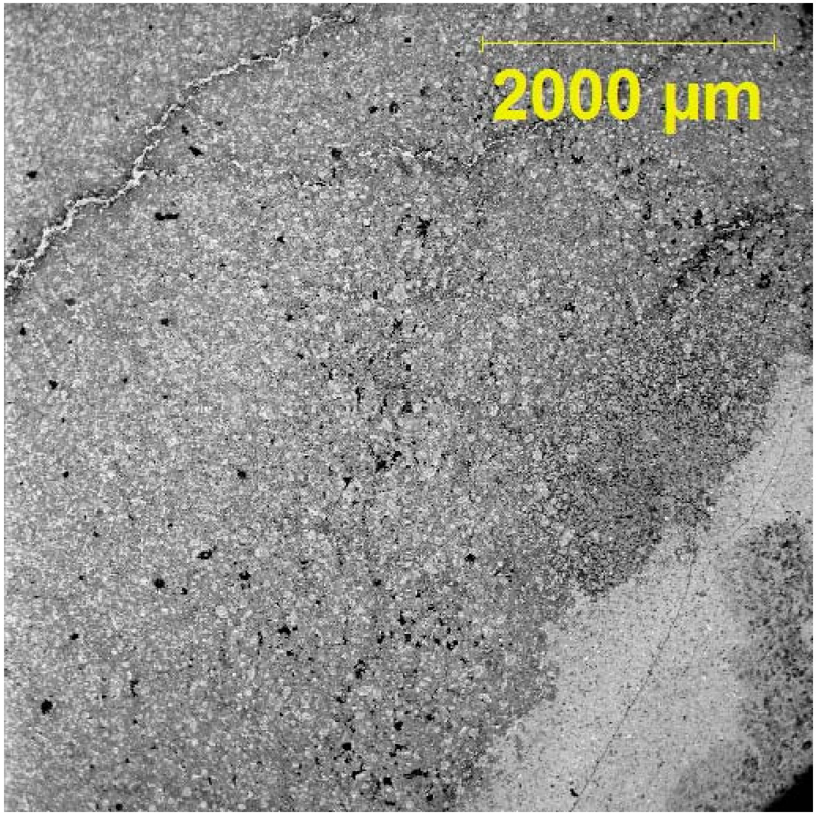
Exposure Length (Years)	Supercritical CO_2[1a]	CO_2-saturated brine[1b]
20	0.73 ± 2.4 mm	0.96 ± 0.06 mm
30	0.89 ± 2.9 mm	1.00 ± 0.07 mm
50	1.15 ± 3.8 mm	1.04 ± 0.08 mm

*Sample mean ± standard deviation of Monte Carlo simulation runs
[1a] T = 50 °C, p = 30.3 MPa; extrapolated using a Fickian diffusion equation
[1b] T = 50 °C, p = 30.3 MPa; extrapolated using the Elovich equation

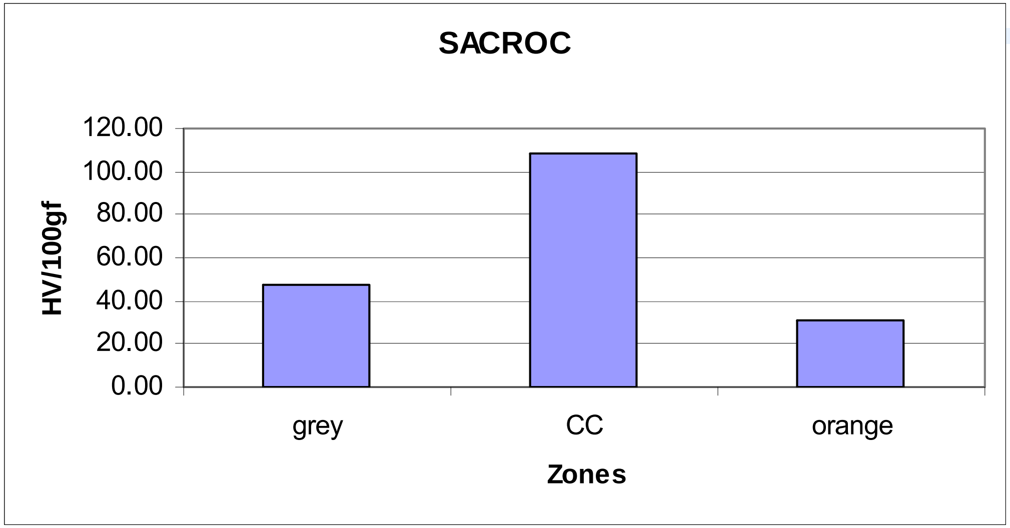
Field Sample Comparison

Comparison of laboratory results with SACROC samples

– Collaborative work with Los Alamos National Laboratory

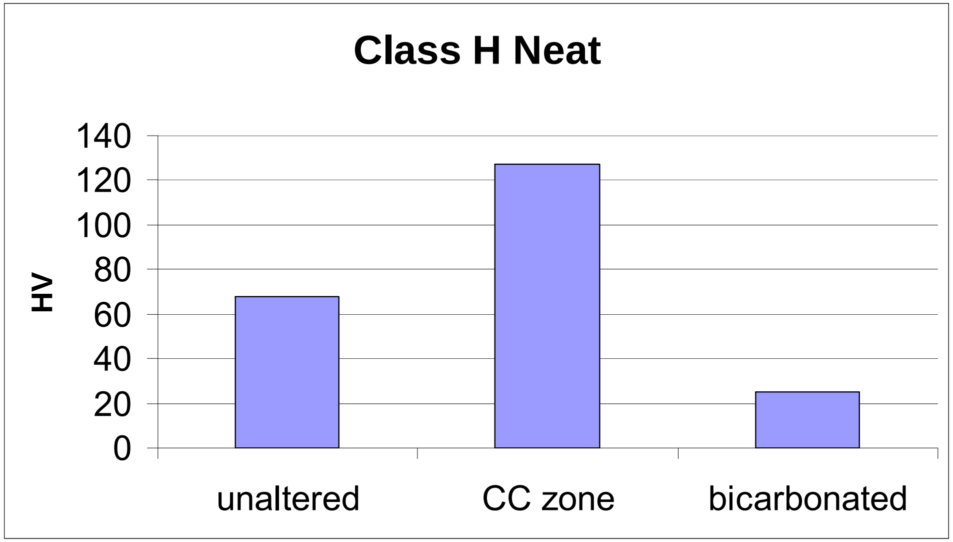


- **Neat cement - 30 years of CO_2 exposure**
- **Reaction zones as observed in our CO_2-brine experiments**
- **Degradation depth ranged from 2 - 10mm**



Vickers Microhardness Values: SACROC compared to NETL lab samples:

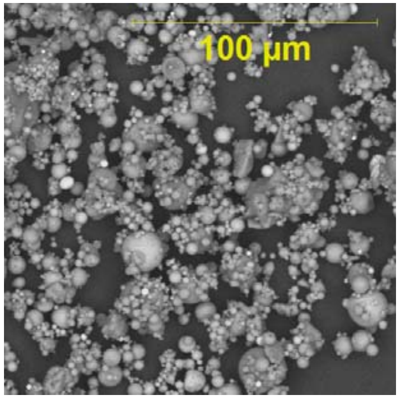
- **Clear reaction zones with similar mechanical properties**



Common Cement Additives/Cement Blends

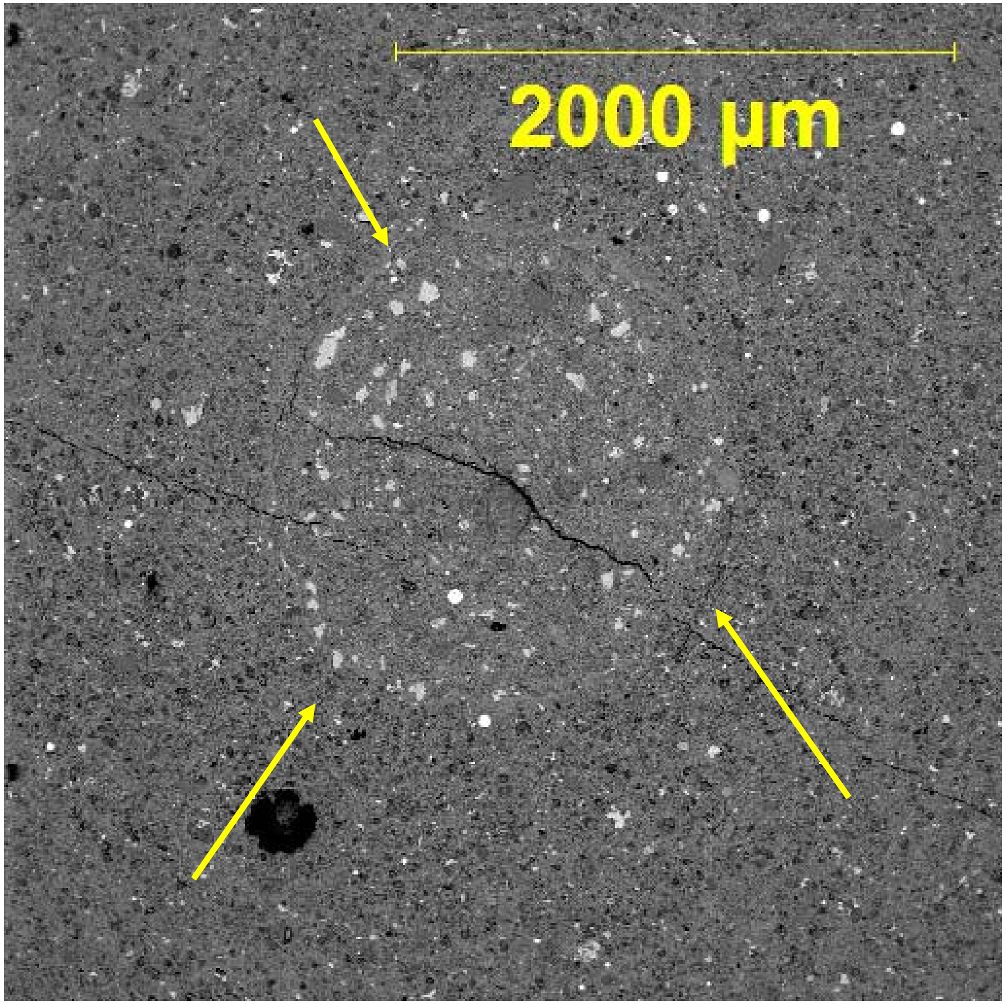
- **Pozzalon Systems**
  - Type F fly ash
  - 2% bentonite added to avoid development of free water

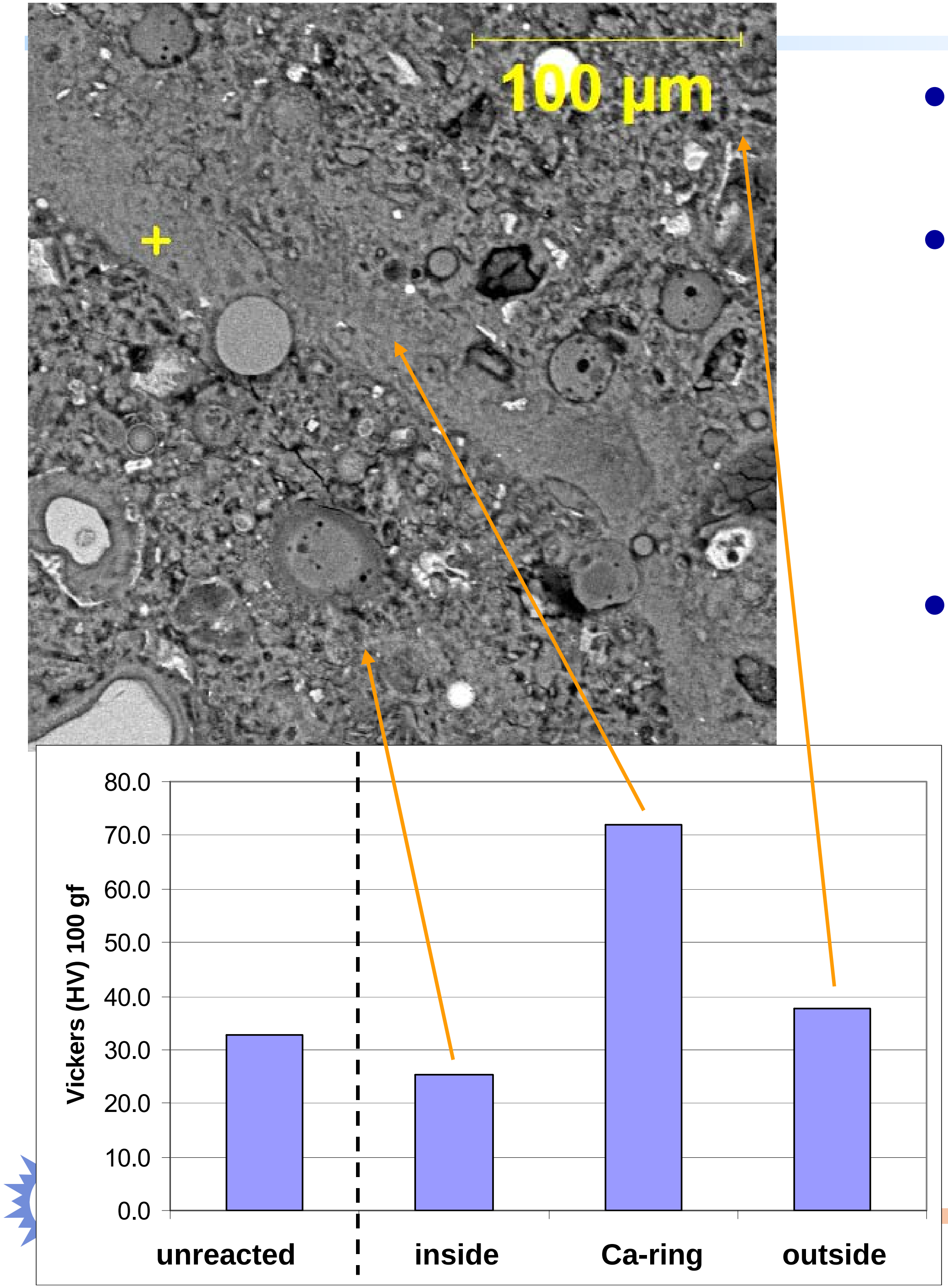
  - **35:65** Pozzolan/Cement by volume
    - Slurry density 14.51 lb/gal
  - **65:35** Pozzolan/Cement by volume
    - Slurry density 13.70 lb/gal



- Formulations based on historic records of well completions
- Slurry densities chosen to represent average water requirements used in field
- Class H neat cement = 16.45 lb/gal

35:65 Pozmix/Cement – 9 days

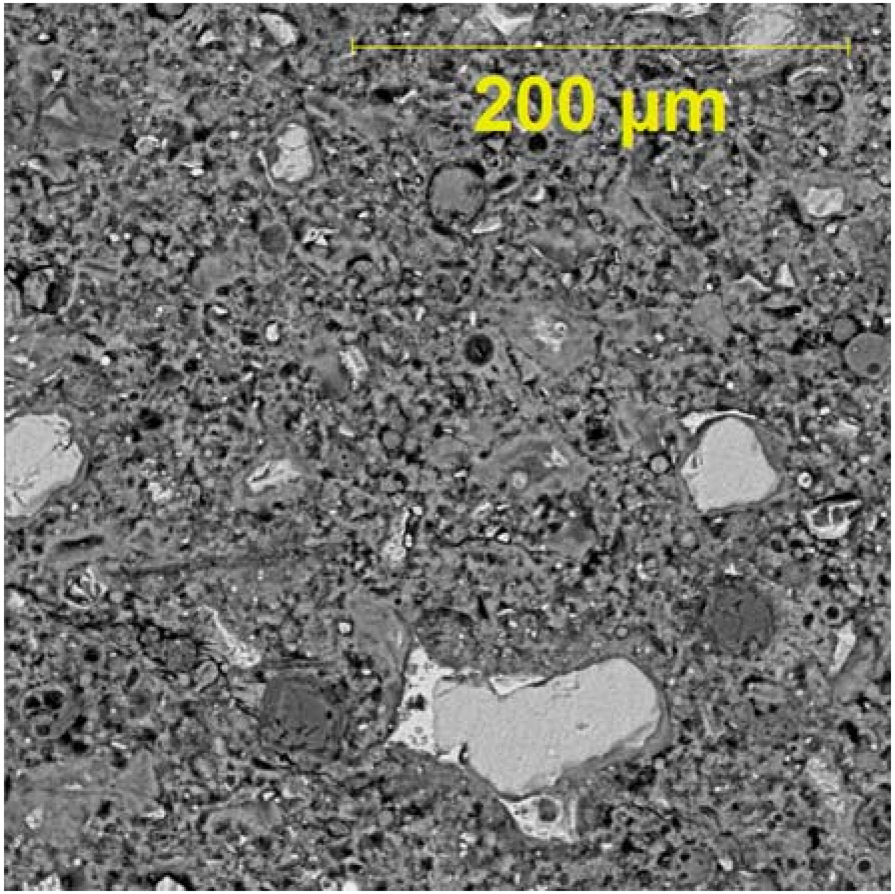


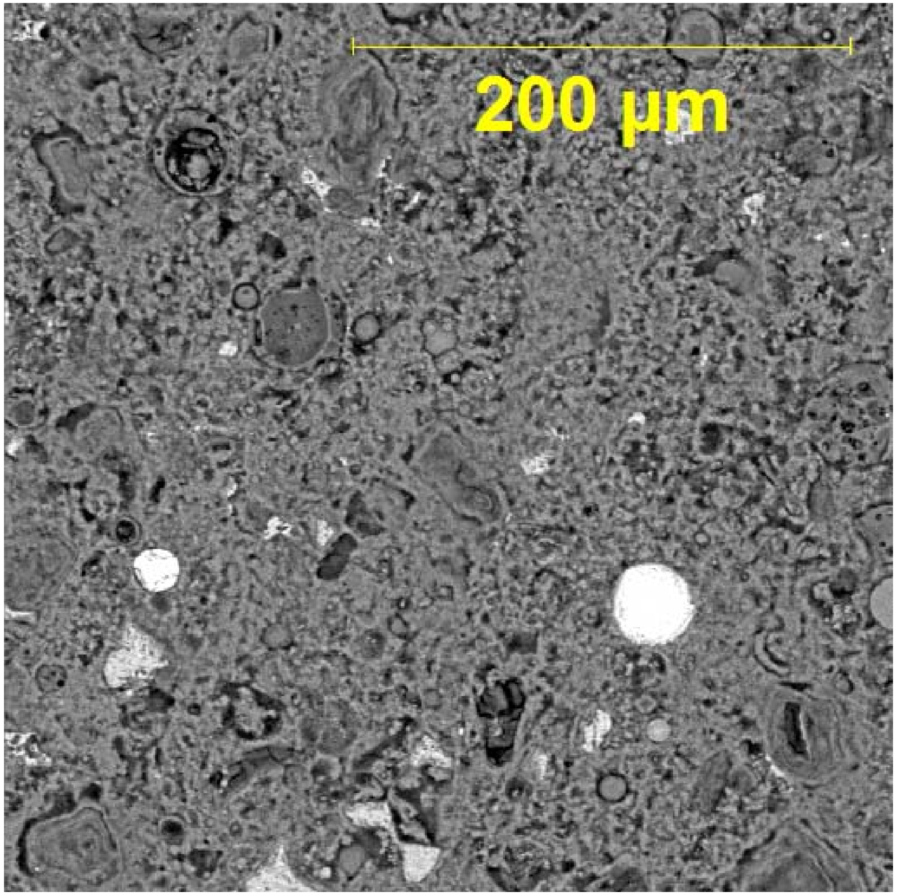


- **Thin CC rim** (at ~5.5 cm depth)
- **Inside Rim**
  - AFt (ettringite)
    - $[Ca_3Al(OH)_6.12H_2O]_2\cdot(SO_4)_3\cdot2H_2O$
  - Chloride
  - Unhydrated Cement grains
- **Outside Rim**
  - No AFt or Chloride
  - Calcium depleted cement grains
  - Fully Carbonated

35:65 Pozmix – 9 days: Vickers Microhardness

35:65 Pozmix/Cement

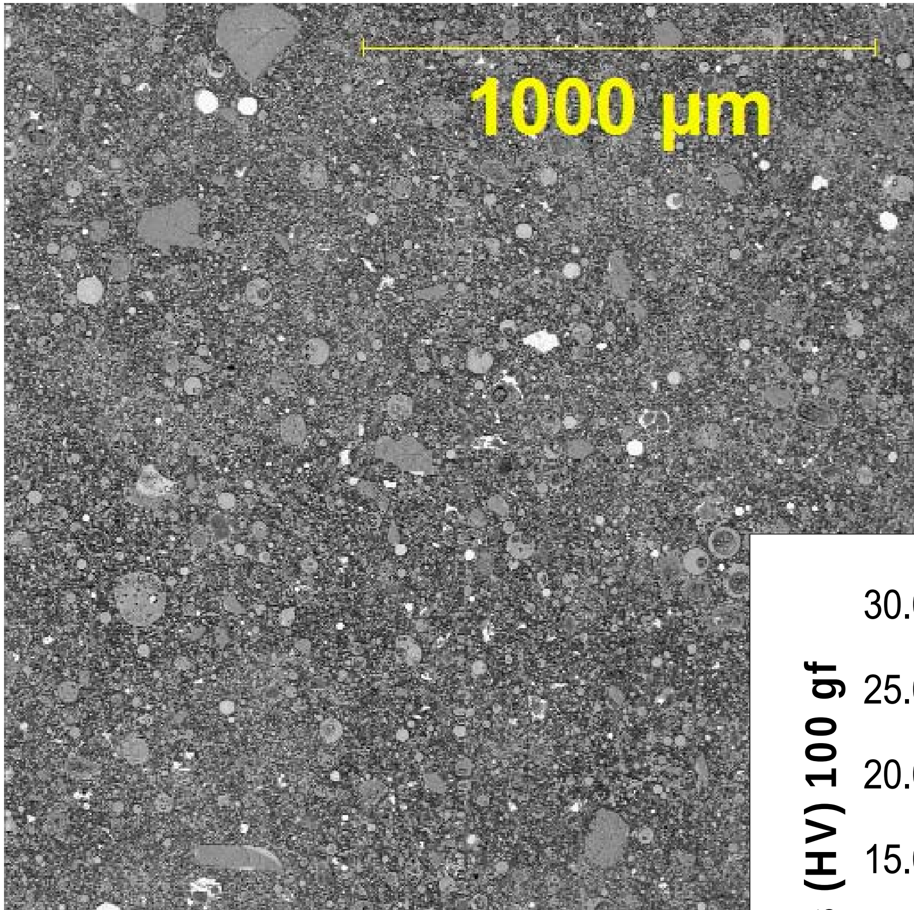




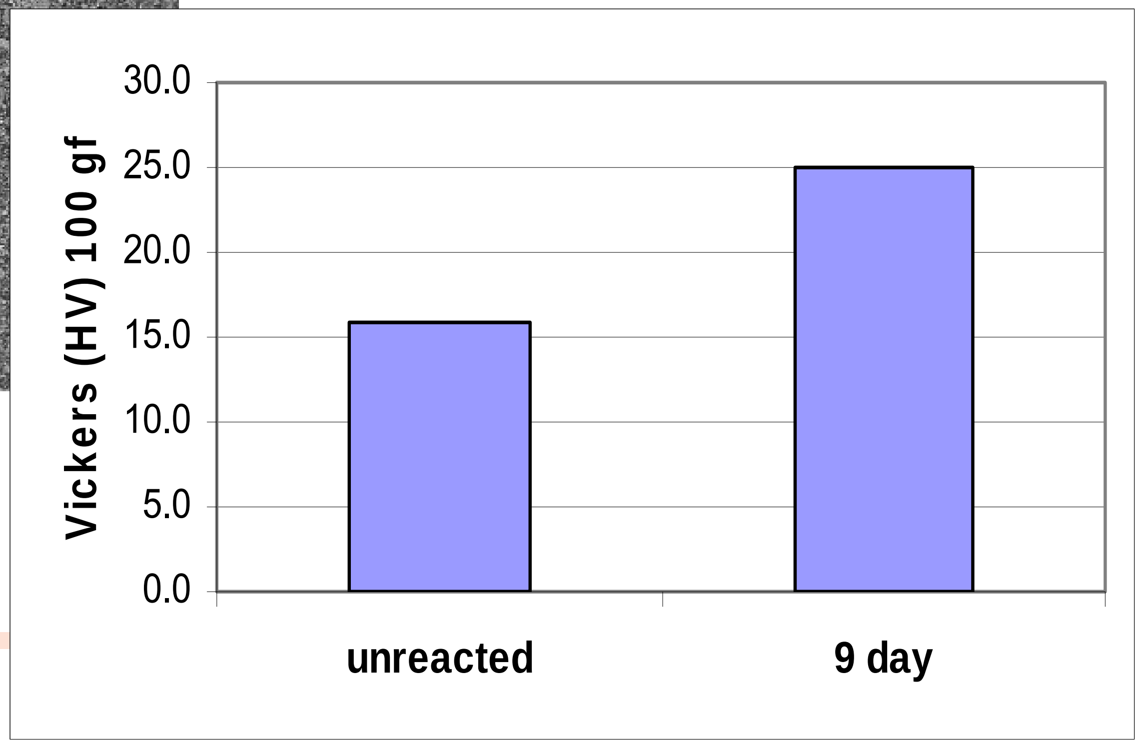
Unexposed cement sample

Exposed to CO_2-saturated brine for 31 days (sample is fully carbonated)

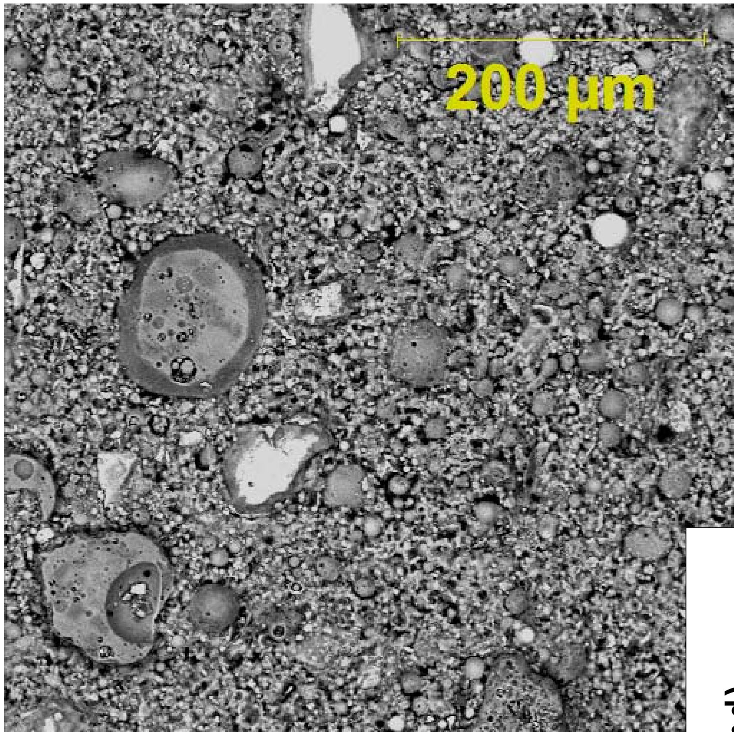
65:35 Pozmix/Cement – 9 days



Fully reacted after exposure to CO_2-saturated brine for 9 days

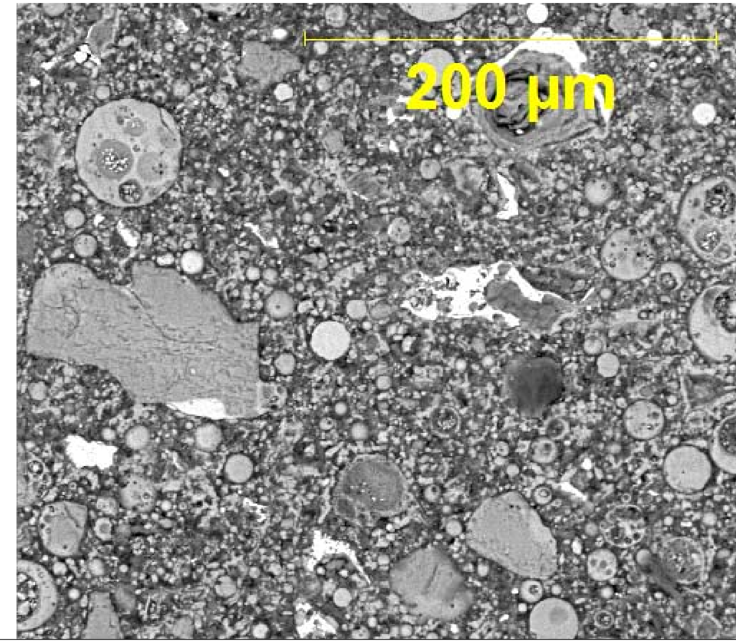


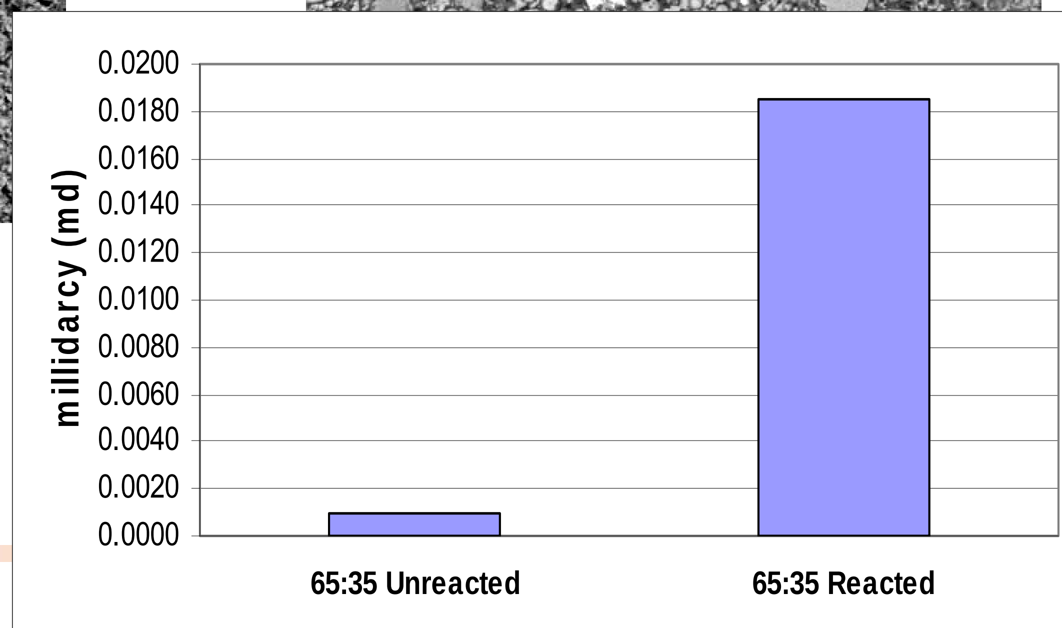
65:35 Pozmix/Cement: Permeability



Unexposed

Exposed to CO_2-saturated brine for 9 days





Key Findings to Date:

- **Leakage due *entirely* to chemical degradation of neat cement will not be a significant concern.**
- **Effect of Additives**
  - Changes in Rate and Mechanism
  - Additives change degradation process significantly, and increase penetration rate in all cases we've tested
  - However, degradation of physical properties is not as damaging in pozmix blend
- **Field Samples indicate that degradation mainly occurs along *existing* or *induced* pathways.**
- **Future Questions:**
  - Will the pathway be sealed or enhanced by CO_2 exposure?

Acknowledgements

- **George Scherer**
  - Princeton University
- **Bill Carey**
  - Los Alamos National Laboratory
- **Ya-Mei Yang**
  - Carnegie Mellon University
- **Andrew Duguid**
  - Princeton University/Schlumberger
- **Craig Gardner**
  - Chevron, Sr. Advisor - Cementing
- **Glen Benge**
  - Exxon Mobile, Drilling – Technical Applications

Some geomechanical aspects of well integrity

Bogdan Orlic, Tjirk Benedictus

TNO | Knowledge for business

4th Meeting of the Well Bore Integrity Network, 18-19 March 2008

Acknowledgements

- CASTOR project (EU-sponsored, 30 partners)
  =*CO_2 from Capture to Storage*
  https://www.co2castor.com/

- CATO project (national research programme)
  =*CO_2 Capture, Transport and Storage in The Netherlands*
  http://www.co2-cato.nl/

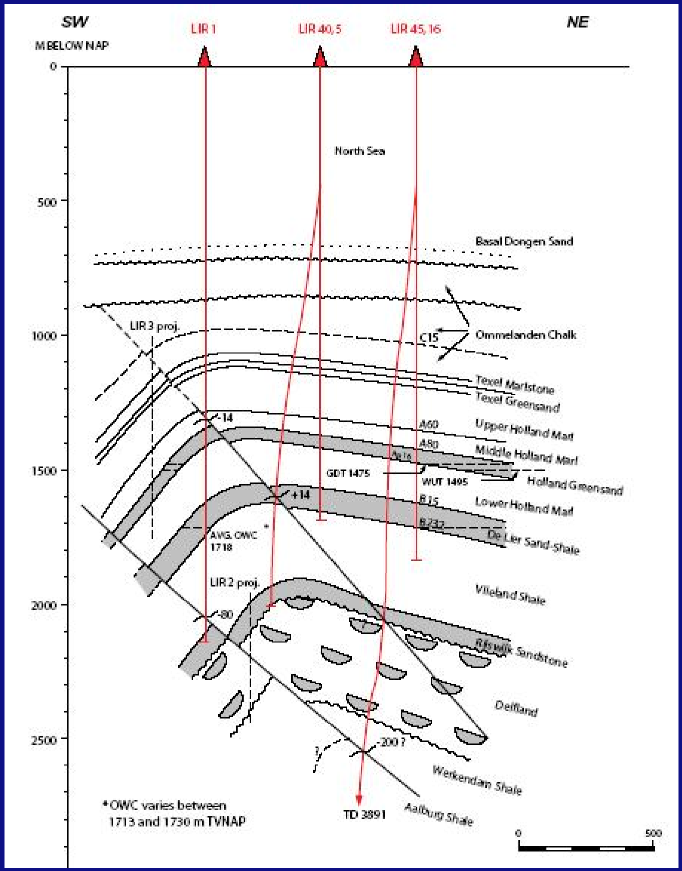
- Collaborators:
  Ton Wildenborg, Rob van Eijs, Frans Mulders

Relevance?

- The feasibility study of effective and safe CO_2 storage in the De Lier gas field (onshore the Netherlands, operator NAM)
- Field life: 1958-1992
- ~ 50 abandoned wells
- The operator decided that the hazards associated with well integrity were unacceptable and uneconomic to mitigate
- Project discontinued

Hofstee et al., 2008, First Break

A cross-section through the De Lier field

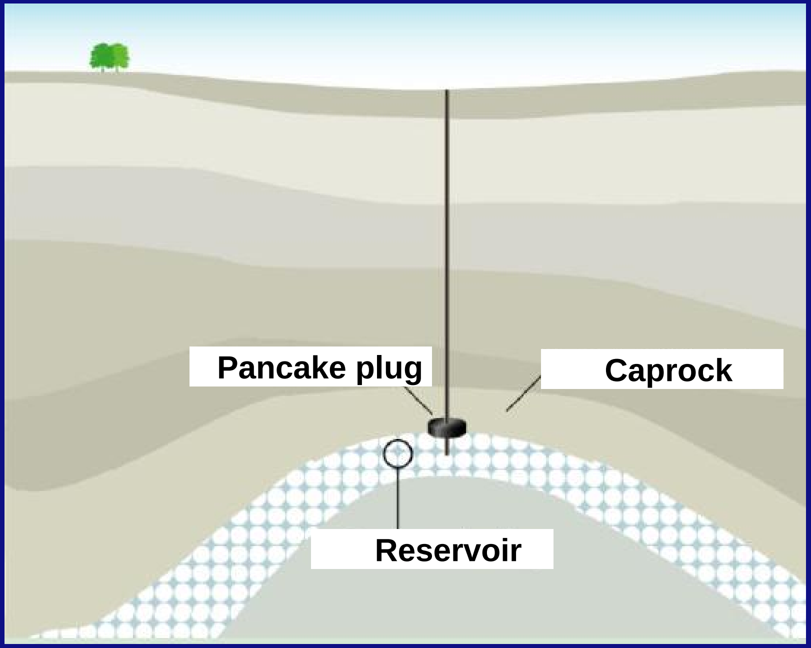


Relevance?

- A different field selected to continue the feasibility study for a CO_2 storage project
- Producing field
- A few accessible wells

http://www.co2opslagbarendrecht.nl/

Recommended procedure for well abandonment



Scope and objective

- The well leakage may occur through:
  - cement
  - microannuli between the casing and the cement sheath or between the cement sheath and the host rock
  - the damaged part of host rock surrounding well construction materials
- We consider the mechanical impact of drilling, production (if applicable) and CO_2 injection on the integrity of:
  - Cement and casing
  - Host rock in the surroundings of cement and casing

Outline

- Well
- Effects of drilling-induced stress alterations on wellbores
- Mechanical effects of HC extraction/CO2 injection on wells
  - Engineering properties of steel casing, cement and reservoir rock
  - Radial deformation: internal and external
  - Axial deformation
  - Shear deformation
- An alternative method for abandonment of wells penetrating rocksalt
- Conclusions

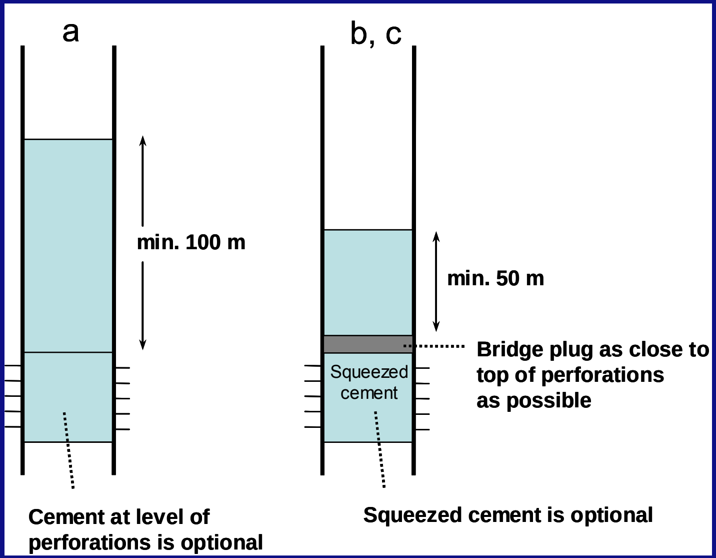
Well and the life of a well

- Well components:
  steel, cement and host rock in the surrounding

- Phases of well life:
  drilling, completion, production/injection, abandonment, post-abandonment

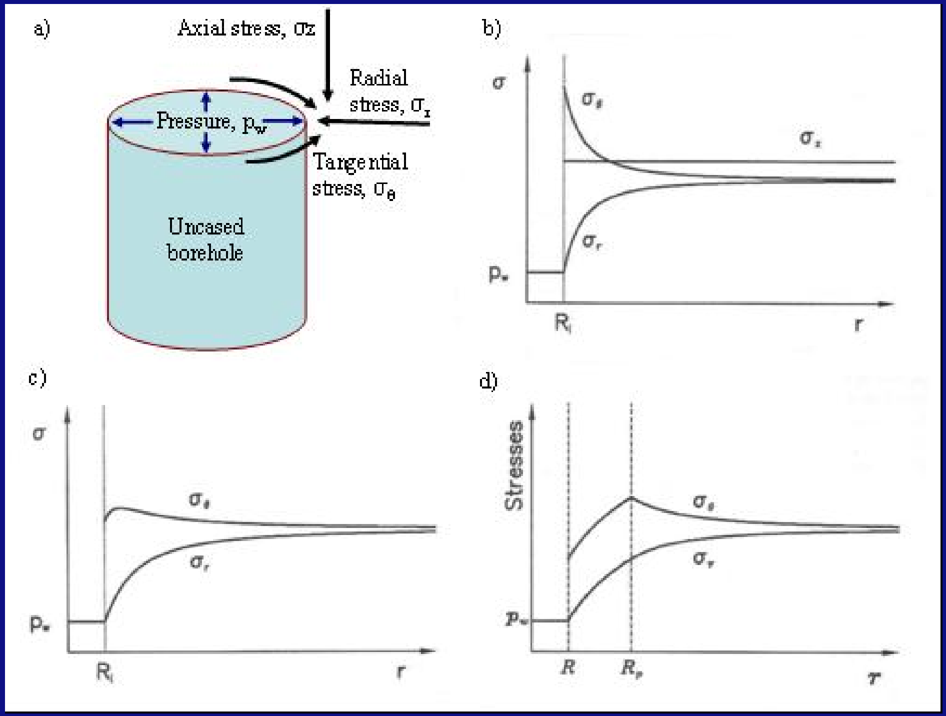
- Well life duration:
  - 10's yrs in oil industry
  - 100-1000's yrs in CO2 sequestration

Well abandonment procedure required by the Dutch Mining Law



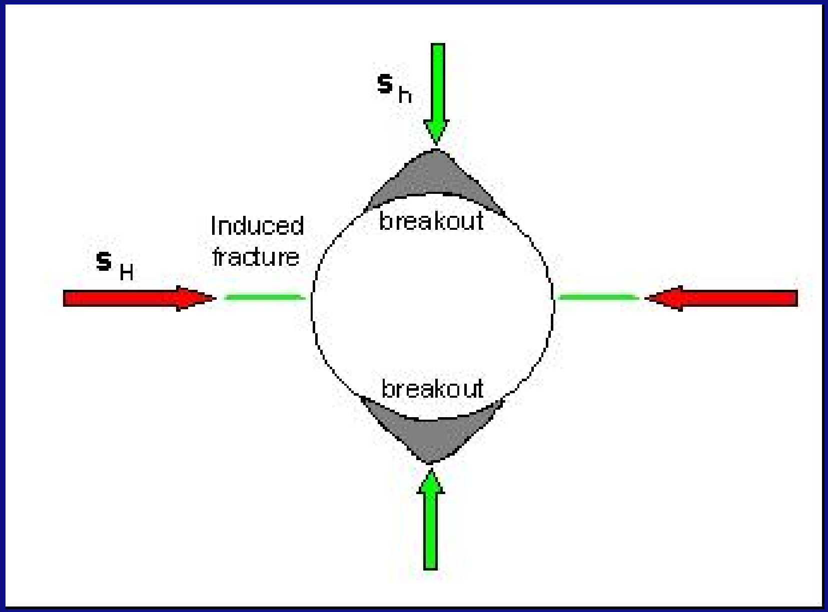
Effects of drilling-induced stress alterations on wellbore

- The rock is characterized by a limited formation strength
- The rock will fail when the stress deviations reach the failure criterion for the rock
- A plastic zone surrounding the wellbore will be formed



a) Schematic representation of stresses around a vertical borehole in:
b) a linear elastic formation
c) a formation with stress-dependent elastic properties
d) an elasto-plastic formation

Effects of drilling-induced stress alterations on wellbore



The geometry of breakouts and induced tensile fractures around a vertical borehole in the case of anisotropic horizontal stresses

- Formation of breakouts and induced tensile fractures in wellbore walls practically unavoidable
- Proper well cementing in the completion phase is essential to seal off breakouts and fractures
- A possible remaining problem is the presence of fractures in the near-well zone that do not daylight in wellbore walls

Outline

- Well
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  - Axial deformation
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- Conclusions

Mechanical effects of production / injection on wells

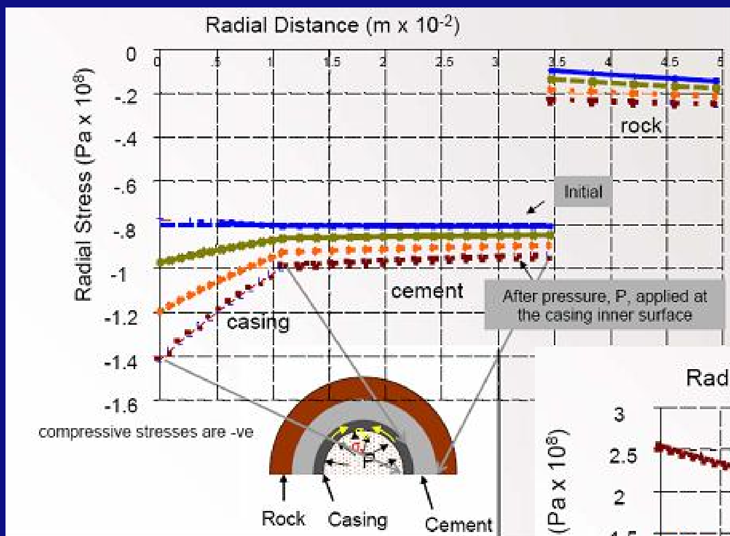
- Engineering properties of steel, cement and the rock are very different!

	Young's mod. E [GPa]
Steel	200
Cement (API)	4-15
Sandstone	10-25

- Tensile strength cement ~1/10 of the compressive strength (~1-3 MPa)
- Shear bond strength (=tensile strength) of the cement-rock interface and the rock-casing interface ~1MPa (0.7-7 MPa)
- The interfaces are the weak spots: debonding along an interface

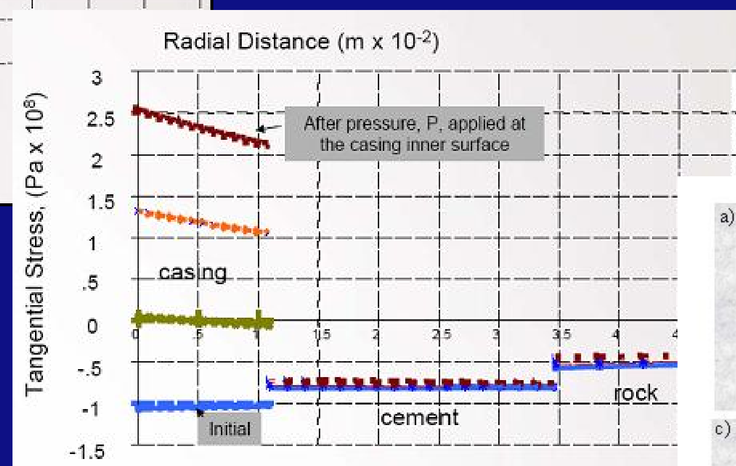
Mechanical effects of production / injection on wells

Change in radial stress

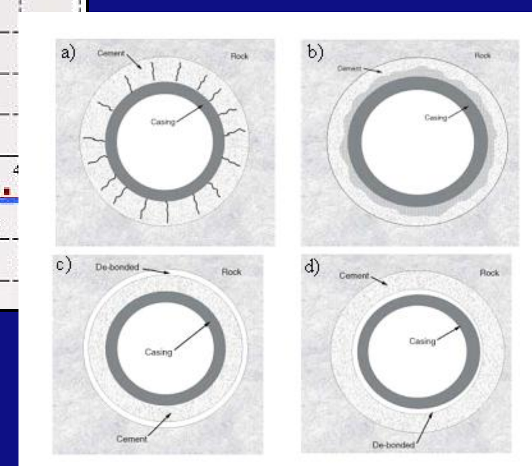


- Radial deformation due to internal load
  - shrinkage during cement hydration, mechanical and temperature loads

Change in tangential stress



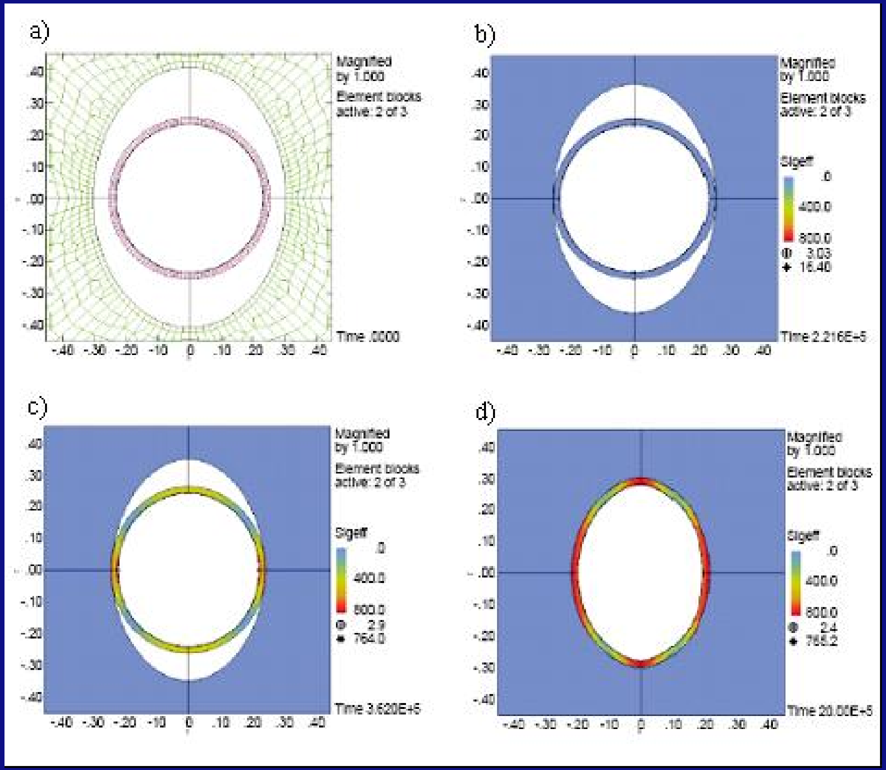
Resulting deformation



Ravi et al., 2002, SPE 74497

Mechanical effects of production / injection on wells

- Radial deformation due to external load
  - creep and viscous behavior of the surrounding rock



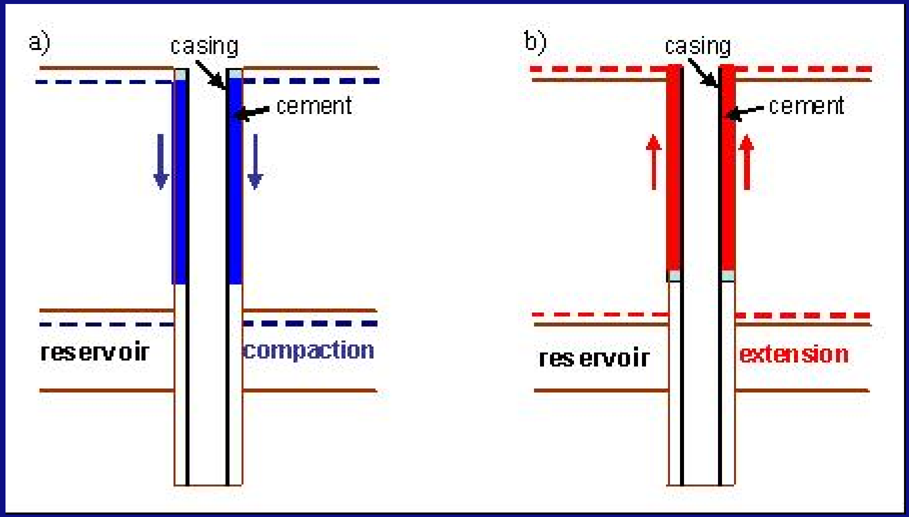
- the risk of damage and collapse of casing present in the case of non-uniform point loading

a) Uncemented borehole
b) Von Misses stress at initial contact of salt with casing (non-uniform point loading of casing)
c) at initial yielding of casing
d) complete encapsulation of casing by salt

Fredrich and Fossum, 2002

Mechanical effects of production / injection on wells

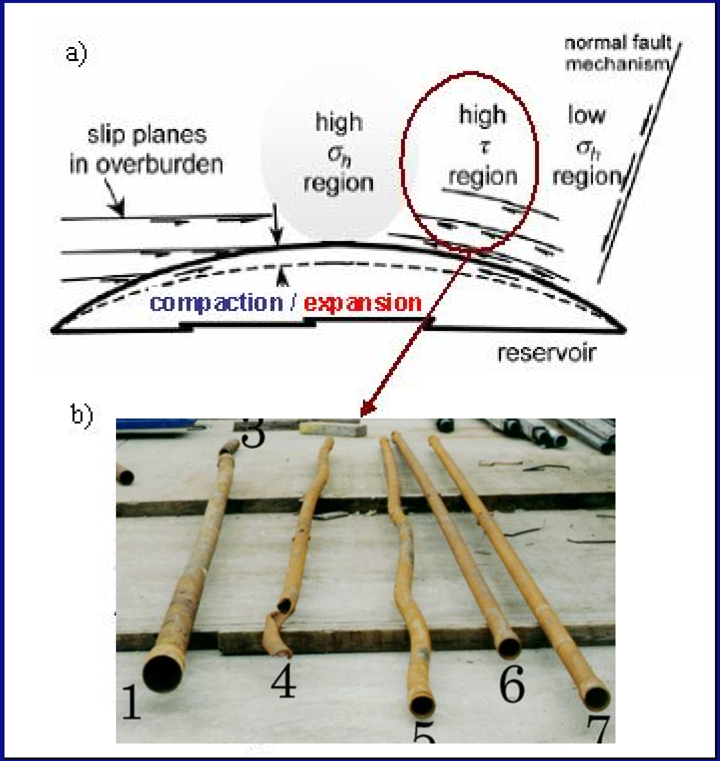
- Axial deformation due to reservoir compaction and decompaction
  - Reservoir compaction in depletion and decompaction/extension in injection
  - Huge strain incompatibility at the casing cement interface: the axial deformation of steel casing is practically negligible with regard to the deformation of cement and the rock! => debonding



a) Compaction and b) decompaction (extension) of the reservoir leading to debonding at cement/casing interface

Mechanical effects of production / injection on wells

- Shear deformation due to reservoir compaction (and decompaction?)
  - Caused by re-activation of existing faults
  - Shear localization zones typically located:
    - in the over-and under-burden close to the edges of compacting reservoir
    - along interfaces between geomaterials of different stiffness e.g. at top seal/reservoir interfaces and at contacts between different lithologies

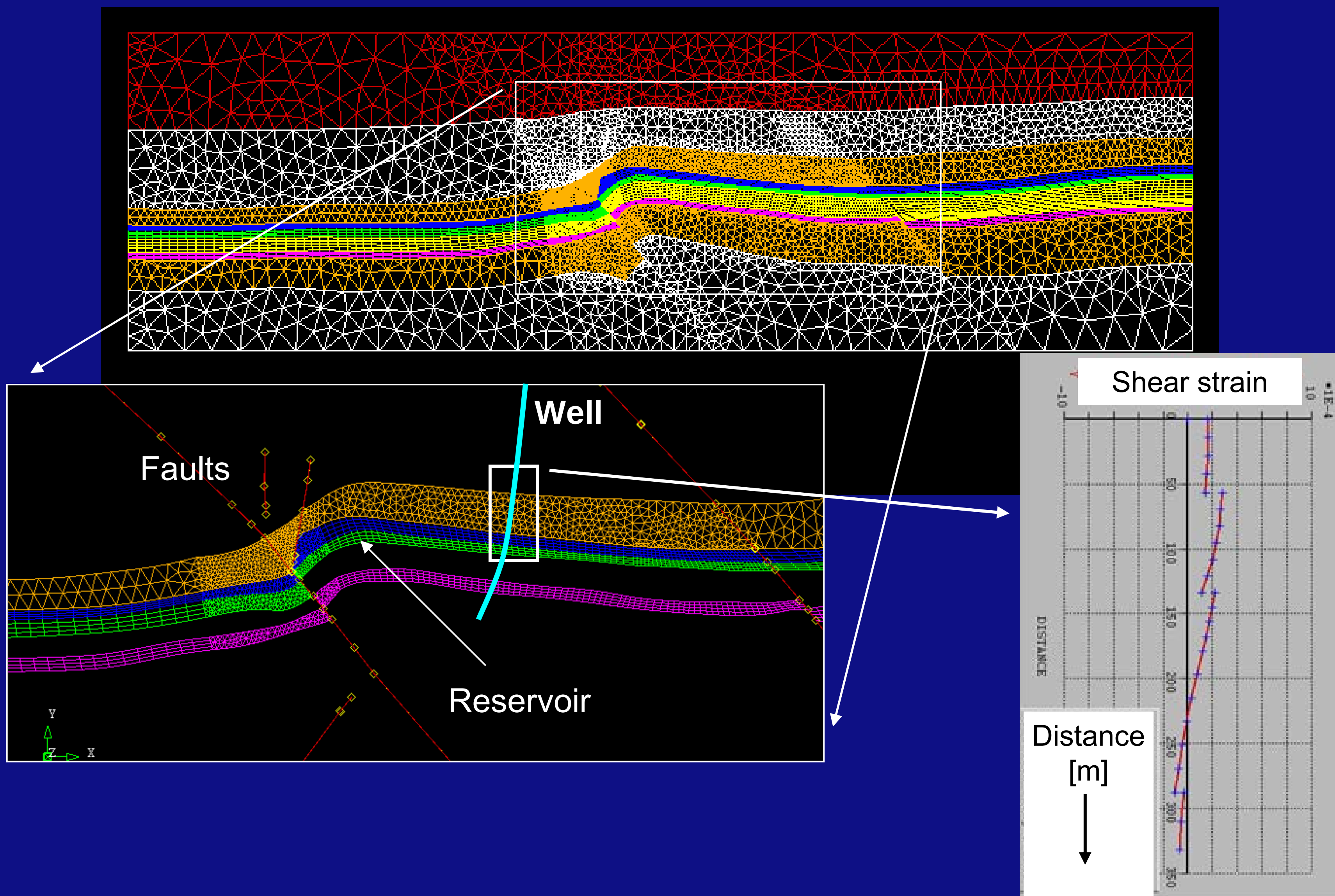


a) Stress changes above the compacting / expanding reservoir causing bedding-plane slip and reactivation of faults
b) casing damage

Dusseault et al. 2001, SPE 72060

Mechanical effects of production / injection on wells:

FE Modelling to assess the mechanical impact on wells



Outline

- Well
- Effects of drilling-induced stress alterations on wellbores
- Mechanical effects of HC extraction/CO2 injection on wells
  - Engineering properties of steel casing, cement and reservoir rock
  - Radial deformation: internal and external
  - Axial deformation
  - Shear deformation
- An alternative method for abandonment of wells penetrating rocksalt
- Conclusions

An alternative method for abandonment of wells penetrating rocksalts

- Zechstein rocks present in the overburden of many North Sea reservoirs
- Zechstein rocksalts have a visco-elastic behavior

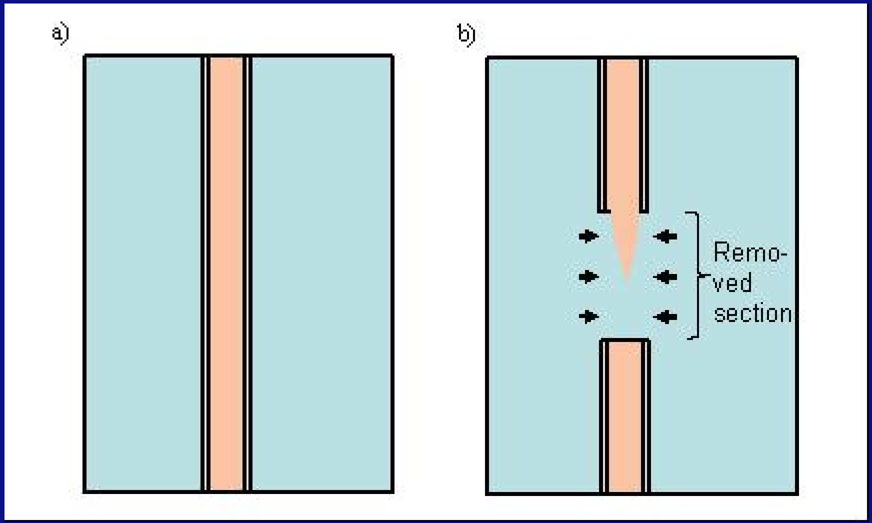
BRITTLE	----------------------------		DUCTILE
clay			
carbonate			
anhydrite			
	thin anhydrite		
		rocksalt (halite)	
			K-Mg salts (squeezing salts)

Zechstein rocks

- Rocksalt does not withstand deviatoric stresses
- It will creep in the near-well zone towards the casing until the mechanical stress on the casing equalizes with the overburden stress
- Result is the closure of microannuli i.e. possible leakage pathways

An alternative method for abandonment of wells penetrating rocksalts

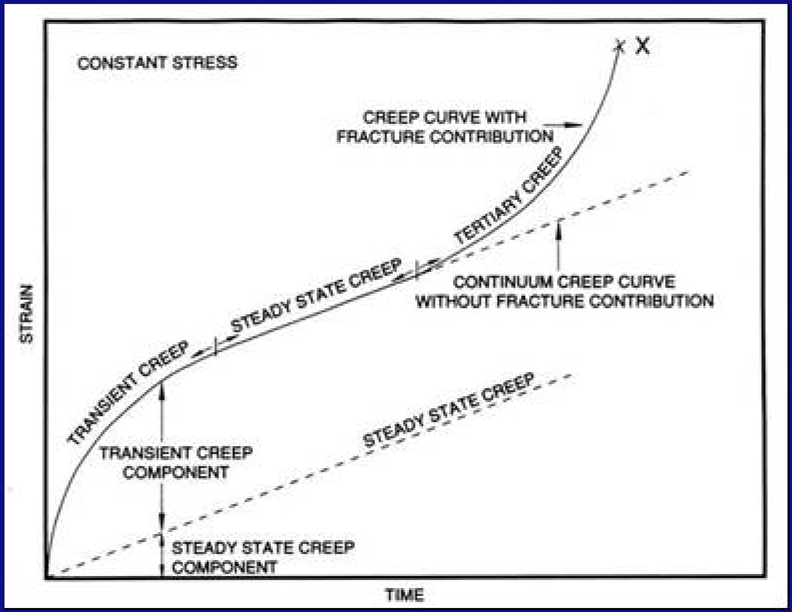
- The viscous behavior of the rocksalt can be utilised to develop an alternative way for permanent and safe well abandonment
- Method:
  - A long section of the well casing running over the salt section in the overburden is milled out
  - The milled out part of the old casing and cement are removed
  - The natural process of creep will develop in rocksalt leading to the complete closure of the uncased section of the wellbore over some period of time



a) Well through salt deposits and
b) the same well after removal of a part of casing leading to salt creep in the open wellbore

An alternative method for abandonment of wells penetrating rocksalts

- Rocksalt deformation under constant loading (lab tests):
  - Primary creep: a work hardening plastic flow
  - Secondary creep: a steady-state visco-elastic behavior (constant strain rate)
  - Tertiary creep: accelerating, with disintegration of salt structure and collapse



Deformation of rocksalt with time

An alternative method for abandonment of wells penetrating rocksalts

- A Dorn-type power law equation is used for the description of steady-state creep:

$$\dot{\varepsilon} = A \exp\left(\frac{-Q}{RT}\right)\sigma^{n}$$

$\dot{\varepsilon}$ is the flow rate [s^{-1}],
T is the temperature [°K]
σ is the stress [MPa]
R is the gas constant [kJ/mol]
Q is the apparent activation energy [kJ]
A is the rate constant in [MPa^{-n} s^{-1}]
n is the stress exponent

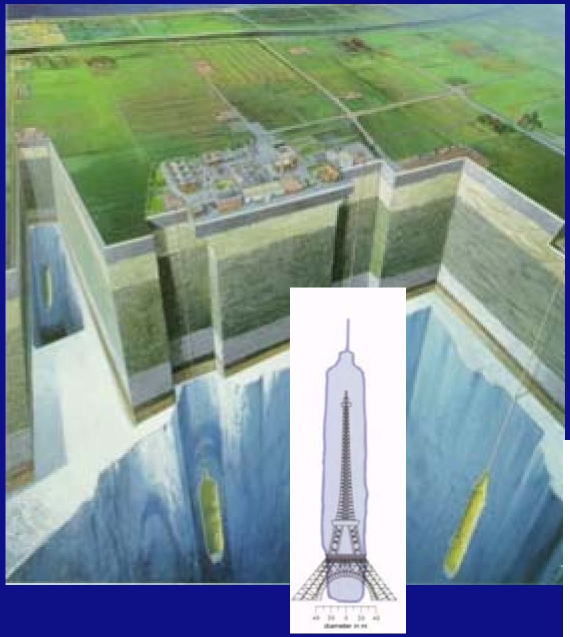
Source	A_1 [$MPa^{-n} day^{-1}$]	n_1	Q_1/R [°K]
Heard (1972)	67067	5.5	11787
Wallner *et al.* (1979)	0.18	5	6495
Carter *et al.* (1993) - high strain-rate	13.7	5.3	8179
Breunese *et al.* (2003)	1.71	3.6	6206
Carter *et al.* (1993) - low strain-rate	6.99	3.4	6206

The parameters obtained by fitting the lab data to a power-law equation, compiled from different literature sources

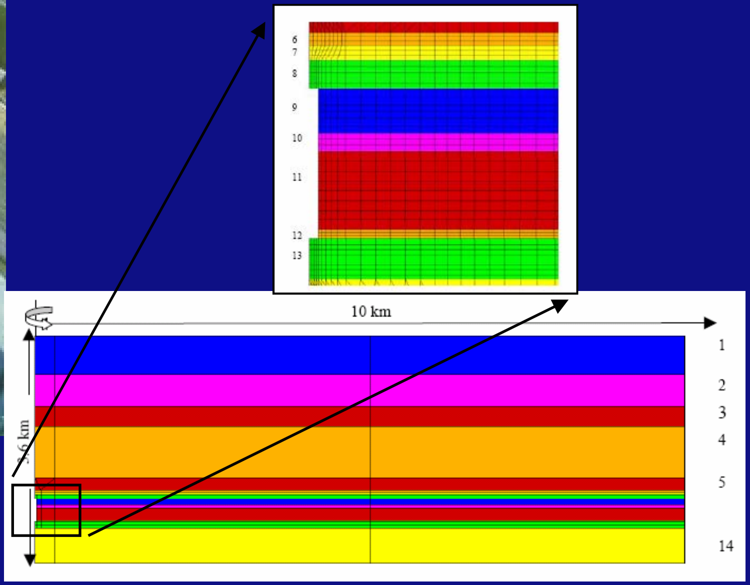
An alternative method for abandonment of wells penetrating rocksalts

- TNO expertise in salt mechanics and modelling; extensive field data (>10yr)

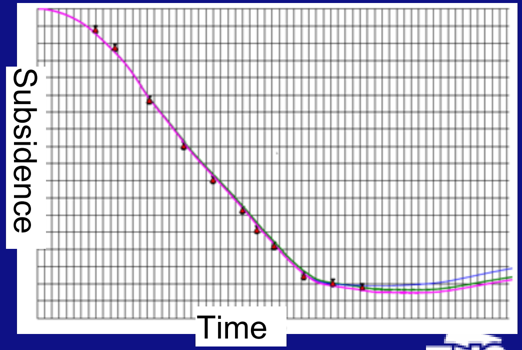
Deep (3km) solution salt mining
In the Netherlands



Numerical modelling of salt extraction for subsidence prediction

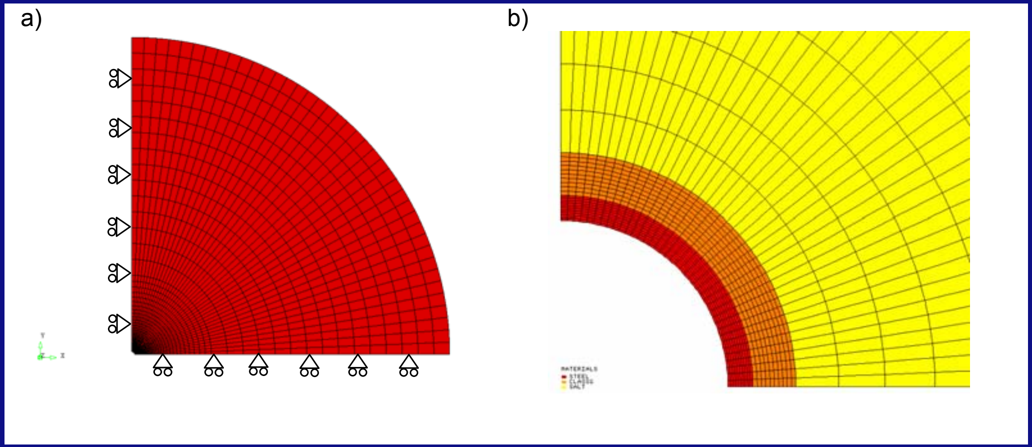


Subsidence data and model predictions



An alternative method for abandonment of wells penetrating rocksalts

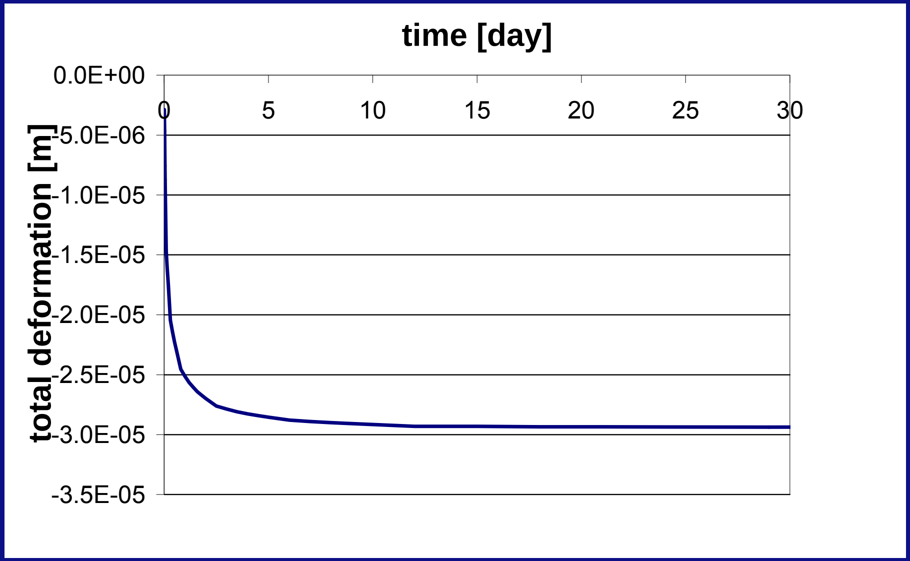
- Well closure modelling
- A plane strain FE model
  - Phase 1:
    - Well casing and cement sheath are present
    - The model is loaded by the isotropic far-field in situ stress 85MPa@3500m, 377°K
    - Internal casing pressure is hydrostatic
  - Phase 2:
    - Well casing and cement are removed from the model
    - The salt creep, resulting in the closure of the wellbore, is simulated taking into account different creep parameters (Base Case from Breunese, 2003)



a) Mesh and boundary conditions on the plane strain model
b) enlarged part of the model showing the casing (red), cement sheath (orange) and the rocksalt (yellow)

An alternative method for abandonment of wells penetrating rocksalts

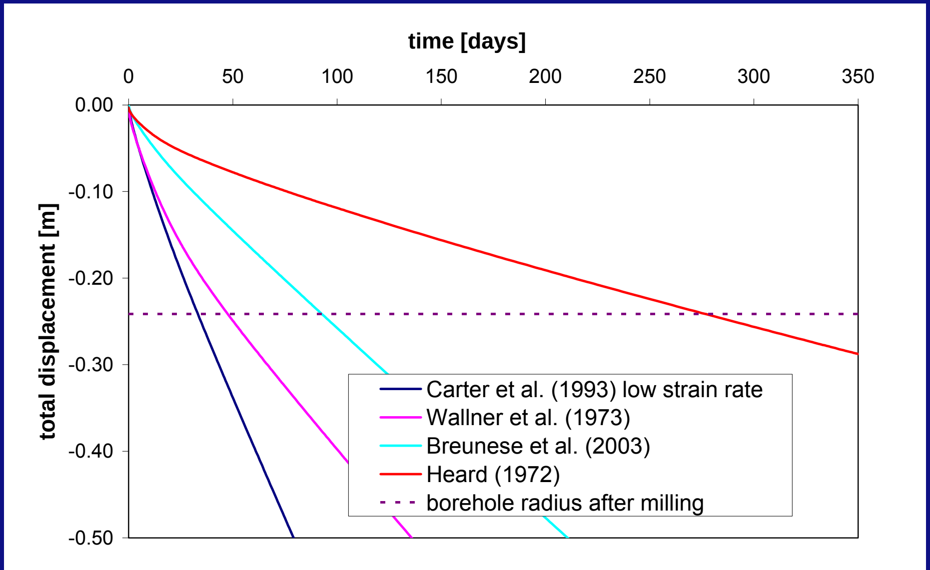
- Well closure modelling
- Results
  - Phase 1:
    - Initial shear stress in the model equal to zero
    - Initial creep deformation in rocksalt is very low
    - Stress equilibrium in the near-well zone reached within several days



Total deformation of the wall of a wellbore as a function of time (phase 1)

An alternative method for abandonment of wells penetrating rocksalts

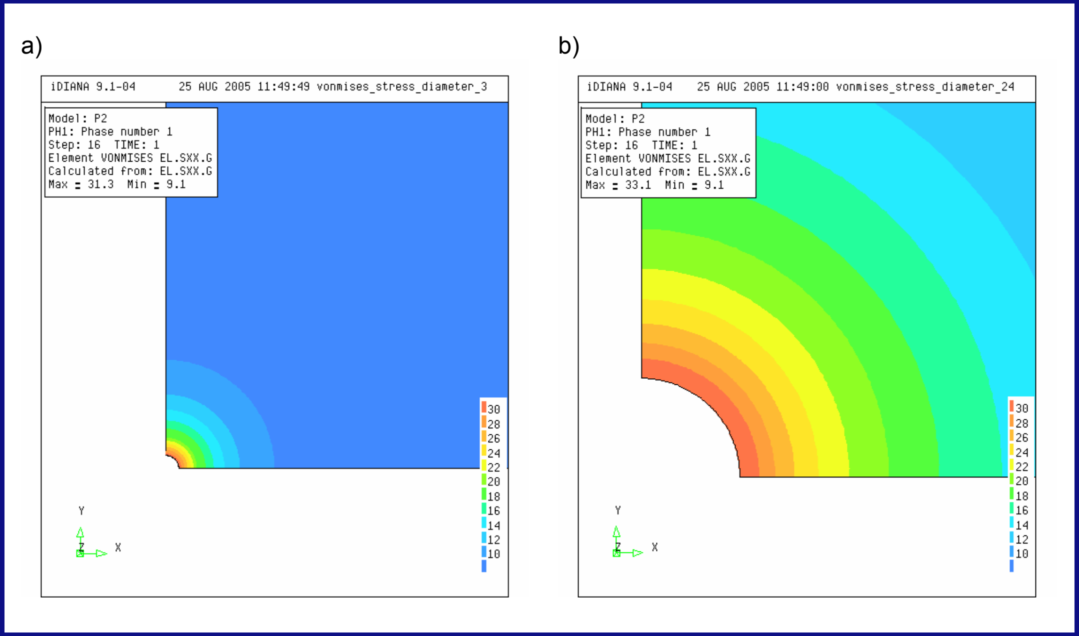
- Well closure modelling
- Results
  - Phase 2:
    - High variation of the deformation rates as a function of different creep parameters from the literature
    - Total closure of the wellbore will occur within 1 year after milling operation



Deformation of the wellbore as a function of time (phase 2); the horizontal dotted line shows the radius of the milled out section of a well

An alternative method for abandonment of wells penetrating rocksalts

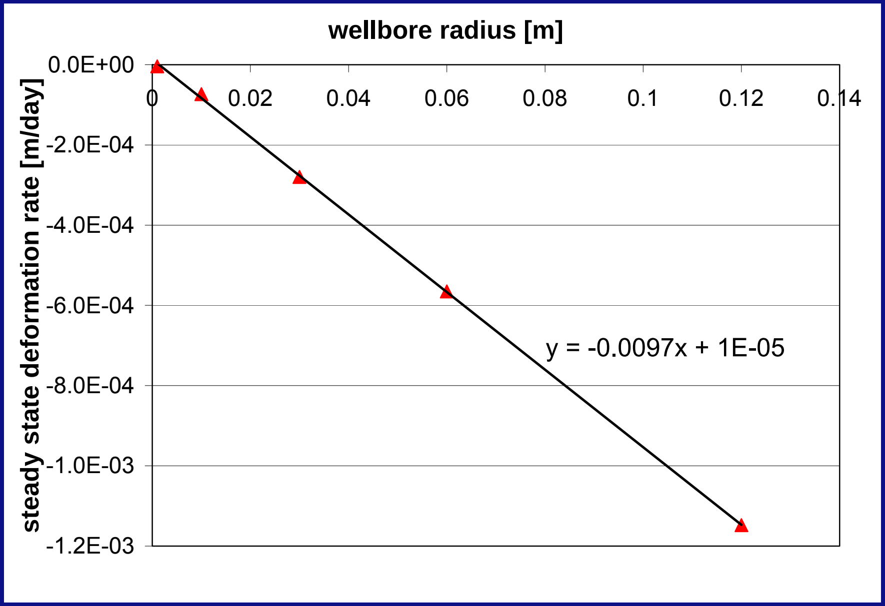
- Well closure modelling
- Results
  - Phase 2:
    - Creep rate dependent on the wellbore radius!
    - A wellbore with a smaller radius will have a much smaller zone with differential stresses and a lower deformation rate



Von Mises stresses around a wellbore after 1 day of creep (phase 2) for:
a) a wellbore with a radius of 3 cm
b) a wellbore with a radius of 24 cm

An alternative method for abandonment of wells penetrating rocksalts

- Well closure modelling
- Results
  - Phase 2:
    - Another set of calculations executed for different wellbore radii and the Base Case creep parameters for rocksalt (Breunese et al., 2003)
    - A linear dependency found between the wellbore radius and the steady-state deformation rate for rocksalt



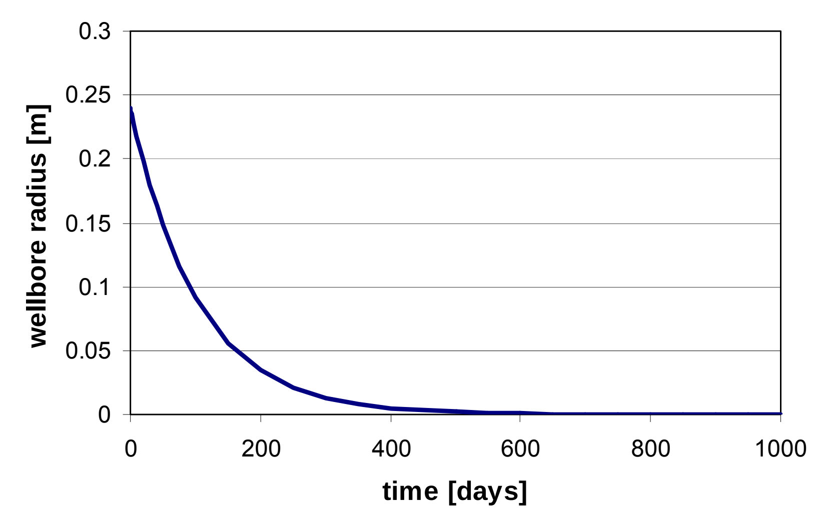
Steady-state deformation rates as a function of wellbore radius

An alternative method for abandonment of wells penetrating rocksalts

- Well closure modelling
- Results
  - Phase 2:
    - The dependency of the wellbore radius as a function of time:

$$r = 0.24e^{-0.0097t}$$

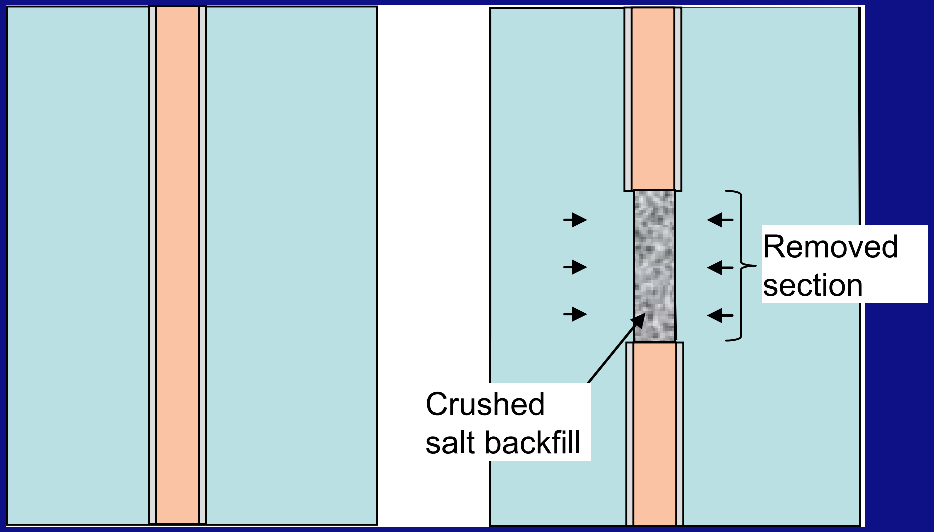
    - The wellbore radius shows an asymptotic behavior with time, leaving a wellbore radius of less than 1 mm after ~600 days



Wellbore radius as a function of time taking into account the radius dependency of the deformation rate

An alternative method for abandonment of wells penetrating rocksalts

- Well closure modelling
  - Crushed salt as a backfilling material to accelerate the process of wellbore closure
  - Investigated in the context of geological disposal of radioactive waste



a) Well through salt deposits and
b) the same well after removal of a part casing and cement and filling the removed section with crushed salt

Conclusions

- Possible leakage pathways: cement sheath and plug, microannnuli and the damaged part of the surrounding rock
- Proper well cementing is essential to reduce the risk of leakage through breakouts and induced fractures caused by drilling
- Creation of microannuli due to debonding at rock/cement or cement/casing interface as a result of reservoir compaction/decompaction is highly likely and practically unavoidable
- The presence of rocksalt in the overburden of a CO2 storage site can be favorable for well integrity as the salt will creep towards the cement sheath and casing closing the existing microannuli
- The viscous behaviour of rocksalt can be utilised to develop an alternative way for permanent and safe well abandonment
- In the proposed method for well abandonment a long section of the well casing running through the salt is milled out. This triggers the natural process of creep in salt leading to the closure of the uncased section of the wellbore

Cementitious Material Behavior under CO_2 environment
A laboratory comparison

V.Barlet-Gouédard, B.Ayache, G.Rimmelé, Well Services, Schlumberger

4nd Well Bore Integrity Network Meeting
18–19 March 2008, Paris, France

Schlumberger

Outline

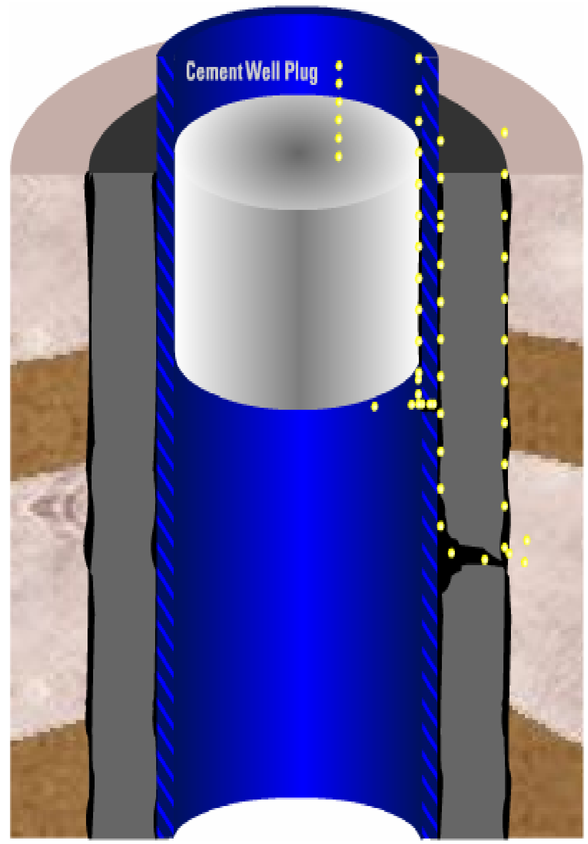
- Motivation and Approach
- Storing supercritical CO_2 underground
- CO_2 testing results
  - How to do a experimental comparison
  - Previous publications for existing well cements
  - Portland /Fly ash type F blend
- Durability Criteria
- How Portland /Fly ash type F blend can be compared with the others cements already tested under the same conditions?

Motivation and Approach

- CO_2 leakage, one major risk for CO_2 storage underground
  - Health and safety risks : e.g. water pollution
  - Storage efficiency
  - Long-term cement zonal isolation

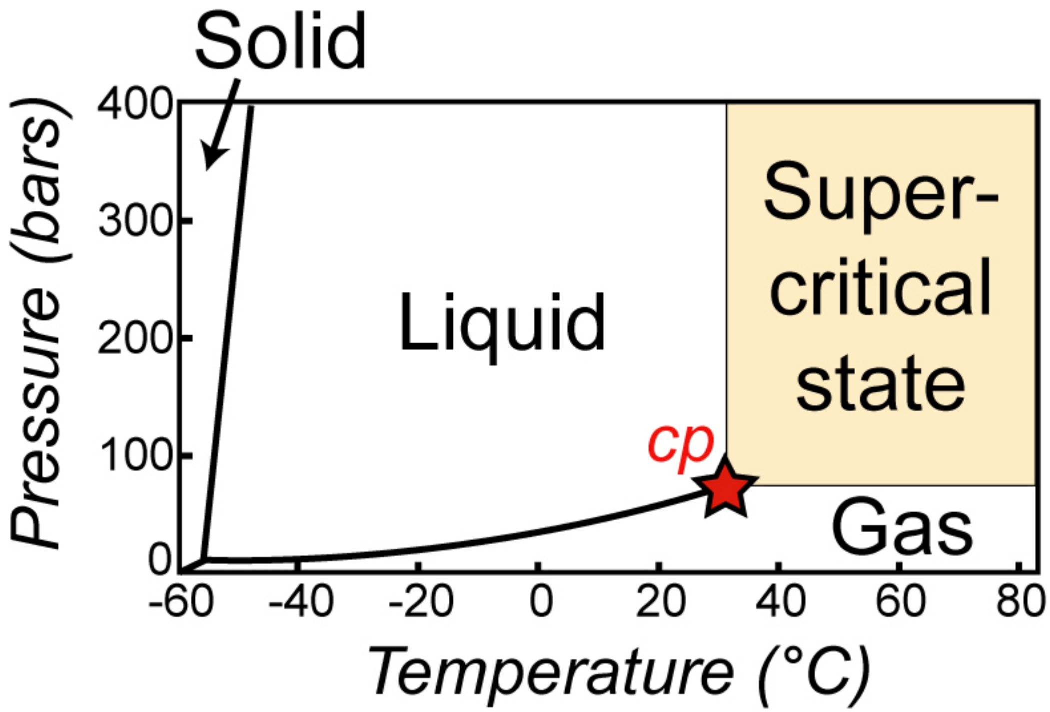
- Portland cement not thermodynamically stable in CO_2 environments.

- A laboratory cement qualification and comparison
  - Develop a standard CO_2-testing procedure
    - Downhole Temperature & Pressure, Salinity
    - Wet/dry CO_2 Supercritical fluids
    - CO_2 dissolved in water or in brine



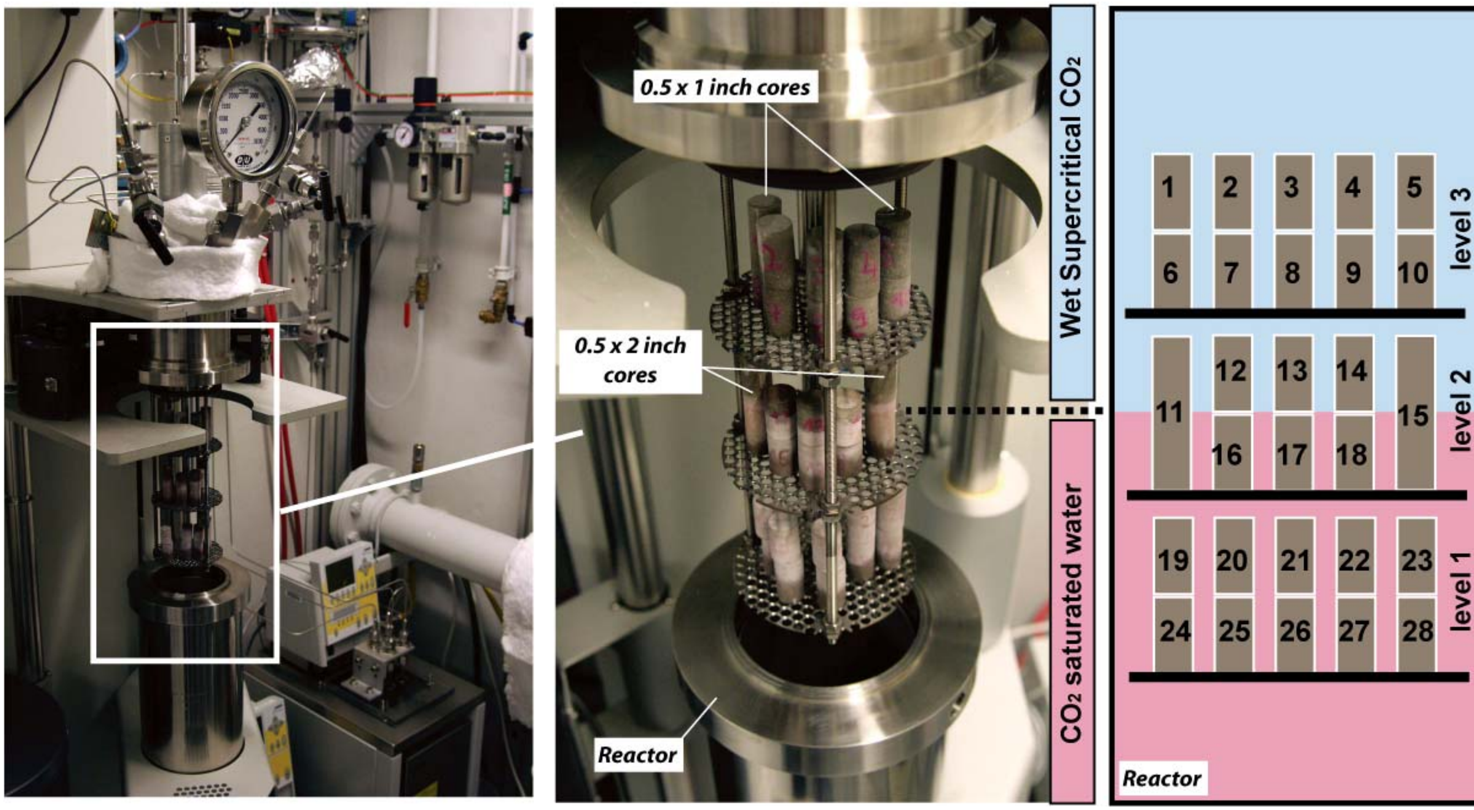
Storing supercritical CO_2 underground

- Supercritical fluid: viscosity of a gas, density of a liquid, high diffusivity
- *cp* (critical point) for CO_2: T=31.6°C and P=73 bars



Schlumberger

CO_2 testing results:
How to do a experimental comparison?

