6th IEAGHG MONITORING NETWORK MEETING

Report: 2010/14

May 2010

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 28 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. IEAGHG is one of these Implementing Agreements.

DISCLAIMER AND ACKNOWLEDGEMENTS

IEAGHG 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 IEAGHG as a record of the events of that workshop.

The 6th IEAGHG Monitoring Network Meeting was organised by IEAGHG in co-operation with The Gulf Coast Carbon Center. The organisers acknowledge the financial support provided by The Gulf Coast Carbon Center for this meeting and the hospitality provided by the hosts at The convention Center, Natchez, Mississippi

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

Tim, Dixon, IEAGHG (Chairman)
Sue Hovorka, University of Texas
Kevin Dodds, BP
Hubert Fabriol, BRGM
Don White, NRCan
Charles Jenkins, CO2CRC
Andy Chadwick, BGS
Julianna Fessenden, LANL
Hilary Olson, University of Texas
Ziqiu Xue, Kyoto University
Millie Basava-Reddi, IEAGHG

COPYRIGHT AND CITATIONS

The report should be cited in literature as follows:

'IEAGHG, "6th IEAGHG Monitoring Network Meeting Report, 2010/14 May 2010"

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Orchard Business Centre,
Stoke Orchard, Cheltenham,
GLOS., GL52 7RZ, UK
Tel: +44(0) 1242 680753 Fax: +44 (0)1242 680758
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

Executive Summary

This is the report for the 6th meeting of the IEAGHG Monitoring Network, held in Natchez, Mississippi from 6th - 8th May 2010.

There are currently several carbon dioxide capture and storage (CCS) projects around the world with extensive monitoring programs. A review and new results for many of these were presented. As this meeting was held in the USA, a session was given to the work being carried out by the US Regional Partnerships (USRPs). This includes projects at various phases, including several at validation phase, planning phase and ongoing development phase. The latter includes the Cranfield site in Mississippi.

A session was given to how projects are able to develop within an evolving political and regulatory environment. In many regions, there are no CCS related regulations and so these will need to be developed alongside projects, making contact and discussion between the regulators, decision makers and those leading the projects imperative. The politics of regulations is evolving, and for each new site, it may be useful to see what is being mandated, in terms of monitoring, by regulations at other sites. The new US EPA reporting rule is in the proposal phase and would require mandatory reporting for geological storage projects, with elective requirements for EOR and R&D projects. Public perception is known to have a great effect on the evolution of a project, and needs to be considered at each site. It is also important to consider the practicalities of moving from small scale to large scale projects, as more commercial scale projects are developed. For example, it is unlikely to be practical to stop injection in order to carry out monitoring on a commercial project.

Following this session there was a panel discussion on the importance of uncertainty. A major issue is that there is such a broad spectrum of what people describe as uncertainty and it may be necessary to define how we are using the term and address that. Now that there are more monitoring results, there can be more comparison with predictive models. If the monitoring results diverge from the model, it is important to know what the reasons for this could be, but more importantly, it is necessary to know if it is a significant divergence. In other words, will it affect the storage security? An idea put forward, was that the injected CO_2 'illuminates the subsurface' as it increases the area of contact and provides new data on the subsurface. This leads to further knowledge, but also further uncertainty, so that the risk profile may not plateau after a certain point, but continue to increase until injection is ceased.

A session was given to post-injection monitoring. If monitoring is required for the long-term and required over many years, then a strategy to deal with that will be needed. If it is over a long time, then it will need to be cheap and effective. It is also necessary to be realistic about what can be seen and what can go wrong, and therefore what needs to be measured.

The final session was on emerging and innovative monitoring techniques, where talk topics included InSAR, ecological monitoring, ERT and geochemical monitoring. It was found to be useful to compare the same technologies used at different sites, as this helps to show some of their limitations as well as their benefits. One idea discussed was a master class or invited reviews for emerging technologies, which have already have been tested and are very likely to be used in large scale projects.

Key outcomes from the meeting are that there has been a big shift in the breadth and quality of work being done. There are more details, more knowledge and more projects from which to learn. However, there needs to be more data integration of geochemical, geophysical and modelling work, as well as more research on permanent installations and developing techniques such as microseismic monitoring.

Contents

Executive Summary 1

Session 1: Reports from Previous Meetings 5
1.1 Welcome Address – Sue Hovorka, University of Texas and Tim Dixon, IEAGHG 5
1.2 Summary from the last Monitoring Network Meeting – Kevin Dodds, BP 5
1.3 SEG CO_2 Update – Don White, NRCan 6
1.4 2010 Modelling Network Meeting Summary – Millie Basava-Reddi, IEAGHG 6

Session 2: Results from International Monitoring Projects 7
2.1 Ketzin Project – Conny Schmidt-Hattenberger, GFZ 7
2.2 An update of the Lacq-Rousse project – Hubert Fabriol 8
2.3 The Energy Technologies Institute – Activities in CO2 Storage – Kevin Dodds 8
2.3 CCP3-SMV – Kevin Dodds 9
2.4 Expert-Based Development of a Site-Specific Standard in CO_2 Sequestration Monitoring Technology – Susan Hovorka 9
2.5 Gorgon CO_2 injection Project Monitoring and Verification Plans – Adi Widyantoro 9

Session 3: Results from US and Canadian Monitoring Projects 12
3.1 Overview of US Regional Partnership Projects – John Beyer, LBNL 12
3.2 Update on Results of SECARB Test of Monitoring Large Volume Injection at Cranfield – Sue Hovorka, University of Texas 13
3.3 Overview of PCOR Partnership's Phase II MVA Activities – Steve Smith, EERC 13
3.4 Subsurface Monitoring Planning in DOE's WESTCARB Partnership and National Risk Assessment Partnership (NRAP) – Tom Daley, LBNL 14
3.5 Microseismic Monitoring of CO_2 EOR in the Aneth Oil Field – Jim Rutledge, LANL 14
3.6 Monitoring Activities under MRCSP Phase II field demonstrations – Neeraj Gupta, Battelle 15
3.7 New Results from Seismic Monitoring at the Weyburn CO_2 Storage Site – Don White, NRCan 16
3.6 Canadian Projects - Don Lawton, University of Calgary 16

Session 4: Monitoring in an evolving Regulatory and Political Environment 18
4.1 Overview of US EPA's Mandatory Reporting of Greenhouse Gases Rule: Injection and Geologic Sequestration of Carbon Dioxide – Barbora Master, EPA 18
4.2 Aquistore Project – Kyle Worth, PTRC 19
4.3 CO_2 Surveillance during CO_2 EOR and CCS Policy Progress in the US – Steve Melzer, Melzer Consulting 19
4.4 Overview of the PCOR Partnership's Phase III Field Demonstration: Spectra Energy's Fort Nelson CCS Feasibility Project – Steve Smith, EERC 20
4.5 Monitoring and Outreach: 21
4.5.1 Carbon Storage Outreach and Education with STORE – Hilary Olsen, University of Texas 21
4.5.2 SECARB ED: Southeast CO_2 Sequestration Technology Training Program – Kimberley Sams, SECARB 21
4.6 Some Remarks on Uncertainty – Andy Chadwick, BGS 21

Panel Discussion 22

Session 5: Post-Injection Monitoring 25
5.1 Otway and the risks of monitoring – Charles Jenkins, CSIRO 25
5.2 Post-Injection Monitoring at the Nagaoka Site – Saeko Mito, RITE 26
5.3 Post-injection monitoring at Frio – Sue Hovorka, University of Texas and Tom Daley, LBNL 27

Session 6: Emerging and innovative monitoring techniques 28
6.1 Surface deformation forward modelling cf InSAR data In Salah – Kevin Dodds, BP 28
6.2 Monitoring Ecosystem Impacts of CO2 Storage – RISCS project – Sarah Hannis, BGS 28
6.3 Evaluation of Geoelectrical Crosshole and Surface-Downhole Measurements – Conny Schmidt-Hattenberger, GFZ 29
6.4 Some Aspects of Seismic Monitoring at Otway – Milovan Urosevic, University of Curtin 30
6.5 Effects of CO_2 Injection on Mineralogy - Ernie Perkins, AIFT 30
6.6 Preliminary Electrical Resistance Tomography Results – Cranfield, Abe Ramirez, LLNL 31

Session 7: Conclusions 32

Monitoring Network Meeting Report

Session 1: Reports from Previous Meetings

1.1 Welcome Address – Sue Hovorka, University of Texas and Tim Dixon, IEAGHG

Sue and Tim welcomed everyone on behalf of the Gulf Coast Carbon Center and IEAGHG. The aims of the network were reiterated:

- **Overall aim:** To facilitate the exchange of ideas and experiences between experts in the monitoring of CO_2 storage, and to promote the improved design and implementation of monitoring programmes.

- **Specific aims and objectives**:
    - Assess new technologies and techniques
    - Determine the limitations, accuracy and applicability of techniques
    - Disseminate information from research and pilot storage projects
    - Develop extensive monitoring guidelines
    - Engage with relevant regulatory bodies

Tim also talked about the monitoring tool on the IEAGHG website, which was one of the early outcomes of the network.

1.2 Summary from the last Monitoring Network Meeting – Kevin Dodds, BP

The previous monitoring network meeting was held in Tokyo. The meeting was a good opportunity for discussion as there had been recent activity at demonstration projects. As the meeting was set in Tokyo, a large focus was on Japanese projects and a session given to discussing monitoring projects there. Key learnings were given from each of the sessions on reports from other initiatives; reports from projects; update on Japanese CCS progress; what regulators want; what monitoring can and cannot do; and emerging and innovative technologies.

The conclusions agreed at the last workshop were:

- Strong recommendation to use pilot-scale projects to focus and learn about post-injection CO_2 behaviour, as at Nagaoka, Japan

- Benefits of multi-scale integration of multiple datasets, e.g. combining seismic and electrical resistivity

- Regulations are based on qualitative rather than quantitative performance and require expert opinion to make decisions. This may become difficult due to a limited number of such independent experts in the CCS field at this early developmental stage.

- Atmospheric and surface monitoring can provide assurance to the public.

- The transmissivity of faults to CO_2 may be different to other molecules such as methane due to the ability of CO_2 to react with some materials in the presence of water. Additionally, more work is required to understand fault and overburden leakage pathways, i.e. Uncertainty over defining what is an acceptable match of predictions and the reality of CO_2 behaviour for the closure and liability transfer of storage sites. The first projects will set the precedent.

- Pressure front monitoring will be required

- Monitoring capabilities are good enough to get on with projects

1.3 SEG CO_2 Update – Don White, NRCan

Don gave a summary of the SEG CO_2 meeting in Banff in October 2009, which largely focussed on the current and future role of geophysicists in CO_2 sequestration. He gave a brief overview of the program with the selected highlights being:

- Observed seismic responses to CO_2 are often stronger than predicted theoretically

- Nature of CO_2 saturation (patchy/ homogeneous) affects seismic response

- Geochemical effects of CO_2 on the rock frame

- More lab studies are needed to understand the behaviour of CO_2 in rocks

Questions and Comments :

Poro-elastic monitoring has the biggest AVO effect, is this greater than 2? 1D modelling was carried out, though in the field there was a bigger response than expected.

Looking at scattered energy in the seismic dataset and remnant scattered energy demultiple techniques, how does this relate to the repeated image in Sleipner? Intrabed multiples are difficult to remove. The seabed multiple has been left in, as removing it, would also remove other data, but it is clear what it is. There is also much scattering, but this doesn't form any new horizons so it is very unlikely to be multiples in the interpretation.

The amount of CO_2 can be predicted using forward modelling in reservoir simulation, matching the image with seismic data, in order to validate results.

Is there evidence of multilayers at Sleipner? If you look at velocity pushdown you need 10's of metres of CO_2 to produce that, irrespective if it's a single layer or multilayers.

Regarding geomechanical issues, how does it affect timelapse? Modelling InSAR data results and transmission of stress into the overburden, shows a stress variation, which could be due to saturation effects.

1.4 2010 Modelling Network Meeting Summary – Millie Basava-Reddi, IEAGHG

The last modelling network meeting was held in Utah in February. There were 4 sessions on modelling methodology and recent advances; integrated roles and objectives; real storage projects: case studies and; best practice and modelling protocols. The agenda was designed to provide ample time for discussions between participants, with both breakout and plenary discussions.

Disscussion:

The discussion focussed largely on the possible integration of networks and ideas for other workshops.

The networks usually relate to each other by having a summary of one network in another network meeting and there is an overlap of attendees at each meeting. There is also the possibility of having two network meetings together, or with some overlapping days. There is also the joint network meeting, the last one of which was held in 2008 and the next one due to take place in 2011.

It was suggested that there could be more opportunity for overlap of the meetings, for example 2 days on the well integrity network followed by 2 days of the monitoring meeting. The floor was invited to suggest network combinations that they would like to see.

Most of the suggestions were for monitoring and risk assessment and monitoring and well integrity. It was noted that sometimes you don't get interpretation of results as well as theory as there may not be both sets of people at each meeting.

It was also pointed out that at any joint network meeting, the talks will not be on everyone's speciality. It was also said that we need integrated talks and that monitoring and modelling are intimately linked and that there is no point getting monitoring data if it cannot be put into a model.

It was noted that this was done in the modelling network, but the problem may be that the modellers assume that the monitoring data is all correct and that any problem is with the model. It might, therefore be useful to have monitoring experts to talk about uncertainties in the data.

Delegates were invited to contribute to a list of possible workshops that could take place next year, which could then be discussed later in the meeting.

Session 2: Results from International Monitoring Projects

2.1 Ketzin Project – Conny Schmidt-Hattenberger, GFZ

The Ketzin site, situated 25km west of Berlin and a former gas storage site, has been well explored and is made up of extremely heterogeneous formations. There are a variety of geochemical and geophysical monitoring methods being conducted at Ketzin and the talk concentrated on the geophysical methods that were able to describe the temporal and spatial behaviour of the CO_2 plume – seismic and resistivity. The seismic methods include 2D and 3D surface surveys as well as VSP and MSP surveys. Both methods show similar results and there is a good match between the modelling and monitoring results, though further refinement of the model is needed. Subjects still to be assessed are the quantitative assessment of competitive use of underground (i.e. geothermal activities) and up-scaling to commercial projects, which will be 2-3 times the size.

Questions and Comments

Will Ketzin have a data review and how will we hear when more data is available? There is a planned extended phase by national funding. We need to match results as the CO2SINK project is over. We have a review meeting this year in Vienna.

At Ketzin, is there any insight into why there was late breakthrough at the observation wells? There is very strong heterogeneity as the storage formation is a fluvial system. The first breakthrough matched the models well, but we are looking at possible permeability barriers that could have affected the flowpath and caused the CO_2 to take an alternate route.

2.2 An update of the Lacq-Rousse project – Hubert Fabriol, BRGM

The Lacq-Rousse project site is a complete CCS chain with a 30MW oxycombustion steam boiler connected to an old depleted gas field by an existing pipeline of 29 km long. The project started in 2006 with injection commencing in January 2010 at a rate of 60 kt/yr with a 2 year injection plan and permission for 3 extra years of observation. Throughout the process there was consultation and dialogue with the local populace and finally close to overall public acceptance. The injection stream has a fairly high proportion of oxygen, 92% CO_2 4% O_2, and is injected at 4500 m depth into the Upper Jurassic dolomitic reservoir, which is overlain with a thick sealing overburden. The main risks identified are geomechanical fracturing or reactivation of faults. There is possible fracturing at the top of the overburden and the pressure limit is set at 70 bar. There is also a shallow potable aquifer above the storage formation and the monitoring plan includes environmental monitoring of underground and surface waters. As there is a very thick overburden, the site is considered to be very unlikely to leak, though soil-gas measurements are still taken to comply with the regulations. The passive seismic array designed to detect induced seismicity is composed of seven vertical arrays (4 geophones each) in seven shallow wells (200 m deep) distributed around the injector (2 km distance) and one deep array within the injector near the top of the reservoir plus one surface seismograph. Results from this are not yet public.

Questions and Comments

At Lacq-Rousse, it is an oxyfuel capture plant, what is the impact of higher quantities of O_2? Is it strongly reducing? A research project is being started at the University of Pau to study the impacts of high O_2 content in the injected stream. Unsure as Total are yet to release that information. Since they started the operation, it is necessary to relate information as they need to be careful regarding public acceptance.

2.3 The Energy Technologies Institute – Activities in CO_2 Storage – Kevin Dodds, BP

The ETI involves several major companies, academic institutions and industrial partners in the UK and covers a broad range of low carbon energy solutions, one of which is CCS. A current project is the MMV project, contracted out to BGS, which includes analysis of the

UK's needs and reviews the current technologies and knowledge gaps and to develop a robust monitoring strategy.

2.3 CCP3-SMV – Kevin Dodds, BP

The aim of this project is to identify gaps that are not being worked on, and then publish them as a peer reviewed paper which will be made public. Kevin talked about the monitoring and verification section of this project. Objectives are to access existing demonstration monitoring experience and the response of emerging technology; to identify performance and cost effective criteria and incorporate all this into a defensible approach to define fit for purpose M&V programs. An important aspect of this is to be able to set up a permanent monitoring system, without having to drill several boreholes. Existing projects can be used to determine which sensitivities need to be measured and how this can be done in a cost effective way. They are also working with the Bureau of Economic Geology's EPA and CCP project to avoid duplication of effort.

2.4 Expert-Based Development of a Site-Specific Standard in CO_2 Sequestration Monitoring Technology – Susan Hovorka, University of Texas

The aim of this project is develop guidance for selection of monitoring approaches for a CO_2 sequestration site that is site specific and based on the quantification of monitoring tool sensitivity. This would be carried out by means of an expert panel providing information to those who need it. The panel is an open group to try and gain as much participation as possible, in order to be able to get real life monitoring experience. Ideally, both the favourable and the unfavourable results and methods, the latter of which is sometimes difficult to get information on as is not often published.

Questions and Comments

How will you get the information to decision makers? By using models to develop test cases. We will make workbooks, which will match available techniques to each site.

The resultant document has been described as general, but to be applied site specific. Who is the target audience? If we are going to inject at a particular site, then we need to determine which tools would work and what is measurable as well as what is required. It can also be a guidance for regulators on 'what to use for where'.

Comment: It might be useful to have an end user review group in order to get that perspective.

2.5 Gorgon CO_2 injection Project Monitoring and Verification Plans – Adi Widyantoro, Chevron

The natural gas produced at the Gorgon site contains 14% CO_2, which is to be extracted and re-injected via 9 injection wells separated by 7 km. There are also 4 brine production wells for pressure relief. One of the major challenges is to get a large amount of monitoring data as well as value for money. There is a comprehensive current MMV program, including 4D surface seismic, for which the baseline survey was taken in 2009 and soil gas measurements taken at Barrow Island. As more data is collected the MMV program can be updated. The risk assessment suggests that he risk is greater at the start of the project and during injection and lower during post-injection and it has been agreed with the regulators that monitoring should take place for 15 years after the end of injection. The project is currently in 'phase 4', which is the project delivery and operations phase. Drilling is planned to start in 2012.

Questions and Comments

How much of the Gorgon program is driven by the requirements of the government? There are currently no regulations, so we evaluate all methods and demonstrate these to the government. There is no regulatory influence at this stage.

What drove the decision to have pressure release wells and how can you evaluate how they perform? The team recognises that we cannot fracture the reservoir and the modelling suggested that this would happen; therefore it was necessary to manage the pressure, by producing a pressure sink. The challenge is in the location of the pressure management system.

The pressure management system could cause plume asymmetry and therefore the risk of early breakthrough. Part of the key to management of pressure is to make sure this doesn't happen. We have carried out several models, over the duration of 100 years, and found that the plume asymmetry was not affected.

Are there any concerns regarding other pressure effects by extracting water and re-injecting it at a shallower depth? There have been studies carried out on compatibility issues, and the aquifer into which the fluid will be injected has already been depleted.

Can you comment on the quality of the baseline seismic data? There are 3 source types how repeatable is it? The data is processed by 4 different companies, as it is complicated and we want good results. Regarding repeatability, we have set up holes levelled with steel caps, to make sure that each survey uses the same points.

How much geomechanical characterisation has been done on this site? We are working with another company, who are carrying out a full stress tensile model and will continue working on this. There are also regional studies.

There has been extensive monitoring, how much of this is due to regulations, what is the minimum? There is no minimum requirement as there are no official regulations yet.

Gorgon appears to be a very thorough and expensive program. What is the cost per tonne? That is not currently publicly available.

Discussion

Regarding reservoir heterogeneity, what could have been done to better characterise the site in order to predict the late breakthrough? We have the well log data and have built several profiles. There is not just the modelling data, but we can use analogues.

Heterogeneity is important and you need a full range of scenarios, but it may not be possible to build a suitable model as it is so complex, especially with only a few wellbores. It is important to use natural analogues to put into the model. This is something for future monitoring and modelling groups to look at.

Monitoring and building the model needs to be carried out at the same time. There is much more information after monitoring to be able to put this back into the original model.

What is important when looking at uncertainty is to determine how relevant it is. Does it affect the overall performance of the reservoir? Is the ultimate storage efficiency different? In the case of Ketzin, it did not affect the operation of the test site and the CO_2 remained securely within the storage formation, so in that way it was not significant. The further work is to understand the reason, because we want to know the reason.

Was the model calibrated to the rock and hydrologic test? Yes, this has been done.

So this shows that it is a 2 phase relative permeability issue? The model was calibrated to a single phase only.

It may be both a heterogeneity and relative permeability issue. There was a similar situation at another site with high heterogeneity and it was significant to storage potential. You need to have site specific injection tests. It's a complicated issue.

Have geoelectric measurements been taken along with seismic?

At Ketzin there has been both cross-hole and ERT. It is important to evaluate them together and match with the seismic. This will be presented fully on the following day.

At Gorgon, the earlier work was promising, but there is a problem with operability as we don't have 1km spaced wells, they are between 1.5km and 7km apart which is usually too great for effective results, however, we are not yet dropping the method.

At Ketzin, the distances are not so far (30m). It is necessary to show the regulator what this means.

Regarding capacity, a critical part of the resistivity model is to predict where the plume is going to be, as it is necessary to plan what to do next for operations. In EOR, we match oil/water production then match CO_2, each bit of information further refines the model

In Lacq-Rousse, why are the permanent geophones not working? There was a problem with the fibre optic data transmission downhole. Signals were received initially at the surface, but after returning in few months to take readings there was nothing. It was seen that temperature and pressure parameters are more important, which are retrievable and kept channels open for that rather than seismic. A workover operation is planned to start end of November 2010 to fix the situation.

How much of a problem is noise for the geophones in the injector? TOTAL is still carrying out preliminary studies. As soon as the downhole sensors will work properly, this question could be assessed.

It is still useful to see which methods don't always work, so that we can look at how to select methods. This could contribute to Sue's project.

Session 3: Results from US and Canadian Monitoring Projects

3.1 Overview of US Regional Partnership Projects – John Beyer, LBNL

The US Regional Partnerships were set up in 2003 to work on characterisation, validation and development phases. The aim is for at least 99% storage permanence, but a large problem is how to measure this. It is possible to monitor for leakage, but one of the major issues is where to monitor. Another is to have a have a value for CO_2; otherwise there is no economic reason for storage. The partnerships are at different phases and can be summed up below:

SWP (Southwest Regional Partnership on Carbon Sequestration) – currently wrapping up phase II projects, with the reports available summer 2010.
MRCSP (Midwest Regional Carbon Sequestration Partnership) - Is now composed of 9 states, all 3 demo projects have completed and there are currently 3 phase II projects.
PCOR (The Plains CO_2 Reduction Partnership) – There are 2 Phase II projects. An EOR project on the Wyoming-Montana border injecting 0.5 – 1 million t/yr.
SECARB – (Southeast Regional Carbon Sequestration Partnership) They have completed a pilot test at Mt Daniels into the Tuscaloosa sandstone. There are 2 coal projects, an anthropogenic test into a saline formation over an oil formation in Alabama and the Cranfield Phase III project.
Big Sky – Currently in negotiation to get CO_2 for their phase III project.
MGSC (Midwest geological Sequestration Partnership) – Phase II and III projects are combined, with the CO_2 being supplied from an ethanol plant. There are 2 monitoring wells with well logs and 3D surface seismic and 3D VSP surveys. Injection is planned to start next year.
WestCarb (West Coast Regional Carbon Sequestration Partnership) – There are phase II projects in Arizona, which is being complicated by a site access issue, as the test site is on Navahoe and Hopi Nation land. The same formation was tested at another location, but with near zero permeability. They are currently in negotiations with the Hopi Nation, who have a large part of their economy in coal. There is another test site in California, in a syncline between 2 depleted gas fields, where the primary trapping mechanism will be dissolution.

More information on the partnerships can be found at: http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html

3.2 Update on Results of SECARB Test of Monitoring Large Volume Injection at Cranfield – Sue Hovorka, University of Texas

Injection takes place at 3000 m depth. This area was originally a producing well, but when the gas cap was removed, the oil was shut in in 1965, after which there was no further exploration until Denbury took over the site for CO_2 flooding.

The phase III test took advantage of this being an easy place to start, as CO_2 was already being injected, permitting was less of a problem than at other sites. The CO_2 is produced from a natural source, so supply is also not an issue.

Denbury shared all the site characterisation data, so injection and monitoring was able to start in 2008. One million tonnes of CO_2 injection was achieved by 20th December 2009, which was earlier than expected.

The storage formation consists of relatively young, uncompacted fluvial sediments and the caprock is mostly marine black shales. The monitoring data shows the fluvial system is highly heterogeneous. There are a lot of wells on this site, from previous production, which can now be used for monitoring, but could also form possible leakage pathways.

The modelled and observed pressure measurements generally match well. Breakthrough times were faster than expected and appear to show CO_2 flow upwards from the 1st monitoring well to the 2nd, which may be due to the heterogeneity. The ERT data shows a secondary plume, though this is thought to be due to the plume migration being out of the measurement plane, although this is still to be fully interpreted.

3.3 Overview of PCOR Partnership's Phase II MVA Activities – Steve Smith, EERC

The PCOR partnership covers an area of more than 1.4 million square miles, over which there has been much oil and gas production and is supported by over 90 industrial partners. There are 4 validation tests. The Zama field and lignite storage in NW Dakota were talked about briefly, though the talk focussed on the Williston basin site at NW McGregor.

The goal of the project at the Williston basin is to evaluate storage with EOR in a deep carbonate reservoir and to determine the effectiveness of the Huff n Puff technique as well as to test RST and VSP monitoring techniques. 440 tonnes of CO_2 were injected over 36 hours, followed by a 2 week shut in and soak period, then further production. The rate of oil production increased by 3 times. This is a thick reservoir with 2 seal layers. Using the RST tool, it is possible to measure the saturation of the injected gas and oil. 5 days after injection the CO_2 was observed between the perforations and the seal and after 115 days it was mostly located at the base of the seal. VSP was used as the casing was in good condition and the tubing would not need to be pulled out of the well, however it did not provide good results. The reason for this is thought to be due the overlying glacial till package causing the signal to attenuate. To compensate for this the tubing was pulled up 100ft, after which the VSP results correlated well with the model. It is possible that the CO_2 plume could be seen using VSP.

Questions and Comments

Was a microseismic monitoring program carried out? Yes, it was successful program, but not sure if it could be combined with cross-well seismic.

3.4 Subsurface Monitoring Planning in DOE's WESTCARB Partnership and National Risk Assessment Partnership (NRAP) – Tom Daley, LBNL

This talk focussed on 2 of WestCarb's test sites in Arizona and California. The Arizona test site includes a single monitoring well and is not yet completed. There is an extensive MMV programme. The California test site is currently in the planning stage and is in a historically seismic area. The plan is to inject 6000 tonnes into a 3.3 km deep saline aquifer in a syncline, with residual trapping the dominant trapping mechanism. The monitoring plan includes monitoring for induced seismicity and the protocol for EGS (enhanced geothermal systems) has been adapted for storage.

NRAP is made up of 5 national laboratories and was formed to provide scientific underpinning for risk assessment with respect to long term CO_2 storage. The aim is to form a quantitative methodology for predicting a site's long term performance. There are focus groups on monitoring, wellbore integrity, groundwater impacts and systems modelling with each one producing a white paper. The monitoring group research priorities are to improve temporal and spatial resolution of monitoring, detection of leakage, quantification of uncertainty, induced seismicity, to improve integration of measurement and interpretation tools and to address scaling issues in monitoring data. The program is currently in the middle of its first year and the focus is on the high level priorities, which include identifying risks and uncertainties.

Questions and Comments

Regarding the earthquakes, where is the injection site in relation to the fault zones? Initial modelling showed pressure perturbation at the faults. At the depth of injection the fault is 5km away on the other side of the axis of the syncline. The plume undergoing residual trapping will migrate away from the fault, showing safe comparable storage.

Comment: At the Otway project, it is a fault bounded reservoir, but it is a depleted gas field, so there were less pressure issues.

3.5 Microseismic Monitoring of CO_2 EOR in the Aneth Oil Field – Jim Rutledge, LANL

CO_2-EOR has been taking place at the Aneth field since the 80's and the aim of this monitoring program is to monitor induced seismicity, which is expected due to the increased pressure and volume accompanying injection. It was stressed that microseismic monitoring should be an important part of an MVA programme. It can be used to map pressure fronts, infer preferred fracture flow direction and map containment of CO_2 in the target reservoir. It can give a sense of deformation and stress field and monitor and map fault activation and growth.

The microseismic locations revealed NW-SE striking structures near the margins of the reservoir and the main structure is resolved beneath the reservoir. It was also found that microseismic activity does not correlate with current injection activity in the reservoir, nor does it appear to correlate with deeper salt-water disposal. A recorded natural earthquake appears to have affected production and reservoir seismicity, possibly by the stress transfer driving an increase in pore pressure.

Questions and Comments

Has a temporal analysis been carried out? We have just started looking at this. Almost all moving fluid is vertically upwards.

How has that affected production? So far this is just the observations. We are working with partners to look at the production scale stress changes.

What were the location errors? It was mostly fairly good data, but there is a 30-40 m error, though further analysis is still needed. The depth of the furthest cluster is very poorly constrained.

There is no changing volume of fluid in the reservoir, what's the best explanation for the ongoing microseismicity? We are not sure, though the volume changes gradually over the years of production.

Would this have happened anyway? It's possible, but the fact that it all occurs on the edge of the reservoir might be too coincidental. One of the difficulties with ongoing EOR is that it has been going on for many years and we don't know what was going on before; we don't have a baseline.

3.6 Monitoring Activities under MRCSP Phase II field demonstrations – Neeraj Gupta, Battelle

The MCRSP consists of 5 states and a complex and diverse geology, where there are 3 deep, mature basins as well as the coastal plains. The projects discussed were 3 completed phase II projects in the Michigan basin, the Appalachian basin and the Cincinnati arch. At the Cincinnati arch site, injection was into the Mt Simon sandstone and was located below a potable aquifer, so the monitoring program included a 3 year groundwater monitoring survey. The vertical and lateral extent of the plume was able to be mapped by using VSP, while the vertical distribution of the CO_2 adjacent to the well was determined from geophysical well logs.

At the Burger power plant site (Appalachian basin site), a seismic survey was conducted and the injection well drilled. However the injection rate of 20 t/day was not able to be maintained and flow was reduced several times during injection testing, in order to maintain the correct pressure.

The Michigan basin site had 10 kt of CO_2 injected into the bass dolomites in 2008 with an extensive MMV program, the results of this enabled the conceptual model to be refined, especially as there is high heterogeneity in the formation. An extended injection program of 15 kt followed this, with a smaller MMV suite, which showed the CO_2 plume remaining stable below the caprock. This is seen as a low velocity zone on the tomographic image and is corroborated by the RST data.

A phase III project is also planned for the near future and several sites are under evaluation for this.

3.7 New Results from Seismic Monitoring at the Weyburn CO_2 Storage Site – Don White, NRCan

As of November 2009, 15 Mt have been stored at the Weyburn site by injection into at least 19 wells with variable injection rates. The storage formation is a fractured limestone and the caprock is anhydrite. This talk focussed on looking at caprock integrity through seismic AVOA analysis and monitoring the overburden by looking at out-of-zone seismic anomalies (OOZ).

Conclusions of the study were:

- Time-lapse amplitude & travel time anomalies are observed immediately above the reservoir caprock, at the base of the storage complex.
- They may be associated with OOZ CO_2 and/or injection induced stress changes in the overburden.
- Isolated anisotropic regions have also been identified at the caprock horizon that may be associated with vertical fracturing.
- Further work (modelling) is needed to assess the geological cause of these anomalies.
- OOZ CO_2 does not necessarily imply upward migration of CO_2; it may be the direct result of EOR injection procedures.

Questions and Comments

Is this going to be backed up with hydrogeologic or fluid sampling? Not yet, though this is a valid question as you need backup evidence.

3.6 Canadian Projects - Don Lawton, University of Calgary

The University of Calgary Rothney Astrophysical Observatory is used as the CCS test and training centre and is situated just outside Calgary at the foot of the Rockies at a depth of around 800m. The storage formation is a lower Tertiary sandstone and is known to be fractured. The controlled leakage pathway comes to the surface 1 km west of the injection site. There is 1 monitoring well and injection is planned to start in early 2011.

The goal of CCS projects in Alberta is to have 4 projects injecting 1 Mt/year by 2015. These are the Shell Quest/ Pioneer, Enhance project, Harp and Wasp projects and are all clustered around the industrial area near Edmonton. The Shell Quest/ Pioneer project involves capturing CO_2 from a power plant and injecting it into a deep carbonate saline aquifer. The Enhance project is an EOR project in the oil-sands. The HARP project is a federally funded project and is situated NE of Edmonton. Phase I of the project involves soil and groundwater sampling and has been completed and phase II has started and involves baseline soil-gas survey. Drilling has not commenced, though the injection well is to be 80 miles from the EOR site.

Discussion and further questions to the speakers

What is the reason for the observation wells being down-dip at Cranfield? The practical reason was that DOE was promised a non-EOR project and there was a limit on how close we were to the lease boundary. The research reason was that at Frio the observation well was up-dip, but there were also gravity forces during injection. We wanted to know how much the structure affected the flow direction and the results show that the CO_2 did flow down dip as predicted in the models. The gradient is only 1%.

At Weyburn, there is no velocity push down, which suggests that the CO_2 layer must be pretty thin. What is the geology and would it be in the caprock itself? The caprock is an evaporite and directly above this is the Ratcliffe formation, where there are permeable zones within the impermeable rock, then the Watton regional seal. Therefore it is difficult to see where it is, but it is above the caprock. It is correct though, that it could only be a small amount and it would be a very thin layer.

Could it be in the fractures? It could be. The reservoir is well characterised, but the caprock is not, so we cannot be completely sure of the geology.

Is it near any wells and can they be accessed to monitor or test well integrity? There are plenty of wells, but at the moment we do not have access to them, so really cannot say for certain what is there yet.

The anomaly is only in the caprock, not in the reservoir. Is it possible to simulate small amounts of CO_2 in an evaporite to model its effect and see if it matches? This is possible, but has not been done yet.

How repeatable is this and what are the number of sources? The source locations are offset less than 5 m. Some source positions cannot always be occupied as there is water in low lying areas.

Has there been analysis on gathers as well as on the migrated data? This work is currently being done. Preliminary results indicate that the prestacked data is noisy.

It looks like there are 50 new wells in that area, could this be a possible cause? Yes it could be, there are so many wells, but the anomaly is over several wells, so I think that this is unlikely, even though there are injector well integrity issues. It is possible that one injector was positioned above the reservoir for a while.

There has been an MIT paper on AVOA coder analysis, which shows that rays in the fast direction do not get scattered as much as rays in the slow direction, which may help in this analysis.

In the PCOR project, did you consider CO_2 storage in lignite and have you considered that methane is a much stronger greenhouse gas than CO_2? Methane production is one of the primary goals of the project. Gas production went online, but we got nothing back. We tried all different stimulation techniques and acidizing and took samples for methane content, but it was not there. We are not currently working on lignites, but are aware of the significant resource in that area.

At the Aneth field has there been any 3-D geomechanical work, would it make sense of the data? We are trying to make a geomechanical model to see if the volume change could have caused stress changes. There is a rough correlation with salt water injection, but it doesn't correlate spatially, so there may be a geomechanical correlation.

At the Michigan basin project have you been able to analyse the microseismic data? Yes, it shows that only one of the microseismic events is related to injections. Other events seem to be only temporally related to injection. There is also a possible leakage pathway along a wellbore, though this is not clear.

In the Aneth field, when you get the velocity anomaly with CO_2, the amplitude anomalies are even greater. Are you using crosshole tomography as an input to crosshole imaging? They take the tomographic velocity image and use it for timelapse seismic imaging. I agree that it would be good thing to do.

Session 4: Monitoring in an evolving Regulatory and Political Environment

4.1 Overview of US EPA's Mandatory Reporting of Greenhouse Gases Rule: Injection and Geologic Sequestration of Carbon Dioxide – Barbora Master, EPA

The role of the EPA is to develop regulatory frameworks and this new proposed rule is a reporting mechanism for facilities that inject CO_2. The rule was proposed 12th April 2010, and is open for a 60 day comment period until 11th June. EPA aims to finalize the rule in time for reporting to begin January 1, 2011. It would amend the greenhouse gas reporting program, under the Clean Air Act. It is intended to be complementary to and to build on UIC Class VI wells requirements.

As proposed, information to be reported would be the amount of CO_2 received onsite from offsite sources, the amount of CO_2 injected into the subsurface and the source of the CO_2 if known. Sites involved in geological sequestration would be required to develop an EPA approved MRV plan and report the amount of CO_2 stored, calculated by CO_2 injected – CO_2 emitted.

These data will enable EPA to track CO_2 flow across the CCS system, but EPA does not intend to prescribe specific monitoring techniques. As proposed, sites involved in EOR or R&D projects would not be required to report, but could choose to opt in.

Questions and Comments

You will be compiling an electronic database, but this can open uncertainty, as CO_2 is sometimes transferred and sometimes emitted, how will you deal with purchased CO_2? The aim is not to track by molecule, but to get data on how much is permanently stored, then we can see how much new CO_2 is being purchased and can understand the sources.

What is permanence defined as and how does this affect credits? We are not specifying permanence and this is not a credit system.

Are there any requirements regarding post-injection monitoring? Yes, we proposed requirements that are similar to the requirements for Class VI wells. Until the plume appears stabilised, it would be necessary to keep reporting, after that reporting would no longer be necessary.

Does EPA have to approve an MRV plan and how complex a plan is needed? There is a proposed general outline, but it still needs to be fleshed out.

Including a risk assessment seems inconsistent as the UIC asks for zero leakage, that everything must be contained within the reservoir, though it should be based on risk not zero leakage. We worked closely with the office of water which aims to protect USDWs. We are building on top of their UIC Class VI proposed rulemaking.

4.2 Aquistore Project – Kyle Worth, PTRC

The Aquistore project is a collaborative project involving industry and governments. It commenced January 2009 and will run until 2013. CO_2 is to be captured from a refinery and will be transported through a pipeline and injected into a saline aquifer at 2200 m depth.

Saskatchewan aims to reduce GHG emissions by 20%, though there are still regulation uncertainties, which are currently being negotiated. The regulations are planned to be defined by spring 2010.

The storage area will be in the NW Williston basin in Saskatchewan, in an area previously explored for oil and gas as well as potash, and so the area is geologically well understood. Most of the surrounding area is used for potash mining; the storage area was considered unlikely to be used for this, so was made available. Plume migration modelling has been carried out and a comprehensive monitoring program is planned. There will be 1 injection well and 1 monitoring well containing permanent downhole geophones to accompany the pressure, temperature and fluid sampling. The injection well is planned to be drilled in November 2010.

There were no questions following this talk.

4.3 CO_2 Surveillance during CO_2 EOR and CCS Policy Progress in the US – Steve Melzer, Melzer Consulting

One of the major expenses of CO_2-EOR is purchasing CO_2, the cost of which is around $20/t, making surveillance of CO_2 necessary to make sure that it is cost effective. It is metered at custody transfer points and at collection/redistribution points and efficiently recaptured at producing wells. At custody transfer points, accurate metering is needed as it involves the sale of CO_2; mass, density and sometimes composition is measured. The types of meters used are differential pressure, displacement, velocity and mass. The most commonly used are differential pressure meters, which are generally either orifice or wedge meters.

The talk ended with a summary about how EOR and CO_2 storage can be used together:

- Retention is proven *(and very high – 95-99% CO_2 stored)*
- Is 'commercial' Storage
- Adds domestic oil production
- Avoids 'waste' perceptions with public
- Provides a bridge to deep saline formations
- Regulatory infrastructure in place

Questions and Comments

What is the accuracy of the amount of CO_2 metered? There is much uncertainty, mainly due to impurities in the stream, such as H_2S and CH_4, which complicates the issue.

Is there also uncertainty in the amount of CO_2? 0.5 % accuracy in the meters is good. It is affected by several other factors, a major one being the seasonal delivery from domes, as the volume changes at different temperatures.

4.4 Overview of the PCOR Partnership's Phase III Field Demonstration: Spectra Energy's Fort Nelson CCS Feasibility Project – Steve Smith, EERC

The PCOR partnership is involved in 2 phase III projects, an EOR project at Bell Creek and the Fort Nelson feasibility project, which is the focus of this talk. British Columbia is addressing the issue of CO_2 injection for non-EOR purposes, but there are currently no regulations regarding this. It is anticipated that the existing legislation will be able to be modified for CCS initiatives and regulatory authority would lie with the oil and gas commission.

The source of CO_2 will be from the Fort Nelson gas plant, which currently produces 1Mt/ year, though this is expected to increase as gas production in the basin increases.

Access permits to the storage area have been obtained, though it is only accessible during winter. The storage formation is a saline aquifer 8000 ft deep and the exploration well was drilled in spring 2009. This well was re-entered and subsequent testing occurred in the winter drilling season of 2010. A risk management plan has been developed and a modelling and MVA plan is being developed. The next steps include drilling the next test well, a 3D seismic survey, core and fluid analysis as well as updating the geological maps and the static and dynamic modelling.

Questions and Comments

Is the 85% H_2S supercritical? Yes, as this is a deeper aquifer.

Is the aquifer sour? Yes, the gas is currently 15% H_2S, and when the 12% CO_2 is added, then it will go down to 5% H_2S.

4.5 Monitoring and Outreach:

4.5.1 Carbon Storage Outreach and Education with STORE – Hilary Olsen, University of Texas

The aim of STORE is to create a skilled workforce for the CCS industry and foster the public understanding required to advance the United States in both energy security and a leadership position with regard to climate change mitigation technology. This is to be done by promoting transfer of scientific knowledge and applied engineering technologies related to CO_2 storage in 4 areas. These are sequestration workforce training, public outreach, R&D Transfer and workforce pipeline education.

Training is carried out by running short courses and workshops for scientists and public outreach events are held in schools and museums. Another initiative was to train teachers who would then train 25 other teachers, who would all then be able to educate their students.

Full details of activities can be found on the store website: www.storeco2now.com

There were no questions following this talk

4.5.2 SECARB ED: Southeast CO_2 Sequestration Technology Training Program – Kimberley Sams, SECARB

The aim of this initiative is to develop a self-sustaining regional CO_2 sequestration training program to facilitate the transfer of knowledge and technologies required for site development, operations and monitoring of commercial CCS projects. This is being done in conjunction with universities within the SECARB partnership, each of which specialise in a certain area.

The objectives of the program are to implement sponsorship development program, develop short courses on CCS technologies, conduct regional training and other activities through outreach and networking and perform region/basin technology transfer services.

There were no questions following this talk

4.6 Some Remarks on Uncertainty – Andy Chadwick, BGS

Monitoring activities will be related to the regulatory framework. Pre-injection predictive models are used, which monitoring can verify once injection has started, then further models are created with the new information, which are further verified. Post-injection models need to show a long-term robust prediction verified by monitoring before transfer of liability can take place.

When using predictive flow modelling, instantaneous uncertainty remains roughly constant, but leads to divergent long-term outcomes. However with geological storage, the long-term process is stable and instantaneous uncertainty decreases with time. When comparing the predictive models with monitoring data, the aim is not just to see if they match, but whether any mismatch is significant. For this it is important to look at what processes could cause the mismatch and whether they could compromise storage security.

There will always be an element of uncertainty, but this can be managed by deciding what uncertainty is acceptable. When looking at the EU directives, for example, to show that actual behaviour of the injected CO_2 conforms to the modelled behaviour, it is necessary to demonstrate basic understanding of the processes and show that uncertainty will not lead to future divergence. When confirming no detectable leakage, it must be taken into account that monitoring tools have finite detection thresholds and it is necessary to accept site characterisation i.e. 'innocent until proven guilty'. To show that the storage site is evolving towards a situation of long-term stability the onset of the key stabilisation processes should be demonstrated, possibly by using analogue data from pilot-scale or similar sites.

Panel Discussion

Panel Members: Andy Chadwick; BGS, Kevin Dodds; BP, Sue Hovorka; University of Texas, Charles Jenkins; CSIRO, Hubert Fabriol; BRGM

The discussion started with the need to define uncertainty as it is a big term and can mean different things to different people. The panel members gave some comments on what they thought the most important aspects are.

AC: There is uncertainty in predictive modelling, every time a predictive model is compared to the following monitoring results, there is always a blurred mismatch between the model and the monitoring dataset. What needs to be determined is when that mismatch is significant.

KD: It is necessary to deal with this in a systematic way for projects in the long term. If there is a project, how can information reduce uncertainty? The project can be divided into stages. At the start there is a large uncertainty in knowledge of the subsurface, so to acquire the information there is the site selection process with drilling and well logging. This means that you start with a very high uncertainty, which decreases as you get more information. During injection the model is updated with the results and uncertainty continues to decrease.

Risk follows a different path, before injection there is no risk (defined as impact times likelihood of leakage), as there is no CO_2 to leak. At injection the risk will increase gradually as the CO_2 interacts with possible leakage pathways in the subsurface, then flattens out. At the end of injection the risk decreases sharply as the maximum risk of leakage is reached and the other processes, such as dissolution etc. take over, though never reaches zero. The risk assessment is essential as it will determine the type of monitoring and when to use it. Baselines will need to be established, but the intensity of monitoring will depend on the risk, and will increase before the end of the project and the number of wells will decrease. The main question is how to choose what monitoring programme is needed.

AC: This describes a convergent site, that behaves as predicted, but if it does not behave as predicted then it will start to diverge. There might be a problem, if injection is into a closure, but the CO_2 then moves to another closure with a fault in it, the risk will increase again and we will need to get back to convergent circumstance. So uncertainty can increase as well.

KD: There is a general decrease in uncertainty as we get a better understanding of the geology, but there may be some intermittent small increases. In Salah is a good example, as there is time to gain a better understanding of the geology, gather more information and update understanding. There was uncertainty about fractures, which were anticipated, but we didn't know if that would be a dominant process. If you start with a risk model, gather data to address risk and then come back and do this again once more information is available, eventually uncertainty goes down.

SH: Proposing a hypothesis: When CO_2 is injected it "lights up" the subsurface that could not be seen before, such as the geochemistry and pressure limits, which the predictive model is dependent on, and as more of the structure is seen, an improved understanding can be gained. In the initial stages of pilot testing, decisions are made as to the viability of the project, so it may be a better indication of the risk if the chance of leakage is given as a percentage, similar to how the weather is predicted. That way a range of uncertainties can be considered.

CJ: Regarding probability as just mentioned, it is necessary to be clear on different kinds of uncertainty, for example that found in financial literature compared mathematical modelling. There is uncertainty, which means you don't know, but also an uncertainty related to probability, where there is a range of possibilities, which is how a risk assessment is formed. This can be shown using breakthrough curves and error bars on data points. The problem is not knowing if the conceptual models are realistic and the concern is a Rumsfeldian uncertainty. If something has not yet been found or has been missed, there is no control over it.

AC: This illustrates a convergent model, there is an initial inaccuracy, due to the uncertainty of the CO_2 behaviour, but is ultimately correct.

HF: A major issue is how to get accurate measurements, which is very important in monitoring. We need to talk about how it is difficult to get good instrumentation and good data. Accurate measurements are a way to reduce uncertainty, It is necessary to find what is the best configuration for tools and which processes to use.

The discussion was then opened to the floor.

The statement 'innocent untill proven guilty' was used, but it was suggested that if there is evidence of leakage then it is certain that there is no containment, but if there is no evidence of leakage, it is not certain. You cannot say if you haven't looked.

Using the EU regulations for example, it can be seen that it would not be possible to get into the situation where the site is not monitored, as there needs to be MMV plans. After injecting for 30 years or so, there will be a significant amount of measurement, and if they show the site to be behaving as expected, there is no reason to think that there might be leakage. The initial characterisation is more important. Take Sleipner as an example, the 3D seismic data shows a uniform unit. There are lots of wells, not at the site, but through the Utsira formation. So it can be said, that it is not likely to be faulted, which is strong evidence of no leakage, then add the extra data, which confirms this, which means that it can be assumed that there is no leak.

Part of the problem is that everyone has different ideas of who is to be convinced that there is no leakage. It is one thing to have a technical discussion with regulators and another to convince the public.

How much uncertainty is ok, depends on who the audience is. The public probably want zero error bars.

There is always uncertainty and unexpected things can happen, so there needs to be some kind of range, which is an acceptable uncertainty and a way to be able to assess what is acceptable.

It was suggested that we need to use probability more. Though saying that 95% certainty of containment and 5% uncertainty, does not mean a 5% chance that things will go wrong and it will leak.

Part of the problem is that policy people and regulators want uncertainty, and therefore risk, to be zero, which is not possible. If we can show something like 65% of outcomes look one way and 25% another, all of which is acceptable, this could be a strategy for managing uncertainty and drive risk towards zero. We can plan to change the injection strategy, depending on new information whenever we have it. So we could have a minimum and maximum and if it falls outside of this, then we would go to the contingency plans. It will be necessary to plan for high probability and contingency.

There will never be zero uncertainty and therefore risk can never be reduced to zero However, uncertainty and risk are not coupled that strongly, so it is possible to have a high uncertainty and low risk.

It was suggested that the uncertainty is not reduced that much beyond the site characterisation and injection stages. During the operational phase, measurements still need to be taken and the uncertainty in that has not decreased.

There was some disagreement as it was pointed out that the CO_2 illuminates the reservoir in a way that you couldn't see in the pre-injection geological characterisation stage.

The front of the plume is much harder to determine, it will quite often diverge from the model after a few years, so it is not definite that uncertainty should decrease once injection is started.

However, he number of measurements taken will increase, which will give more information over time.

In modelling there is uncertainty about permeabilities and how to tighten up the distribution. It is hard to get more information on these input parameters. Sufficient parameters may not always be taken into account, for example there were two possibilities or scenarios at

Sleipner impacting on different containment risks. The westwards migration scenario can now be seen to be not happening, so uncertainty, in that respect is massively reduced.

Uncertainty drops greatly during the site characterisation phase, but there is still uncertainty as to what the plume will do, and more measurements will need to be taken. In the injection phase, you will be tightening up some things and also eliminating some things, but a range of parameters will be taken into account. It may then be possible to reduce 3 model possibilities into 1. There is a change in the uncertainty curve, but it is still not flat, unexpected things may still happen.

The area of convergence between predictions and observations keeps growing, if injection continues for a long time. An increasing amount of space is affected, so the amount of relevant things that will be known increases. It is necessary to find out more, retesting the hypothesis with the same data.

There are other factors that are not taken into account. It could be possible to reduce the amount of information required to understand these factors and accept a level of uncertainty (although rigorous processes are needed to properly define those uncertainties). They may be outside of control, for example earthquakes, but when we follow processes, there is a close interaction with the risk assessment, which will dictate the amount to measure.

There is uncertainty in many things and we need to assume that some uncertainty exists. It will be necessary to go into the field and acquire data to improve confidence. Then it needs to be decided what mismatch between predictions and observations needs to be acted on. For example, if the model is off by 5 days after 350 days of injection, do we act on it? A worst case scenario example could be unexpected fault related containment failure, and then it would be necessary to make adjustments to the operation. Uncertainty needs to be handled throughout the whole project.

Session 5: Post-Injection Monitoring

5.1 Otway and the risks of monitoring – Charles Jenkins, CSIRO

Monitoring is carried out for public assurance, quantification and climate change regulations. When measuring for public assurance, the stakeholders wish to see that nothing has changed and that that storage of CO_2 has had no adverse effects.

There are 2 types of error Type I and II. A Type II error is when you do not see a change that has taken place due to noisy data. A Type I error is when you see a change, but is in fact caused by noise; this is also called the “false alarm rate”.

The assurance program at Otway consists of 4 components, groundwater, soil-gas, headspace gas and atmospheric monitoring. The groundwater survey showed an anomaly post-injection, but when the data was scrutinised more closely, it was found to be a false positive and well within the noise level.

In summary, it is necessary to understand, ahead of time, how you will draw conclusions from monitoring, which will involve some heavy-duty statistical work if monitoring techniques are being pushed to the operational limits.

5.2 Post-Injection Monitoring at the Nagaoka Site – Saeko Mito, RITE

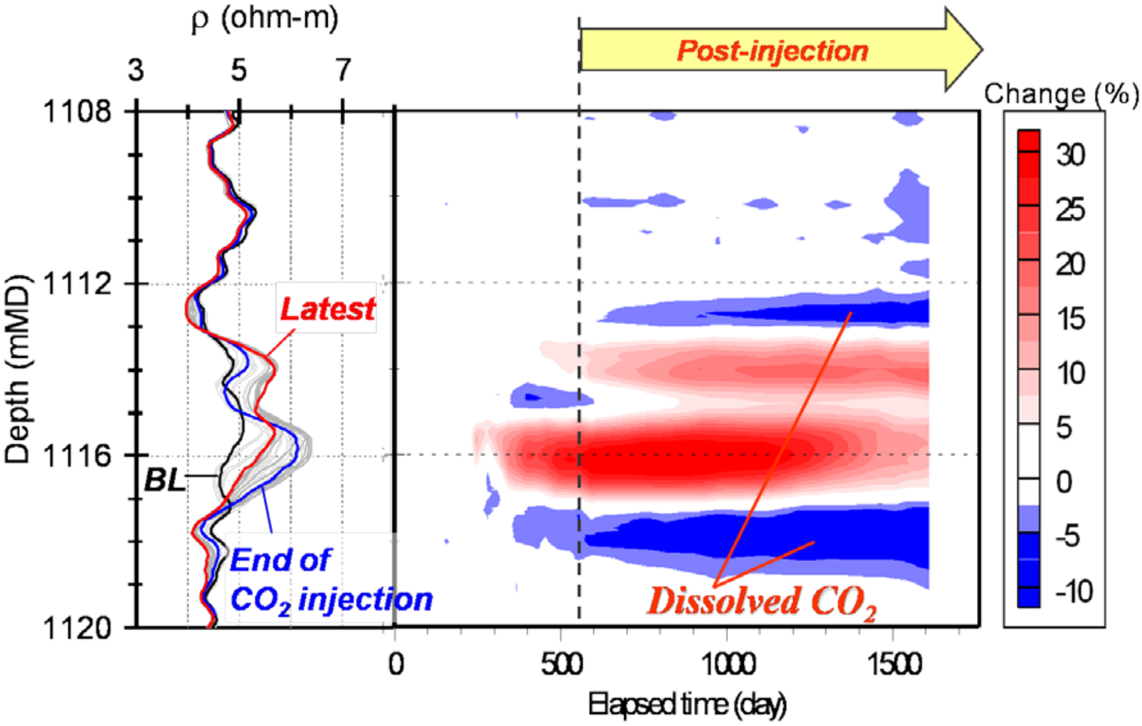
10,400 tonnes of CO_2 was injected into the Pleistocene sandstone of the Haizume Formation by 2007. There is 1 injection well and 3 observation wells (OB1-3), 2 up-dip, 1 down-dip and seismic tomography sections between OB2 and OB3. The post-injection monitoring program has been completed, but is planned to start up again later this year. The aim of the future program is to monitor pressure and CO_2 distribution and to predict the long-term fate of the injected CO_2.

The modelling results correspond closely to the monitoring results, which is important for site abandonment to take place.

During injection, increased pressure was seen and breakthrough was detected in OB2 and OB4, but not in OB3. The seismic tomography section shows the CO_2 at the top of the reservoir. The anomaly seen is 100 m by 30 m, which is a good match to the model, which predicted 105 m by 20 m. Preliminary trapping data showed CO_2 trapped as a gas phase. In OB2, after breakthrough there was a decrease in neutron porosity followed by an increase. Over time there is a decrease in resistivity at the top of the reservoir. This is evidence of solubility trapping of the CO_2 (Figure 1).

The future monitoring plan involves well logging, seismic tomography and 3D VSP, all with the aim of improving the understanding of CO_2 distribution.

Figure 1 Resistivity monitoring at OB2; Mito, 2010



5.3 Post-injection monitoring at Frio – Sue Hovorka, University of Texas and Tom Daley, LBNL

1600 tons of CO_2 were injected in 2004 at a depth of 1500 m, which was followed by a second injection in 2006 of 300 tons at 1650 m. VSP surveys were taken, the third VSP, before plug and abandon (P&A), was taken in 2009. The storage formation is a steeply dipping (11-16˚), mineralogically complex reworked fluvial sandstone saline aquifer, with a multilayered shale caprock.

The 3 VSP surveys were re-processed together and there is a response seen from the 2 plumes formed from the 2 injections, but not from the known leak. The two known plume amounts are monitored in the same VSP dataset, leading to implications of a minimum quantity of CO_2 detectable using the VSP technique.

As the VSP reprocessing did not show the observed changes, current research is looking at the raw data. With limited source points the imaging (using VSP-CDP and migration) is less clear, probably due to velocity heterogeneity. The data will be used to study repeatability, quantification and storage permanence.

Questions and Discussion

At Frio the anomaly is greater than during the earlier survey, so will there still be free phase? Yes, we still expect to have some free phase. The model showed that it would not have dissolved at all at that stage.

It appears that the 3rd survey is of higher quality. Not if you look at the entire dataset, where it is all pretty consistent. There are still a lot of changes in there.

Is there a reason why there is no difference map? There is an interval time shift in here, and so I don't want to arbitrarily apply it.

Not saying that the interpretation is not valid, but if you were looking for a leak and did not know where it was, this wouldn't be determinable from the data. Yes this is true, this interpretation of the results can really only show this as we know where the location of the leak was, otherwise we would need corroborating evidence.

Looking at the Nagaoka data on the dissolution slide, the lower resistivity area is getting thicker – is that real? You can see the blue colour at the top and bottom. Where the blue becomes narrower, it could be an increased density of the formation water, because of dissolution, but we do need further data and are planning to sample again to find out. (see Figure 1).

Session 6: Emerging and innovative monitoring techniques

6.1 Surface deformation forward modelling of InSAR data at In Salah – Kevin Dodds, BP

An accurate elastic earth model is necessary to calculate what surface deformation is caused by subsurface flow. The data can become complicated by atmospheric and soil changes, which will need to be corrected for. The modelling carried out by Lawrence Livermore shows the effect of the reservoir and fractures. Surface deformation is not very sensitive to the vertical extent of the fault, so it is hard to determine if the fault is in the overburden and reservoir.

The coupled geomechanical analysis indicates that the uplift is consistent with pressure-induced volumetric expansion of reservoir rocks within the 20 m thick injection zone and perhaps within the 100 m thick zone of shaley sands just above the injection zone. The partial pressure drop and slow subsidence after shut-in of KB502 is consistent with pressure-induced elastic volumetric changes in the reservoir rock. The double uplift lobe is consistent with lateral expansion of a jointed zone extending about 200 m up from the reservoir (i.e. to below 1600 m).

Questions and Comments

InSAR is sensitive to the pressure field, but this is not the same as the plume. Are people looking at that to try and map the plume? Yes, you can assume they are looking at that. From the graphs you can distinguish between the two fairly well.

6.2 Monitoring Ecosystem Impacts of CO_2 Storage – RISCS project – Sarah Hannis, BGS

This is a 4 year project, started in January 2010 with no results as yet, the ultimate aim is to produce a guide for impact assessment. The project will involve experiments and observations of natural analogues in both marine and terrestrial environments.

The guide for impact assessment aims to inform stakeholders on key issues:

- What to consider when appraising potential impacts in the event of leakage from a storage site.
- How to evaluate the potential impacts of storage project development: design stage, construction, operation, post-injection and to enable transfer of site liability to the competent authority.
- Options for directly assessing the potential scales (temporal and aerial, realistic leakage ranges (fluxes, masses)) and ecosystem responses.
- Options for identifying, predicting and verifying the nature of impacts.

Questions and Comments

The benefits could be as good as the detriments. Are they looking at this? Yes they are looking at any and all impacts.

If there is a leak, it might not arrive at the surface, so there would be non pure CO_2. Will they look at effects of the impure gas? In the experimental part of the project it will be only pure CO_2. The natural analogues will contain impurities.

6.3 Evaluation of Geoelectrical Crosshole and Surface-Downhole Measurements – Conny Schmidt-Hattenberger, GFZ

Geoelectrical monitoring along with seismic is intended to measure the migration of the injected CO_2. The vertical electrical resistivity array (VERA) has 45 permanent electrodes, with 15 electrodes per well, giving an electrode spacing of around 10 m across an installation depth of 590 to 735 m. The area covered was the same as that covered by the seismic survey, in order to be able to compare the results.

The VERA system has been successfully installed and operating for three years. The pre-injection resistivity model was built based on site-specific data relating Archie's law with standard sandstone parameters. It is a low-resistivity environment (few Ωm to below 1 Ωm), with a thin reservoir layer (max. 20 m) and small resistivity contrasts due to partial CO_2 saturation.

Studies incorporating multi-phase fluid flow modelling were performed. These indicated a significant dependency of apparent resistivity alteration to hydraulic conductivity within the reservoir (due to time-dependent CO_2 distribution). Inversion results are in good correspondence with current information from other monitoring systems (seismic, gas monitoring, RST and DTS) and contribute to the "big picture", although more detailed investigations need to be conducted.

Questions and Comments

Does how deep you measure, depends on the distance between electrodes? There is an advantage to being a shallow reservoir as what we have seen is not only noise. It is still limited and we could enlarge the area, by making the dipole larger at the surface, but then it would be mostly noise. 1000-1200 m should be the maximum depth. We were asked if this method can be applied for industrial wells, which it could, but it is necessary to use a complementary method as well.

If it was a commercial project, would the longevity of the fibre-glass casing be an issue? Possibly, and it is unsure how stable the system would be with a metal casing as the measurements would not be as good. It depends on what is planned for the wells, but it would likely need a compromise with steel, maybe using a textile casing.

6.4 Some Aspects of Seismic Monitoring at Otway – Milovan Urosevic, University of Curtin

This is a multi-injection plan into the Naylor reservoir. The first stage is 65 kt of 80:20 CO_2/ CH_4 transported and injected into one well, then the second stage is 10 kt of the same stream injected into a second well under the Huff n Puff method. The Naylor reservoir is a depleted gas field and is small, thin, relatively deep and heterogeneous making monitoring difficult, and so the most sensitive seismic techniques are needed.

The decision was taken to include time lapse 3D surface seismic in the monitoring plan. Although it is the least sensitive and repeatable, it provides coverage of the entire reservoir and is necessary for assurance monitoring. Also included is time lapse borehole seismic; 3D VSP with 3C geophones. This has improved sensitivity and resolution relative to surface data, improved repeatability and has increased the chance for direct CO_2 monitoring, albeit with limited coverage. Lastly there is 2D seismic monitoring with permanent sensors, which is potentially the most sensitive and repeatable technique.

Conclusions were:

- Good quality timelapse 3D surface data were acquired with Uni-crew.
- Base line seismic data recorded with free fall weight drop source, next two repeats with minivibroseis; very good (post-stack) repeatability achieved!
- Changes in soil saturation produce kinematic effects and different ground roll patterns
- CO_2 upward migration (“Leak”) would be readily detectable with 3D timelapse seismic.
- 3D repeatability much higher than 2D repeatability.
- Low signal to noise ratio and low NRMS can be improved with either strong source or high-fold.
- M&V of CO_2 storage in depleted gas fields could be achievable with high resolution 3D timelapse seismic. Analysis at Otway is ongoing
- Repeatability is important and may need to be determined ahead of timelapse seismic (NRMS is a function of S/N which is dependent on several variables)

Questions and Comments

An easy way to get repeatability is to take a legacy survey, take gathers, take out half of ray set then stack both halves, and compare. Unfortunately this won’t help with any seasonal repeatability problems. Most of the problems are with seasonal repeatability, though this method is better than nothing.

6.5 Effects of CO_2 Injection on Mineralogy - Ernie Perkins, AIFT

The Penn West monitoring program was completed in 2008 and the geochemical monitoring is ongoing. The mineral reactions were evaluated by direct observation of the core, predictive modelling and interpretation of fluid samples. The site had undergone water flooding before CO_2 flooding and changes caused by one were not able to be distinguished from the other.

General conclusions reached were that a significant amount of mineral reaction will only be observed in limited areas and that field chemical/ operational history may interfere with/ hide mineralogical (and fluid) changes.

Site specific conclusions were that core studies, geochemical modelling predictions and interpretation of monitoring data all indicate that mineralogical changes are small, that the impact of mineralogical changes on flow is minimal and that formation water chemistry is very a sensitive monitoring tool for monitoring mineralogical changes.

Questions and Comments

How does this relate to other reservoirs? Different reservoirs operate differently and the mineralogy is critical. Silicates react slower than what we are sampling for. Massive changes can be predicted if experiments are saturated and out of equilibrium. The water flooding process is destructive, because the minerals are dissolved then new water is introduced.

Is this typical? This is typical of silicate reservoirs as they have low reactivity and most of the reactions will take place at the front edge. Carbonates can be thought of as 'fast' reactors and amorphous iron oxides are much faster and it is possible to mobilise a lot of iron. Silicate reactions are slow enough that they will still be happening 10, 50 or 100 years down the line.

Is there any difference if there is fracture permeability? Yes, that is one inadequacy of the reservoir model. It is much different to matrix flow, because of the type of reactions.

6.6 Preliminary Electrical Resistance Tomography Results – Cranfield, Abe Ramirez, LLNL

ERT is a fairly robust system as there are no moving parts, it has a relatively low cost and can be operated remotely and continuously. The deepest ERT array is at 3200 m. There are 2 vertical cross-well electrode arrays 41 m apart and 10,000 measurements per day are collected.

The conclusions reached were:

- CO_2 produces a strong signal.
- ERT reconstructs basic plume details, but to a coarse resolution.
- Resistive anomaly appears associated with CO_2 movement in Lower Tuscaloosa formation with December 9, 2009 arrival at the F2 well.
- Significant positioning and resolution loss due to electrode damage in well F2, analysis continues.
- Conductive anomaly apparently due to work over fluids appears just after start of injection
- The system continues to remotely log ~10,000 ERT measurements/day (May 2010).

Lessons learnt from the experiment are that the robustness of electrode centralisers need improvement, the time required for cabling installation needs to be shortened while maintaining array robustness, for which the choice of electrical connectors may be very important and more well centralisers may be needed to protect wiring and electrodes.

Questions and Comments

Would it be possible to use surface current dipole with the sensors at that depth? No, as they would not have enough sensitivity.

The electrode is on fibreglass casing, could an insulator on steel casing be used? The electrodes need to be on outside of the casing, though other ways of insulating could be with epoxy paint.

Comment: That is what is used at Ketzin. If it is very shallow a plastic casing centralisers can be used.

Could another option be to have a dedicated well and cement it in? This is possible, but then the well is no longer multiuse.

It was pointed out that it is important to look at the completion costs compared to not completing it like this. At the Cranfield site a dedicated well would be $1.3 million, whereas this well with 'the works' was $1.6million. This means that lowering the pipe must be done slowly to avoid losing the hole. Pressure control is also important due to water flooding. A bigger hole of 12" had to be drilled rather than the normal 9.5".

In the CO_2 ReMoVe project, dedicated downhole electrodes were not used, but instead the whole metallic casing was used to inject the current. It was possible then to play with the frequency, though there were problems of resolution.

In Ketzin, there were 15 electrodes, at Cranfield only 7, which would severely limit the amount of information. If that can be fixed it would be a large step forward. Then you can bring in the other data to join the inversions.

Session 7: Conclusions

In the discussion following session 1, delegates were invited to suggest possible other workshops or ideas for joint meetings. A list of these were created throughout the meeting and then discussed.

Firstly it was noted that it is important not to reproduce what the other meetings are accomplishing, the ideas were:

Cement quality impacts on MMV: can we have missing/ bad cement affecting monitoring results. Permeability pathways don't work through coring very well. At the Michigan site the entire MMV program was changed due to some missing cement higher up.

Some MMV equipment installations (e.g. making casing non-conductive for ERT) can make it harder to get a good cement job. An idea is to put a geophone behind the casing, but would this compromise well integrity?

Microseismics: though there may be a lack of data so far.

Geochemical activity and induced seismicity, in terms of stress concentrations. This could look at InSAR as well.

It was also thought by many delegates that the network meetings could be more interactive. The best combinations were considered to be the monitoring network with the risk assessment or modelling networks. The most popular was to have the combination with the modelling network, because joint discussion as to why monitoring and modelling results do not always match up, and what the subsequent best course of action would be, was brought up during the panel discussion on uncertainty.

Key Learnings:

Projects

The speakers from CO_2 storage projects were asked to give a sentence summarising what is currently the most important aspect that is being worked on or needs to be worked on for their site.

Aquistore: Key drill and instrument injection well.
Weyburn: Well integrity – program of wells exposed to CO_2 – special tool.
HARP: Data well and baseline monitoring.
Fort Nelson: injection commencing.
PCOR: Injection commencing.
MGSC: Developments and baseline monitoring and maybe injection.
SECARB: Anthropogenic site: permit and install wells. Integrate geophysical and geochemical data – time lapse gravity.
WESTCARB: 2 wells, 1 in Arizona, 1 in north California – start drilling to 14k.
MRCSP: Phase II monitoring – best practice.
SWP: Site characterisation and drafting a monitoring plan (using the RA) started.
Lacq: Results from passive seismic monitoring.
Gorgon: Cross-well evaluation and phase IV EM.
Ketzin: Further data matching / data integration.
Otway: Do residual trapping Huff-and-Puff experiment (leave for 1 week) and integration for timelapse post-injection surface seismic and VSP. Follow up HnP with a permanent installation of geophones along the service well.
Nagaoka: Coupling modelling and monitoring for the post-injection phase.
Sleipner: Gravity CSEM – interpret it.
In Salah: Fracture analysis and microseismics.

Monitoring in an evolving political environment

The politics of regulations is evolving, and for each new site, it may be useful to see what is being mandated, in terms of monitoring, by regulations at other sites.

The new EPA rule is in the discussion phase until 11th June and involves mandatory reporting for geological storage projects, with elective requirements for EOR and R&D projects. EPA requirements for storage sites are a risk assessment and a strategy to quantify leakage, but are non-prescriptive on techniques. Monitoring is required until plume stabilisation.

Injection of mixed gases is going on at some sites. There needs to be more thought about well installation and design and integration with injection. The practicalities of moving from small scale to large scale need to be thought of as it will not be possible to stop injection to carry out monitoring on a commercial project.

Public perception needs to be discussed for each site as it can be a ‘showstopper’. Talks on public outreach have shown how this is being addressed. The programs discussed are comprehensive and highly geared to information transfer. It is important to see how this can be reproduced elsewhere.

A comment was made that it could be useful to speak on outreach on a particular project, though it was agreed that this would be more appropriate for the social research network. However, it was considered useful to have a talk on outreach, regarding the interaction with monitoring and that it could be useful to have one at each network meeting, but in a way that would be appropriate for each meeting.

Uncertainty

A major issue is that there is such a broad spectrum of what people think of as uncertainty and it may be necessary to define how we are using it and address that.

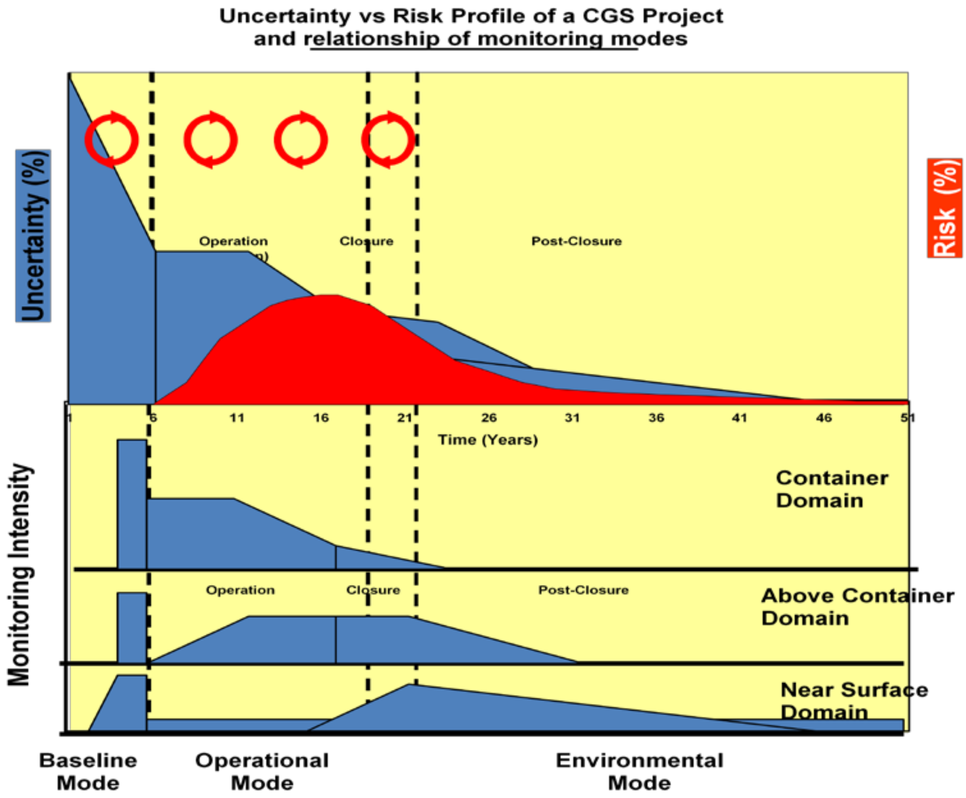
There are measurement related uncertainties and uncertainties related to modelling results, which will never completely match the monitoring results. A large part of dealing with uncertainty is recognising when a mismatch is significant.

There is also a difference in the uncertainty relating to unexpected events and the broad probability and uncertainty ranges on parameters.

Uncertainty is critical for risk assessment processes and updating monitoring information. Uncertainty and risk over time are interactive but not dependent on each other.

It was put forward that the injected CO_2 illuminates the subsurface, by increasing the area of contact and providing new data on the subsurface. This leads to further knowledge, but also further uncertainty, so that the risk profile may not plateau after a certain point, but continue to increase until injection is ceased (Figure 2).

Figure 2



Dodds, 2010

Post-Injection

Monitoring is required for the long-term and required over many years and so we need a strategy to deal with that. If it is over a long time, then it will need to be cheap and effective. There will need to be data integration of geochemistry, geophysics and modelling.

In the USA, the EPA perspective is that each site needs to be monitored until plume stabilisation.

It was also agreed that some 'mythbusting' may be necessary. Stakeholders want monitoring for 50 years, but it is necessary to be realistic about what can be observed and what can go wrong.

A note from Charles' talk on the risks of monitoring, highlights dealing with what happens when you get data that looks like something that isn't something (false positives). It is necessary to deal with this situation before it happens, by deciding what you are monitoring for as you cannot just remove a data point. A communication plan is needed to explain a false positive to the public.

Emerging and Innovative Monitoring Techniques

It was found to be useful to compare the same technologies used at different sites, as this helps to show some of their limitations as well as benefits.

An idea was a master class or invited reviews for emerging technologies, but at the stage where a lot of potential technologies would have been ruled out. There could possibly be a keynote on technology opportunities, which is not project specific.

Key Outcomes and Learning Points

There is a big shift in the breadth and quality of work being done. There are more details, more knowledge and more projects from which to learn.

There needs to be more data integration of geochemical and geophysical and modelling work, as well as more research on permanent installations and microseismics.

Recommendations on future network combinations

Networks	**Joint Meeting Topics**
Risk & Monitoring	Integration process Risk-Monitoring -Mitigation
Monitoring and modelling	• History matching. How close? • Geomechanical interpretation of induced microseismics • Faster iterations between model and data
Well integrity	• Cement quality impact on MMV • Integrity and MMV with perforations
Permanent monitoring	1. Stress concentration 2. Instrument wells 3. Did monitoring result in negative outcome?

All the presentations are available on the web site:
http://www.ieaghg.org/index.php?/2009112020/monitoring-network.html

The next meeting Monitoring Network meeting will be hosted by the GFZ, Potsdam, Germany in 2011.

6th Monitoring Network Meeting

6th-8th May 2010
Natchez, Mississippi, USA

Organised by

IEAGHG and Bureau of
Economic Geology at the
University of Texas

Hosted and sponsored by
Gulf Coast Carbon Centre at the Bureau of
Economic Geology at the University of Texas

6th May 2010 Day 1

08.30 to 09.00 Registration

Session 1: Report from previous Meetings Chair - Tim Dixon; IEAGHG & Susan Hovorka; University of Texas

09.00 to 09.20	Welcome Address: Susan Hovorka; University of Texas & Tim Dixon; IEAGHG
09.20 to 09.40	Summary from the last Monitoring Network Meeting: Kevin Dodds; BP
09.40 to 10.00	SEG CO_2 Update: Don White; NRCan
10.00 to 10.10	2010 Modelling Network Meeting Summary: Millie Basava-Reddi; IEAGHG
10.10 to 10.30	**Discussion**

10.30 to 11.00 Coffee Break

Session 2: Results from International Monitoring Projects Chair - Don White; NRCan

11.00 to 11.20	Ketzin Project; Conny Schmidt-Hattenberger, GFZ
11.20 to 11.40	The Lacq Rousse Project (France): Hubert Fabriol; BRGM
11.40 to 12.00	ETI Review Outcomes and CCP Projects: Kevin Dodds; BP
12.00 to 12.20	EPA-CCP Study: Susan Hovorka; University of Texas
12.20 to 12.40	Gorgon CO_2 Monitoring & Verification Planning: Adi Widyantoro; Chevron
12.40 to 13.10	**Discussion**

13.10 to 14.10 Lunch

Session 3: Results from US and Canadian Monitoring Projects Chair Susan Hovorka; University of Texas

14.10 to 14.30	Overview of US Partnership Projects: John Beyer; Lawrence Berkeley National Laboratory
14.30 to 14.50	Phase III SECARB Project Cranfield: Susan Hovorka; University of Texas
14.50 to 15.10	Overview of the PCOR Partnership's Phase II MVA Activities: Steve Smith; EERC

15.10 to 15.50 Coffee Break with Poster Session

15.50 to 16.10	MMV Planning WESCARB and DOE's National Risk Assessment Partnership (NRAP): Tom Daley; Lawrence Berkeley National Laboratory
16.10 to 16.30	Microseismic Monitoring of CO_2 EOR in the Aneth Oil Field: Jim Rutledge; Los Alamos National Laboratory
16.30 to 16.50	Monitoring Activities under MRSCP Phase II Field Demonstrations: Neeraj Gupta; Battelle
16.50 to 17.10	Status of Canadian Projects: Don White; NRCan
17.10 to 17.40	**Discussion**

Close Day 1

Evening cocktail reception (cash bar) and hoer d'oerves Dunleith Plantation and Historic Inn

ieaghg

7th May 2010 Day 2

Session 4: Monitoring in an Evolving Regulatory and Political Environment Chair -Tim Dixon; IEAGHG

08.30 to 08.50	Overview of US EPA's Mandatory Reporting of Greenhouse Gases Rule: Injection and Geologic Sequestration of Carbon Dioxide: Barbora Master; US EPA
08.50 to 09.10	Aquistore Project: Kyle Worth; PTRC
09.10 to 09.30	CO_2 Surveillance During CO_2 EOR and CCS Policy Progress in the US: Steve Melzer; Melzer Consulting
09.30 to 09.50	Overview of the PCOR Partnership's Phase III Field Demonstration: Spectra Energy's Fort Nelson CCS Feasibility Project: Steve Smith; EERC
09.50 to 10.10	Monitoring and Outreach: Carbon Storage Outreach and Education with STORE: Hilary Olsen; University of Texas SECARB ED: Southeast CO_2 Sequestration Technology Training Programe: Kimberley Sams; SECARB

10.10 to 10.40 Coffee Break

10.40 to 11.00	How do we Deal with the Question of Uncertainty? Andy Chadwick; BGS
11.00 to 12.00	Panel discussion: How do we deal with the question of uncertainty? Chair: Andy Chadwick; BGS Panel members: Kevin Dodds; BP, Hubert Fabriol; BRGM, Charles Jenkins; CSIRO, Susan Hovorka; University of Texas

12.00 to 13.00 Lunch

Session 5: Post-injection Monitoring Chair –Andy Chadwick; BGS

13.00 to 13.20	Otway and the Risks of Monitoring: Charles Jenkins; CSIRO
13.20 to 13.40	Post-injection Monitoring at the Nagaoka Site: Saeko Mito-Adachi; RITE
13.40 to 14.00	Post-injection Monitoring at Frio: Susan Hovorka; University of Texas and Tom Daley; LBNL
14.00 to 14.30	**Discussion**

Session 6: Emerging and Innovative Monitoring Techniques Chair –Charles Jenkins; CSIRO

14.30 to 14.50	Surface Uplift at In-Salah: Kevin Dodds; BP
14.50 to 15.10	Monitoring Ecosystem Impacts of CO_2 Storage– the RISCS Project: Sarah Hannis; BGS
15.10 to 15.30	Geoelectric Monitoring at Ketzin: Conny Schmidt-Hattenberger; GFZ

15.30 to 16.00 Coffee Break

16.00 to 16.20	Some aspects of Seismic Monitoring at Otway: Milan Urosevic; Curtin University
16.20 to 16.40	Effects of CO_2 Injection on Mineralogy: Ernie Perkins; AIFT (Formerly ARC)
16.40 to 17.00	Preliminary Electrical Resistance Tomography Results -Cranfield: Abelardo Ramirez; LLNL
17.00 to 17.30	**Discussion**

Session 7: Key Outcomes form Meeting Chair –Kevin Dodds; CSIRO

17.30 to 18.30	Outcomes and recommendations from the 6th monitoring Network Workshop Panel members: Kevin Dodds; BP, Susan Hovorka; University of Texas, Tim Dixon; IEAGHG

Close Day 2

Site Visit to the Cranfield Injection Site - Saturday 8th May 2010

08.30 Bus departs from the Natchez Convention Center for Cranfield

16.00 Depart Cranfield for Natchez Convention Center

Steering Committee

Tim Dixon, IEA GHG (Chair)
Millie Basava-Reddi, IEA GHG
Susan Hovorka, University of Texas (Representative of the hosts and co-Chair)
Andy Chadwick, BGS
Charles Jenkins, CSIRO
Don White, NRCan
Hubert Fabriol, BRGM
Julianna Fessenden, LANL
Kevin Dodds, BP
Hilary Olson, University of Texas
Ziqiu Xue, Kyoto University

Evaluating technology options to mitigate greenhouse gas emissions

The Gulf Coast Carbon Centre at the Bureau of Economic Geology at the University of Texas is supported by

ATTENDEE LIST

6th Monitoring Network Meeting

6th-8th May, 2010 Natchez, Mississippi, USA

Millie Basava-Reddi, IEAGHG

Adnand Bitri, BRGM

John Henry Beyer, Lawrence Berkeley National Laboratory

Bob Butsch, Schlumberger

Andrew Chadwick, British Geological Survey

Charles Christopher, BP Alternative Energy

Marcia Coueslan, Schlumberger

Tom Daley, Lawrence Berkeley National Laboratory

Tim Dixon, IEAGHG

Kevin Dodds, BP

Hubert Fabriol, BRGM

Neeraj Gupta, Battellle

Sarah Hannis, British Geological Survey

Susan Hovorka, Gulf Coast Carbon Center, Bureau of Economic Geology

Charles Jenkins, CSIRO

Robert Kiker,

Keigo Kitamura, RITE

Don Lawton, University of Calgary

Barbora Master, US EPA

Franz May, BGR

Tip Meckel, Gulf Coast Carbon Center, TX BEG

Steve Melzer, Melzer Consultants

Saeko Mito-Adachi, RITE

Modesto Montoto, Fundación Ciudad de la Energía

Nobumichi Morishita, Japan NUS Co.

Jean-Philippe Nicot, Texas Bureau of Economic Geology

Hilary Olsen, University of Texas

Jennifer Owens, St Francis Xavier University

Ernie Perkins, Alberta Innovates—Technology Futures

Guillemette Picard, Schlumberger

Albelardo Ramirez, Lawrence Berkeley National Laboratory

Richard Rhudy, EPRI

Kaylene Ritter, Stratus Consulting Inc.

Will Roadarmel, Pinnacle

Katherine Romanak, University of Texas

Jim Rutledge, Los Alomos National Laboratory

Kimberley Sams, SECARB

Sohei Shimada, RITE

Conny Schmidt-Hattenberger GFZ

Steven Smith, Energy & Environment Research Center

Nobukazu Soma, AIST

Daiji Tanase, J-Power

Robert Trautz, EPRI

Kirk Trujillo, Halliburton

Milovan Urosevic, Curtin University

Hans-Dieter Vosteen, State Authority for Mining, Energy and Geology

Don White, NRCan

Adi Widyantoro, Geological Survey of Canada

Kyle Worth, Petroleum Technology Research Centre

IEA Greenhouse Gas R&D Programme

6th Monitoring Network Meeting

Hosts : University of Texas
Sponsors : Gulf Coast Carbon Center at Bureau of Economic Geology at University of Texas

Natchez, USA, 6-8 May 2010

Sponsors 6th Monitoring Network meeting

Sponsors : Gulf Coast Carbon Center at the Bureau of Economic Geology at the University of Texas is supported by :

LCRA
Environmental Defense
Kinder Morgan
Austin Energy
Jackson School of Geosciences at the University of Texas
STORE
Luminant Energy
BP
Entergy
Chevron
Marathon

IEA Greenhouse Gas R&D Programme (IEAGHG)

- A collaborative international research programme founded in 1991
- Aim: To provide information on the role that technology can play in reducing greenhouse gas emissions from use of fossil fuels.
- Producing information that is:
  - Objective, trustworthy, independent
  - Policy relevant (but NOT policy prescriptive)
  - Peer reviewed by external Expert Reviewers
- Focuses on Carbon Dioxide Capture and Storage (CCS)
- **Activities:** Studies and reports (>120); International Research Networks: *Wells, Risk, Monitoring, Modelling, Oxy, Capture, Social Research;* Communications (GHGT conferences, IJGGC, etc); facilitating and focussing R&D and demonstration activities eg Weyburn; working with IEA (including Regulators Network), GCCSI, CSLF, EU ZEP, US RCSP, CO2CRC, etc.

IEA GHG is an IEA Implementing Agreement in which the Participants contribute to a common fund to finance the activities.

IEAGHG R&D Networks

- Bring together international key groups of experts to share knowledge and experience
- Identify and address knowledge gaps
- Act as informed bodies, eg for regulators
- CO2 geological storage – assessing and managing risks
- Started in 2004/5
  - *Risk Assessment Research Network*
  - *Monitoring Research Network*
  - *Wellbore Integrity Research Network*
  - *Modelling Network (2009)*
- Benefit experts and wider stakeholders
- Depend on experts' time and inputs – valuable and widely appreciated

6th Monitoring Network Meeting, Natchez, USA 2010

5th Tokyo, 2009

4th Edmonton, 2007

3rd Melbourne, 2006

2nd Rome, 2005

1st California, 2004

Monitoring Network -

- **Overall aim:** ***To facilitate the exchange of ideas and experiences between experts in the monitoring of CO2 storage, and to promote the improved design and implementation of monitoring programmes***.

- **Specific aims and objectives**:
  - Assess new technologies and techniques
  - Determine the limitations, accuracy and applicability of techniques
  - Disseminate information from research and pilot storage projects
  - Develop extensive monitoring guidelines
  - Engage with relevant regulatory bodies

  - Monitoring Selection Tool

    http://www.ieaghg.org/index.php?/ccs-resources.html

6th Meeting Agenda

1. Welcome and Reports from Previous Meetings
2. Results from International Monitoring Projects
3. Results from US and Canadian Monitoring Projects
4. Monitoring in an Evolving Regulatory and Political Environment – Discussion on Uncertainty
5. Post-injection Monitoring
6. Emerging and Innovative Monitoring Technologies
7. Key Outcomes and Conclusions from Meeting

Cranfield Injection Site Visit

Steering Committee for 6th Monitoring Meeting

Tim Dixon – IEAGHG

Susan Hovorka – University of Texas

Kevin Dodds - BP

Hubert Fabriol – BRGM

Don White - NRCan

Charles Jenkins – CO2CRC

Andy Chadwick – BGS

Julianna Fessenden – LANL

Hilary Olson – University of Texas

Ziqiu Xue – Kyoto University

Millie Basava-Reddi - IEAGHG

IEA Greenhouse Gas R&D Programme

6th Monitoring Network Meeting

Hosts : University of Texas
Sponsors : Gulf Coast Carbon Center at Bureau of Economic Geology at University of Texas

Natchez, USA, 6-8 May 2010

IEA Greenhouse Gas R&D Programme

Conclusions from 5th Monitoring Network Meeting

Kevin Dodds
BP Alternative Energy

- Hosts : RITE, JAPEX, AIST, Kyoto University

Tokyo – 2-3 June 2009

Key Learnings

Reports from other initiatives

Reports from Projects

Update on Japanese CCS Progress

What Regulators Want

Reality Check – What can and can't monitoring do

Emerging and Innovative Technologies

Recurring key learnings and other points

Workshop Conclusions and Key Points for other Networks

Learnings from Reports from Other Initiatives

- Using benchmarks
- Understanding fault activation (from EI workshop) leading to leaks
- Understanding leakage through overburden processes – hydrologists and reservoir engineers collaborate
- Natural CO2 analogues not same as leaks from reservoirs (eg leaching)
- Risk and Monitoring Networks together
- Comprehensive coverage of workshops' areas and summaries
- Modelling – coupling effects, basin scale

Learnings from Reports from Projects

- Ketzin
- CO2CRC Otway
- US RCSP

- Get support of stakeholders
- Regulation approval takes longer
- Learning from faults in projects is recommended, proving not leaking, studying fault behaviour in seismic activity
- Natural faults not same as faults associated with reservoirs
- Use literature for man-made release (brine, not CO2)
- Usefulness of these workshops in sharing learnings between regions/countries

Learnings from Japanese CCS

- Integrated multiscale study provides calibration of fluid processes over time
- Gives insight to post injection processes and monitoring – imaging of dissolved CO2 — welcome and encourage to take further, sensitivities, error-bars – appropriate site for this work
- first study providing evidence of stabilisation – providing lots of learning
- Instrumenting injection wells

Learnings from What Do Regulators Want?

- Better understanding now of regulatory requirements
- Qualitative performance targets, not quantitative
- Evidence required at liability transfer?
- Accuracy required of leakage measurement (ETS)
- Pressure front monitoring and hydraulic connectivity at distance – how to monitor?
- Uncertainty over defining acceptable match of predictions and reality
- First regulated projects will set precedence, and larger scale will need more data
- Emphasis on good site characterisation and prediction in advance
- First time hearing on Japanese Marine Pollution Prevention Law

Learnings from....What Can and Can't Monitoring Do

- Example of closing Sleipner to EU CCS Directive – does it satisfy criteria?
- Results from research-intensive pilot-scale projects should inform regulators – commercial scale projects won't monitor to the same level
- Monitoring can be good enough to get on with projects in a regulatory- and caveated- sense
- What do we need to quantify? Eg not plume in situ
- Measurement of dissolved CO2
- Reliance on expert opinions – who? – well recorded and transparent judgements
- Atmospheric monitoring can provide assurance – challenges to prove/determine sensitivities of different techniques
- Soil/water – fit for purpose measurements only
- Coupling surface behaviour with subsurface behaviour

Learnings from Emerging Technologies

- Satellite monitoring success
- Satellite data - anyone can buy data and use or mis-use (also for other monitoring data) – develop standards for interpretation
- Coupling surface behaviour with subsurface behaviour
- Real-time and integrated monitoring has value (cost efficient, safety)
- Gravity measurements may have a role for gaseous and dissolved CO2

Recurring learnings, themes, gaps and points identified:

- Use pilot-scale projects to focus on and learn on post-injection behaviour.
- Leakage should be approached as 'Innocent until proven guilty'. There should be an assumption of zero leakage until monitoring indicates otherwise.
- How can we define the edge of the plume in terms of pressure and hydraulically linked units and what happens if neighbouring sites interact?
- Study faults more including their transmissivity to CO2 in different phases.
- Monitor geochemistry processes in-situ close to injection wells.
- Multi-scale integration of multiple datasets, e.g. combining seismic and electrical resistivity.

Conclusions agreed by the workshop:

- Strong recommendation to use pilot-scale projects to focus and learn on post-injection CO2behaviour, as at Nagaoka.
- Benefits of multi-scale integration of multiple datasets, e.g. combining seismic and electrical resistivity.
- Regulations are based on qualitative rather than quantitative performance and require expert opinion to make decisions. This may become difficult due to a limited number of such independent experts in the CCS field at this early developmental stage.
- Atmospheric and surface monitoring can provide assurance to the public.
- The transmissivity of faults to CO2 may be different to other molecules such as methane due to the ability of CO2 to react with some materials in the presence of water. Additionally, more work is required to understand fault and overburden leakage pathways, i.e. Uncertainty over defining what is an acceptable match of predictions and the reality of CO2 behaviour for the closure and liability transfer of storage sites. The first projects will set the precedent.
- Pressure front monitoring will be required.
- Monitoring capabilities are good enough to get on with projects.

IEA Greenhouse Gas R&D Programme

IEA Greenhouse Gas R&D Programme

5th Monitoring Network Meeting

Hosts : RITE, JAPEX, AIST, Kyoto University

Tokyo – 2-3 June 2009

www.ieagreen.org.uk

UWA

CO_2 Sequestration Geophysics

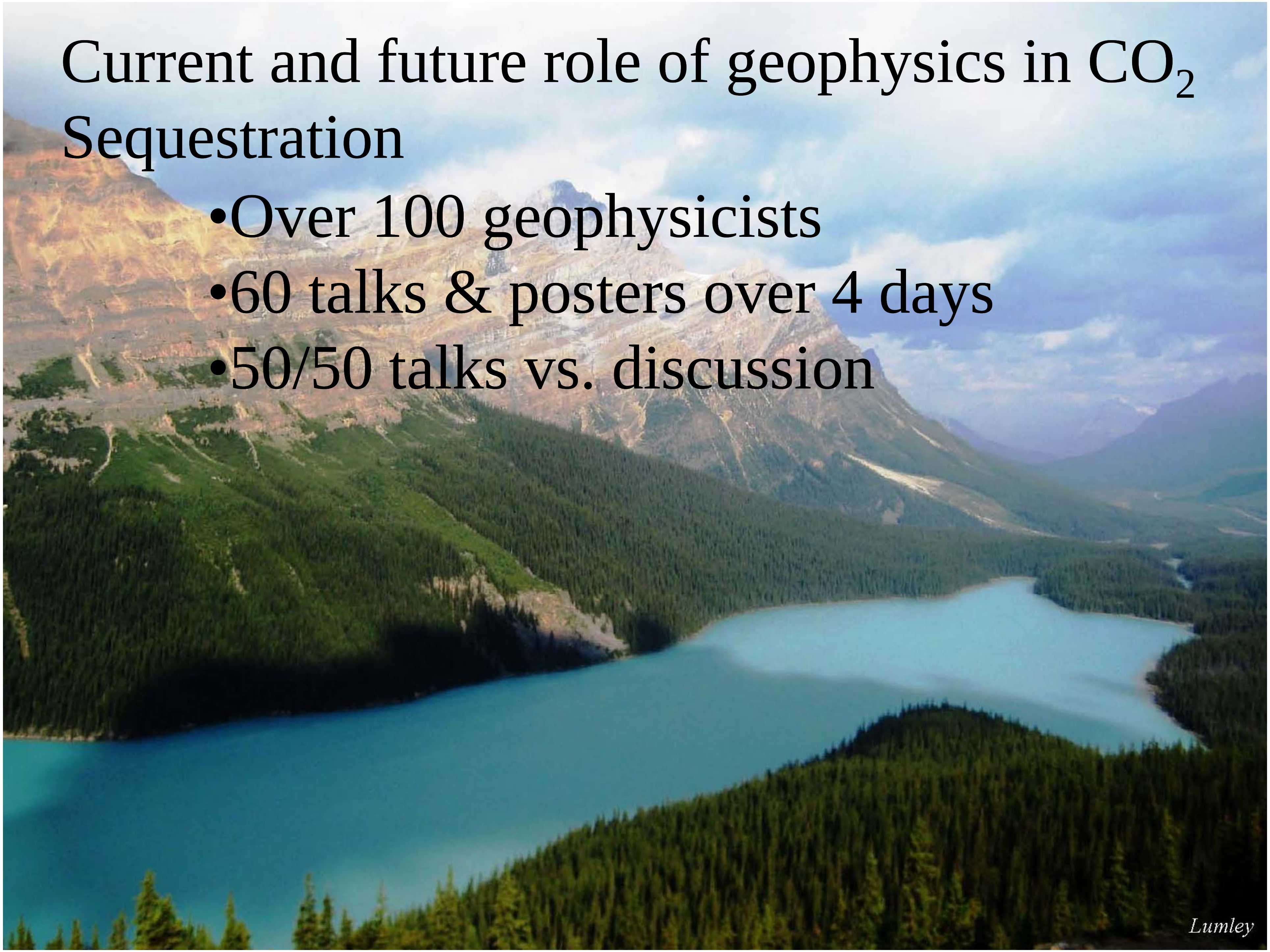
2009 SEG Summer Research Workshop, Banff, August 23-27

david lumley

david.lumley@uwa.edu.au

Current and future role of geophysics in CO_2 Sequestration

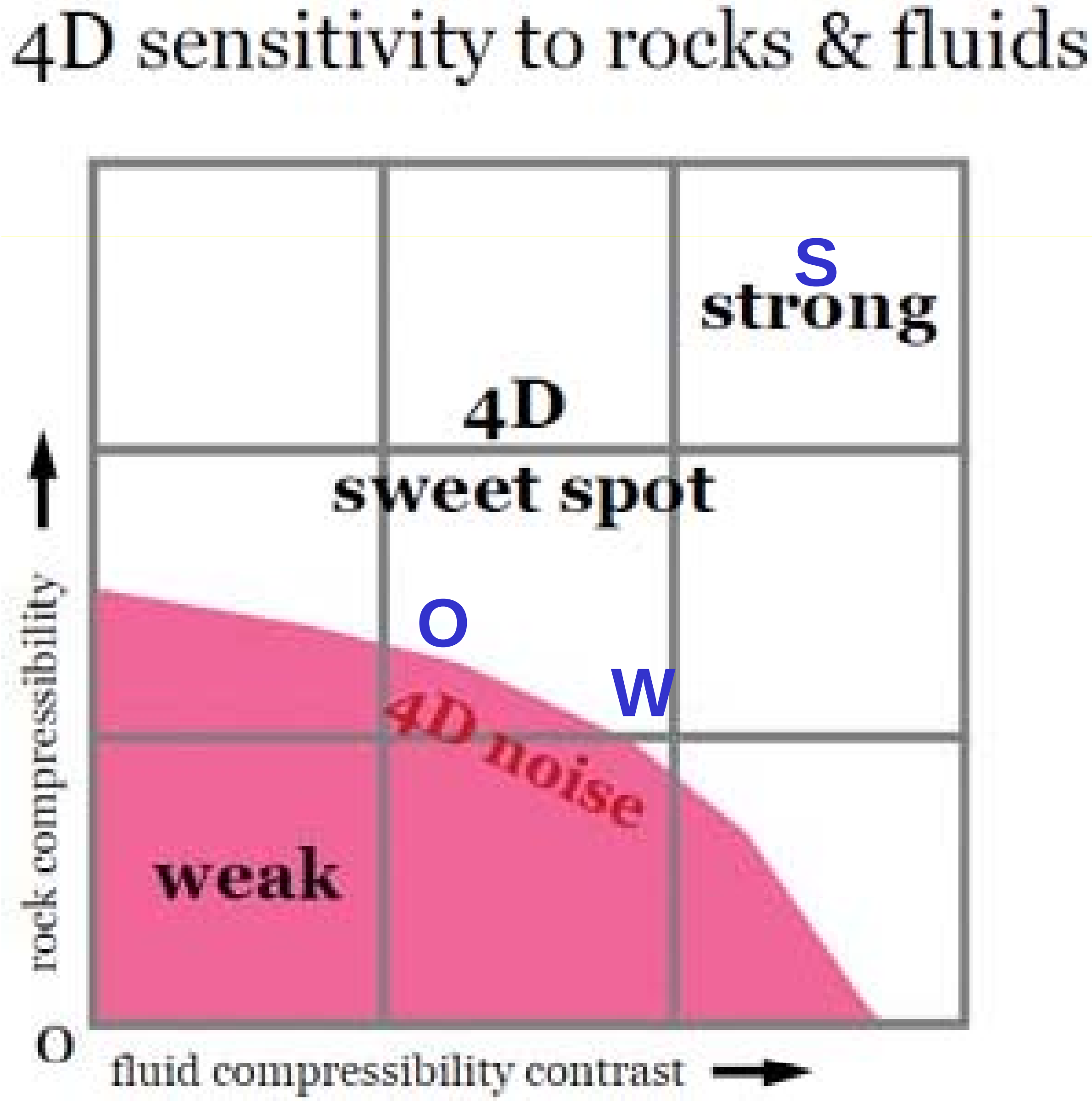
- Over 100 geophysicists
- 60 talks & posters over 4 days
- 50/50 talks vs. discussion




Program:
•Site Selection and Characterization
•Rock and Fluid Physics
•Geophysical Modeling
•Geophysical Monitoring
•Interpretation and Inversion
•Risk Assessment
Lumley

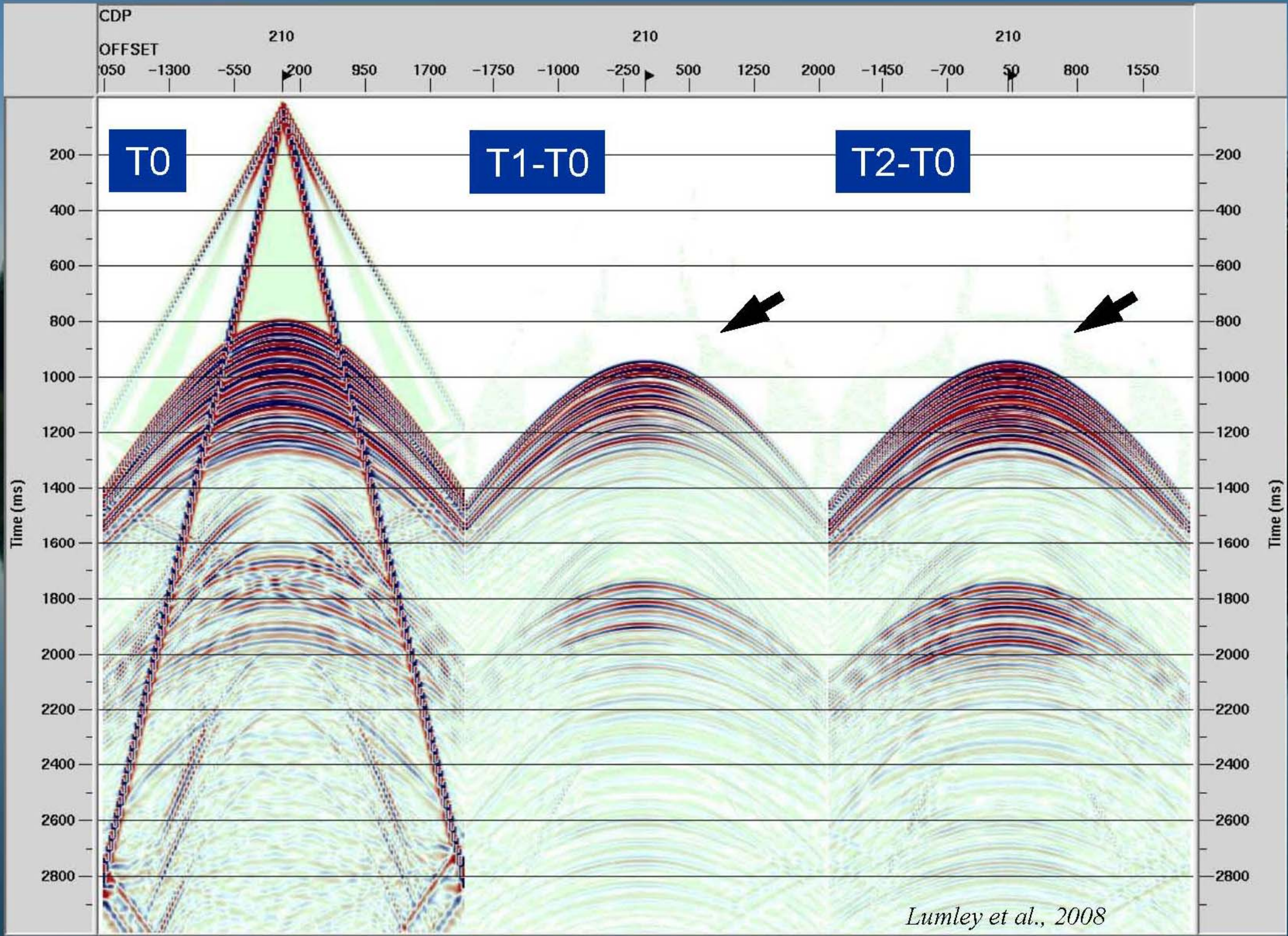
Selected Highlights

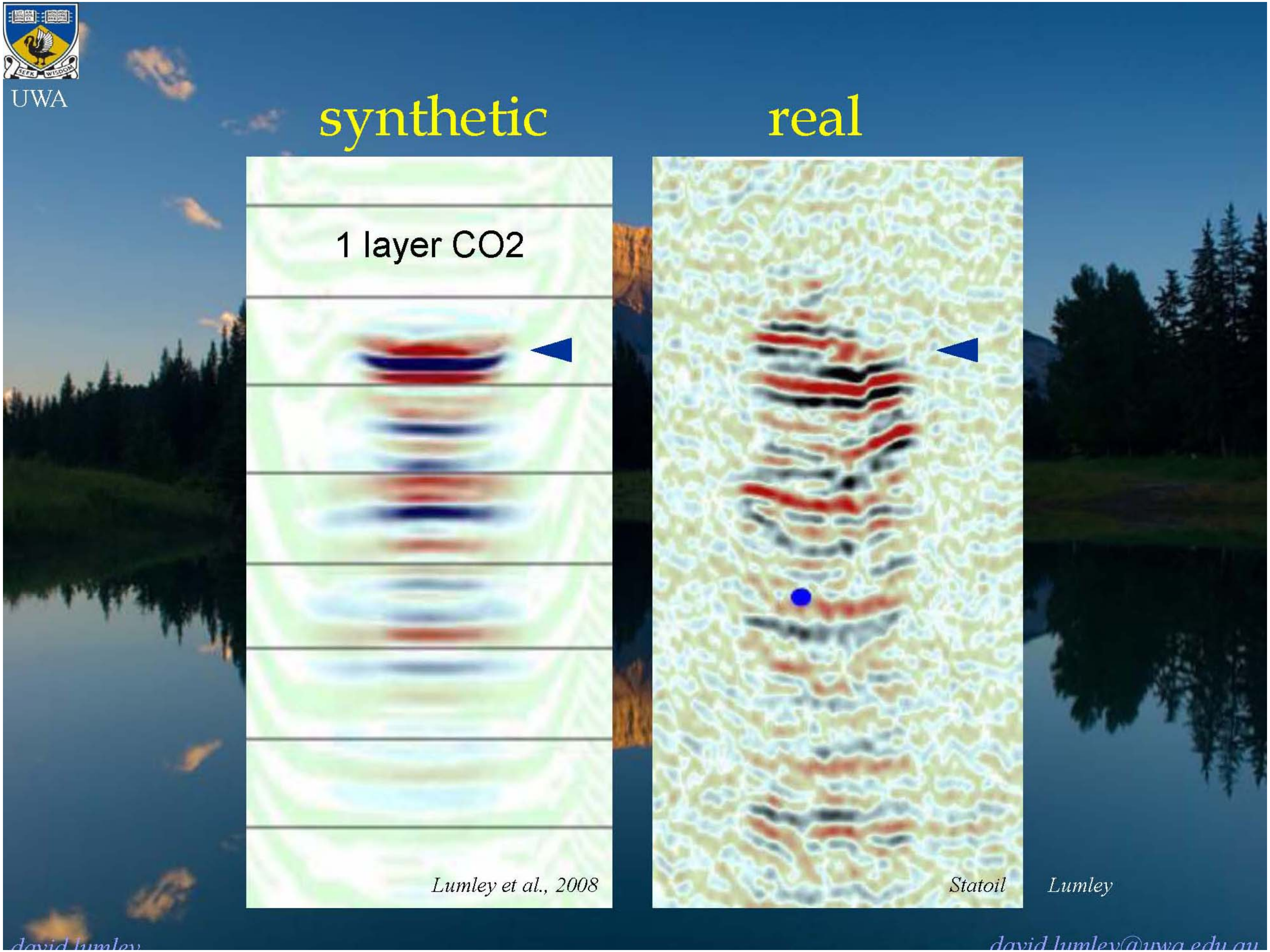
- Observed seismic responses to CO_2 are often stronger than predicted theoretically.
- Nature of CO_2 saturation (patchy/ homogeneous) affects seismic response.
- Geochemical effects of CO_2 on the rock frame.
- More lab studies are needed to understand the behaviour of CO_2 in rocks.