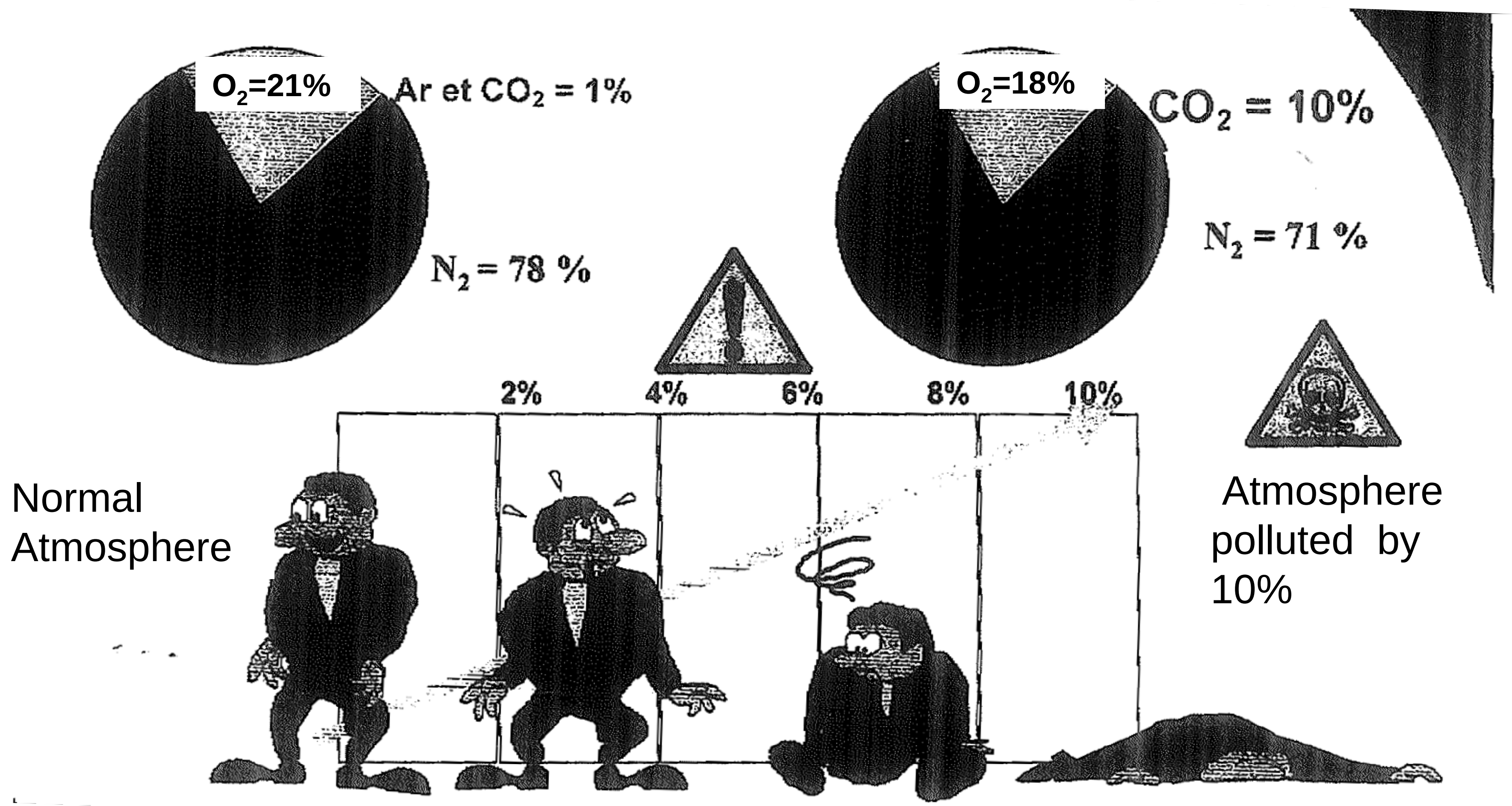


TEST CONDITIONS:
P=100, 280 bars
T=40 °C, 90°C
120°C

Pmax = 350 bars/ Tmax = 500°C

Safety equipments: CO_2 leakage sensor, strong air extractor, bunker, remote control

CO_2 testing results: CO_2 effect on human health



CO_2 testing results: Previous publications for existing well cements

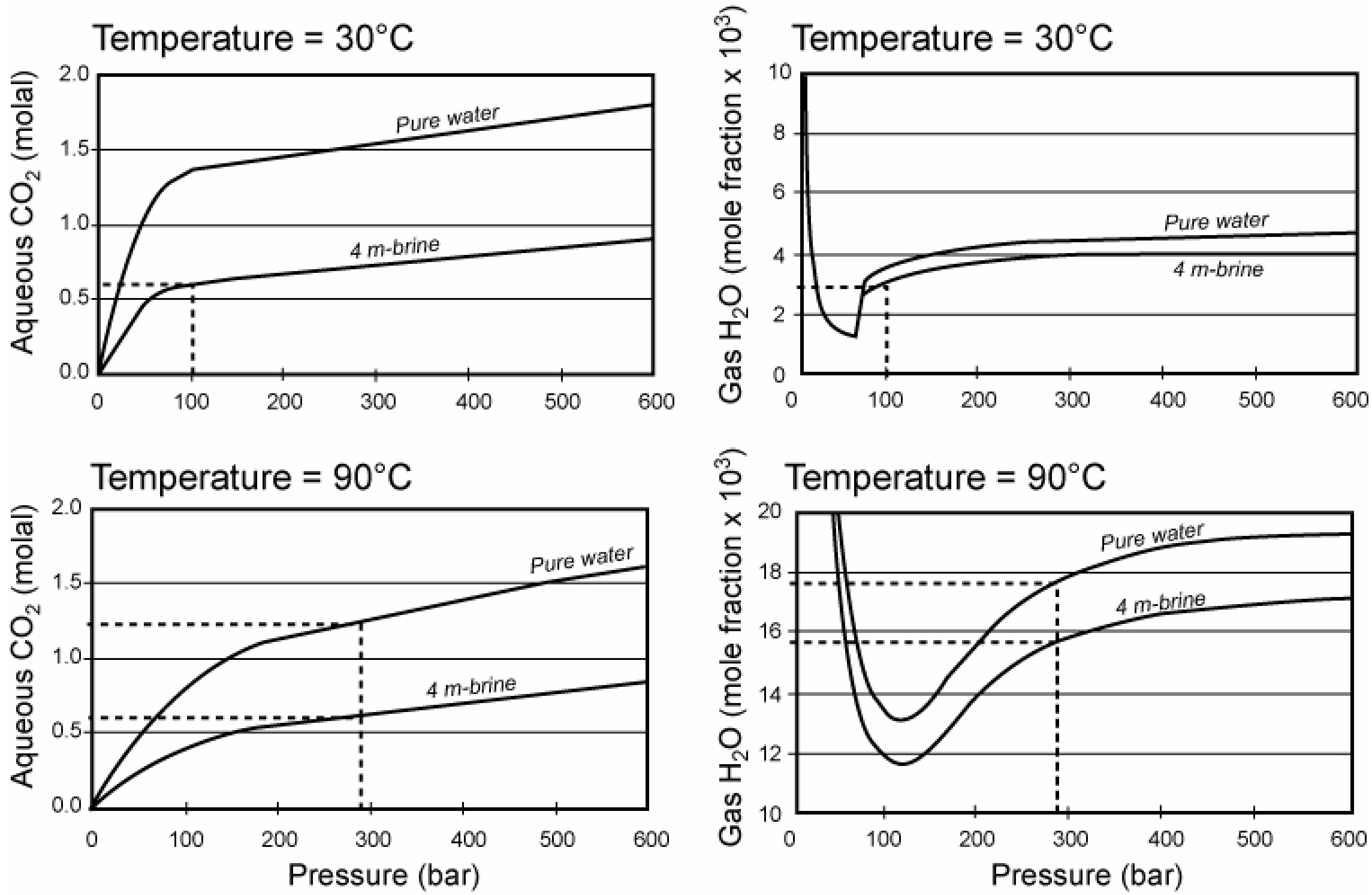
- **Portland Cement: already published**
  - "Mitigation strategies for the risk of CO_2 migration through wellbores" V. Barlet-Gouédard & all, IADC/SPE 98924, February 2006
  - "Well Technologies for CO_2 Geological Storage: CO_2-resistant cement" V. Barlet-Gouédard, G. Rimmelé & all, Oil & Gas Science and Technology, Review June 2007
  - "Heterogeneous porosity distribution in Portland cement exposed to CO_2-rich fluids" G.Rimmele, V. Barlet-Gouédard & all, Cement and Concrete Research, in press
  - A solution against well cement degradation under CO_2 geological storage environment." V. Barlet-Gouédard, G. Rimmele, O.Porcherie, N.Quisel & all , IJGGC under review
- **Calcium aluminate phosphate, Magnesium Potassium Phosphate cements**
  - **"**Well Technologies for CO_2 Geological Storage: Construction, Repair, Plugging Material and Procedures for Long Term Integrity" V. Barlet-Gouédard, G. Rimmelé, B. Goffé, 8th International Conference On Greenhouse Gas Control Technologies, June 2006, Trondheim, Norway

CO_2 testing results: Portland /Fly ash type F blend

CO_2 testing conditions:

- 90deg.C, 280 bars
- Wet supercritical CO_2 and in CO_2 dissolved in water (Spycher and Pruess, 2005)
- 3 weeks, 3 and 6 months CO_2 exposure

Effect of the salinity on CO_2 saturation



(Spycher and Pruess, 2005)

CO_2 saturation ↘ with salinity ↗

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15.8 ppg Portland /Fly ash type F blend

- After 6 months in CO_2 fluids
  - Cores placed in both CO_2 fluids are <u>all broken</u>
  - High level of carbonation inside cores and at cores surface
  - Discoloration after three and six months (dissolution pattern)
- Important weight (+16%) and density increase (+11%) after 3 weeks
- No measurable properties after 3-6 months due to the loss of integrity

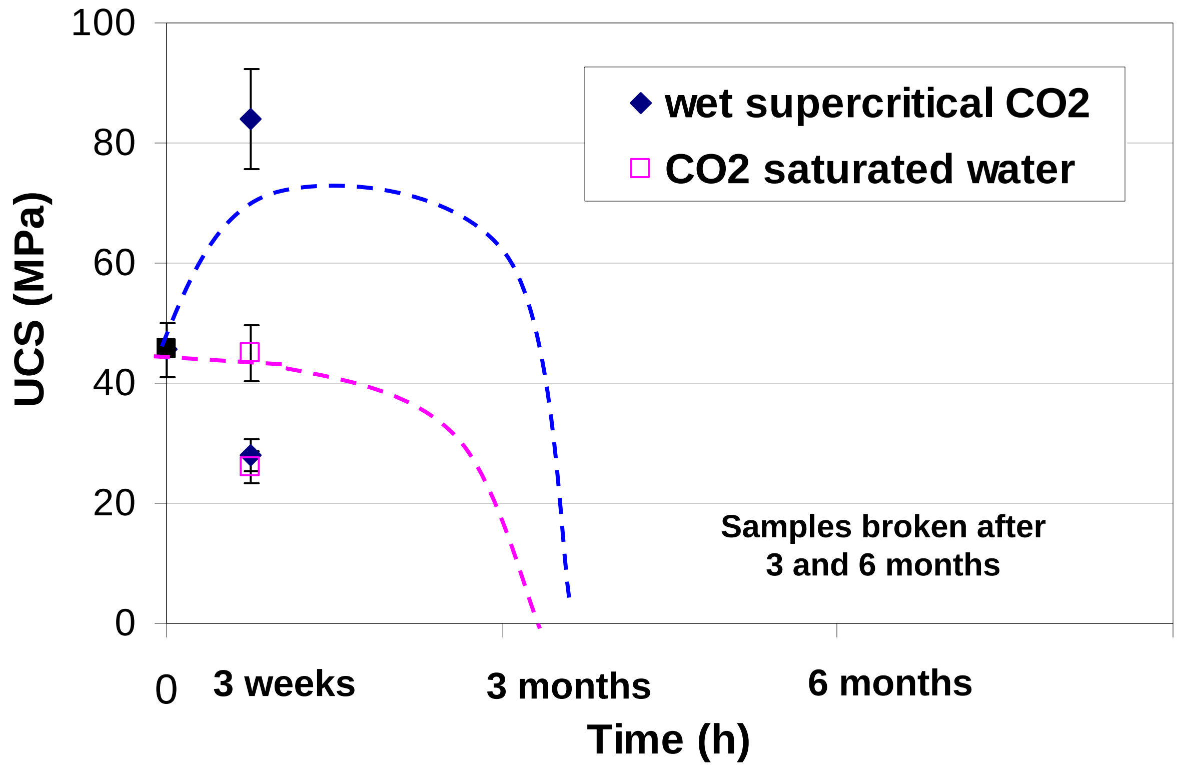
t_0

6 months

Dissolution front

cutting

Portland /Fly ash type F blend
Mechanical Properties

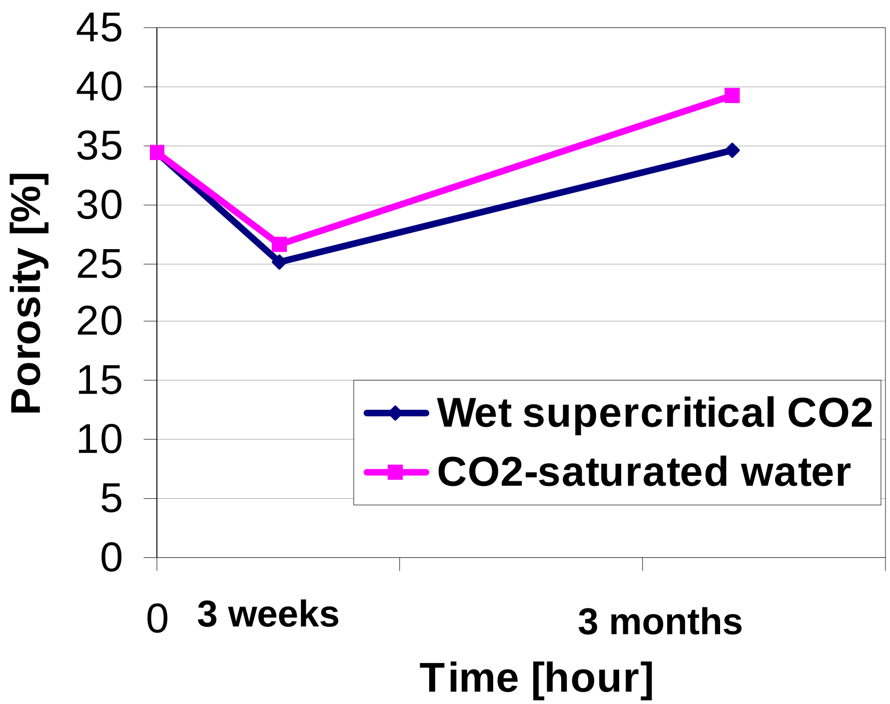


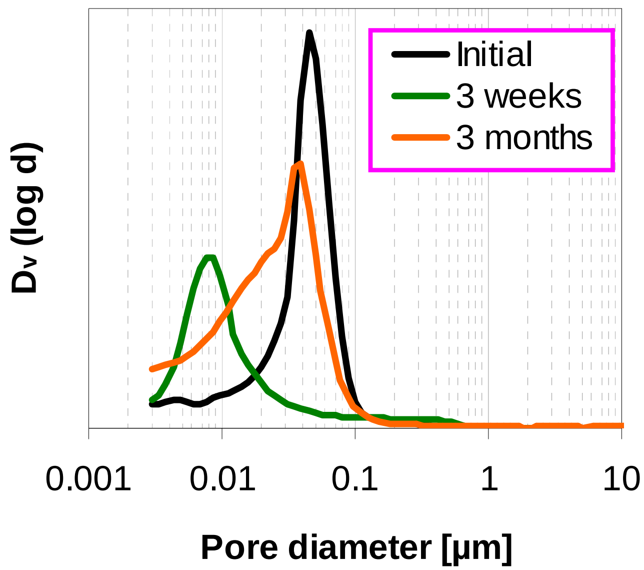
➢ Initial strength gain after 3 weeks: **carbonation sealing effect due to pore plugging as observed for Portland cement**

➢Mechanical properties not measurable after three and six months: **dissolution process effect**

Portland /Fly ash type F blend
Permeability / Porosity evolution

Mercury Intrusion Porosimetry

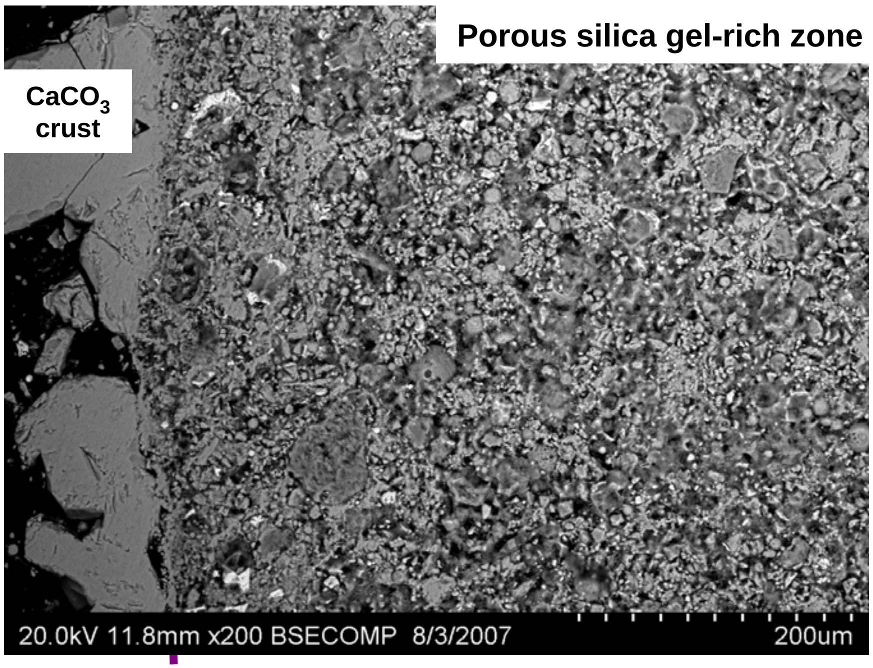




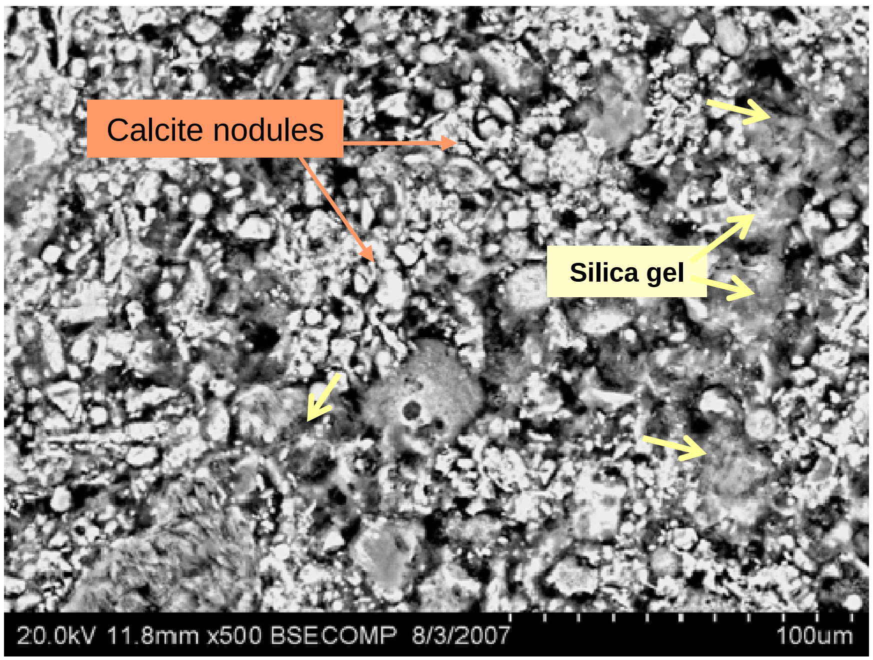
- Initial sealing stage followed by a dissolution stage

Portland /Fly ash type F blend:
After 6 months in the edge of cement sample

Sample's edge x200



Sample's edge x500



- Pop-corn like structure, lots of visible silica gel and $CaCO_3$ nodules
- More carbonated in CO_2-saturated water
- $CaCO_3$ dissolution visible in samples after 6 months of CO_2 exposure

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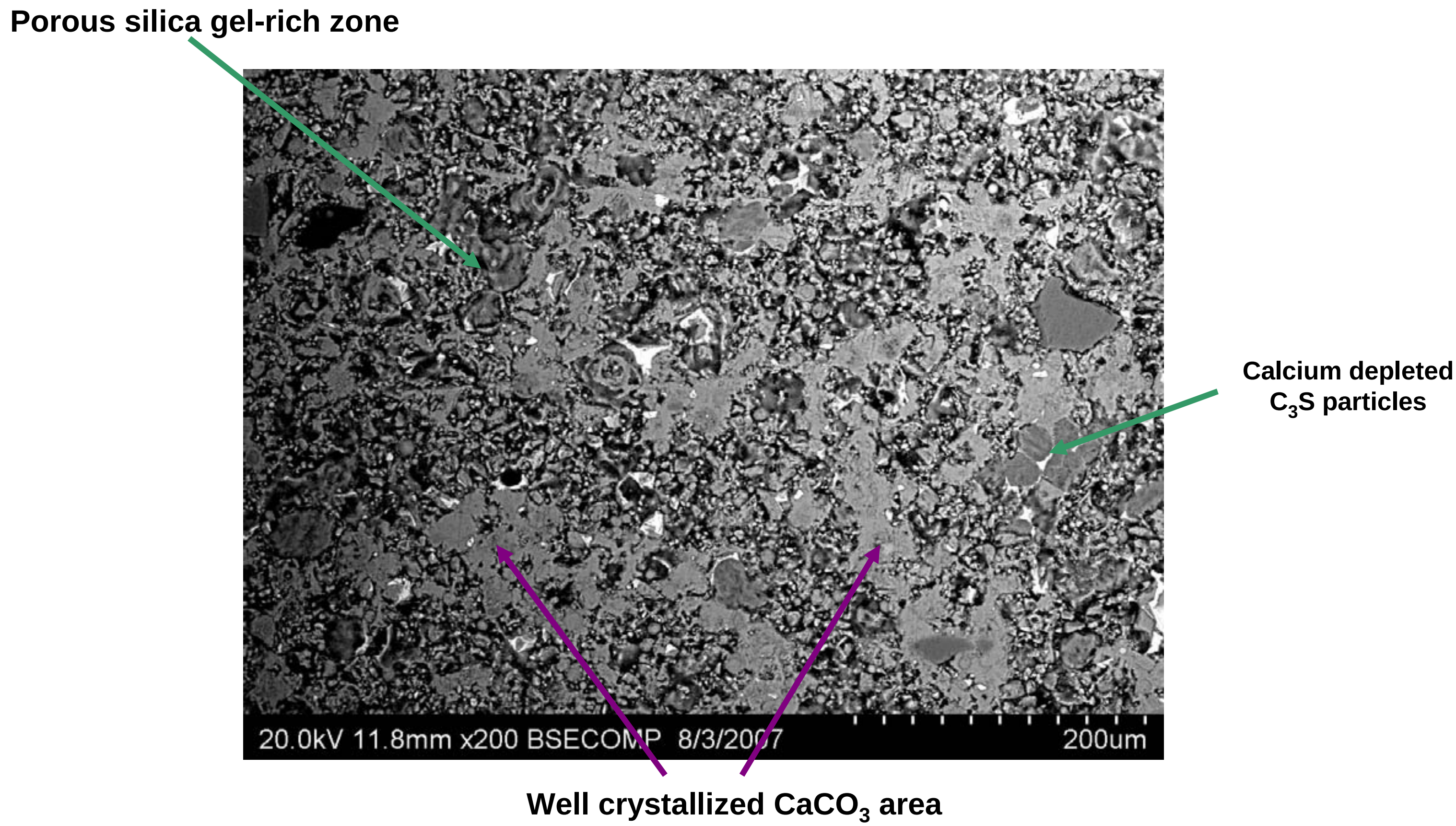
Portland /Fly ash type F blend: After 6 months in the core of cement sample



- Mix of silica gel-rich area and well crystallized $CaCO_3$ area
- Complete carbonation after three weeks (Calcite and its polymorphs)

Portland /Fly ash type F blend: Summary

- Strong brittleness (broken samples) after 6 months at 90 degC, 280 bars, in wet supercritical CO_2 and CO_2 dissolved in water fluids

- Two-stage chemical evolution:
  - Initial sealing stage ($CaCO_3$ precipitation)
  - Dissolution stage ($CaCO_3$ dissolution)

- Intense and complete carbonation already after 3 weeks

- Strong integrity loss after three and six months in CO_2 fluids

- Dissolution stage earlier than Portland cement

Durability Criteria

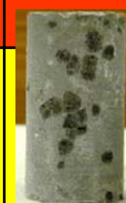
Green: CS above 20 Mpa whatever the cement density
Permeability stays below 0.01 mD up to 6 months
Stability after 2 days of CO_2 exposure up to 6 months

Yellow: CS above 20 MPa
No stability observed throughout CO_2 exposure

Red: CS below 7 MPa
High mechanical degradation
No stability observed with CO_2 exposure duration

How Portland /Fly ash type F can be compared with the others cements already tested under the same conditions?

Durability validation at 90deg.C- 280 bars - CO_2 + water					
System	1 week	3 weeks	1months	3 months	6 months
Magnesium Potassium Phosphate	Not tested			Not tested	Not tested
Calcium Aluminate Phosphate	Not tested			Not tested	Not tested
Portland cement					
Portland/Fly ash type F	Not tested		Not tested		
Portland/Fly ash type C	Not Tested		Not Tested		
CO_2 Resistant cement					



Thanks for
your attention!

Questions?

Schlumberger

Cement Carbonation: Effects on Mechanical Properties

Brice Lecampion, Schlumberger *Carbon Services Engineering*

Contributors:
C. Germay, A. Macieri (Epslog), F.J. Ulm, J. Vanzo (MIT), G. Rimmelé (SLB)

International Energy Agency Greenhouse Gas R&D Programme

4th WELL BORE INTEGRITY NETWORK meeting, Paris, March 18-19 2008

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Materials

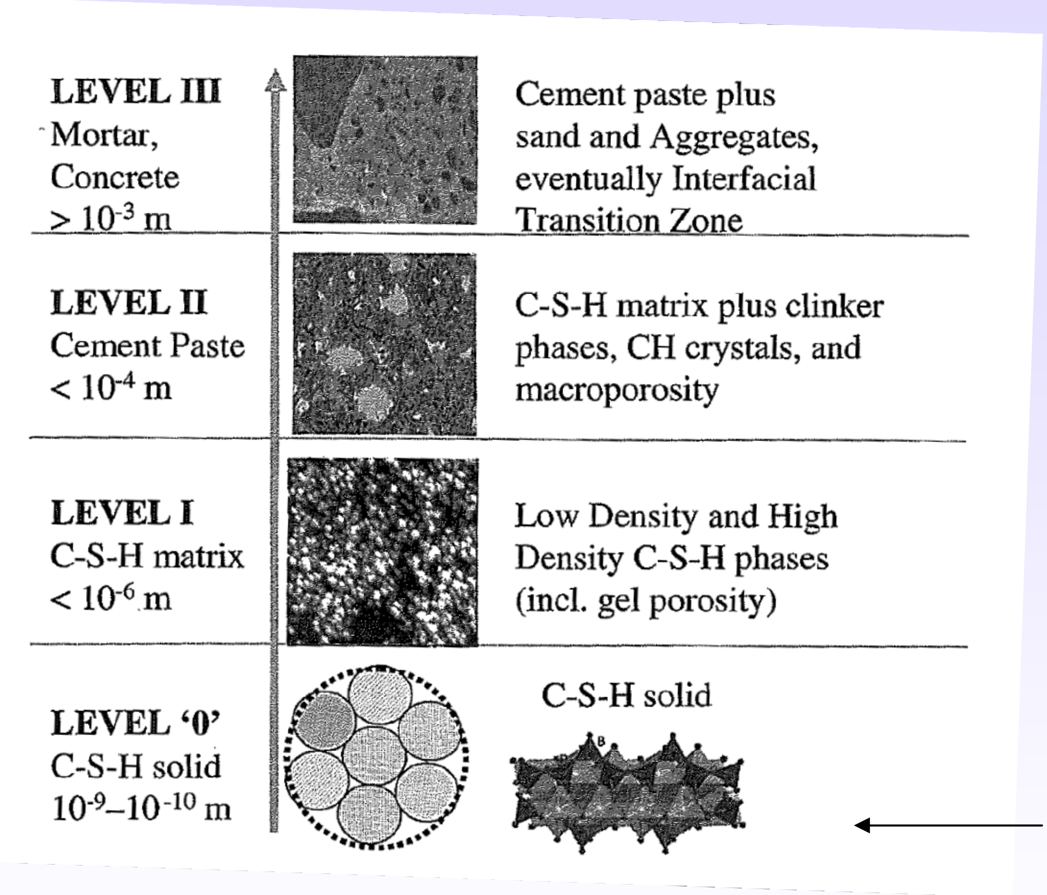
- Class G (Portland), 15.8 ppg, 41% SVF (w/c=0.45), P=3000PSI, T=90C
- Exposure in Co2 reactor (CORE) [Rimmelé et al., 2006]

Samples #	1	2	3	4	5
Fluid type	-	Wet supercritical CO2	Co2+H2O	Wet supercritical CO2	Co2+H2O
Duration	-	88h	88h	523h	523h
Thickness	-	2 mm	3 mm	5 mm	6-7mm

• *Investigate the mechanical behavior of the different zones at different scales*

• *Focus on the early stage of the carbonation process (no leaching of CaCO3)*

Cement is a multi-scale porous material



Scratch tests (l~0.25mm)

Nano-Indentation (l~0.1μm)

Intrinsic elastic properties of CSH "globule"

E~63GPa φ=0.18

[Constantinides & Ulm, 04,07; Ulm et al. 07 etc.]

[Jennings et al.,1994, 2007, Ulm et al. 2007]

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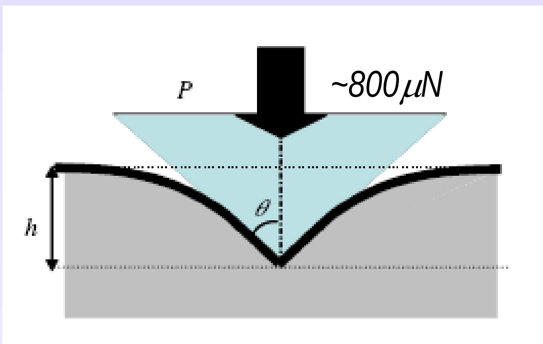
Experiments at two different scales

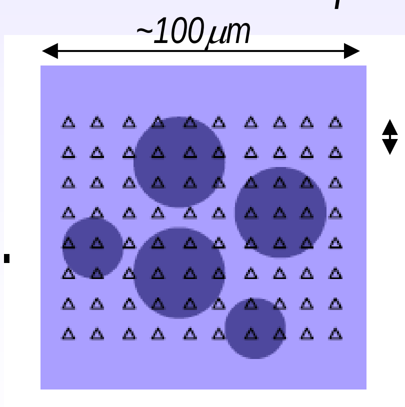
- NanoIndentation

[Ulm et al., 2007, Oliver & Pharr 1992]

~300nm



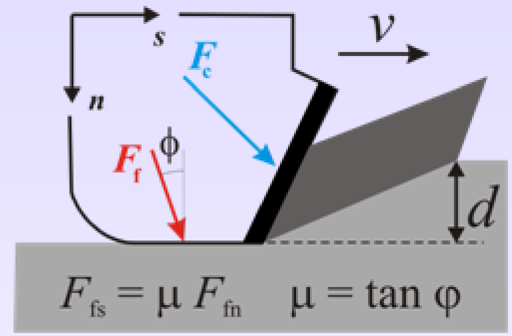
Grid of indentation tests to probe the CSH matrix



~20μm

→ *Statistical de-convolution* [Ulm et al., 2004-2007]

- Scratch Tests

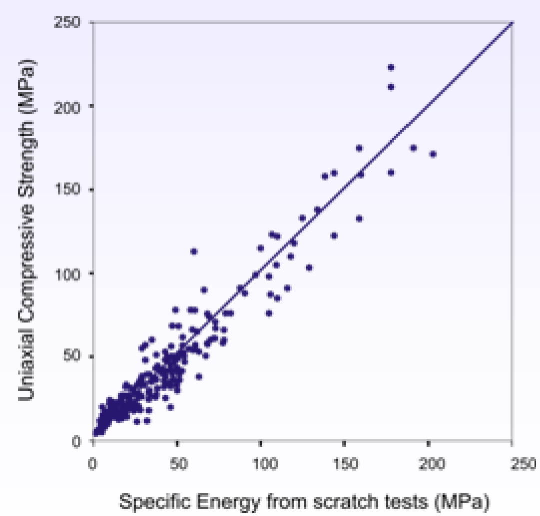


d ~ 0.1/0.25mm

w: 10/5/2.5mm

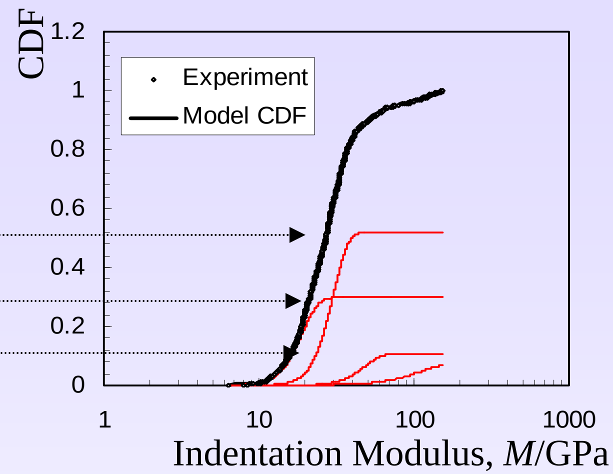
v ~ 1 cm/s

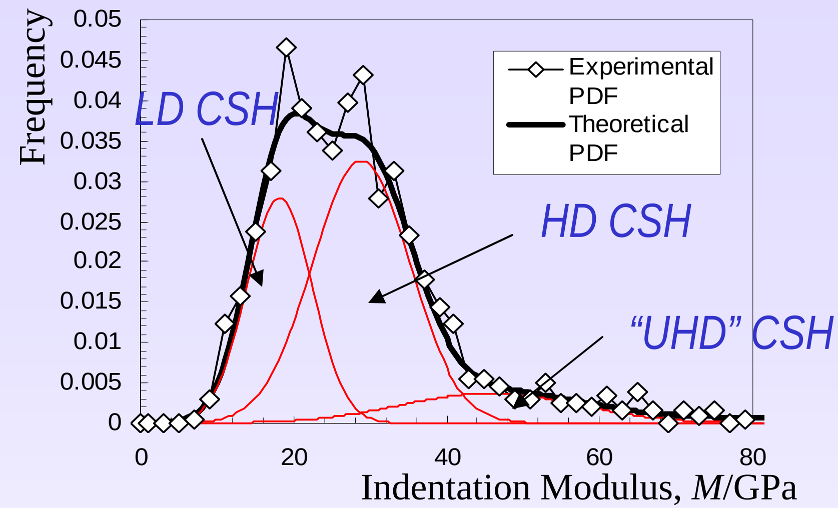
[Detournay & Defourny, 1992]

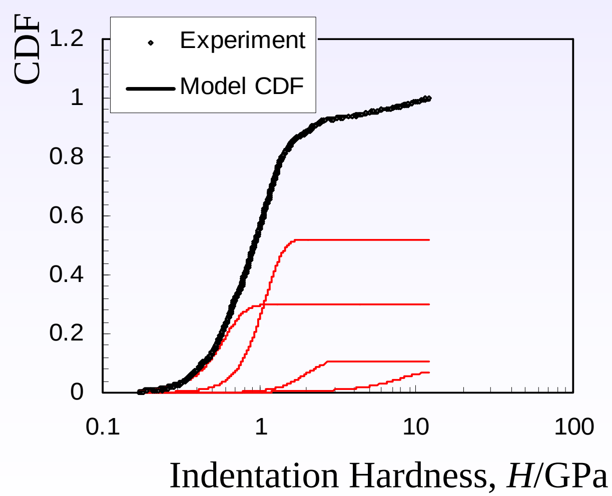


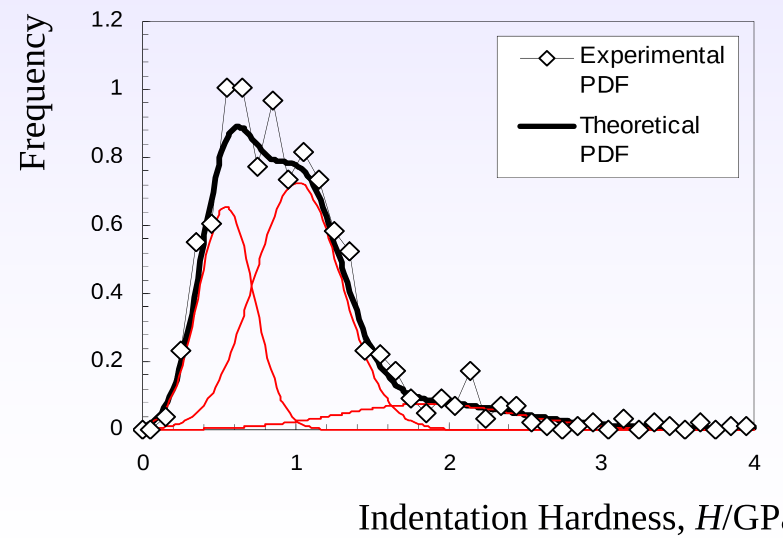
Un-degraded Material: CSH matrix, nano-indentation

Volume fractions of the # type of CSH forming the CSH matrix

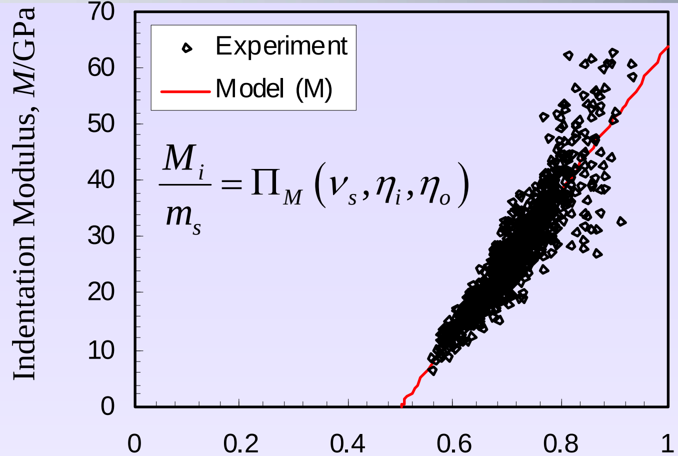


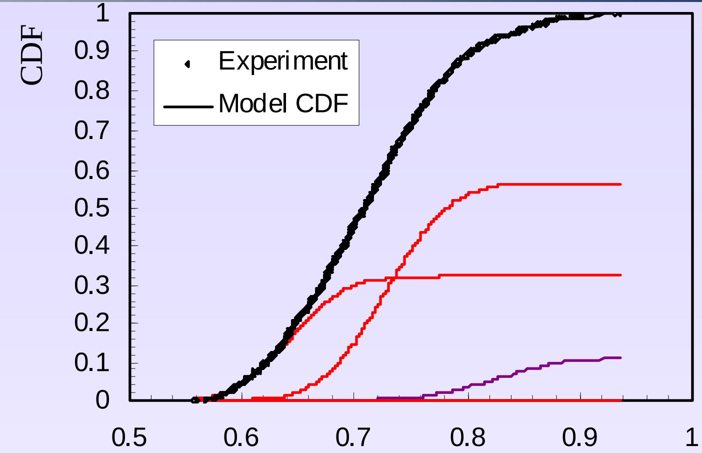


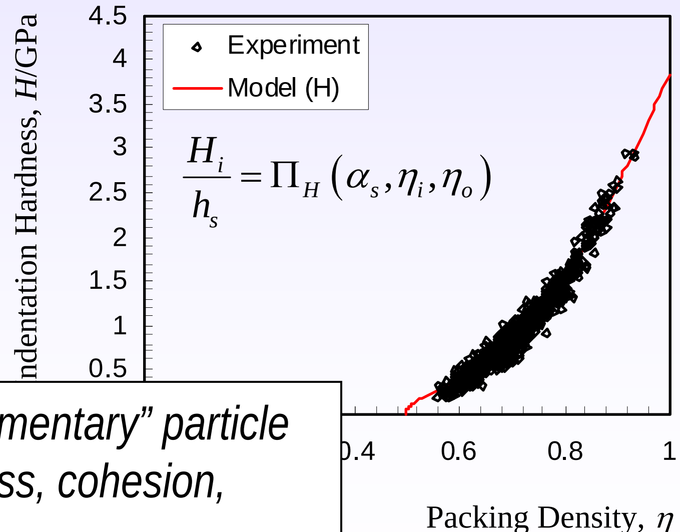


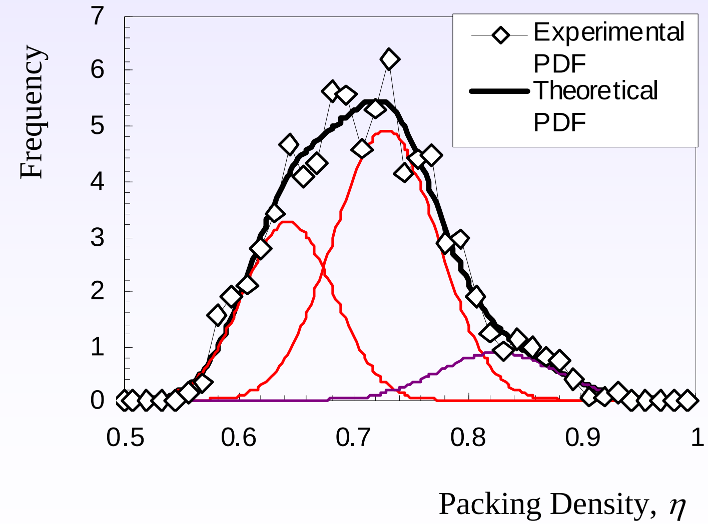


Un-degraded Material: CSH matrix





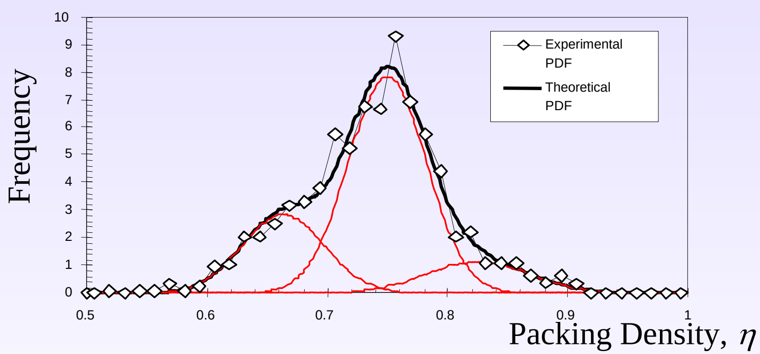


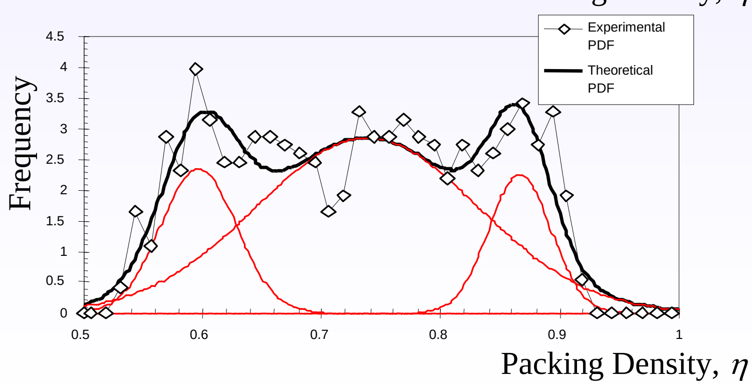


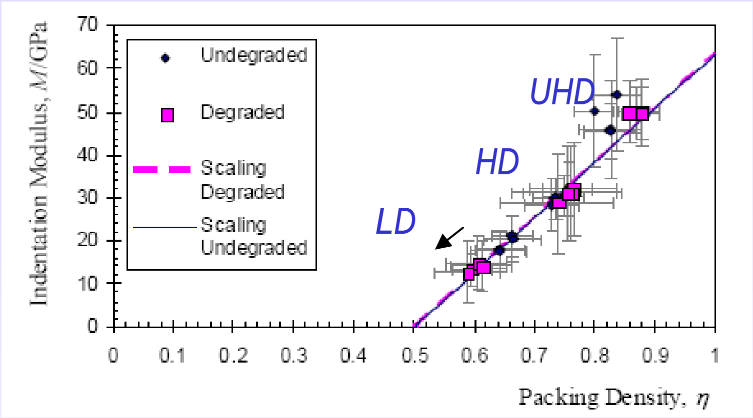
Estimation of "elementary" particle properties (stiffness, cohesion, friction)

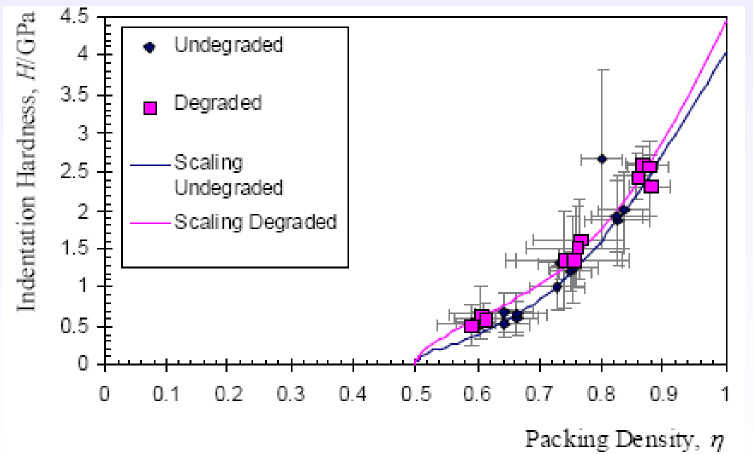
Evolution of CSH matrix: nano-indentations

- No evolution of the CSH matrix in the center of the sample
- HD CSH properties unchanged, LD packing density slightly decreases
- … the phases packing densities are more widespread,
- "Elementary particle" cohesion increases…. but friction decreases



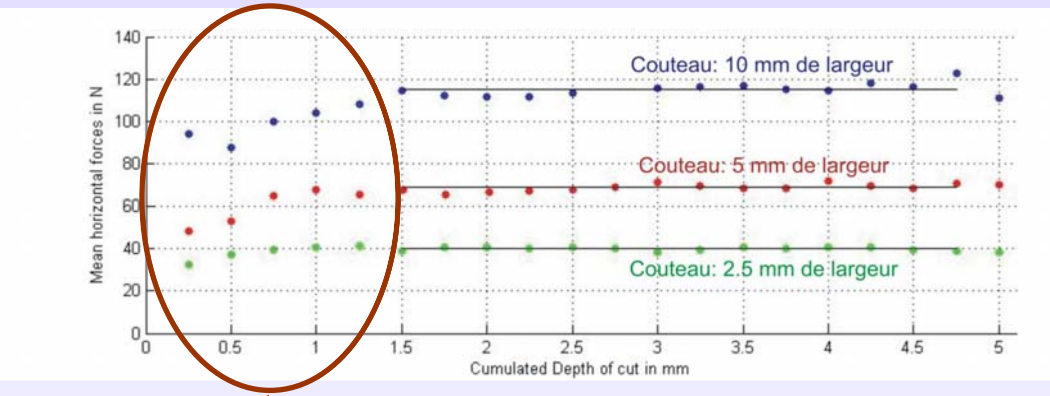


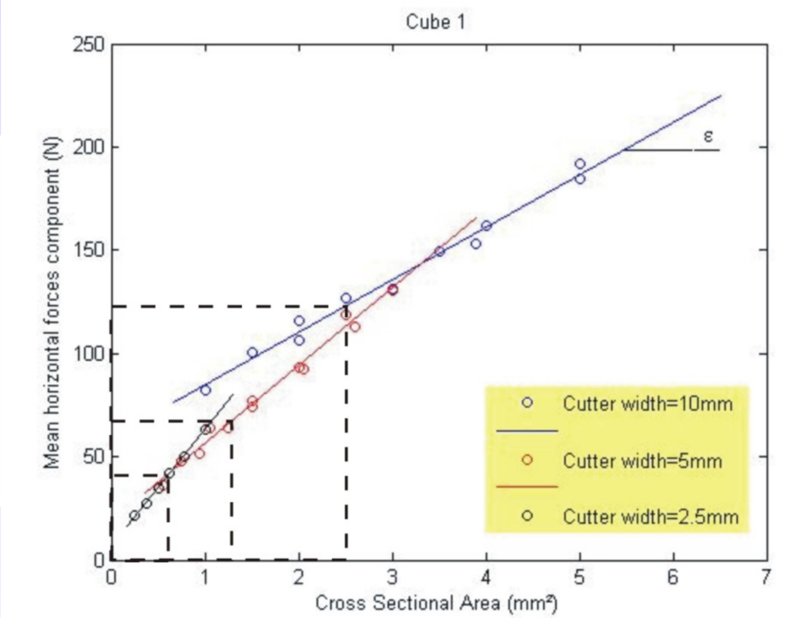




Un-degraded Material: Scratch tests, UCS

Forces vs Depth?

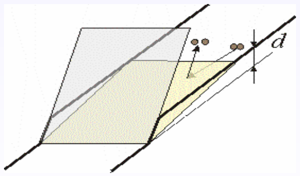


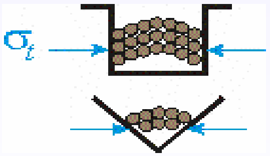


Weaker material + chipping

Front can be captured if it is > 1.5mm from the surface !!!

Dilatancy- Arching





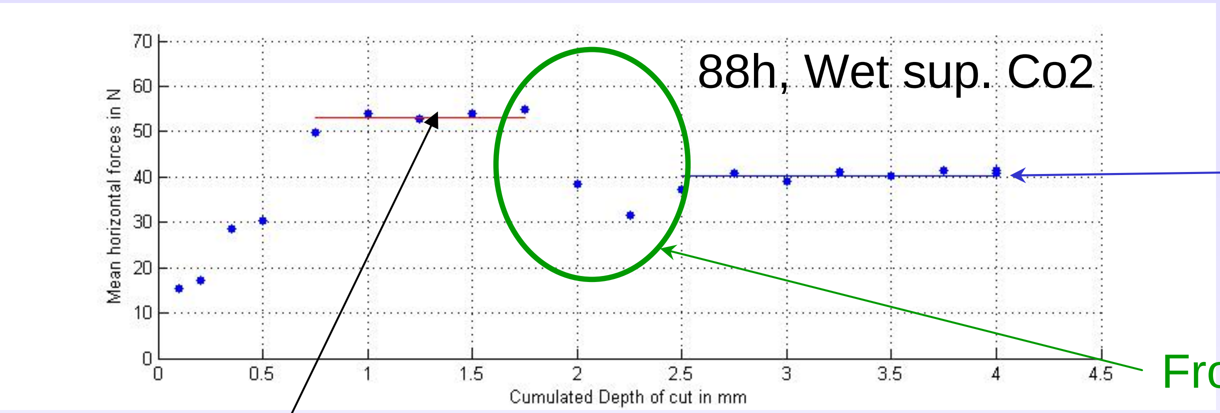
Cutter width Effect

- UCS ~ 44 MPa, E_{stat} ~ 11GPa

There is still a lack of data on cementitious material to validate UCS / Specific Energy correlation … but the trend is there.

Macroscopic Evolution: Scratch Tests

Forces with depth? (depth of each cut : 0.25mm)

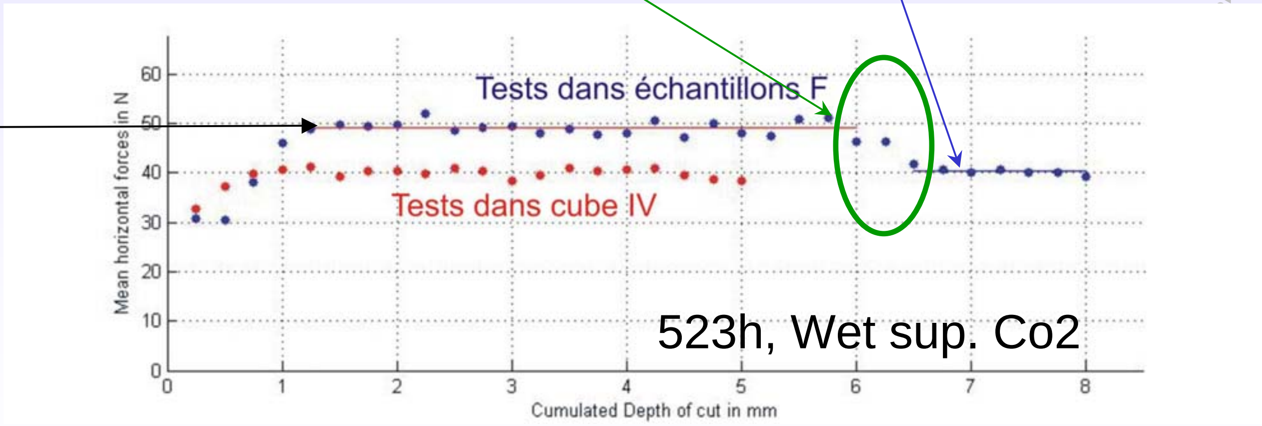


The center of the sample keeps the properties of the original material

Un-degraded zone

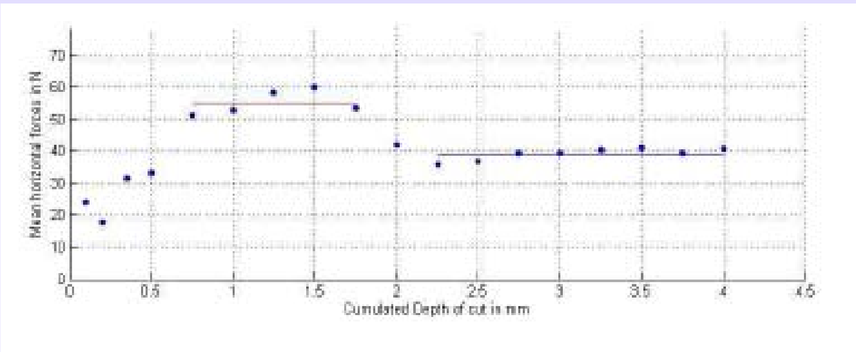
Fronts

Carbonated zones

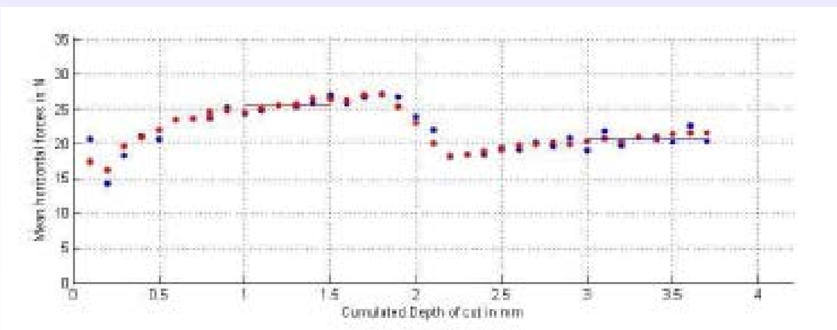


Improving fronts detection

d=0.25mm

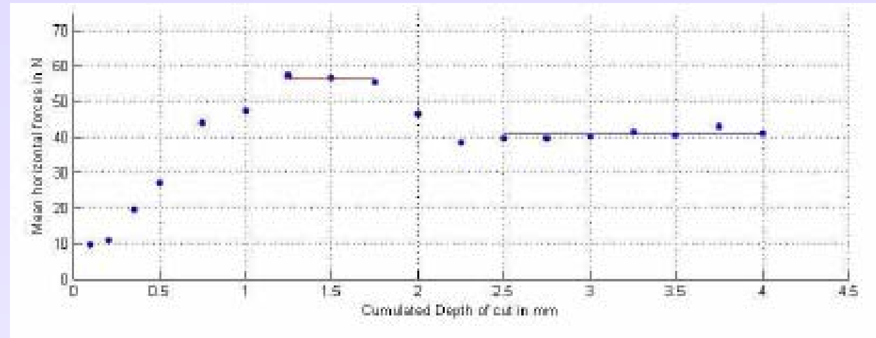


d=0.1mm

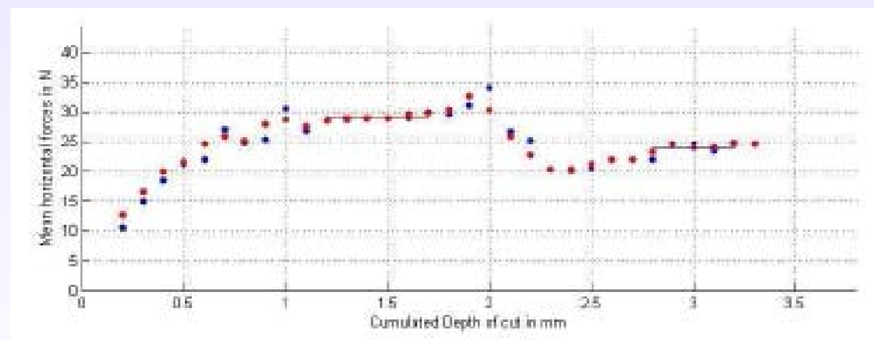


88h, Wet sup. Co2

d=0.25mm



d=0.1mm



88h, Co2+water

Macroscopic Evolution: Scratch Tests

Samples	Intrinsic specific energy (MPa) 10 mm – Carbonated zone	Equivalent UCS (MPa) – Carbonated Zone	Intrinsic specific energy (MPa) 10 mm – Un-degraded zone	Equivalent UCS (MPa) – Un-degraded Zone
88h, wet Sp Co2	36.96	60.73	24.92	40.95
88h, wet Sp Co2	35.42	58.20	25.76	42.33
88h, Co2+H20	37.93	62.32	26.03	42.77
88h, Co2+H20	37.06	60.89	27.27	44.81
523h, wet Sp Co2	33.43	54.93	25.37	41.69
523h, wet Sp Co2	32.34	53.14	25.54	41.97
523h, Co2+H20	34.72	57.05	25.58	42.03
523h, Co2+H20	32.65	53.65	24.41	40.11
Mean	35.06	57.61	25.61	42.08

Un-degraded Material: XRD, up-scaling

- Mass fractions from XRD

Converted in volume fractions (length-scale of cement paste)

- Microporomechanics up-scaling

[Dvorak & Benveniste 1992, Berryman 1997, Dormieux et al. 2002]

- *First up-scaling to estimate the CSH matrix properties*

(using results from the __nano-identation__ campaigns)

- *… second up-scaling to estimate cement paste properties*

Mori-Tanaka scheme (with *Huang et al. 1993*, sliding inclusion solution)

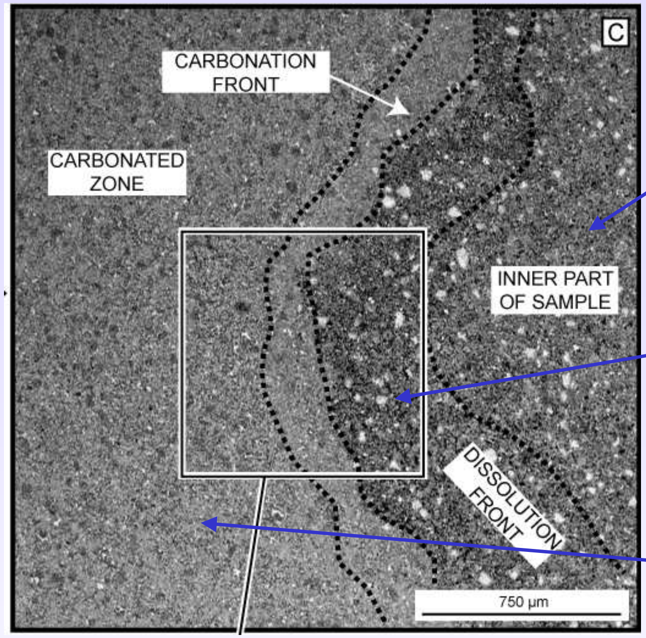
$$E = 18.8GPa, \nu = 0.3,$$
$$b = 0.59, M = 4.2GPa$$
$$V_p = 3590m/s, V_s = 1915m/s$$

	Volume fraction	k (GPa)	g (GPa)
CSH-like	0.31	16.2	10.8
C4AF	0.082	104	48
Calcite	0.018	73	32
Quartz	0.008	37	44
Ettringite	0.06	27.3	9.9
Katoite	0.06	99	66
CH	0.27	33.3	15.38
Macro-porosity	0.192	-	-

Similar material (from UPV)

$$V_p = 3450m/s$$

Macroscopic Evolution: mechanical up-scaling



Taken from Rimméle et al., 2006

Un-degraded material:

$$E = 18.8 GPa, \nu = 0.3,$$
$$b = 0.59, M = 4.2 GPa$$

Dissolution Front: CH replaced by pores

$$E = 8.2 GPa, \nu = 0.3,$$
$$b = 0.83, M = 4.2 GPa$$

Carbonated zone: Original CH replaced by Calcite (+11% volume increase)

$$E = 23.9 GPa, \nu = 0.304,$$
$$b = 0.608, M = 4.18 GPa$$

Using the un-degraded properties of the CSH matrix

Ratio Carbonated / Un-degraded :

Scratch	Up-scaling
$\frac{\varepsilon_{carbonated}}{\varepsilon_o} = \frac{35.05}{25.6} = 1.37$	$\frac{E_{carbonated}}{E_o} = \frac{23.9}{18.8} = 1.27$

Concluding remarks : *Early stage of carbonation*

- Inner part of the samples have similar properties than the original material (*at all scales*)

- CSH matrix properties do not *significantly* evolve *although*:
  - CSH packing assemblies are more wide-spread (i.e. disordered)
  - "Elementary CSH particle" sees an increase of its cohesion, but a decrease of its frictional performance

- Scratch tests capture the location of the carbonation front
  - Dissolution front is a weaker zone
  - Carbonated zone is stiffer (classical results in Civil Engng), higher intrinsic specific energy (i.e. higher cohesion), friction ?

- Up-Scaling allows to *estimate* elastic properties in the different zones

- Mechanical performance of the cement sheath will be associated with the thickness of the dissolution zone (in the "early" stage of Co2 / cement interaction)

Hydro-Mechanical Properties of Carbonated Cements

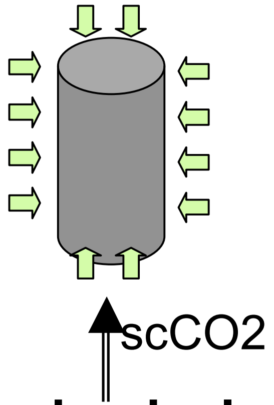
A. Fabbri[1,3] , J. Corvisier[1], A. Schubnel[1], F. Brunet[1]
J. Fortin[1], B. Goffé[1], V. Barlet-Gouédard[2], G. Rimmele[2], Y. Leroy[1]

[1]Laboratoire de Géologie
[2]Schlumberger
[3]BRGM

4th MEETING of the WELL BORE INTEGRITY NETWORK, Paris - 18t/19th March 2008

Motivation

1) Carbonation under in situ conditions (P=30MPa, T= 90degC and sc CO2)



1) Wet or Dry scCO2
2) Wet or Dry cement samples

Existence or Non- of a carbonation front

2) Mechanical properties under in-situ pressure (Pc=30Mpa, Pp=28Mpa)
tri-X stress conditions

1) Loading/Unloading cycles on wet and ry Carbonated cement samples

Static elastic moduli

2) Permeability measruments and Elastic wavespeed determination

Evaluation of damage

3) Macroscopic rupture strength

Evaluation of aging/wear

Sample carbonation

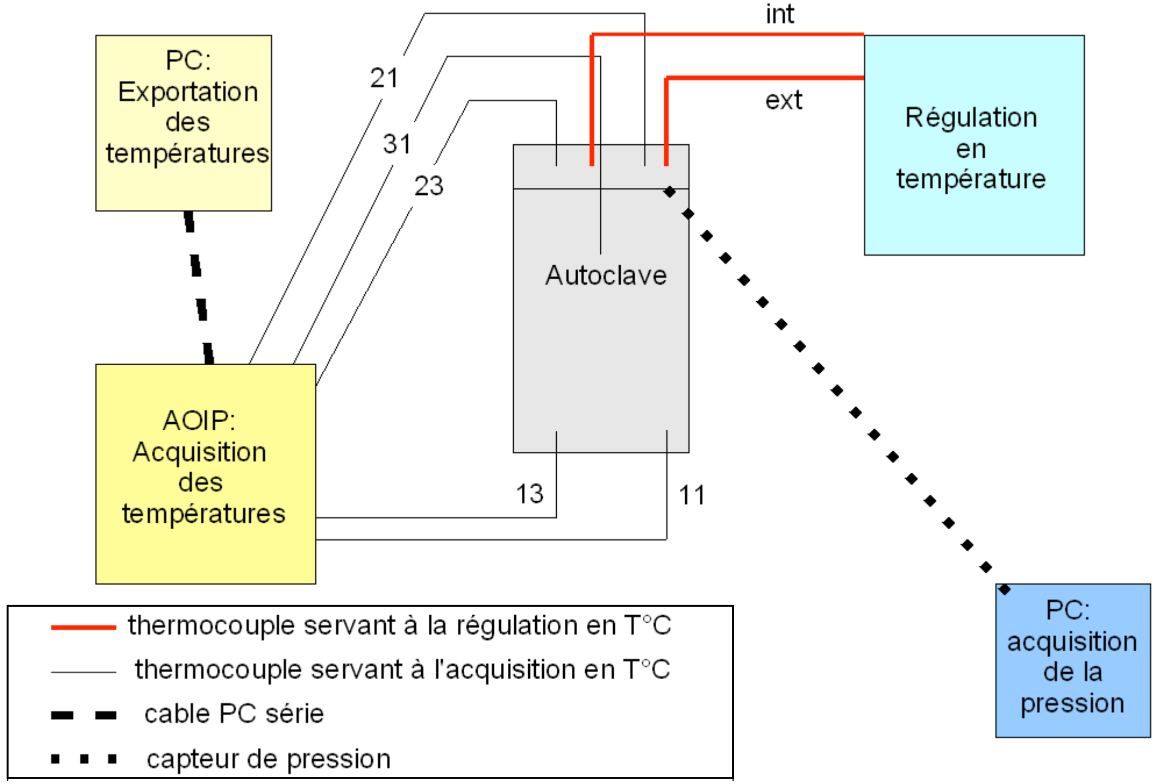
Experimental Set-up

Technical characteristics

Sample maximum diameter
30 mm

Maximum Pressure
350 bars

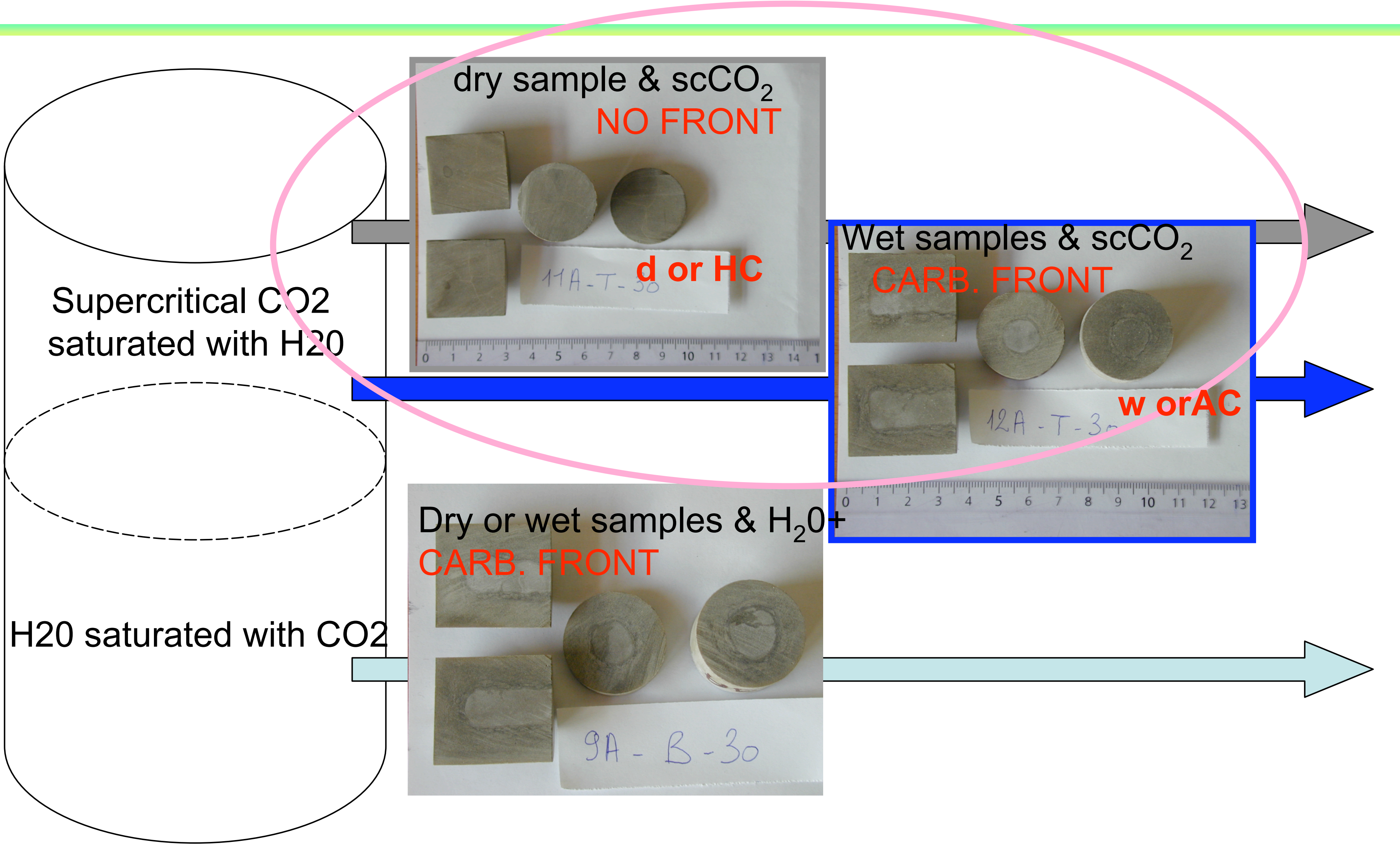
Temperature heterogenities
<3°C



Carbonation at 90°C and 28 MPa (Pc=Pp)

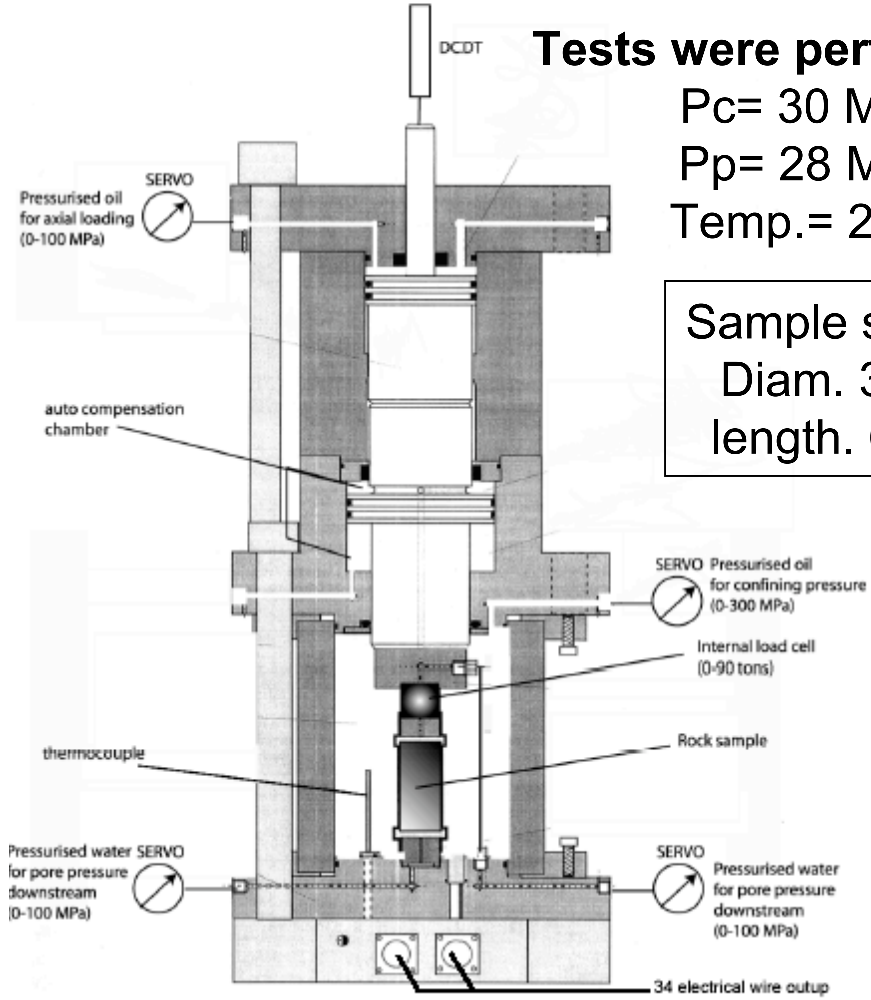
Sample Carbonation Results

Example for a carbonation time of 35 days



Mechanical and Physical Properties under in-situ cond.

Experimental set-up



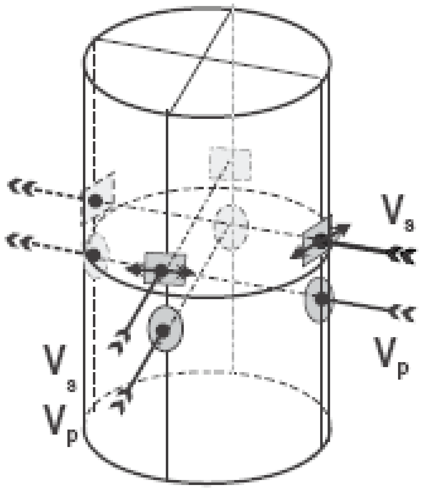
Tests were performed @
Pc= 30 MPa
Pp= 28 MPa
Temp.= 20°C

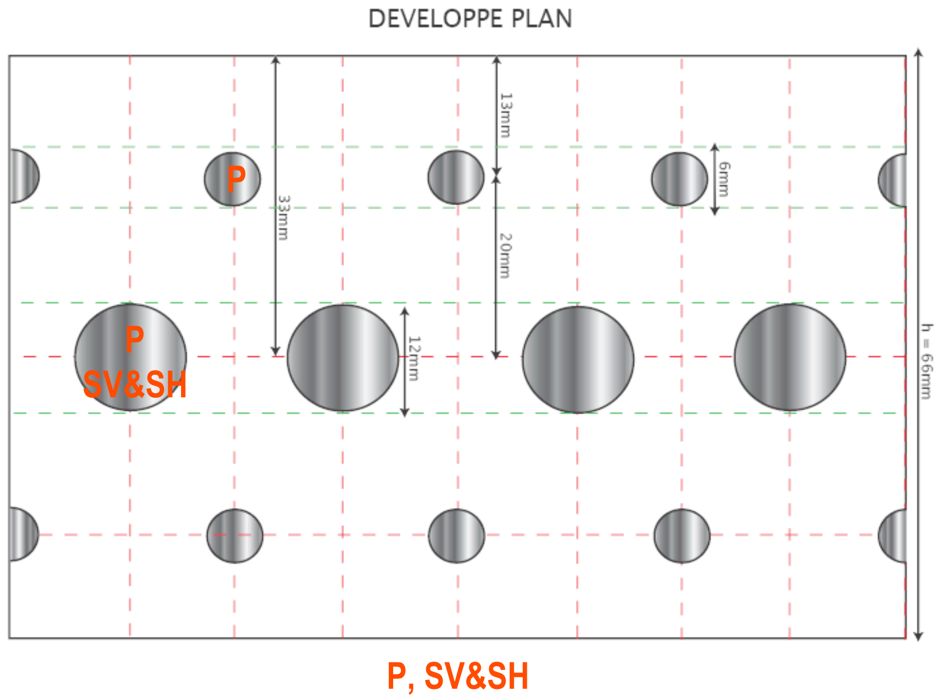
Sample size
Diam. 30
length. 60

Mechanical and Physical Properties under in-situ cond.

Experimental set-up - wavespeed measurements

PZT sensors: Piezo-ceramic (Lead Zirconate Transducers, 0.1-1MHz)
Active source : Elastice wavespeed and travel time





4 couples of Source - receivers Triband (1P, 2S)
→ Autopicking & Crosscorrelations: 0.5% of relative error on wavespeeds

Mechanical and Physical Properties under in-situ cond.

Theoretical background - Crack density determination

$$G = \rho V_s^{\,2}$$ S wave

$$K = \rho\left(V_p^{\,2} - \frac{4}{3}V_s^{\,2}\right)$$ P wave

$$\frac{K_m}{K} = 1 + \frac{d_f}{1-\phi}\frac{h(2-\nu_m)}{2(1-2\nu_m)} + \frac{\phi}{1-\phi}\frac{3(1-\nu_m)}{2(1-2\nu_m)};$$

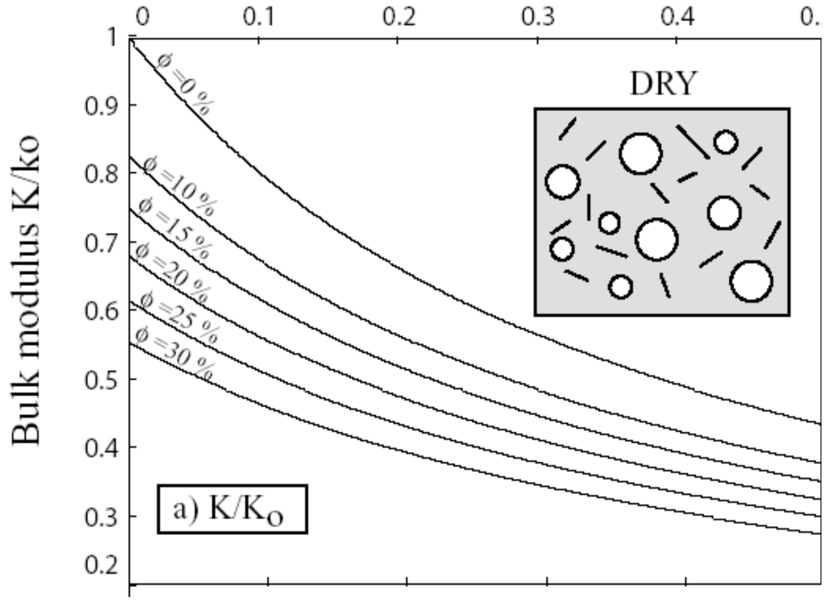
$$\frac{G_m}{G} = 1 + \frac{d_f}{1-\phi}\frac{h(5-\nu_m)}{5(1-2\nu_m)} + \frac{\phi}{1-\phi}\frac{15(1-\nu_m)}{7-5\nu_m}$$

porosity

avec

$$h = \frac{16(1-\nu_m^{\,2})}{9(1-0.5\nu_m)}$$

Crack density



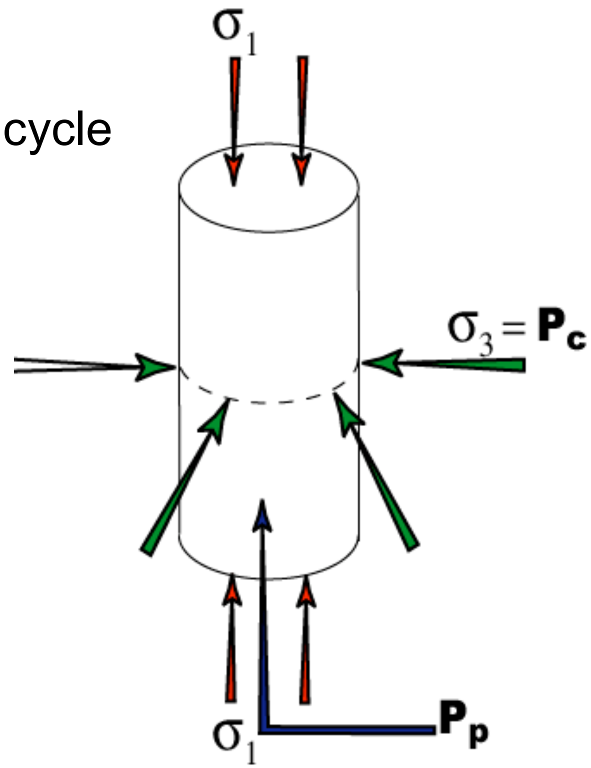
Effective Medium Modelling of rock containing Pores and Cracks using NIA approximation

[Fortin, Gueguen and Schubnel, J.Geol.Res., 2007]

Experimental procedure

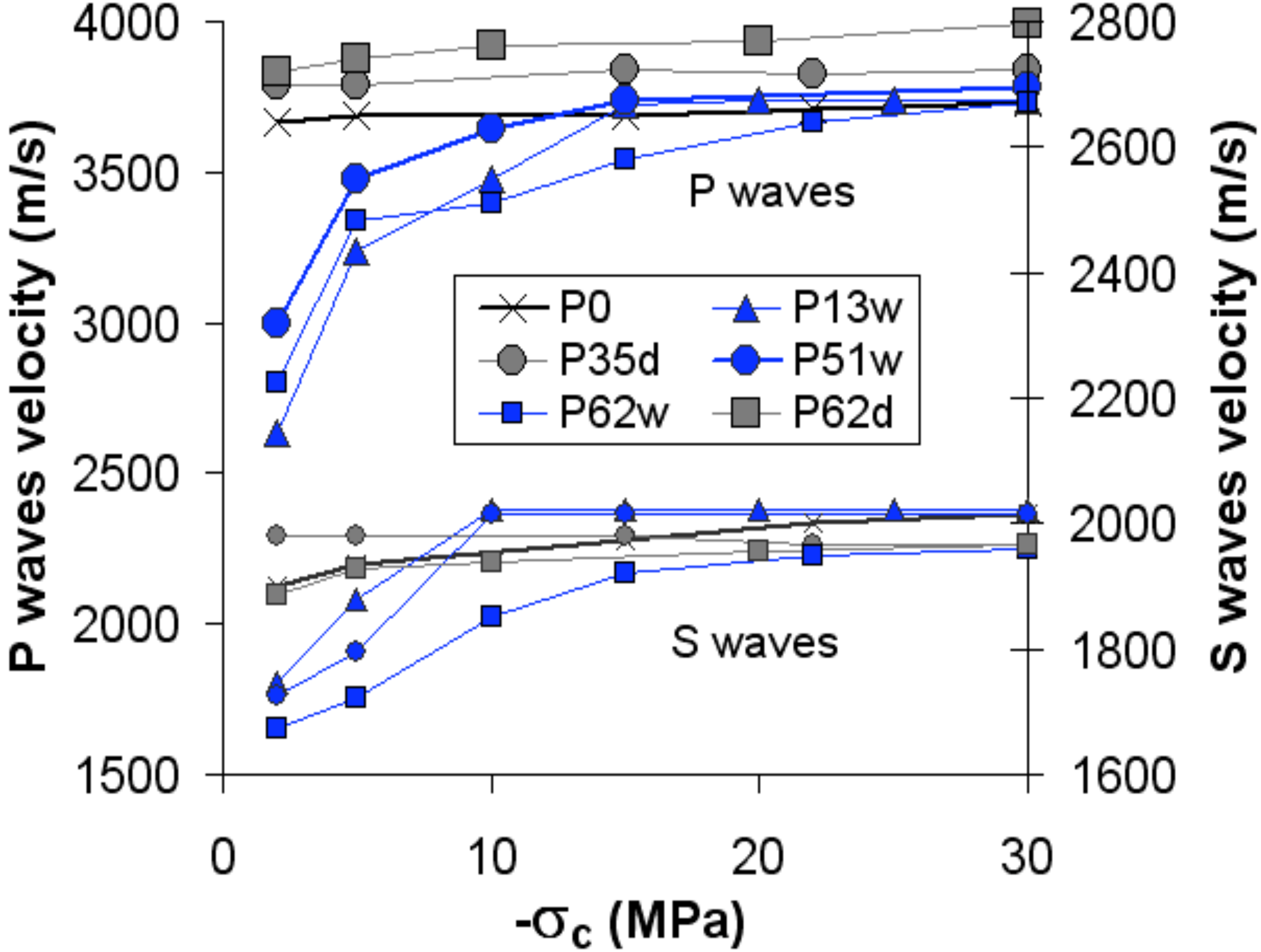
Running a single test… on a (pre)carbonated cement sample

1) Confinement from 0 to 30MPa in dry conditions
2) Deviatoric stress (Gzz) from 0 to 30 MPa / Load-unload cycle
3) Pore volume saturation with Argon gas at 28MPa
4) Argon gas permeability
5) Water saturation from 0 to 28 MPa
6) Water permeability
7) Deviatoric stress (Gzz) from 0 to 30 MPa
8) Water permeability
9) Deviatoric stress (Gzz) from 30 to 50 MPa
10) Water permeability
11) Deviatoric stress (Gzz) from 50 to rupture



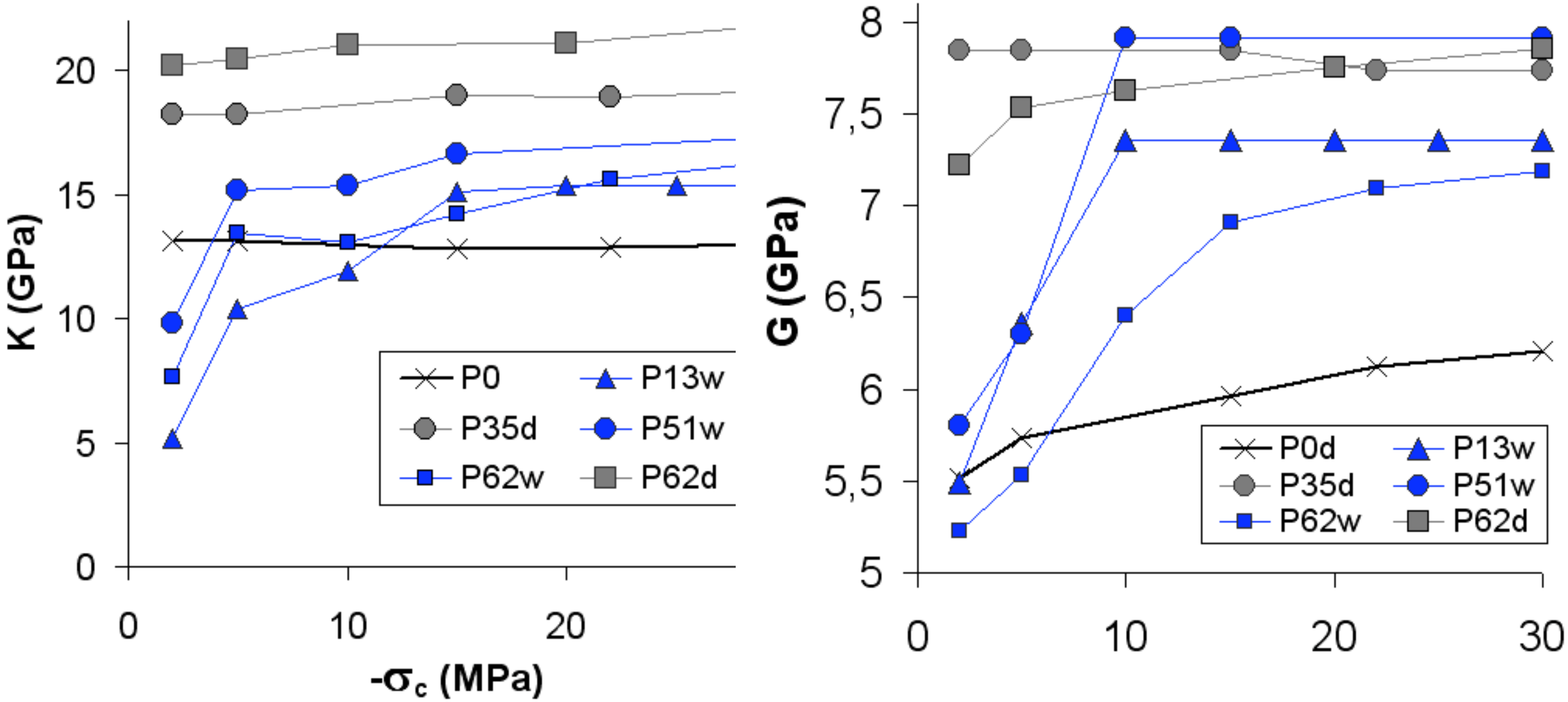
Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength



Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength



Some experimental results

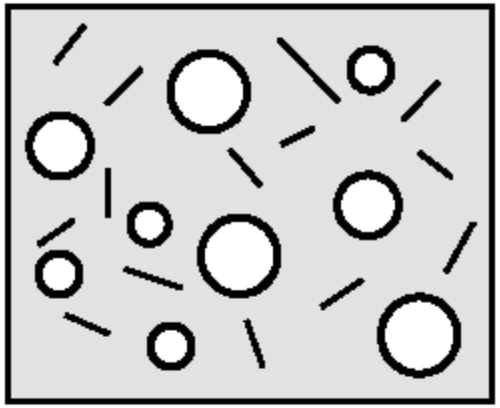
Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

Elastic properties of porous rocks : *modelling using EMT, DRY*
non-interactive theory (isolated penny shaped cracks and holes)
Counteracting effects of pore and cracks

The elastic potential can be written:

$$\Delta f = \frac{1}{\Gamma}\left(\Delta f^{\text{holes}}_{\text{non-int}} + \Delta f^{\text{cracks}}_{\text{non-int}}\right)$$

Stress interactions between holes and cracks



DRY:

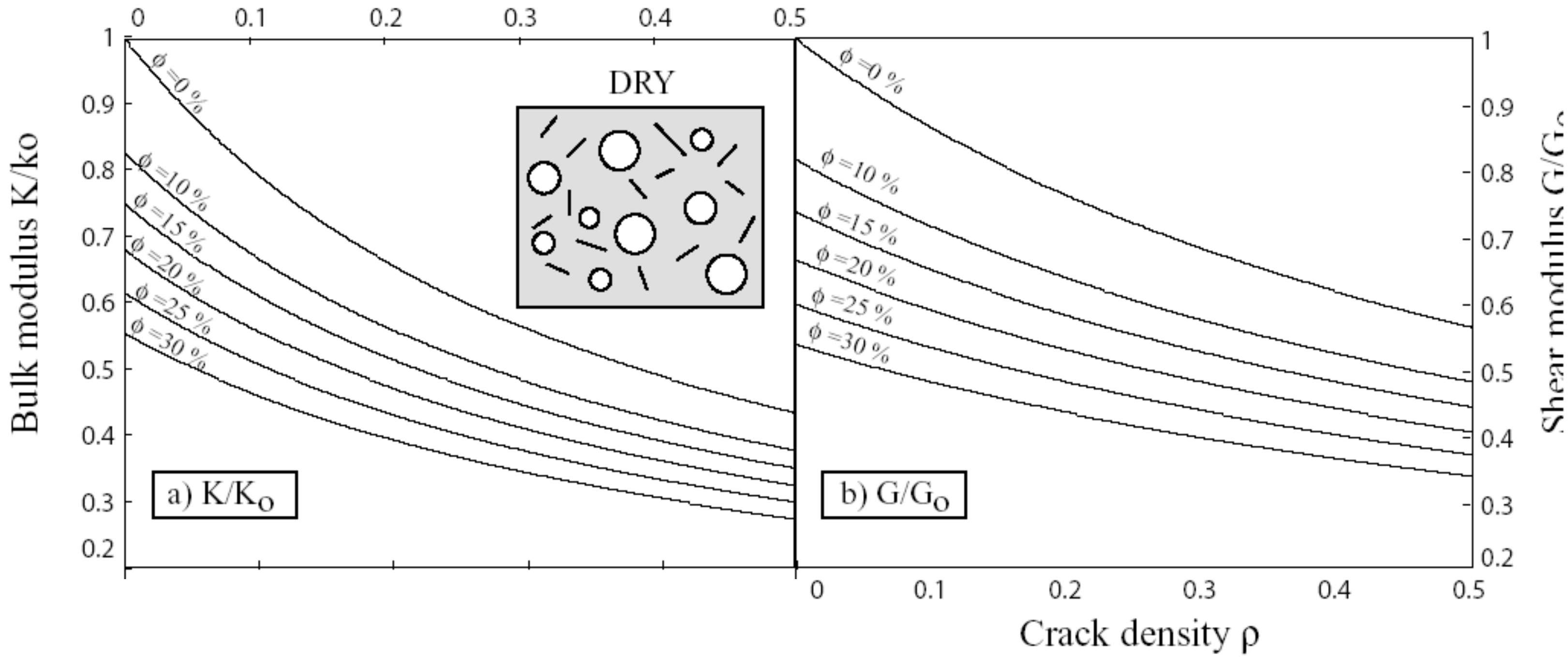
$$\frac{K_o}{K} = 1 + \frac{\rho}{1-p}\,\frac{h}{1-2\nu_o}\left\{1 - \frac{\nu_o}{2}\right\} + \frac{p}{1-p}\,\frac{3(1-\nu_o)}{2(1-2\nu_o)},$$

$$\frac{G_o}{G} = 1 + \frac{\rho}{1-p}\,\frac{h}{1+\nu_o}\left\{1 - \frac{\nu_o}{5}\right\} + \frac{p}{1-p}\,\frac{15(1-\nu_o)}{7-5\nu_o}.$$

Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

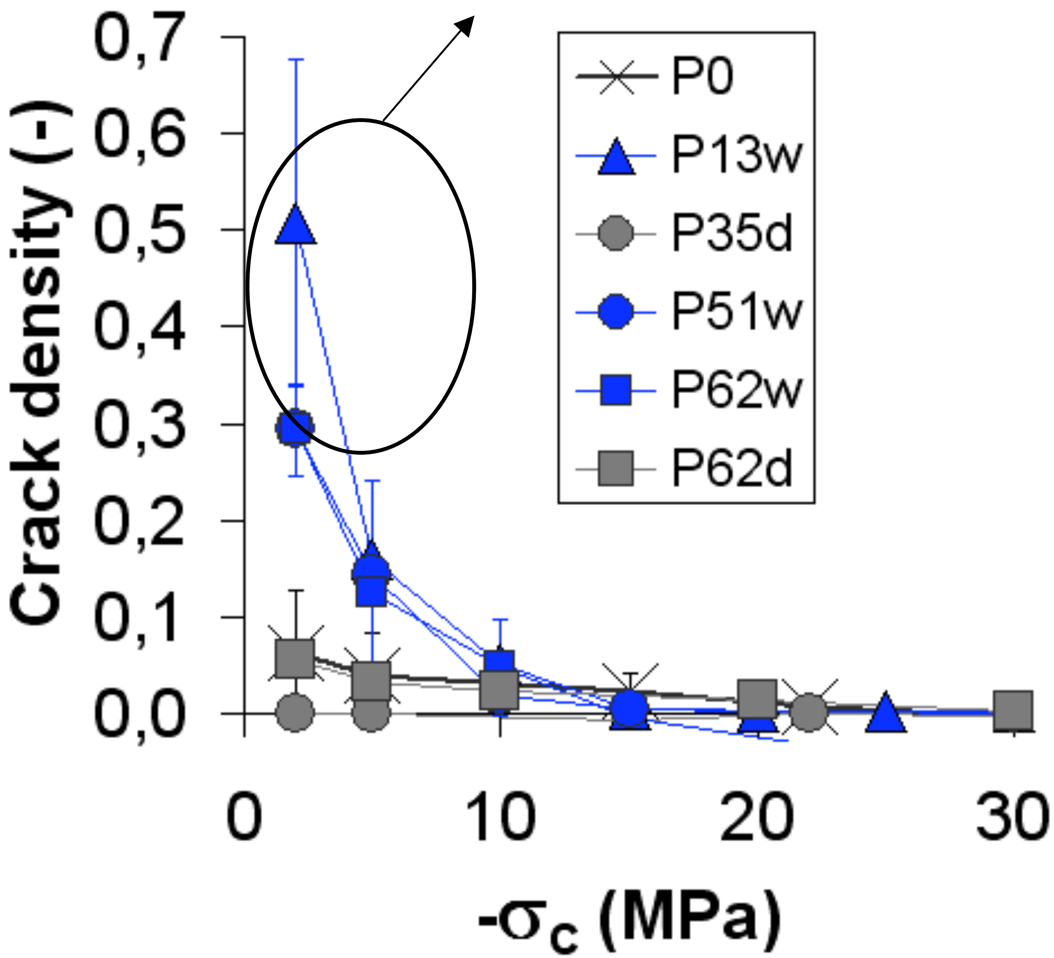
Elastic properties of porous rocks : *modelling using EMT, DRY*
non-interactive theory (isolated penny shaped cracks and holes)
Counteracting effects of pore and cracks



Some experimental results

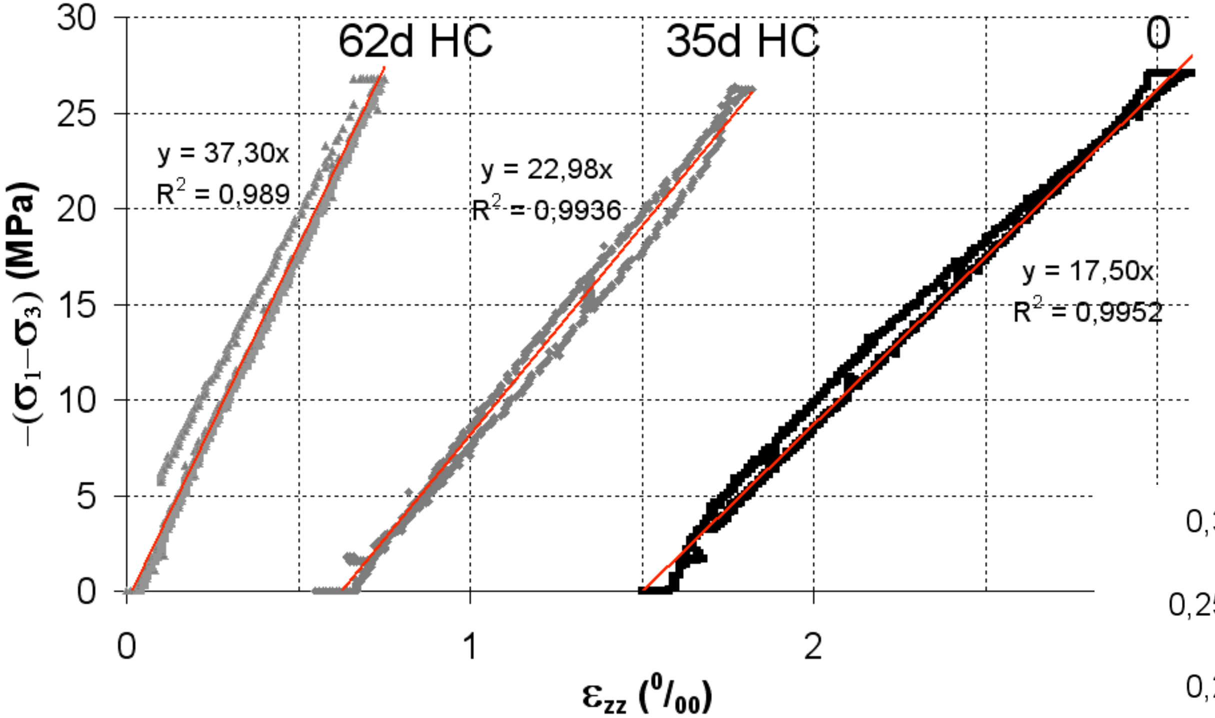
Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

Connected domain ⇨ CO_2 migration

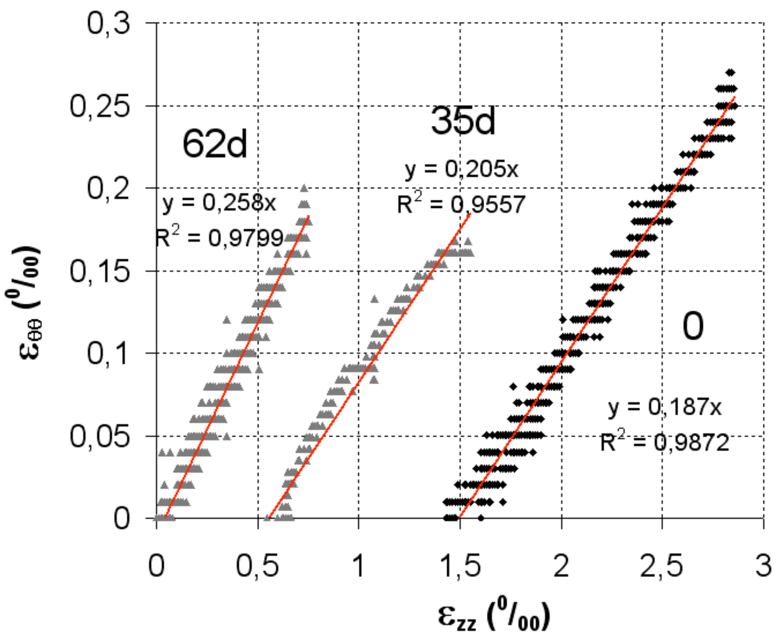


Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

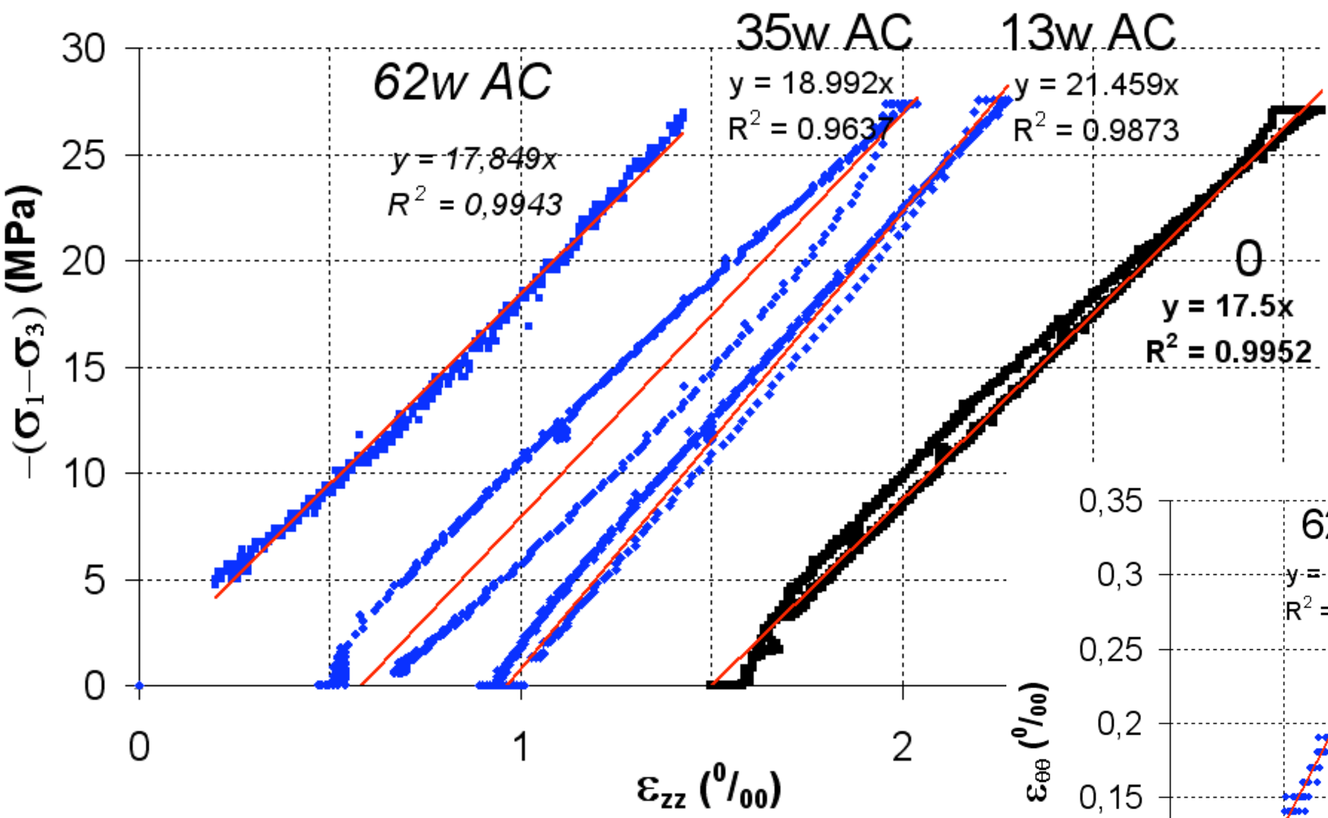


HC sample hardened with carbonation

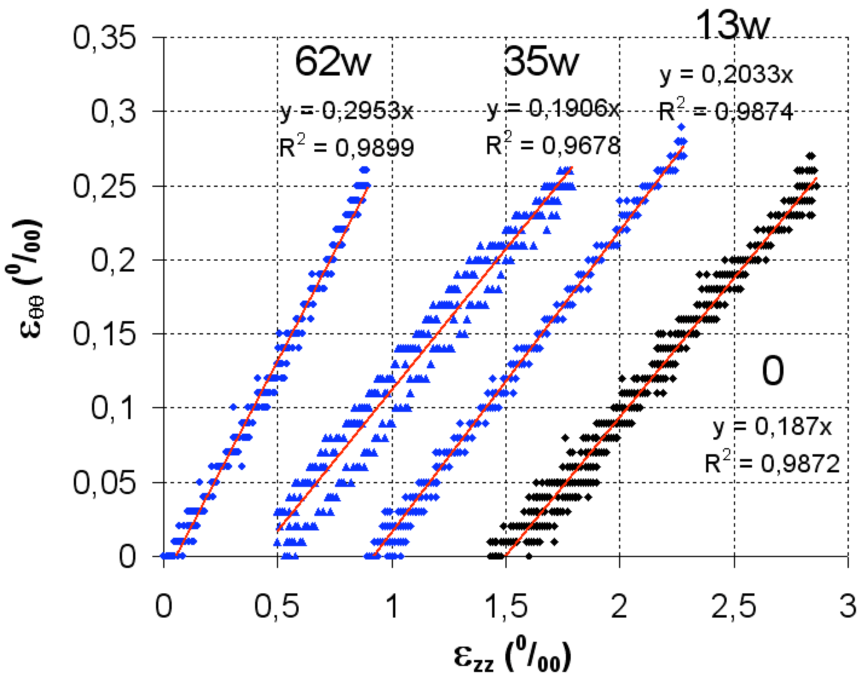


Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength



AC sample ~ softened with carbonation

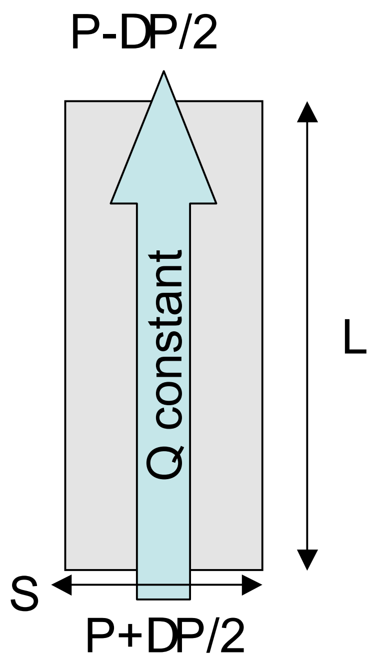


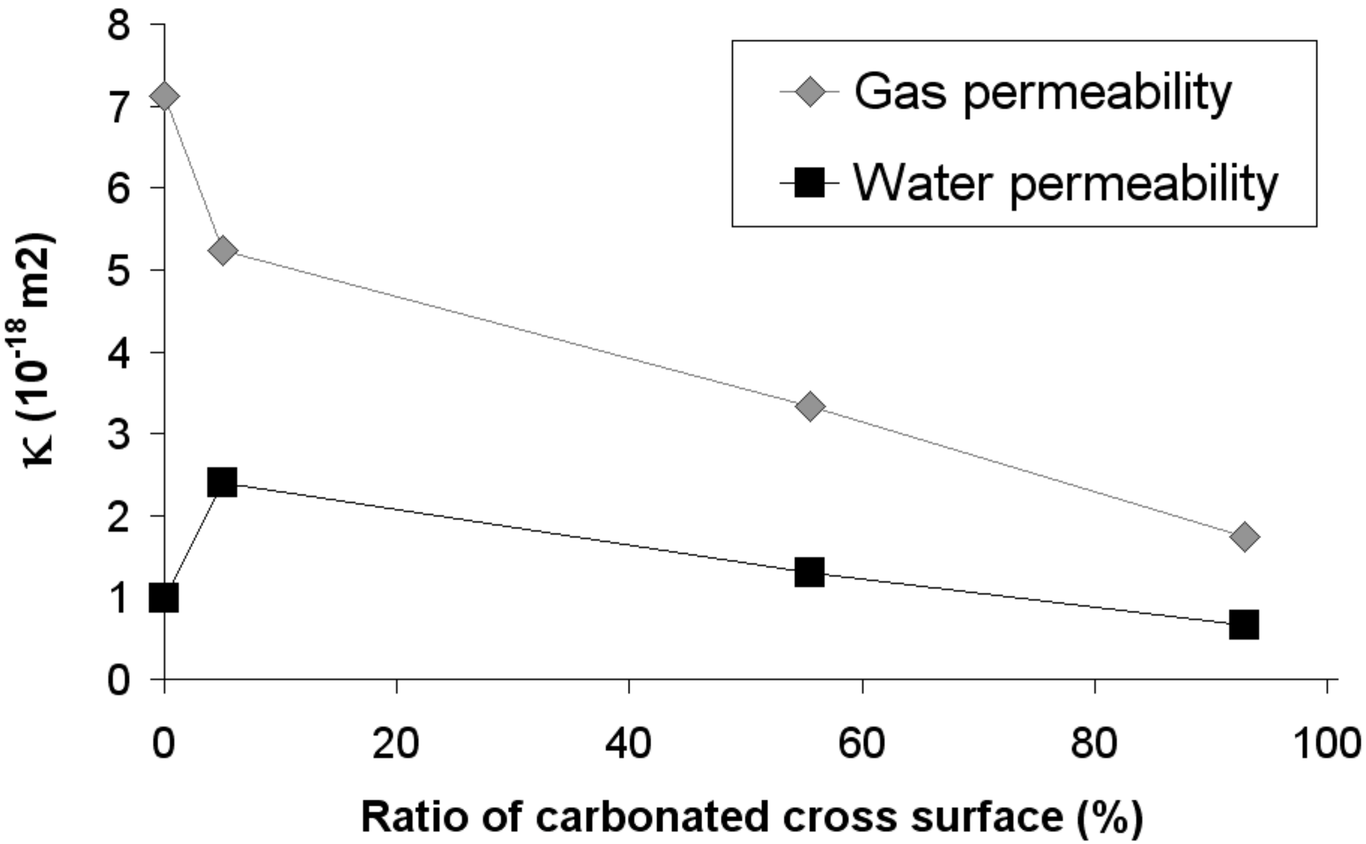
Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

AC samples permeability decreases with carbonation….

$$\kappa = \frac{Q\eta\, L}{S\,\Delta P}$$

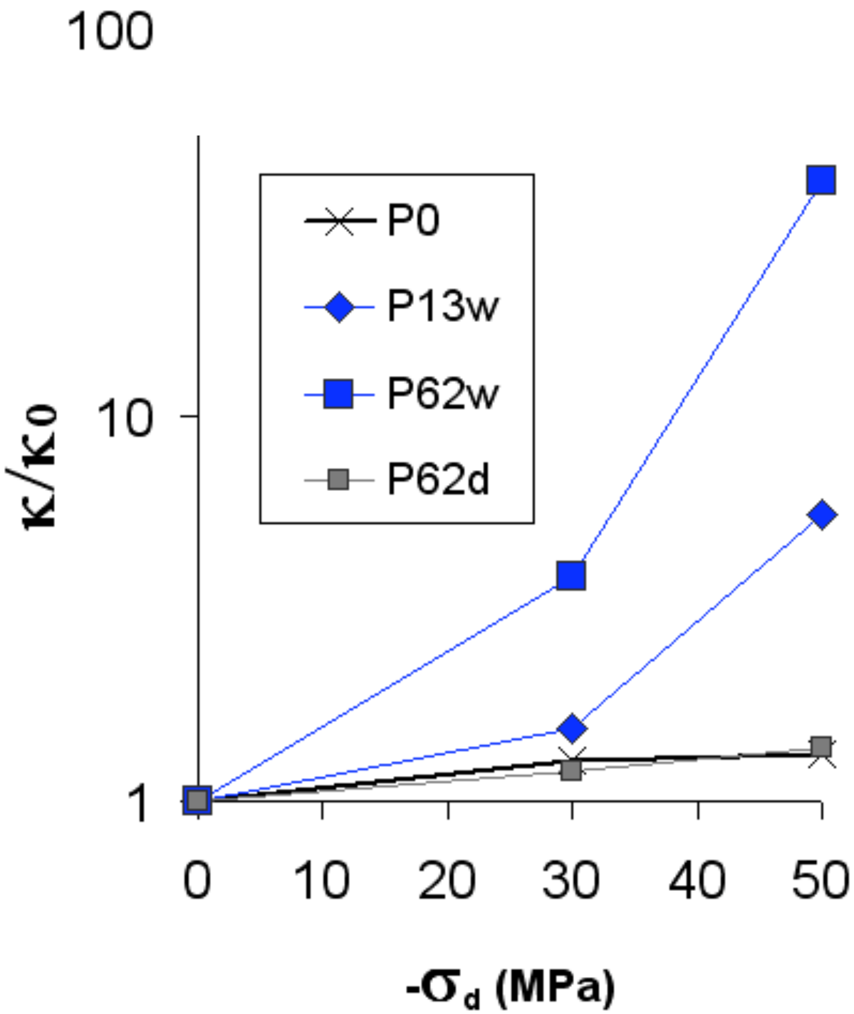




Some experimental results

Dry Confinement	Dry deviatoric	AC permeability	Rupture Strength

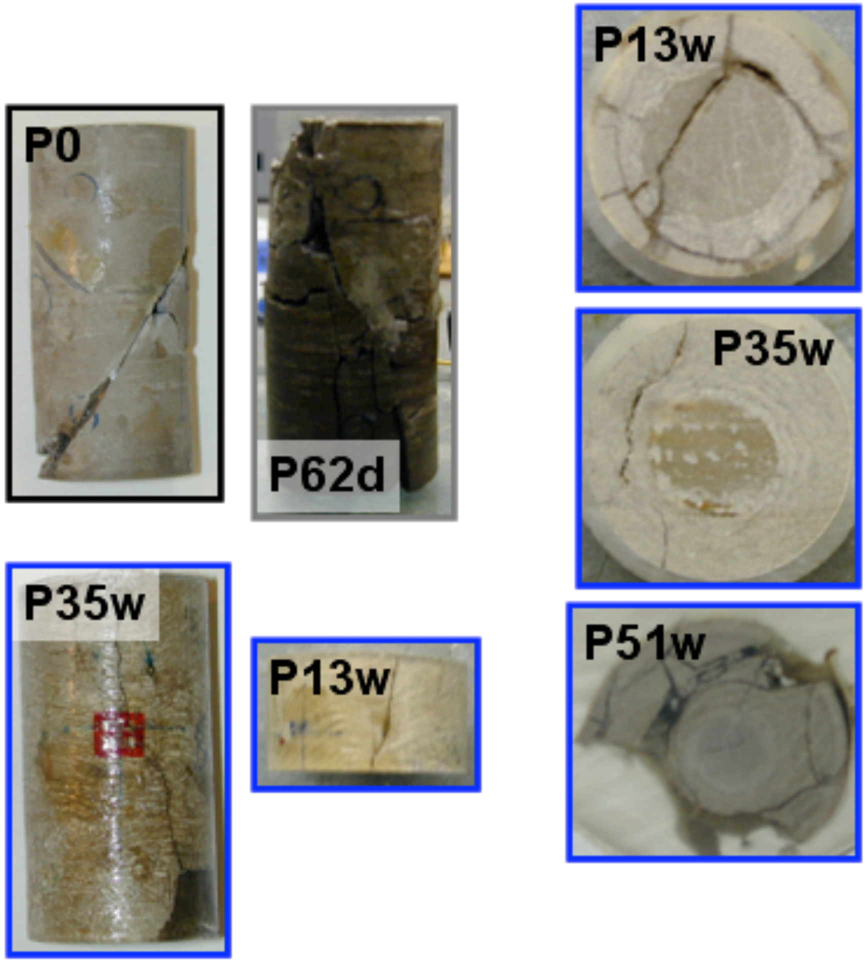
But increases dramatically with Gzz….