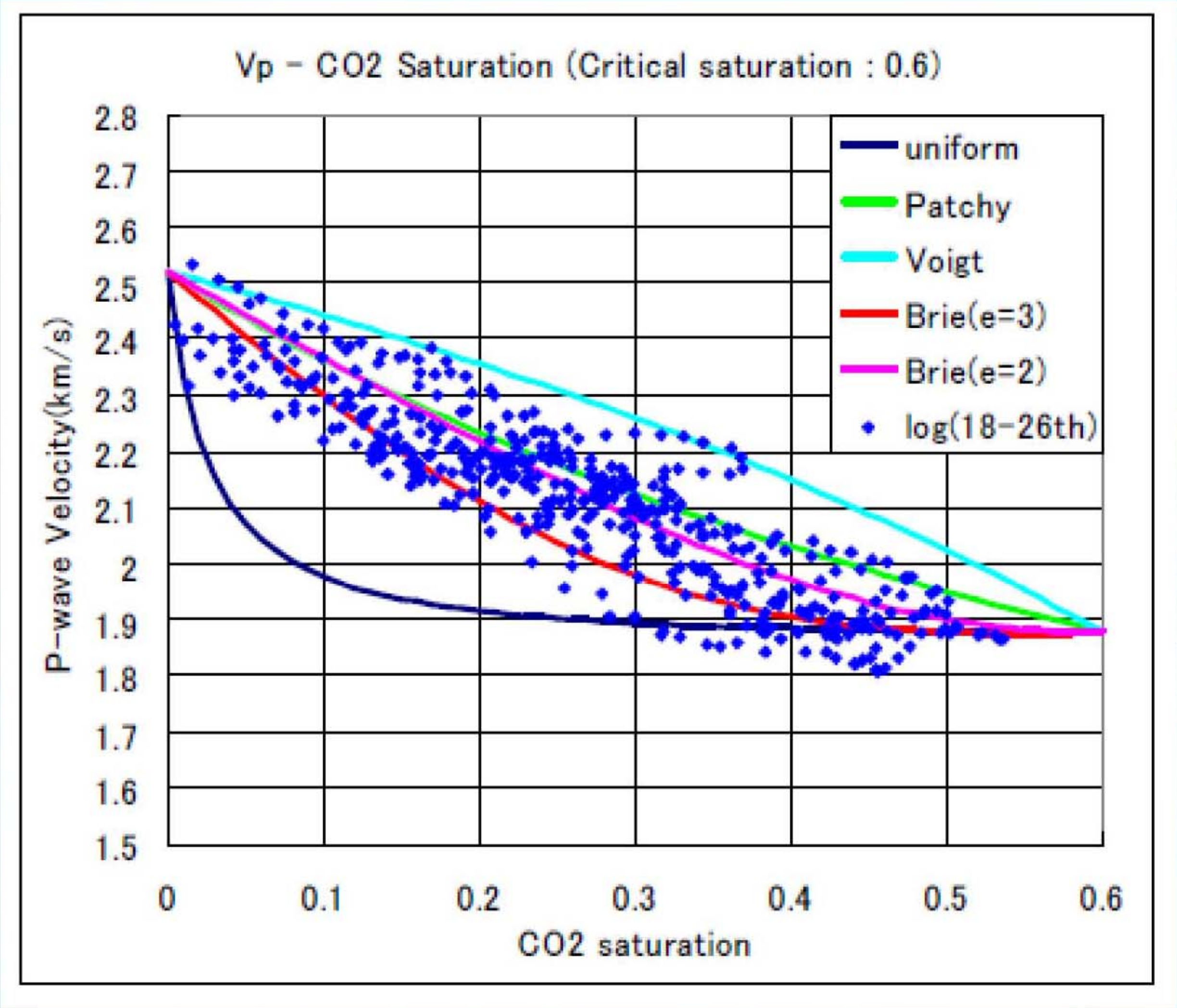
After Lumley (2010)

FD Gathers Z-Component



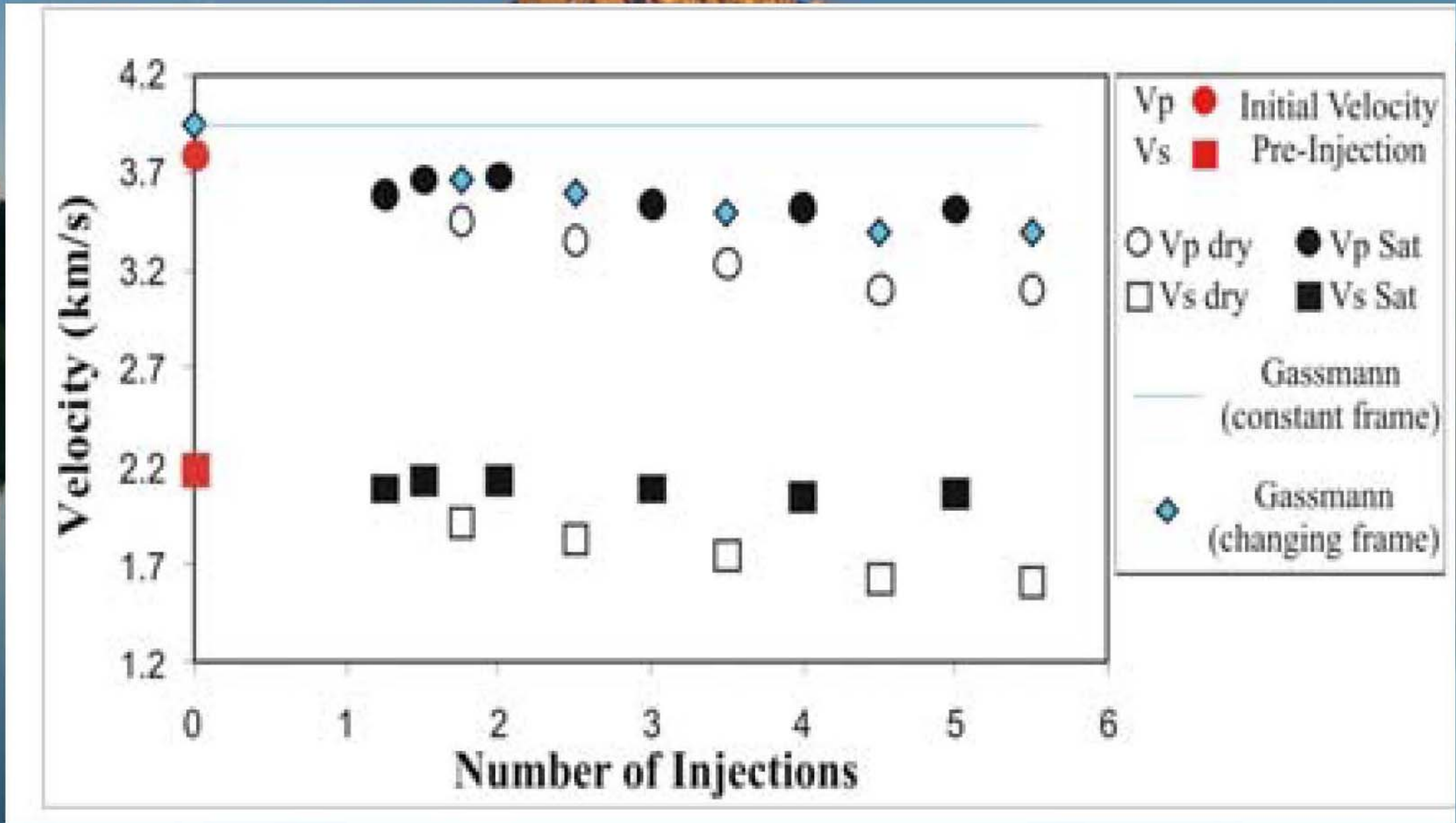

UWA
synthetic
real
1 layer CO2
Lumley et al., 2008
Statoil
Lumley
david lumley
david.lumley@uwa.edu.au

saturation distribution & rock properties



Konishi, OYO

geochemical effects on rock properties



Tiziana Vanorio, Stanford

(Carbonated water injection in a carbonate)


Lumley


The End
Lumley

2010 Modelling Network Meeting Summary

Neil Wildgust,

Millie Basava-Reddi

Introduction

Second meeting of modelling network held in University of Utah, Salt Lake City, February 16 – 17, 2010

60 participants

Four sessions:

- Modelling Methodology and Recent Advances
- Intergrated Roles and Objectives
- Real Storage Projects: Case Studies
- Best Practice and Modelling Protocols

2011 meeting: Perth, W Australia?

Session 1: Recent Advances

Talks on numerical vs analytical methods, coupling of processes, experimental advances, pore scale research

Breakout groups identified progress in research work……..but agreed on need for new large scale injection projects to provide data for model calibration

Session 2: R&D Priorities

Storage engineering, e.g. brine extraction;

Wettability and relative permeability;

Rates of dissolution in formation brines;

Efficiency of capillary trapping;

Coupling of processes, or merits of modelling processes separately to aid upscaling (the 'divide and conquer' approach);

Realistic boundary conditions for flow modelling.

Session 3: Real Projects

Presentations on modelling experiences from:

- Sleipner and In-Salah;
- Otway;
- Nagaoka
- Mount Simon Sandstone
- Shell Australia

Session 3 Experiences

Objectives of modelling must be defined. Fluid models often not critical to history matching, but heterogeneity is important.

Models provide range of possible outcomes, can be refined with time.

Initial pilot/demonstration injection projects vital to obtain data.

Current models give good estimations, despite knowledge gaps.

Quality of input data is vital for modelling and it is important to understand the limitations of simulations and associated outputs.

Session 4: Best Practice

Talks from SACS/CO2Store, Weyburn-Midale, US Regional Partnerships

Discussions highlighted possible role of network:

- placing and regional efforts in international context;
- Promoting recommendations for best practice.

Crystal Geyser, Utah, USA

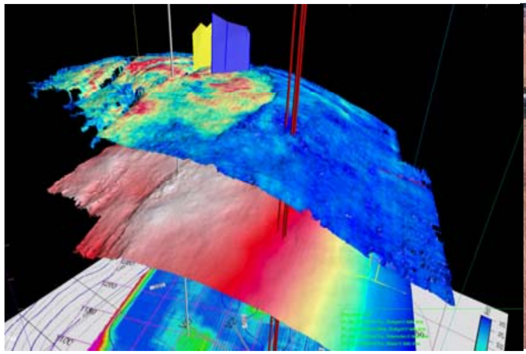
Thank you for your attention

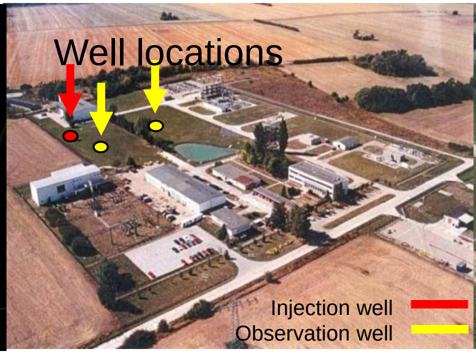
Report from Ketzin –

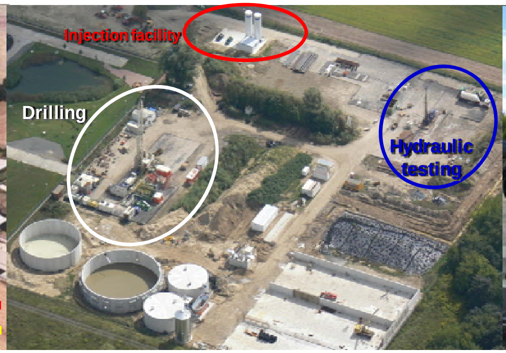
the CO_2 storage pilot site in Germany

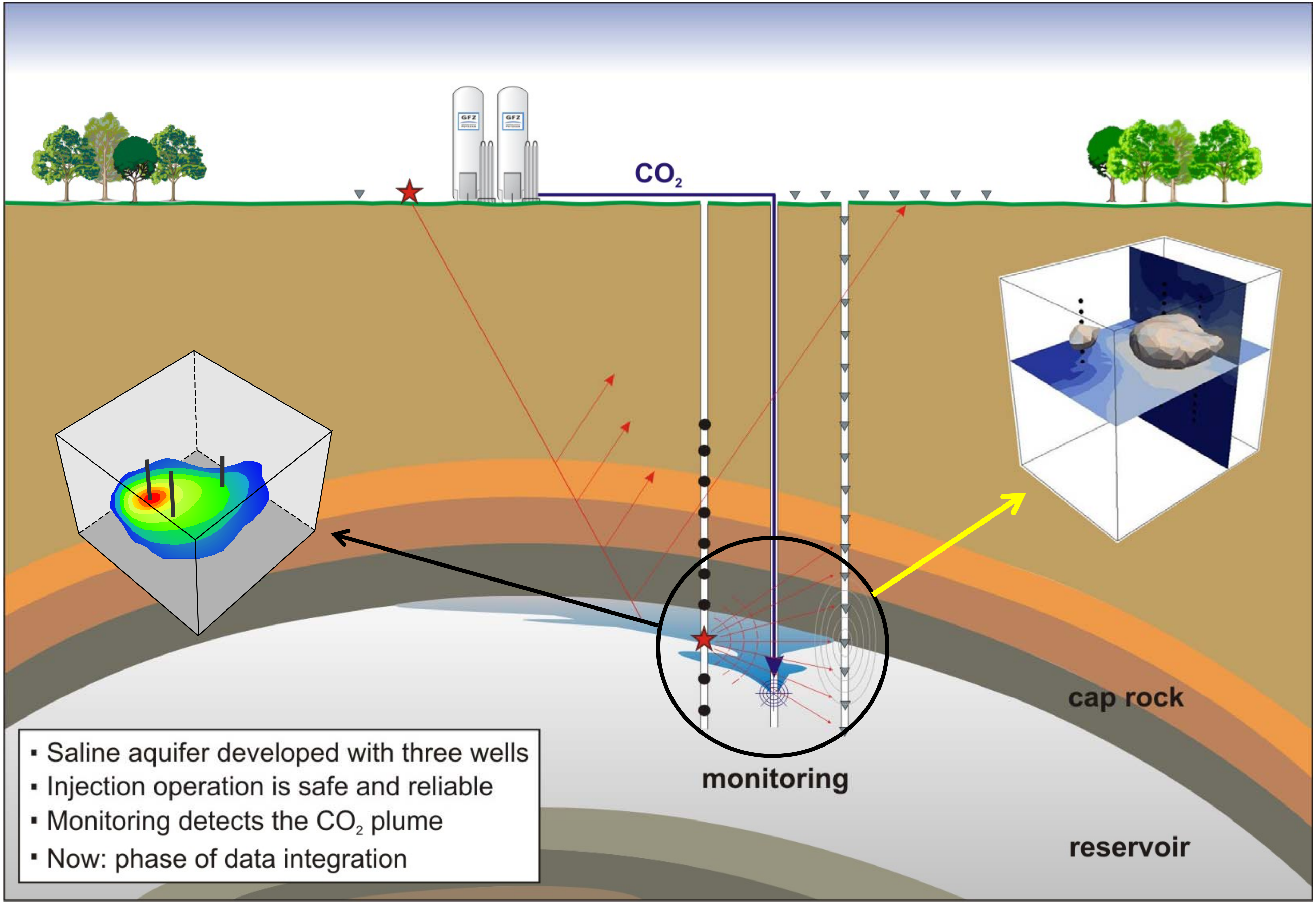
German Research Centre for Geosciences – GFZ
Centre for CO_2 Storage

Ketzin Team – presented by Conny Schmidt-Hattenberger









CO_2
monitoring
cap rock
reservoir
▪ Saline aquifer developed with three wells
▪ Injection operation is safe and reliable
▪ Monitoring detects the CO_2 plume
▪ Now: phase of data integration

Ketzin saline aquifer –

Site specifics

Location of the Ketzin storage site

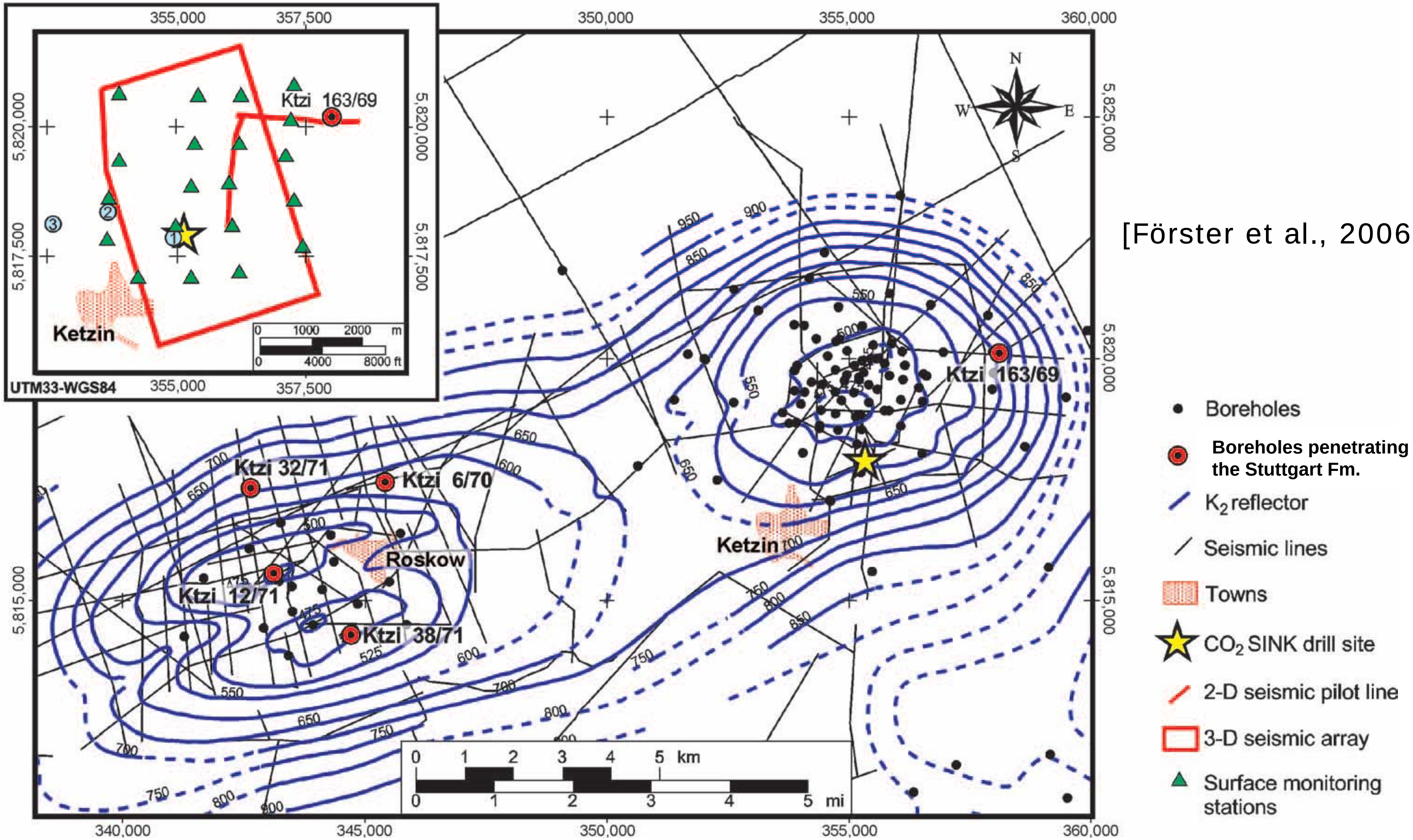
25 km west of Berlin

S-E slope of Roskow-Ketzin double anticline

Storage horizon: Stuttgart Fm./Keuper

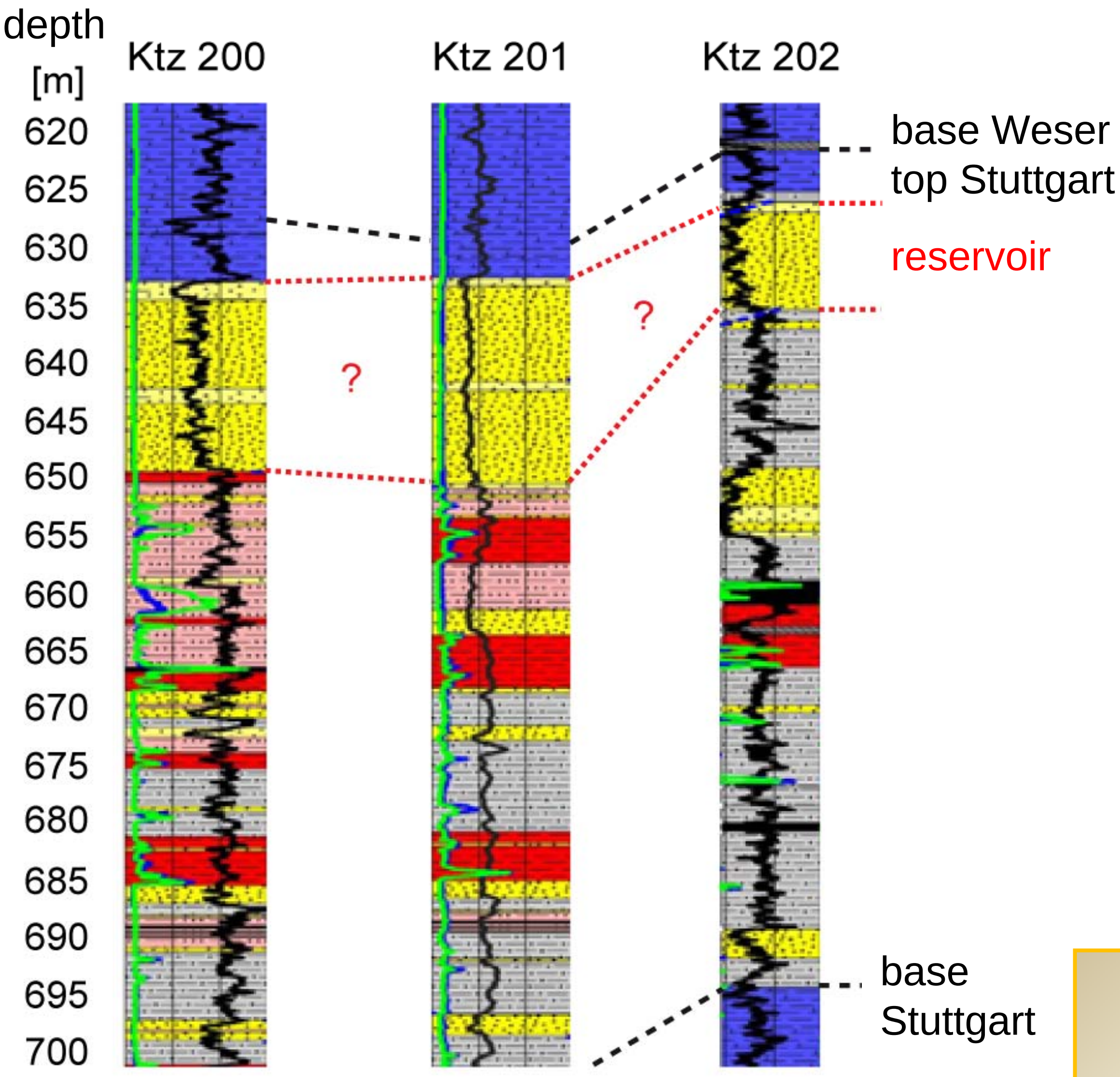
Depth: 625 – 650 m

Status of former exploration - Roskow-Ketzin double anticline



[Förster et al., 2006]

The reservoir – part of the Ketzin anticline



[Norden et al., 2007]

cap-rock:
mudstone (Weser formation)
porosity ~ 8 %, permeability ~ µD

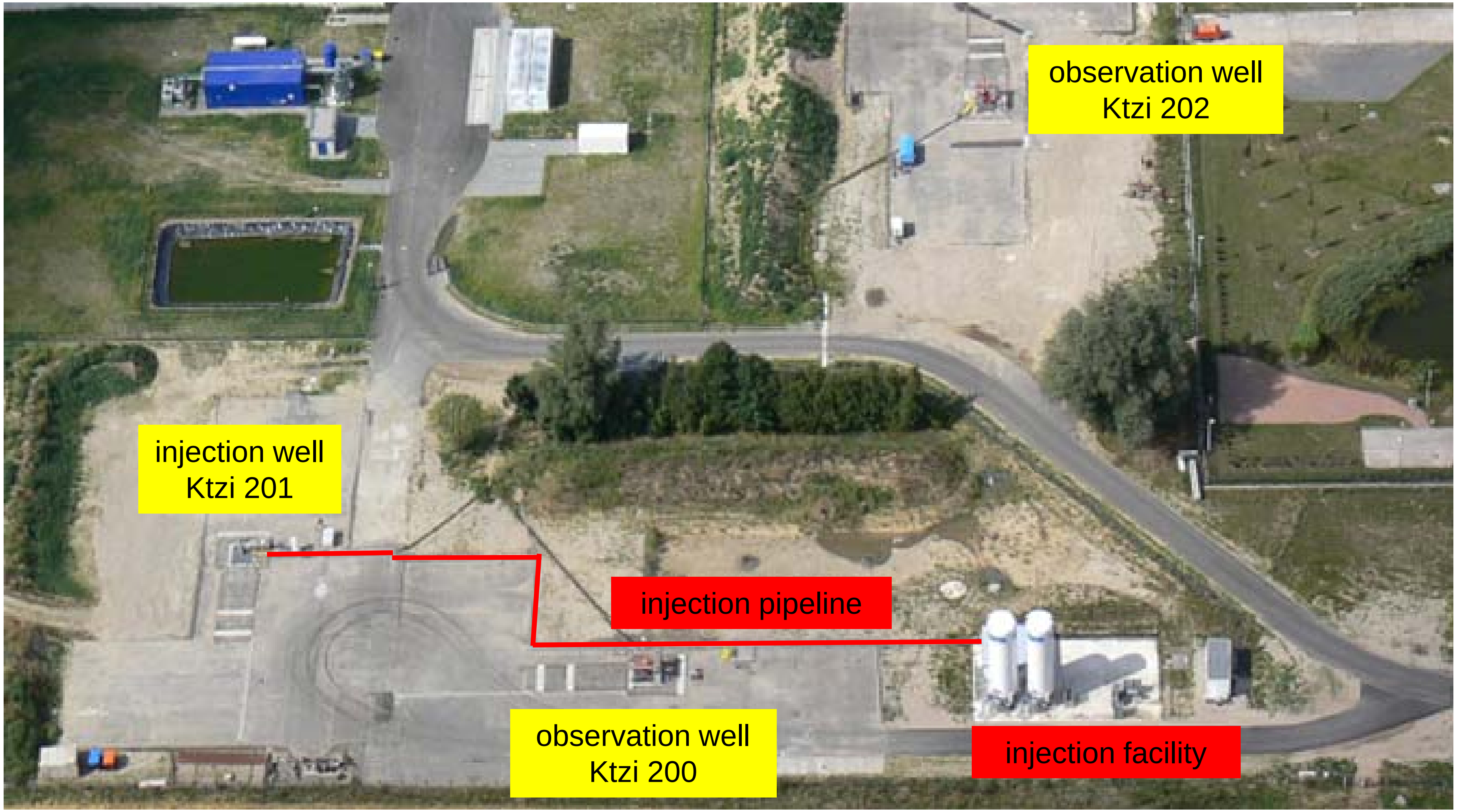
reservoir:
sandstone (Stuttgart formation)
30 – 40 % quartz
25 – 30 % feldspar
10 – 20 % illite
5 – 15 % anhydrite
+/- analcim, hematite

porosity ~ 26%
permeability
laboratory: Ø 300 – 400 mD
(but extreme variable)
hydraulic tests: 40 – 80 mD

fluvial system
extreme heterogeneous

Injection operation

The storage site at Ketzin in aerial view



1 injection and 2 observation wells (distances: 50 and 112 m)

CO_2 injection facility and basic data

Start of injection: June 30th, 2008
Goal: ~ 100.000 t CO_2 (until summer 2013)

CO_2 quality: 99.9%, food-grade

cumulative mass
of injected CO_2: **~ 34,058 t** *(May 02, 2010)*

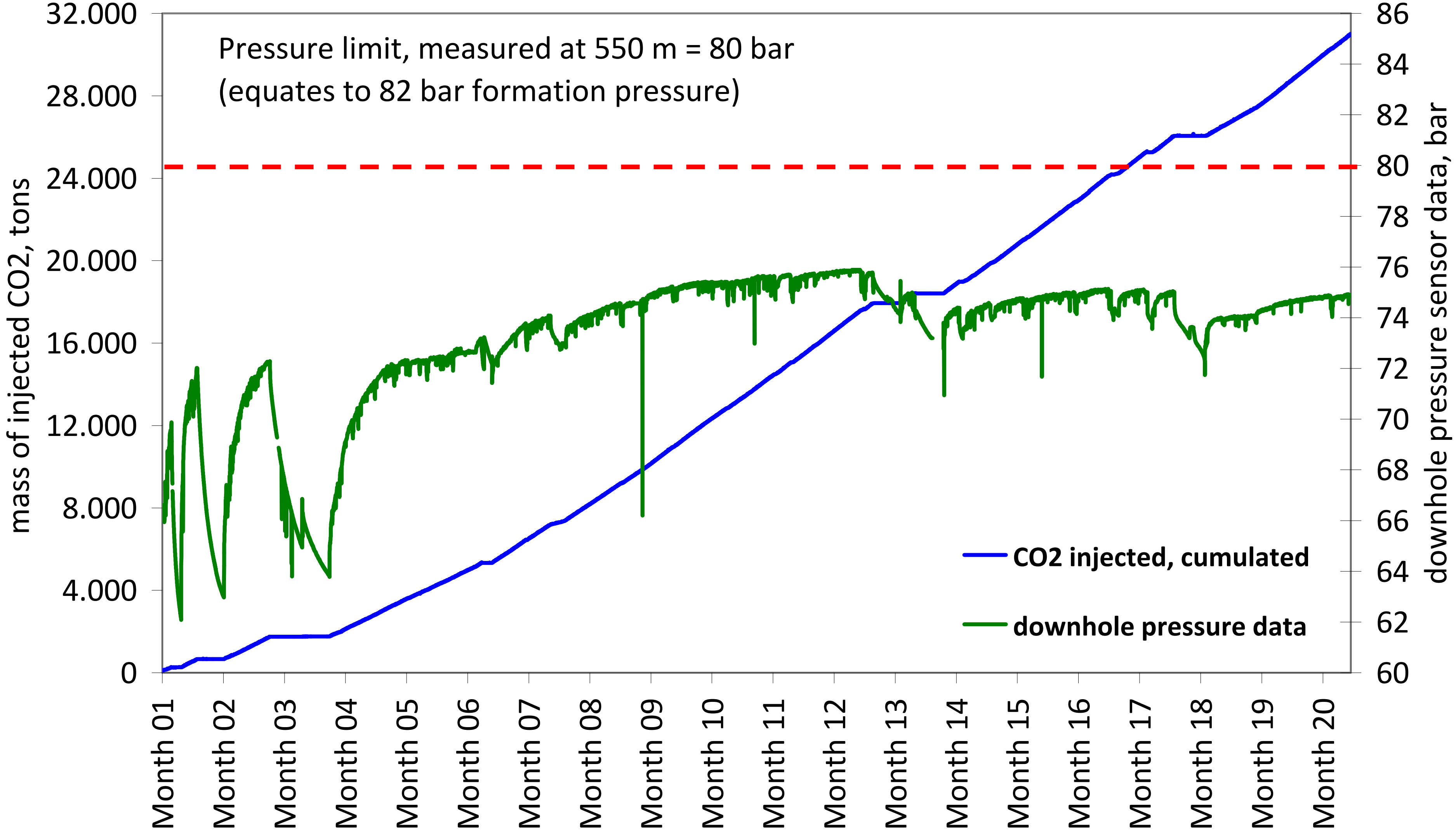
actual injection rate:

~ 3.2 t/h or ~ 77 t/d

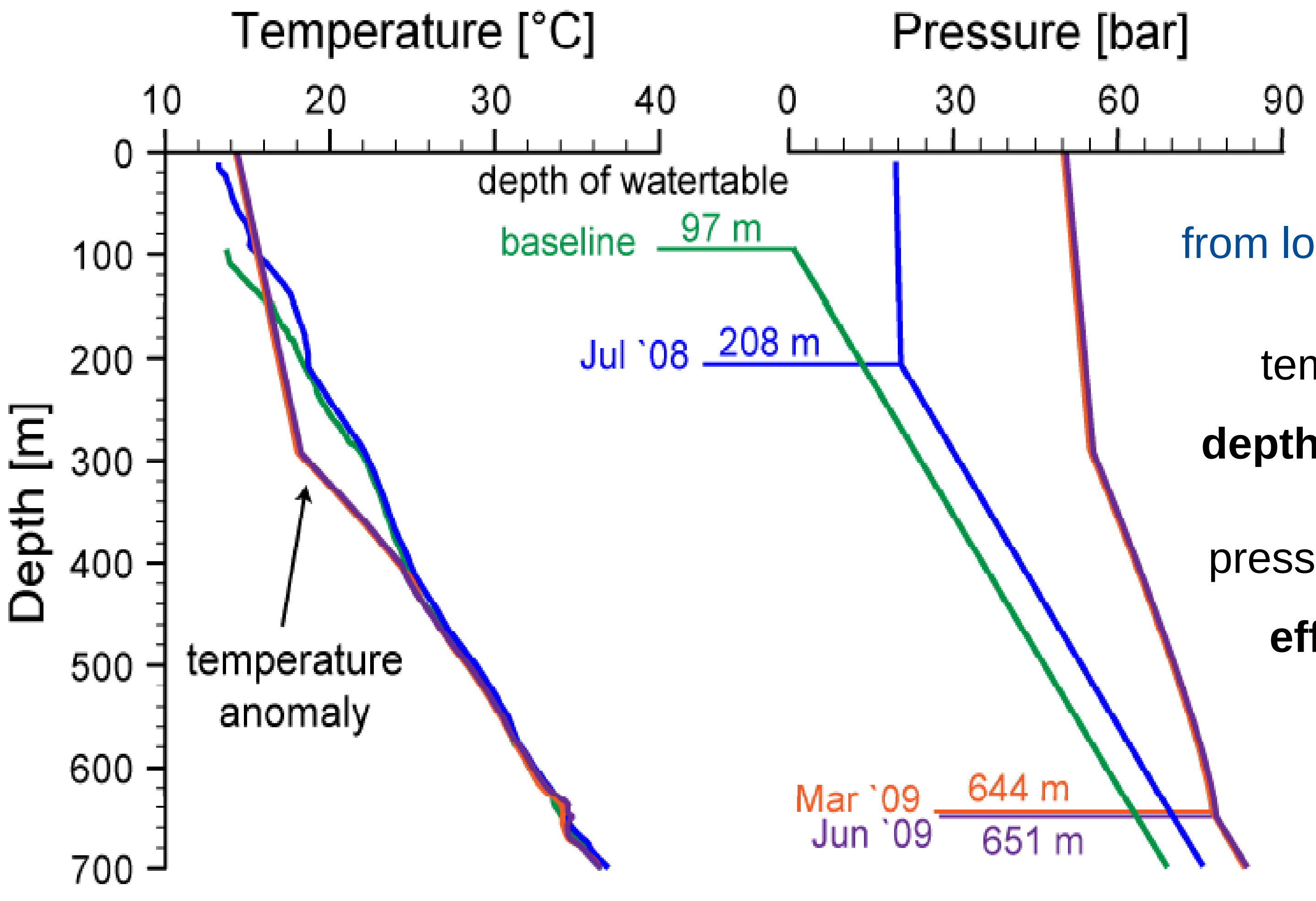
mean injection rate since
start of injection: ~ 46 t/d

arrival @Ktzi200(50 m):
~ 530 t
arrival @Ktzi202(100 m):
~ 11,200 t

Formation pressure and injected mass of CO_2



P-T-ρ conditions in Ktzi 200



from logging-data Jun ´09:

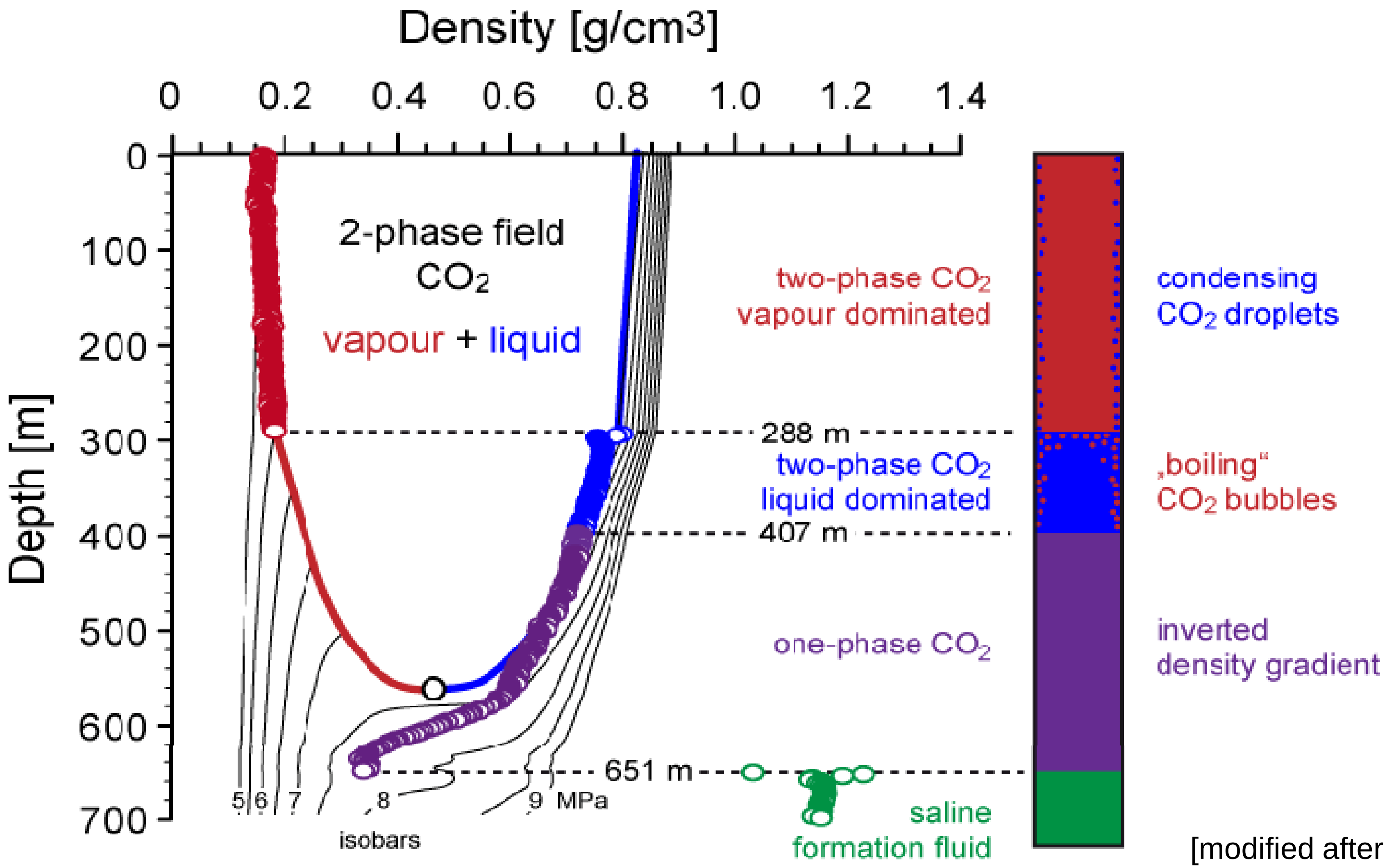
temperature yields

depth-ρ phase diagram

pressure gradient yields

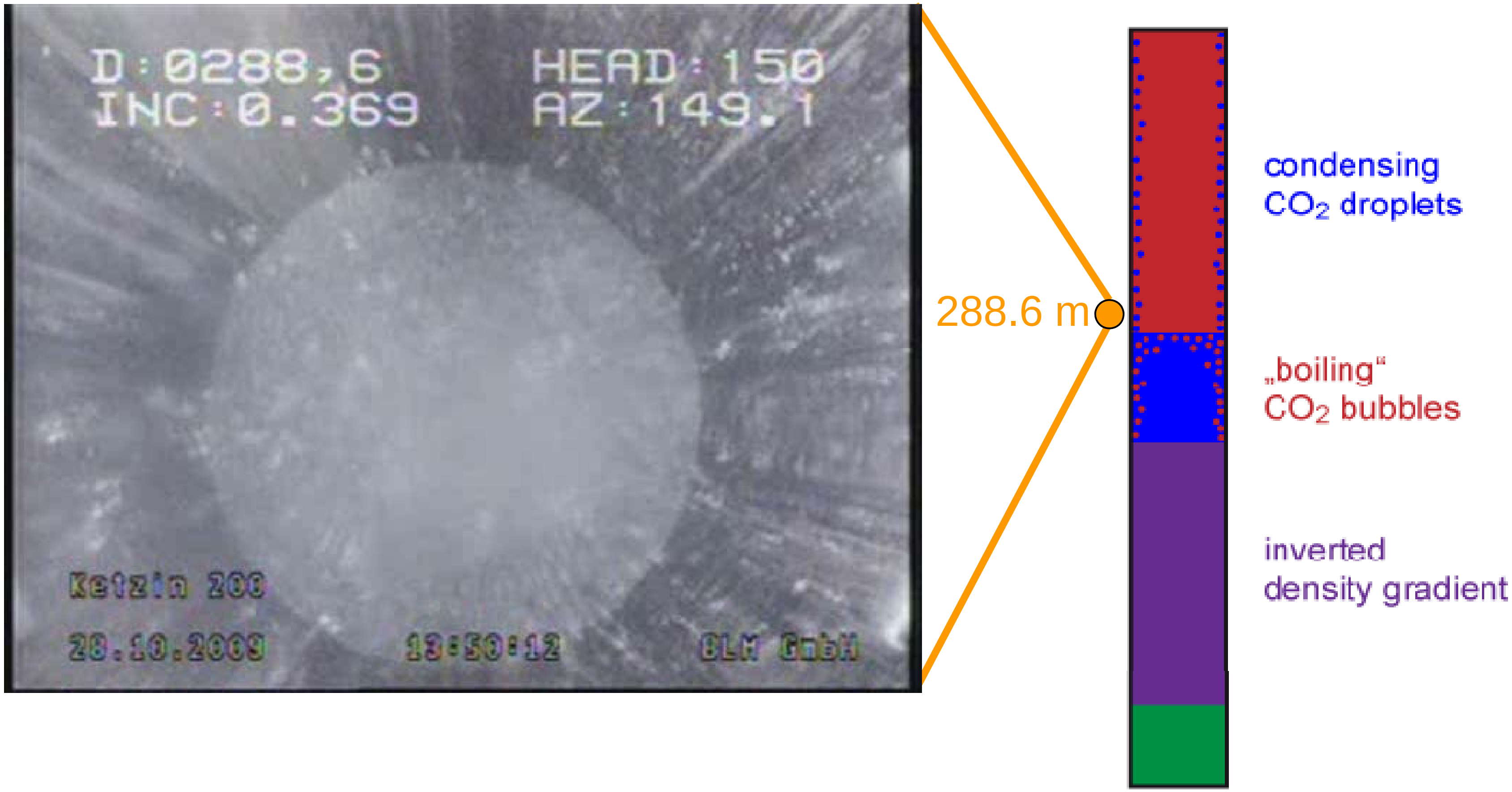
effective density

P-T-ρ conditions in Ktzi 200

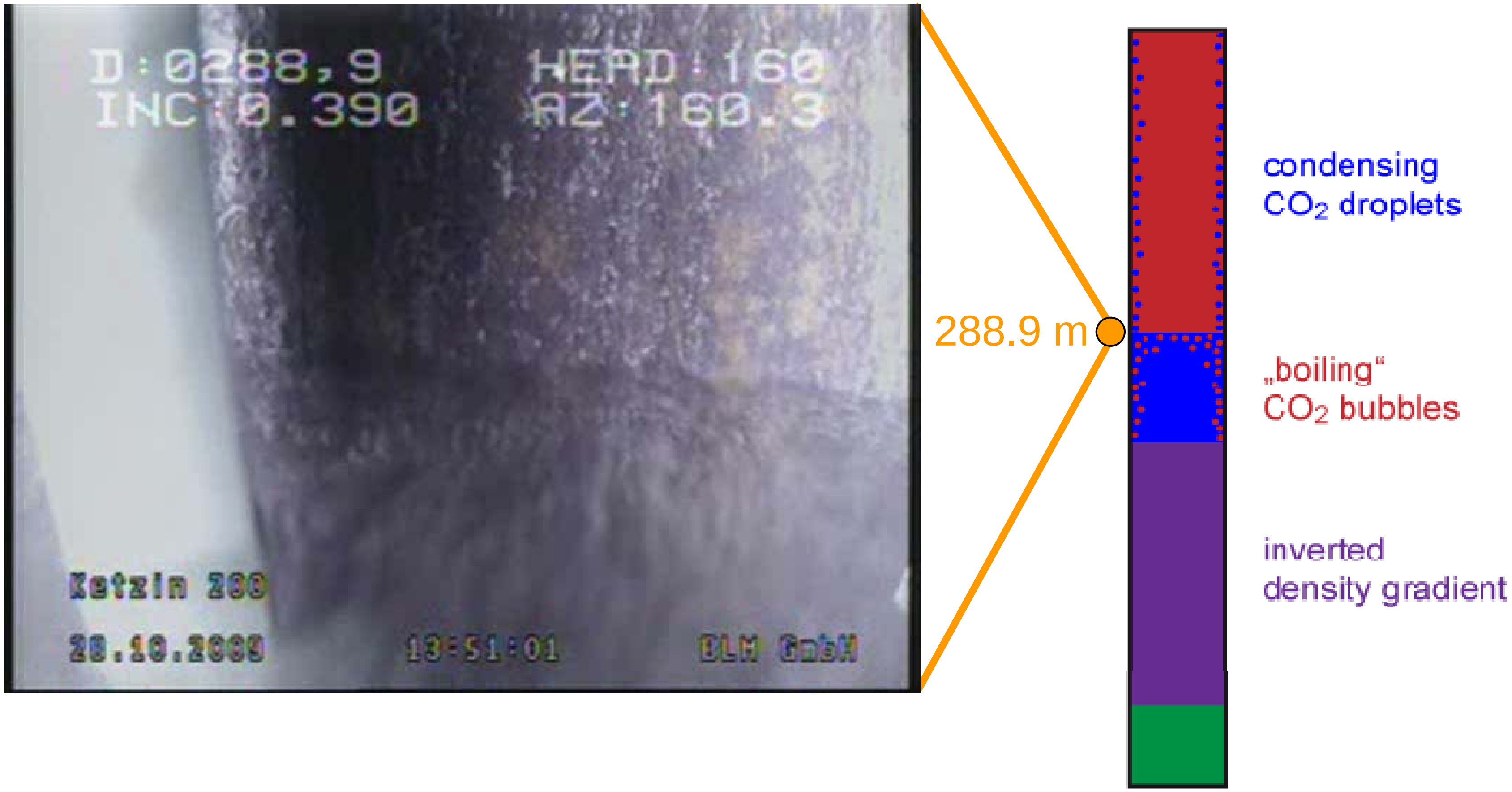


[modified after
A. Liebscher, 2010]

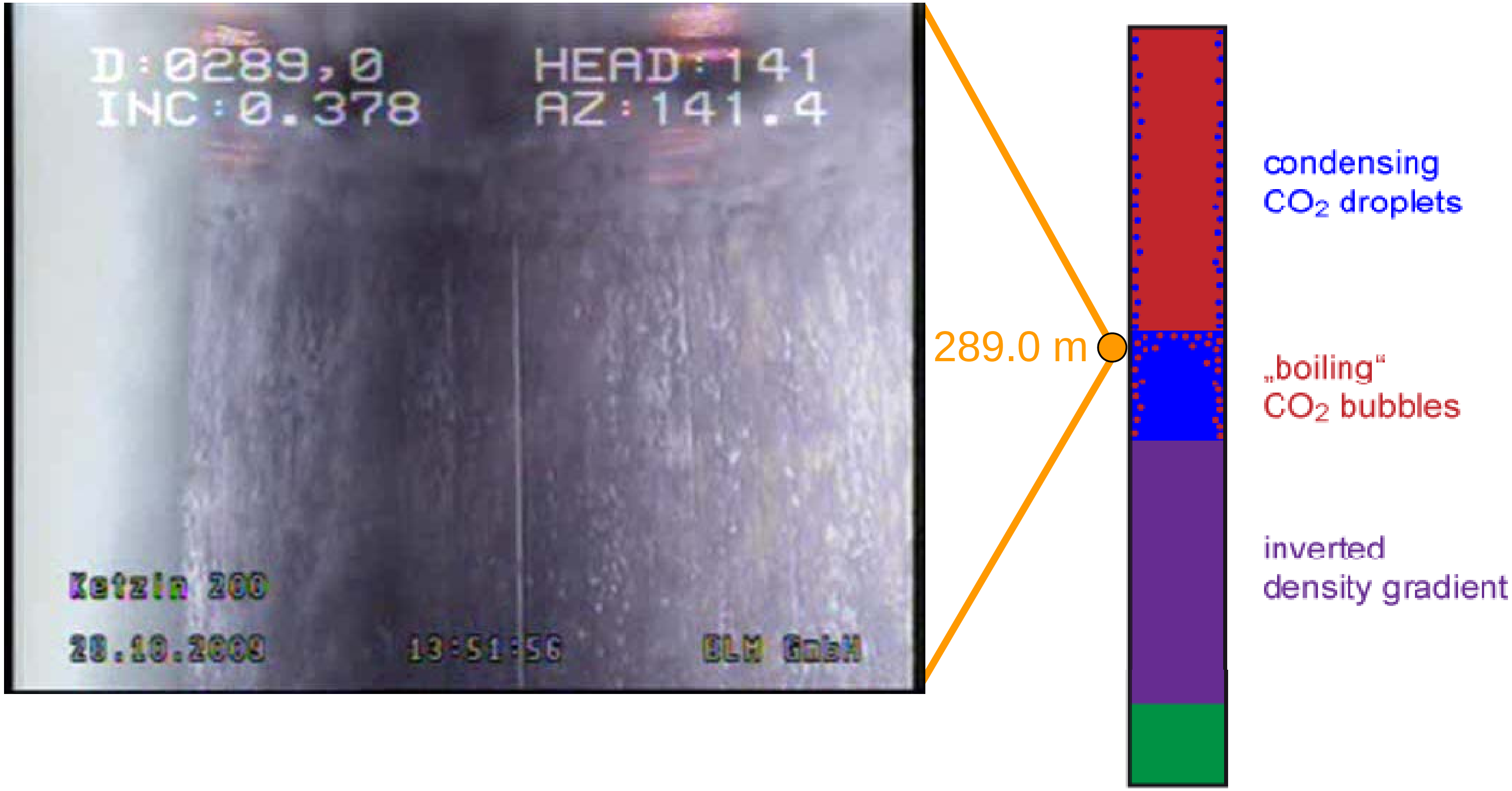
P-T-ρ conditions in Ktzi 200



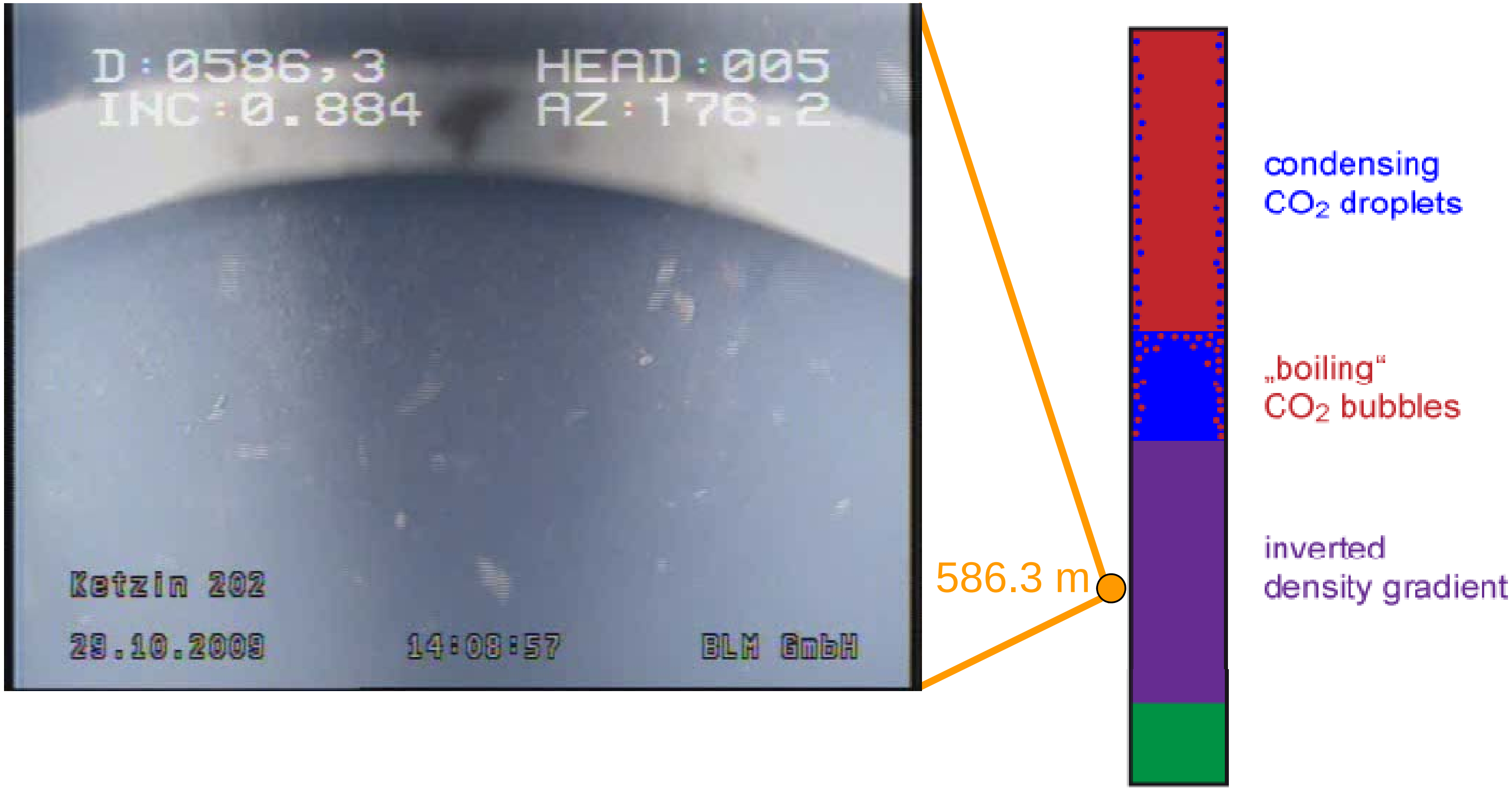
P-T-ρ conditions in Ktzi 200



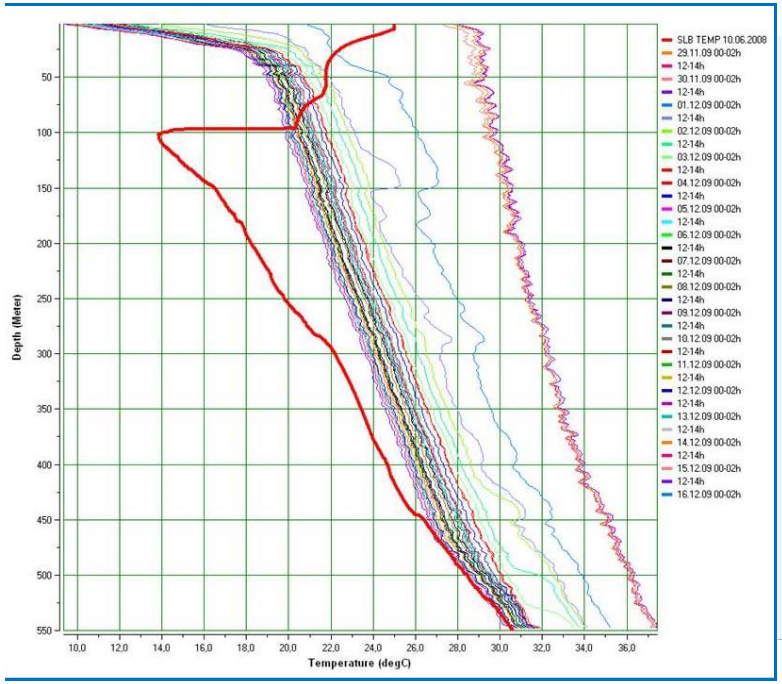
P-T-ρ conditions in Ktzi 200

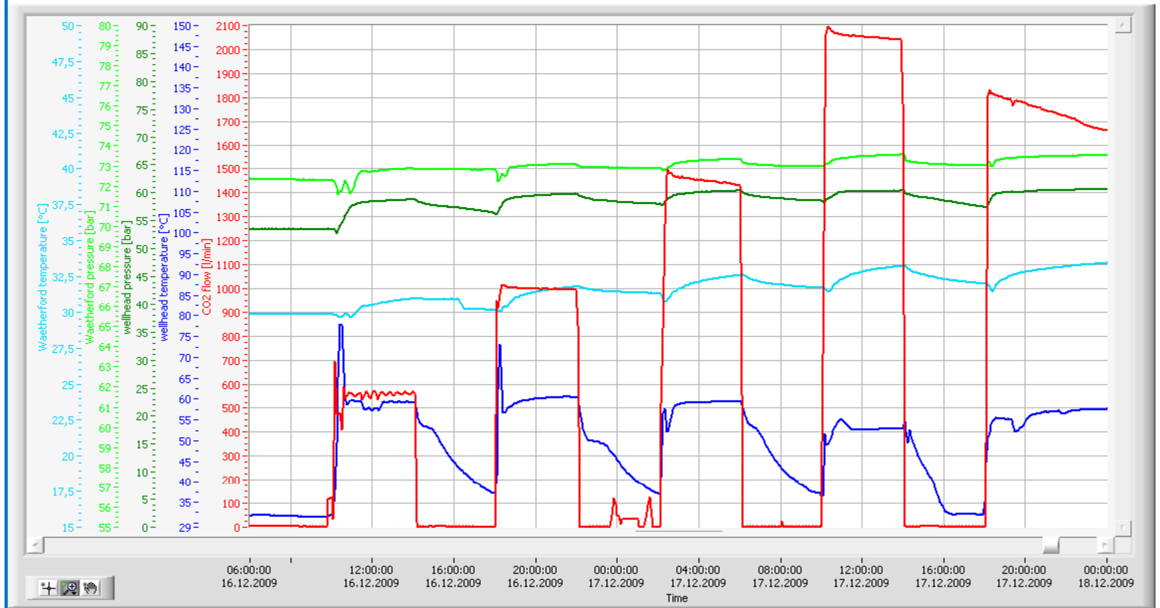


P-T-ρ conditions in Ktzi 200



Safety monitoring of injection operations in Ktzi 201 (example: Isochronal test)





Temperature decay for the stop period 29/11/09 – 16/12/09 before the isochronal test starts. **No N_2 stacking in this operation!**

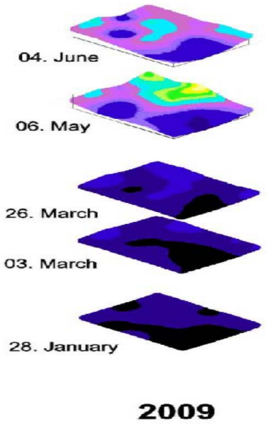
Bottom-hole (BH) temperature and pressure (Weatherford pT-point gauge @550m), wellhead pressure and CO_2 flow measurements at Ketzin showing alterations during an isochronal test in Ktzi 201, on December 16-17, 2009.

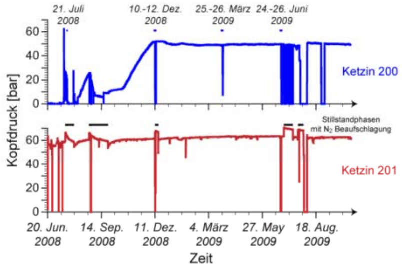
Safe shut-in process !

four ramps with increasing CO2-flow – same holding time → *reservoir response test*

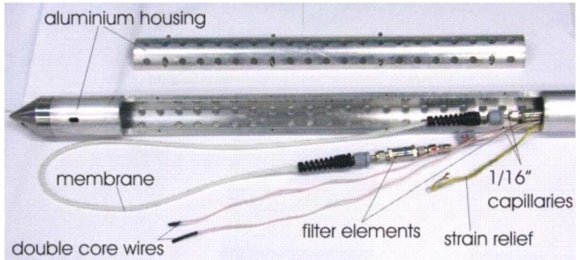
Monitoring methods detecting the CO_2 plume

Components of the monitoring program



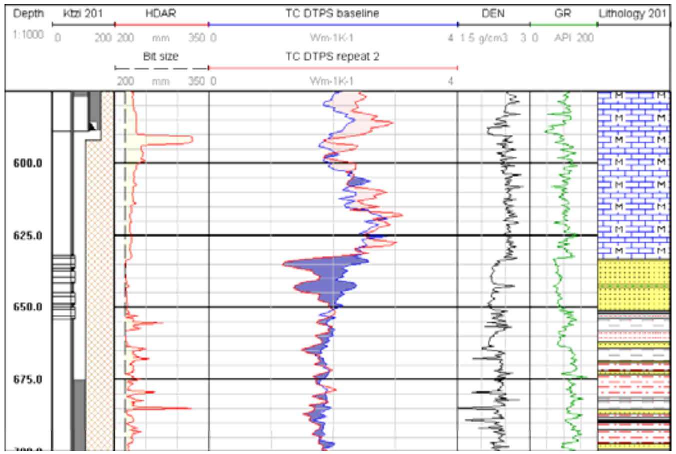


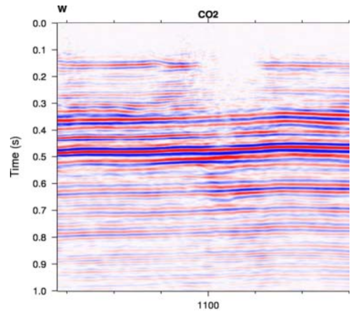
- Surface CO_2 flux
- Wellhead P-T
- Gas membrane sensor
- Downhole fluid sampling

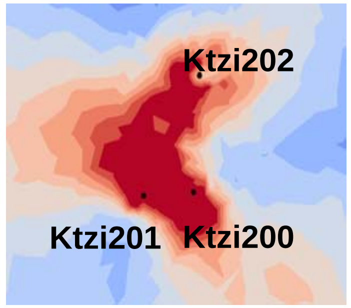


- Logging
- DTS
- Heat-pulse experiments

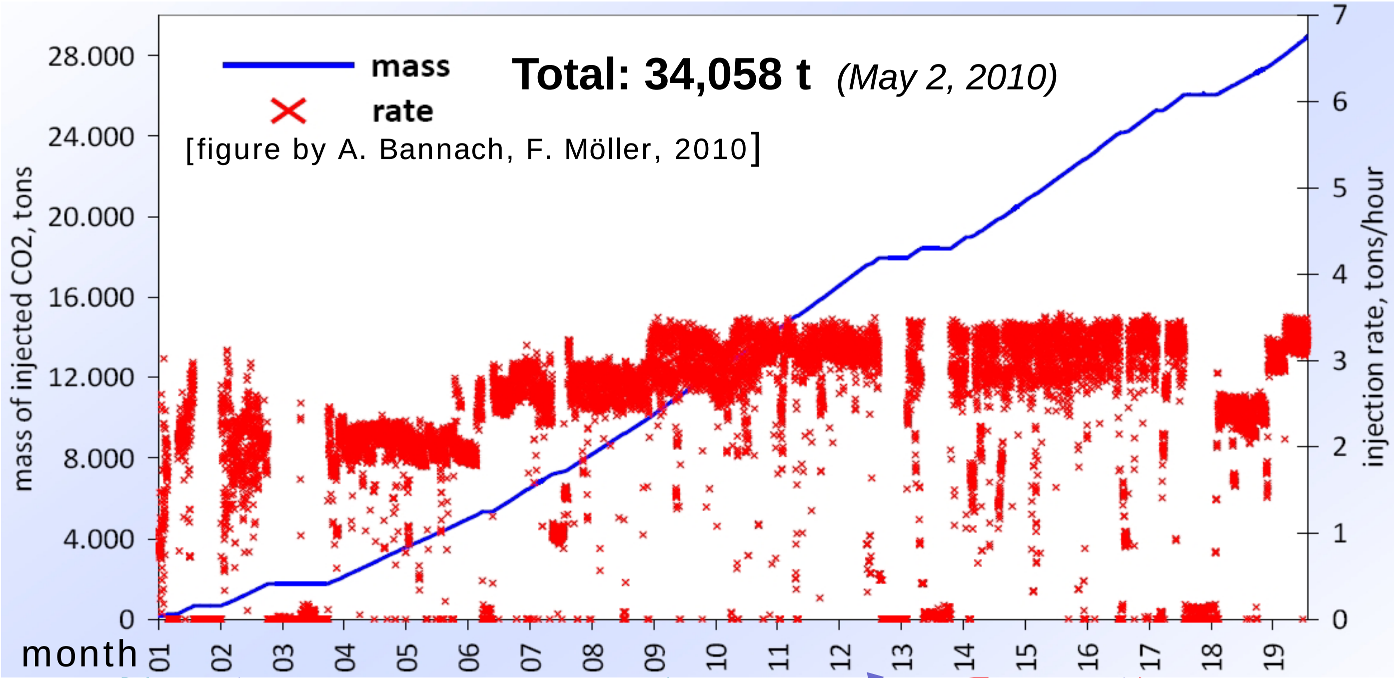
- **Seismics**
- **Resistivity**







Timeline of seismic monitoring activities at the Ketzin site



Pre-injection:
Baseline measurements
2D-surface: Fall '05
3D-surface: Fall '05
2D-MSP/VSP: Nov/Dec '07
Crosshole: May '08

Start of injection: June 30th, '08

1st and 2nd repeat **crosshole** July & Aug '08

3rd repeat **crosshole** June/July '09

TNO active & passive monitoring with buried receivers Start: Aug '09

Repeat **2D-MSP 2D & 3D surface** Sep/Oct '09

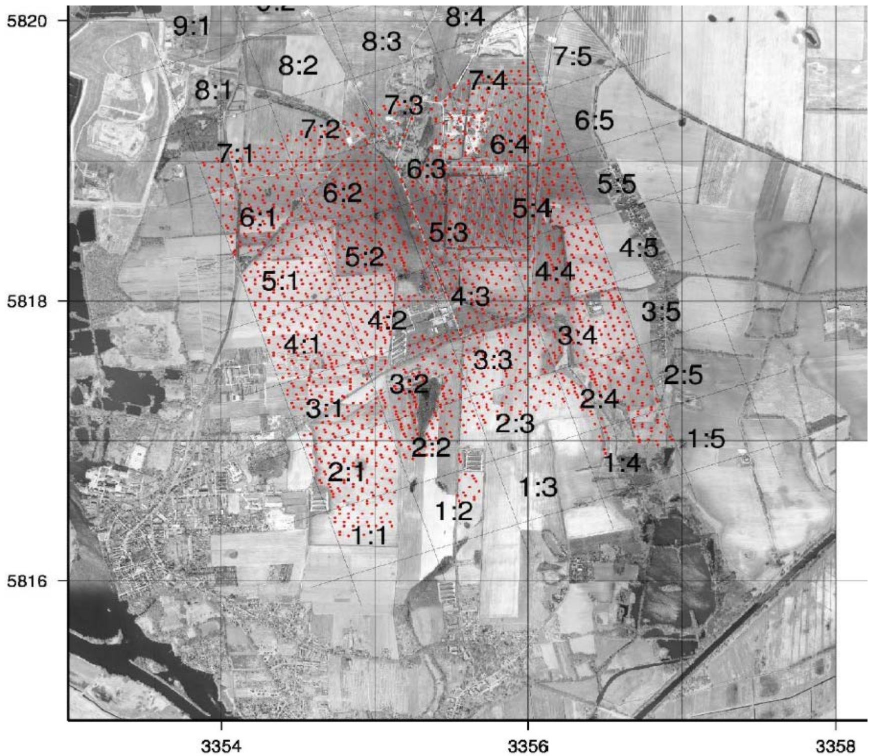
Baseline **3D-MSP** Sep/Oct '09

OGS passive monitoring Sep/Oct '09

Breakthrough well 200 July '08 after ~500t CO_2

Breakthrough well 202 March '09 After ~11000t CO_2

Seismic monitoring at various scales



Shot points of the 3D-surface seismic repeat measurement [Ch. Juhlin, 2009] – covering ~50% of the baseline survey.

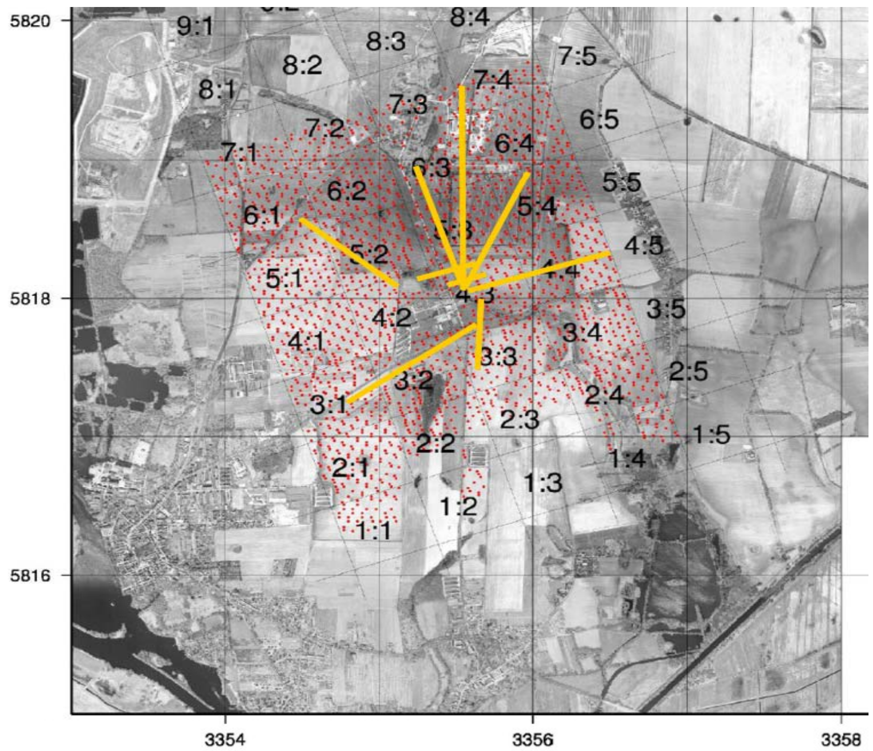
Source: Accelerated weight drop (EWG III)
Receiver: single geophone

3D-surface seismic

- Follow the migration of CO_2 at a large scale.
- Provide a detailed structural model of the uppermost 1000 m of the Ketzin anticline.

[photo by R. Giese, 2009]

Seismic monitoring at various scales



Seven 2D-surface seismic profiles around the injection site [Ch. Juhlin, 2009, modified]

Source: VIBSIST-1000/3000

Receiver: single geophone

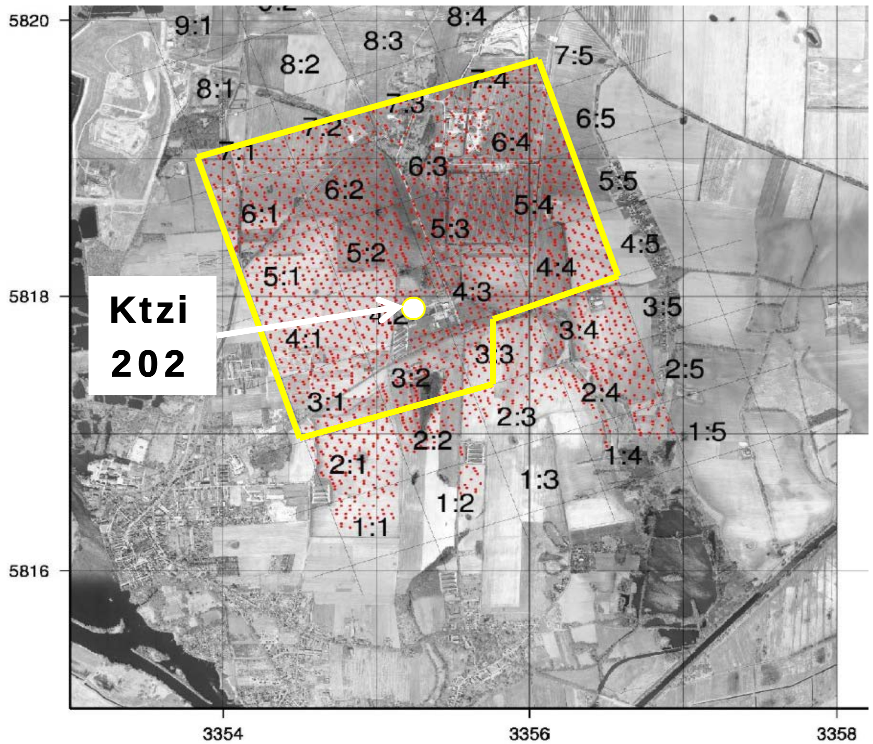
2D-surface seismic

➢ Enhance the spatial resolution around the injection.

➢ Assess alternatives to the logistically and financially demanding 3D surveys.

[photo by R. Giese, 2009]

Seismic monitoring at various scales



Shot points inside the yellow polygon are recorded in the observation well Ktzi 202 at 470 m depth [Ch. Juhlin, 2009, modified]

Source: Accelerated weight drop (EWG III)
Receiver: 3-component geophone

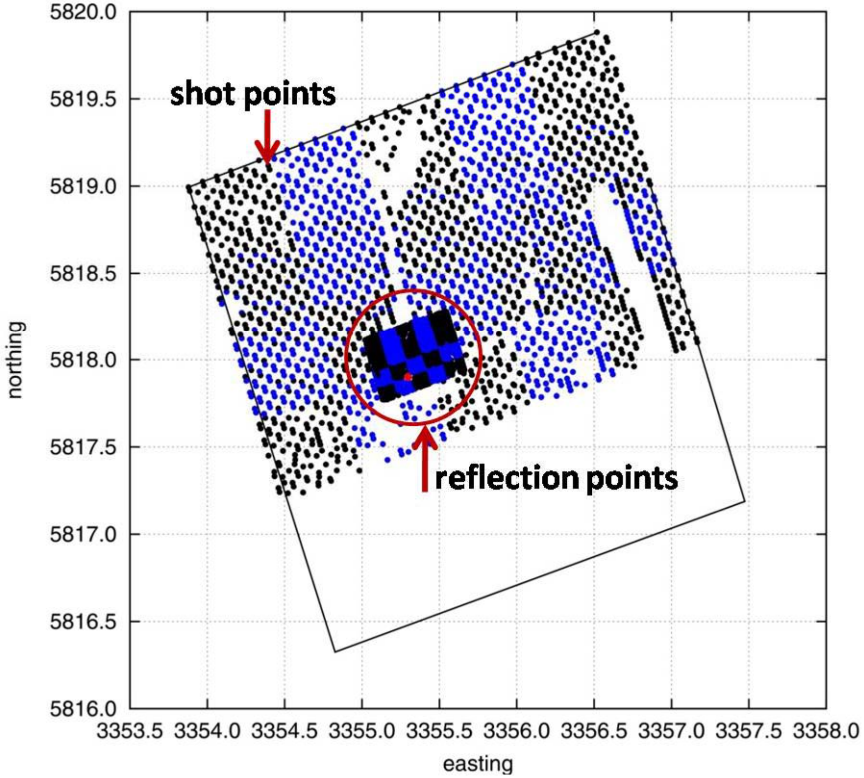
3D-MSP (Moving Source Profiling)

• Record the shotpoints of the 3D-surface measurements with a receiver in the observation well Ktzi 202.

➢ this method provides high underground coverage close to the wells

[photo by R. Giese, 2009]

Seismic monitoring at various scales



The reflection points from top of Stuttgart formation are focused into an area of ~200 m around the injection site (red circle).

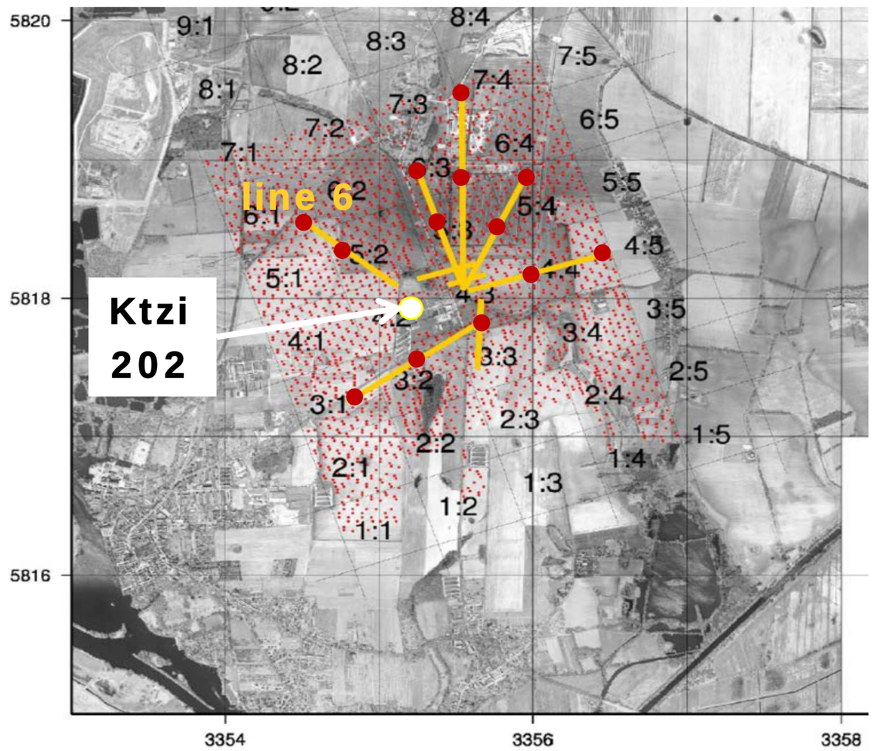
3D-MSP (Moving Source Profiling)

• Record the shotpoints of the 3D-surface measurements with a receiver in the observation well Ktzi 202.

➢ this method provides high underground coverage close to the wells

[photo by R. Giese, 2009]

Seismic monitoring at various scales



Shot points on the seven 2D-surface profiles are recorded in the observation well Ktzi 202 as VSP [Ch. Juhlin, 2009, modified]

Source: VIBSIST-1000/3000

Receiver: 3-component geophone

2D-MSP (Moving Source Profiling)

- Record the shotpoints of the 2D-surface measurements with a receiver in the observation well Ktzi 202 at 470 m depth.

VSP (Vertical Seismic Profiling)

- Record two shotpoints on every 2D-surface line with 80 receivers in the observation well Ktzi 202.

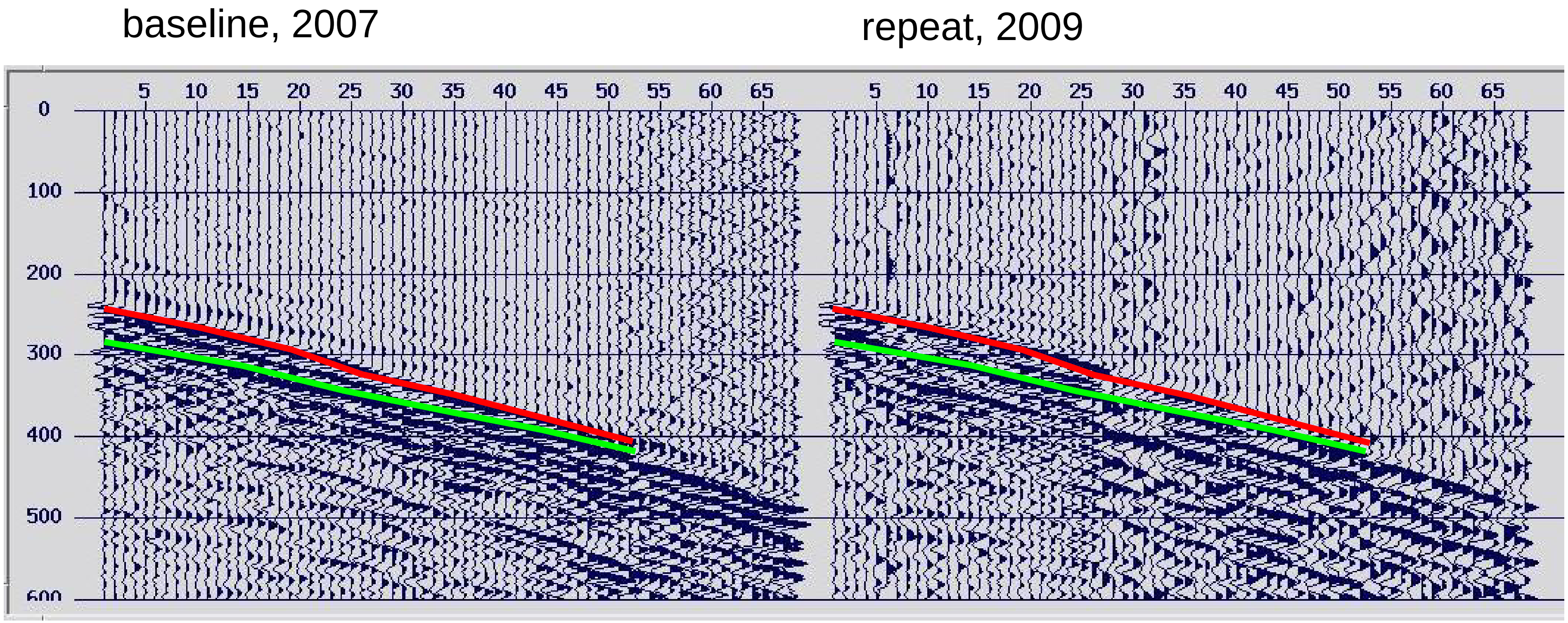
➢ Higher resolution at reservoir depth.

[photo by R. Giese, 2009]

Seismic – Preliminary results

MovingSourceProfiling - MSP

receiver @ 470 m depth, line 6



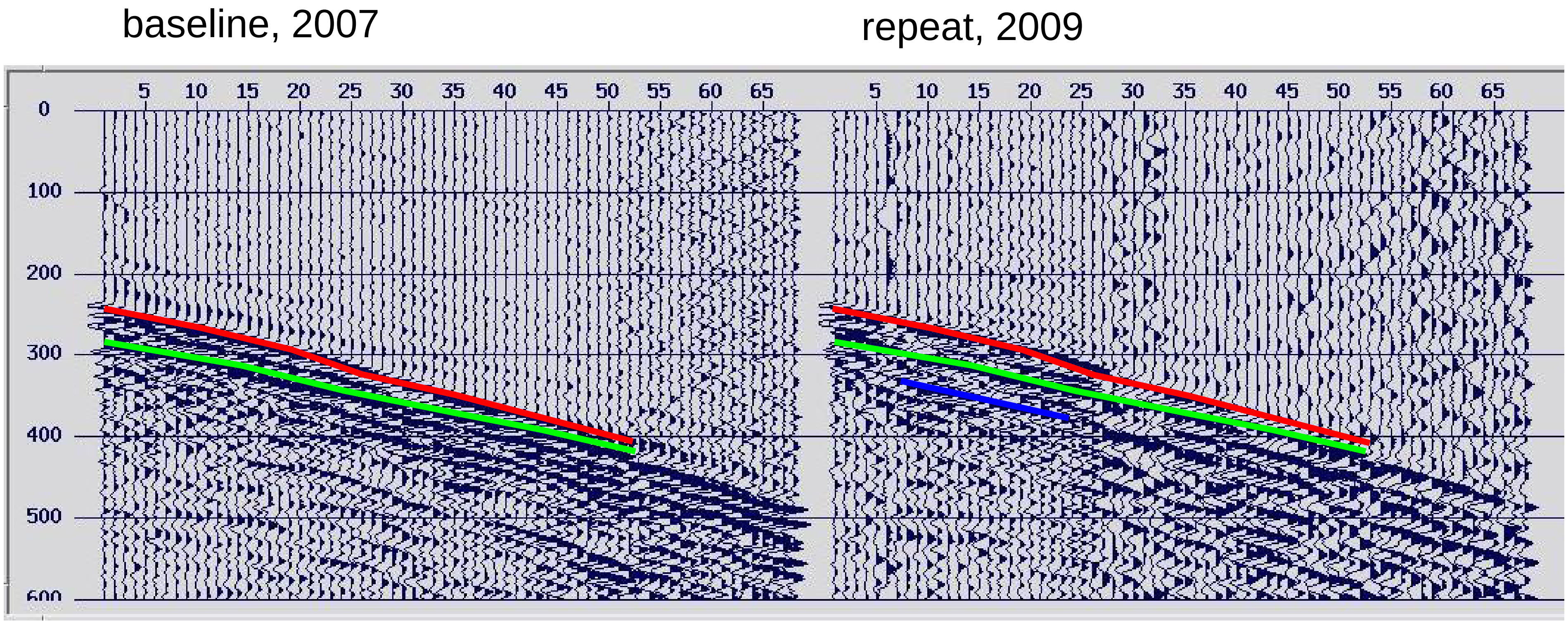
P_{dir} PP (K2, Anhydrite, Top Weser) PP (Top Stuttgart)

[S. Lueth, Ch. Juhlin]

Seismic – Preliminary results

MovingSourceProfiling - MSP

receiver @ 470 m depth, line 6



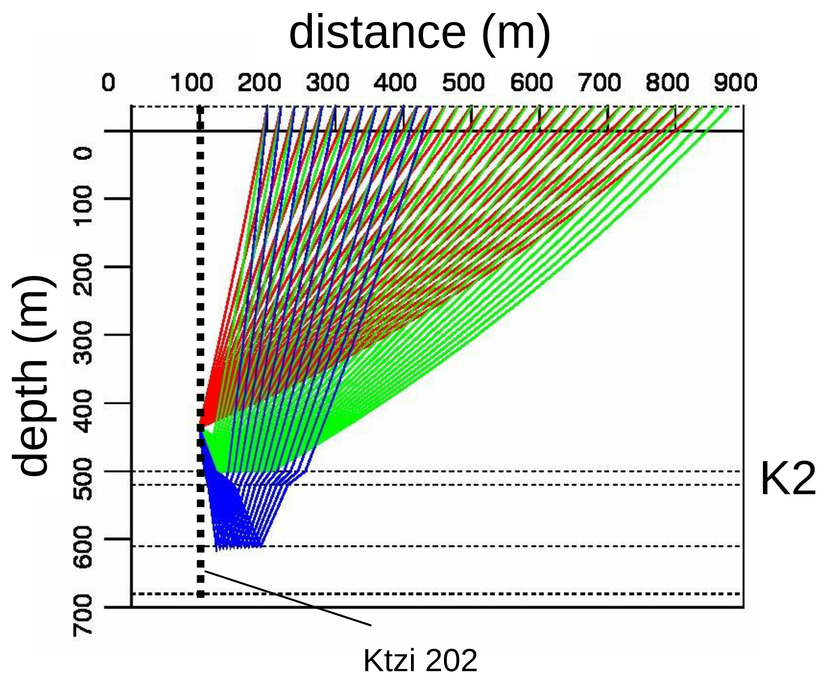
P_{dir} PP (K2, Anhydrite, Top Weser) PP (Top Stuttgart)

[S. Lueth, Ch. Juhlin]

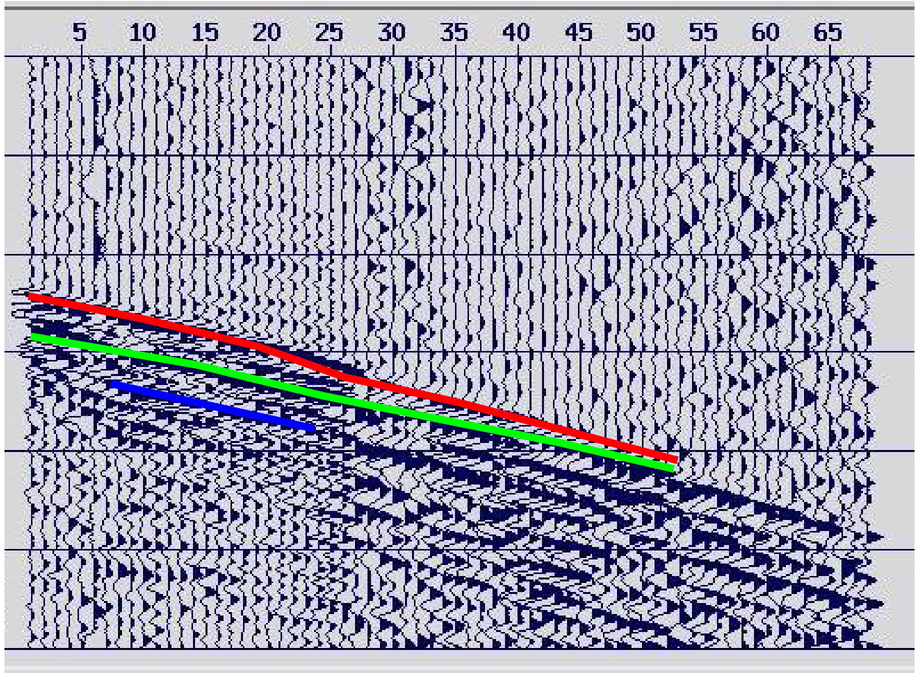
Seismic – Preliminary results

Moving**S**ource**P**rofiling - **MSP**

receiver @ 470 m depth, line 6



repeat, 2009

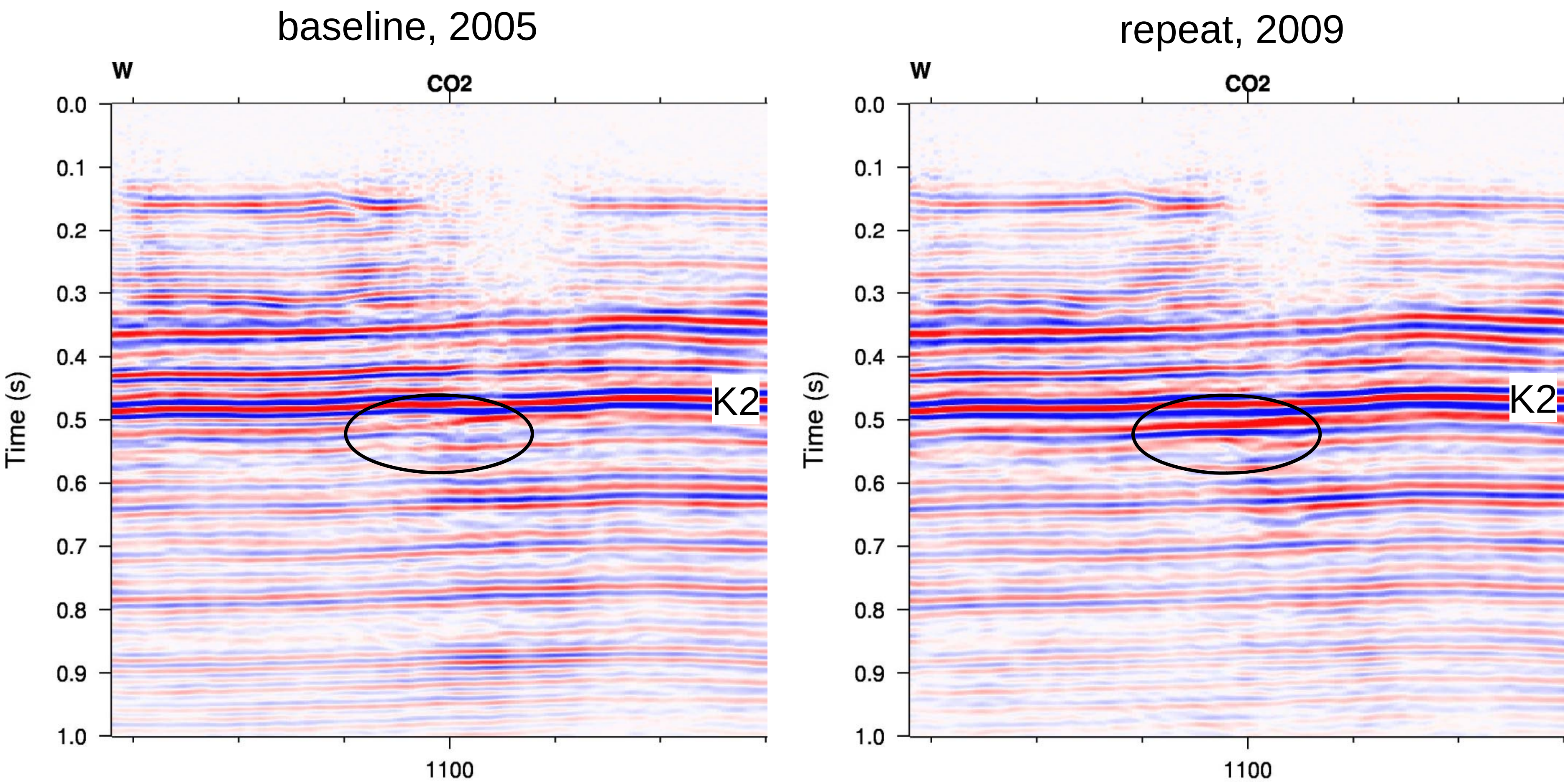


P_{dir} PP (K2, Anhydrite, Top Weser) PP (Top Stuttgart)

[S. Lueth, Ch. Juhlin]

Seismic – Preliminary results

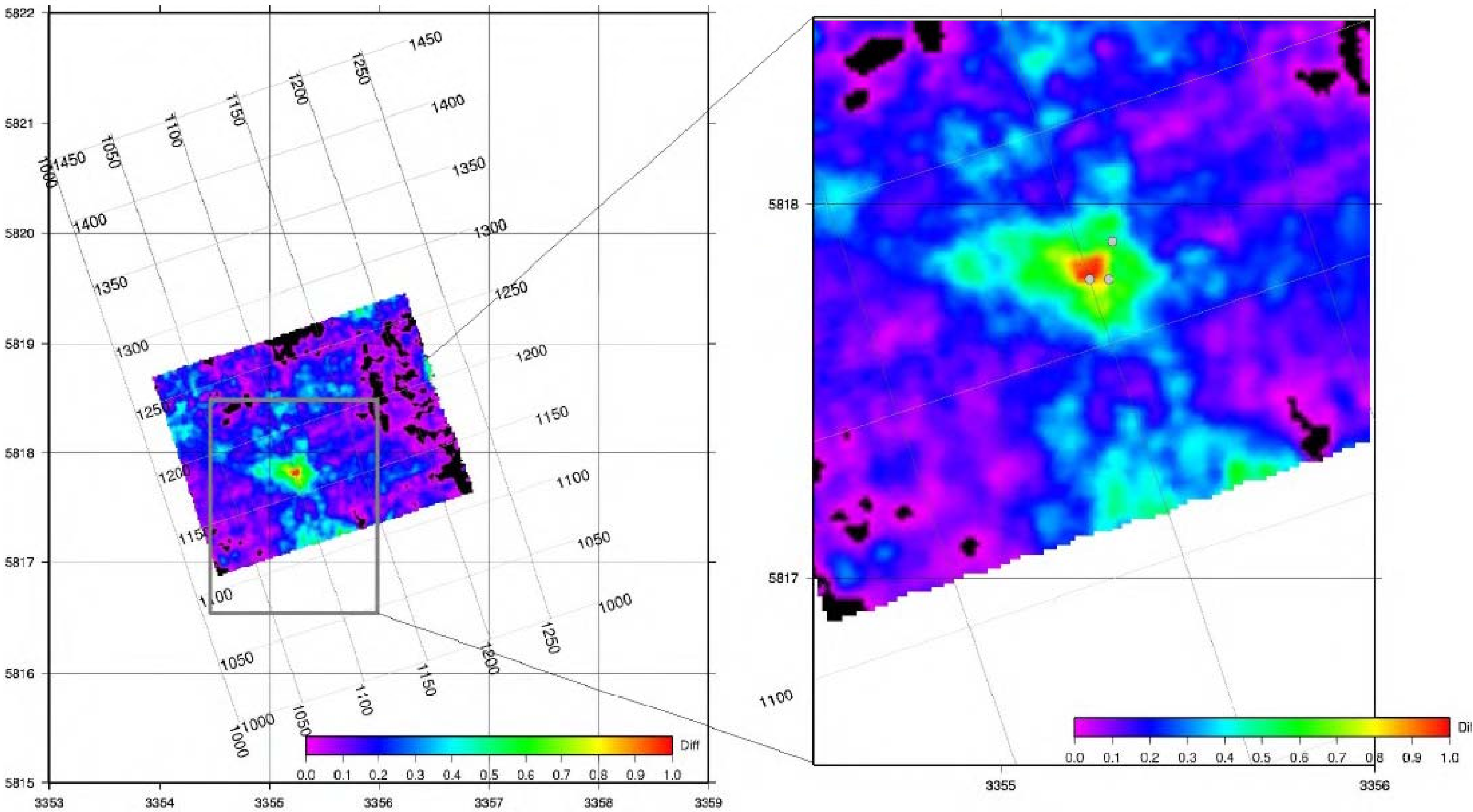
3D-surface seismic



[Ch. Juhlin et al., 2010]

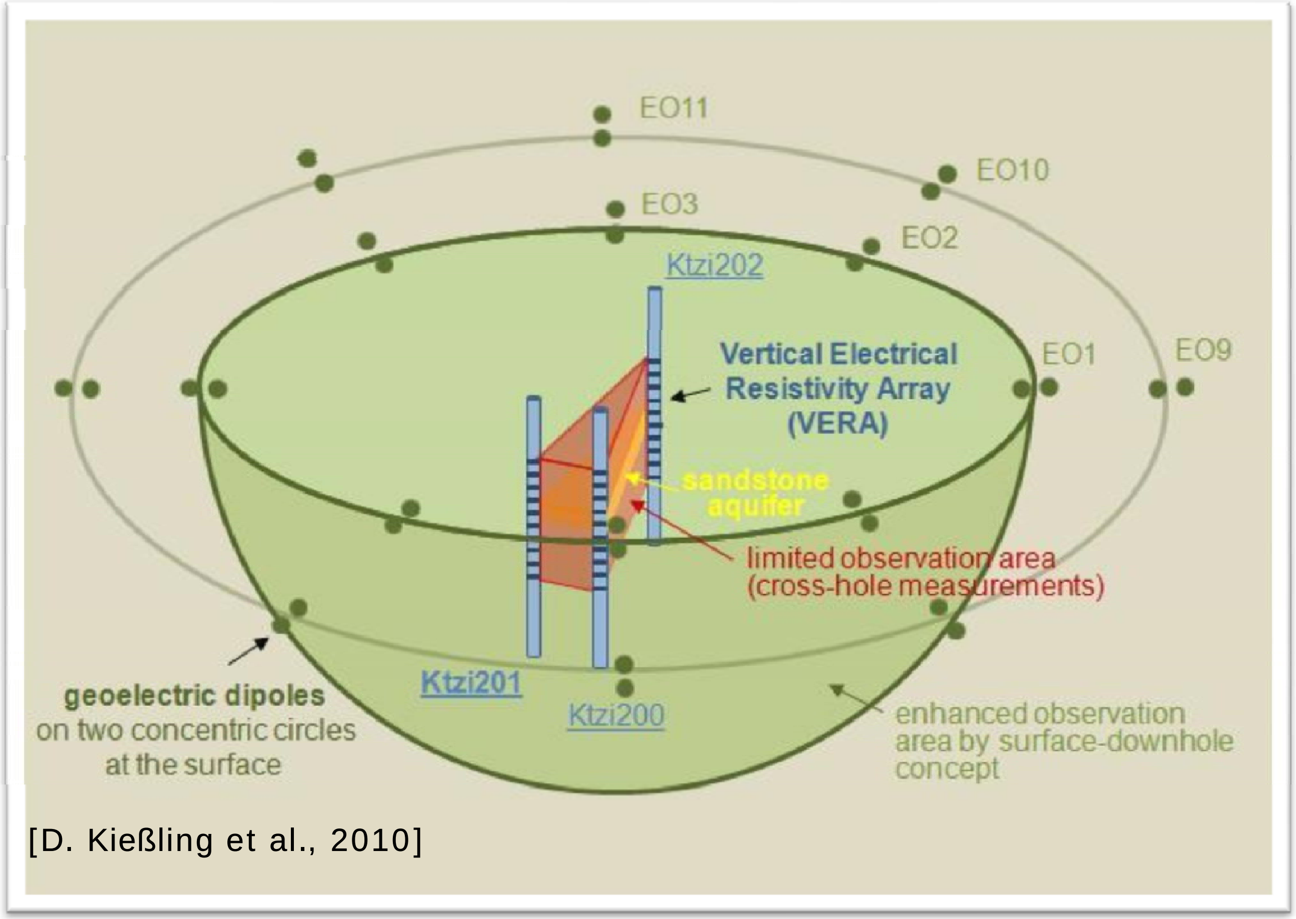
First results of the 3D-surface seismic repeat measurement

Preliminary (!) comparison of reflection amplitudes from top of Stuttgart formation



[Ch. Juhlin et al., 2010]

Geoelectric – the combined concept



Crosshole measurements

45 electrodes in the wells
distance: 10 m
depth: 590 – 735 m

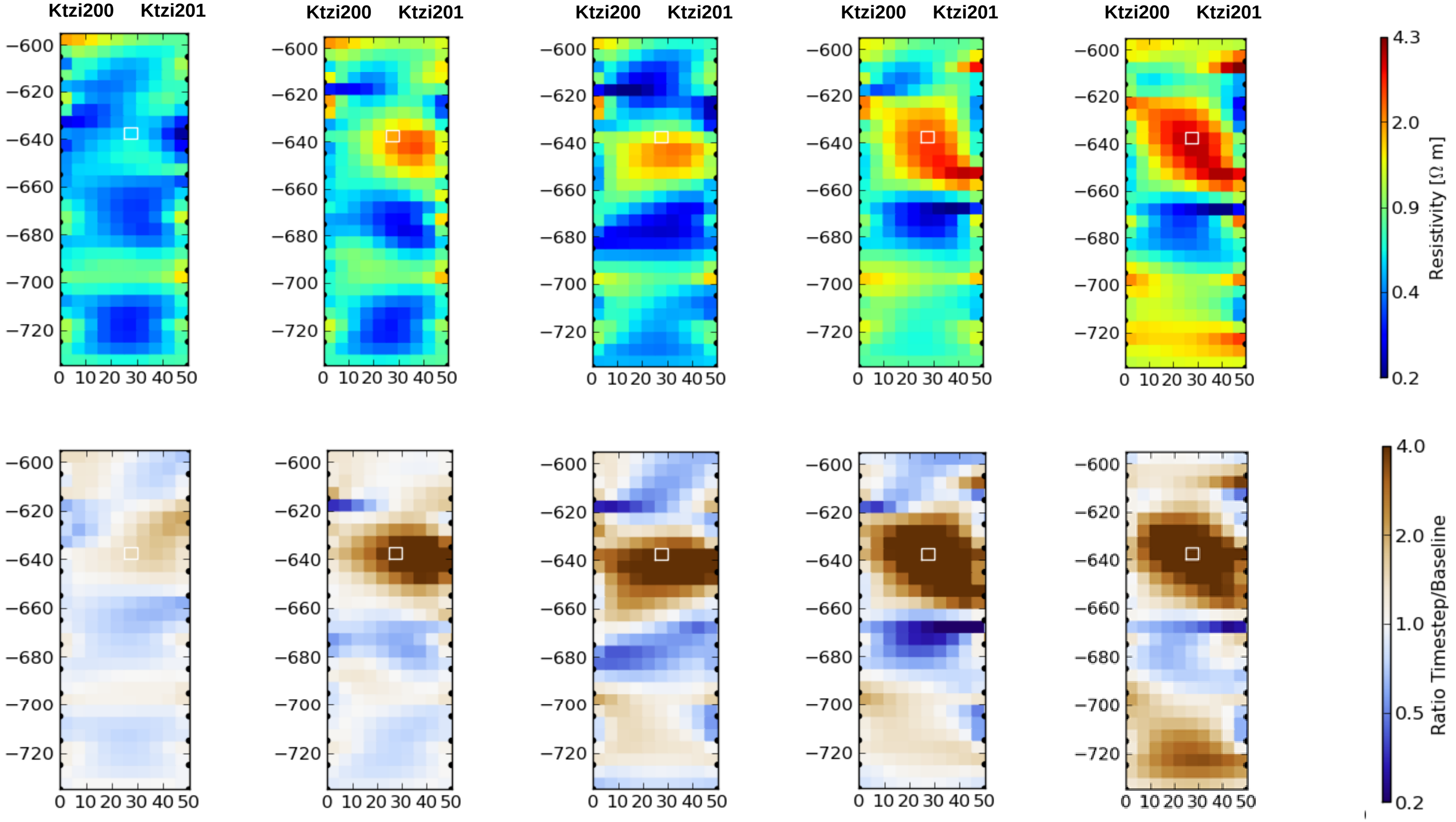
Large-scale measurements

16 dipoles at the surface
Dipole length: 150 m
r_1 = 800 m, r_2 = 1500 m

Geoelectric – first inversion results

Crosshole ERT

[ERT Team]

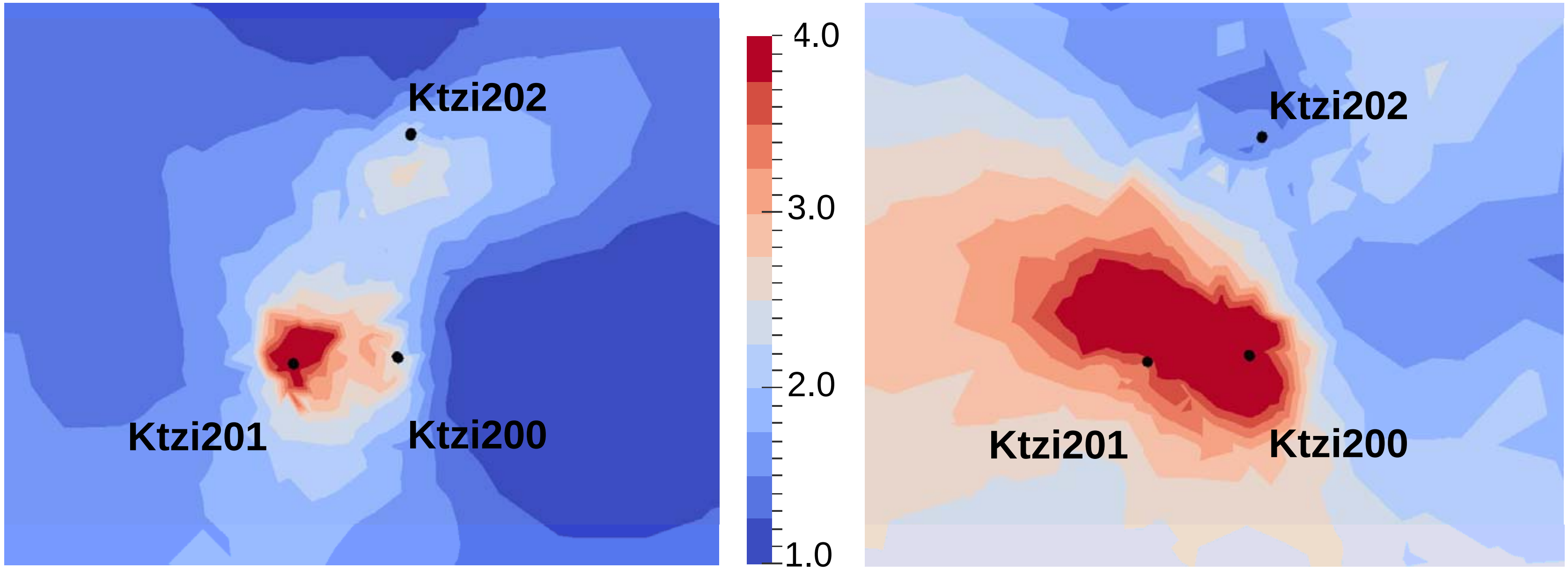


August 11, 2008 **December 29, 2008** **July, 7, 2009** **December 4, 2009** **April 1, 2010**

Geoelectric – first inversion results

Surface Profiles & Surface-Downhole Measurements

Resistivity-Ratios at 635 m depth slice (top of reservoir Ktzi 201-Ktzi 200)



Resistivity-ratio

[D. Kießling & C. Rücker, 2010]

2nd Repeat: 11/2008

- after 4,500 t CO_2
- CO_2 arrival at Ktzi 200 (07/2008)

Vs. 2nd Baseline: 04/2008

3rd Repeat: 04/2009

- after 13,500 t CO_2
- CO_2 Arrival at Ktzi 202 (03/2009)

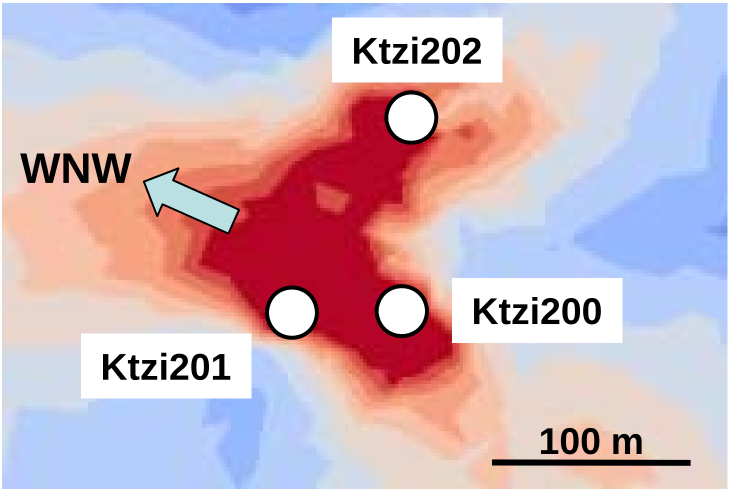
Vs. 2nd Baseline: 04/2008

Phase of data integration

Geoelectric - Seismic

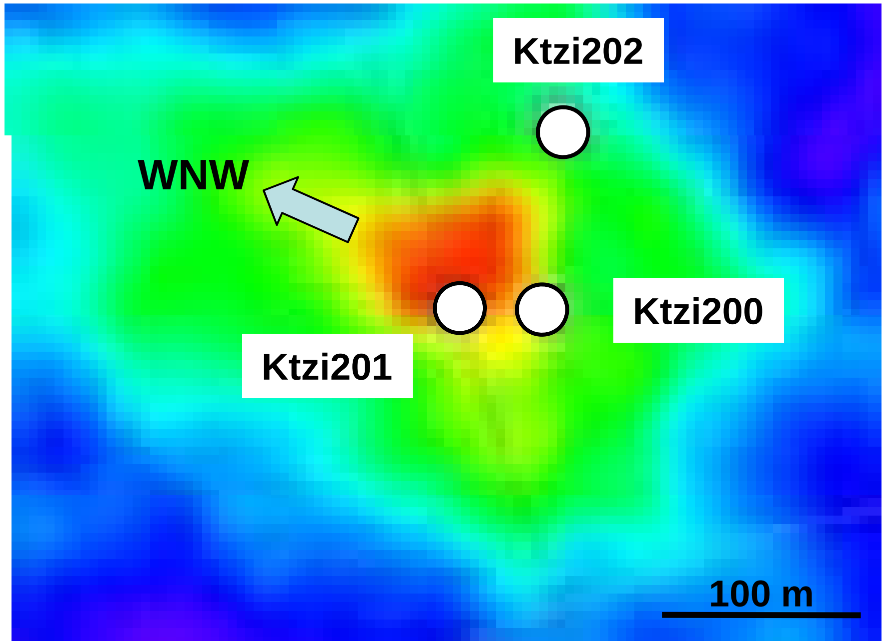
Geoelectric

April 2009; injected: 13,5 kt CO_2



Seismic

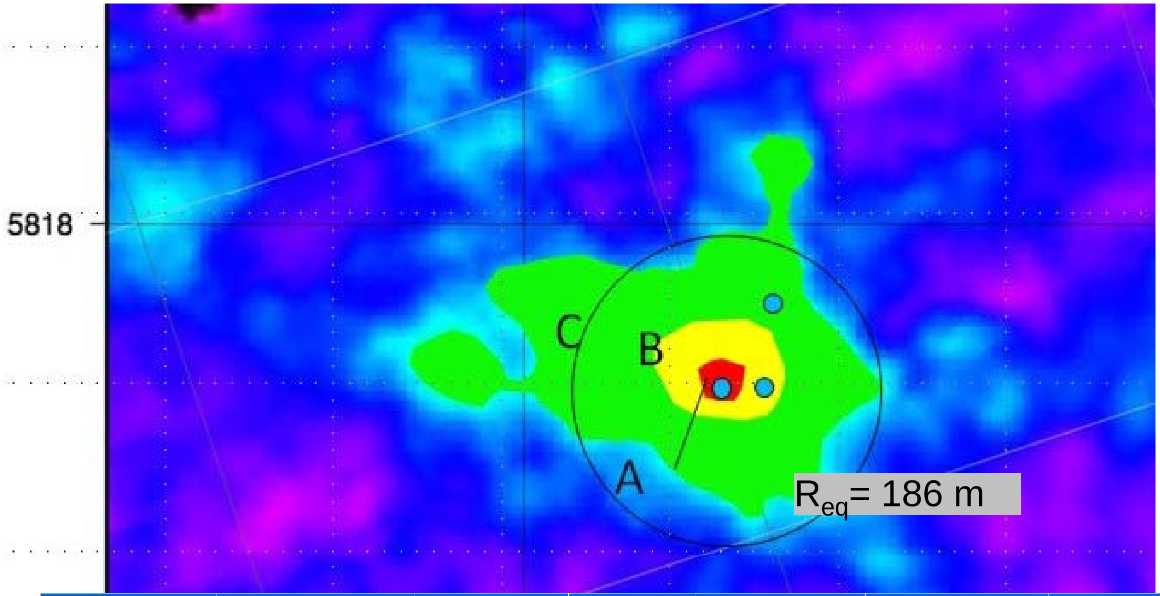
Autumn 2009; injected: 22 - 25 kt CO_2



In principle, results from both methods agree.