Some experimental results

Dry Confinement | Dry deviatoric | AC permeability | **Rupture Strength**

Side view   Cross sections



Conclusion

-Micro-cracks

-Elastic moduli evolutions

-Permeability evolution

Damage accumulation in sample with Carbonation front

Damage is localized at the front

	t_c days	ϕ %	ρ_d g/cm^3	e_c mm	E_d GPa	ν_d -	E_u GPa	ν_u -	E_w GPa	ν_w -	κ_{ar} u	κ_w u	f_{rupt} MPa
P0	0	41	1.53	0	17.5	0.19	16.1	0.29	16.4	0.24	7.1	1.0	63
P13*w*	13	33	1.80	5	21.5	0.20	19.0	0.29	17.4	-	5.2	2.4	50
P35*w*	35	29	1.90	8	19.0	0.20	18.5	0.31	13.4	0.18	3.3	1.3	57
P51*w*	51	28	1.95	10	19.1	0.22	20.6	0.30	-	-	-	-	-
P62*w*	62	31	1.87	11	17.8	0.30	18.8	0.31	15.4	0.33	1.7	0.7	48
P35*d*	35	26	1.99	-	23.0	0.21	20.5	0.32	19.9	0.28	1.4	0.2	80
P65*d*	65	24	2.03	-	37.3	0.24	21.1	0.33	26.6	0.32	-	52	57

Table 1. *Hydro-mechanical characteristics of the cement pastes. u stands for 10^{-18} m^2.*

Conclusion

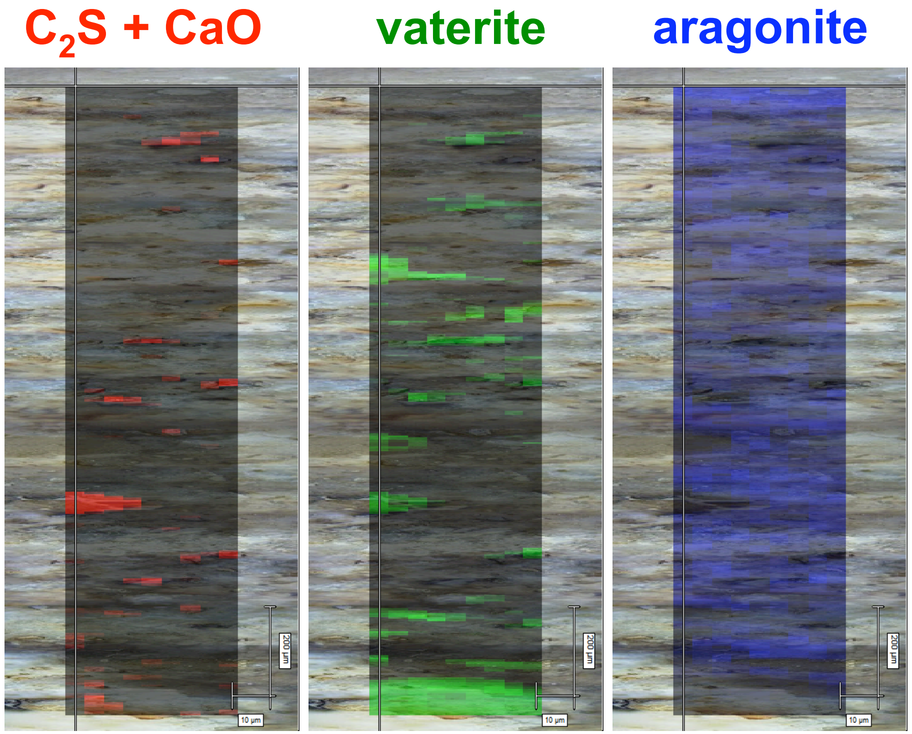
-Micro-cracks

-Elastic moduli evolutions

-Permeability evolution

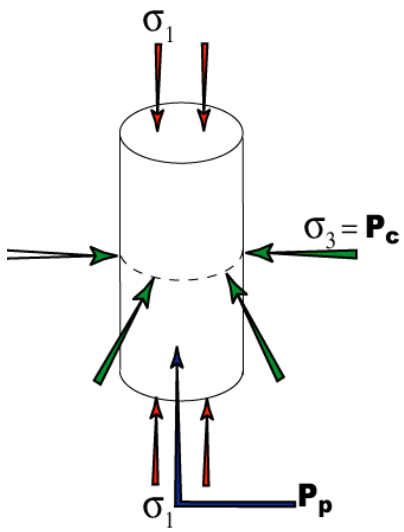
Damage accumulation in sample with Carbonation front

Damage is localized at the front (real or due to deP?)



NEW EXPERIMENTAL SET UP

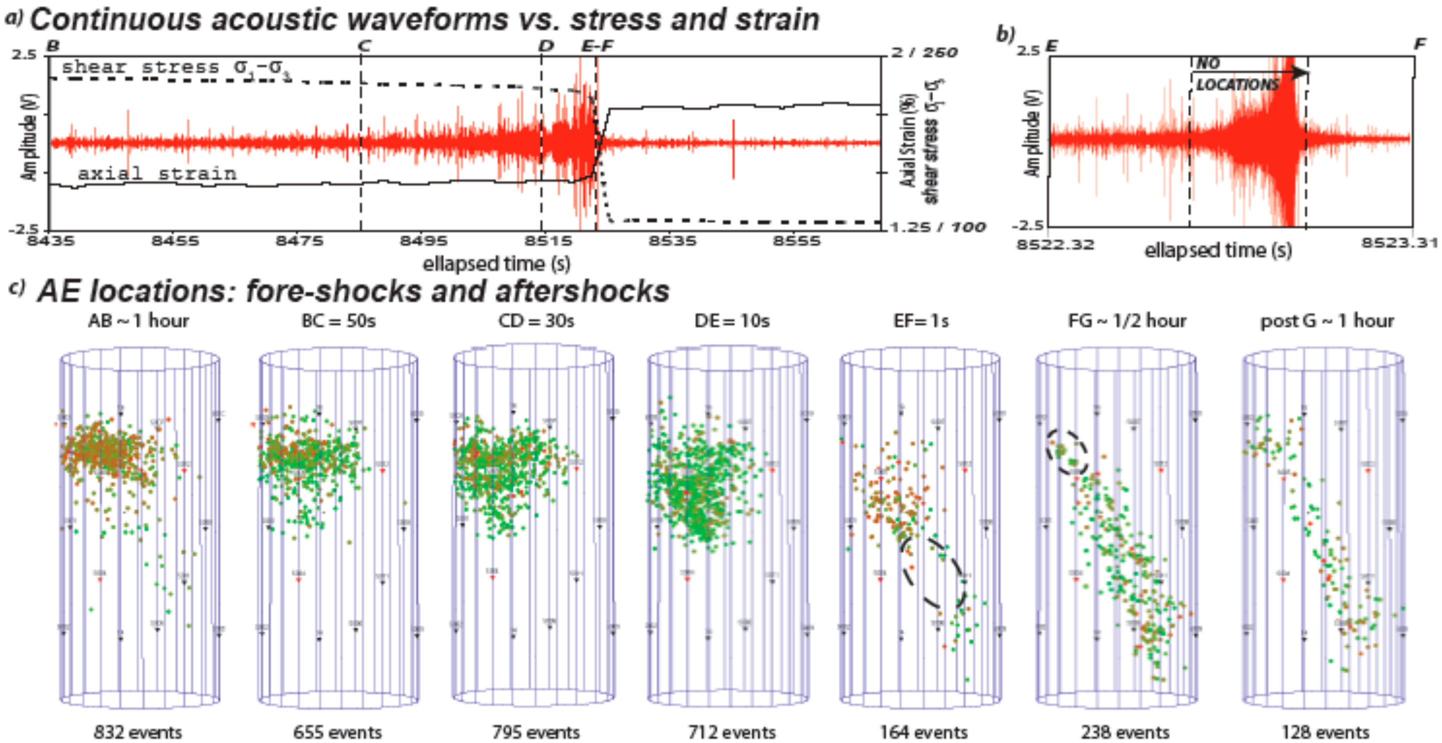
100MPa, température 200degC
Corrosive Pore fluids
16 coaxial feedthrough for acoustics
Cylindrical samples (diameter 40mm)



Tri-X MP-MT RIG

NEW EXPERIMENATL SETUP

AE monitoring : recording, localization, energy



COMING SOON….

8th Euroconference of Rock Physics and Geomechanics
***Rock Physics, fluids and Society*.**
Focus on Thermo-Hydro-Chemo-Mechanical coupling applied to CO2 sequestration, waste disposal, oil and geothermics.

FIRST CIRCULAR DRAFT

Venue: Ascona (CH), 9-13 September 2009 (see http://www.csf.ethz.ch)
Conveners: L. Burlini (ETH Zurich); A. Schubnel (ENS Paris); P. Baud (Uni Strasbourg)

The Venue: CSF in Ascona (Ticino, CH), on Lago Maggiore

The Centro Stefano Franscini is the congress centre of the Swiss Federal Institute of Technology of Zurich(ETHZ) situated at Monte Verità. It is an ideal meeting point for all members of the international scientific community who wish to discuss about the state of the art and new challenges of any field of research.

If interested, please email aschubnel@geologie.ens.fr

Motivation

➔ Development of an accelerated ageing method to model cement degradation in CO_2 fluids for CCS application

In building industry / radioactive waste repository: development of accelerated ageing methods to model concrete chemical ageing over time

Most used:

- Degradation in acid water
- Degradation in NH_4NO_3 solution
- Degradation by application of a potential gradient :

  LIFT procedure = Leaching Induced by Forced Transport (B. Gérard, 1996)

- **Can this method be adapted for CCS application?**

  → "LIFTCO_2 procedure"

- **What is the effect of applying a voltage through cement in CO_2 fluid?**

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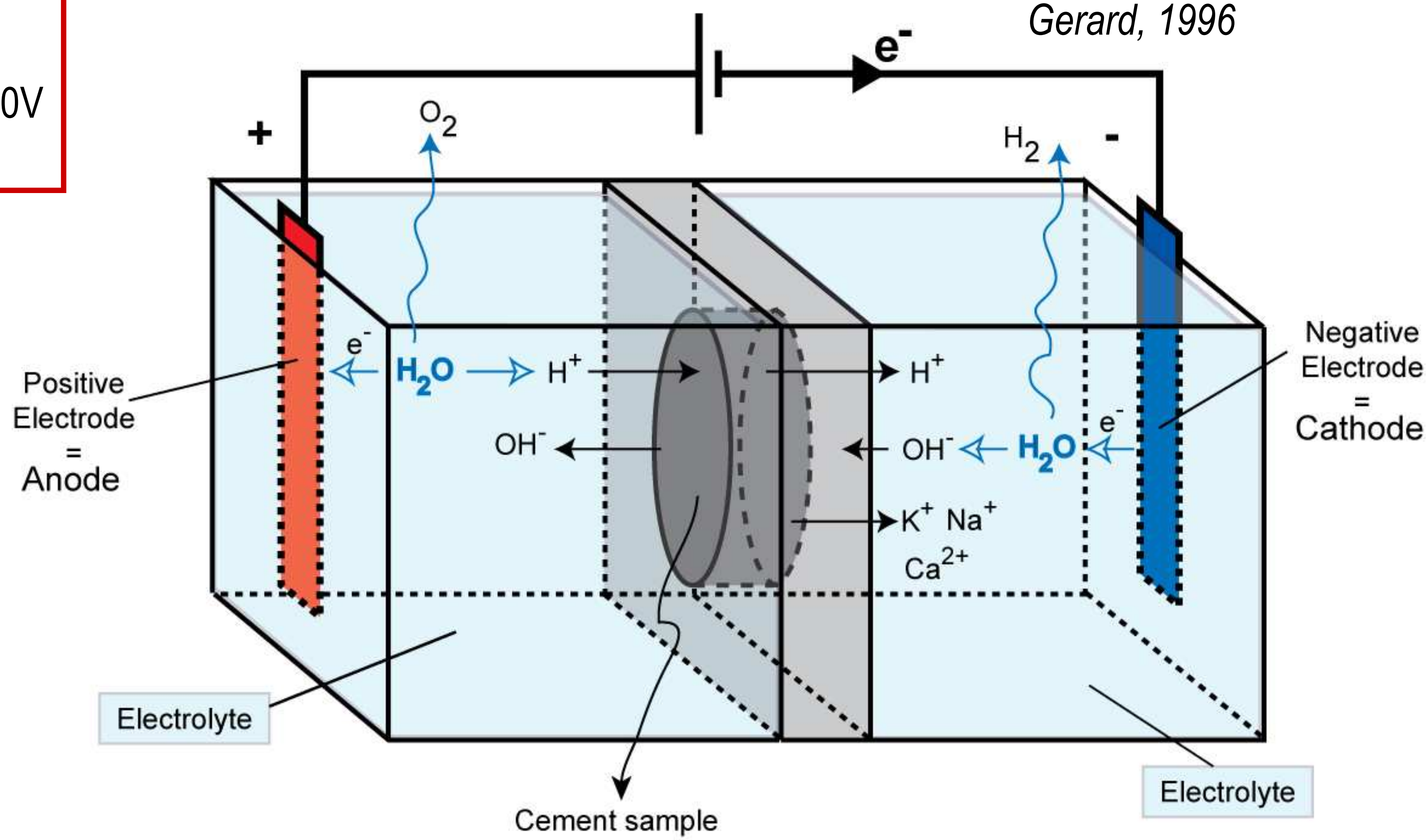
The LIFT procedure

$P_{atm.}$
T → 40°C
Voltage: 0-30V
water/brine

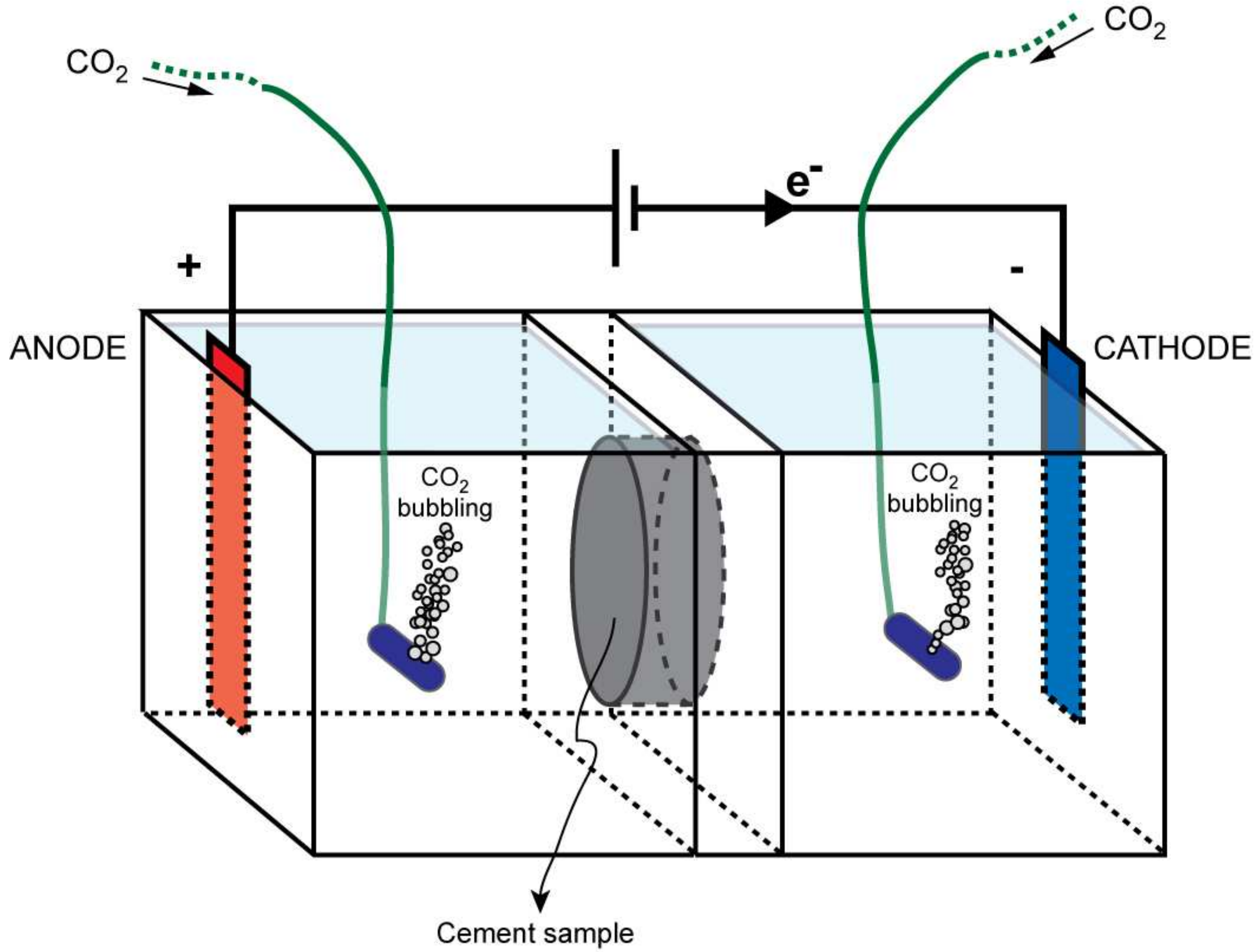
Saito et al., 1992
Gerard, 1996



→ **Migration of the cement ionic species towards the anode and the cathode**
→ **Decalcification of CSH and dissolution of Portlandite (cathode)**

The LIFTCO$_2$ procedure

$P_{atm.}$
T → 40°C
Voltage: 0-30V
CO_2+ water
CO_2+ brine
$\Delta[CO_2]$



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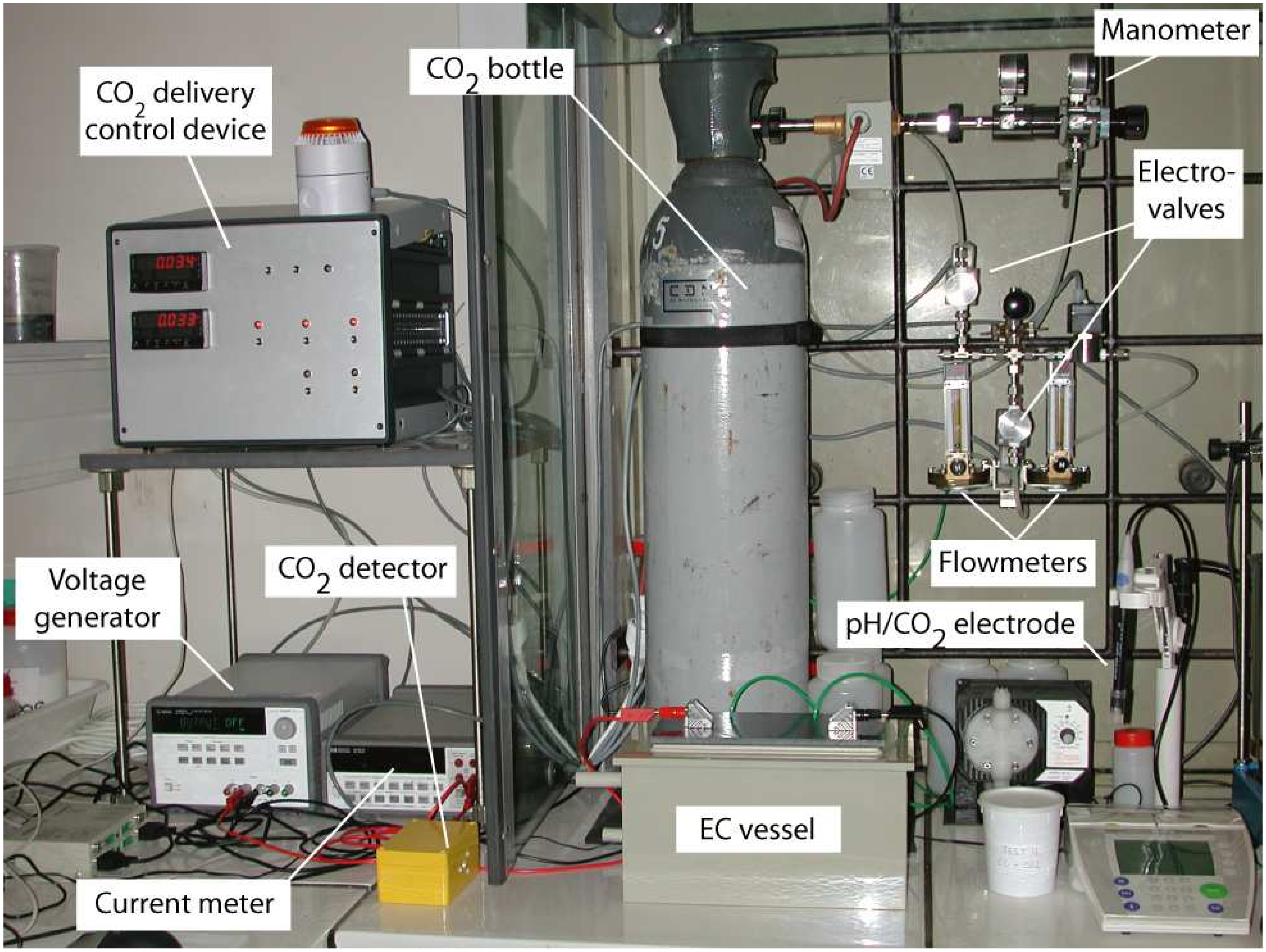
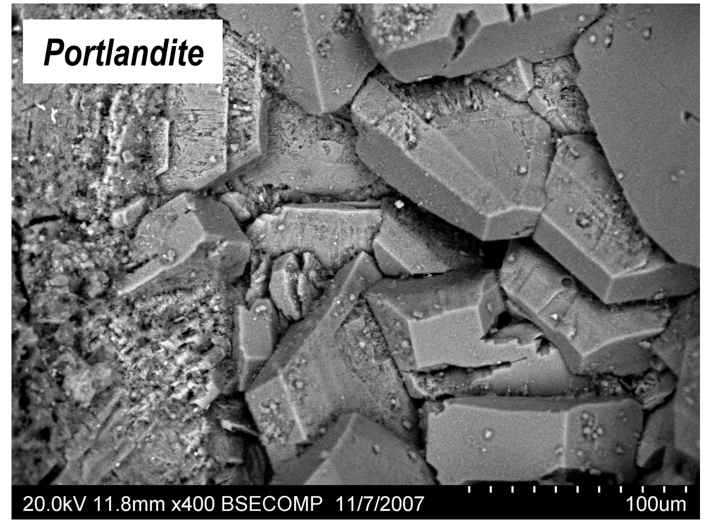
The LIFTCO_2 procedure

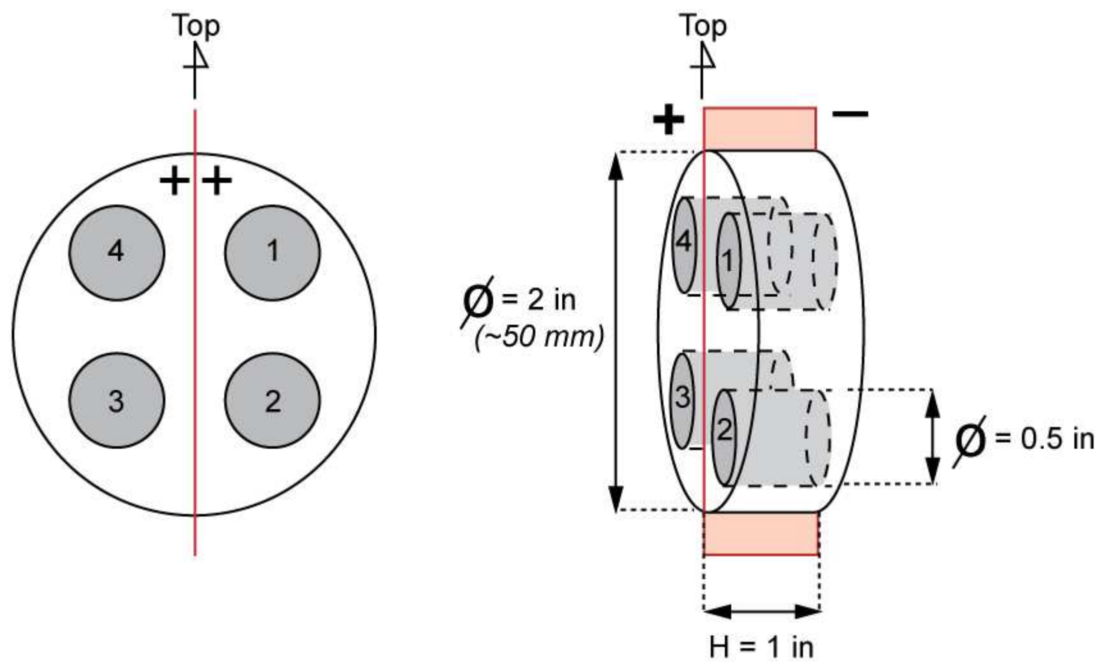


Material

Portland cement, class G, 1.89 SG

→ set at atmospheric P and ambient T





Characterization of alteration

- Weight and density
- pH
- [CO_2]
- Current intensity
- Porosity (water diffusion and mercury intrusion porosimetry)
- Relative permeability (water diffusion)
- Mineralogical evolution (X-ray diffraction spectroscopy)
- Microstructural analysis (SEM images and EDS analyses)

Evolution of pH with time

- Cement curing conditions:
  - $P_{atm.}$, $T_{amb.}$
- Test conditions:
  - $P_{atm.}$, $T_{amb.}$
  - CO_2 bubbling = 25 mL/min.
  - Voltage=0V, 10V, 30V.
  - test duration=1 week / 3 weeks

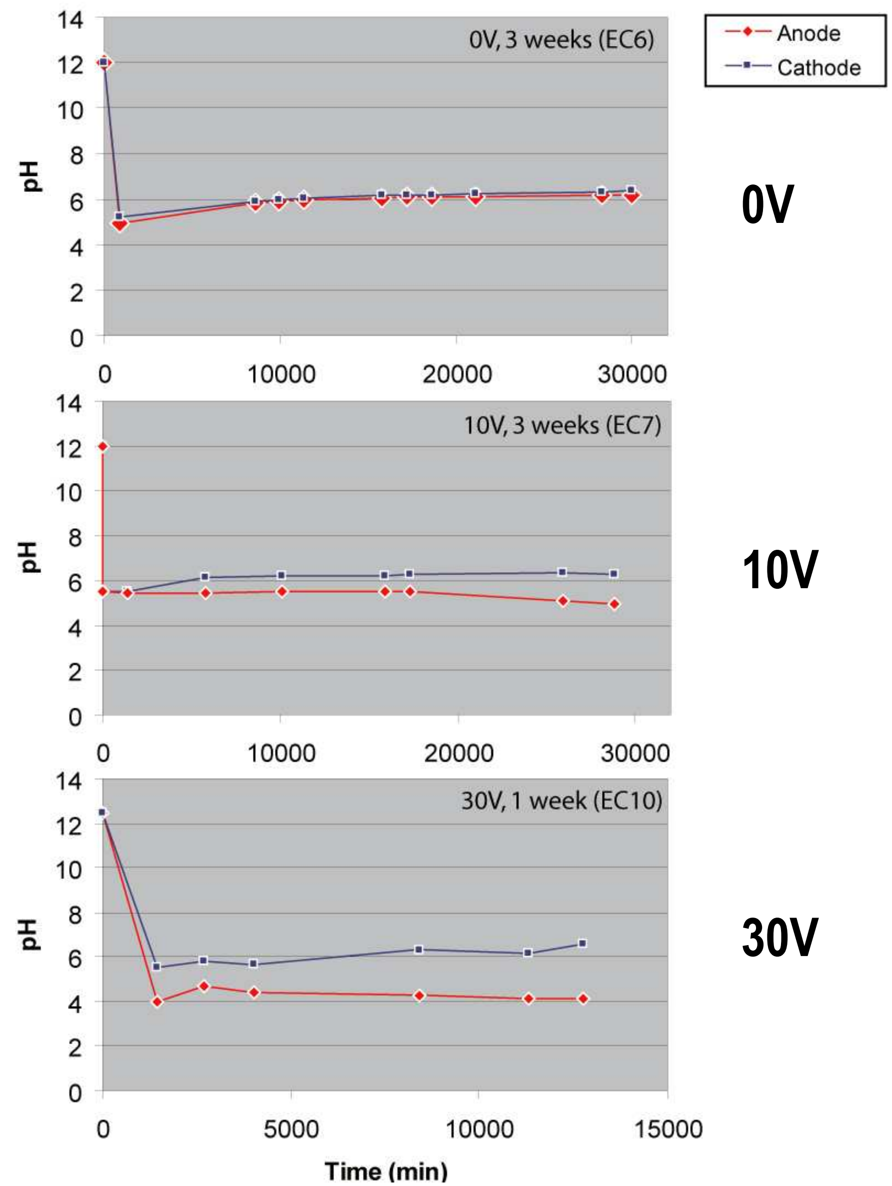
→ Water electrolysis

Anode side

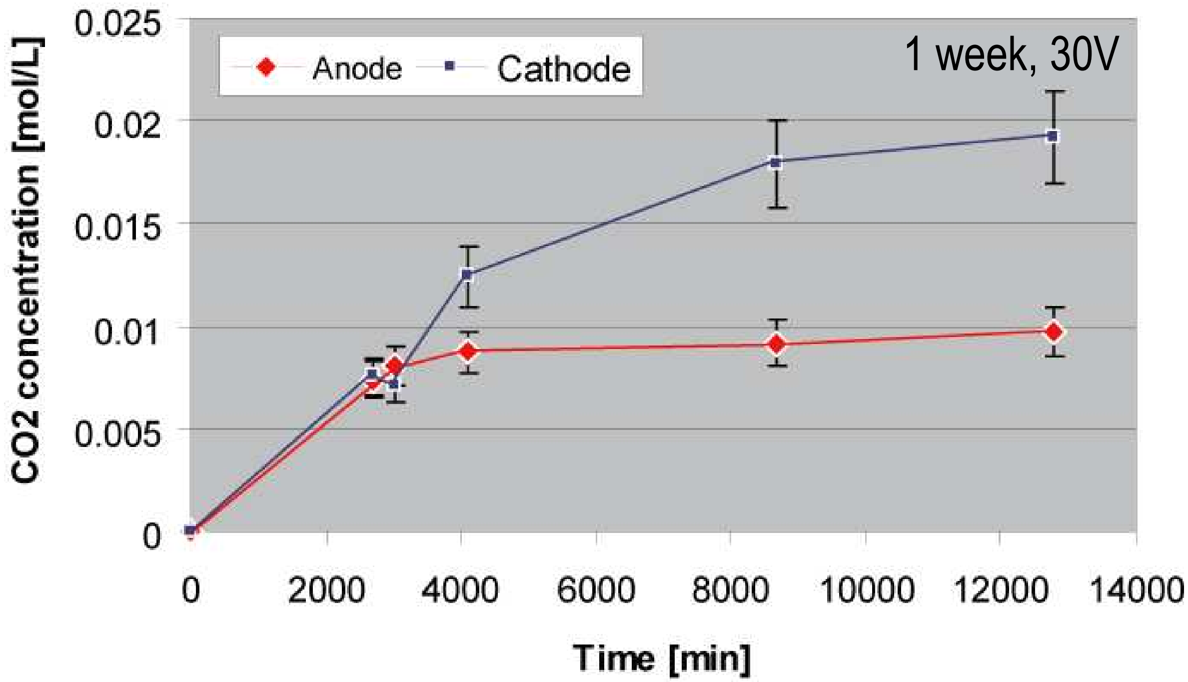
$H_2O \rightarrow 2\,H^+ + 0.5\,O_2 + 2e^-$

Cathode side

$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$



Evolution of $[CO_2]$ with time



→ Saturation of the solution by CO_2 after one week

- $[CO_2]_{cathode} = 2.10^{-2}$ mol/L ← Where most of the reaction between dissolved CO_2 and Ca^{2+} : Higher availability of carbonic species in this electrolyte
- $[CO_2]_{anode} = 1.10^{-2}$ mol/L

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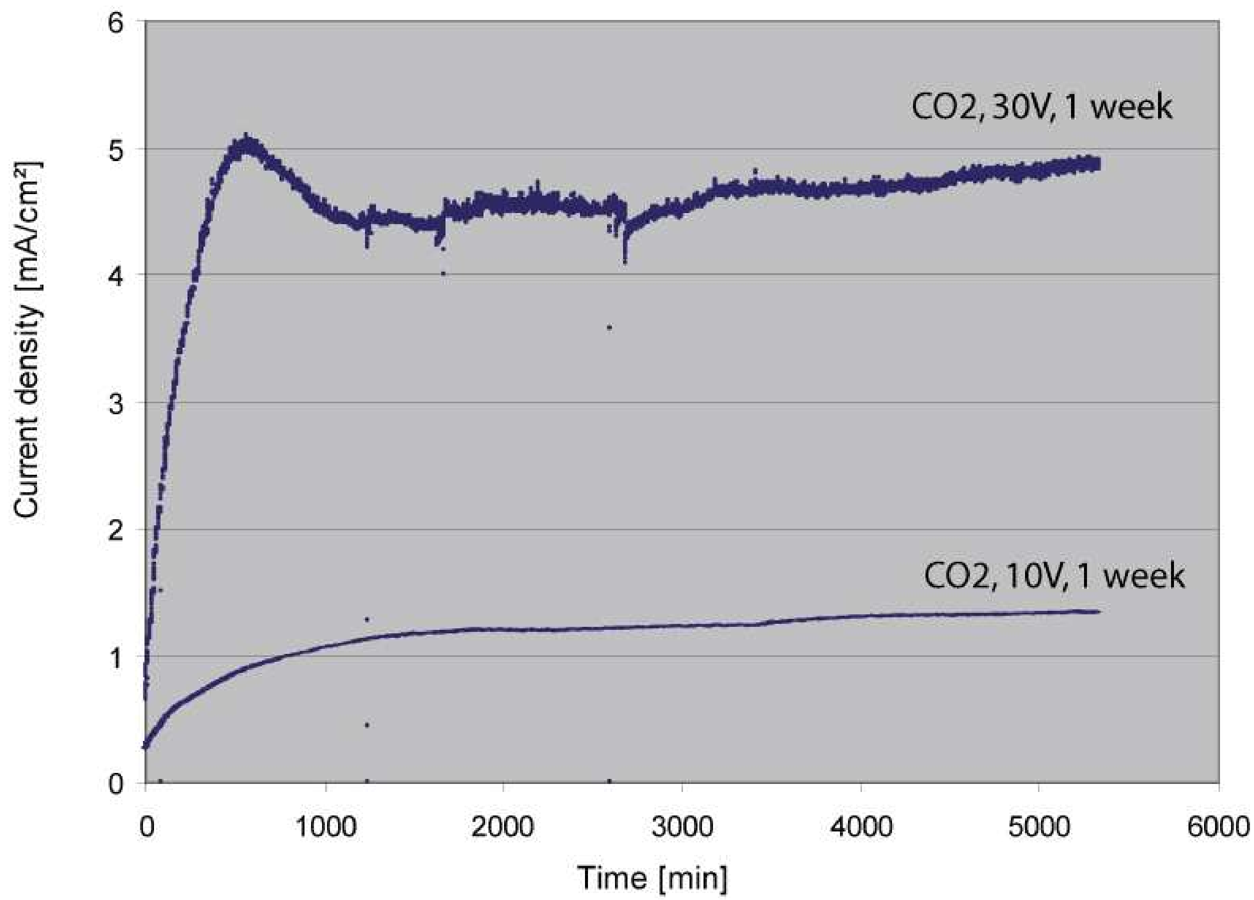
Evolution of the current intensity



Electric conductivity directly linked to the ionic composition of the electrolyte
→ Significant amount of lixiviated cement ionic species during the first day

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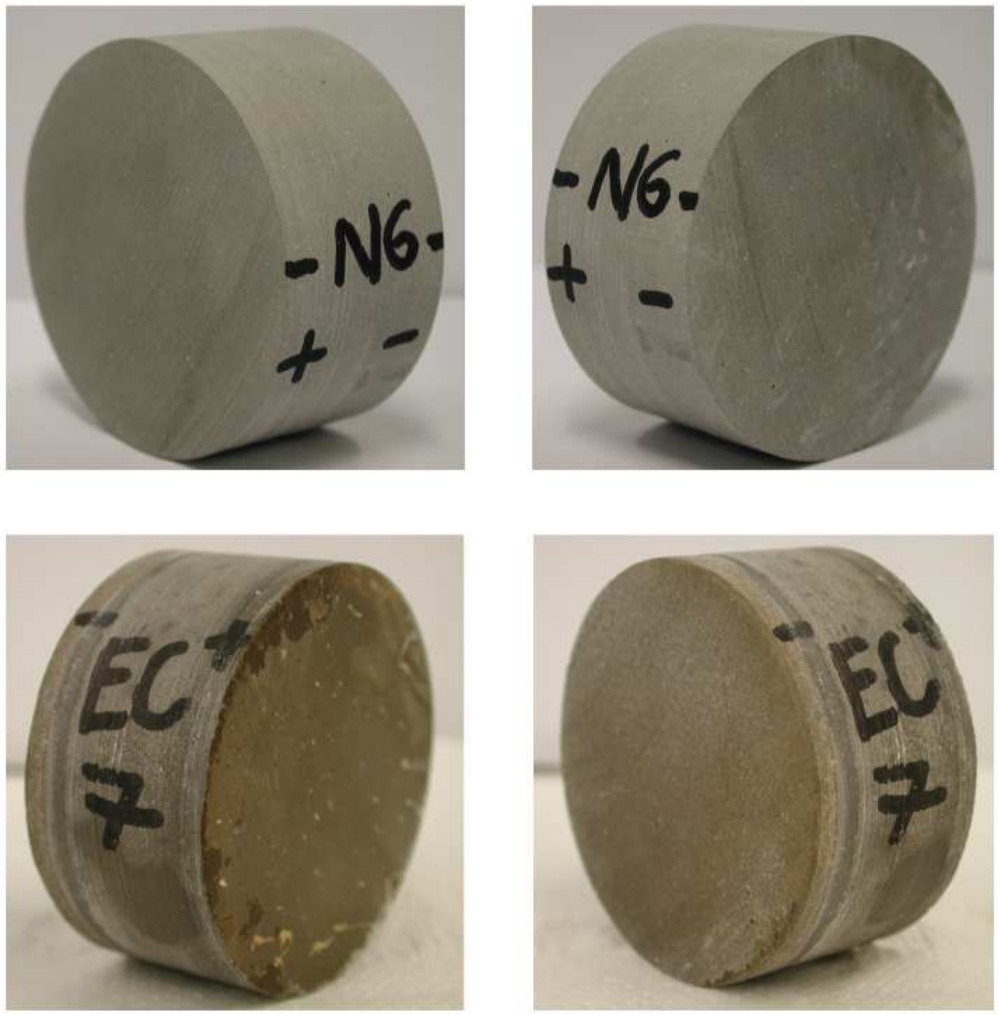
Mineralogical changes

ANODE SIDE | CATHODE SIDE

Before exposure

After 3 weeks in CO_2, 10V

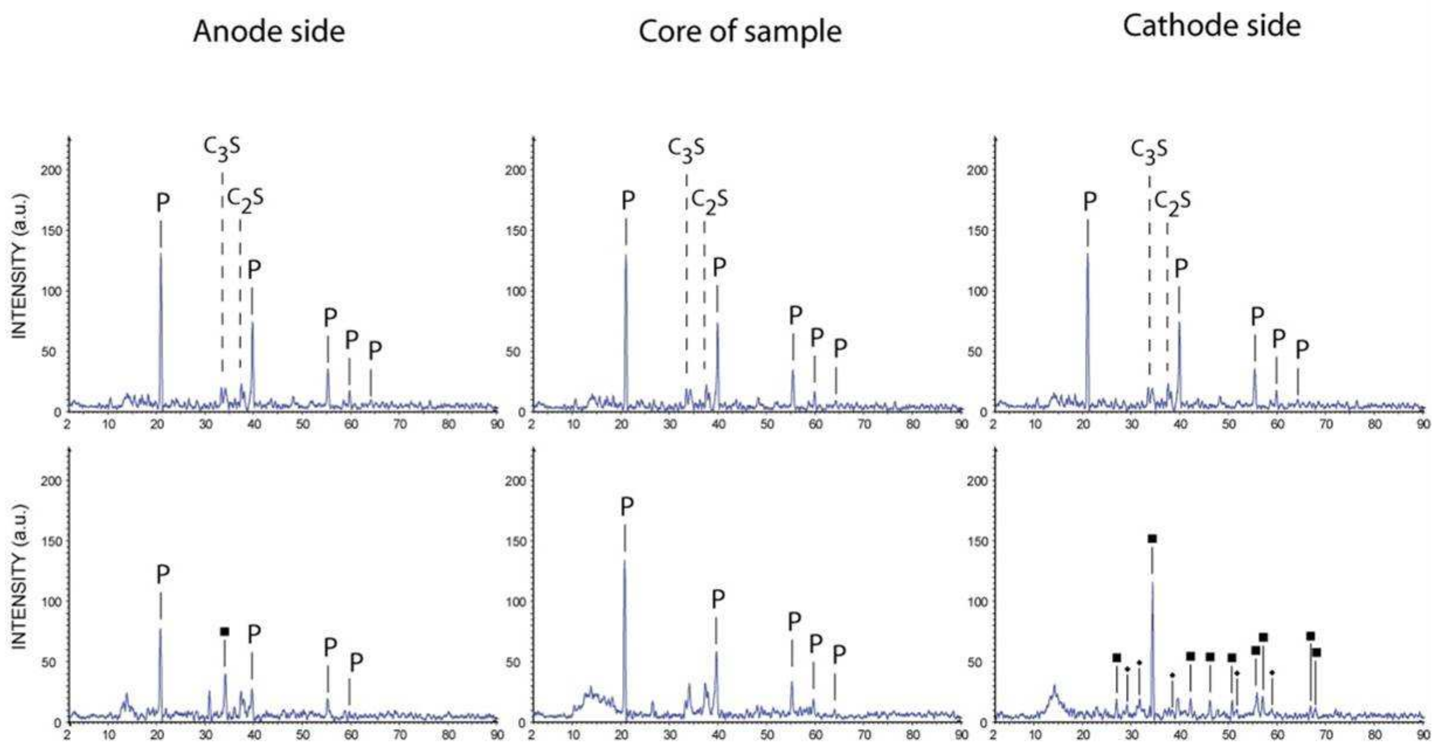


Mineralogical changes

P	Portlandite
C_3S	Tricalcium silicate
C_2S	Dicalcium silicate
■	Calcite
•	Vaterite

Before exposure

After 1 week
30V
CO_2-saturated water



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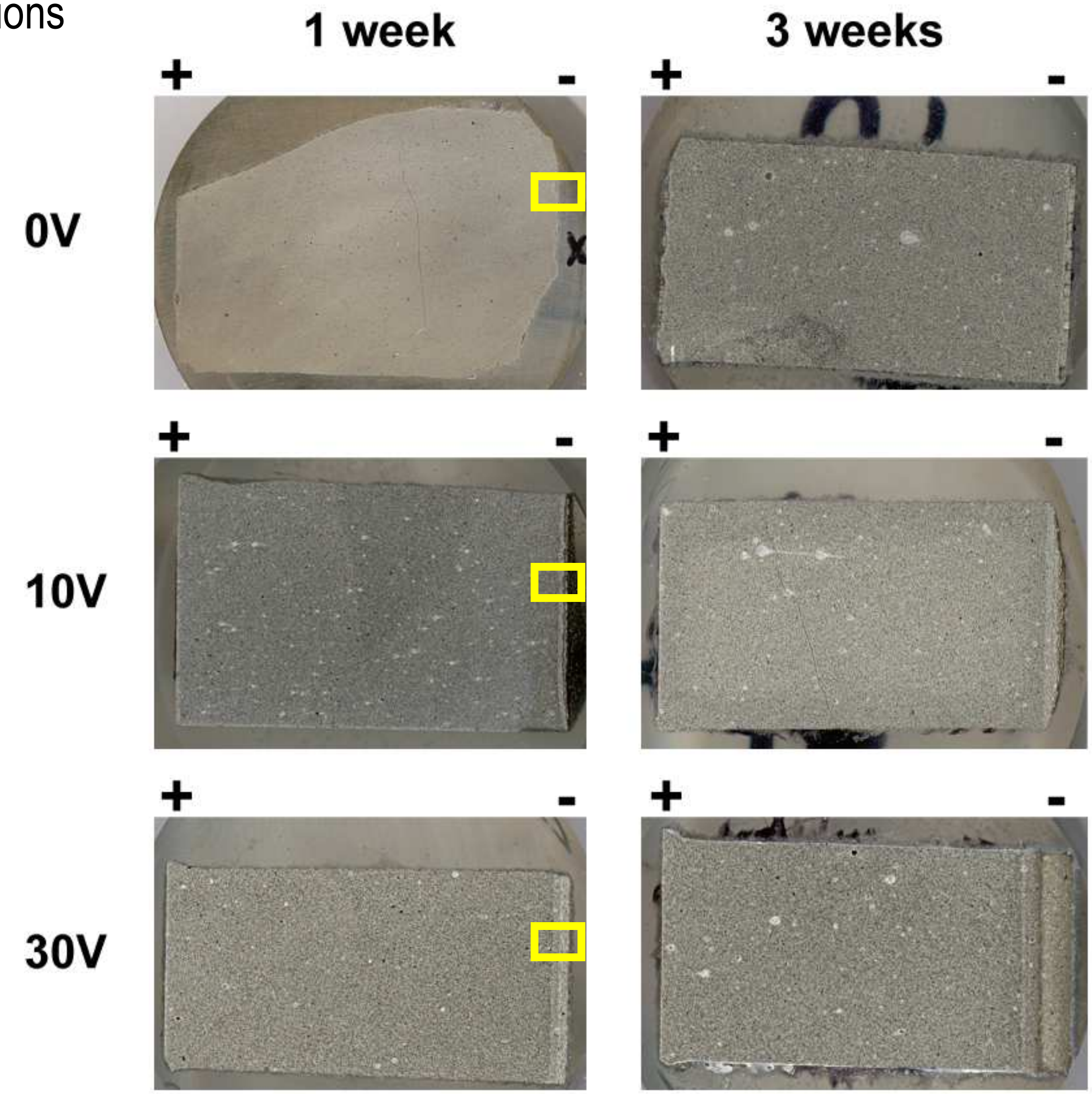
Alteration front thickness

Sample cross-sections



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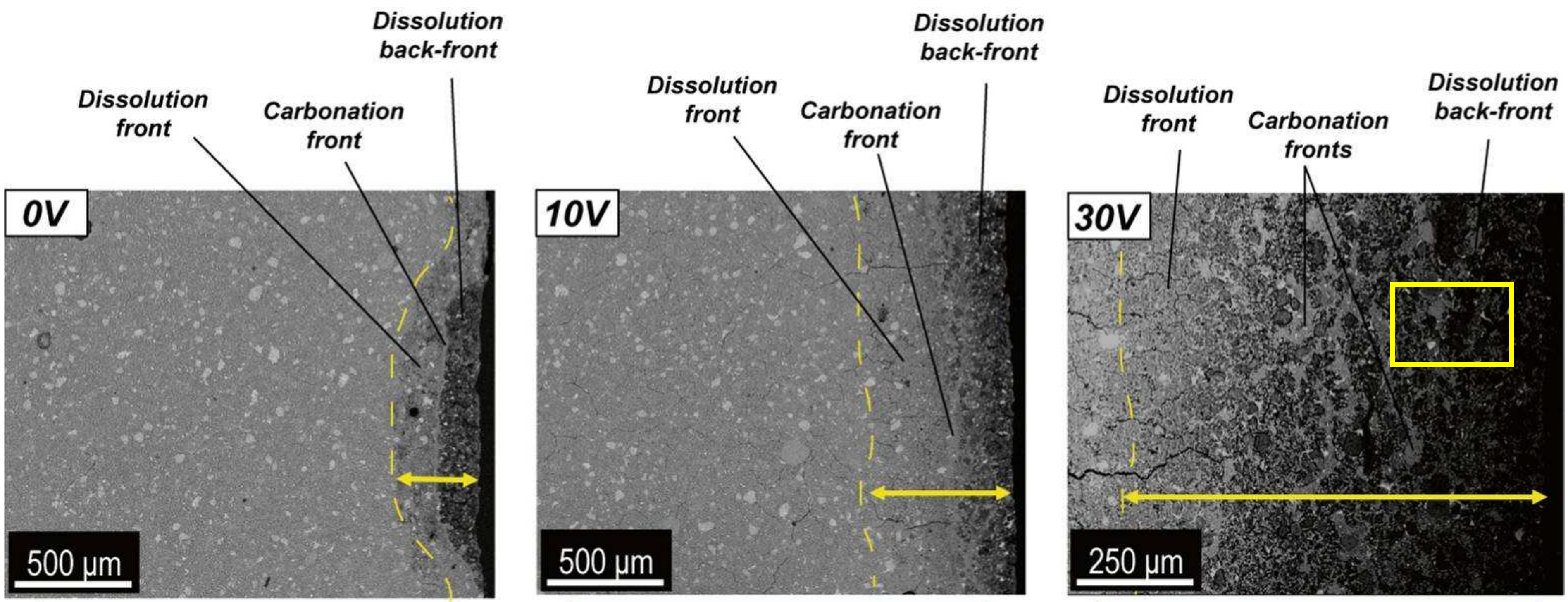
Alteration front thickness

After one week in CO_2-saturated water, cathode side



Alteration front = 0.3 mm

Alteration front = 0.6 mm

Alteration front = 1 mm

~10 times thinner than at HPHT

← *Material properties*

← *CO_2 solubility*

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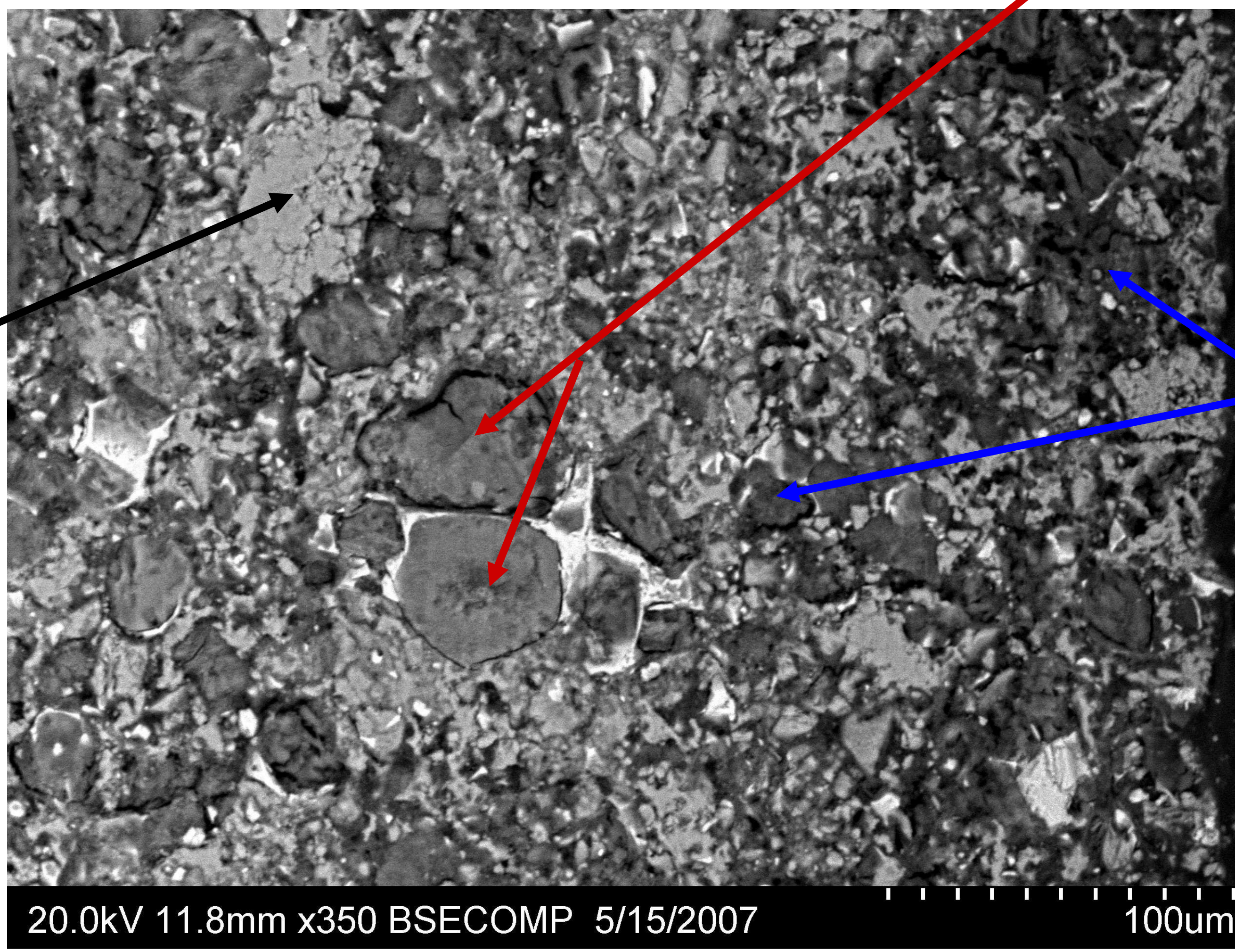
Alteration front thickness

After one week in CO_2-saturated water
30V

Ca-depleted C_2S/C_3S

$CaCO_3$

Silica gel



SEM-BSE

No Portlandite

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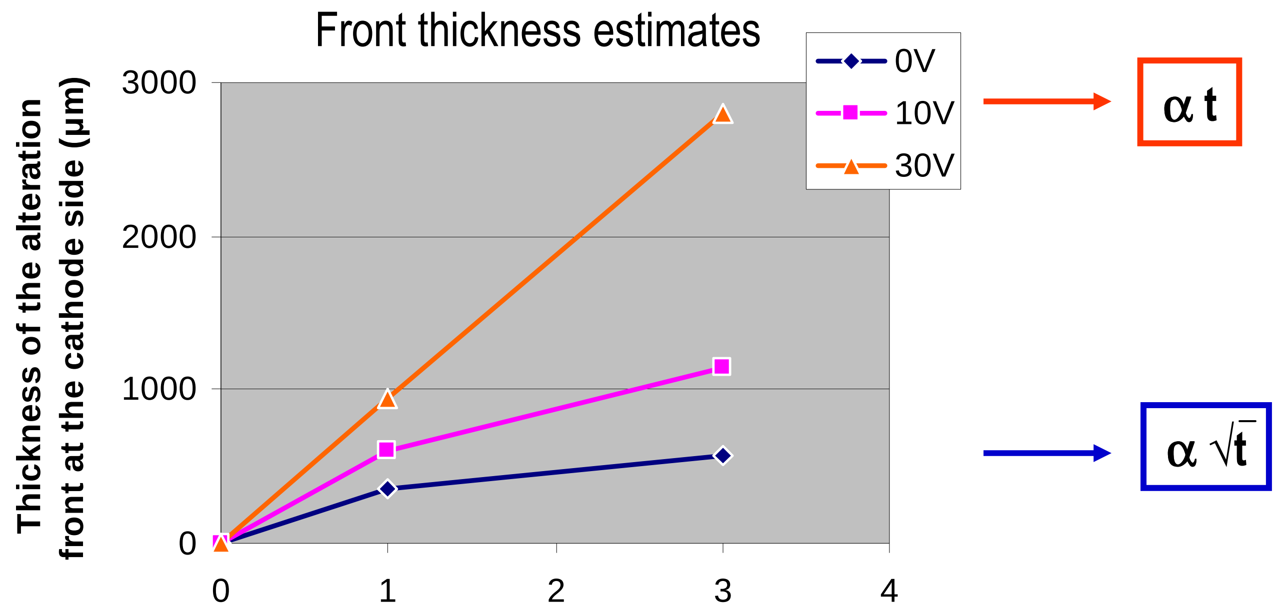
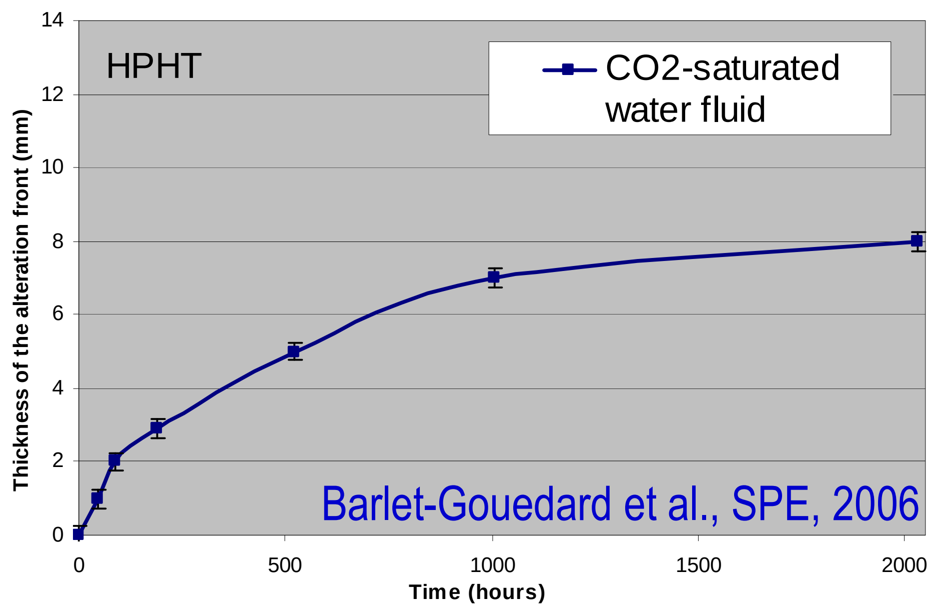
Alteration front thickness



➢ Application of a

➢ Increasing the

➢ 0V to 30V ⇔ c ... ration



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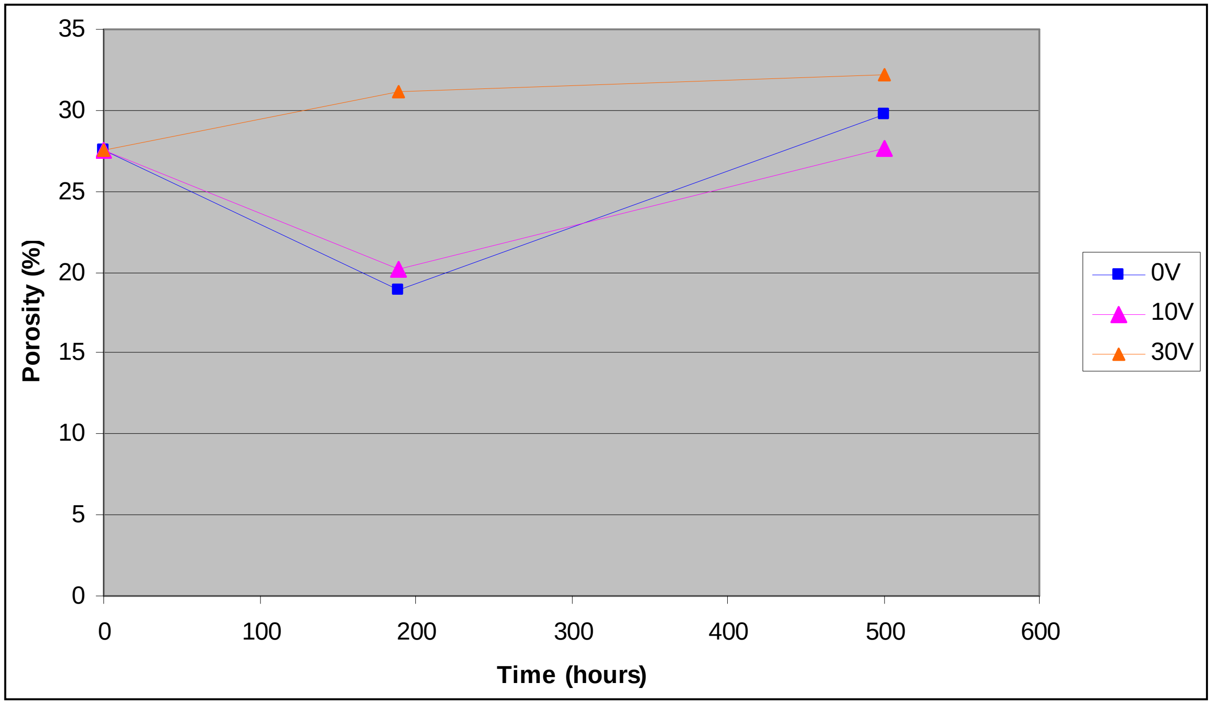
Evolution of porosity with time

Mercury Intrusion Porosimetry



→ 0-10V: initial porosity plugging then dissolution
→ 30V: plugging phase by carbonation is by-passed

➔ The higher the voltage, the higher the dissolution and forced transport of the cement species occurs, the higher is the increase of the porosity with time

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Conclusions

- **Cement exposed to CO_2 bubbling alone (0V):**

  - Alteration front pattern: dissolution front, carbonation front and dissolution back-front
  - Similar pattern as at HPHT, thickness = 10 times smaller than at HPHT
  - Slower kinetics of alteration ← lower CO_2 solubility (under lower pressure)
    ← lower cement permeability (cement set at 20°C)

- **Cement exposed to CO_2 bubbling and 10-30V:**

  - Cement degradation is accelerated: validation of the LIFTCO_2 method
  - Voltage increases
    → amplification of the forced transport of the cement ionic species
    → decalcification and dissolution of cement components is enhanced
    → carbonation sealing effect due to pore plugging disappears at high voltage
    → more ions are released in the electrolyte to react with CO_2
    → penetration of the alteration front into the sample is accelerated

- **… also** acceleration of cement ageing → when increasing temperature of test
  → when increasing the amount of CO_2 in the vessel

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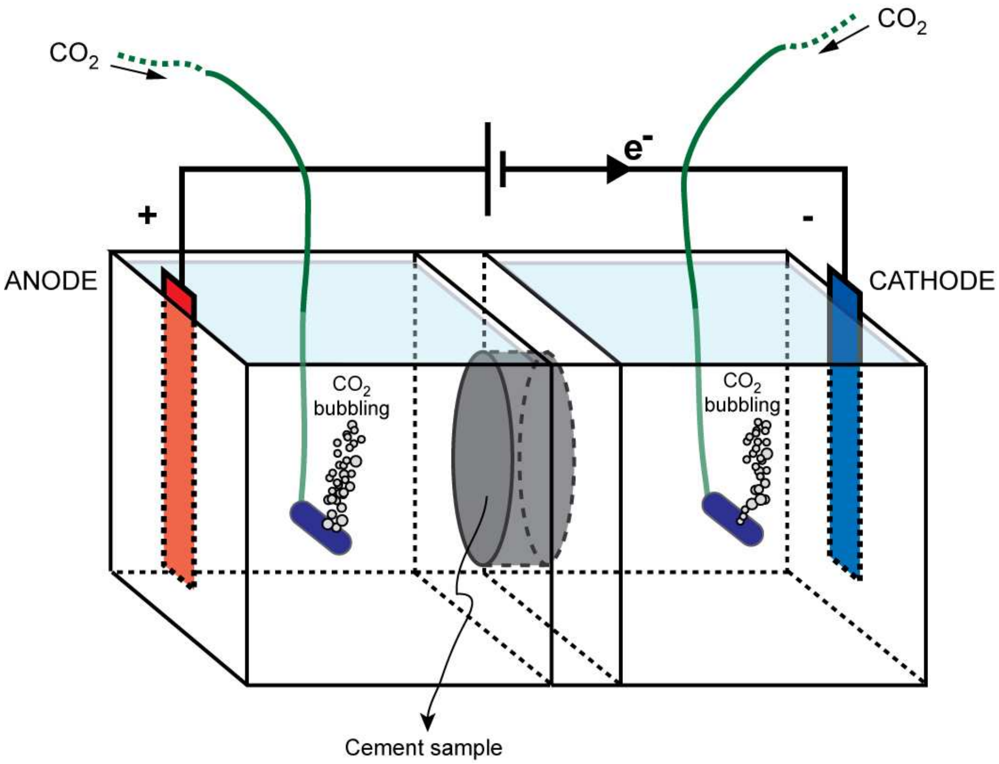
Perspectives

➢ $LIFTCO_2$ can be a good method to acquire data for modeling the long-term behavior of cement for CCS

➢Adapting this method for HPHT experiments (higher solubility of CO_2, more realistic conditions for CCS application…)



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Numerical Simulations of Wellbore Leakage in Large-Scale CO_2 Injection Incorporating Wellbore Details and Complexities of Phase-Change

Rajesh J. Pawar

Los Alamos National Laboratory

LA-UR 07-8449

Motivation

- At-scale implementation of Carbon Capture & Storage (CCS) would require injection of large volumes of CO_2 in geologic formation
- One of the major concerns for geologic sequestration is potential for leakage through poorly-abandoned wellbores
  - Wellbore leakage is a critical aspect of current CCS research
  - Field wellbore cement permeability as well as fluid migration through wellbore cement are poorly characterized
  - To date only two samples of CO_2 exposed wellbore cement have been collected from field (LANL-Kinder/Morgan, CCP)
- Numerical simulations of CO_2 injection and subsequent migration would be extremely useful to characterize CO_2 migration through plugged/poorly-plugged wellbores (given the scarcity of field data)
  - To help quantify the risks associated with CO_2 migration

Wellbore release is a complex process

- Possible flow in wellbore and/or annulus
- Multi-phase, multi-fluid flow including phase change
  - Extremely non-linear thermodynamics near the critical point
- Coupled with:
  - Heat and mass transfer with formations
  - Stress effects
  - Geochemical reactions

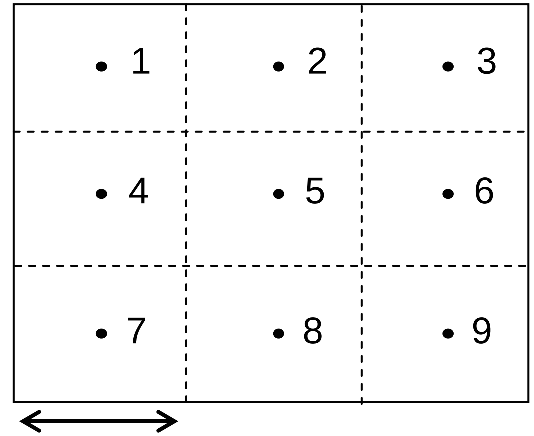
To characterize CO_2 leak through wellbores and to develop effective mitigation strategies it is important to accurately capture wellbore flow physics and couple wellbore flow with reservoir flow
(Lynch et al., JPT, July 1987)

How do you represent wellbore details in basin scale problems efficiently?

- Need to effectively represent details of wellbore (casing, annulus, types of completions), wellbore flow physics and near wellbore conditions (P, T, S) in a large scale (10s – 100s km) flow simulation at low computational penalty
- Traditional approaches to incorporate wellbore and/or wellbore details in large-scale models have limitations:
  - Peaceman approximation: Can not effectively capture near well bore conditions
  - Grid refinement & hybrid grid approaches: Require significant effort in re-gridding and usually results in large computational grids
  - Analytical models in numerical simulators: cannot effectively capture flow physics (phase-changes)
- We have developed a novel, flexible approach in FEHM to incorporate detailed wellbores in large-scale simulations without a need for re-gridding or effective parameters:
  - Radial representation of wellbore and near wellbore region at any desired spatial resolution in a coarser, 3-D grid
  - Computationally efficient simulation of short-term and long-term wellbore processes

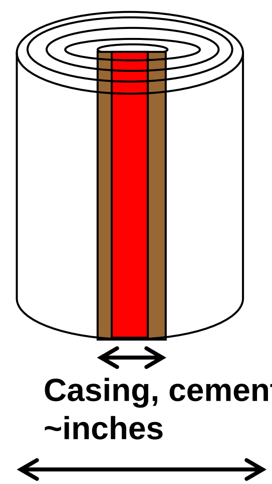
How does the wellbore incorporation algorithm work?

Create the primary reservoir grid (prior to creating input file or in the input file)



Specify wellbore details in the input file:

- Wellbore location (x,y), wellbore radius
- Specify desired spatial resolution (radial in wellbore vicinity)
- Explicitly specify properties (thickness, permeability) of casing, cement annulus etc.



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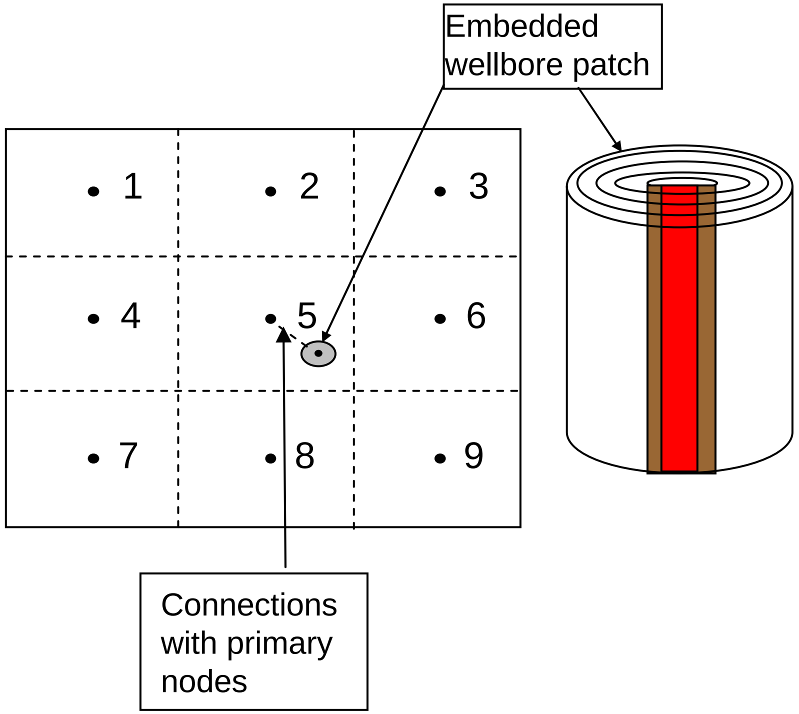
Wellbore incorporation algorithm (continued)

The code identifies connections, modifies resistance terms, adjusts node control volumes to embed the wellbore in the primary grid.