Preferred direction of migration: WNW trend

Preliminary min-max estimate of CO_2 mass in anomaly



First preliminary attempt to estimate mass distribution:

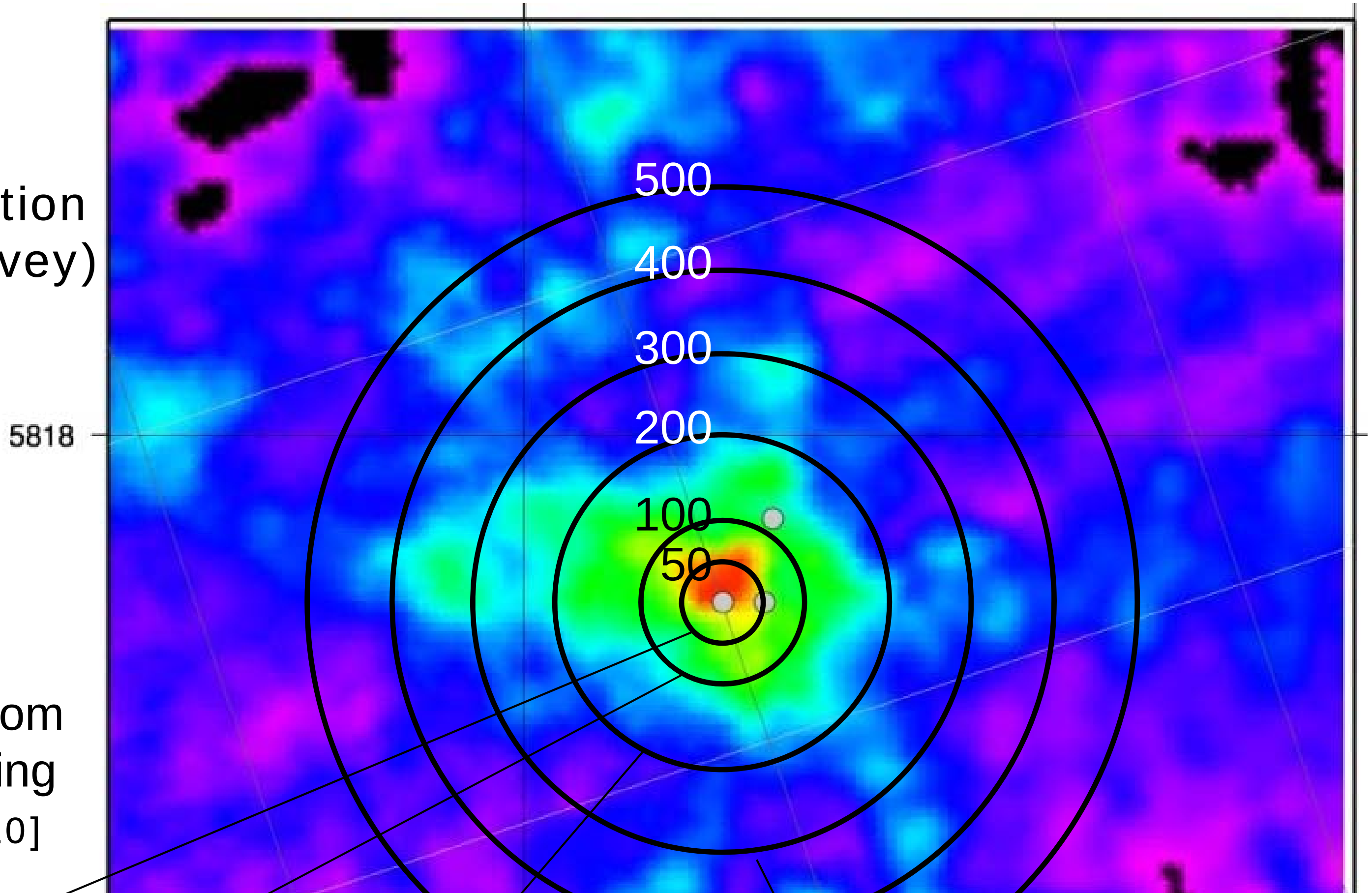
- **Define sectors and assign typical properties.**
- **Consider results from borehole monitoring and petrophysics.**
- **Derive CO_2 mass and compare to actually injected amount.**

Sector	Area (m^2)	H CO_2 (m)	eff. Por.	Den. (kg/m^3)	Sat co2 (1)	Sat co2 (2)	M co2 (kg) (1)	M co2 (kg) (2)
A	2293	20	0.20	280	60%	80%	1.540.896	2.054.528
B	12656	14	0.20	280	60%	80%	5.953.382	7.937.843
C	93862	7	0.20	280	10%	30%	3.679.390	11.038.171
Total	108811						**11.173.668**	**21.030.542**
Injected								~22.000.000 - ~25.000.000

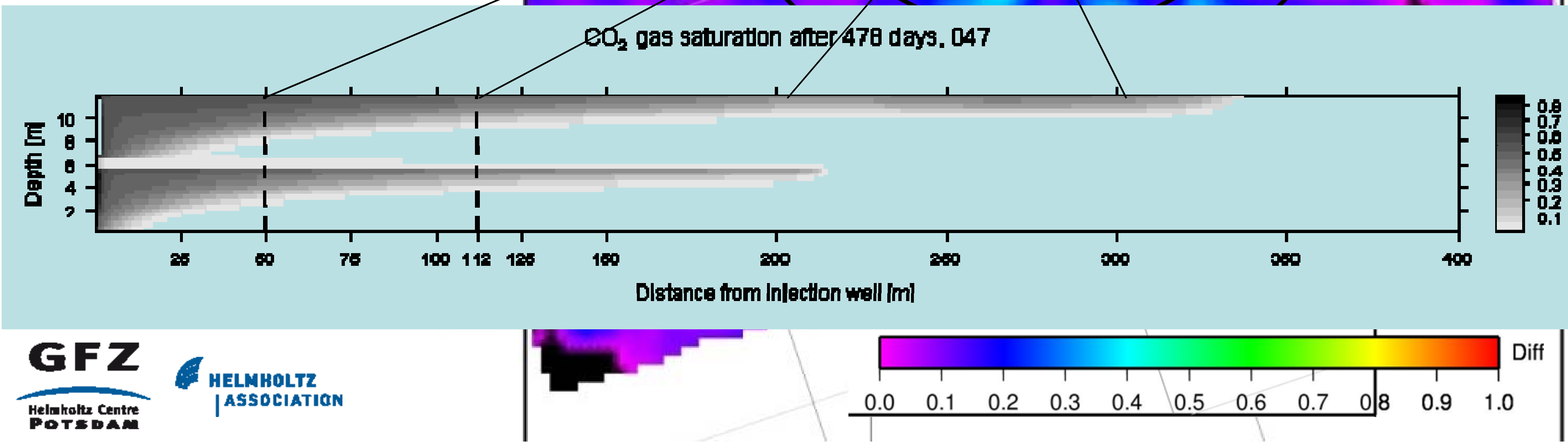
[after S. Lueth, A. Liebscher, J. Henninges]

Comparison with modelling results 478 days after injection started (seismic survey)

[modified after Ch. Juhlin et al., 2010]



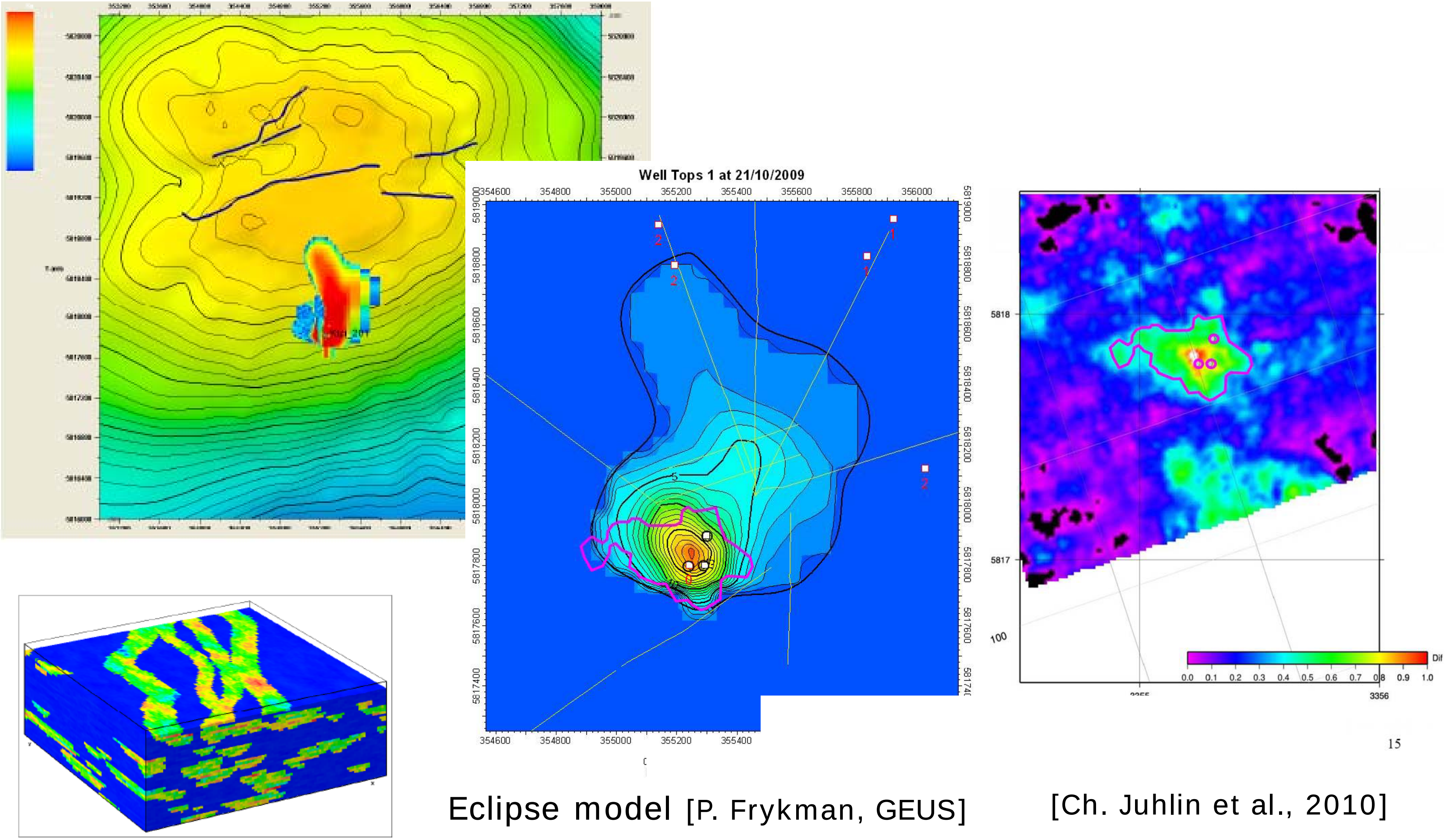
Propagation scenario from Multiphase-Flow modelling TOUGH2 [U. Lengler, 2010]



GFZ Helmholtz Centre Potsdam

HELMHOLTZ ASSOCIATION

Dynamic flow modelling and 3D seismic



Eclipse model [P. Frykman, GEUS]

[Ch. Juhlin et al., 2010]

Summary & Outlook for Ketzin

- Arrival of CO_2 in both observation wells detected
- No CO_2 leakage at surface detected
- Normal reservoir response, good flow into formation, stable down hole pressure $\Rightarrow$ below safety threshold
- Geophysical monitoring promising
- Match with numerical simulation
- High local, national and international interest with a lot of good press response, high awareness of CCS technique

Questions not yet answered by Ketzin:

- Quantitative assessment of competitive use of underground (i.e. geothermics)
- Up-scaling to commercial projects

large-scale demo projects are necessary

Upscaling

Ketzin		Commercial site
~ 630 m	depth	>> 1000 m
~ 75 bar/36 °C	pressure/temperature	*> 100 bar/> 50 °C*
6 x 10^{4} t	total mass CO_2	x 10^{6} – 10^{7} t
~ 10^{0} km^2	extension	x 10^{2} km^2
~ 7 x 10^{1} t/Tag	injection rate	x 10^{3} – 10^{4} t/Tag
~ 3,3 m^3/t	spec. volume CO_2	*< 1,5 m^3/t*
> 99,9 %	purity CO_2	> 85 – 95 %

commercial sites are 2 to 3 orders of magnitude larger

Thanks to all involved persons

German Research Centre for Geosciences

D-14473 Potsdam, Telegrafenberg, Germany

Thank you very much for your attention

An update of the Lacq-Rousse project

Hubert FABRIOL

h.fabriol@brgm.fr

Joëlle Hy-Billiot, Marc Lescanne, Nicolas Aimard

TOTAL

Géosciences pour une Terre durable

brgm

Outline

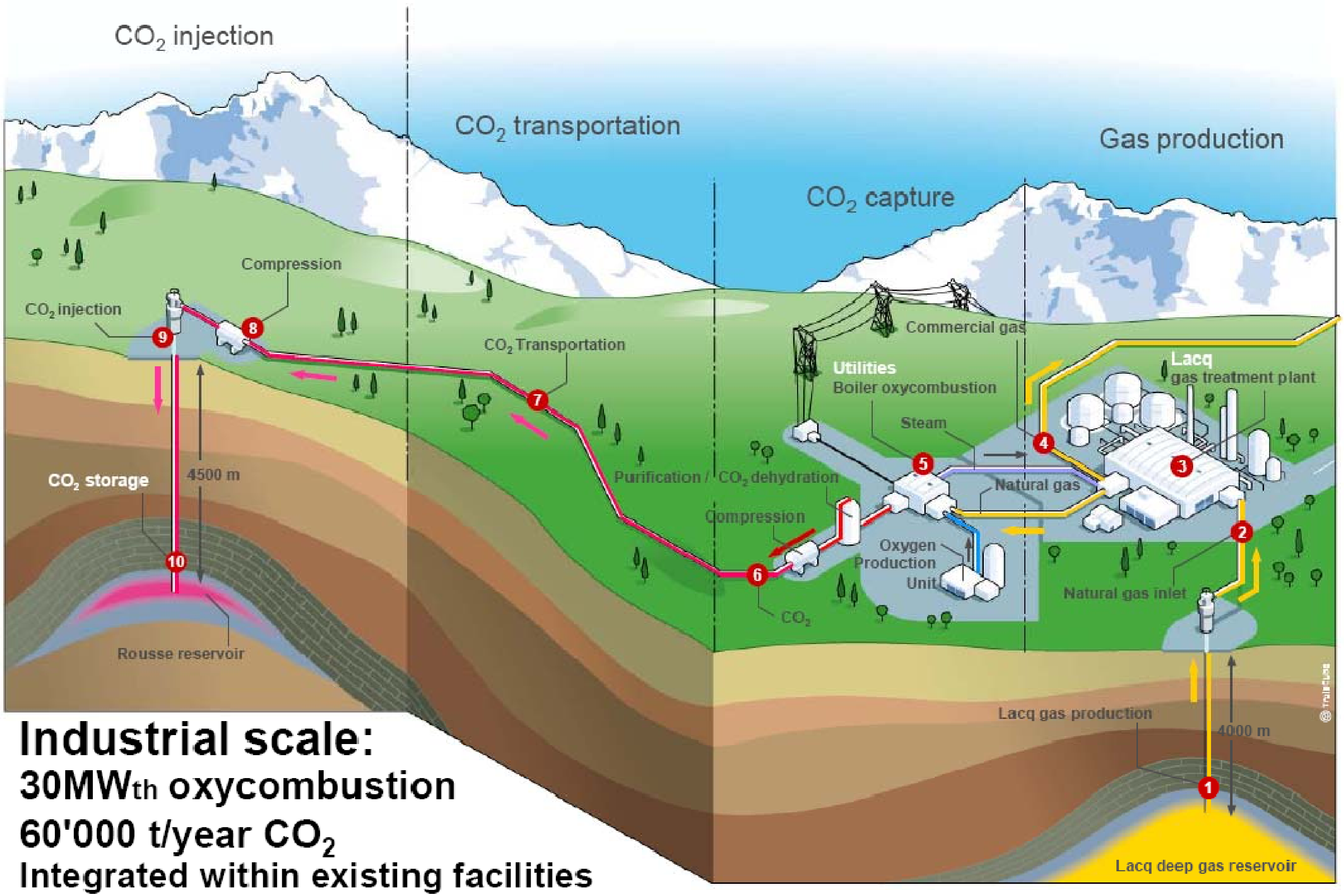
> **Presentation of the Lacq-Rousse CCS project**

> **The monitoring plan**

> **Passive seismic monitoring**

> **Surface monitoring (soil gas sampling)**

An integrated carbon capture, transportation and geological storage in a depleted gas field project



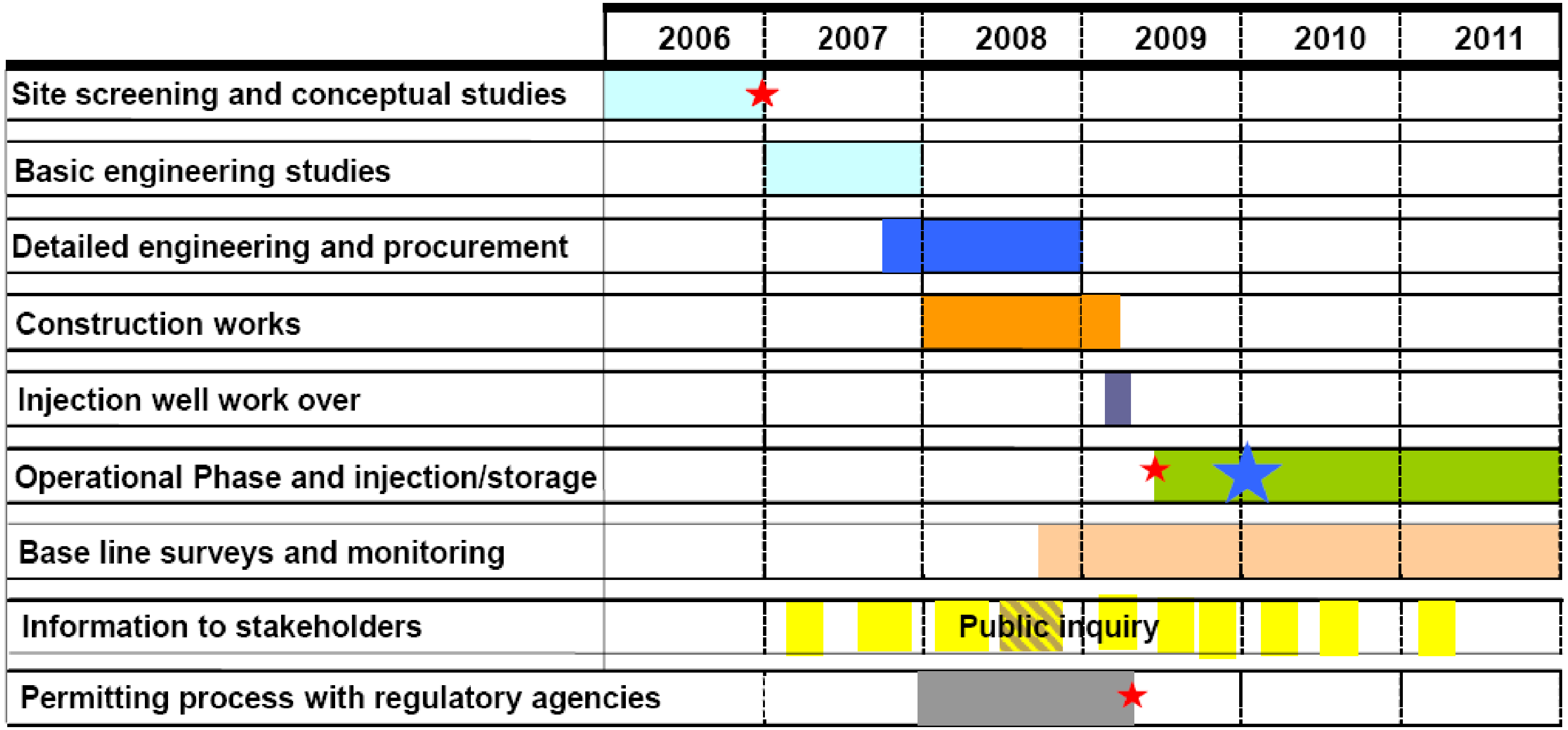
Industrial scale:

30MWth oxycombustion

60'000 t/year CO_2

Integrated within existing facilities

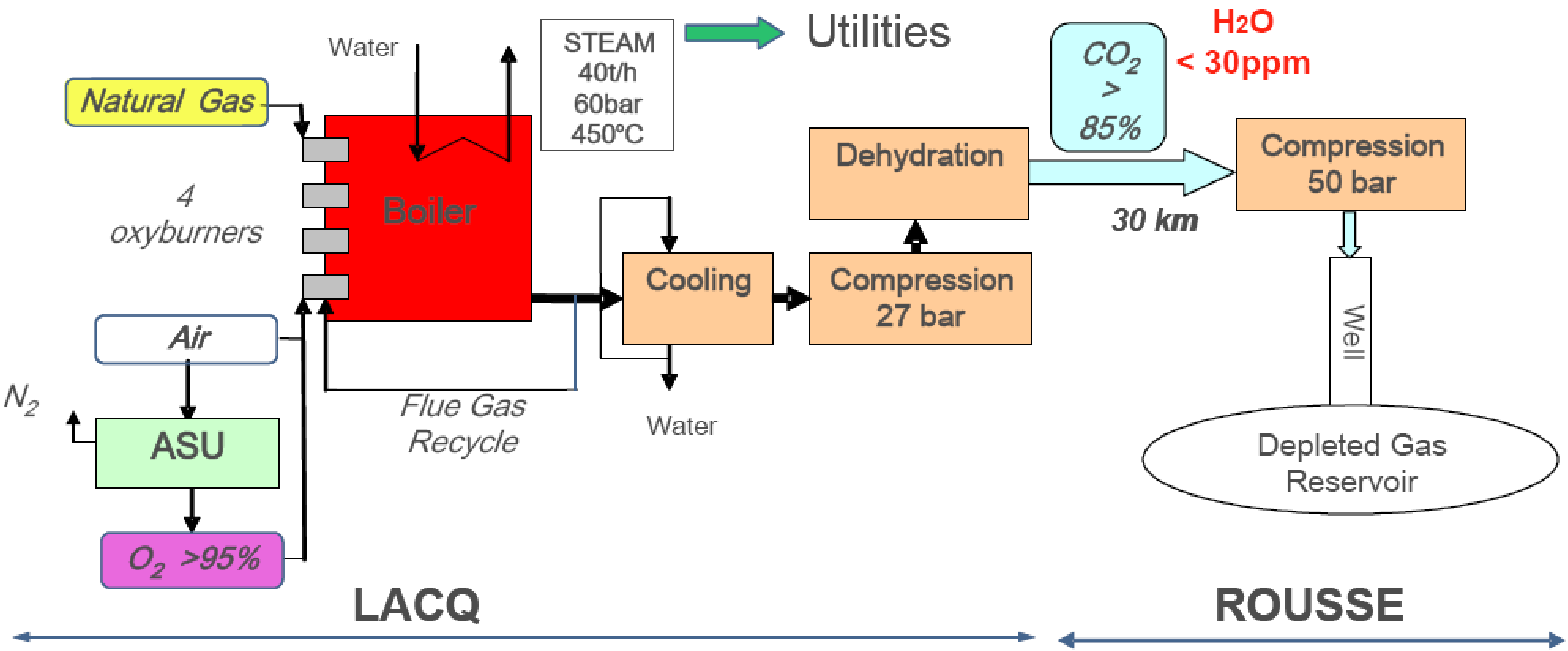
Project schedule milestones



Start up of operational phase : July 3rd, 2009

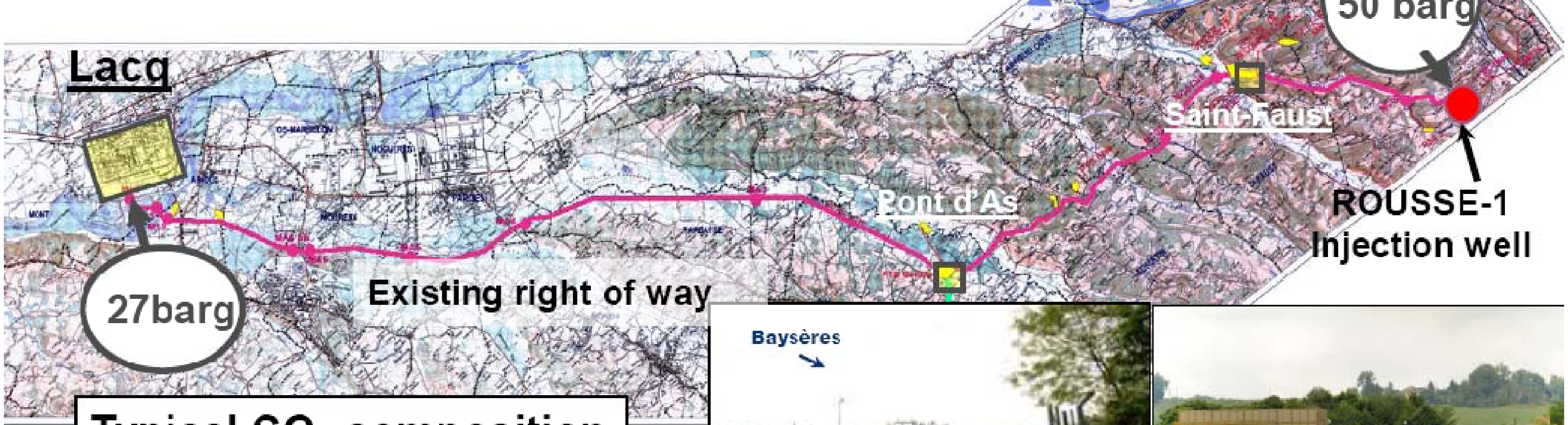
Injection started January, 8th 2010

Oxycombustion as part of a CCS integrated pilot



- Industrial scale 30MWth oxycombustion unit with gas
- Revamping of a conventional boiler
- CO_2 transport and injection for 2 years
- 120 kt CO_2 storage in a depleted reservoir
- First CO_2 injection for storage in France
- Public acceptance with consultation and dialogue
- Upscaling of oxyboilers for high steam/power generation

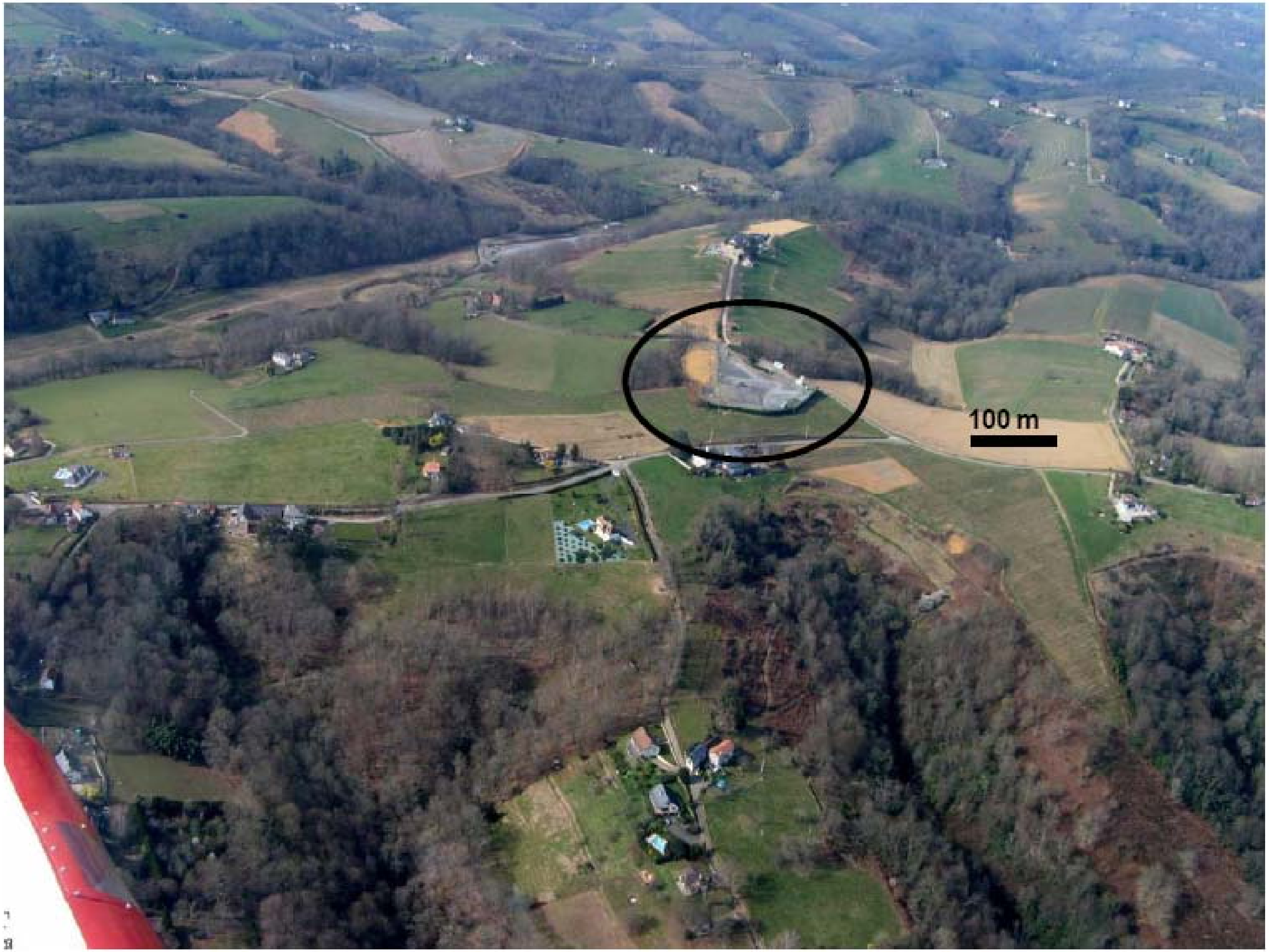
Transportation and injection into a gas depleted reservoir



Typical CO_2 composition

CO_2: 92.0 %
O_2: 4.0%
Ar: 3.7%
N_2: 0.3%
water content # 30ppm

Puits Rousse 1

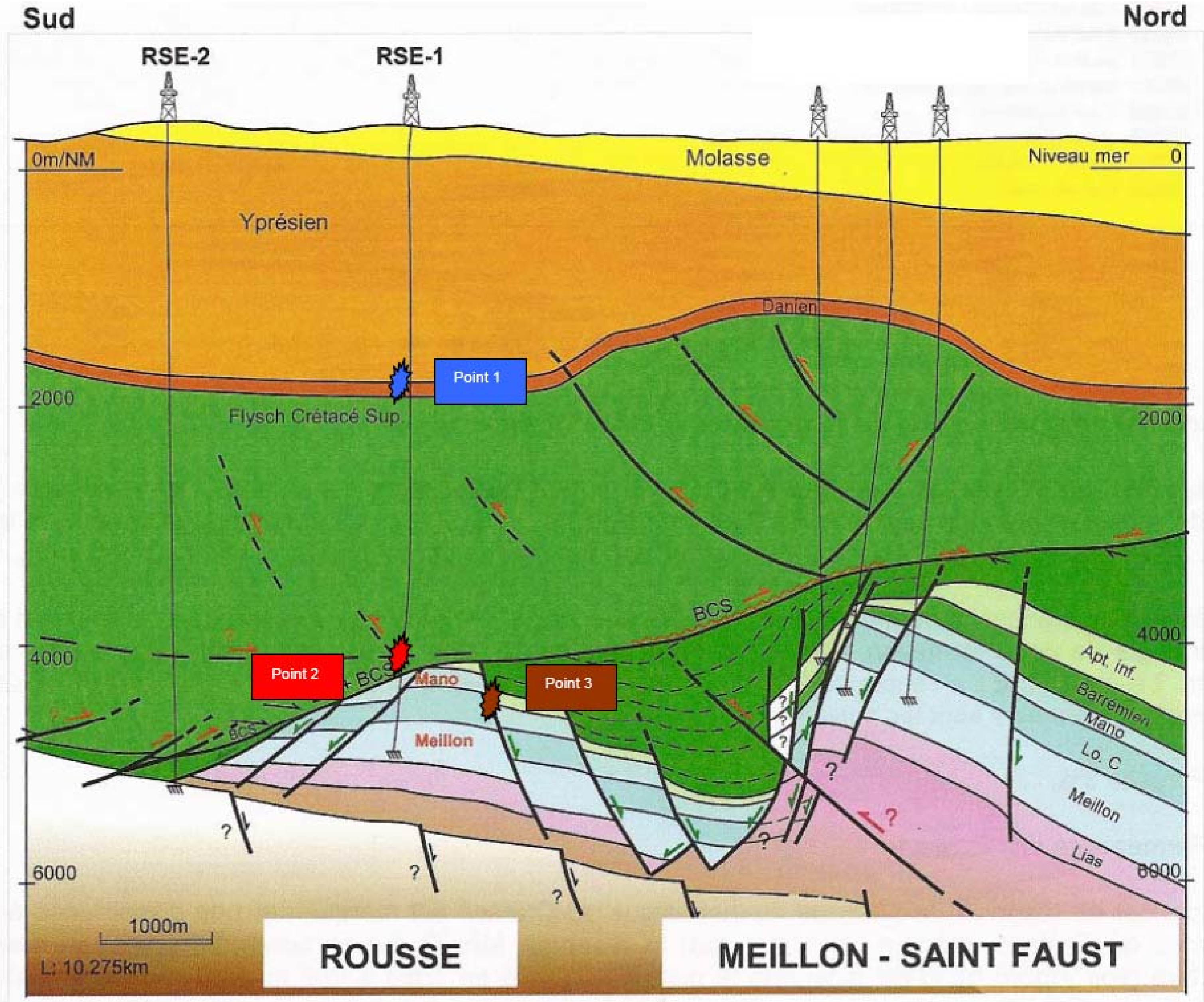


TOTAL

Main characteristics of the storage complex

- 120 Kt injected at 4500 m depth in the Jurassic dolomites of the Mano formation
- Injection rate (nominal): 80 000 Sm^3/day
- Small depleted gas reservoir (circular structure, bottom diameter ca. 750 m)
- Reservoir initial pressure 485 bars, present pressure 40 bars
- Porosity: 3 %, primary permeability: 1 mD, fractured
- Overburden: 2300 m of Cretaceous flysch

Geological cross-section



Pressure profile (history matching and predicted)

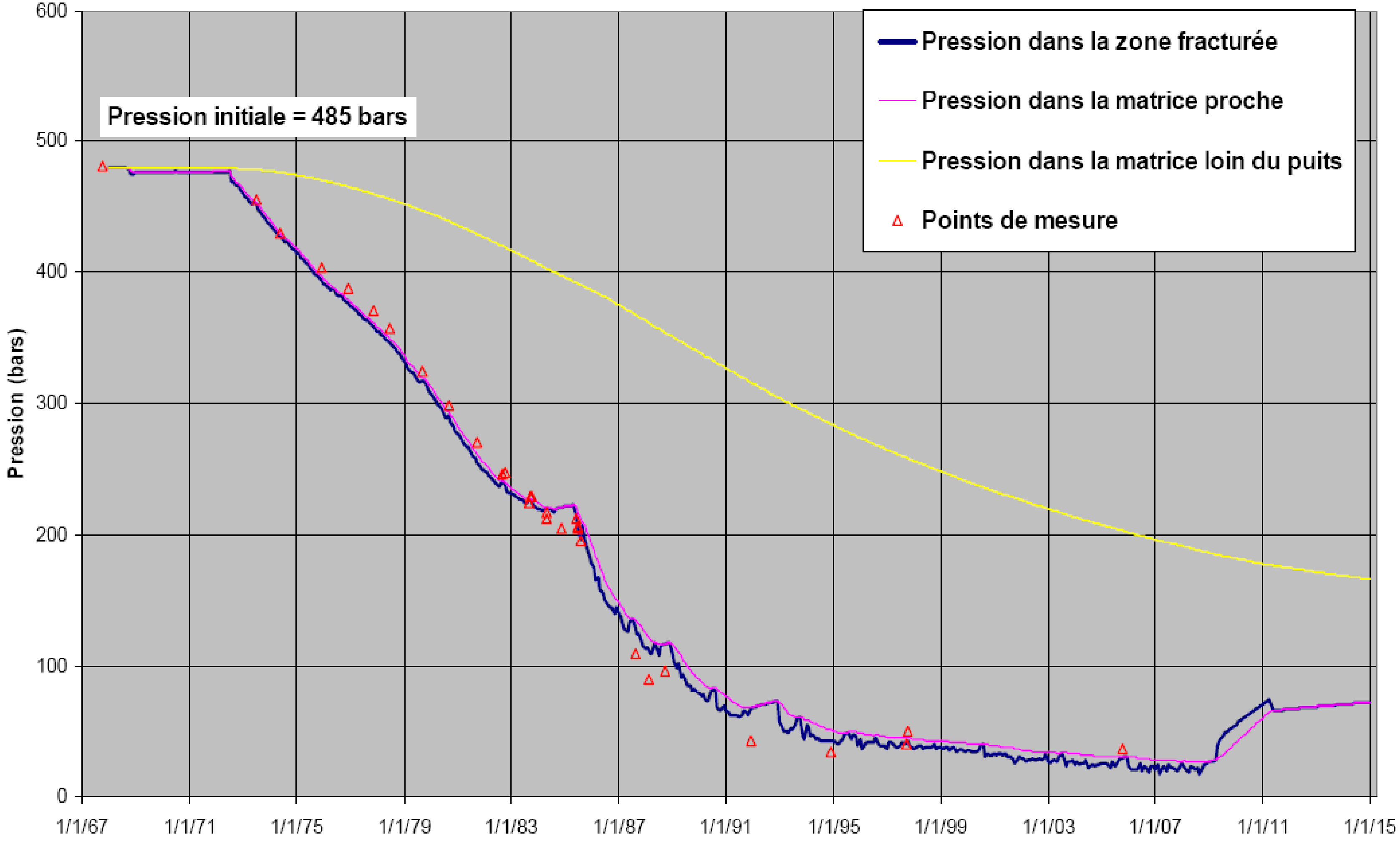
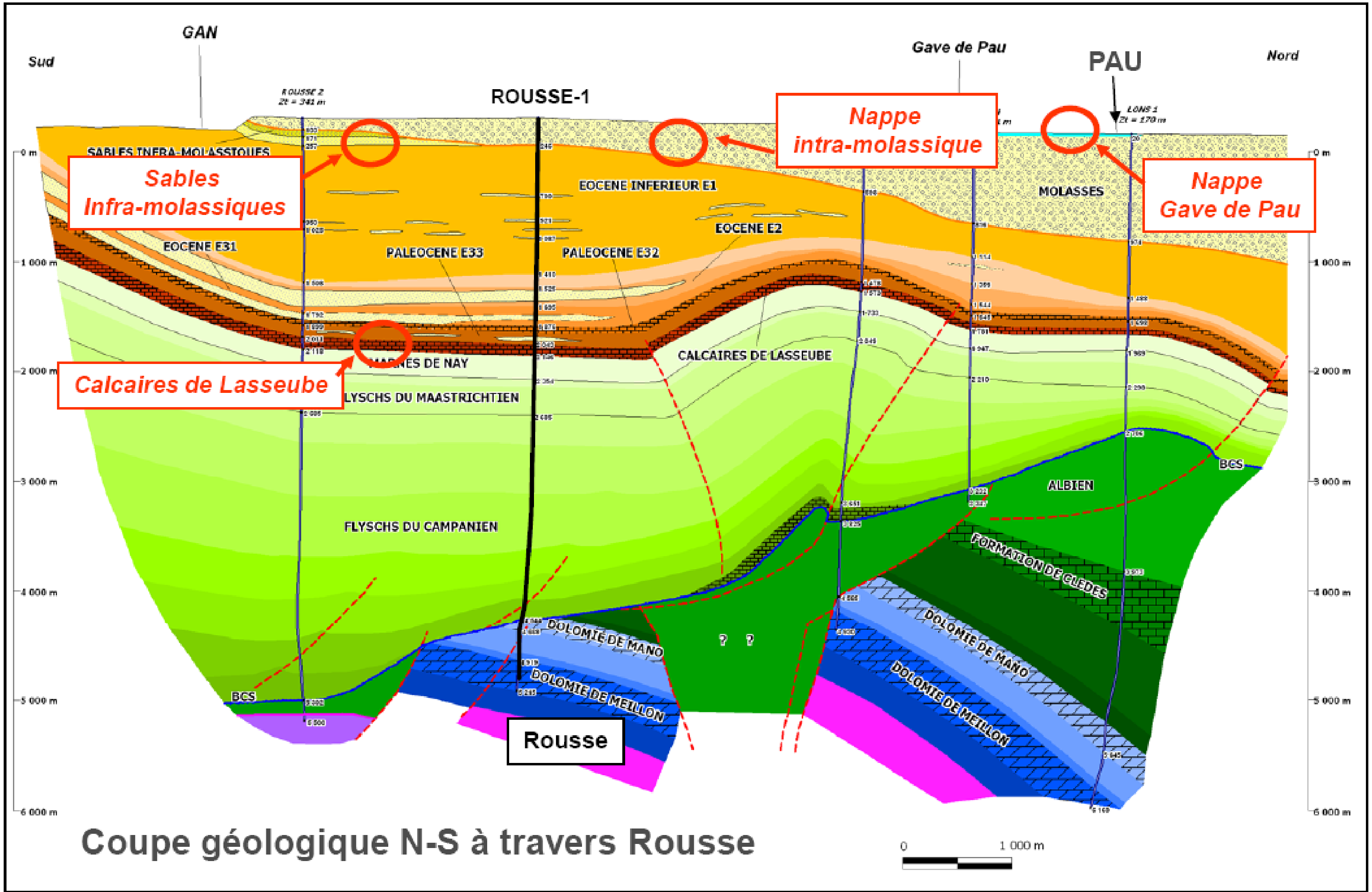
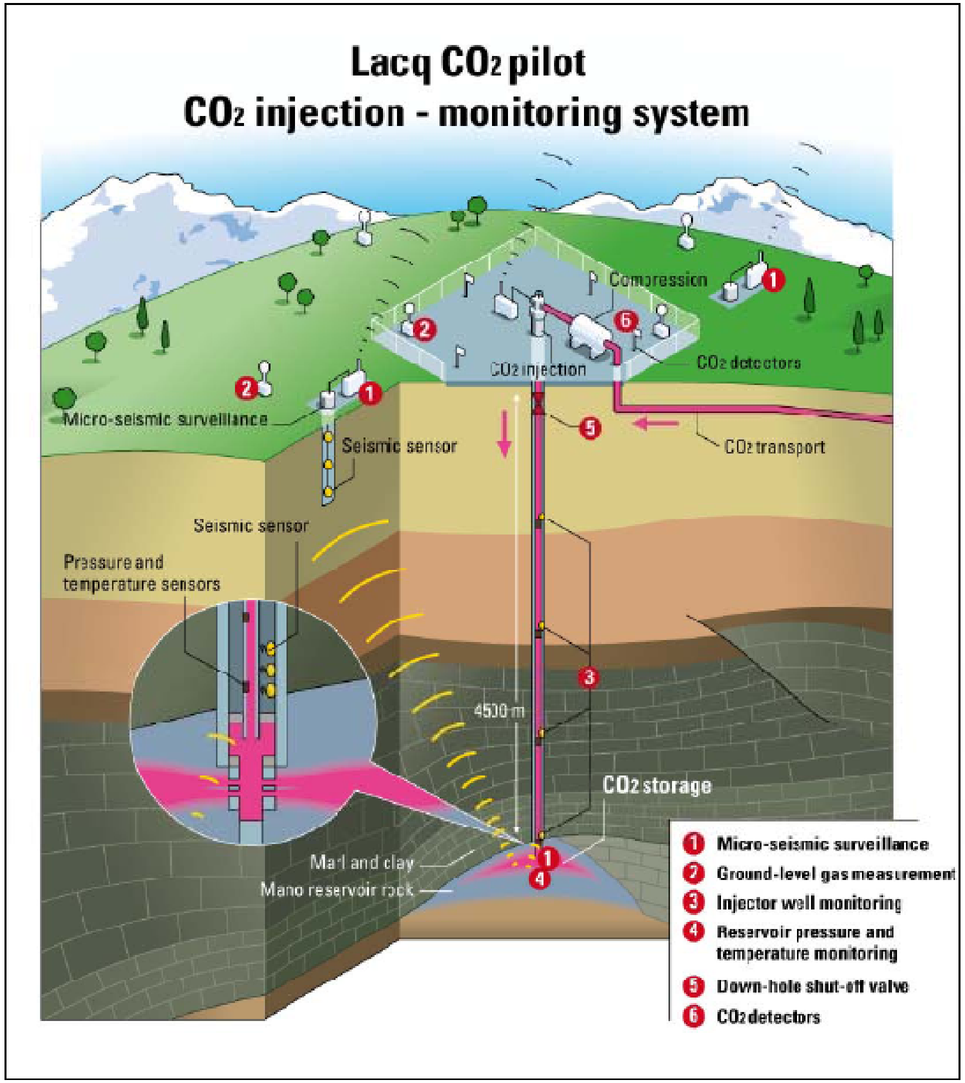


Figure 6 : Production du puits Rousse-1 - calage de l'historique de production et prévisionnel

Aquifers within the storage complex



CO_2 Monitoring plan



Lacq CCS project - NA

Injection phase

- Flowrate & composition of injected gas
- P and T borehole and reservoir pressure (optical fibre)
- Microseismic monitoring of reservoir and caprock
  - baseline before injection
- Gas migration at the surface :
  - soil gas survey (baseline before injection)
  - surface detectors on well pad
- Environmental monitoring
  - Underground aquifers and surface water
  - Fauna and flora

Post injection phase

- P and T bottom hole and reservoir pressure
- Microseismic monitoring of reservoir and caprock
- Gas migration at the surface
- Environmental monitoring

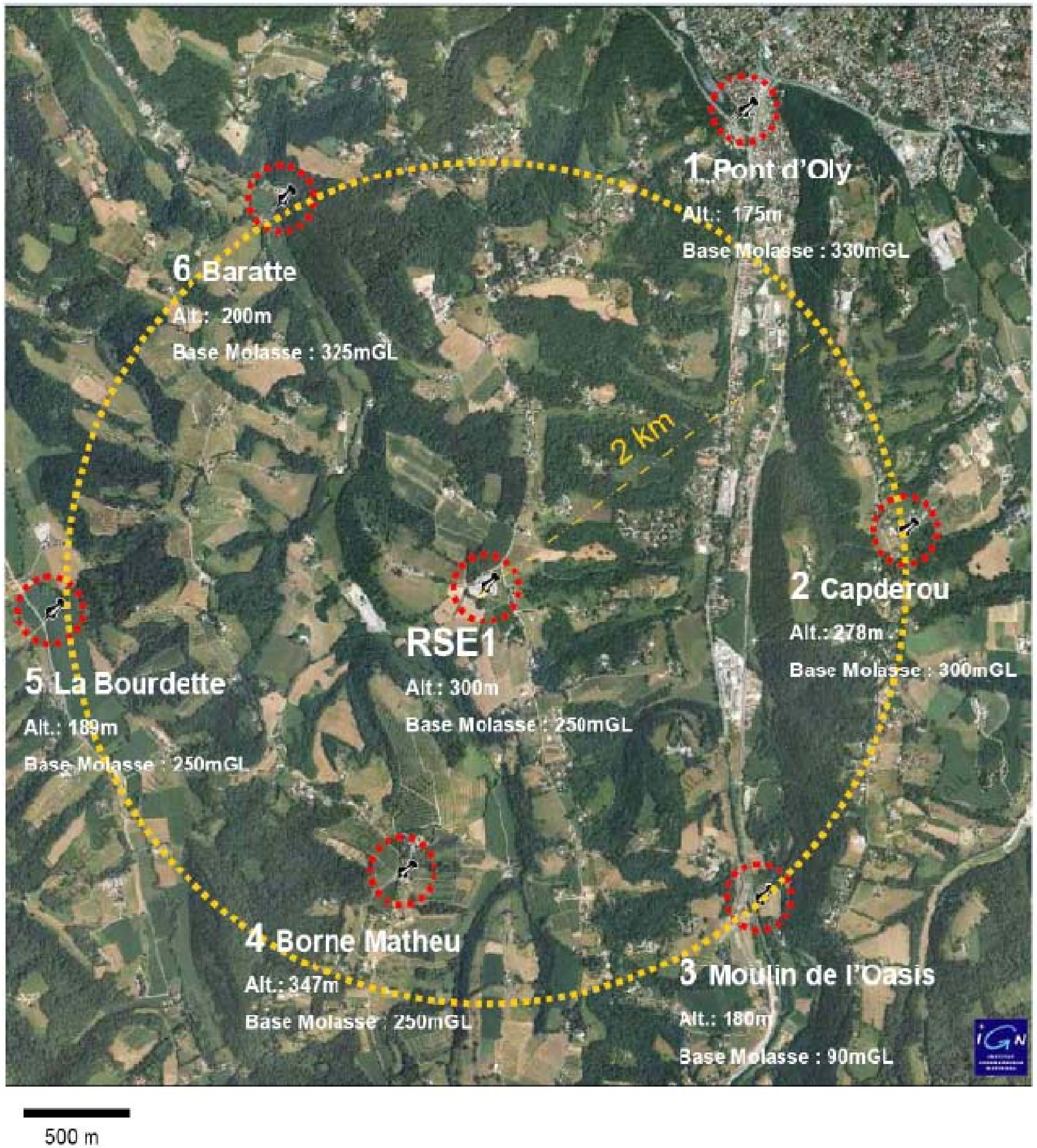
The passive seismic array

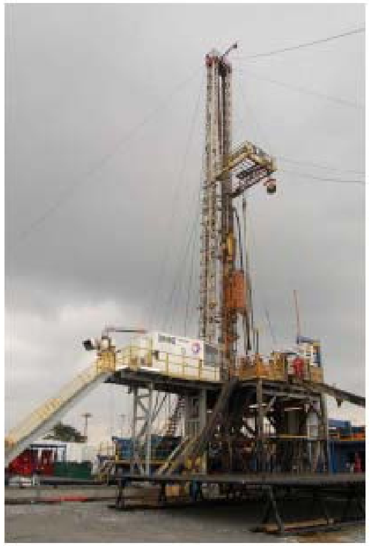
- **Designed to detect induced seismicity, either in the reservoir, nearby faults or in the overburden**
- **Previous modelling study to optimize detection thresholds, errors location and redundancy of sensors**
- **Shallow monitoring array : 7 wells (200 m deep) with 4 downhole 3-C geophones (10 Hz)**
- **3 deep downhole Weatherford-Clarion 3-C accelerometers, bandwidth 1 to 800 Hz, (at 4180, 4280 and 4380 m)**
- **1 surface seismometer close to the centre of the array**

TOTAL

Géosciences pour une Terre durable
brgm

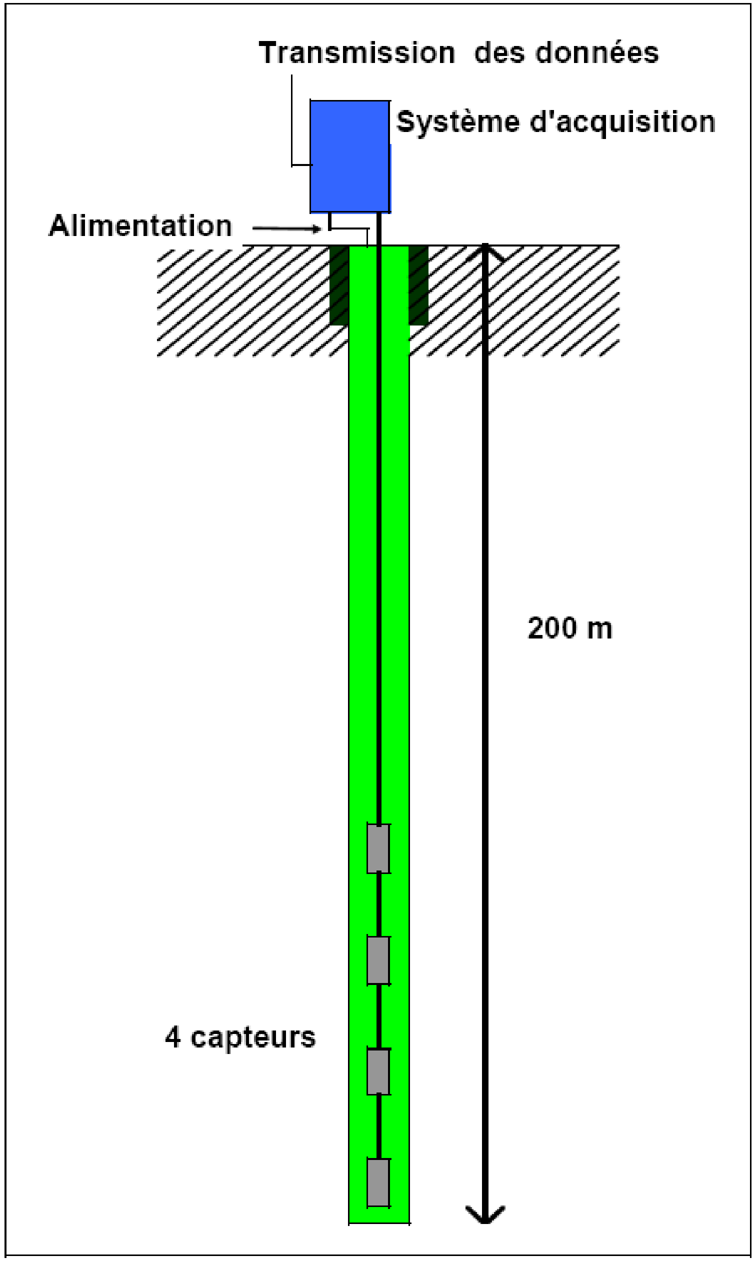
Microseismic monitoring and RSE1 well work over

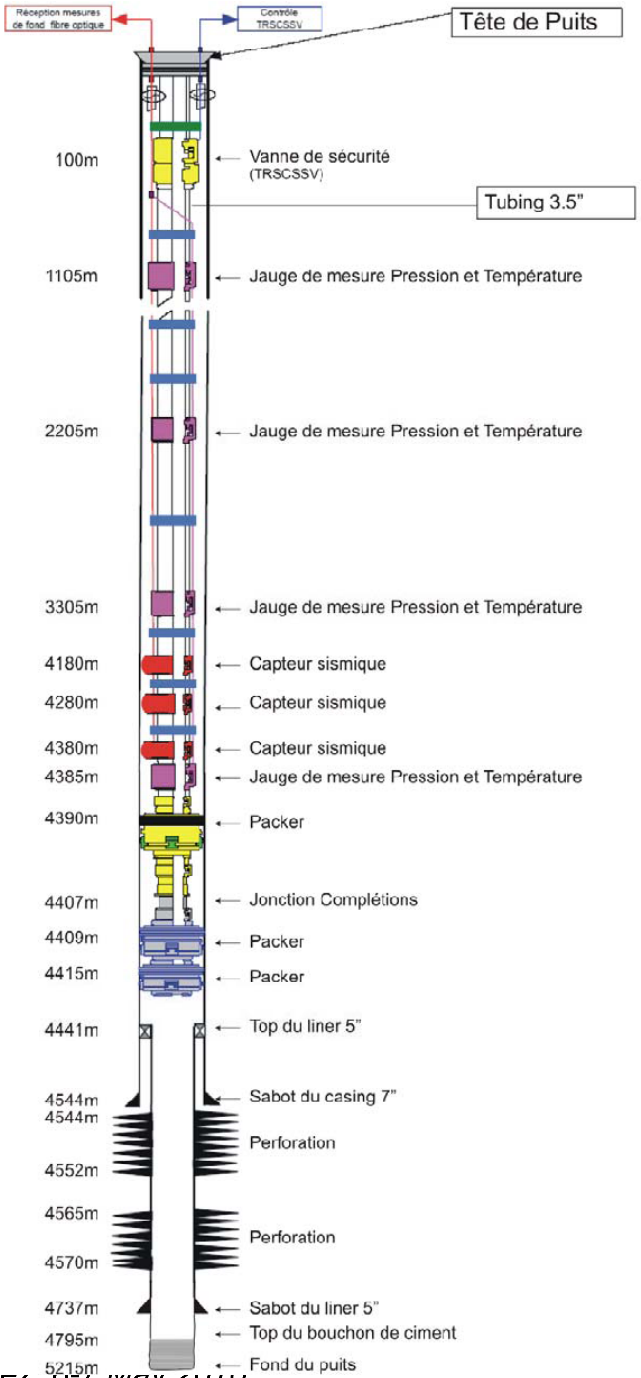




TOTAL

The passive seismic array





Terre durable

Seismic data management

- Calibration shots to check and orientate sensors and improve the velocity model
- Signals are pre-processed on site and transmitted to Magnitude offices.
- TOTAL receive a seismic bulletin on a regular basis
- Actions are triggered if anomalous behaviour is detected (different steps in function of magnitude and locations of events)
- Presently only the shallow array is working, but downhole instrumentation was more dedicated to research aspects (detection of magnitudes < 1,6)

TOTAL

Géosciences pour une Terre durable brgm

Monitoring system installation during work over




Theoretical detection levels and location errors (shallow array only, all antennas working)

Point 1: m= ~ - 1.7, +/- 100 m

Point 2: m= ~ - 1.6, +/- 240 m

Point 3: m= ~ - 1.5, +/- 260 m

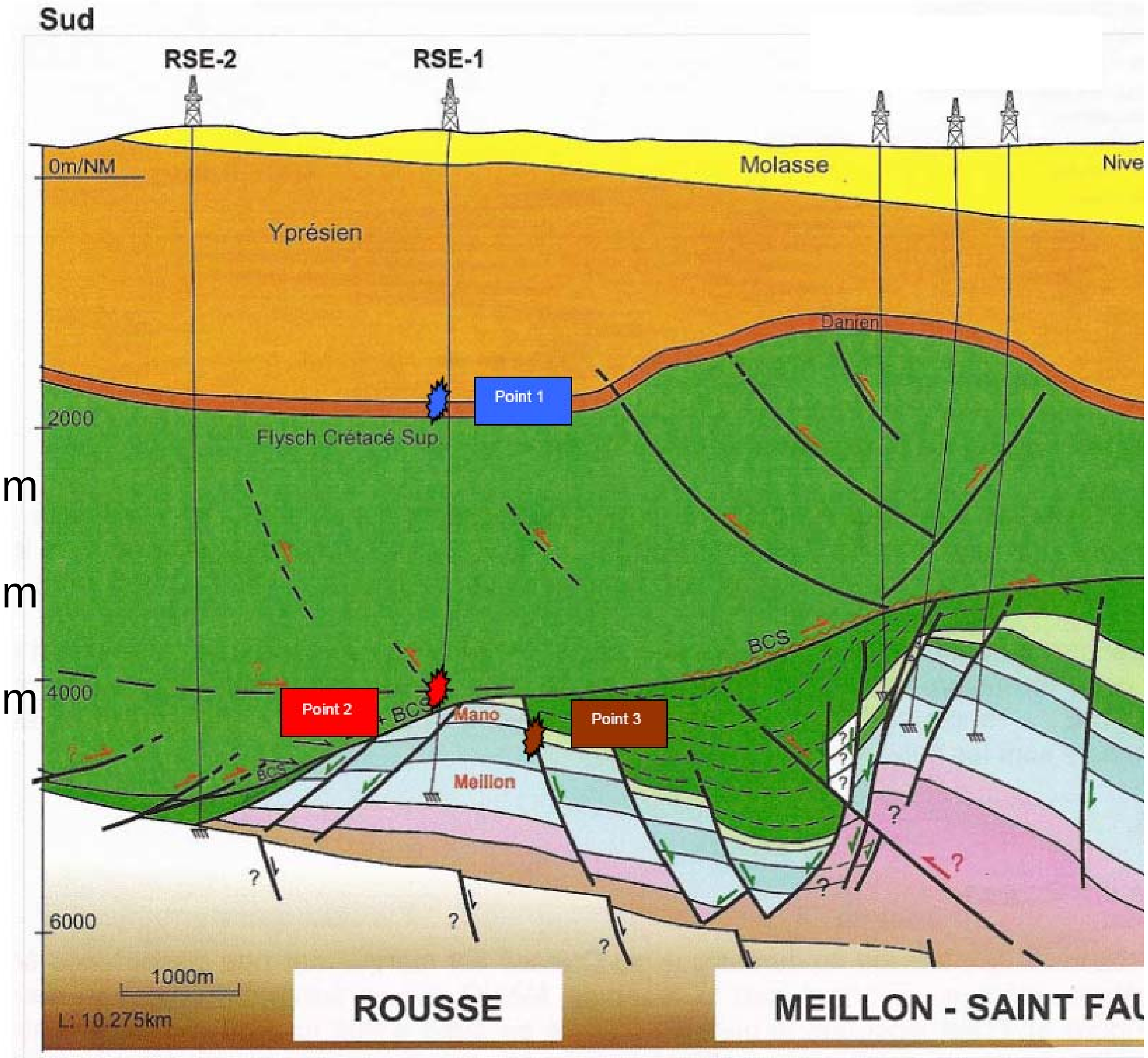
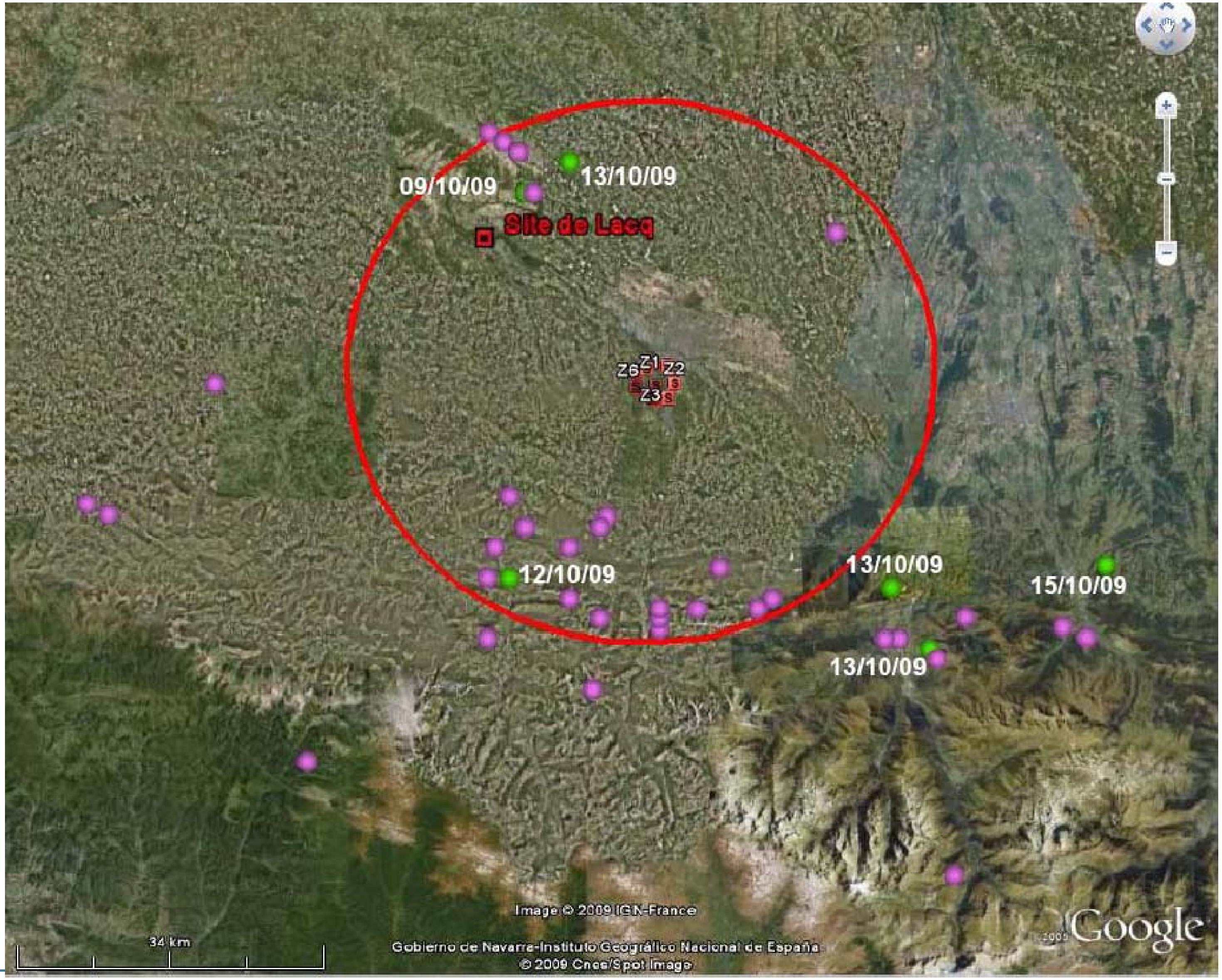
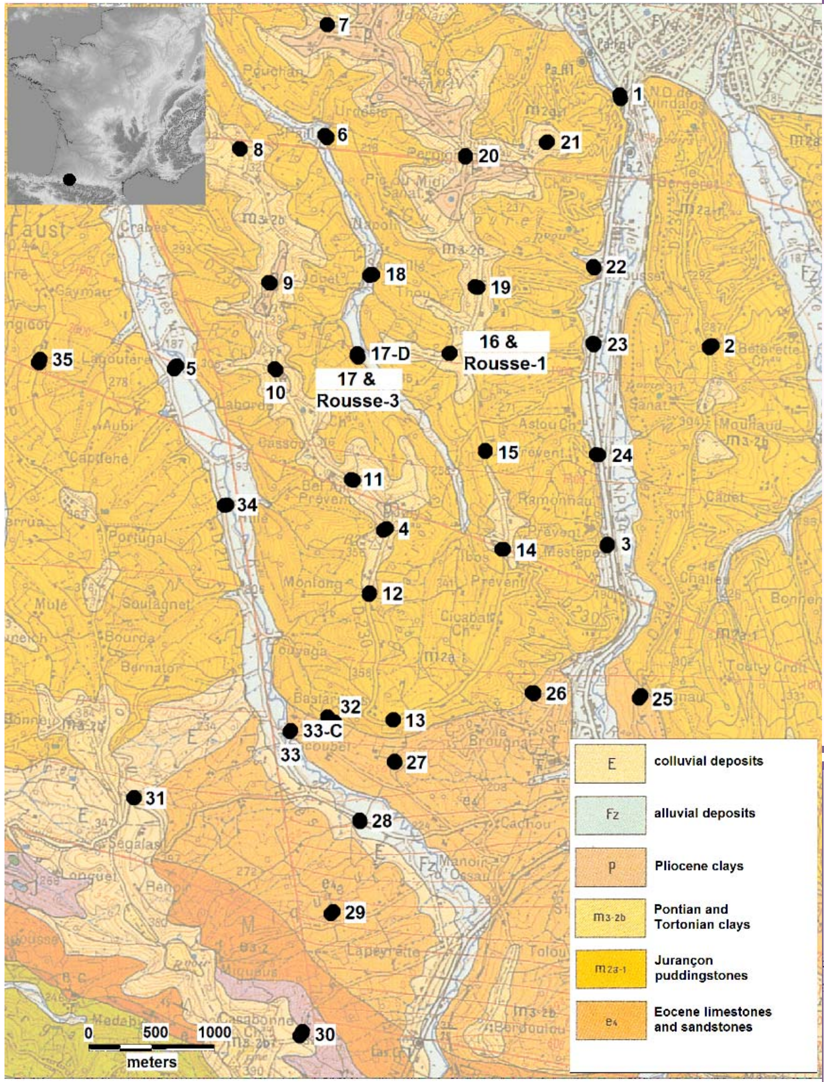


Figure 11 : Coupe Nord Sud de la structure de Rousse avec les trois événements sismiques simulés

Seismicity recorded by the shallow seismic array (April to October 2009), locations by RENASS national seismological array

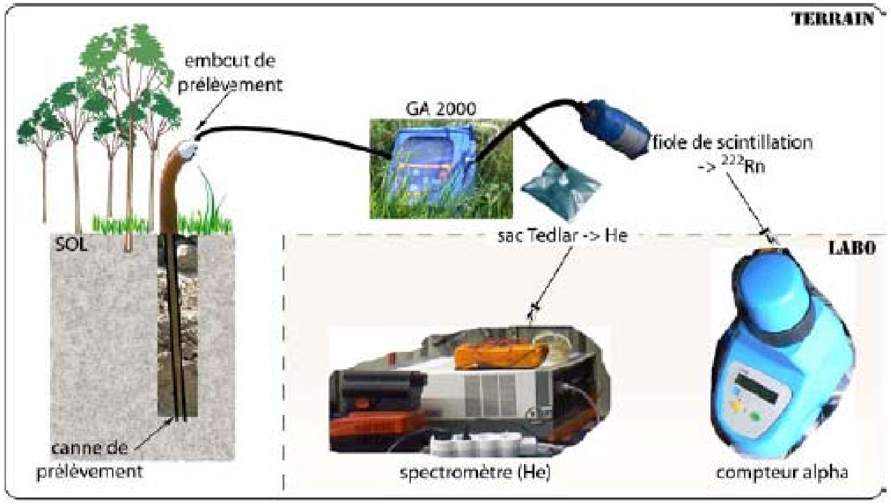


Soil gas surveys

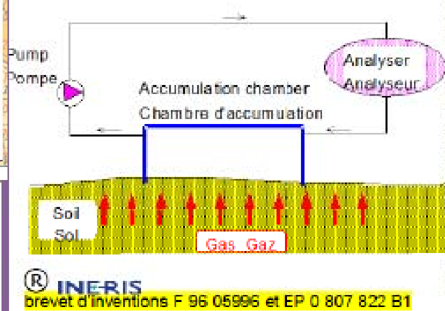


35 spots identified
4 campaigns (2008/09) sept, dec, march, june

- Soil gases concentration - BRGM
  - CO2, O2, CH4 at site
  - He, 222Rn in lab



- CO2 and CH4 fluxes - INERIS



Lacq CCS project - NA

TOTAL

Soil gas sampling

> **Baselines : 6 surveys since 2008, among which 4 used to define thresholds for CO_2 emissions:**

- Level 1: change to mode "**vigilance"** if CO_2 concentration > 5,4% in 5 points, and flux > *average + 2*σ;
  - Action triggered : repeat measures during several hours and days
- Level 2: change to level "**alert"** if CO_2 concentration > 50% (idem for flux);
  - Actions triggered: repeat measures during several hours and days, extend area around anomalous points; sample gas for isotopic analysis
- Threshold for isotopic anomaly: average between soil gas and CO_2 stream injected (-33,6‰ VPDB).

> **During injection: 4 campaigns foreseen in 2010 (March, June, September, December)**

Géosciences pour une Terre durable brgm

TOTAL

What it is observed now?

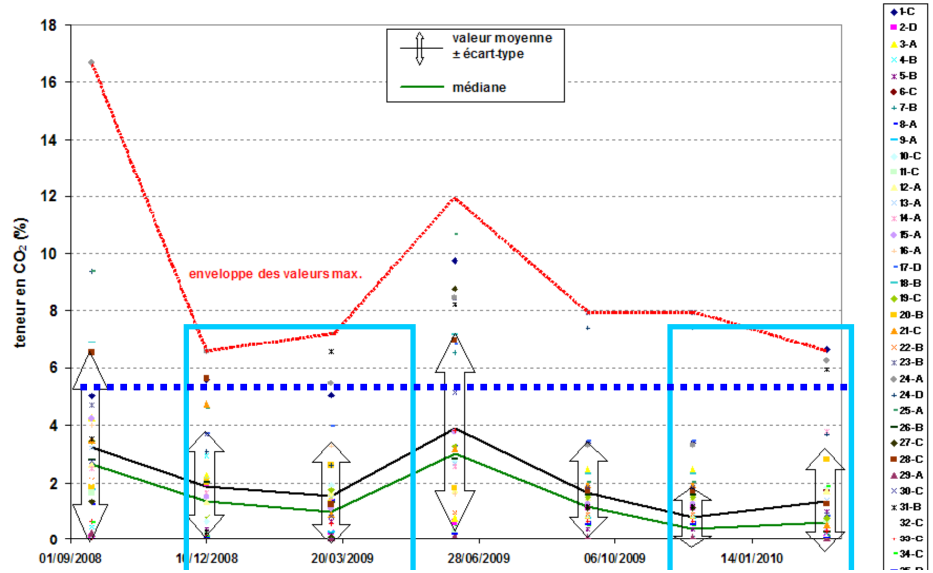
> **CO_2 concentration exceeds very rarely level 1 in winter**

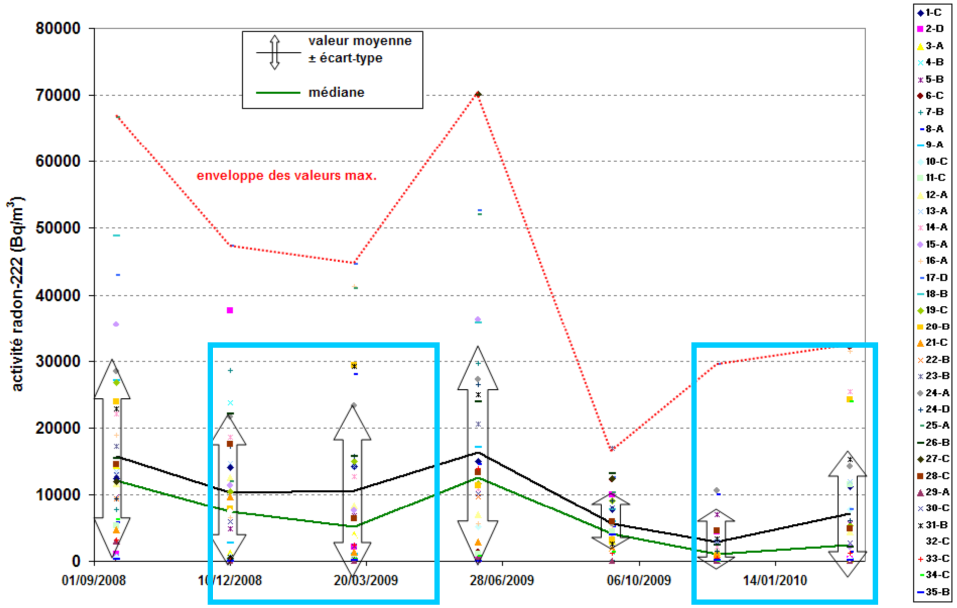
> **Radon evolution is similar to CO_2, the contrary for O_2 (one phase is replaced by the other)**

> **No impact on Helium (no gas from deep origin)**

> **Complex variability in time due to external (seasonal) parameters: temperature, water content of soils**

> **Variability linked to subsurface geology**





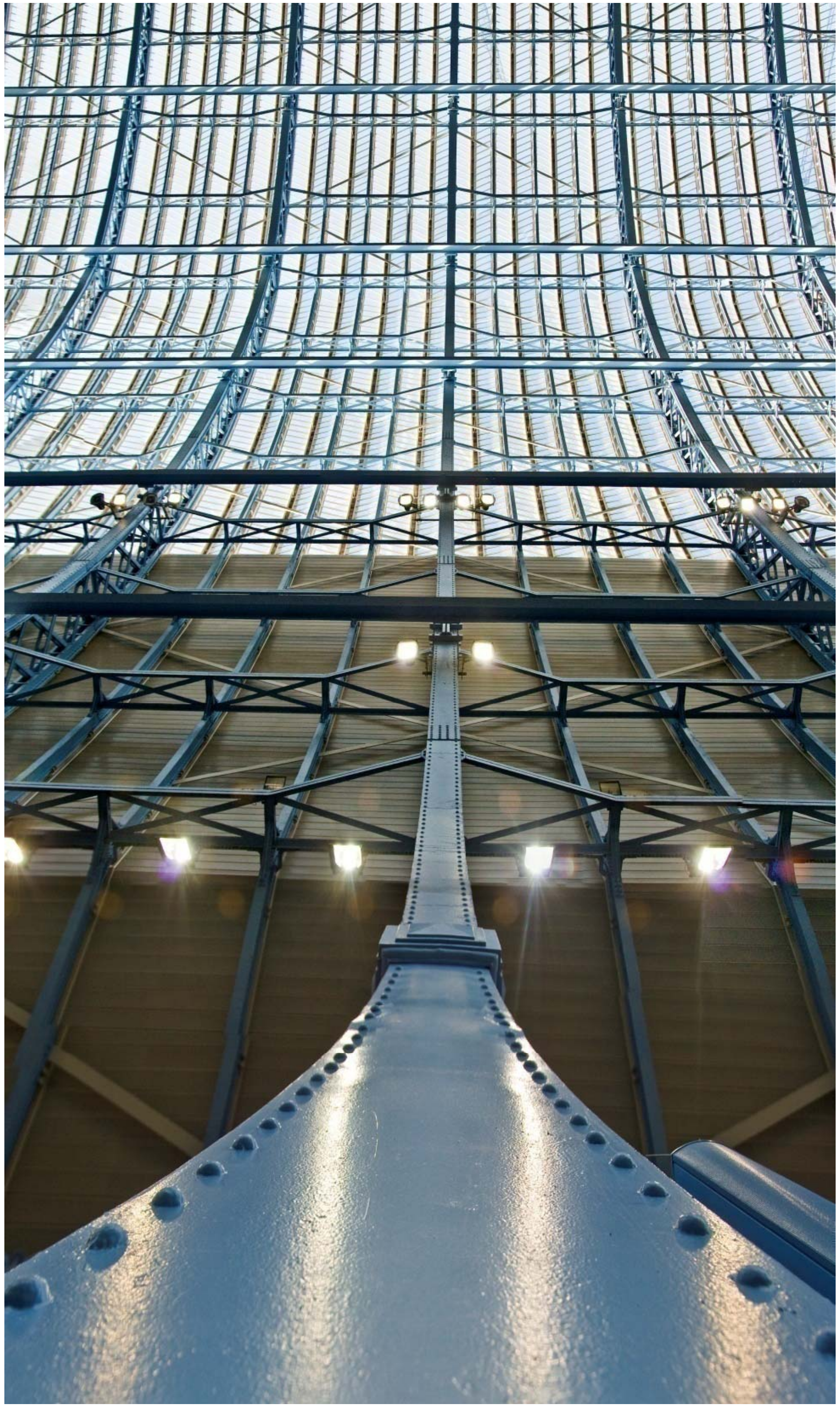
TOTAL

A major stake: demonstrate that CO2 can be stored safely and permanently into Rousse

The Energy Technologies Institute – Activities in CO_2 Storage

Kevin Dodds BP Alternative Energy

www.energytechnologies.co.uk



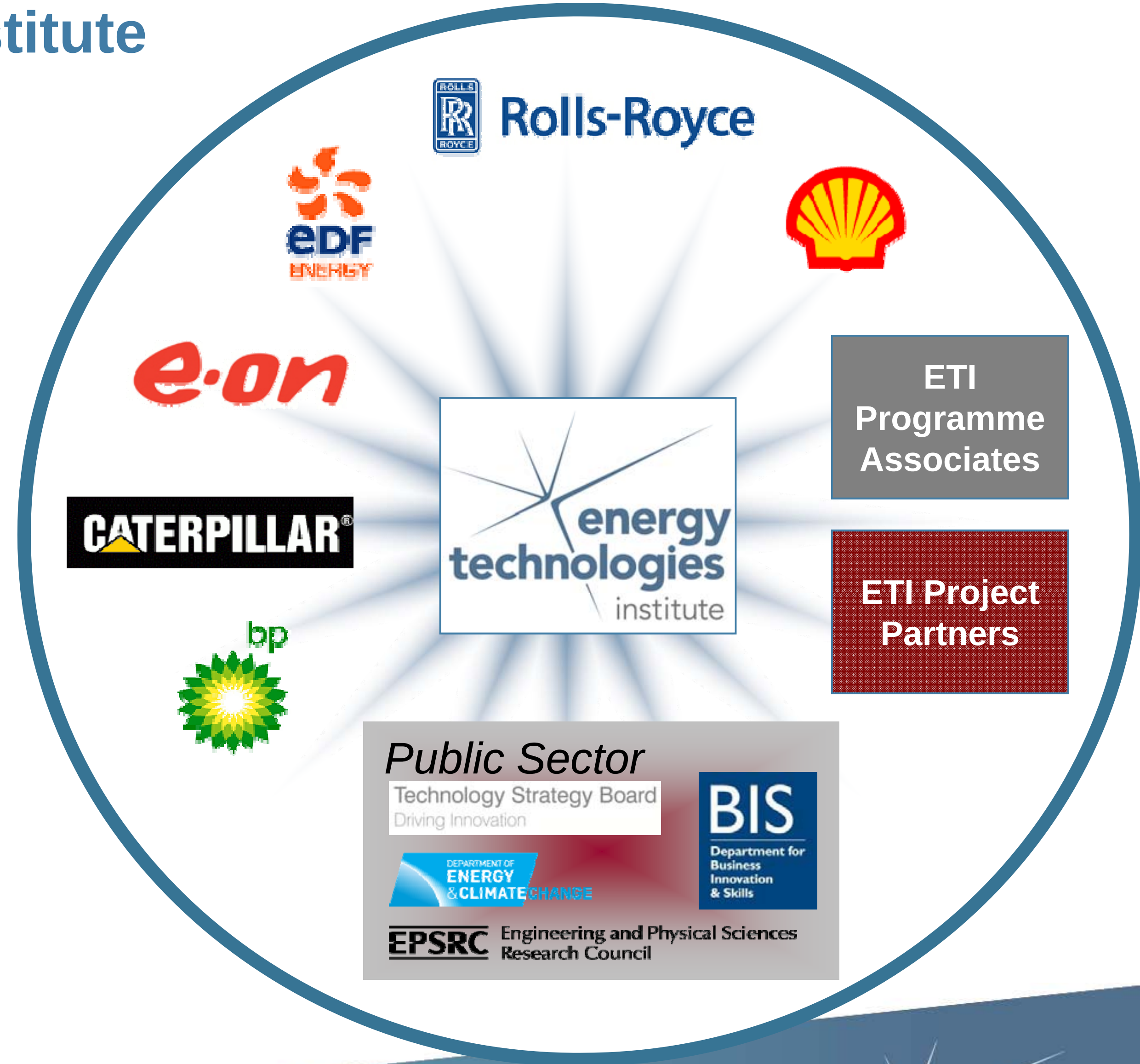
Bringing together the **complementary capabilities** of global industrial groups in a unique approach with UK government

Operating at a **national strategic level** to deliver large scale complex **engineering solutions for the UK energy system** helping **to meet 2050 challenges**

Energy Technologies Institute

Addressing the challenges of climate change and low carbon energy

- **Improving energy usage**, efficiency, supply and generation
- **Demonstrating systems** and technologies
- **Developing knowledge**, skills and supply-chains
- **Informing development of policy,** regulation and standards
- **Enabling deployment of affordable, secure, low carbon energy systems**

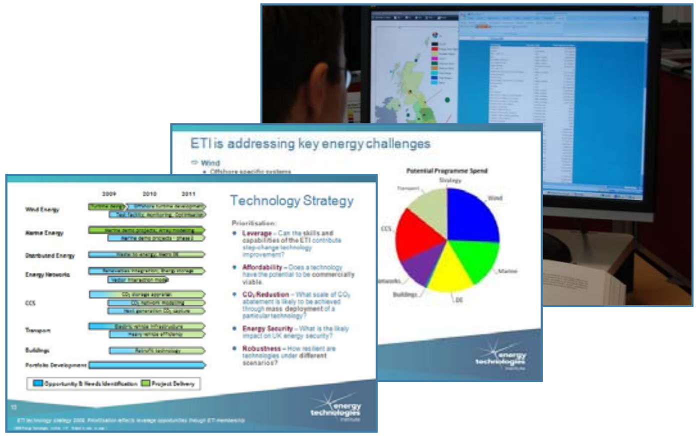


energy technologies institute

ETI – a unique platform for industry and Government

Delivering system level engineering demonstrations of innovative low carbon energy systems

With unique access to the complementary technology, skills, market access and policy development capabilities of the ETI Members



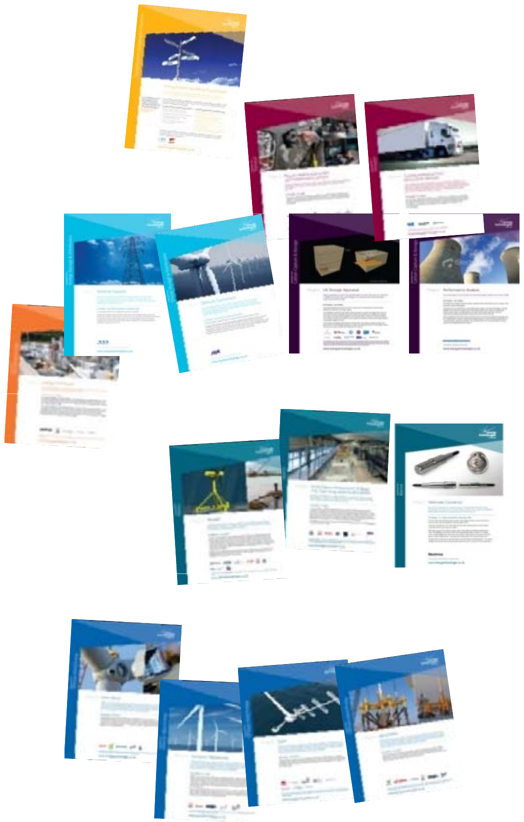
Achieved through world-class capability in strategic analysis and energy system modelling

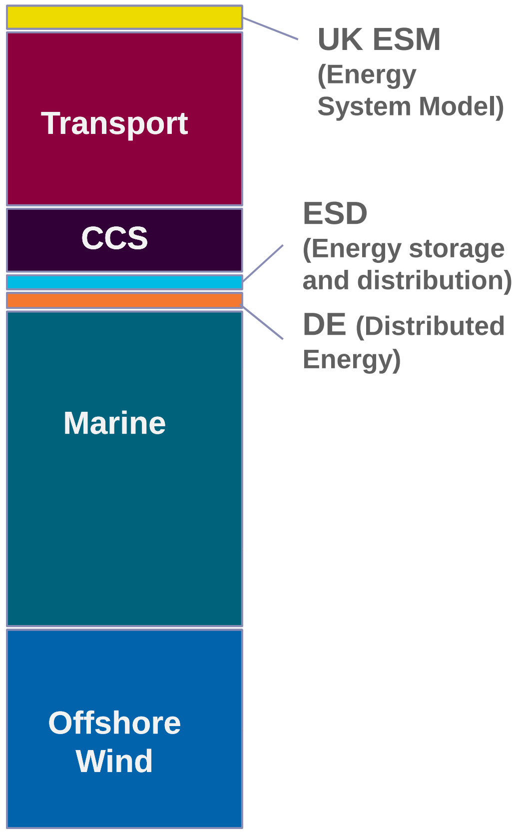
Focused on the integrated UK energy system – power, heat, transport and associated infrastructure

energy technologies institute

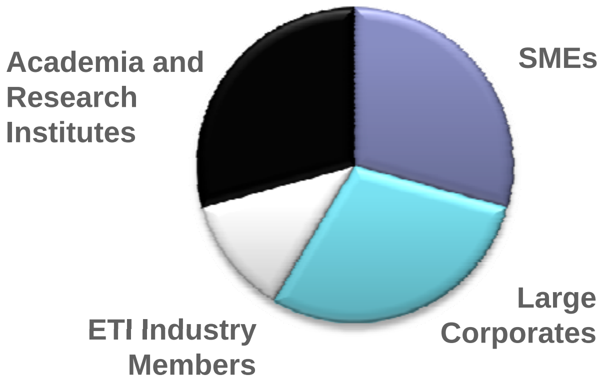
>£50m of projects announced in 2009

>£70m of further projects in development for announcement over early 2010 ...
..... CCS, DE, energy storage, smart systems, transport



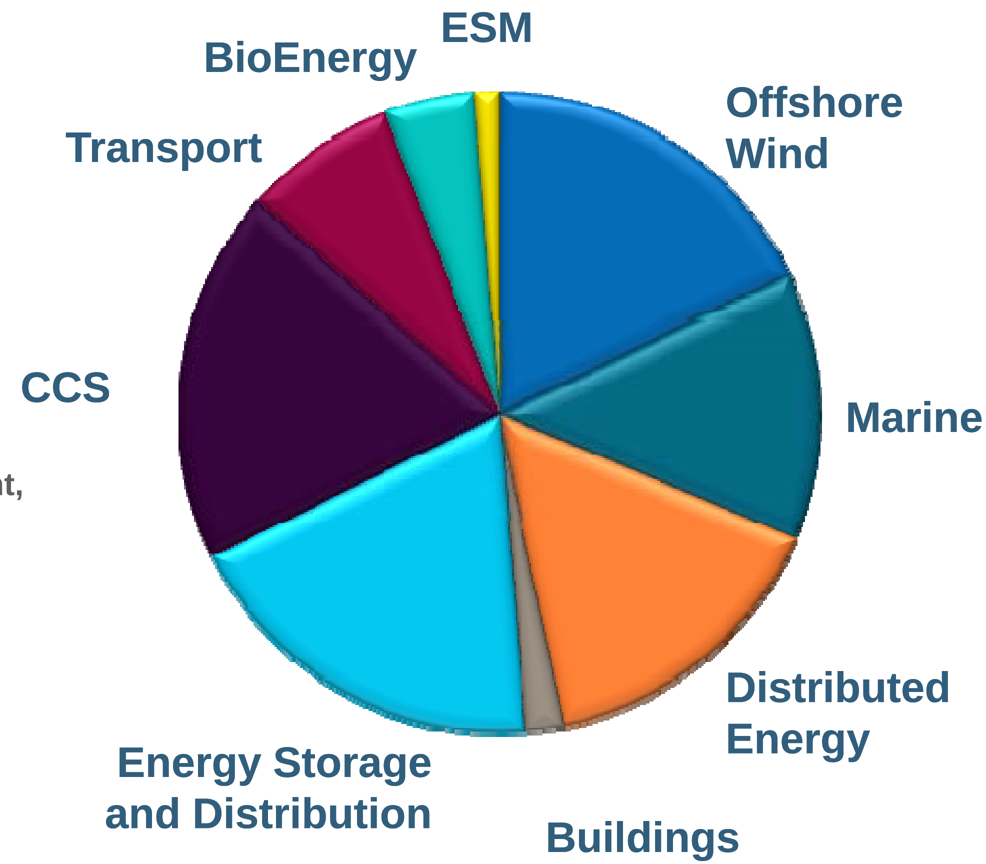


2009 - £54m of projects announced



ETI 2010 portfolio addresses key energy challenges

- **Wind**
  - Offshore specific system design and engineering
- **Marine**
  - Tidal Stream and Wave
- **Distributed Energy (DE)**
  - Combined Heat and Power (CHP), demand management, efficiency
- **Buildings**
  - Retrofit of new technologies and systems
- **Energy Storage and Distribution**
  - Infrastructure, heat and energy storage, fault management, smart networks
- **Carbon Capture and Storage (CCS)**
  - Storage appraisal & MMV, capture technologies, CCS system modelling, mineralisation
- **Transport**
  - Electric vehicle infrastructure, heavy duty vehicle efficiency
- **BioEnergy**
  - Soil chemistry and agronomy, value chains, energy conversion
- **Energy Systems Modelling (ESM)**



2009 - £54m of projects announced

Storage: Measurement, Monitoring & Verification (MMV)

- 'Seed' Project – inform ETI of requirements & priority projects
- Analysis of UK needs
  - UK/EU legislative drivers
  - Quantitative ('how much is there'), not qualitative ('where is it') measurements
  - Offshore application
  - UK geologies
- Review of current technologies & gap analysis
- Lead Contractor BGS (+ TNO & Quintessa)
- Andy Chadwick BGS
- Project Completion – May 2010
- Priority technology projects kick off in Q4 2010

Image Courtesy of SEG, The Leading Edge, July 2009

MMV Workpackage 1 Objectives

- Identify the latest regulatory and technical requirements for MMV in the UK offshore context.
- Define the amounts and rates of potential CO_2 leakage in different circumstances.
- Update existing reviews of MMV technologies
- Review four suitable projects relevant to the UK offshore to learn from actual or planned MMV deployments.
- Quantify current measurement capabilities and identify and quantify gaps in MMV capability.

- Status:
  - Completed – WP1 report delivered to Members

energy technologies institute

MMV Workpackage 2 Objectives

- Describe and rank the maturity, potential and practicality of novel techniques.
- Identify requirements for additional focussed development work:
  - Deployment in offshore environments
  - identify potential technology providers
  - estimate development costs and timescales.
- Develop a robust strategy for monitoring a range of UK offshore storage projects including current and novel monitoring tools, regulatory requirements and cost.
- Status:
  - In progress
  - Delivery of report in May

energy technologies institute

CO_2 Capture Project®

CCP3-SMV

The CO2 Capture Project

http://www.co2captureproject.org/

The CO2 Capture Project (CCP) is a partnership of the world's leading energy companies, working with academic institutions and government organisations to research and develop technologies to help make CO2 capture and geological storage (CCS) a practical reality for reducing global CO2 emissions and tackling climate change.

CO2 Capture and Geological Storage is a technological process to capture CO2 emissions from fossil fuel-fired power plants and other industrial processes and then store the CO2 deep underground in geological formations securely away from the atmosphere.

CCP3-SMV

Theme 1. Assurance R&D

Address real and perceived uncertainties, risks and opportunities associated with CO2 storage through prioritized R&D programs culminating in conclusive study results or field demonstrations / deployments (field trialing).

A. **Well Integrity** - Through field surveys, associated analyses, modeling and simulation, qualify containment risks of CO_2-exposed well systems over time. Contribute to industry standards development for establishing existing well integrity and new well design / installation.

B. **Subsurface Processes** - Through laboratory analyses / experiments and simulation, address outstanding uncertainties and risks surrounding subsurface processes associated with CO_2 injection. Develop testing and modeling protocols and tools to more accurately simulate such processes and their potential impact to GCS projects.

C. **Monitoring & Verification** - Assess existing demonstration monitoring experience and response of emerging technology, identify performance and cost effective criteria and incorporate into defensible approach to define fit for purpose M&V programs. Provide a design for a modular downhole completion as a means for conveying multiple sensors in monitoring wells applicable to storage projects

D. **Storage Optimization** – Using CCP2's Certification Framework (CF) concept, develop tools that improve storage performance through flood optimization and pressure management. As needed continue developing the CF application to facilitate communication of storage processes and risk. Leverage DOE RP case studies using the CF to continue developing the CF as an assessment and communications tool.

Theme 2. Field Trialing

Identify and negotiate access to prospective upcoming or ongoing field pilot / demonstration sites suitable to conduct subsurface experiments and test emerging suites of existing M&V technology (potentially including those identified and / or developed in 1B and IC).

Theme 3. Stakeholder Issues

Working with CCP's Policy and Communication teams, develop a process to improve communication of CO2 storage technology and risk to stakeholder groups.

Monitoring & Verification

Objective

- Access existing demonstration monitoring experience and response of emerging technology, identify performance and cost effective criteria and incorporate into defensible approach to define fit for purpose M&V programs. Provide a design for a modular downhole completion as a means for conveying multiple sensors in monitoring wells applicable to storage projects

Motivation

- There is a need to show how a monitoring plan can be drawn up that incorporates appropriate and cost effective monitoring yet is adaptable to specific site requirements and risks.
- It is important to assess through modeling and practical experience the bounds of uncertainty of each of the measuring technologies and how combinations can optimize the process of confirming storage safety and volumes contained.
- Equally there are aspects of storage and monitoring in terms of automation, permanent sensors and quantification that provide the drive to encourage the design of an integrated cost-effective downhole means to acquire multiple borehole data

Approach

- Assess monitoring technologies in terms of their resolution, sensitivity and bounding criteria applied to a large number of demonstration projects and emerging technologies (SMV6)
- Identify gaps in current data acquisition and gaps in technology in addressing key risks and support their evaluation
- Evaluate design criteria for a modular and integrated downhole completion for site specific applications.

BEG-EPA / CCP Susan Hovorka

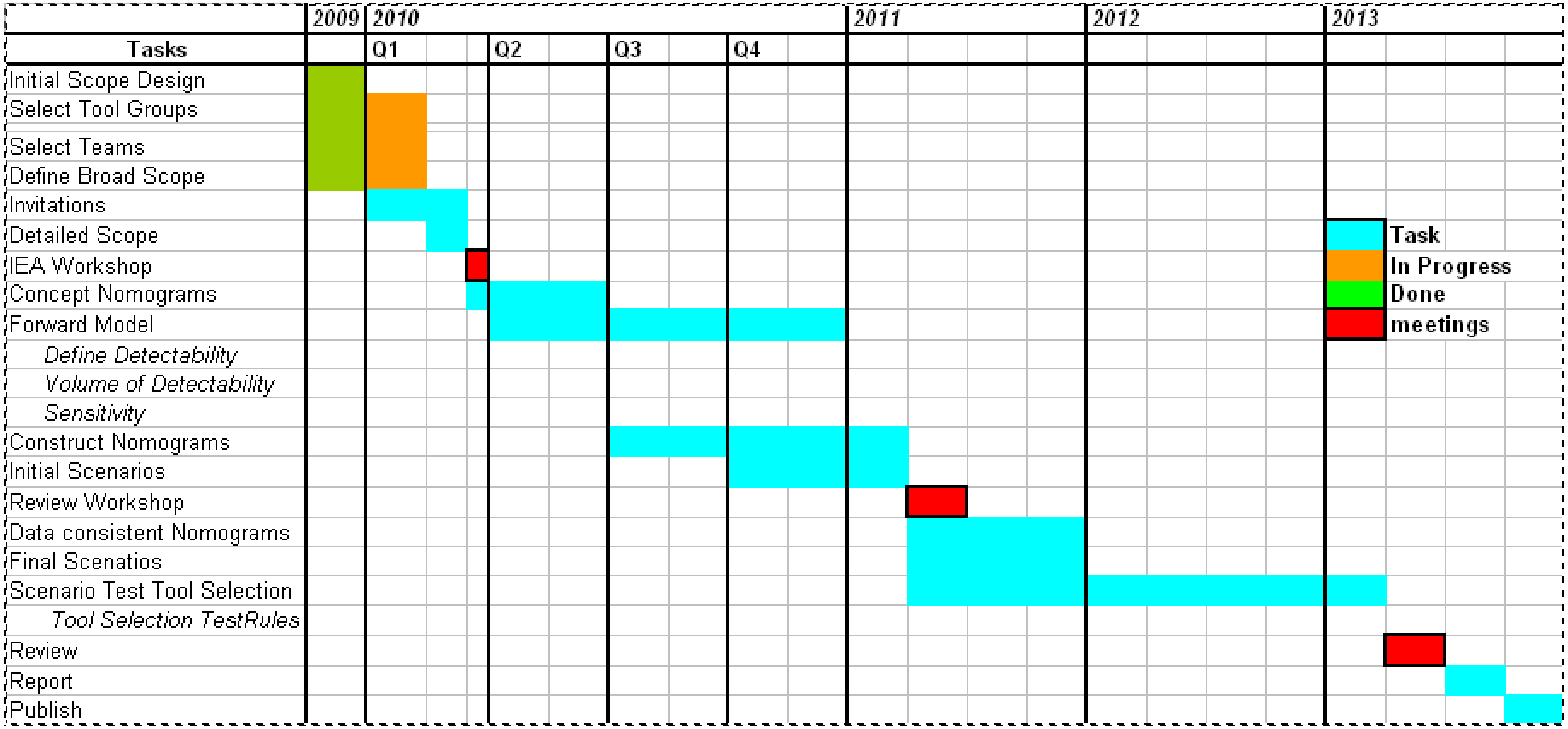
Review of current experience - Coordinated with BEG/GCCC - EPA Project

- Assemble a panel of experts from a range of demonstration projects
- Develop a common matrix questionnaire for monitoring tools, sensitivities, risks, regulations, costs, measurements and objectives
- Workshop appropriate information against monitoring criteria
- Expert panel gathers and evaluates data within criteria
- Intensive workshop by panelists to develop cross reference material for range of M&V technologies

Monitoring sensitivity analysis – Coordinated with BEG/CCP

- Outcome from Review identifies sensitivity and modelling issues
- Input from forward modelling for existing scenarios
- Plan single sensor field trials, eg ERT, Gravity and seismic
- Detailed laboratory and field input data against expected response
- Assemble information and develop sensitivity statements

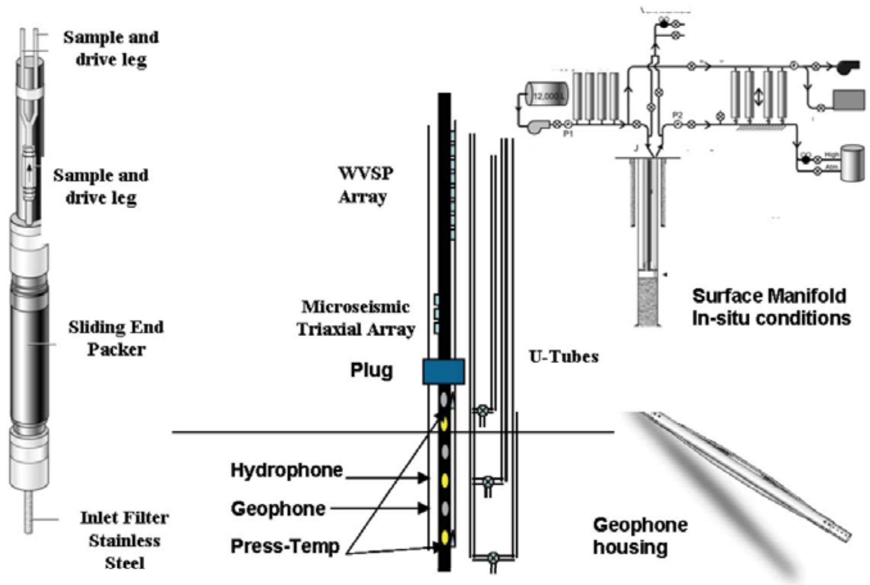
Assessing demonstration performance



CCP-LBNL

Integrated platform design – Coordinated with LBNL 3 yrs project

1. Design Scope
   - State of art of downhole integrated systems
   - Review of conveyancing bus - coiled tubing, sucker rods, umbilical, and casing/tubing conveyed systems
   - State of art for sensor systems, fibre optic sensors gravity sensors, ERT, sources
   - Constraints of size, costs, slimhole, injection wel system, retrievable vs non-retrievable, open hole,
   - Conceptual designs
2. Industry based review committee CCP based.
3. Construction of a prototype system(s)
4. Testing
5. Upgraded Engineering model and tests



CCP3 bp Chevron ConocoPhillips eni BR PETROBRAS Shell SUNCOR ENERGY EPRI

2. Field Trialing

1. **Current Projects**
   - CO2CRC Otway – Through Casing Resistivity (TCR) and Time Lapse 3D VSP (4D VSP)
   - CO2CRC Otway - Thru-casing resistivity
   - SECARB Delhi - Cranfield – Time Lapse Borehole gravity (BHG)
   - MGSC Decatur – Satellite detection of ground movement w/ injection (PS InSAR)
   - In Salah - Multi-Azimuth Walkaway (CO2 movement through fractures) proposed

2. **Identification of Gaps, Overlaps & Synergies**
   - Previous technology priority assessment by team is being executed
   - Leveraging Field Trialing results and current M&V / Subsurface Processes studies will maximize value to CCP3 (strong engagement of BP, COP & Shell)

Expert-Based Development of a Site-Specific Standard in CO_2 Sequestration Monitoring Technology EPA-CCP3

Susan Hovorka and J.-P. Nicot

susan.hovorka@beg.utexas.edu

jp.nicot@beg.utexas.edu

Project Status

- First meeting of Expert Panel - May 5, Natchez, Mississippi
- Follow on meetings – remote and in person

Historic Natchez

Cranfield Site visit

Project Goals

- Develop guidance for selection of monitoring approaches for a CO_2 sequestration site
  - Site specific
  - Based on quantification of monitoring tool sensitivity
- Expert Panel
  - Data based input
  - Develop wide consensus
- Useful end product
  - Not a list of tools –resource book
  - Case-based training workbook

Gulf
Coast
Carbon
Center

Expert panelists

- Researchers with specialty in monitoring techniques and field data:
  - RCSP - 7 US partnerships, Otway, Nagaoka, ZERT, Weyburn, Penn West, In Salah, Sleipner

Gulf Coast Carbon Center

Techniques to be assessed

- Hydrological (P&T)
- Geochemical
- Geophysical
- Geomechanical

Focus on commonly used and accepted techniques

Cooperation with CCP-3

- Broaden and deepen assessment of techniques
- Increased international expertise
  - Information exchange with monitoring project now being conducted by British Geological Survey for ETI
  - Data from international projects to increase sample size
  - Geophysics

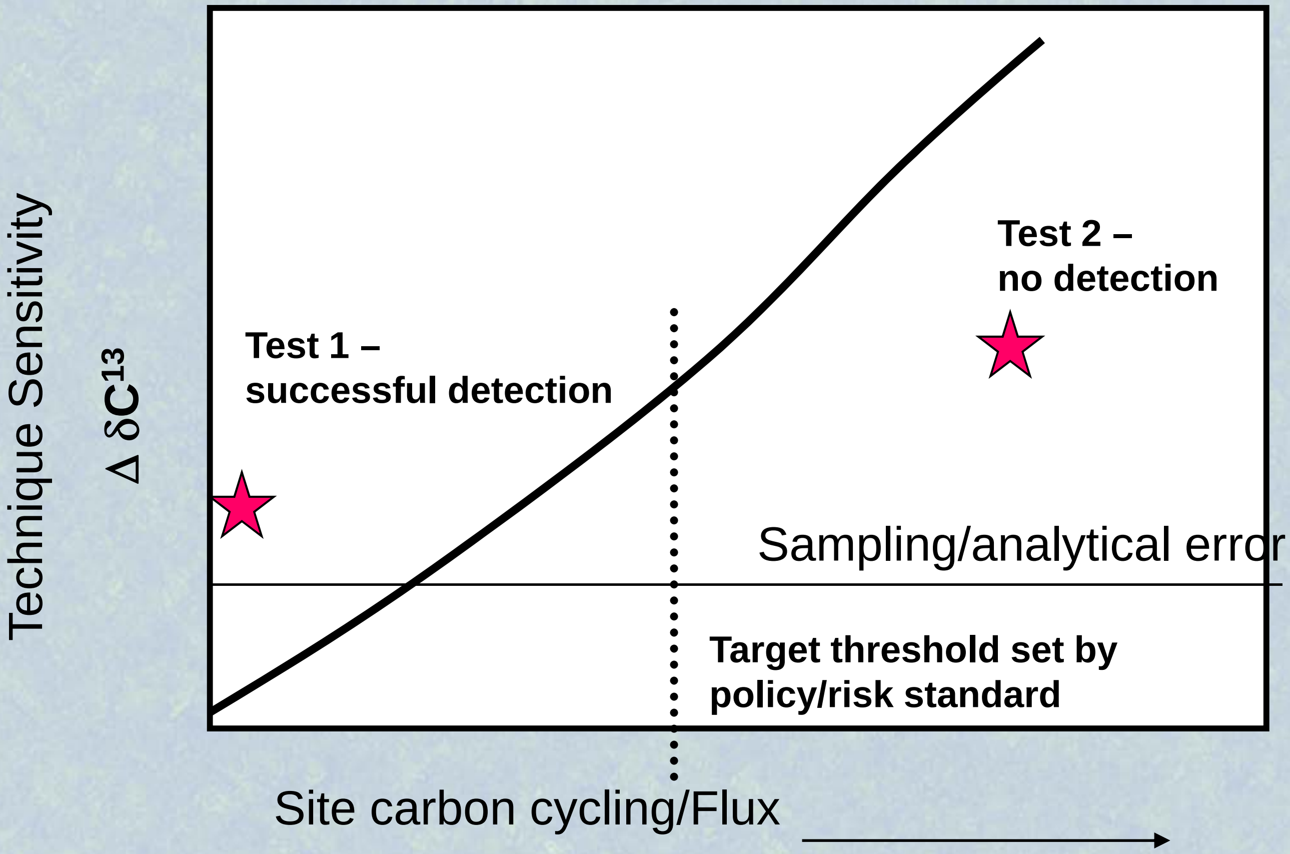
Examples of Site-Specific Parameters

- Contrast of introduced characterisitcs with ambient charateriisitics
- Repeatability
- Rock physics
- Cycling processes

Gulf
Coast
Carbon
Center

Nomogram Concept

example case for soil gas leakage detection via repeat sampling soil gas

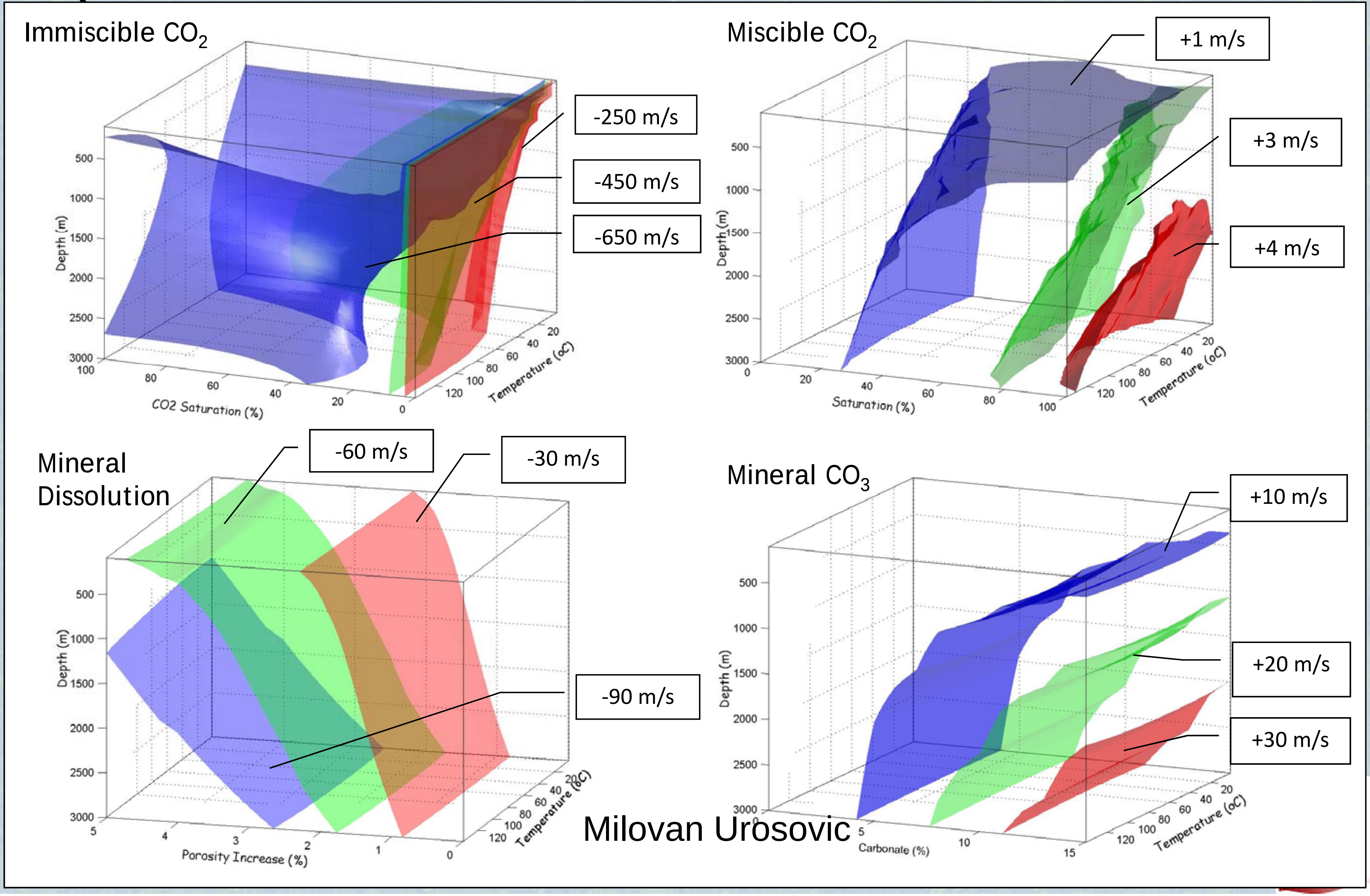


Key site specific parameter (amount of CO_2)

Gulf Coast Carbon Center

Nomogram examples

(Change in P-wave Velocity 4D response)



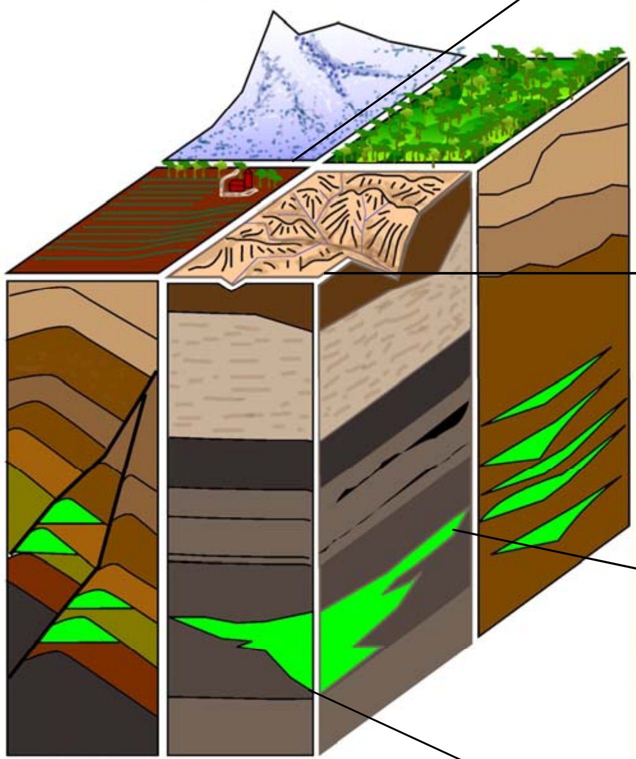
Milovan Urosovic

Examples of Cases Unfavorable for Detection

- SACROC – direct detection of dissolved CO_2 in USDW – natural CO_2 content too variable
- Surface seismic did not get a clear detection of CO_2 – need expert assessment of reason for non-detection

Gulf Coast Carbon Center

Role of Models in Developing Test Cases –and Workbook



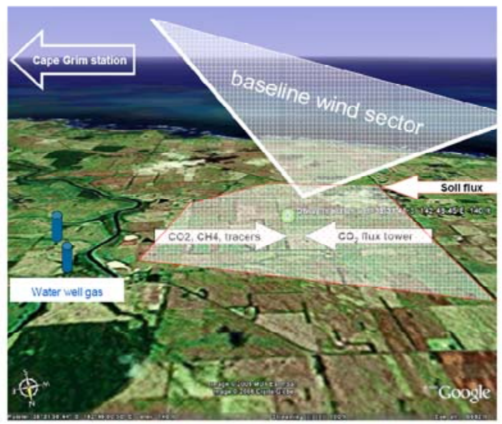
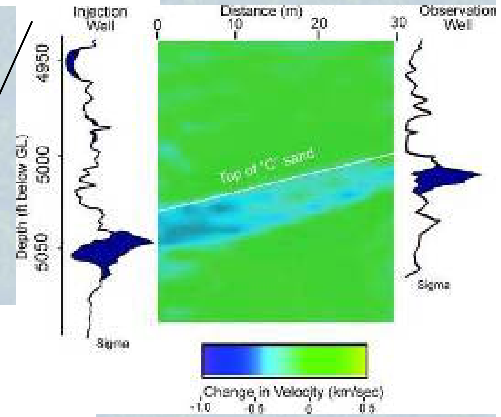
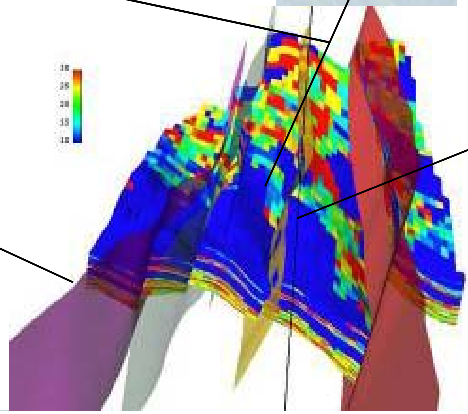


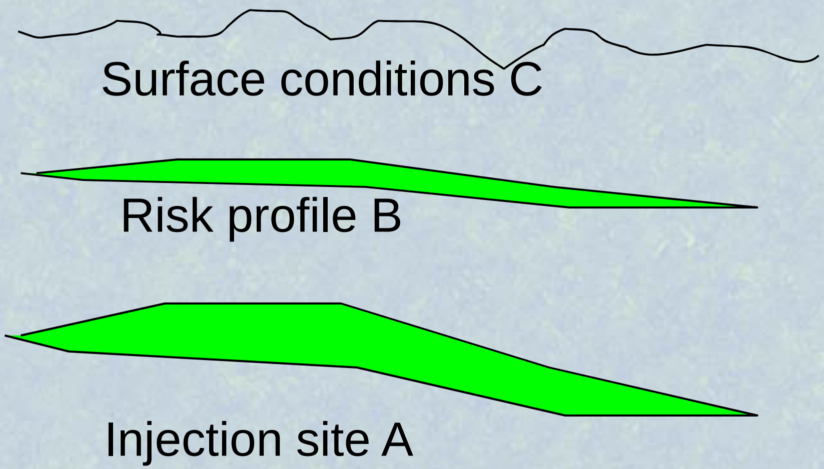
Figure 1. Otway Project atmospheric monitoring layout.

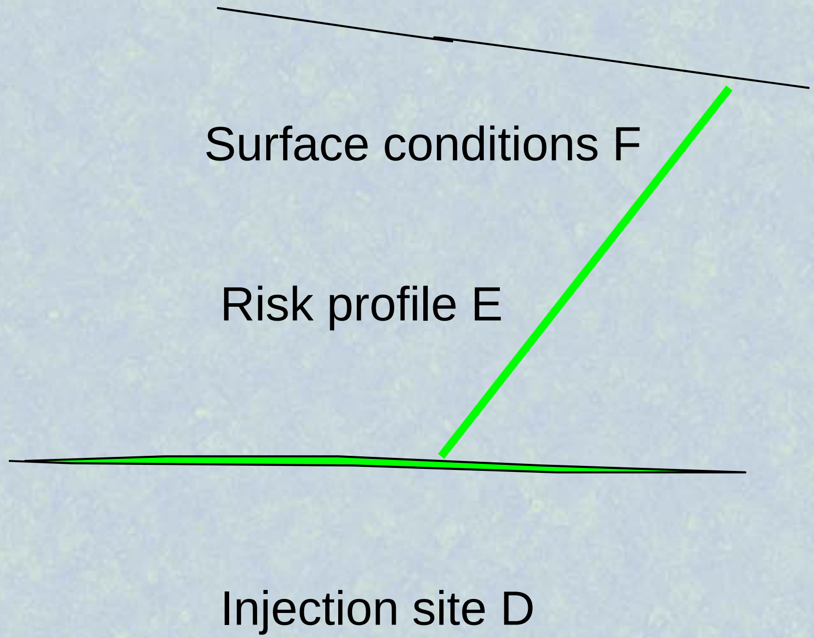




Gulf Coast Carbon Center

Matching Techniques to Sites – Training Workbook





Successful documentation that risk B is not occurring though MVA strategy 1

Successful documentation that risk E is not occurring though MVA strategy 2

Thanks

- Welcome comments and input
- Look forward to additional collaborations
- Especially welcome site specific data and model that could be used a realistic cases

- www.gulfcoastcarbon.org

Gulf
Coast
Carbon
Center

U.S. Department of Energy Regional Carbon Sequestration Partnership Program

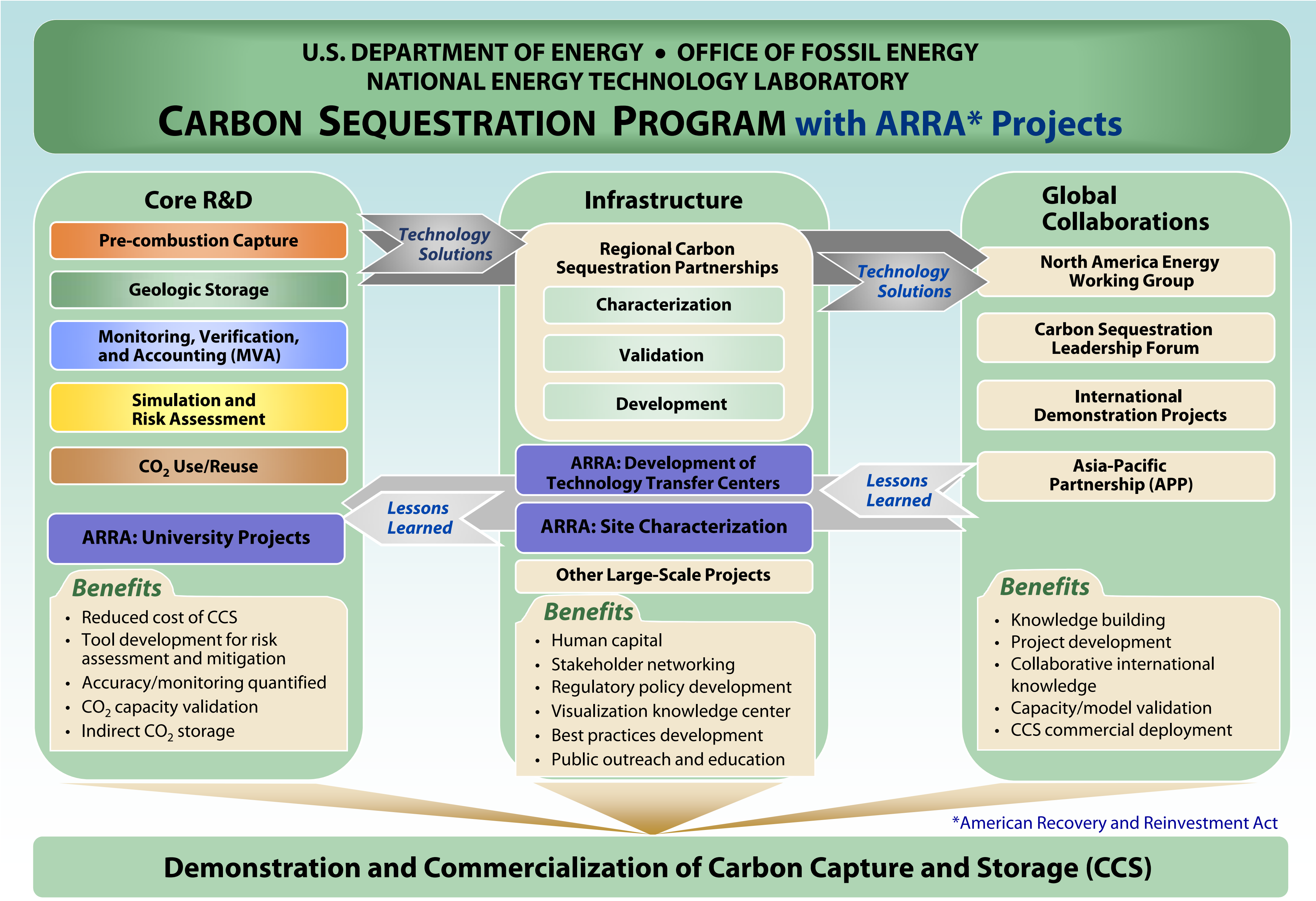
6th IEAGHG Monitoring Network Workshop
Natchez, Mississippi

6-8 May, 2010

Dawn Marie Deel
PMP Project Manager
National Energy Technology Laboratory

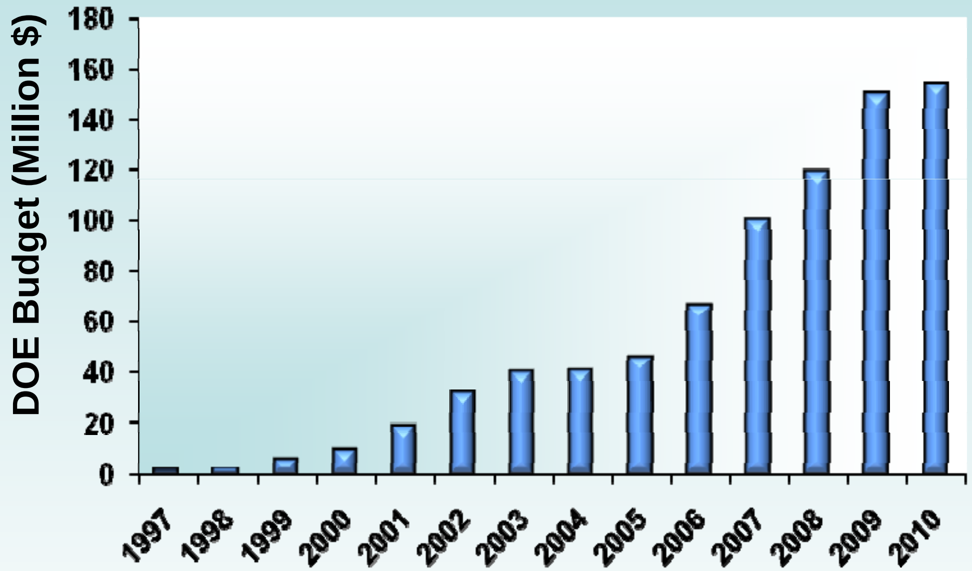
Julianna Fessenden, Ph.D.
Program Manager
Los Alamos National Laboratory

John Henry Beyer, Ph.D.
WESTCARB Program Manager, Geophysicist
Lawrence Berkeley National Laboratory
510-486-7954, jhbeyer@lbl.gov


U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
CARBON SEQUESTRATION PROGRAM with ARRA* Projects
Core R&D
Pre-combustion Capture
Geologic Storage
Monitoring, Verification, and Accounting (MVA)
Simulation and Risk Assessment
CO_2 Use/Reuse
ARRA: University Projects
Benefits
• Reduced cost of CCS
• Tool development for risk assessment and mitigation
• Accuracy/monitoring quantified
• CO_2 capacity validation
• Indirect CO_2 storage
Technology Solutions
Lessons Learned
Infrastructure
Regional Carbon Sequestration Partnerships
Characterization
Validation
Development
ARRA: Development of Technology Transfer Centers
ARRA: Site Characterization
Other Large-Scale Projects
Benefits
• Human capital
• Stakeholder networking
• Regulatory policy development
• Visualization knowledge center
• Best practices development
• Public outreach and education
Technology Solutions
Lessons Learned
Global Collaborations
North America Energy Working Group
Carbon Sequestration Leadership Forum
International Demonstration Projects
Asia-Pacific Partnership (APP)
Benefits
• Knowledge building
• Project development
• Collaborative international knowledge
• Capacity/model validation
• CCS commercial deployment
*American Recovery and Reinvestment Act
Demonstration and Commercialization of Carbon Capture and Storage (CCS)

Sequestration Program Total Funding

2009 Program Funding

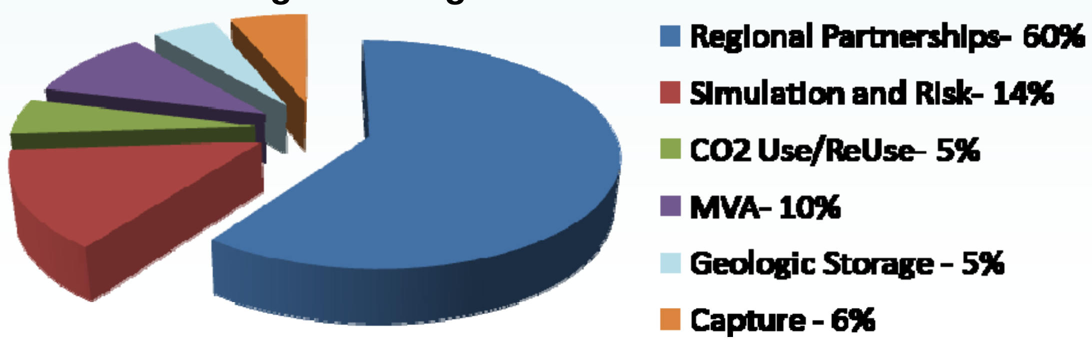


Diverse Research Portfolio
~ 80-100 Active R&D Projects

Strong industry support
~ 39% cost share on projects

Federal Investment to Date
~ $631 Million

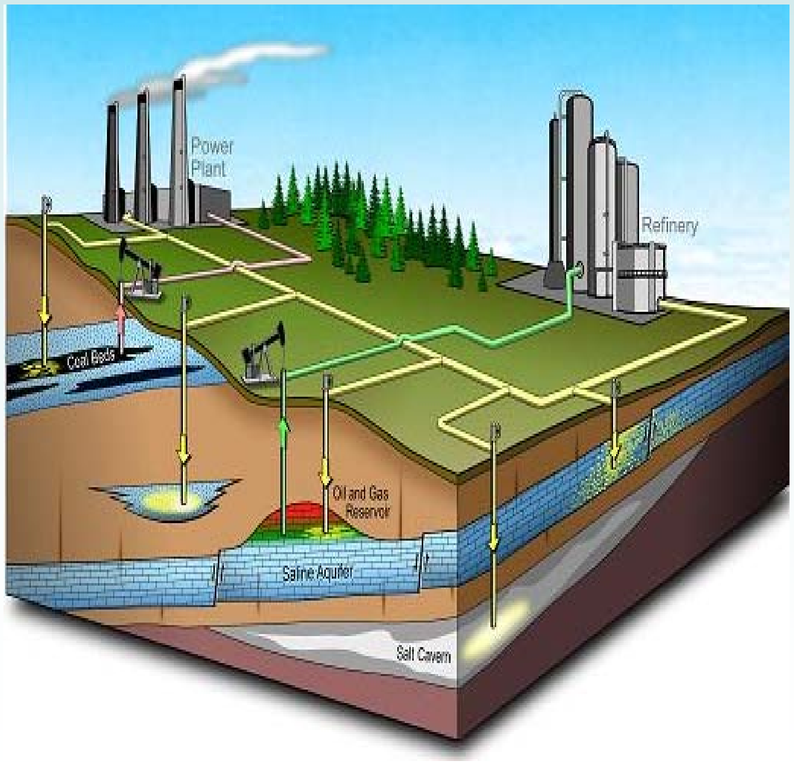
2009 Program Budget Breakdown



Carbon Sequestration Program Goals

Develop technology options that...

- **Deliver technologies & best practices that provide Carbon Capture and <u>Safe</u> Storage (CCSS) with:**
  - 90% CO_2 capture at source
  - 99% storage permanence
  - < 10% increase in COE
    - Pre-combustion capture (IGCC)
  - < 35% increase in COE
    - Post-combustion capture
    - Oxy-combustion



Key Challenges to Carbon Capture and Storage

Focus Infrastructure to Address Both Types of Issues

Technical Issues

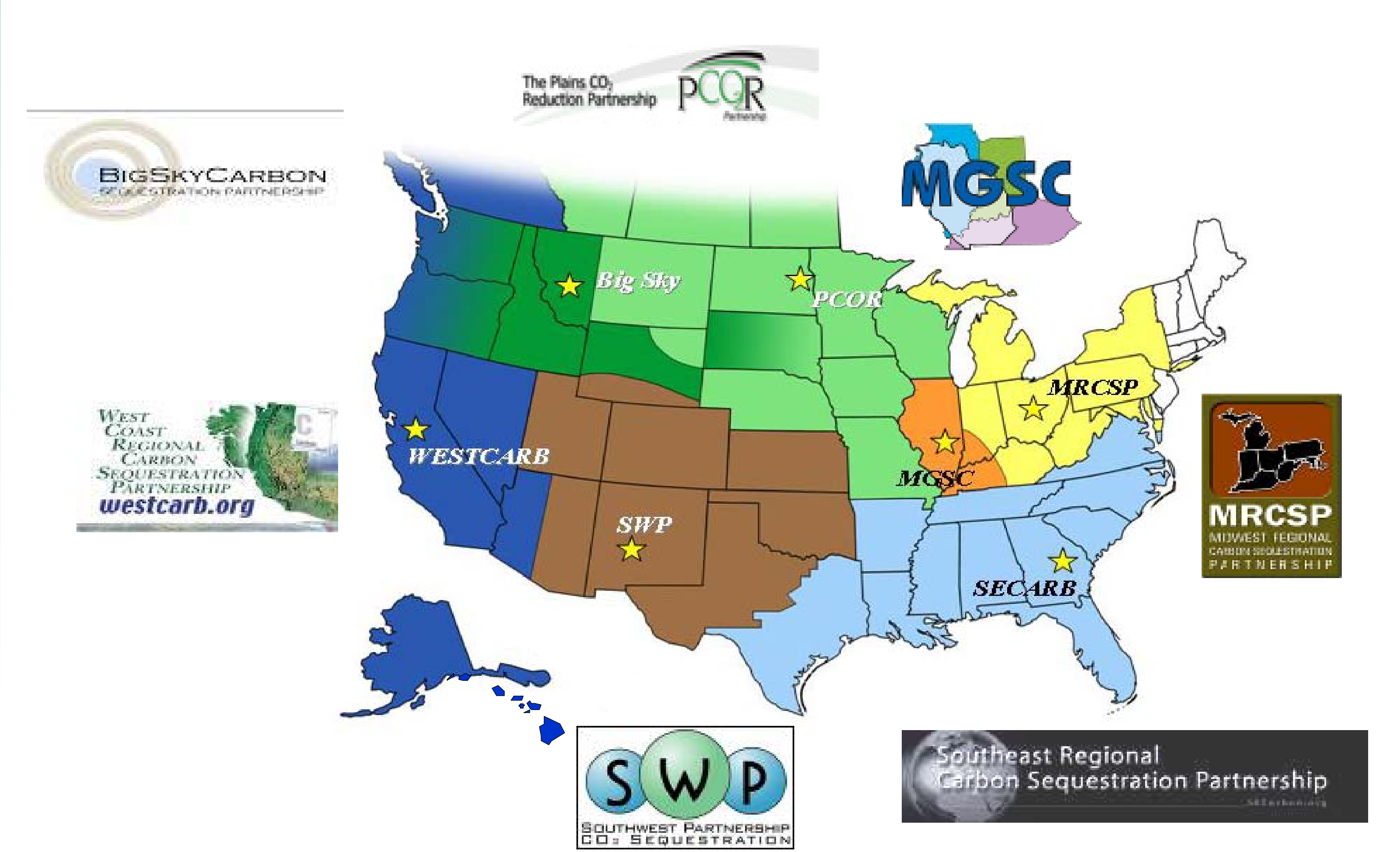
- **Capture Technology**
  - Existing Plants
  - New Plants (PC)
  - IGCC
- **Cost of CCS**
- **Storage Capacity**
- **Permanence**
- **Best Practices**
  - Storage Site Characterization
  - Monitoring/Verification
  - Accounting
  - Site Closure
  - Etc. …

Legal / Social Issues

- **Regulatory Framework**
  - Permitting
  - Treatment of CO_2
  - Accounting
- **Infrastructure**
- **Human Capital**
- **Legal Framework**
  - Liability
  - Ownership
    - Pore space
    - CO_2
- **Public Acceptance** (NIMBY → NUMBY)

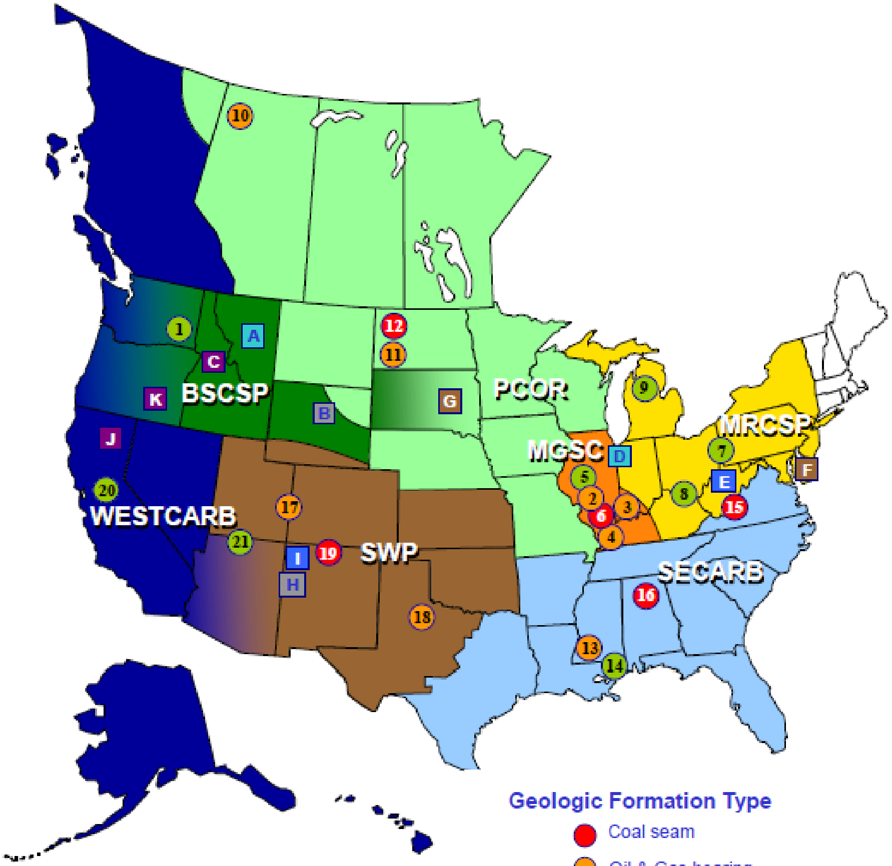
Regional Carbon Sequestration Partnerships

“Developing the Infrastructure for Wide Scale Deployment”



RCSP Phase II: Validation Phase

Small-Scale Geologic and Terrestrial Tests



Geologic Formation Type

- Coal seam
- Oil & Gas bearing
- Saline formation

Terrestrial Project Categorization

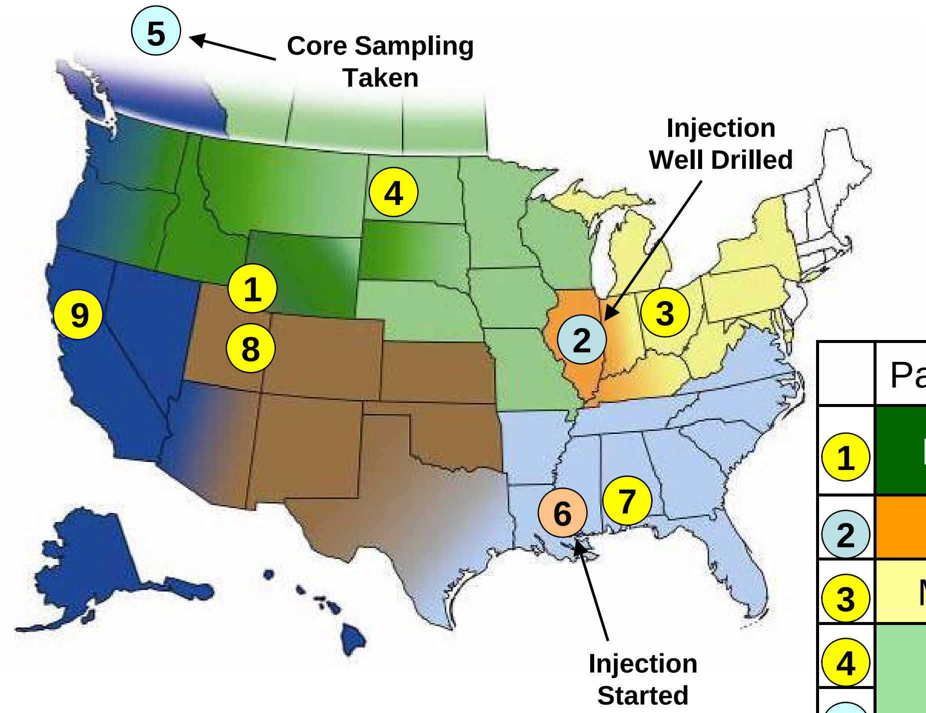
- Agricultural Soils
- Soil Reclamation
- Afforestation/Forest Treatment

	Partnership	Geologic Province/ Location	Geologic: Total CO_2 Injection (tons CO_2)	Geologic: Approximate Depth (feet)	Terrestrial: Estimated CO_2 Capacity
1	Big Sky Carbon Sequestration Partnership	Columbia Basin	0*	2,500 – 4,000	
A		North Central MT			30 Mt over 20 years
B		Eastern WY			30 Mt over 10 years
C		Region-wide			640 – 1,040 Mt over 80 years
2	MGSC	Loudon Oil Field	< 50	1,550	
3		Mumford Hills Oil Field	2,700*	1,551	
4		Sugar Creek Oil Field	4,600*	1,548	
5		Illinois Basin	0*	6,650 – 7,050	
6		Illinois Basin	100	1,000	
7	MRCSP Midwest Regional Carbon Sequestration Partnership	Appalachian Basin	< 100	5,900 – 8,300	
8		Cincinnati Arch	1,000	3,200 – 3,500	
9		Michigan Basin	60,000	3,200 – 3,500	
D		Region-wide			25 Mt over 20 years
E		Region-wide			100 Mt over 20 years
F		Cambridge, MD			TBD
10	The Plains CO_2 Reduction Partnership PCOR	Keg River Formation	30,000	5,000	
11		Duperow Formation	440	10,000 – 10,500	
12		Williston Basin	90	1,600 – 1,800	
G		Great Plains wetlands complex (PPR)			14.4 Mt
13	SECARB Southeast Regional Carbon Sequestration Partnership	Gulf Coast } stacked	500,000	10,304	
		Gulf Coast		10,400	
14		Mississippi Coastal Plain	3,082	8,600	
15		Central Appalachian	1,000	1,600 – 2,300	
16		Black Warrior Basin	0*	1,500 – 2,500	
17	SWP Southwest Partnership CO_2 Sequestration	Paradox Basin–Aneth Field	250,000	5,600 – 5,800	
18		Permian Basin	475,000	5,800	
19		San Juan Basin	18,430	3,000	
H		Region-wide			TBD
I		San Juan Basin Coal Fairway (Navajo City, NM)			TBD
20	West Coast Regional Carbon Sequestration Partnership westcarb.org	Sacramento Basin*	0*	8,000	
21		Colorado Plateau	0	4,000	
J		Shasta County, CA			4,600 Mt over 80 years (CA)
K		Lake County, OR			900 Mt over 80 years (OR)

* Currently injecting or will begin injecting in 2010

RCSP Phase III: Development Phase

Large-Scale Geologic Tests



2010/2011 Injection Scheduled

2011/2012 Injection Scheduled

✓ ***Nine large-volume tests***

✓ ***Injections initiated 2009 – 2011***

	Partnership	Geologic Province	Type
1	Big Sky	Triassic Nugget Sandstone / Moxa Arch	Saline
2	MGSC	Deep Mt. Simon Sandstone	Saline
3	MRCSP	Shallow Mt. Simon Sandstone	Saline
4	PCOR	Williston Basin Carbonates	Oil Bearing
5	PCOR	Devonian Age Carbonate Rock	Saline
6, 7	SECARB	Lower Tuscaloosa Formation Massive Sand Unit	Saline
8	SWP	Regional Jurassic & Older Formations	Saline
9	WESTCARB	California Central Valley	Saline

Update on Results of SECARB Test of Monitoring Large Volume Injection at Cranfield

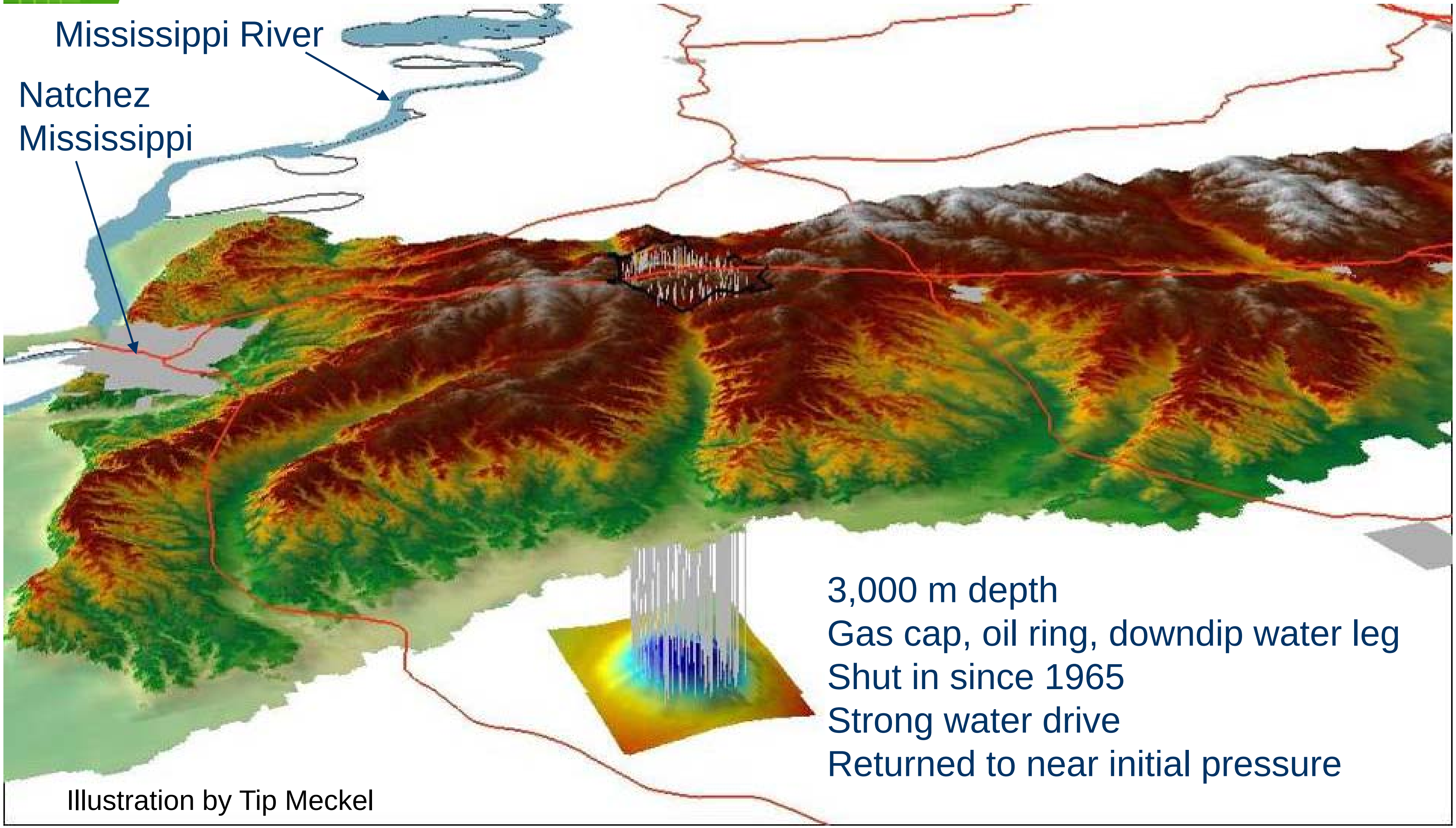


Illustration by Tip Meckel

Cranfield "Early" Field Test Collaboration

Denbury Onshore LLC

Sandia Technologies, LLC

LBNL
LLBL
USGS
ORNL
NETL
Schlumberger
Carbon Services
QEA
BP
U Mississippi
Miss State
UTPGE
UT DoG
University Tennessee
Princeton
Stanford
University Edinburgh

Gulf Coast Carbon Center Staff

Susan Hovorka
Ramon Trevino
Tip Meckel
Changbing Yang
Jiemin Liu
Katherine Romanak
Rebecca Smyth
Sigrid Clift
Masoumeh Kordi
Stuart Coleman
Yihua Cai
Hamid Lashgari

BEG staff

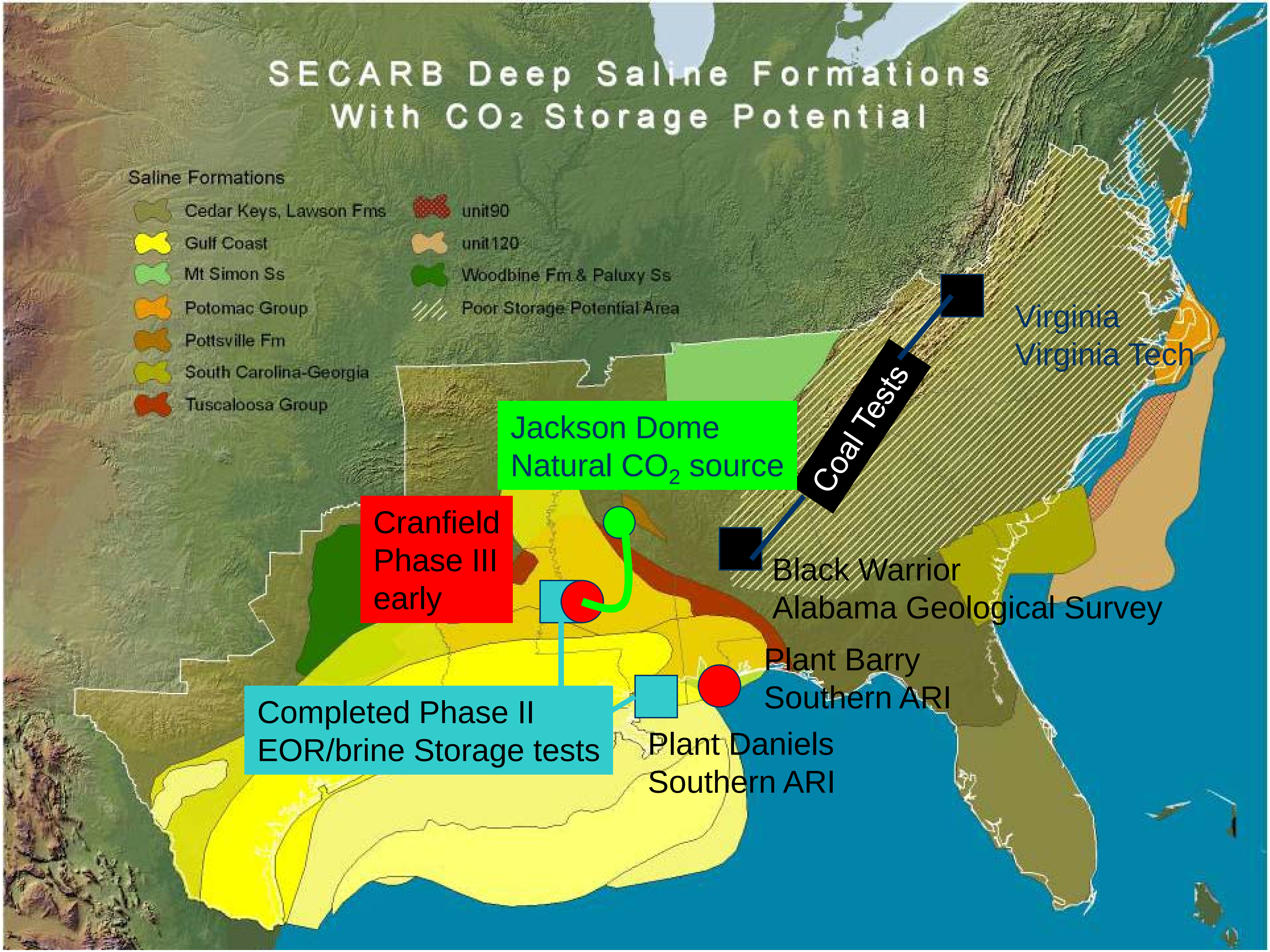
Tongwei Zhang
Jeff Paine
Bob Reedy
Robert Reed
Kitty Millikan

Gulf Coast Carbon Center Industrial Associates

SECARB Cranfield Research: Theoretical Approaches Through Commercialization

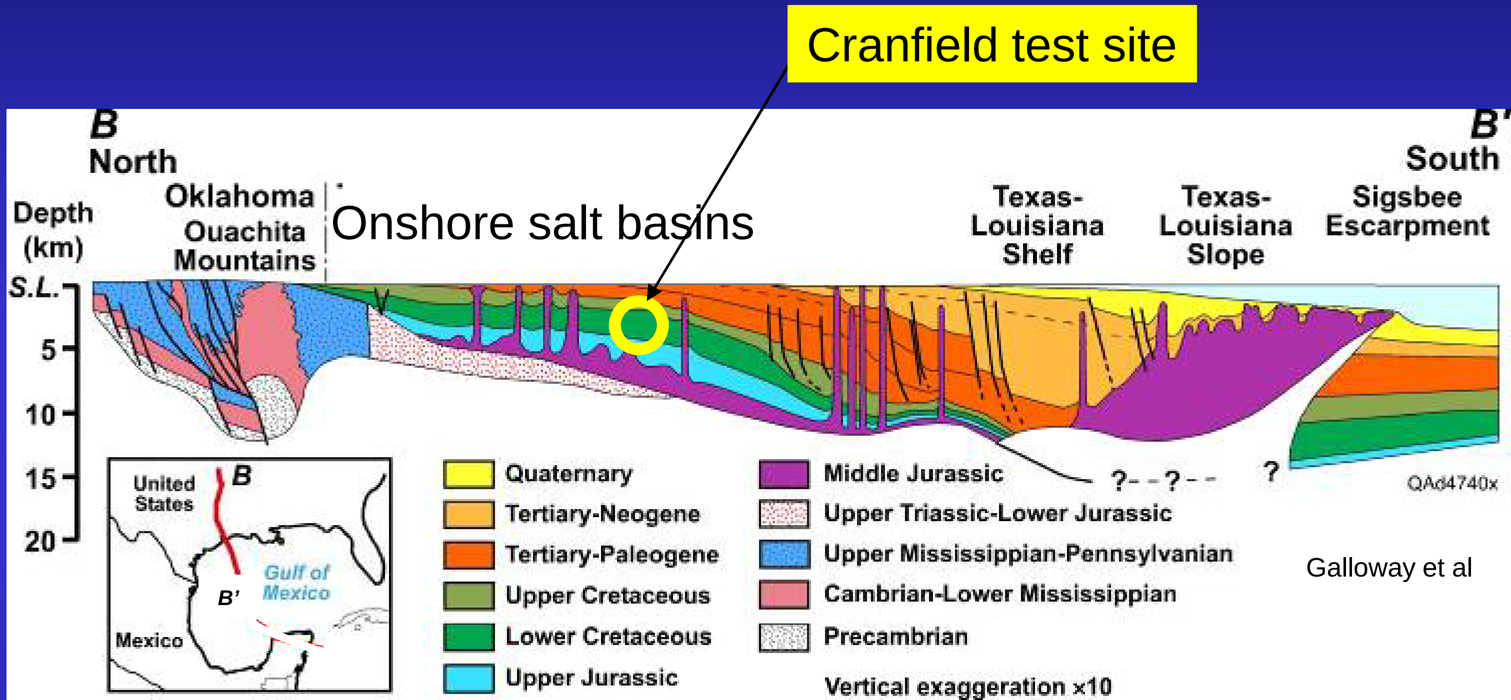
Commercial Deployment by Southern Co.

Toward commercia-lization	Contingency plan Parsimonious public assurance monitoring	Subsurface perturbation predicted	
Hypothesis tested	CO_2 retained in-zone-document no leakage to air-no damage to water	CO_2 saturation correctly predicted by flow modeling	Pressure (flow plus deformation) correctly predicted by model
Field experiments	Surface monitoring: approach verification Groundwater program Gas variation over time Above-zone acoustic monitoring (CASSM) & pressure monitoring	CO_2 saturation measured through time – acoustic impedance + resistivity Tomography and change through time 3- D time lapse surface/ VSP seismic Dissolution and saturation measured via tracer breakthrough and chromatography	Microseismic test, pressure mapping Acoustic response to pressure change over time
Theory and lab	Sensitivity of tools; saturated-vadose modeling of flux and tracers	Lab-based core response to EM and acoustic under various saturations, tracer behavior	Advanced simulation of reservoir pressure field



SECARB Deep Saline Formations
With CO2 Storage Potential
Saline Formations
Cedar Keys, Lawson Fms
Gulf Coast
Mt Simon Ss
Potomac Group
Pottsville Fm
South Carolina-Georgia
Tuscaloosa Group
unit90
unit120
Woodbine Fm & Paluxy Ss
Poor Storage Potential Area
Jackson Dome
Natural CO_2 source
Coal Tests
Virginia
Virginia Tech
Cranfield
Phase III
early
Black Warrior
Alabama Geological Survey
Plant Barry
Southern ARI
Completed Phase II
EOR/brine Storage tests
Plant Daniels
Southern ARI

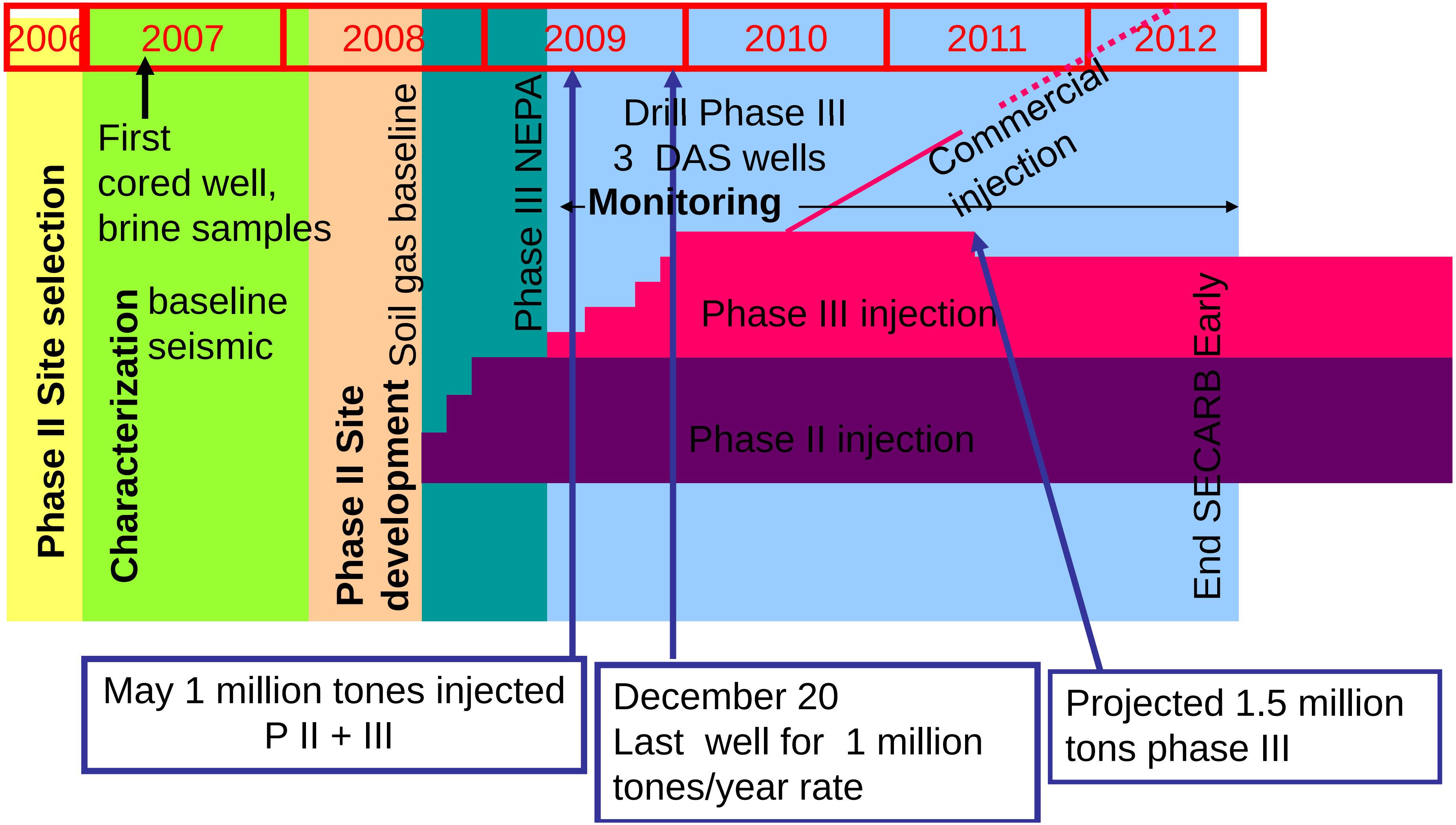
Natural CO_2 Available Now in large Volumes Shipped via Sonant Pipeline to Test Lower Part of the Gulf Coast Wedge



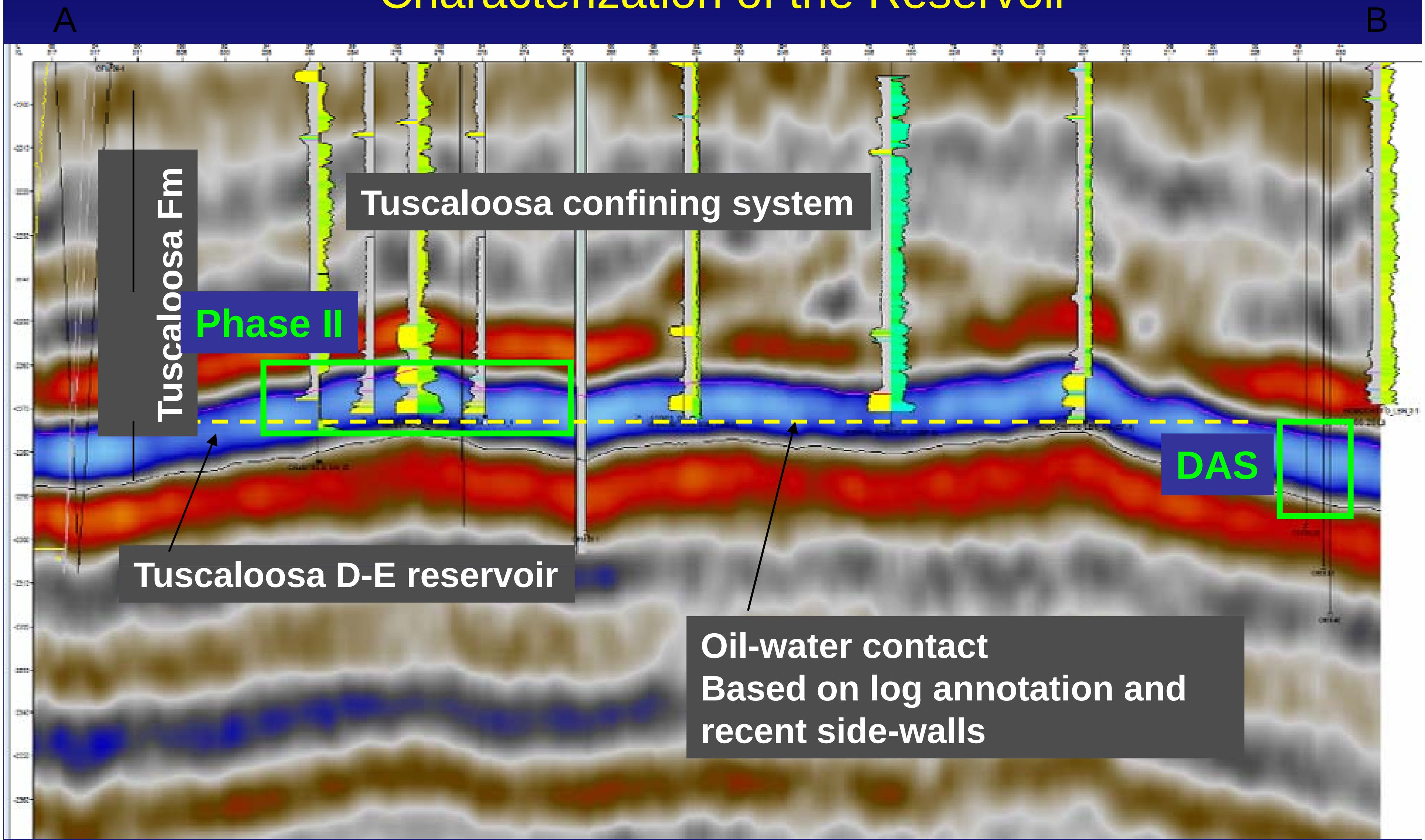
Relatively young sandstones with shale seals
Heterogeneous, high porosity sediments
Salt tectonics and growth faults
Heavy industry

Characteristics of the Gulf Coast wedge

Cranfield Progress



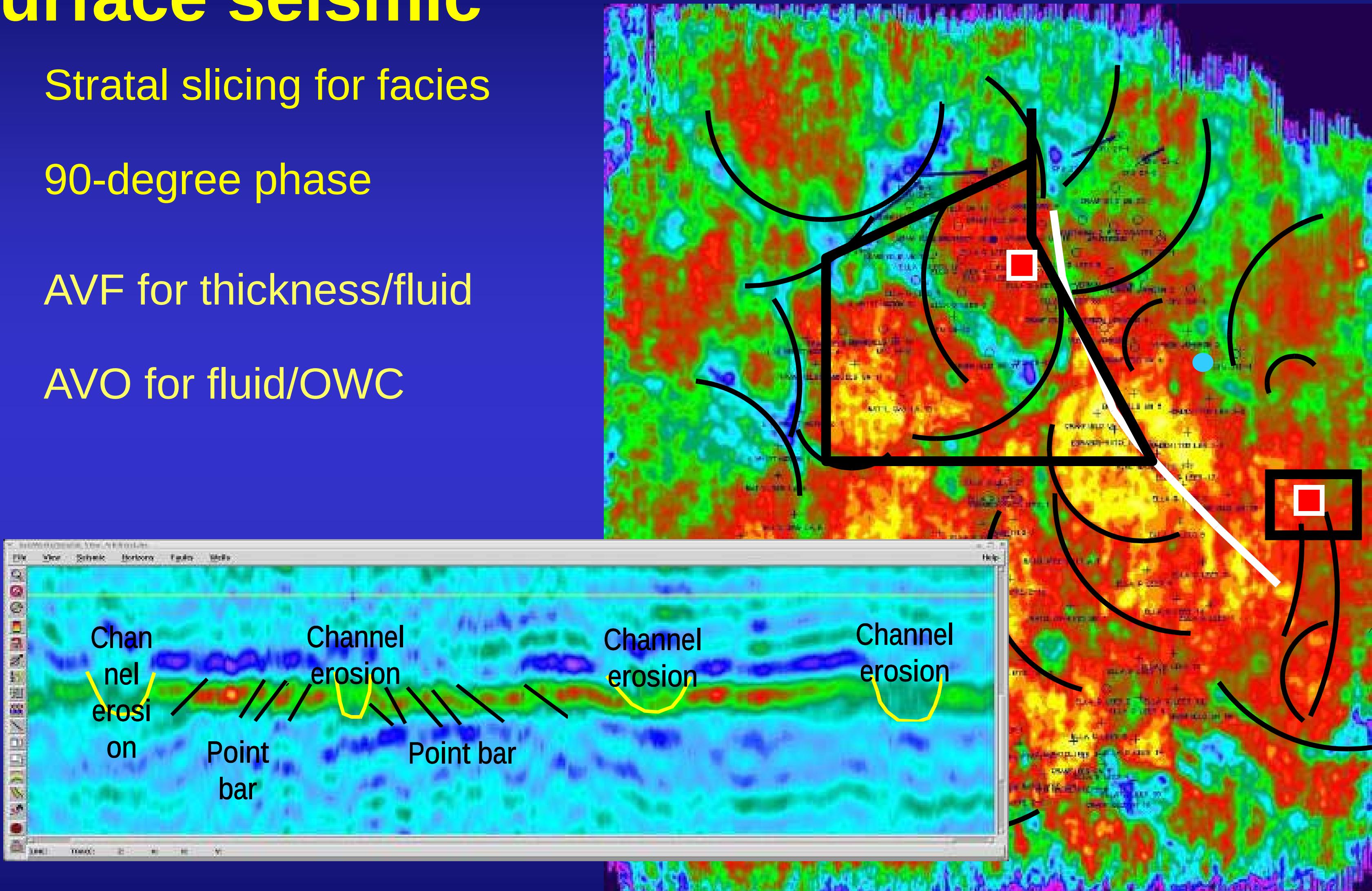
Characterization of the Reservoir



3D Denbury - interpretation Tip Meckel BEG

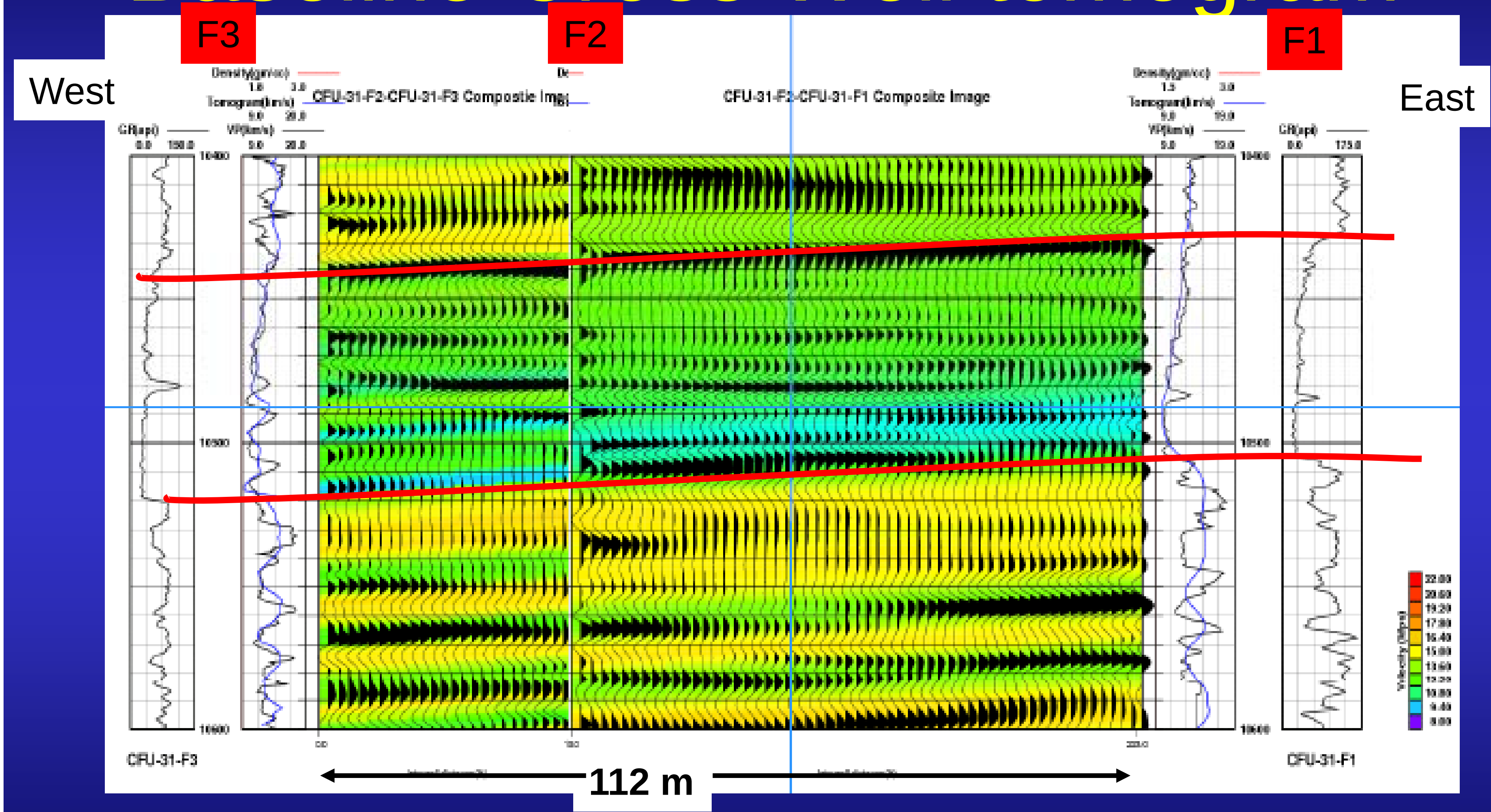
Reservoir heterogeneity from surface seismic

- Stratal slicing for facies
- 90-degree phase
- AVF for thickness/fluid
- AVO for fluid/OWC



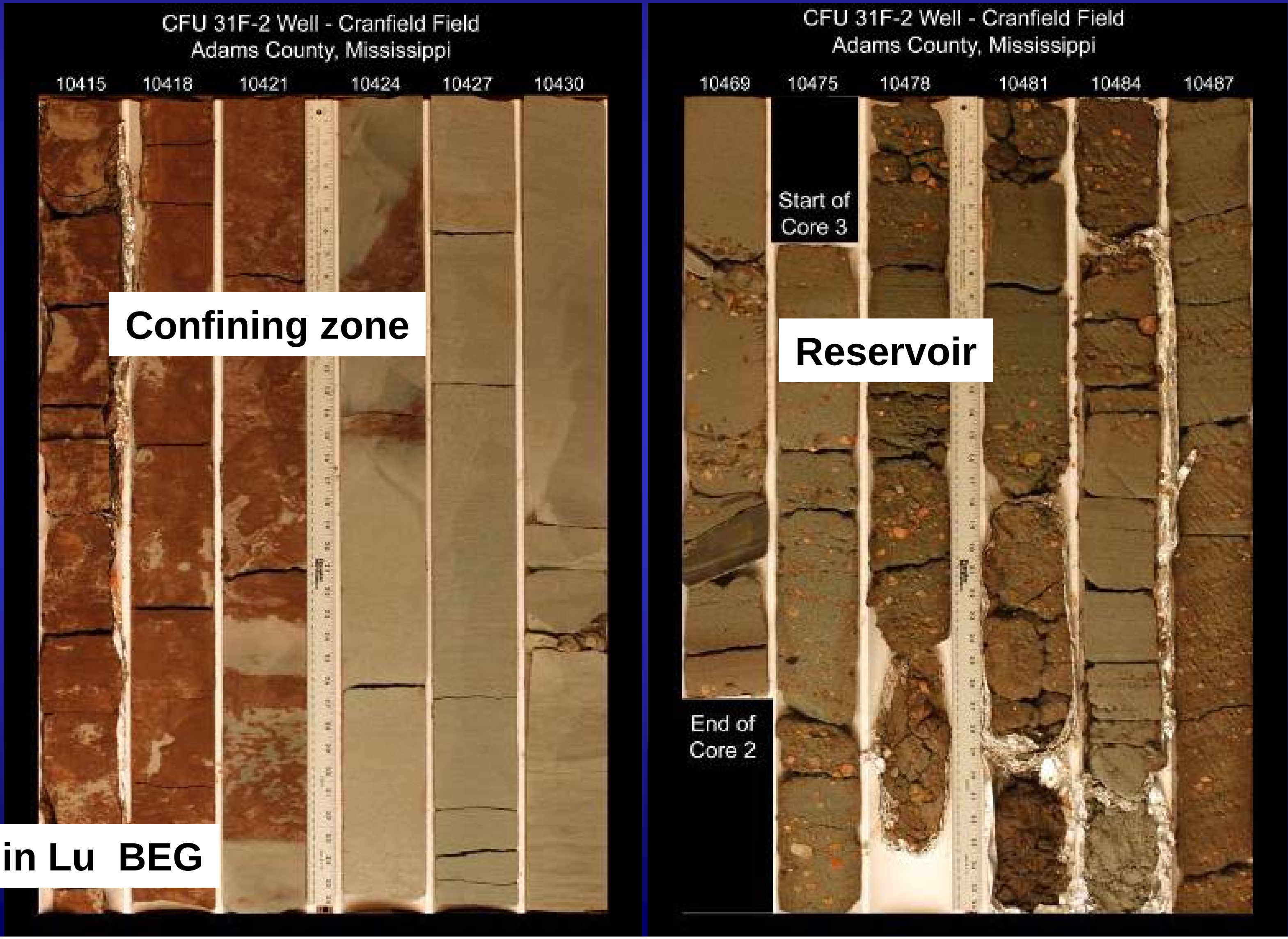
Denbury 3-D survey interpretation Hongliu Zeng, BEG

Baseline Cross Well tomogram

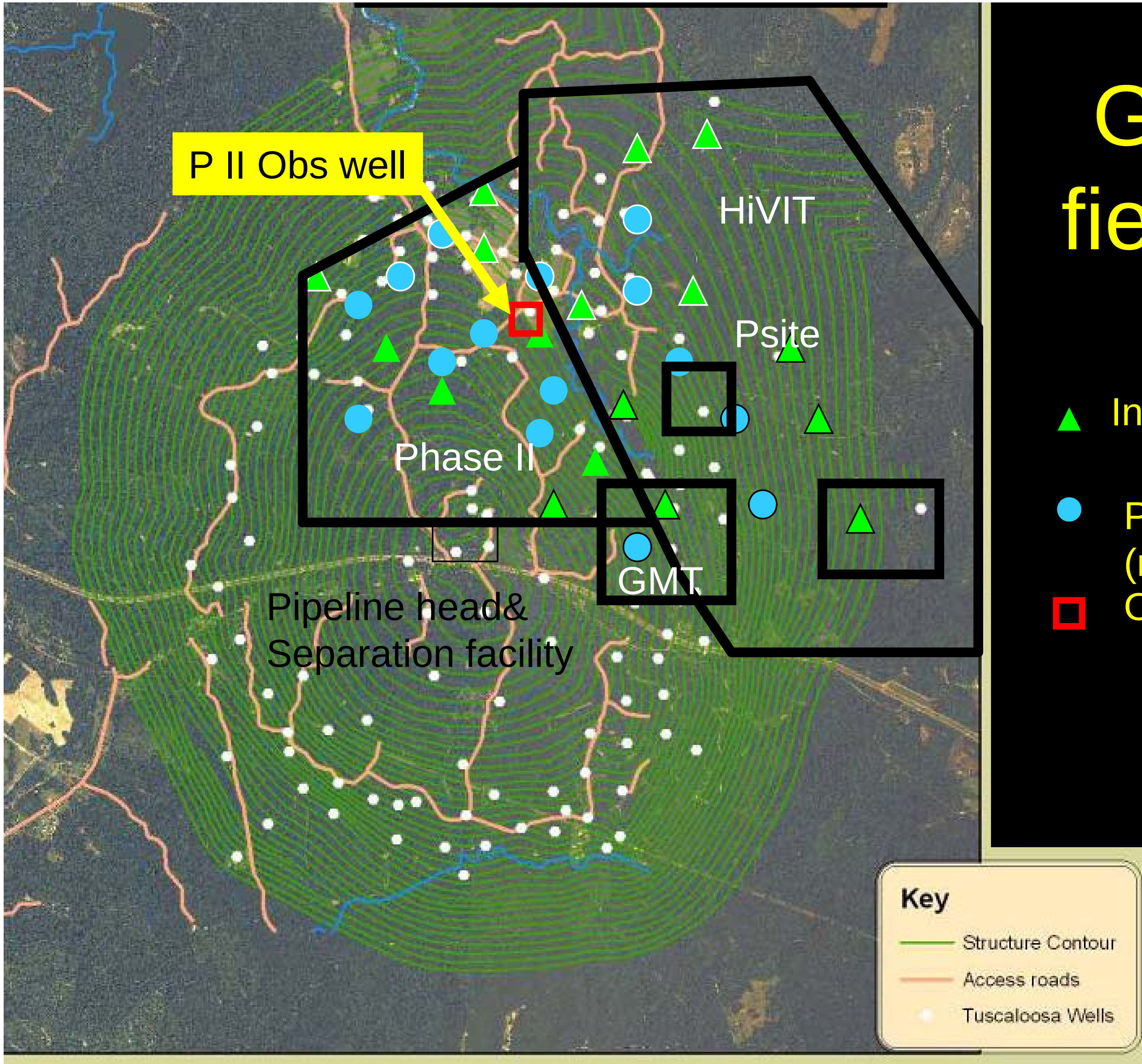


Z-Seis & Tom Daley Jonathan Franklin in review at LBNL

Upward fining fluvial sandstone and conglomerates of the lower Tuscaloosa Fm



Jiemin Lu BEG



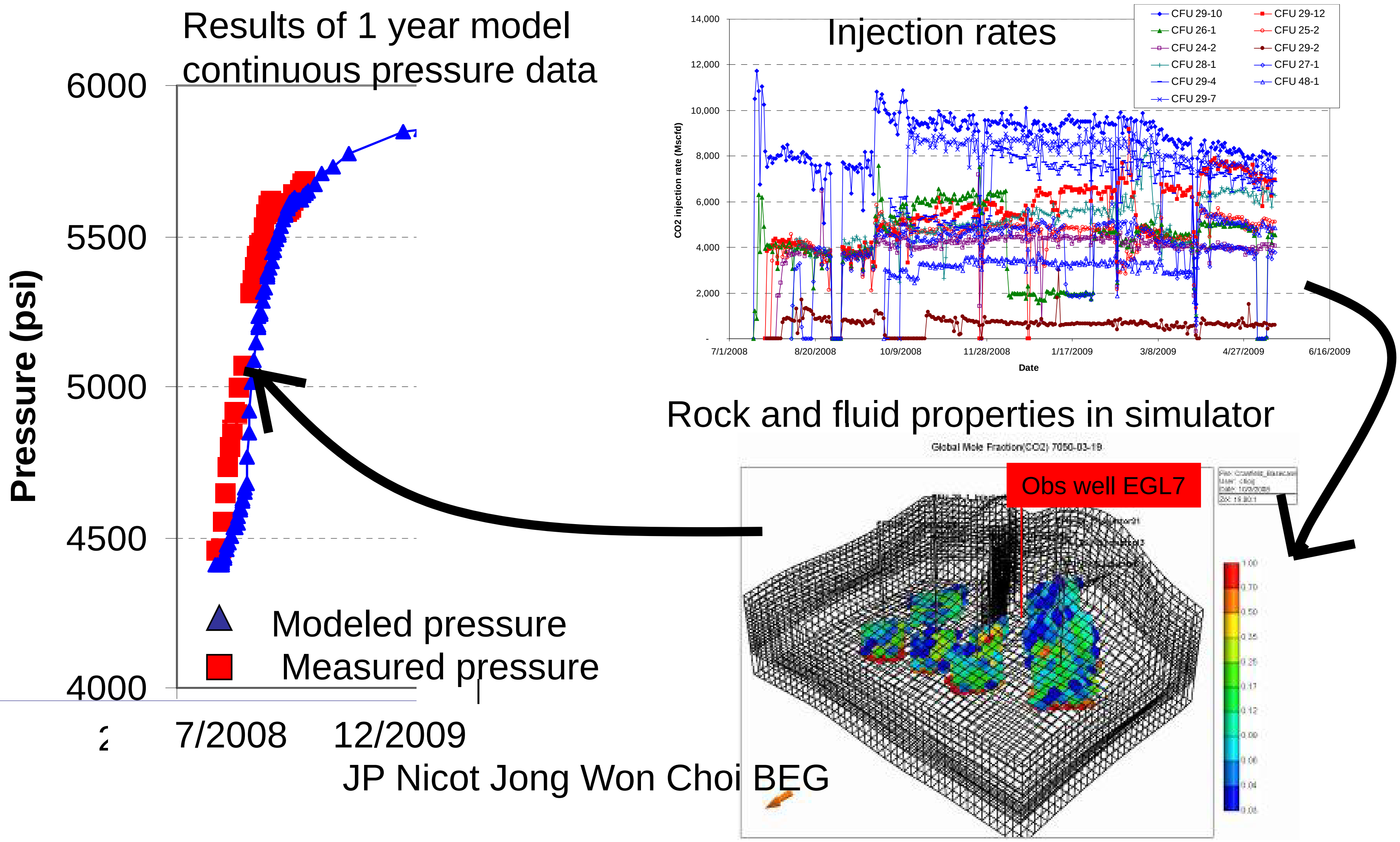
Go to the field to test

Injector

Producer (monitoring point)

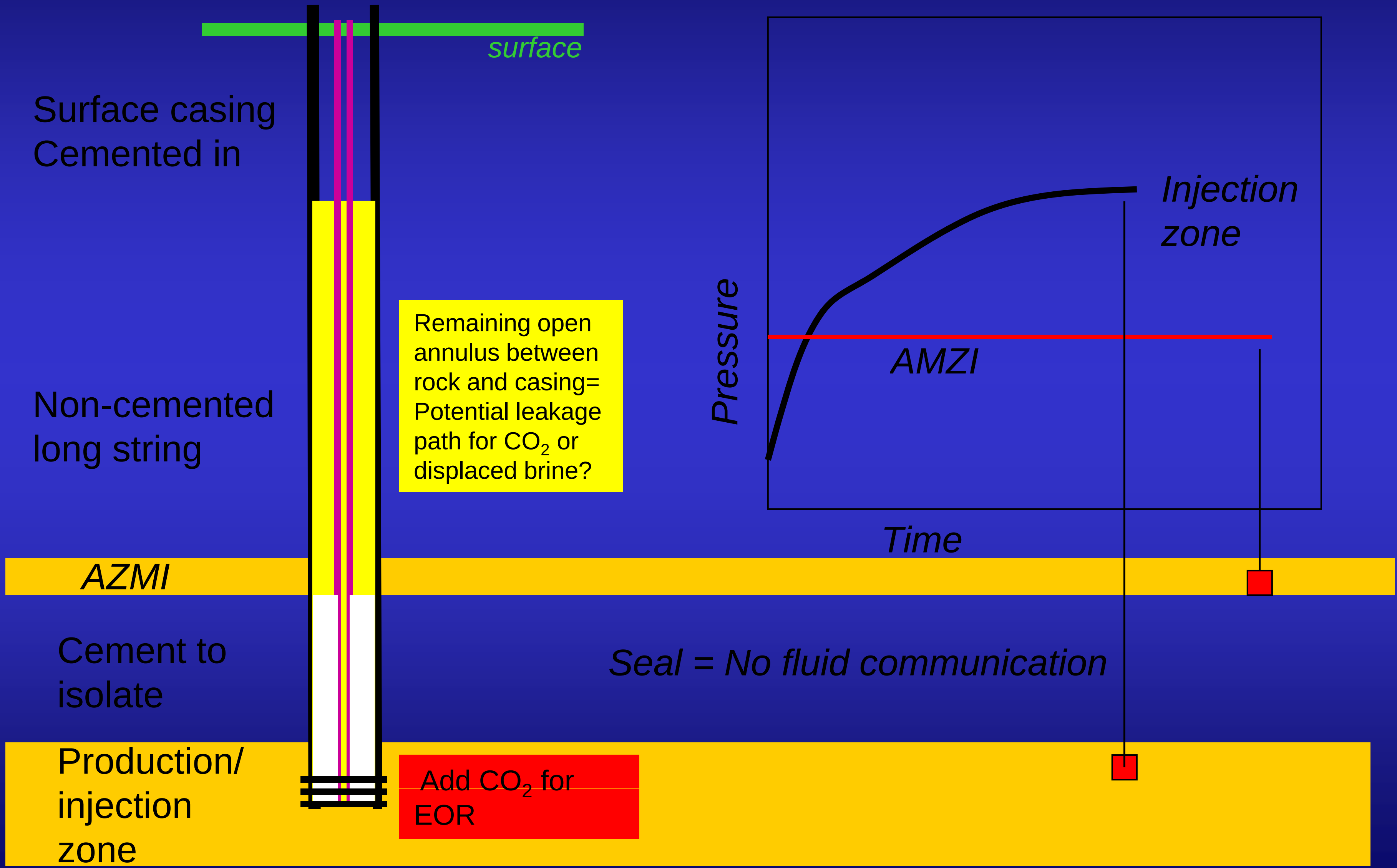
Observation Well

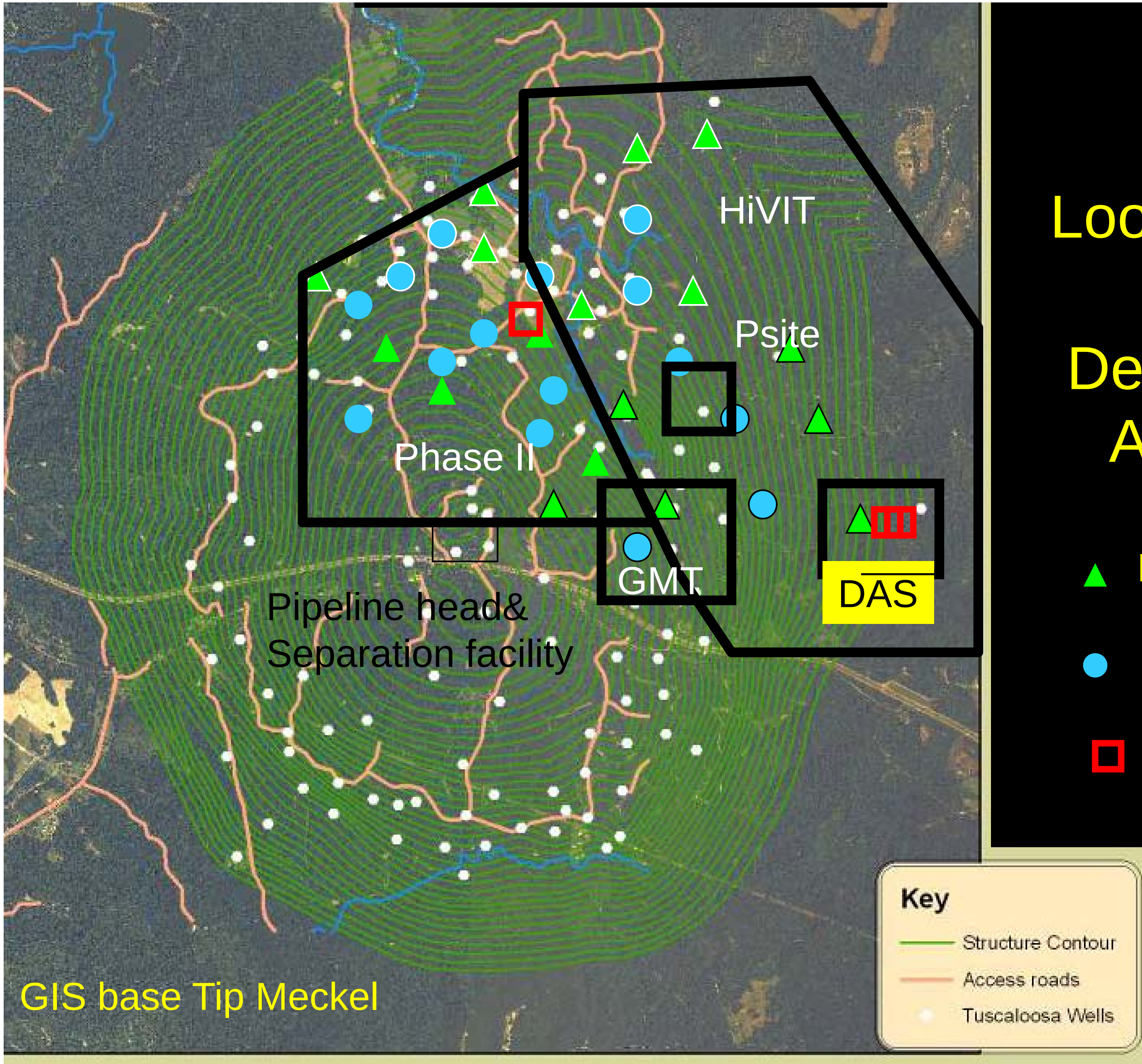
Model –history match pressure at real-time monitoring well



JP Nicot Jong Won Choi BEG

Using pressure to show no leakage





Look in Detail at Flow Detailed Study Area (DAS)

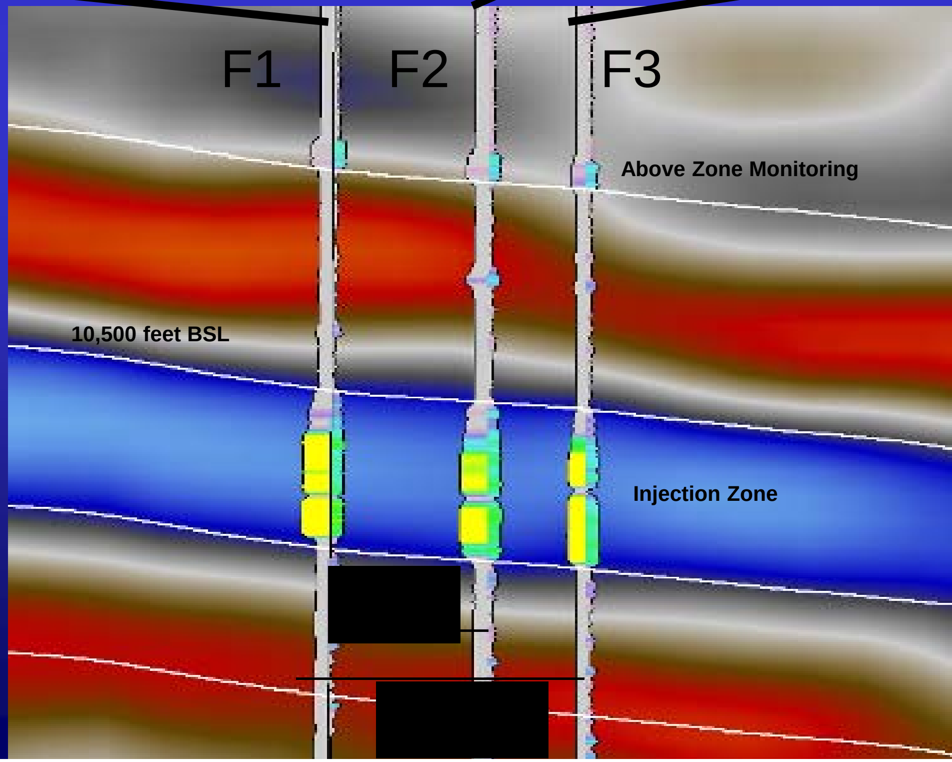
Injector

Producer (monitoring point)

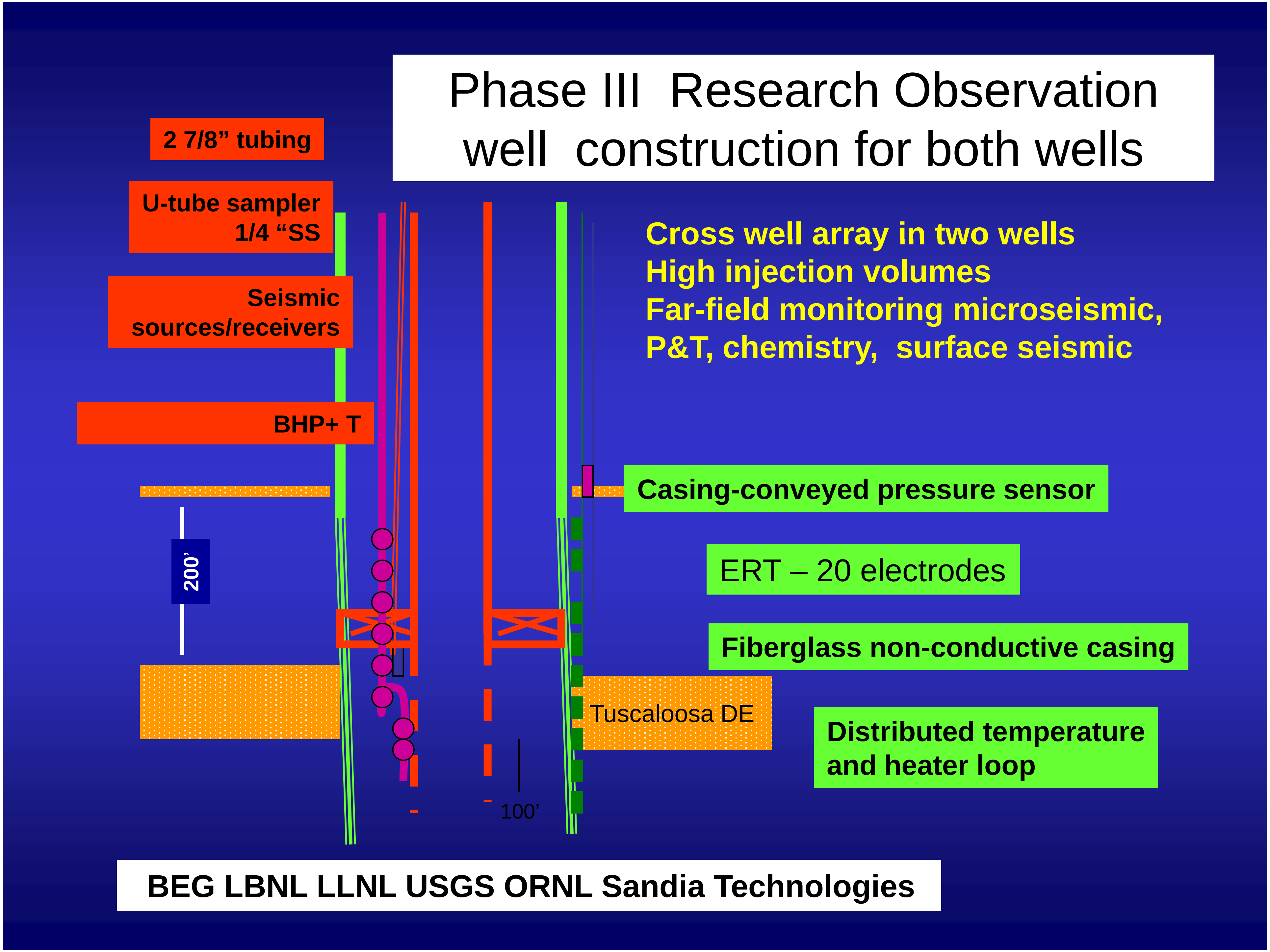
Observation Well

DAS Monitoring

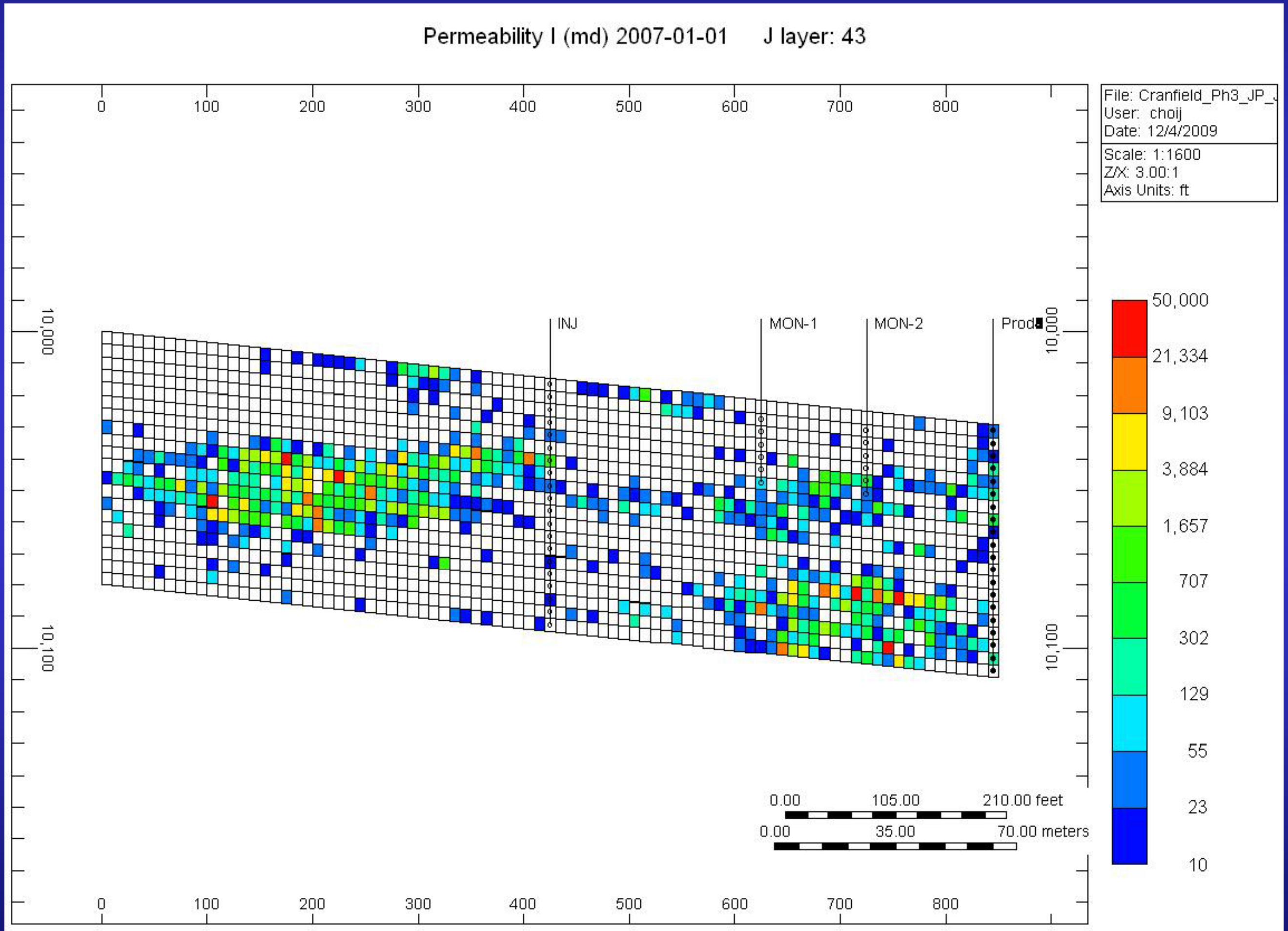
Closely spaced well array to examine flow in complex reservoir



Petrel model Tip Meckel

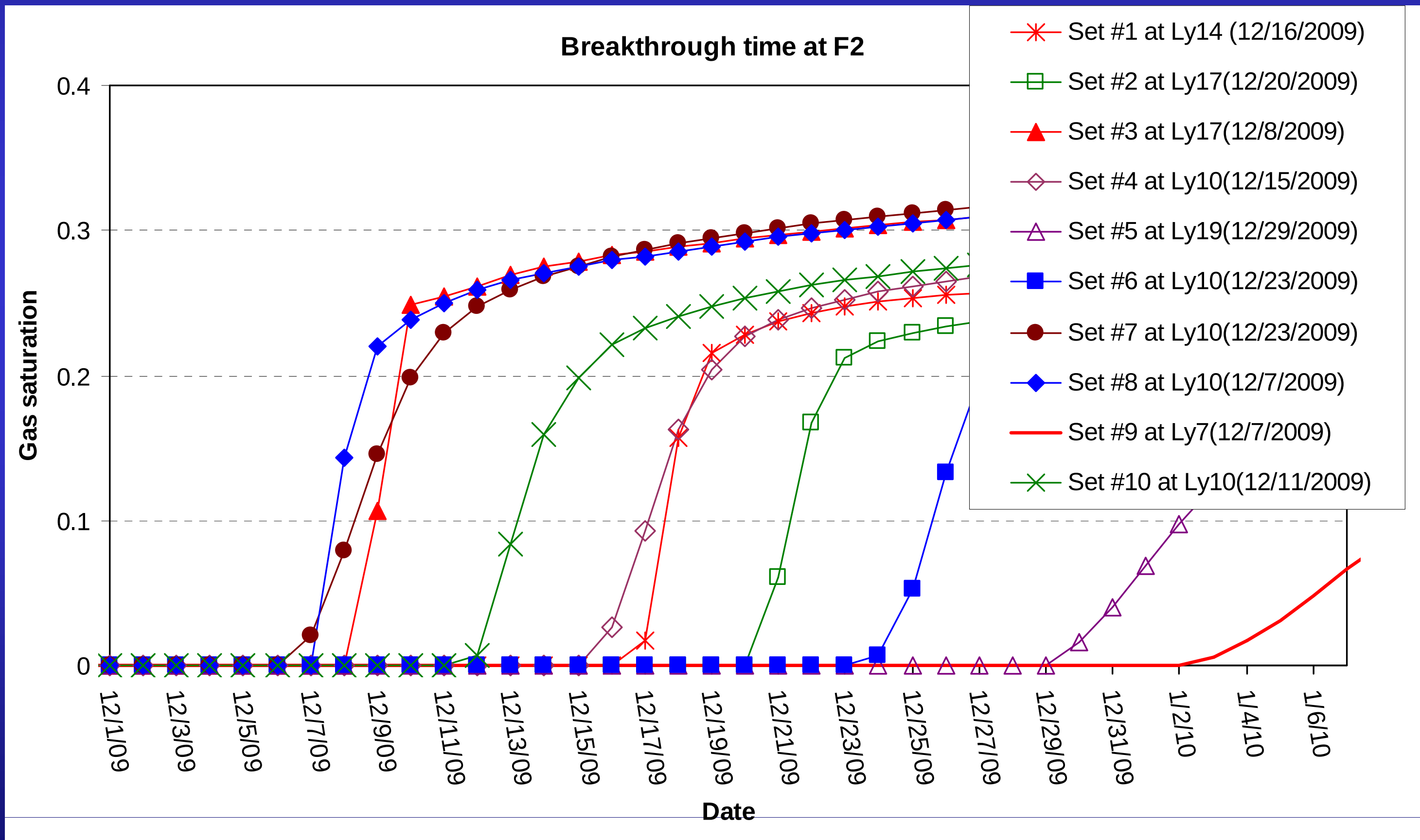

Phase III Research Observation well construction for both wells
2 7/8” tubing
U-tube sampler 1/4 “SS
Seismic sources/receivers
BHP+ T
200’
Cross well array in two wells
High injection volumes
Far-field monitoring microseismic, P&T, chemistry, surface seismic
Casing-conveyed pressure sensor
ERT – 20 electrodes
Fiberglass non-conductive casing
Tuscaloosa DE
Distributed temperature and heater loop
100’
BEG LBNL LLNL USGS ORNL Sandia Technologies

Probabilistic realization of permeability



Jong-won Choi and JP Nicot BEG

First breakthrough time at well F2 for each of the 10 permeability fields



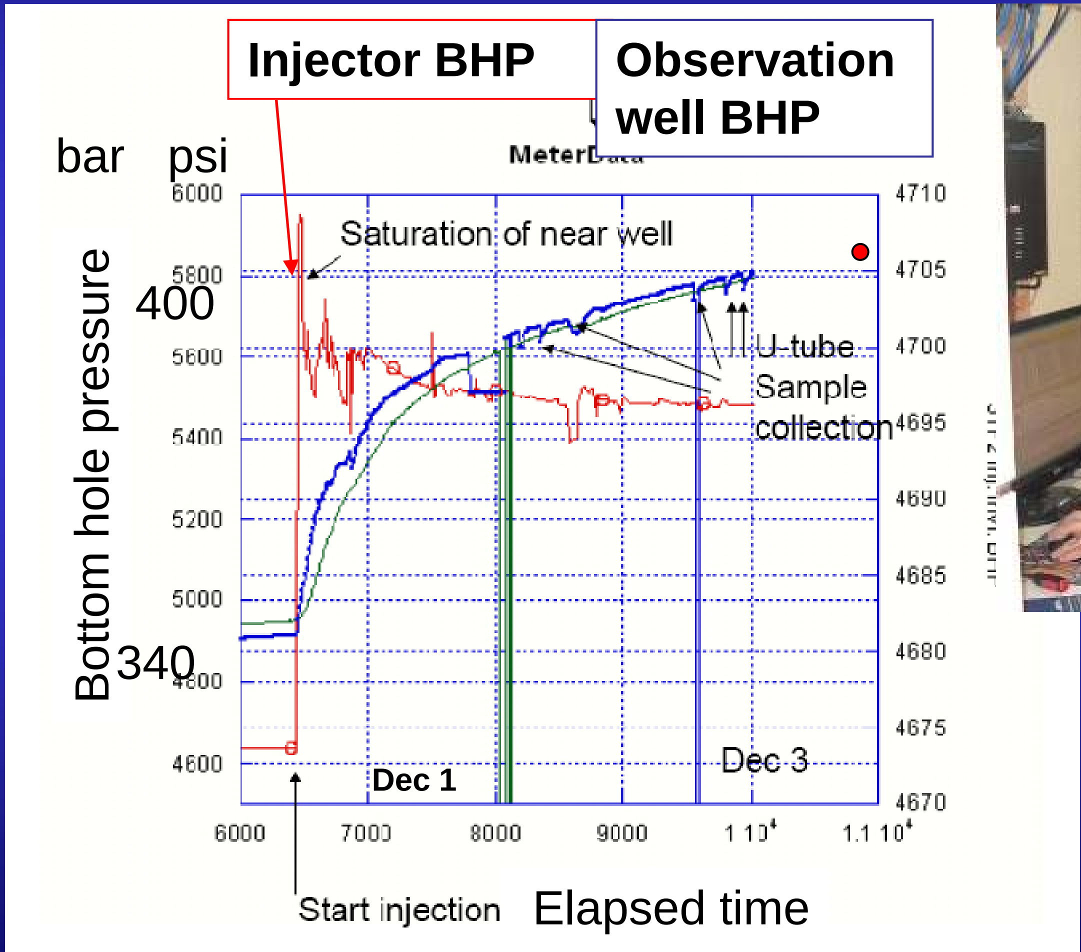
Jong-won Choi and JP Nicot BEG

Start injection at DAS Dec 1, 2009

175 kg/min step up to 350kg/min

Start injection at DAS Dec 1, 2009

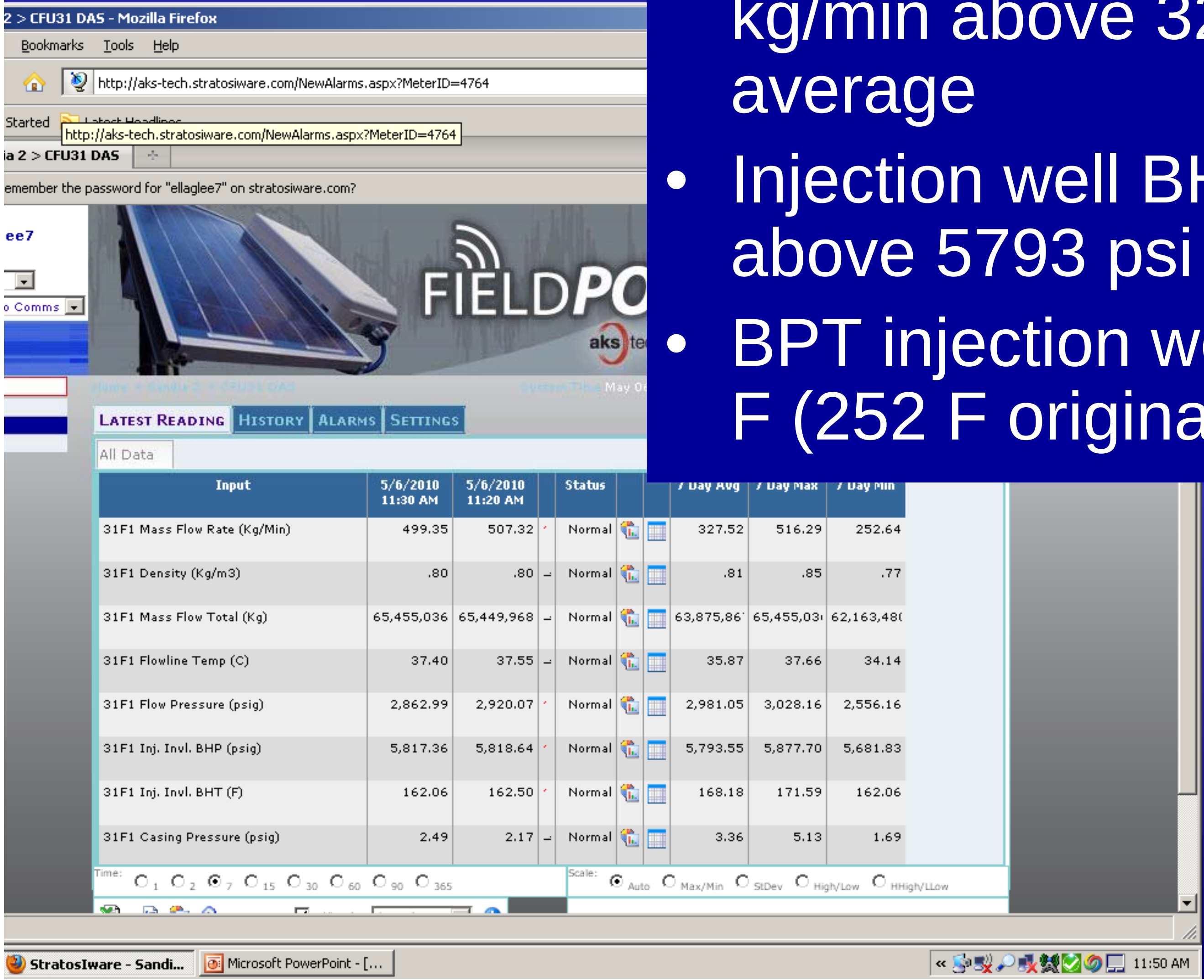
175 kg/min step up to 520 kg/min



It's all about pressure

Today at DAS

- Mass flow increased to 507 kg/min above 327 kg/min average
- Injection well BHP 5,818 psi above 5793 psi
- BPT injection well 162 degrees F (252 F original)

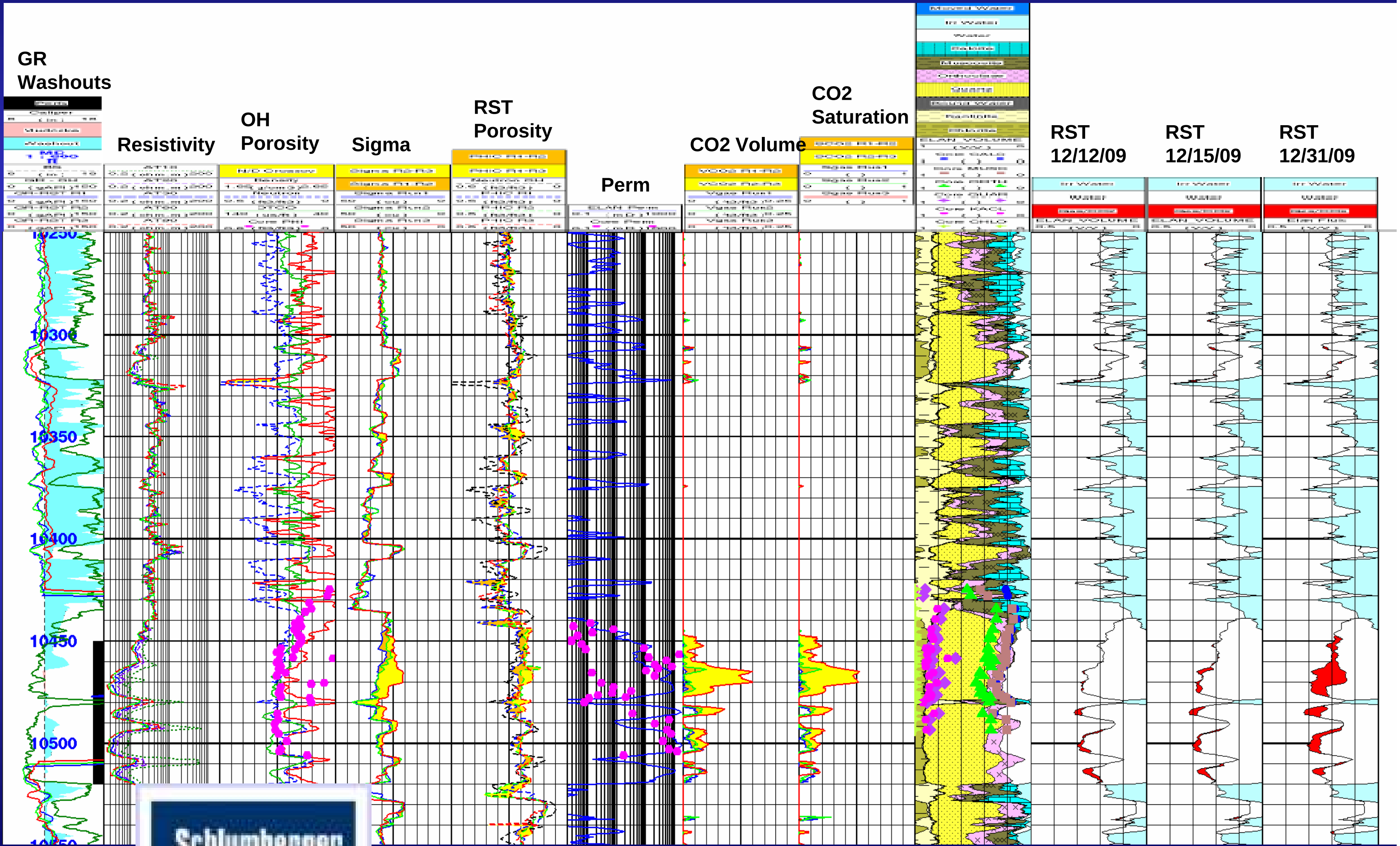


Input	5/6/2010 11:30 AM	5/6/2010 11:20 AM	Status	7 Day Avg	7 Day Max	7 Day Min
31F1 Mass Flow Rate (Kg/Min)	499.35	507.32	Normal	327.52	516.29	252.64
31F1 Density (Kg/m3)	.80	.80	Normal	.81	.85	.77
31F1 Mass Flow Total (Kg)	65,455,036	65,449,968	Normal	63,875,86	65,455,03	62,163,48
31F1 Flowline Temp (C)	37.40	37.55	Normal	35.87	37.66	34.14
31F1 Flow Pressure (psig)	2,862.99	2,920.07	Normal	2,981.05	3,028.16	2,556.16
31F1 Inj. Invl. BHP (psig)	5,817.36	5,818.64	Normal	5,793.55	5,877.70	5,681.83
31F1 Inj. Invl. BHT (F)	162.06	162.50	Normal	168.18	171.59	162.06
31F1 Casing Pressure (psig)	2.49	2.17	Normal	3.36	5.13	1.69

Measuring distribution of CO_2 in the reservoir

- Well-based methods
  - Wireline logs in time lapse -RST
  - Temperature
- Cross well methods
  - Time- lapse ERT
  - Time – lapse acoustic (seismic)

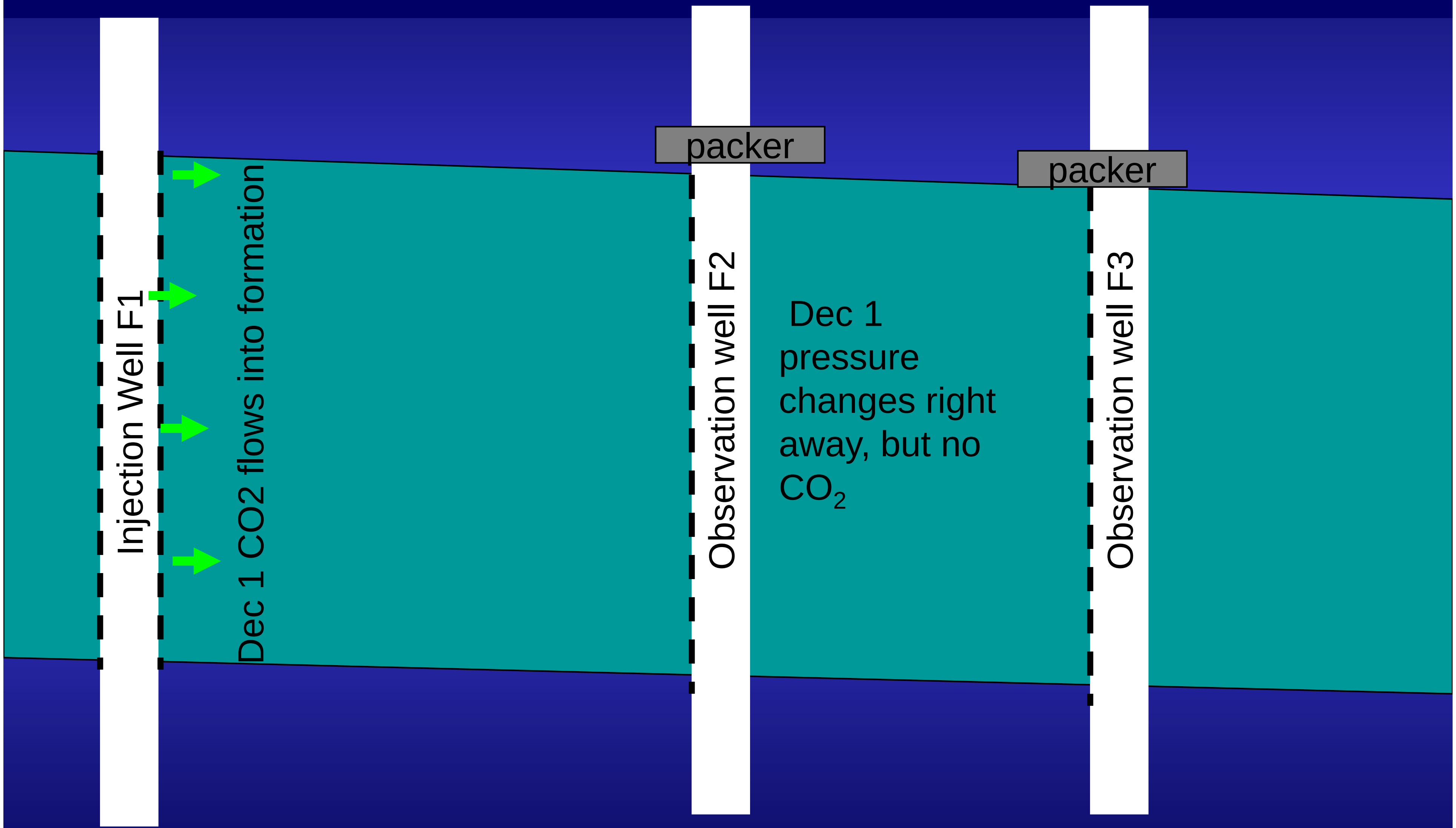
Wireline Formation Evaluation - ELAN – RST CFU 31 – F#3



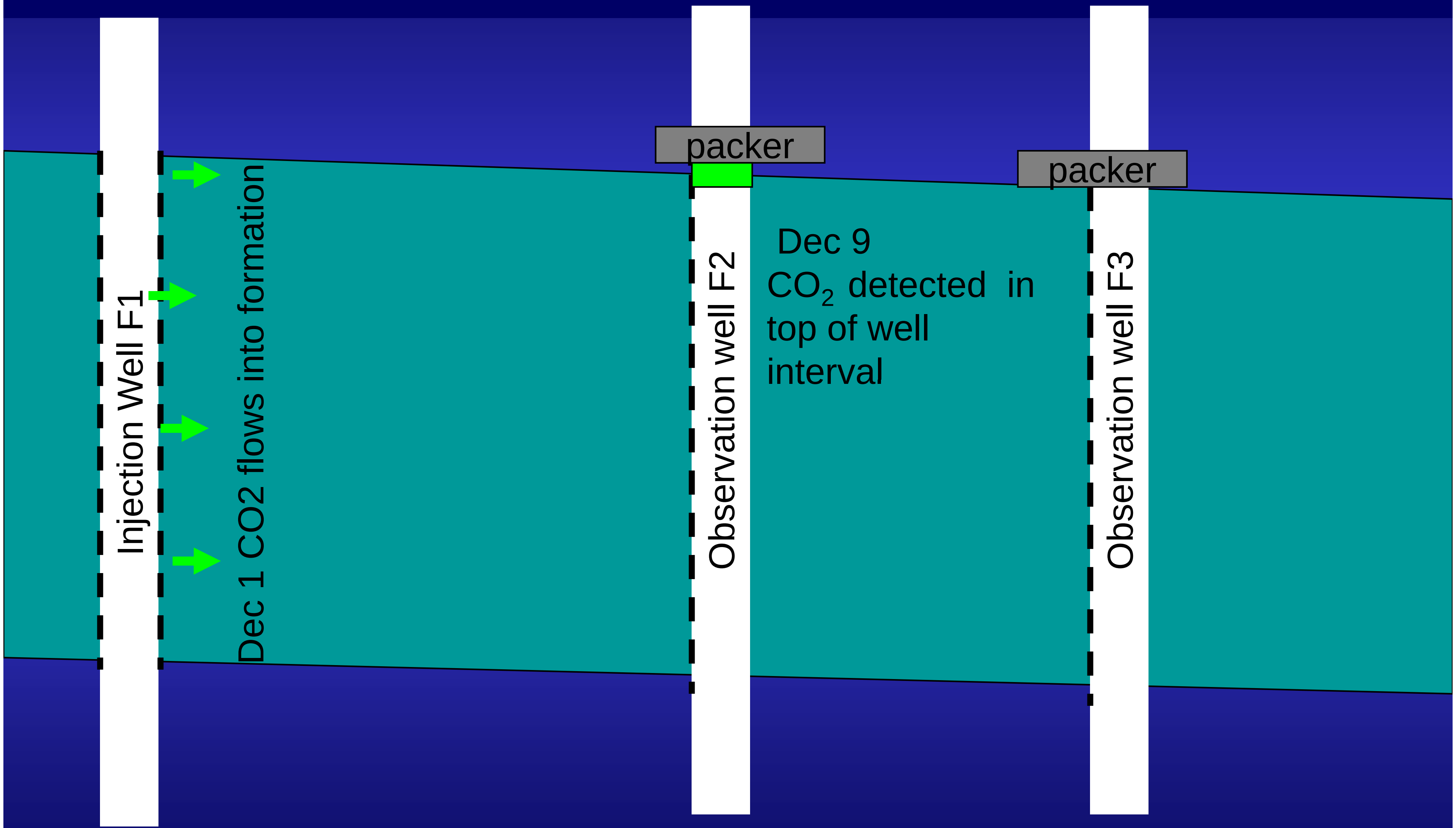
Schlumberger

Bob Butch

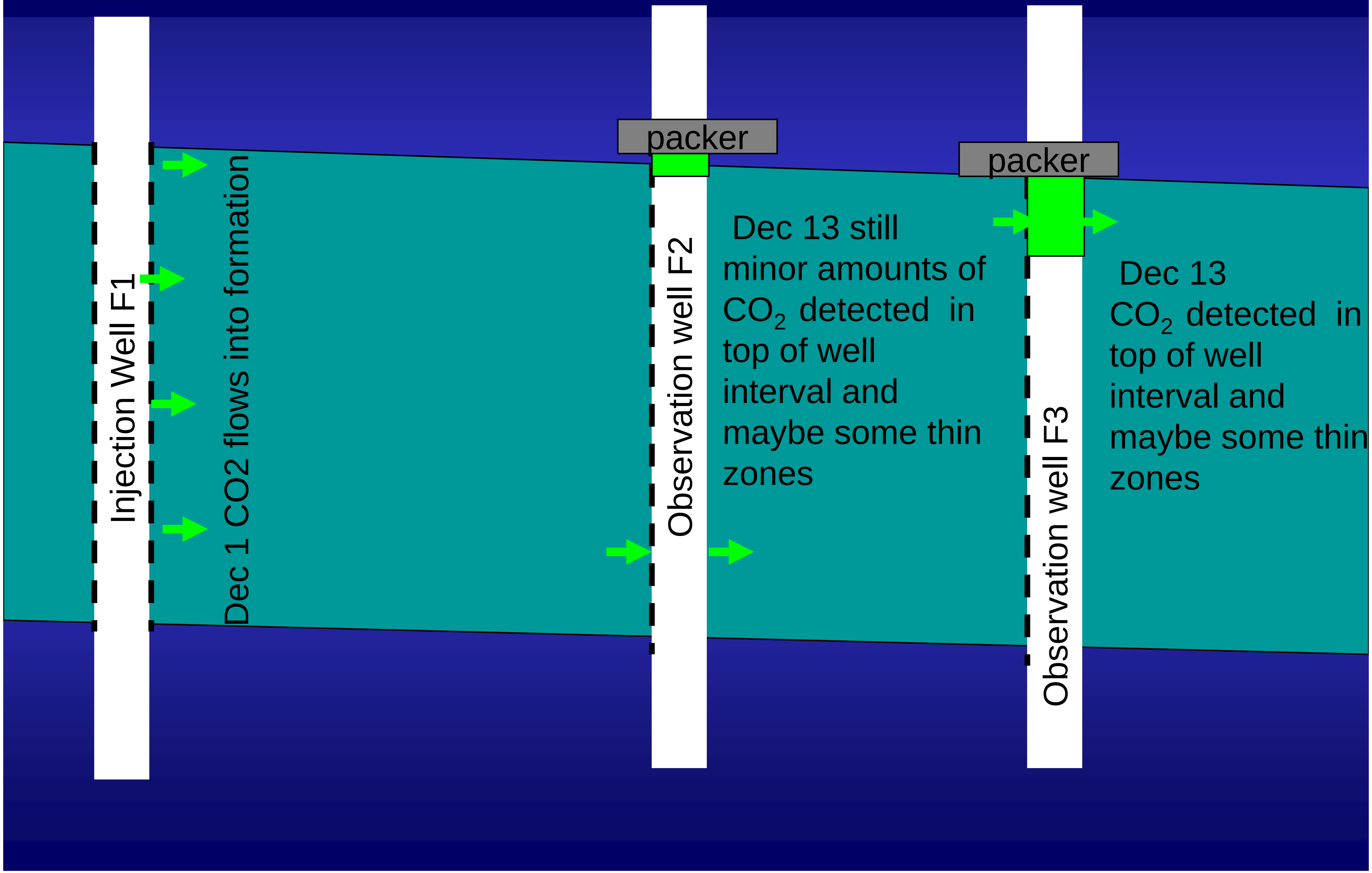
What happened at the wells?