Large-scale CO_2 injection: problem definition

- 60 km x 60 km x 30 m target reservoir
- A shallow aquifer, 2000 m above
- Base case:
  - Reservoir Permeability: 10^{-13} m^2 (100 mD)
  - porosity: 20%
- A leaky (poorly plugged) well in the center of injectors
- Cement permeability varied (10^{-8} - 10^{-17} m^2), Base case permeability 10^{-8} m^2 (equivalent of a leaky well)
- Inject CO_2 output from a 500 MW power-plant for 50 years, simulate migration 450 years post injection
- 10 injectors @ 810 tons/day

Goal: Simulate CO_2 migration through leaky/poorly-plugged wellbore

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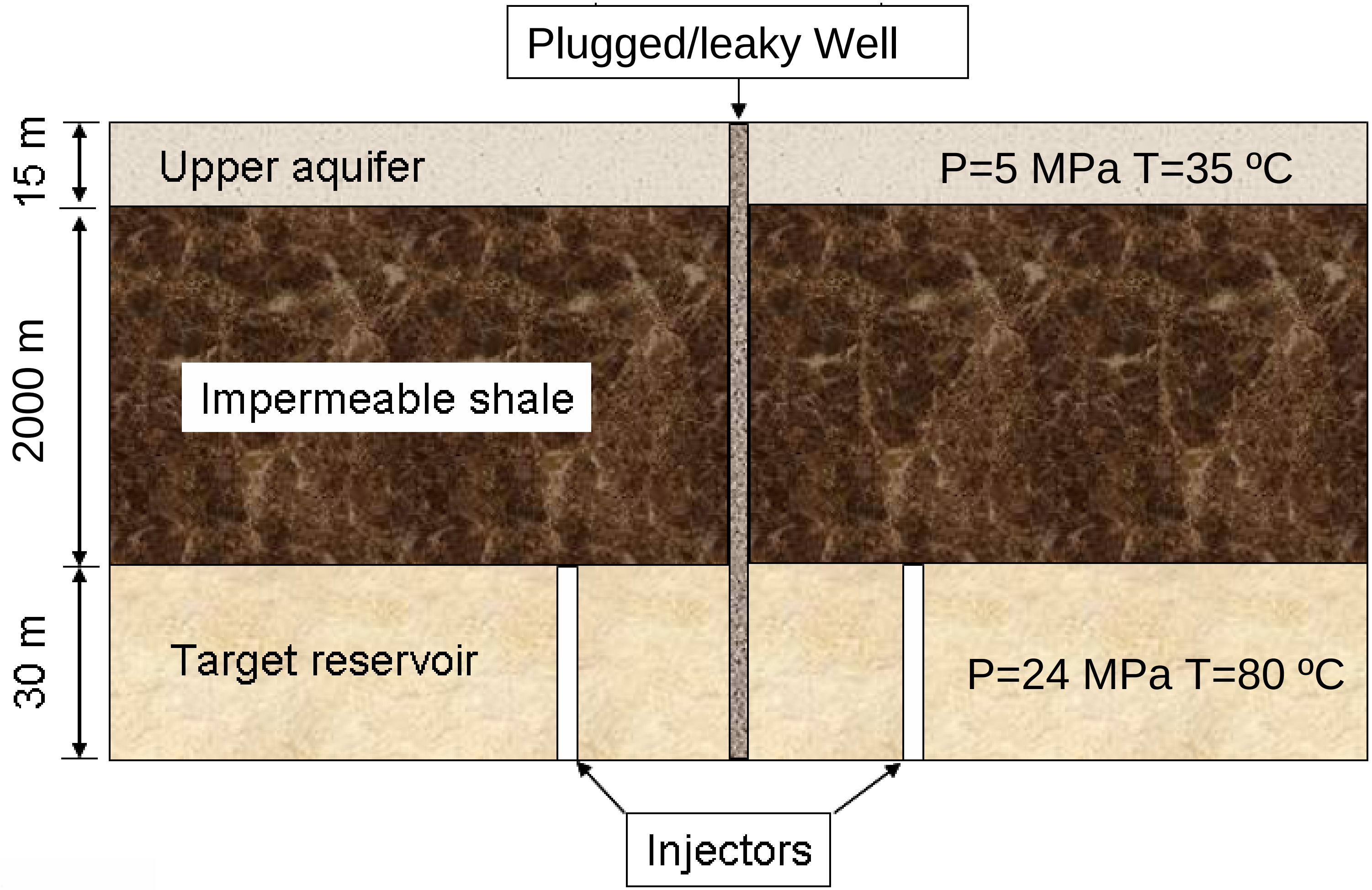
Schematic in vertical direction



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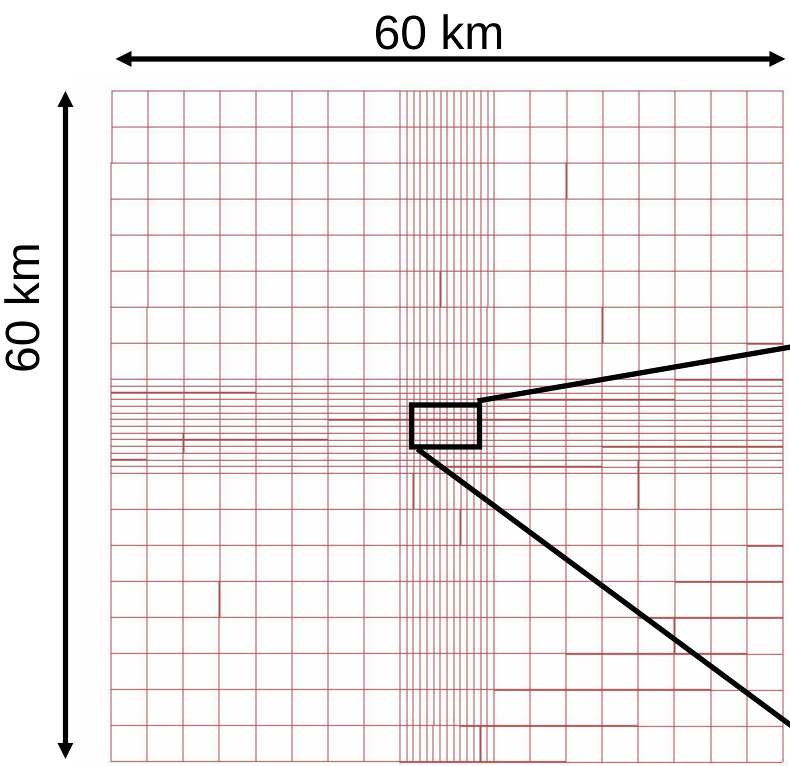
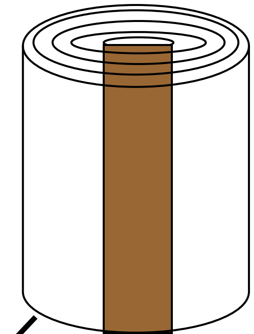
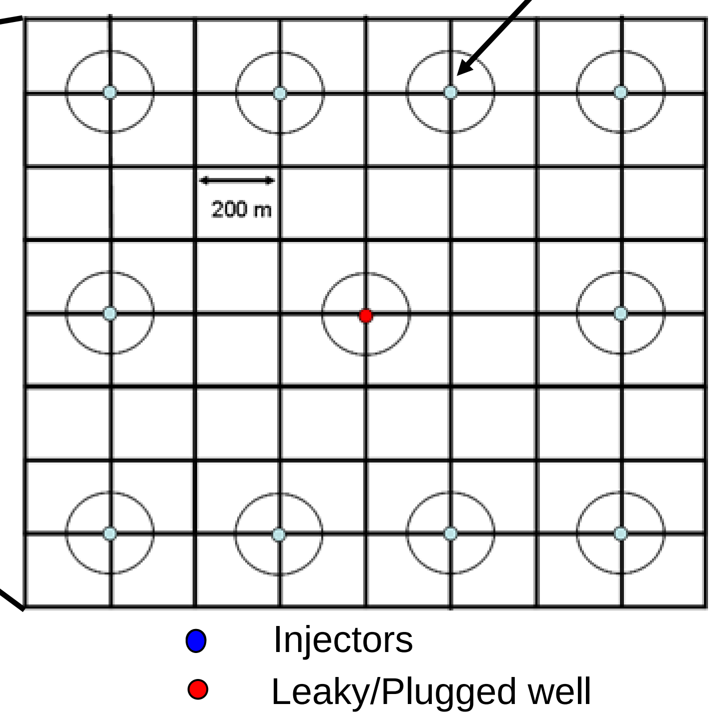
Numerical grid with wellbores: plan view

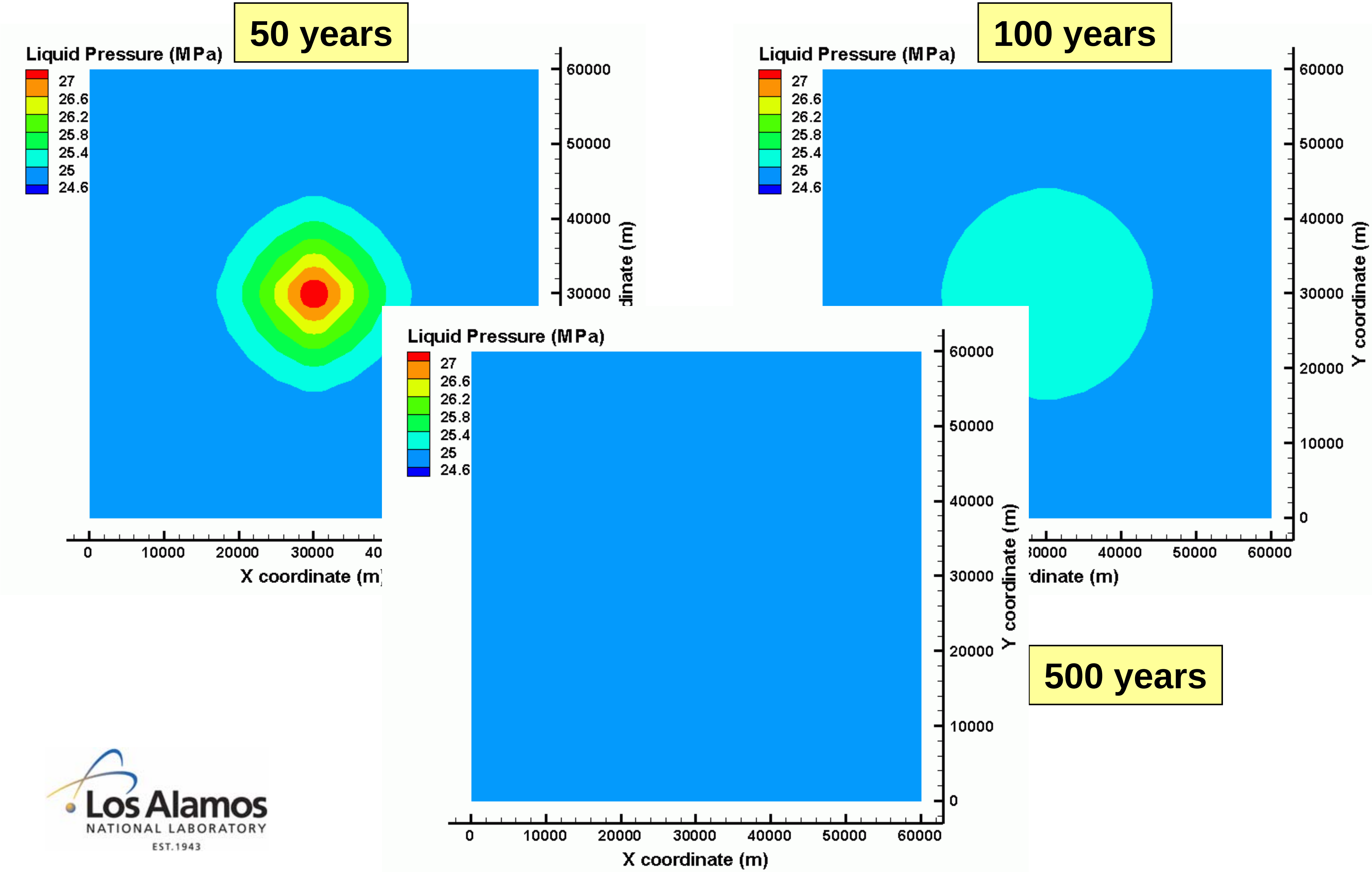


Embedded wellbore patch
Wellbore radius: 10cm
Outer patch radius: 100m
11 radial elements
10 vertical elements





Simulated pressure in the reservoir



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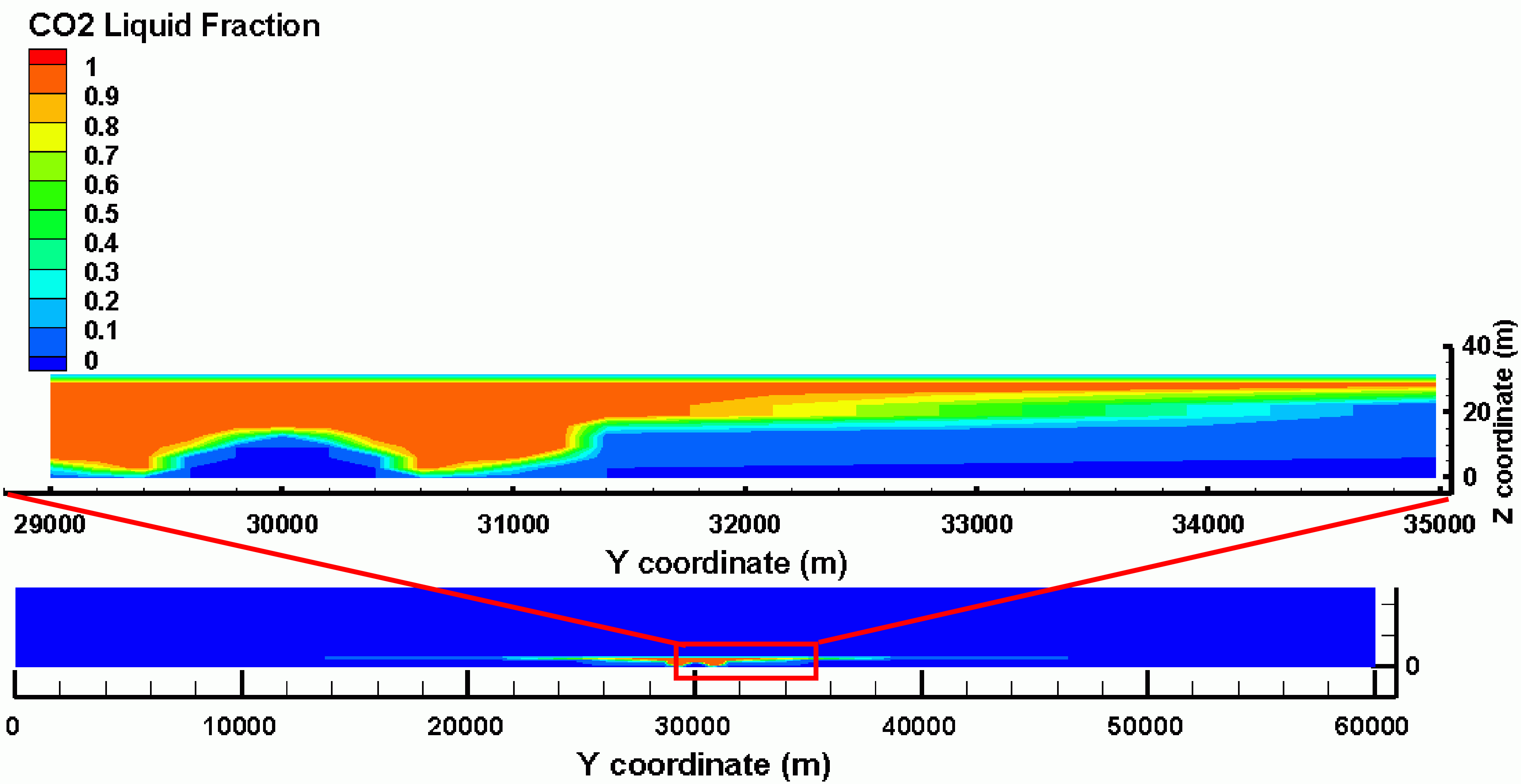
CO_2 plume @ 50 years: X-sectional view



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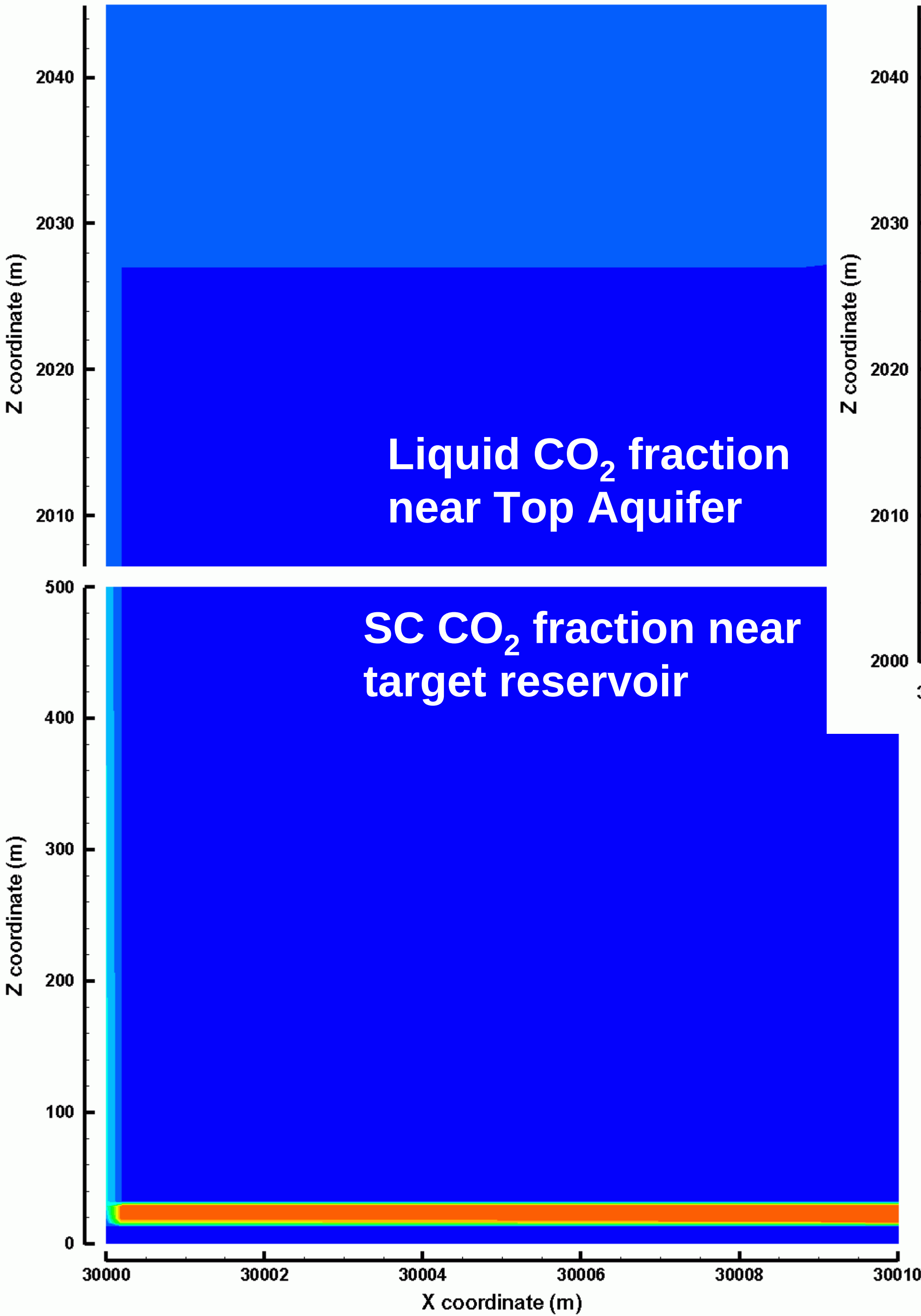
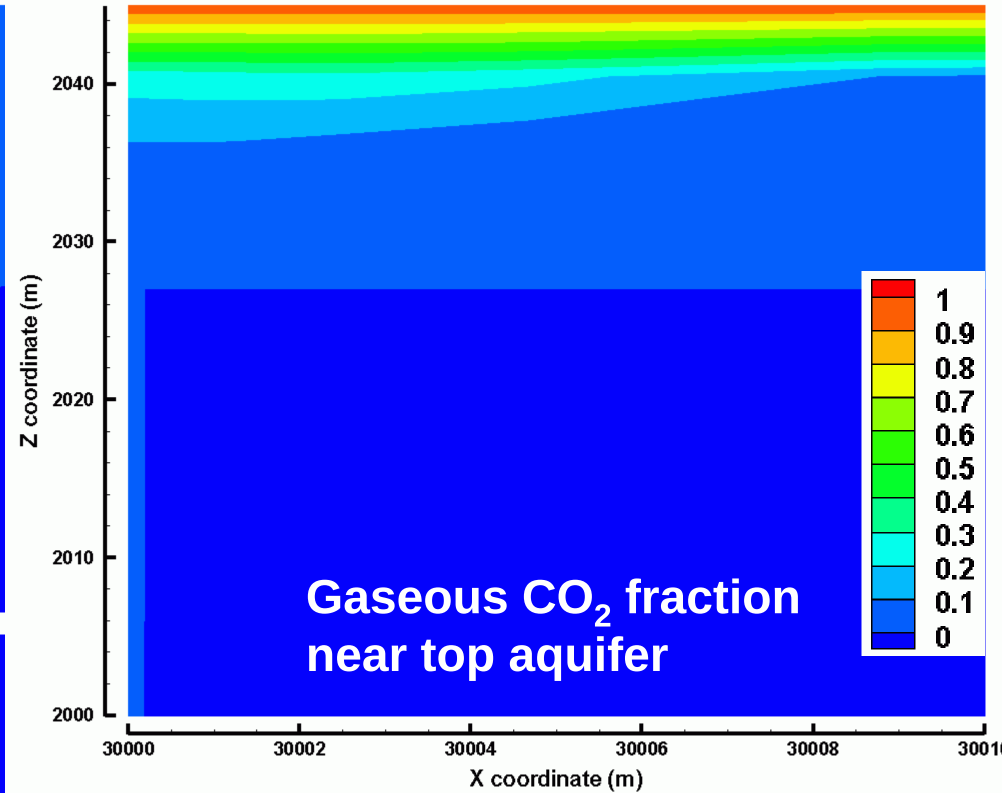
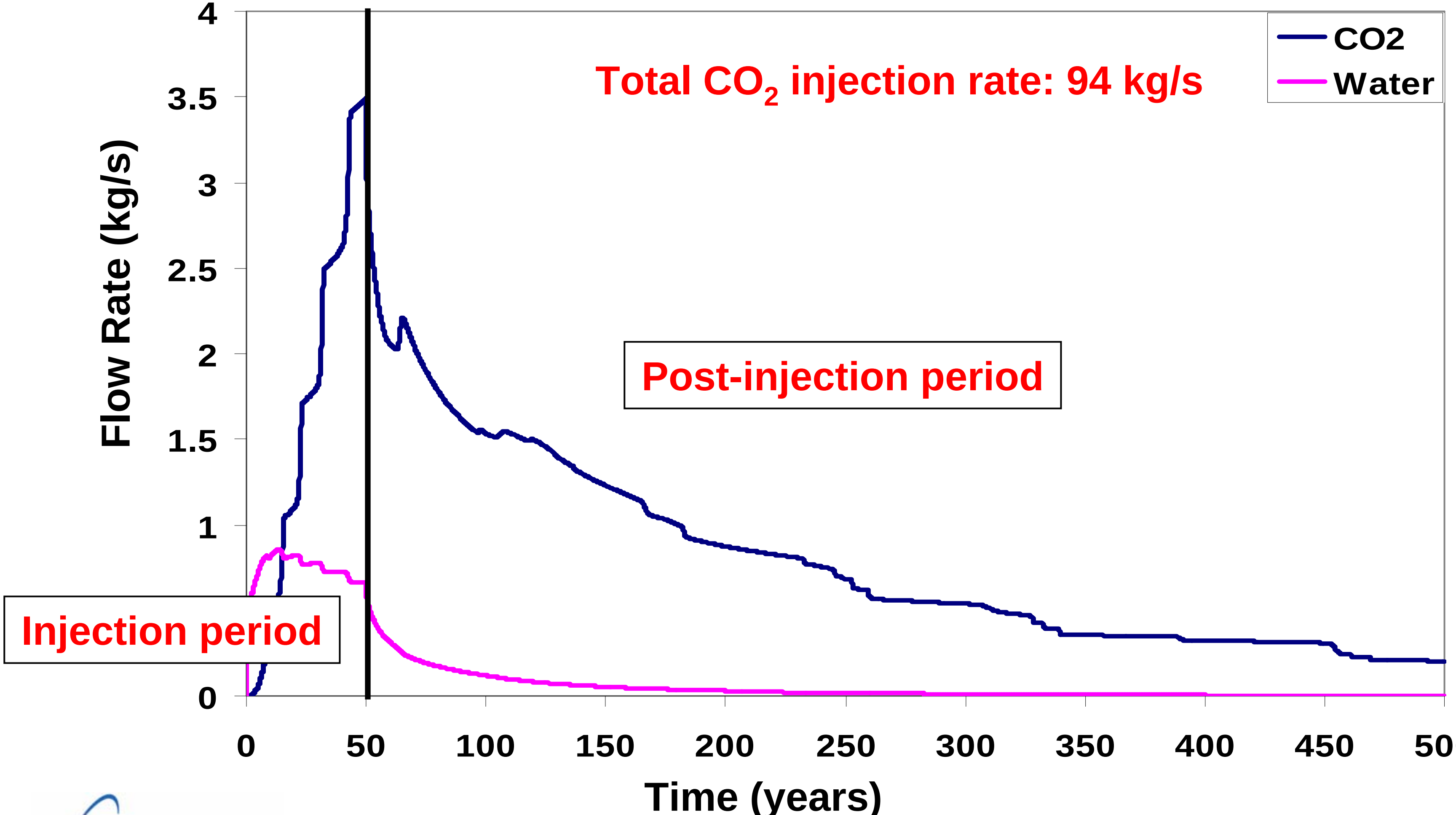




CO_2 migration through/near wellbore after 50 years

CO_2/water migration through wellbore



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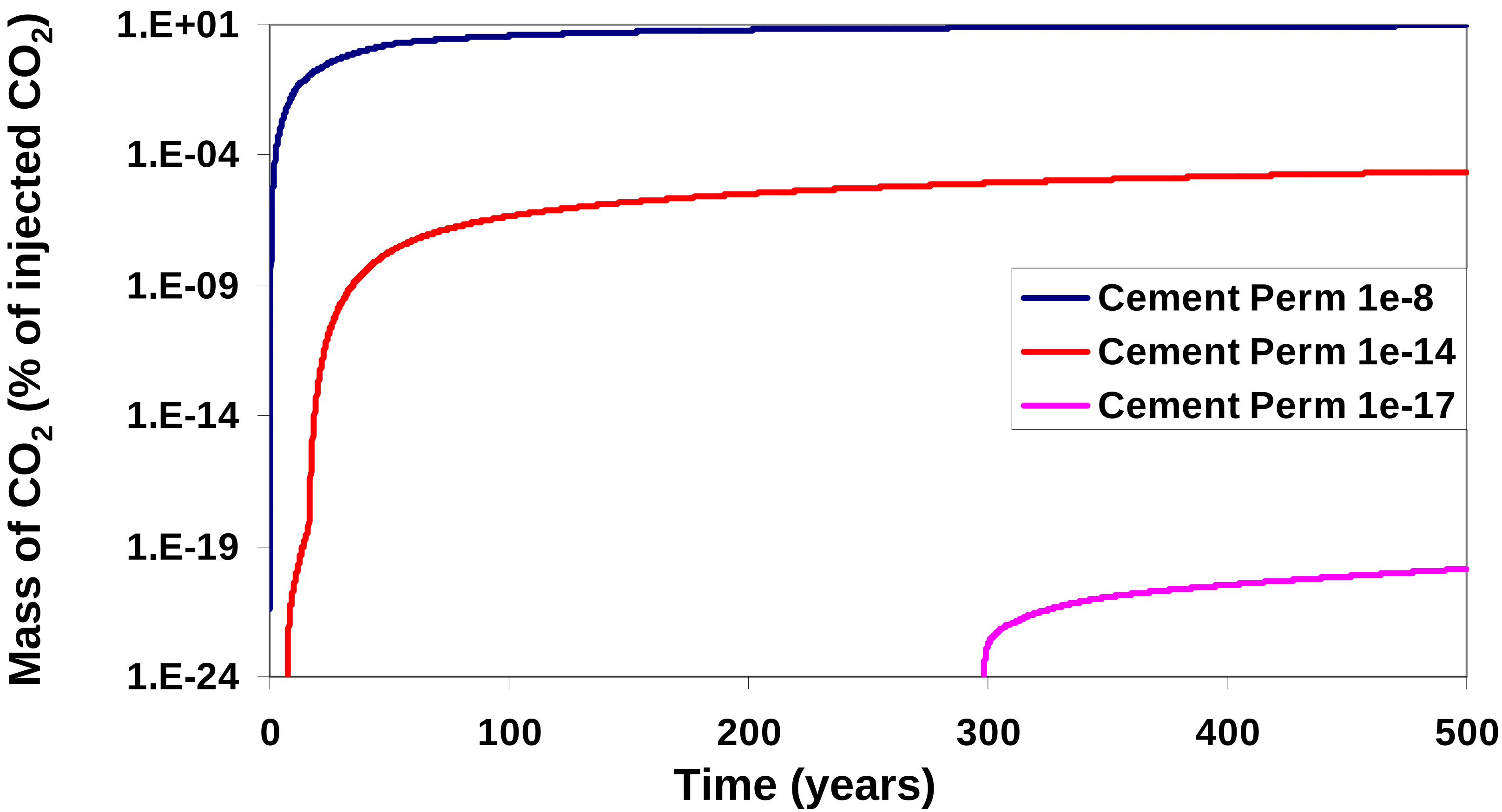
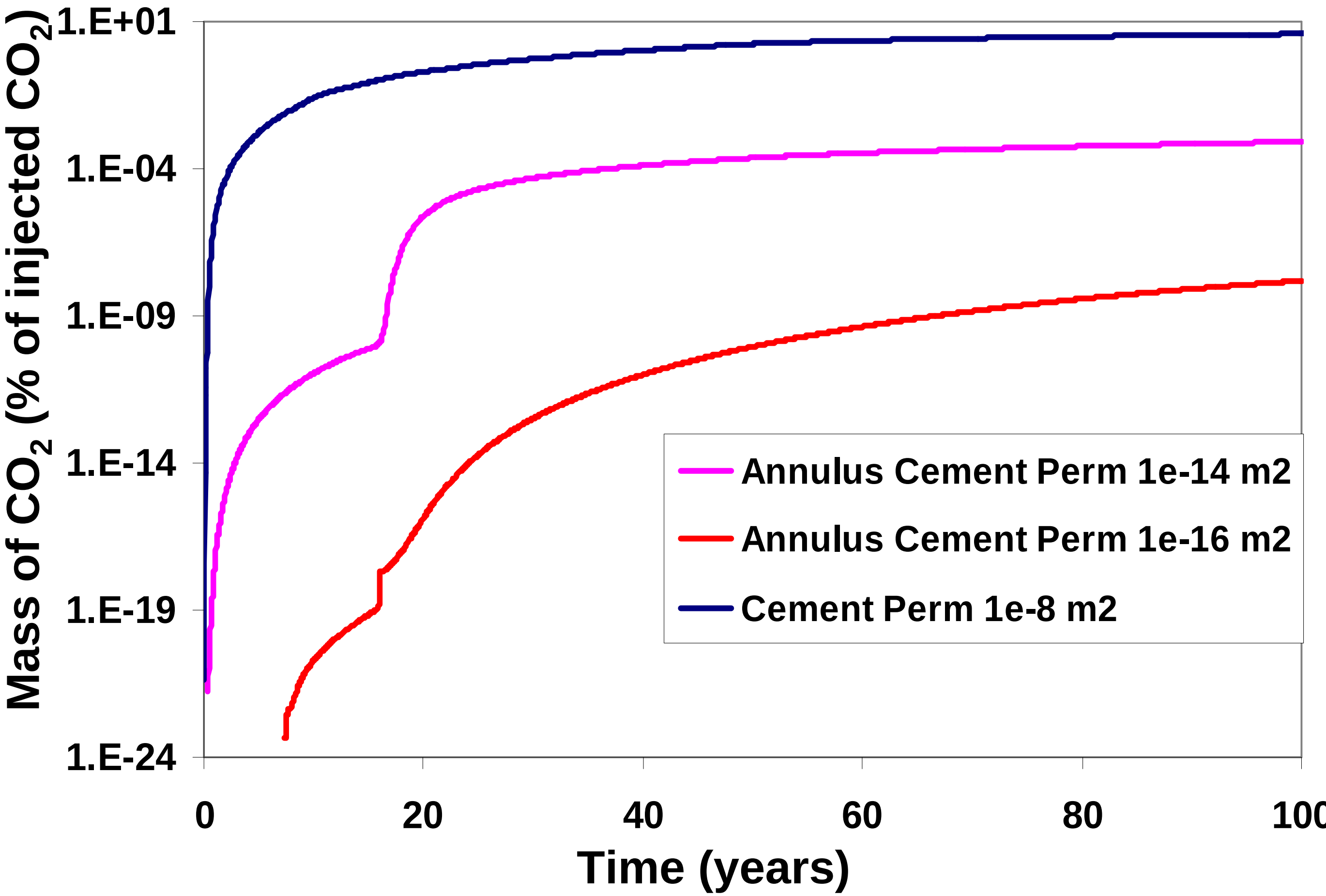
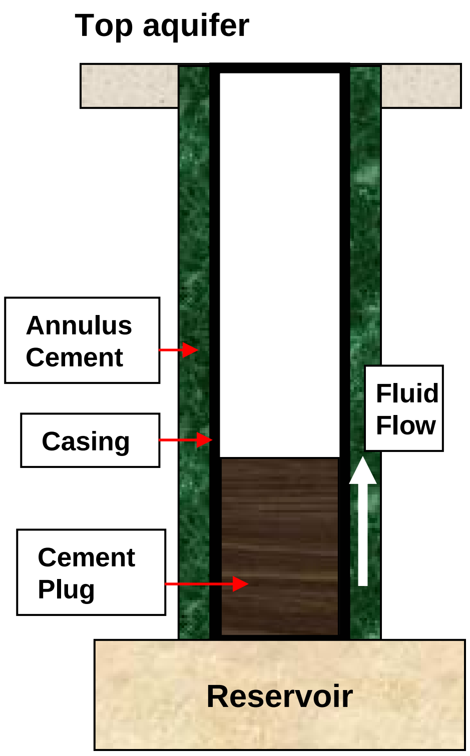
Effect of wellbore cement permeability on mass of CO_2 leaked in top aquifer



Measurements of field wellbore cement permeability have been "extremely limited"

Simulating details of well completions: flow through annulus cement





3” casing ID
0.1” casing thickness
3” annulus thickness

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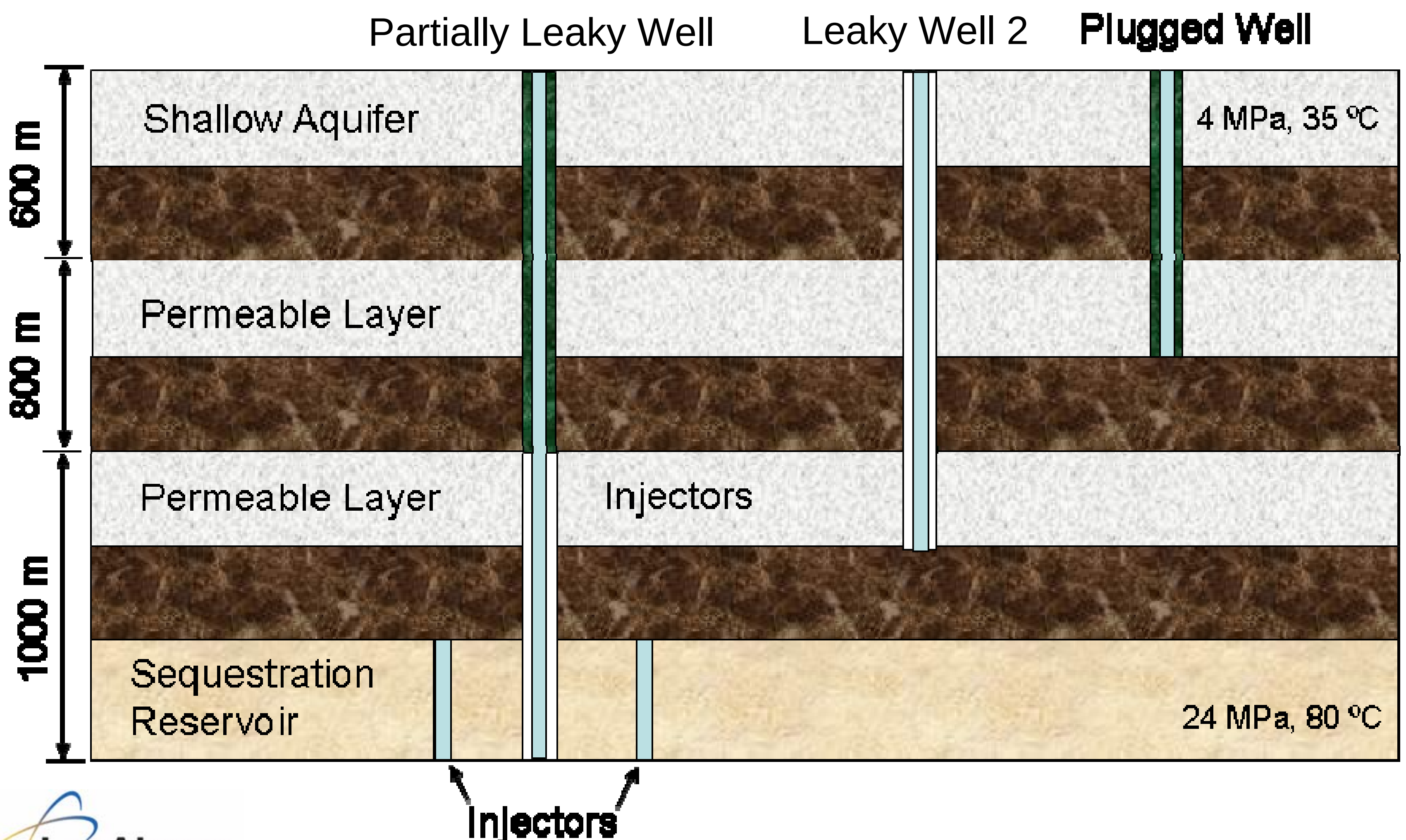
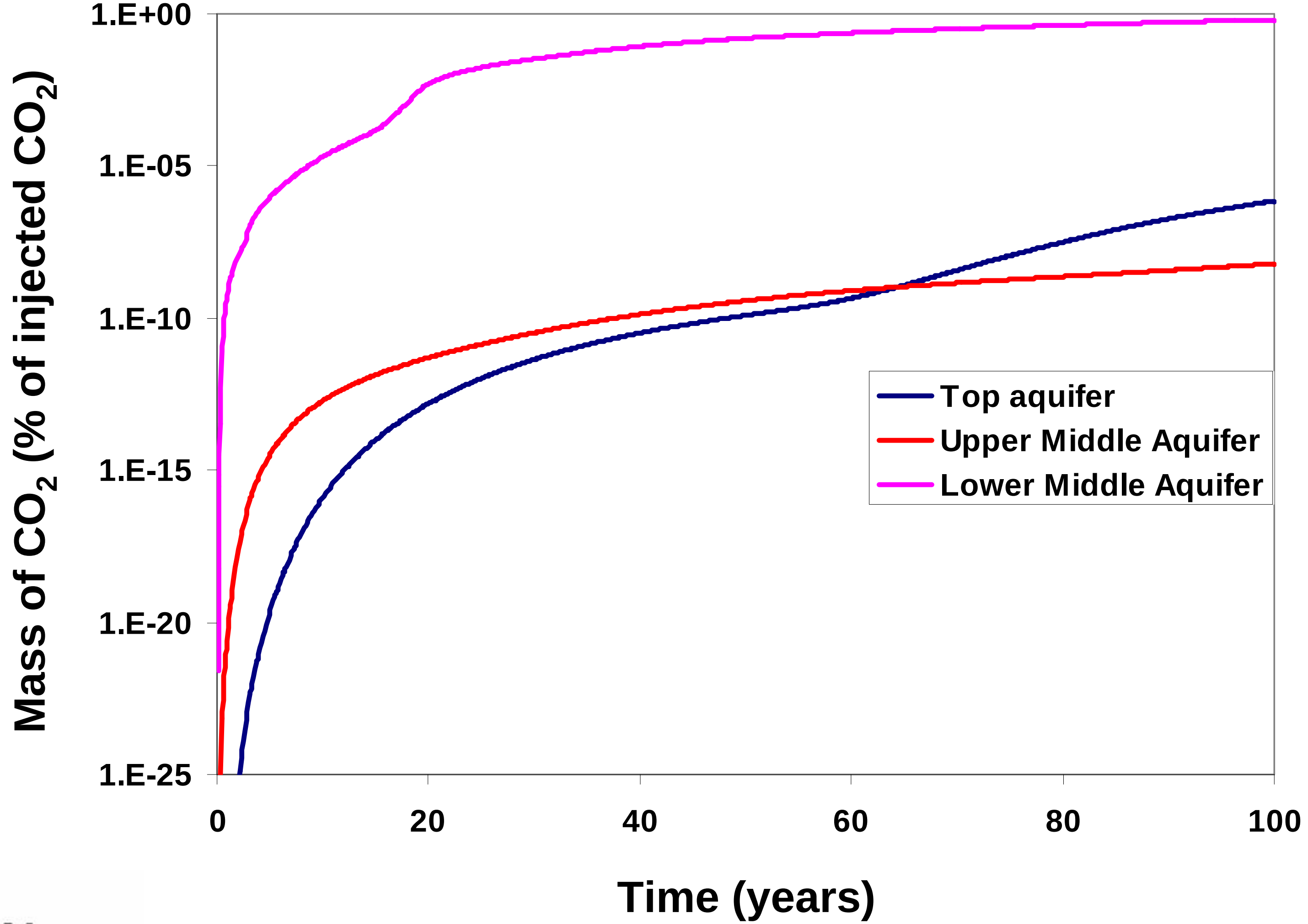
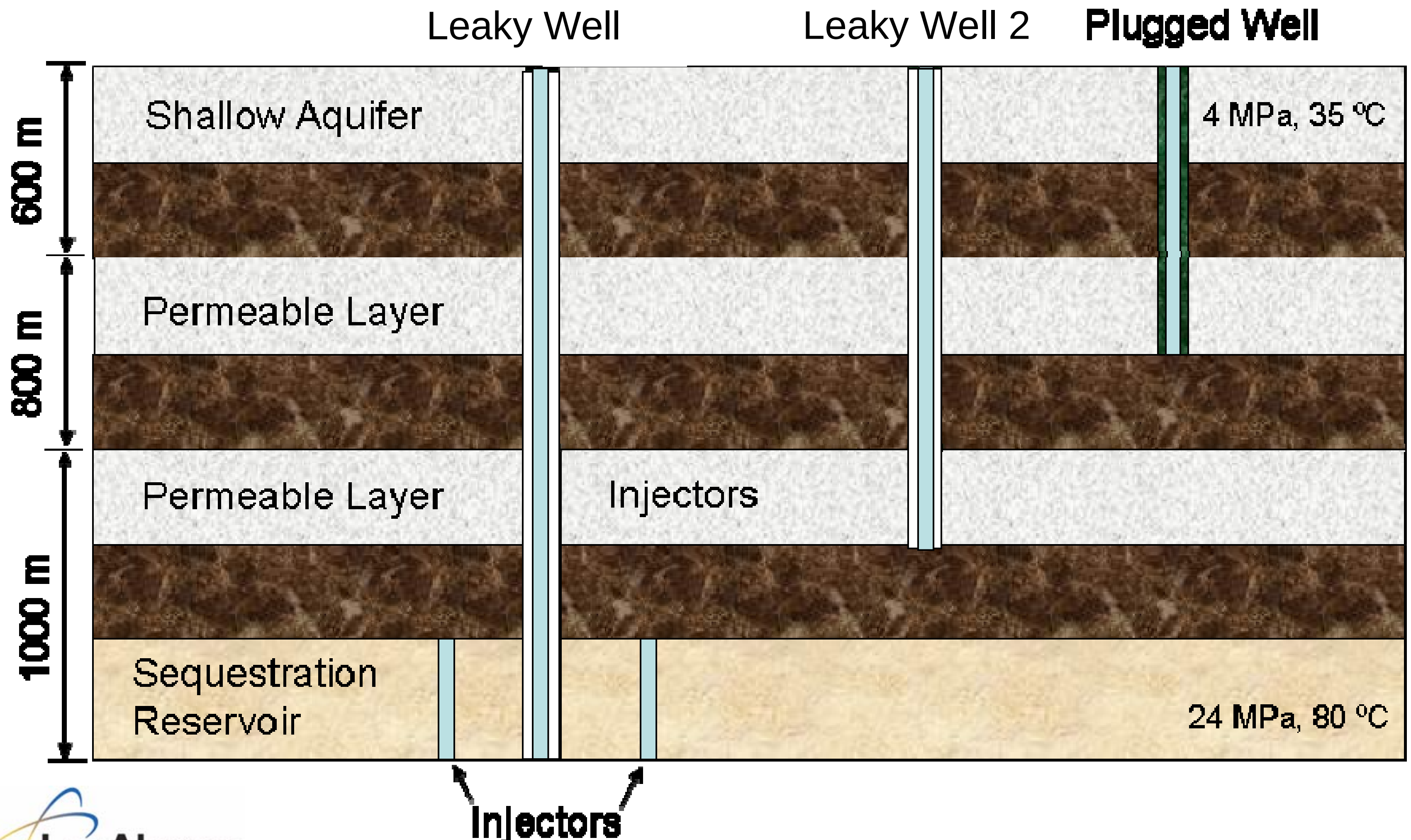
Multiple layers, multiple wells (Case I)



Amount of CO_2 leaked in shallower formations



Multiple layers, multiple wells (Case II)



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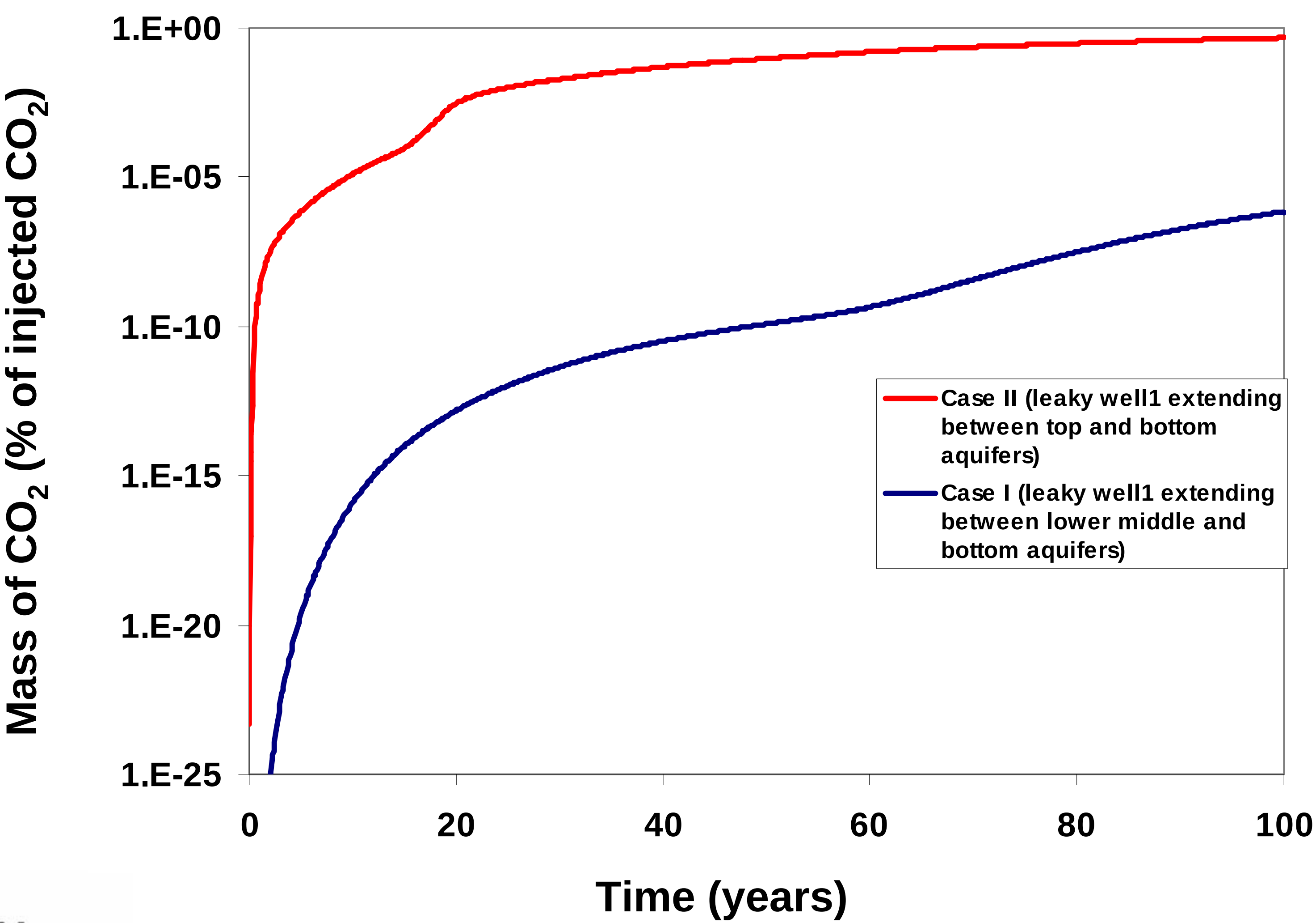
Comparison of amount of CO_2 leaked into top aquifer



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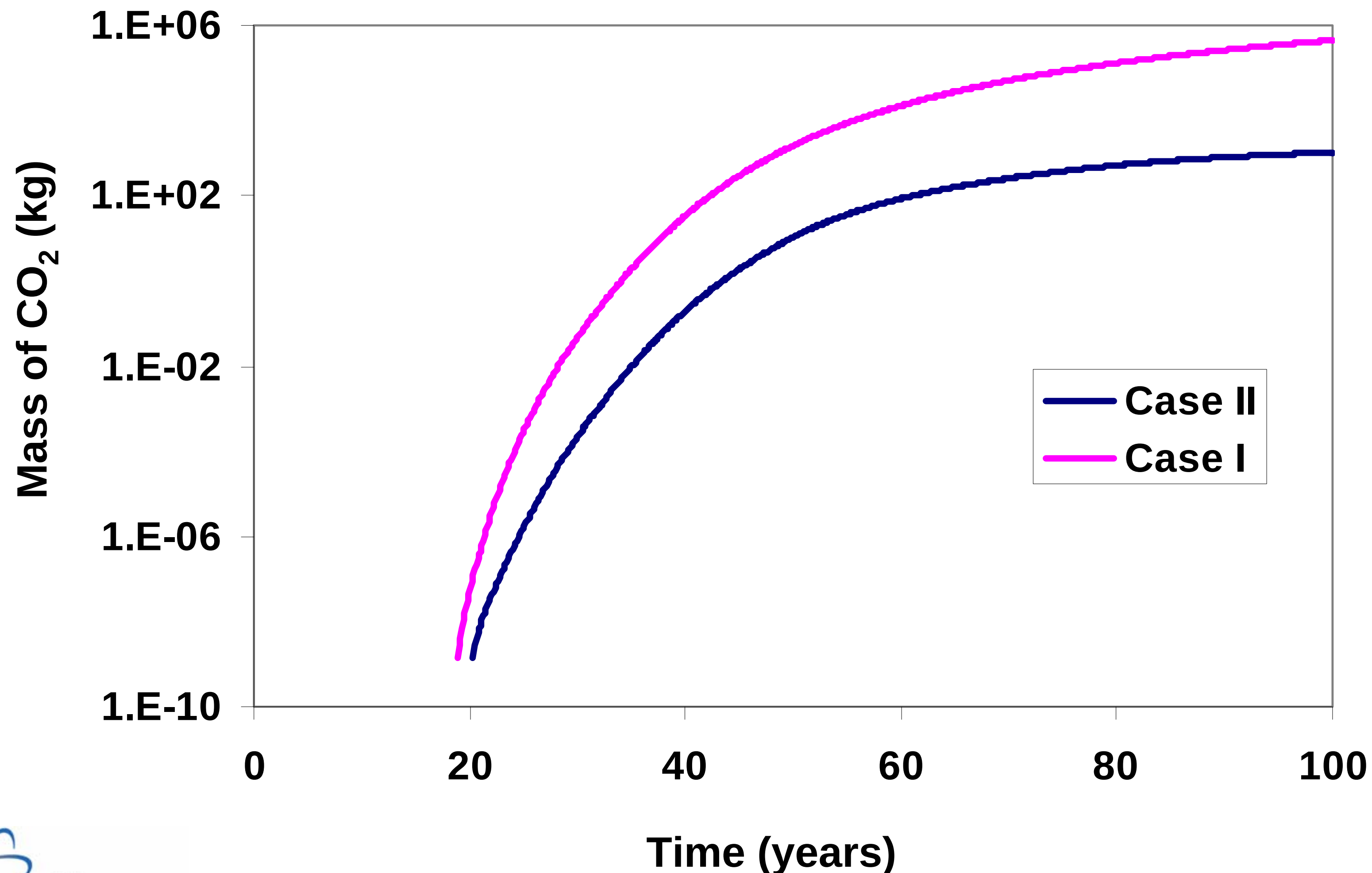
Amount of leaked CO_2 within 100 meters of well 2



Conclusions

- Impact of poorly-plugged/leaky wellbores on overall performance of large-scale injection operations will have to be characterized for CCS deployment
- Numerical simulations capturing the details of wellbore geometry and dynamic evolution of wellbore/near-wellbore conditions can be useful to characterize CO_2 migration through leaky/plugged wellbores
- We have developed computationally efficient numerical capabilities that can be used to simulate detailed wellbore/near-wellbore behavior in a large-scale sequestration operation

Acknowledgements

This work was funded by US-DOE through the Zero Emission Research Technology (ZERT) program

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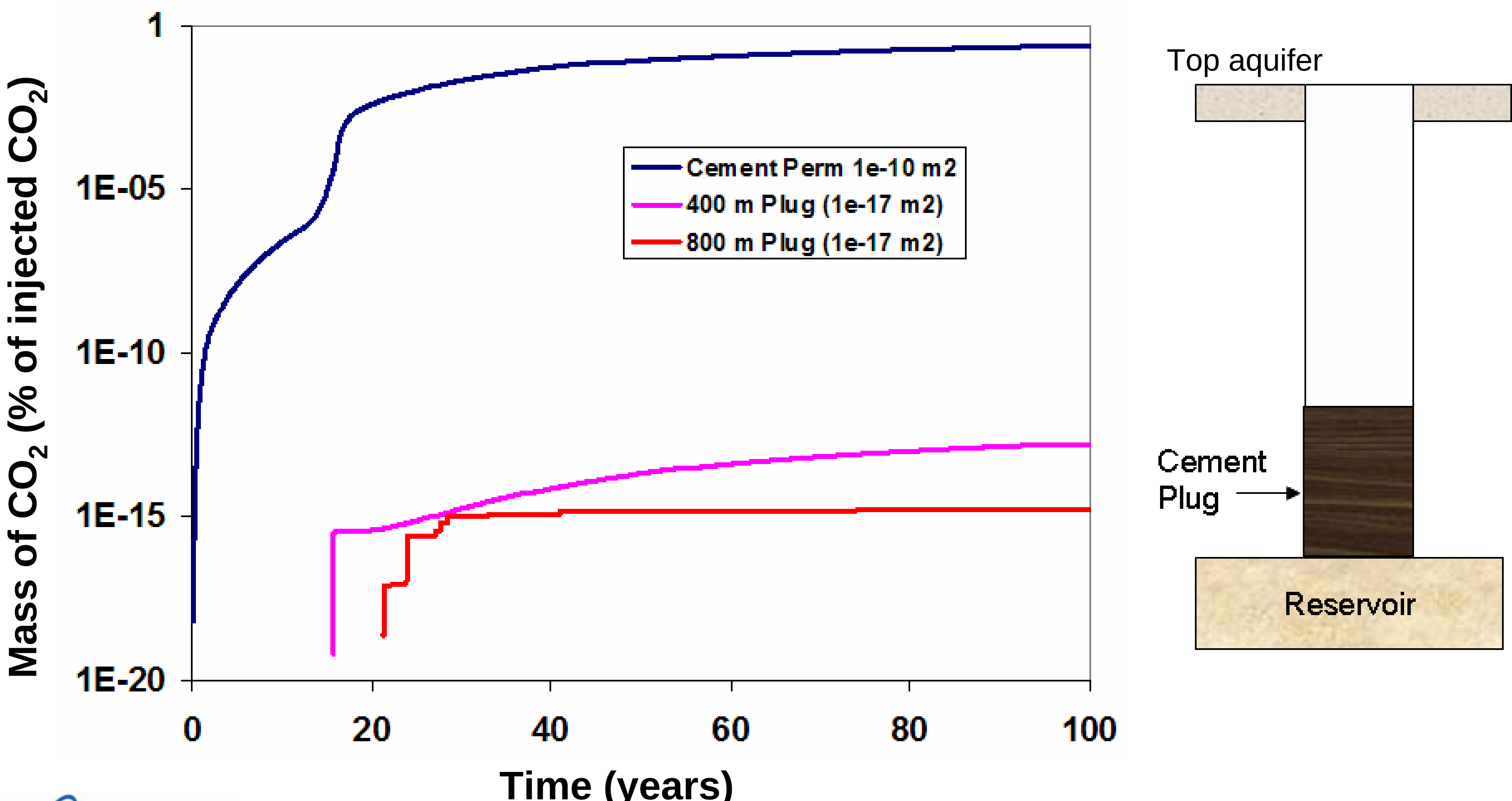
Simulating detailed well completions: effect of cement plug on mass of CO_2 in top aquifer



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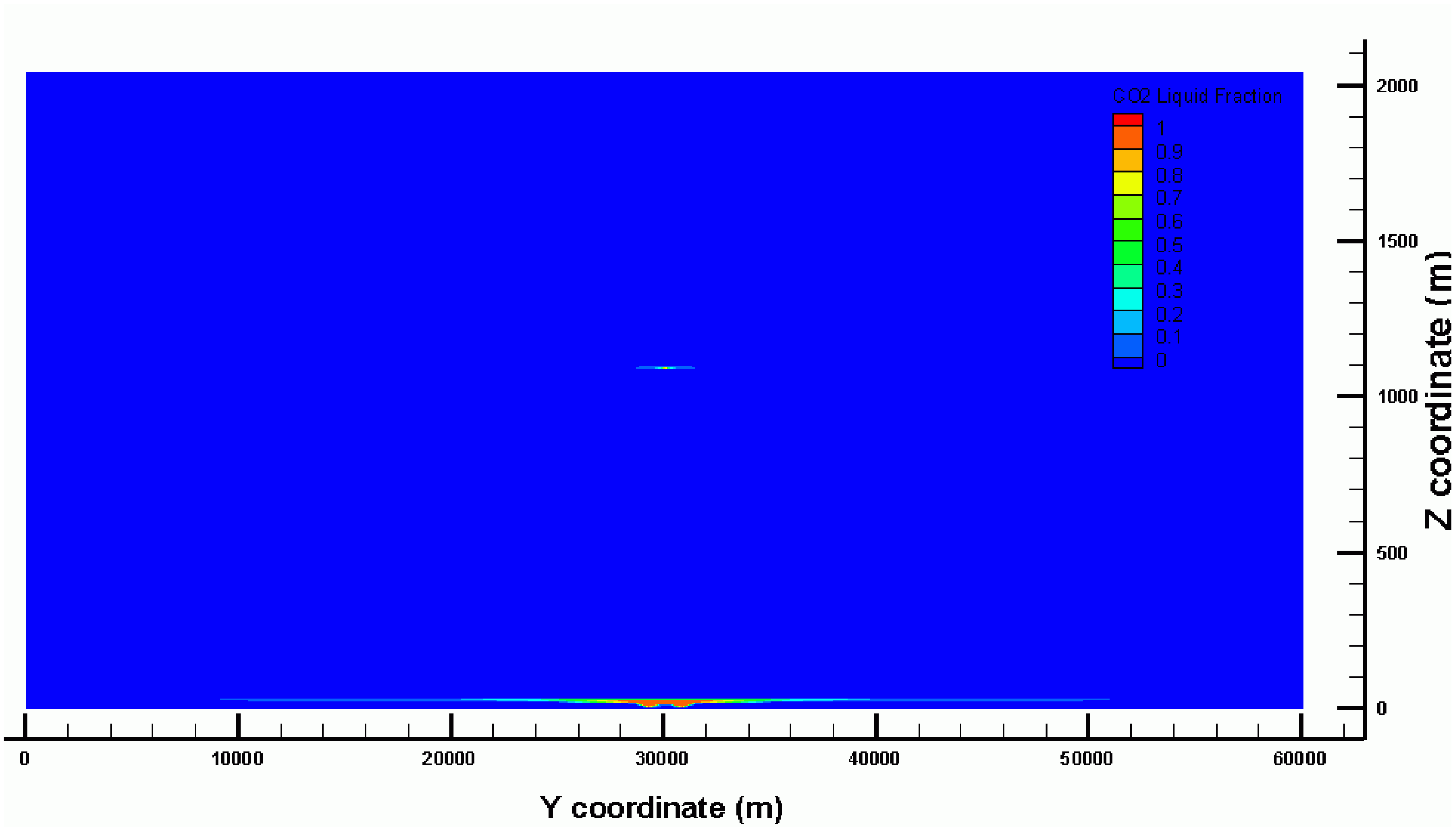
Migration of leaked CO_2 in shallower formations



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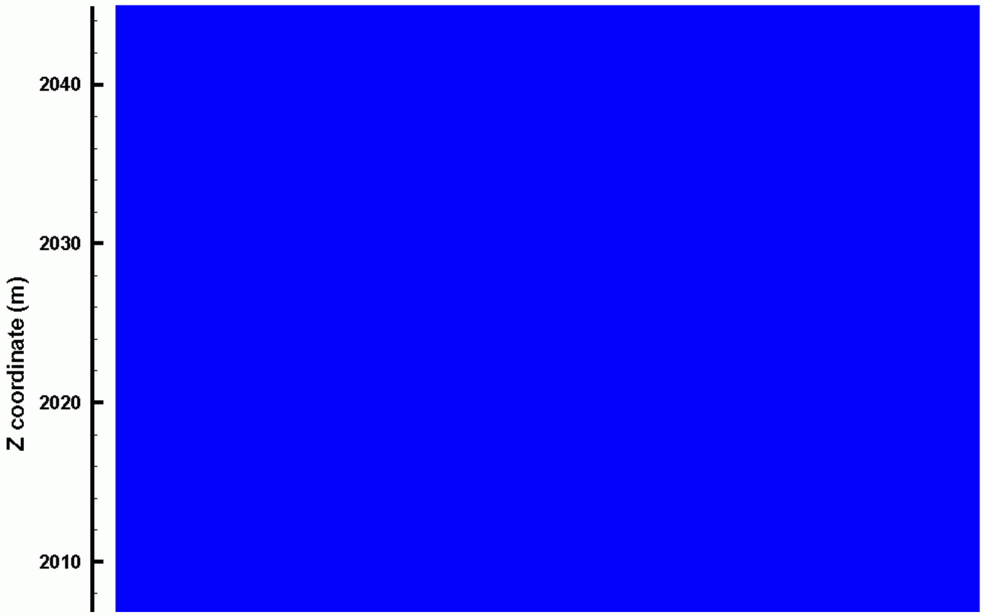
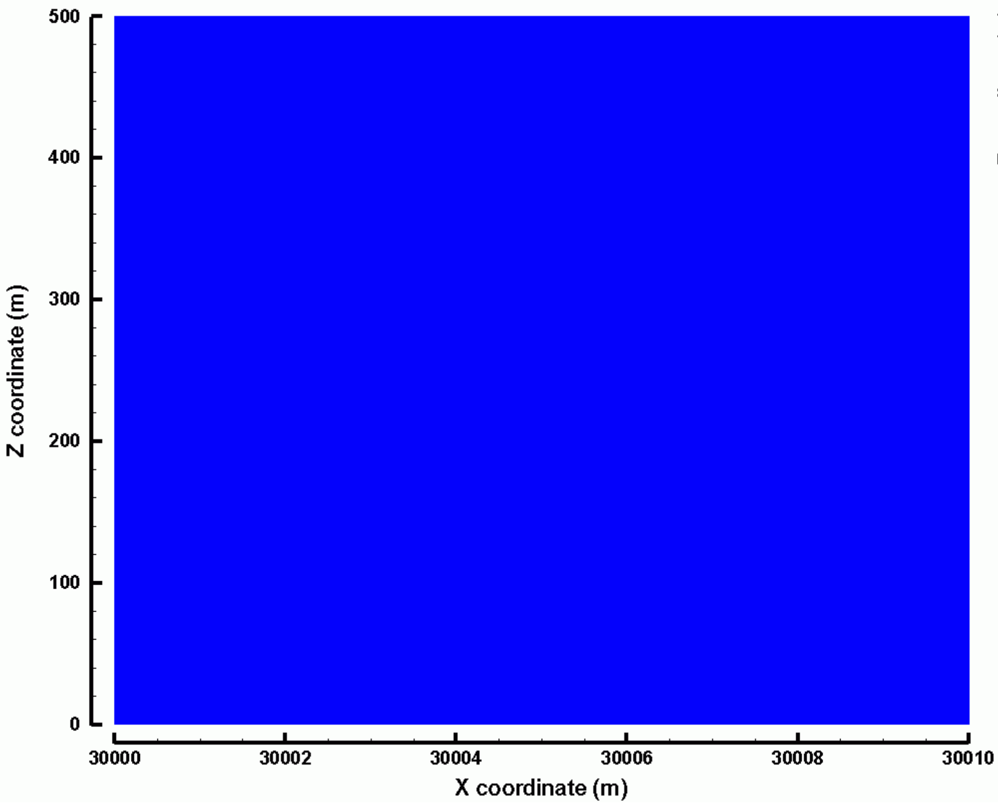
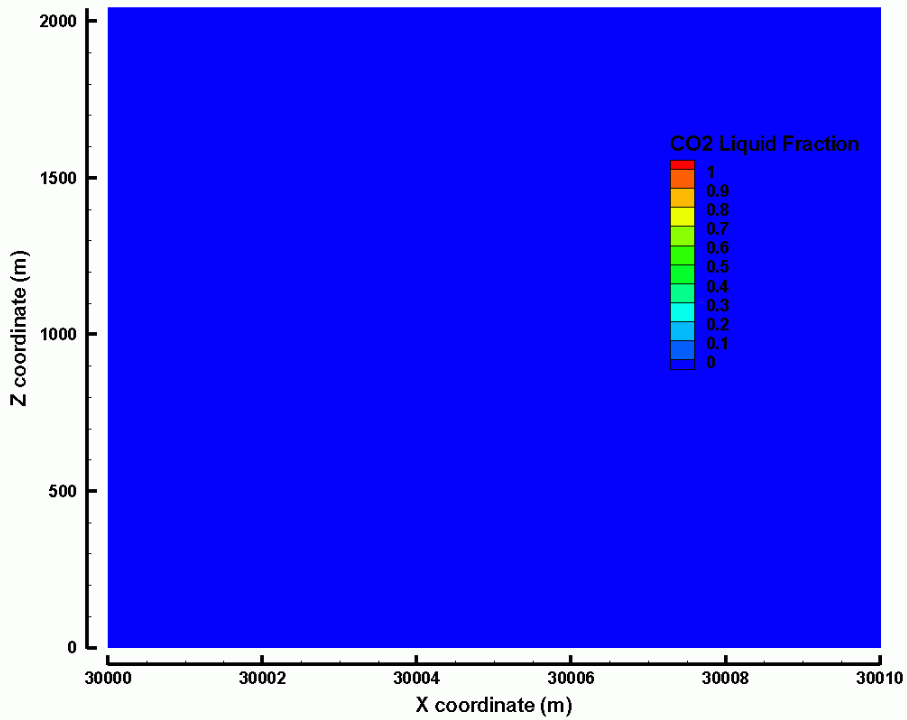
CO_2 (liquid/sc) migration through/near wellbore

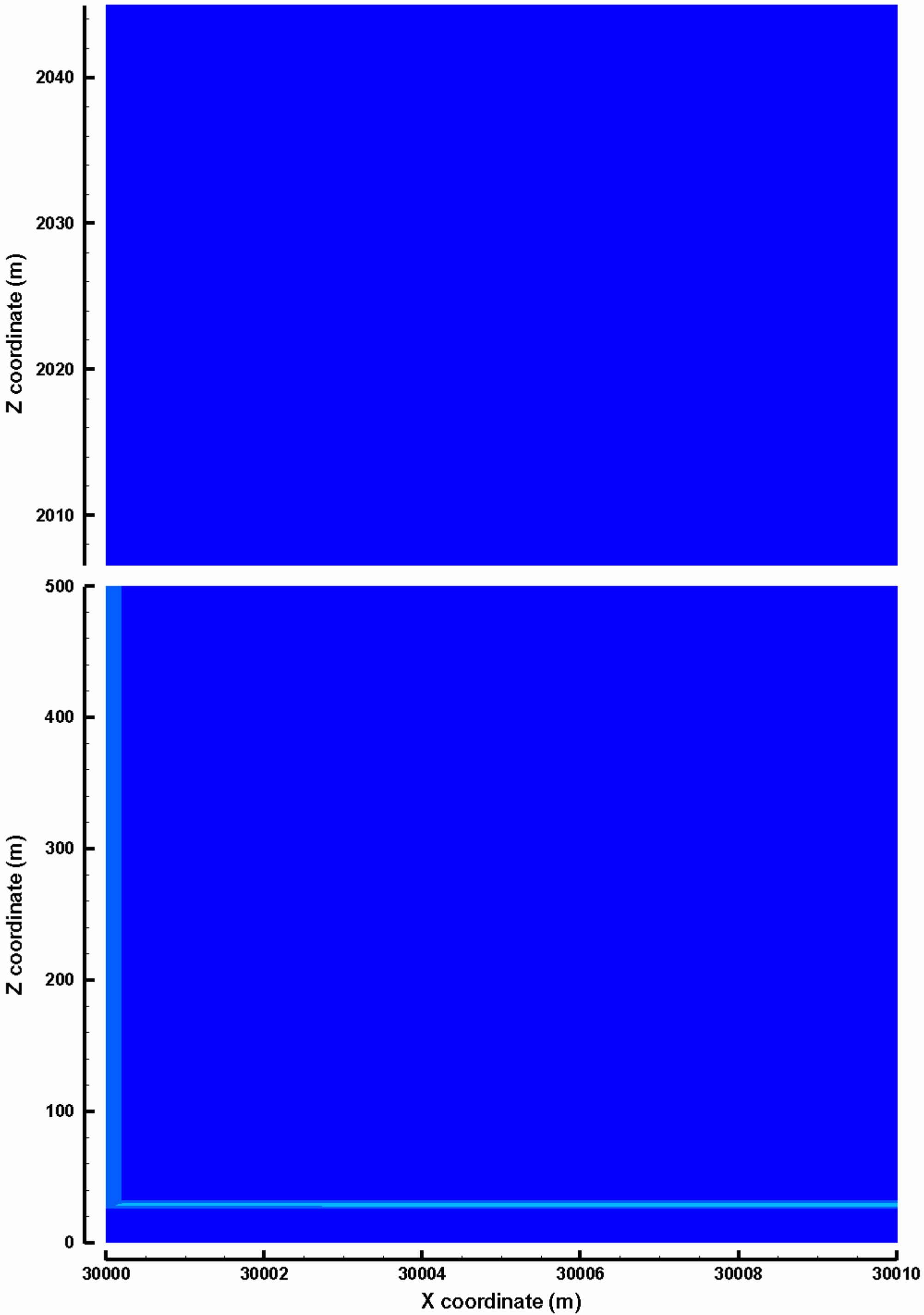




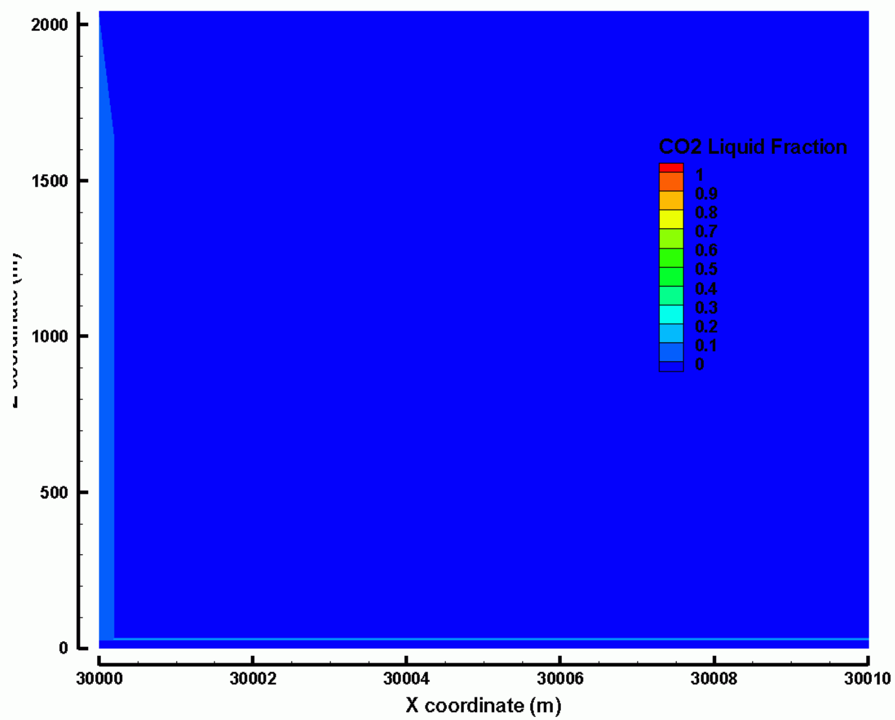
Time = 0 Years



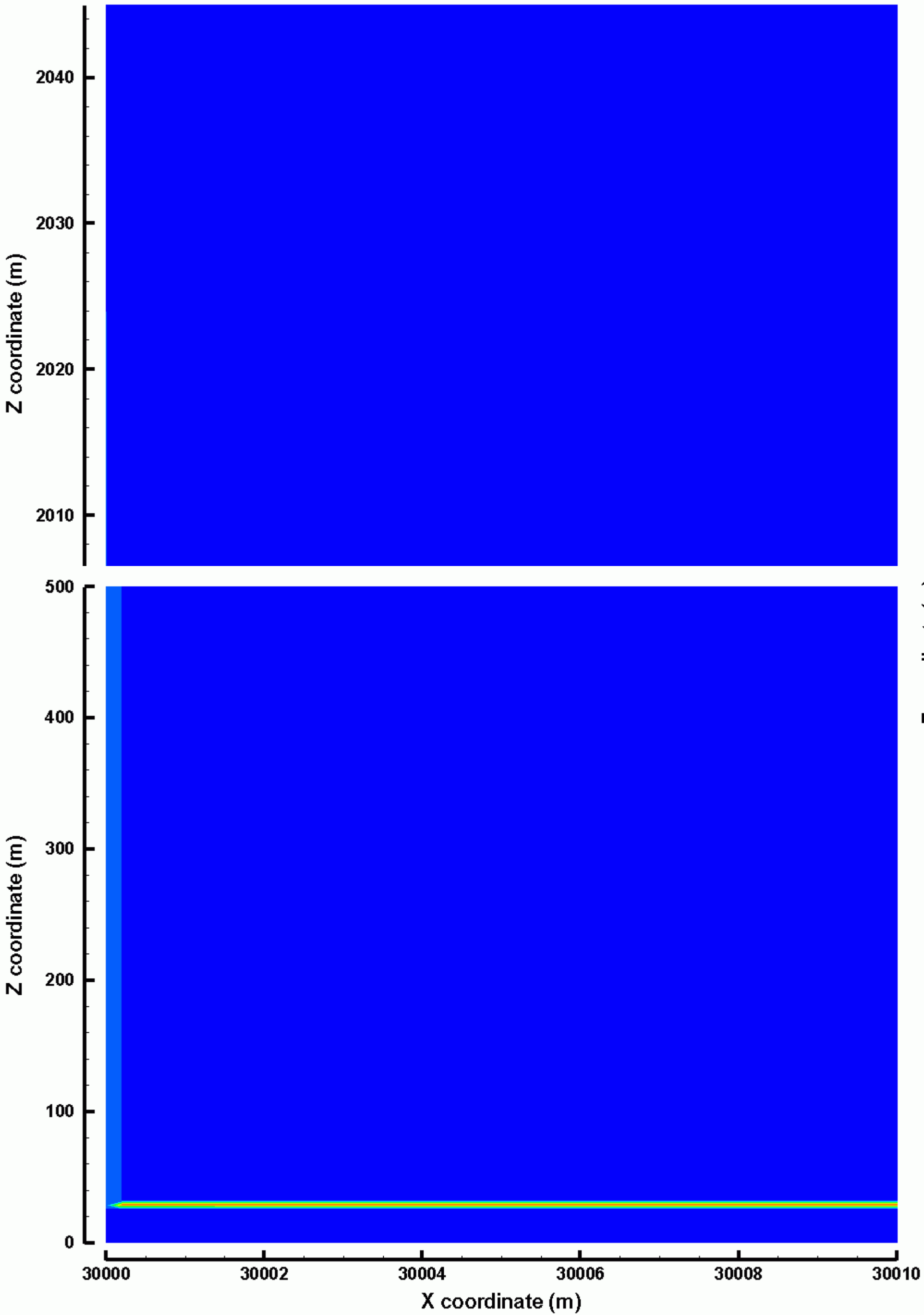
CO_2 (liquid/sc) migration through/near wellbore



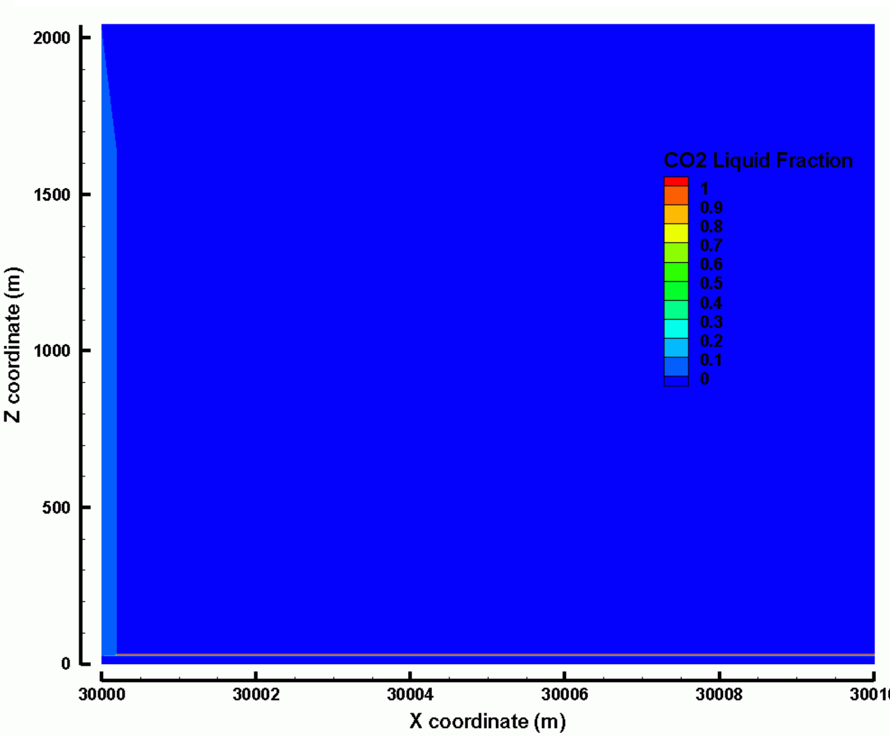
Time = 5 Years



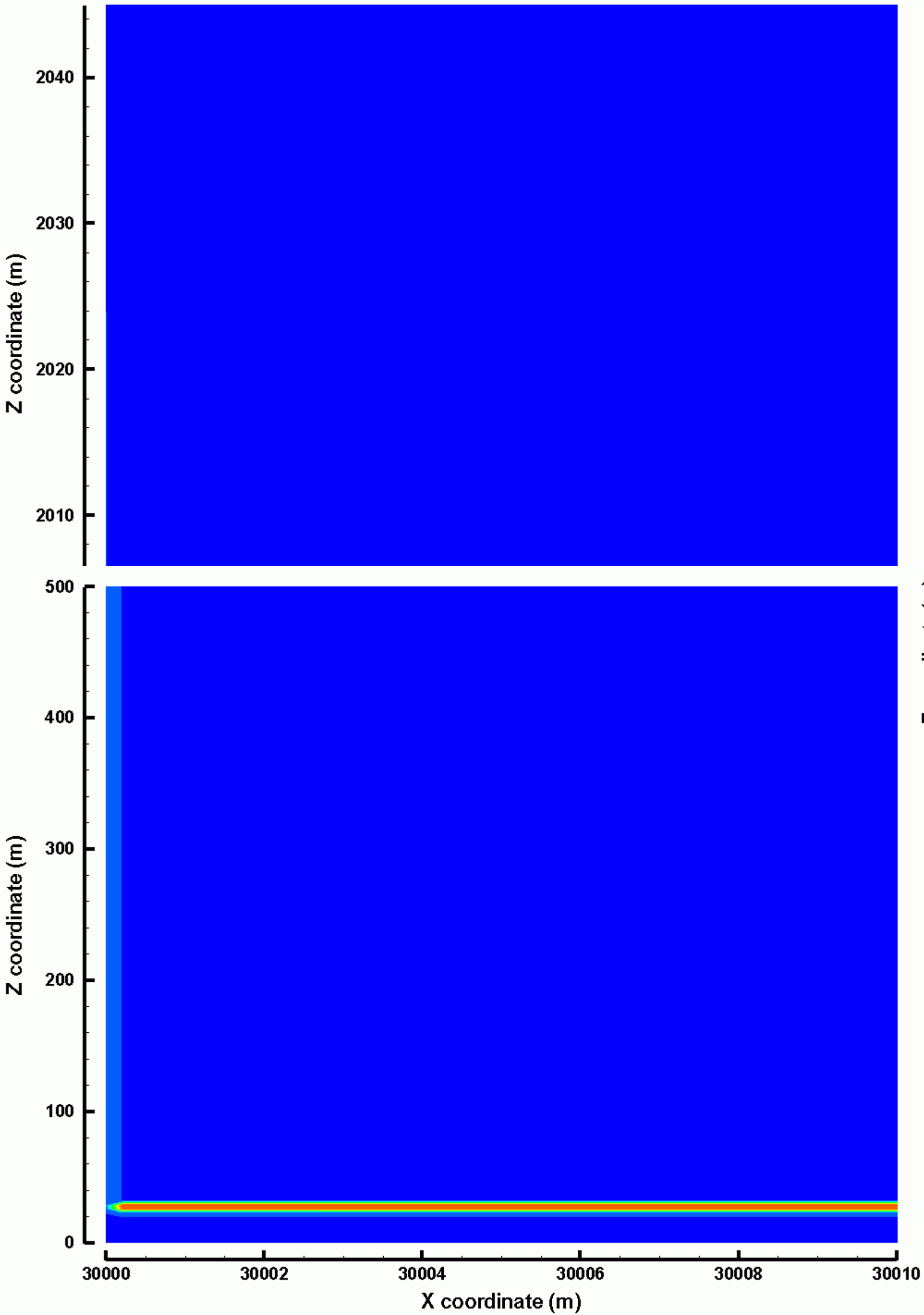
CO_2 (liquid/sc) migration through/near wellbore



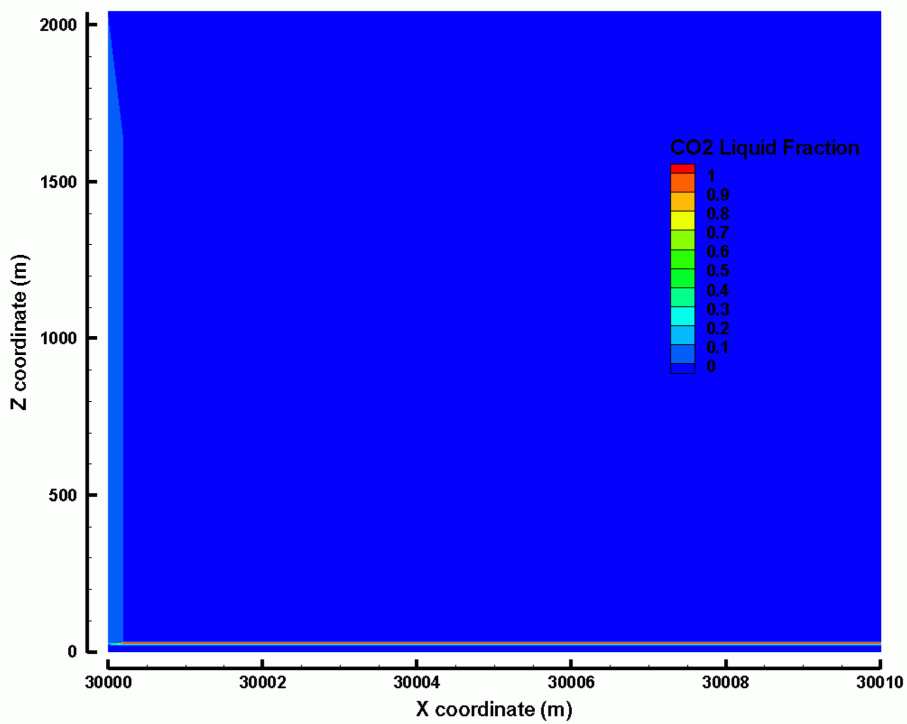
Time = 10 Years



CO_2 (liquid/sc) migration through/near wellbore

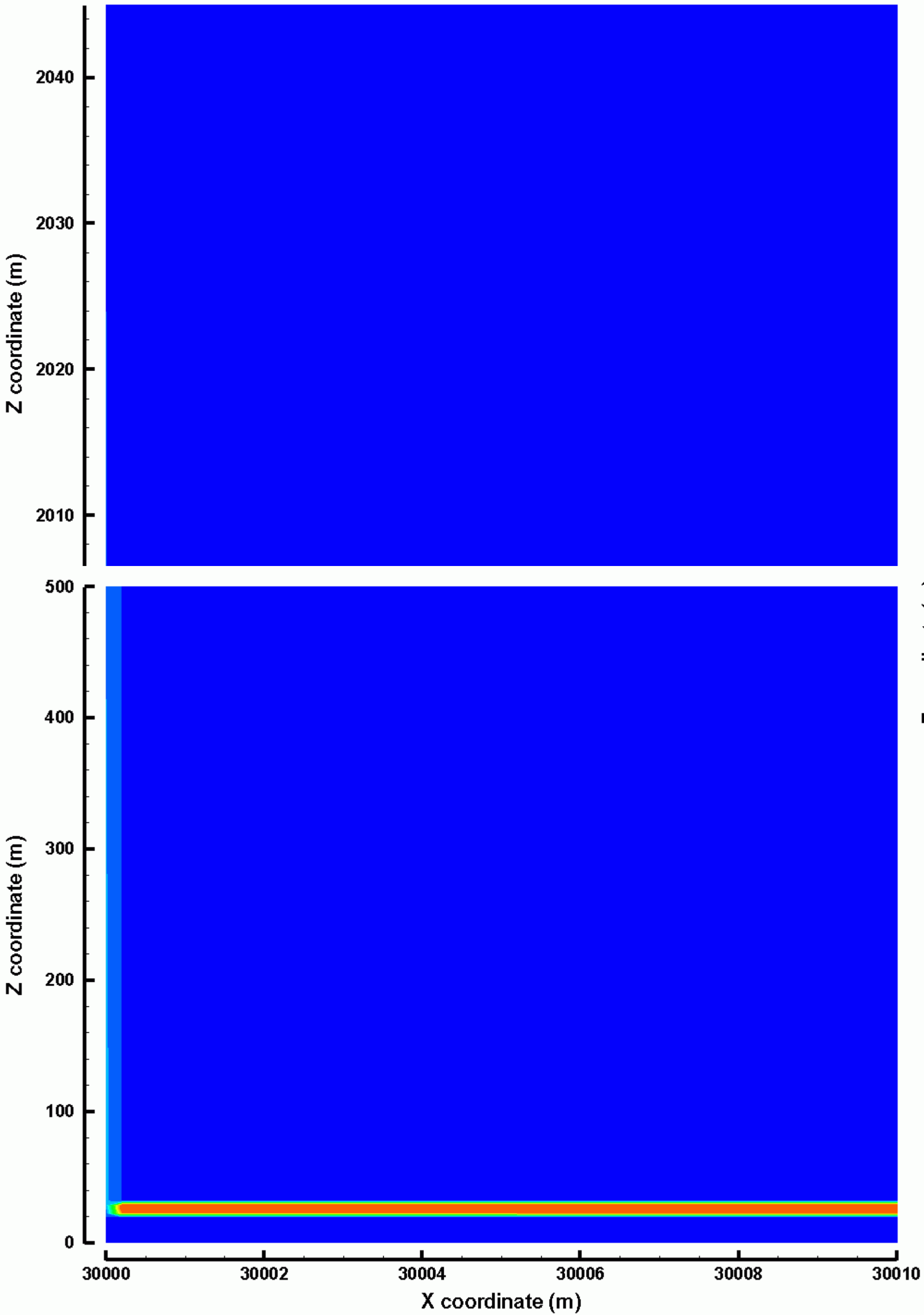


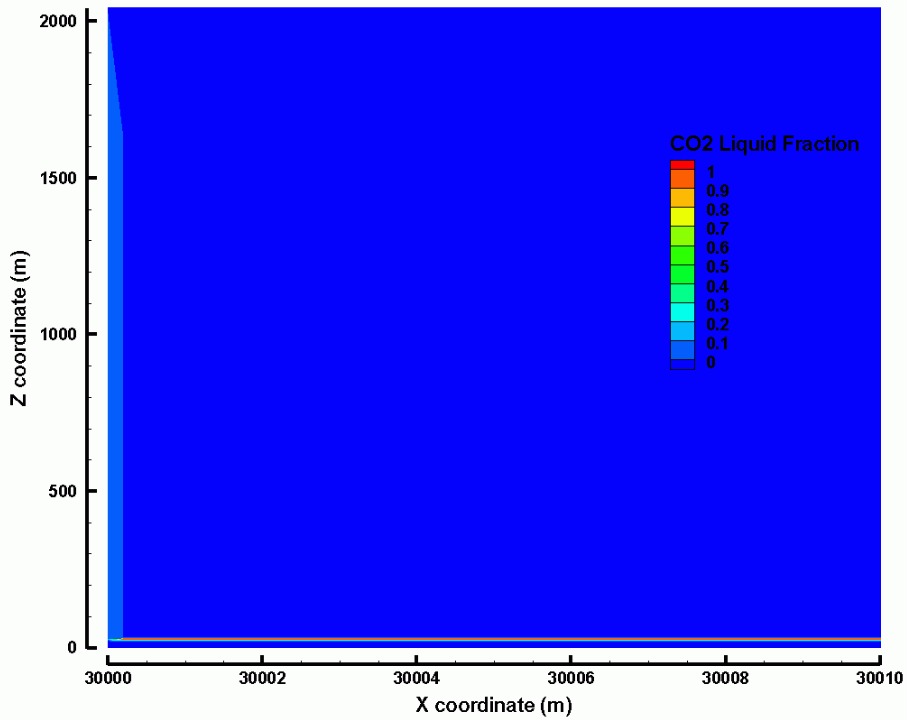
Time = 20 Years



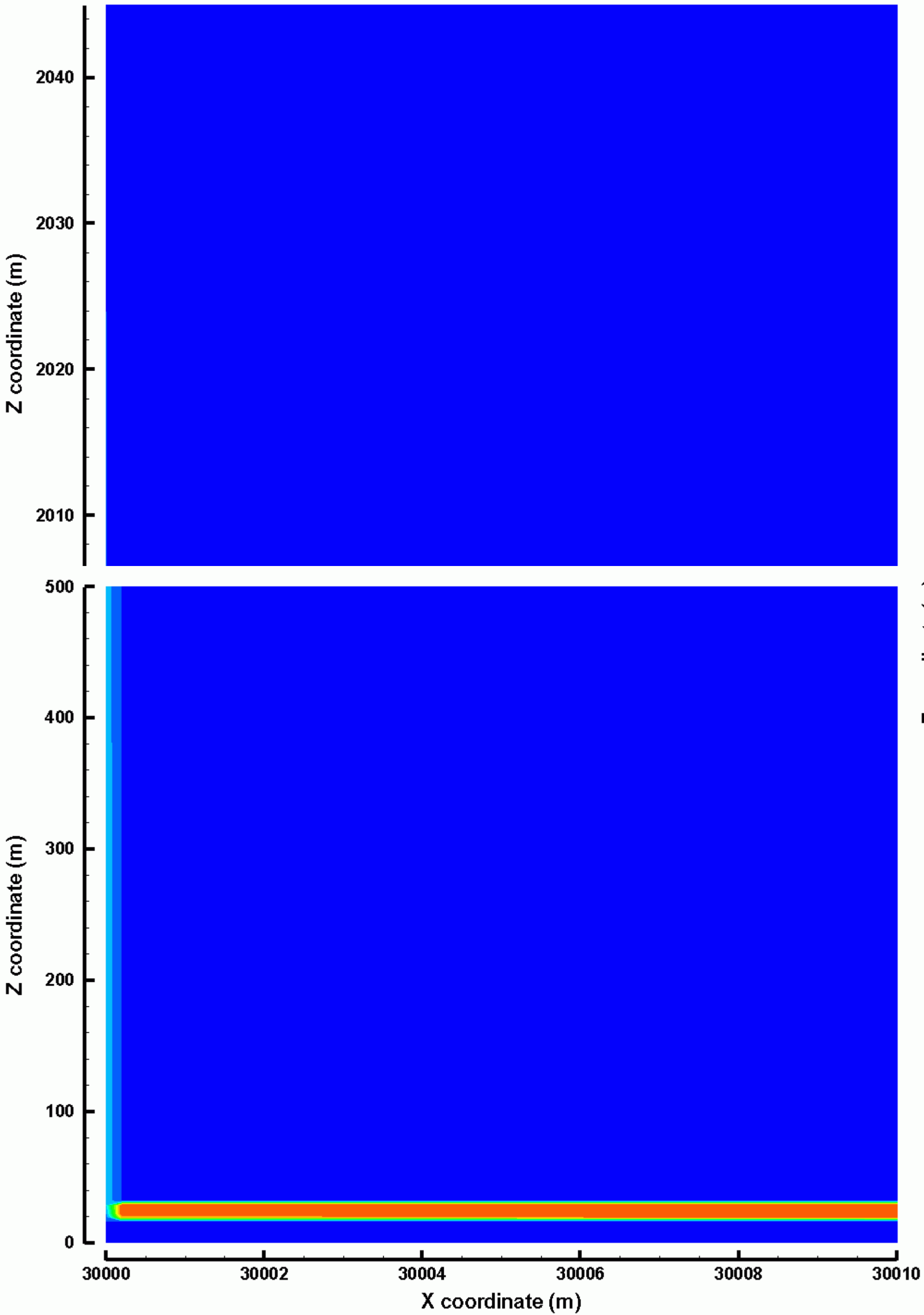
CO_2 (liquid/sc) migration through/near wellbore

Time = 25 Years

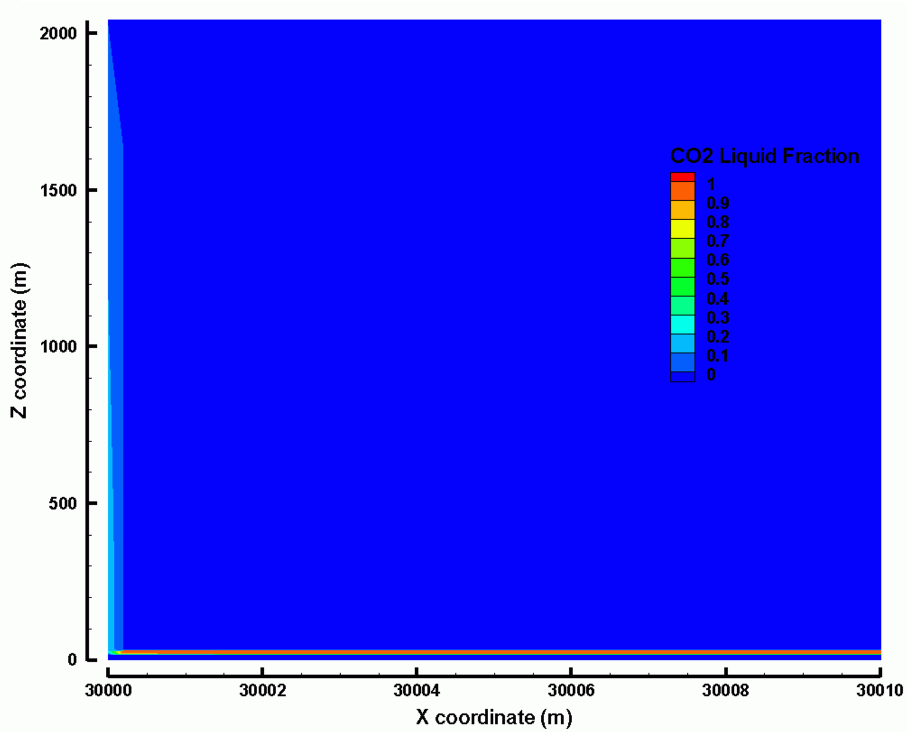




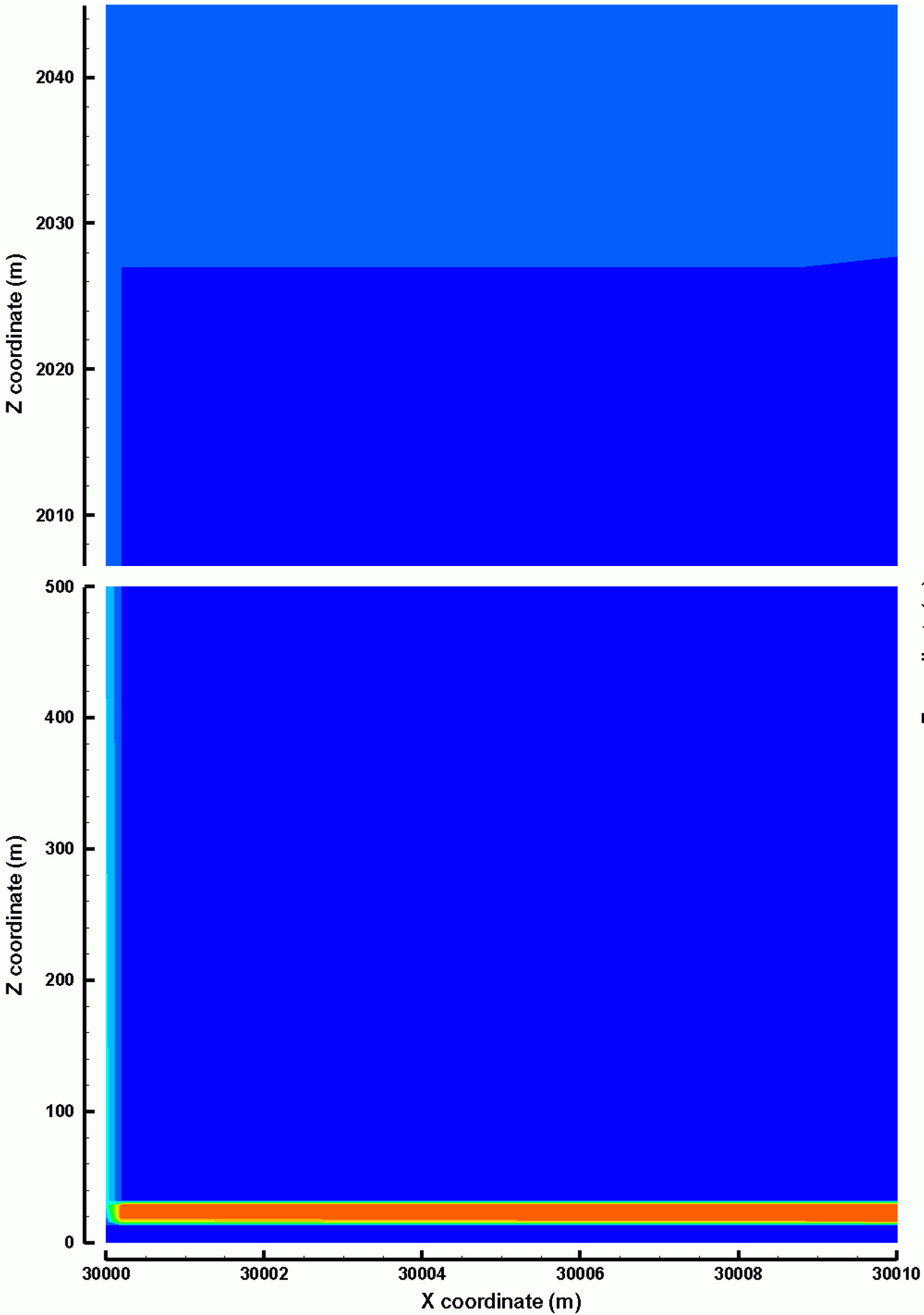
CO_2 (liquid/sc) migration through/near wellbore



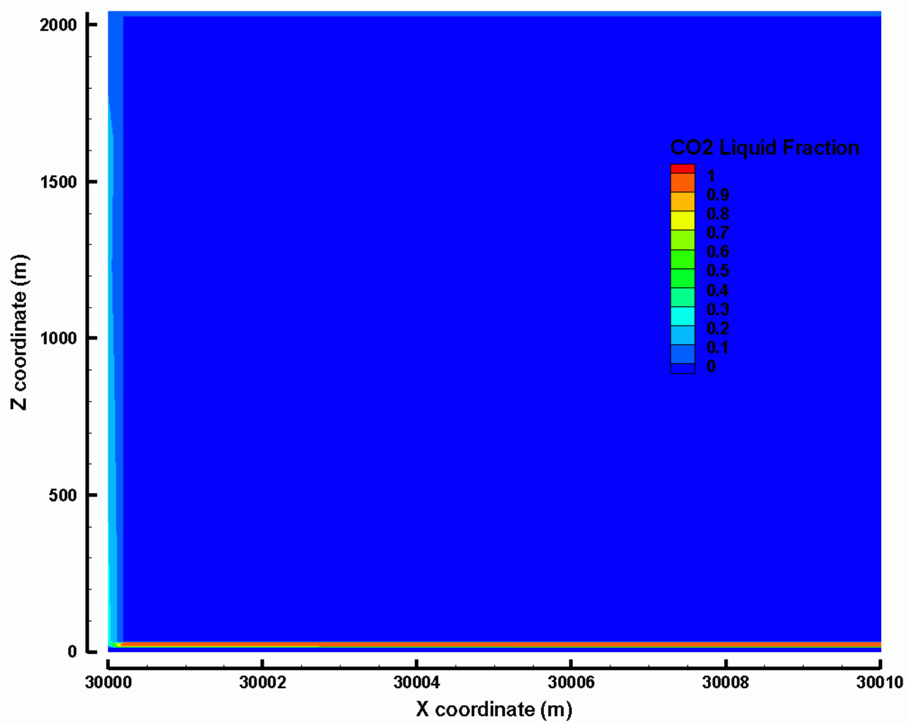
Time = 35 Years



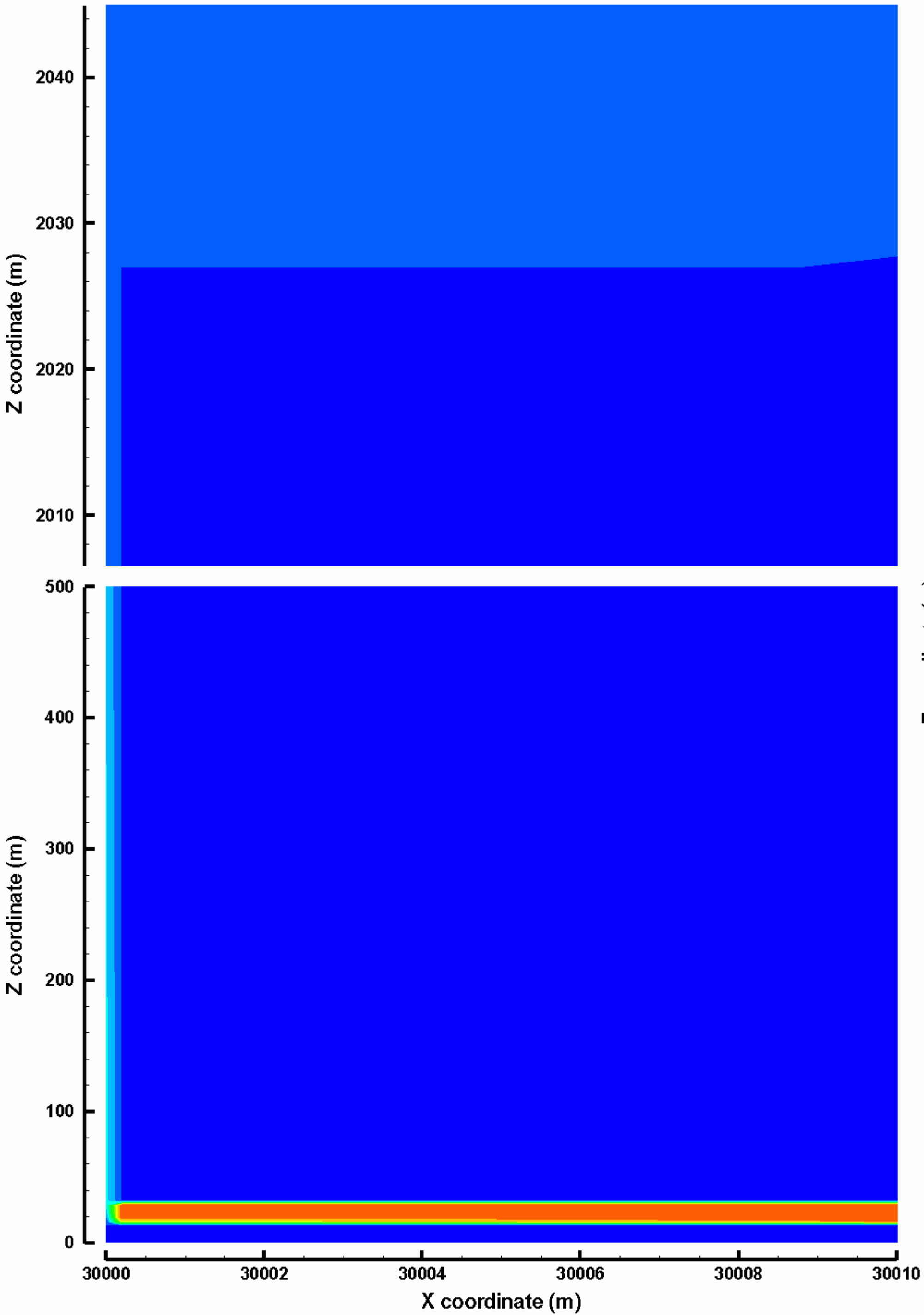
CO_2 (liquid/sc) migration through/near wellbore



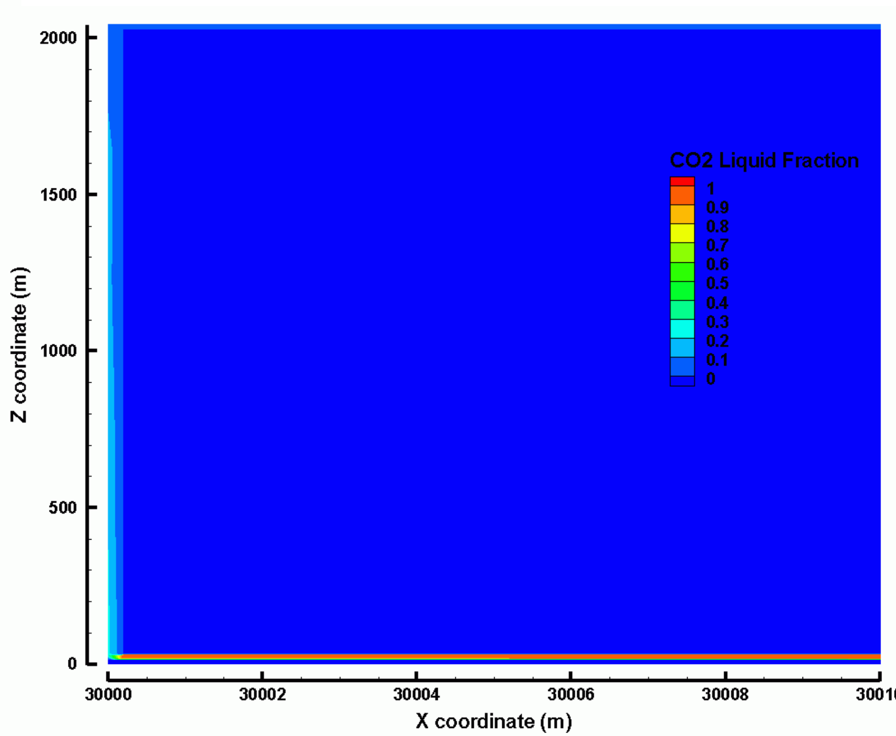
Time = 45 Years



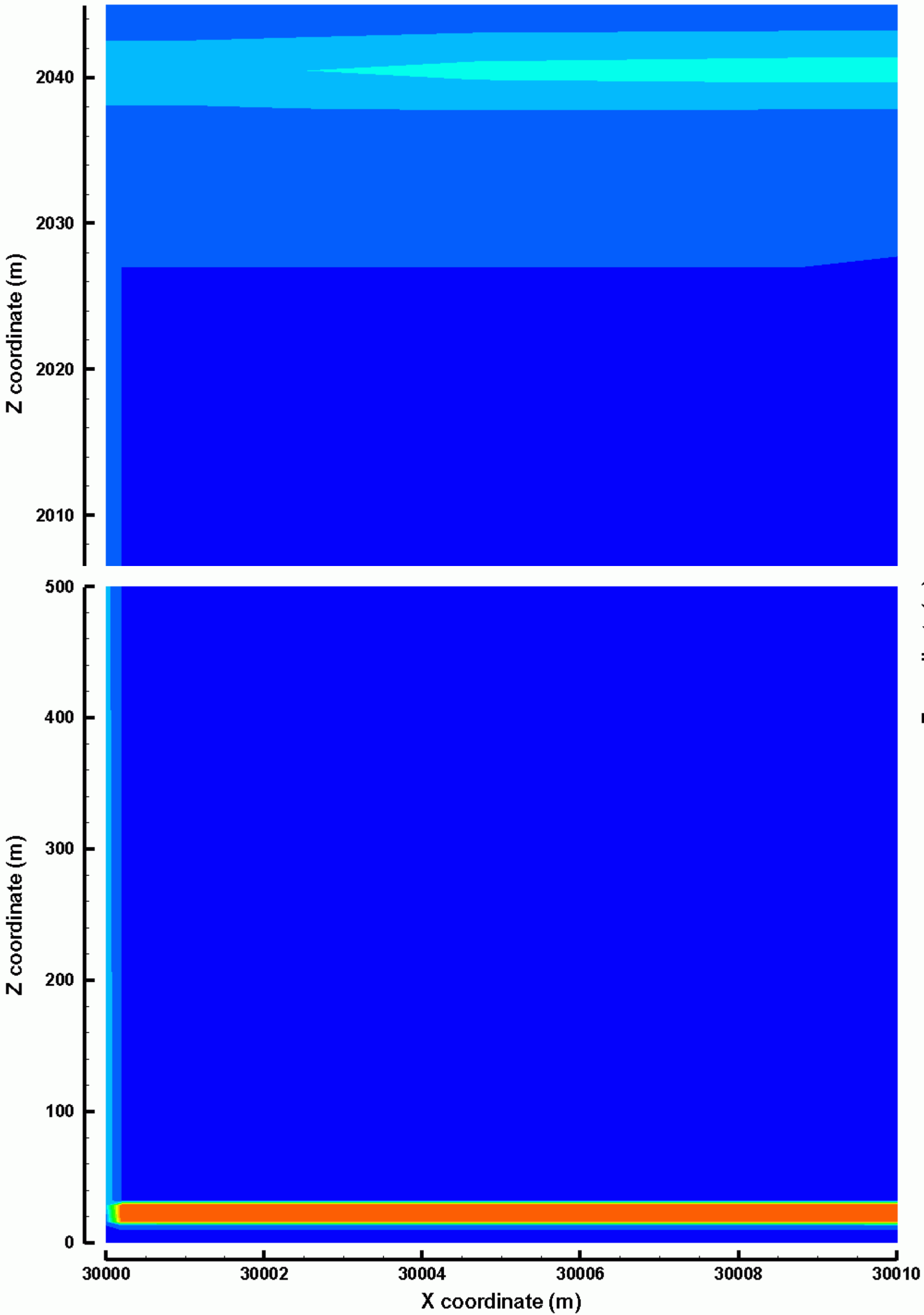
CO_2 (liquid/sc) migration through/near wellbore