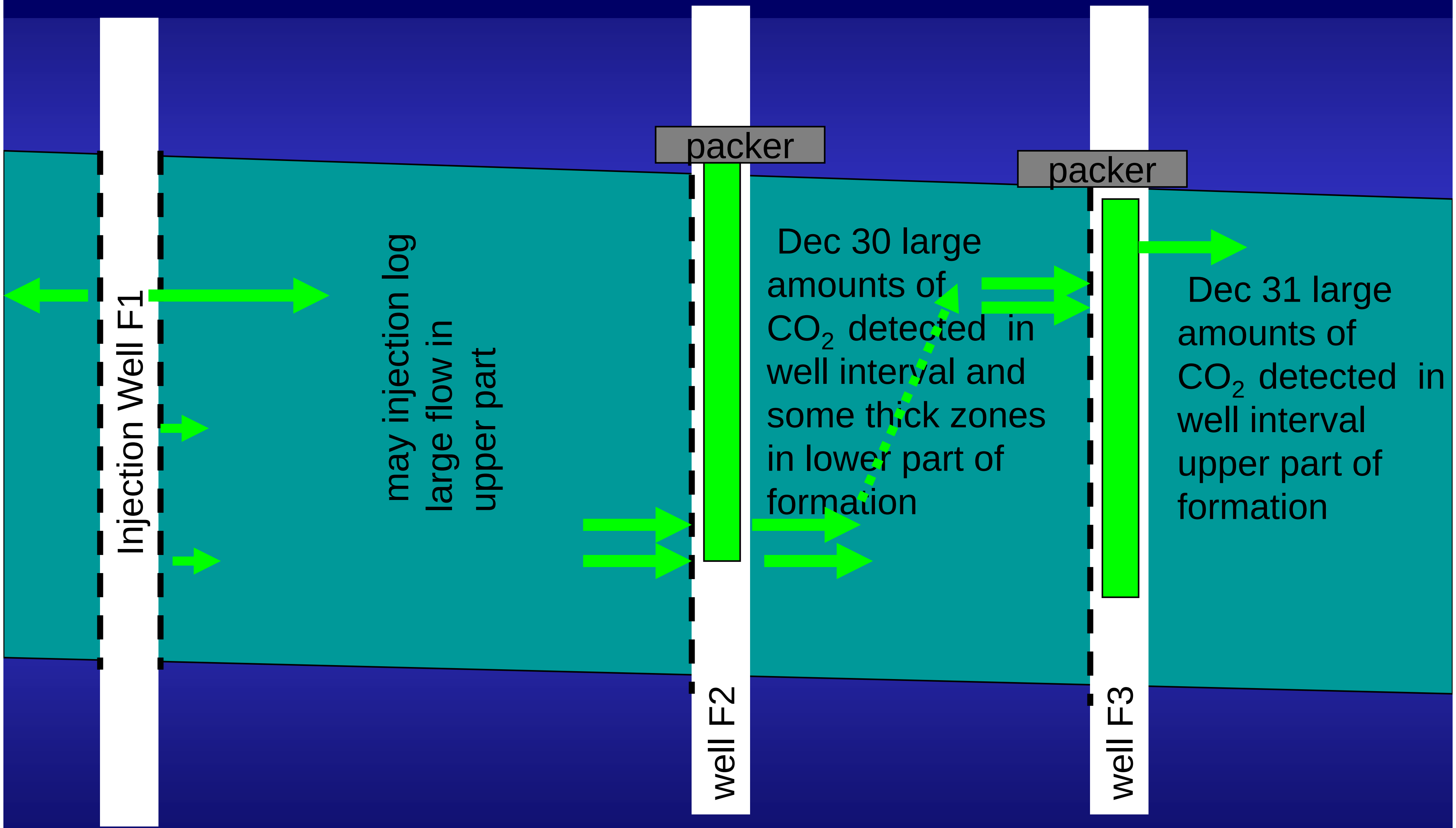
Day 9


packer
packer
Injection Well F1
Dec 1 CO2 flows into formation
Observation well F2
Dec 9
CO_2 detected in top of well interval
Observation well F3

Day 13

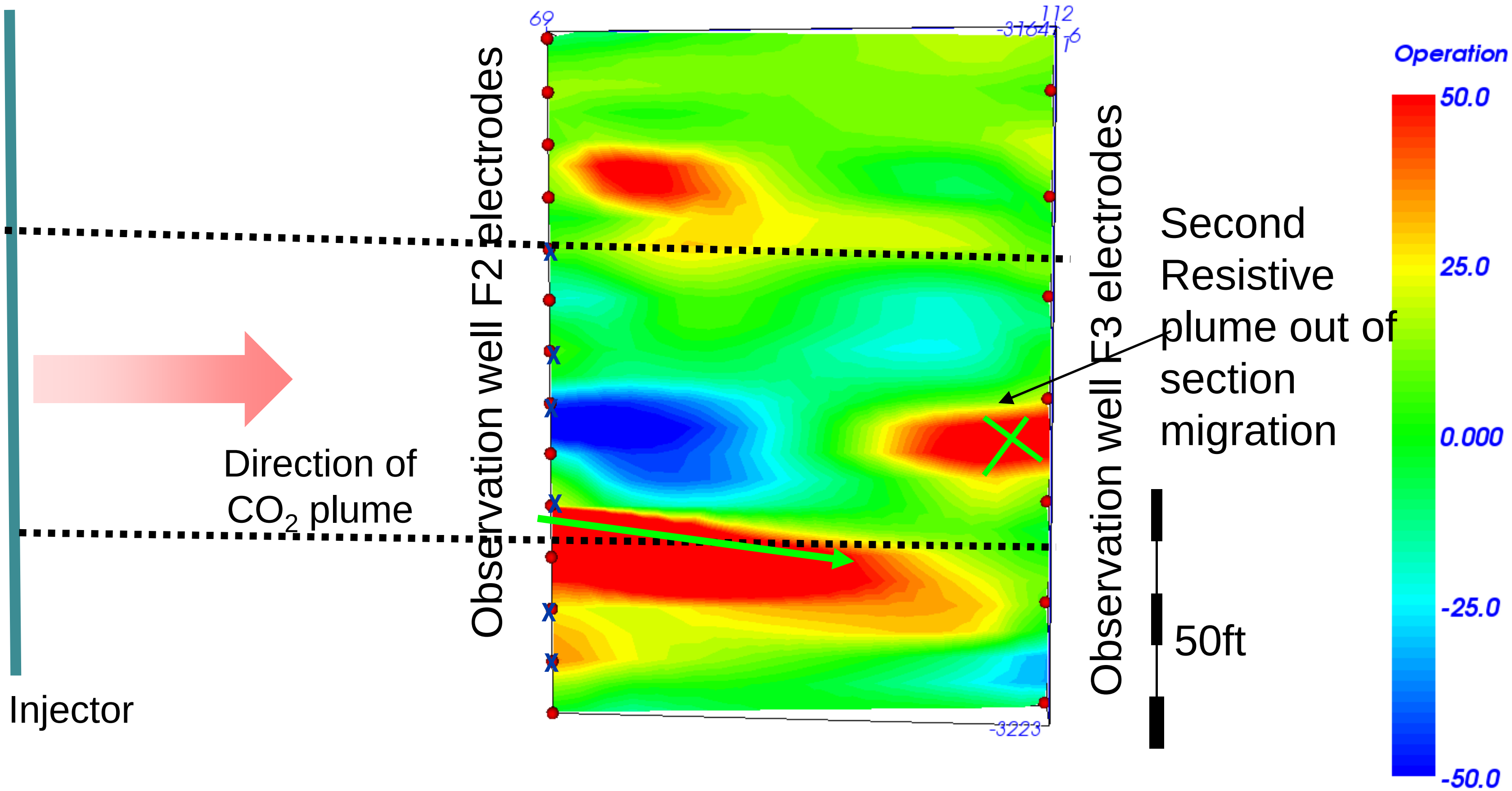

Injection Well F1
Dec 1 CO2 flows into formation
packer
Observation well F2
Dec 13 still minor amounts of CO_2 detected in top of well interval and maybe some thin zones
packer
Observation well F3
Dec 13 CO_2 detected in top of well interval and maybe some thin zones

Day 31



Injection Well F1
may injection log
large flow in
upper part
packer
well F2
Dec 30 large amounts of CO_2 detected in well interval and some thick zones in lower part of formation
packer
well F3
Dec 31 large amounts of CO_2 detected in well interval upper part of formation

Cross Well ERT tells us how flow occurred

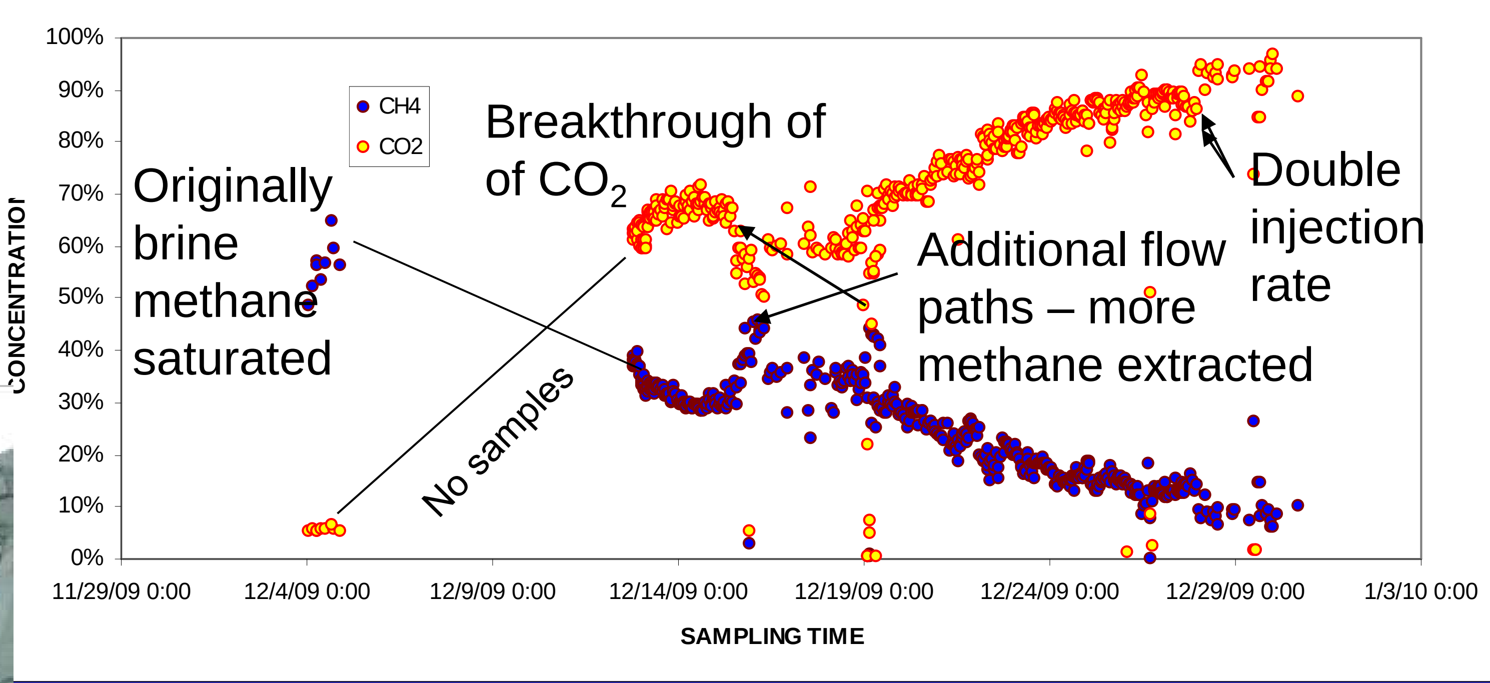


Resistive plume = $CO2$ in reservoir

Conductive plume= workover fluids?

Charles Carrigan, LLNL

High frequency fluid sampling via U-tube yields data on flow processes

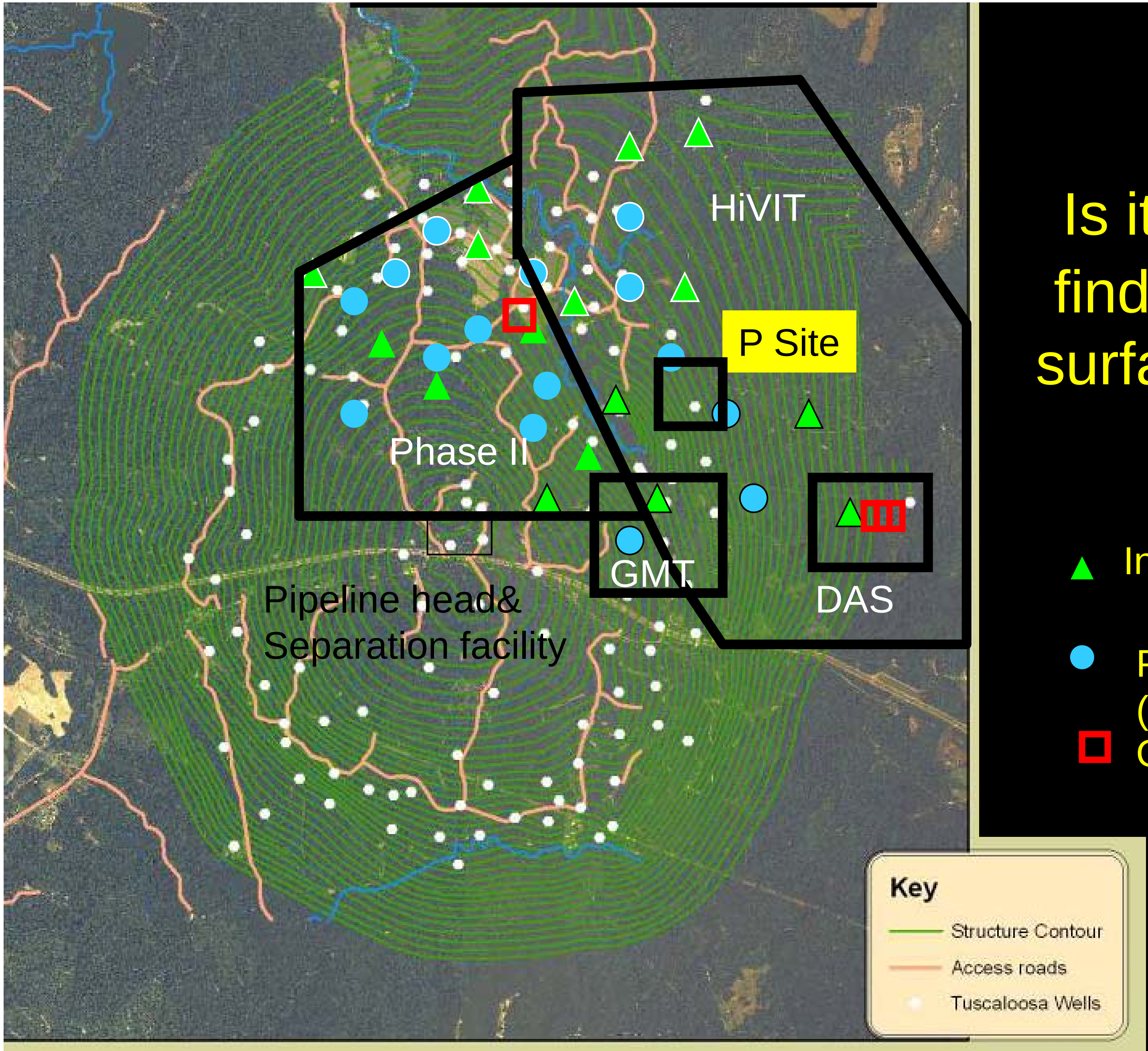


Small diameter sampler with N_2 drive brings fluids quickly to surface with tracers intact

CO_2 dissolution into brine liberates dissolved CH_4

BEG, LBNL, USGS, ORNL, UTDoG,

data compiled by Changbing Yang BEG



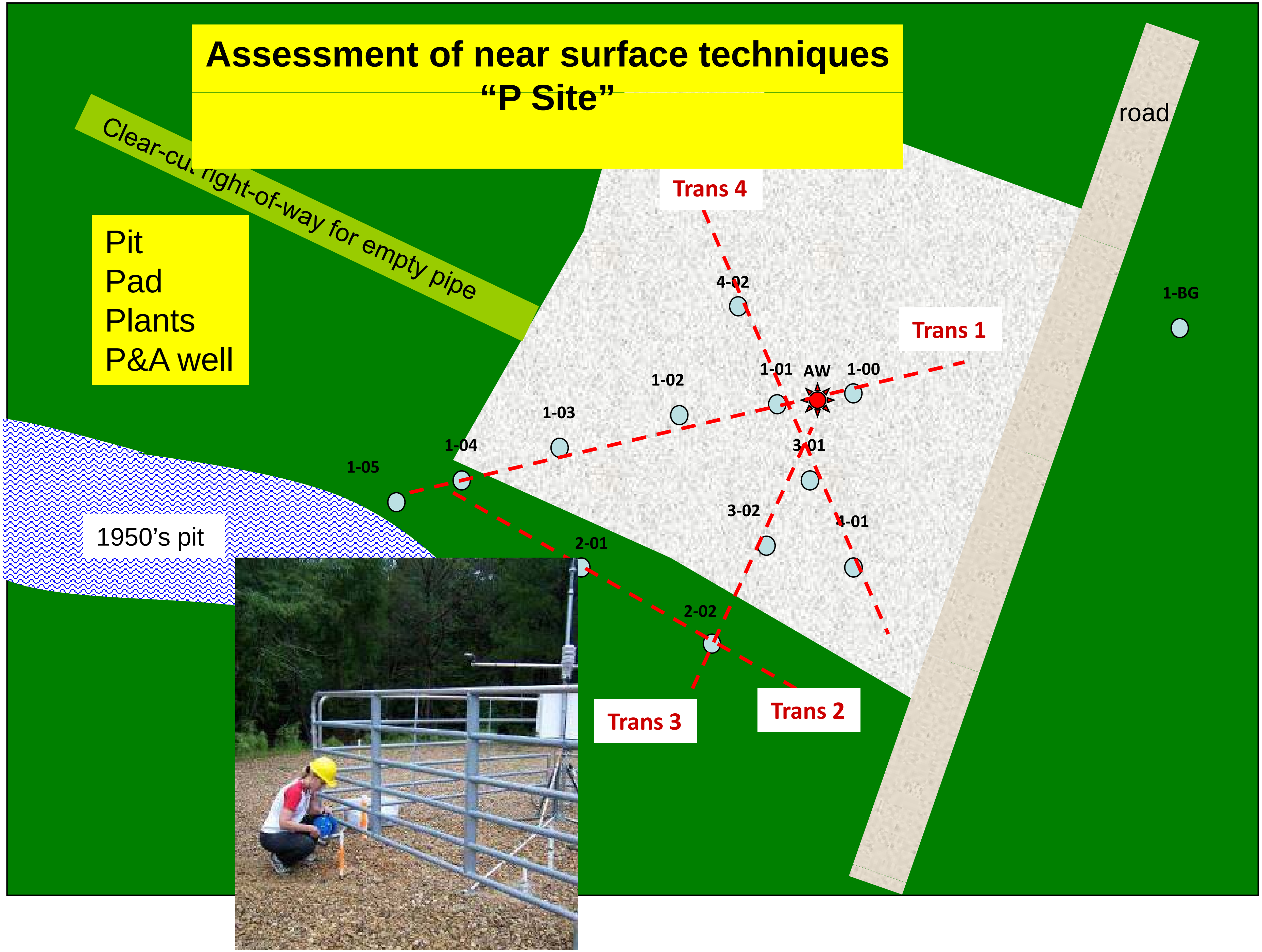
Is it possible to find leakage at surface ? P-Site tests

Injector

Producer (monitoring point)

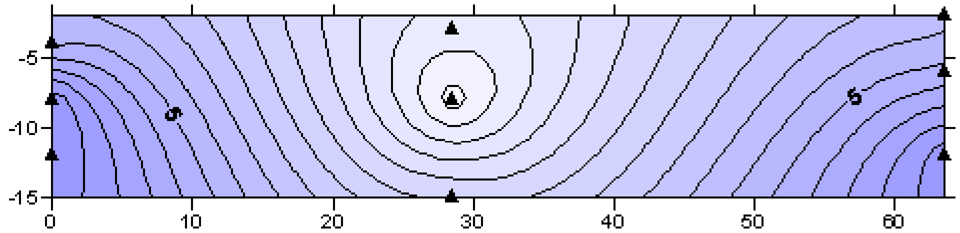
Observation Well

Assessment of near surface techniques "P Site"

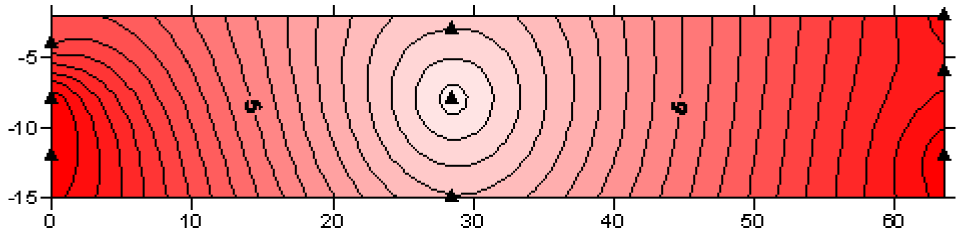


Preliminary Soil Gas data

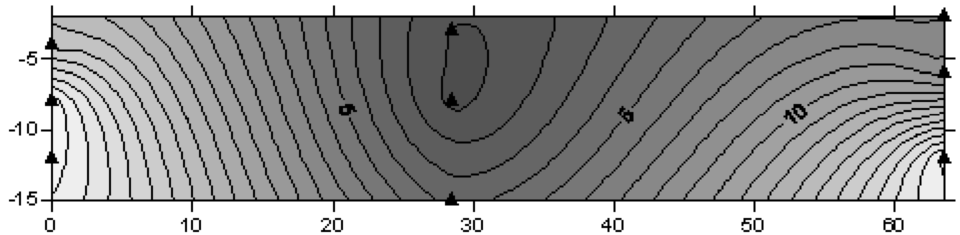
CO_2 (vol %)



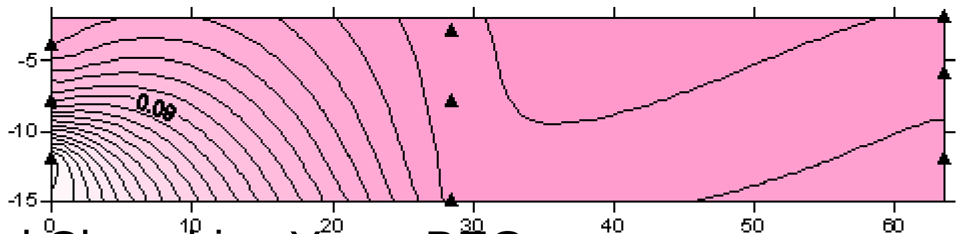
CH_4 (vol %)



O_2 (vol %)



Pressure
(inches H_2O)



Katherine Romanak and Changbing Yang, BEG

Interim Conclusions of Study at Cranfield

- Phase III 1 million ton/year rate achieved Dec 20, 2009, 2 Million tones monitored since July 2008
- Rate to be maintained >15 months
- Monitored with standard and novel approaches
  - History match pressure response
  - No leakage into Above-Zone Monitoring Interval
  - Fluid flow measured/monitored with multiple tools in complex flow field
  - First US use of Electrical Resistance Tomography (ERT) for sequestration
  - Quantification of dissolution
- Export to commercial EOR/sequestration projects

EERC Technology… Putting Research into Practice

Overview of Phase II PCOR Partnership MVA Activities

IEAGHG Monitoring Network Meeting

Natchez, MS

May 6-8, 2010

Steven A. Smith,
Energy & Environmental Research Center

PCO2R Partnership

The Plains CO_2 Reduction (PCOR) Partnership

The PCOR Partnership region includes nine states and four provinces, covering over 1.4 million square miles.

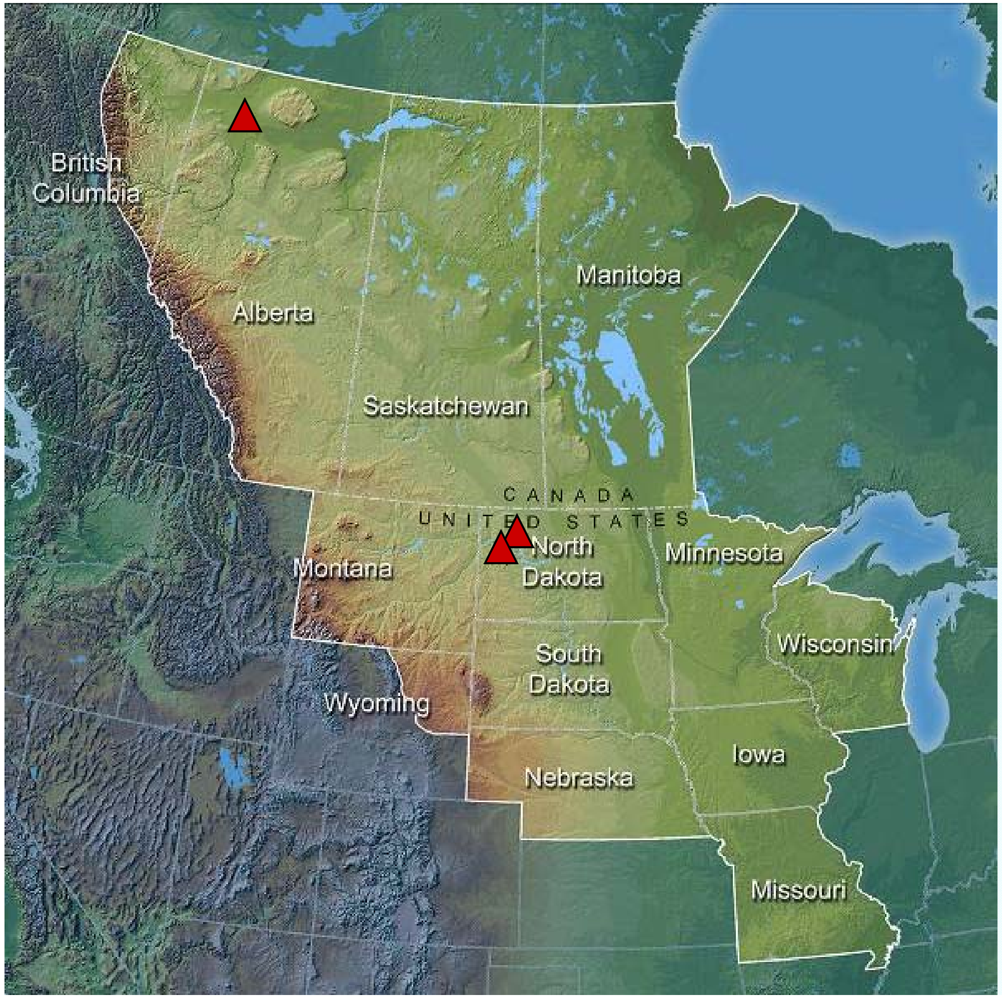
The PCOR Partnership has brought together the key stakeholders to make large-scale geologic CO_2 sequestration a near-term reality.

The PCOR Partnership currently has over 90 partners representing public agencies, utilities, oil and gas companies, engineering firms, associations and nonprofit organizations, and universities.

PCOR Partnership 2003 – Present

10/09

Phase II – Three Geological Field Validation Tests



<u>Zama</u>

Northwestern Alberta

EOR utilizing acid gas (70% CO_2 and 30% H_2S)

Over 40,000 tons injected since December, 2006

Over 25,000 incremental bbls of oil produced

Robust characterization and MVA activities

<u>Lignite</u>

Northwestern North Dakota

Evaluation of lignite coal seam using CO_2 for methane potential

MVA activities included geophysical logging and seismic surveys

<u>Northwest McGregor</u>

PCOR Partnership

NETL

EERC Energy & Environmental Research Center

UND University of North Dakota

Ranking Monitoring Tools

They will be assessed and ranked based on their ability to effectively monitor the site-specific risks.

Leading to a monitoring plan tailored specifically for the CCS project being considered.

The toolbox of monitoring techniques is large.

Not all are appropriate for every CCS project.

Lignite Field Validation Test
Burke County, North Dakota

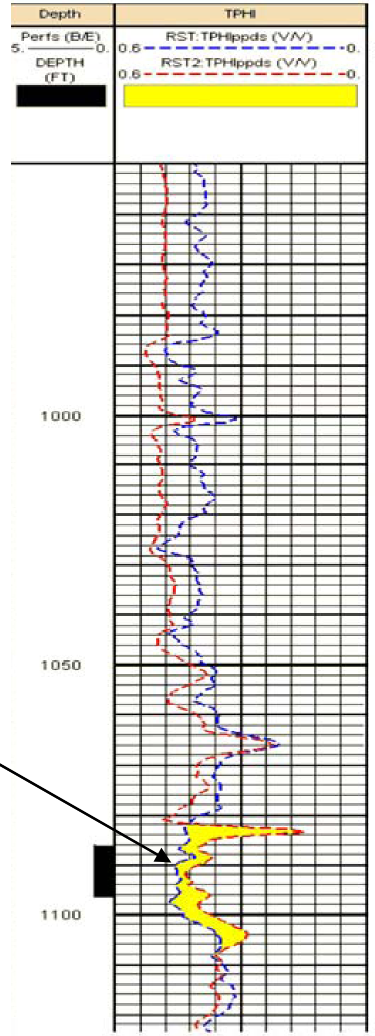
MVA

- Wells outfitted with downhole and surface data acquisition telemetry.
- Reservoir Saturation Tool (RST) used to identify free gas.
- Microseismic – potentially locate CO_2 during injection.
- Cross-well seismic – potentially locate CO_2 after injection.
- Fluorocarbon gas tracer – used to positively identify injected gas.
- Gas and fluid sampling.

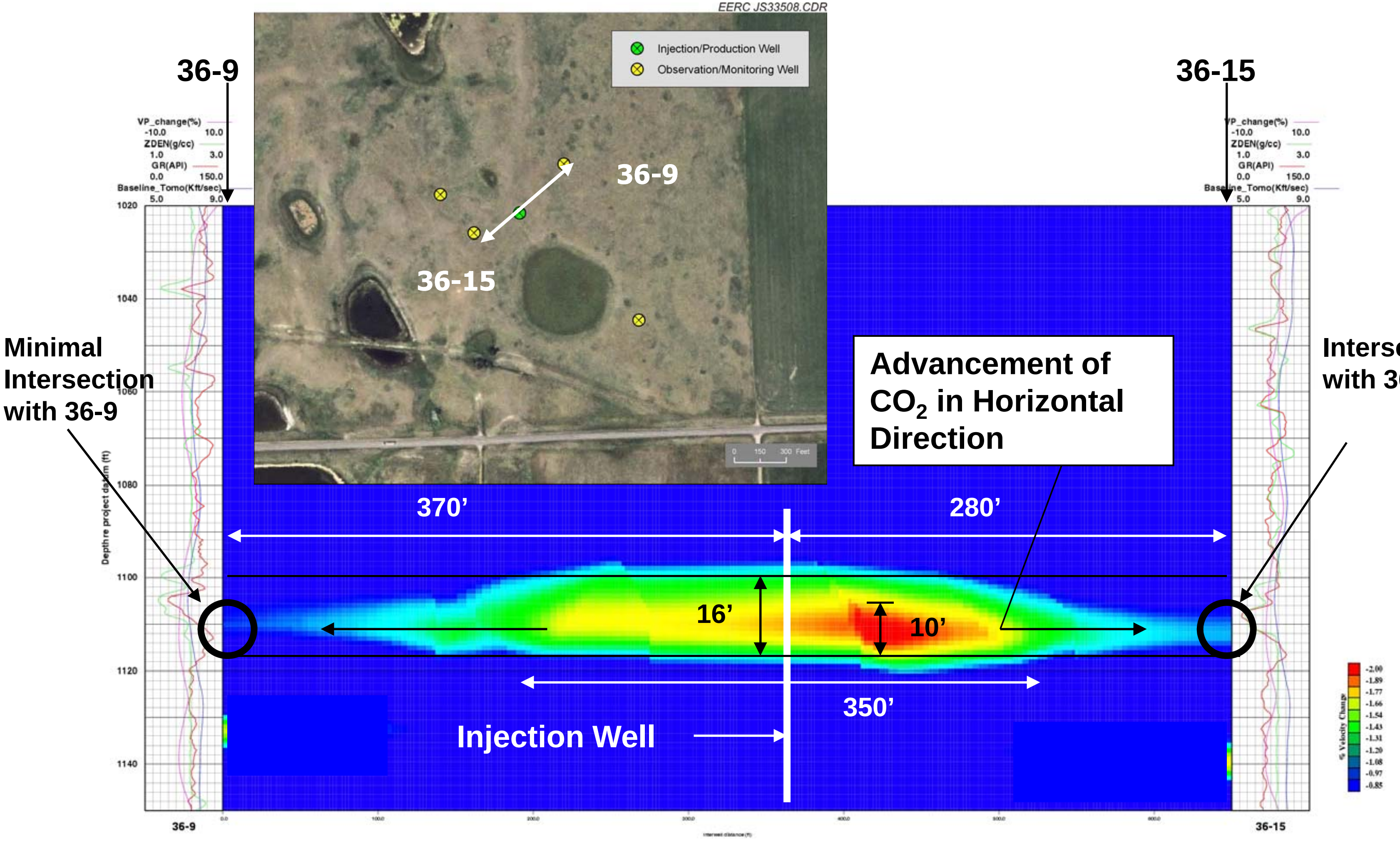
RST Results

- RST completed in all five wells.
- CO_2 identified in the injection well within the coal zone.
- CO_2 identified in the closest monitoring well.

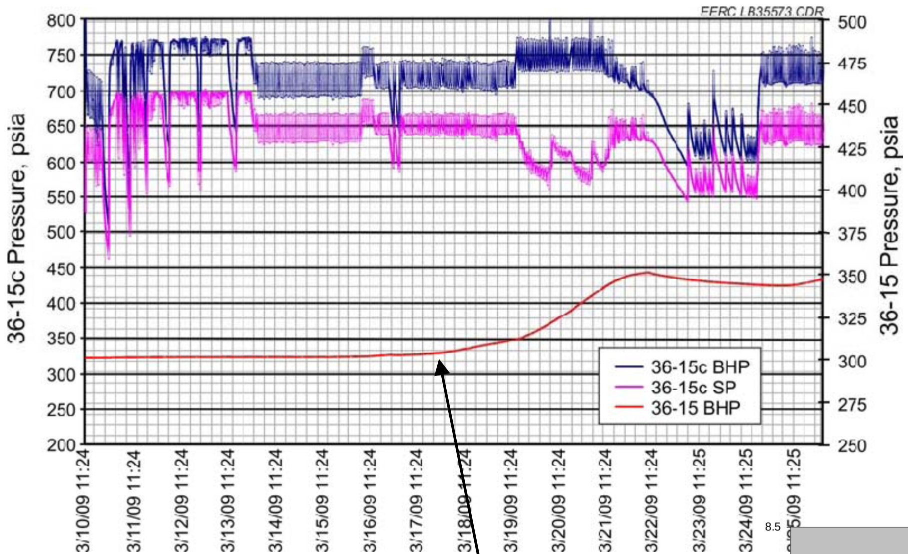
Identification of Free Gas



Seismic Results



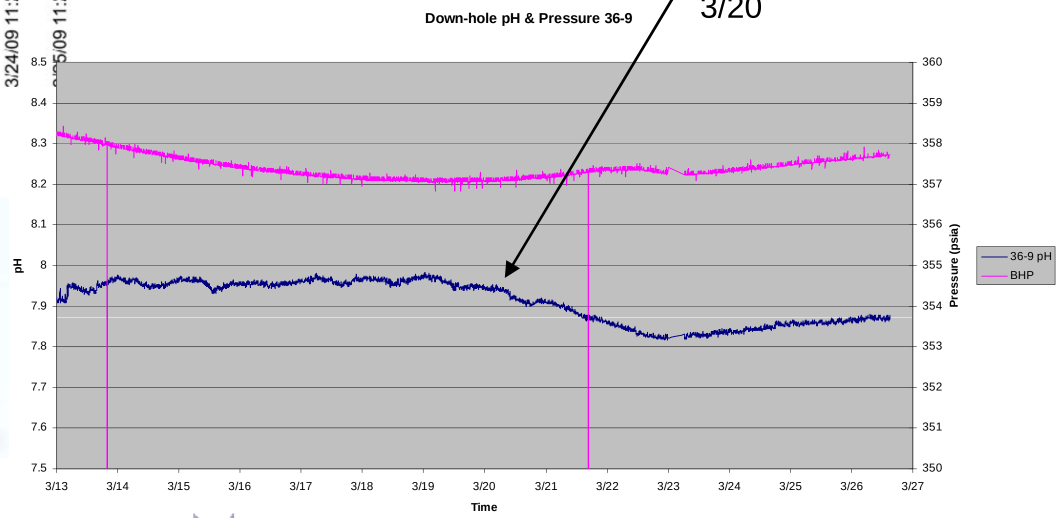
Verification Measurement Results



- Downhole sensing included temperature, pressure, conductivity, and pH.
- pH decrease is a good indicator of CO_2.
- pH deflection appears to occur at the same time of pressure rise

36-9 beginning of pH deflection and pressure rise on 3/20

36-15 beginning of pressure rise on 3/17



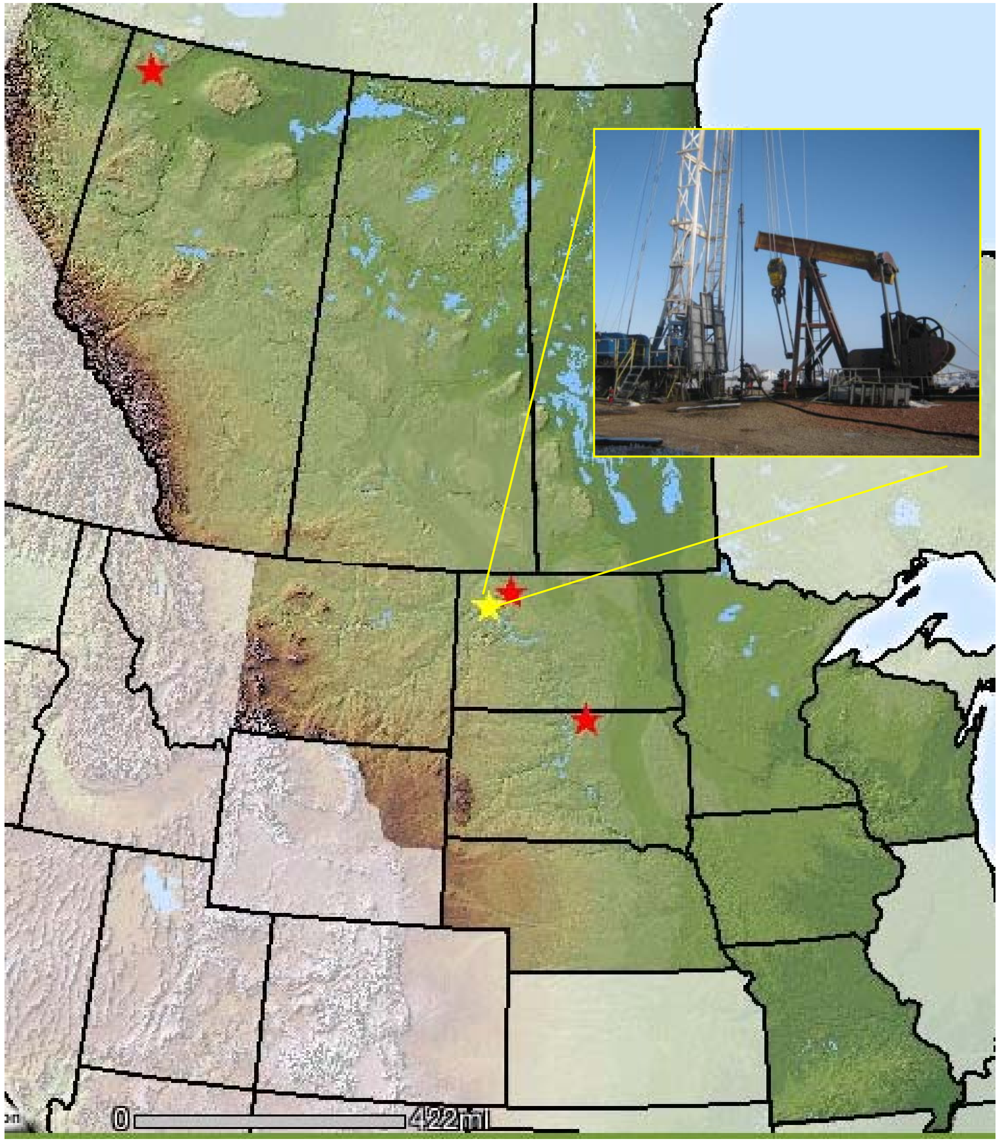
PCOR Partnership

NETL

EERC Energy & Environmental Research Center

University of North Dakota

Williston Basin CO_2 Huff 'n' Puff Test
Williams County, North Dakota



Technical goals:

- Evaluate the feasibility of simultaneous CO_2 storage and enhanced oil recovery (EOR) in a deep (>8000 ft) carbonate oil reservoir.
- Determine the effectiveness of the CO_2 huff 'n' puff (HnP) approach to stimulate oil recovery in the Williston Basin.
- Test the ability of two geophysical tools to monitor CO_2 in the reservoir under deep reservoir conditions.

Key Elements of Northwest McGregor HnP

1. Preinjection site characterization.
2. Inject 440 tons of CO_2 over the course of 36 hours in late June 2009 into the Mission Canyon reservoir using a single well.
3. Shut in the well.
   – Allows CO_2 to "soak" into the oil.
   – Soak period lasted approximately 2 weeks.
   – Conduct second round of logging.
4. Brought the well back onto production in mid-July 2009.
5. Rate of oil production was >3x higher than preinjection rate and slowly decreased over time.
6. Monitored oil production and fluid analysis over the production period for 3 months.
7. Conducted final round of logging in mid-October to determine effects and fate of injected CO_2.

PCO2R Partnership

EERC Energy & Environmental Research Center

UND University of North Dakota

Reservoir Characteristics

Formation: Mission Canyon

Lithology: primarily limestone

Average pay thickness: 14 ft

Porosity: 15%

Matrix permeability: 0.35 md

Secondary permeability: fractures

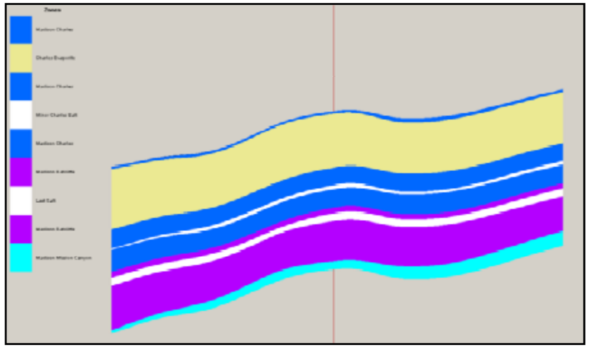
Depth (from surface) to pay: 8050 ft

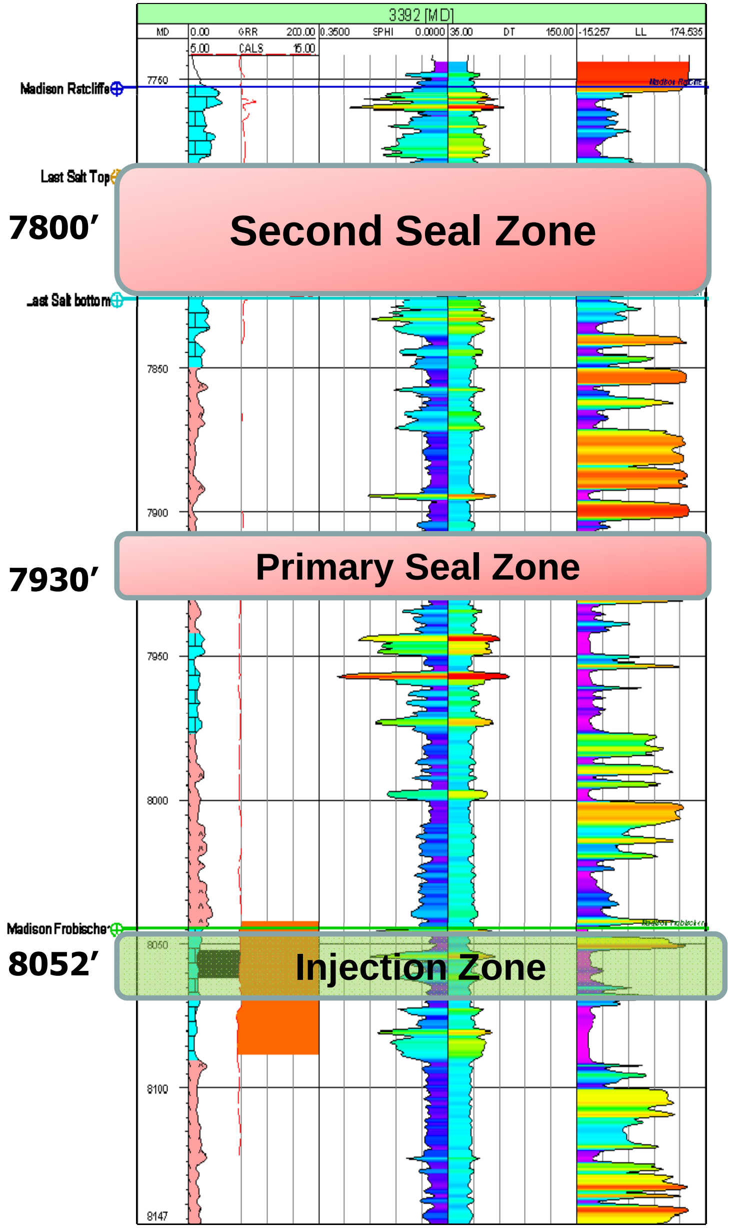
Average temperature: 216°F

Pre HnP pressure: 2700 psig

Oil gravity (API): 41.7

Cumulative oil production: 2.2 Mbo since 1964





Key Elements of Monitoring, Verification, and Accounting (MVA)

- Site characterization
  - Establish baseline geologic, geochemical, and geomechanical conditions.
- Estimate CO_2 fate through mass balance
  - Surface flows, samples and analyses
- Effects on formation properties
  - Pressure buildup test before and after (formation pressure, permeability, skin factor)
- **Movement of CO_2**
  - **Specialized geophysical tools before and after injection**
- Out-of-zone migration
  - Observation and shallow water well samples, perfluorocarbon tracer

Specialized Geophysical Tools

- Reservoir Saturation Tool
- Vertical Seismic Profiling

PCOR Partnership

EERC Energy & Environmental Research Center

UND University of North Dakota

RST

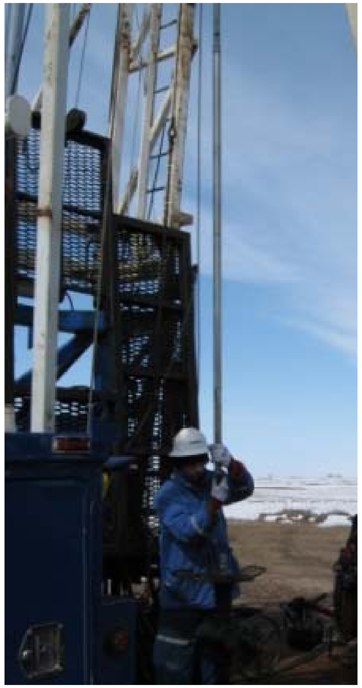
This Schlumberger tool provides data on near-wellbore gas/fluid saturation.

Allows for cased-hole evaluation of reservoir fluids.

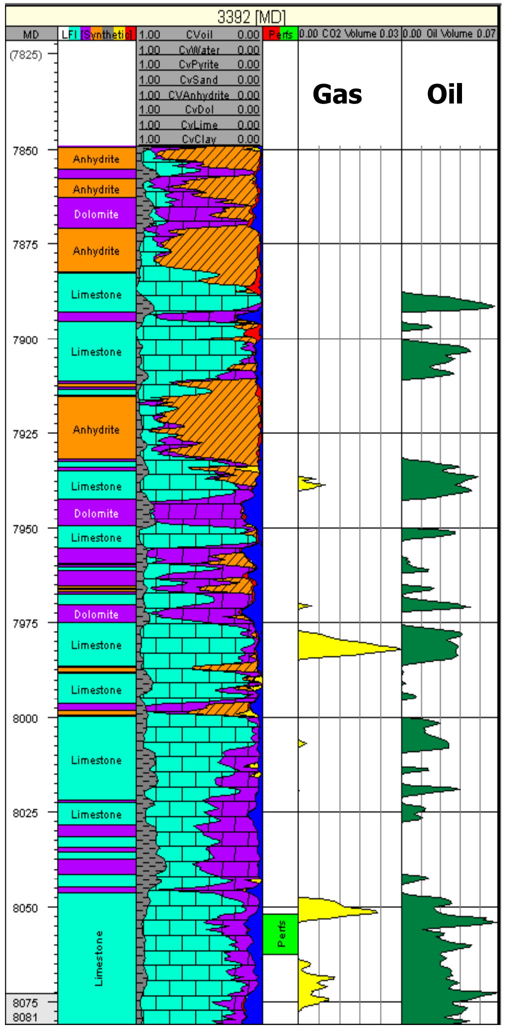
Can be run with no need to pull tubing or kill the well.

The tool uses pulsed neutron techniques to determine:

- Reservoir saturation (oil, gas, water).
- Lithology.
- Porosity.
- Borehole fluid profiles.



Inserting the RST sonde.



Northwest McGregor RST Results

Comparison of Times 1, 2, and 3.

T 1 = Preinjection baseline

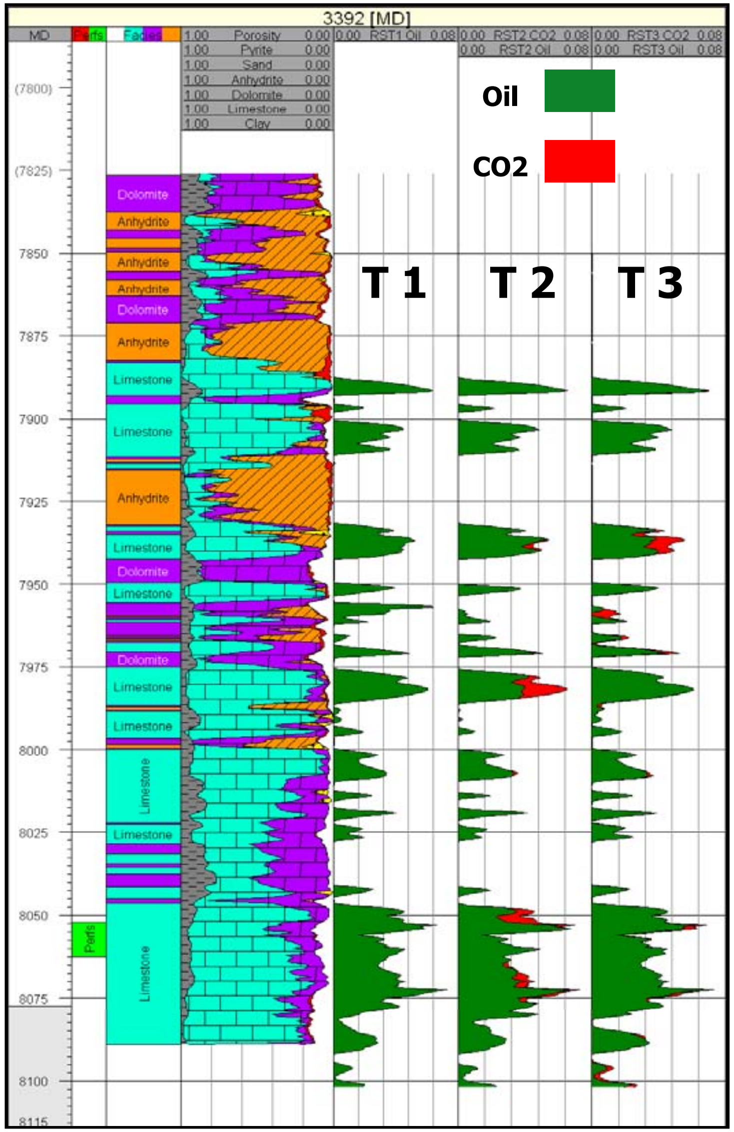
- Identified multiple oil banks.
- No gas.
- Lithology matched historical log data.

T 2 = 5 days after injection

- During the “soak period.”
- CO_2 identified at multiple intervals above and below perfs.
- Rapid vertical migration likely due to fractures.

T 3 = 115 days after injection

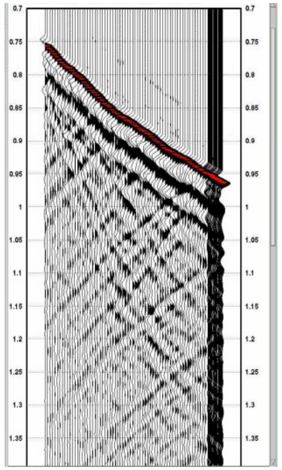
- Largest CO_2 concentration is beneath the anhydrite seal.
- Other occurrences likely trapped in fractures.

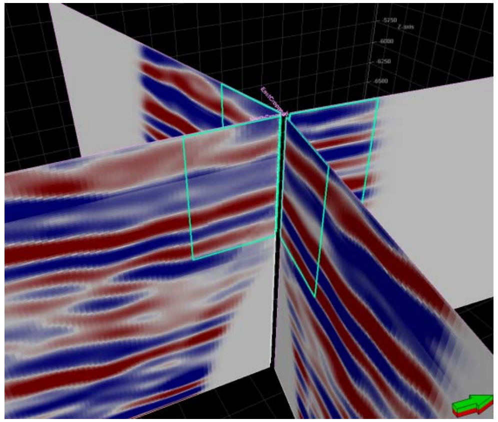


VSP

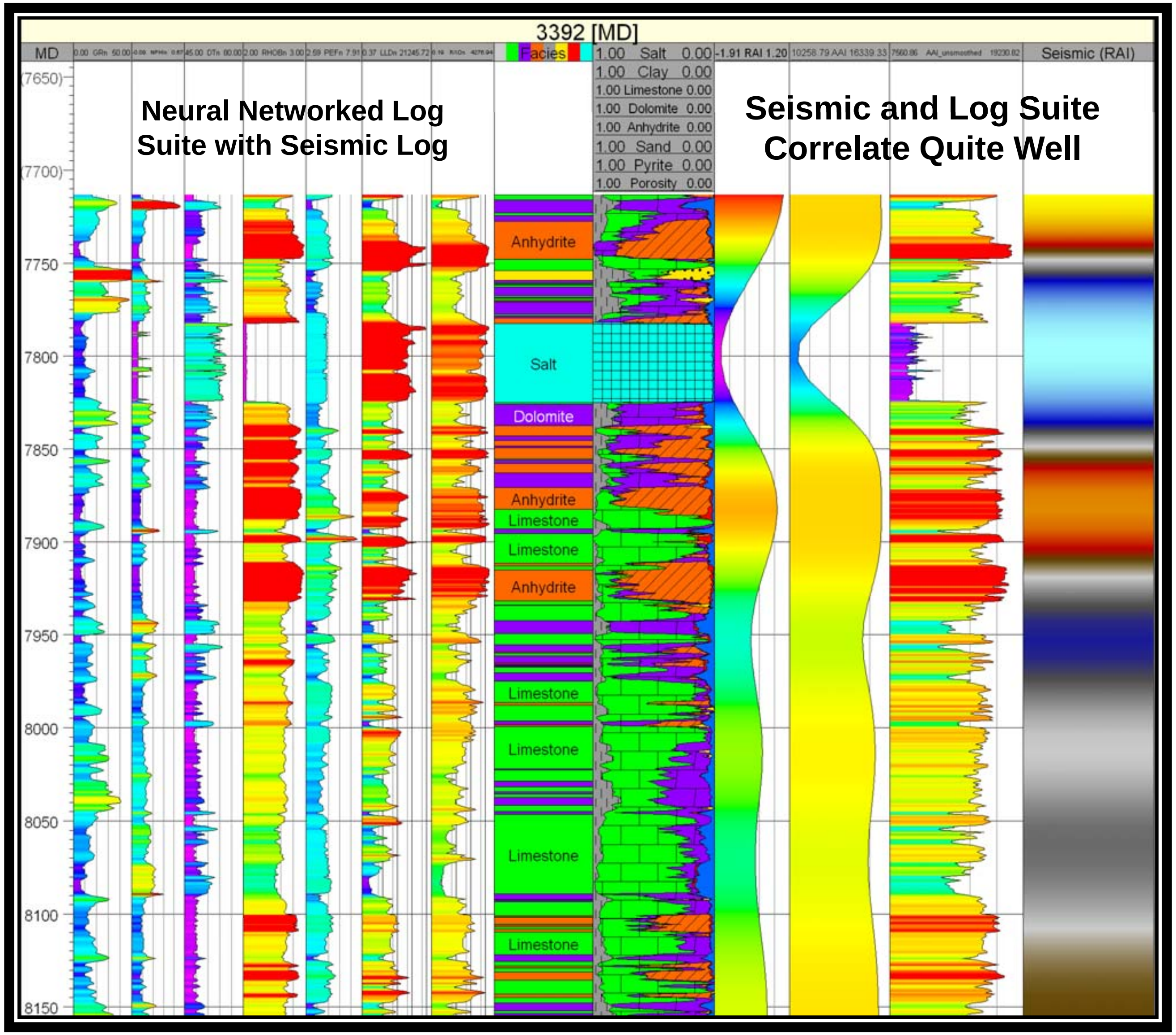
This tool provides data on reservoir properties away from the wellbore.

- Couples downhole wireline acoustic monitoring tool with surface seismic sources.
- Creates 2-D seismic maps of reservoir and seals.
- Used multiple lines to provide third-dimension view.



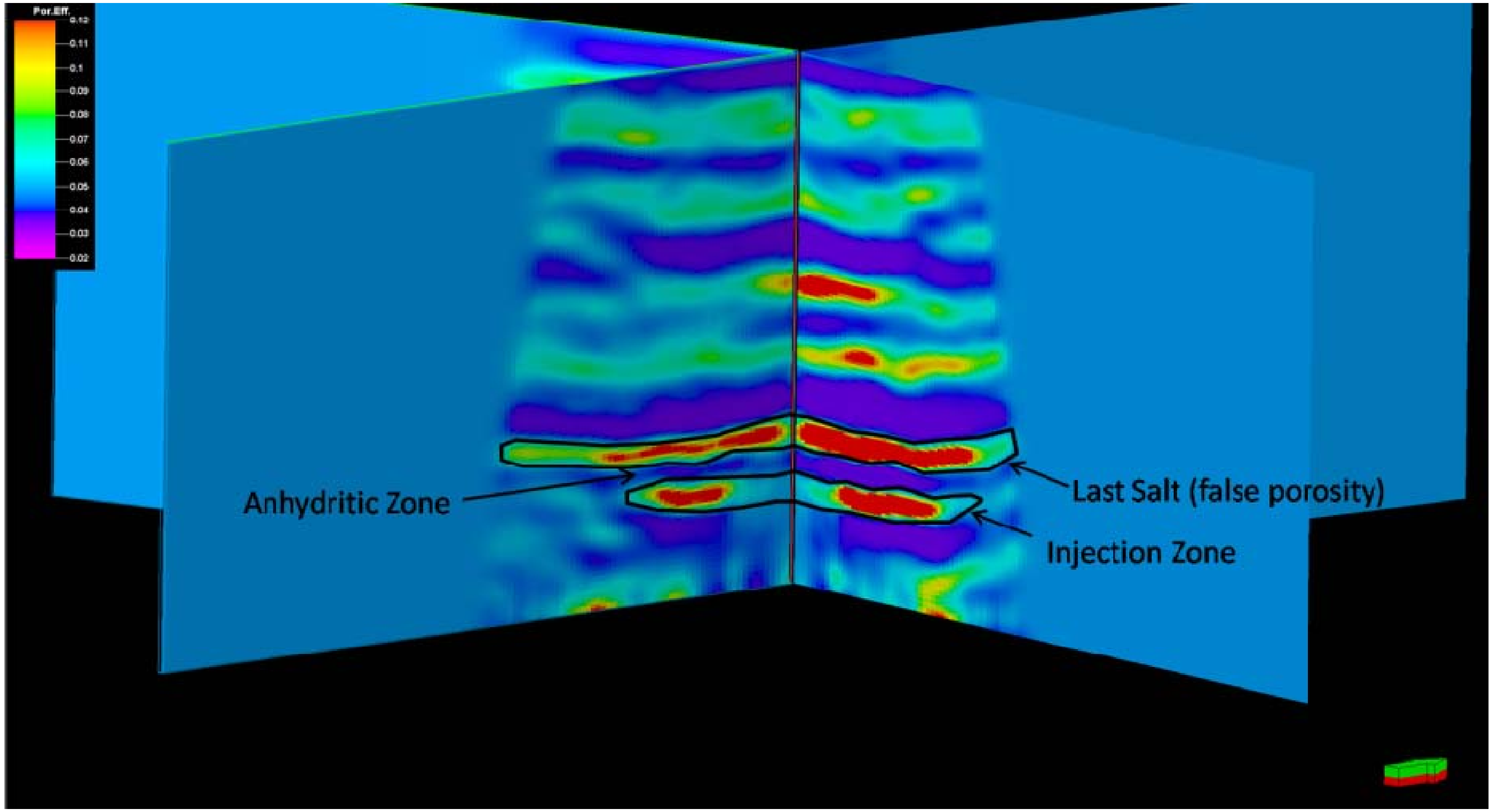


Correlation of VSP to Other Logs



Northwest McGregor Key VSP Results

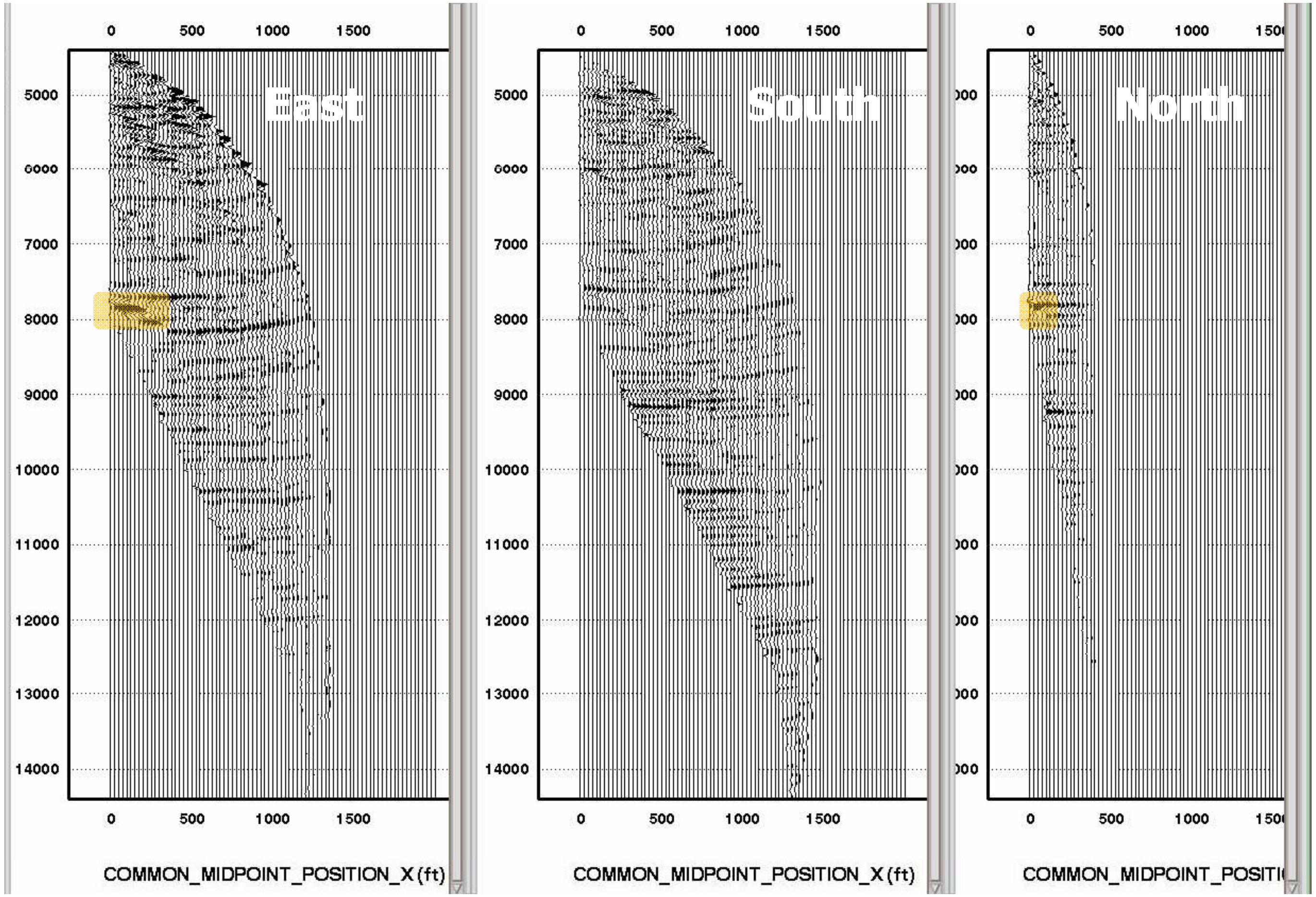
VSP data were invaluable in the creation of the petrophysical model of the Northwest McGregor sink–seal system.

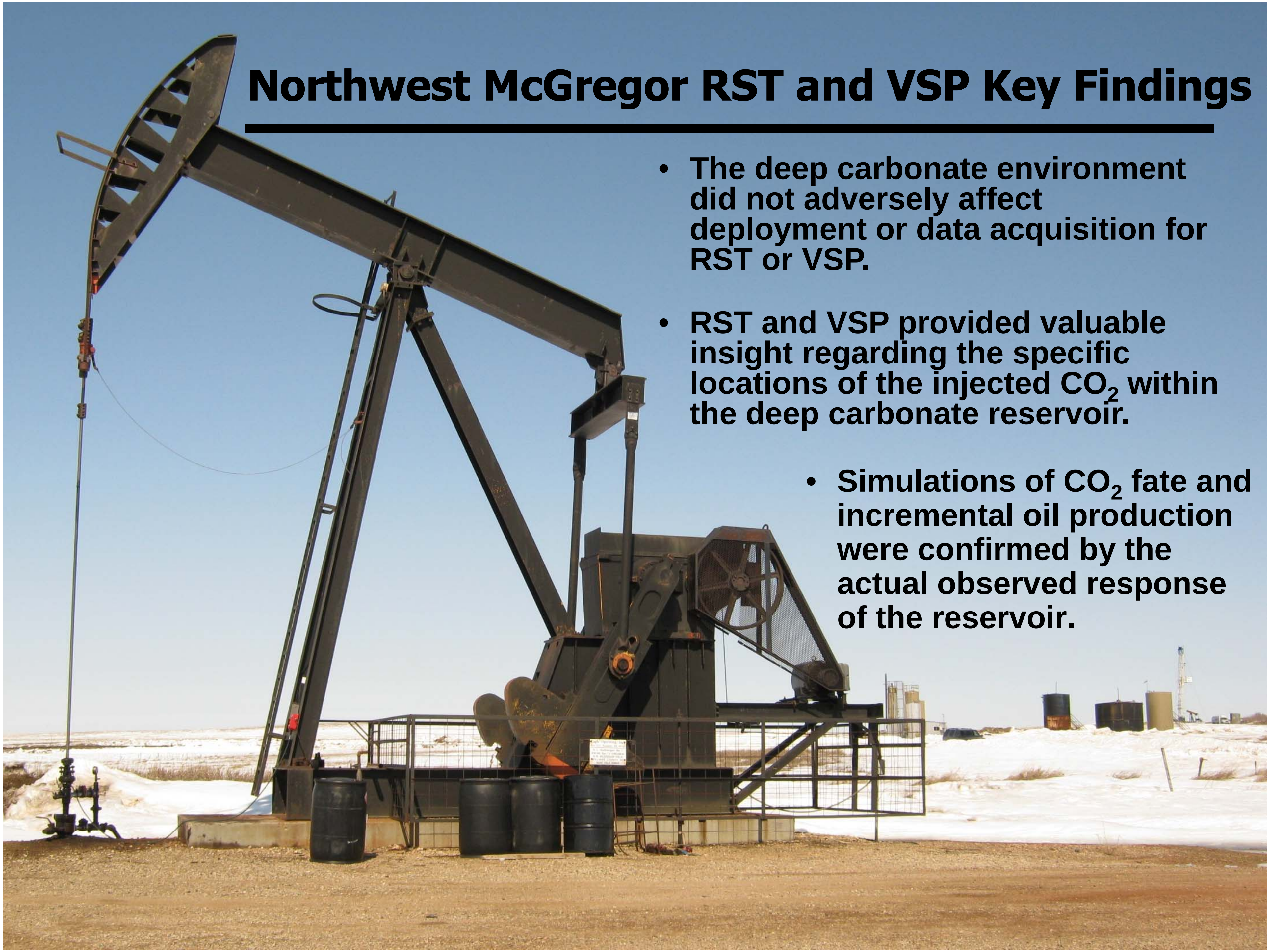


Seismic Inverted to Effective Porosity

Northwest McGregor Key VSP Results

Difference CDP maps: Interpreted as possibly being CO_2 plume.





Northwest McGregor RST and VSP Key Findings

- The deep carbonate environment did not adversely affect deployment or data acquisition for RST or VSP.
- RST and VSP provided valuable insight regarding the specific locations of the injected CO_2 within the deep carbonate reservoir.
- Simulations of CO_2 fate and incremental oil production were confirmed by the actual observed response of the reservoir.

Contact Information

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, North Dakota 58202-9018

www.undeerc.org
Telephone No. (701) 777-5000
Fax No. (701) 777-5181

Steven Smith
ssmith@undeerc.org

Subsurface Monitoring Planning in DOE's WESTCARB Partnership and National Risk Assessment Partnership (NRAP)

Tom Daley

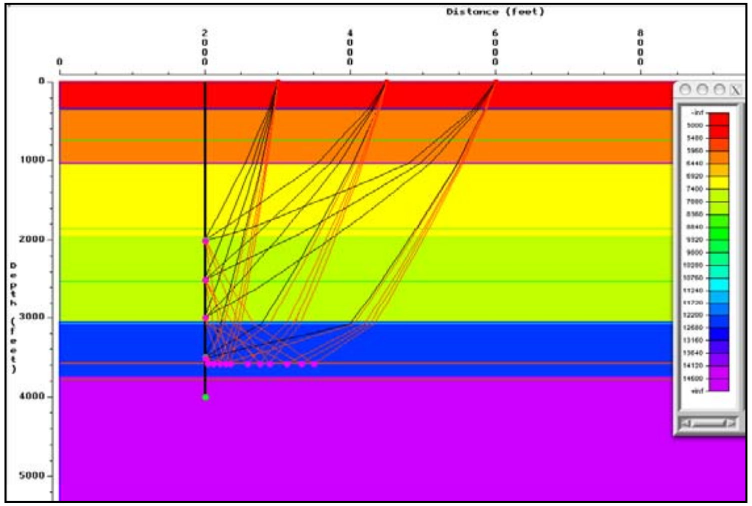
Lawrence Berkeley National Laboratory

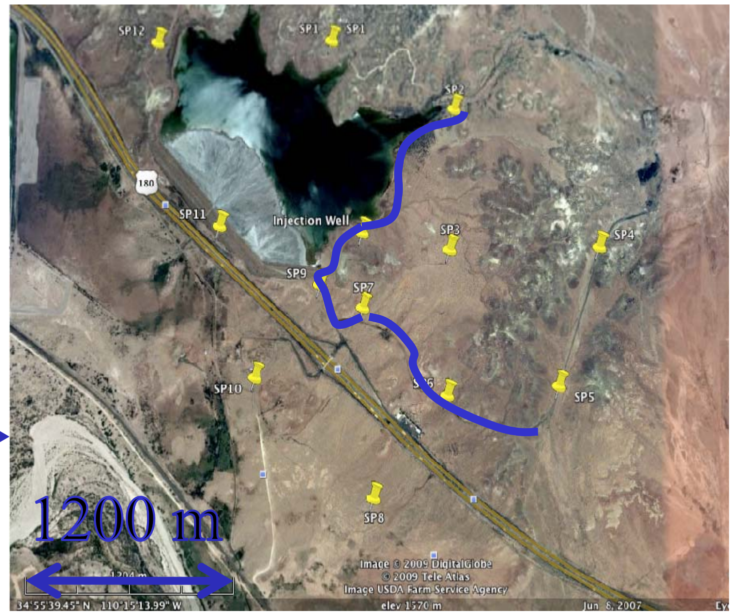
Outline

- WESTCARB Field Test Monitoring Plans
  - Arizona Test (single well: not completed)
  - California (planning mostly done)
    - CO2 Monitoring
    - Natural/Induced Seismicity Monitoring
- NRAP
  - Background
  - Mission
  - Monitoring Group
  - Current Plans

WESTCARB Arizona Test

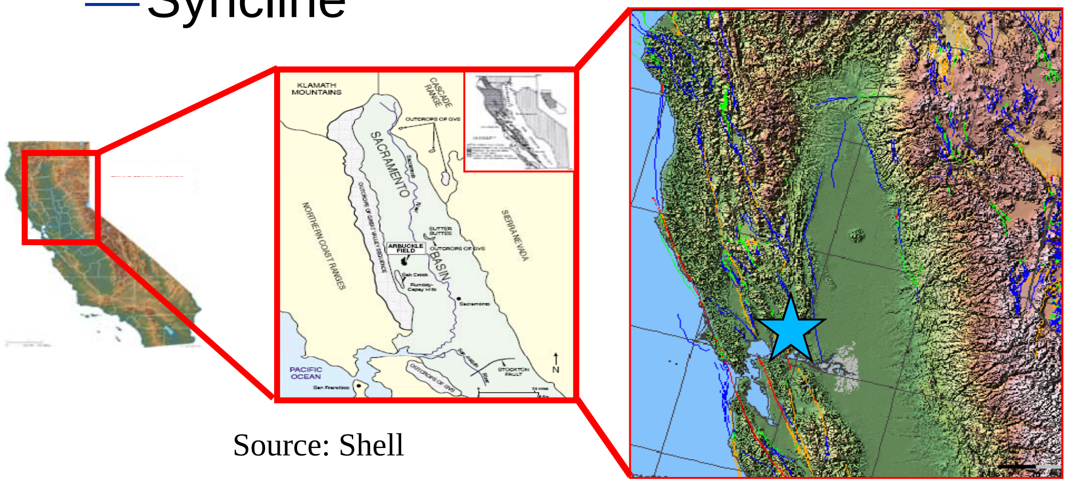
- **Single Well 'Exploratory'**
- **Subsurface Monitoring Plan:**
  - **Geochemical**
    - **U-Tube Sampling**
    - **'Huff-n-Puff' with tracers**
  - **Well Logging**
    - **Time-Lapse RST**
  - **Seismic**
    - **Time-Lapse VSP**
      - **Simple Raytracing**
      - **Simple Flow Model**
      - **Multi-offset, multi-azimuth**



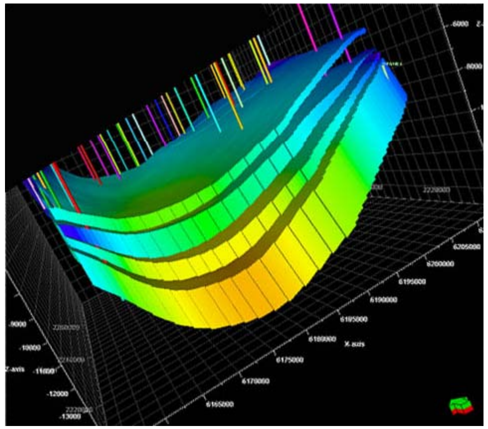


WESTCARB California Test

- **Location: Western Sacramento Valley**
- **Industry Partner: Shell**
  - Shell has worked on regional and site-specific geologic characterization, planning for well design and field logistics/operations
- Notable Characteristics
  - Deep (~3.3 km); ~6000 ton Injection
  - Saline Aquifer
  - Syncline



Source: Shell



Model showing general thickening along the axis of the syncline

Source: Shell

California Subsurface Monitoring Plan

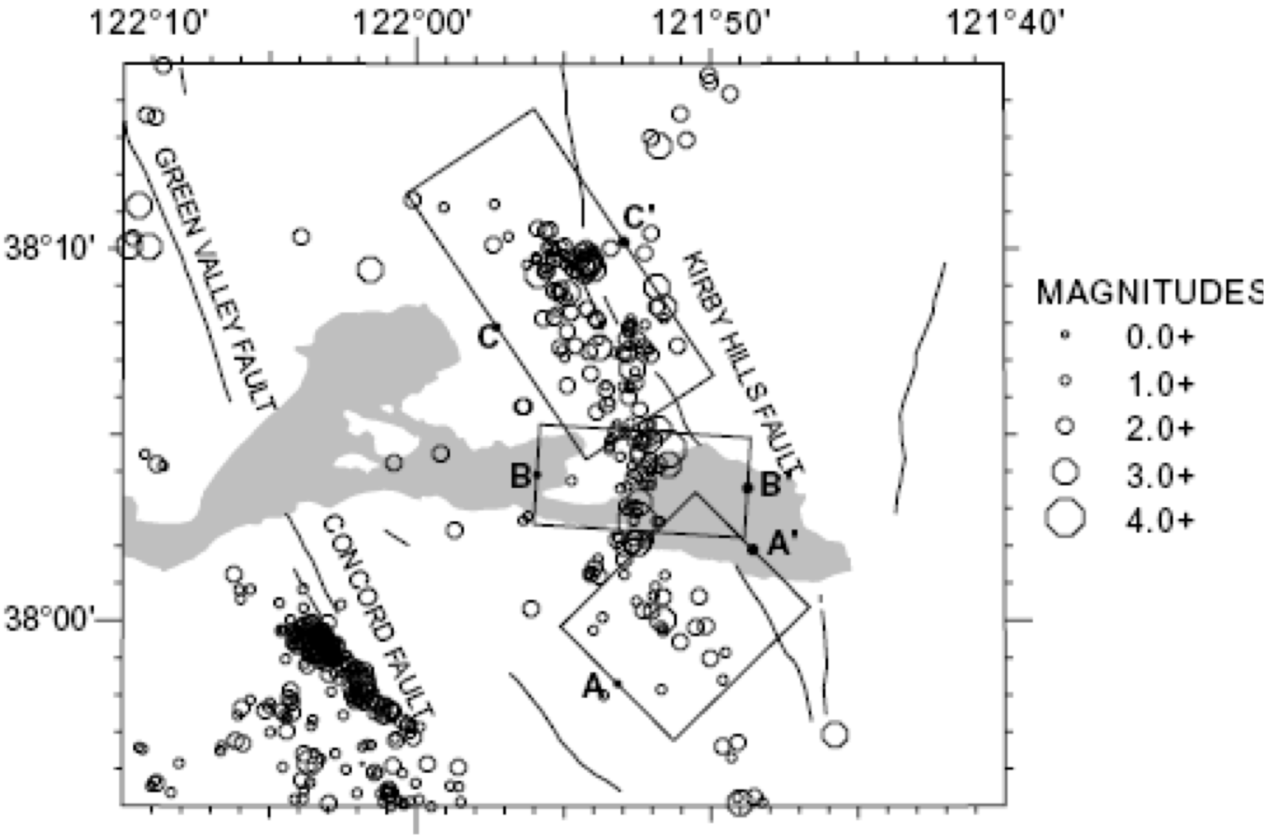
- Two Well Test
  — Injector and Monitor Wells, ~ 50 m spacing at ~3.3 km depth
- Geochemical Monitoring
  - U-Tube in Monitoring Well
    — Continuous Plume sampling with tracers
- Well Logging
  - Time-Lapse RST, Sonic
- Seismic
  - Time-Lapse VSP
    — Multi-azimuth, multi-offset
  - Time-Lapse Crosswell
  - Possible 4D surface
- Microseismic

Induced Seismicity Protocol

1. **Review existing regulations and establish dialogue with regional authorities.**
2. **Assess natural seismic hazard potential**
3. **Assess induced seismicity potential**
4. **Educate stakeholders.**
5. **Decide whether to establish a microseismic monitoring network.**
6. **Interact with stakeholders *(Current WESTCARB Activity)***
7. **Implement procedures for response to events.**

Adapted from IEA Enhanced Geothermal Program (Majer, et al, 2008)
Submitted to GHGT-10 (Myer and Daley)

Local Natural Seismicity (Last 30 Years)



Kirby Hills Fault zone and associated seismicity from 1974-2001, recorded by the Northern California Seismic Network and relocated by Parsons et al. (2002).

National Risk Assessment Partnership

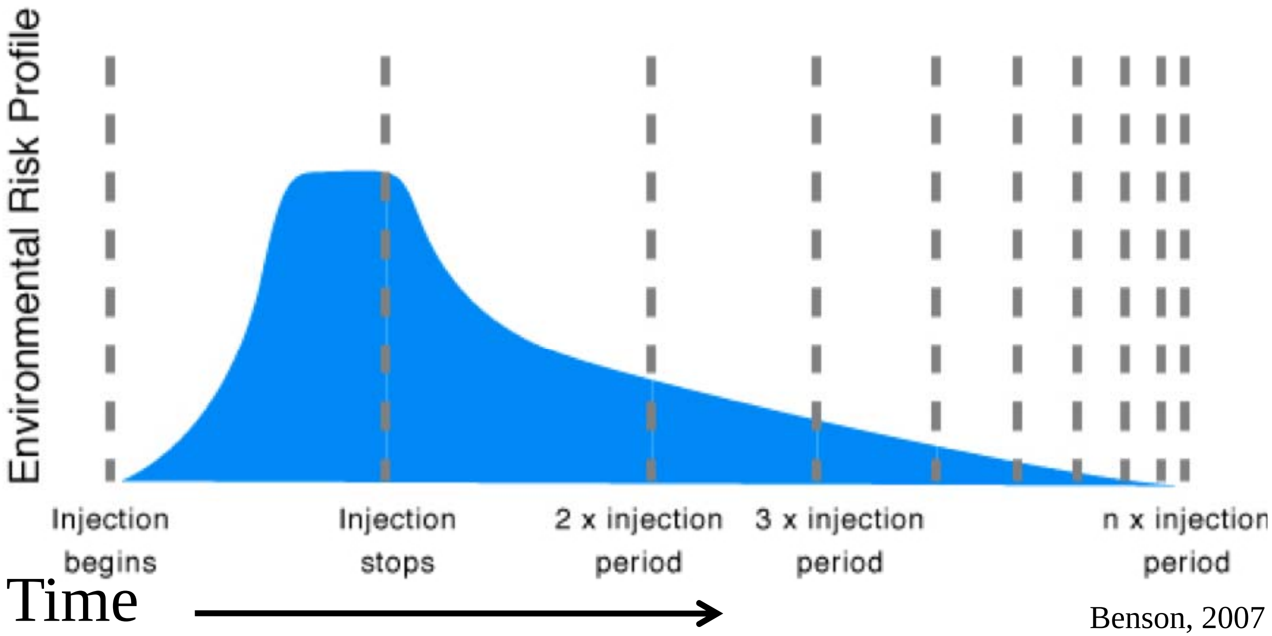
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Energy Technology Laboratory
- Pacific Northwest National Laboratory

NRAP's MISSION

To provide the scientific underpinning for risk assessment with respect to the long-term storage of CO_2, including assessment of residual risk associated with a site post-closure.

Risk profile is assumed to:

1.increase with injection pressure
2.peak with completion of injection
3.decay over time



Benson, 2007

NRAP Background

- Want a quantitative methodology for predicting a site's long-term performance
- Calculation of risk profiles is a common approach to large-scale projects, serving as an important tool for:
  - comparison of potential site options;
  - quantification of long-term project costs and potential liabilities;
  - ensuring that sites are characterized and operated in a manner that minimizes key uncertainties and maximizes performance.
- Need to address gaps in knowledge

NRAP Initial Focus Areas

- **Monitoring for risk assessment**
- **Wellbore Integrity**
- **Pathways Through Natural Systems**
- **Groundwater Impacts**
- **Systems Modeling**

Monitoring White Paper
To be released soon

Authors in Alphabetical Order:

John Beyer[1], Christopher Bradley[2], Grant Bromhal[3], Tom Daley[1], Julianna Fessenden[2], William Harbert[3], Lianjie Huang[2], Robin Newmark[4], Rajesh Pawar[2], Abelardo Ramirez[4], Charlotte Sullivan[5]

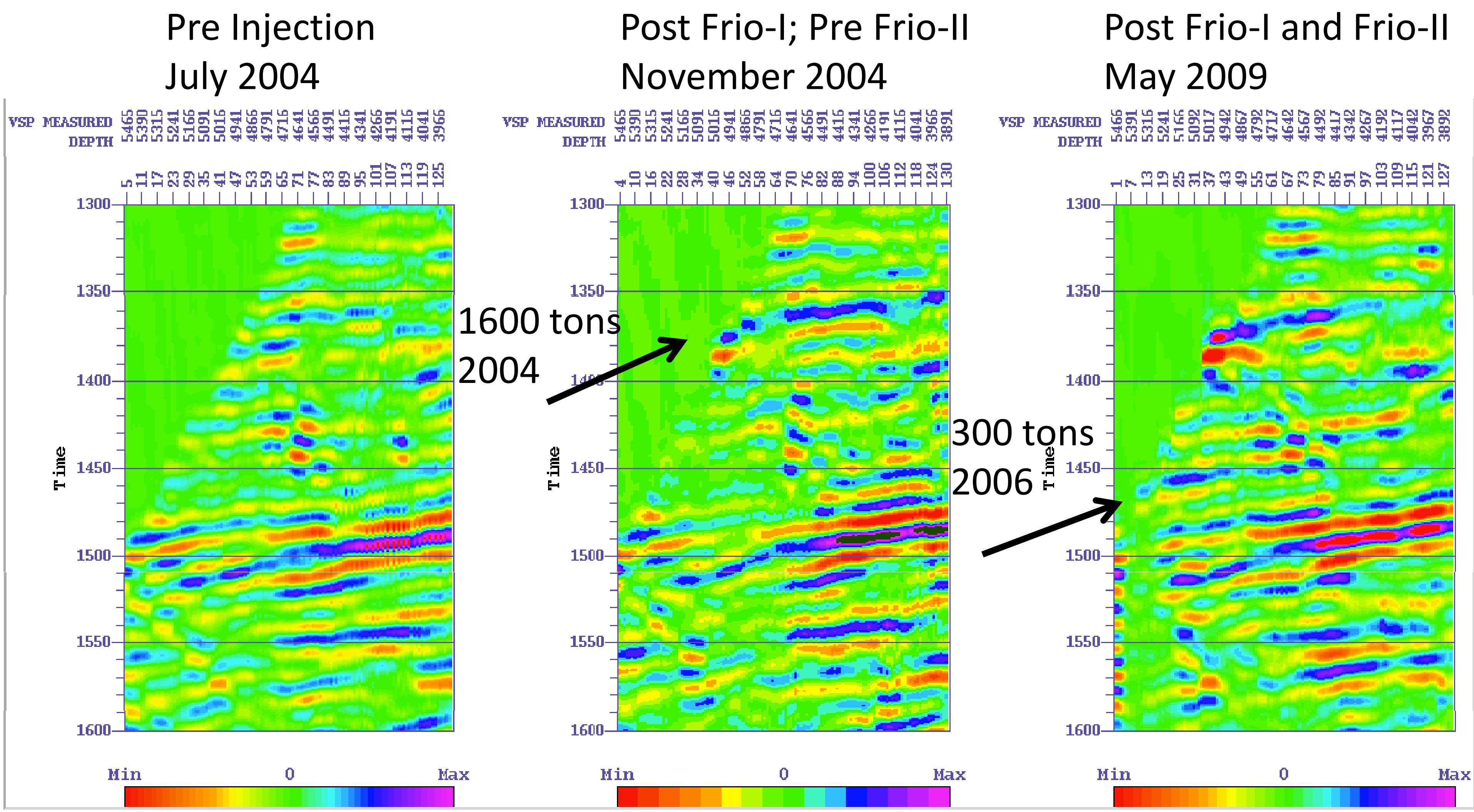
[1]Lawrence Berkeley National Laboratory,
[2]Los Alamos National Laboratory,
[3]National Energy Technology Laboratory,
[4]Lawrence Livermore National Laboratory,
[5]Pacific Northwest National Laboratory

NRAP Monitoring White Paper Research Priorities

- Improve temporal & spatial resolution of monitoring
- Monitoring and detection of leakage
- Quantification of Uncertainty

- Induced Seismicity
- Improve integration of measurement and interpretation tools
- Address scaling issues in monitoring data
- Development of an approach to selecting the optimal MVA program, rather than specific tools.

Example of Specific Monitoring Research:
Frio VSP
Quantification, Leakage Detection, Permanence



NRAP High Level Priorities

Year 1

- **identify proxies for risk components**
- **Complete first-generation predicted curves (risk profile) for generic, idealized sites**
- **Prioritize key uncertainties in predictions that require improved scientific understanding and/or improved treatment in methodology**
- **Identify analog case studies to be used for validation**
- **Initiate field studies**

Summary

- **WESTCARB Monitoring**
  - —**Arizona test designed, canceled**
  - —**California test designed, in progress**
    - **Natural and induced seismicity an issue**

- **NRAP**
  - —**New partnership of DOE national labs to address risk assessment limitations**
  - —**Monitoring is a focus area**

Southwest Regional Partnership on Carbon Sequestration

Microseismic Monitoring of CO_2 Injection at the Aneth Oil Field

Jim Rutledge
Los Alamos National Laboratory

Nobukazu Soma,
National Institute of Advanced Industrial Science and Technology

Brian McPherson,
University of Utah - Energy and Geosciences Institute

Monitoring Induced Microseismicity

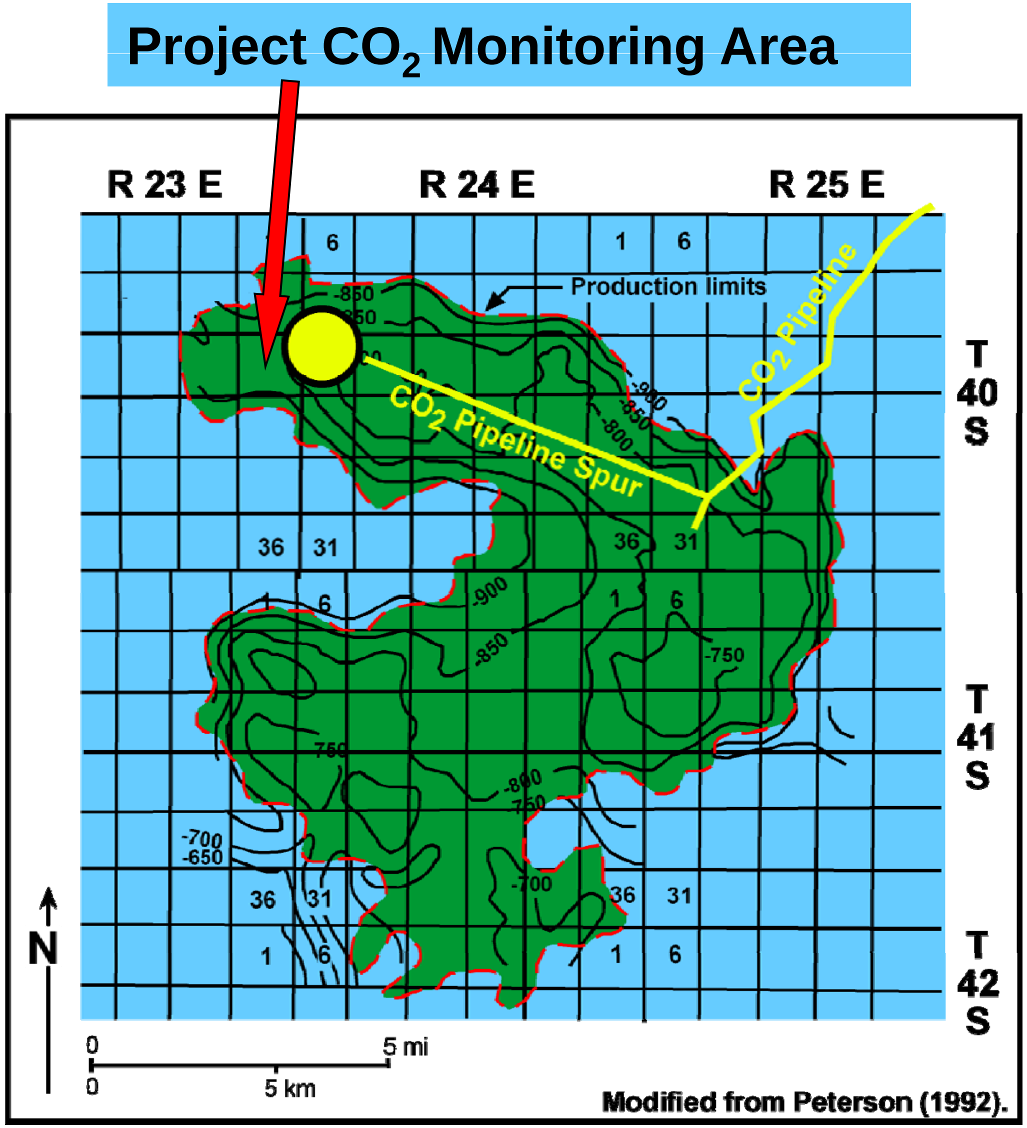
Seismicity should be expected during CO2 sequestration due to increased the pressure and volume accompanying injection.