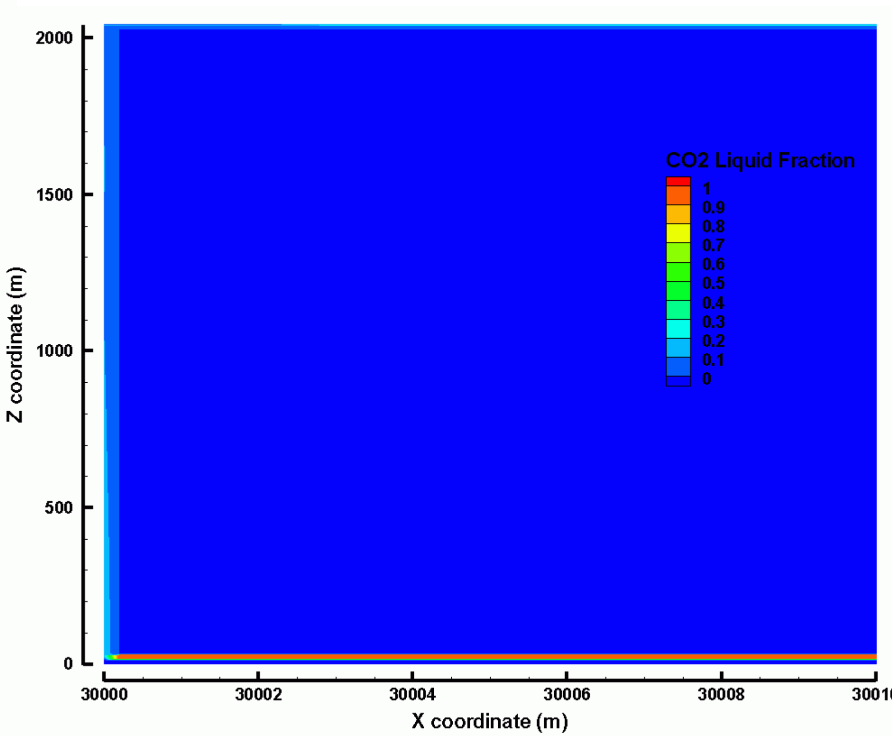
Time = 50 Years

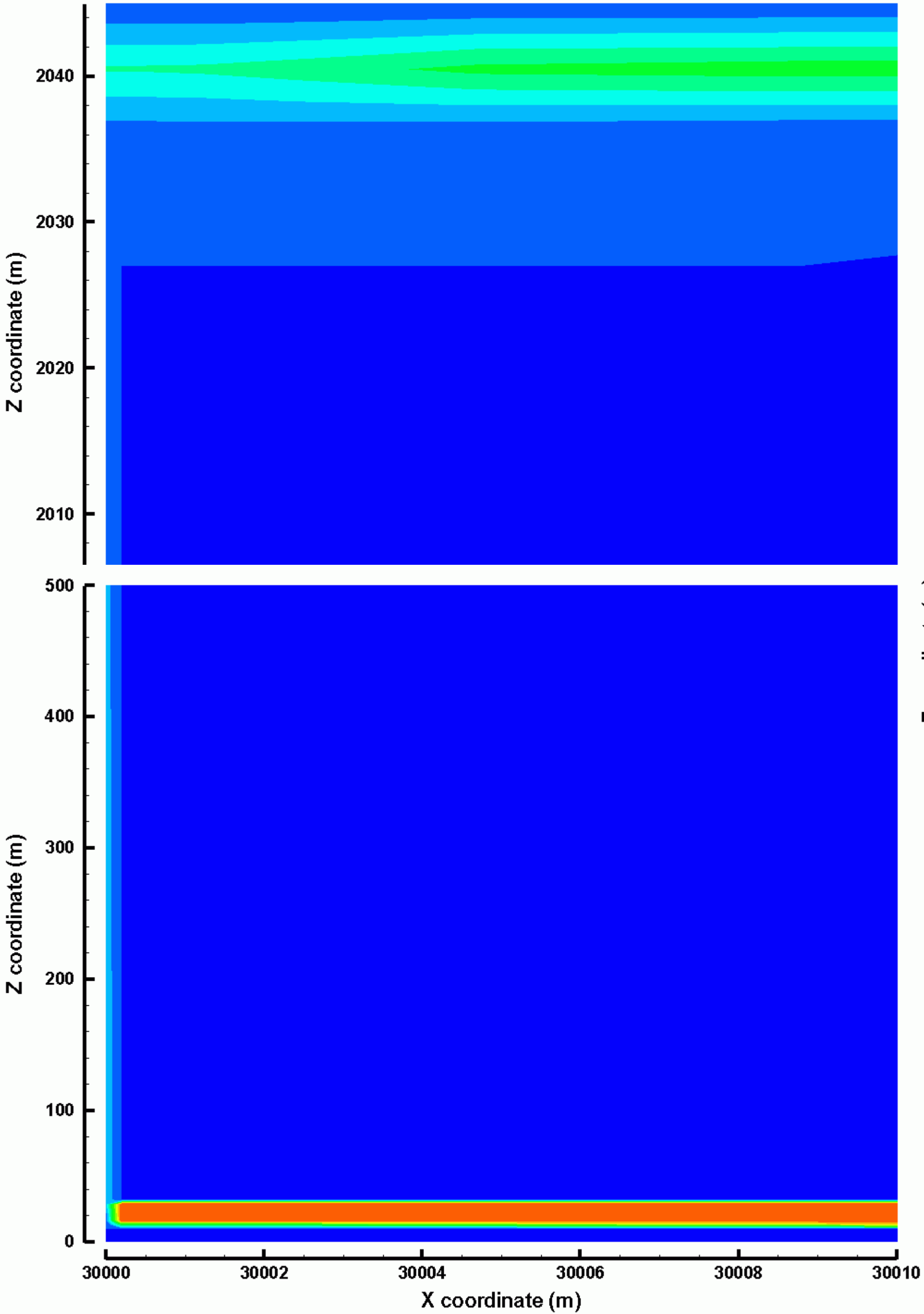


CO_2 (liquid/sc) migration through/near wellbore



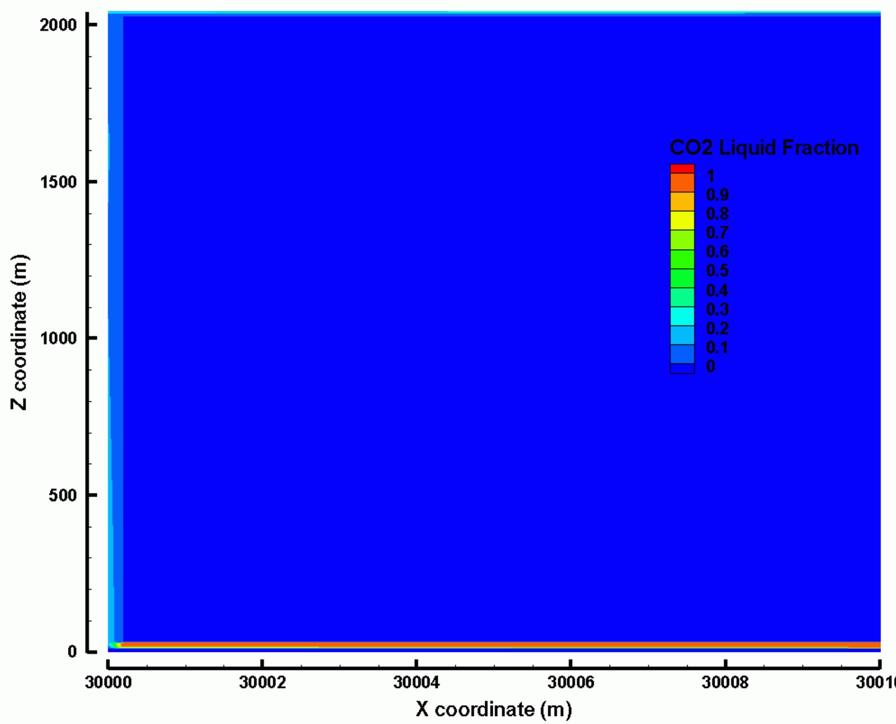
Time = 60 Years





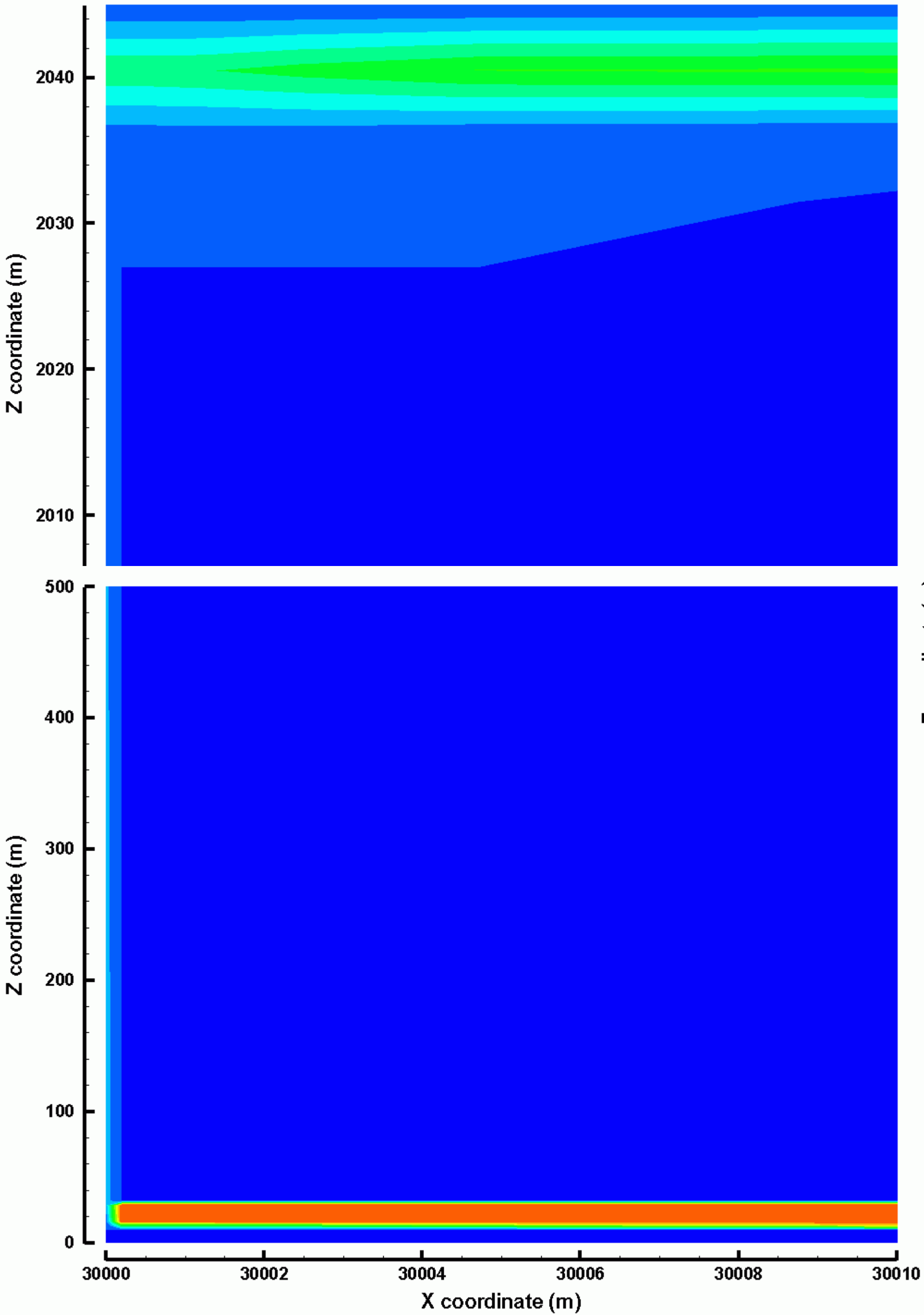
CO_2 (liquid/sc) migration through/near wellbore

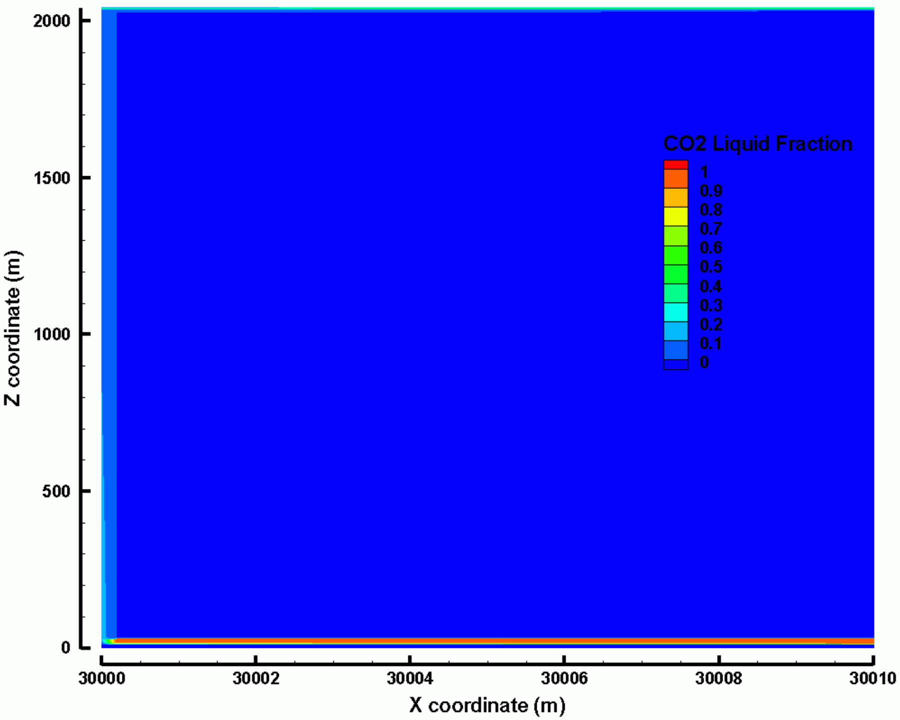
Time = 70 Years



CO_2 (liquid/sc) migration through/near wellbore

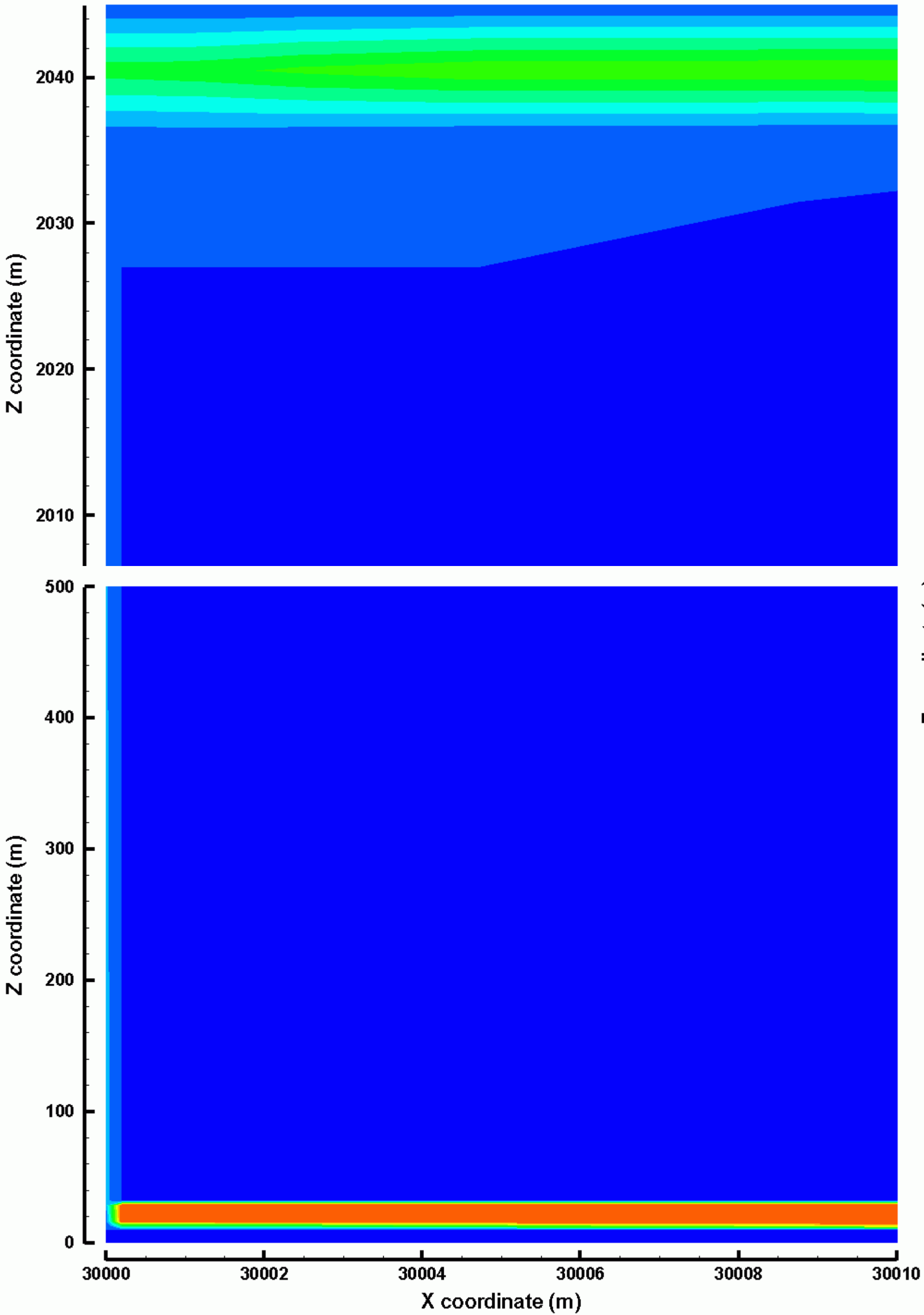
Time = 80 Years

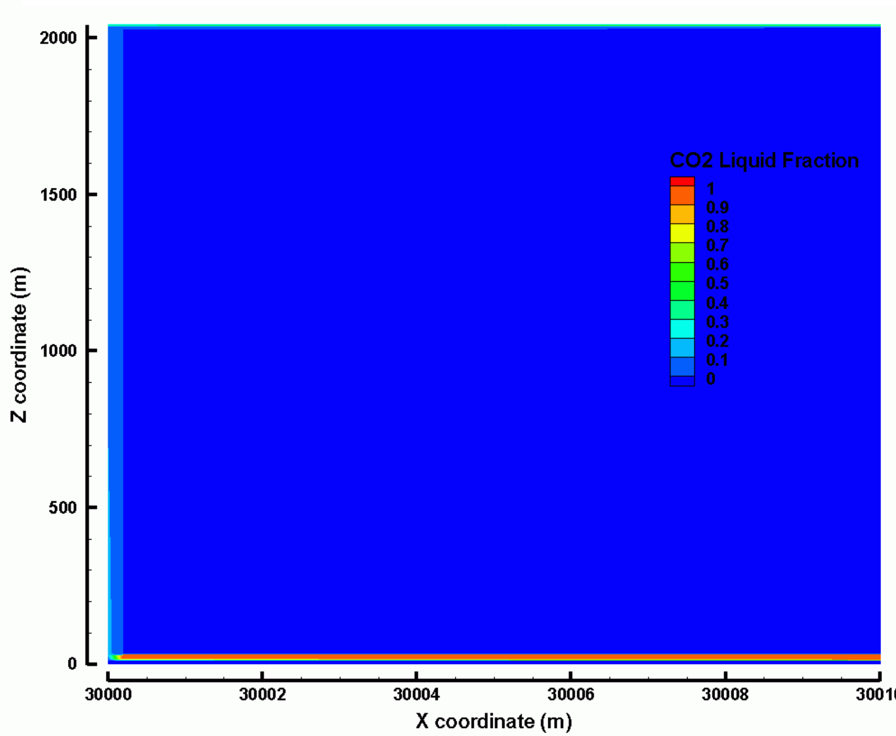




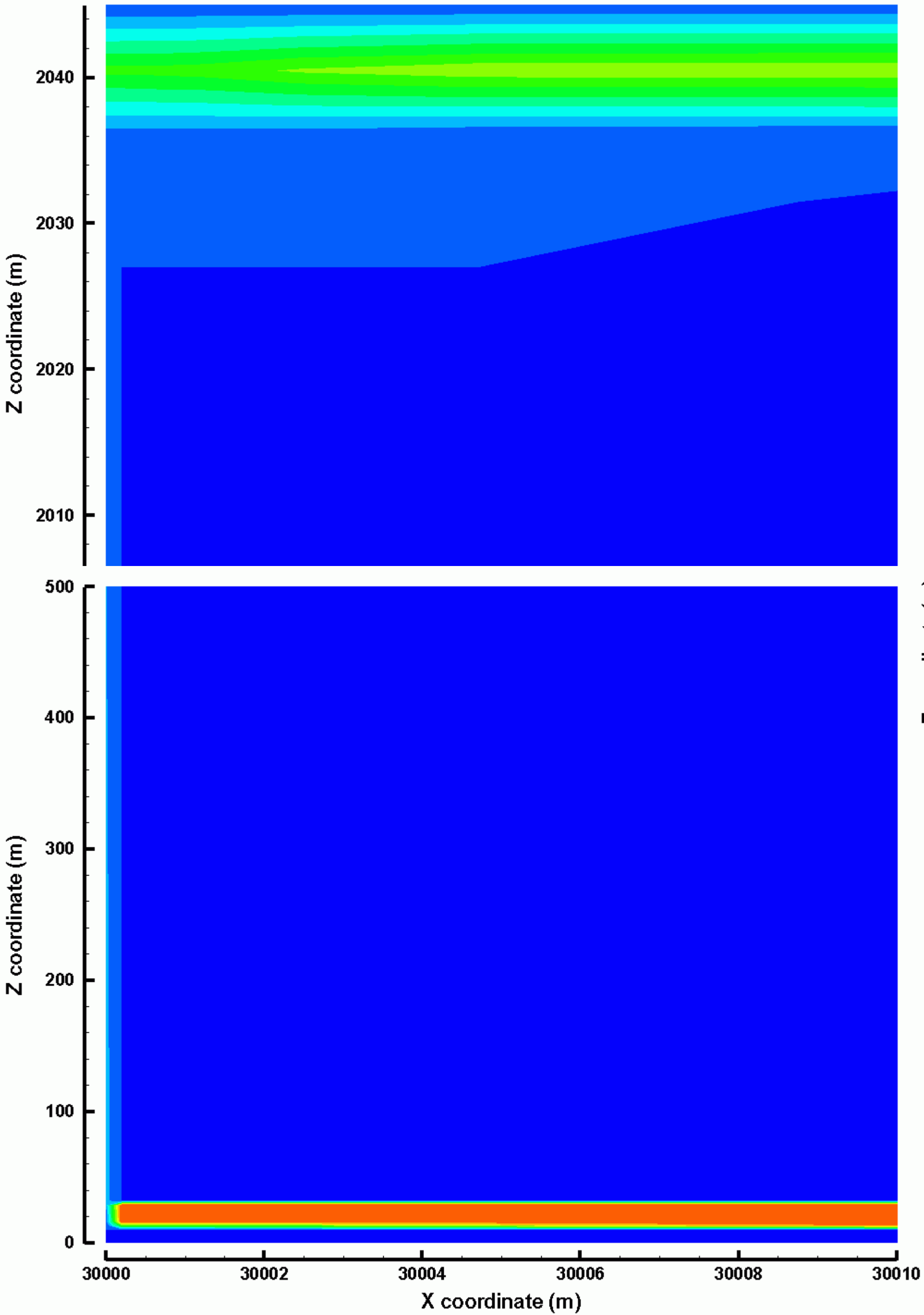
CO_2 (liquid/sc) migration through/near wellbore

Time = 90 Years

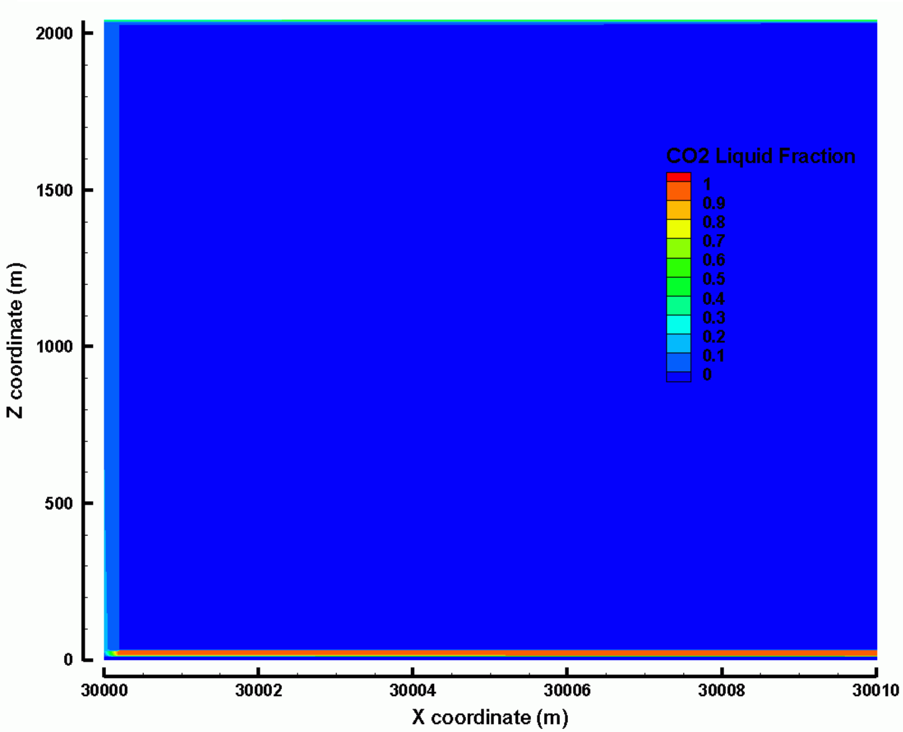




CO_2 (liquid/sc) migration through/near wellbore



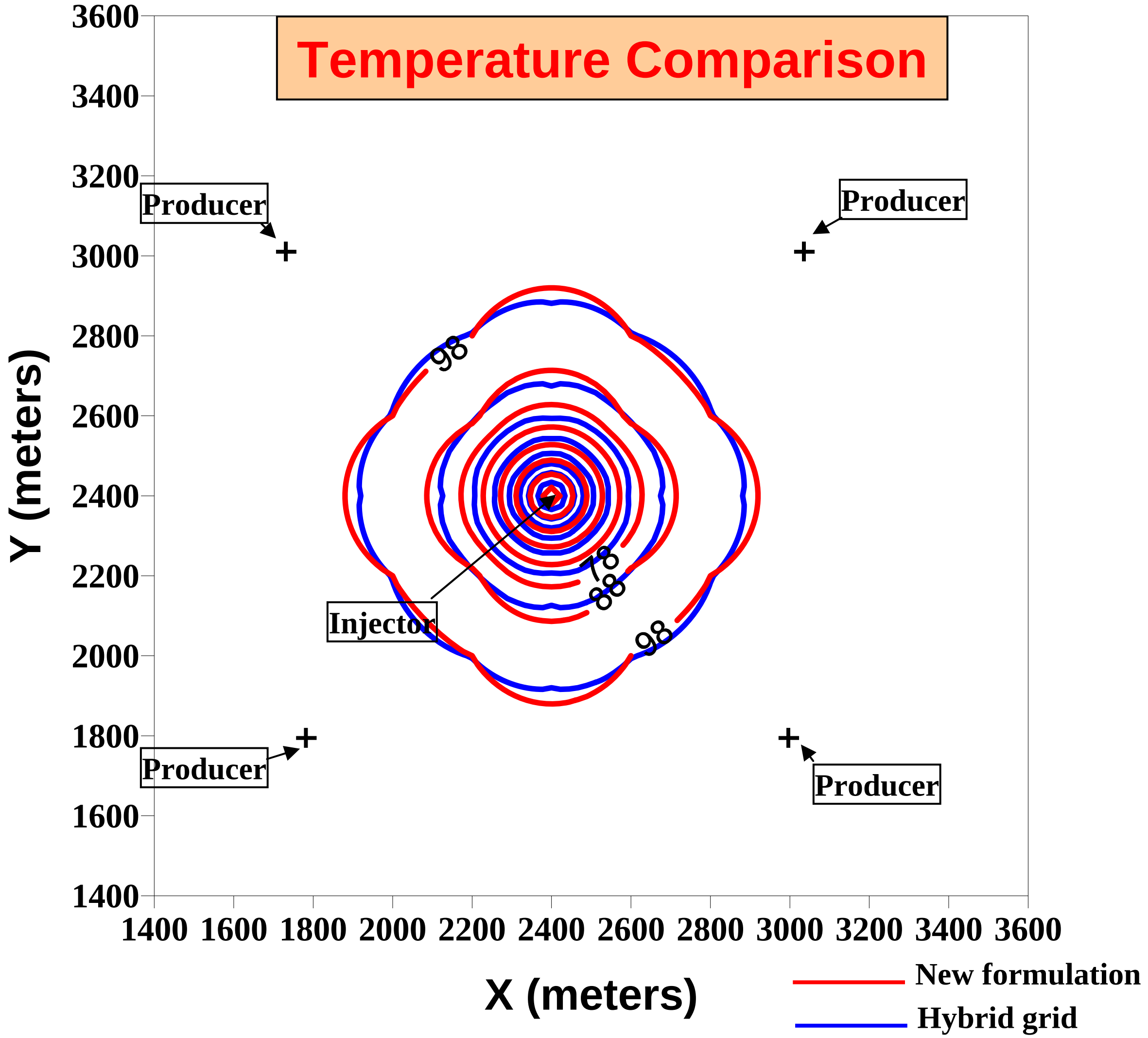
Time = 100 Years



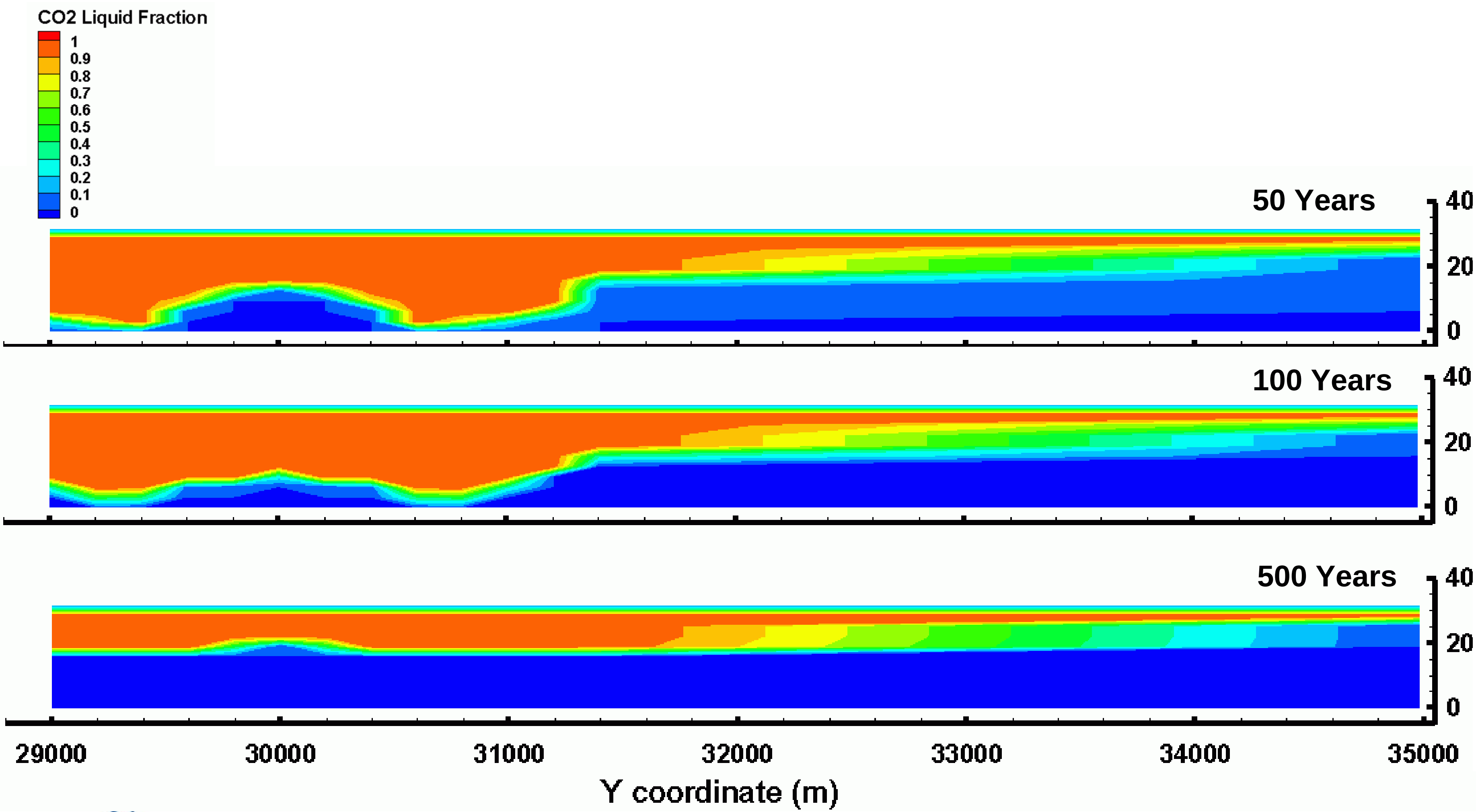
Wellbore incorporation algorithm performance: comparing temperature predictions

Computational Times

Hybrid grid – 248 sec
New algorithm – 147 sec
Refined grid approaches ~ 2 orders of magnitude slower



CO_2 plume evolution : X-sectional view



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Influence of pH and CO_2 content of the brine on the degradation rate of cement.

Bruno Huet*,
Profs. J.-H. Prevost and G.W. Scherer,
Princeton University

Work supported by a grant from **BP** and **Ford**

* now at Schlumberger Carbon Services

Context:

Assess the integrity of the CO_2 storage with time.

1. Geological storage capability may be affected by the presence of engineered high permeability path via abandoned well bores.

2. Degradation of well cement plugs when exposed to CO_2 saturated brine may engender CO_2 leaks

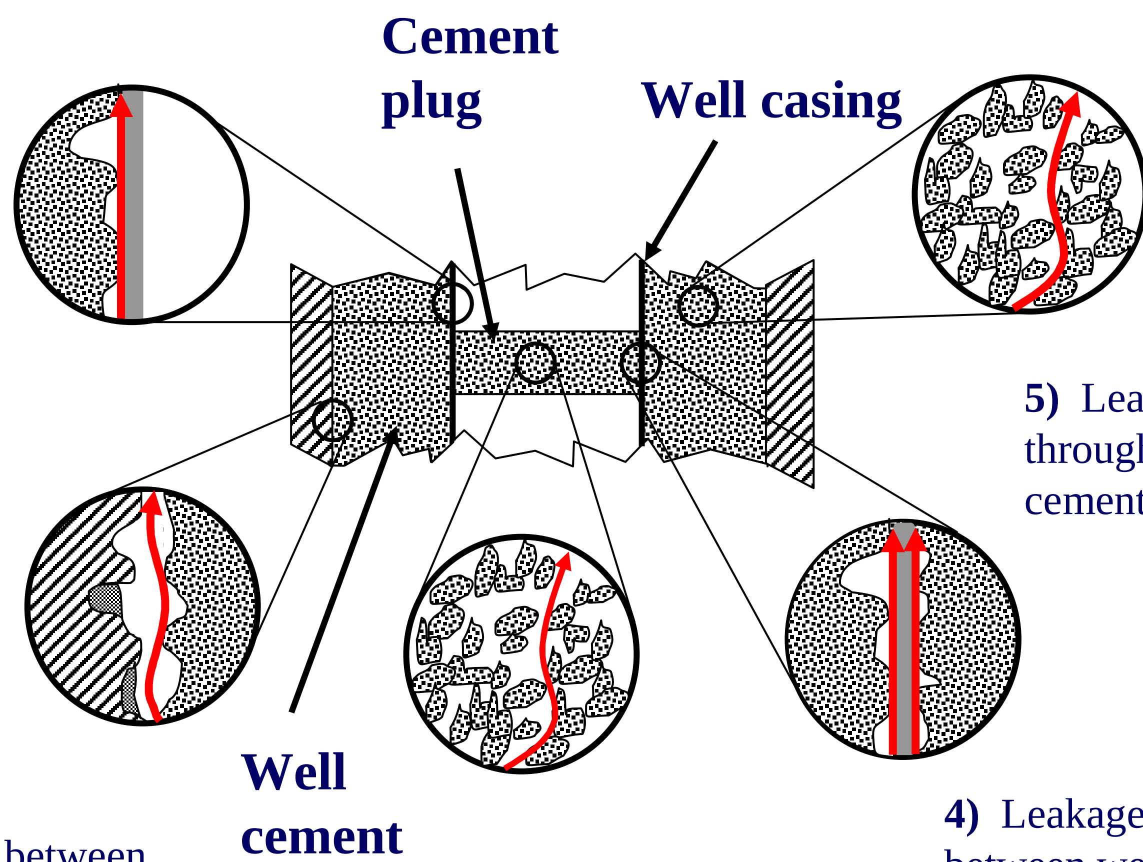
Objectives:

Understanding mechanism(s) of cement reactivity in CO_2/brine

- **Reactive transport modeling** of cement reactivity in CO_2 saturated brine
- **Validation** against experiments

Potential leakage pathways within a well

1) Leakage between well cement and well casing



5) Leakage through well cement

LEGEND
- Cement
- Drilling mud
- Rock
- Well casing
- Open casing
- Migrating gas

2) Leakage between geologic formation and well cement

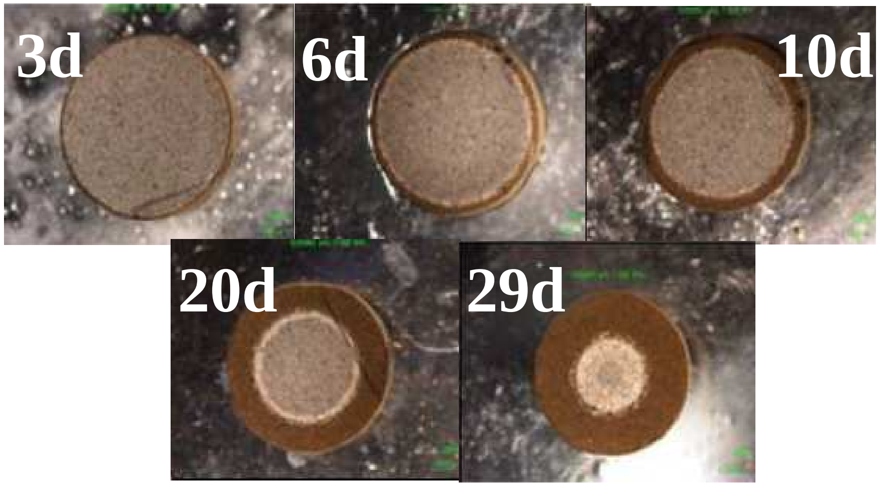
3) Leakage through plug cement

4) Leakage between well or plug cement and well casing

1) Experiments [Duguid et al [1]]:

Cement paste samples immersed in CO_2 saturated brine :

- Constant boundary conditions: pH~3, c_{CO2}=0.057 Molal, c_{NaCl} = 0.5 Molal
- Mineral zoning over time: layer composition and dynamics [1]



2) Deterministic modeling:

1. PDE for Transport in porous medium
2. Local Geochemical modeling
3. Input Data: physical and chemical properties

[1] Duguid, A, et al. ' 'The effect of CO_2 sequestration on oil well cements', 7th International Conference on Greenhouse Gas Control Technologies, September 5–9, 2004, Vancouver, Canada.

1. Transport of aqueous components [3]:

$$\frac{\partial(\phi C_{i'})}{\partial t} = \nabla \bullet \left(D_e \nabla \hat{c}_{i'} \right) \qquad i' \in \{1, (N_c - 1)\}$$

2. Local equilibrium [4] (slow transport) :

Mass Balance

- Water $$M_w = n_w \left(55.5 + \sum_j \nu_{wj} \, m_j \right)$$
- Aqueous $$M_i = n_w \left(m_i + \sum_j \nu_{ij} \, m_j \right) \qquad i \in \{1, N_i\}$$
- Minerals $$M_k = n_k + n_w \left(\sum_j \nu_{kj} \, m_j \right) \qquad k \in \{1, N_k\}$$

- Equilibrium $$m_j = \frac{K_j}{\gamma_j} . a_w^{\nu_{jw}} . \prod_i (\gamma_i \, m_i)^{\nu_{ji}} \qquad j \in \{1, N_j\}$$

3. Coupling [5]:

$$\begin{bmatrix} M_w \\ M_i \\ M_k \end{bmatrix}^{t+dt} = \begin{bmatrix} M_w \\ 0 \\ 0 \end{bmatrix}^{t} + \frac{n_w^{\,t}}{\rho_w} \left(\beta_{'n}^{-1} \right)^T \bullet \begin{bmatrix} 0 \\ C_{i'} \end{bmatrix}^{t+dt}$$

[2] J. H. Prevost, 'DYNAFLOW: a nonlinear transient finite element analysis program', Princeton University, New Jersey, 1981, revision 2007.
[3] J. Van der Lee, PhD thesis, 1997, Ecole des Mines de Paris, Fontainebleau (France)
[4] C.G. Bethke, 'Geochemical Reaction Modeling', 1996, New York, Oxford University Press
[5] B. Huet, 'Reactive transport modeling of cement paste in CO_2 saturated brine', submitted to GCA

Conditions of the numerical experiments:

T = 25 °C, P = 1 bar

1. Cement composition of a Class H cement (w%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Alkali
21.66	2.78	4.41	63.8	3.18	2.96	0.21

2. Hydrated cement paste composition (mol/kg)

porosity = 0.4

Portlandite	Jennite	Monosulfoaluminate	Ettringite	Calcite	Na^+	K^+	Cl^-	OH^-
12.9	5.2	0.605	0.131	0.001	0.10298	0.0801	0.0001	0.18298

3. Transport parameters:

$D_{e,0} = 1.0\ 10^{-11}\ m^2.s^{-1}$,

$\phi_0 = 0.4$, $\phi_r = 0.02$, m = 3.32

$$D_e = D_{e,0}\left(\frac{\phi - \phi_r}{\phi_0 - \phi_r}\right)^m$$

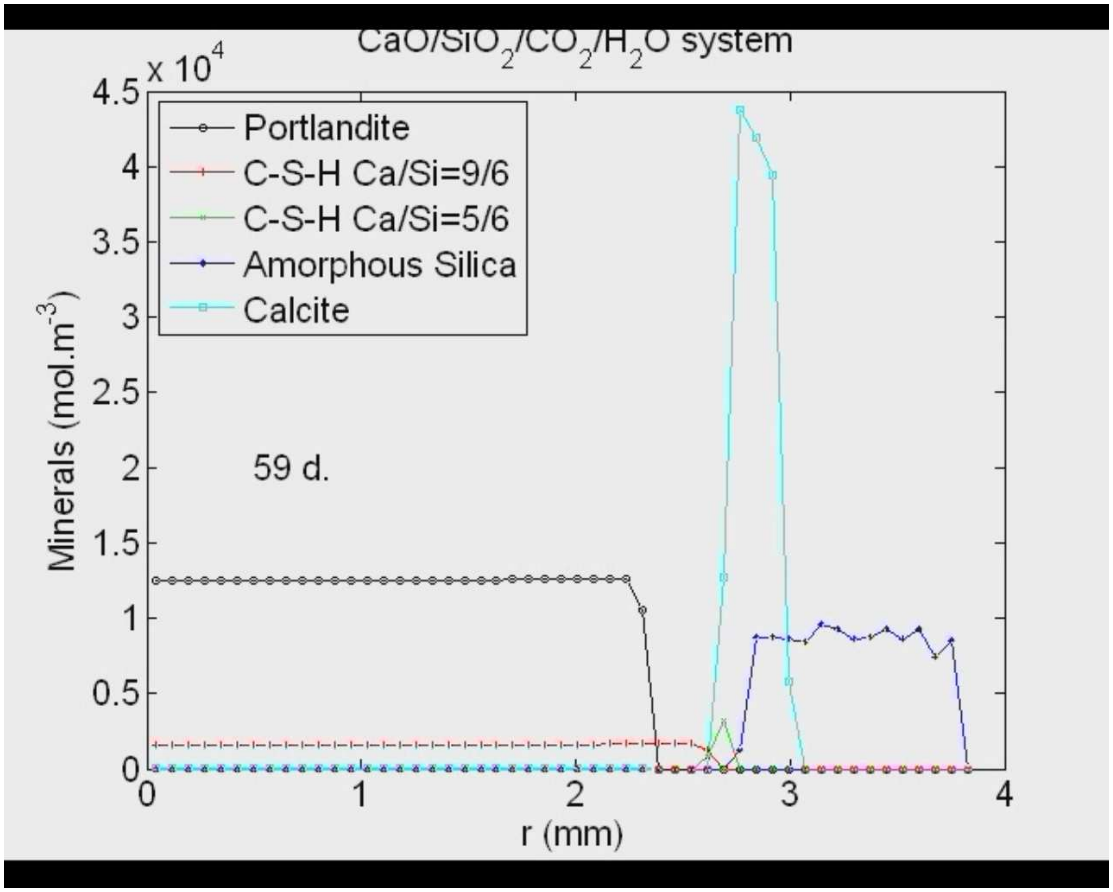
4. Geometry:

Axisymmetric, ∅ = 7.5 mm, mesh size: 75 µm

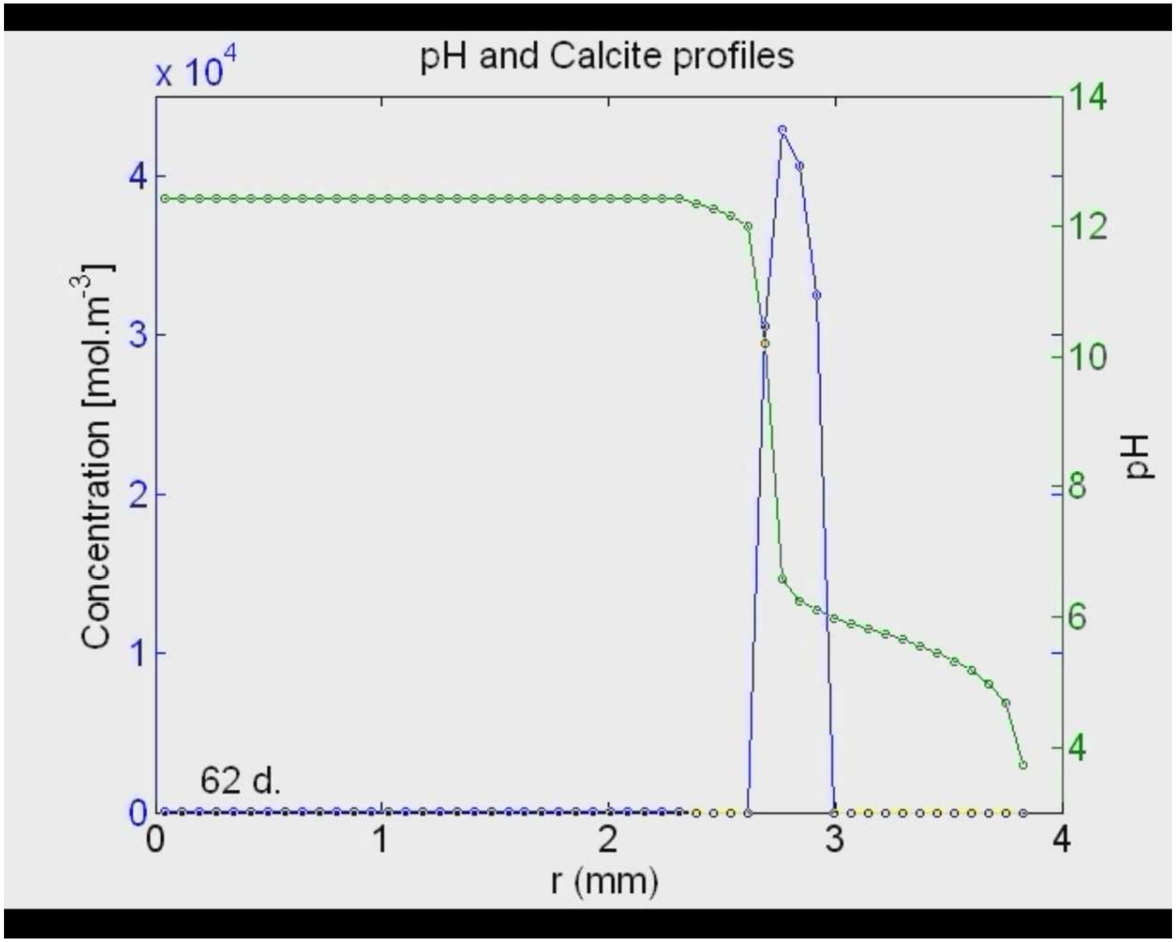
5. Boundary conditions (case of reference):

NaCl: 0.5 M CO_2 : 0.05M,

Minerals profiles (I)



1. Same mineral zoning as in experiments [1]: a) Undegraded cement, b) C-S-H layer, c) Calcite layer, d) Gel layer
2. Degradation fronts propagation delayed compare to experiments



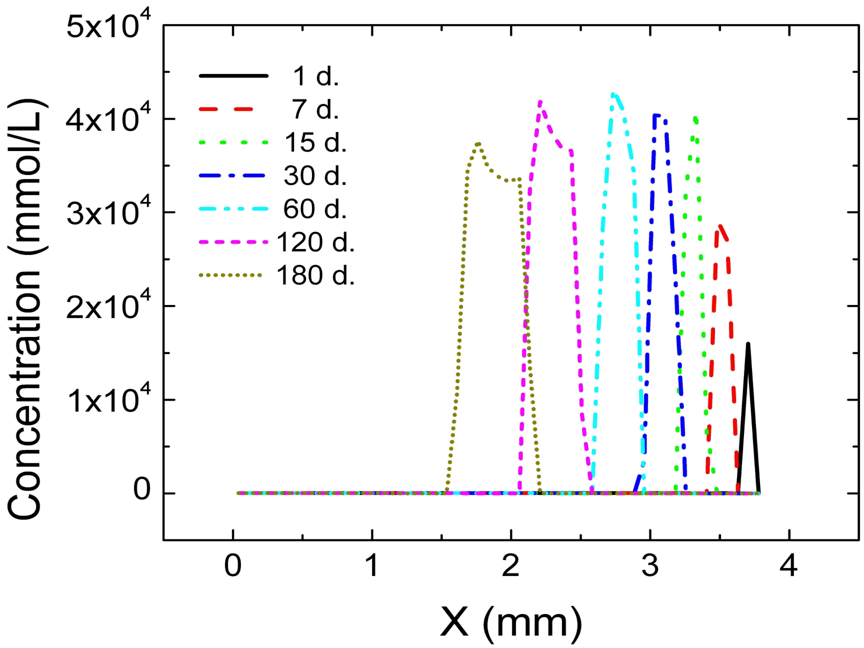
1. Very steep pH profile in calcite layer

   ⇒ High pH (~12) at calcite precipitation front

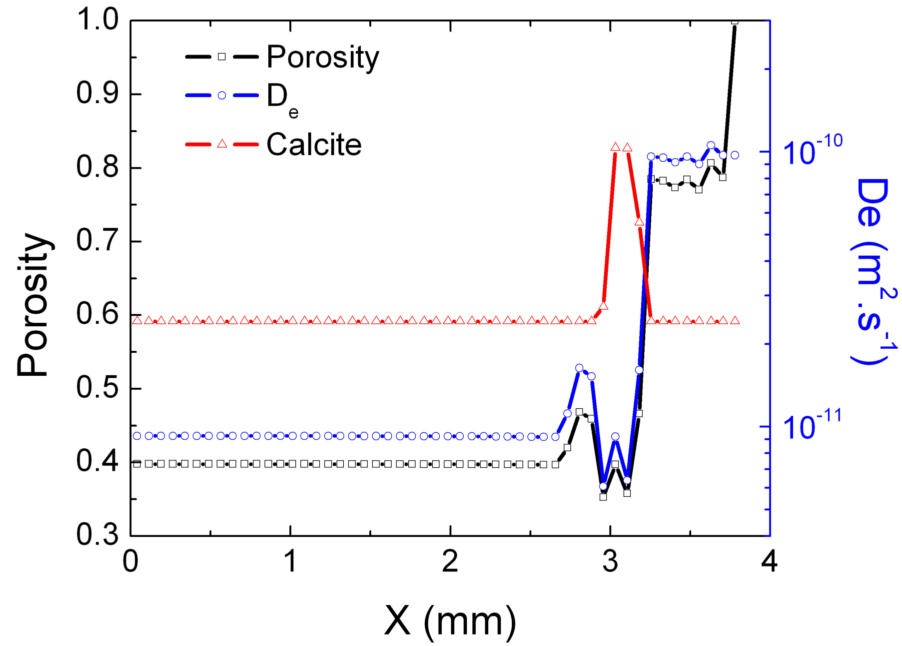
   ⇒ low pH (~6) at calcite dissolution front

General mechanisms

Calcite:

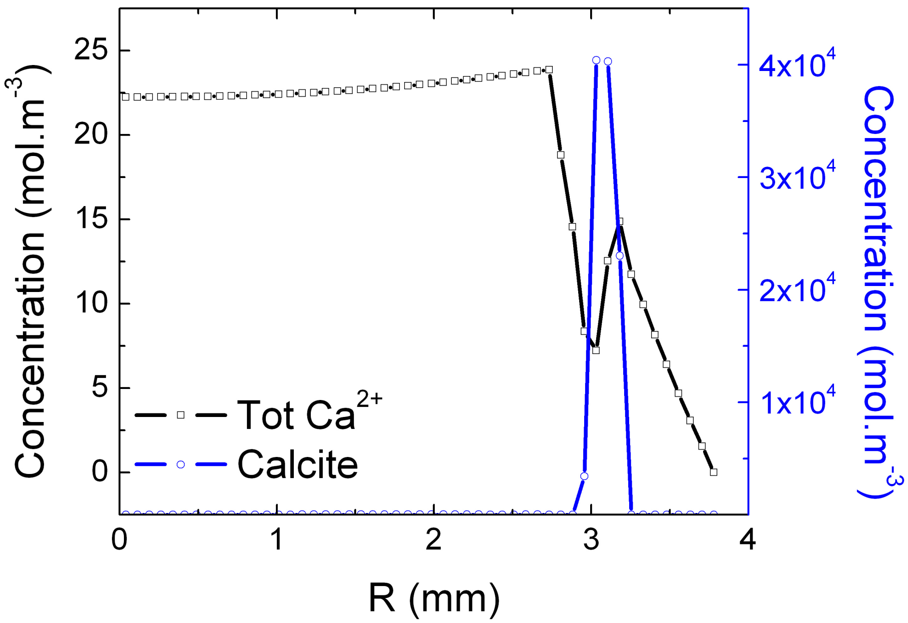


Transport properties at 30 d.

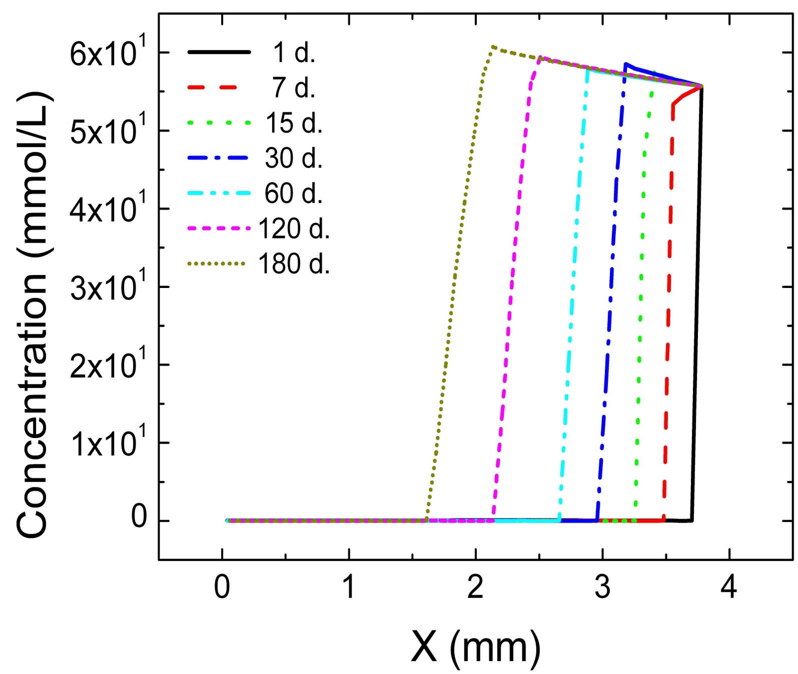


1. Thickening of calcite layer over time.
2. Opening of the porosity in the gel layer, closing in the calcite layer, opening in the C-S-H layer

General mechanisms

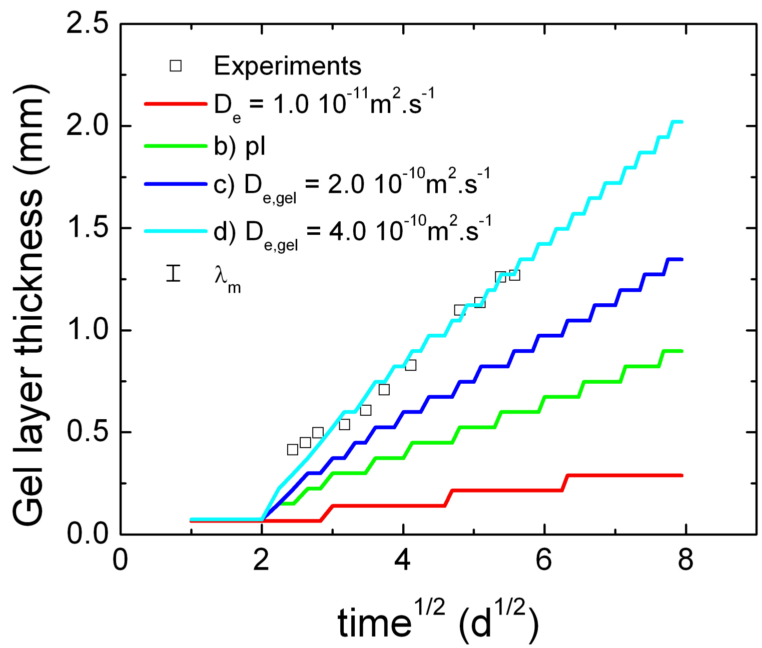


Tot HCO_3^-



3. Large calcium gradient due to large solubility of calcite at high CO_2 content ($CaCO_{3(s)} + CO_2^0 + H_2O \Leftrightarrow Ca^{2+} + 2\ HCO_3^-$ and $Ca^{2+} + HCO_3^- \Leftrightarrow CaHCO_3^+$)
4. CO_2 uptake followed by a slight CO_2 release

Layer dynamics

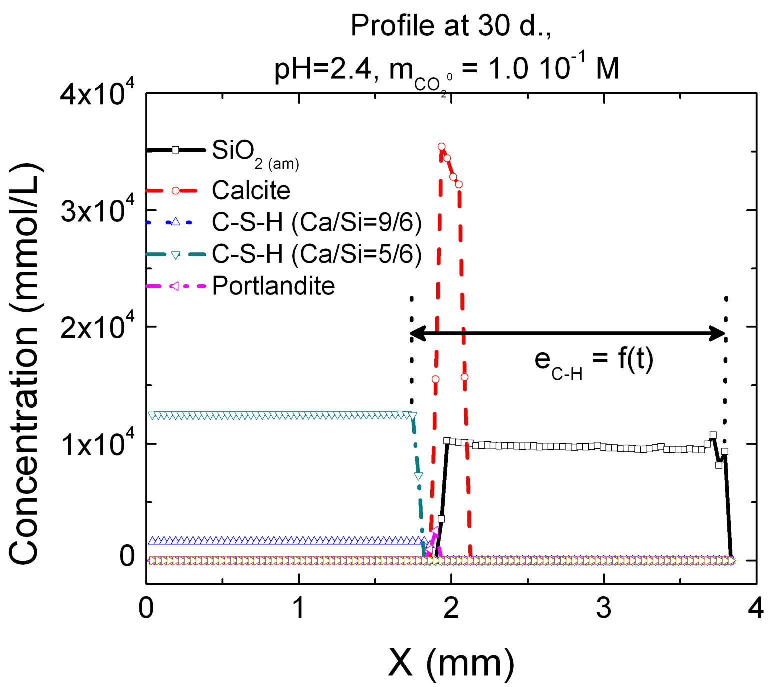


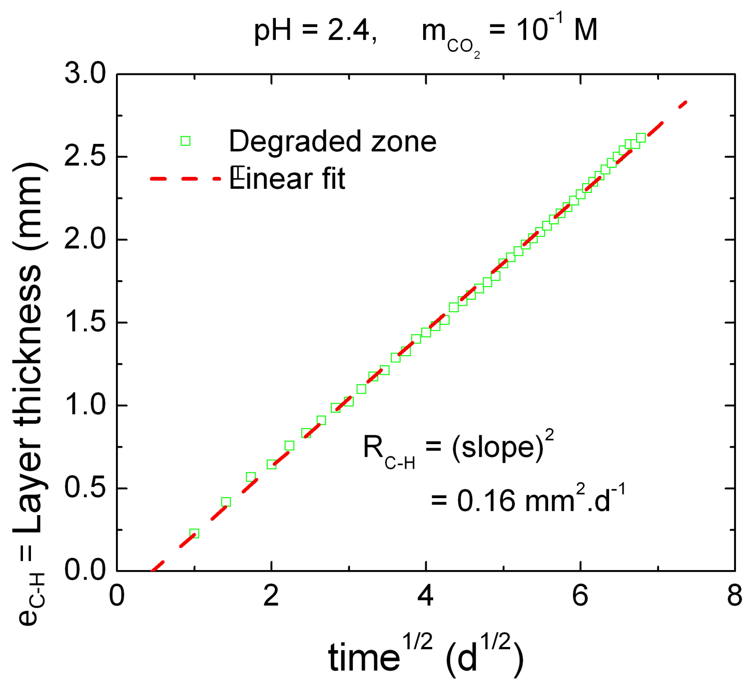
1. Results far from experiments when D_e = cst
2. Updating transport property with porosity is mandatory
3. Layer dynamics controlled by gel layer diffusivity.

History matching yields $D_{e,gel} = 4.0\ 10^{-10}\ m^2.s^{-1}$

Effect of pH and CO_2 content:

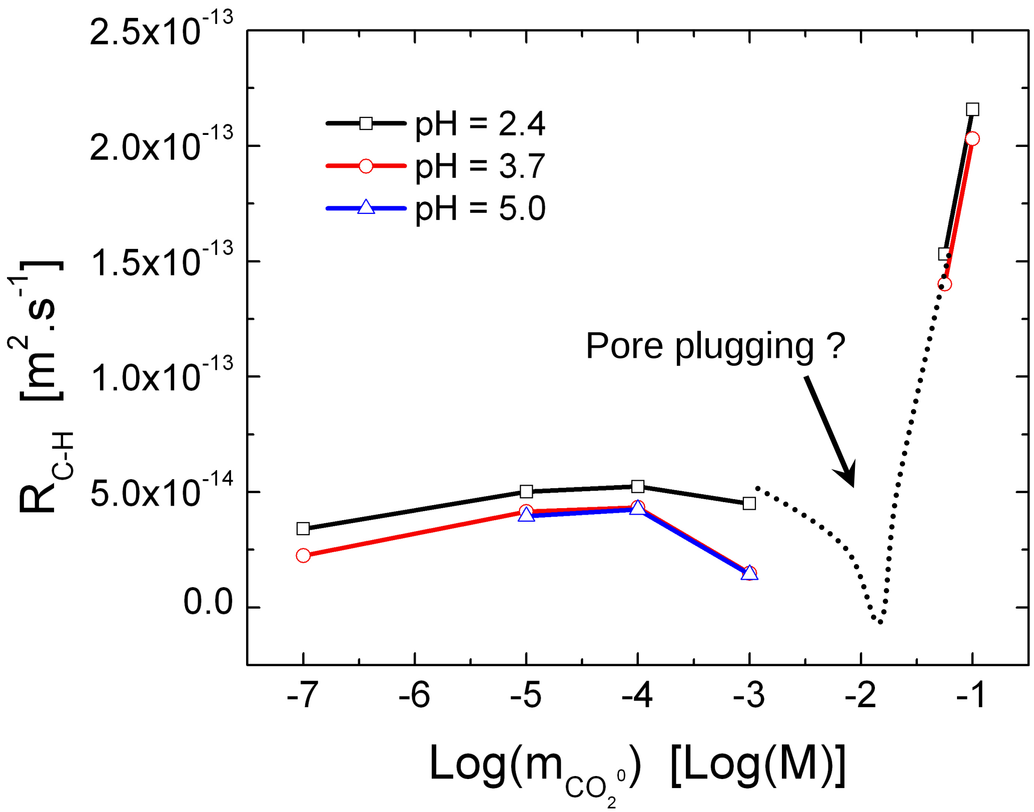
1. Mapping of cement reactivity as function of pH and CO_2^0 molality:
   1. pH = { 2.4, 3.7, 5.0 } *
   2. m_{CO2} = { 10^{-7}, 10^{-5}, 10^{-3}, 10^{-2}, $10^{-1.25}$, 10^{-1} }
2. Evaluation of degraded zone thickness (e_{C-H}) with time for each cases





* pH adjustment with slight amount of HCl or NaOH

Effect of pH and CO_2 content:



1. Negligible effect of pH
2. Strong effect of dissolved CO_2 content

➡ Aqueous phase **salinity = key parameter** at given P,T conditions

Conclusion

- Equilibrium approach is sufficient (slow transport)
- CO_2 uptake during $CaCO_3$ layer formation
- At later time, no CO_2 uptake (slight release) and only Ca leak (diffusion)
- Catalytic effect of CO_2: Degradation rate $R_{C\text{-}H}$ of cement paste very sensitive to CO_2 content and less to pH

Future Challenges

- Get **transport properties** of **reacted layers**
- **Pressure equation (density gradient)**
- **Multiphase** transport to model cement reactivity exposed to wet or dry CO_2
- Analysis of **sealing or widening** of annulus (2D simulations).
- CO_2 boiling and heat effects (next talk !)

Fully Coupled Geomechanics, Multi-Phase, Thermal and Equation of State Compositional Simulator

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URL: http://www.princeton.edu/~dynaflow
URL: http://denali.princeton.edu

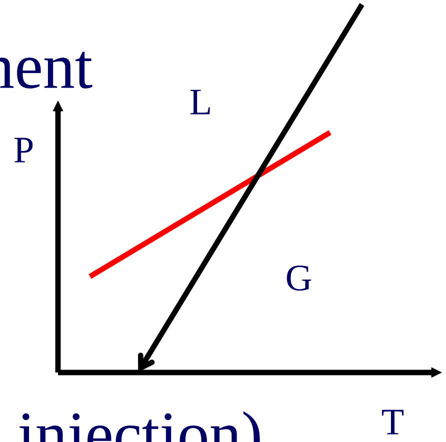
collaborators: G. Scherer, R. Fuller, B. Huet
sponsors: BP, Ford

Department of Civil and Environmental Engineering
Princeton University

**ConocoPhillips, Bartlesville, Oklahoma*

Research Focus: CO2 leaks

- Wells cement degradation / leakage paths:
  - Geochemical interaction with wells cement
    - » cement degradation; seal loss
  - Leakage:
    - » thru seepage across overburden
    - » via abandoned wells (damage due to injection)
  - Super-critical/sub-critical CO_2 flow; crossing saturation line; CO_2 bubbling/condensing
  - Thermal/heat transfer effects w/ rock



Dynaflow

- Fully Coupled Multiphysics Simulator
  - Geomechanics
  - Multi-Phase flow; Multi-components
  - Heat flow (including heat of reaction)
  - Flash via equation of state
- *Modular* flash and geochemistry
  - Transportable to other codes (e.g., Eclipse)
- Related models:

TOUGH2 (K. Pruess, LBL): similar flash capabilities but not modular; no coupled poromechanics; no cement geochemistry

NUFT (Nitao, Wolery, J. Johnson, LLNL): no extensive thermodynamic data base for cement geochemistry; no coupled poromechanics

FLOTRAN (Lichtner, J. Carey, LANL): reactive transport; no coupled poromechanics

ECLIPSE (Schlumberger), VIP (Halliburton),….: no accurate CO_2 flash; no cement geochemistry; no coupled poromechanics

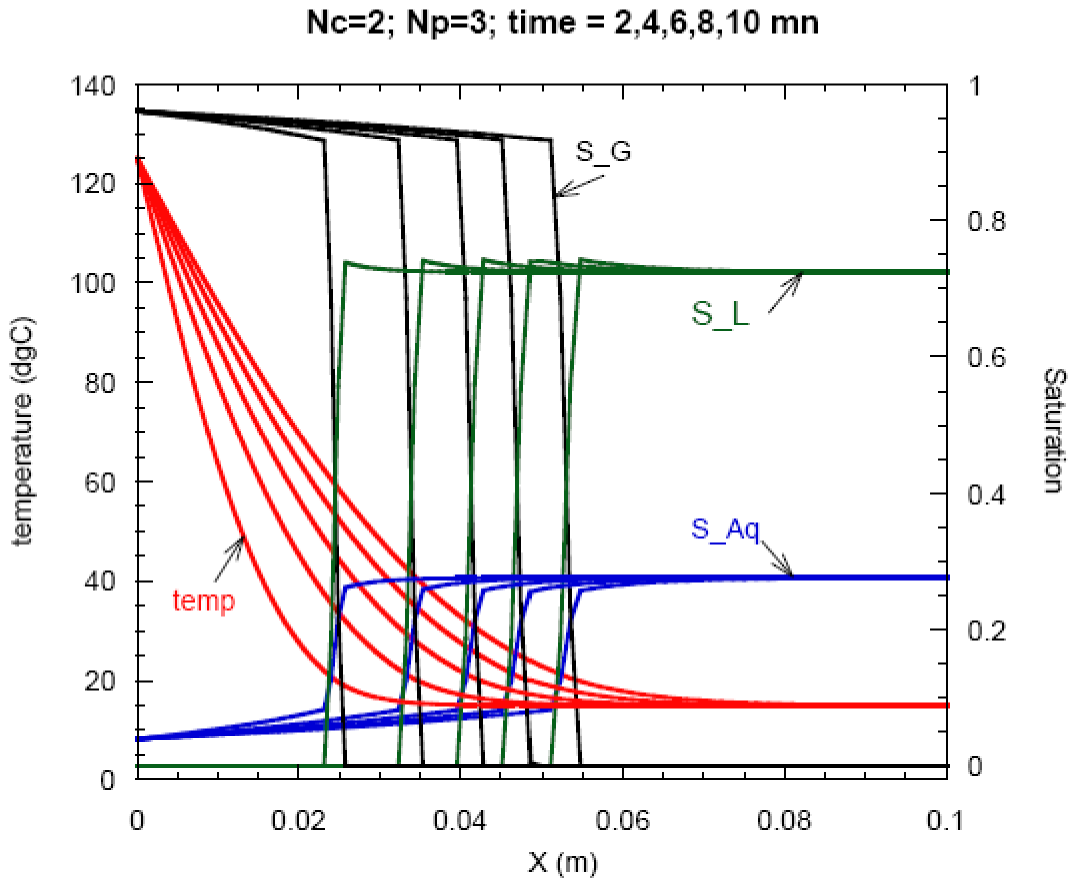
Dynaflow

- finite element based (arbitrary meshing)
  - » Galerkin, stabilized Galerkin (SUPG)
  - » Finite volume (cell centered; vertex centered)
- staggered implementation to allow flexible/versatile algorithmic options for integration of coupling effects
- multiphase flows
  - » compressible; incompressible flows
  - » miscible; immiscible flows
  - » heat transfers
- fluid flows fully coupled with geomechanics
- reactive transports capabilities for cement attack/degradation by CO_2 (B.H.)
- eos based flash (L.Y.C.)
- 1D/2D/3D capabilities
- parallel computing on shared and/or distributed memory/architectures (openMP/MPI)

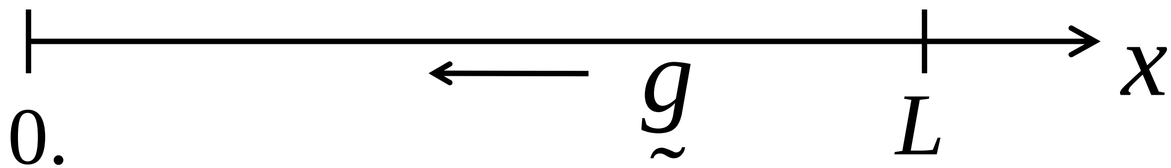
Modeling Leakage

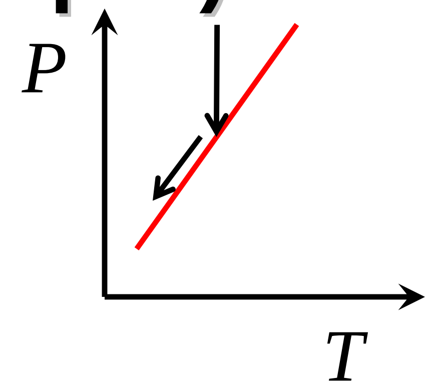
◆ If a gap exists, the escaping (super-critical) fluid will react with the cement, but it will also boil

- Simulation shows advance of boiling front (gas, aqueous phase and CO_2-rich liquid
- Other flash models are unable to handle this case



adiabatic CO2 leak (Nc=2, Np=3)





$$domain: \quad x = [0., L] \quad Area = [1 \times 1] \qquad L = 600.\, m$$

$$\underset{\sim}{g} = -10.\, m/s^2 \qquad \rightarrow T = T(x,t) \quad P = P(x,t)$$

- $initial\ conditions:$

$$T(x, t=0) = 15\,^0C$$

$$P(x=0, t=0) = 5.23MPa, \quad P(x=L, t=0) = 0.1MPa$$

$$Z^{CO_2}(x, t=0) = 0, \quad Z^{H_2O}(x, t=0) = 1.0$$

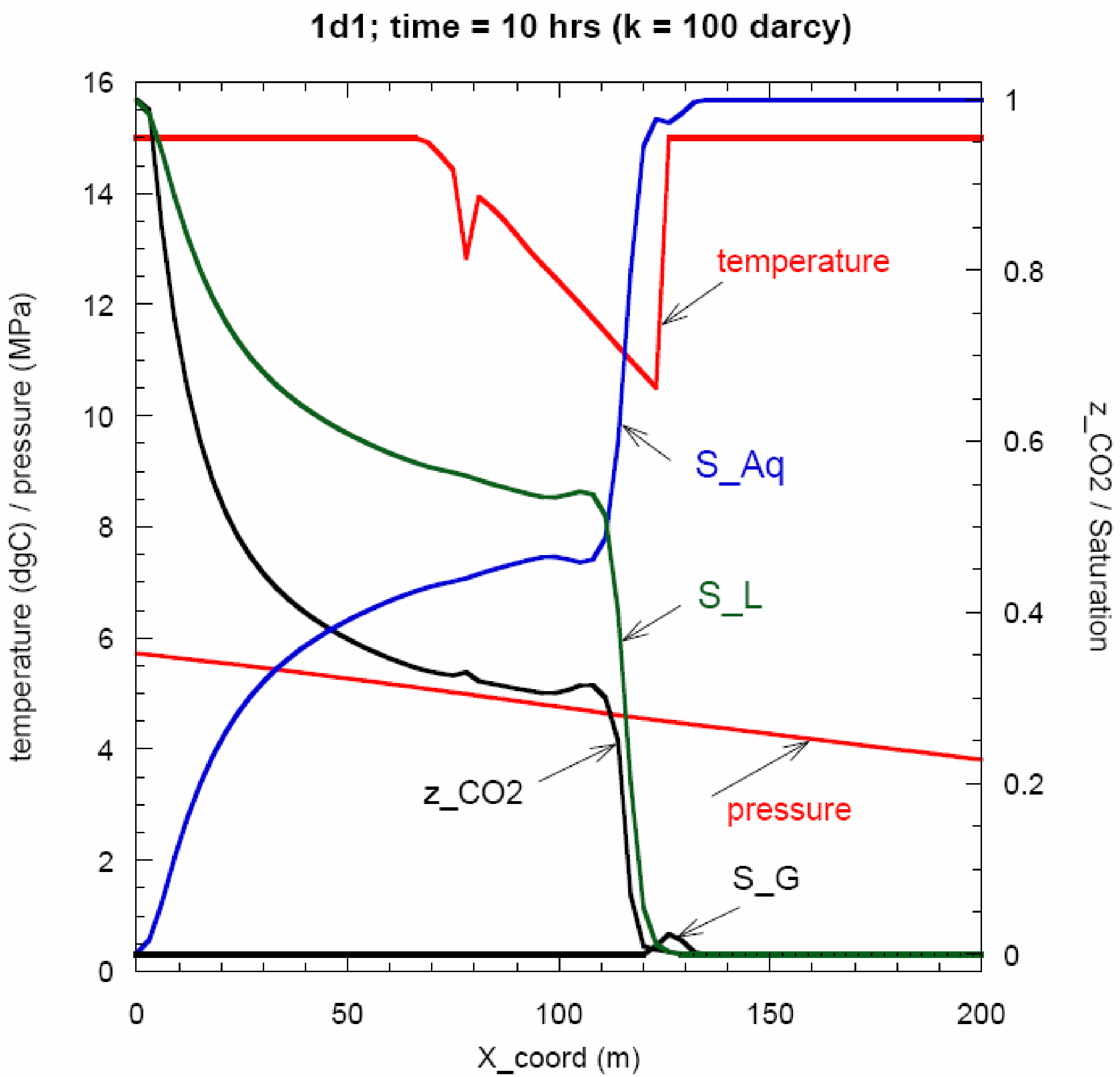
- $boundary\ conditions:$

$$T(x=0, t=0^+) = 15^0C$$

$$P(x=0, t=0^+) = 5.73MPa, \quad \Delta P = 0.5MPa, \quad P(x=L, t=0^+) = 0.1MPa$$

$$Z^{CO_2}(x=0, t=0^+) = 1.0$$

adiabatic CO2 leak (Nc=2, Np=3)



Radial steam injection (Nc=3, Np=3)

$$domain: \quad r = [r_0, r_1] \qquad r_0 = 0.1m \quad r_1 = 250.\,m$$

$$\rightarrow T = T(r,t) \quad P = P(r,t)$$

- *initial conditions*:

$$T(r,t=0) = 65\,^0C$$

$$P(r,t=0) = 6.0MPa$$

$$Z^{C3}(r,t=0) = 0.4, \quad Z^{C16}(r,t=0) = 0.4, \quad Z^{H_2O}(r,t=0) = 0.2$$

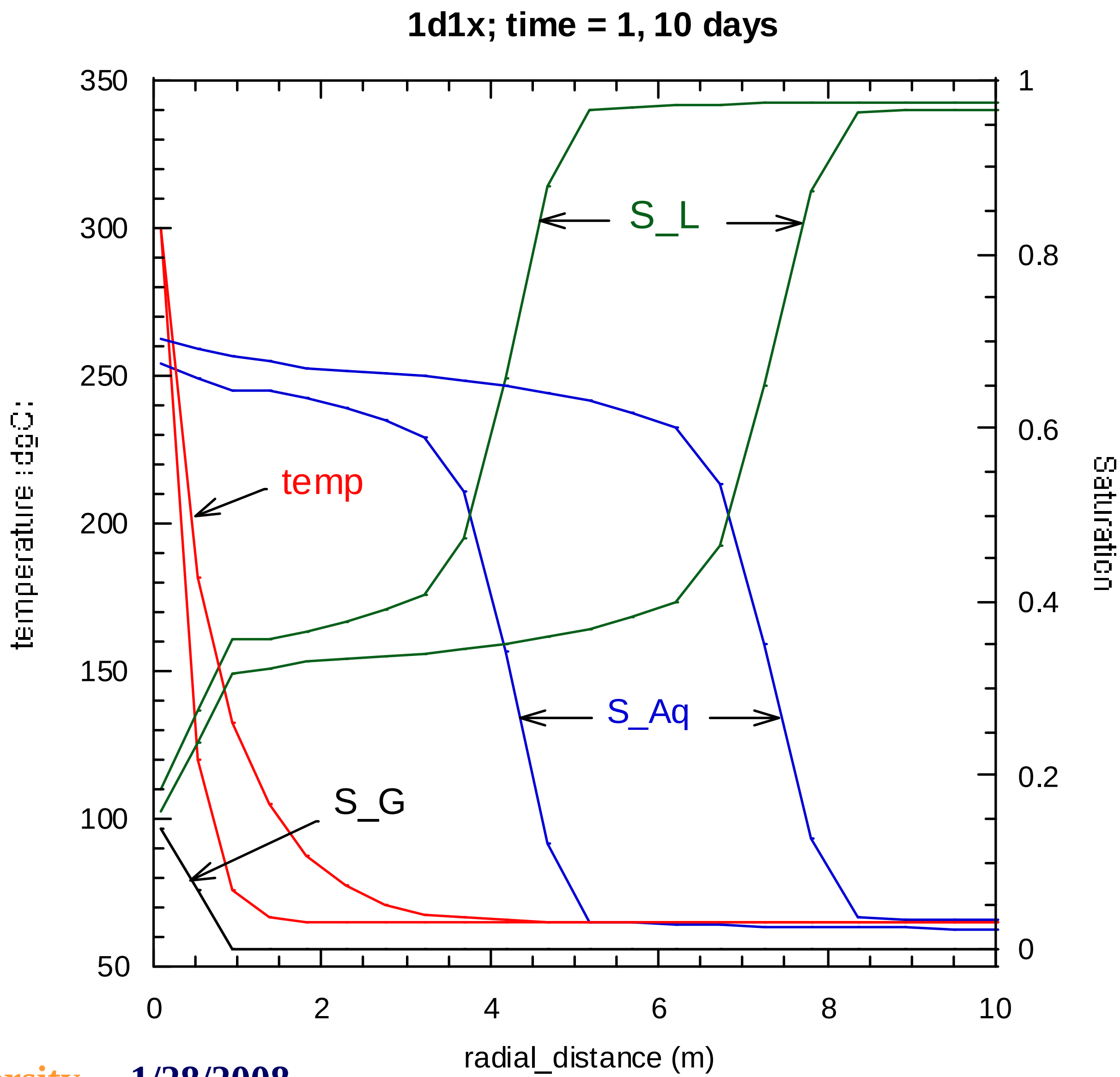
- *boundary conditions*:

$$T(r=r_0,t=0^+) = 300^0C$$

$$P(r=r_0,t=0^+) = 7.0MPa, \quad \Delta P = 1.0MPa$$

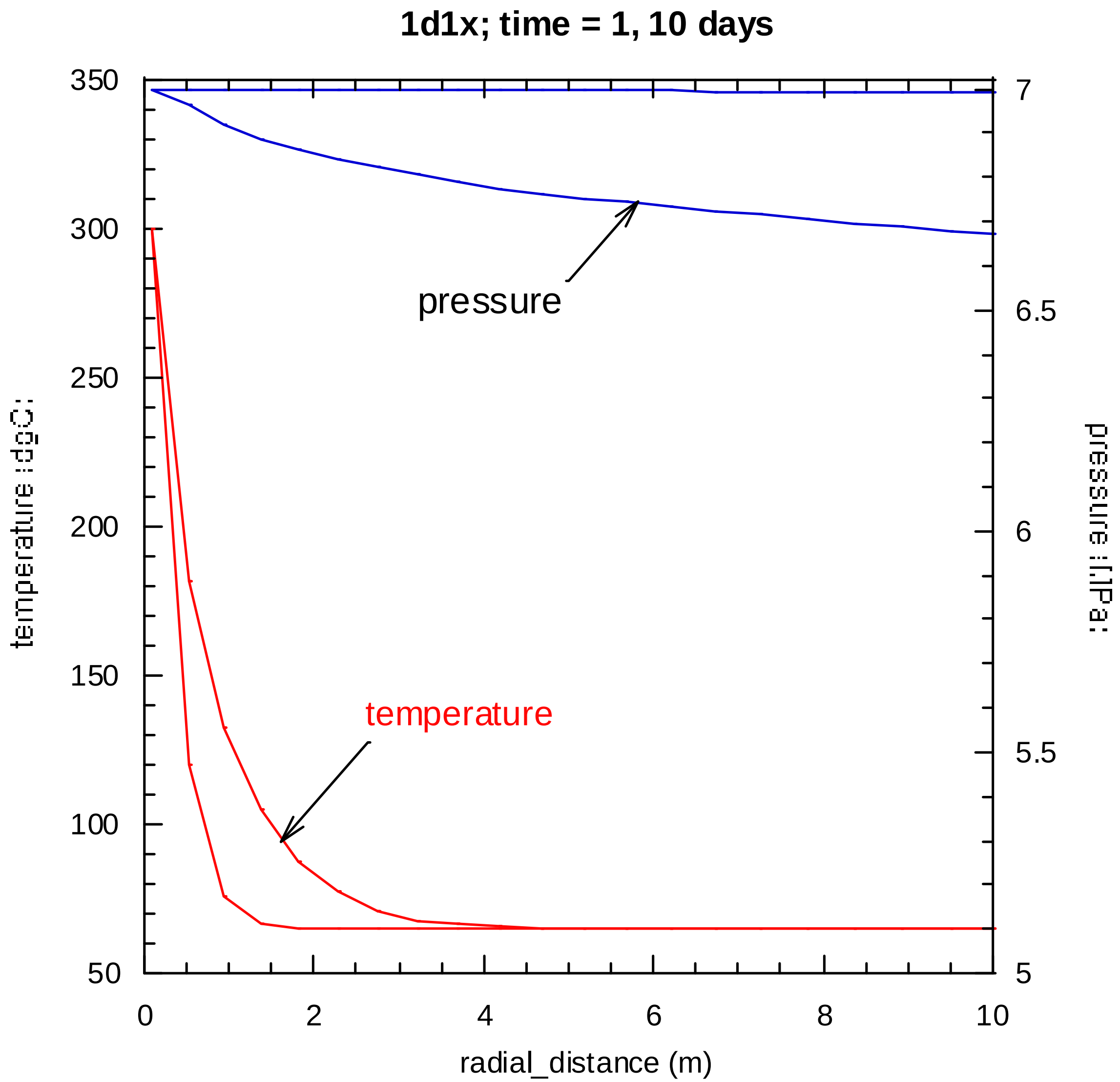
$$Z^{H_2O}(r=r_0,t=0^+) = 1.0$$

Radial steam injection (Nc=3, Np=3)



Radial steam injection (Nc=3, Np=3)

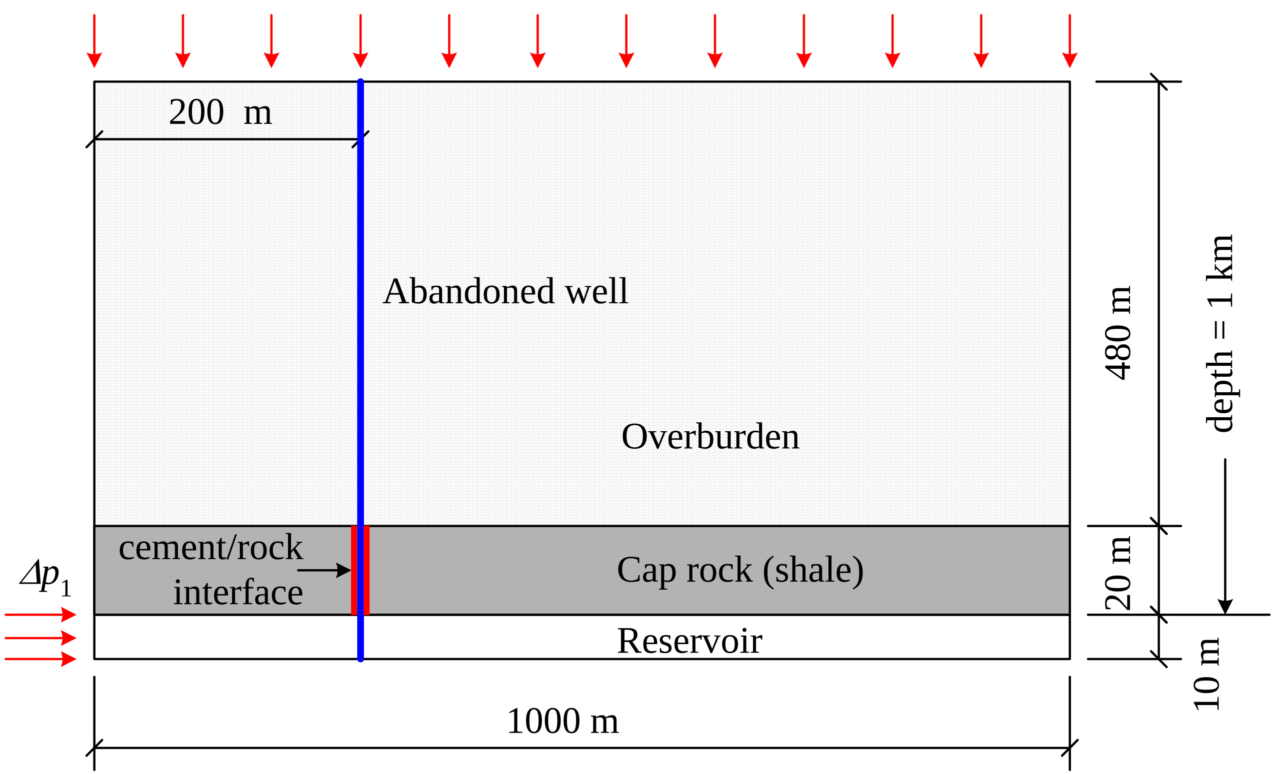
Loss of injectivity

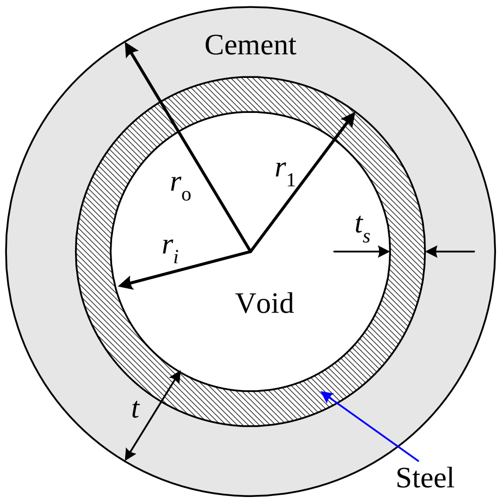


Geomechanics and Well Leakage

- Pressure created by injection of CO_2 deforms overburden
- Simulation investigates stresses from bending of cap rock and shear of cement relative to cap rock

$$\sigma'_{H,reservoir} = 10.4\,MPa$$

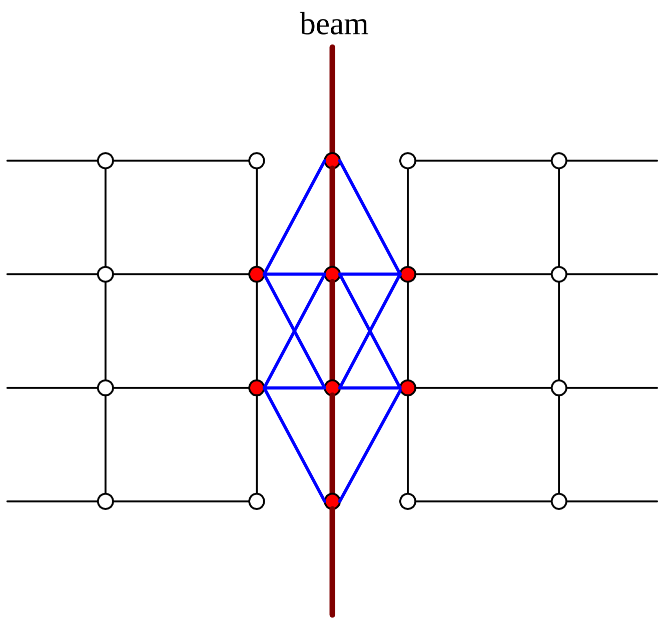




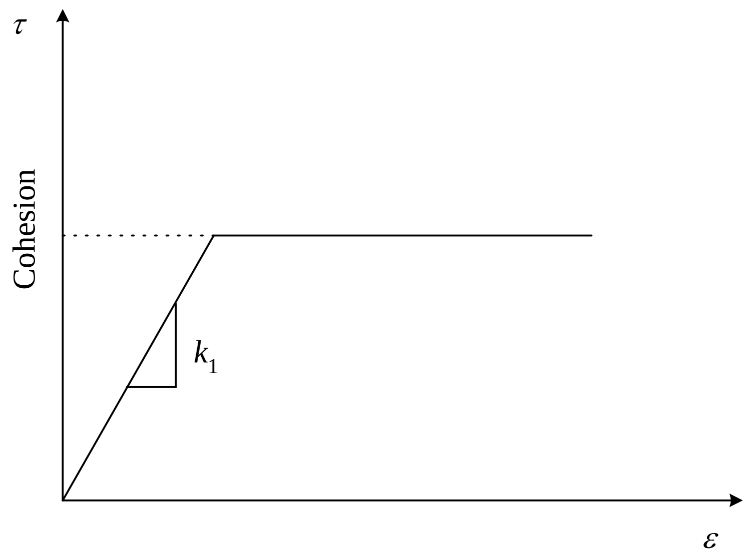
Not to scale!!!

interface (slide-line) elements

- Modeling the well (cement)-rock interface



Schematic of interface element



Tangential constitutive relation for interface elements

Material properties

- Geological layers

	Young's Modulus	Poisson's ratio	Density	Permeability
	E (Pa)	υ	ρ (kg/m^3)	κ (m^2)
Overburden	3.45E+09	0.35	2.50E+03	1.0E-15 (1 mD)
Reservoir	2.00E+09	0.40	2.60E+03	1.0E-13 (100 mD)
Shale	1.00E+10	0.35	2.50E+3	1.0E-17 (10 μD)

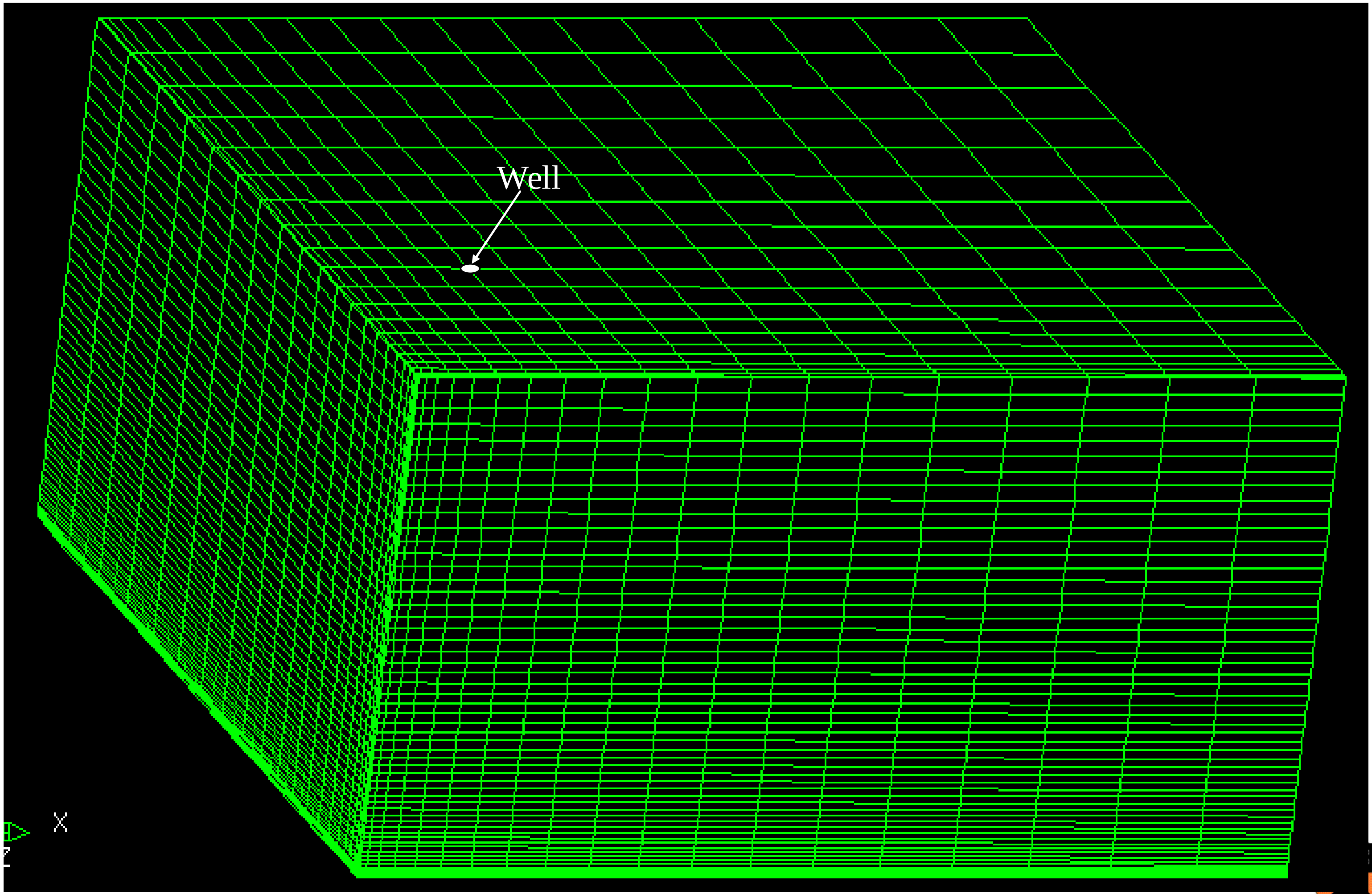
Material properties

◆ Geological layers

	Parameters	Value
Materials	Young's Modulus of cement E_c (Pa)	6.90E+09
	Poisson's ratio of cement υ_c	0.2
	Young's Modulus of steel E_s (Pa)	2.07E+11
	Poisson's ratio of steel υ_s	0.28
	Young's Modulus of composite beam E (Pa)	5.15E+10
Dimensions	Inner radius r_i (m)	7.74E-02
	Outer radius c or r_o (m)	1.21E-01
	Beam thickness t (m)	4.33E-02
	Steel layer thickness t_s (m)	1.15E-02
	Solid section area, A (m^2)	2.69E-02
	Bending inertia, I (m^4)	5.53E-04
	S, I/c (m^3)	4.58E-03
	EI ($N.m^2$)	2.85E+07
Rock-cement interface	Tangential stiffness k_1 (Pa)	3.00E+09
	Normal stiffness k_2 (Pa)	2.00E+12
	Cohesion (Pa)	4.00E+05

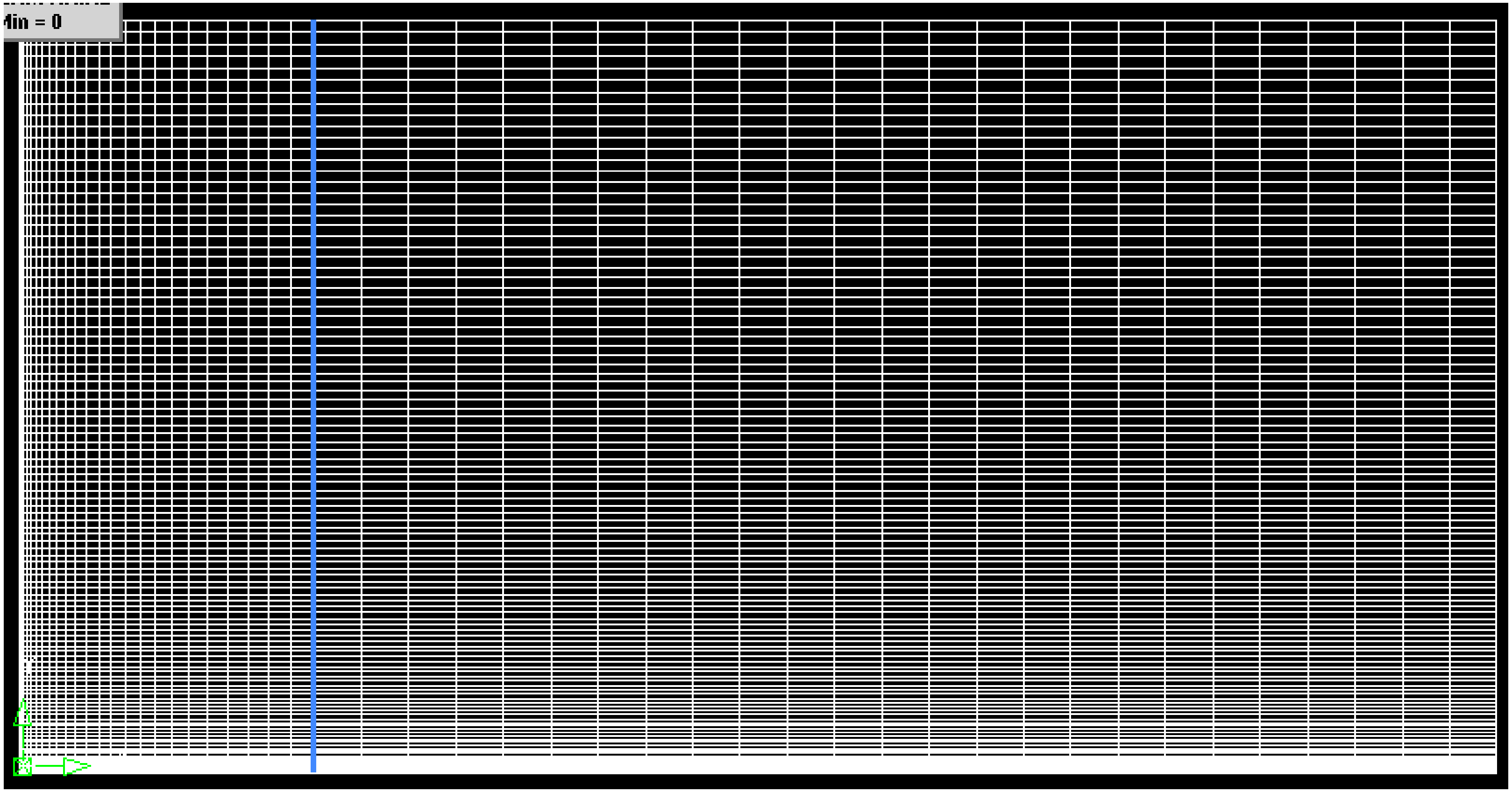
Finite element mesh

- 3D

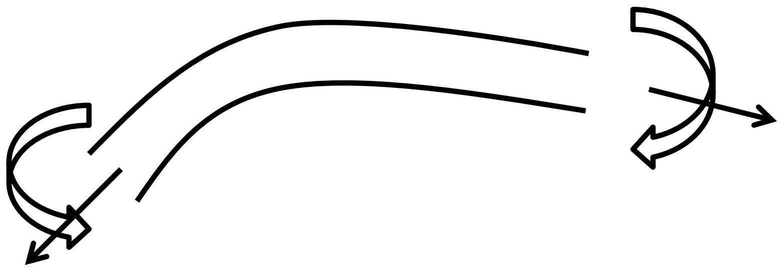


Finite element mesh

- 2D axisymmetric

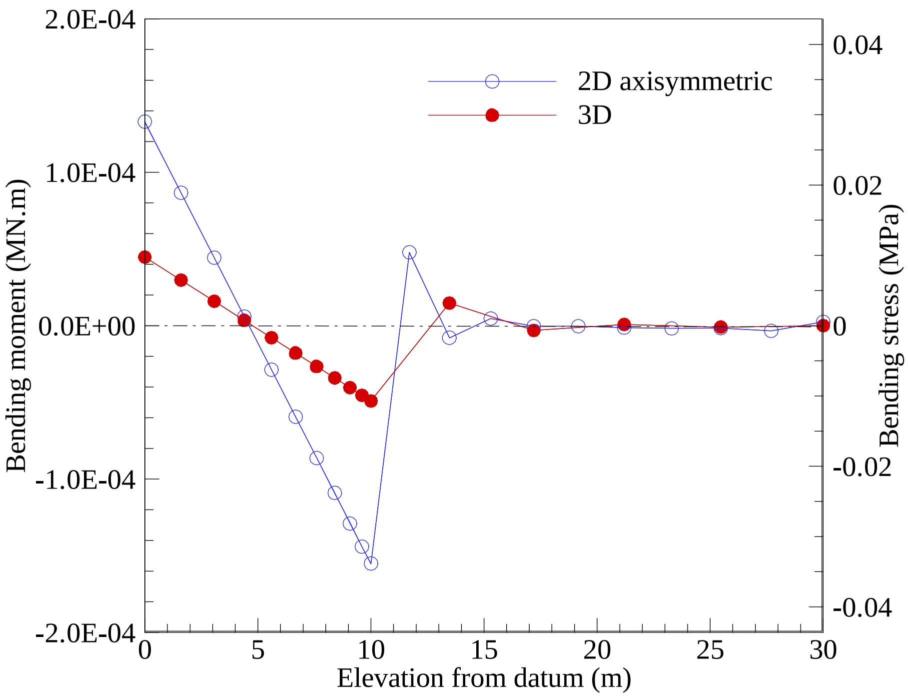


Beam bending: 3-layer formation (w/ shale)

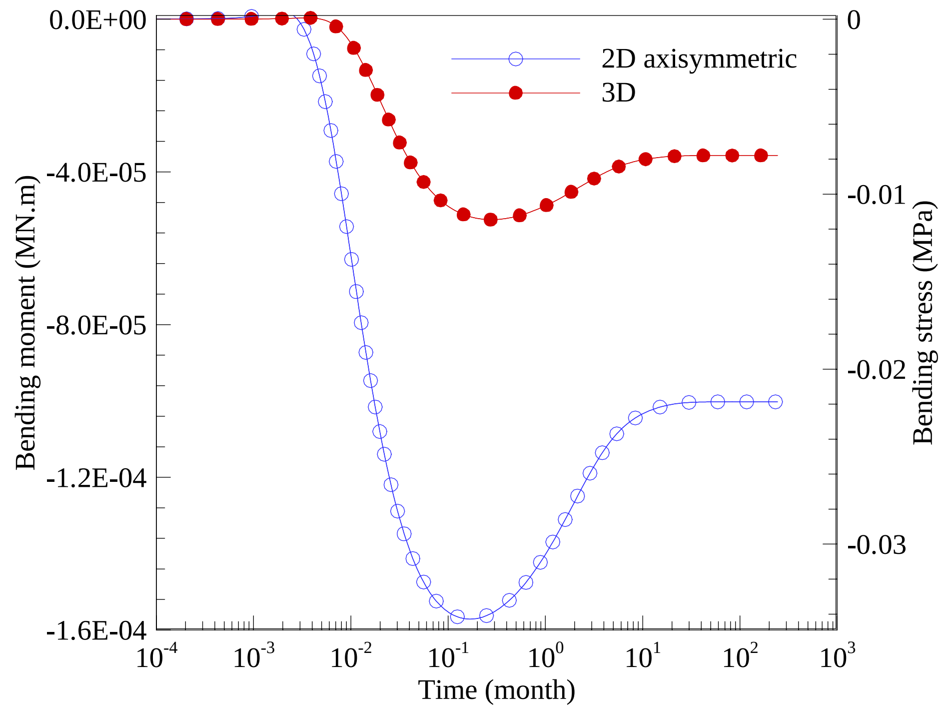


$$\sigma_{bending} = N / A + M / S$$

$$\sigma_{bending} \ \square \ 3MPa$$

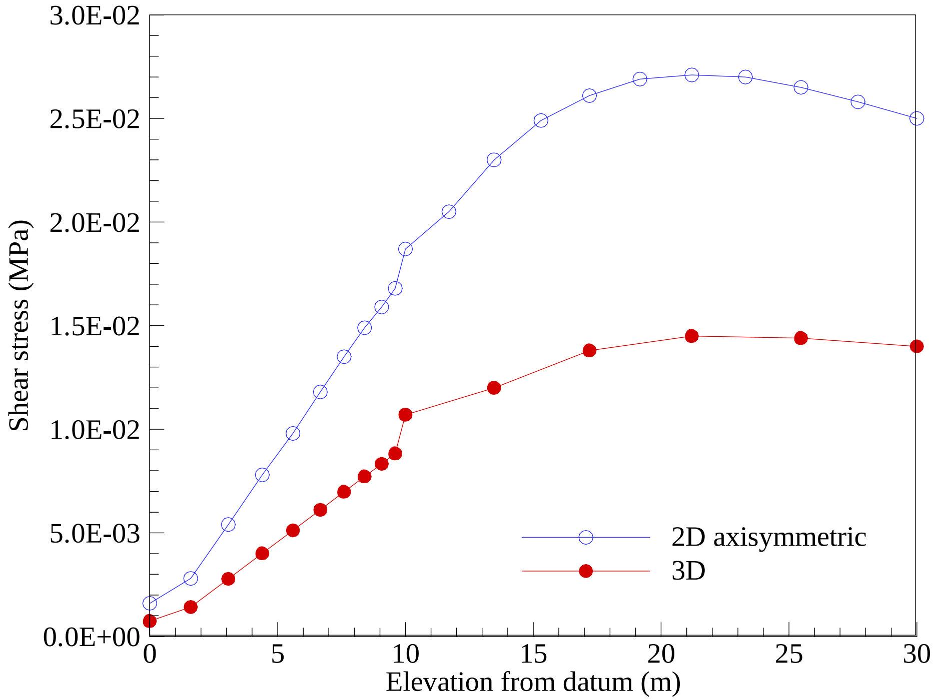


Spatial distribution of bending moment/stress at t = 3 days

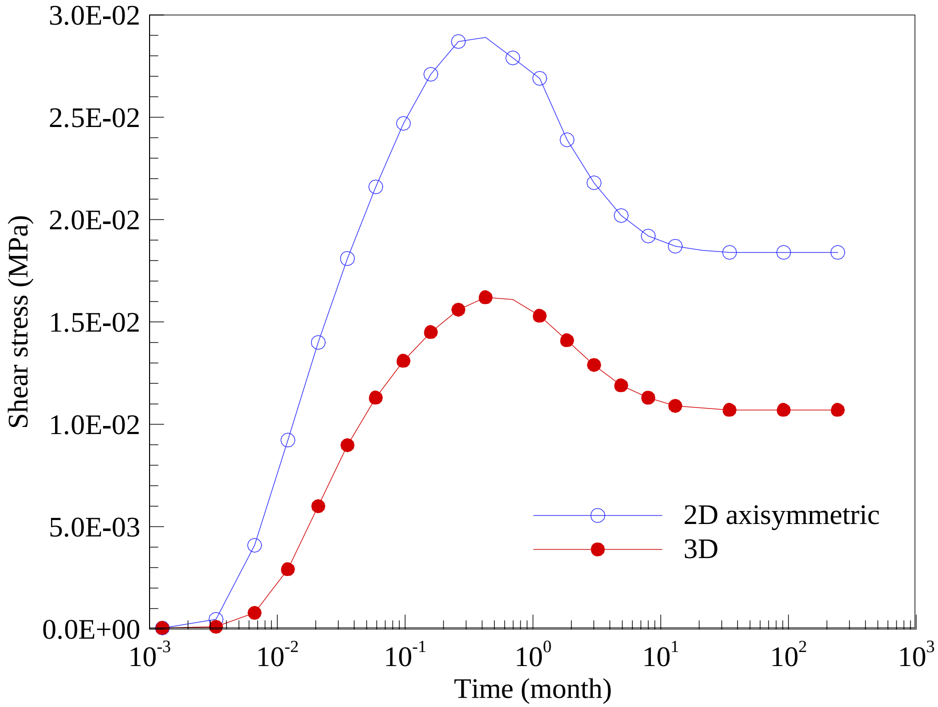


Time history for maximum bending moment/stress

shear stress in formation

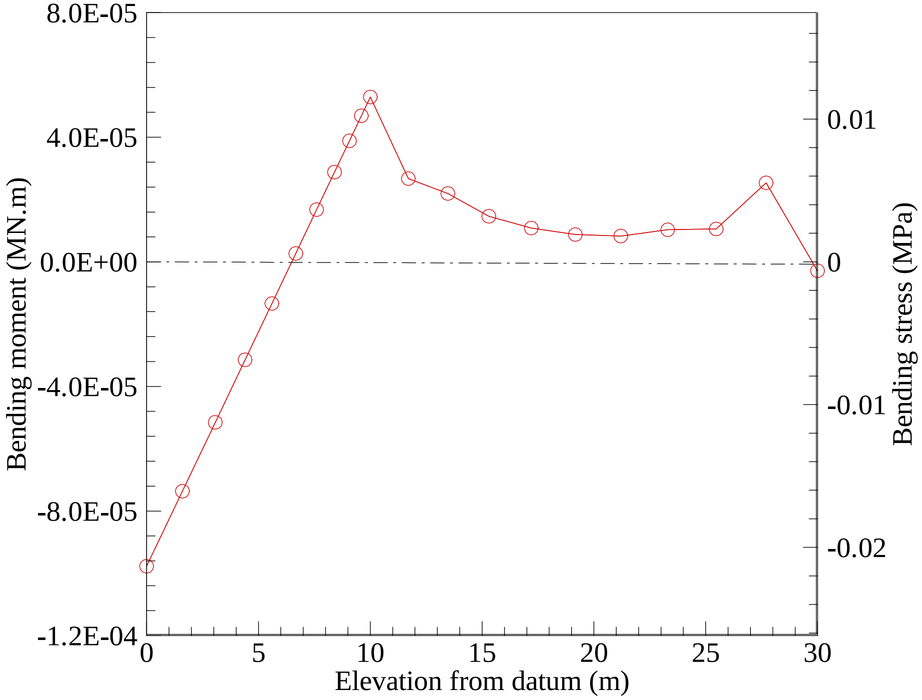


Spatial distribution of shear stress t = 5 days

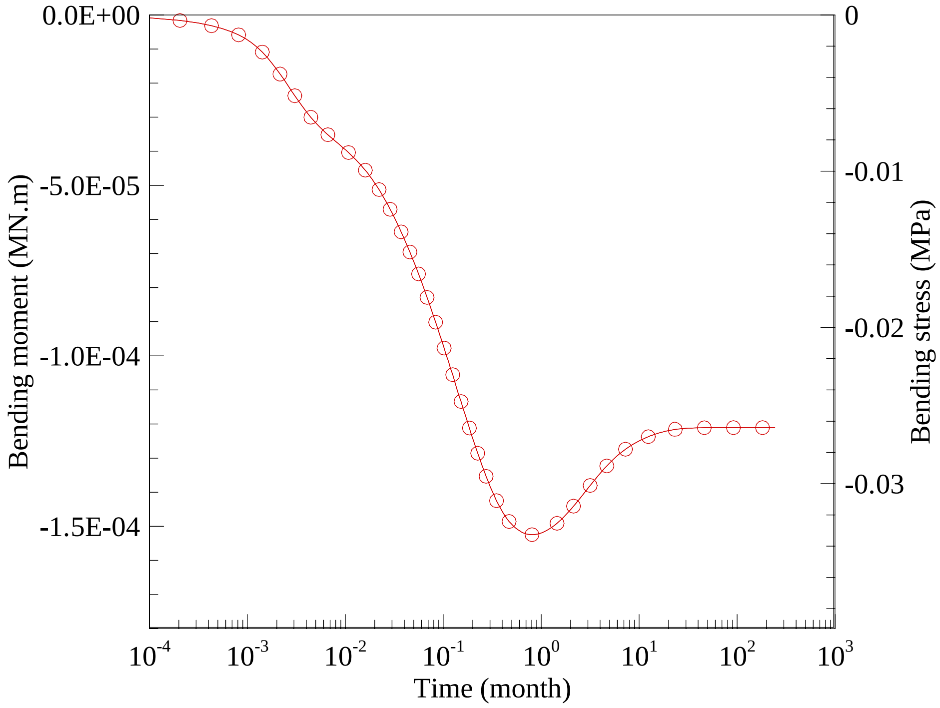


Time history for maximum shear stress

w/ slip at rock-cement interface

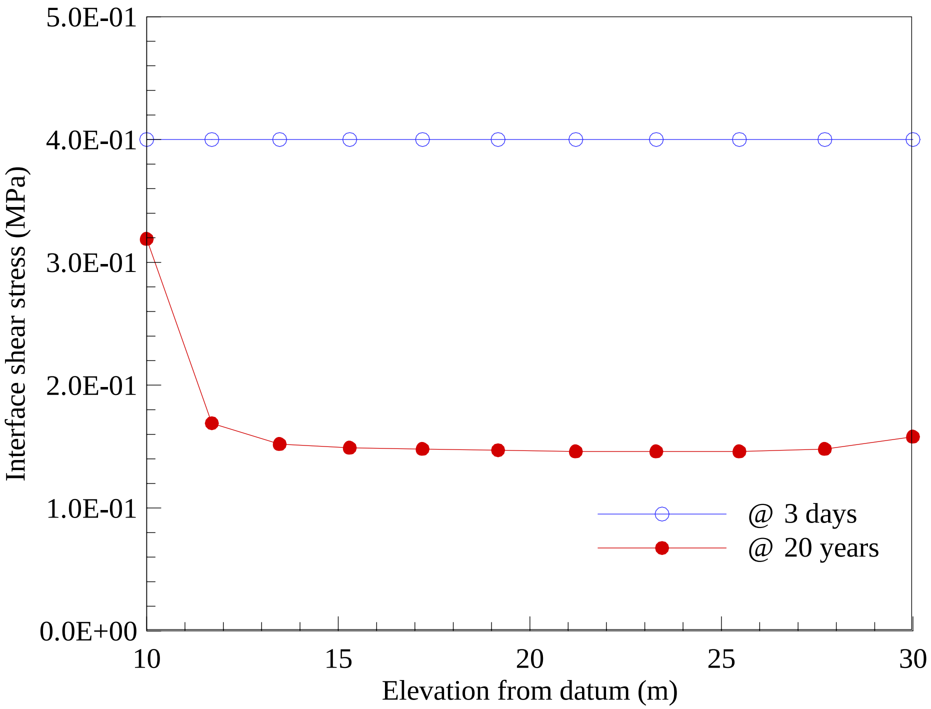


Spatial distribution of bending moment/stress at t = 3 days



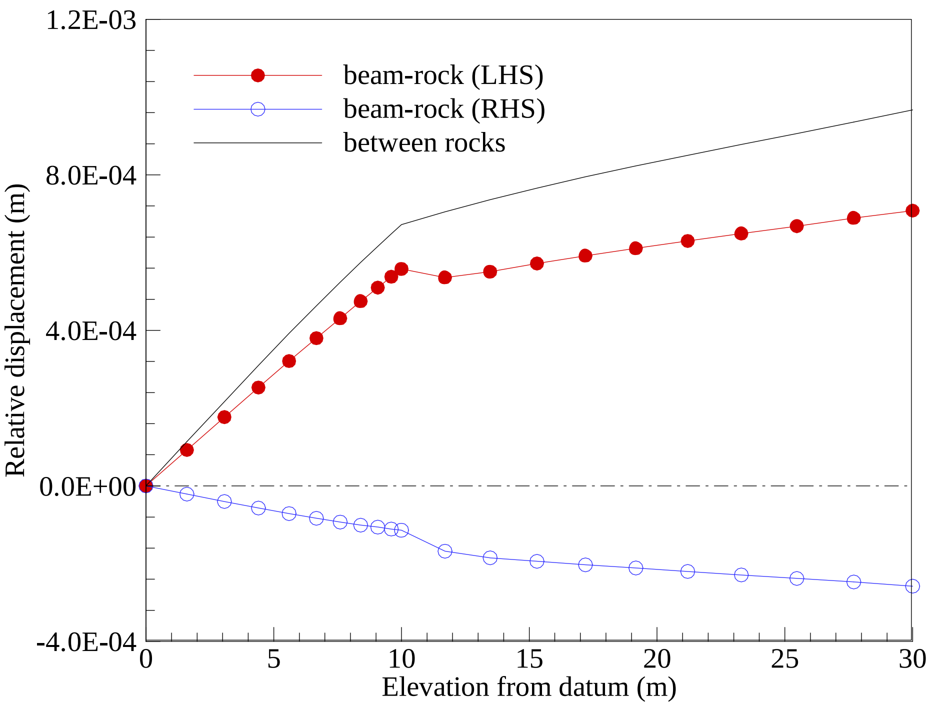
Time history for maximum bending moment/stress

w/ slip at rock-cement interface



Spatial distribution of interface shear stress

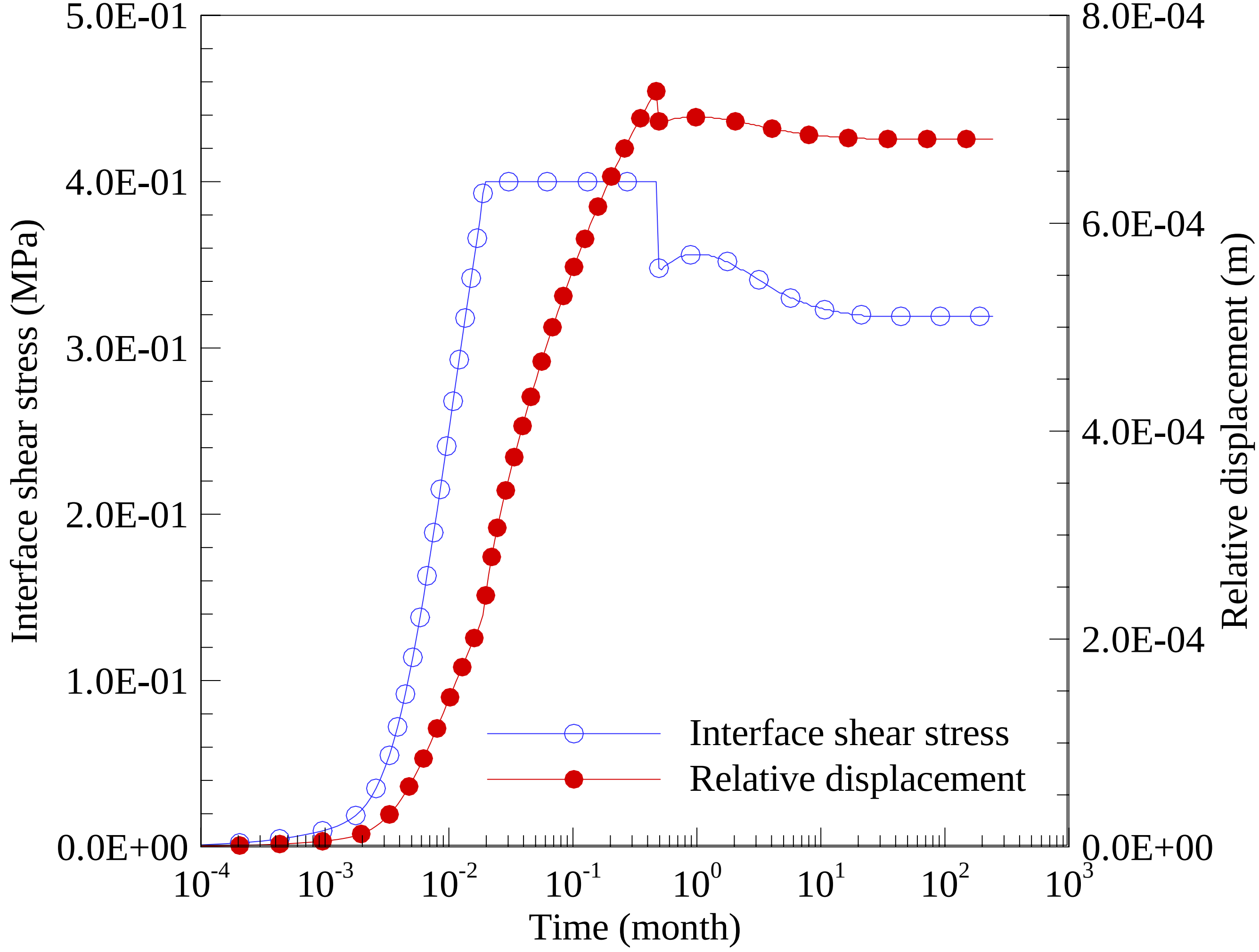
t = 3 days



Spatial distribution of interface shear displacement

t = 3 days

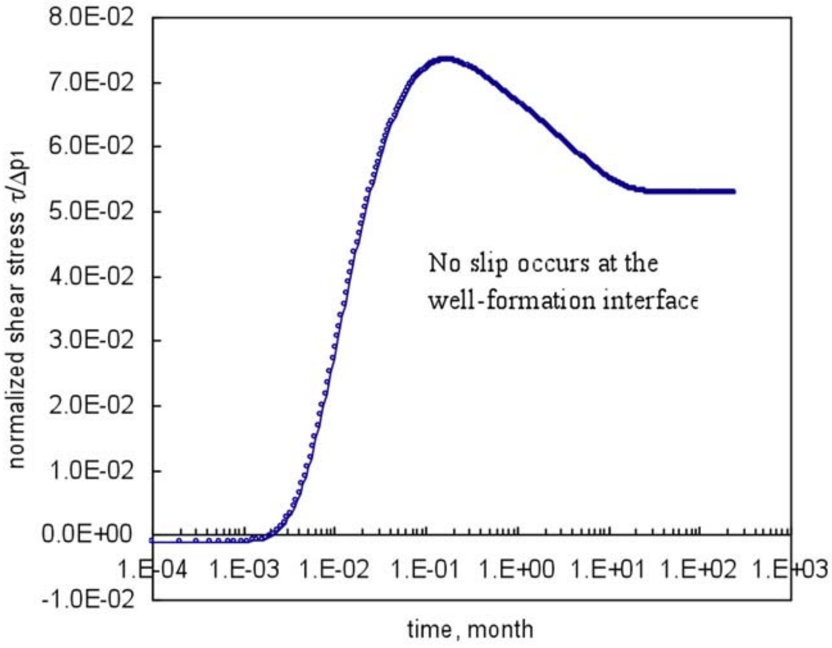
w/ slip at rock-cement interface

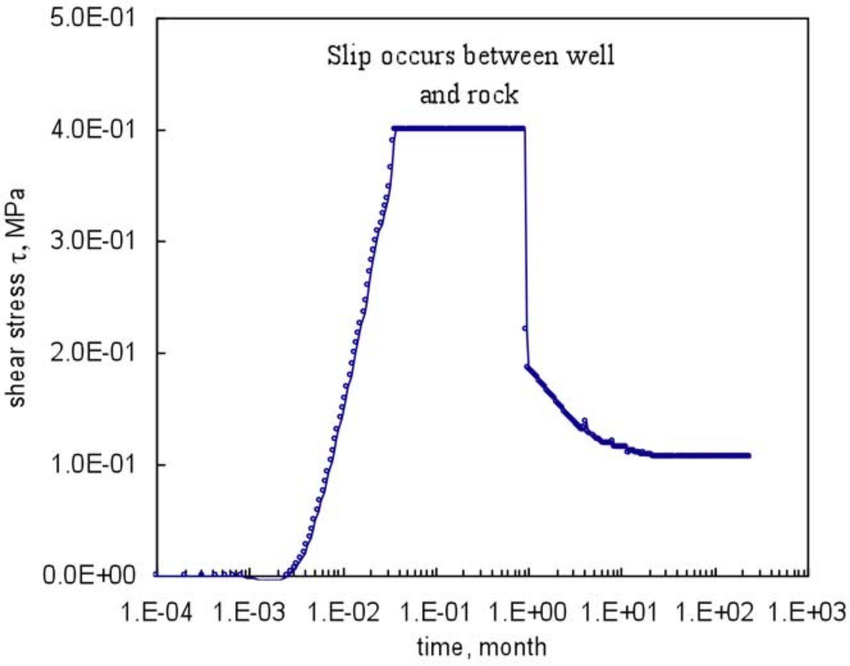


Time history for shear and relative displacement

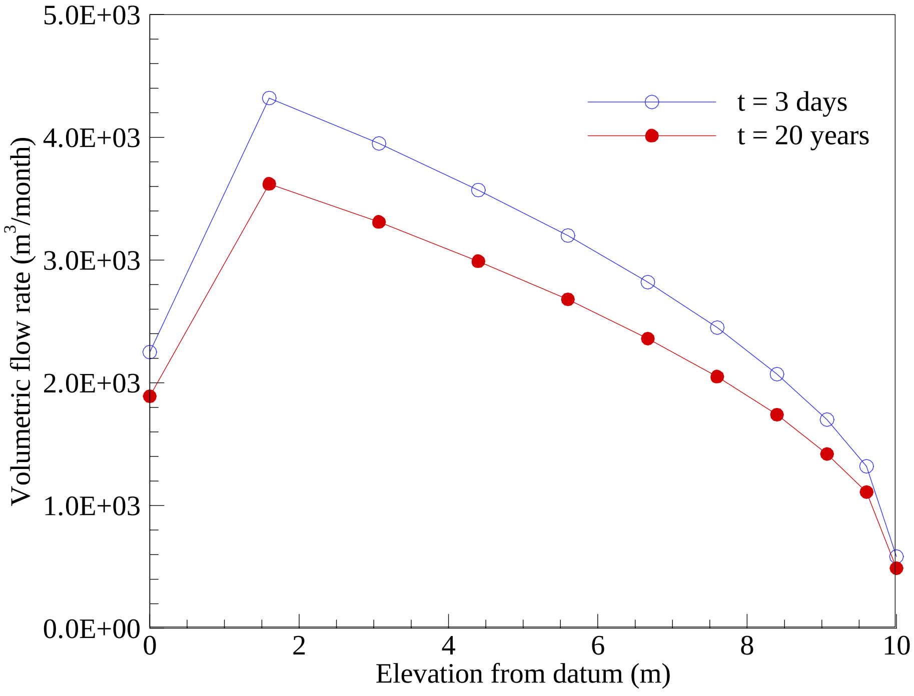
Geomechanics and Well Leakage

- Pressure created by injection of CO2 deforms overlying formation
- Simulation investigates stresses from bending of cap rock (found to be negligible) and shear of cement relative to cap rock (causing sliding, and possibly leakage???)

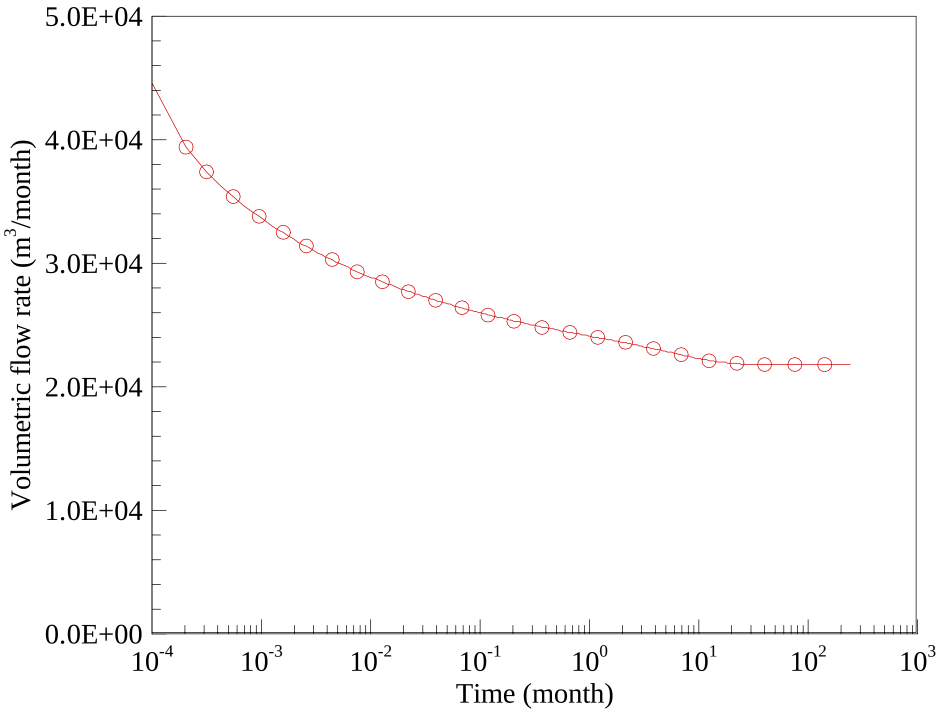




Volumetric flow rate at injection site

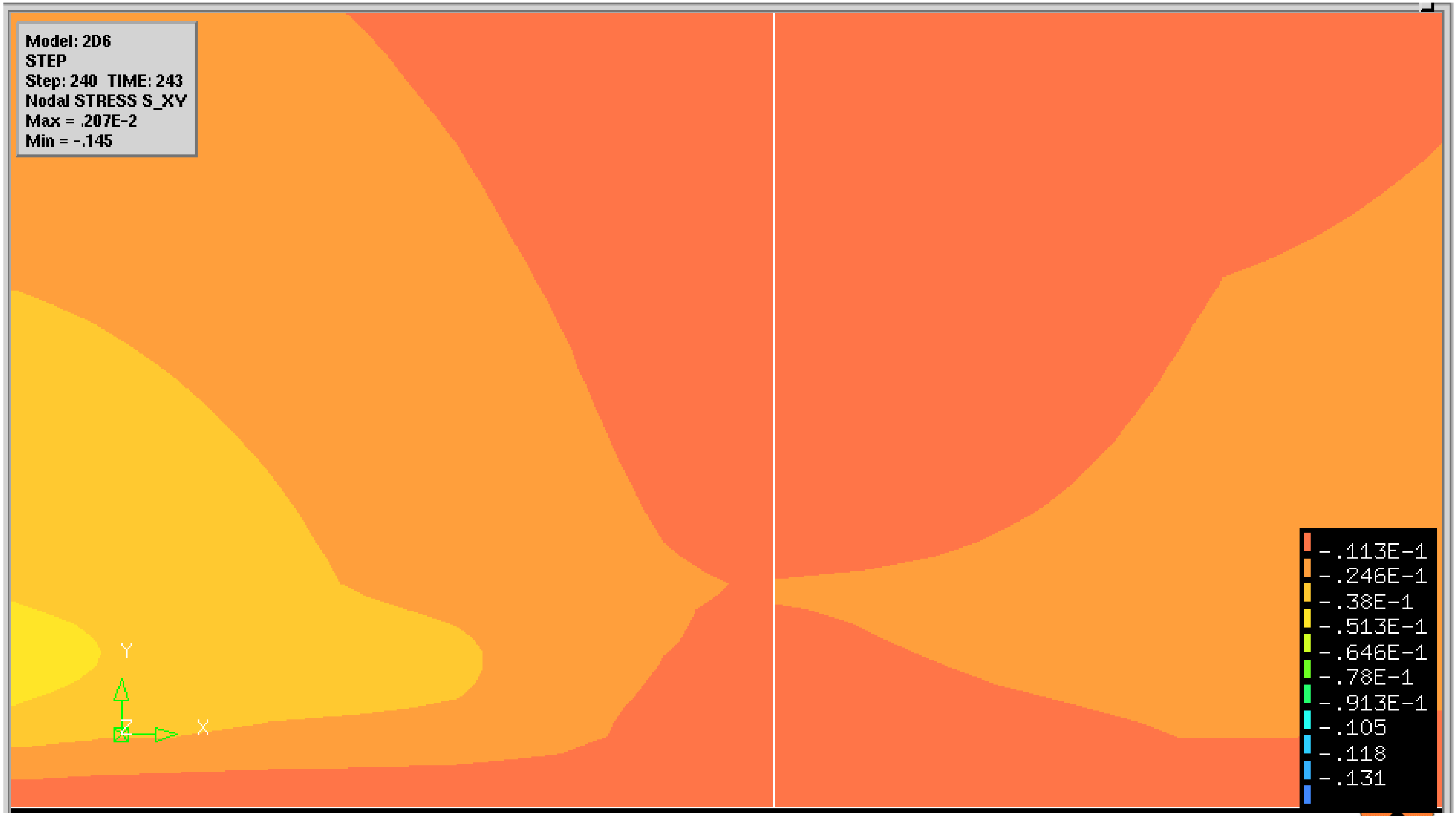


Spatial distribution of volumetric flow rate



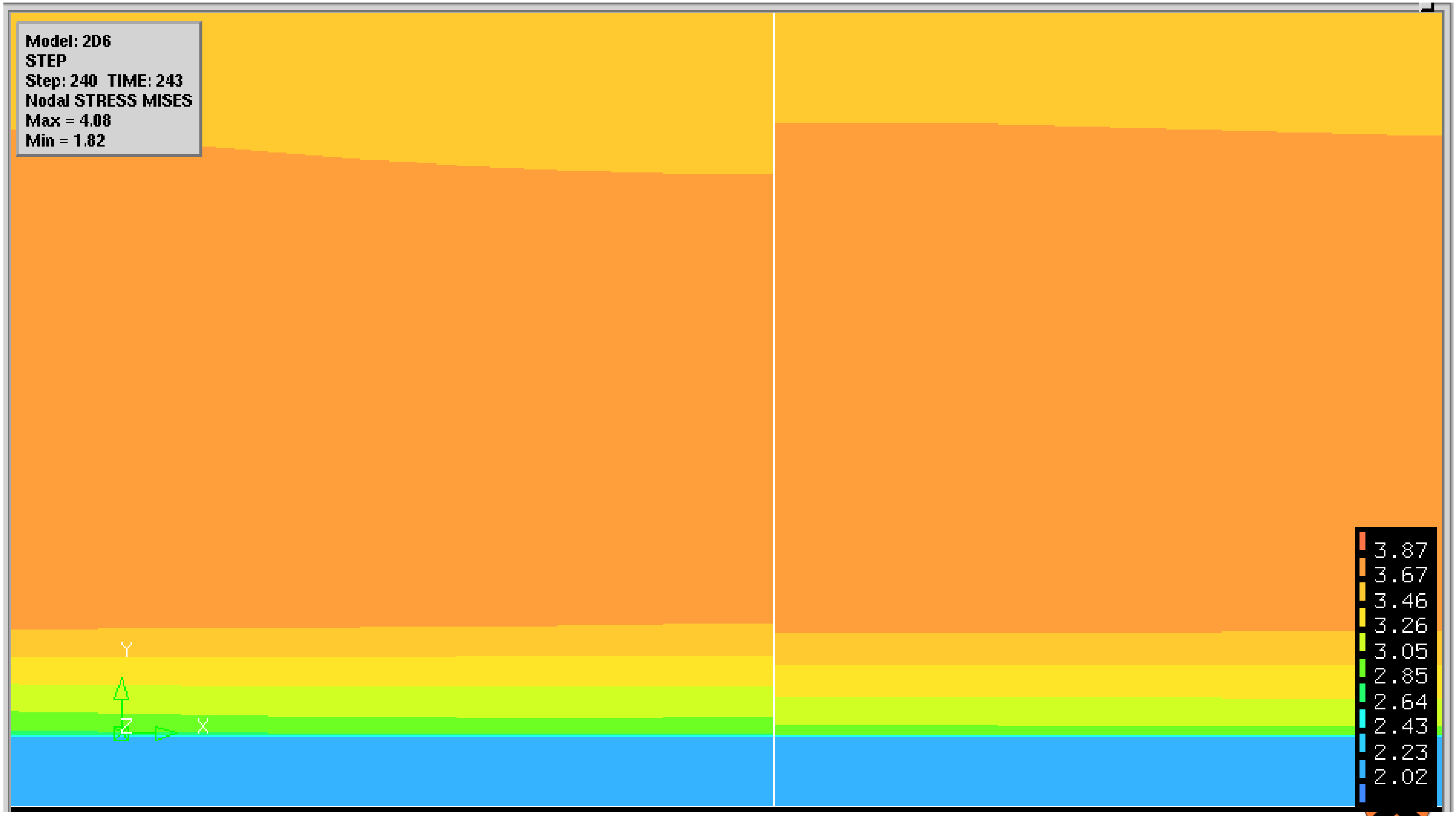
Time history for total flow rate

Numerical results: Shear stress τ_{xy}



Numerical results: Mises stress, Caprock failure?

$$mobilized\ \varphi \approx 17^0 \quad shear\ stress\ \tau \geq 3\ MPa$$



Future work

- Stabilize flash (Nc=2, Np=3)
- Investigate failure in cap rock
- Incorporate interface in 3D model
- Parametric studies
- “Detailed “ leak simulation: viz., fluid (P,T, composition) – cement exposure vs depth

Hydrogeologic parameters

- $permeability: \quad K = 10^{-13} m^2 = 100\ mdarcy$
- $porosity: \quad \varphi = 0.15 \qquad pore\ compressibility: \quad C_m = 0.$
- $relative\ permeability: \quad Stone's\ first\ 3-phase\ method$

$a: Aqueous\ phase:$

$$k_{rAq} = \left[\frac{S_{Aq} - S_{ar}}{1 - S_{ar}}\right]^n \qquad S_{ar} = 0.15 \qquad n = 3$$

$b: Liquid\ phase:$

$$k_{rL} = \left[\frac{\widehat{S} - S_{Aq}}{\widehat{S} - S_{ar}}\right]\left[\frac{1 - S_{ar} - S_{lr}}{1 - S_{Aq} - S_{lr}}\right]\left[\frac{(\widehat{S} - S_{ar})(1 - S_{Aq})}{1 - S_{ar}}\right]^n$$

$$\widehat{S} = 1 - S_G - S_{lr} \qquad S_{lr} = 0.05 \qquad n = 3$$

$c: Gas\ phase:$

$$k_{rG} = \left[\frac{S_G - S_{gr}}{1 - S_{ar}}\right]^n \qquad S_{gr} = 0.01 \qquad n = 3$$

- $thermal\ parameters:$

$thermal\ conductivity: \quad K_T = 2.00\, W/m\ {}^0C$

$rock\ specific\ heat: \quad c_R = 1000\ J/kg\ {}^0C$

$rock\ density: \quad \rho_R = 2600\ kg/m^3$

4th Wellbore Integrity Network Meeting

Numerical Simulations in Support of the Design of In-Well Verification Testing of Well Integrity

Rick Chalaturnyk and Alma Ornes

Geological Storage Research Group
Department of Civil and Environmental Engineering
University of Alberta

18th – 19th March 2008
Hotel Concorde Montparnasse,
Paris, France

Outline

- Background
- Concept of Well Verification Testing
- Simulation Tool
- Results
- Summary

Weyburn Phase I Well Integrity Studies

- ability to capture the "exact" state of all wellbores is extremely difficult; consequently, the approach was to combine both "real" field data and analytical or numerical simulations to quantify processes associated with the hydraulic integrity of the wells.

Background - Wellbore Transport Properties

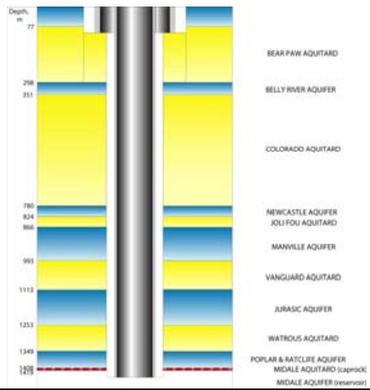
- Material behavioral models
- Damage mechanisms during drilling
- Damage mechanisms during completion
- Damage mechanisms during production
- Mud removal
  - Turbulent flow
  - Laminar flow
  - Mud conditioning
  - Mud displacement
- Cement transport properties
  - Undamaged cement
  - Damaged cement
- Cement degradation
  - 1.7.1 Carbonation
  - 1.7.2 Sulfate attack
  - 1.7.3 Acid attack and leaching
- Wellbore transport properties changes
- Wellbore geometry (statistical analysis)
- Loading and temperature effects
- Cement shrinkage effect on wellbore integrity
- Cement aging
- Mud removal

Degradation rates due to sulfate attack at different formation

Degradation rate		Ratcliffe		Poplar		Jurassic		Manville		Newcastle	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Atkinson and Hearne (5)	mm y^{-1}	0.342	0.683	0.685	1.027	-	-	0.077	0.256	0.043	0.120
Atkinson and Hearne (6)	mm y^{-1}	1.798	3.595	3.595	5.393	-	-	0.404	1.348	0.225	0.629

$$R(mmy^{-1}) = 5.5C_A(\%)c_0(M)$$

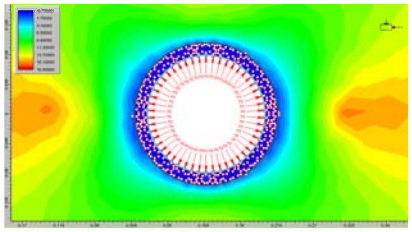
[Equation 5 for t < 40 years]



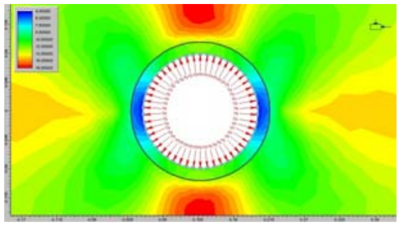
R = degradation rate
C_A = tricalcium aluminate content of the cement
c_0 = sum of concentrations of sulphate and magnesium ions in the groundwater

Tangential stress distribution inside the cement and formation for a stable borehole condition

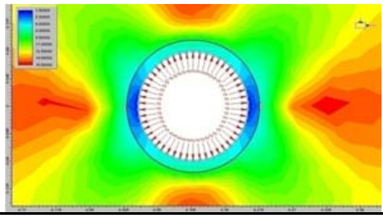
$E_{cement} > E_{rock}$



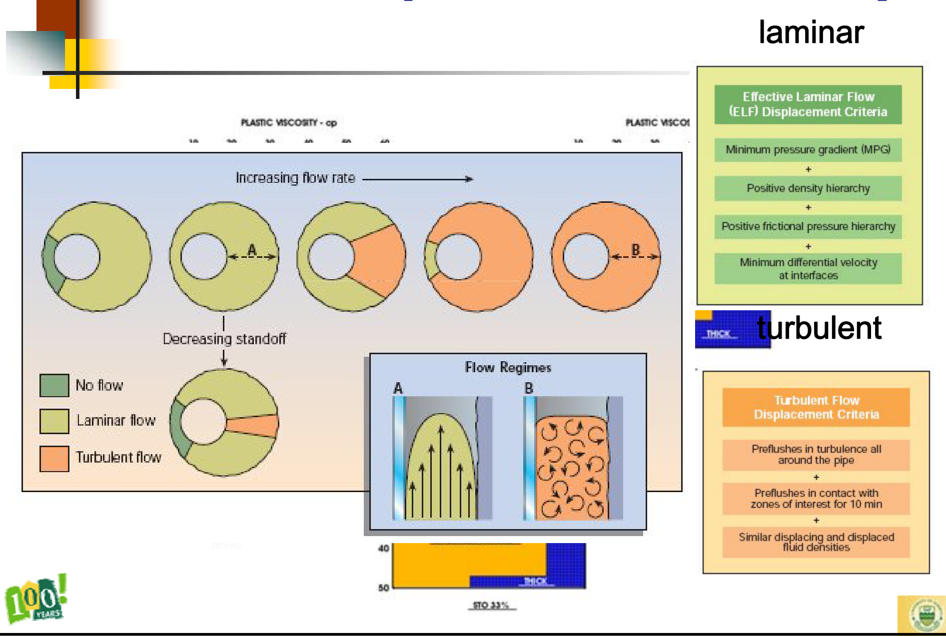
$E_{cement} < E_{rock}$



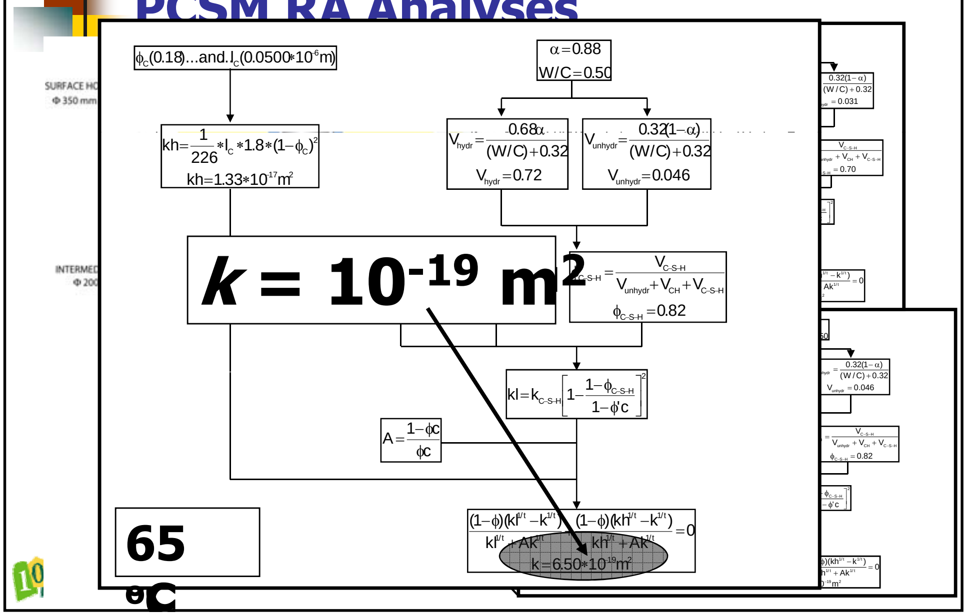
$E_{cement} \approx E_{rock}$



Cement Displacement Efficiency



Cement Transport Properties for PCSM RA Analyses

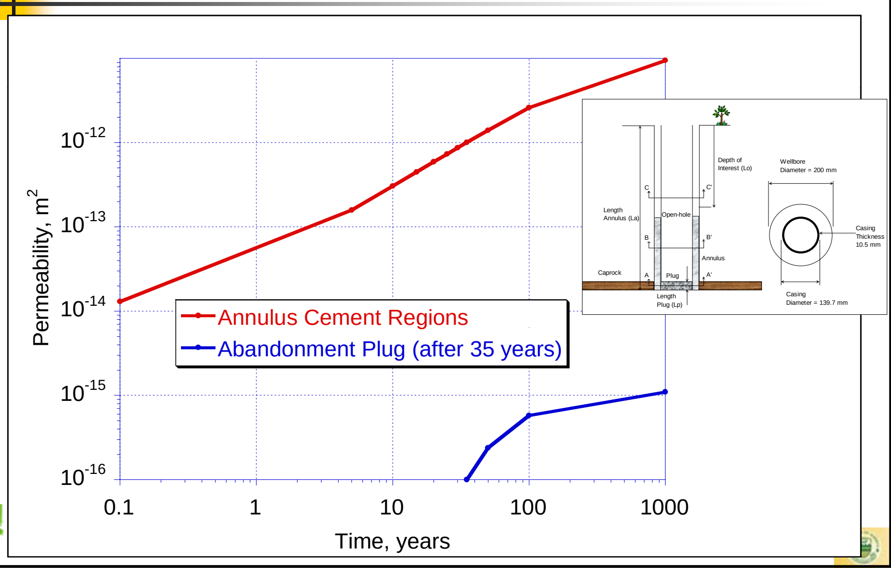


Abandoned Wells – (1956-1967) Plug & annulus cement degrade similarly.
Permeability at 2000: 10 $^{-14}$ m^2.
Permeability at 2100: 10 $^{-13}$ m^2. Aging, mechanical, temp. effects are not large. Meanly leaching.
Permeability at 3000: 10 $^{-11}$ m^2. Degradation to amorphous silica.

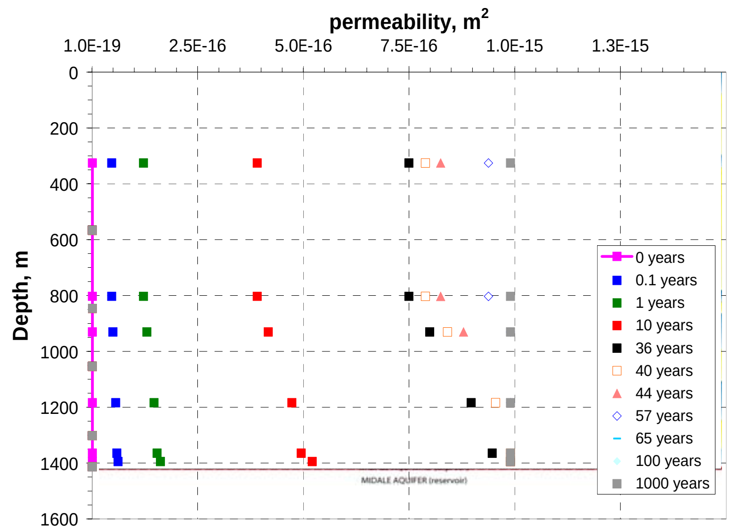
Oil Wells, Water Injectors & WAG Injectors
(1956-1967) Plug & annulus cement degrade independently
Annulus
Permeability at 2000: 10 $^{-14}$ m^2.
Permeability at 2035: 10 $^{-12}$ m^2. Mechanical & thermal effects, although (leaching) important.
Permeability at 3000: 10 $^{-11}$ m^2. Degradation to amorphous silica.
Plug: Installed 2035, length 8 m, state of the art
Permeability at 2035: 10 $^{-16}$ m^2.
Permeability at 3000: 10 $^{-15}$ m^2. Chemical degradation (aging). Better cement quality and only the bottom is exposed.

CO_2 Injectors and Producers - Age: 1998-2001) Plug & annulus cement degrade independently
Annulus
Permeability at 2000: 10 $^{-17}$ m^2.
Permeability at 2035: 10 $^{-15}$ m^2. Mechanical & thermal effects, although (leaching) important.
Permeability at 3000: 10 $^{-12}$ m^2. (Affected during operational life of well)
Plug: Installed 2035, length 8 m, state of the art
Permeability at 2035: 10 $^{-16}$ m^2.
Permeability at 3000: 10 $^{-15}$ m^2. Chemical degradation (aging). Better cement quality and

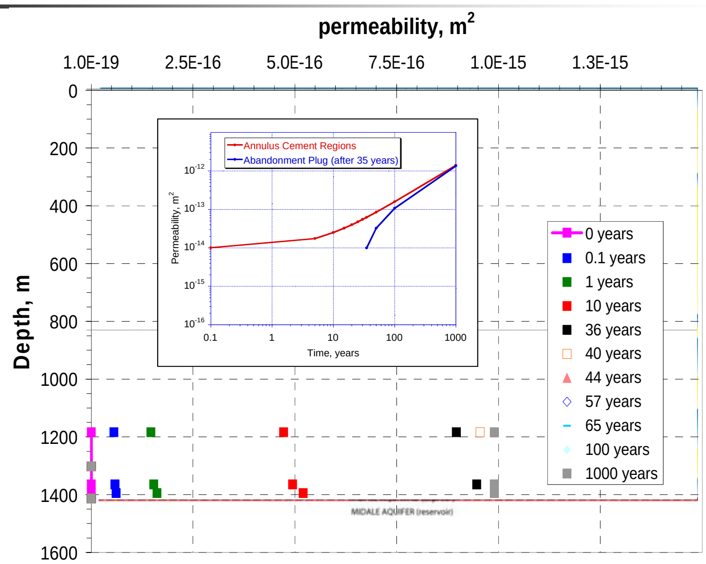
Oil & Water Injection Wells



CO_2 Production/Injection Well



Abandoned Wells



No One Believed the Predictions!!!!

Simulations to Support Design of Field Verification Test

- Simulations completed in COMSOL Multiphysics platform
- Two modules from COMSOL:
  - Earth Science Module - Darcy's flow transient analysis to study pressure transient responses that arise from applying a periodic pressure pulse)
  - Structural Mechanics Module – include the solid deformations due to the packers' sealing force on the well casing

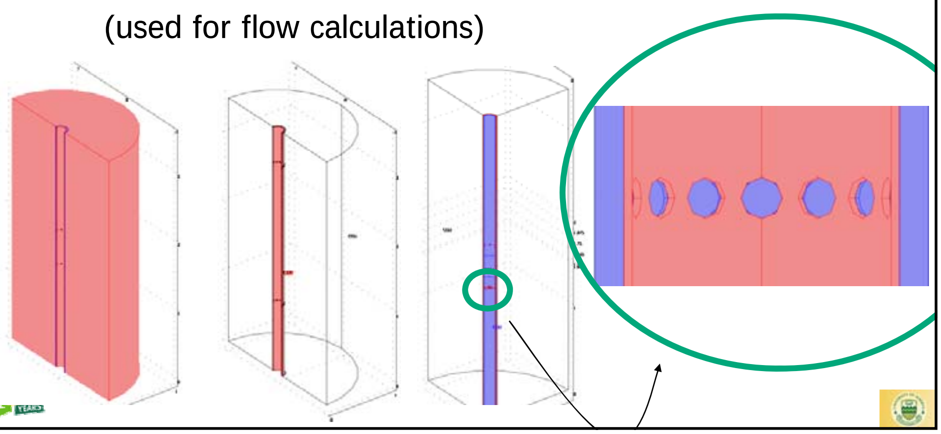
Problem Geometry

- Three concentric cylindrical rings, divided in half by a plane of symmetry perpendicular to the x-axis.
  - Outer ring = geology
  - Middle ring = cement
  - Inner ring = steel casing
- Model height = 3.5 m

Domain	Outer Radius (m)	Inner Radius (m)	Thickness (mm)
Formation	1.00	0.10	900
Cement	0.10	0.0825	17.5
Steel Casing	0.0825	0.0775	5.0

Well Geometry

- Microannulus is a curved surface within the cement domain. The element has a radius of 0.093m and no material thickness but a theoretical thickness of 0.1mm (used for flow calculations)

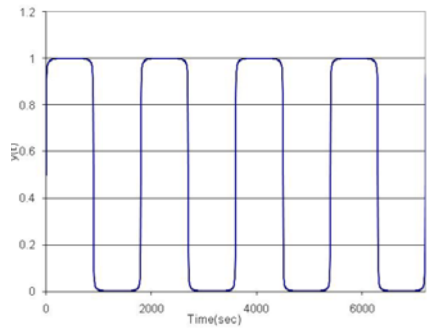


Pulse Pressure Boundary Condition

- The periodic pressure applied on the concrete can be represented by a square wave function.
- During the first 900 seconds, a pulse of 1.5MPa is applied, then the pressure is removed from 900-1800 sec. The process repeats every 1800sec.
- Equations model a continuous square wave with slightly curve edges which allow for a shorter computation time.

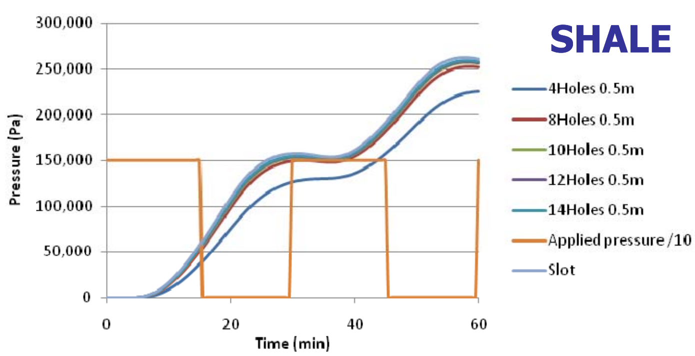
$$y(t) = c + b \cdot \mathrm{atan}\left(\frac{x(t)}{a}\right)$$

Parameter	Description	Value
a	Scalar	0.01
b	Scalar	0.3204
c	Scalar	0.5
θ	Phase angle	0
t	time	0 to 3600 sec
T	Period (1/f)	1800 sec

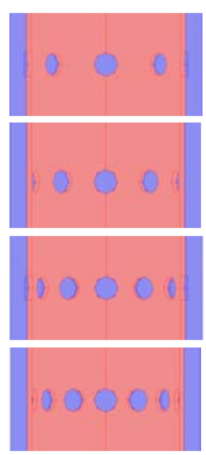


Effect of Number of Perforations

(Separation distance = 0.5 m)

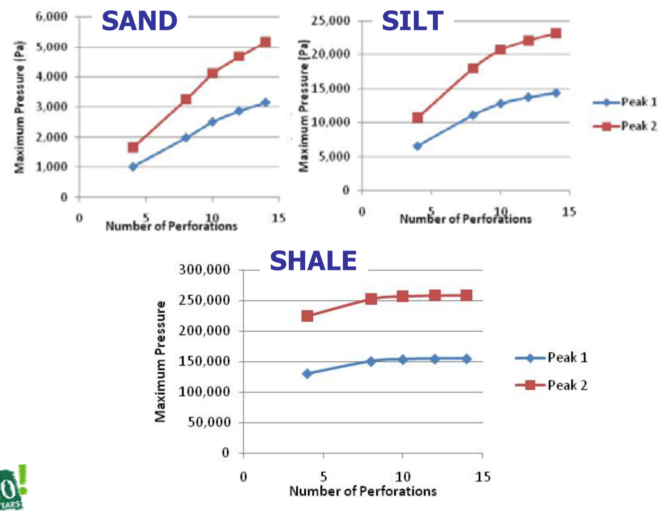


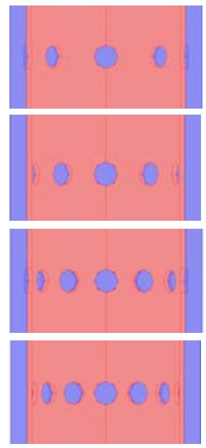
SHALE



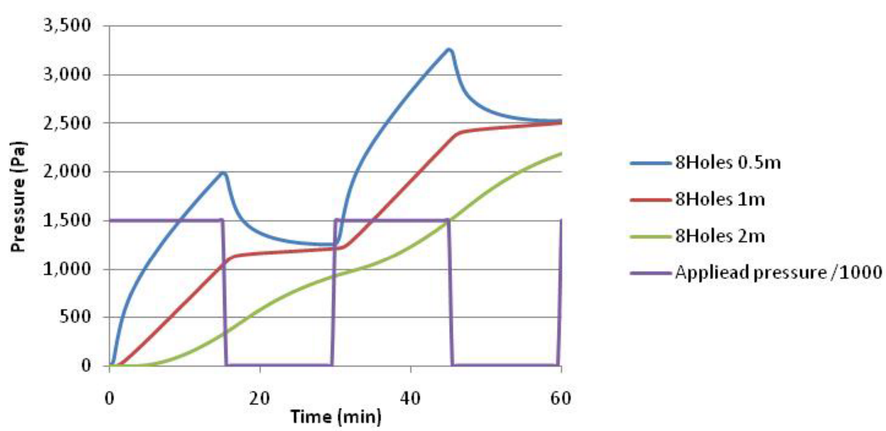
Effect of Number of Perforations

(Separation distance = 0.5 m)

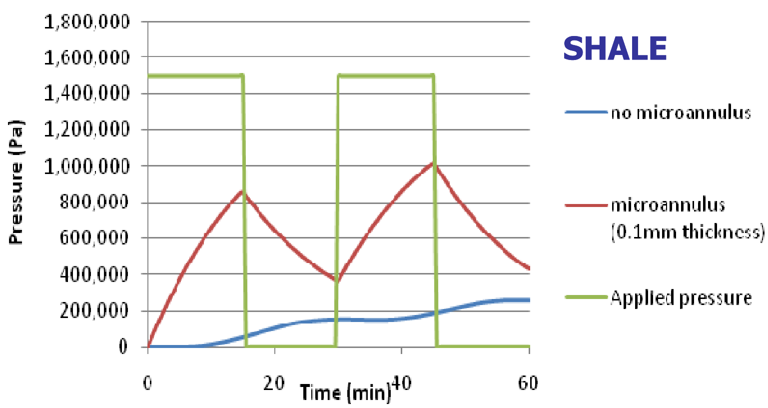




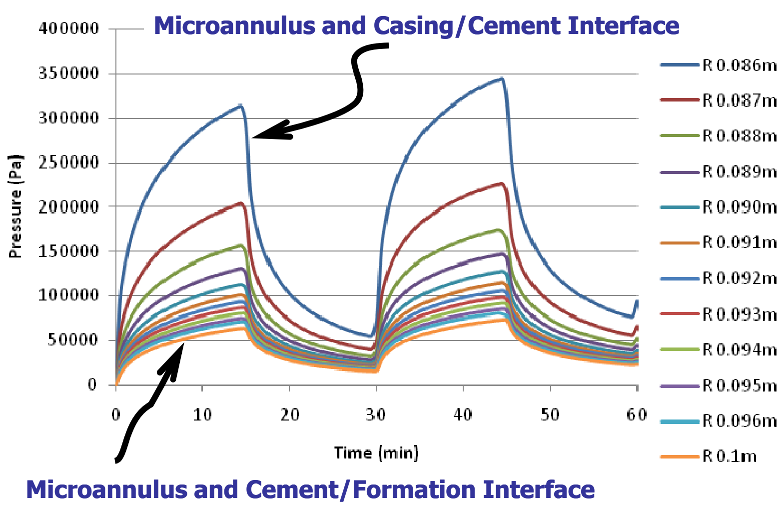
Effect of distance from the pressure source



Pressure Signature with and without Microannulus



Other Design Variables

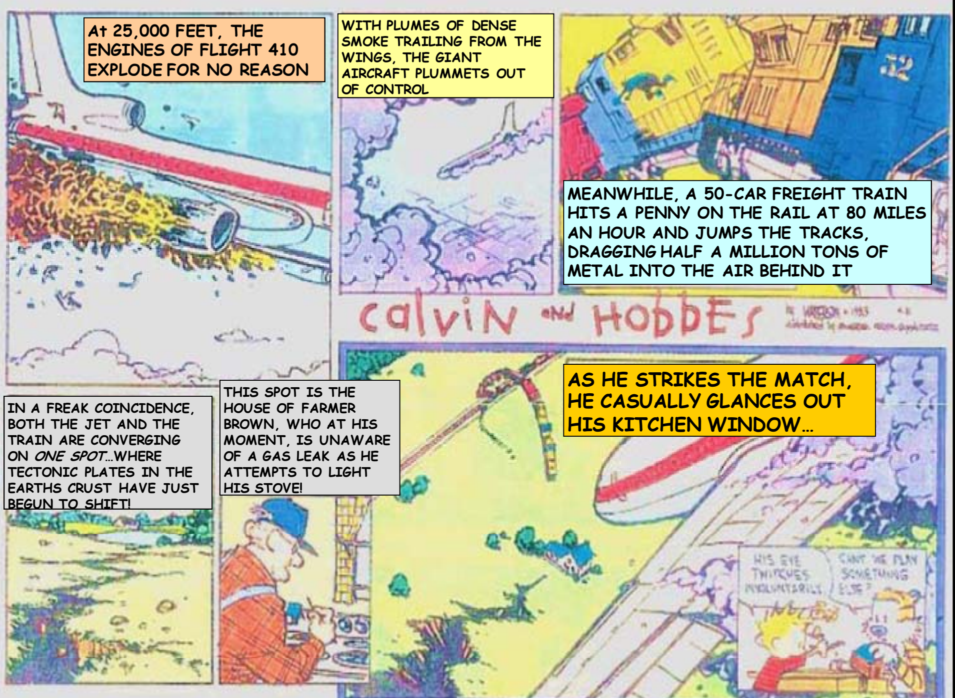


Well Program to Conduct Sampling

- Non-destructive logging suite to assess well/cement system condition
- Three testing intervals – full pressure transient characterization of hydraulic behavior of casing/cement/formation system
- MDT/RFT type tests to collect fluid samples
- Abandon well

			COMPLETION COSTS - INTANGIBLES	
C	IS	01	ROADS, LOCATION, DIRTWORK	
	IS	02	RIG MOVE	
	IS	03	RIG ANCHORS	
	IS	04	SERVICE RIG	
	IS	05	COILED TUBING	
	IS	06	BOILER	
	IS	07	HOT OIL SERVICES	
	IS	08	CASED HOLE LOGGING & PERFORATING	
	IS	09	SETTING PACKERS / PLUGS / RETAINERS	
	IS	10	PERMANENT PLUGS / RETAINERS / PACKERS	
	IS	11	REMEDIAL CEMENTING	
	IS	12	EQUIPMENT RENTAL & REPAIR - DOWNHOLE	
	IS	13	EQUIPMENT RENTAL & REPAIR - SURFACE	
	IS	14	ACID/ CHEMICAL STIMULATION	
	IS	15	FRAC STIMULATION	
	IS	16	COMPLETION FLUIDS - LOAD / FRAC	
	IS	17	FLUID DISPOSAL	
	IS	18	TRUCKING - FLUIDS	
	IS	19	TRUCKING - TANGIBLES & EQUIPMENT	
	IS	20	SLICKLINE SERVICES	
	IS	21	SAFETY SERVICES	
	IS	22	SPECIALIZED SERVICES	
	IS	23	PRODUCTION TESTING	
	IS	24	PRESSURE SURVEYS	
	IS	25	ANALYSIS - FLUID / PRESSURE	
	IS	26	MISCELLANEOUS COMP. COSTS	
	IS	27	CO. LABOUR/TRAVEL/EXPENSES	
	IS	28	WELLSITE SUPERVISION - COMPLETION	
	IS	29	ENGINEERING/ SUPT.	
	IS		CONTINGENCY (20%)	
			COMPLETION COSTS - TANGIBLES	
C	TE	01	TUBING & ACCESSORIES	
	TE	02	WELLHEAD	
	TE	03	NIPPLES / SUBSURFACE VALVES	
	TE	04	PACKER / ANCHOR	
	TE	05	HEAT / CHEMICAL INJECTION STRING	
			COMPLETION COSTS - OVERHEAD	
C	IS	30	OVERHEAD 3,2,1	

TOTAL DRILLED & COMPLETED COSTS ~ $1,000,000



4th Wellbore Integrity Network Meeting

Numerical Simulations in Support of the Design of In-Well Verification Testing of Well Integrity

Rick Chalaturnyk and Alma Ornes

Geological Storage Research Group
Department of Civil and Environmental Engineering
University of Alberta

18th – 19th March 2008
Hotel Concorde Montparnasse,
Paris, France

Reactive Transport Modelling of the Effect of Transport Parameters on the Breakthrough Time for Vertical migration of CO_2 in a Micro-annulus of a Cement Plug

Jonathan Ennis-King

CSIRO Petroleum

Presented at 4th IEA Wellbore Integrity Workshop

March 19th, 2008

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Outline

- 2D Reactive transport simulations with TOUGHREACT, for gas phase transport up a micro-annulus in a cement plug, in an old well completed with conventional Portland cement.

- Fracture-matrix theory for vertical migration rate – geochemistry contained in a single parameter, with the aim of capturing some basic physics.

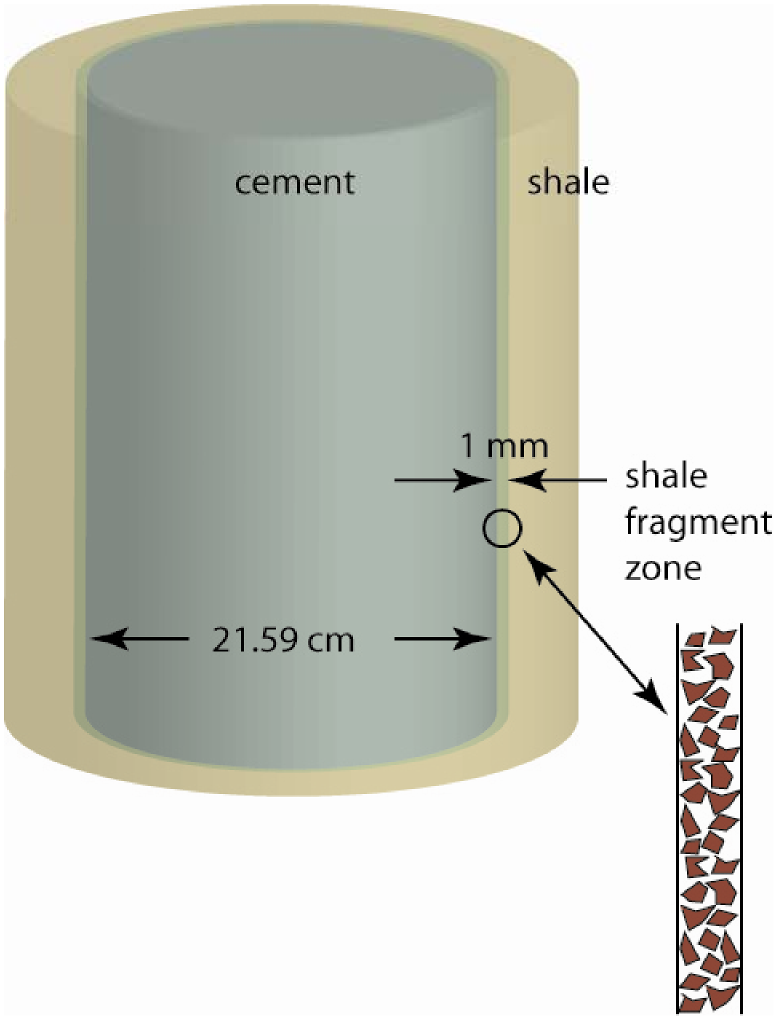
Geochemical model

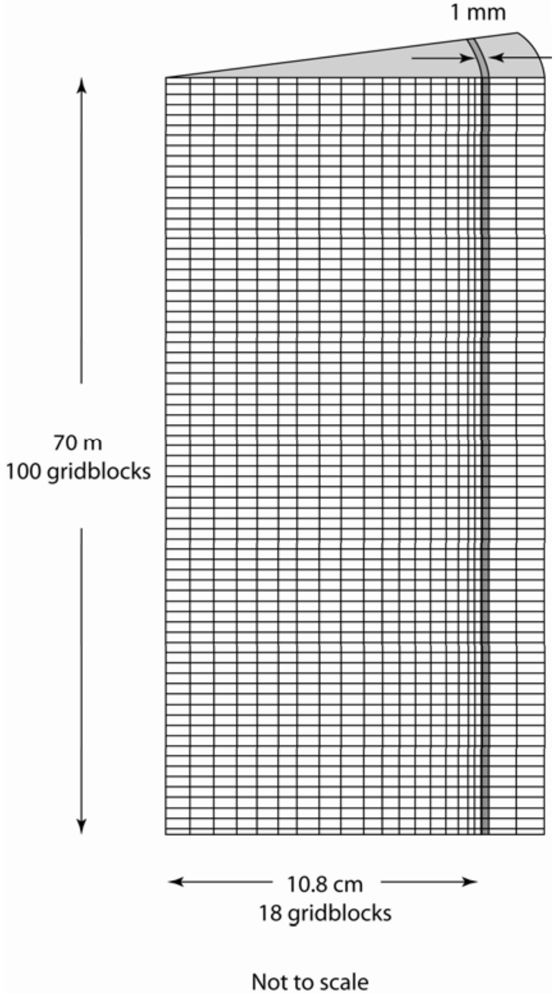
- The C-S-H phase is a challenge, because of its variable composition.
- Following Carey and Lichtner (2007), CSH is represented as a discrete set of solid phases that span the range of composition.
- Behaviour was matched to the SACROC sample: a low value of tortuosity (10^{-2} to 10^{-3}) was needed
- The TOUGHREACT (LBNL) code was used for simulations.

Transport mechanisms

- **Diffusive transport alone is very slow: distance is $2\,(D\,t)^{1/2}$, so after 1000 years, it moves ~ 1 m.**
- **The SACROC study suggests vertical transport can occur in between the cement and the shale – the "shale fragment zone". This is treated as a porous medium with higher permeability.**
- **The challenge is to estimate transport parameters: micro-fracture width and permeability, capillary pressure threshold and permeability of intact cement. How continuous is the transport path?**

Simulation geometry





Transport parameters

Property	Micro-annulus	Intact cement
Width	1 mm	N/A
Permeability	0.1 mD	0.01 mD
Capillary pressure threshold	0.1 MPa	1 MPa
Porosity	30 %	30%

Reservoir conditions

No upward flow (other than diffusion) occurs until the capillary entry pressure P_c has been exceeded.

This can occur if:

- **The CO_2 column height exceeds the sealing capacity of the micro-annulus – P_c=0.1 MPa gives about 30 m**
- **The reservoir is overpressured by at least P_c - for base use an overpressure of 0.7 MPa.**

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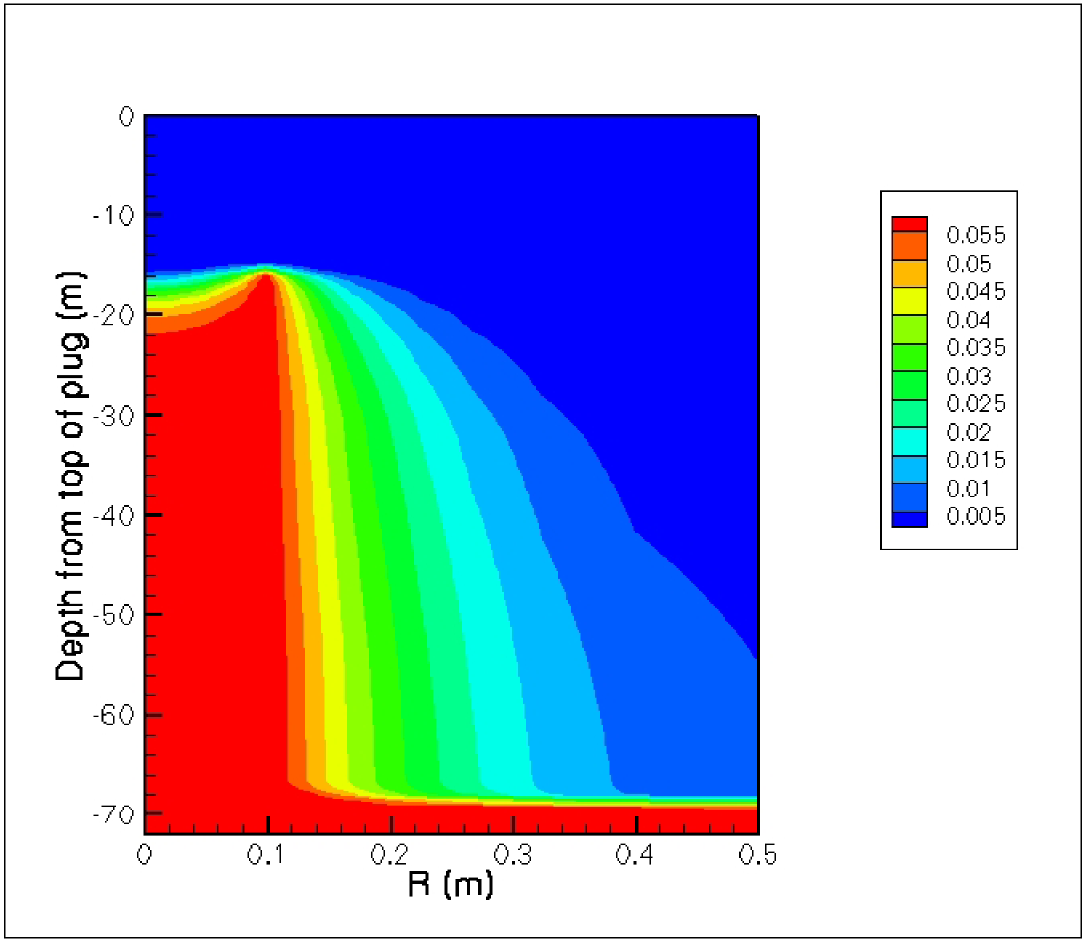
Flow but no reactions



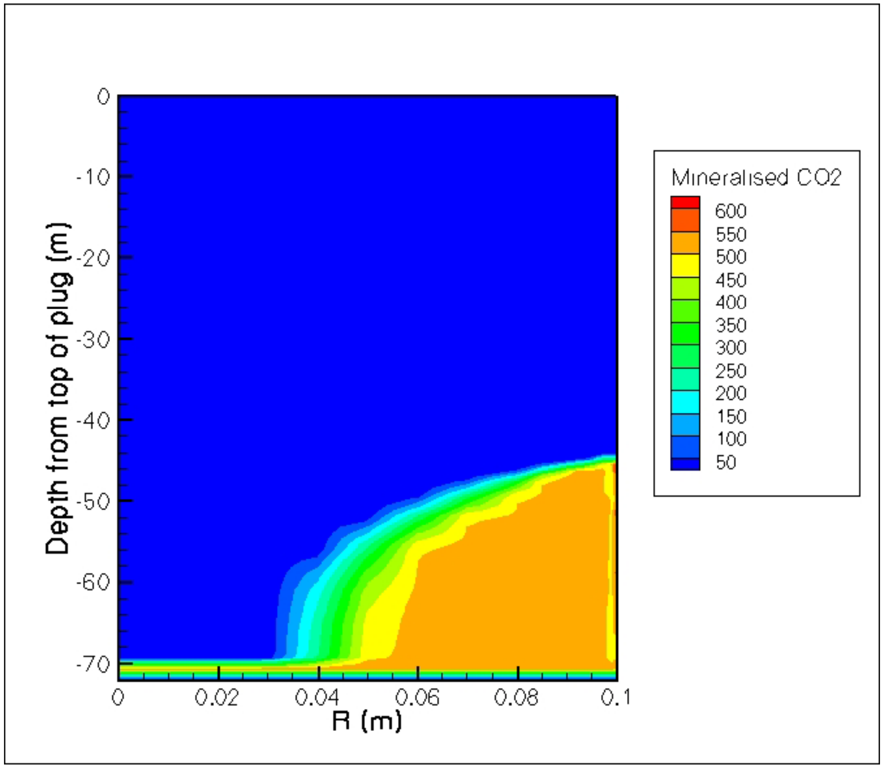
Dissolved CO_2 after 580 years

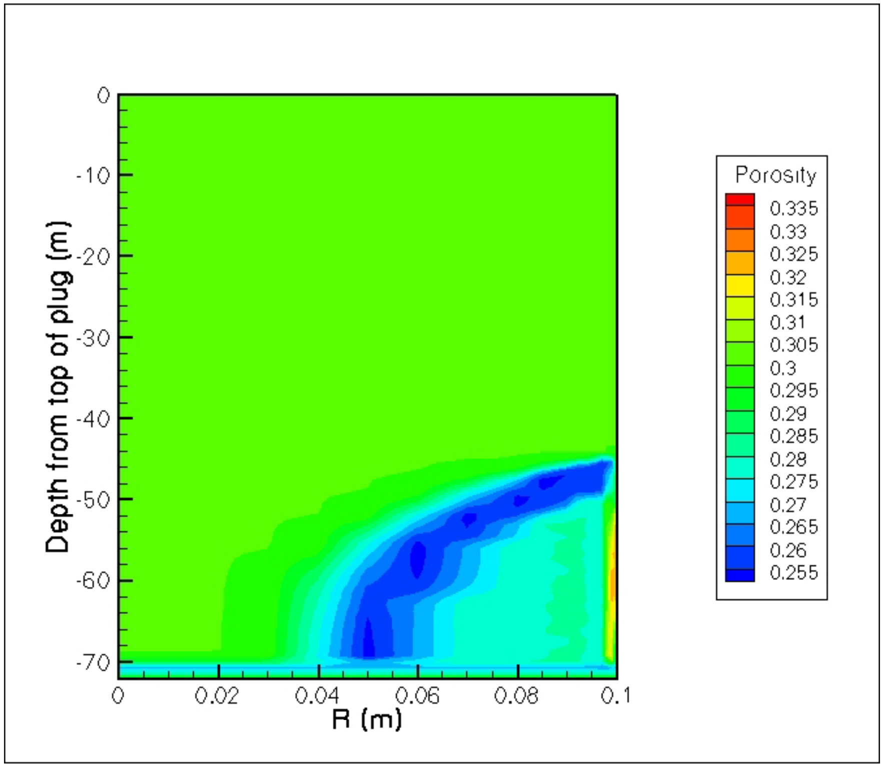
Allow diffusion into surrounding rock

Vertical migration velocity of

~ 0.07 m/year

Flow with reactions: 1000 years





Mineralised CO_2 (kg /m^3)

Porosity

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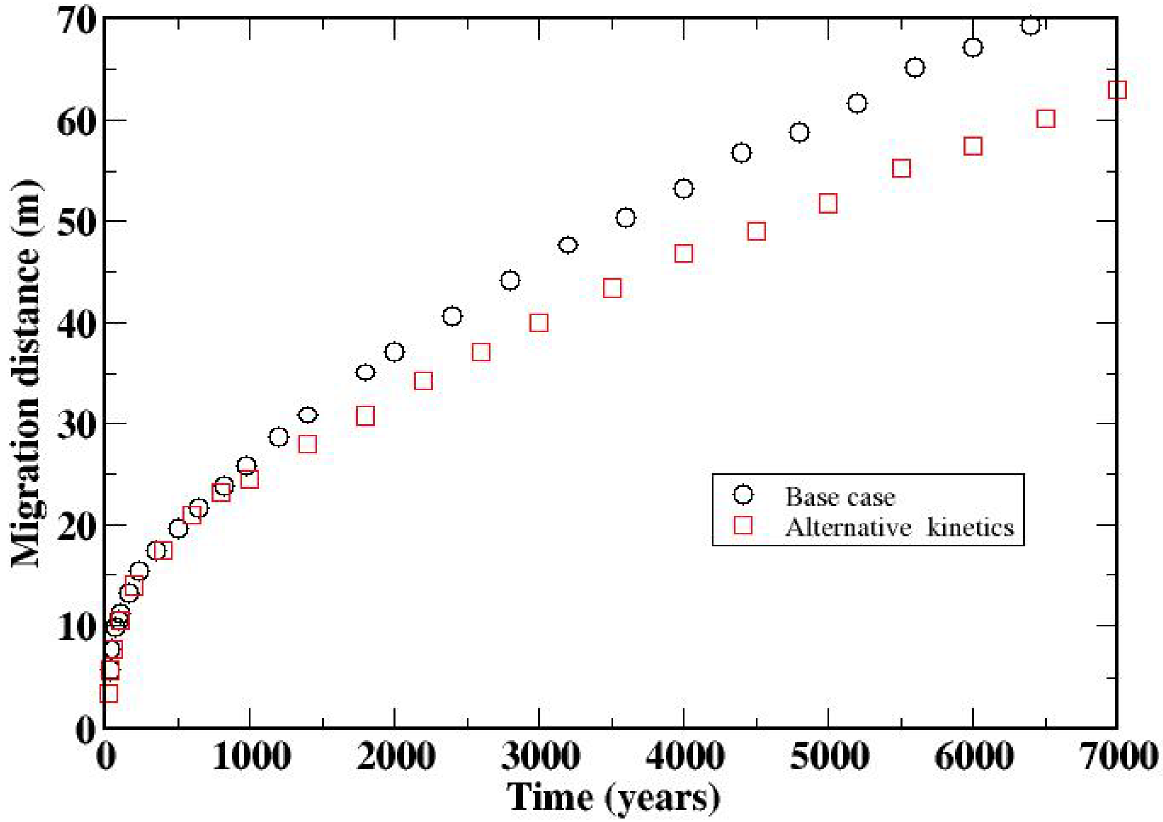
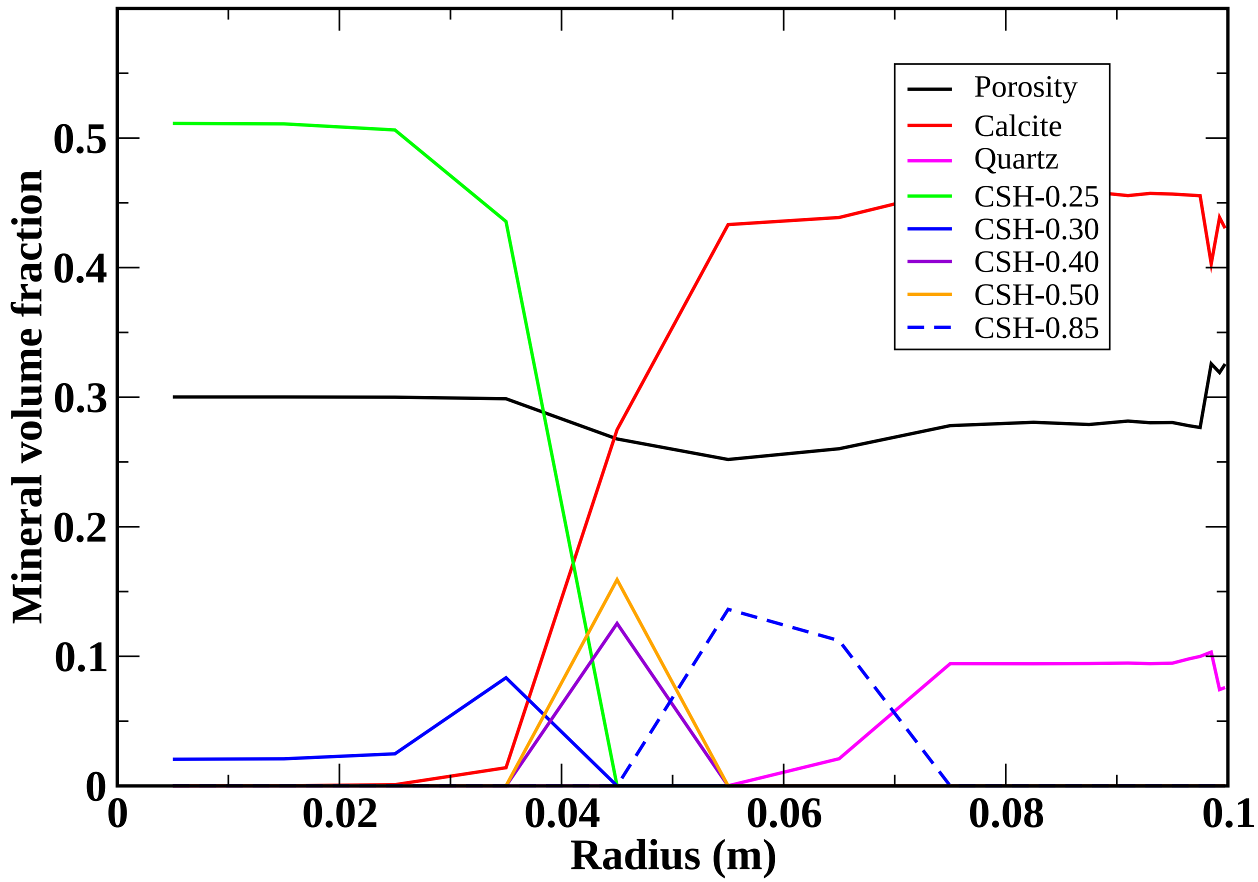
Vertical migration distance (with reactions)



Cross-section of mineral changes



10 m above reservoir, 1000 years

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Effect of reactions and diffusion

Dimensionality	Lateral diffusion	Reactions	Av. Migration velocity (m/yr)
1D	N	N	0.4
1D	N	Y	0.17
2D	Y	N	0.07
2D	Y	Y	0.01

Sensitivities for breakthrough time

Case	Breakthrough time
Base case	6400
No por-perm coupling	7100
Alternative por-perm coupling	4800
Alternative relative permeability	4800
Halved micro-annulus width	9400
Doubled micro-annulus perm	3100

Fracture-Matrix theory

The aim is to use the results of Sudicky and Frind (1982) and Tang, Frind, Sudicky (1981), based on the convection-diffusion equation with adsorption.

Assume:

- Thin fracture with complete mixing across it.
- Matrix permeability low, so transport in matrix by diffusion.
- Transport along the fracture is much faster than in the matrix

Leads to two orthogonal coupled 1D systems.

Modifications of Sudicky and Frind

- Adapt adsorption-diffusion formulation to reaction-diffusion
- Adapt planar diffusion problem to cylindrical geometry
- Adapt single-phase approach to two-phase problem (challenge of non-linearity)

Relation of adsorption formulation to reaction.

For fast reaction (local equilibrium approximation), reactions occur at at a sharp front characterised by a dimensionless parameter $r = C_0\phi_f / \rho_{\min} \sim 0.01\text{-}0.1$

For linear adsorption, s= K_m C, key parameter is

$$R = 1 + \frac{\rho_{\min}}{\phi} K_m$$

Comparing the total reacted/absorbed amount, agree for r << 1 if

$$R \approx \frac{\pi}{4r}$$

Adaptation of plane geometry to cylindrical

Comparing solutions of diffusion in the two geometries, reasonable agreement is achieved if the equilibrium amount is the same. Then the effective cement thickness *l* is given by

$$l = d - \frac{d}{2a}$$

Where *d* is actual cement thickness, and *a* is radius of wellbore. If *d*=*a* (uncased), then *l* =*a*/2

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Adaptation single phase to two phase

Sudicky & Frind have a single phase influx with constant concentration C_0. For a fracture width b, the amount of solute per length of fracture is $b\ C_0\ \theta_f$

In a two phase problem, the concentration of dissolved CO_2 saturates at a maximum level once the gas phase is present. To limit the concentration while having the same mass, use an effective fracture width

$$b_{\mathrm{eff}} = \frac{b\,\theta_f\,\rho_{\mathrm{gas}}}{\rho_{\mathrm{diss}}}$$

θ_f is the fracture porosity, and $\rho_{gas}/\ \rho_{diss} \sim 10\text{-}20$

Result

Vertical distance migrated has the form

$$v\,t \quad f(t\,;t_f\,,t_m)$$

$$v = \frac{k k_r}{\mu}\left(\frac{dP}{dz} - \rho g\right)$$

$$t_m = \frac{R l^2}{D} \qquad\qquad t_f = \frac{b_{eff}^2}{\theta_m^2 R D}$$

Note that breakthrough time is linear in *v*

Scaling of migration velocity

- For $t < t_f$, velocity v
- For $t_f < t < t_m$, velocity $v\sqrt{\dfrac{t_f}{\pi t}}$
- For $t_m < t$, velocity $v\sqrt{\dfrac{t_f}{t_m}}$

For $t \ll t_m$, $v \exp(t/t_f)\,\mathrm{Erfc}(t/t_f)$

What are the time scales?