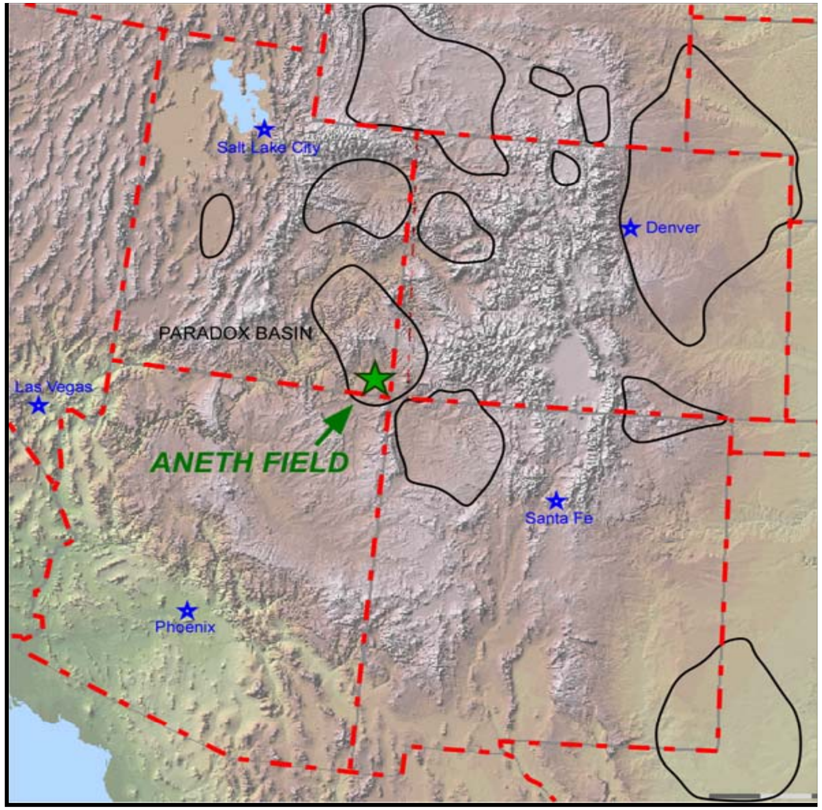
It should be an important component of MVA

- Map pressure fronts
- Infer preferred fracture flow direction and map containment of CO2 in target reservoir
- Sense of deformation and stress field
- Monitor and map fault activation and growth
- Mitigating felt seismicity

Outline

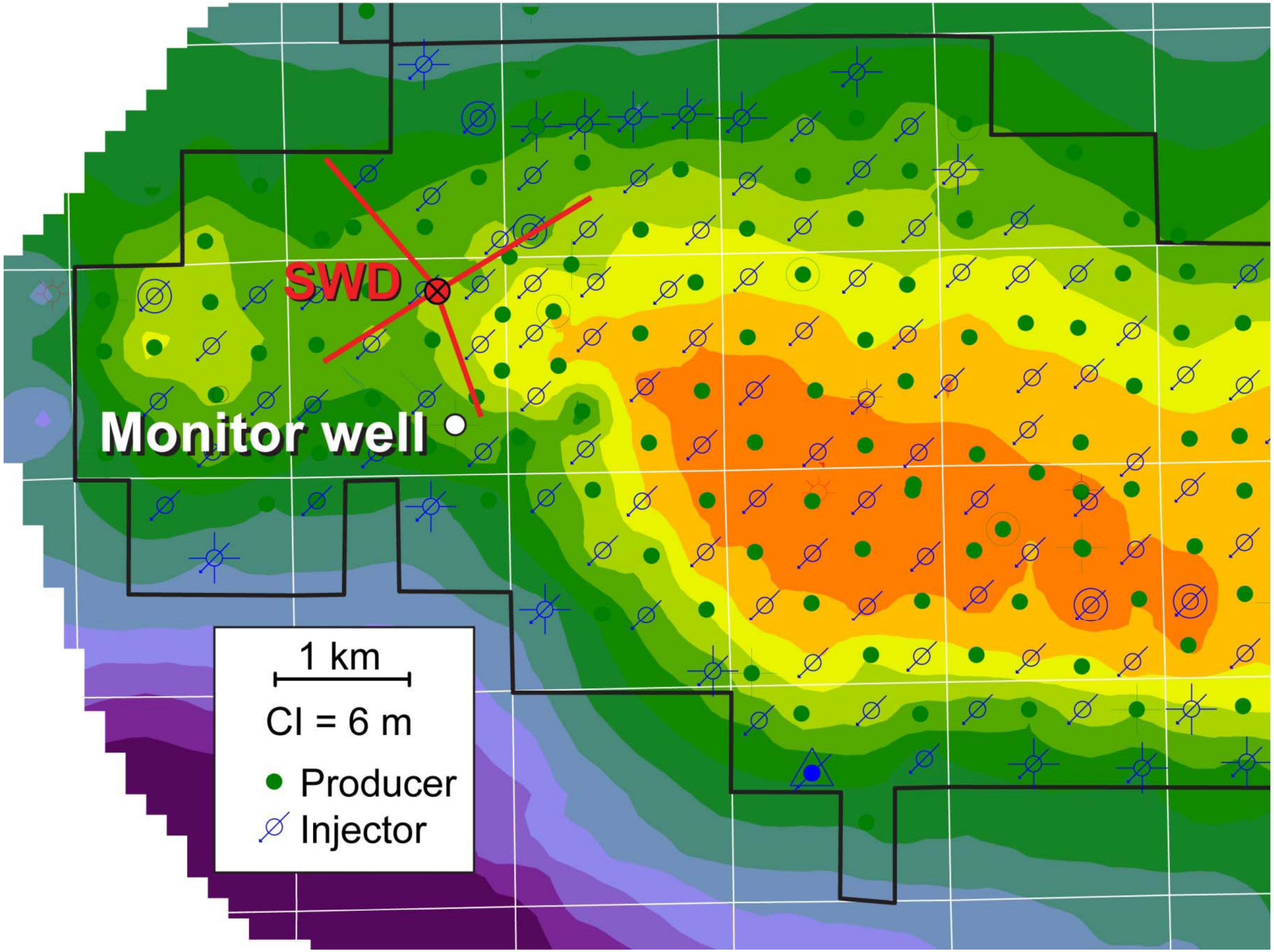
- Field setting and monitoring set up
- Data and data analysis
- Interpretation of the microseismicity
- Summary





- Stratigraphic trap
- Discovered in 1956
- Waterflood initiated in 1961
- CO2 initiated in 1985
- Current gross production rates
  - Aneth - 3,500 BOPD
  - McElmo Creek - 3,400 BOPD
  - Ratherford - 2,600 BOPD

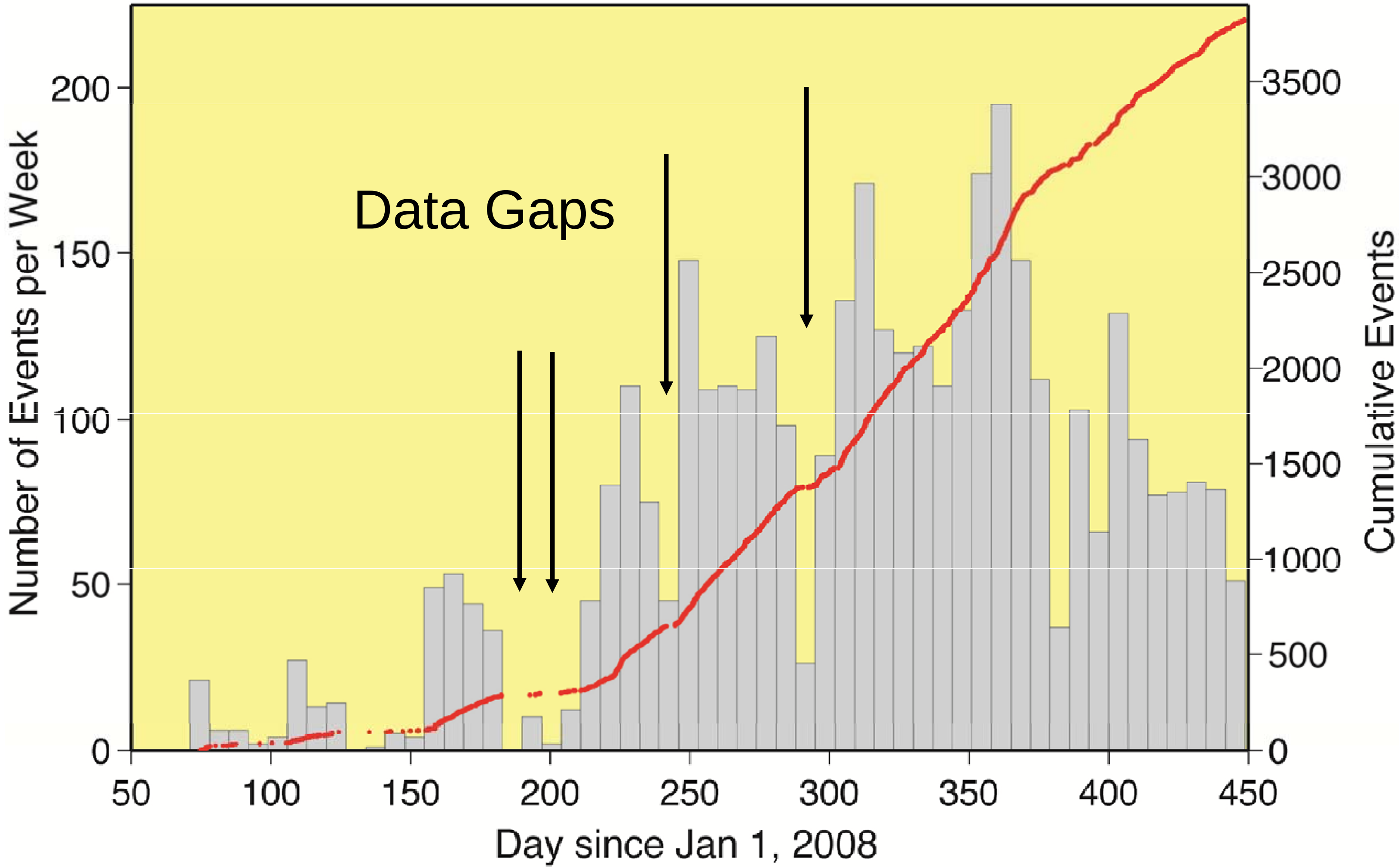
RESOLUTE
NATURAL RESOURCES


SWD
Monitor well
1 km
CI = 6 m
Producer
Injector

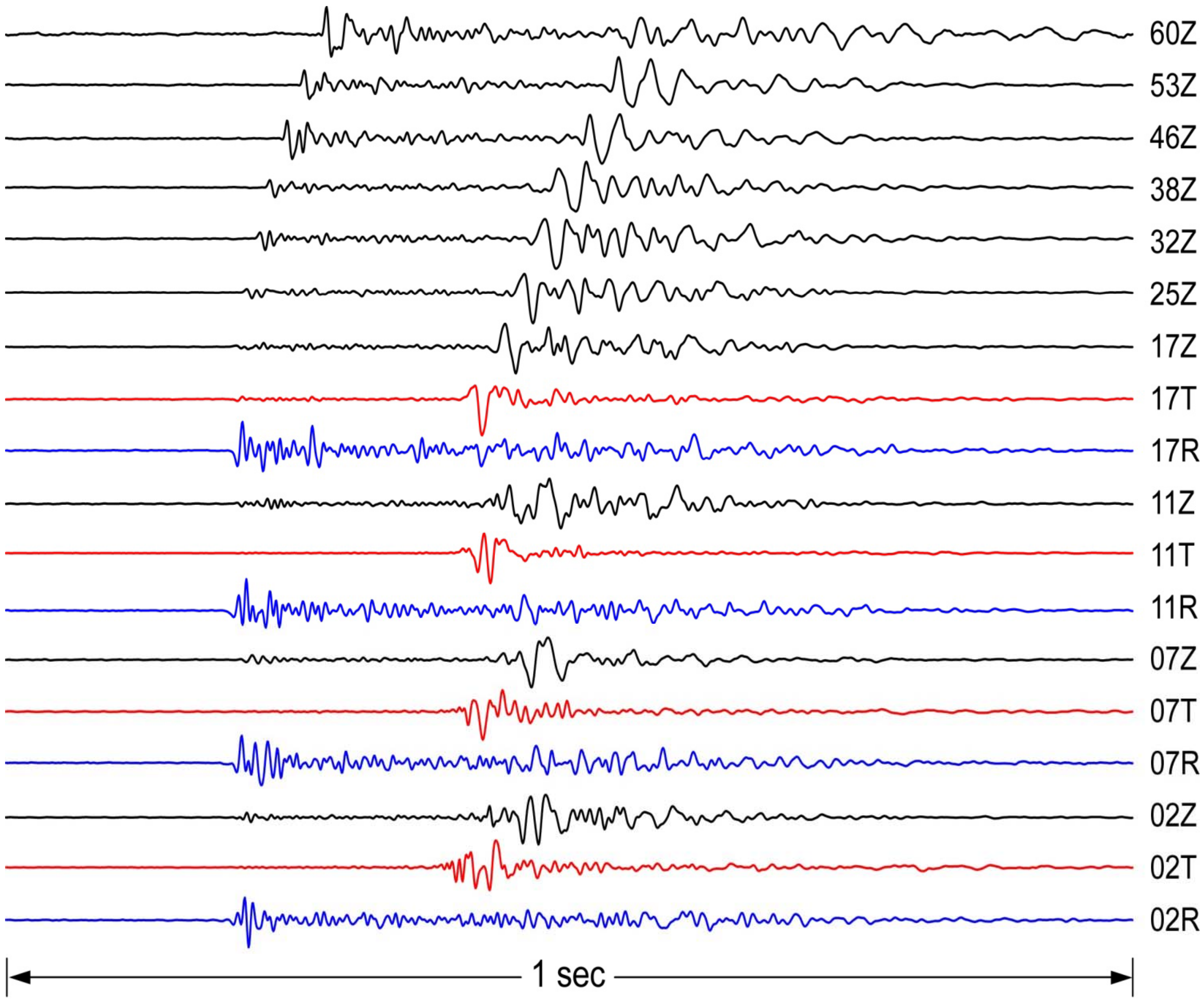
Geophone cable deployment – October, 2007

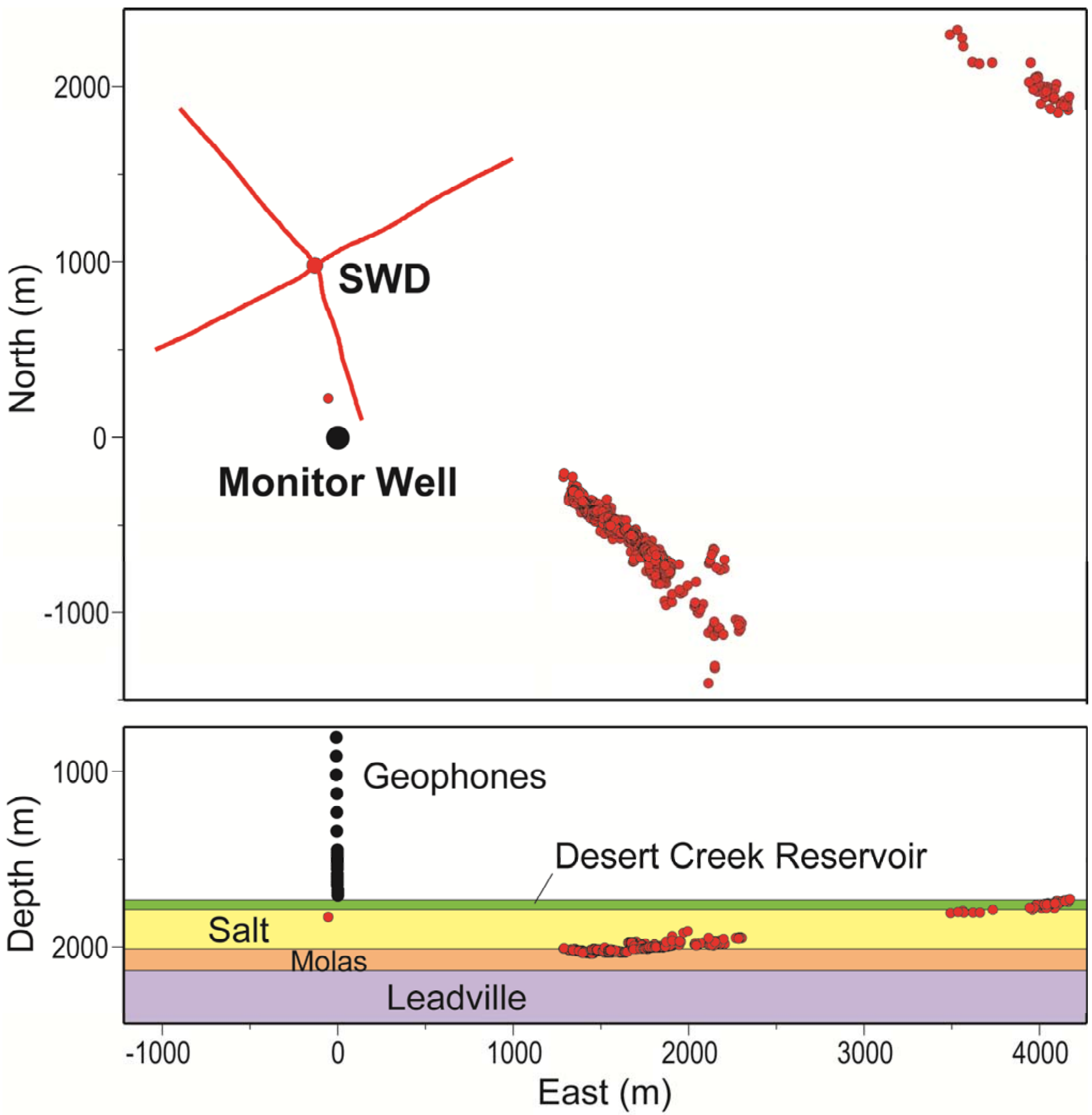
Los Alamos NATIONAL LABORATORY EST. 1943

Cumulative and Weekly Event Counts

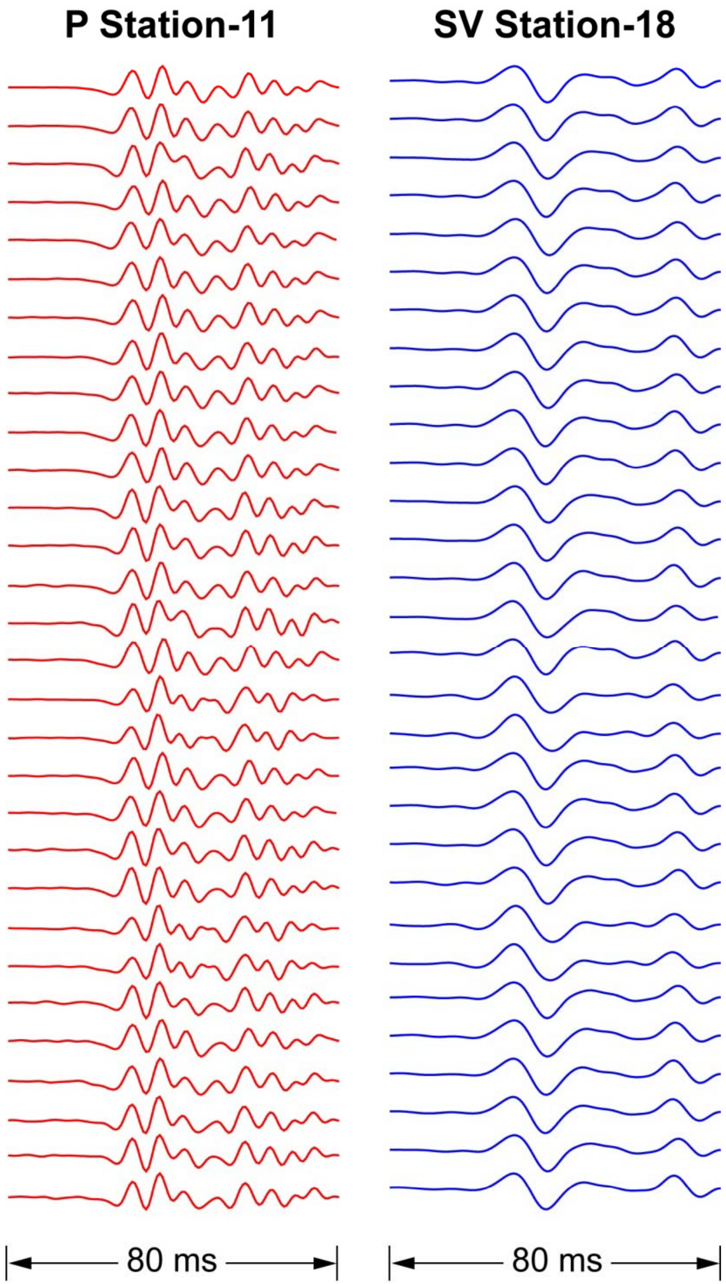


Microseismic Waveforms from Aneth





2000
1000
0
-1000
North (m)
SWD
Monitor Well
1000
2000
Depth (m)
Geophones
Desert Creek Reservoir
Salt
Molas
Leadville
-1000
0
1000
2000
3000
4000
East (m)

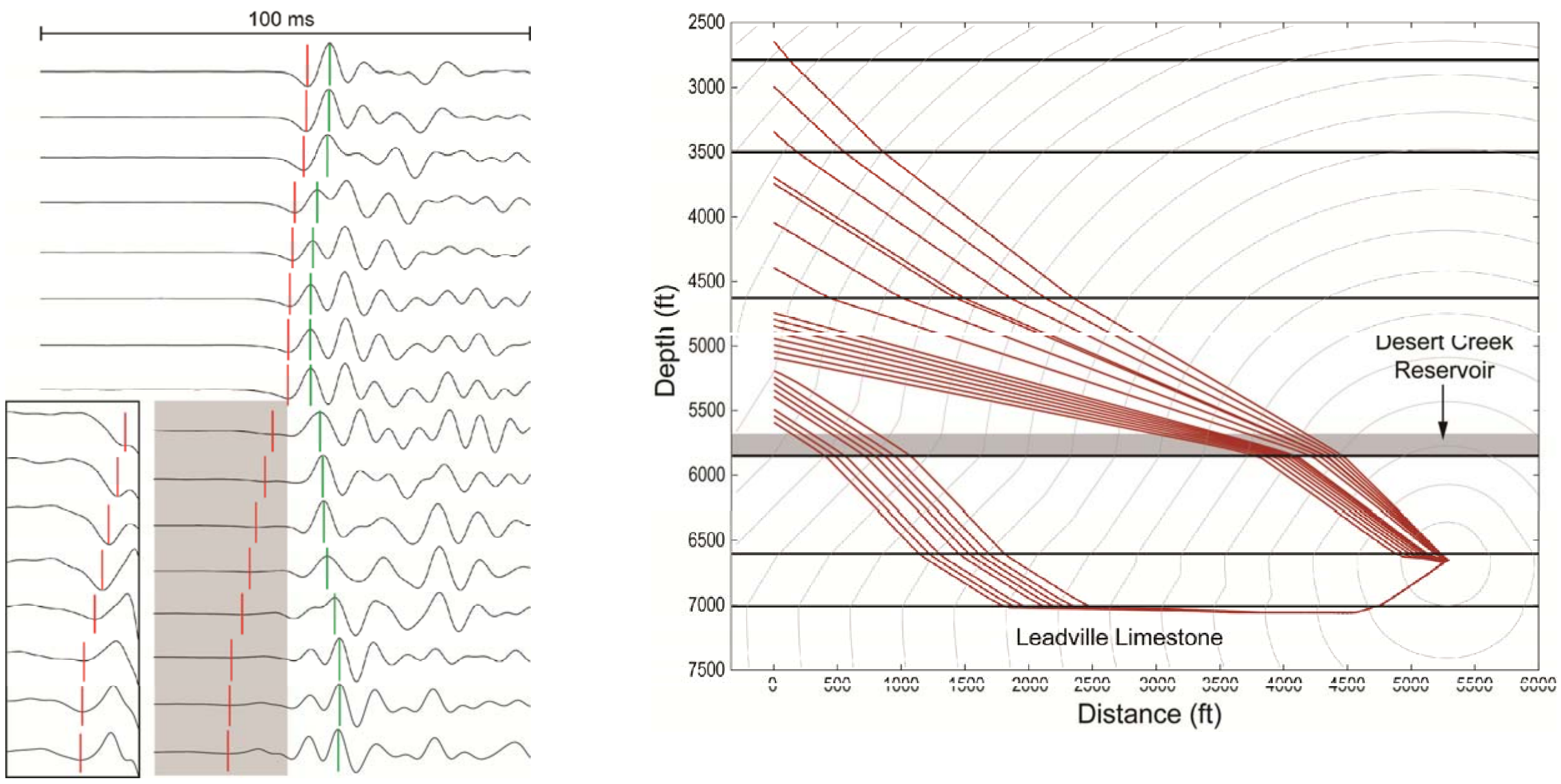


Microseismic Source Location

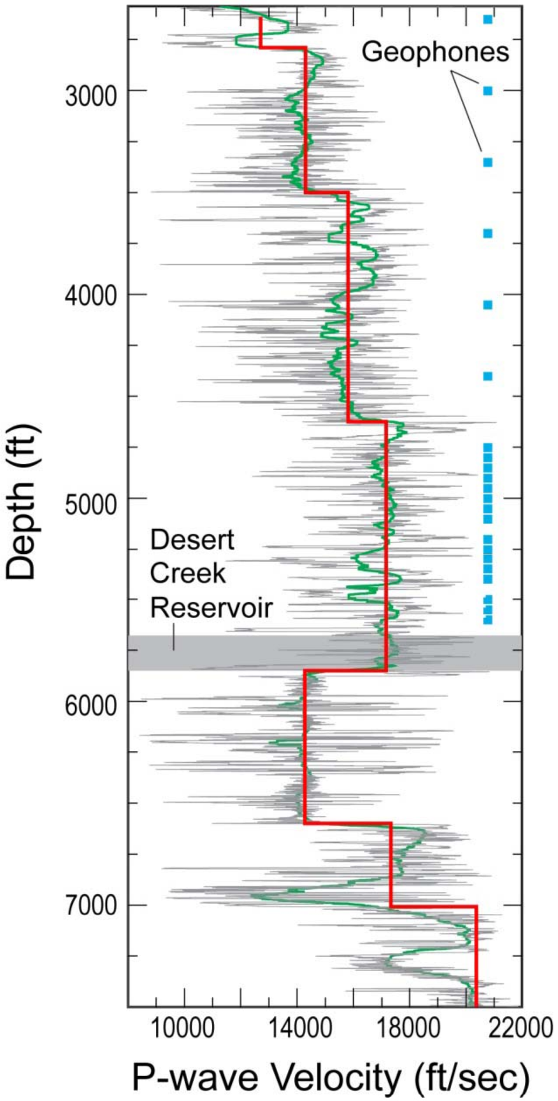
- Clustering and waveform correlation
  - extract precise arrival time picks
  - improve “image” resolution
- Velocity analysis
- Investigating use of reflected phases to help constrain source depth

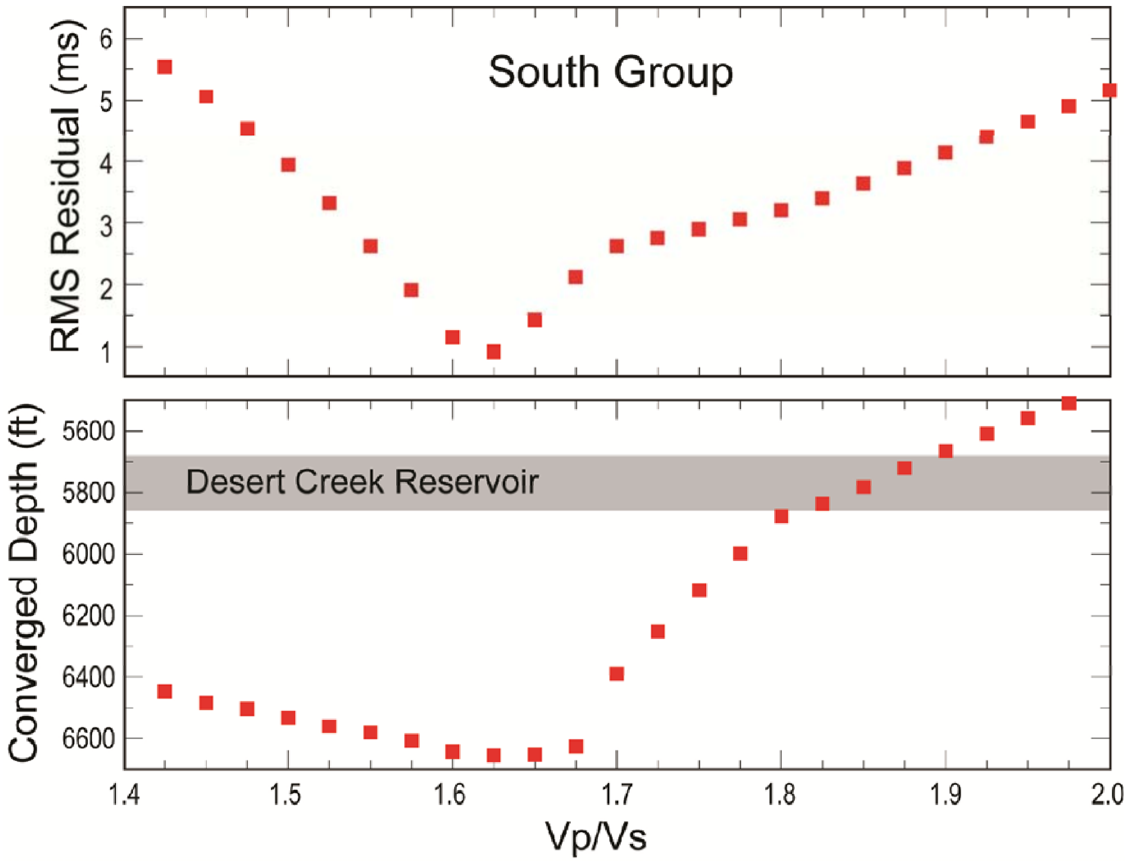
Master Event Location Scheme

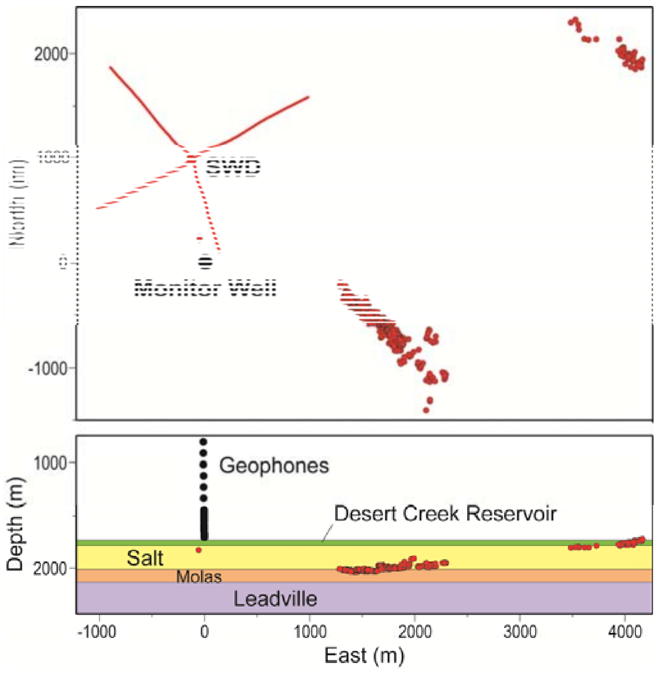
- Stack multiplets to build S/N
- Get best estimate of true 1st arrivals
- Locate event and compute travel time residual
- Apply the residuals as time corrections to the remaining events of the cluster

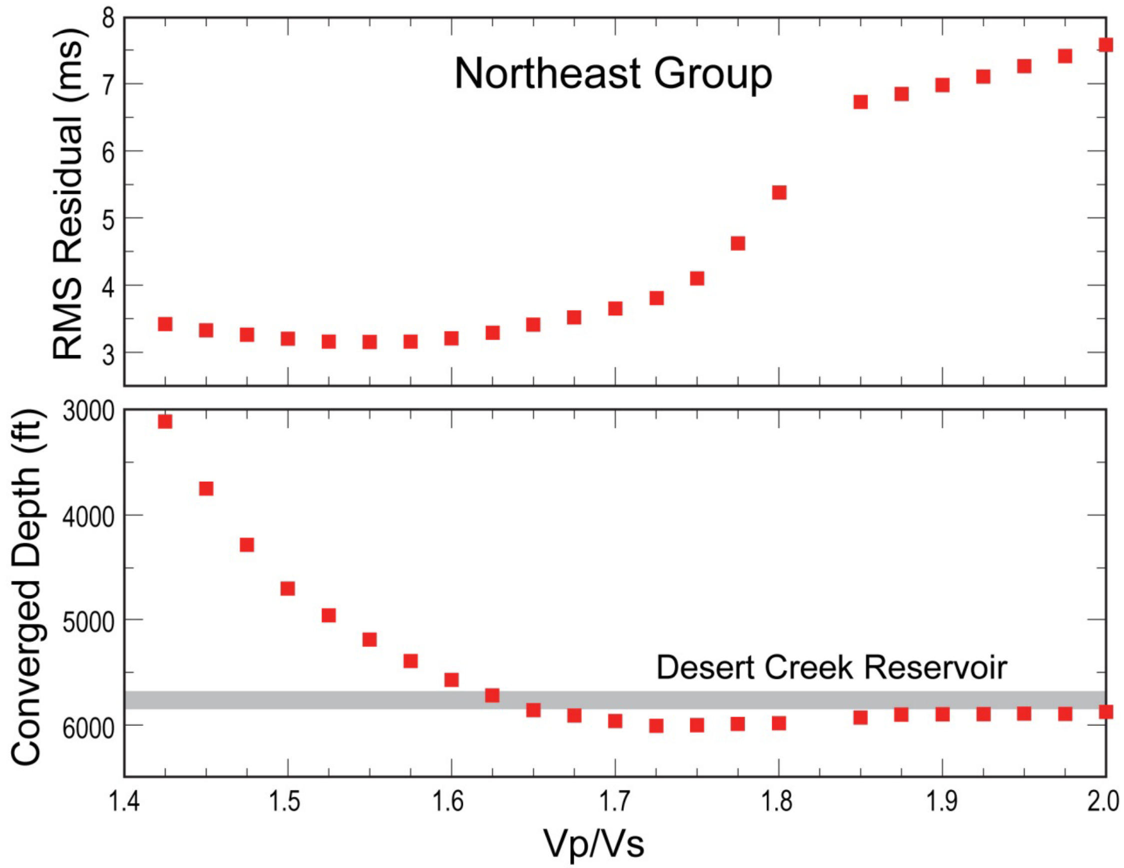


Search for best-fit Vp/Vs

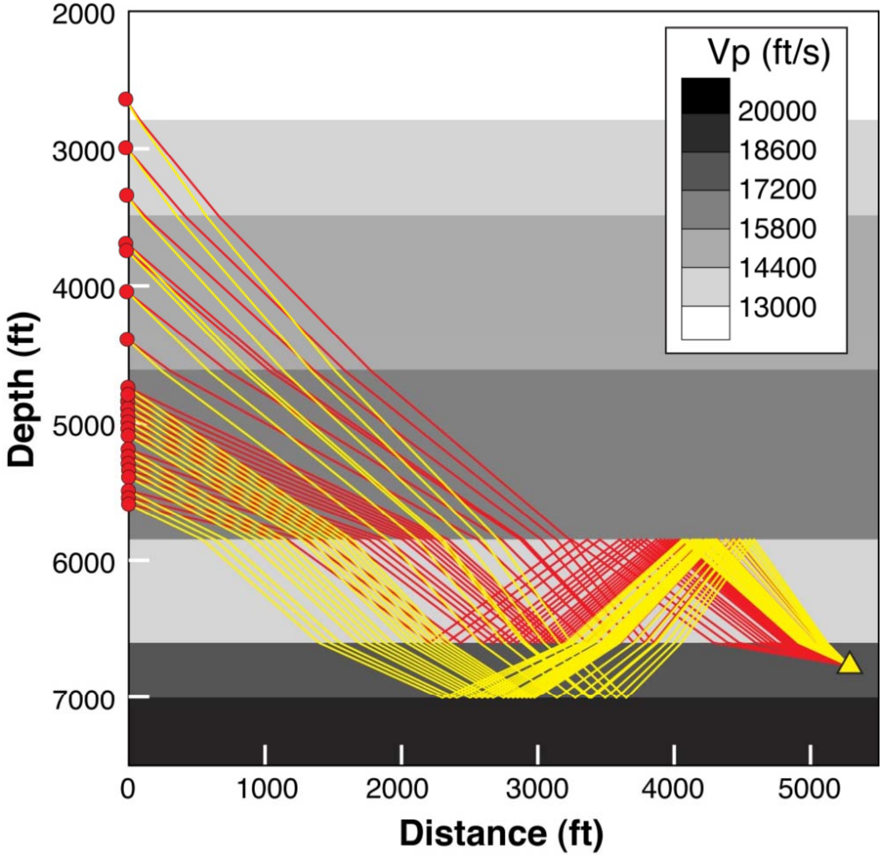


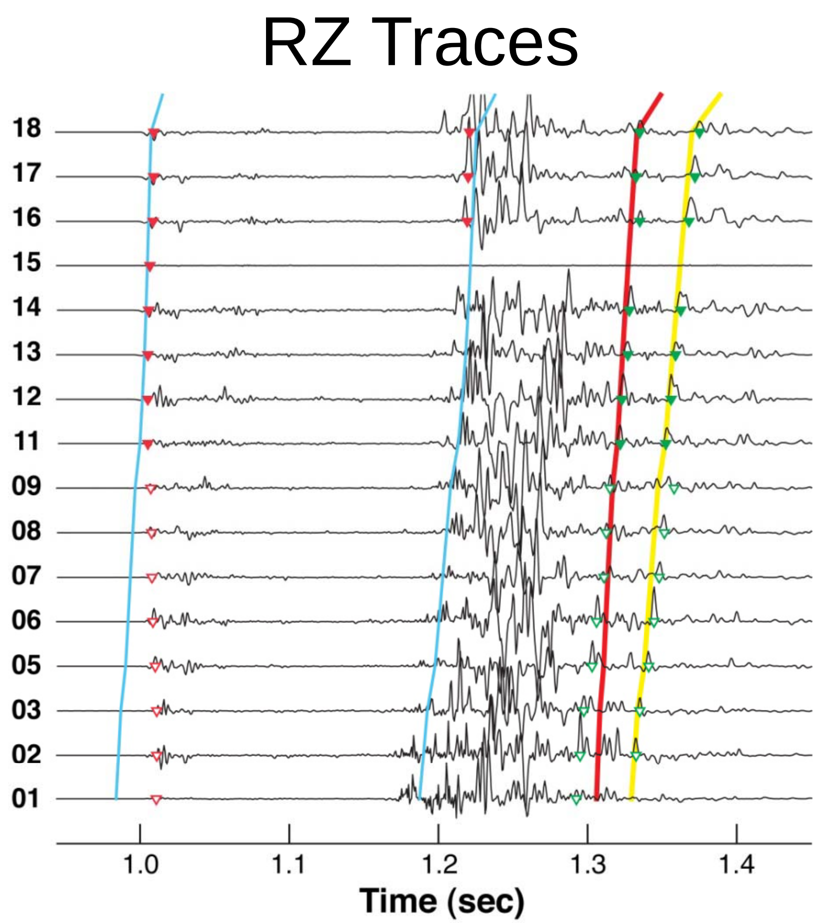



2000
1000
SWD
0
Monitor Well
-1000
1000
Geophones
Desert Creek Reservoir
Salt
Molas
Leadville
2000
Depth (m)
-1000
0
1000
2000
3000
4000
East (m)

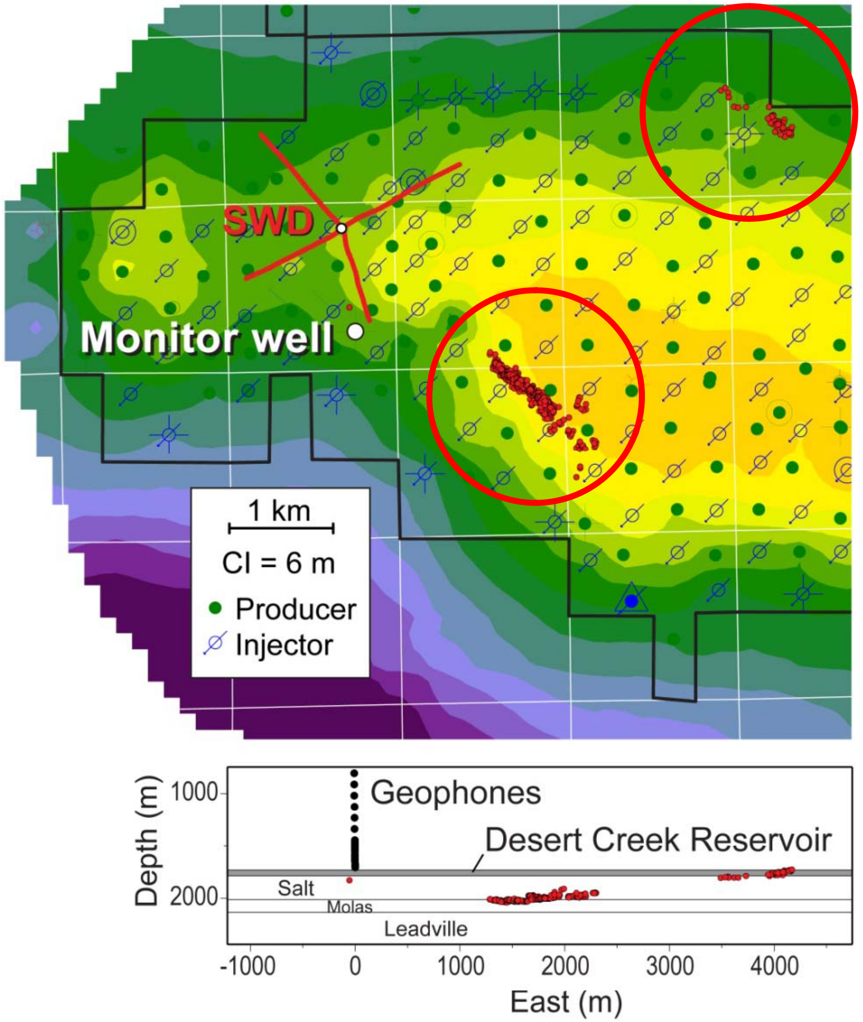

Northeast Group
RMS Residual (ms)
8
7
6
5
4
3
Converged Depth (ft)
3000
4000
5000
6000
Desert Creek Reservoir
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Vp/Vs

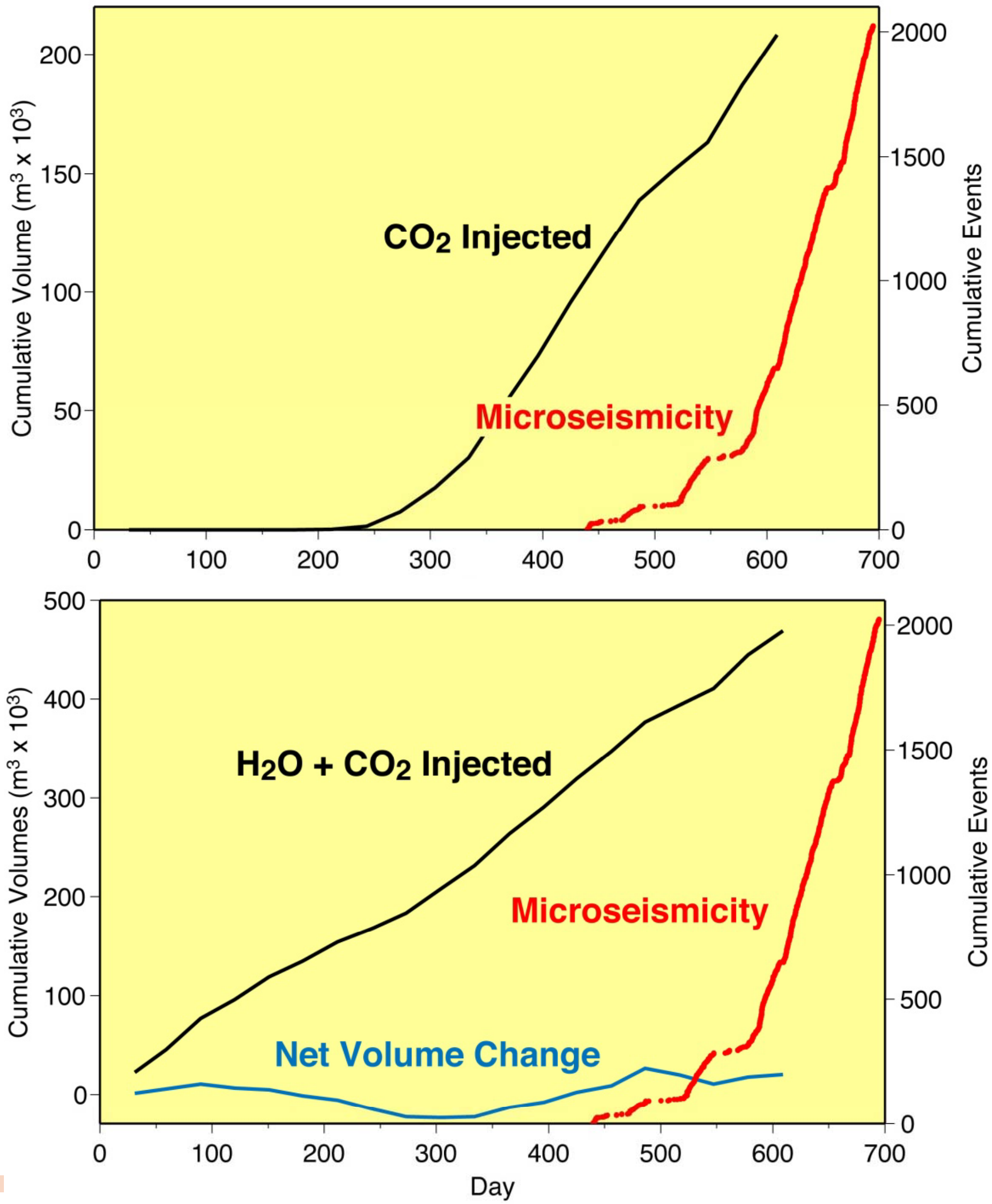
Using Reflected Phases to Constrain Depth





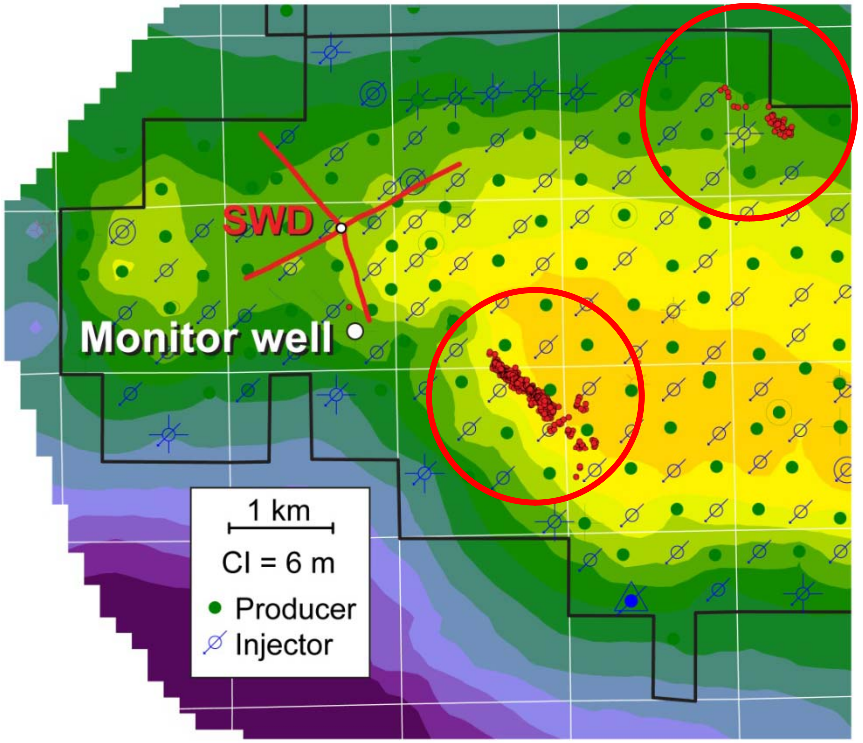
CO_2 Injection and Seismicity

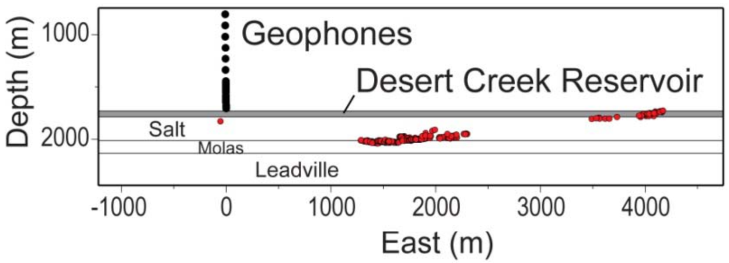


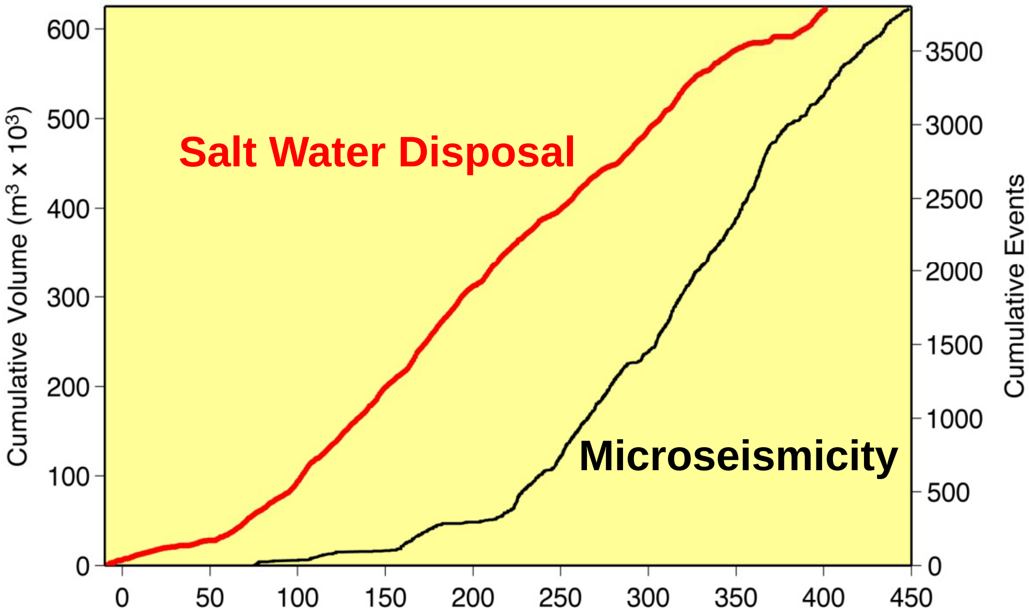


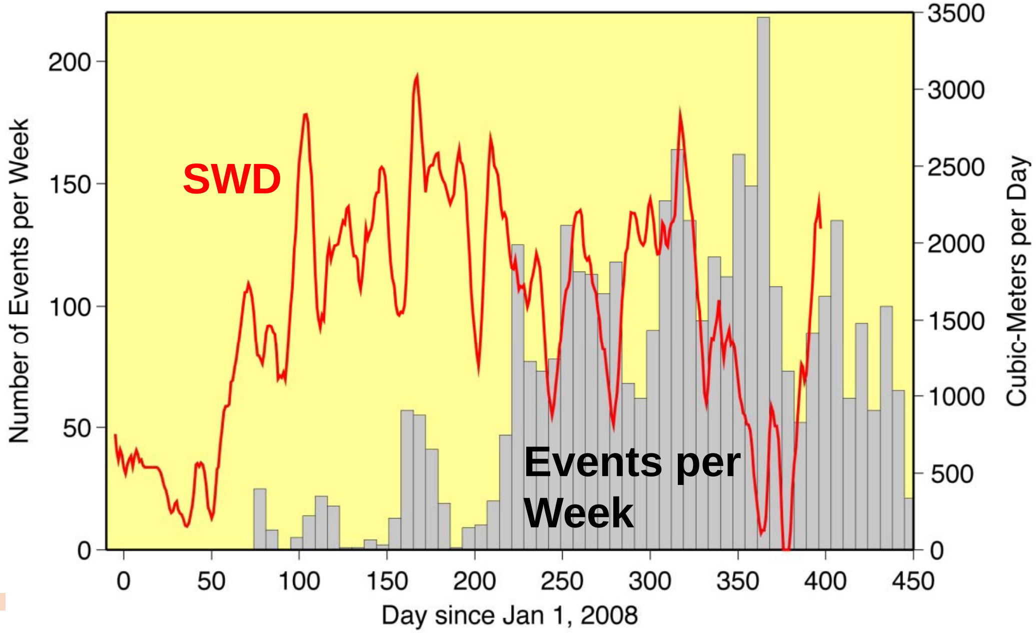
Los Alamos
NATIONAL LABORATORY
EST. 1943

Salt Water Disposal and Seismicity



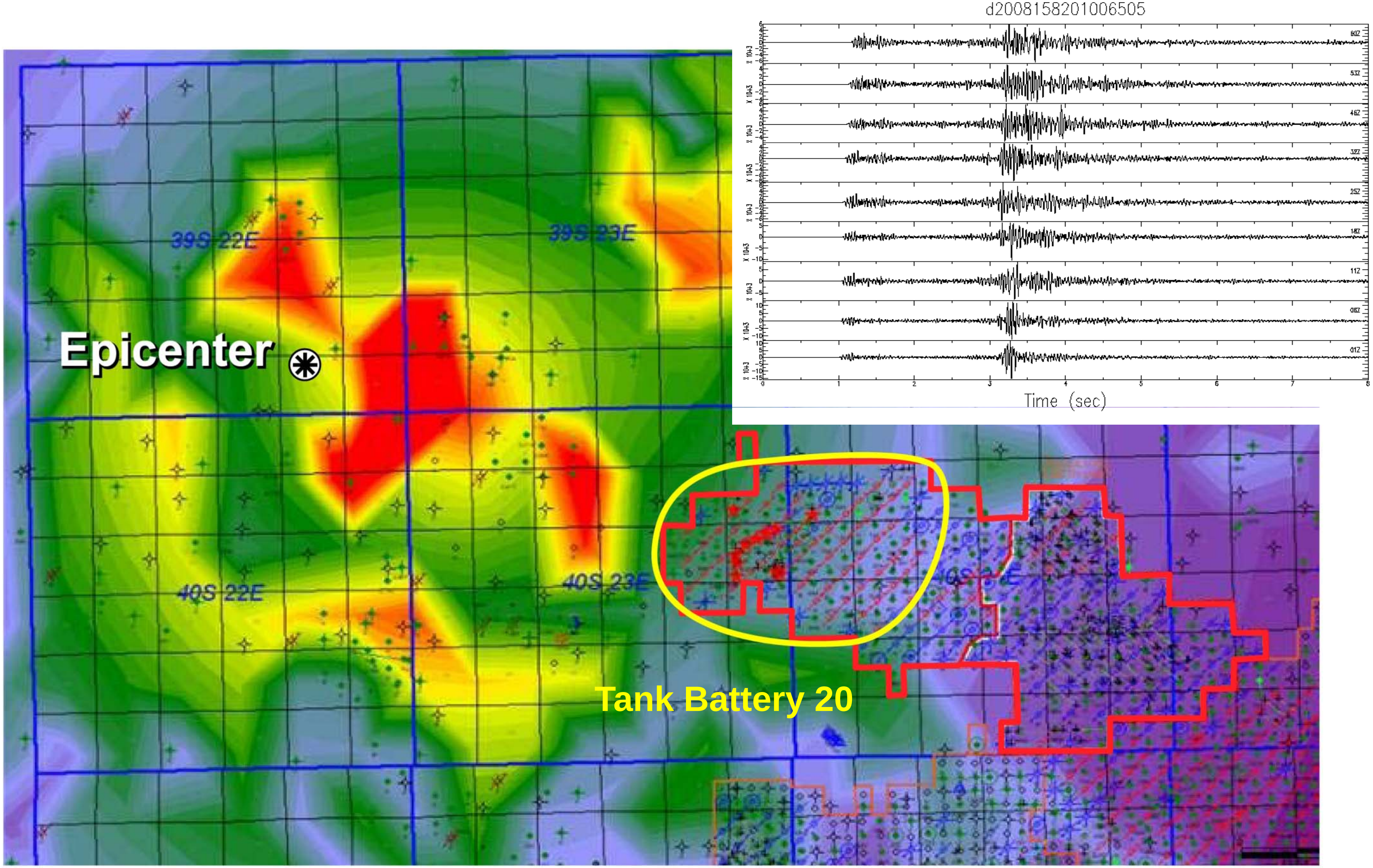


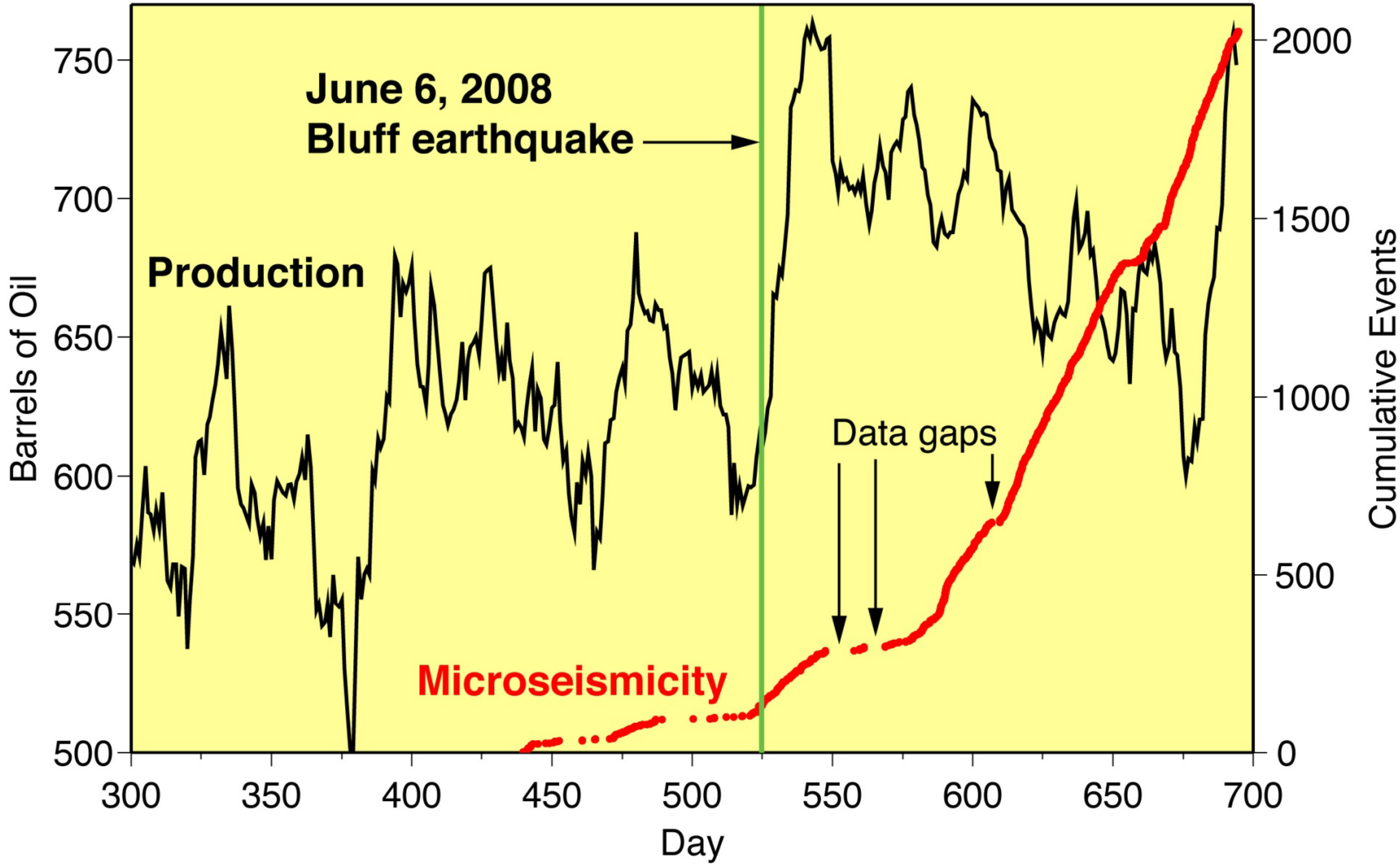




Los Alamos
NATIONAL LABORATORY
EST. 1943

Shake Intensity – Bluff M3.6 Earthquake June 6, 2008





Los Alamos
NATIONAL LABORATORY
EST. 1943

Summary

- **Microseismic locations reveal NW-SE striking structures near the margins of the reservoir**
  - The main structure resolved is beneath the reservoir
- **Microseismic activity does not correlate with current injection activity in the reservoir**
- **Seismicity does not appears correlate with deeper salt-water disposal.**
- **June 6 Bluff M3.6 earthquake may have affected production and reservoir seismicity**
  - Stress transfer driving pore pressure increase?

Los Alamos
NATIONAL LABORATORY
EST. 1943

Needs in Understanding Induced Seismicity

Cheap, reliable placement of downhole receivers and sensors.

- improve coverage for better source location and mechanisms
- improve imaging coverage and resolution
- lower detection thresholds
- identify changes earlier

Geologic Storage Monitoring Under MRCSP and Other Projects

Neeraj Gupta, Ph.D.
Senior Research Leader, Battelle Energy Technology
Battelle, Columbus, Ohio
gupta@battelle.org, 614-424-3820

Presented on behalf of MRCSP Geology Team
Funded by US DOE and Several Other Partners

IEAGHG Monitoring Network Meeting, May 6-8, 2010, Natchez, MS

The Midwest Region: Complex and Diverse Geology

Diverse and Complex Geology

- Three deep mature basins
- Atlantic coastal plains
- Differing local nomenclature

MRCSP Geologic Test Sites*

Michigan Basin: DTE and Core Energy gas and oil operations, Gaylord, Michigan
- Permitting: EPA Region 5, Class V, Granted Jan 2007.
- Target: Bass Islands Dolomite, ~3500 ft
- Status: Injected 10,000 tonnes 2008. Additional 50,000 tonnes injected February-July 2009
- Host: DTE Energy, Core Energy

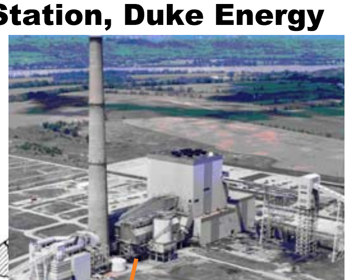
Appalachian Basin: FirstEnergy's RE Burger Power Plant, Shadyside, Ohio
- Permitting: Ohio EPA, Class V, Granted Sep 2008
- Target: Oriskany, Salina, and Clinton, 6500-8000 ft
- Status: Injection testing completed, reporting underway
- Host: FirstEnergy

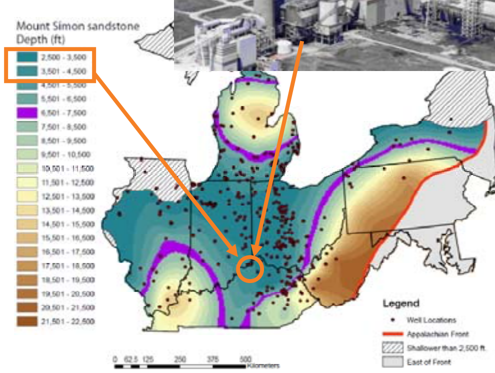
Cincinnati Arch -- Mount Simon: Duke's East Bend Power Station, Rabbit Hash, Kentucky
- Permitting: EPA Region 4, Class V, Granted Feb 2009.
- Target: Mt. Simon Sandstone, 3,500 ft
- Status: Drilling Jun 2009, Injection completed Sep 2009
- Host: Duke Energy

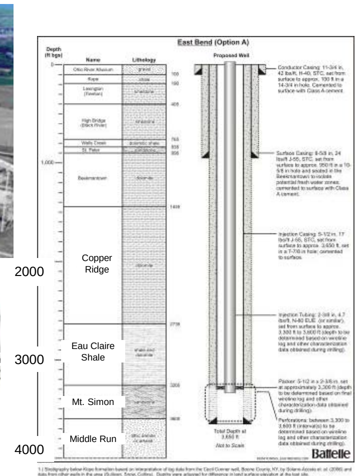
Large Scale (1 million tonnes of CO_2) Phase III Site
- Various sites under evaluation

* All deep saline tests

Cincinnati Arch Site
East Bend Station, Duke Energy



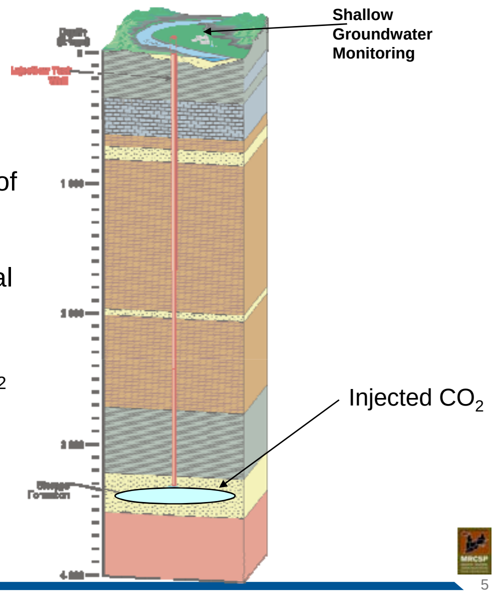




1,000 tonnes of CO_2 injected in September 2009.

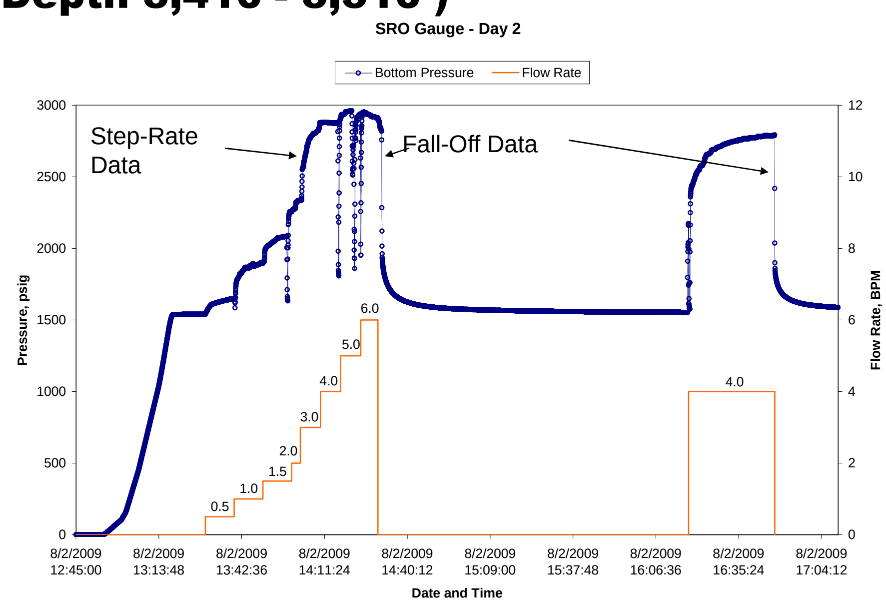
Monitoring Program

- Drinking Water Aquifer groundwater monitoring program
  - •10 shallow wells
  - •1 new deep well
- *Geophysical borehole logging to determine the vertical distribution of CO_2 adjacent to well
- *Vertical Seismic Profile (VSP) Survey to detect lateral and vertical extent of the CO_2 plume in the injection reservoir
- Numerical modeling to predict CO_2 distribution and migration

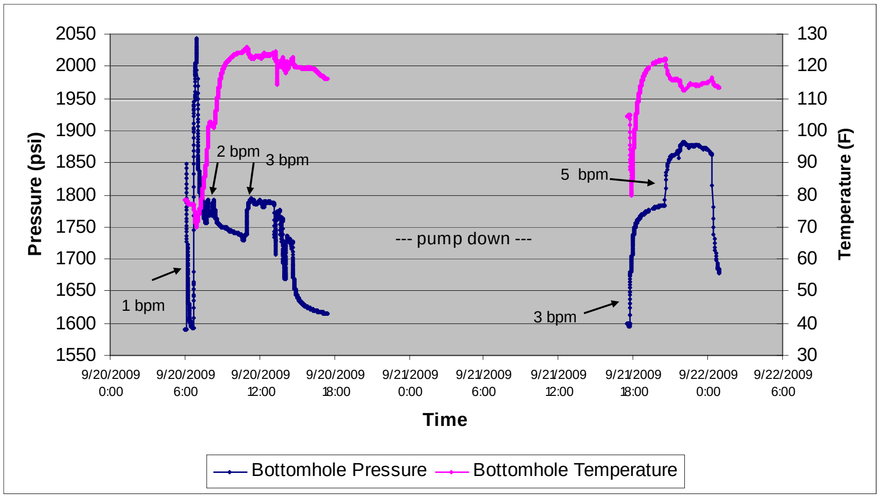


**baseline geophysical borehole logging and VSP survey have been completed – repeat monitoring tentative*

Brine Injection Test #2 (Depth 3,410′- 3,510′)

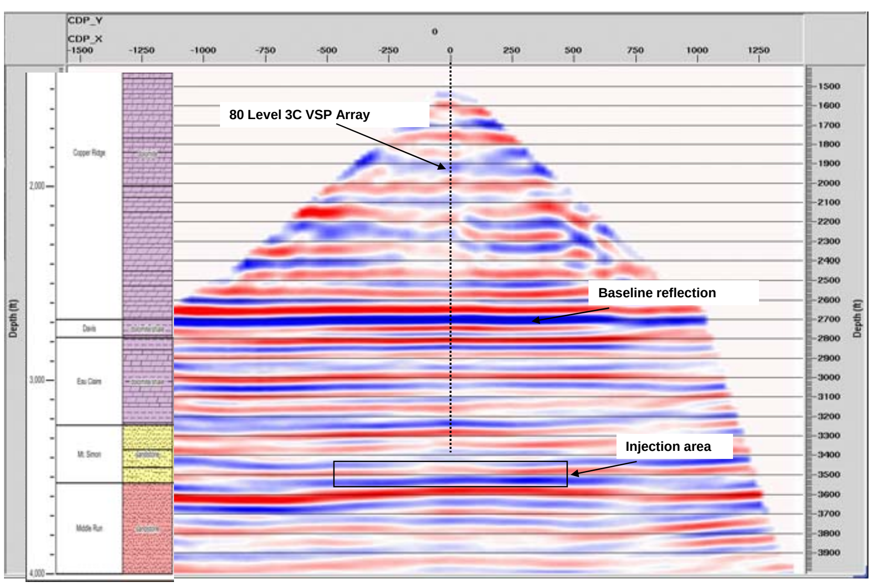


East Bend CO_2 Injection Data – 9/20-9/21

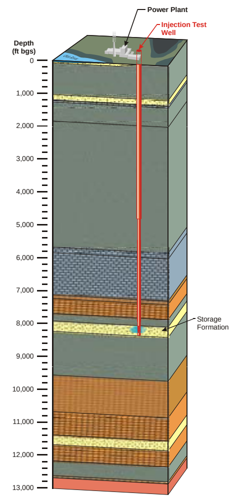


PRELIIMINARY

Image After Processing



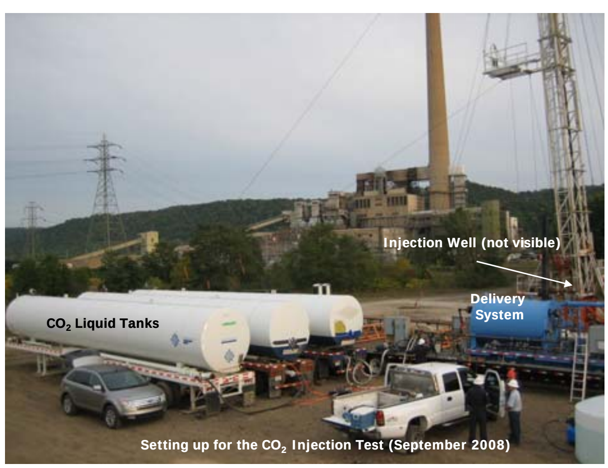
RE Burger Power Plant (FirstEnergy)



8000 Foot Test Well

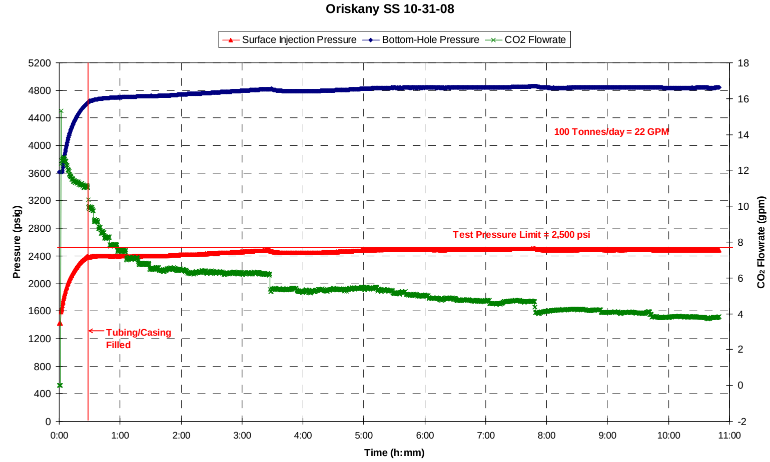
Injection Operations and Monitoring

- Injectivity testing phase started late September 2008 and ended in November



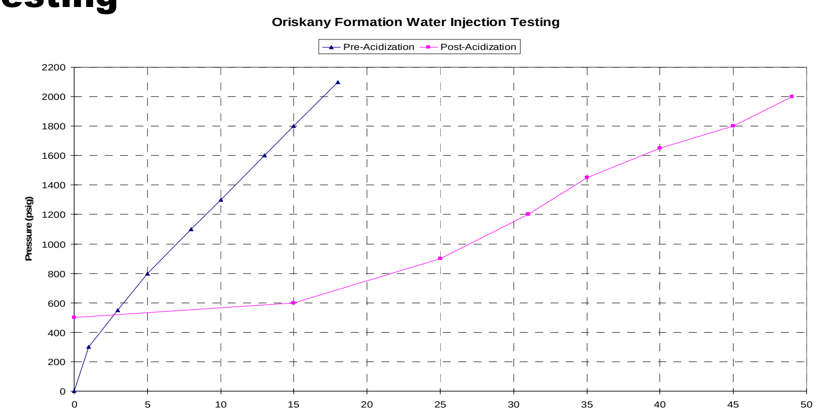
Setting up for the CO_2 Injection Test (September 2008)

Pressure/Flow Test of Oriskany SS



- Attempt CO_2 injection while maintaining pressures <2,500 psi and flow rates >20 ton/day (approximately 4.5 gpm)
- Injection parameters could not be achieved after 8 hours of injection
- Flow was reduced several times during injection testing.

Pre- and Post-Acidization Brine Injection Testing



- Brine injection tests before and after acid treatment to determine effectiveness of acid
- Injection rates at 0.2 bbl/min with upper pressure limit of approx. 2,000 psi.
- Pressure limit achieved after 18 minutes before and 49 minutes after acidization.
- Indicates acid treatment improved injection capabilities of the formation.

Michigan Basin, Gaylord, Michigan

Leverages existing EOR infrastructure from DTE and Core Energy

Gas processing plant, source of pure CO_2

600 T/d Compressor

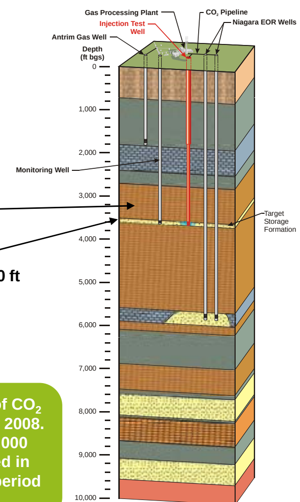
5000 Foot Deep Test Well Drilled in November 2006

180 feet of core taken

Injection well head

Confining Layer: Amherstburg Limestone

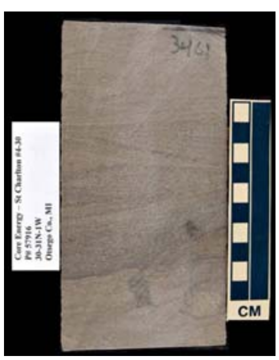
Injection Target: Bass Islands Dolomite 3,500 ft



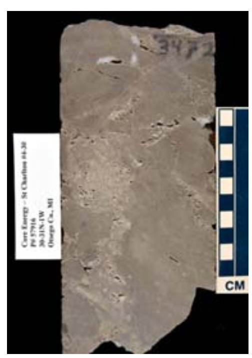
Well Column

10,000 tonnes of CO_2 injected in early 2008. Additional 50,000 tonnes injected in February-July period of 2009.

Michigan Basin Site – Understanding Carbonate Rocks



- Sandy dolo-grainstone with visible X-bedding
- Depth = 3461.2 feet
- Permeability = 91 mD
- Porosity = 17%



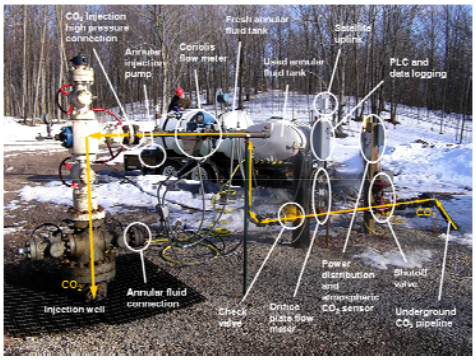
- Karst collapse breccia
- Depth = 3472.1 feet
- Permeability = 52 mD
- Porosity = 27%

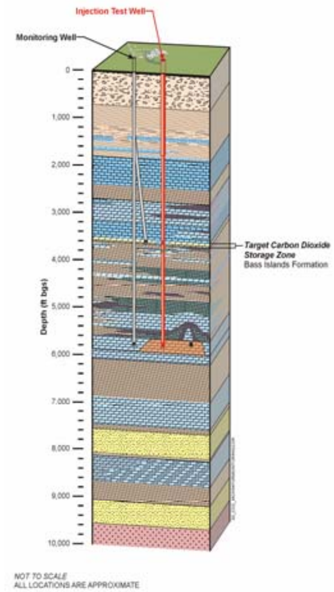
- Laminated and mud-cracked Algal dolo-mudstone
- Depth = 3488.4 feet
- Permeability = 0.5 mD
- Porosity = 12%

Core sample from Bass Islands Dolomite showing vertical heterogeneity

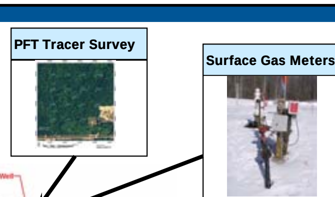
Injection System

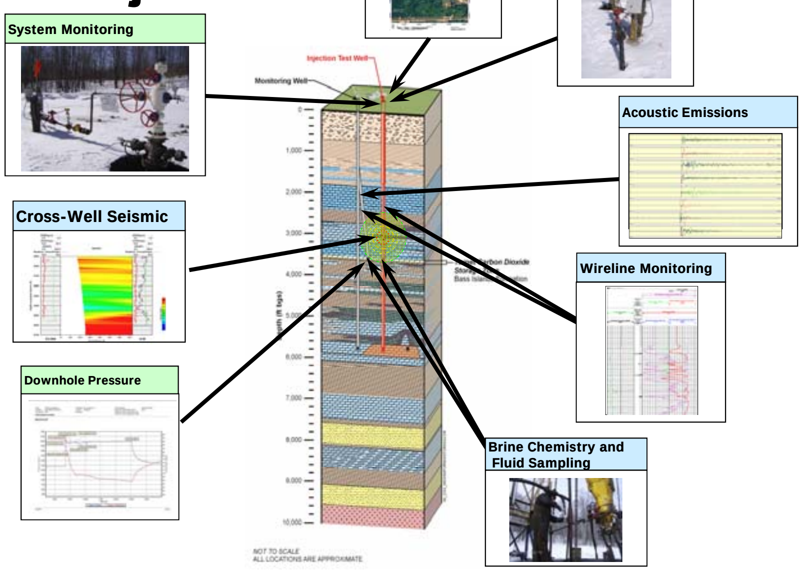
• New well (State-Charlton 4-30) drilled for injection.
• Nearby well 3-30 used for monitoring.
• Variety of well head instrumentation used.





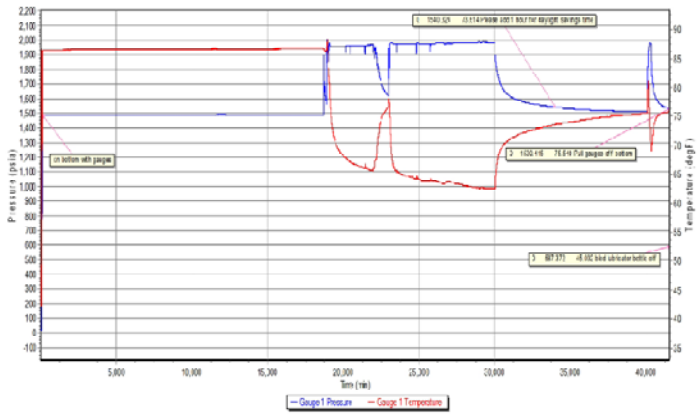
MMV Program – Initial Injection





Injection Operations

- Bottomhole injection pressures and temperatures during the first half of injection showed fall-off towards ambient conditions

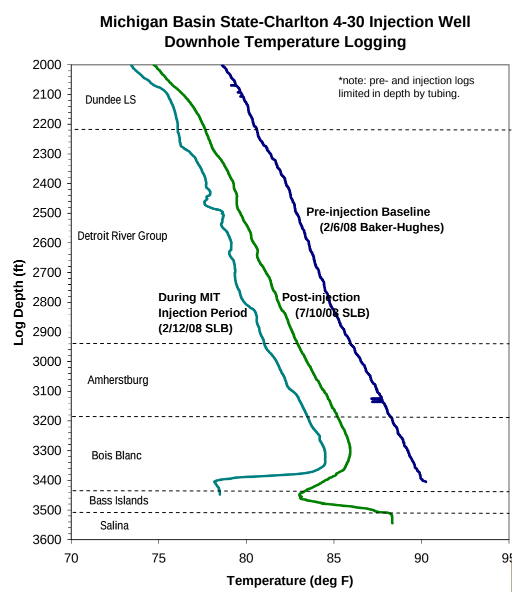


17

Post-Injection Thermal Response

- Sequential, downhole temperature logs provide very direct, understandable evidence of vertical CO_2 distribution.

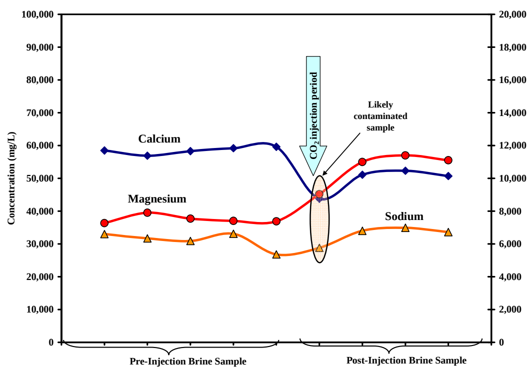
- No change in temperature change was observed in 3-30 monitoring well.



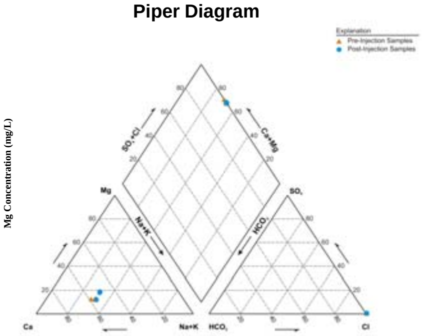
18

Michigan Brine Sampling Analysis (pre and post injection)

- Calcium levels decreased and Magnesium increased, possibly due to dissolution of dolomite and precipitation of anhydrite.
- These are very subtle indications of CO_2. More, sequential sampling was needed and was collected in the extension.

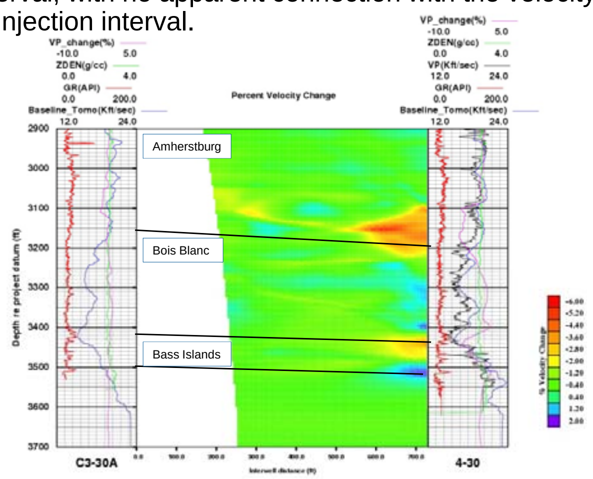


Piper Diagram



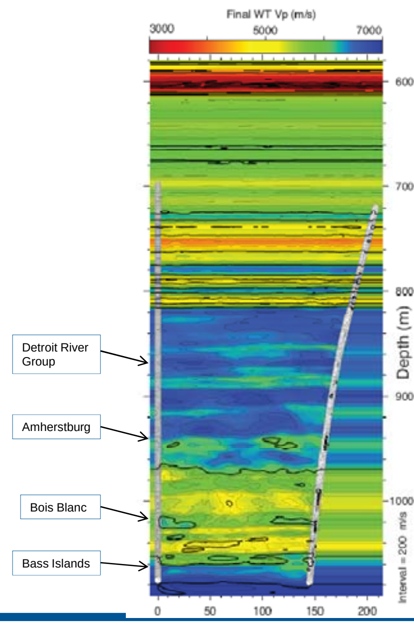
Crosswell Seismic Repeat Survey

- The difference between the two surveys shows a velocity decrease in the Amherstburg formation, approximately 300 ft above the perforated injection interval, with no apparent connection with the velocity change area at the injection interval.



Additional Crosswell Processing
(Collaboration with RPI)

- Full waveform tomography can yield much more detailed information on the formations
  - Takes advantage of the additional information in the waveforms, beyond the first arrival time differences
- Figure shows reprocessed first (June, 2008) repeated survey.

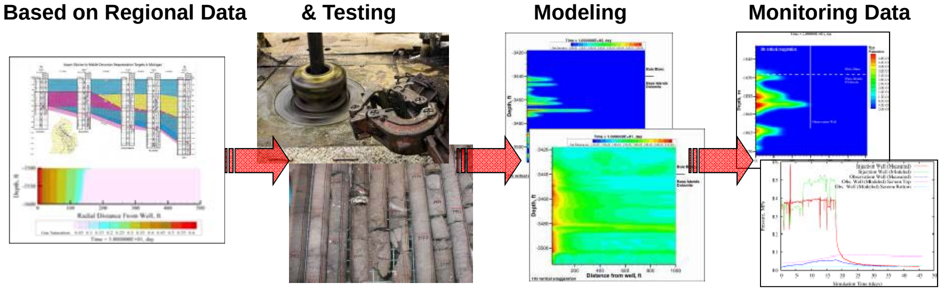


21

MRCSP Michigan Site, Simulation and Monitoring

STOMPCO2 simulations were calibrated to test data to improve model capabilities and demonstrate confidence in reservoir models.

Preliminary Modeling Based on Regional Data	Site Drilling & Testing	Site Specific Modeling	Calibration to Monitoring Data



Measured vs predicted results from falloff test

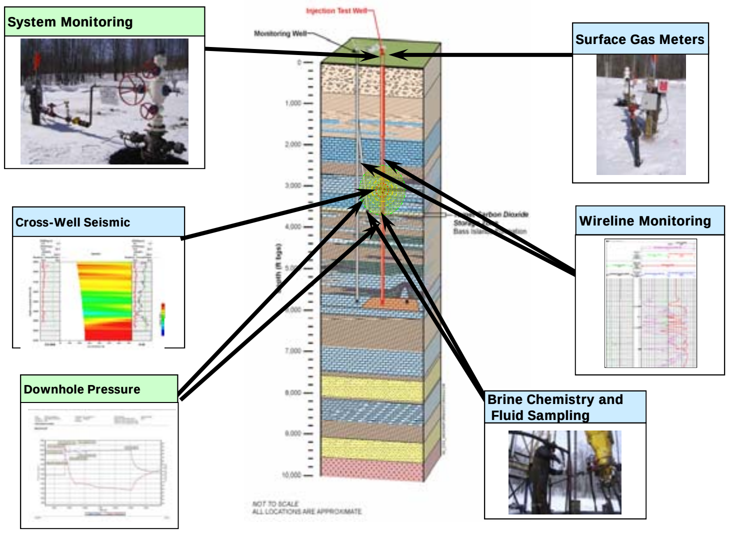
- Monitoring includes: Crosswell seismic, Microseismic, PFT tracers, Fluid sampling, Pressure and Temperature
- Measured results correlate well with model
- Permeability higher than predicted

22

Extended Injection- Monitoring Program

Battelle
The Business of Innovation

- Monitoring program designed to address uncertainties uncovered in the initial CO_2 sequestration tests.



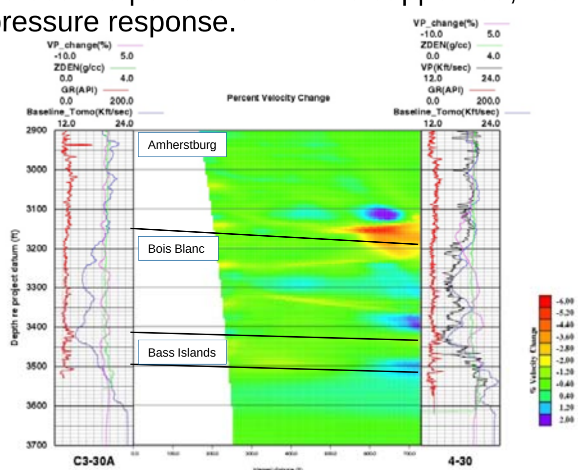
MRCSP

23

Repeat Crosswell Prior to 50,000 Tonnes Injection

Battelle
The Business of Innovation

- The difference between the baseline survey and the second repeat continues to show a velocity decrease in the upper section. The decrease across the perforations has disappeared, indicating it may be a pressure response.

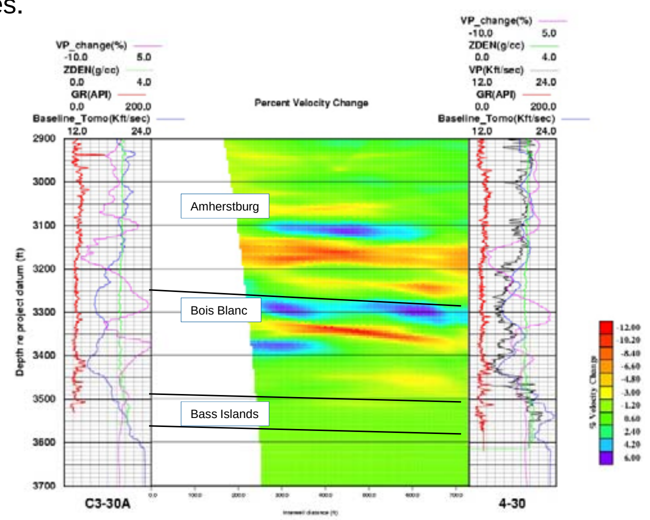


MRCSP

24

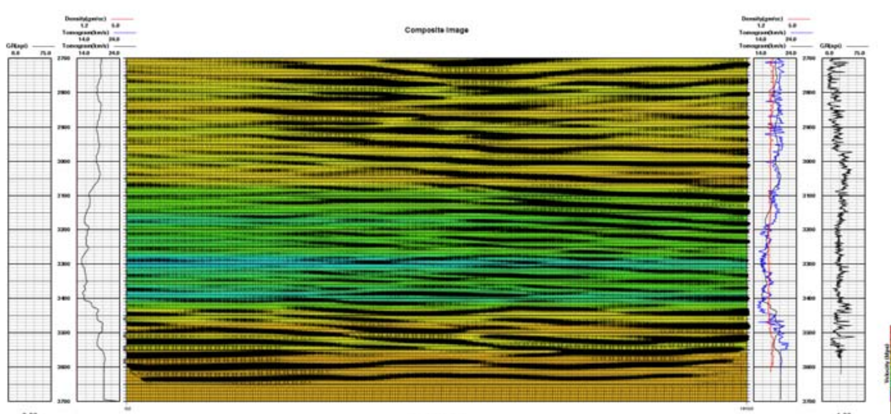
Final Surveys

- Tomographic image shows significant stratification of the velocity decreases.



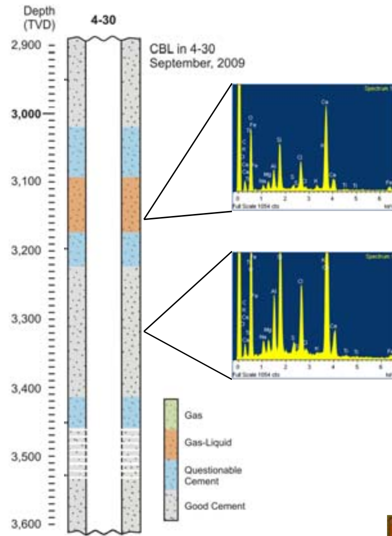
Crosswell Survey between Injection and Distant Monitoring Well

- An additional cross section was collected and will be repeated post injection to help determine geologic heterogeneity over a larger area



Cement Evaluation

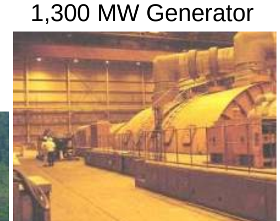
- Cement bond log indicated a gap in cement across from the upper velocity decrease
- Over time, the cement bond log indicated an apparent change in the cement both above and below the decrease
- Cement samples were taken from two locations in the well
    - The sample in the interval the CBL indicated had poor quality cement was carbonated cement
    - The lower sample in the interval the CBL indicated had high quality cement was non-altered, high quality cement
- A fluid sample taken from the interval with the velocity decrease was analyzed to be over 99% CO_2.



AEP Mountaineer Plant

Initial DOE Funded Project, evolved into a Private AEP-Funded Project. Separate from MRCSP Demonstrations


Mountaineer Plant

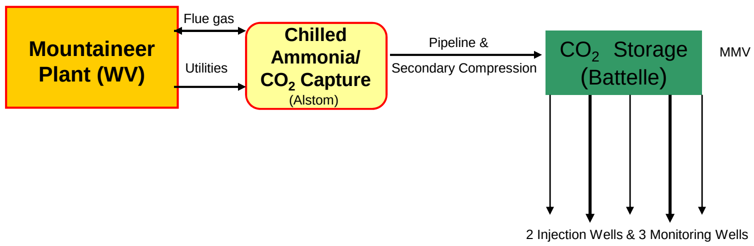
1,300 MW Generator



9,000 ft deep test well (c.2003)

Project Location
New Haven, WV

Product Validation Facility (PVF) at AEP's Mountaineer Plant

Battelle
The Business of Innovation



- 20 MW (electric) slip stream from FGD outlet
- Capture and store ~100k–165k tonnes of CO_2 per year
- Started engineering, planning, and permitting in Sep 07
- Started construction 2Q 2008, in operation ~ 1 Sep 09
- Alstom responsible for CAP island, AEP responsible for utilities to/from CAP island and CO_2 storage with Battelle as contractor

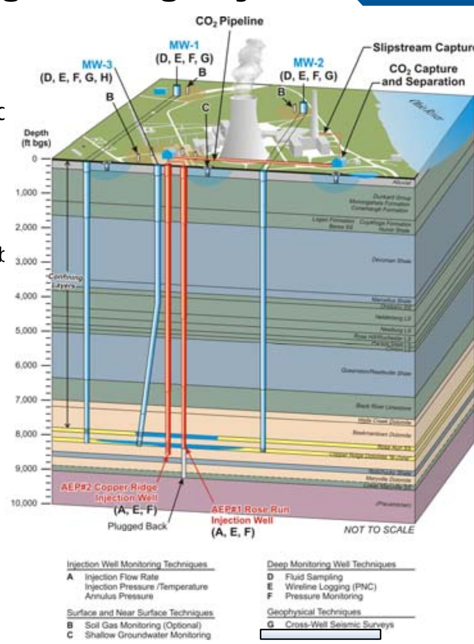
29

AEP Mountaineer Geologic Storage System

Battelle
The Business of Innovation

(Gupta, et al, 2008 – Subject to change)

- Extensive monitoring will be conductec for leak detection and plume tracking. The monitoring suite includes:
  - Pressure, Temperature at well head, at bottomhole, and in annular space
  - Corrosion monitoring of the injection tuk and pipeline
  - Three deep monitoring wells for:
    - Pressure, temperature
    - Fluid sampling
    - Cross-well seismic surveys
    - Repeat wireline logging
  - Shallow groundwater monitoring
  - Soil gas monitoring



30

Battelle Energy Technology: Poised to Deliver Battelle's Core Purposes

New Results from Seismic Monitoring at the Weyburn CO_2 Storage Site

D.J. White

Geological Survey of Canada

May 6, 2010 • Natchez

Outline

- Caprock integrity
  - AVOA analysis
- Overburden Monitoring: Out-of-zone seismic anomalies
  - Amplitude analysis
  - Interval travel time analysis

Goals of Monitoring

- **Storage Security & Leakage**
- Model verification
- **Reservoir integrity**
- Efficient storage
- Accounting

Weyburn Field

Weyburn Unit:

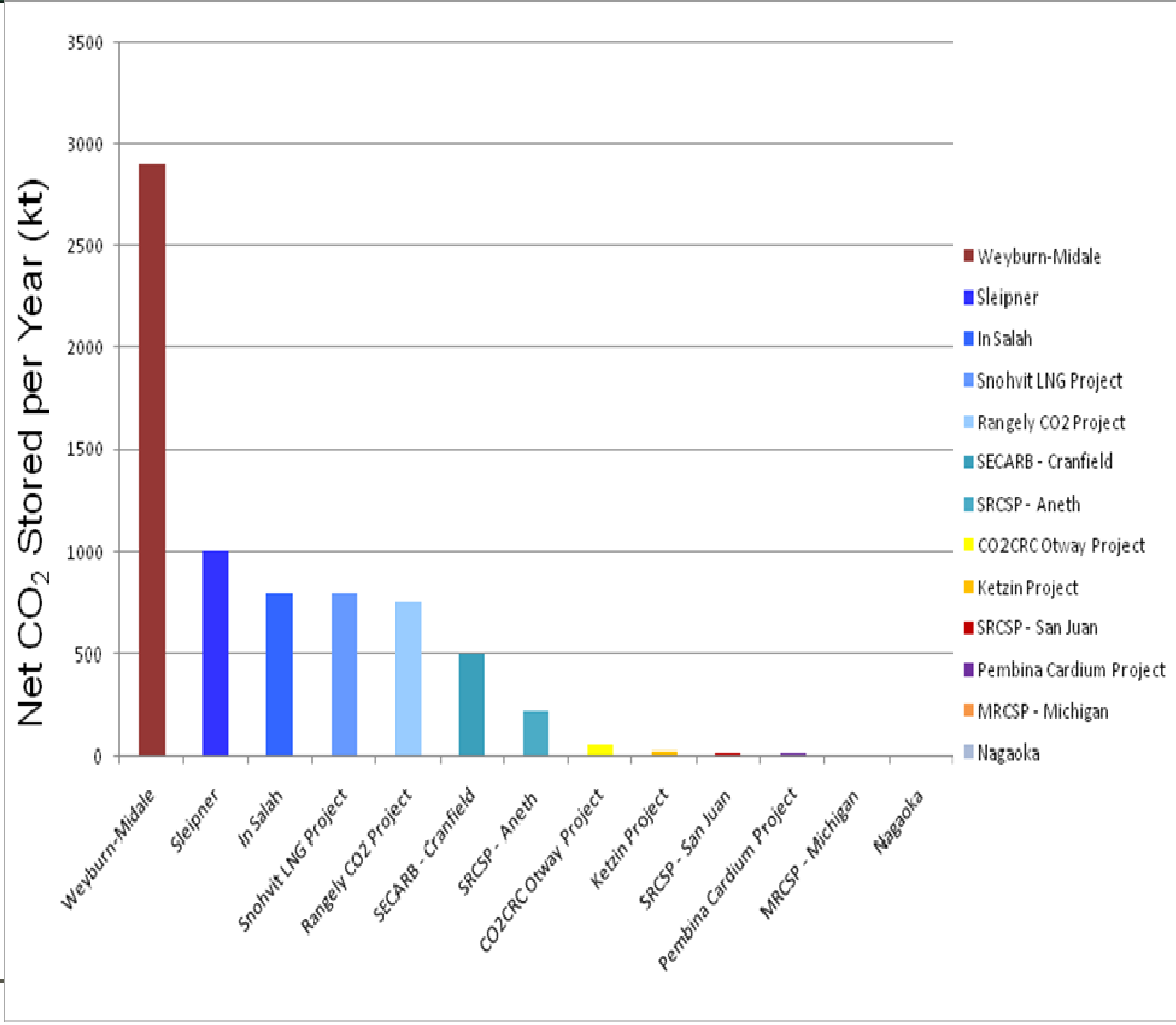
Field Size: 70 sq. miles

Oil Recovered: 370 million bbls

OOIP: 1.4 billion bbls

CO2 IR: 130 million bbls

IEA Greenhouse Gas R&D Programme

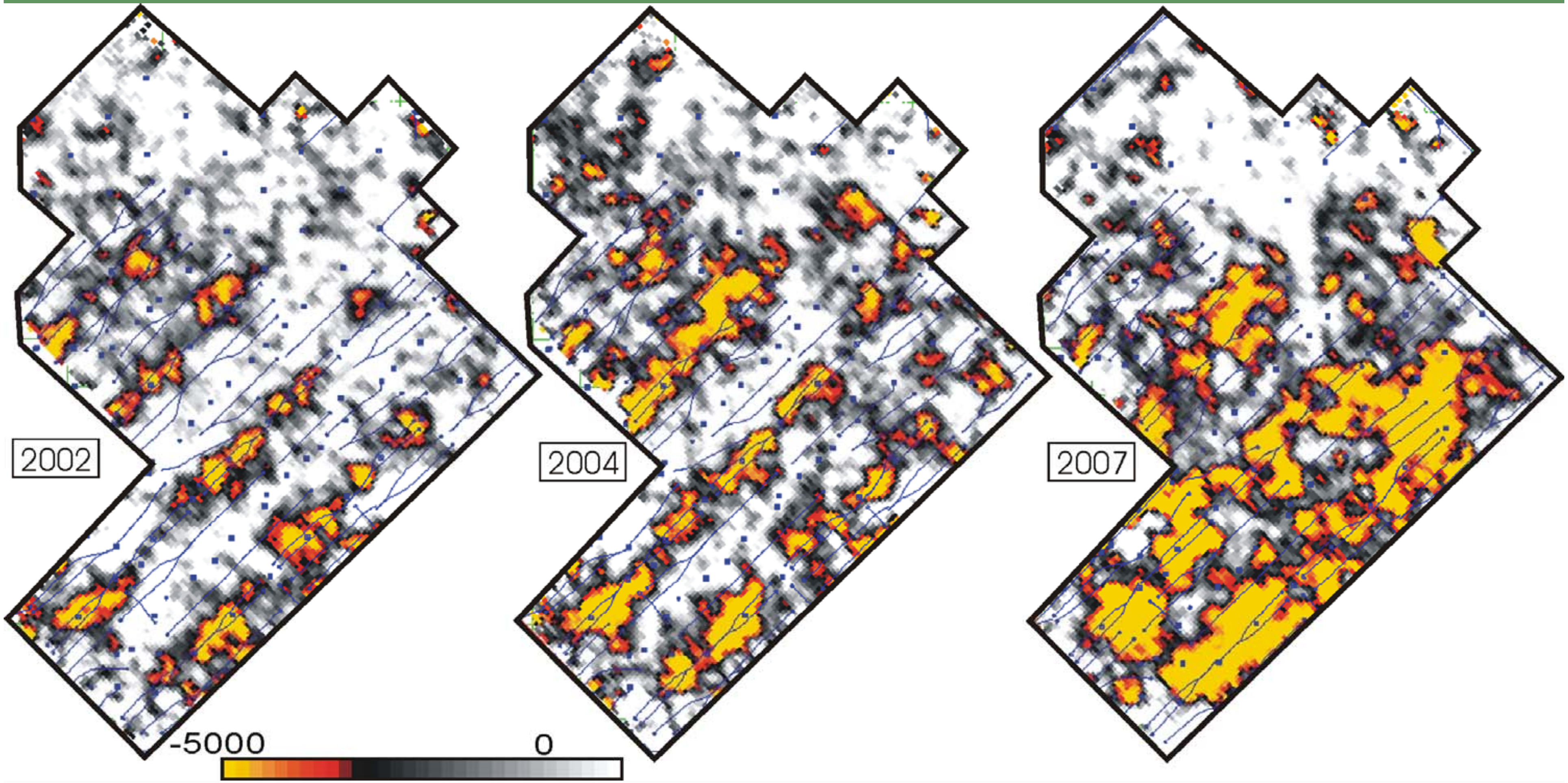


Weyburn Operations Update (Nov. 2009)

- **Total CO_2 stored: 15 Mt**
- **Injection rate: 13,000 T/day (50/50 new vs. recycle)**
- **Individual wells: 50-500 T/day**
- **Target Storage at end of EOR: ~30 Mt**
- **Current oil production: 27,600 bbl/day**

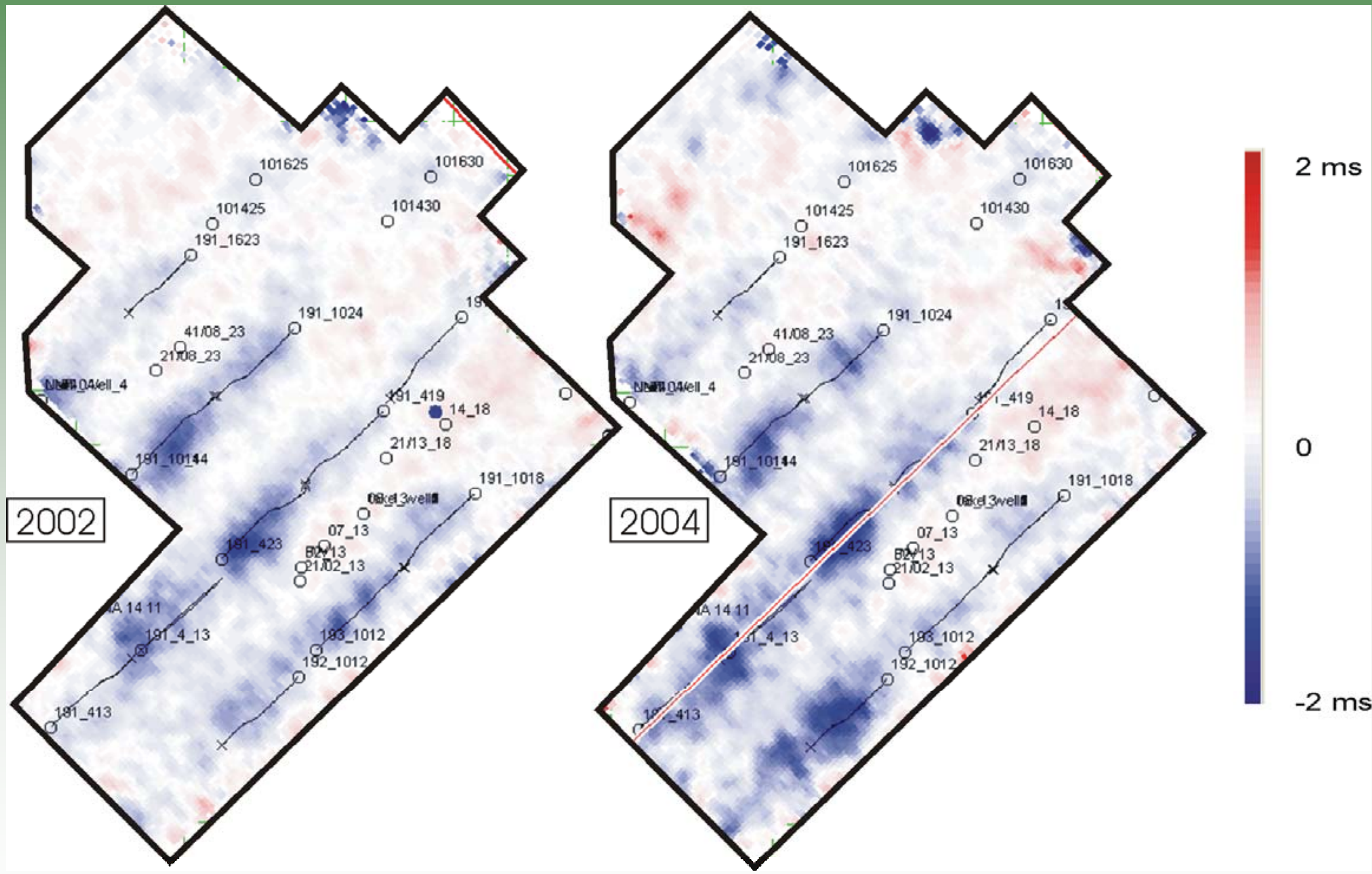
Reservoir: Marly Amplitude Differences

2.8 MT CO_2 | **3.7 MT CO_2** | **7.4 MT CO_2**



Traveltime Differences incl Reservoir (to Bakken)

2.8 MT CO_2 | **3.7 MT CO_2**

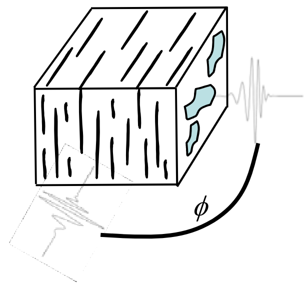


Caprock Integrity: AVOA Anisotropy Analysis

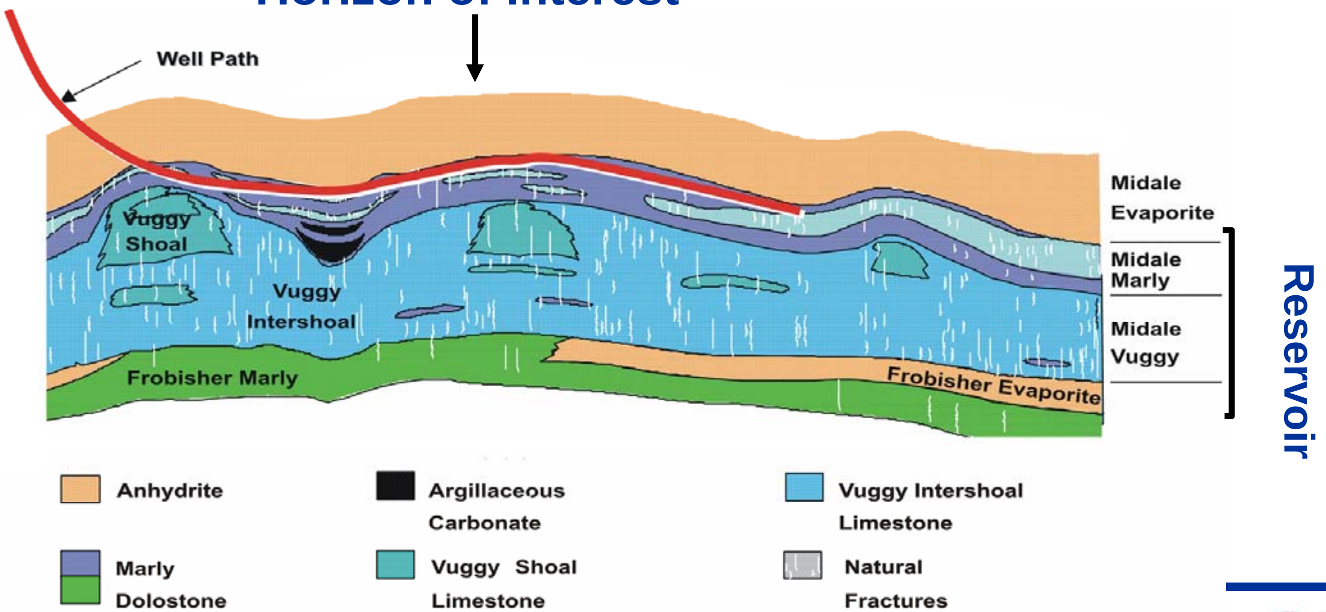
Anisotropy can result from:

- Horizontal stress field
- Mineral fabrics
- Faults, fractures or micro cracks

HTI anisotropy (aligned vertical fracture set)



Horizon of Interest



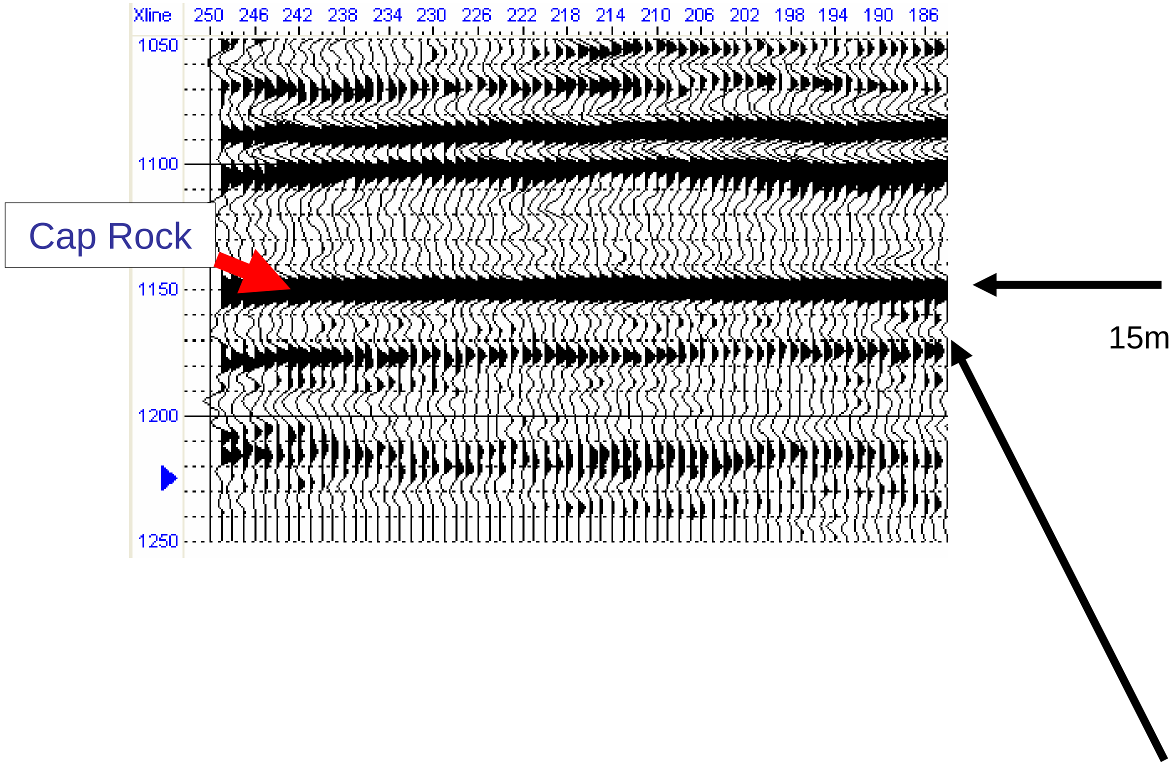
Natural Resources Canada Ressources naturelles Canada

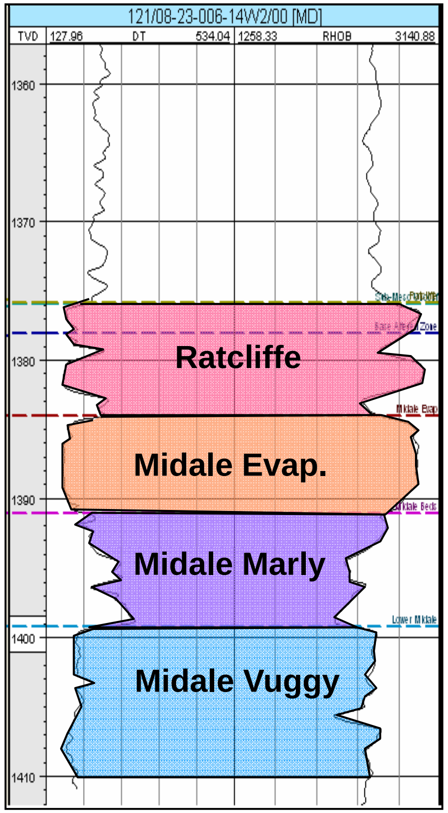
ptrc Petroleum Technology Research Centre

Carleton UNIVERSITY

Introduction - Seismic Data

Seismic Stack Image

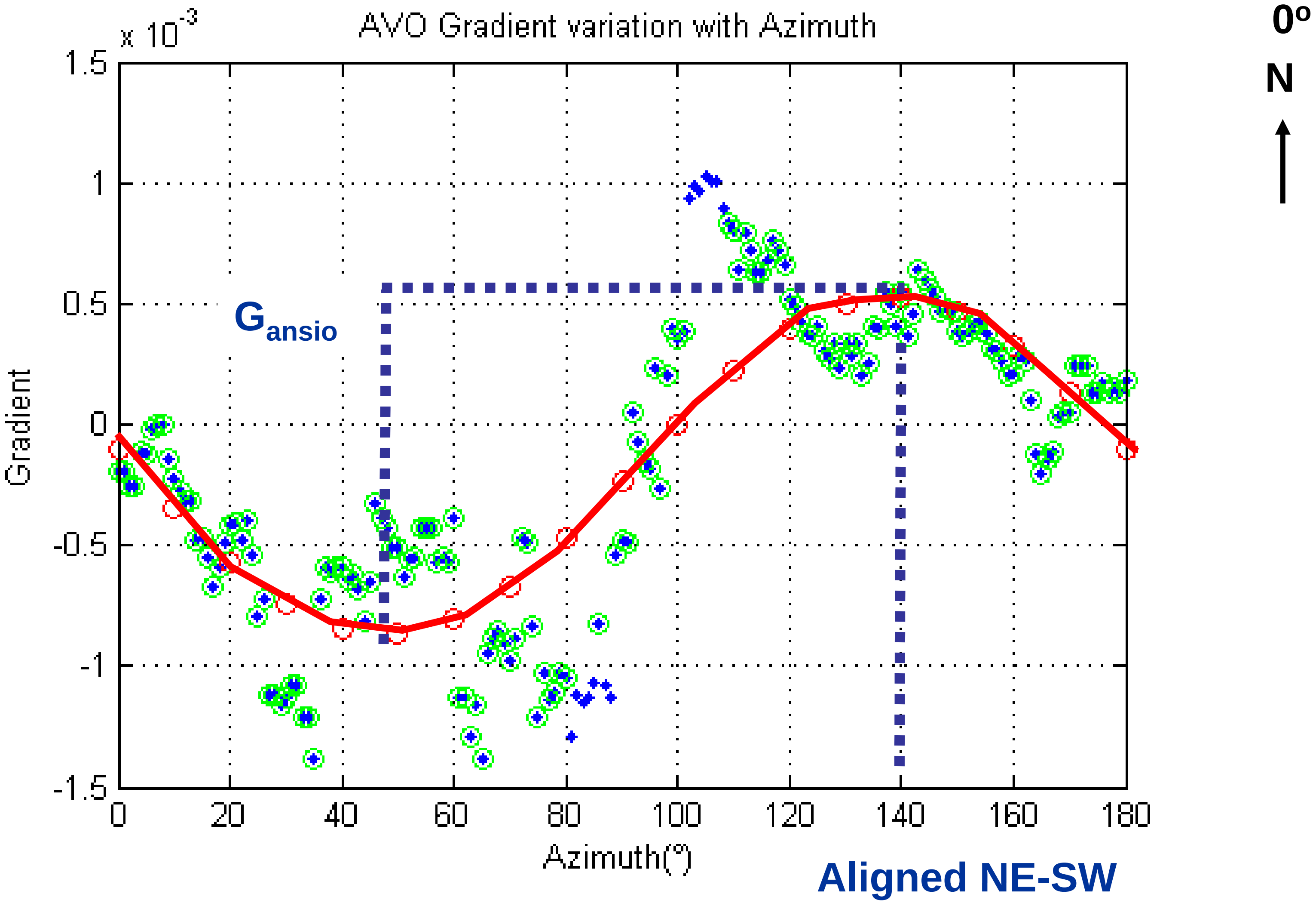




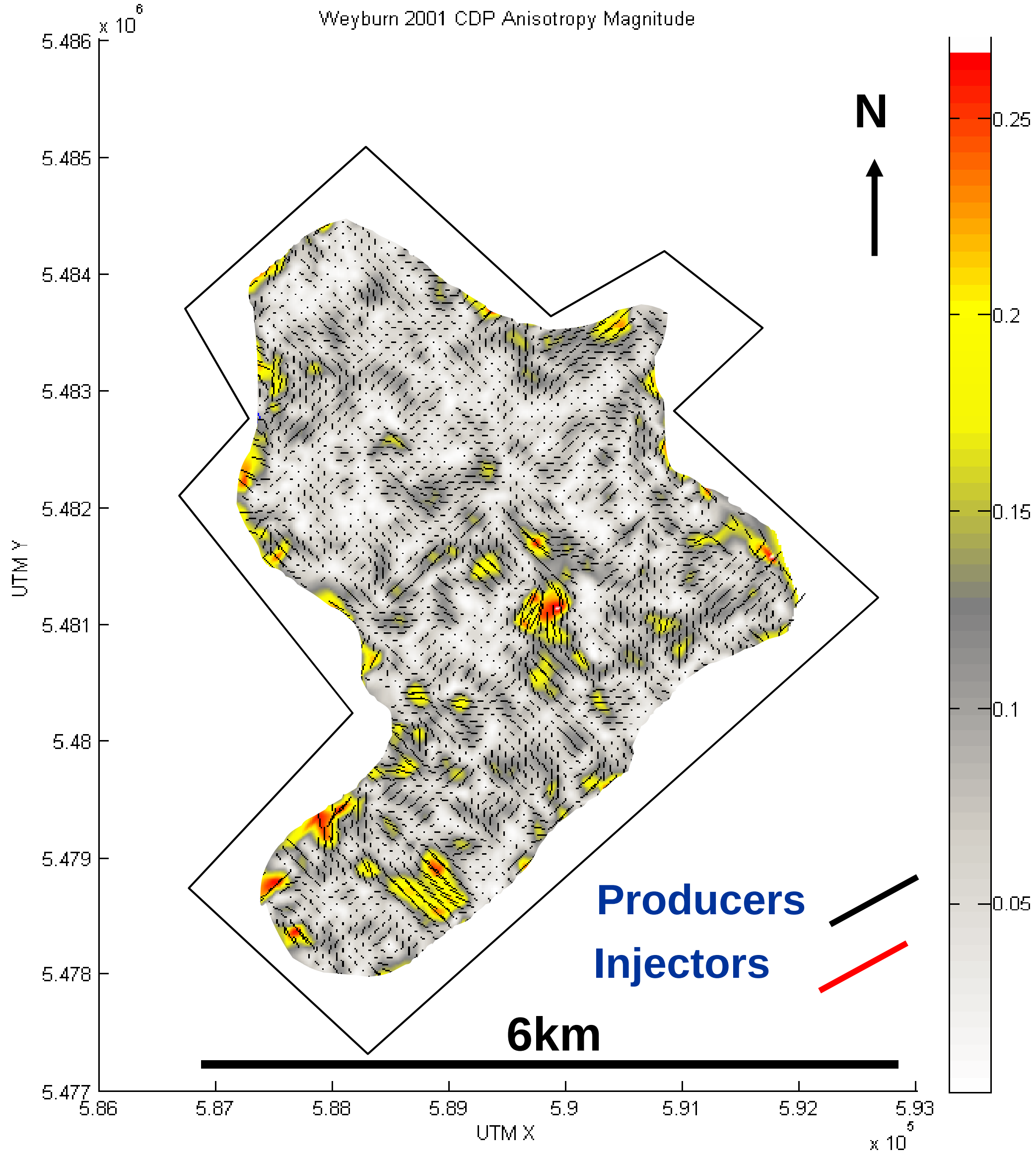
Cap Rock

Reservoir

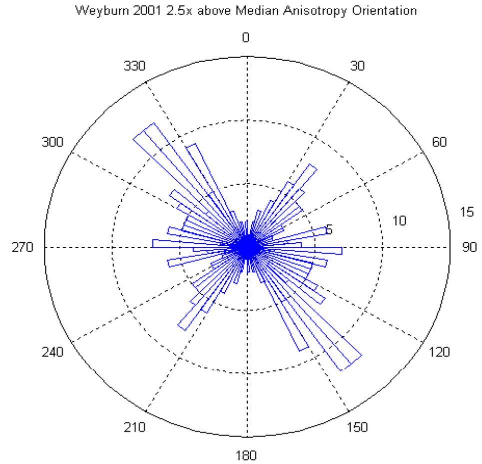
Field Data - AVOA



Field Data - Anisotropy Maps



High Anisotropy



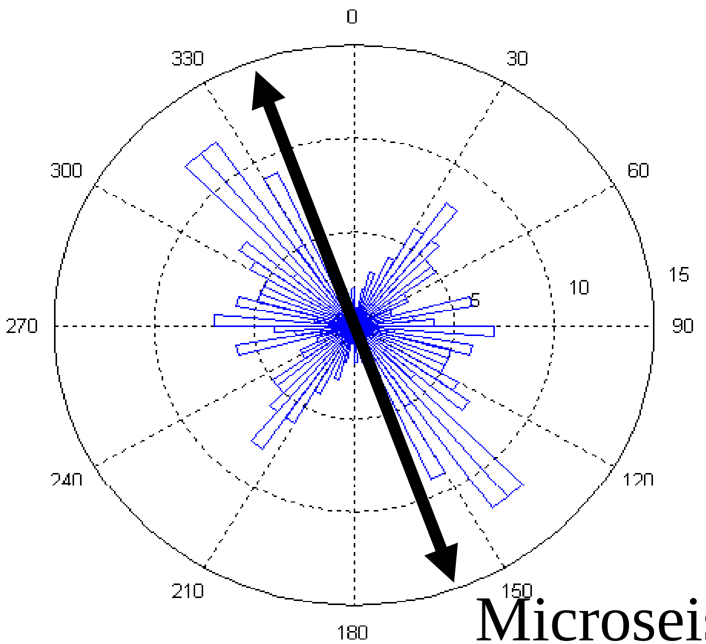
Anisotropy above 2x the median value

Approx 200 of 3995 points

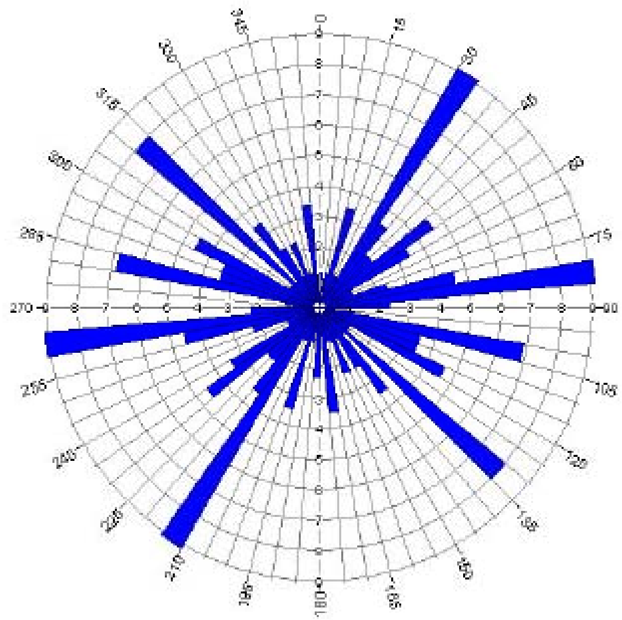
No Anisotropy

Anisotropy = Fractures?