Here v ~ 0.1 m/year (depending on k_{rg})

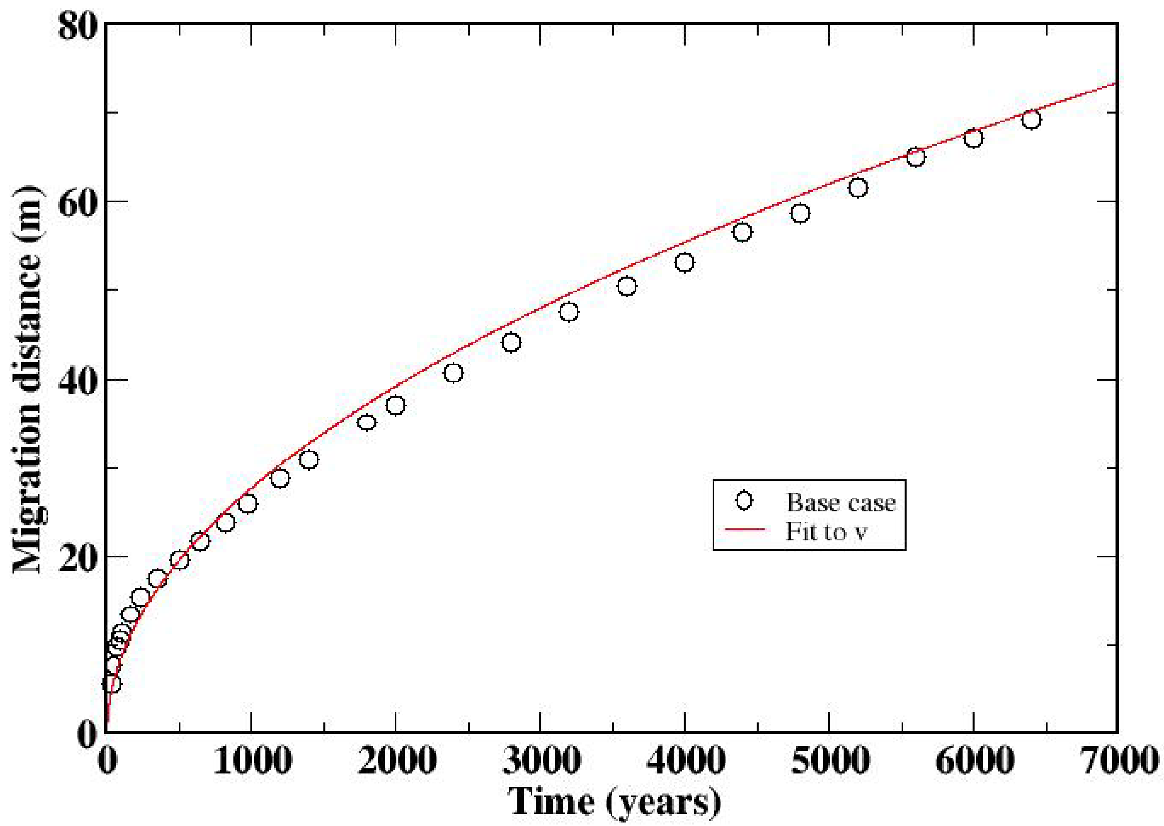
t_f ~ 0.1 year and t_m ~ 2500 years.

For typical applications, expect:

- **$t_f \ll 1$ year**
- **t_m is $10^2 - 10^4$ years.**

The geochemistry is all folded into the R parameter, and depends on ρ_{min}

Fitting fracture-matrix theory



Conclusions

- For a continuous micro-annulus leak with overpressure, breakthrough can be retarded, mainly due to consumption of CO_2 in reactions with cement.
- The key uncertainties are in the transport parameters of the cement, especially the capillary pressure threshold, micro-annulus width and permeability.
- Fracture-matrix theory predicts the scaling of the retardation, with geochemistry lumped into one parameter.

Directions

• The geochemical model needs to be explored in much more detail, and matched to new experiments.

• All the transport parameters need to be much better characterised.

• The fracture-matrix theory isn't quantitative and doesn't allow for permeability changes in the micro-annulus, nor for relative permeability effects – could this be fixed?

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CO_2 Resistant Cements & Chemical Sealants

Ron Sweatman – Halliburton

4th MEETING
of the
IEA WELL BORE INTEGRITY NETWORK

Paris, France

18th - 19th March, 2008

Few wells have sealing issues and most don't?

Who says no CO_2 leaks into Drinking Water zones?

- US EPA studied MIT results over last 25 years
  - Class I wells: no DW impacts (2% poor external MIT)
  - Class II wells: no DW impacts (11.1% poor internal MIT)
- US State Regulators & GWPC in UIC Program
  - No evidence of DW contamination from UIC wells
  - GAO audits confirm UIC practices & uncontaminated DW
- 2007 API survey of CO_2 EOR well operations in USA
  - Portland based cements in all enhanced oil recovery wells
  - No leaks into drinking water zones or to atmosphere
- CO_2 well operator testimonials claim no DW contamination

Any CO_2 leaked from EPA Class II wells?

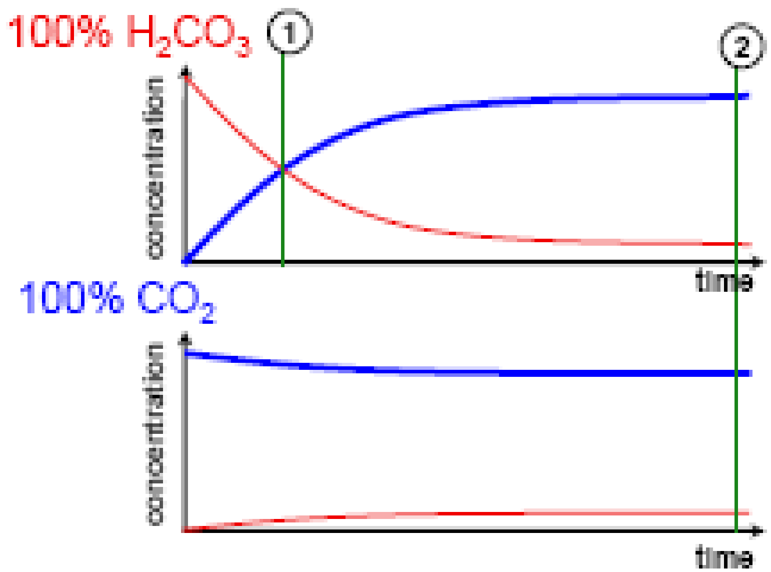
What prevents sealing issues?

- **API, SPE, and UIC well practices**
  – Well design & drilling practices
  – Cements tested & designed for the job
  – Mud removal & cement placement
  – Zone isolation evaluations (average <10% need remediation)
- **Downhole conditions minimize pipe & cement corrosion**
  – Dry CO_2 removes connate water & limits H^+ protons
  – Solvated molecular CO_2 dominates in solutions & slow kinetics = H_2CO_3
    » *"Less than 1% is truly as hydrated H_2CO_3"* (Kinetic Theory in the Earth Sciences by Antonio C. Lasaga, Princeton U. Press, p.47, 1998)
    » Most H_2CO_3 created after flowing away from near wellbore region
  – Flow rates limit erosion of carbonated seal barriers in cement
  – Portland cements resist CO_2 via low perm, autogenous healing, poz, etc
  – High salinity water & other factors reduce CO_2 solubility
  – Skin damage by mud/cement filtrates limit CO_2 contact with cements
- **Well operations prevent cement cracks & microannuli**
  – Max ΔP & ΔT on casing & liners within cement integrity limits
  – Cyclic T & P under cement fatigue limits
  – Monitoring practices control flow rates, BHP & BHT

CO_2 Solubility & Hydration Rates

The position of a chemical equilibrium is independent of the initial state

$$CO_2\ (aq.) + H_2O\ (l) \rightleftharpoons H_2CO_3\ (aq.)$$



① State 1

$[H_2CO_3]/[CO_2] = 1 \neq K_{eq}[H_2O]$

② State 2 (equilibrium)

$[H_2CO_3]/[CO_2] = K_{eq}[H_2O]$

When the ratio of concentrations of products to reactants stop changing, you have reached equilibrium

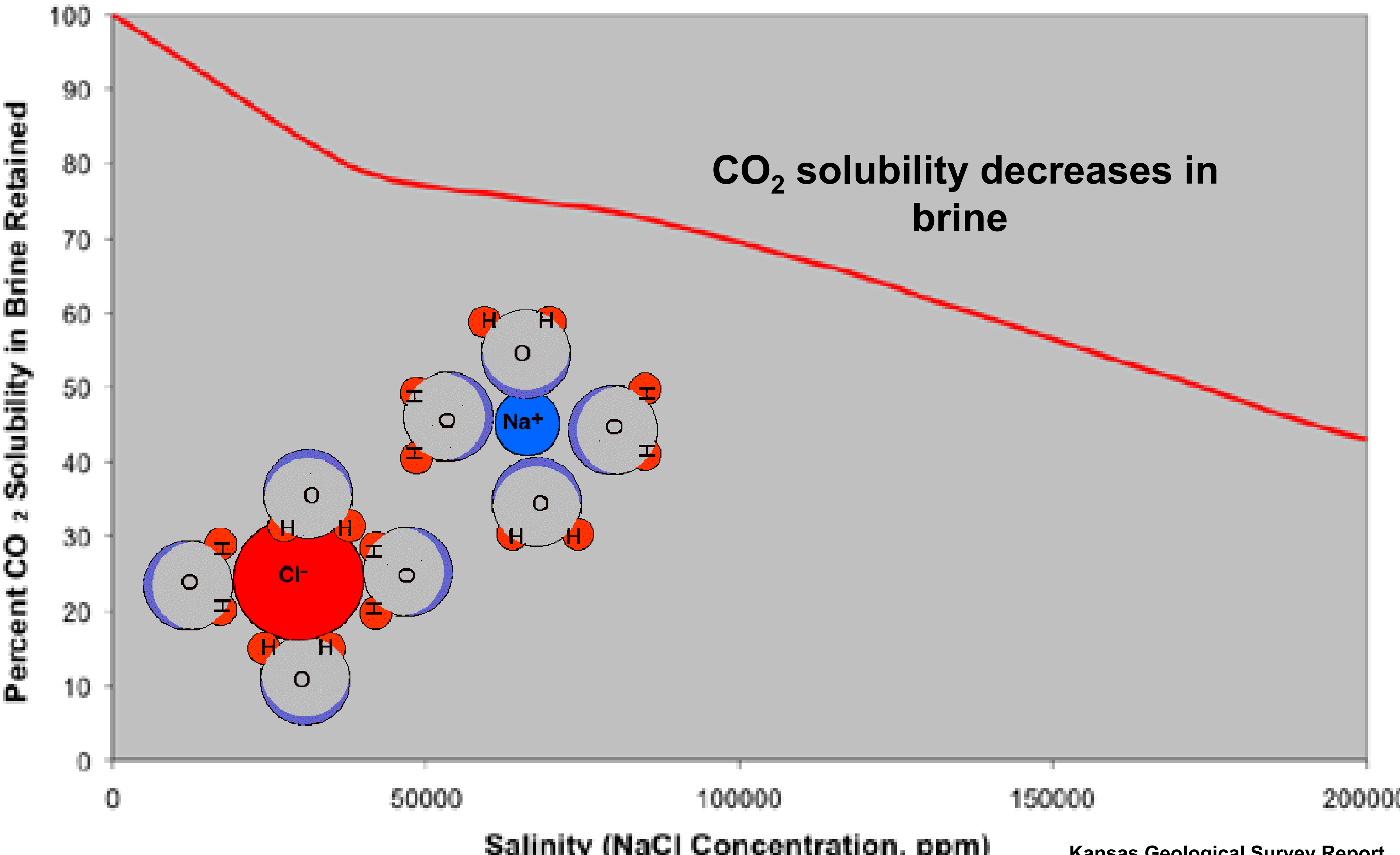
Typical Brines Chemical Analysis

Gas storage project SPE 7010

RADICAL(ppm)	API BRINE	COCKFIELD BRINE
SODIUM	31,760	42,383
CALCIUM	9,090	440
MAGNESIUM	0	91
IRON	0	0
CHLORIDE	64,150	64,892
SULFATE	0	943
BICARBONATE	TRACE	1,886
CARBONATE	0	0
HYDROXIDE	0	0
S.G.	1.077	1.082
pH	6.8	7.5

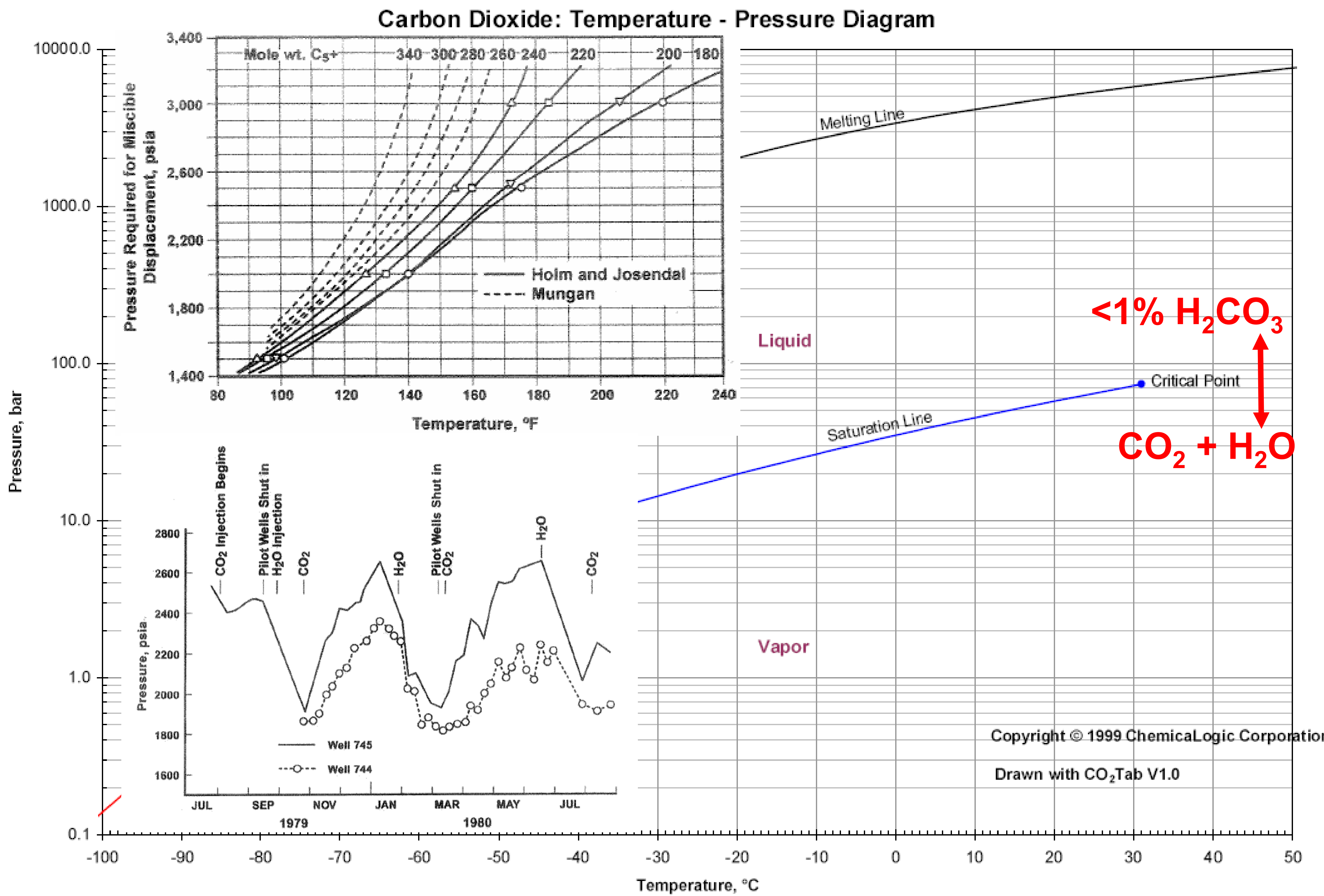
Cement exposure to CO_2 can be substantially reduced!
Both brines block near wellbore formation permeability upon contact with drilling fluid or cement filtrates!

High salinity water reduces CO_2 solubility

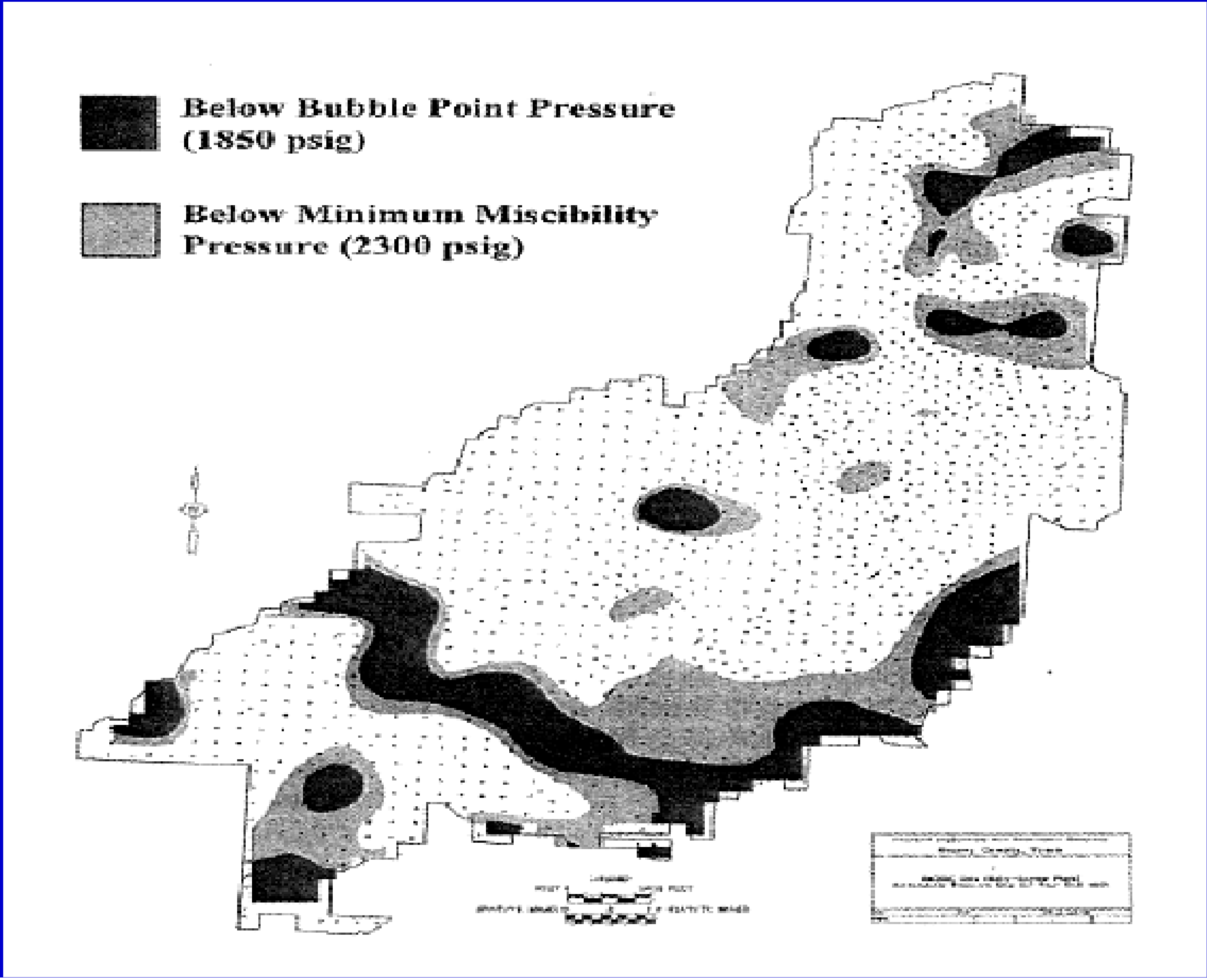


Kansas Geological Survey Report

No CO_2 Solubility & H_2CO_3 in Gas Phase



SACROC CO_2 Pressure Contour Map



Concerns on conventional methods and materials?

- **Portland cement can degrade or seal?**

  $CO_2 + H_2O \rightarrow H_2CO_3$ (Carbonic acid) $\rightarrow H^+ + HCO_3^-$

  H_2CO_3 + C-S-H* $\rightarrow$ amorphous silica gel + $CaCO_3\downarrow$

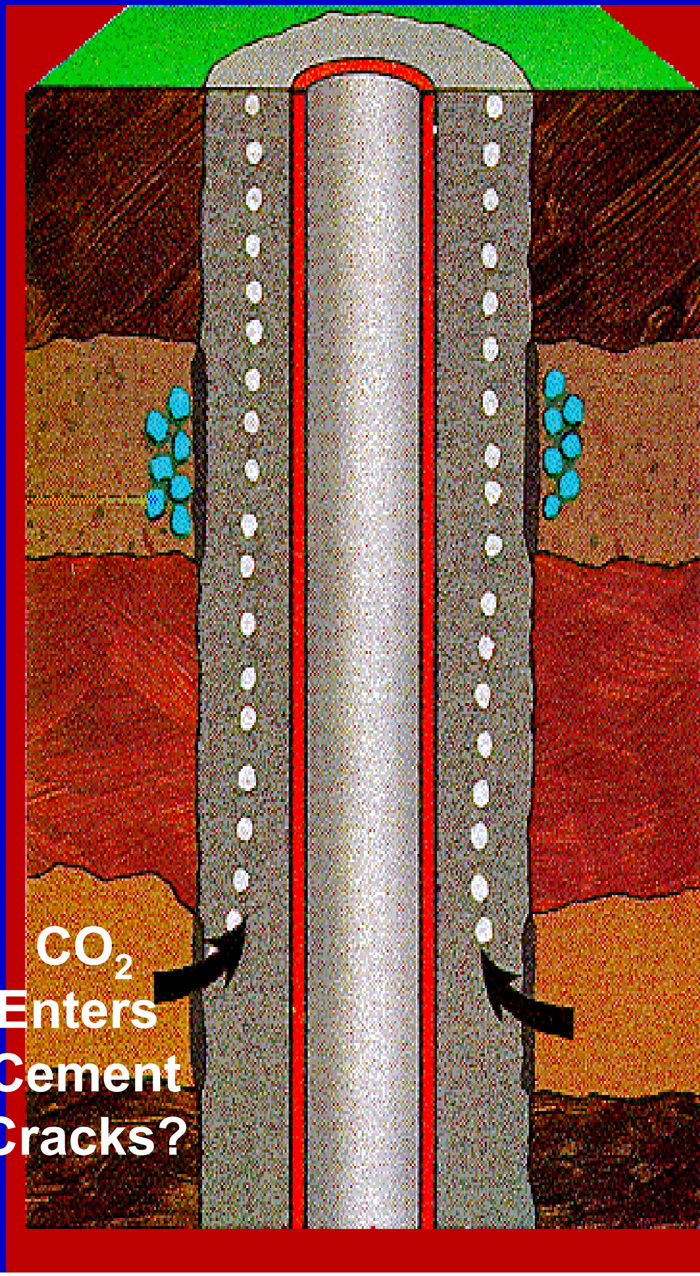
  $H_2CO_3 + Ca(OH)_2$** $\rightarrow CaCO_3\downarrow + 2\ H_2O$

  (autogenous healing mechanism)

  * C-S-H (calcium-silica-hydrate) compounds in Portland cement

  ** Hydrated free lime. CaO is minor component in Portland cement

- **Cement placement is challenging**
- **Many wells have gas migration**
- **No well history of 1000 year sealing**



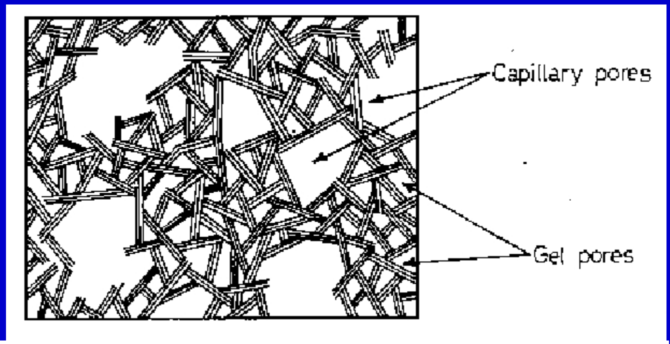
What is autogenous healing in cement?

Chemical self-sealing by CO_2 in water

- Discovered in 1836 by French Academy of Science
- Same found decades ago in oil & gas industry
  - Pumping acid to increase O&G production
  - Cement lined pipe for wet CO_2 in wells & flow lines
- CO_2 carbonates Portland cement via free CaO & UCN to create mechanical bridging & gel sealing

H_2CO_3 + C-S-H* ➔ amorphous silica gel + $CaCO_3\downarrow$
$H_2CO_3 + Ca(OH)_2$** ➔ $CaCO_3\downarrow + 2\,H_2O$
* C-S-H (calcium-silica-hydrate) compounds
** Free lime hydrated (CH)

- Solid reaction products plug pore throats, fill small cracks & some types gain strength



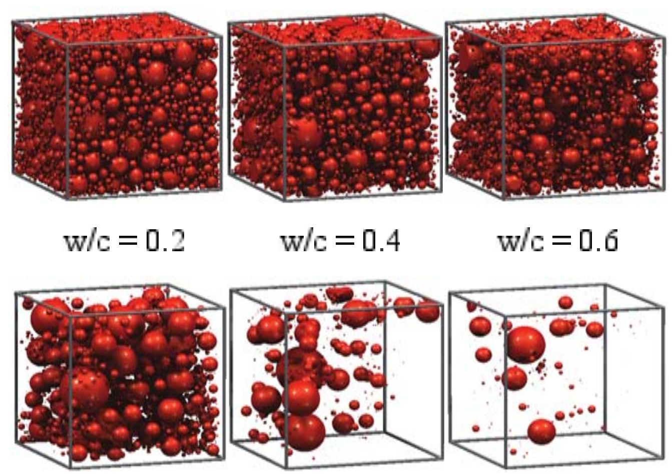
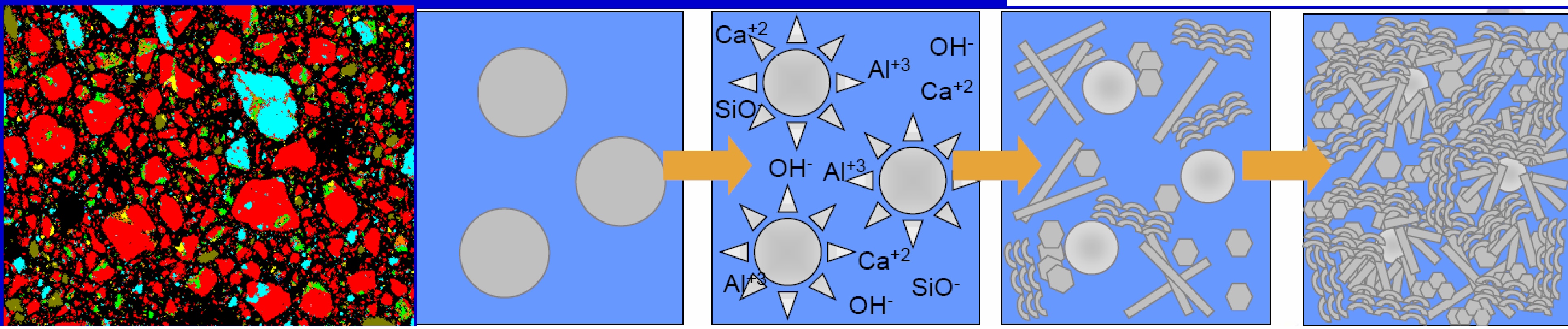


Fig. 2. *Cement pastes (top) and UCN (bottom) of C206 after 1 year of hydration.*



How does the pozzolanic effect seal cement?

$$1.1\ CH + S + 2.8\ H \rightarrow C_{1.1}SH_{3.9}$$

$$C_{1.7}SH_{4.0} + 0.5\ H \rightarrow C_{1.1}SH_{3.9} + 0.6\ CH$$

Solid reaction products ($C_{1.1}SH_{3.9}$) plug pore throats, fill small cracks & increase strength

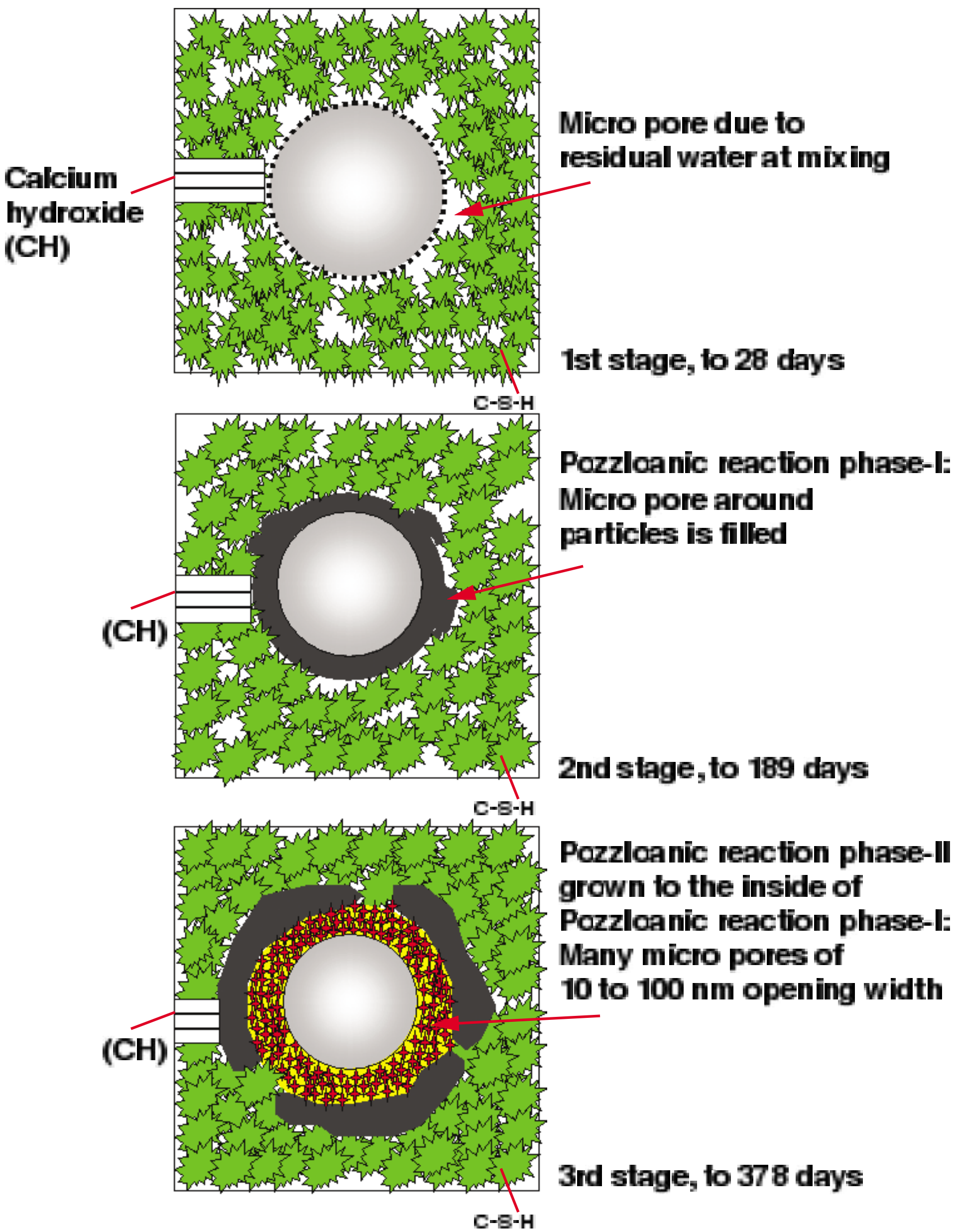
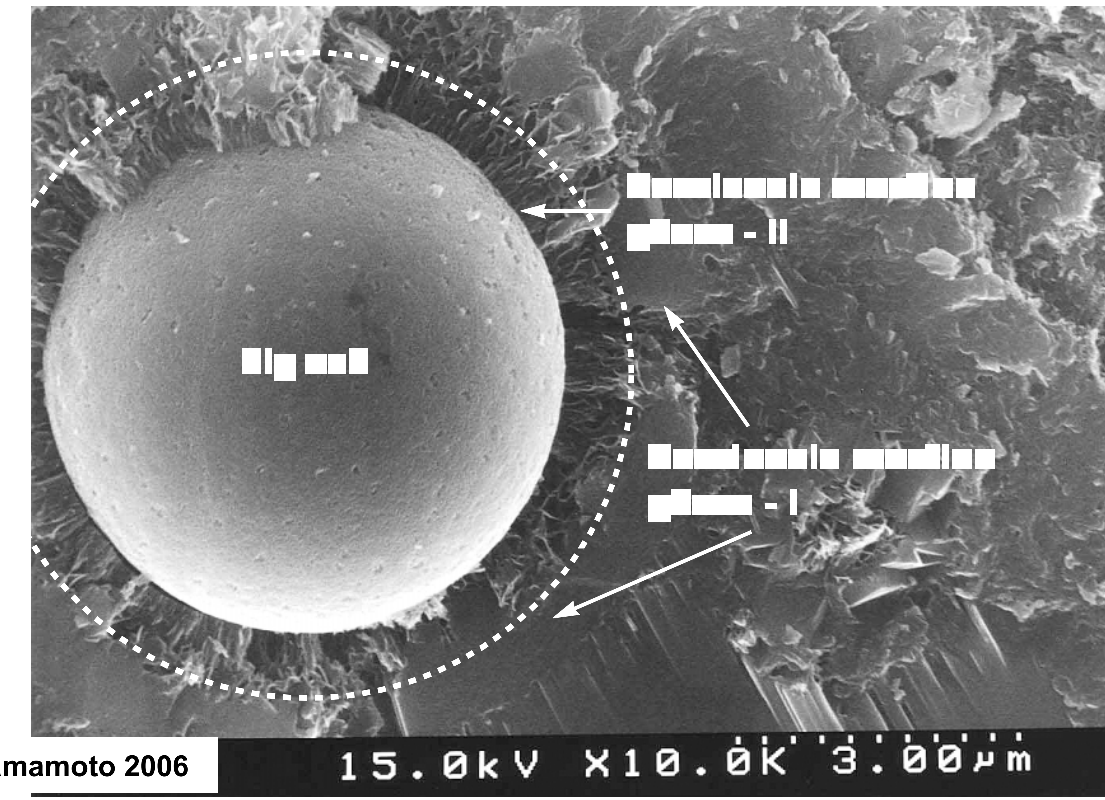


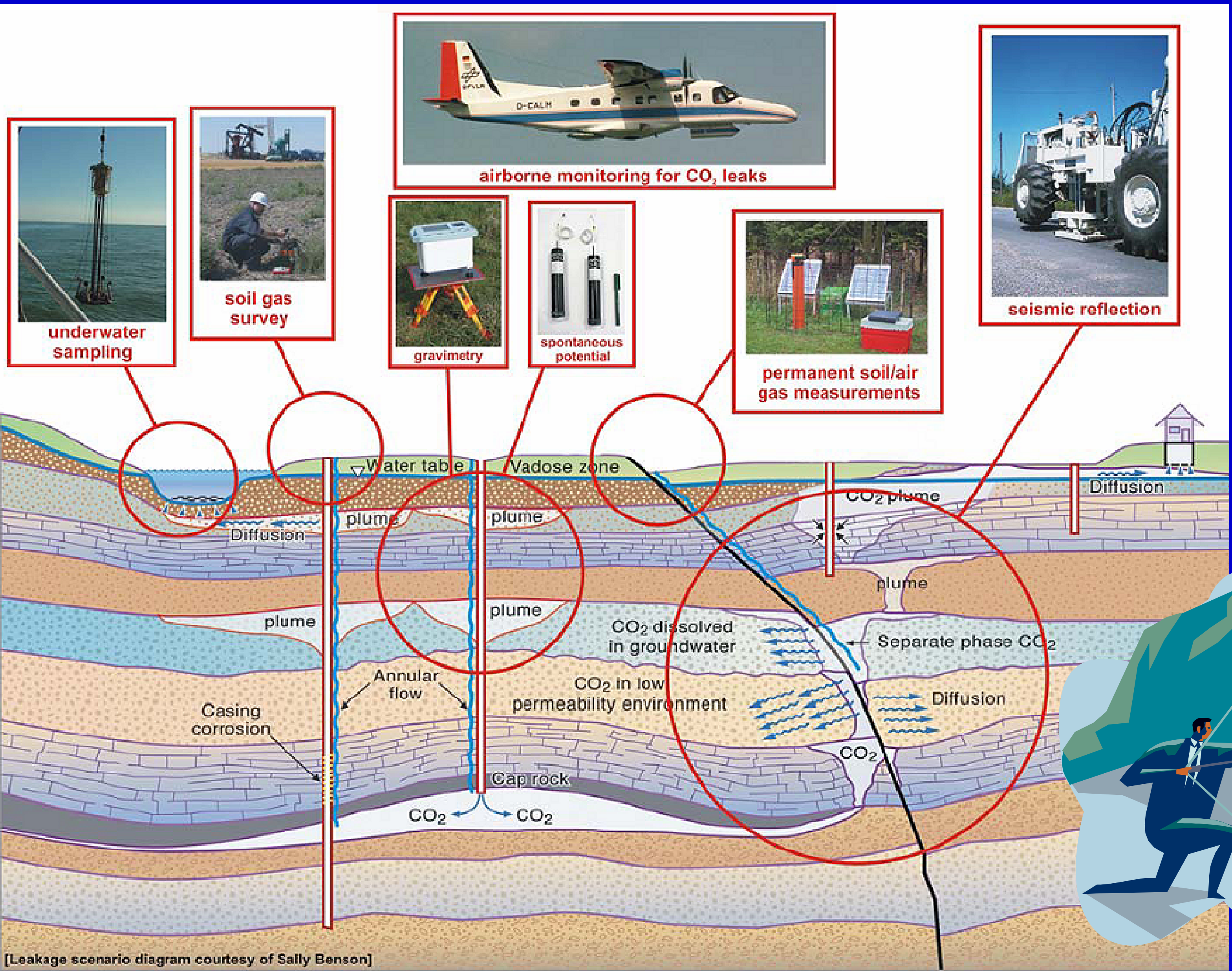
Figure. Strength development mechanism



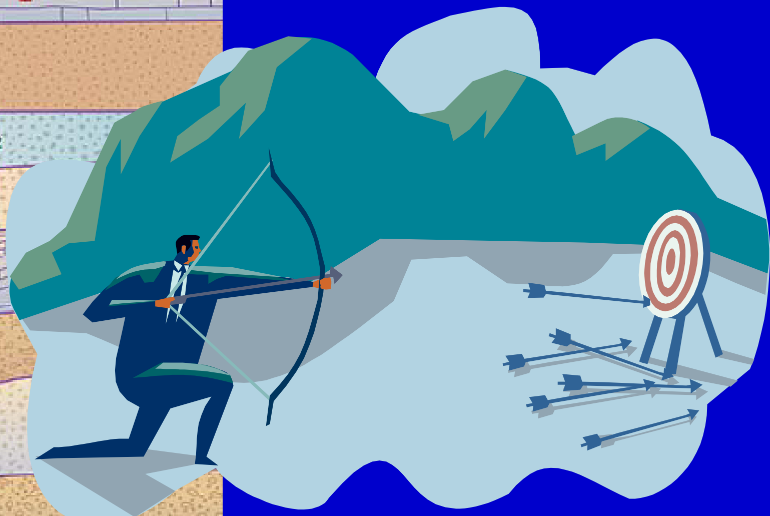
Yamamoto 2006

How can leaks be detected and remediated?

MMV methods being studied in various projects



Results so far



Will wells eventually leak?

- **Yes if conditions and practices are poor……however**
  - **>95% of leaks should be very small**
  - **e.g., Rangely CO_2 leakage <0.01% in 15 years** (IEA Report)
  - **Wells are designed to contain annular leaks** (API RP 65 & 90, etc)
  - **Contained leaks can be captured and returned to storage**
  - **Most leaks can be detected and sealed via remedial treatments**

- **Not likely with good conditions and practices**
  - **Annular sealants matched to chemical & physical conditions**
  - **Wells designed & drilled for good cementing results** (API RP 65)
  - **Leaks detected & sealed before getting too far** (SPE CO_2 Monograph)
  - **Periodically check operating pressure barriers** (API RP 90, SPE, EPA, etc)

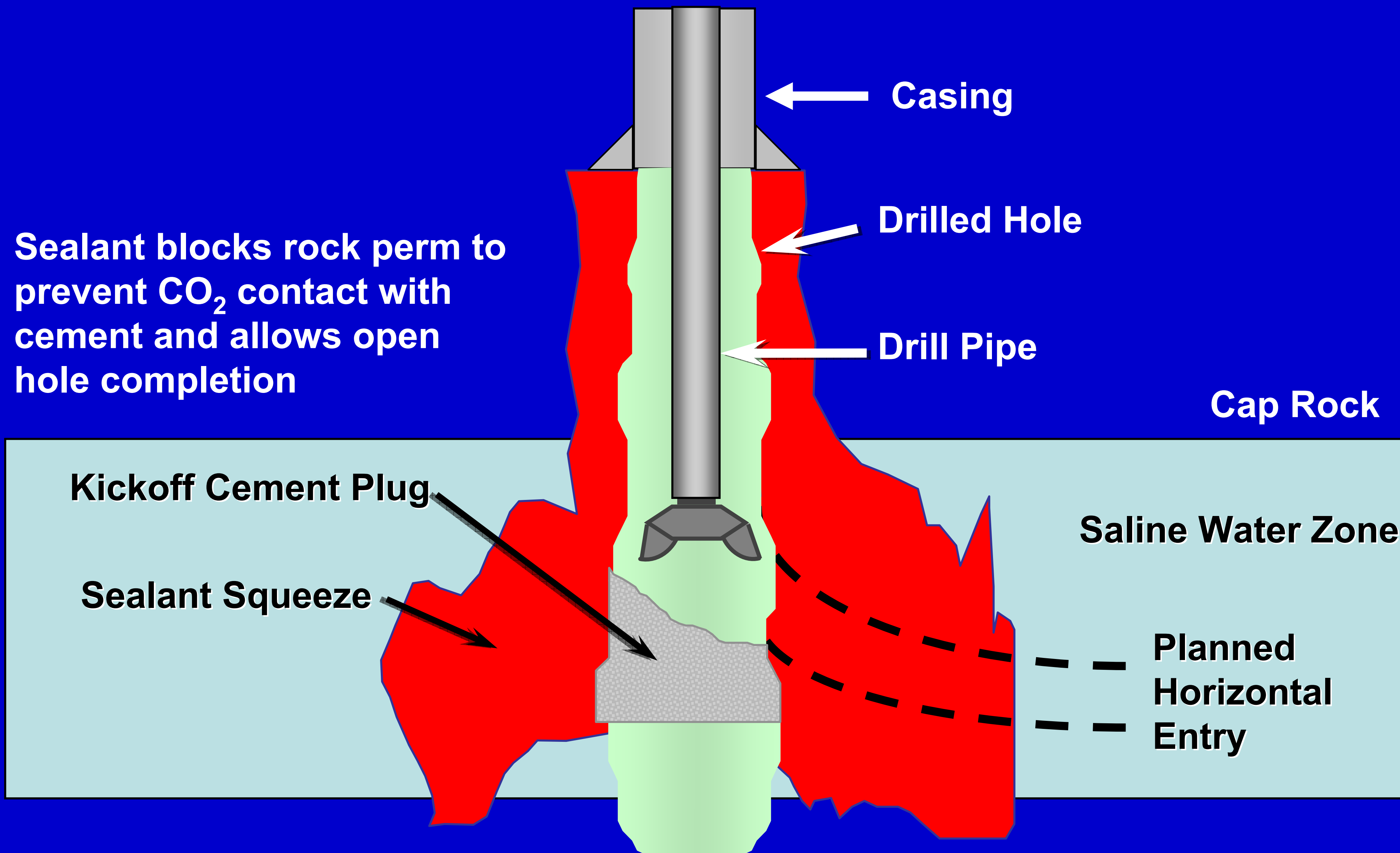
Alternative Sealing Methods

- **Perm blocking sealant applied before cementing pipe or for barefoot completion** (SPE 53312)
- **Perm sealing drilling fluids** (CaO, PHPA etc) **& cement spacers** (silicates etc)
- **Swell packers & seal rings**
- **CO_2 resistant tubulars & elastomers**
  - Better sealing packer elements (BNL-41162)
  - New pipe corrosion lab tests (API/ISO doc's)
  - Fiberglass liners (SPE book, etc)
  - New expandable casing alloy rated for CO_2

In-situ Polymerizing Monomer Squeeze

SPE 36482

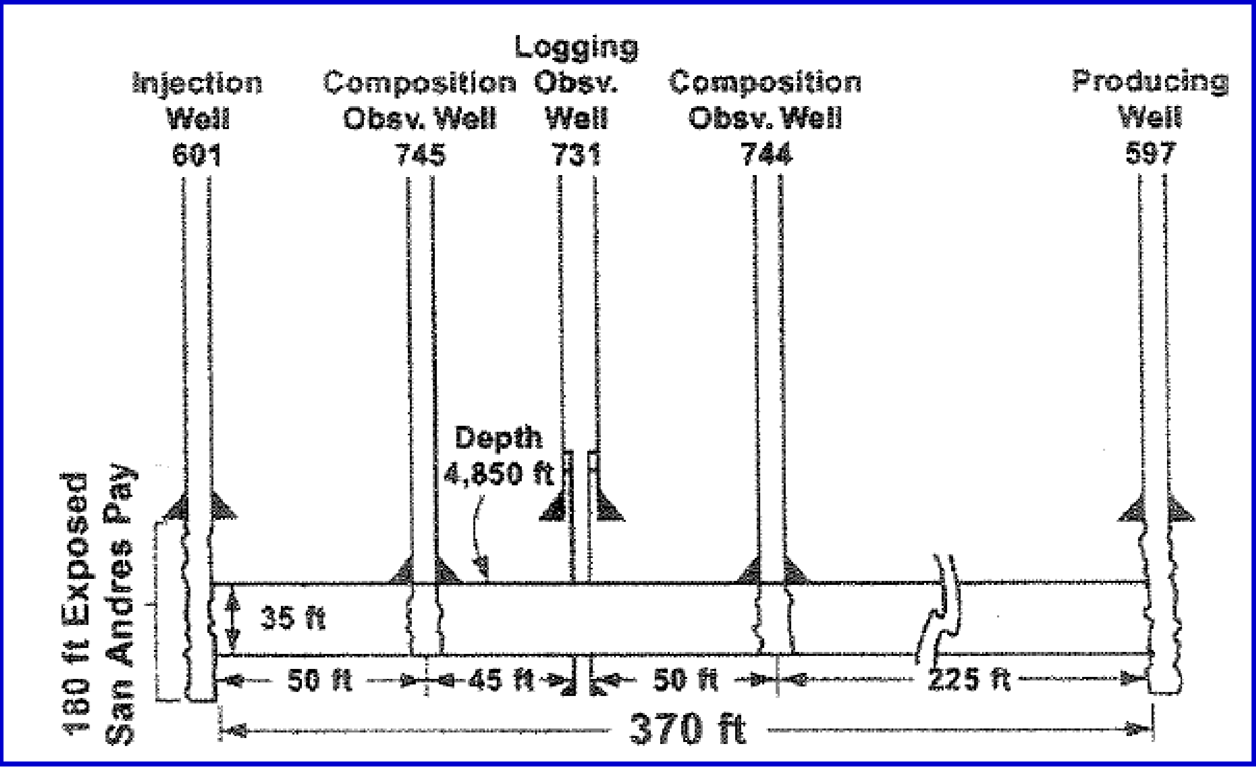
Sealant blocks rock perm to prevent CO_2 contact with cement and allows open hole completion

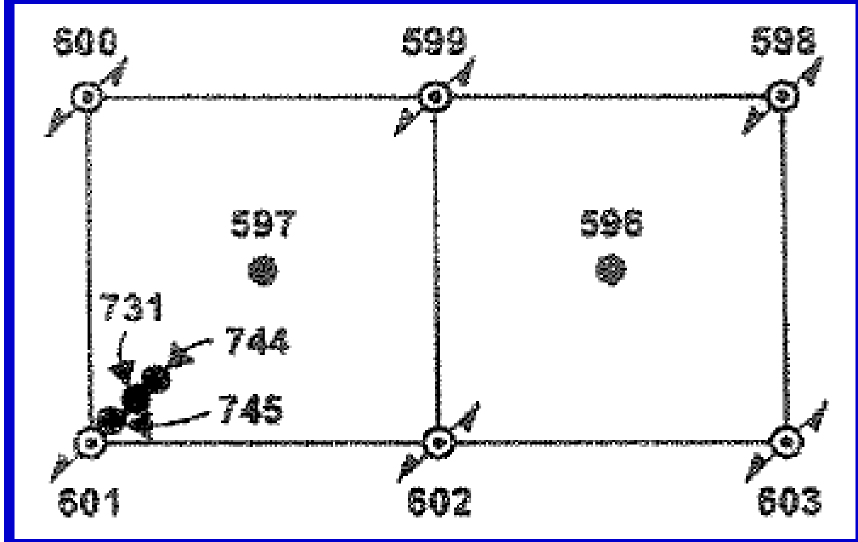


How are CO_2 EOR Wells Monitored?

Field Proven MMV Methods Developed Over 40 Years

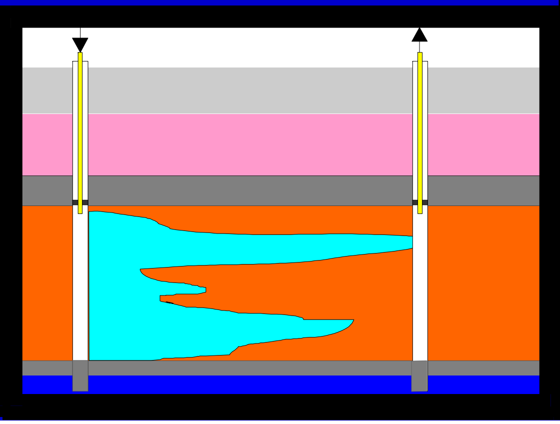
- **API study report on CO_2 EOR well technology**
- **Monitoring practices** (SPE Monograph & papers, API RP 90, etc)
  - Material balance method in patterns of production wells around injection wells
  - Detects early breakthroughs, thief zone losses, poor sweep profiles, etc
  - Pressure, temperature, and in/out flow rate measurements & data analysis
  - Out of limit data signals a closer look to confirm, analyze, run e-line logs, etc
  - Injection profiles & material balance modeling determines need for remediation

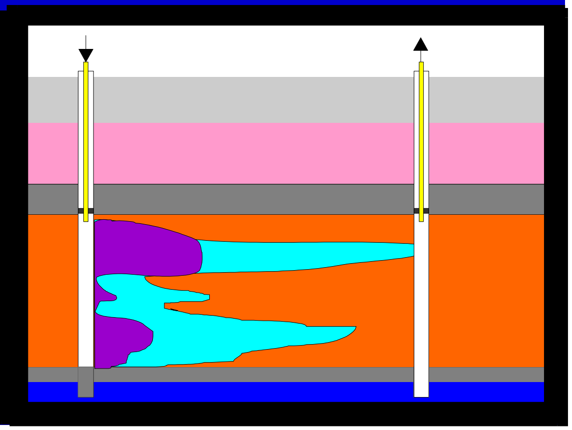


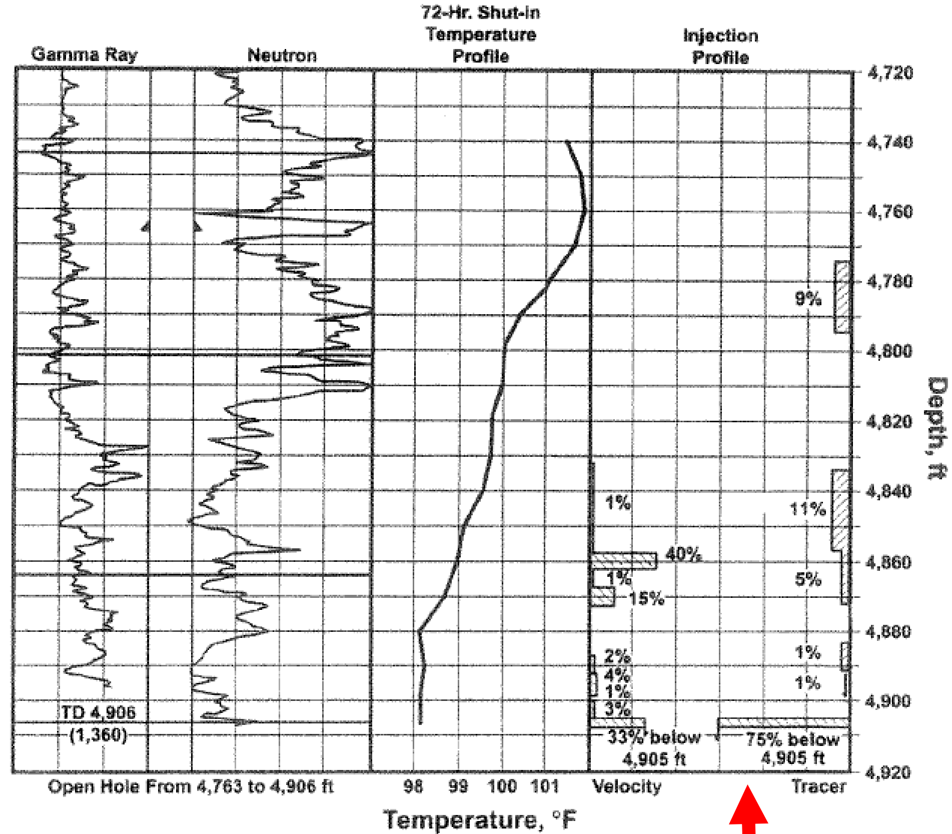


How to Control Profiles?

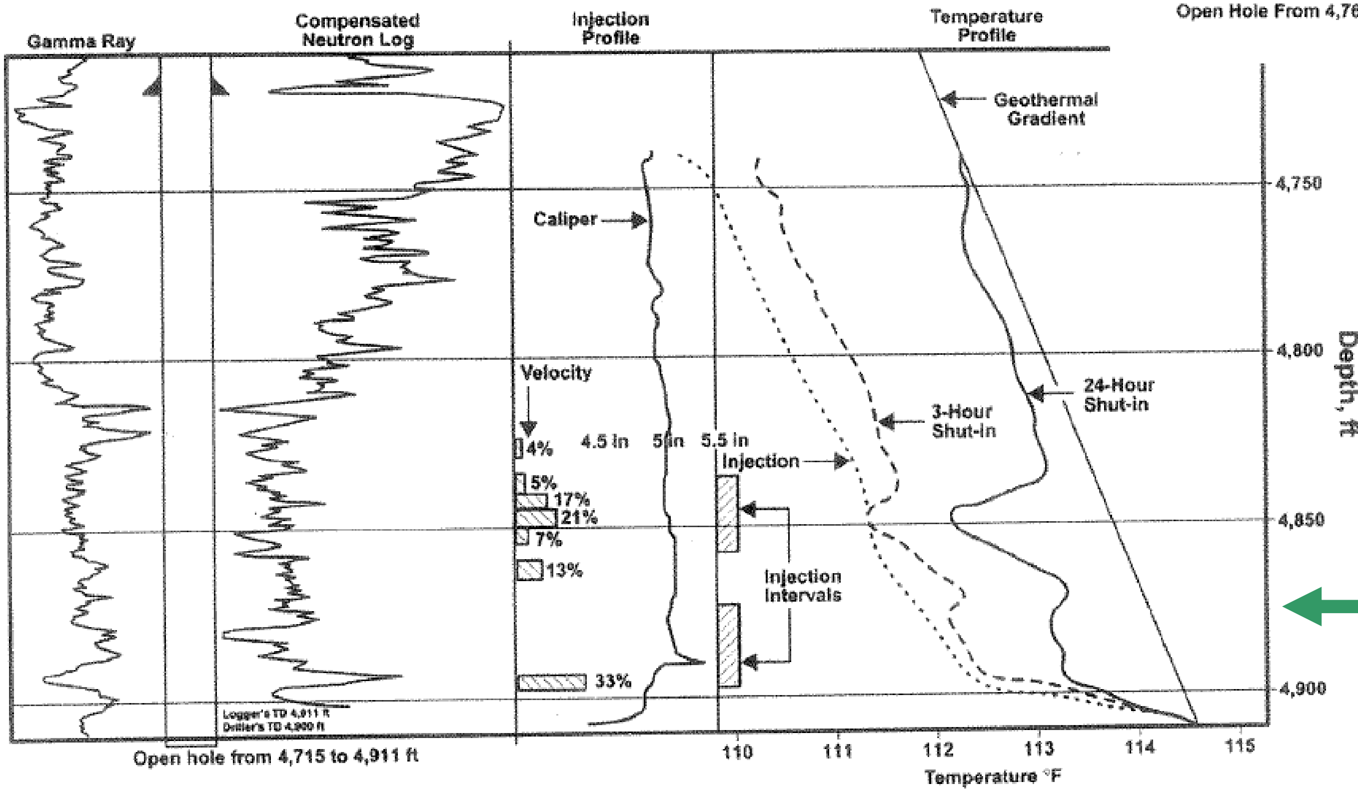
- Adjust flow rates & pressures
- Inject diverting fluids
- Squeeze jobs with sealants







Poor Conformance

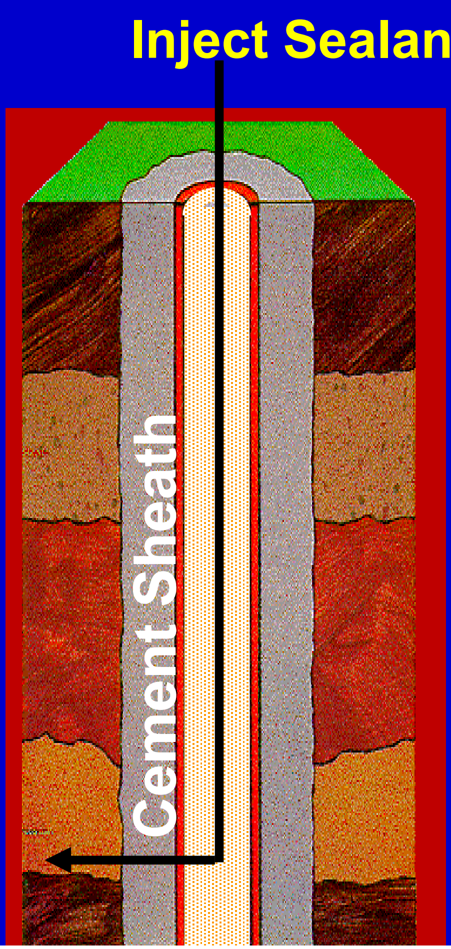


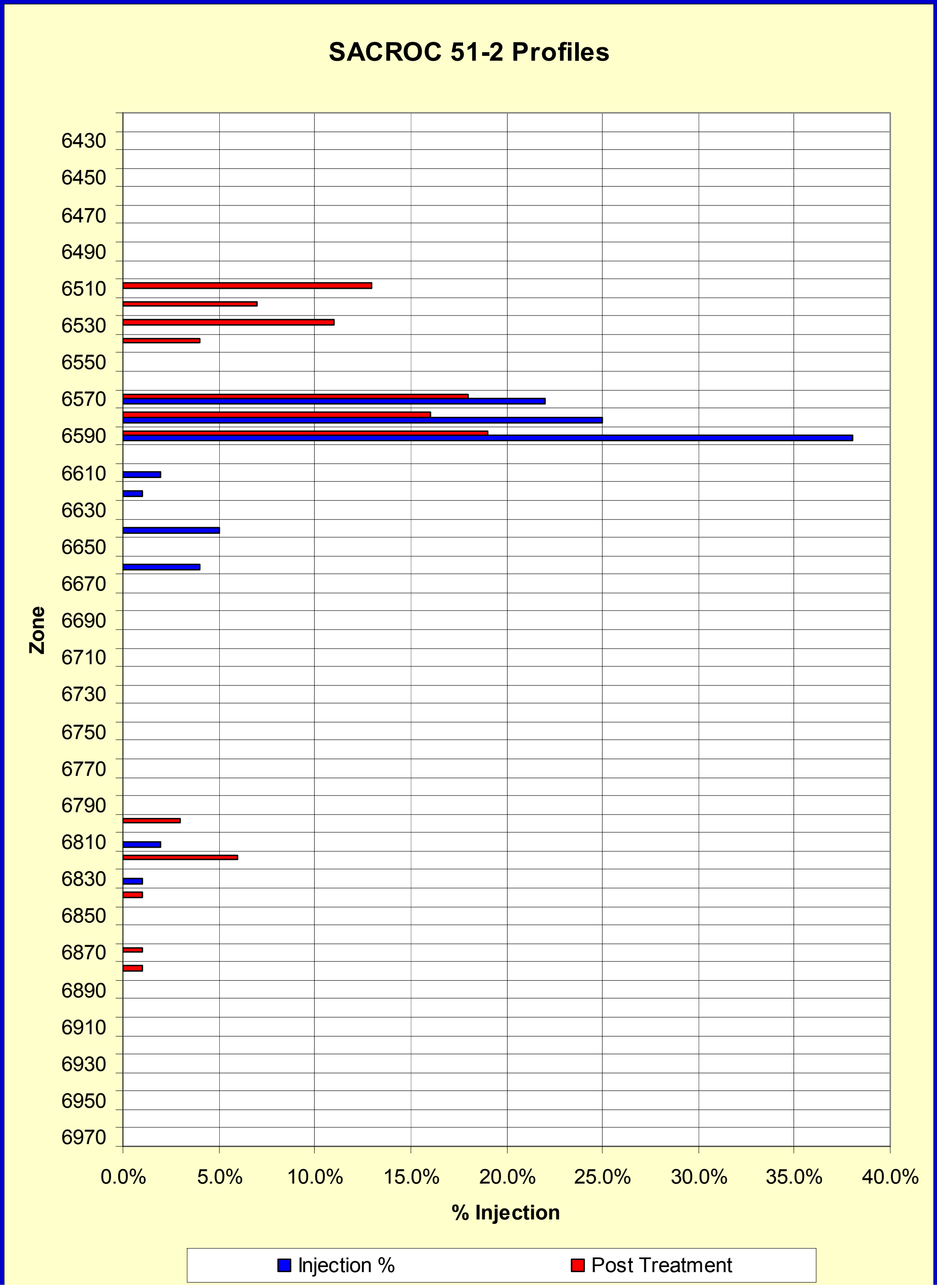
Good Conformance

What are Remedial Squeezes?

Pump CO_2 sealants to:

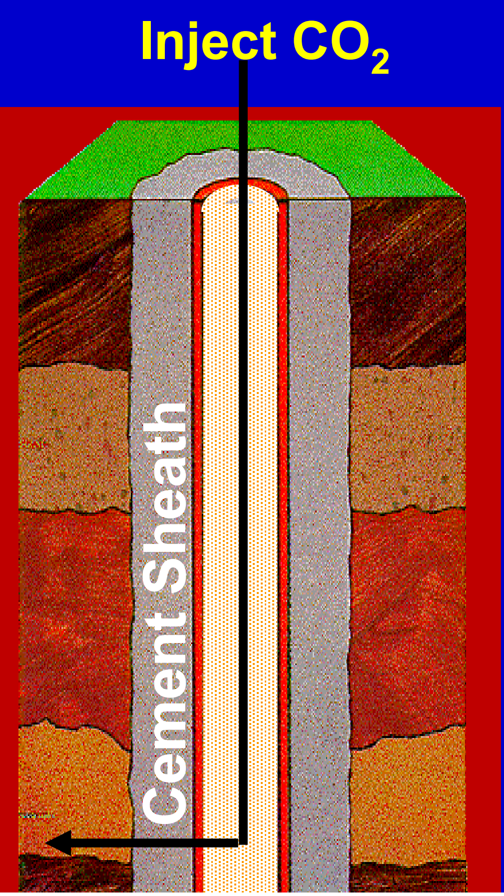
- Seal leaks in cemented annulus
- Penetrate/seal rock leak paths
  - Rock permeability
  - Fractures, fissures, etc
- Control injection profiles





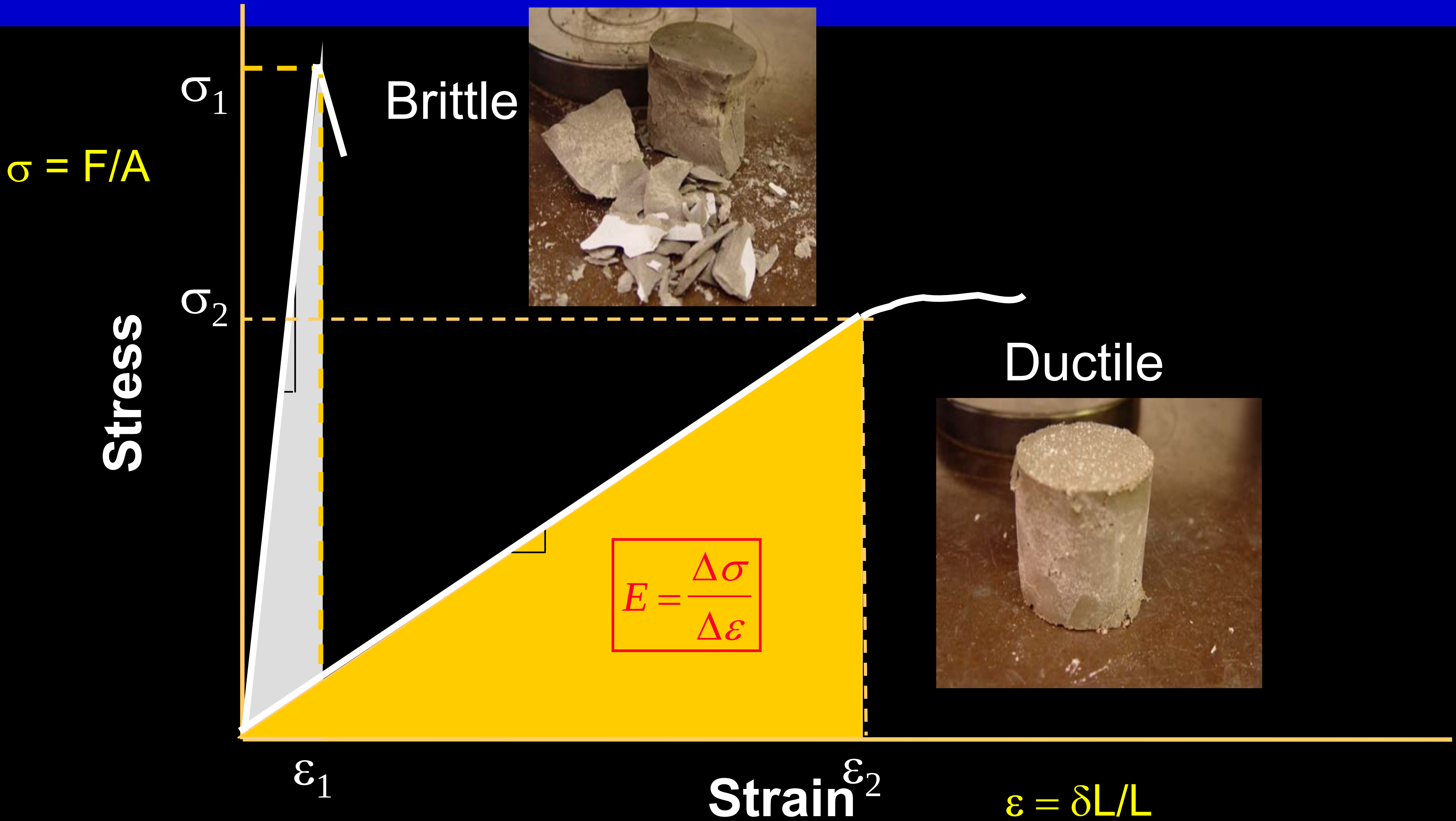
What are sustainable primary CO_2 sealants?

- **Portland cements & additives** (SPE Monograph, API survey report, etc)
- **Non-Portland cements** (API report, SPE 91861, 18618, etc)
- **Light versions: Portland & poz blends** (SPE 112703)**, foam cement** (Statoil Snøhvit) **and others** (API report)
- **Catalyzed epoxy or other resins with inert fillers**
- **Rubber cements with inert fillers** (CADE97-136)

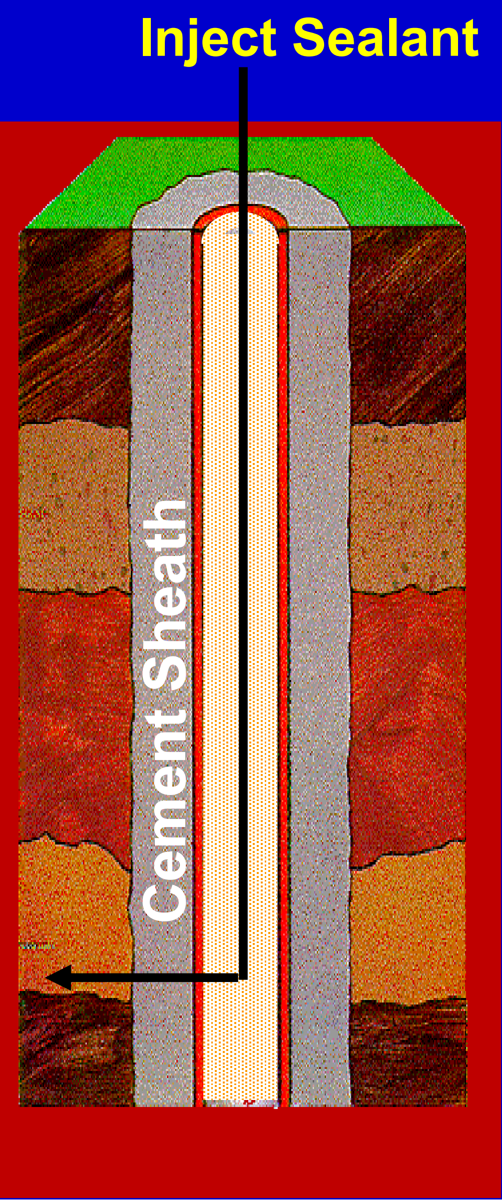


Cement Type	Longevity: sealing years so far vs well life designed for physical & chemical stresses	Young's Modulus (10^3 psi)
Portland systems: neat, poz, foam, etc	36 vs 50-100 well life (>99% CO_2 EOR wells)	100 to 1700
Calcium Phosphate cements: neat, foam	8 vs 50-100 well life (acid gas, geothermal, severe CO_2 etc)	35 to 1200
Rubber cement systems	15 vs 50-100 well life (acid gas & severe CO_2)	.7 to 25
Epoxy cement systems	+20 vs 10,000 seal life (EPA Class I wells)	50 to 600

Annular Sealant Strength and Deformation



What are sustainable secondary CO_2 sealants?



- **Primary sealants formulated for secondary jobs**
  - **Profile Control Treatments** (SPE Monograph, etc)
  - **Squeeze annular & out-of-zone flows** (SPE103044)
  - **Plug-backs**
- **In-situ cross-linked polymers**
- **In-situ polymerized monomers** (SPE 70068, etc)
- **Latex-resin systems externally activated**
- **Internally or externally catalyzed silicates**
- **Thermally activated low melting point metals?**
- **Crystallized copolymer** (SPE 101701, etc)
- **Rubber cement squeezes** (SPE 26572)

Longevity:....all sealant types maintain sealing except few cases with Portland cement

Lab testing cement's CO_2 resistance?

Match actual H^+ conditions on cement!!!

- CO_2 path of least flow resistance: cement vs rock
  - Further decreases ultra-slow diffusion rates
- Skin damage limits CO_2 contact
  - Connate water compositions & induced precipitates
  - Limited cement surface area exposed
  - Rock & cement pore plugging
- Carbonated cement pore collapse
- Molecular vs. hydrated/ionized CO_2 (H_2CO_3)
  - H^+ proton count vs. time & location
  - H^+ removal by conversion back to molecular CO_2
  - Formation dehydration radius around wellbore
- No erosion/removal of carbonated layers
- Temperatures & confining pressures
- ΔP & ΔT induced by injection, etc

Next Steps?

- Get WI Network on the Same Page
- Then get others
  - Inform legal and regulatory people
  - Publish in variety of media
  - New API/ISO standards
  - Document success stories
  - Address issues with the facts

Thank You

What do you think?

Wellbore Leakage Potential in CO_2 Storage or EOR

Fourth Wellbore Integrity Network Meeting
Paris, France
March 19, 2008

Theresa Watson
T.L. Watson & Associates Inc.
theresa.watson@tlwatson.com

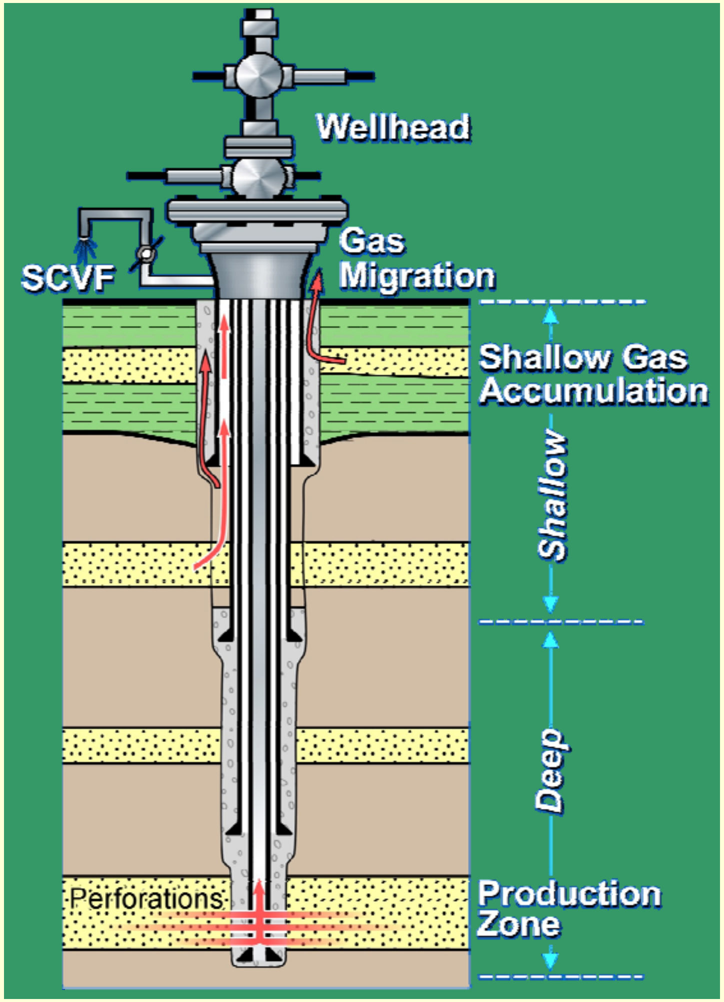
Dr. Stefan Bachu
Energy Resources Conservation Board
Stefan.Bachu@gov.ab.ca

Introduction

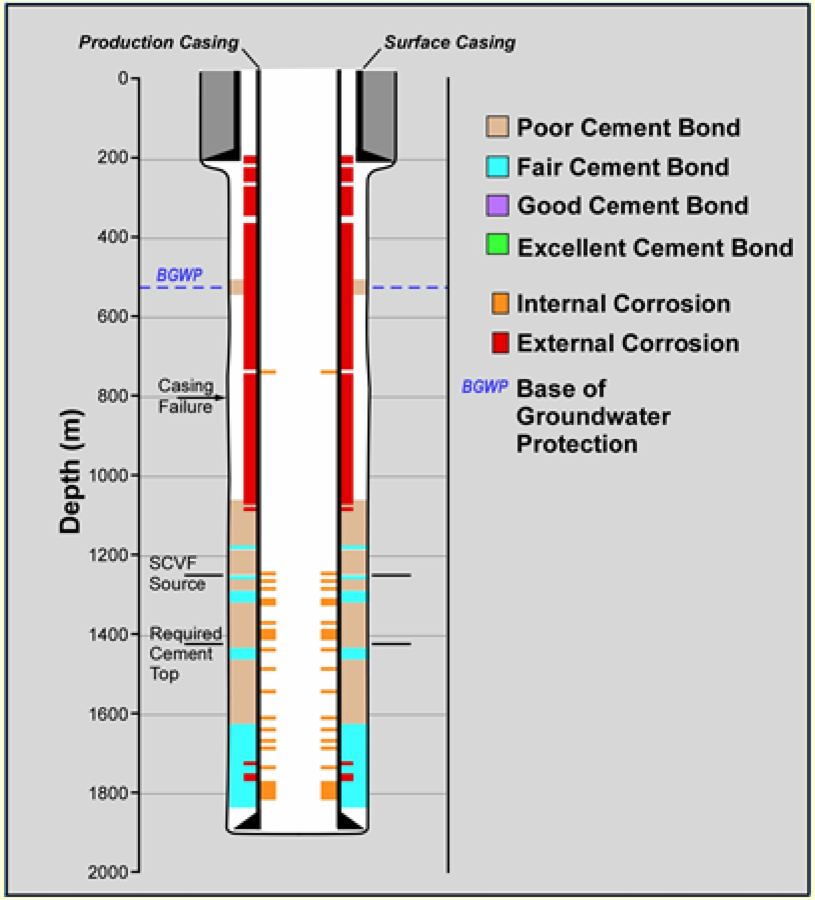
- Wellbore Leakage
- Shallow Leakage
- Tool Development
- Deep Leakage
- Case Studies
- Risk Analysis

Wellbore Leakage

- Wellbore leakage is separated into two distinct areas of the wellbore
- Shallow leakage generally due to poor cementing practices
- Deep leakage generally due to stimulation or perforating
- Only deep leakage is generally associated with CO_2
- CO_2 leakage in the shallow areas are due to secondary events



Example of Cement and Casing Quality in a Well in the Haynes Field, Alberta



Shallow Leakage

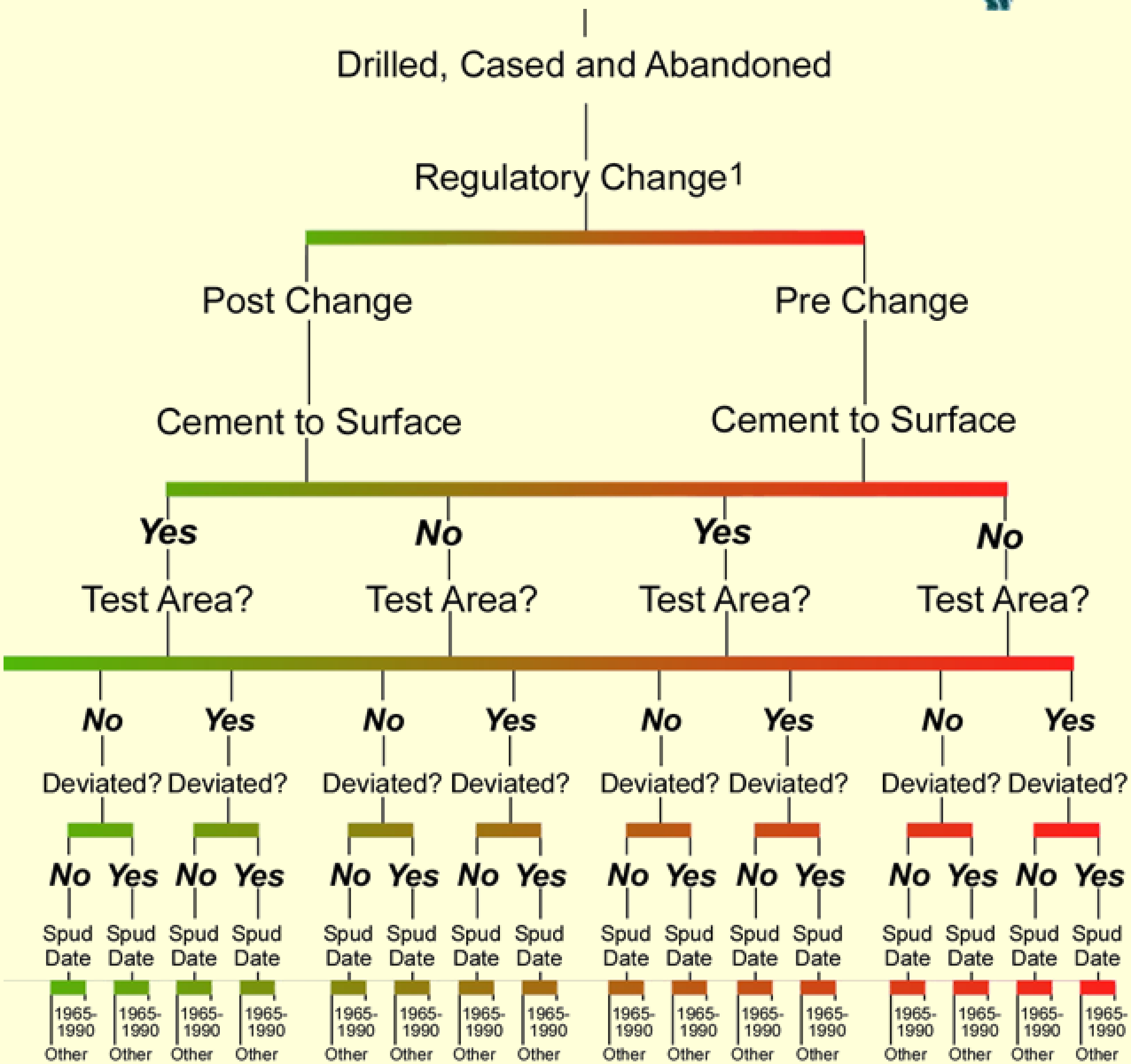
- Surface Casing Vent Flow
- Gas Migration
- Casing Failure

Factor with Significant Impact on Shallow Well Leakage

- Well Type (Open Hole or Cased Hole)
- Regulatory Change
- Spud Date (Historical Impacts)
- Geographic Area
- Wellbore Deviation
- Cement Top
- Cased Hole Abandonment Method

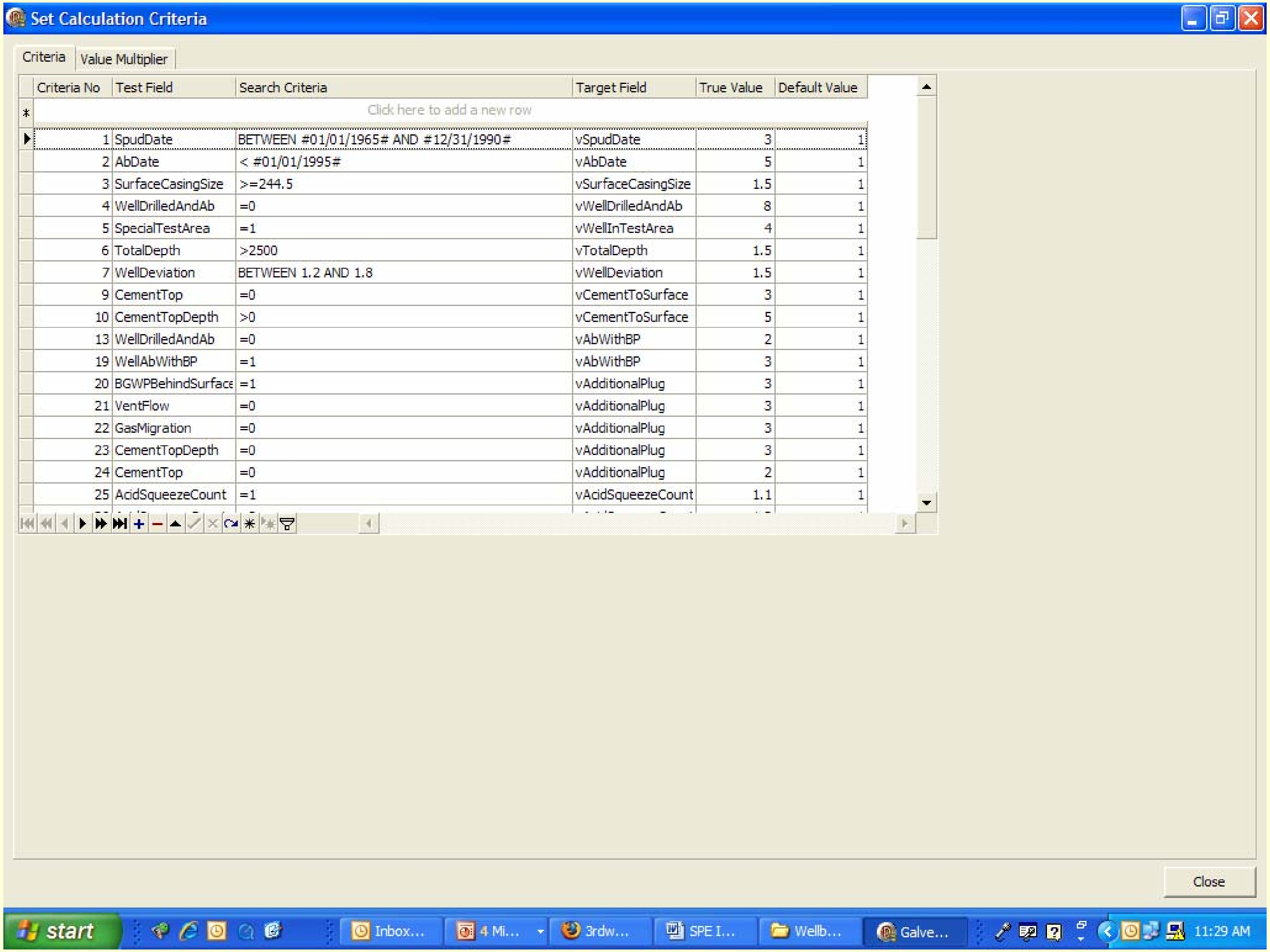
T.L. WATSON & ASSOCIATES INC.

ERCB Energy Resources Conservation Board

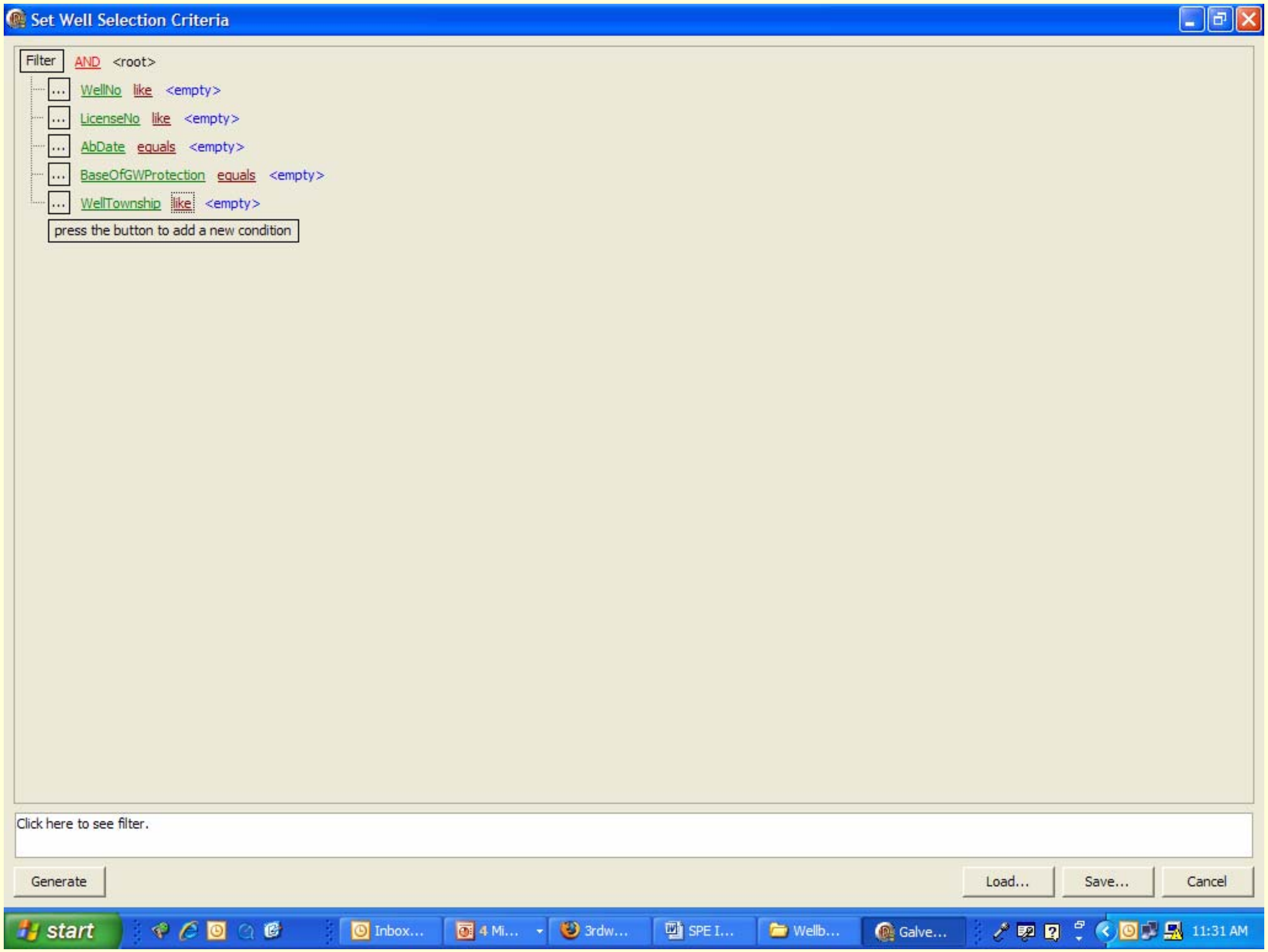


Tool Development

- Data gathering
  - ERCB well data
    - Depths, sizes, location, type, dates, H_2S/CO_2 levels, SCVF/GM, CF, etc.
  - Alberta Environment
    - Groundwater depth
    - Water well location
- Database creation
  - All data for Alberta dumped into SQL database
  - Data manipulated to calculate various fields such as; required cement top, proximity to water wells, well density, exposure to H_2S
- User interface
  - Choose a smaller subset (Spawned Database) to work with
  - Set the values to be assigned to various factors
- Output Analysis
  - Small database created in Access to allow for easy analysis or special manipulation of the data.



Criteria No	Test Field	Search Criteria	Target Field	True Value	Default Value
1	SpudDate	BETWEEN #01/01/1965# AND #12/31/1990#	vSpudDate	3	1
2	AbDate	< #01/01/1995#	vAbDate	5	1
3	SurfaceCasingSize	>=244.5	vSurfaceCasingSize	1.5	1
4	WellDrilledAndAb	=0	vWellDrilledAndAb	8	1
5	SpecialTestArea	=1	vWellInTestArea	4	1
6	TotalDepth	>2500	vTotalDepth	1.5	1
7	WellDeviation	BETWEEN 1.2 AND 1.8	vWellDeviation	1.5	1
9	CementTop	=0	vCementToSurface	3	1
10	CementTopDepth	>0	vCementToSurface	5	1
13	WellDrilledAndAb	=0	vAbWithBP	2	1
19	WellAbWithBP	=1	vAbWithBP	3	1
20	BGWPBehindSurface	=1	vAdditionalPlug	3	1
21	VentFlow	=0	vAdditionalPlug	3	1
22	GasMigration	=0	vAdditionalPlug	3	1
23	CementTopDepth	=0	vAdditionalPlug	3	1
24	CementTop	=0	vAdditionalPlug	2	1
25	AcidSqueezeCount	=1	vAcidSqueezeCount	1.1	1


Set Well Selection Criteria
Filter AND <root>
WellNo like <empty>
LicenseNo like <empty>
AbDate equals <empty>
BaseOfGWProtection equals <empty>
WellTownship like <empty>
press the button to add a new condition
Click here to see filter.
Generate
Load...
Save...
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Wellb...
Galve...
11:31 AM

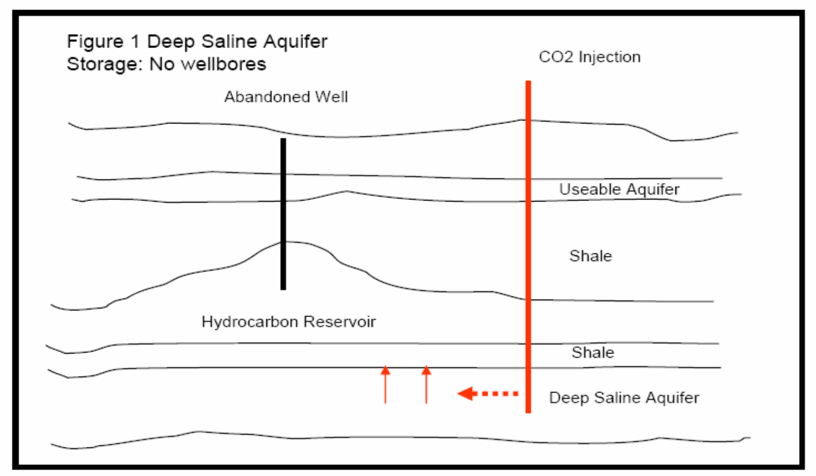
Factors Used in Shallow Analysis

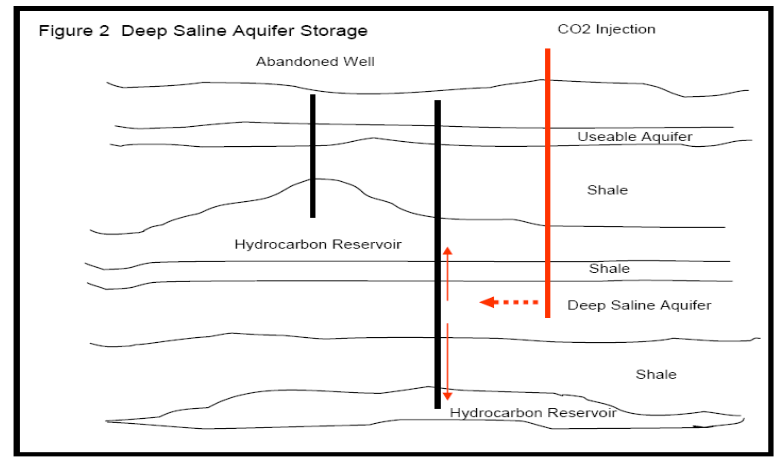
Shallow leakage factors.			
Factor	**Criterion**	**Meets Criterion Value**	**Default Value**
Spud Date	1965-1990	3	1
Abandonment Date	<1995	5	1
Surface Casing Size	≥244.5 mm	1.5	1
Well Type	Cased	8	1
Geographic Location	Special Test Area	3	1
Well Total Depth	>2500 m	1.5	1
Well Deviation	1.2-1.8	1.5	1
Cement to Surface	No	5	1
Cement to Surface	Unknown	4	1
Additional Plug	No	2	1
Additional Plug	Unknown	1.5	1

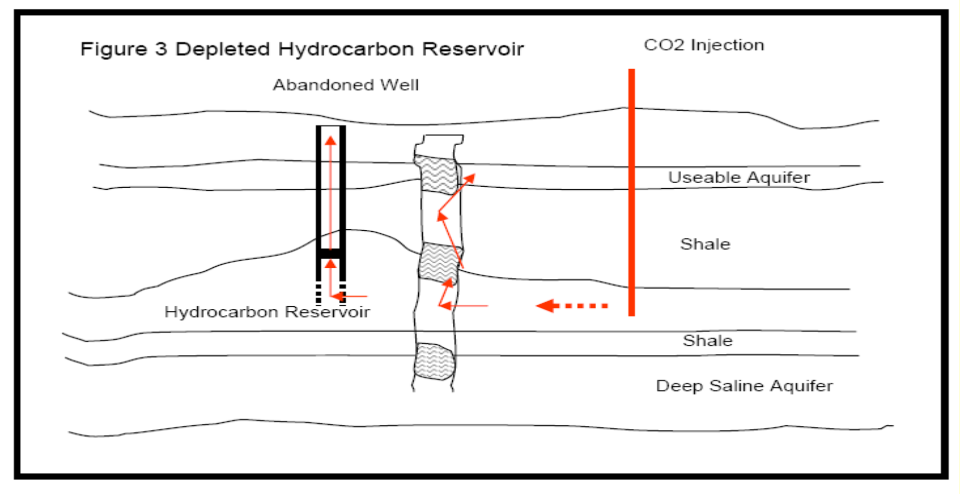
Deep Leakage

- To adjacent zones
- To groundwater
- To atmosphere

Deep Leakage







Deep Leakage Factors

- Stimulation
- Perforated intervals
- Abandonment mode
- Cement type

Stimulation and Perforating

Potential to create pathways in wellbore cement during perforating, acidizing or fracturing.

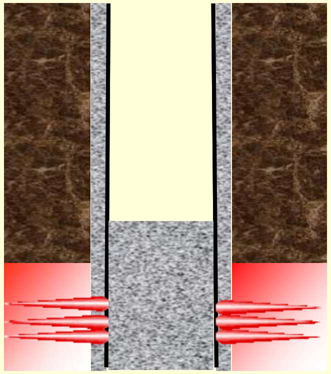
High pressure fracturing may also affect zonal isolation near the wellbore within the reservoir itself.

Multiple perforated intervals may increase the potential for cement sheath damage as well as provide leak pathways within the wellbore for zone to zone communication.

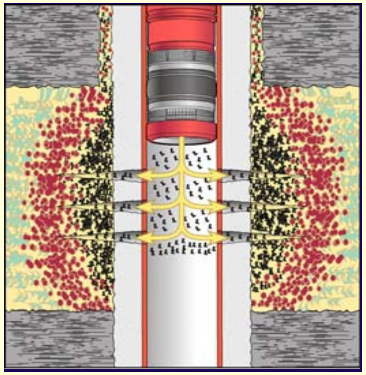
Photograph courtesy of Halliburton Energy Services

Zonal Abandonment

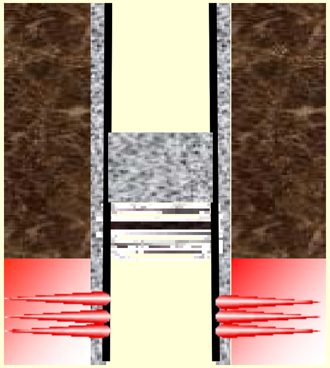
Cement plug set across perforations.



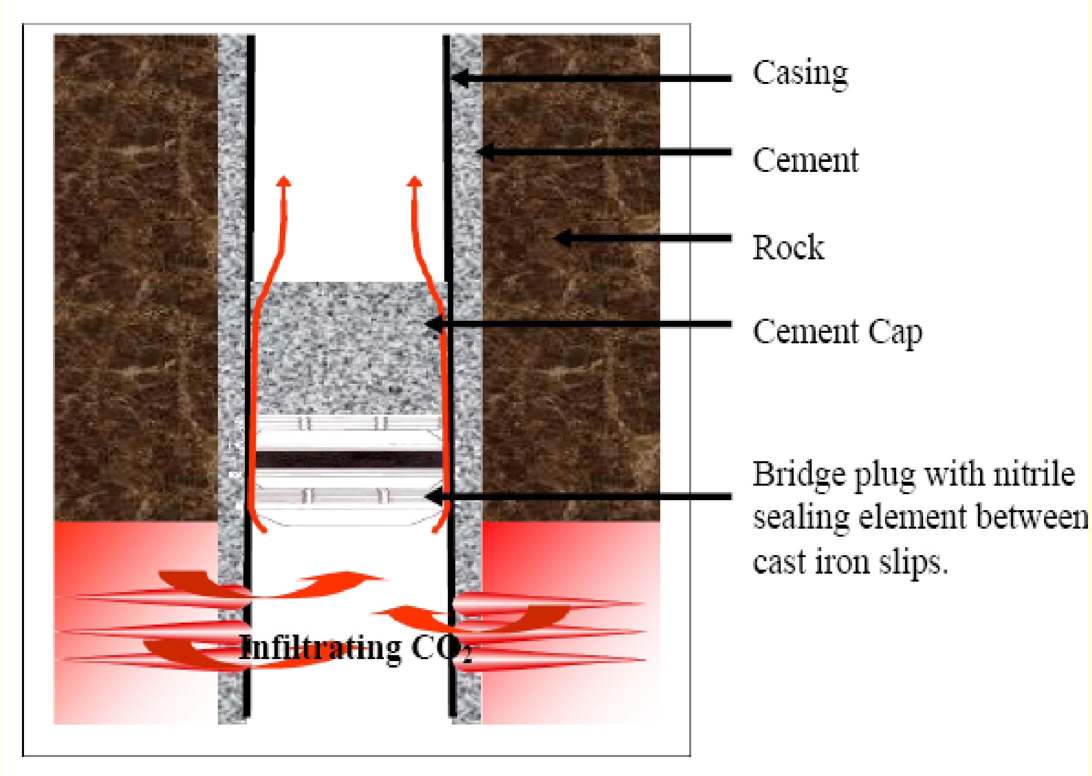
Cement squeeze with retainer to perforations.



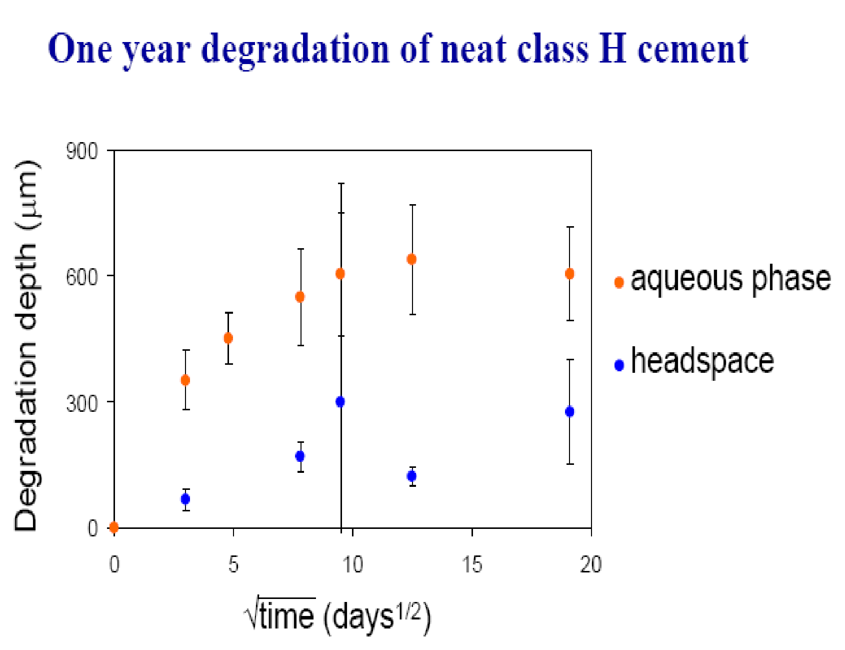
Bridge plug capped with 8 meters of cement.

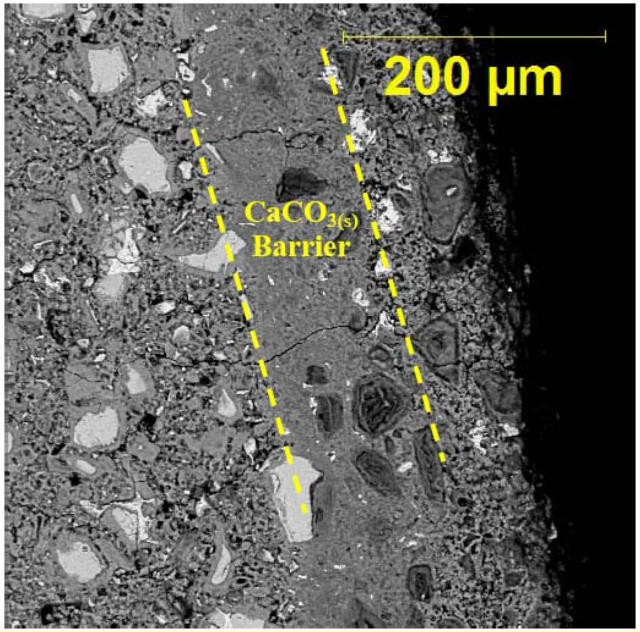


Zonal Abandonment Failure



Cement Type





Data and photograph courtesy Barbara Kutchko, DOE

Deep Leakage Factors

Deep leakage factors.			
Factor	**Criterion**	**Meets Criterion Value**	**Default Value**
Fracture	count =1	1.5	1
Fracture	count >1	2	1
Acid	count=1	1.1	1
Acid	count=2	1.2	1
Acid	count>2	1.5	1
Perforations	count>1	2	1
Abandonment type	Bridge Plug	3	1
Abandonment type	Not abandoned	2	1

Cement types and values.		
Cement Type	**Assigned Value**	**Description**
1:1 POZ MIX	1	Cement and fly ash
1:1:# POZ	3	Cement, fly ash and various quantities of bentonite
BLACKGOLD	1	Unknown
CAP (NEAT)	1	Cap pumped on top of foam cement, not applicable.
CLASS X NEAT	1	Various neat cements
FILL ECP	1	Cement to fill annular packer, not applicable
FOAMED	1	Cement foamed with nitrogen
G + # PC SALT	1	Cement with various percent salt additive
G + # PC SAND	1	Cement with various percent silica sand additive
GPSL/GPCEM/THX	3	Gypsum and gel additives
LIGHT WEIGHT	3	Assumed gel additive to reduce density
SELF STRESS	3	No cement, hole allowed to slough in on casing
SLAG	1	Blast furnace slag, reduces cement porosity
SLOTTED LINER	3	No cement
SLURRY 6D	1	Unknown
TAPERED CASING	3	No cement
TH CEM/CEM FNDU	1	Thermal cement, usually sand or silica additive
UNCEM CSG/LINER	3	No cement

Scores

Shallow leak potential.	
Shallow Leak Potential (SLP)	**Score**
Low	<50
Medium	50-200
High	200-400
Extreme	>400

Deep leak potential.	
Deep Leak Potential (DLP)	**Score**
Low	<2
Medium	2-6
High	6-10
Extreme	>10

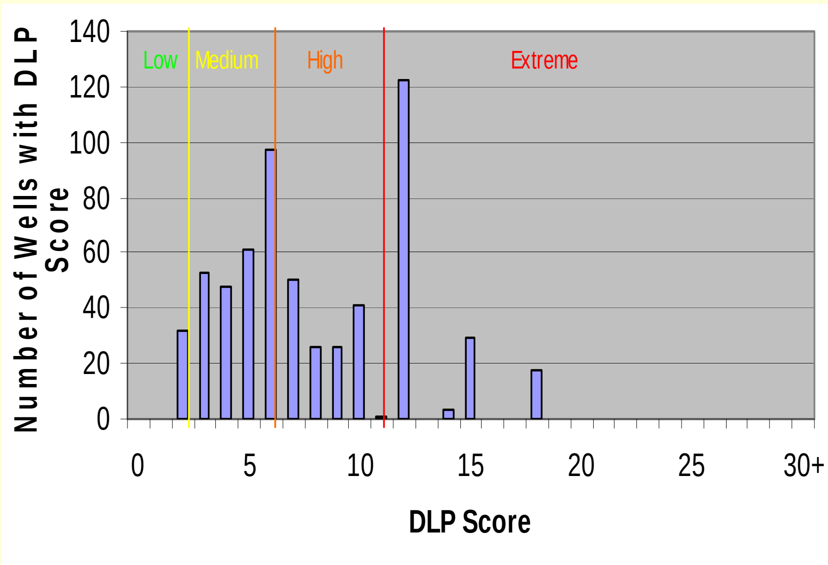
SLP = v(spud date) X v(aban date) X v(SC size) X v(well type) X v(location) Xv(TD) X v(dev) X v(cement top) X v(additional plugs)

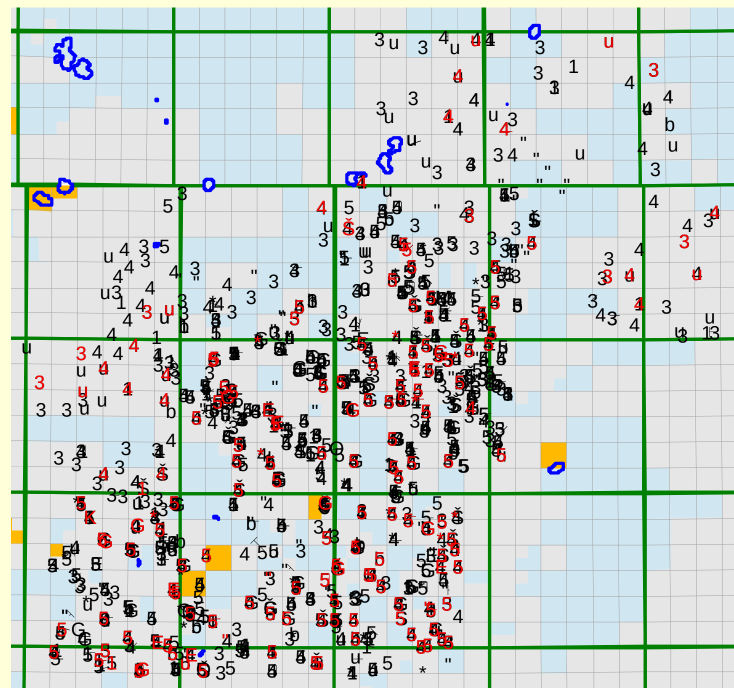
DLS= v(fracture count) X v(acid count) X v(perforated interval count) X v(aban type) X v(cement type)

Case Studies

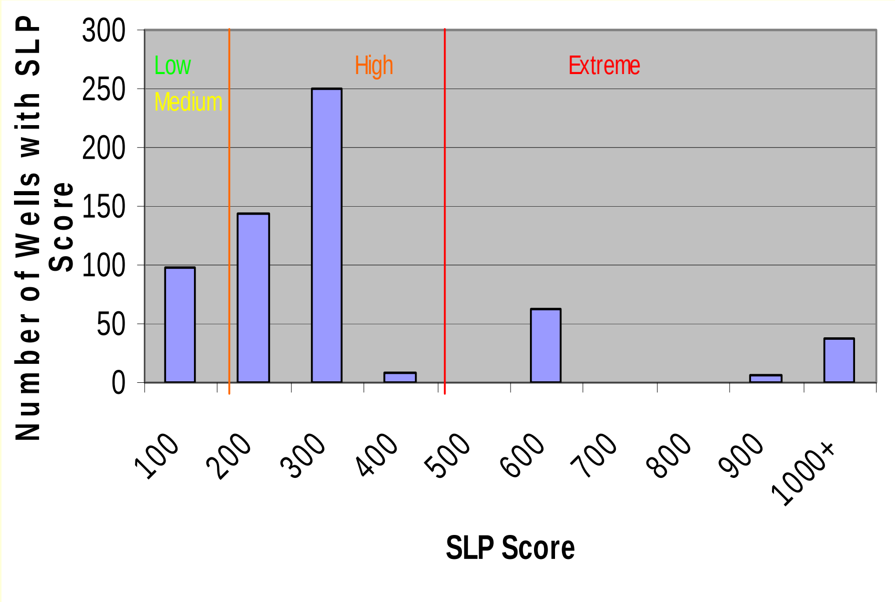
Field data and results summary.		
	Pembina	Zama
Number of cased wells	9860	607
Number of wells drilled and abandoned	1050	106
% of wells with cement data	40%	64%
% of wells with high DLP cement score	28%	20%
% of wells fractured	75%	2%
% of wells acidized	47%	80%
% of wells abandoned	12%	13%
% of wells with multiple completions	11%	55%
% of wells with extreme DLP	14%	28%
% of wells with extreme SLP	7%	18%
% of wells with extreme SLP and DLP	1.6%	4.3%

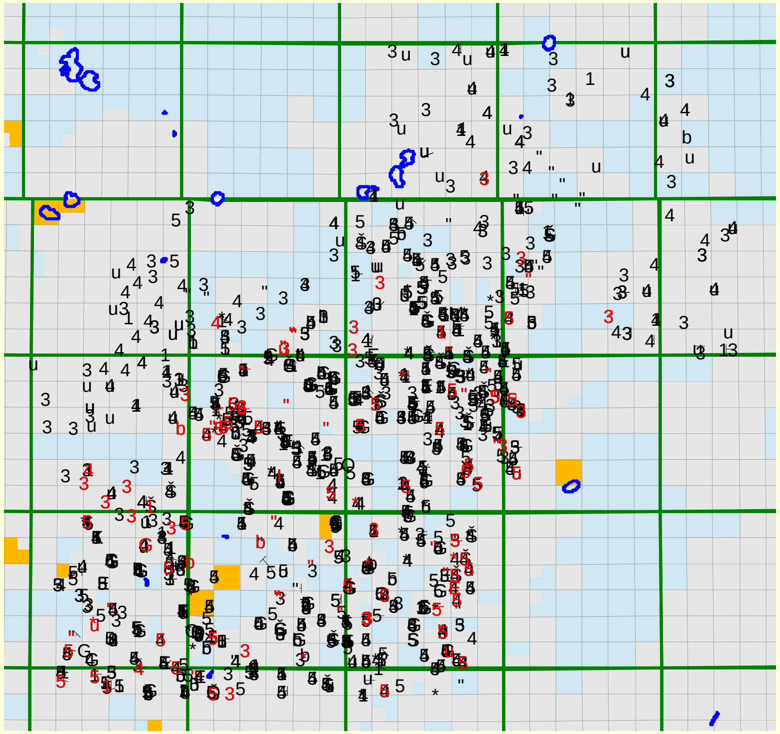
Zama Deep Leakage Potential



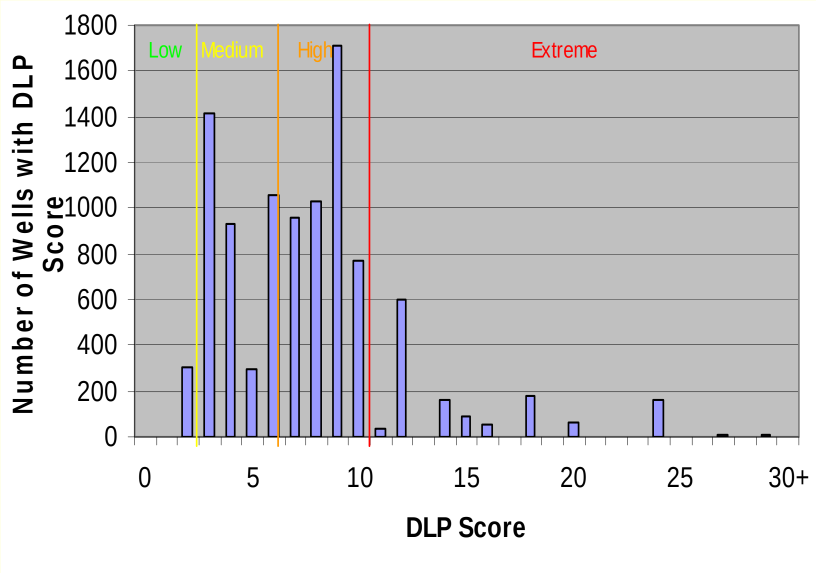


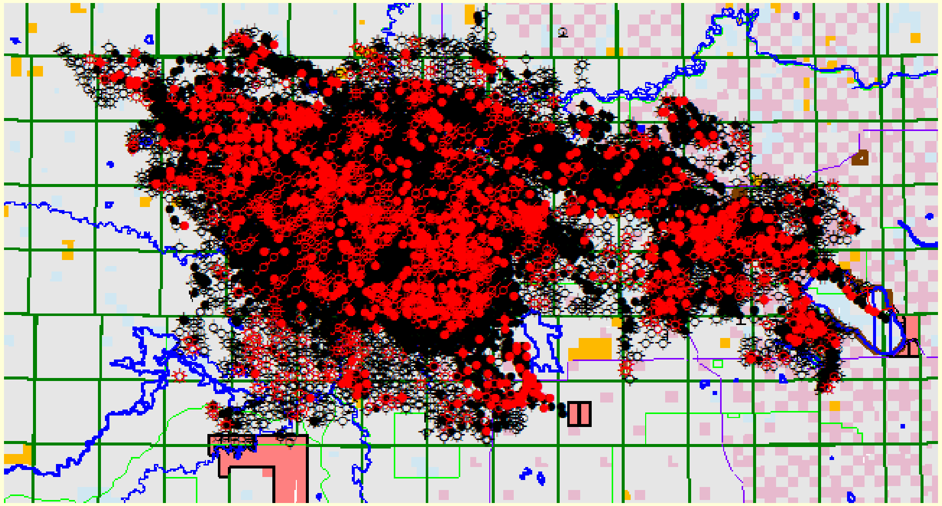
Zama Shallow Leakage Potential



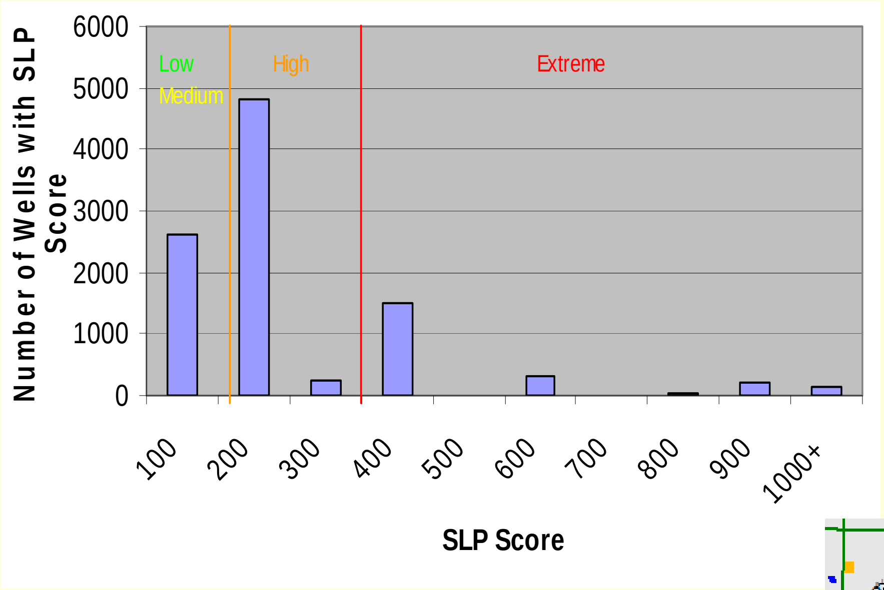


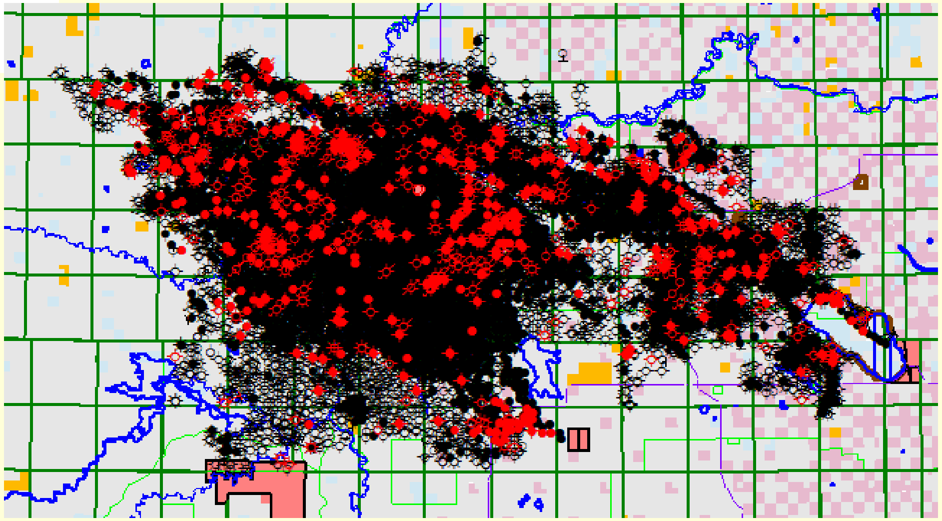
Pembina Deep Leakage Potential





Pembina Shallow Leakage Potential



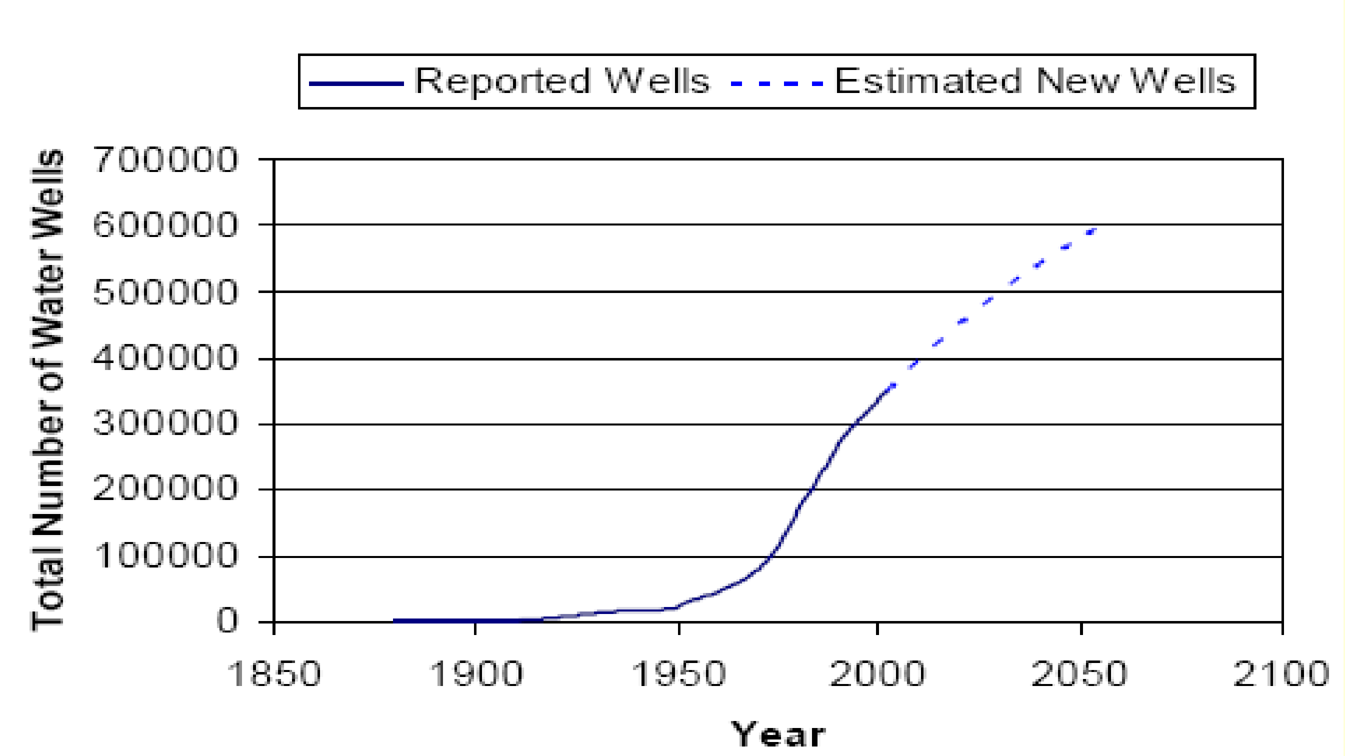


Potential Risk

- Groundwater exposure
- Proximity to groundwater well
- Proximity to other oil and gas wells
- Toxic gas release
- Encroaching population

Increase in Water Wells Associated with Population Increase

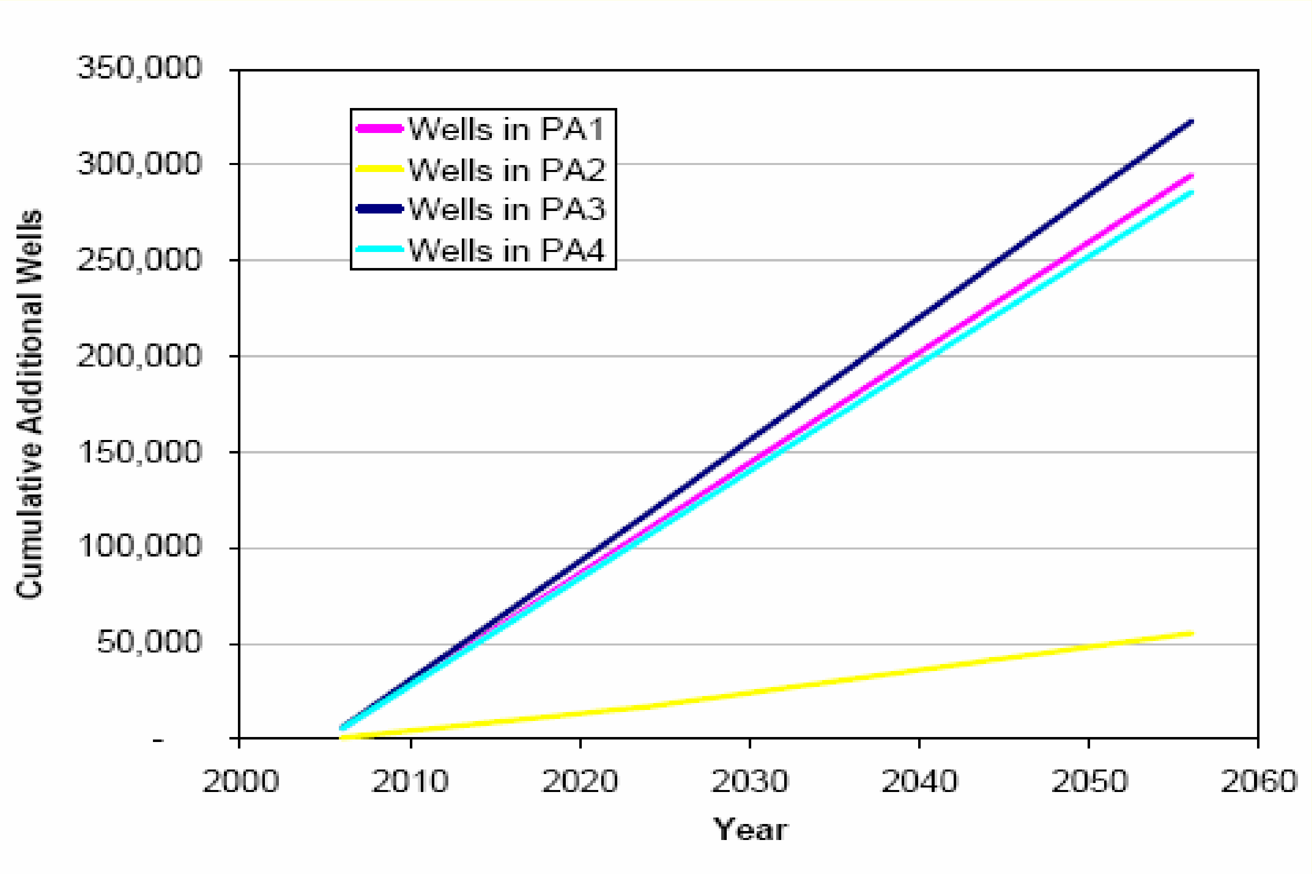
An increase in the number of water wells increases the likelihood that gas, due to migration through shallow zones, can accumulate in buildings.



Deep Leakage to Surface and Groundwater in Central Alberta

Increasing Wellbores

It is estimated that there will be 959,000 wells in the province by 2056 compared to 343,000 in 2006.

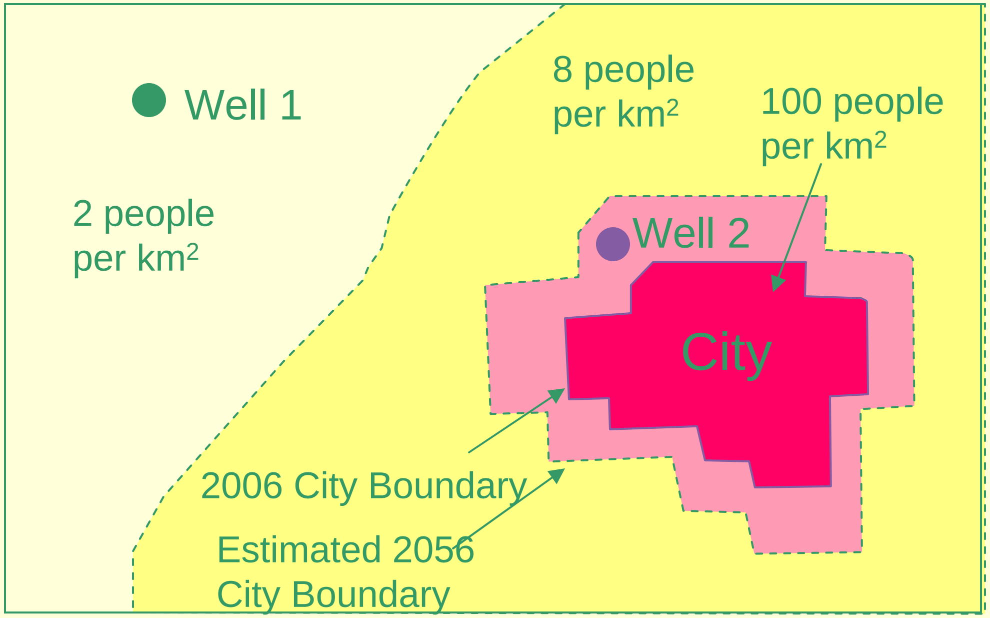


Wellbore Strike by Farming Equipment

Toxic Gas Release

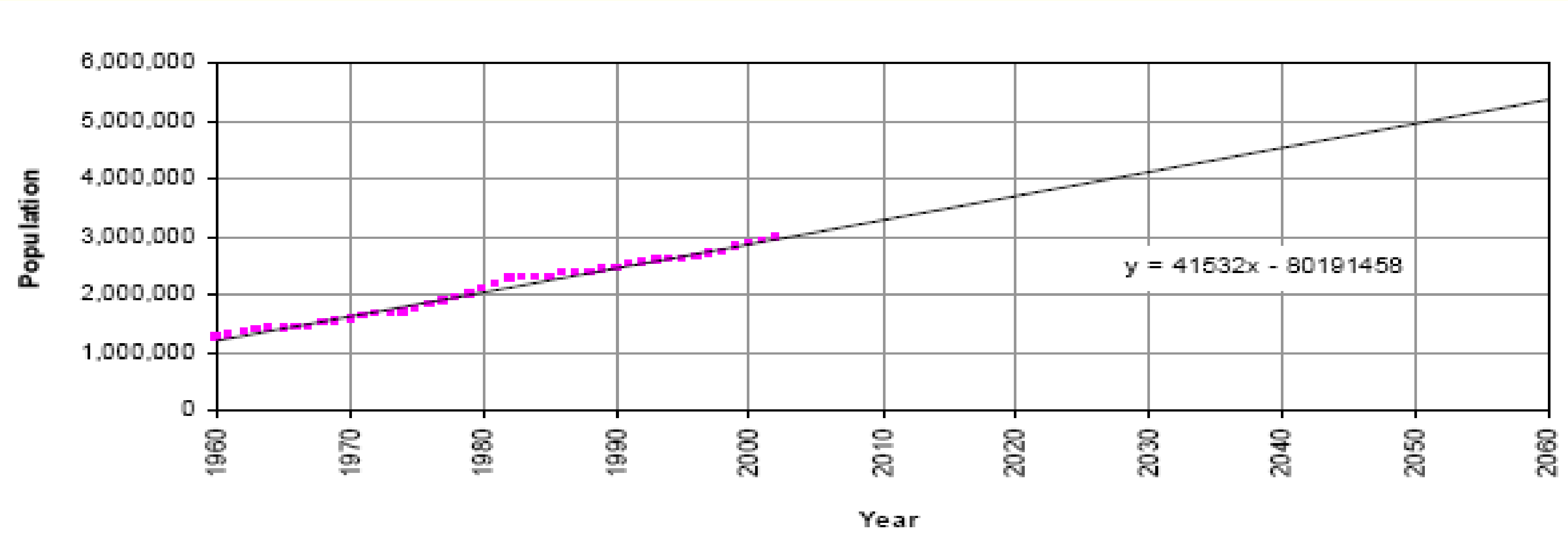
- The program calculates which wells penetrate horizons that contain H_2S.
- This information can be used in conjunction with the potential for leakage to determine the risk to a population in the event of a leak from the well.

Urban Encroachment



Population growth by expanding urban centres

Population Growth



Population is expected to increase from 3,000,000 to almost 6,000,00 people by 2056

This growth will take place in the large urban centres such as Calgary, Edmonton, Red Deer etc.

Wellbore Strike during Development

Conclusions

- The development of this tool provides the ability to evaluate large numbers of wells on a first pass look.
- Will enable operators/regulators to zoom in on wells or areas with high potential for leakage.
- Can be used to determine risk, not only due to CO_2 but also other toxic gas releases.
- More work needs to be done to verify the factors that contribute to deep well leakage.

4th Wellbore Integrity Network Meeting

Monitoring of Wellbore Performance at Penn West CO_2-EOR

Rick Chalaturnyk

Geological Storage Research Group
Department of Civil and Environmental Engineering
University of Alberta

18th – 19th March 2008
Hotel Concorde Montparnasse,
Paris, France

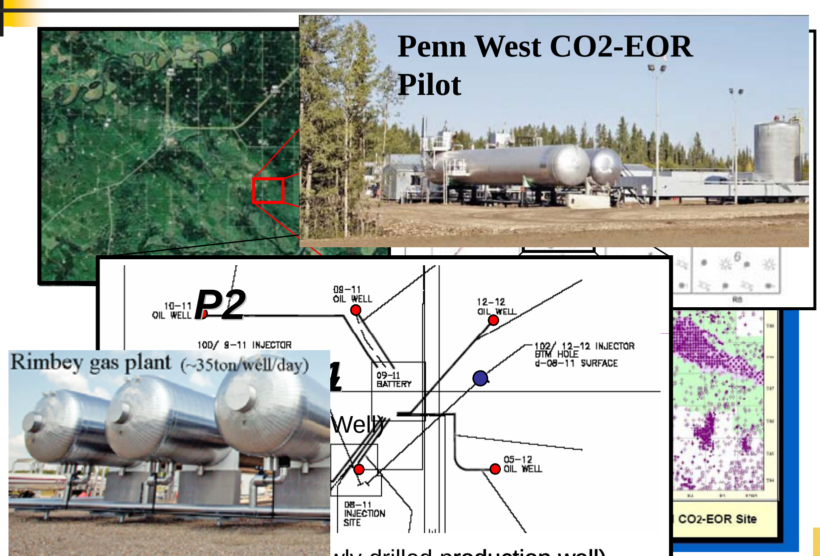
Outline of Presentation

- Penn West CO2-EOR Monitoring Project
- Integrated Instrumentation System in Observation Well
- Summary

Penn West CO2-EOR Monitoring Pilot Project

- A multi-year, multi-agency project for the monitoring of CO2 used for an enhanced oil recovery pilot in central Alberta owned and operated by Penn West Energy Trust.
- The Alberta Energy Research Institute, Alberta Environment, Western Economic Diversification, Environment Canada, Natural Resources Canada and Penn West Energy Trust are partners in this three-year CO2 monitoring pilot project, the first of its kind in Alberta.
- Five organizations involved in research program
  - Penn West Energy Trust
  - Alberta Research Council
  - Alberta Geological Survey
  - University of Calgary
  - University of Alberta

Penn West CO2-EOR Pilot Location



Penn West CO2-EOR Monitoring Pilot Project

- The project will further advance the understanding of the fate of CO_2 injected into petroleum reservoirs and enhance our understanding of the role that geological CO_2 storage can play in responding to the risks of climate change.
- This project, which is utilizing leading-edge CO_2 monitoring tools and applications, will add to the growing body of knowledge that is being developed in Canada on the capture and storage of carbon dioxide and its potential as a greenhouse gas mitigation option.

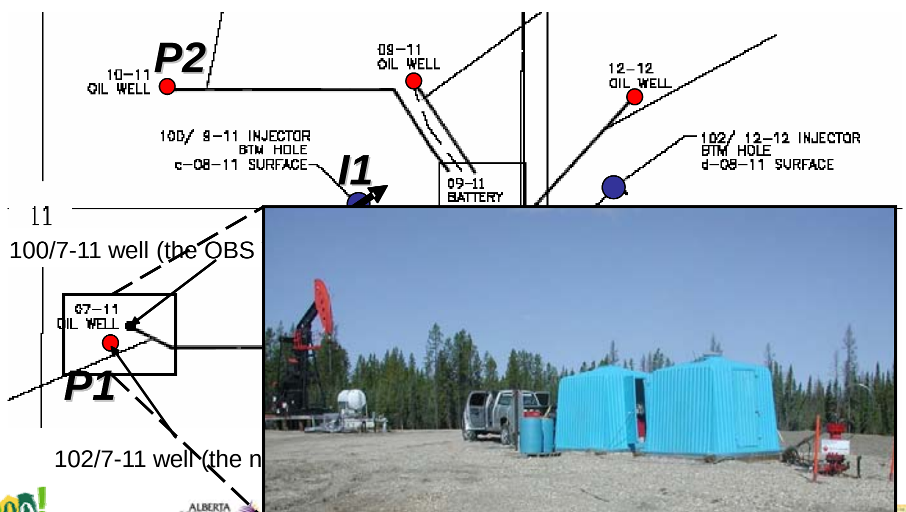
Goals of Research Program

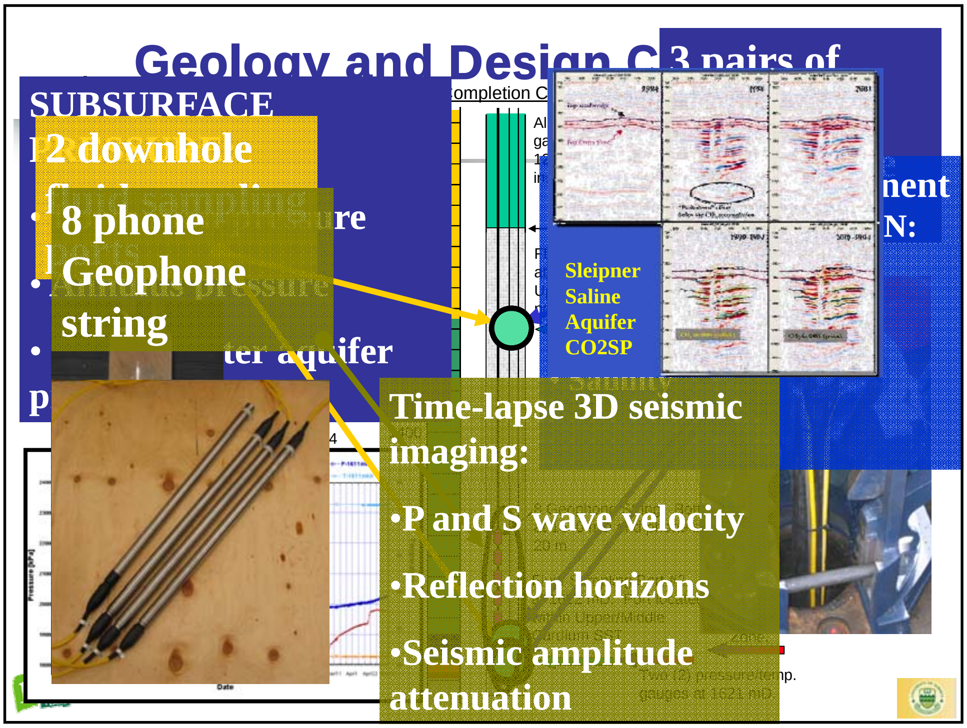
- Suitability of existing oil and gas pools for CO_2-EOR and CO_2 storage
- Cost effective monitoring programs for detecting and quantifying fate of CO_2
- Informing long-term (post-closure) monitoring programs
- Acquisition of experience in implementing monitoring technologies to assist in future development of regulatory framework
- Evaluation of verification and environmental monitoring methods for CO_2 storage

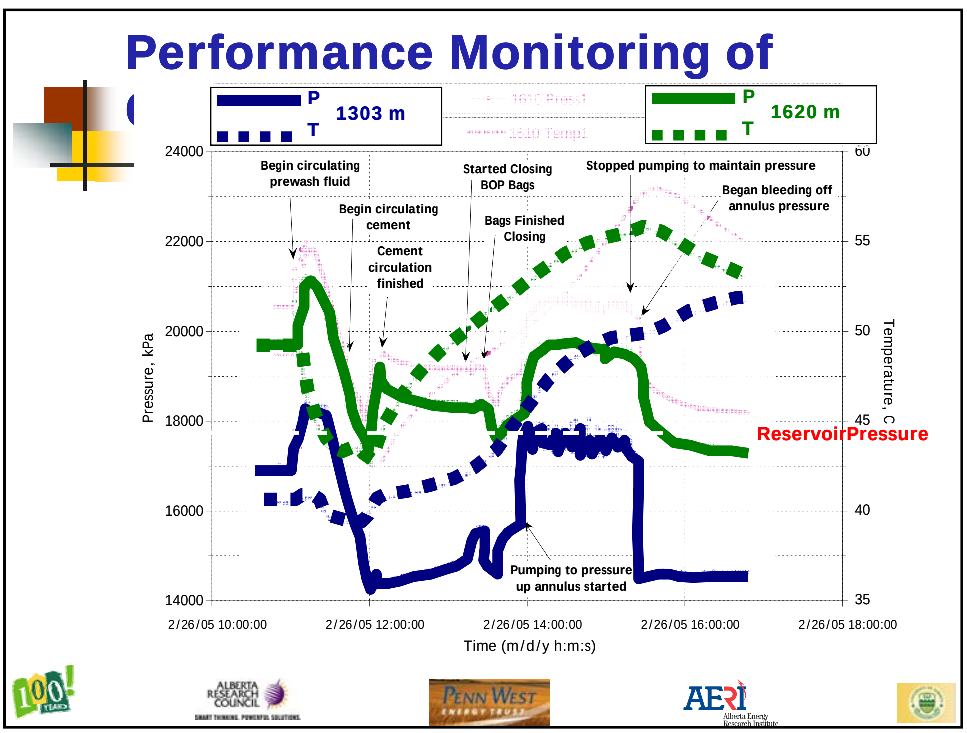
Elements of the Intregrated Instrumentation System

- Overview of Instrumentation Well Design
- Wellbore Completion
- P/T Data Interpretation

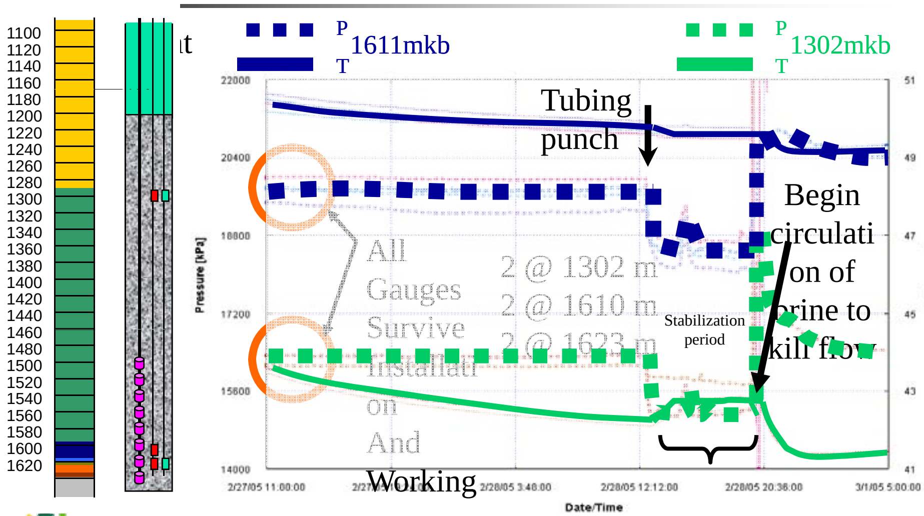
Observation Well, 6 Production Wells and 2 CO2 Injection Wells



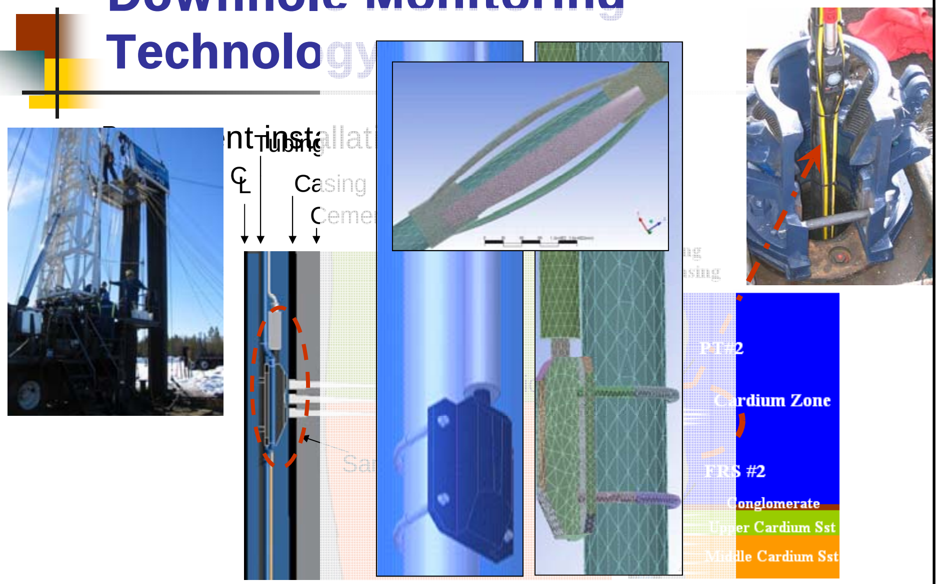

Geology and Design C
3 pairs of
SUBSURFACE
2 downhole
8 phone
Geophone
string
Sleipner
Saline
Aquifer
CO2SP
Time-lapse 3D seismic
imaging:
•P and S wave velocity
•Reflection horizons
•Seismic amplitude
attenuation


Performance Monitoring of
P
T
1303 m
P
T
1620 m
Begin circulating
prewash fluid
Begin circulating
cement
Cement
circulation
finished
Started Closing
BOP Bags
Bags Finished
Closing
Stopped pumping to maintain pressure
Began bleeding off
annulus pressure
Pumping to pressure
up annulus started
ReservoirPressure
Pressure, kPa
Temperature, C
Time (m/d/y h:m:s)
24000
22000
20000
18000
16000
14000
60
55
50
45
40
35
2/26/05 10:00:00
2/26/05 12:00:00
2/26/05 14:00:00
2/26/05 16:00:00
2/26/05 18:00:00

Wellbore Completion
Feb 27 to Mar 1

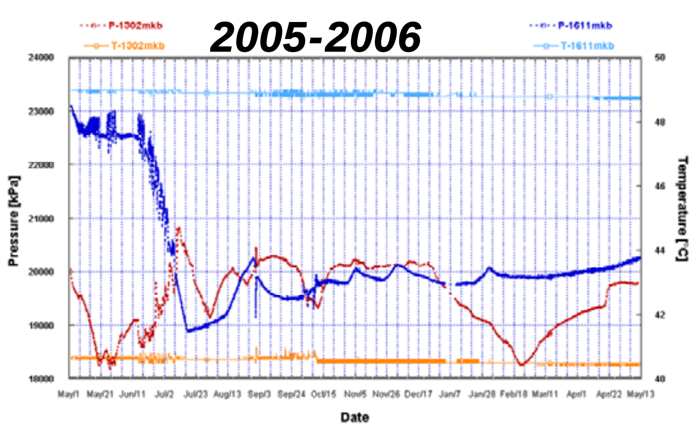


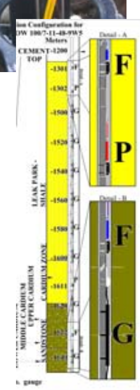
Downhole Monitoring Technology



ALBERTA RESEARCH COUNCIL SMART THINKING. POWERFUL SOLUTIONS.   PENN WEST ENERGY TRUST   AERI Alberta Energy Research Institute

Pressure and Temperature





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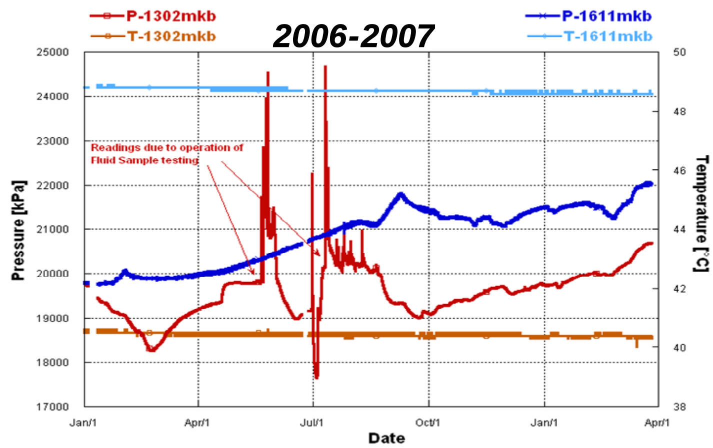
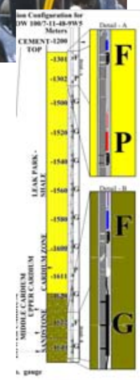
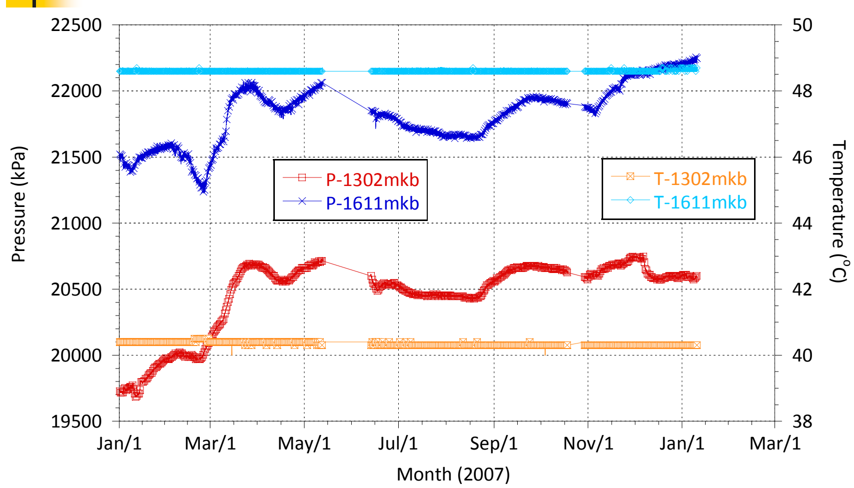
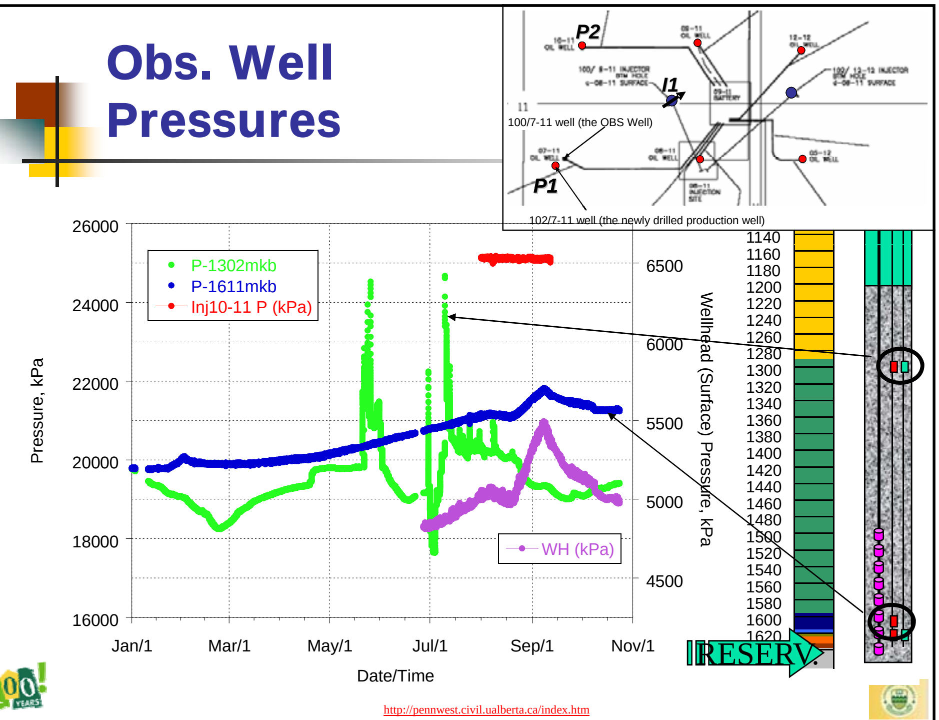




Pressures within Well Sheath - 2007

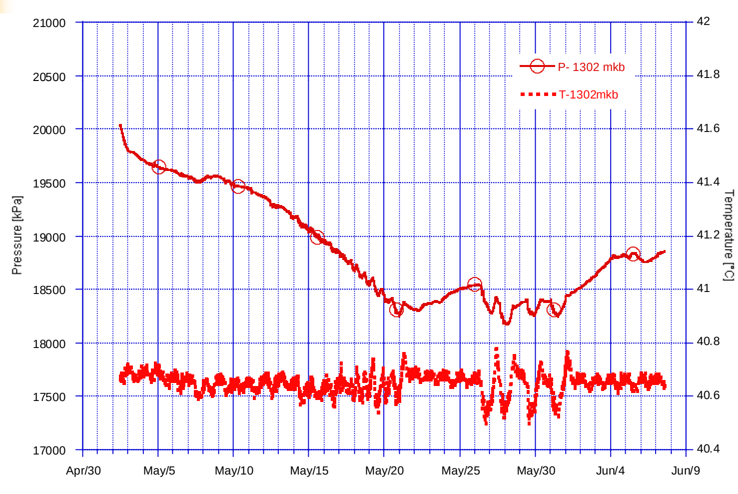


Obs. Well Pressures

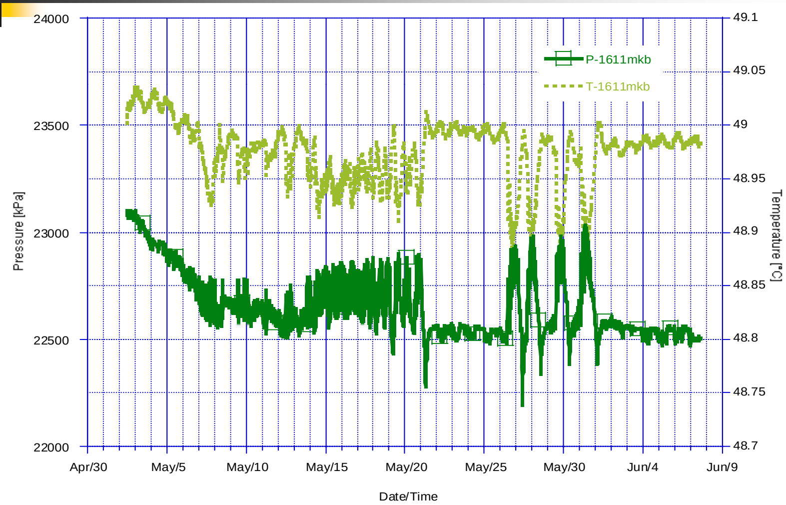


http://pennwest.civil.ualberta.ca/index.htm

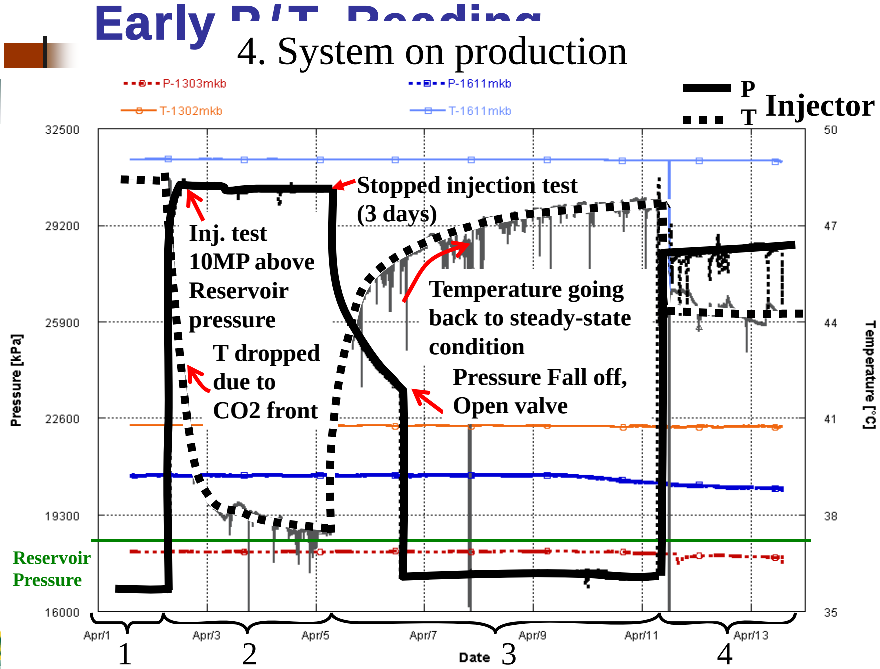
Shallow Sensor – May 2005



Deep Sensor – May 2005



Early P/T Reading



We're sticking my house down this hole!!

Monitoring of Wellbore Performance at Penn West CO_2-EOR

4th Wellbore Integrity Network Meeting

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Acknowledgements

Alberta Energy Research Institute
Alberta Environment
Western Economic Diversification
Environment Canada
Natural Resources Canada
Penn West Energy Trust
EnergyINet - CO_2 Management Program

Managing Well Integrity for Safety and Performance of CO2 Geological Storage: A risk-based approach

Application to CO2 injection phase

Yvi Le Guen*, J. Le Gouevec*, Laurent Jammes**

*OXAND S.A.
**Schlumberger Carbon Services

IEAGHG Well bore Integrity network
March, 19th 2008

Summary

Introduction

Context of the study: issues for the operator

Purposes of the study

Key steps of the study, main results and recommendations

Risk assessment

Risk management

Decision support

Conclusions

The case study – What was achieved ?

Operator assessment

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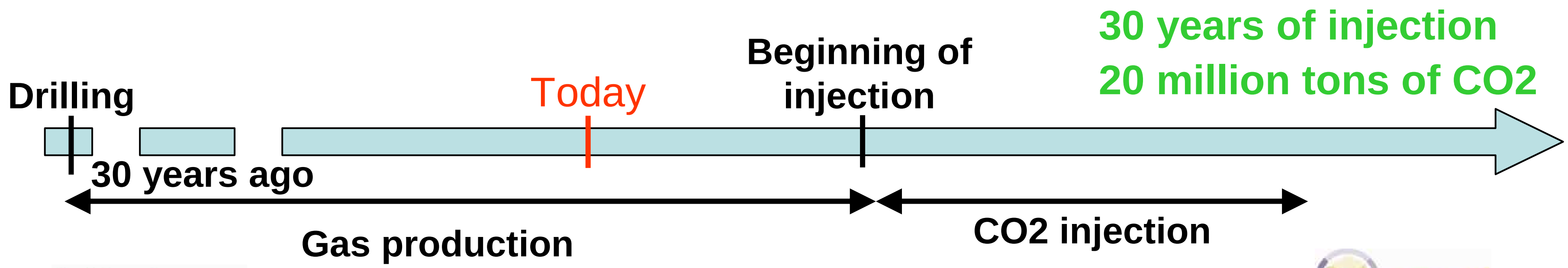
Introduction : Context & Issues

- An Oil & Gas company interested in EGR by injecting and storing supercritical CO_2
- The company wants to choose 3 wells out of 9 that could be suitable for conversion into injectors
- Use the well integrity as one of the criteria for the decision
  - OXAND & Schlumberger performed in partnership a Performance and Risk assessment (P&R™) of well integrity over the injection phase



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Introduction : Purposes of the study

- **On the basis of existing and available data, the general goals were:**
  - *To propose a risk mapping for each of the 9 wells vs. potential CO_2 leakage over the injection phase*
  - *To understand the impact of variables on risk levels and identify sources of risk (e.g. contributors to CO_2 migration along injection wells)*
  - *To identify and prioritize actions for risk mitigation in terms of cost/benefit*
  - *To use the risk as a decision criteria*
  - *To find out 5 best wells for conversion, and to be able to justify the choice*

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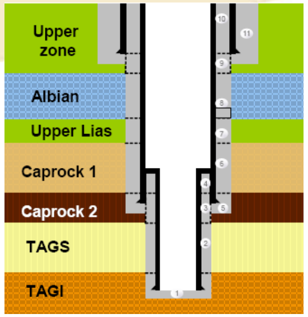
Well Integrity Management Workflow

Data collection

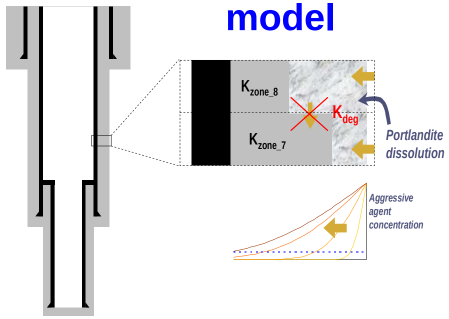
Cement logs
Drilling reports
Geological profiles
…

Static model



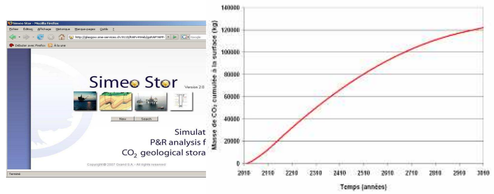
Cement degradation
Casing corrosion
CO_2 migration
Initial and limit conditions

Dynamic model



Well Integrity Management Workflow

CO_2 leakage mass and probability



X

Severity
(Consequence grid)

STAKES	TOTAL INJECTION STOPS	SAFETY / HEALTH	CORPORATE: Perception of know-how	CORPORATE: Reputation	PUBLIC OPINION	POLLUTION: Air	POLLUTION: Aquifer
1: Minor							
2: Low							
3: Serious							
4: Major							
5: Critical							
6: Extreme							

SEVERITY LEVELS

Risk mapping

F_k \ $Sev_{sc\,k}$	1	2	3	4	5	6
6	7	8	9	10	11	12
5	6	7	8	9	10	11
4	5	6	7	8	9	10
3	4	5	6	7	8	9
2	3	4	5	6	7	8
1	2	3	4	5	6	7

Recommendations

1. Characterization/ Inspection
2. Design recommendations
3. Operational recommendations
4. Monitoring recommendations

Best practices

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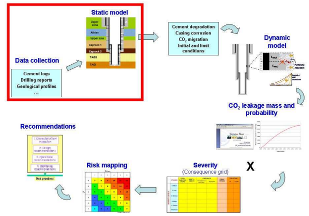
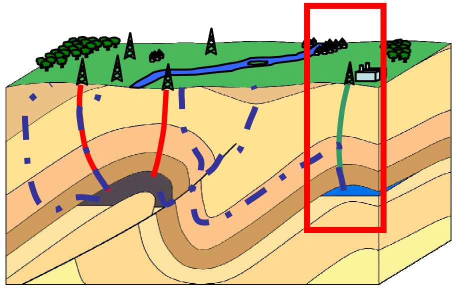
Construction of static model
Wellbore : geology + well

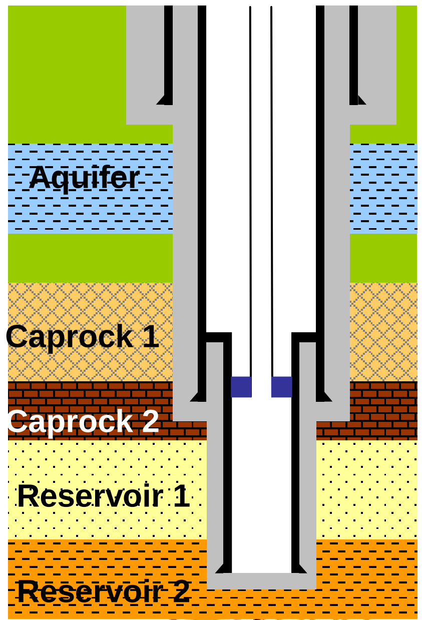


- **Geology in the wellbore environment**
  - *Geological formation*
  - *Position of aquifers*
  - *Pressure, temperature, fluids, …*

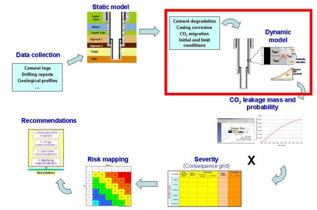


- **Well parameters**
  - *Wellbore*
  - *Casing location and properties*
  - *Cement sheath geometry and properties*
  - *Plugging strategy*

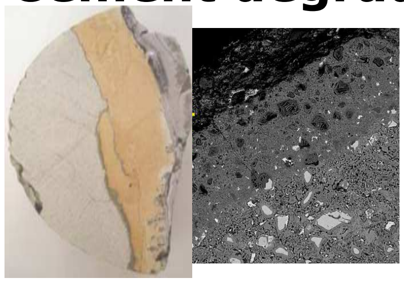
- **Initial degradation**
  - *After 30 years of gas production*



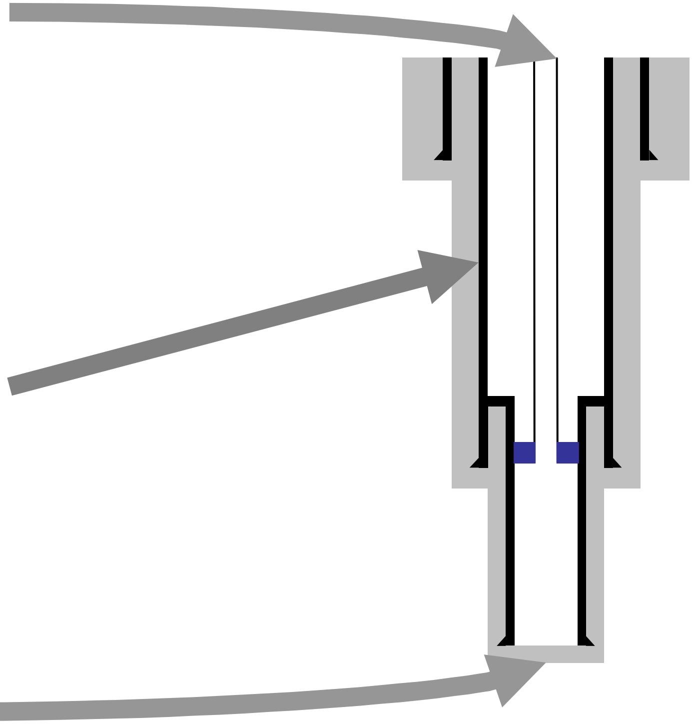
Dynamic model
Degradation mechanisms & fluid transport



Cement degradation



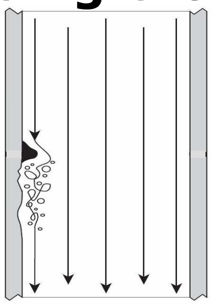
- Initial state
- Cement leaching
  - *Kinetics : $e(t) = a\sqrt{t}$*
  - *Permeability increase*



Steel degradation

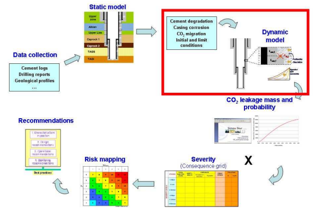
- Generalized corrosion
- Pitting corrosion
  - *Kinetics : $e(t) = b.t$*
- Annulus formation, …

Casing erosion

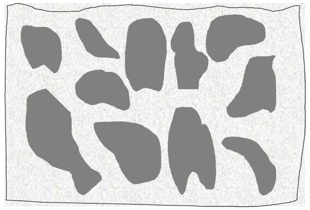


- Depends on :
  - ***Fluid flow***
  - ***Fluid composition, …***
- Decrease in casing thickness

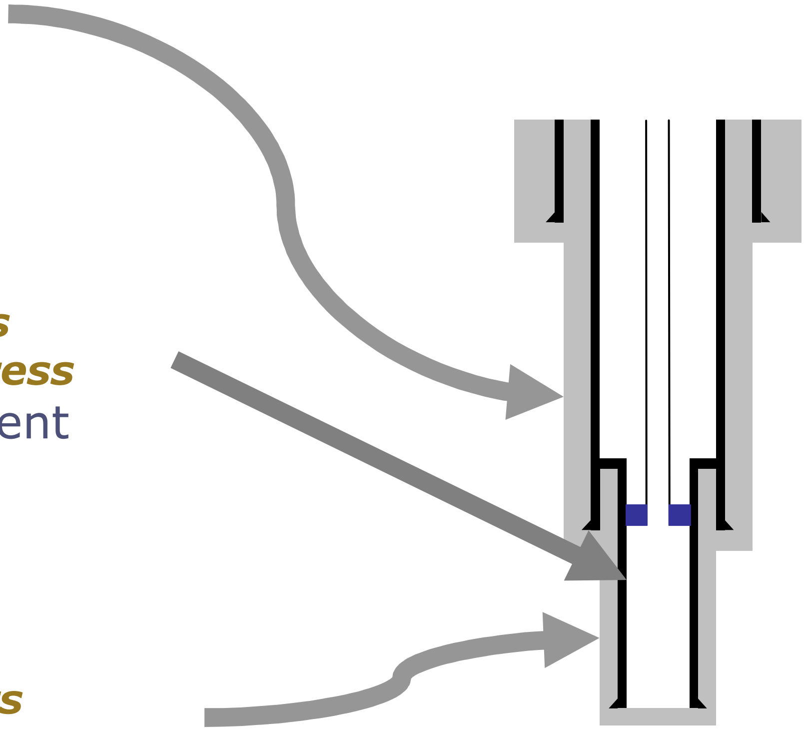
Dynamic model
Degradation mechanisms & fluid transport



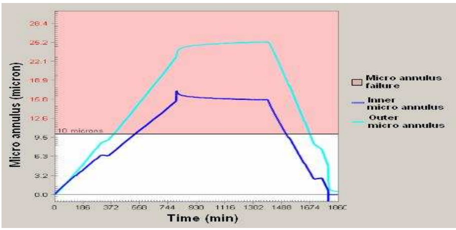
Transport



- Gas migration
- Porosity
- Capillary pressure, …



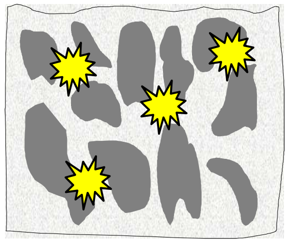
Micro annulus



Micro-annulus (CemSTRESS by SLB)

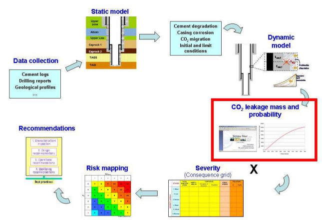
- Effect of
  - ***Thermal stress***
  - ***Mechanical stress***
- Debonding of cement

Dry out



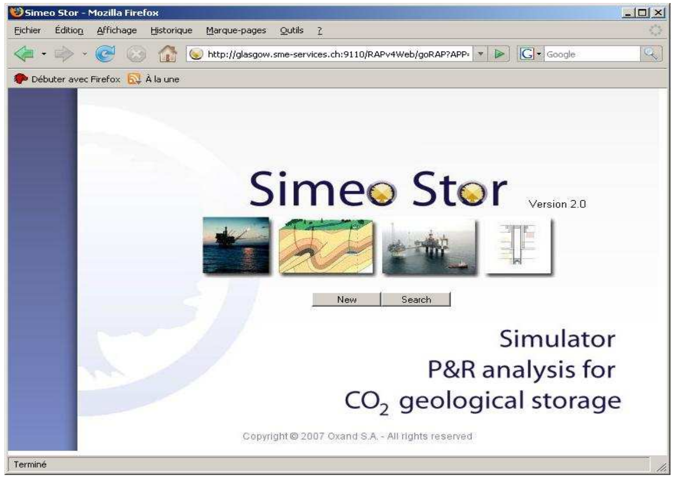
- Depends on :
  - ***injection parameters***
- Degradation of cement
  - ***Decrease in permeability***

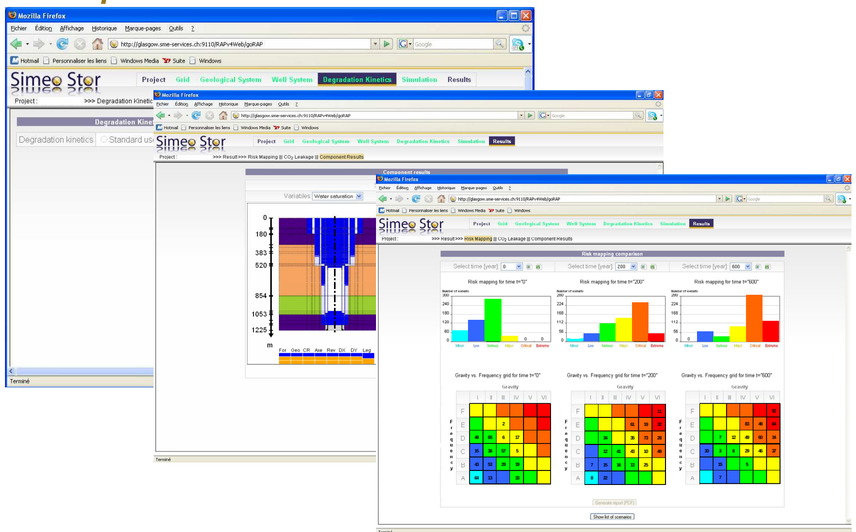
Simulation of gas migration along the wellbore



- **Selection of scenarios to assess risk level**
  - *Combinations of well components in a certain degraded state*
  - *With an associated probability*

- **Simulation of scenarios in SIMEO-STOR™**
  - *Evaluation of well components degradation over time (30 years)*
  - ➔ *Gas migration during the injection period ?*





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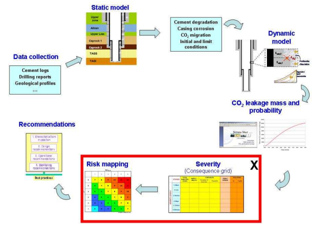
How to quantify the risk ?

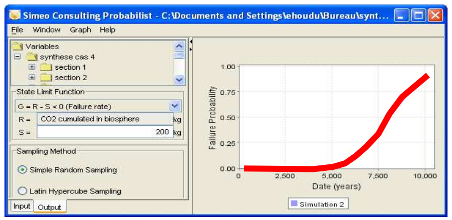


- **Risk = frequency x severity**
  - *Frequency = probability of a scenario to occur*
    - **Frequency grid**
  - *Severity : impact on defined targets (based on simulation results)*
    - **Consequence grid**

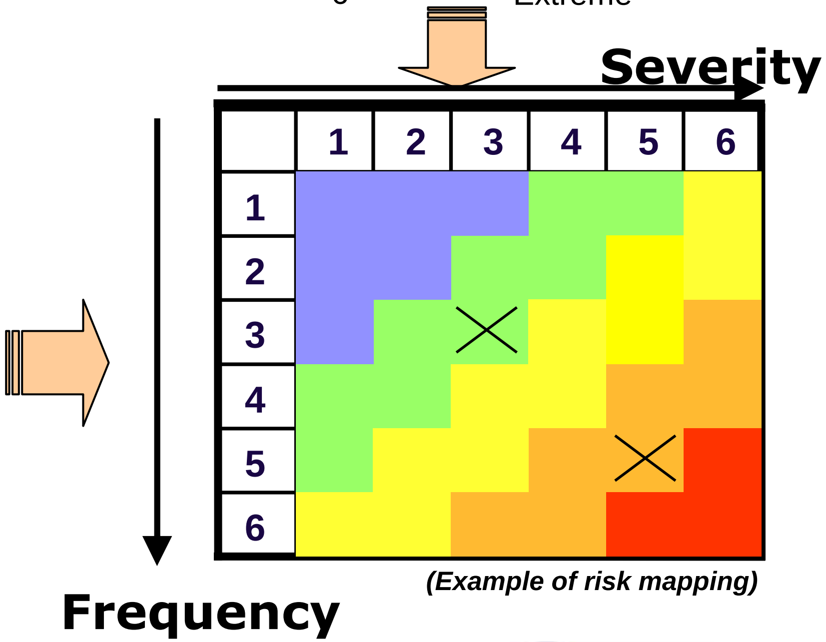
Severity assessment

Severity level	Impact
1	Low
2	Minor
3	Serious
4	Major
5	Critical
6	Extreme

Frequency of scenarii

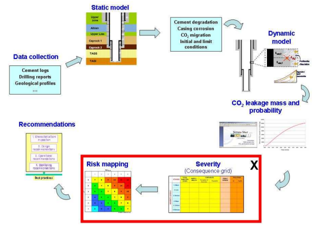


Frequency level	Min probability	Max probability
1	0	0,00001
2	0,00001	0,0001
3	0,0001	0,001
4	0,001	0,01
5	0,01	0,1
6	0,1	1



(Example of risk mapping)

Consequence grid

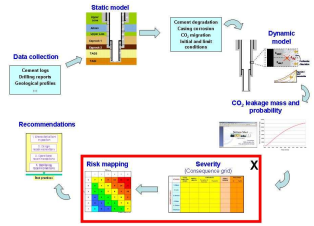


- **The consequence aims at gathering stakes involved in the project to evaluate the consequences of well integrity failure**
  - *The stakes illustrate the responsibility of the corresponding stakeholder*
  - *The severity level translates the magnitude of a failure*

- **Example of stakes identified:**
  - *Safety of people*
  - *Pollution : air, aquifers*
  - *Know-how*
  - *Public opinion*
  - *Financial (OPEX)*

SEVERITY LEVELS / STAKES	TOTAL INJECTION STOPS	SAFETY / HEALTH	CORPORATE		PUBLIC OPINION	POLLUTION	
			Perception of know-how	Reputation		Air	Aquifer
1: Minor							
2: Low							
3: Serious							
4: Major							
5: Critical							
6: Extreme							

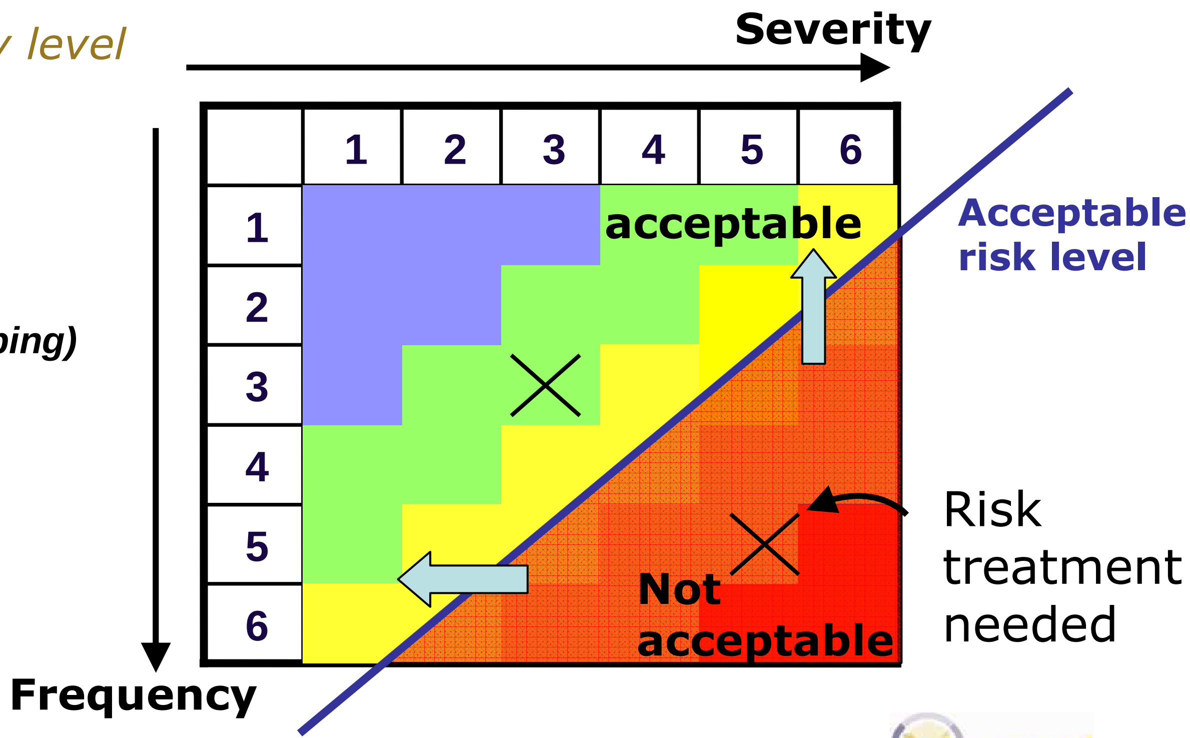
Risk treatment



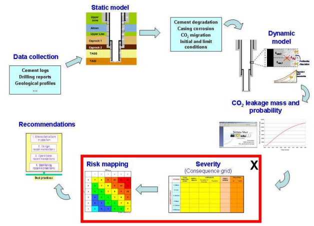
- **Define "acceptable" level of risk**
  - *Input from the methodology user*

- **Risk treatment achieved by**
  - *Decreasing frequency level*
    and / or
  - *Decreasing severity level*

(Example of risk mapping)

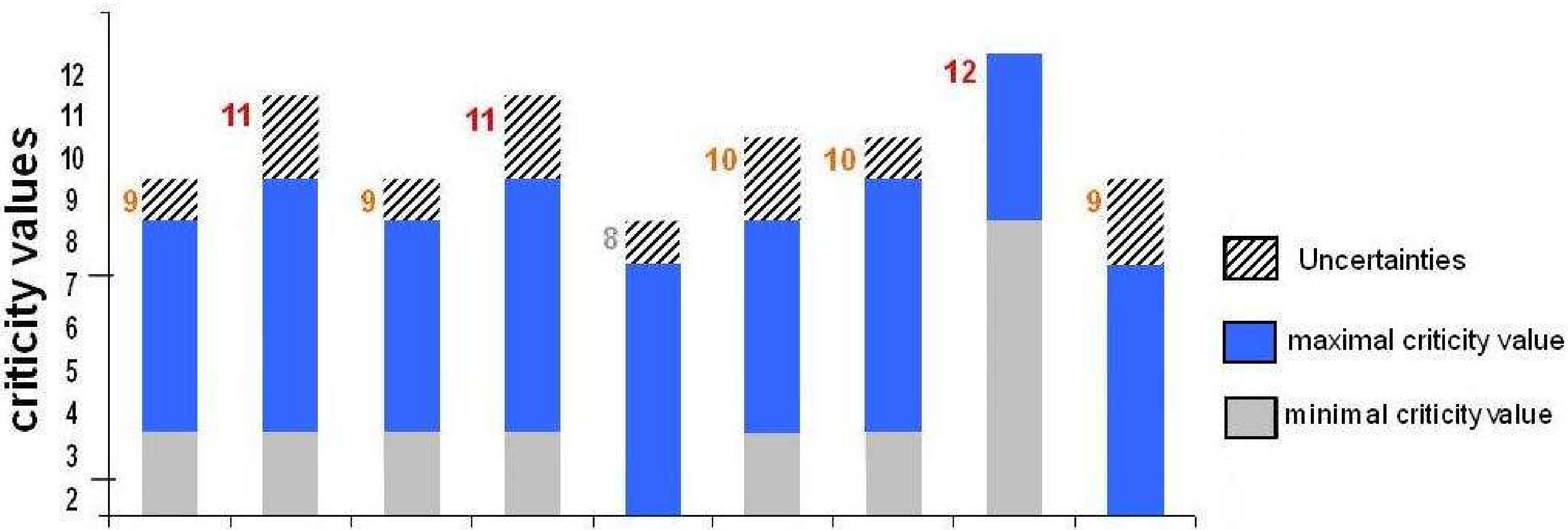


Risk mapping of the 9 wells

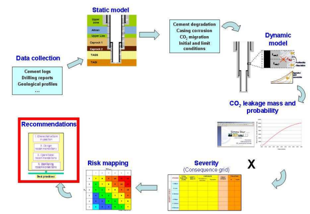


Risk quantification

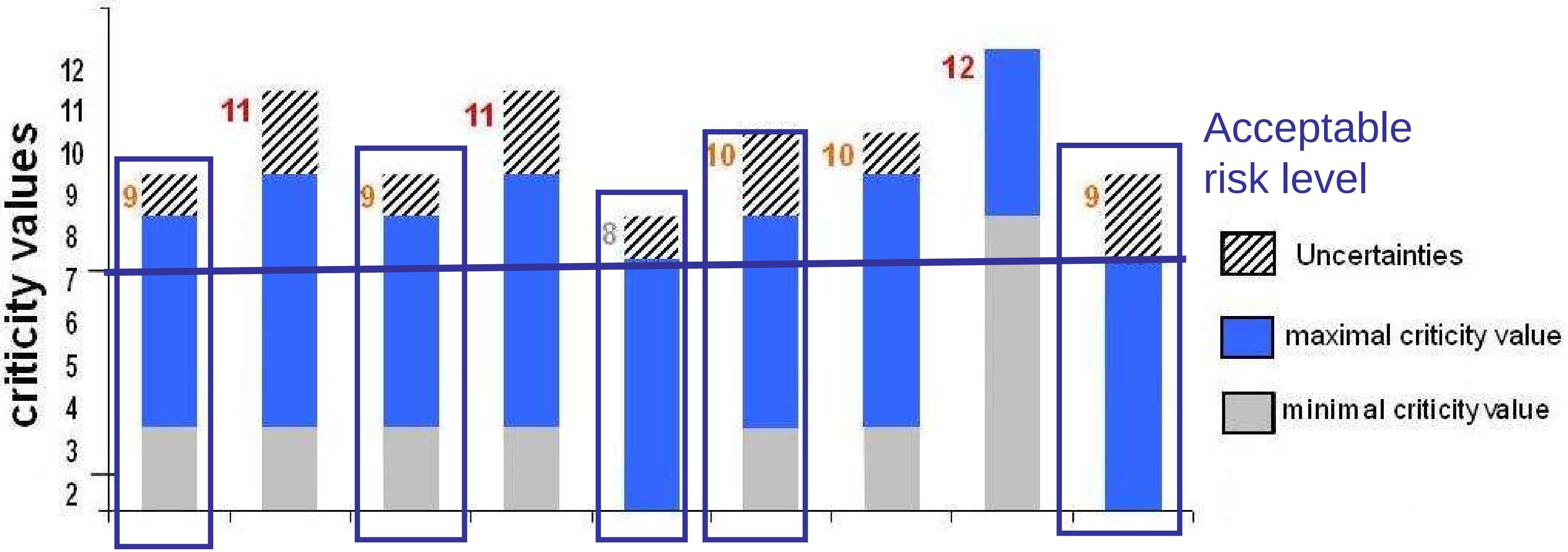
- *Minimum criticity*
- *Maximum criticity*
- *Risk associated to parameters not taken into account in the model*



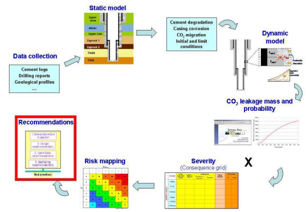
Acceptable level of risk



- **Acceptable criticity level set to 7**
- **Selection of 5 wells :**
  - *1st rule : well(s) with risk level equal or lower than 7*
  - *2nd rule : wells with maximum risk the closest to 7*
    - **➔ Action to manage risk level of selected wells**



Risk management



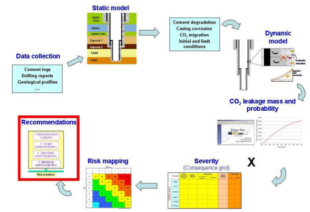
- **<u>Recommend relevant actions</u> that contribute to ensuring the acceptable level of risk for each well selected**

- **That will clarify the <u>uncertainties</u> associated to the well integrity**

- **That will treat the <u>risk sources</u>**

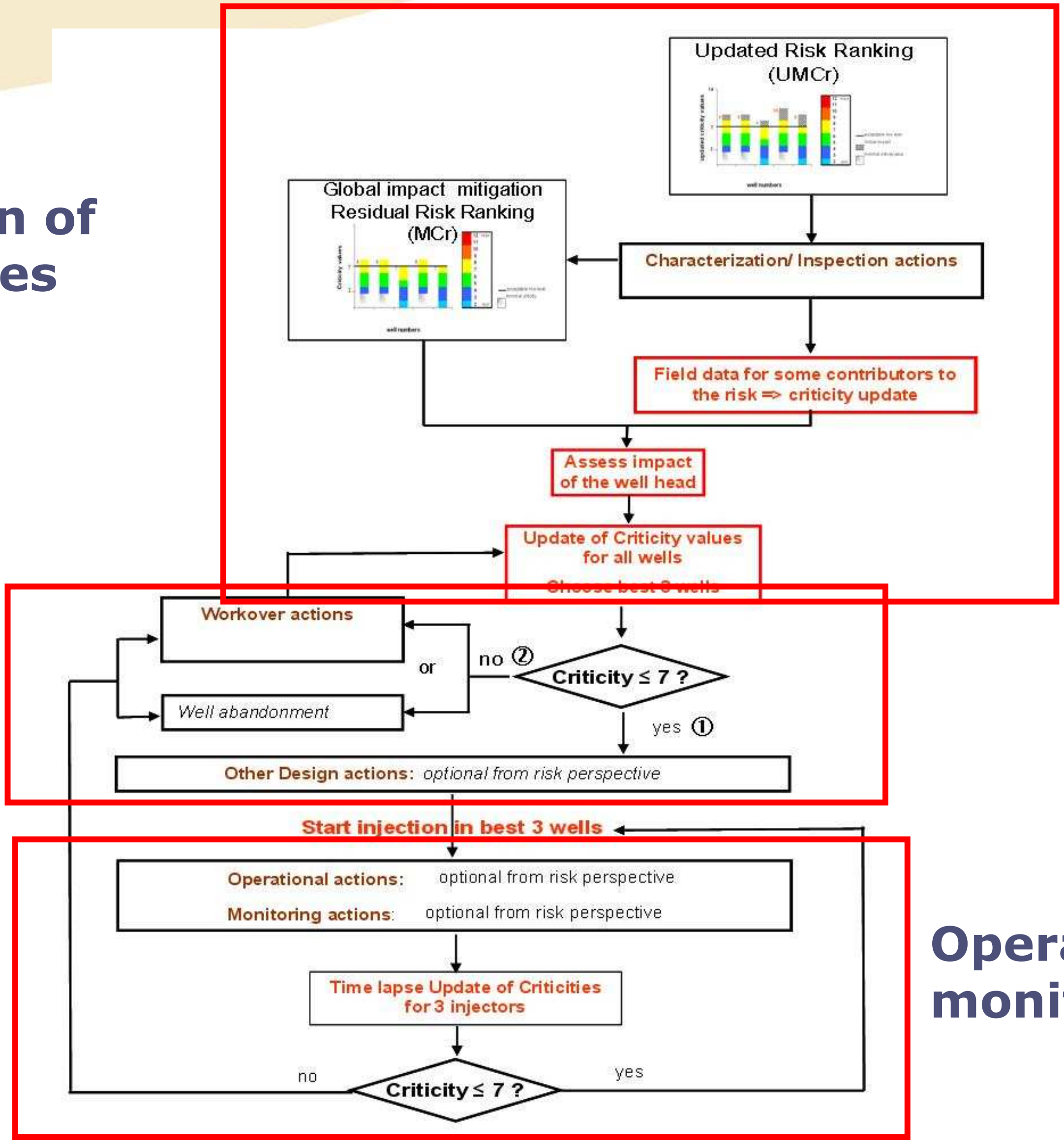
➔ Operational response : decisions tree…

Example of decision tree applied to risk treatment



Clarification of uncertainties

Workover & design actions



Operation & monitoring actions

Summary

Introduction

Context of the study: issues for the operator

Purposes of the study

Key steps of the study, main results and recommendations

Risk assessment

Risk management

Decision support

Conclusions

The case study – What was achieved ?

Operator assessment

What was achieved ?

- **Use of a risk-based approach as a criterion for decision support for conversion of wells**
  - *Quantitative risk assessment*

- **Among 9 wells, 5 candidates were proposed for conversion into injectors**
  - *Justification / Demonstration of selection*

- **Actions for risk management were proposed**
  - *Prioritization*
  - *Operational response for the operator*

Operator assessment

- **A good overview of well integrity before and at the end of the injection period vs. uncertainties**
- **The consequence grid**
  - *The operator is able to relate a well integrity failure to a severity level (no questioning)*
- **The risk level as an objective metric for the project**
- **Demonstration / Justification of decisions**
  - *To the top management prior to apply any action*

CO2 Cementing
Where Are We Now?

Bob Carpenter
Craig Gardner

4th Meeting of the Wellbore Integrity Network

Paris, France
19 March 2008

 DOC ID

Do We Truly Have a Problem?

- We must keep one eye on the lab but the other on our field experience

- How many wells in existing CO_2 projects leak?

Laboratory Testing

- Laboratory findings may be the result of the conditions imposed
    - Intended and un-intended bias – reality check
    - Surface area versus sample mass
    - Conditions of shear
    - Effect of pressure and temperature
- How can we accelerate the test to simulate long time periods without exaggerating the results?

Mechanical Properties Testing

- Long term zonal isolation often depends on the ability of the cement sheath to successfully withstand imposed stresses.
- Little to no laboratory work has been done evaluating mechanical properties of CO_2 resistant cement or any cement after long-term exposure to CO_2.
- Testing protocols and simulation capabilities just being developed (with or without CO_2)

Historical Approaches

- Reduce the percentage of Portland Cement by using non-CO_2 reactive materials as diluents
- Lower the permeability to slow reaction rate

Alternatives to the Current Approach

- There are no alternatives suitable for broad application.
  - Non-Portland formulations
  - Proprietary CO_2 Resistant formulations
- Cost of special materials is 4-10 times Portland

Field Implementation

- Blending
  - Specialty Blends require special care
  - Must isolate materials and use representative samples for testing
  - Not all bulk plants are up to the job
- Availability
  - Only two commercial solutions
  - Problems with either one
- Logistics
  - Aluminates not compatible with Portland
  - Transport Issues
  - Manufacturing and Aging issues

Wells

- New wells and old wells present different challenges
- Can we separate the two, will there not be old wells adjacent to new wells?
- New wells can be purpose built with additional emphasis upon isolation, old wells were likely not.
- How do we ascertain whether old wells in the area are acceptable risks?

Leakage Paths

- Through the matrix
- Through a damaged sheath
  - Microannulus
  - Stress cracking
- Through a poor primary cement job

Leakage Rates

- What is the implication?
- Is CO_2 more prone to leakage?
- Are the consequences of CO_2 leakage worse than not injecting? Worse than Methane or H_2S leakage?
- Is there an acceptable leakage rate?

In Closing

There is a lot we don't know:

- The evidence of vulnerability of conventional cement formulations is not overwhelming.
- Need to balance lab work with field surveillance for calibration
- If a special CO2 Resistant cement is needed, the current systems need work; performance, value, logistics, mechanical properties
- Need to balance lab work with field surveillance for calibration