Weyburn 2001 2.5x above Median Anisotropy Orientation



All Fractures



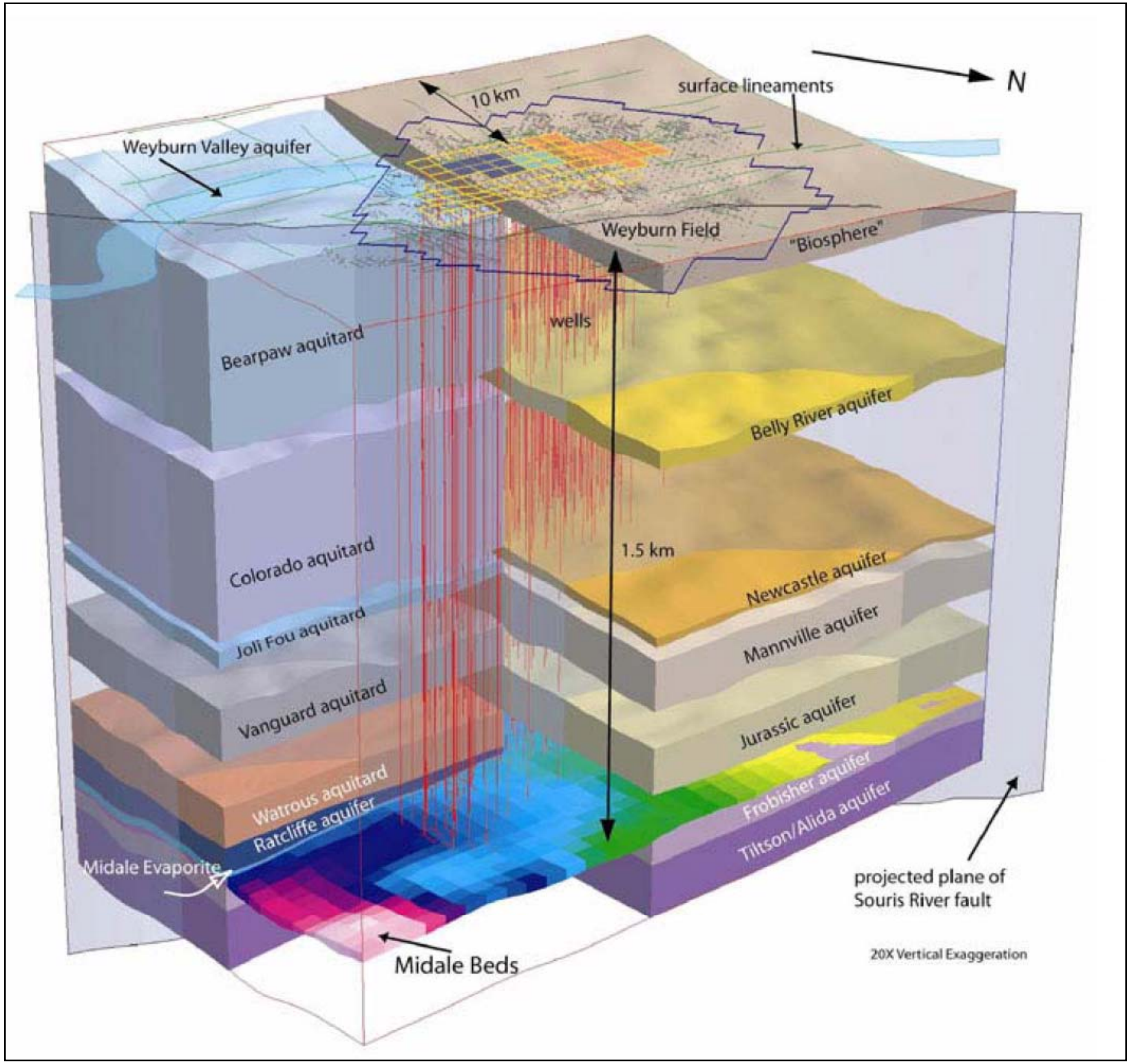
Microseismic
Shear-wave splitting

N=88 (100%)

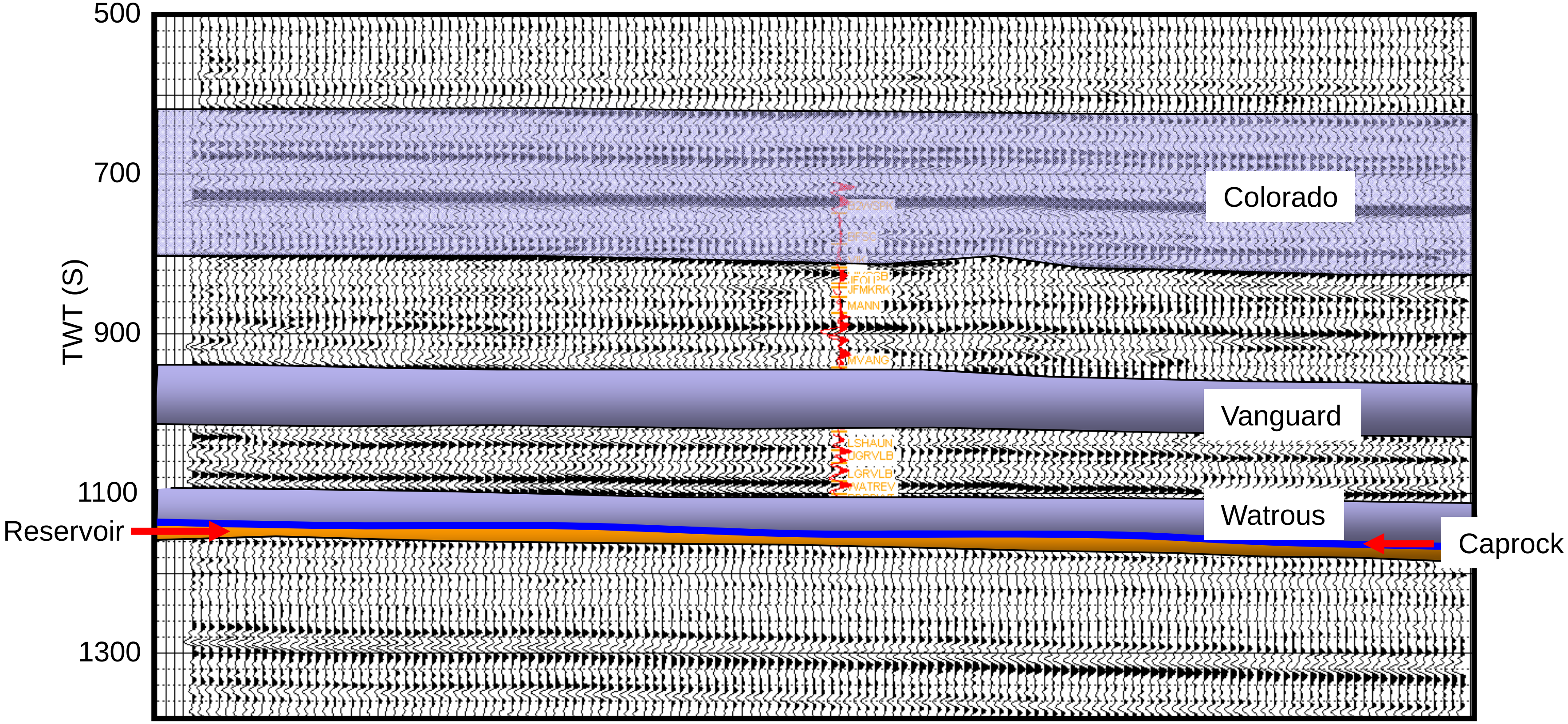
Bunge (2000)

Storage Security: Overburden Monitoring

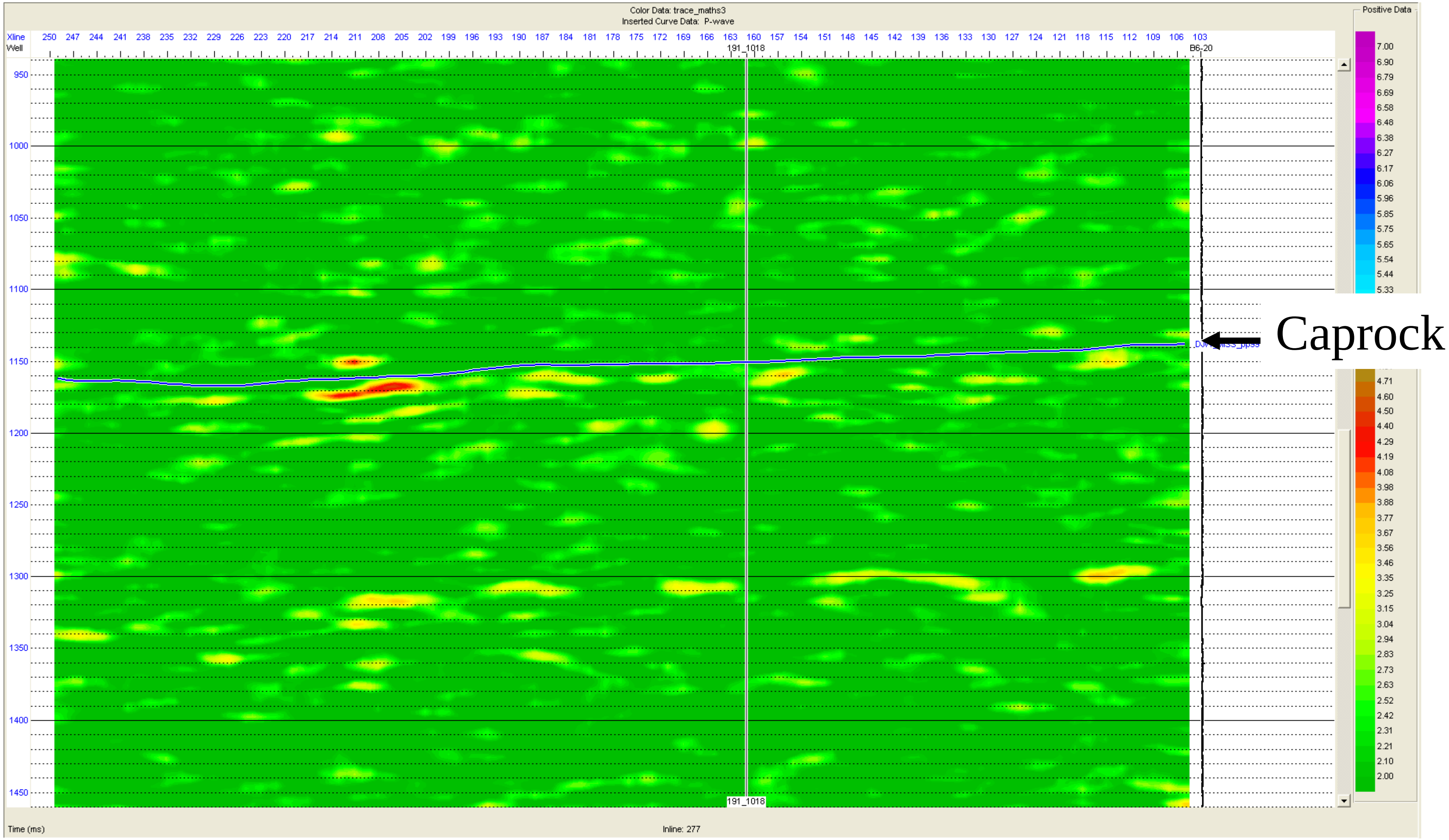
Geological Model



Regional Seals

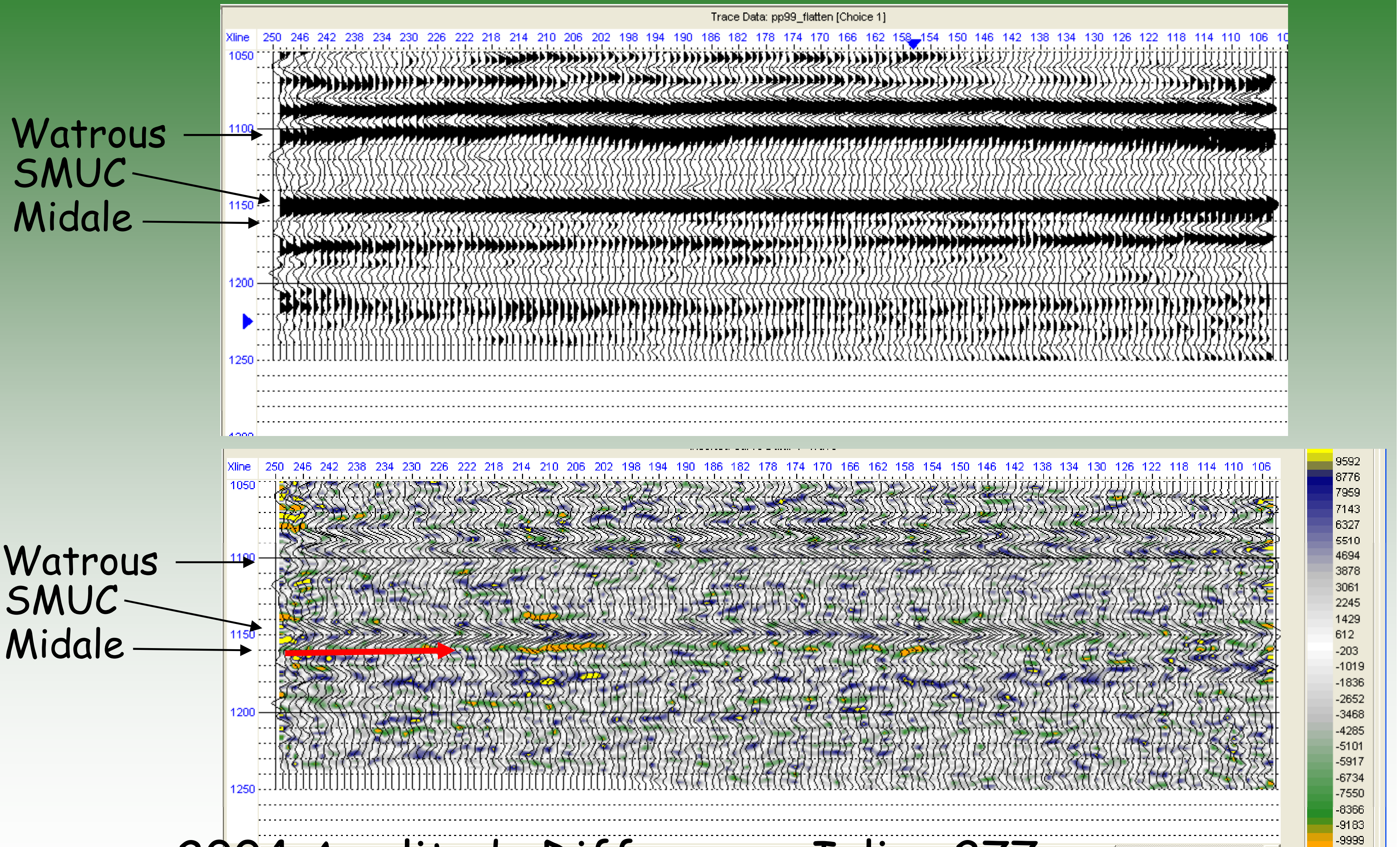


2004 Amplitude Difference: Vertical Slice



Post-stack matching including time-variant stretching

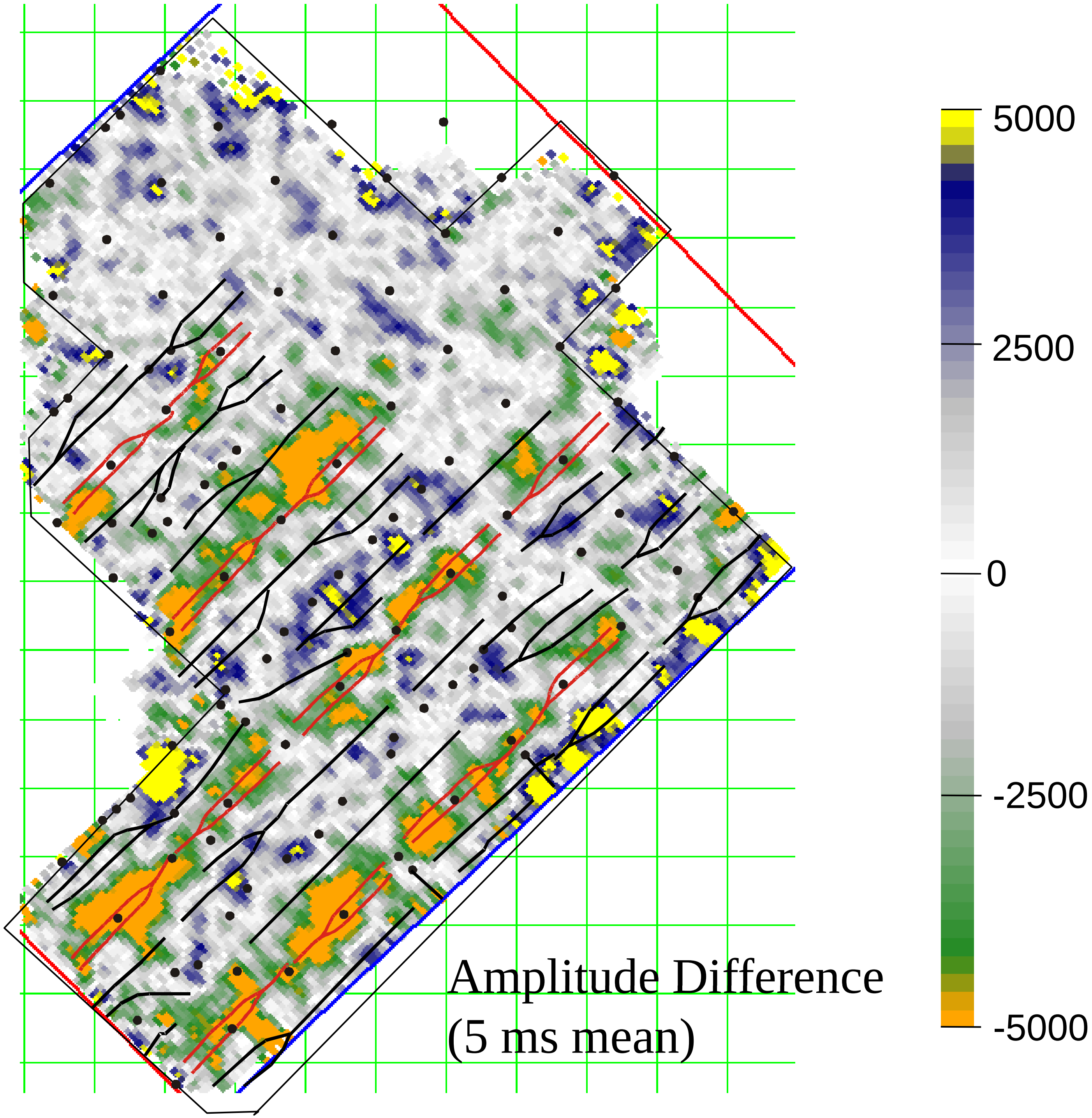
Weyburn Seismic



2004 Amplitude Difference: Inline 277

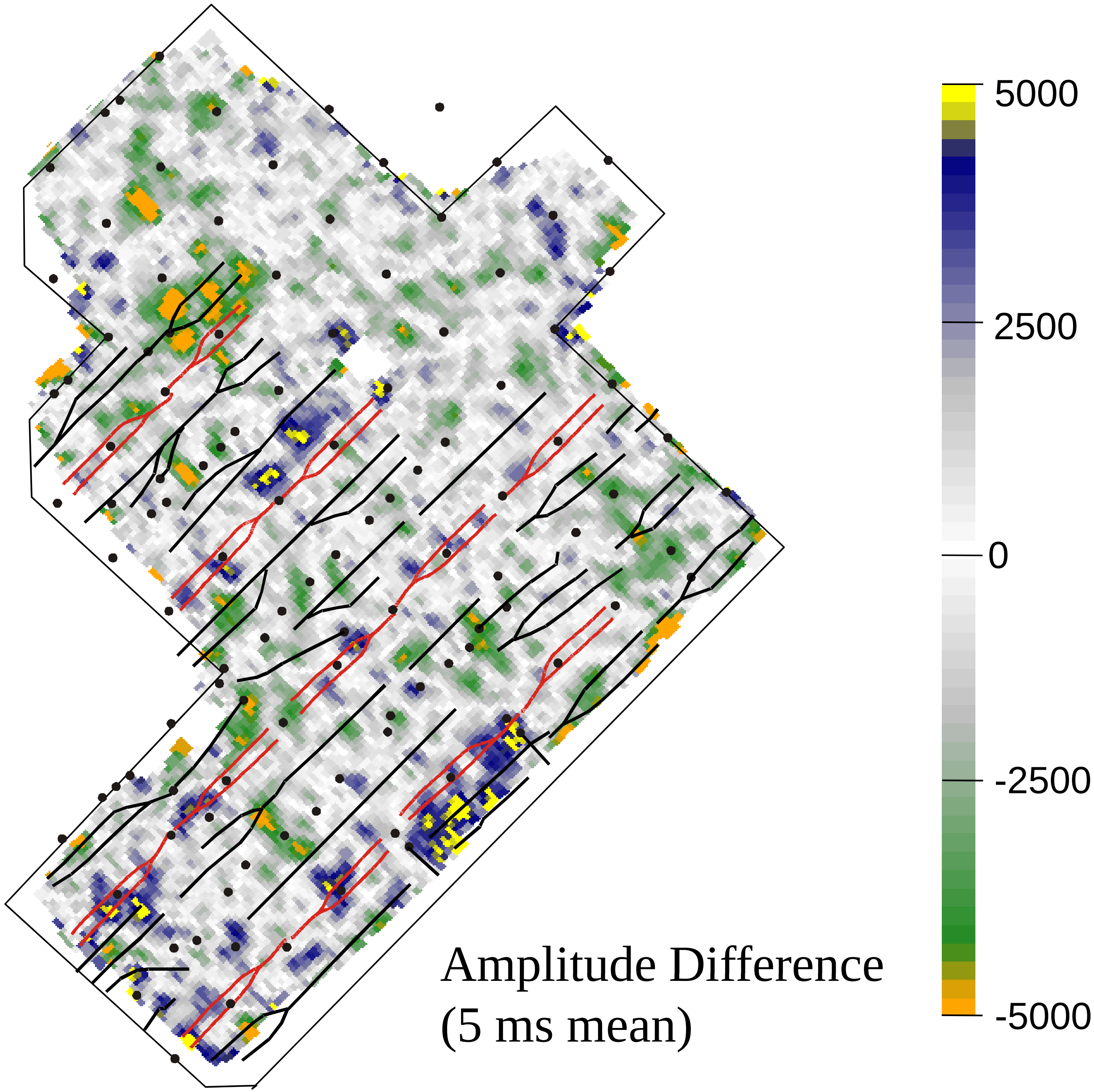
2004

Reservoir
(1158 ms)

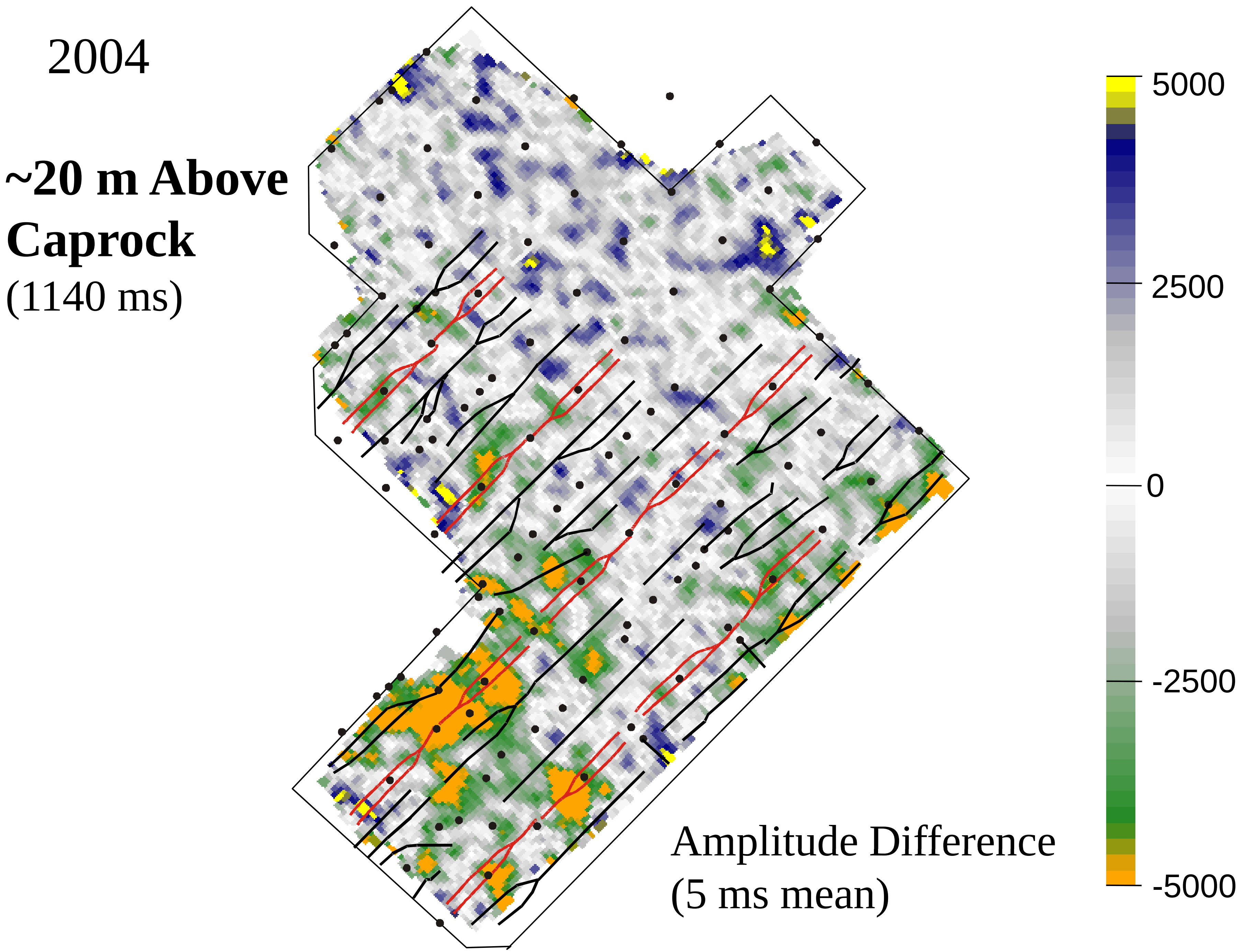


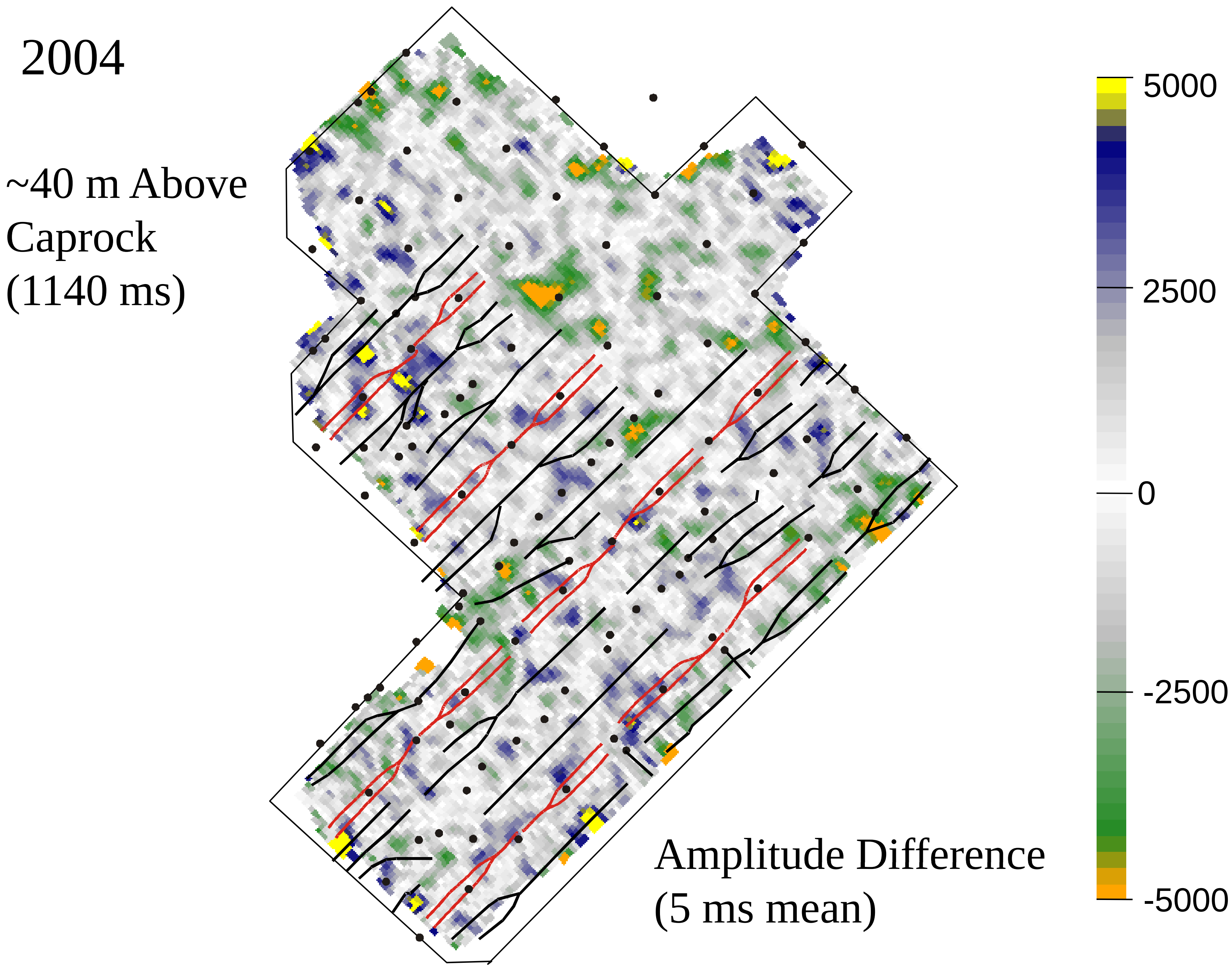
2004

Caprock
(1150 ms)

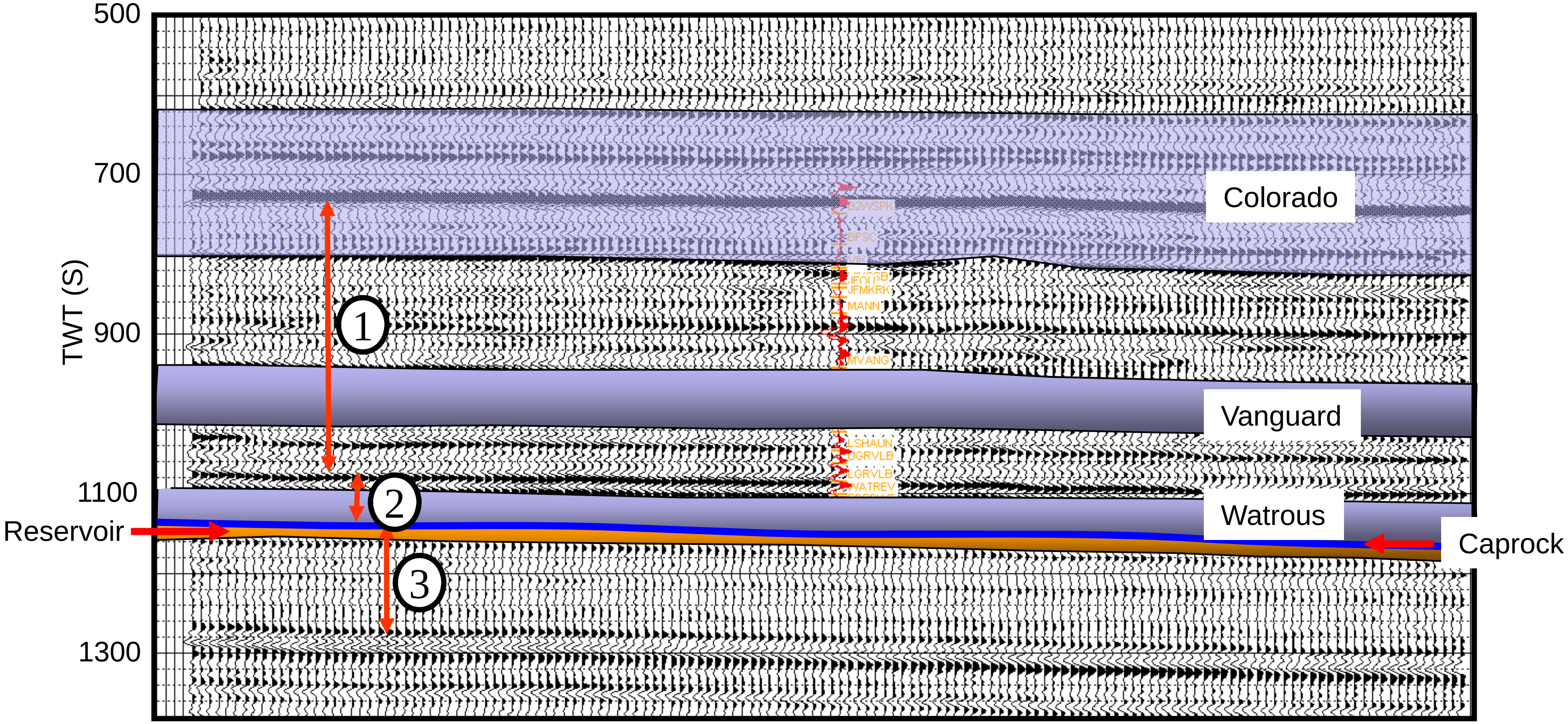


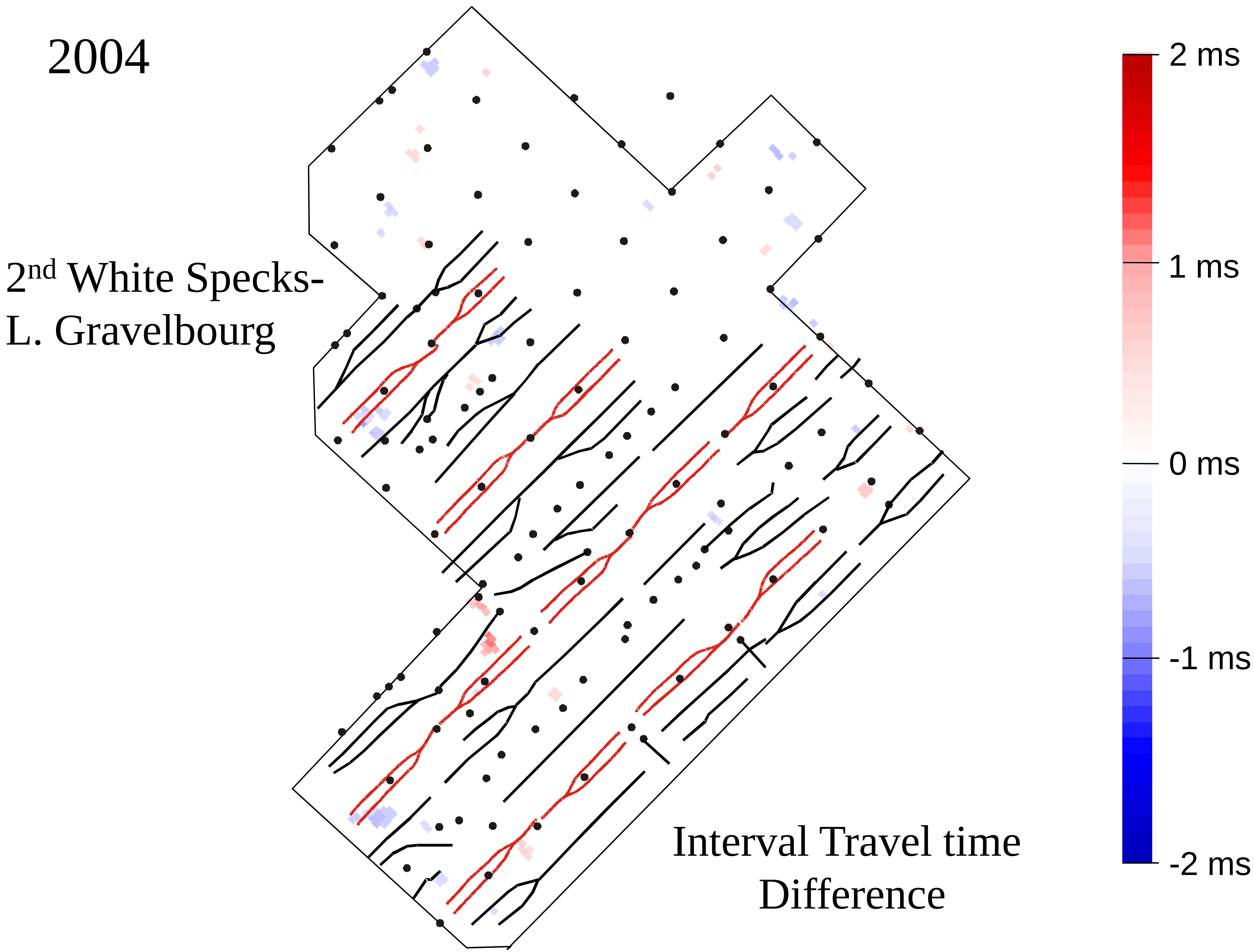
Amplitude Difference
(5 ms mean)

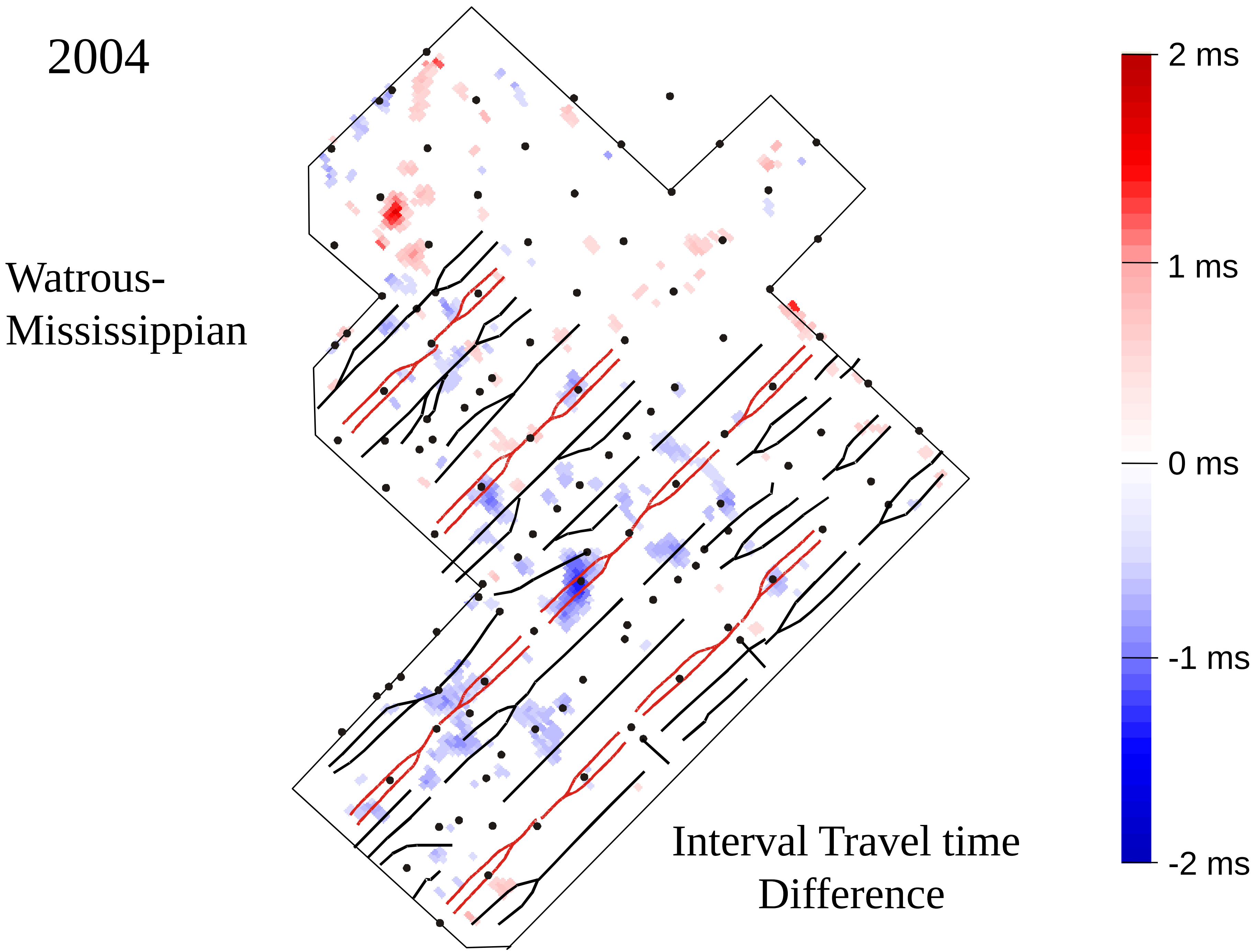

2004
~20 m Above
Caprock
(1140 ms)
Amplitude Difference
(5 ms mean)
5000
2500
0
-2500
-5000

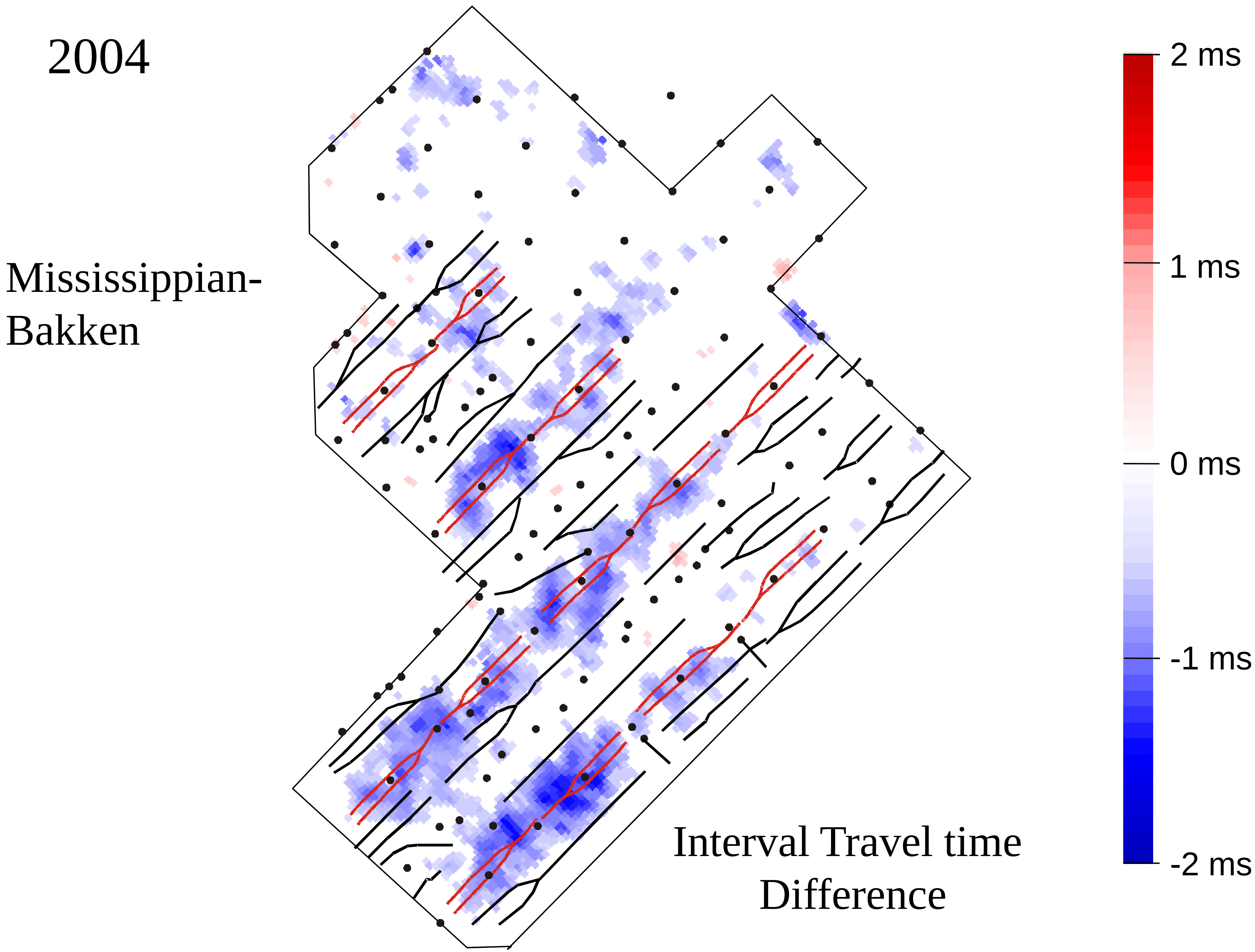

2004
~40 m Above Caprock (1140 ms)
Amplitude Difference (5 ms mean)
5000
2500
0
-2500
-5000

Regional Seals




2004
2nd White Specks-
L. Gravelbourg
Interval Travel time
Difference
2 ms
1 ms
0 ms
-1 ms
-2 ms


2004
Watrous-
Mississippian
Interval Travel time
Difference
2 ms
1 ms
0 ms
-1 ms
-2 ms

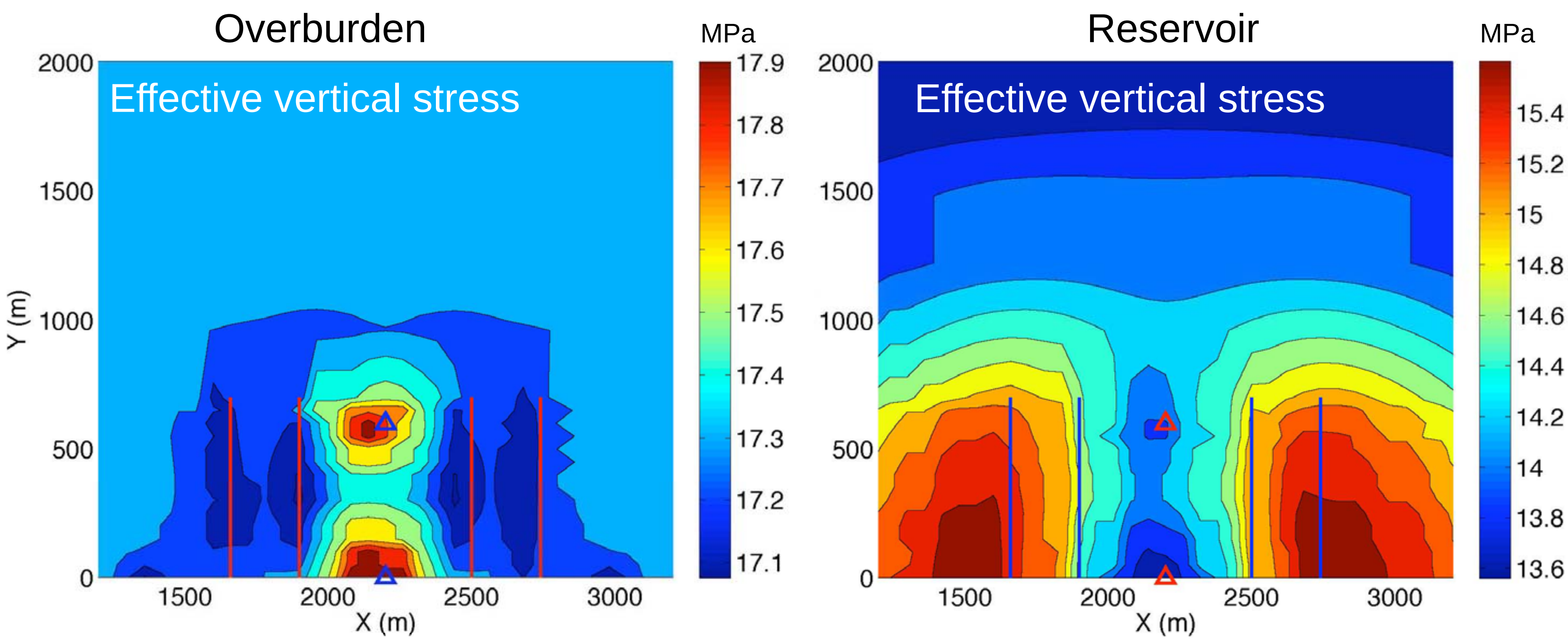


2004
Mississippian-
Bakken
Interval Travel time
Difference
2 ms
1 ms
0 ms
-1 ms
-2 ms

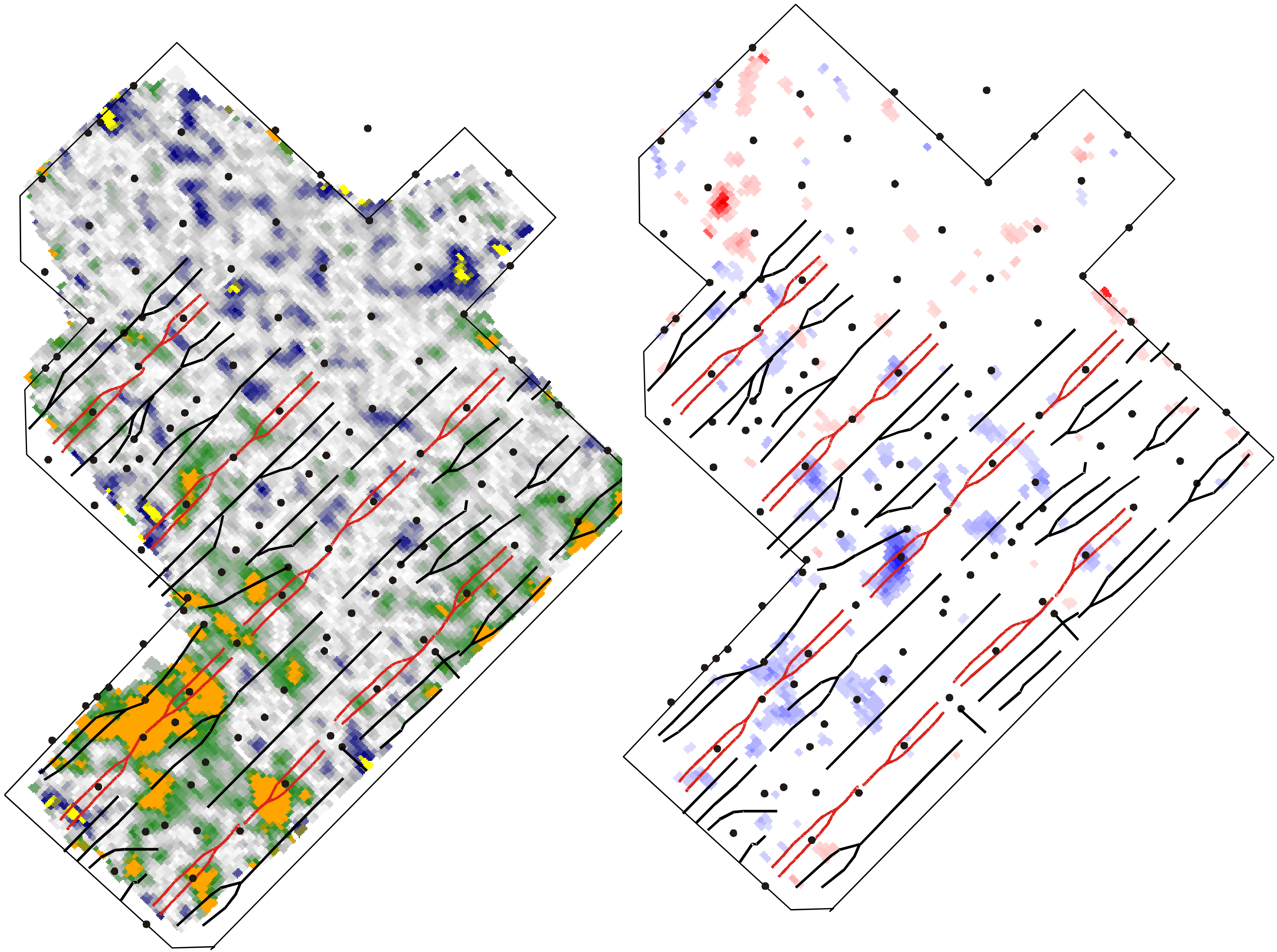
OOZ Anomalies: Possible Causes

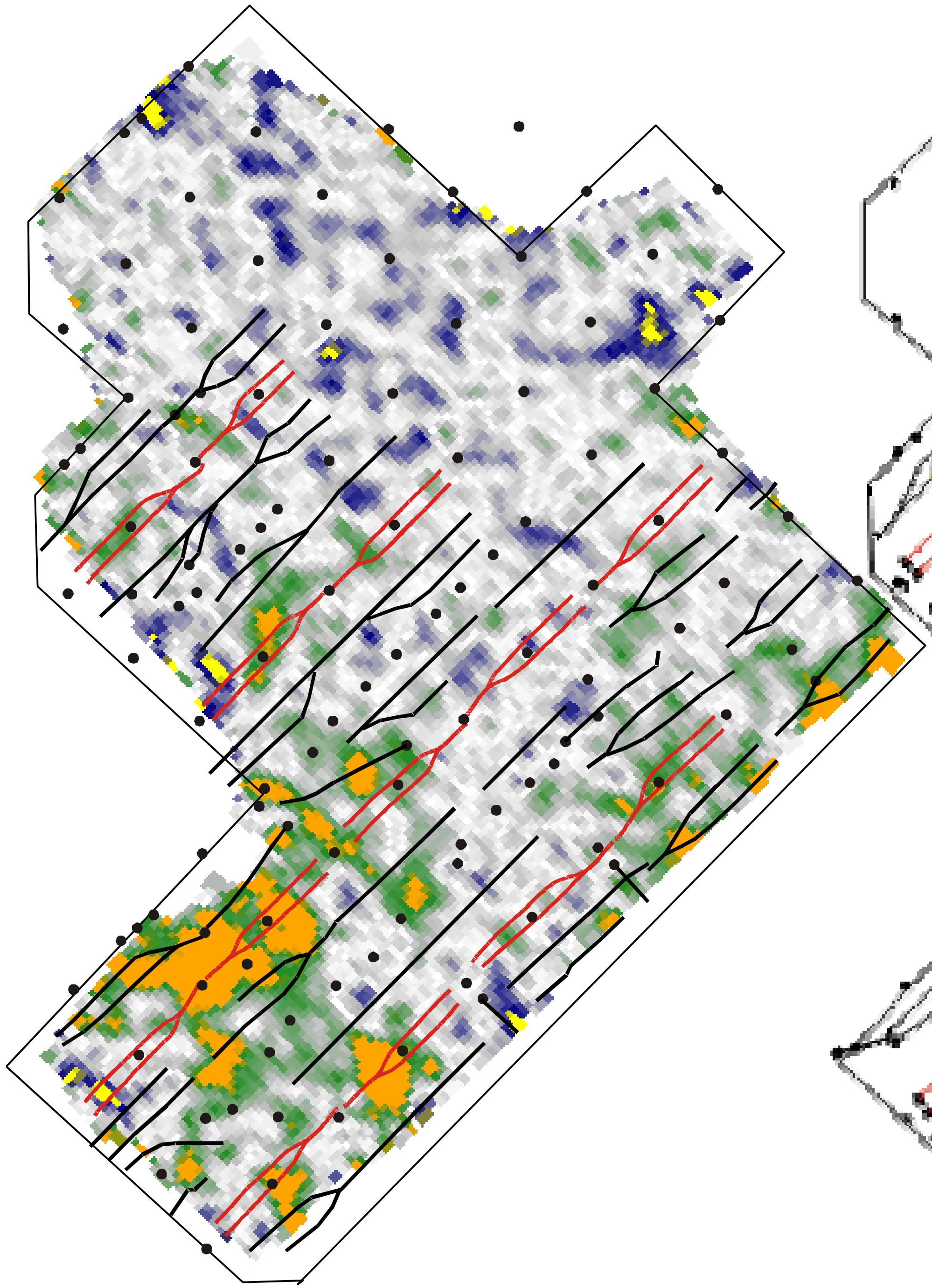
- Induced stress changes in the immediate overburden
- Seismic artifacts (non-repeatability, etc.)
- Out-of-zone CO_2

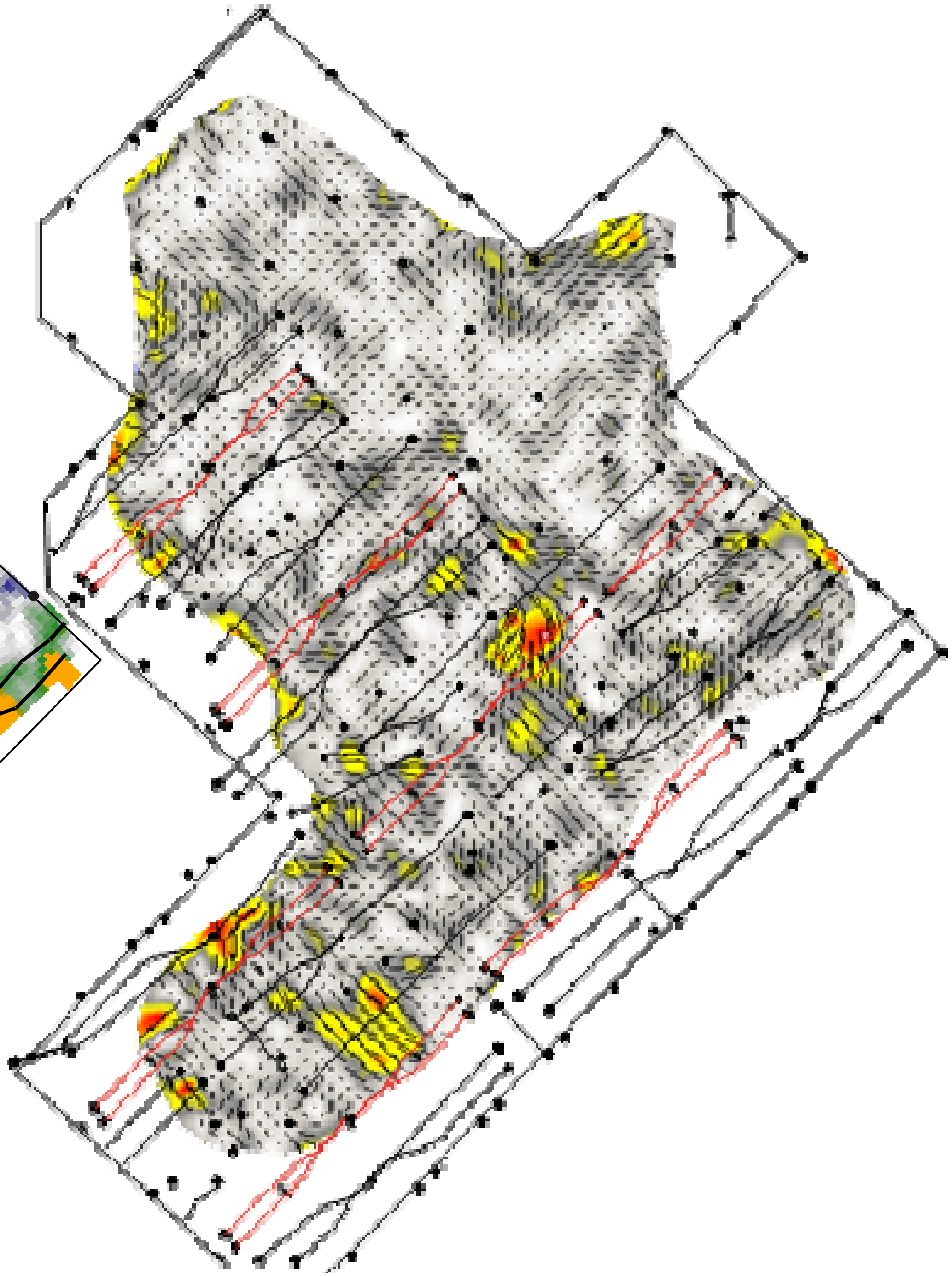
Stress in the overburden



J. Verdon, Bristol University







Conclusions

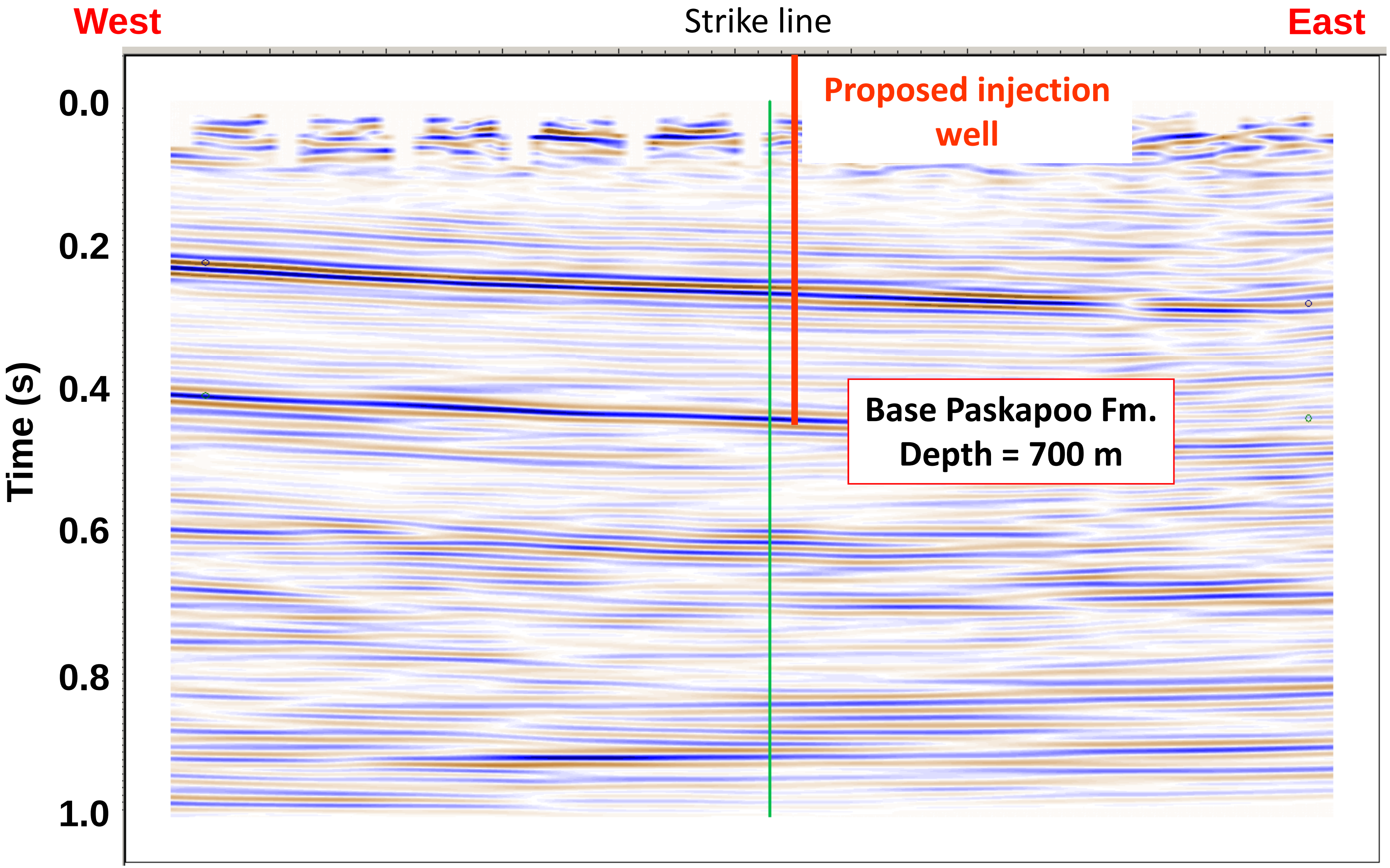
- Time-lapse amplitude & travel time anomalies are observed immediately above the reservoir caprock, at the base of the storage complex.
- They may be associated with OOZ CO2 and/or injection induced stress changes in the overburden.
- Isolated anisotropic regions have also been identified at the caprock horizon that may be associated with vertical fracturing.
- Further work (modelling) is needed to assess the geological cause of these anomalies.
- OOZ CO2 does not necessarily imply upward migration of CO2; it may be the direct result of EOR injection procedures.

Acknowledgements

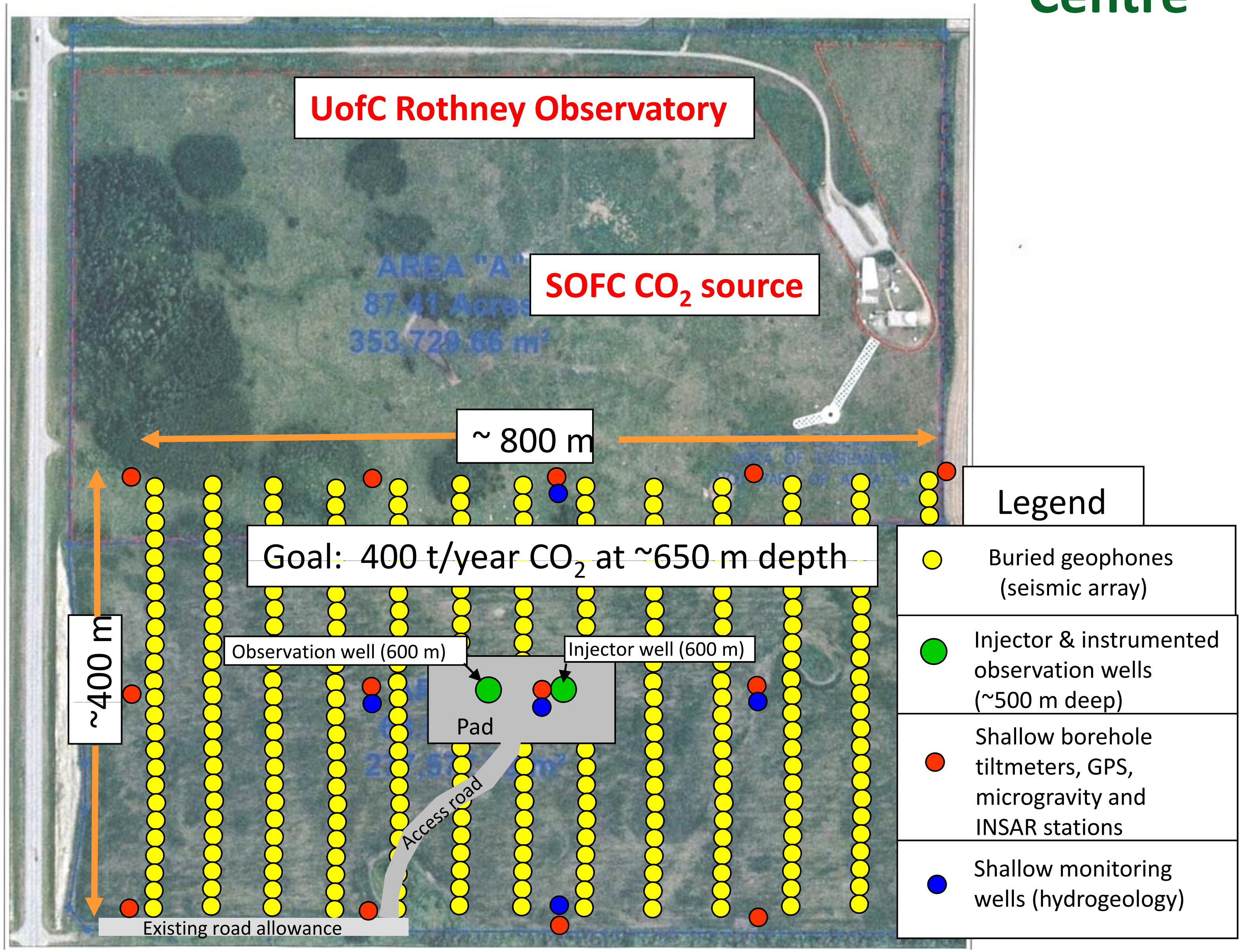
- Mike Kendall, James Verdon, U Bristol
- Sandy Duxbury, Claire Samson, Carleton U
- Mark Meadows, Fugro Imaging
- Steve Whittaker, Barbara Dietiker, PTRC
- David Cooper, Geoff Burrowes, EnCana

UofC Rothney Astrophysical Observatory

Line from seismic volume

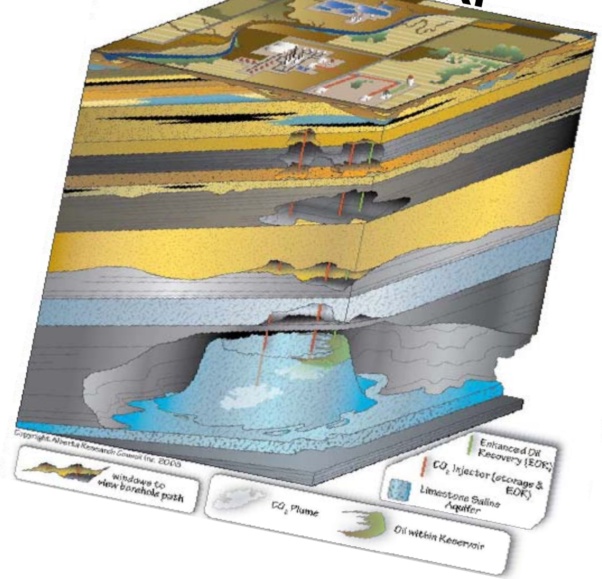


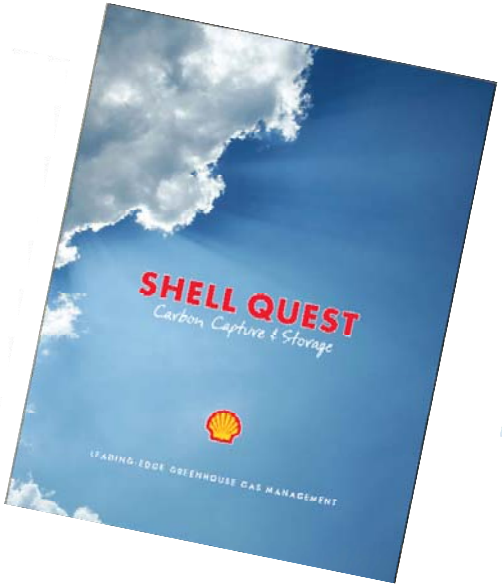
UofC/CMC Priddis CCS Field Research Centre

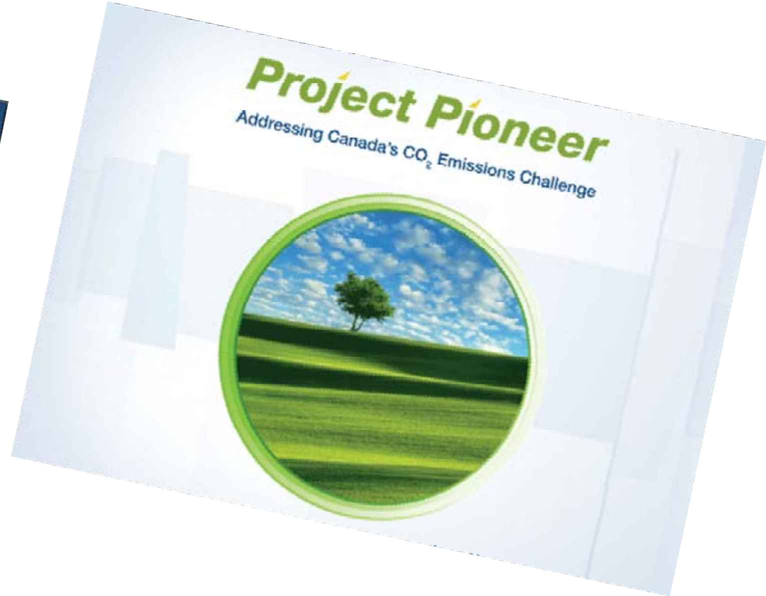


Alberta CCS Projects

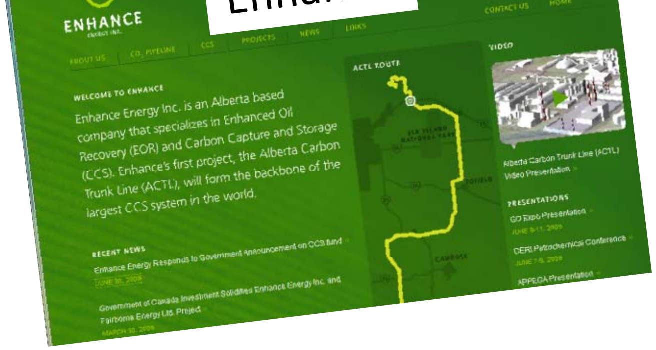
HARP



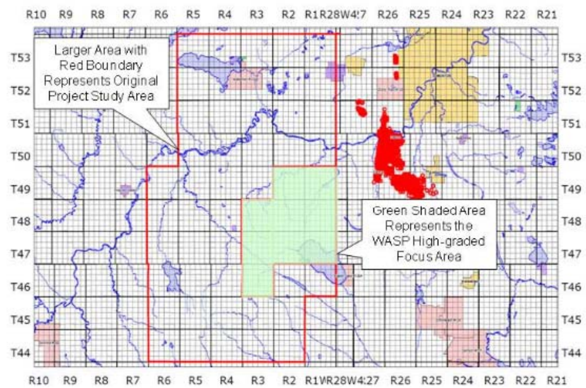




Enhance



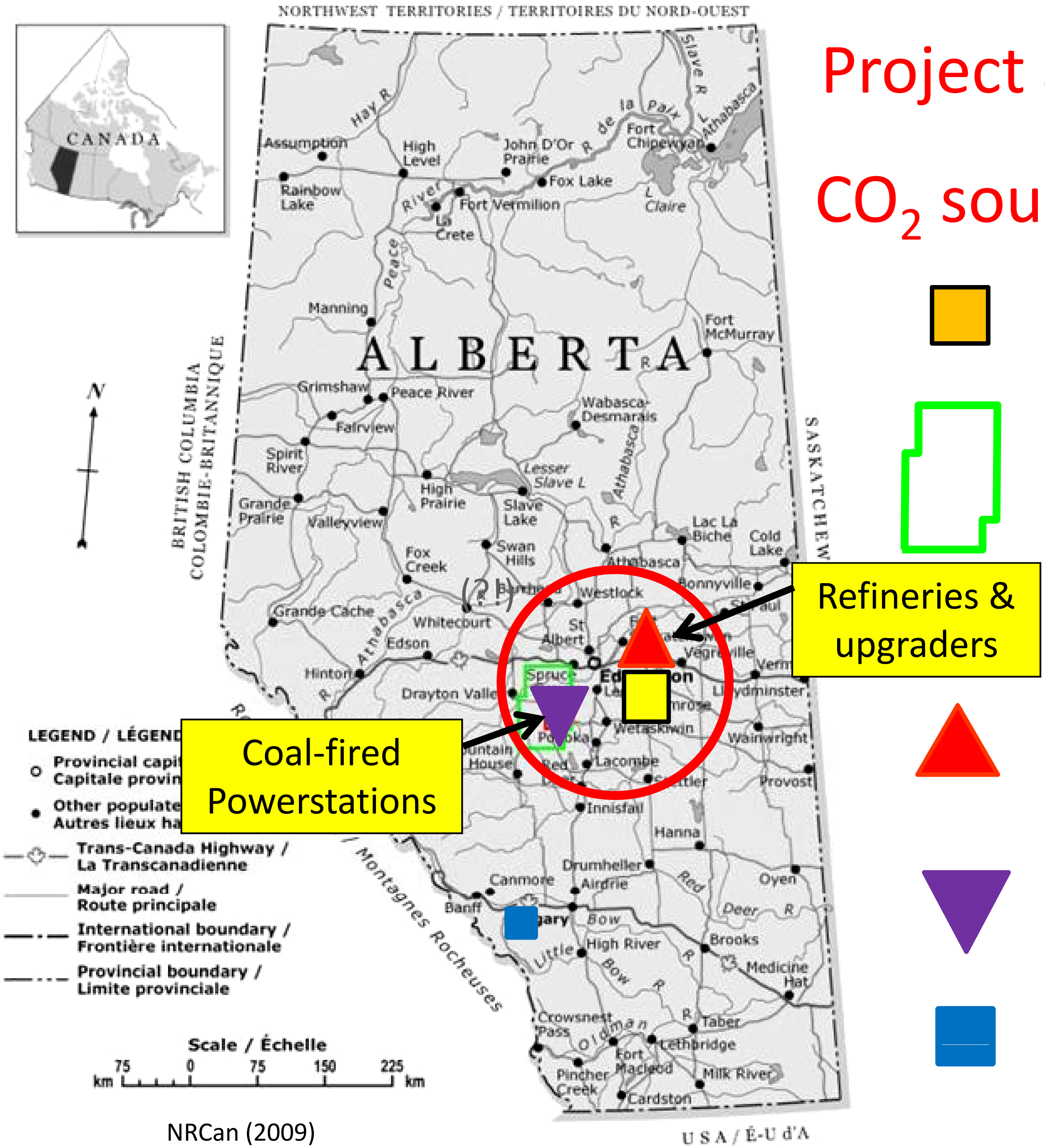
WASP



Goal: 4 projects each storing 1 Mt/year by 2015

Project areas

CO_2 sources



NRCan (2009)

U.S. EPA's Proposed Greenhouse Gas Reporting Rule for Carbon Dioxide Injection and Geologic Sequestration

6th IEA GHG Monitoring Network Workshop
May 7, 2010

Barbora Master, Office of Air and Radiation, EPA

Presentation Outline

- Introduction
- EPA's GHG Reporting Program
- EPA's UIC Program
- EPA's proposal for CO_2 Injection and GS Reporting

Introduction: EPA Role

- Evaluating and developing appropriate regulatory frameworks
- Evaluating risks to human health and the environment
- Working to understand and address CCS public acceptance issues
- Designing inventory and accounting methodologies
- Improving cost estimates

EPA's Proposal for CO_2 Injection and GS Reporting: Introduction

- EPA is proposing reporting mechanisms for facilities that inject carbon dioxide (CO_2) underground, such as for enhanced oil and gas recovery (ER) or for long-term geologic sequestration (GS).
  - Proposal published in FR April 12, 2010
  - 60 day comment period ends June 11, 2010

- Relationship to other EPA rulemakings:
  - The proposal amends EPA's Greenhouse Gas Reporting Program promulgated under the authority of the Clean Air Act
  - The proposal is complementary to and builds on EPA's proposed Underground Injection Control (UIC) Class VI requirements for geologic sequestration wells promulgated under the authority of the Safe Drinking Water Act.

Background on EPA Greenhouse Gas (GHG) Reporting Program

- Directed by Congress in 2008 Appropriations Act
  - Final rule signed September 22, 2009
  - Went into effect January 1, 2010
- EPA issued the rule pursuant to its authority under the Clean Air Act
- The rule provides for reporting of GHG data from all sectors of economy above appropriate thresholds to inform future climate change policies and programs
  - Covers all six GHGs
  - 25 source categories
  - 5 types of suppliers of fuel and industrial GHG – including CO_2 suppliers
  - Motor vehicle and engine suppliers (except light duty sector)
  - Does not require control of GHGs

Background on EPA GHG Reporting Program

- Subpart A: General Provisions
  - Applicability provisions
  - Schedule
  - Reporting and recordkeeping requirements common to all reporters
  - Definitions
  - Report submission procedures
  - Other (e.g., calibration procedures, monitoring plan)

- Subparts C-PP: Source-Specific Requirements
  - Definition of source category
  - GHG to report
  - Calculation methods
  - Monitoring and QA/QC
  - Missing data procedures
  - Reporting and recordkeeping elements unique to each subpart

- Subpart PP: Suppliers of CO_2
  - In the final package, EPA committed to developing a mechanism in the near future for industry to report the CO_2 supply that is permanently sequestered

Background on EPA UIC Program

- The Safe Drinking Water Act (SDWA) created Federal regulations for protection of Underground Sources of Drinking Water (USDWs)
  - SDWA requires EPA to develop requirements for underground injection of all fluids – Underground Injection Control (UIC) program
- In July 2008, EPA proposed a rule for the Geologic Sequestration of CO_2 using Safe Drinking Water Act authorities and the UIC Program
  - Priority placed on avoiding endangerment of underground sources of drinking water
  - Existing UIC program provides a regulatory framework (baseline)
  - UIC Class VI proposal
- The proposal creates a new well class for injection of CO_2 for GS and builds on UIC program elements (e.g. Site Characterization, Area of Review, Well Construction, Well Operation, Site Monitoring, Post-Injection Site Care, etc)

EPA's Proposal for CO_2 Injection and GS Reporting: Overview

- The proposal takes a measured, tiered approach:
  - EPA is proposing that all facilities that inject CO_2 underground would report basic information:
    - Amount of CO_2 received onsite from offsite sources
    - Amount of CO_2 injected into the subsurface
    - Source of the CO_2 if known
  - In addition to the reporting requirements listed above, facilities that conduct geologic sequestration would also:
    - Develop and implement an EPA approved site-specific monitoring, reporting, and verification (MRV) plan
    - Report the amount of CO_2 geologically sequestered using a mass balance approach

EPA's Proposal for CO_2 Injection and GS Reporting: Overview (cont'd)

- Data collected under this proposal would:
  - Enable EPA to track the flow of CO_2 across the CCS system and to better understand the quantity of CO_2 supplied to emissive and non-emissive end-uses.
  - Enable EPA and others to track growth and efficacy of GS (and therefore CCS) as a mitigation technology over time and to evaluate relevant policy options.
- EPA has designed this proposal so that facilities can comply without disrupting or delaying normal operations.

EPA's Proposal for Reporting:
Who reports GS

- GS defined as the long-term containment of a gaseous, liquid, or supercritical CO_2 stream in subsurface geologic formations.

- Facilities that inject CO_2 for ER would be required to report basic CO_2 injection data but would not be required to develop MRV plans or report the additional information required for GS. However, they could choose to opt-in to these requirements.

- Geologic sequestration R&D projects would be required to report basic CO_2 injection data, but would not be required to develop MRV plans or report the additional information required for other GS facilities. However, they could choose to opt-in to these requirements.

EPA's Proposal for Reporting:
MRV Plans

- EPA is not prescribing specific monitoring technologies
- GS facilities would develop and implement a site-specific MRV plan which would include:
    1. Assessment of Risk of Leakage
    2. Strategy to Detect and Quantify CO_2 Leakage to Surface
    3. Strategy for Establishing Pre-Injection Environmental Baselines at Surface
    4. Tailor Mass Balance Equation
- Once MRV plan is approved by EPA, GS facility would implement it and begin collecting data for reporting to EPA

For More Information

- Information on the proposal and supporting background information is available electronically at www.regulations.gov, EPA's electronic public docket and comment system. The Docket ID number is: EPA-HQ-OAR-2009-0926.
- For additional information about this rulemaking, visit EPA's Web site at: www.epa.gov/climatechange/emissions/subpart/rr.html. If you have questions that cannot be answered through the Web site, please contact us by filling out a form at www.epa.gov/climatechange/emissions/ghgrule_contactus.htm.
- Comment period open until June 11, 2010
- EPA has open door policy during comment period to hear from stakeholders

Aquistore

Saskatchewan's Deep Geological CO_2 Storage Project

6th IEA GHG Monitoring Network Workshop
Natchez, Mississippi, 6th – 8th May 2010

Kyle Worth, P.Eng, PMP
Petroleum Technology Research Centre

ptrc
Petroleum Technology Research Centre

Overview

- Aquistore Background
- Saskatchewan Provincial Regulators
- Update on Saskatchewan's proposed climate change policy
- Guidelines for developing well permit
- Aquistore MMV Program

Project Details

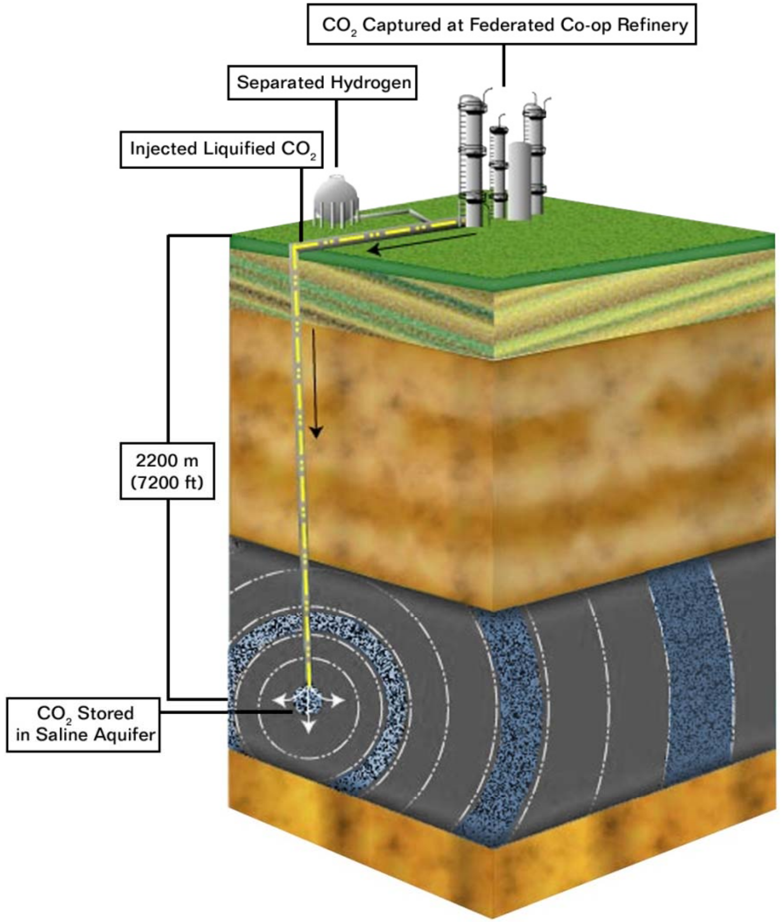
Current project runs from January 2009 to Early 2013.

Capture 550 t/d of CO_2 from a refinery complex

Transport CO_2 pipeline to injection site.

CO_2 injected into a suitable deep saline aquifer around 2200m depth.

Implement a Comprehensive Measurement, Monitoring and Verification Program.



Williston Basin

Aquistore is a collaborative project involving Industry & Governments

Current Partners

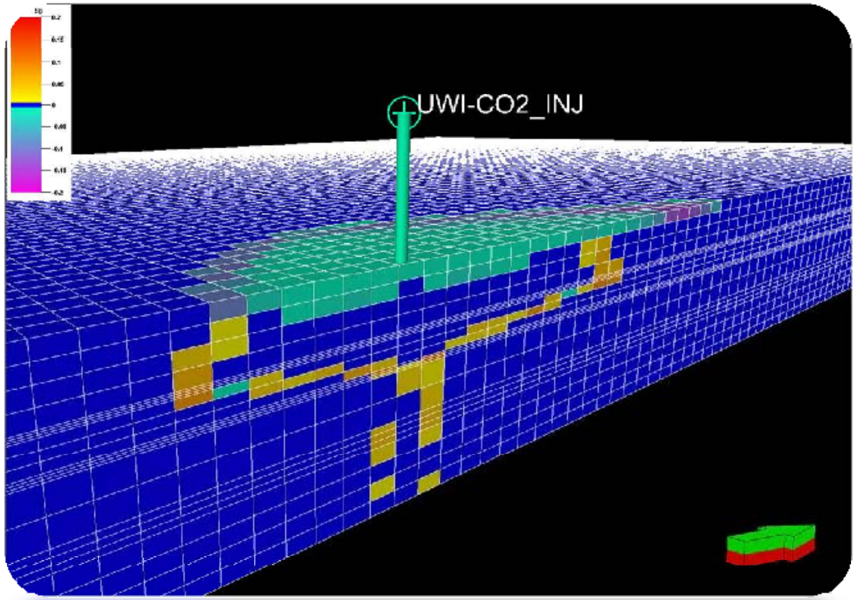
- Consumers' Co-operatives Refineries Limited
- SaskEnergy
- Enbridge
- Schlumberger Carbon Services
- SaskPower
- Sustainable Development Technology Canada
- SaskEnvironment GoGreen Fund
- PTRC

CO_2 Capture & Transportation

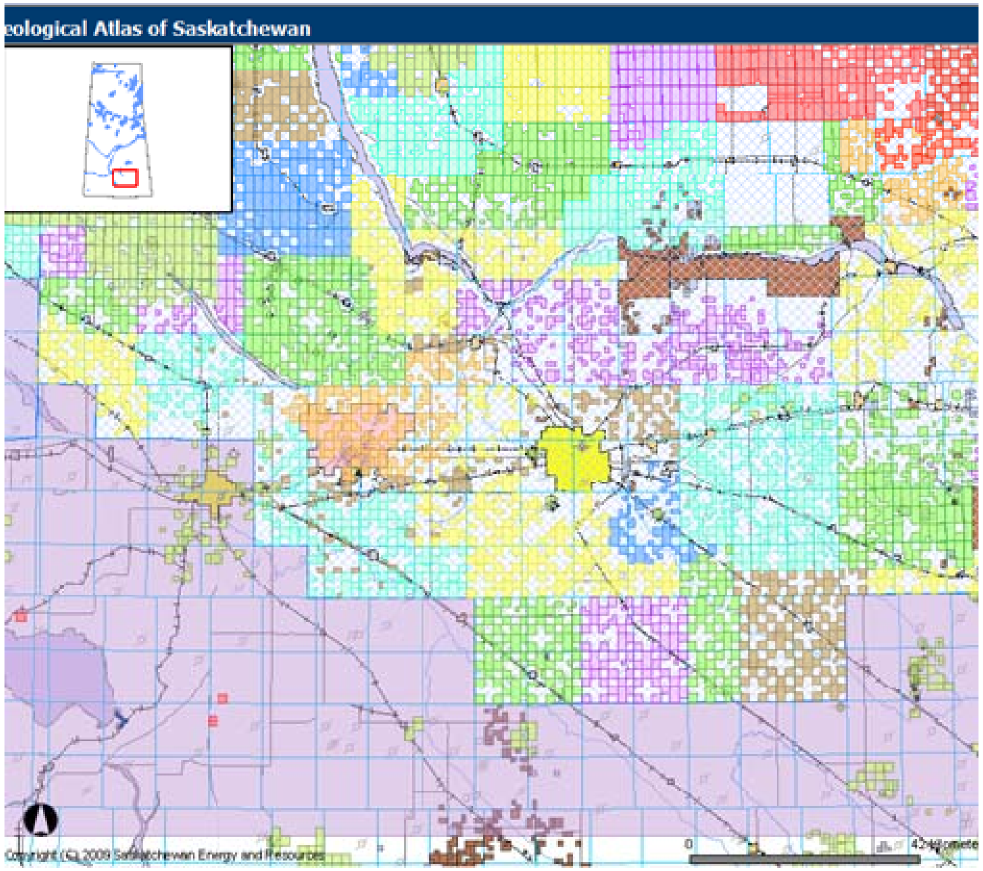
- Consumers' Co-operative Refineries Limited (CCRL)
  - Refinery – Upgrader complex
  - $1.9 Billion expansion
- Amine based capture process
  - Initially 550 t/d; potentially up to 1600 t/d
  - > 99% purity CO2
- Delivery of CO_2 late 2012 or 2013
- SaskEnergy & Enbridge to build pipeline

Plume Migration Modelling

- Static geocellular model
  - 4 x 4 Township Area
  - 1600 km2
- Export to flow simulator (Eclipse)
- Model Plume Migration
- Required by regulator to obtain well license and determine Lease of Space

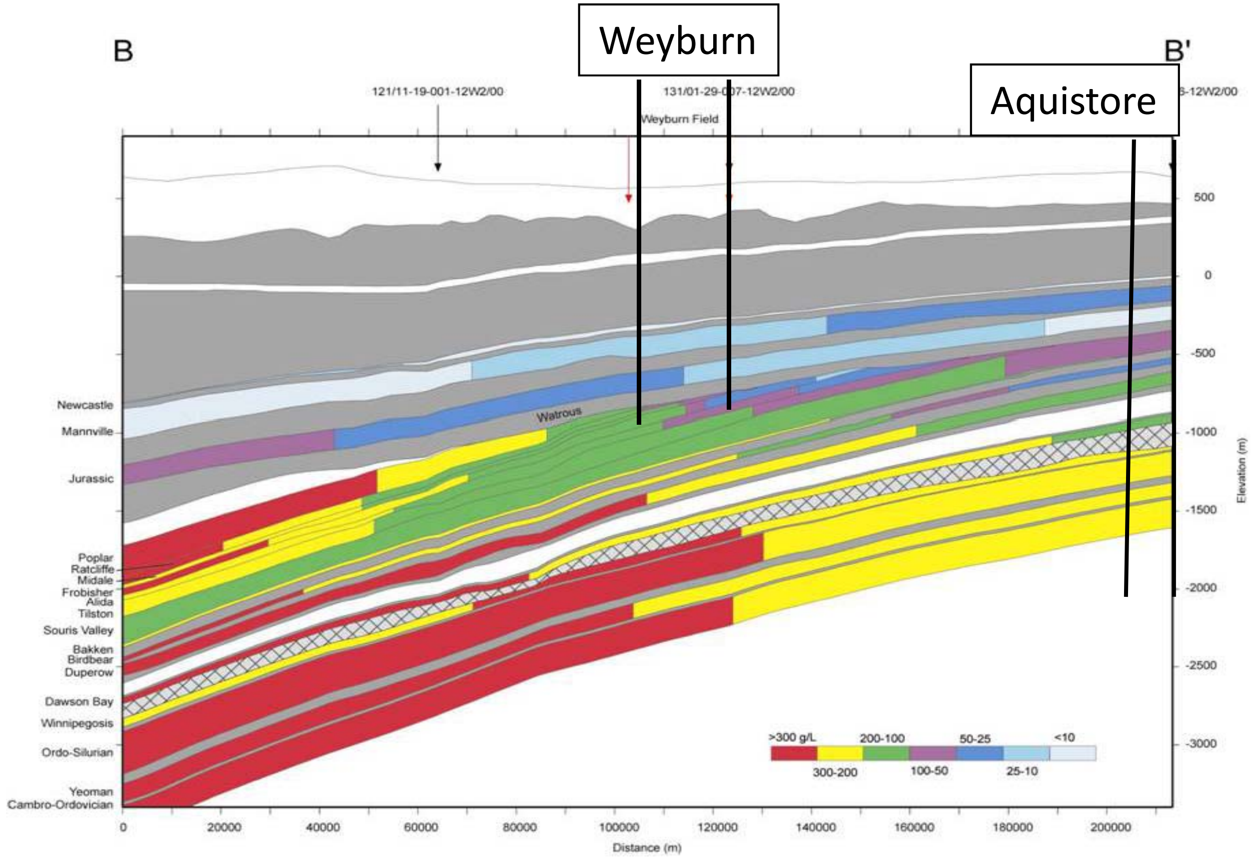


Potash Industry



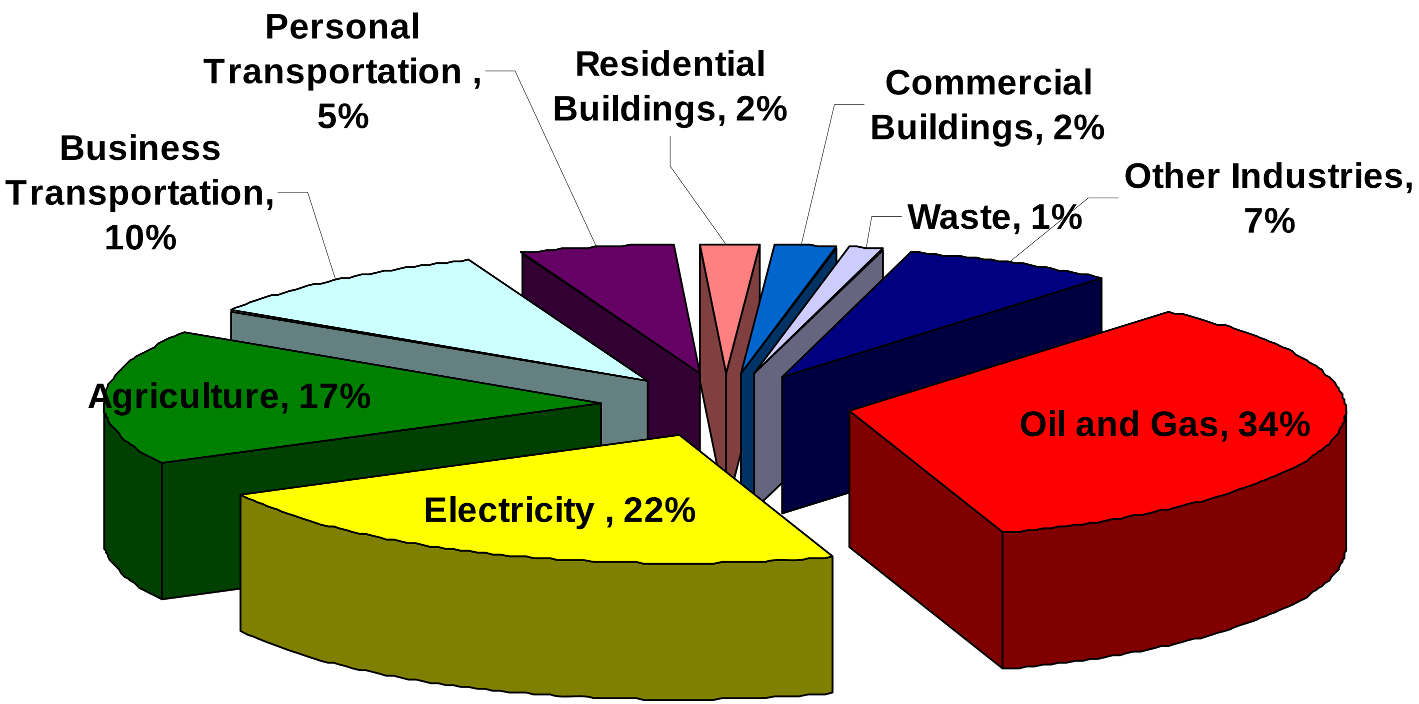
Regional Geological Setting

- Northeastern flank of Williston Basin
- Area of interest 2 to 3 km depth
- Resources include oil and gas, minerals (potash and coal) and brines and geothermal potential
- Geology generally well understood



Williston Basin Cross-Section

Saskatchewan GHG Emissions



Provincial Regulators

Ministry of Energy and Resources

- **Saskatchewan Ministry of Energy and Resources** regulates CCS activities, including issuance of injection/disposal well permits.

Ministry of Environment

goGreen Saskatchewan

- **Saskatchewan Ministry of Environment** will regulate the issuance of credits for GHG emission reduction.

Provincial Climate Change Plan

- Proposed regulations require CCS projects to comply with all applicable statutes.
- Bill 126, was introduced on December 1, 2009.
- GHG emissions by large emitters will be regulated and monitored.
- Carbon compliance price applied to emissions over targets will be paid to the Technology Fund.

The Management and Reduction of Greenhouse Gases Regulations

Saskatchewan's emissions reduction target

- 20% reduction of GHG emissions from 2006 levels by 2020.

Measurement, Verification and Reporting

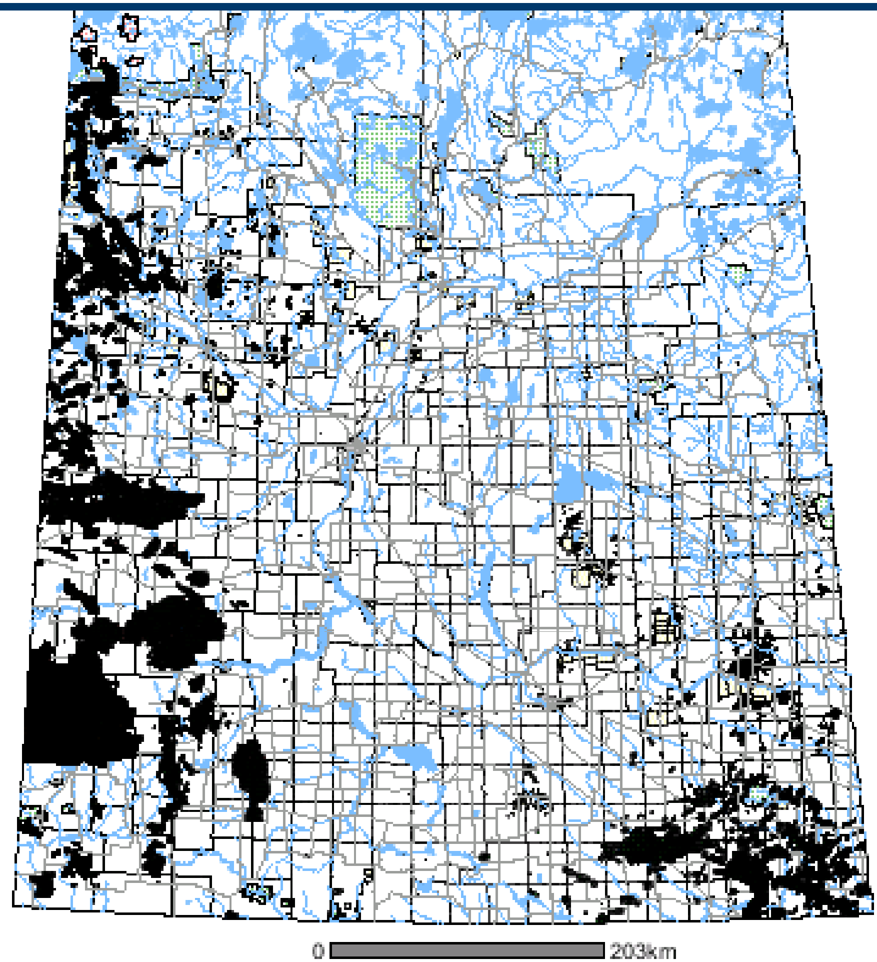
- Regulated emitters required to submit baseline emission level application by July 1, 2010 – must be verified by a qualified person.
- ISO 14064 standards for GHG emission measurement and verification.

Regulation Uncertainties

- Saskatchewan climate change legislation and regulations expected to be enacted in spring 2010.
- Negotiate a Canada/Saskatchewan equivalency agreement that maximizes economic benefits for Saskatchewan.
- Emerging US legislation and EPA regulation of GHG emissions pose challenges for aligning Canadian and US climate change frameworks.

Guidelines for Monitoring Program

- Saskatchewan Application for Waste Water Disposal Well
- Saskatchewan Application for Gas Storage Project
- Alberta Application for Acid Gas Disposal
- Canadian Standards Act: Z341 Storage of hydrocarbons in underground formations
- ISO 14064: Specification with guidance for quantification and reporting of GHG emissions and removals.



ptrc

Aquistore

Guidelines for Monitoring Program

In development

- Potential collaboration with IPAC-CO_2 (International Performance Assessment Centre for Geological Storage of CO_2)

  - Developing new CSA Standard

MMV Program

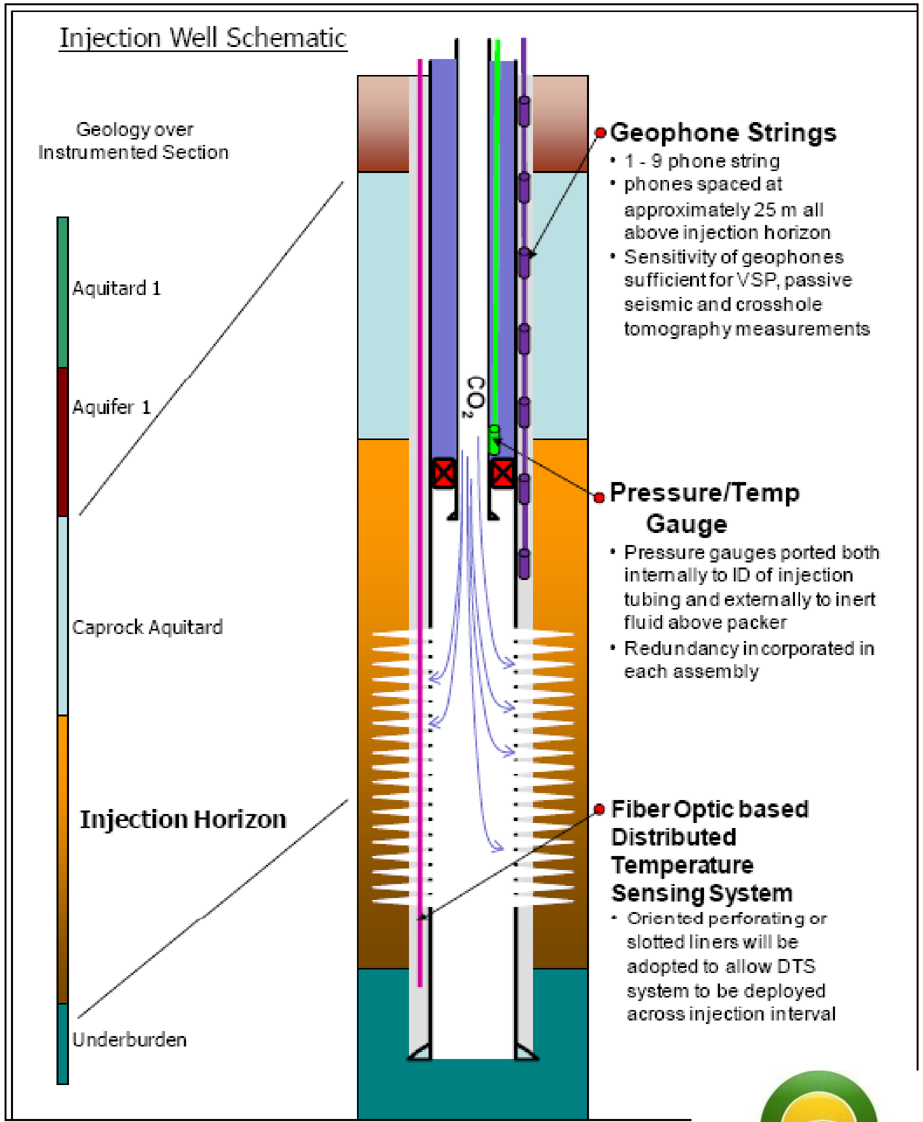
Designed for (1) project/plume monitoring; (2) public assurance; (3) research objectives

- Key Elements Proposed:
  - Baseline 3D seismic survey
  - Real-time pressure & temperature monitoring
  - Passive seismic
  - Cross-well seismic
  - Downhole fluid sampling
  - Time-lapse logging
  - Time-lapse VSP's
  - Groundwater monitoring
  - Soil gas monitoring
- Potential Additional Elements:
  - Time-lapse surface seismic
  - InSAR
  - Permanent sparse seismic array
  - Downhole cross-well electrical monitoring
  - Surface-to-downhole electrical monitoring
  - Surface controlled-source electromagnetic monitoring
  - Surface gravity
  - Permanent tiltmeters

Injection / Data Well

- **Significant data acquisition proposed:**
  - Core from 15m above reservoir, continuous through reservoir
  - Core overlying aquifer and secondary seal
  - Intensive core analysis for mechanical, thermal, hydraulic, mineralogic properties
  - DST's in reservoir
  - Full log suite including VSP

- **Completed for injection & MMV:**
  - Permanent downhole geophones
  - Distributed temperature sensors
  - Downhole pressure/temp gauge

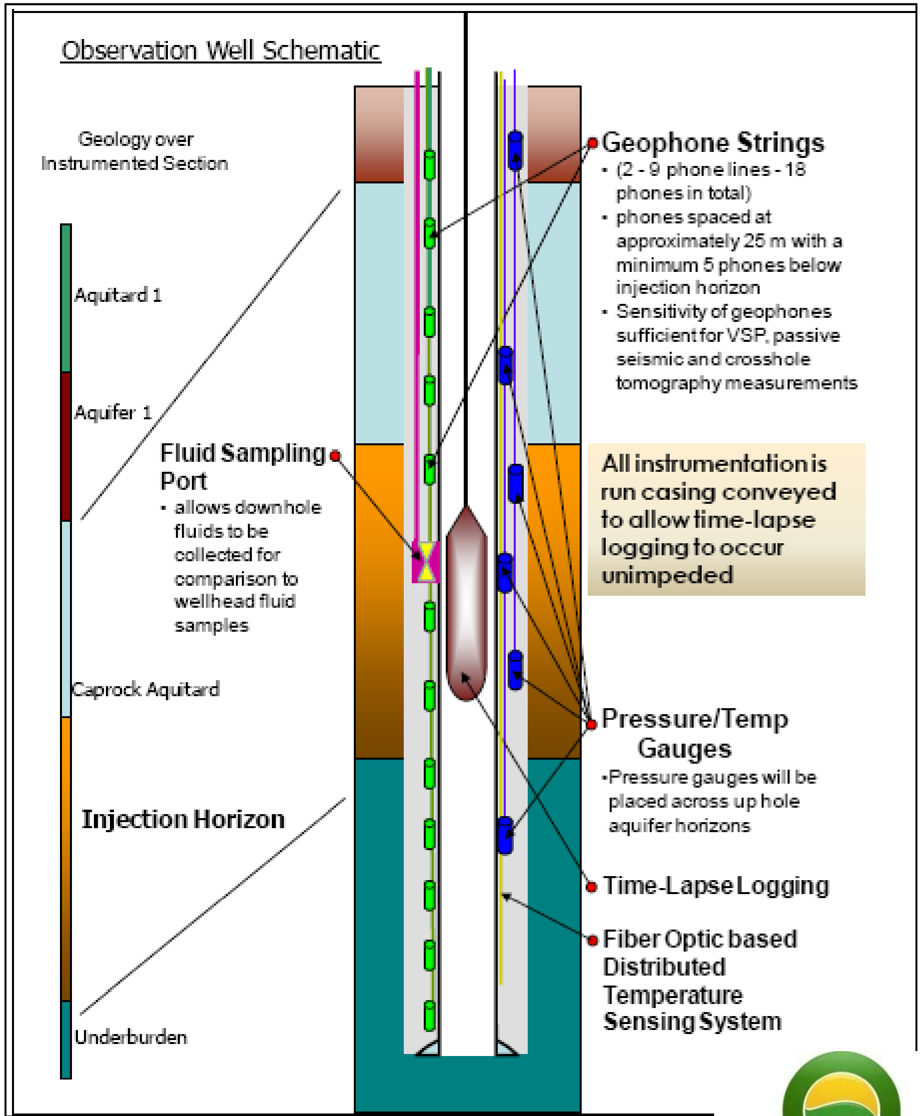


ptrc

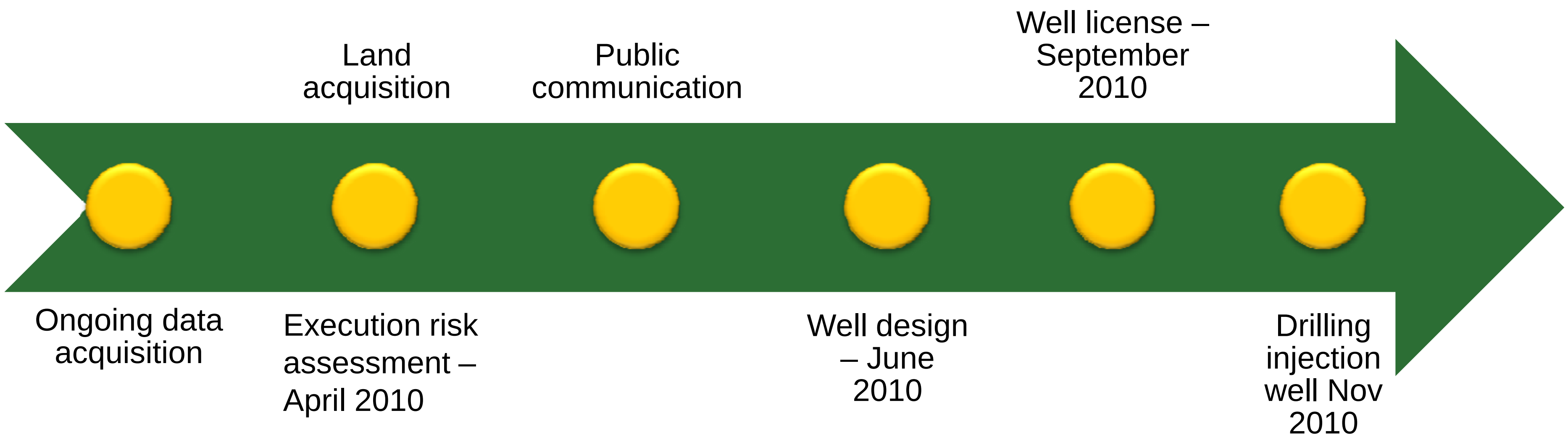
Aquistore

Observation Well – SaskWatch #1

- **Placement close to injector ~100-200m spacing – monitor early plume development**
- **Significant data acquisition proposed:**
  - Similar to injection well
- **Completed for injection & MMV:**
  - Permanent downhole geophones
  - Distributed temperature sensors
  - Multiple downhole pressure/temp gauges
  - Fluid sampling port
  - Full access for time-lapse logging



Near-term activities



CO_2 SURVEILLANCE DURING CO_2 ENHANCED OIL RECOVERY and CCS POLICY PROGRESS IN THE U.S.

Presentation at the IEAGHG Natchez Meeting
of the Monitoring Network
May 6-8, 2010

L. Stephen Melzer
Consulting Engineer

Midland, Texas

CO_2 SURVEILLANCE DURING CO_2 ENHANCED OIL RECOVERY and CCS POLICY PROGRESS IN THE U.S.

I. Surveillance: Definition and Objectives

II. Surveillance vs. Monitoring

III. Proven Tools

IV. Challenges *(through the eyes of the companies)*

V. CCS Policy and Regulatory Overview

VI. A View on Where is this Going in the U.S.

VII. Questions/Discussion

Many of the Following Insights (Slides) Come from the CEED CO_2 Flooding Shortcourses

14. CO_2 Injection in Subsurface Reservoirs: Geological Parameters Affecting CO_2 EOR and CO_2 Storage, December 2007 (Repeated at the SPE Intn'l Conference on SPE International Conference on CO_2 Capture, Storage, and Utilization, Nov '09)
13. CO_2 Sourcing for Enhanced Oil Recovery, December 2006
12. CO_2 Flood Surveillance and Monitoring, December 2004
11. Wellbore Management in CO_2 Floods, December 2002
10. Reservoir Modeling and Simulation for CO_2 Flooding, December 2001
9. Issues for Beginning CO_2 Flooders, December 2000.
8. CO_2 Flooding: Sandstones vs. Carbonate Reservoirs, December 1999.
7. CO_2 Facilities and Plants, December 1998.
6. CO_2 Measurements and Metering, December 1997.
5. How to Put Together a CO_2 Flood, December 1996.
4. How CO_2 Flood Surveillance Helps Assure a Successful EOR Program, May 1996.
3. Equipping and Day-to-Day Operations of a CO_2 Flood, December 1995.
2. Is My Field a Candidate for CO_2 Flooding?, September 1995 (Twice).
1. Making Money on CO_2 Flooding...Some Innovative Development Concepts for Independents..., May and July (repeat) 1995.

Surveillance: Definition and Objectives

- THE EOR Industry in the U.S. currently injects ~3 bcfpd (60 million tons/yr) of "new" purchased CO_2.
- Their cost of carbon (CO_2) is at an average value of roughly $1.00 / mcf or almost $20/ton.
- The aggregate value of that commodity CO_2 to the companies is $3 million per day or over a billion $/yr.
- CO_2 is produced with the fluids (needs recycling)
- **Keeping track of the CO_2** and knowing that it is making money for them is ACUTELY critical.
- The Industry calls that Surveillance

CO_2 FLOOD SURVEILLANCE vs. CCS MONITORING, VERIFICATION & ACCOUNTING (MVA)

SUBSURFACE NEEDS

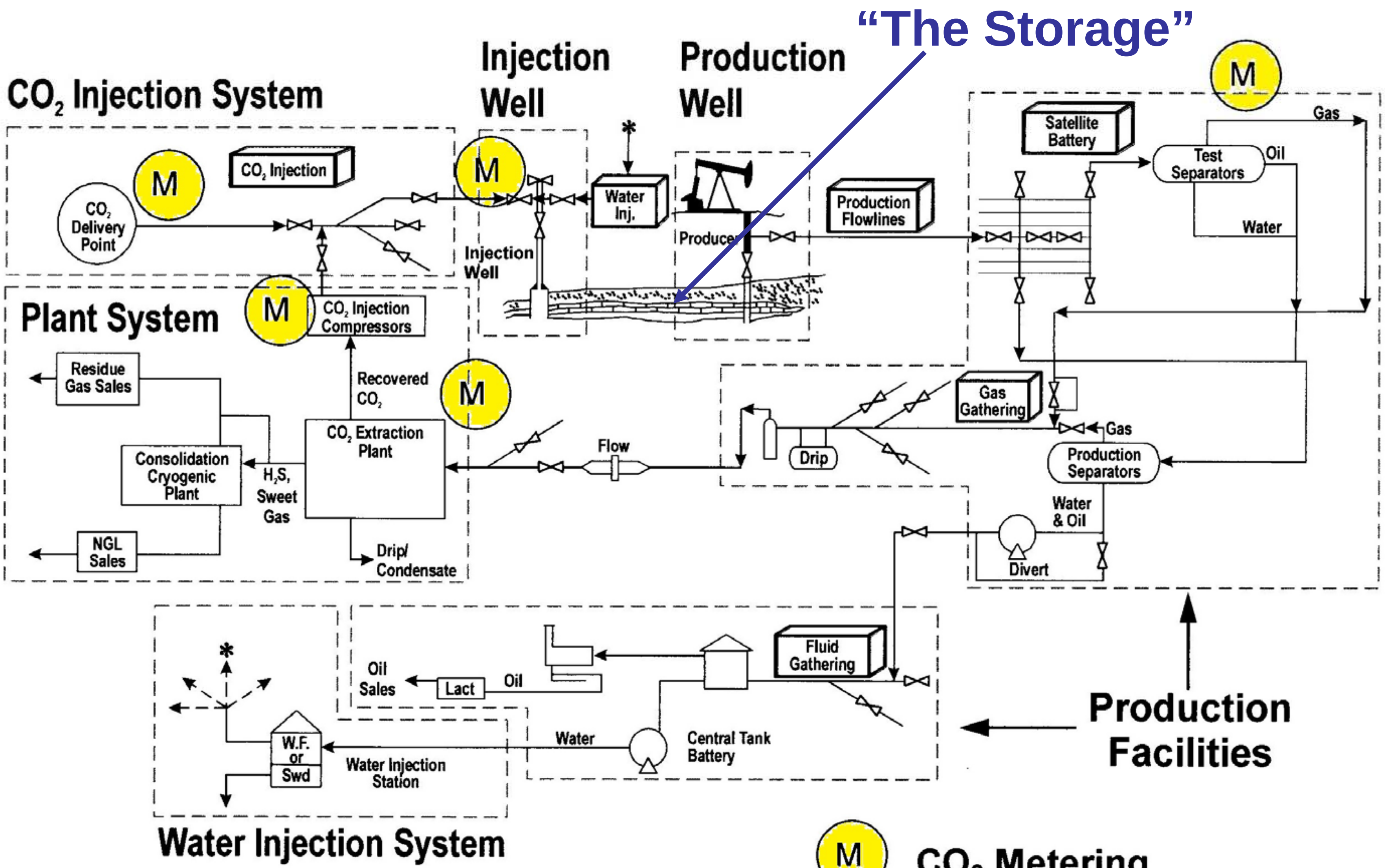
FLOODING	MVA
1) INJECTION IN ZONE	INJECTION IN ZONE
2) FLOW PATHS	FLOW PATHS
3) PRESSURE CONTAINMENT	PRESSURE CONTAINMENT
4) WELLBORE INTEGRITY	WELLBORE INTEGRITY
5) SWEEP EFFICIENCY	N/A ?
6) N/A ?	LONG TERM STORAGE

How Does the Industry Do it?

A Mix of Purist and Practical Approaches

- First, we put CO_2 in Reservoirs that have had proven trapping capability (where it will stay)
- Carefully meter it at Custody Transfer points (mass, density, occasionally composition – orifice meters, over the years, have become the standard)
- Efficiently (re)Capture it at producing wells
- Meter it less expensively at collection/ redistribution points (Because There Are Many)
- Check for Losses at key points (stay efficient)

CO_2 Flood Production Systems



Source: *Practical Aspects of CO2 Flooding, Figure 5.1*

The Experience: Historical Source of CO_2 "Losses"

- Subsurface
  - Lateral Off-lease
- Surface
  - Plant Upsets (Power outages)
  - Flow Through to Oil
  - Amine Regeneration
  - Pipeline Blowdown
  - Well Workovers

Very minor (but 'Cumulative')

- Consumption of the Oil Produced
- Power for Lift, Compressors and Processing

Benefits of Concurrent EOR & Storage (CCS EOR)

- Public Perceptions about Commercial vs. Waste Injection
- Regulatory Infrastructure
- Domestic Oil (Less Imports)
- Less Cost to Tax- or Rate-payor
- Retention is Demonstrated
- Storage Capacity (Voidage)

Complications of Concurrent EOR & Storage

- Production (Recycle) and gas composition
- More Complicated Monitoring (Surface & Subsurface)
- Transportation (Pipeline Access) to get to EOR

Proven Tools

- Subsurface
  - Logging
    - Open Hole (Density/Neutron, Sonic, Resistivity/Induction, C/O)
    - Cased Hole (Casing Integrity, Temperature)
  - Seismic Reflection
- Surface*
  - Metering (Predominately Orifice-type but Wedge-type is popular to save money within unit)
  - Density
  - Composition
  - IR

* Emissions are Carefully Monitored for Criteria Pollutants

Metering

DEFINITIONS

- <u>Accuracy:</u> The Degree of Conformity of an Indicated Value to a Recognized Accepted Standard of Value
- <u>Repeatability:</u> The Degree of Agreement of Repeated Measurements of the Output for the Same Value of Input Made Under the Same Operating Conditions over a Period of Time

CATEGORIES OF METERS

- CUSTODY TRANSFER
  - NEED FOR ACCURACY (SINCE PURCHASE/SALE INVOLVED)
  - USUALLY IN BULK
- ALLOCATION
  - USED WHERE COSTS ARE AN ISSUE
  - MANY METERS REQUIRED

CUSTODY TYPE EXAMPLE: DENVER CITY METER STATION

Re: The 16" Centerline Pipeline; Presentation at the 2003 CO_2 Flooding Conference, J Gross, Kinder Morgan

Types of Meters

- Differential Pressure (Predominately Used)
- Displacement
- Velocity
- Mass

DIFFERENTIAL PRESSURE METERS

Differential pressure meters have some type of restriction which creates a difference in pressures which is proportional to the stream's flowrate.

TYPES:

- Venturi
- Flow Nozzle
- Orifice
- Wedge
- Elbow

Both Cust Transfer and Allocation Applications

Only Allocation Applications

DISPLACEMENT METERS

Displacement meters include those devices which have sliding vanes or rotating elements that segment the flowing stream into discrete volumes and have some methodology of counting the number of volumes.

VELOCITY METERS

Velocity meters employ paddles, rotating paddle wheels or rotating turbine blades to measure the velocity of a stream which can be translated into its flow rate.

MASS METERS

Direct mass flow meters involve a tube (or tubes) in the shape of a bend or loop that is vibrated at high frequency and the Coriolis effect is used to determine the stream's mass flow rate.

CUSTODY TRANSFER MEASURMENT

- $$$$ Changing Hands
- Accuracy Critical
- Measured In Dense (Critical) Phase

SECONDARY DEVICES

- Chart Recorder
- Flow Computer
- Transducers (Transmitters)
  - Differential Pressure
  - Static Pressure
  - Temperature
- Densitometer

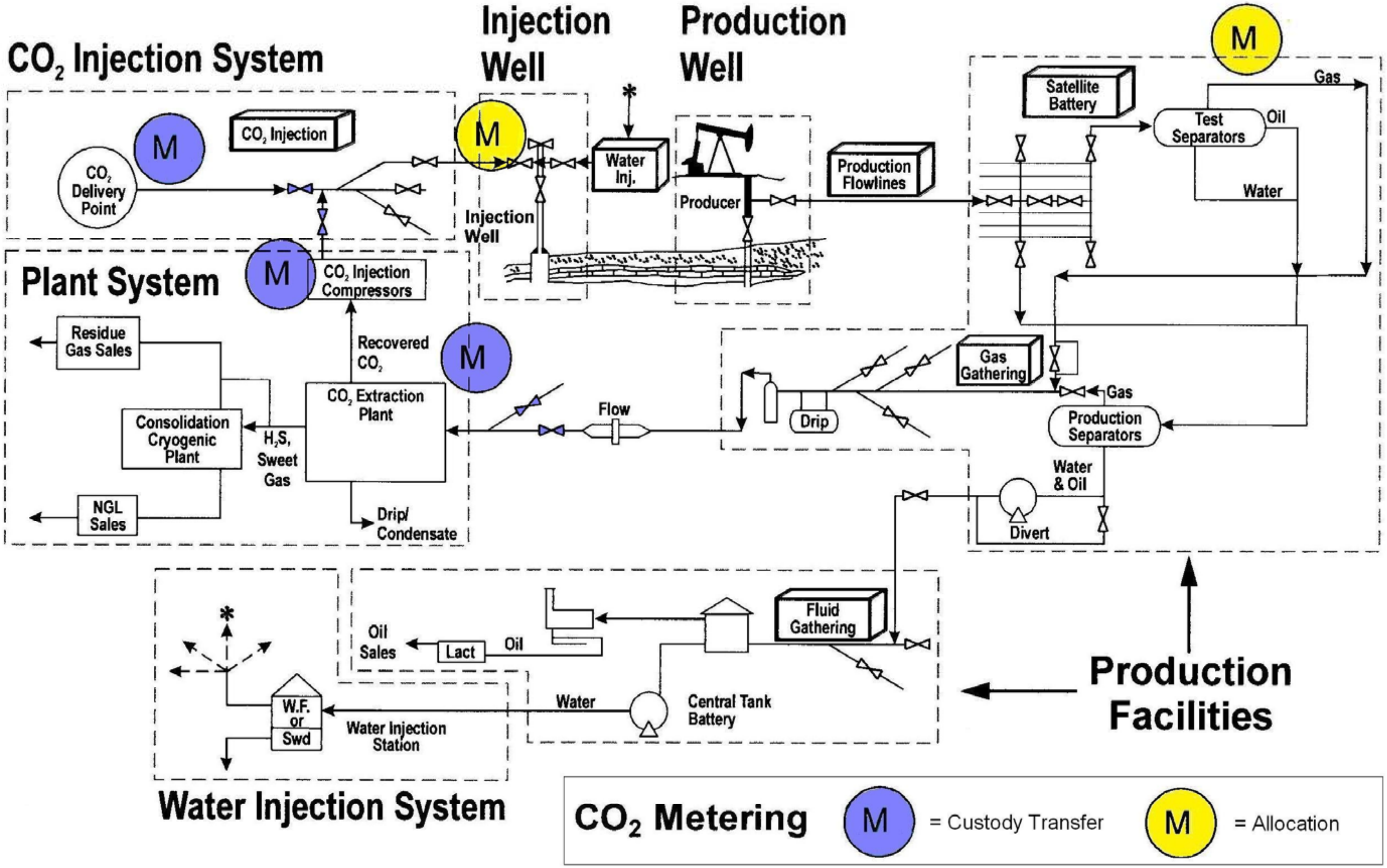
CATEGORIES OF METERS

- CUSTODY TRANSFER
  - PURCHASE/SALE INVOLVED
  - USUALLY IN BULK
- ALLOCATION
  - MANY METERS REQUIRED
  - WHERE COST IS AN ISSUE

ALLOCATION METERS

- Non-custody Transfer
- On Lease
- Data for Reservoir Management
- Data for Lease Management and Control

CO_2 Flood Production Systems



Source: *Practical Aspects of CO_2 Flooding, Figure 5.1*

The Seminole CO_2 Processing Plant*

*CIRCA 2004

A Short Sidebar

“Chipping Away at Some Myths”

- CO_2 Storage in CO_2 EOR is 50% or less *(This is a CO_2 Retention Briefing for Another Day)*
- DSF CO_2 Storage Capacities are Very Limited
- CO_2 EOR Capacities are Negligible in the Large Scheme of Things *(A Briefing for Another Day)*
- Maximum Storage Pressures Must Stay Below Original Bottom Hole Pressures *(Safe Pressures are VERY site dependent)*

Challenges

Summary
So Why Do Sequestration Using EOR?

- Retention is Proven *(and very high)*
- Is ‘Commercial’ Storage
- Adds Domestic Oil Production
- Avoids ‘Waste’ Perceptions with Public
- Provides a Bridge to Deep Saline Formations
- Regulatory Infrastructure in Place

U.S. Policy Initiatives

National Initiatives (U.S.)

- UIC Class VI Rules
- CO_2 Declared a Pollutant
- Emission Sources Defined (>80,000 tons/yr)
- Does not Discriminate Natural vs. Industrial Sources (Monitoring Implications for Both)
- (Comments on) Draft Rules on Sequestration (EPA Draft Reporting Rule, SubPart RR)

Qualifying Texas

Texas* CO_2 Background

- Has 38 years of Experience with CO_2 Handling
- Injecting about 1.8 bcfpd (36 million {mm} tons/yr) of **new** CO_2, *Estimated ~70% of world total*
- Recycling ~1100 mmcfpd (22 mm tons/yr)
- Making 175,000 bopd *(20% of Tx total)*
- Injecting in over 5000 wells *(78% U.S. total)*
- Producing from 8000 wells in over 300,000 project acres (~500 sq miles)

* Tx hereby “Annexes” SE NM for these stats

Texas Regulatory Infrastructure

- Texas Railroad Commission (TRRC) has 80 years of regulatory oversight for almost all underground activity (injection & production)
- Texas Commission on Environmental Quality (TCEQ) has regulatory oversight for surface and USDWs

The question was posed in the last session (2009)

- *Is CCS a commercial injection activity or waste injection?*

Texas' Pathway Forward

- Write Rules for Storage with Incidental Oil Production *(TRRC to take lead, draft published last month)*
- Write Rules for Oil Production with Incidental Storage *(TRRC to take lead – draft by early winter)*
- Commissioned Inter-agency Study (w/ BEG) on How to Proceed with Waste Injection (Deep Saline Formations) – *They are meeting now*

Goal: Remove Obstacles for First Mover Projects

(Get policy out of the way of real business)

Other States

- North Dakota
- Wyoming
- Louisiana
- Others

Where and What Next?

The Future of Coal*: Are We ‘Stuck’ & Going Nowhere?

1. Technology bog? *Not really*
2. Storage Capacity Bog? *(Not in my head)*
3. Policy bog? *(Perhaps, becoming less likely)*
4. Public Perception Bog *(An Ohio “Wake-up” Call?)*
5. Rights aggregation bog? *Big Projects have huge footprints*
6. Transportation bog? *To get to Tier 1 Secure Sites*

* Coal used here as a proxy for a CO_2 emission stream industry)

Supplemental (Federal) Policy Slides

Review Of EPA Draft Reporting Rule: Subpart RR*

April 2010

* As it is Believed to Affect On-going CO_2 EOR and Commerciality of Concurrent EOR and CCS

Background

Natural Sourced CO_2

- Relationships and Contracts between Sellers and Users (Buyers) have not Considered Retention (or it's Companion, " losses* ") as factor in those Contracts
- Documentation and Proof of Numbers in those Documents will Require Monitoring Expenses
- Many, if not all, Contracts will Have to be Modified
- Effects on BAU CO_2 EOR will be a Function of How Onerous New Monitoring Requirements will Become

** Defined herein as the volume of CO_2 purchased but not sequestered*

Anthropogenic CO_2

- Same Comment as Naturally-sourced CO_2 for existing Contracts (Req'd Mods)
- Degree of Modification May be a Function of Whether Source Gets Status of Anthropogenic (e.g., Nat'l Gas By-product, ethanol, fertilizer)
- These Subpart RR Rules are Set to Play a Huge Factor in those Pending and Future Contracts and perhaps, as a result, the commercial viability of those flood projects

A Framework:
The Critical Steps in Monitoring and Reporting

Steps in Monitoring/Reporting (1)

(as Seen at the Sink Site)

No Production (or Recycle)*

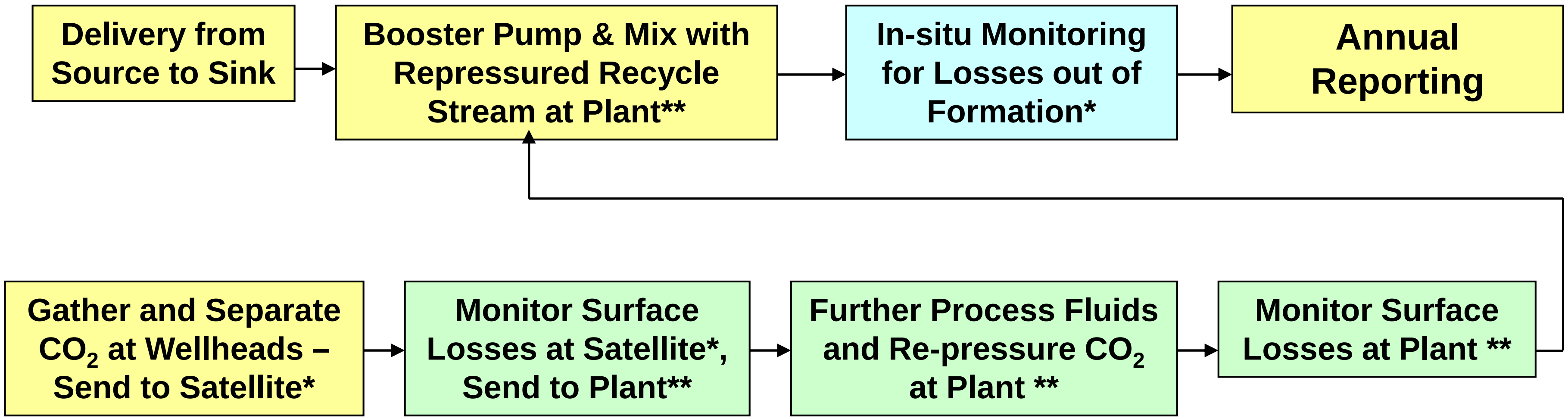
Delivery from Source to Sink → Booster Pump & Distribution to Injection Wells → Surface Monitoring for Losses → In-situ Monitoring for Losses out of Formation → Annual Reporting

** It should be noted that even a Deep Saline Injection Project may require production for purposes of Plume Management. If it does, the next chart applies*

Steps in Monitoring/Reporting (2)

(as Seen at the Sink Site)

With Production (and Recycle)



* *A collector location for multiple wells where fluids are Separated and Measured (Tested)*

** *The facility wherein all production fluids are gathered and fully processed*

With That as the Framework

How will the (draft) EPA reporting rules work?

1) Equation RR-1, Custody Transfer to Sink (Total Mass* Concentration)
2) Equation RR-2, Custody Transfer to Sink (conv to "standard conditions")
3) Equation RR-3, Facility Aggregated Transfers
4) Equation RR-4, Mass Injected*concentration at each injection point
5) Equation RR-5, CO_2 Mass Injected above (conv to "stand. conditions")
6) Equation RR-6, Aggregated Injection Mass
7) Equation RR-7, Produced Mass at gas-liquid separators (Satellites)
8) Equation RR-8, Above Masses Converted to Standard Conditions
9) Equation RR-9, Summed satellites measurements with consideration of pass through mass
10) Equation RR-10, MVA (emitted) Leakage Mass
11) Equation RR-11, Total Sequestered Mass Calculation (by Differences)
12) Equation RR-12, Same as above but for facilities not producing oil or gas

Considerations for producing back fluids; exempts deep saline fms for some reason?

Melzer CO_2nsulting

Subpart RR Equations

$$CO_{2,v} = \sum_{p=1}^{4} Q_{p,v} * C_{CO_{2},p,v} \quad \text{(Eq. RR-1)}$$

$$CO_{2,v} = \sum_{p=1}^{4} Q_{p,v} * D_{p,v} * C_{CO_{2},p,v} \quad \text{(Eq. RR-2)}$$

$$CO_{2T} = \sum_{v=1}^{V} CO_{2,v} \quad \text{(Eq. RR-3)}$$

$$CO_{2,u} = \sum_{p=1}^{4} Q_{p,u} * C_{CO_{2},p,u} \quad \text{(Eq. RR-4)}$$

$$CO_{2,v} = \sum_{p=1}^{4} Q_{p,v} * C_{CO_{2},p,v} \quad \text{(Eq. RR-1)}$$

$$CO_{2I} = \sum_{u=1}^{U} CO_{2,u} \quad \text{(Eq. RR-6)}$$

$$CO_{2,w} = \sum_{p=1}^{4} Q_{p,w} * C_{CO_{2},p,w} \quad \text{(Eq. RR-7)}$$

$$CO_{2,w} = \sum_{p=1}^{4} Q_{p,w} * D_{p,w} * C_{CO_{2},p,w} \quad \text{(Eq. RR-8)}$$

$$CO_{2,w} = \sum_{p=1}^{4} Q_{p,w} * C_{CO_{2},p,w} \quad \text{(Eq. RR-7)}$$

$$CO_{2E} = \sum_{x=1}^{X} CO_{2,x} \quad \text{(Eq. RR-10)}$$

$$CO_{2} = CO_{2I} - CO_{2P} - CO_{2E} - CO_{2FI} - CO_{2FP} \quad \text{(Eq. RR-11)}$$

$$CO_{2} = CO_{2I} - CO_{2E} - CO_{2FI} \quad \text{(Eq. RR-12)}$$

Issues (1)

- Industry Needs “One-stop Shopping”
  - Meaning One Regulatory Body has Primacy*
  - Solves Most Problems of Competing Regulations (Becoming Acute as Regs (and Regulatory Agencies) Proliferate
- Who has Regulatory Primacy?
  - Seems to us that too much emphasis on monitoring minimizes the issue of security of storage in order to emphasize measurement, we don’t think that serves sequestration very well
  - What about assuring good sites are chosen? Who does that? The Primary Subsurface Regulator Needs to have that responsibility above all else! “Regionality” is a huge risk
  - This is all about security of storage, primary subsurface enforcer needs to be that kind of regulator

* In U.S. in Most States, Probably too idealistic, one for subsurface and one for emission (surface)

Issues (2)

- Item (eq) 12 exempts equations 7-11 from sequestration projects. For deep saline formation sequestration projects that produce fluids, those equations should pertain since they can have surface losses as well – current rule appears to exempt them since it is not oil/gas that they produce????
- CO_2 is a tough beast to measure precisely; one has to realize that a very high level of accuracy is impossible and significant uncertainties can exist
  - Accuracy of Measurement is currently required only at custody transfer points
  - Sequestration Reporting may attempt to change that wherein accuracy may be required at every measurement point
  - This will be very expensive to accommodate in a flood due to the multitude of measurement points

EERC Technology… Putting Research into Practice

Overview of the PCOR Partnership's Phase III Field Demonstration: Spectra Energy's Fort Nelson Carbon Capture and Storage (CCS) Feasibility Project

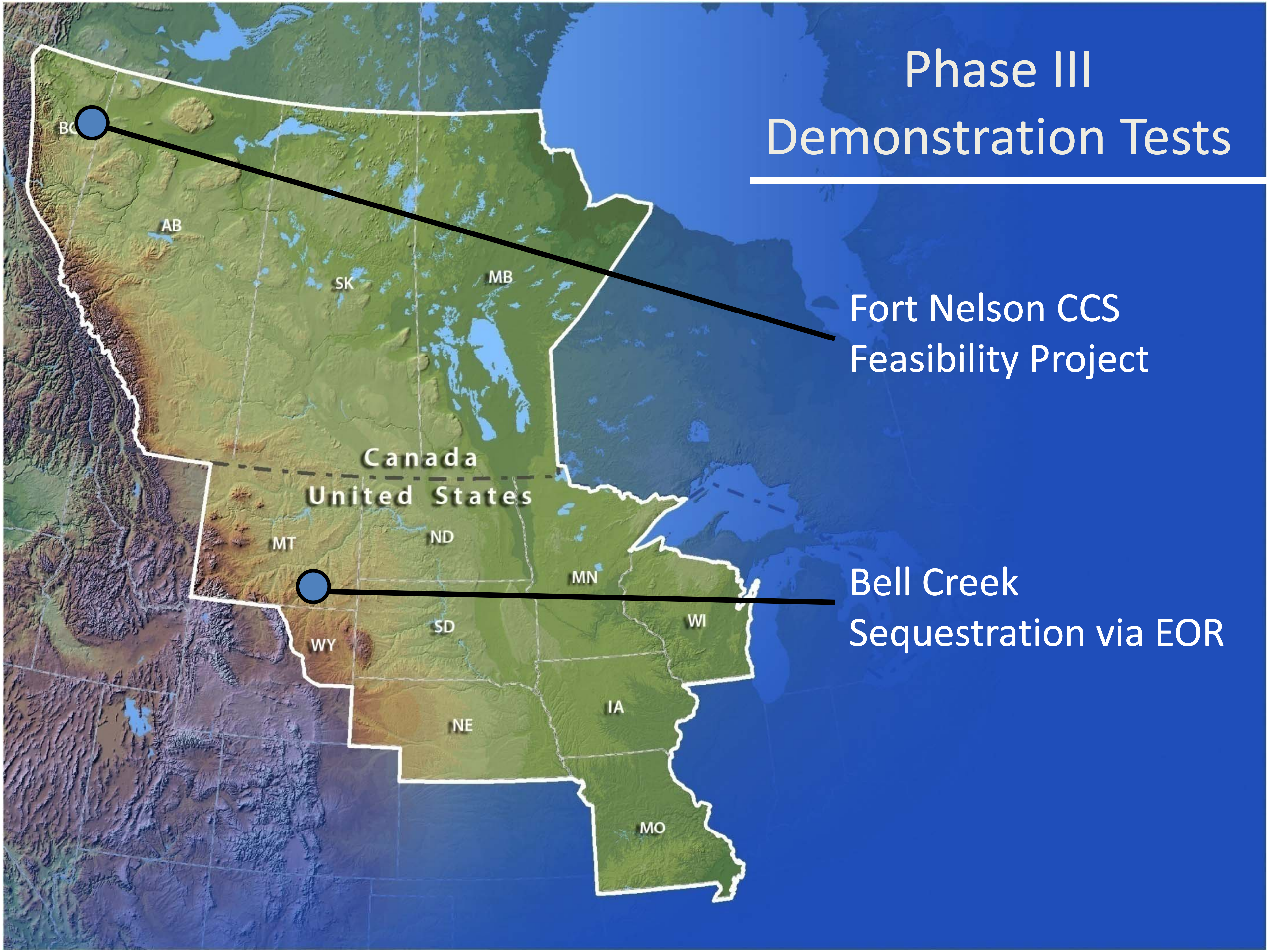
Steven Smith

IEAGHG Monitoring Network Meeting
Natchez, MS
May 7, 2010

PCOR Partnership

The Plains CO_2 Reduction (PCOR) Partnership, one of seven regional partnerships funded by the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory Regional Carbon Sequestration Partnership (RCSP) Program, is led by the Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks, North Dakota.

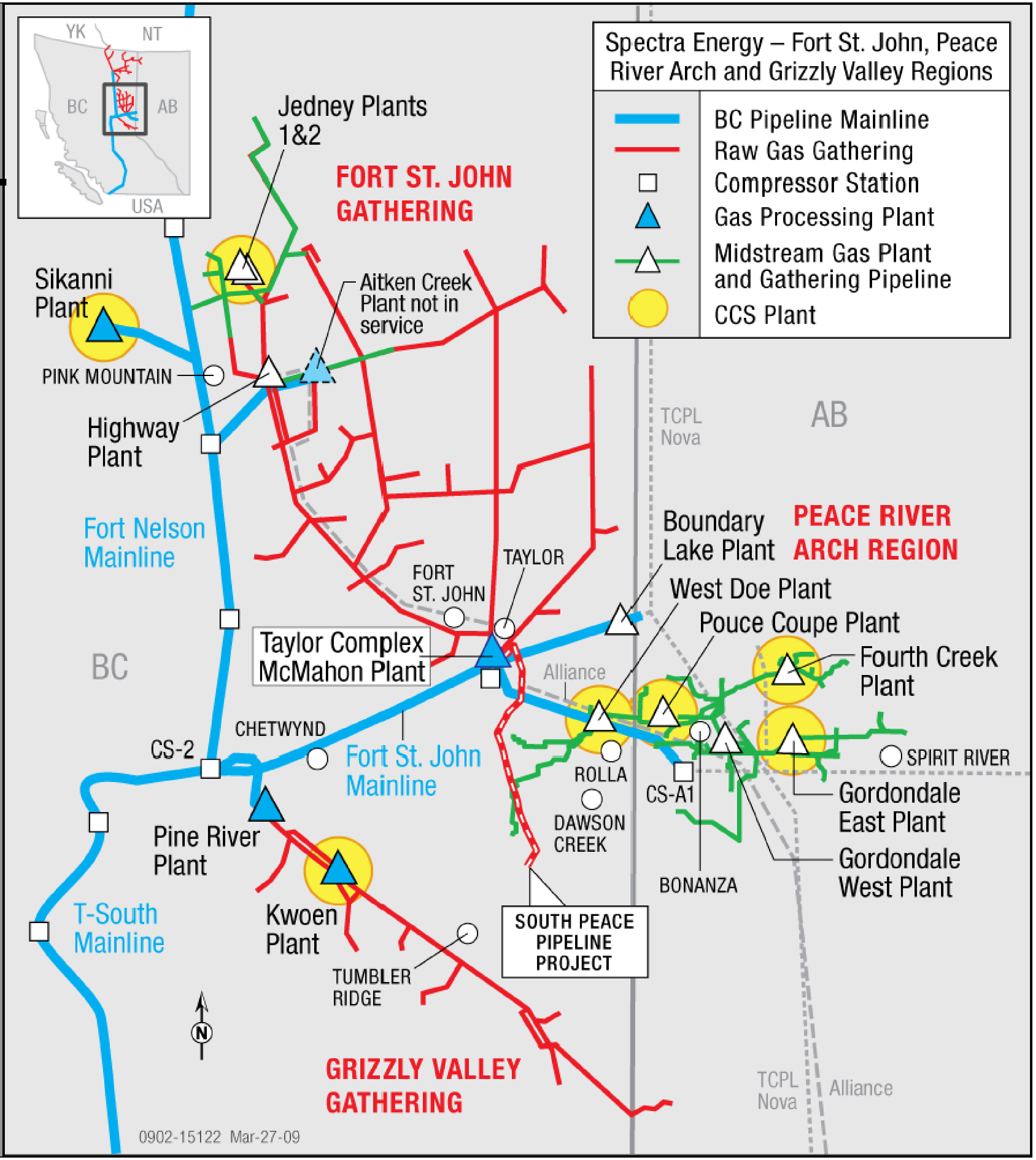
Phase III Demonstration Tests



Fort Nelson Carbon Capture and Storage (CCS) Feasibility Project

Spectra Energy and Subsurface Injection

- 8 Facilities Online
- More than 15 years experience in designing, constructing and operating safe, reliable, CCS facilities
- Projects have been developed in a mixture of saline formations and depleted reservoirs
- Current sequestration across our facilities exceeds 200,000 tonnes of GHG's annually, with our Kwoen Plant averaging more than 100,000 tonnes/year



British Columbia Regulatory Status

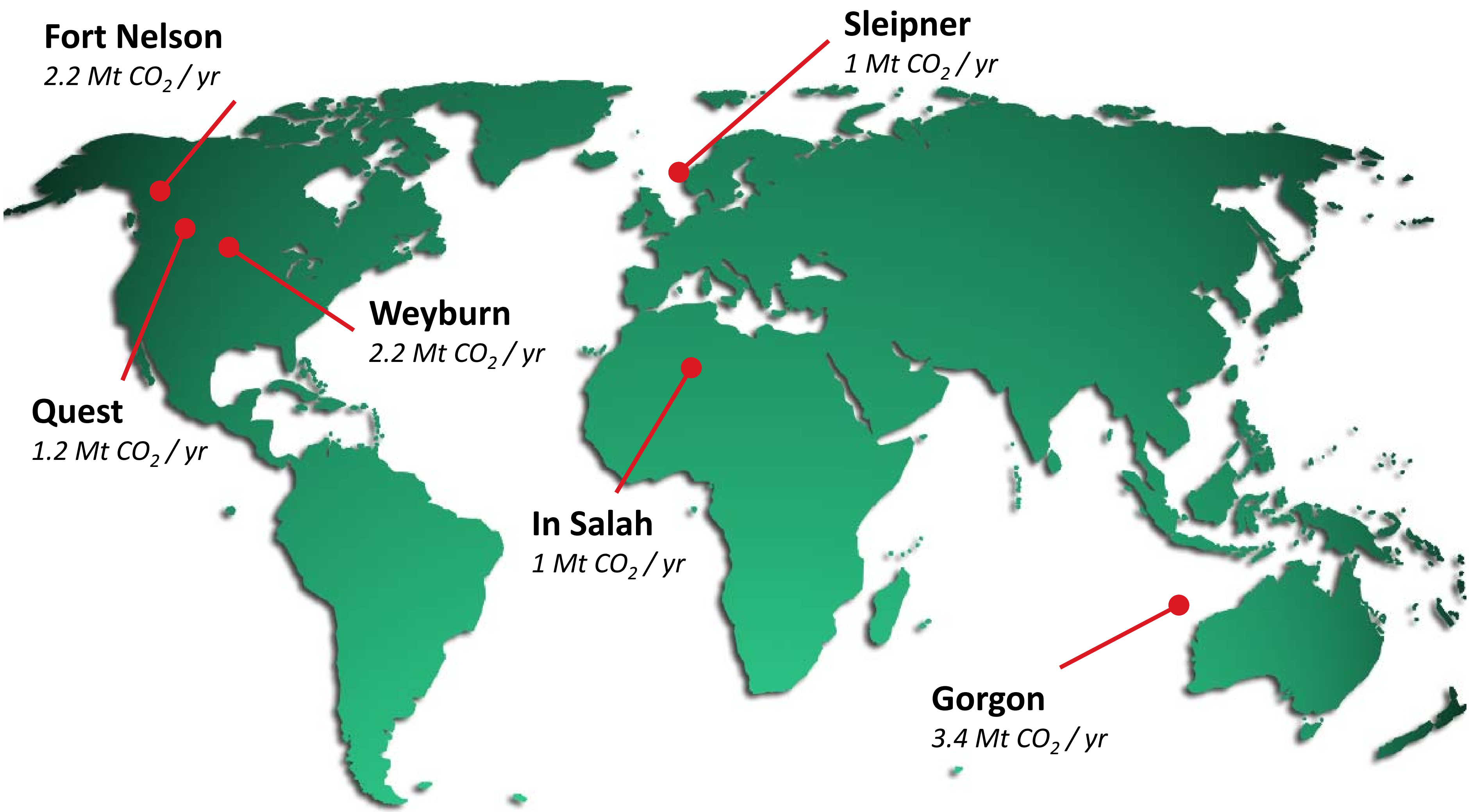
- The province of British Columbia is in the process of addressing the issue of CO2 injection for non-enhanced oil recovery (EOR)-related activities.

- The update received at the regulatory brainstorming session indicated that existing legislation can be modified slightly to accommodate non-EOR injection.

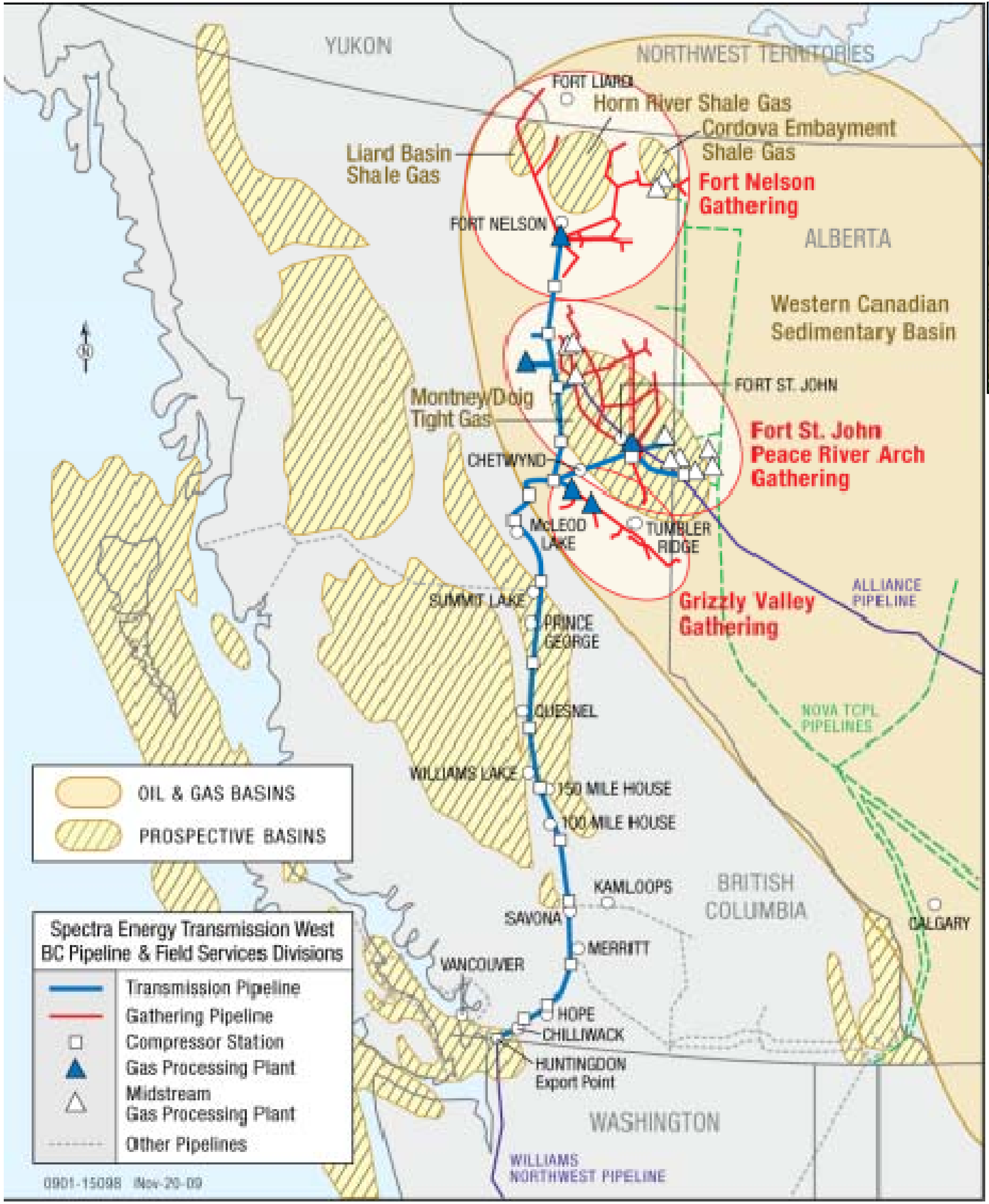
- Regulatory authority for those initiatives would lie with the British Columbia Oil and Gas Commission.

- Alberta is currently updating their Directives to address CCS in the Province.

Fort Nelson Compared to World CCS Projects



Modified from IEAGHG



<u>Fort Nelson Gas Plant:</u>

1.1 Bcf/d raw gas processing capacity, with current sales gas throughput at ~50% of capacity & CO_2 emissions of ~1 Mt/year

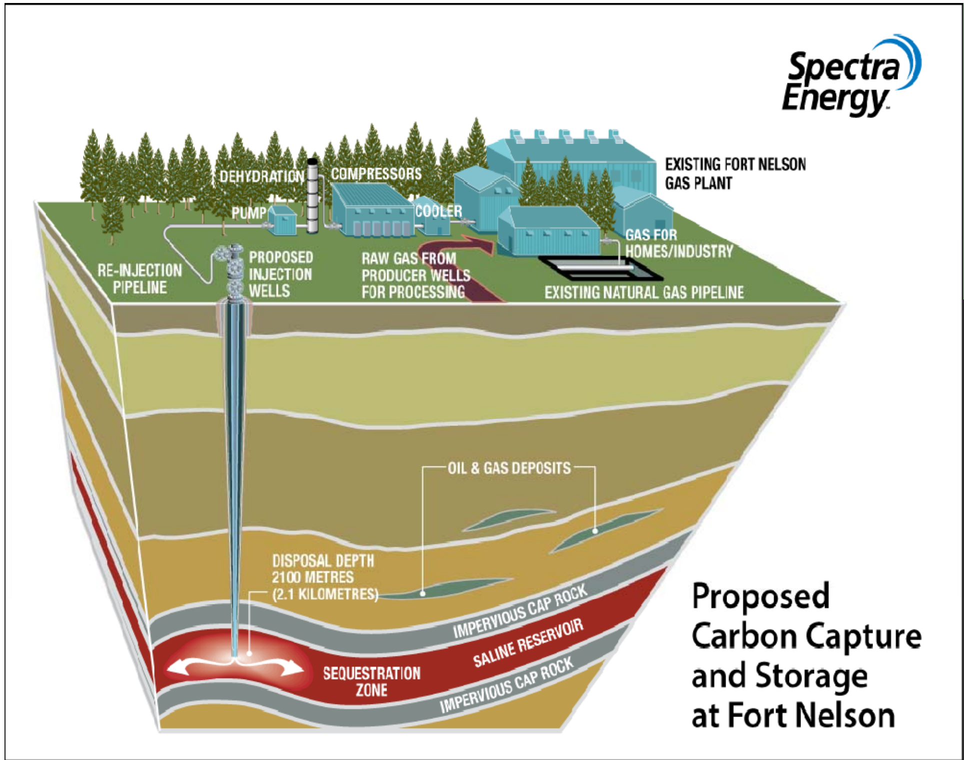
2. Natural gas production from all unconventional shale plays in BC are anticipated to grow

3. The proposed Fort Nelson CCS project is a potential solution to mitigate CO_2 emissions as production from the basin is forecast to grow

Fort Nelson Compared to World CCS Projects

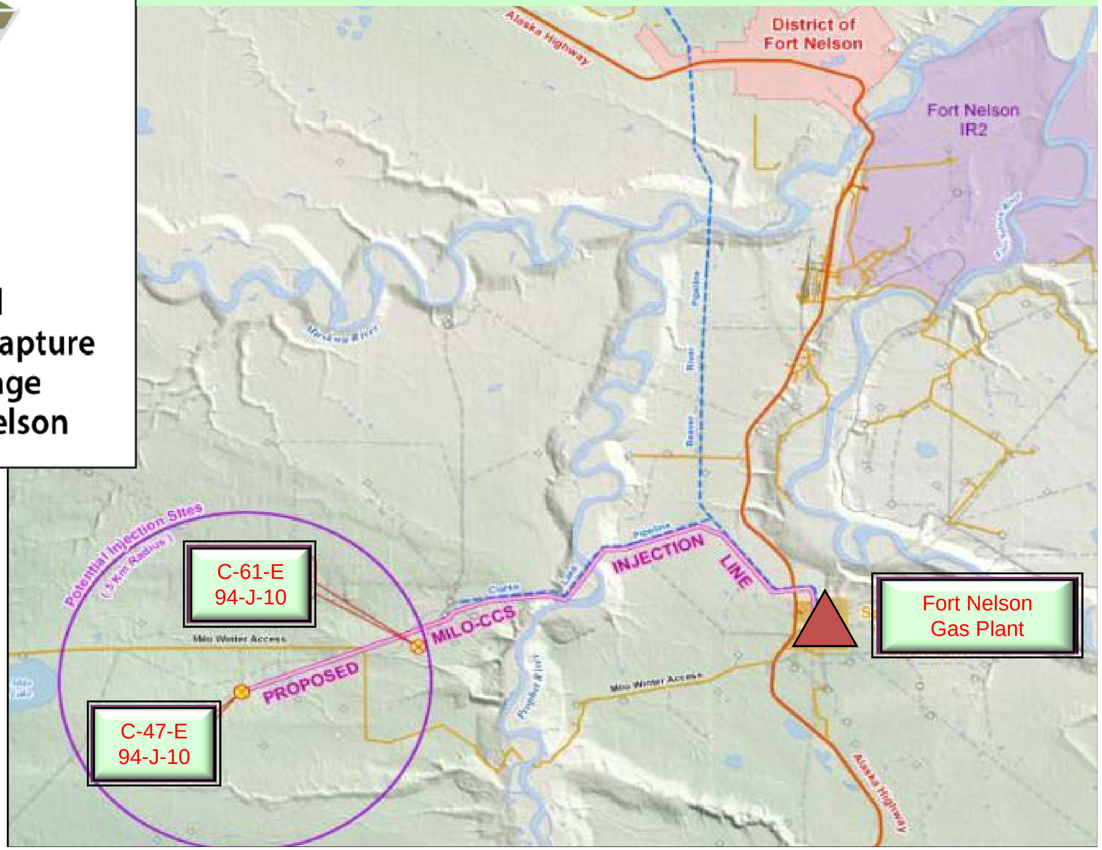
Modified from IEAGHG

Current Plan Considerations



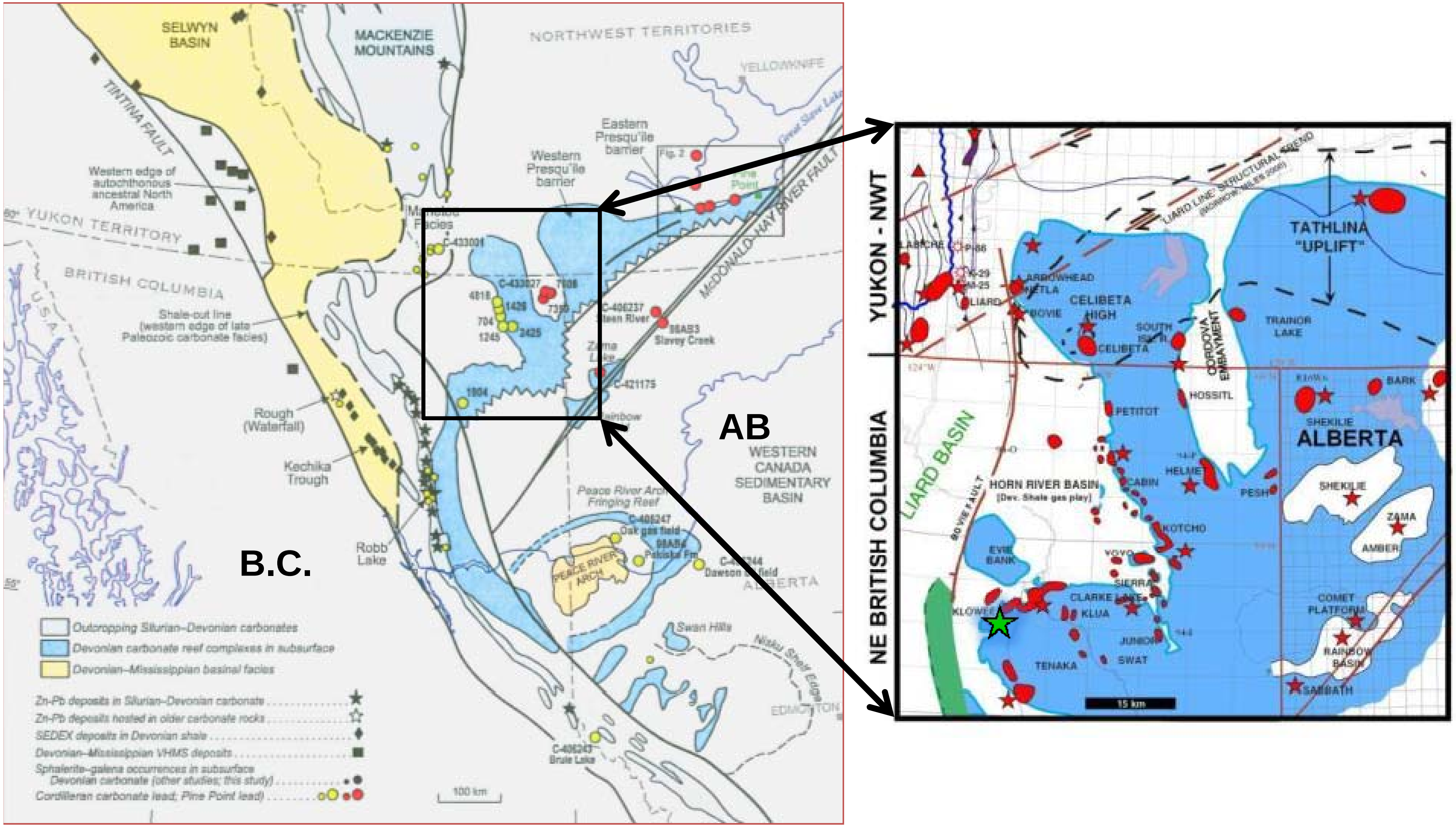
<u>Major Features:</u>

- 8000 feet deep
- Saline formation
- Fort Nelson gas plant owned 100% by Spectra Energy.
- Access and storage rights for deep saline formations of interest are obtained.

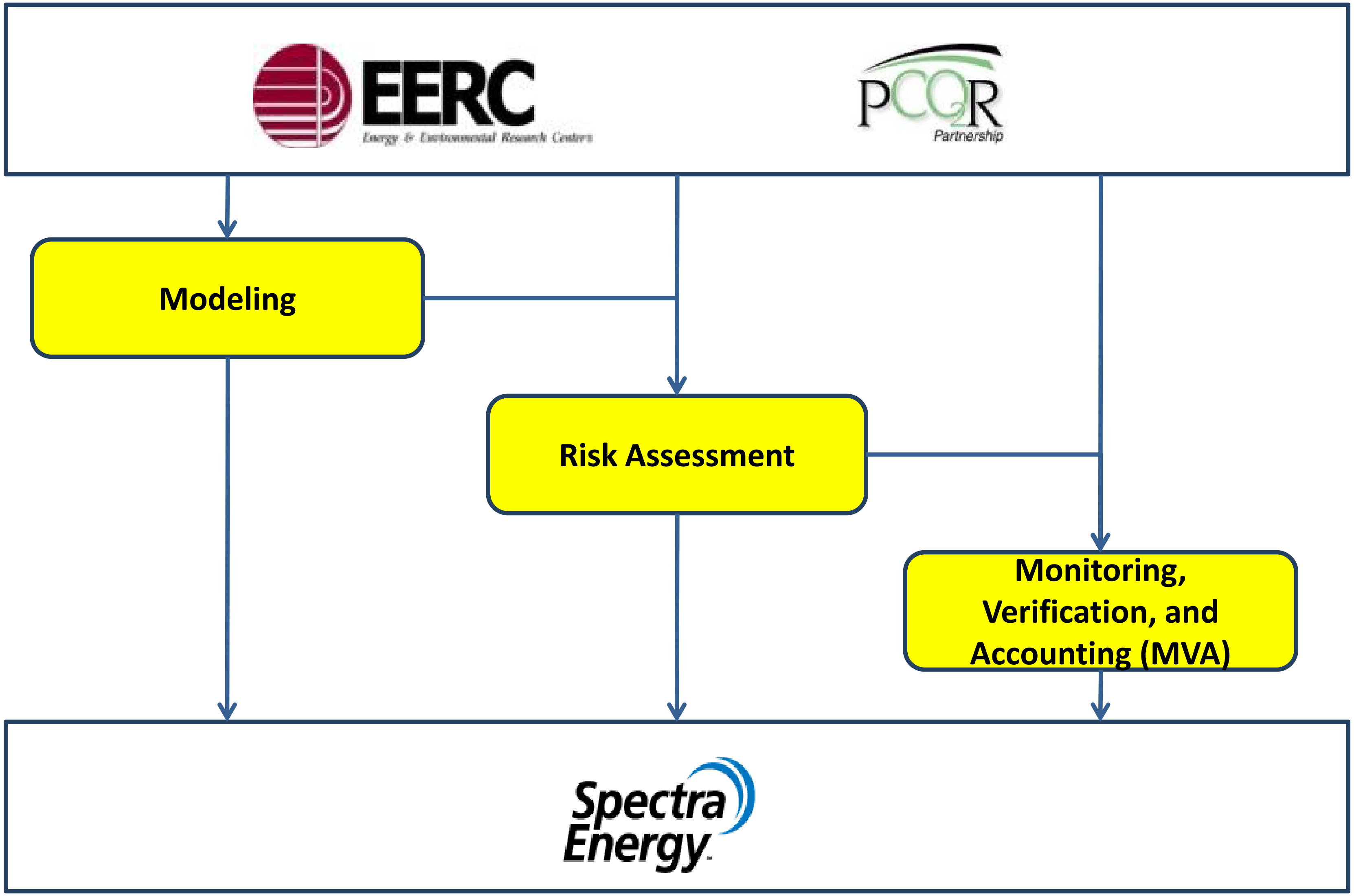


Across the Prophet River
Winter Access Only

Local Gas Production

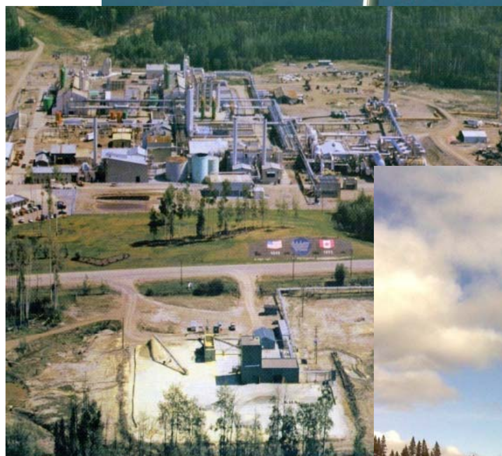


Fort Nelson CCS Project Involvement



Phase III Fort Nelson – Current Status

- Exploration well was drilled spring 2009.
- Re-entry and subsequent testing occurred in the winter drilling season 2010
- PCOR Partnership has provided a preliminary risk management plan (RMP) and we are developing an integrated RMP, modeling, and MVA program.



Next Steps

Establish Technical & Commercial Feasibility

- Working with the Province of British Columbia, Government of Canada and the private sector to develop a viable, long-term commercial model
- Risks & liabilities
- Secure funding to support project economics

Continued Communication with Stakeholders

- Continue to share learnings with project partners and to consult with local community , First Nations, and other interested stakeholders

Proposed Winter 2009-2010 Field Program:

- Prepare for drilling next test well & 3D seismic survey
- Core & fluid analyses, geo-mechanical & geochemical work
- Update geology maps, static model and dynamic model

MMV Program Updates:

- Risk scenarios with dynamic model
- Continue groundwater baseline development
- Geochemical study on groundwater
- Update risk assessment study
- Start site specific MMV plan in addition to groundwater

Acknowledgments

Collaborative work with:

Support from:

PCOR Partnership 2003 – Present

NETL; EERC, University of North Dakota; Abengoa Bioenergy; Air Products; Alberta; AERI Alberta Energy Research Institute; Alberta Innovates Technology Futures; Allete; Ameren; ACCCE American Coalition for Clean Coal Electricity; American Lignite Energy

Apache Canada Ltd.; Baker Hughes; Basin Electric Power Cooperative; Bechtel; Biorecro; Blue Source; BNI Coal; British Columbia Ministry of Energy, Mines and Petroleum Resources; Carbozyme Inc.; CCX Chicago Climate Exchange; CMG; Dakota Gasification Company; Ducks Unlimited Canada

Ducks Unlimited; Eagle Operating Inc.; EICCD; Enbridge; Encore Acquisition Company; ERCB Energy Resources Conservation Board; AGS Alberta Geological Survey; Environment Canada; Excelsior Energy; Fischer Oil and Gas, Inc.; Great Northern; Great River Energy; Hess

Huntsman; Indian Land Tenure Foundation; Interstate Oil and Gas Compact Commission; DNR; Kiewit; Lignite Energy Council; Manitoba; Manitoba Hydro; Marathon; MEG Energy Corp; Melzer Consulting; Minnesota Pollution Control Agency; Minnesota Power

Minnkota Power Cooperative, Inc.; Missouri Department of Natural Resources; Missouri River Energy Services; Montana-Dakota Utilities Co.; Montana Department of Environmental Quality; Montana Public Service Commission; Murex Petroleum Corporation; National Commission on Energy Policy; Natural Resources Canada; Nebraska Public Power District

Nexant; North American Coal Corporation; North Dakota Department of Commerce; North Dakota Department of Health; North Dakota Geological Survey; North Dakota Oil and Gas Division; Industrial Commission of North Dakota Lignite Research, Development and Marketing Program; Industrial Commission of North Dakota Oil and Gas Research Council; Natural Resources Trust; North Dakota Petroleum Council; NDSU; Otter Tail Power Company; Oxand Risk Management Solutions

PTRC Petroleum Technology Research Centre; PTTC; Prairie Public; Pratt & Whitney; Ramgen Power Systems; RPS Energy; Saskatchewan Industry and Resources; SaskPower; Schlumberger; Shell Canada Limited; Spectra Energy; Strategic West Energy Ltd.; Suncor Energy

TAQA; Tesoro; TGS; University of Alberta; University of Regina; USGS; Weatherford; Advanced Geotechnology; Western Governors' Association; Westmoreland Coal Company; Williston Basin Interstate Pipeline Company; Wisconsin Department of Agriculture, Trade & Consumer Protection; Xcel Energy

10/09

Contact Information

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, North Dakota 58202-9018

www.undeerc.org
Telephone No. (701) 777-5000
Fax No. (701) 777-5181

Steven Smith
ssmith@undeerc.org

STORE

sequestration training, outreach, research & education

Hilary Clement Olson
Institute for Geophysics
The University of Texas at Austin

An Alliance at
The University of Texas at Austin

Partners

Funding

FOA from DOE/NETL – summer, 2009

- Grant applications are sought from… organizations that can develop regional sequestration **technology training [& outreach]** to facilitate transfer of knowledge and technologies required for … **commercial CCS projects**. This training will focus on the applied engineering and science of CCS.

Gulf Coast Carbon Center

STORE

STORE Alliance proposed

- Create a skilled workforce for the CCS industry and foster the public understanding required to advance the United States in both energy security and a leadership position with regard to climate change mitigation technology
- Promote transfer of scientific knowledge and applied engineering technologies related to CO_2 storage in 4 areas:

Sequestration Workforce **T**raining

Public **O**utreach

R&D Transfer
(Research and Technology Dissemination)

Workforce Pipeline **E**ducation

Gulf Coast Carbon Center

STORE

Training

TOPICS: Resources Assessment (O&G, water), Site Characterization, Subsurface Geology, Permitting, Well Drilling and Completion for CO2, Reservoir Engineering, EOR-CO2, CO2 Injection, CO2 Monitoring, Petrophysics, Geophysics, Geochemical Impacts, Geomechanical Impacts, Project/Risk Assessment

- Train scientists and engineers (employed and unemployed) who would be candidates for the emerging sequestration workforce.
- workshops, short courses, CEUs

Gulf Coast Association of Geological Societies
60th Annual Convention
San Antonio, Texas
October 10-12, 2010

Outreach

- foster the public understanding of geologic carbon sequestration
- public outreach events – schools, museums

Gulf Coast Carbon Center

STORE

Research and tech transfer

- Propagate understanding of the latest research results and technological advances in the area of carbon sequestration.
- field trips, conferences, website, tech alerts, blogs with video enhancement

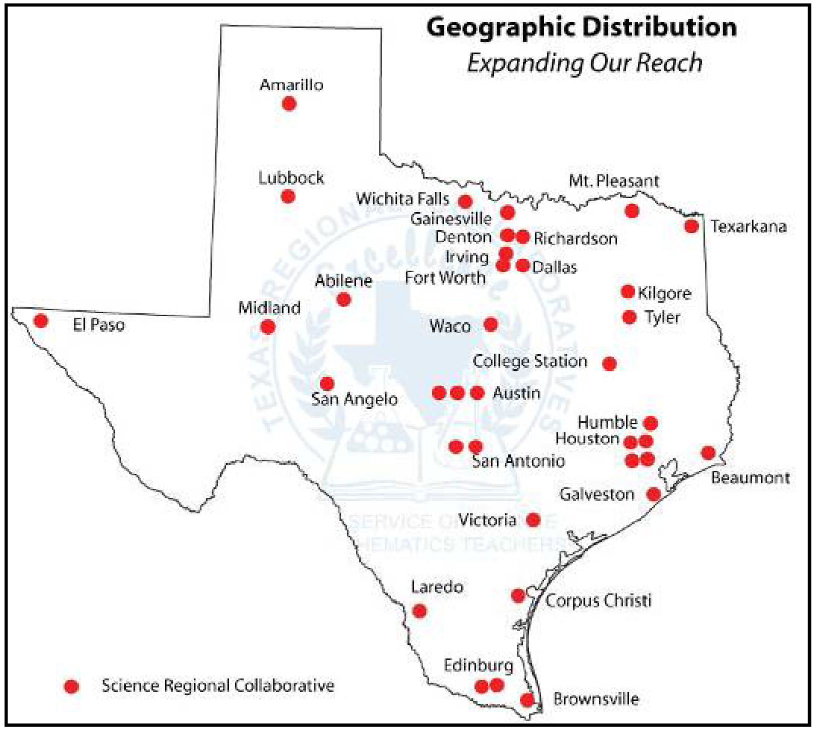
Gulf Coast Carbon Center

STORE
sequestration training, outreach, research & education

Education

- Impact the workforce pipeline related to GCS.
- training at universities; professional development training for teachers/profs who could broaden their students' work vision to include GCS industry

Energy Institute for Teachers – GCS Module



Gulf Coast Carbon Center

STORE

Rio
Grande
Valley
Science
Association

Schlumberger

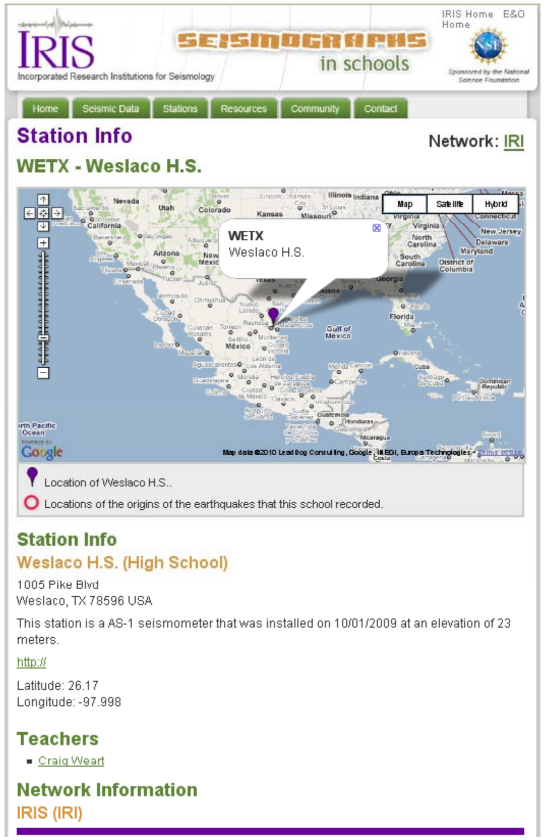
Gulf
Coast
Carbon
Center

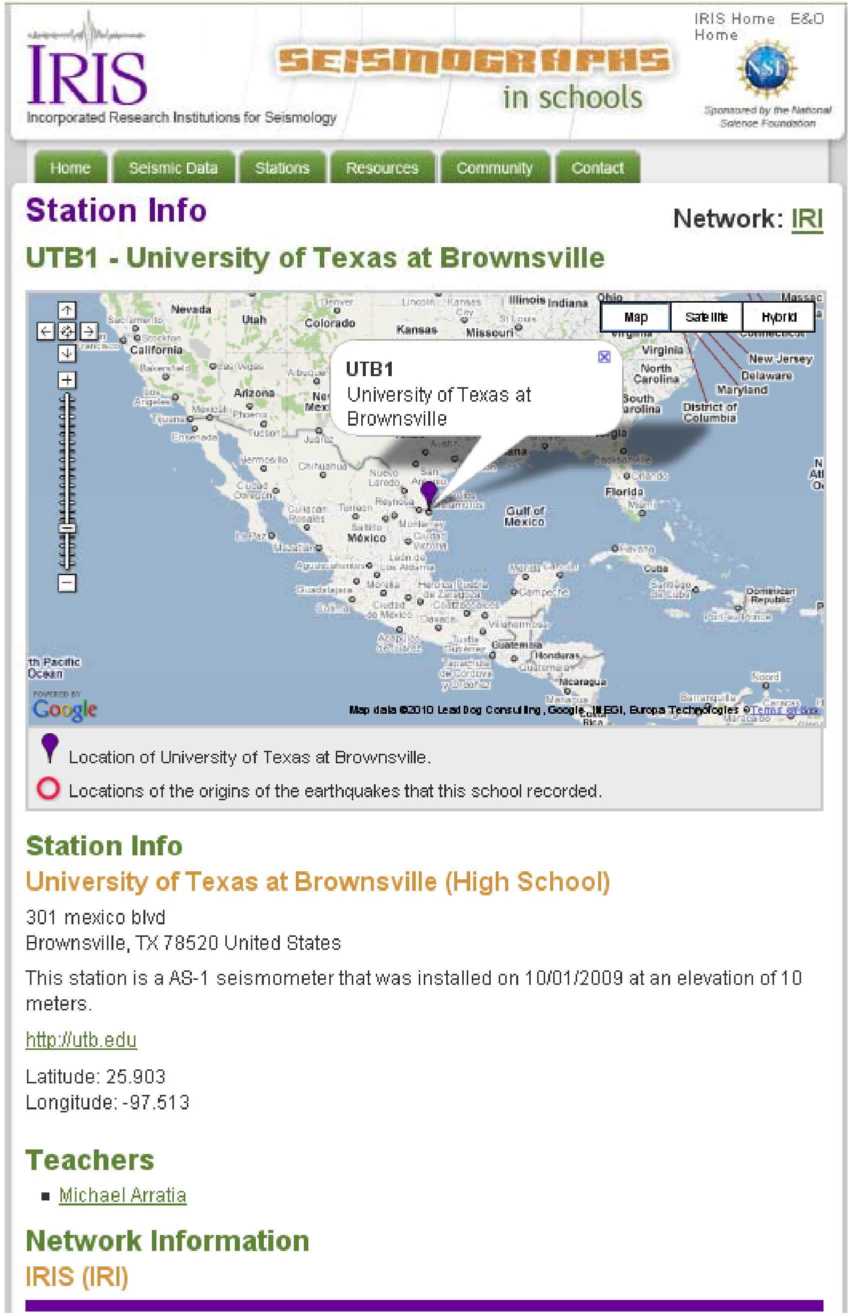
STORE

Gulf Coast Carbon Center

STORE

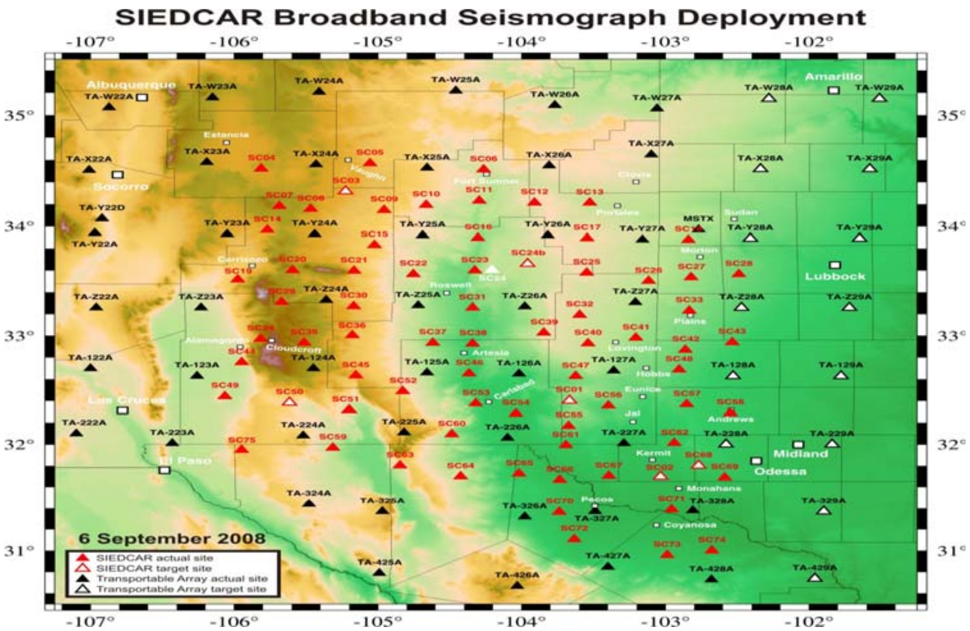
sequestration training, outreach, research & education





Gulf Coast Carbon Center

STORE



Land

Owners

Gulf Coast Carbon Center

STORE

STORE

sequestration training, outreach, research & education

www.StoreCO2Now.com

SECARB-Ed

Southeast Regional CO_2 Sequestration Technology Training Program

A Southern States Energy Board Carbon Management Program

Presented to:
IEA GHG
6th Monitoring Network Meeting
Natchez, Mississippi
May 7, 2010

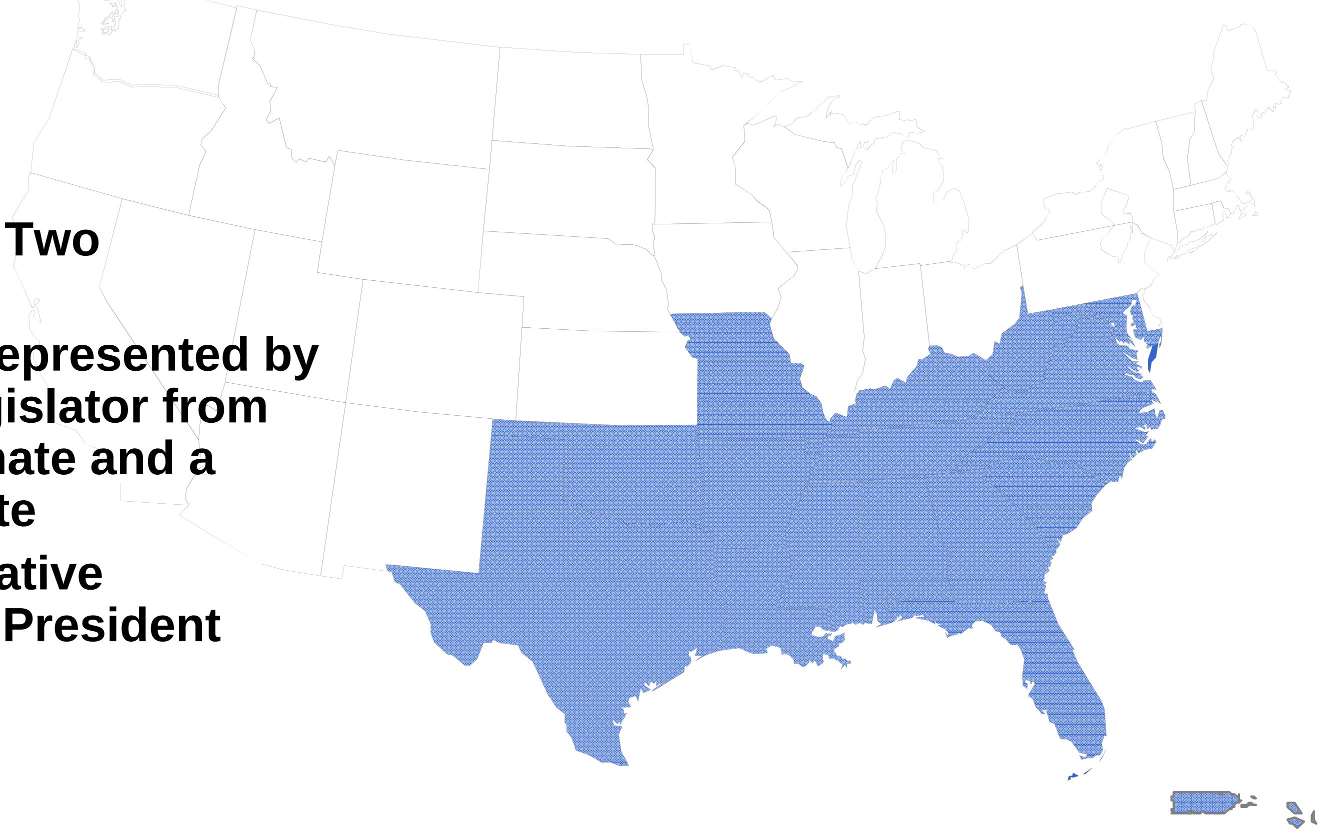
Presented by:
Kimberly Sams
Assistant Director, Geoscience Programs
Southern States Energy Board

SOUTHERN STATES ★ENERGY BOARD★

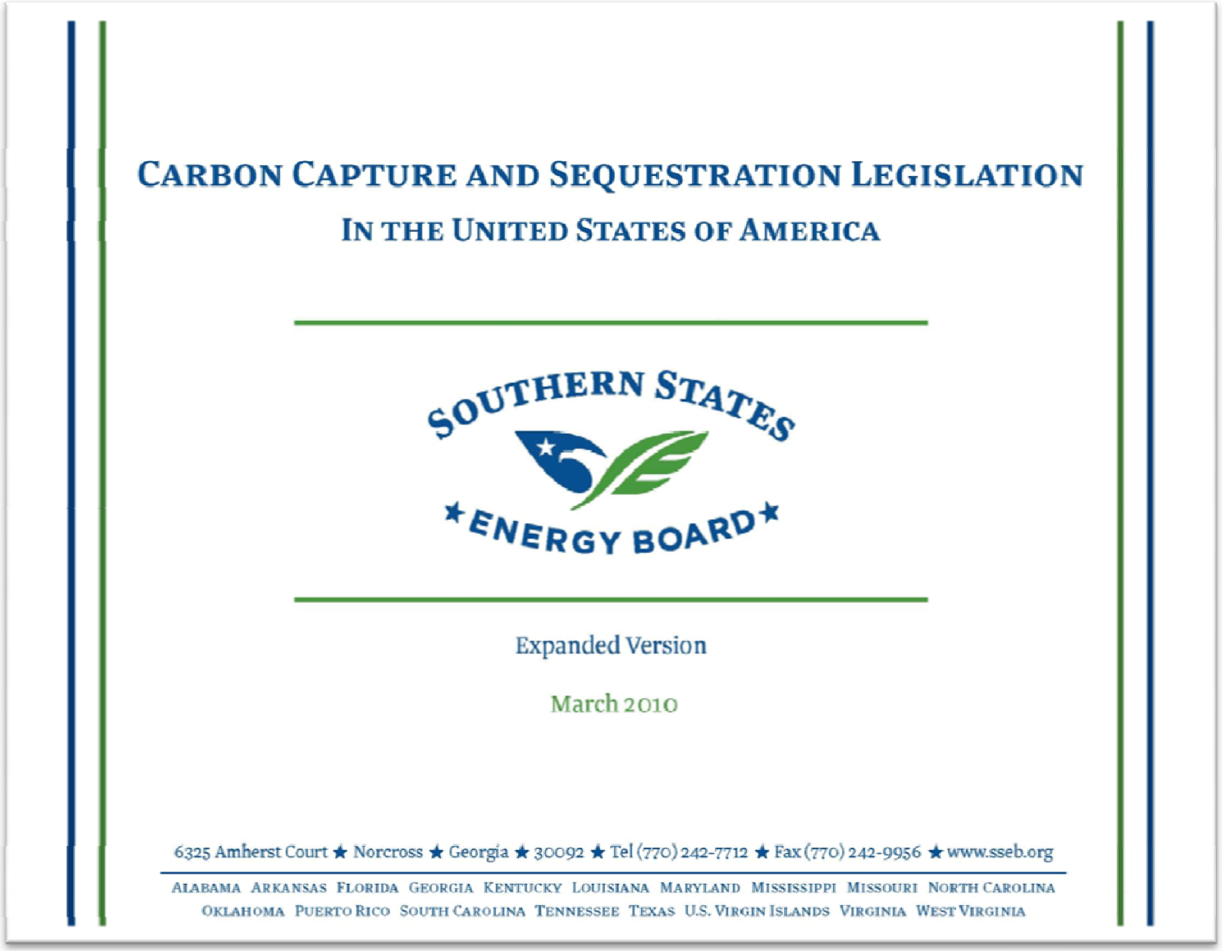
Through innovations in energy and environmental policies, programs and technologies, the Southern States Energy Board enhances economic development and the quality of life in the South.

- SSEB Mission Statement

- **Established 1960**
- **16 U.S. States and Two Territories**
- **Each jurisdiction represented by the governor, a legislator from the House and Senate and a governor's alternate**
- **Federal Representative Appointed by U.S. President**



State Legislative Activity



CARBON CAPTURE AND SEQUESTRATION LEGISLATION

IN THE UNITED STATES OF AMERICA

SOUTHERN STATES ENERGY BOARD

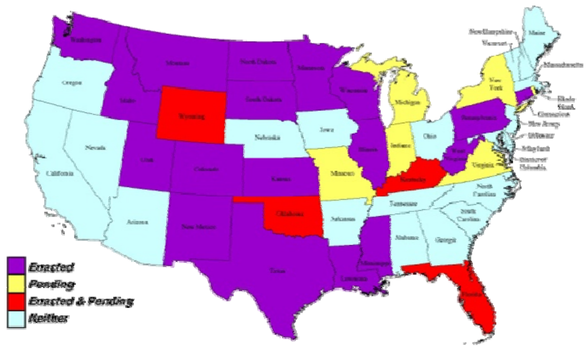
Expanded Version

March 2010

6325 Amherst Court ★ Norcross ★ Georgia ★ 30092 ★ Tel (770) 242-7712 ★ Fax (770) 242-9956 ★ www.sseb.org

ALABAMA ARKANSAS FLORIDA GEORGIA KENTUCKY LOUISIANA MARYLAND MISSISSIPPI MISSOURI NORTH CAROLINA OKLAHOMA PUERTO RICO SOUTH CAROLINA TENNESSEE TEXAS U.S. VIRGIN ISLANDS VIRGINIA WEST VIRGINIA

- Project Authority
- Pore Space and CO_2 Ownership
- Liability
- Financing Sources



www.sseb.org/documents

SSEB Outreach & Education

Outreach and Education is a key component of Project Management for all SSEB Programs

- American Energy Security
- **Carbon Management**
- Coal and Advanced Power Systems
- Biobased Products and Bioenergy Development
- Environmental Technology Development, Deployment and Training
- Pipeline Safety and Infrastructure
- Radioactive Materials: Emergency Response and Transportation Planning
- Regional Recycling Market Development
- Industry Partnerships
- Water for Energy

- Annual Board meetings (governors, legislators, federal representative, state energy office directors and government officials, industry, etc.)
- Annual Report to Board Members
- Annual Briefing to State Legislators
- Special briefings during National Governors' Association and Southern Governors' Association Meetings

SSEB Outreach & Education

Outreach and Education is a key component of Project Management for all SSEB Programs

- American Energy Security
- **Carbon Management**
- Coal and Advanced Power Systems
- Biobased Products and Bioenergy Development
- Environmental Technology Development, Deployment and Training
- Pipeline Safety and Infrastructure
- Radioactive Materials: Emergency Response and Transportation Planning
- Regional Recycling Market Development
- Industry Partnerships
- Water for Energy

- Annual Board meetings (governors, legislators, federal representative, state energy office directors and government officials, industry, etc.)
- Annual Briefing to State Legislators
- Special briefings during National Governors' Association and Southern Governors' Association Meetings

SSEB Carbon Management Program

- Established in 2003 (Chairman's Initiative)
  - Knowledge Sharing through Partnerships
  - Workforce Development
- **Southeast Regional Carbon Sequestration Partnership (SECARB)**
- **Southeast CO_2 Sequestration Technology Training Program (SECARB-Ed)**

Southeast Regional Carbon Sequestration Partnership

Outreach and Education

This material is based upon work supported by the

U.S. Department of Energy National Energy Technology Laboratory.

Cost share and research support provided by SECARB/SSEB Carbon Management Partners.

SECARB Partners: Diverse and Numerous (100+)

Advanced Resources International
Alabama Power Company
Alpha Natural Resources
American Coalition for Clean Coal Electricity
Amvest Gas Resources, Inc.
AMVEST Oil and Gas
ARCADIS US
Arch Coal
Augusta Systems, Inc.
Baker Hughes, Inc.
Blue Source
Bright Energy, LLC
BP America, Inc.
BP Alternative Energy
CDX Gas, LLC
ClemsonUniversity
CNX Gas
CONSOL, Inc.
CSX Transportation
Dart Oil & Gas Corporation
Dart Energy Corporation
Denbury Resources, Inc.
Dominion Energy
Dominion Resources
Duke Energy
Eastern Coal Council

Electric Power Research Institute (EPRI)
Entergy Services
Equitable Production Company
Exxon Mobil Production Company
F.D. Robertson
Florida Municipal Electric Association
Florida Power & Light Company
Geological Survey of Alabama
GeoMet
Halliburton
Hilcorp Energy Company
Kentucky Energy & Environment-Division of Energy Development & Independence
Kentucky Geological Survey
Interstate Oil and Gas Compact Commission
Marshall Miller & Associates
Massachusetts Institute of Technology
McJunkin Appalachian Oilfield Company
Mississippi Power Company
Mississippi State University (MSU)
Natural Resources Partners
NRG Energy
Old Dominion Electric Cooperative
Penn Virginia Operating Company, LLC
Penn Virginia Resources
Petron Resources

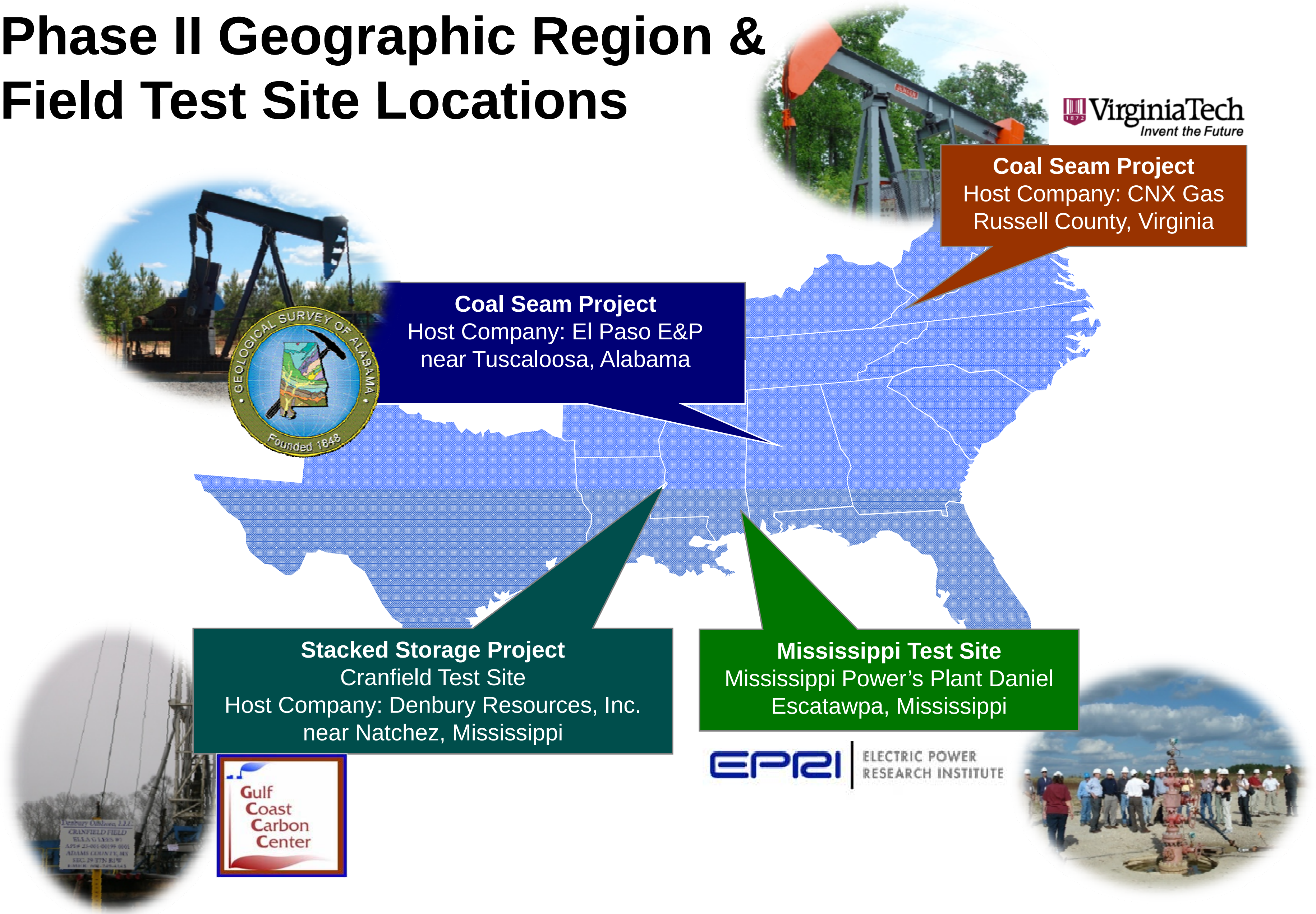
Piney Land Company
Pocahontas Land Corporation
Praxair
Progress Energy
RMB Earth Science Consultants, Ltd.
Santee Cooper Power
SCANA Energy
Schlumberger
Shell Exploration & Production Company
S&ME, Inc/ EMS Services
Smith Energy
South Carolina Electric & Gas Company
Southern Company
Southern Company Services
Southern Natural Gas & El Paso Exploration and Production
Southern States Energy Board
Teco Coal Corporation
Tennessee Valley Authority
Texas Bureau of Economic Geology -Gulf Coast Carbon Center
U.S. Department of Energy/National Energy Technology Laboratory
Virginia Tech
VA Center for Coal and Energy Research
West Virginia University

Plus 350+ Stakeholders!

Communication: Research Team & Stakeholders

- **Annual SECARB Stakeholders' Briefing**
  - Next Meeting: March 2011 in Atlanta, Georgia
  - 100+ partners and stakeholders
  - Field test details PLUS:
    - 2008: Project Integration & Capture Technologies
    - 2009: Carbon Sequestration 101
    - 2010: ARRA funded CCS project reports
- Membership Program for Industry Associates, Public, Special Projects
- Regular Email Alerts/Press Releases and Website
- Working Groups

Phase II Geographic Region & Field Test Site Locations



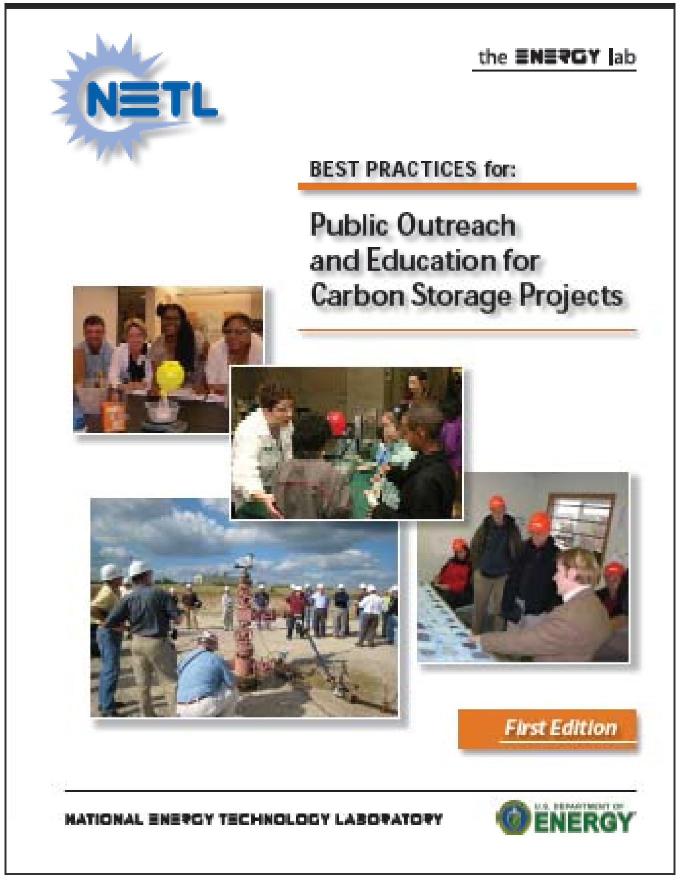
Phase III Geographic Region & Field Test Site Locations

2009-2010 Selected Outreach & Education Activity

- Congressman Hank Johnson (GA)
- Southeast Public Utility Commissioners
- Kentucky Mining Foundation Distinguished Lecture
- Law Schools
- Central Appalachian Leadership Forum- KY
- Georgia Environmental Conference
- South Carolina Chamber of Commerce
- South Carolina State Legislators
- Georgia Environmental Facilities Authority
- American Water Works Association (AWWA)
- EPA
- Economic Development Councils of several states
- Mississippi Energy Coordinators
- West Virginia CCS Working Group

Public Outreach & Education

- **RCSP Outreach Working Group**
  - Best Practices Manual: Framework to aid developers in designing and implementing effective outreach programs
  - Outreach should account for needs and concerns of target audience as well as the extent to which the developer already has relationships in the community



http://www.netl.doe.gov | Select "Publications" then "Carbon Sequestration"

SECARB-Ed

Southeast Regional CO_2 Sequestration Technology Training Program

A Southern States Energy Board Carbon Management Program

This material is based upon work supported by the

U.S. Department of Energy National Energy Technology Laboratory.

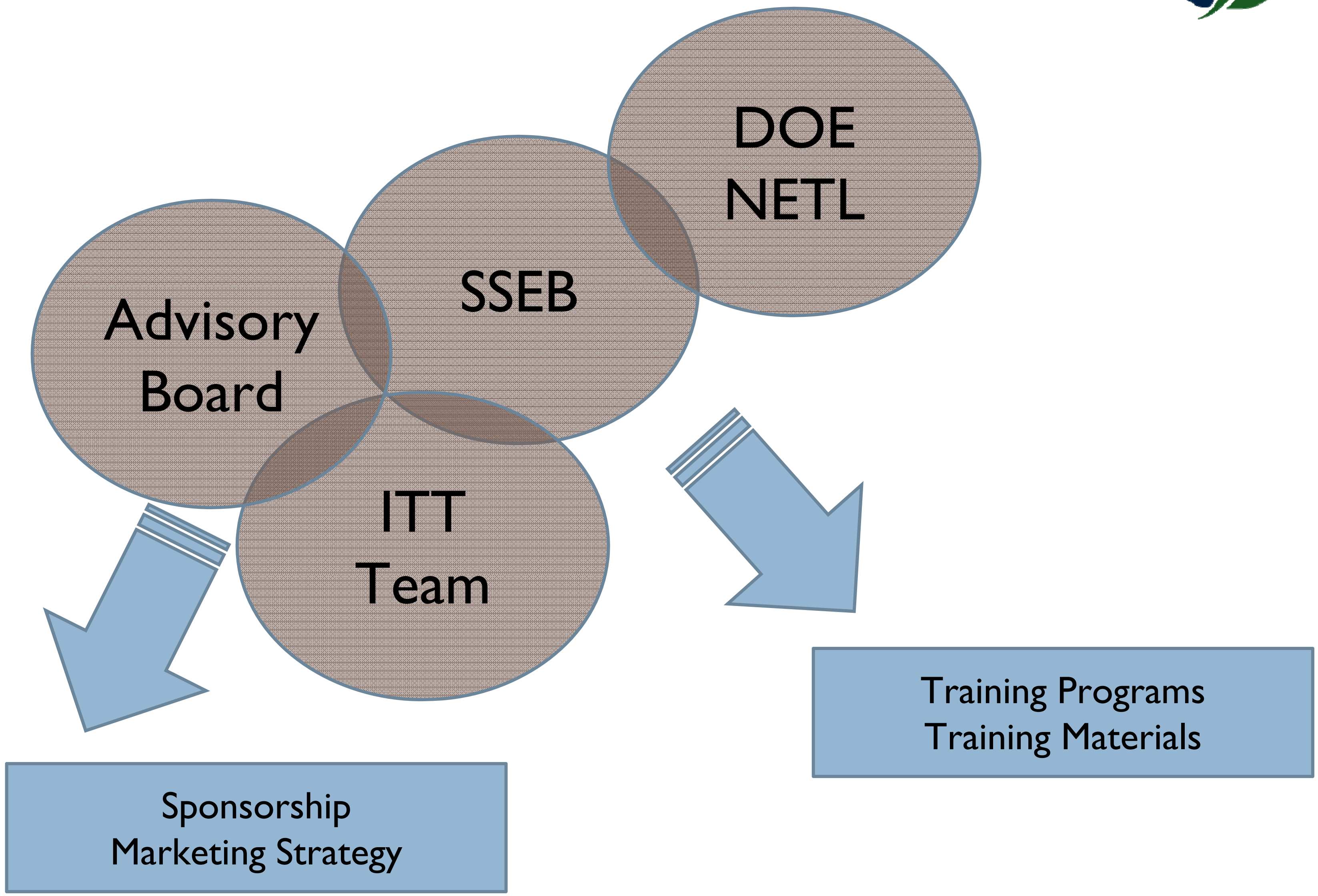
Cost share and research support provided by SECARB-Ed Partners.

Purpose, Duration & Investment

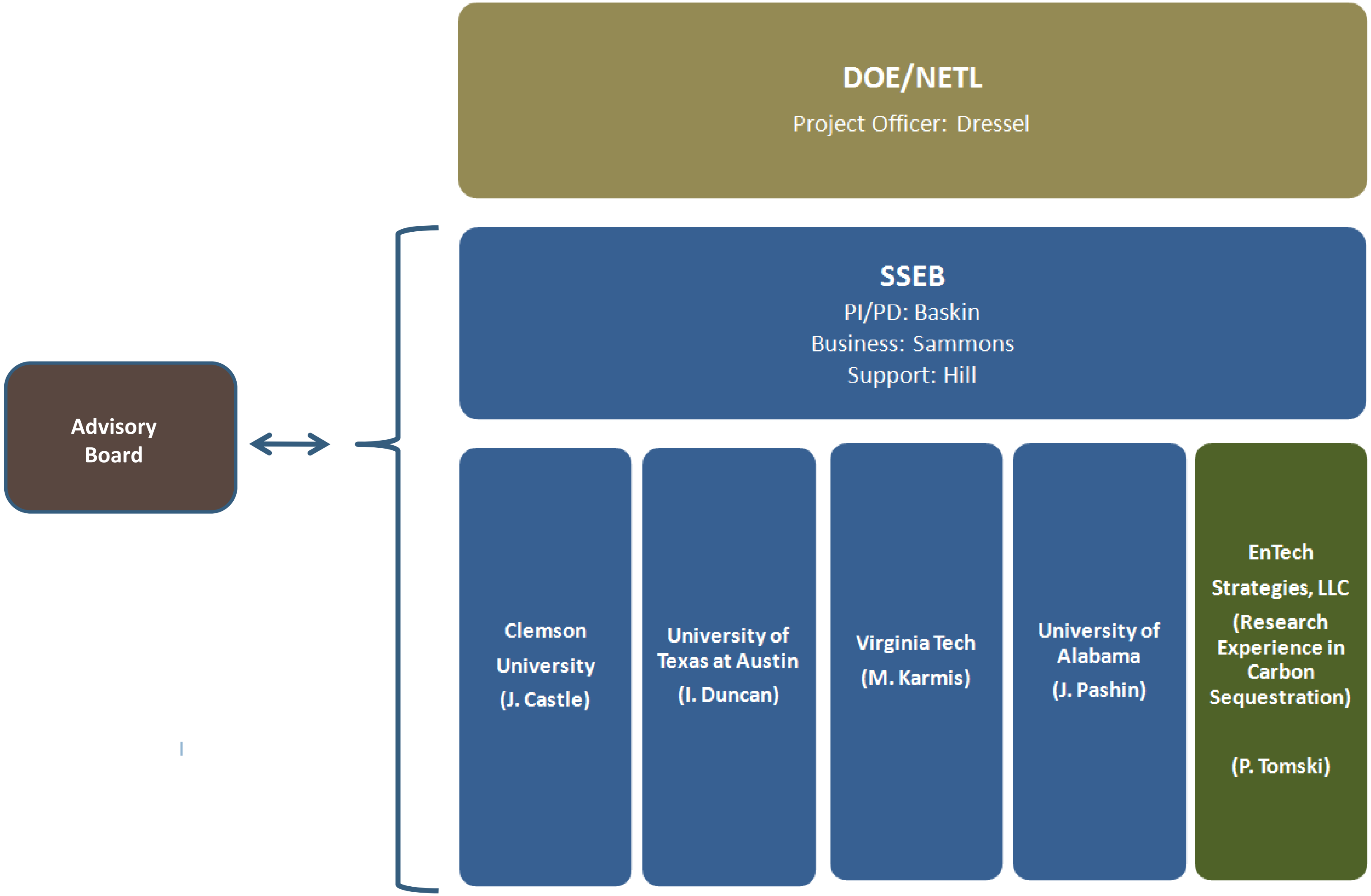
- **Purpose:** Develop a self-sustaining regional CO_2 sequestration training program to facilitate the transfer of knowledge and technologies required for site development, operations and monitoring of commercial CCS projects.
- **Objectives:**
  - Implement sponsorship development program
  - Develop short courses on CCS technologies
  - Conduct regional training and other activities through outreach and networking
  - Perform region/basin technology transfer services
- **Duration:** 36 months (Began November 2009)
- **Initial Investment (ARRA Funding):**

Total Federal Funds	Total Non-federal Funds	Total Project Cost	Cost-share Percentage
$994,368.00	$167,126.00	$1,161,494.00	14%

SECARB-Ed Relationships



SECARB-Ed Communication



Integrated Technology Training (ITT) Team Members in Blue

Training Programs & Materials

- **Training Programs**
  - CEU/PDU
  - Topical Short Courses
  - Train the Trainer
  - Webinars
  - CCS Camp
- **Training Materials**
  - CCS Modules
  - Newsletters
  - Website Content
  - Email Alerts

Management & Coordination (SSEB)

- Manage the SECARB-Ed project and coordinate team activities and CCS module development
- Guide CEU/PDU development/certification and technology training implementation
- Support functions of the Advisory Board, secure sponsorship and implement a marketing strategy
- Interface with other regional sequestration technology training teams and DOE-NETL
- Manage CCS newsletters, website content, email alerts, project services and deliverables

CCS Topics by Partner

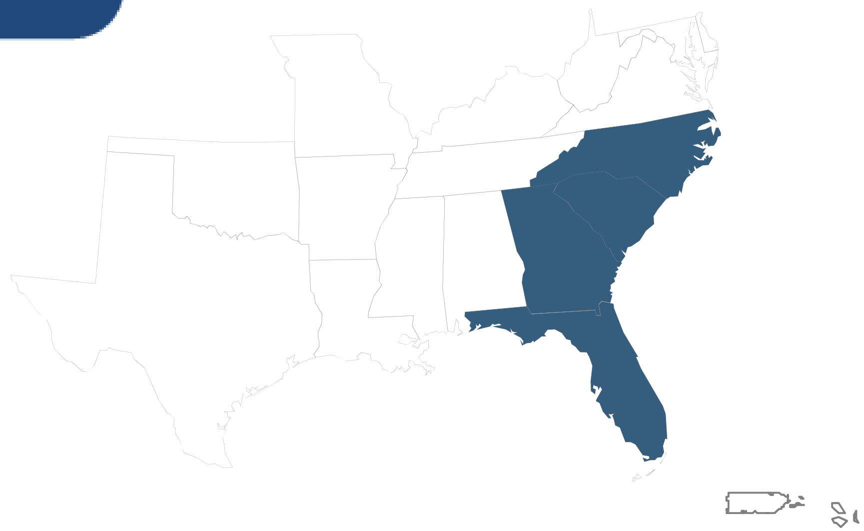
Southern States Energy Board

- GHG Fundamentals
- Legal, Regulatory, Institutional
- CO_2 Transportation

CCS Topics by Partner

Clemson University

- CO_2 Capture
- Treatment & Compression
- Produced Water Treatment

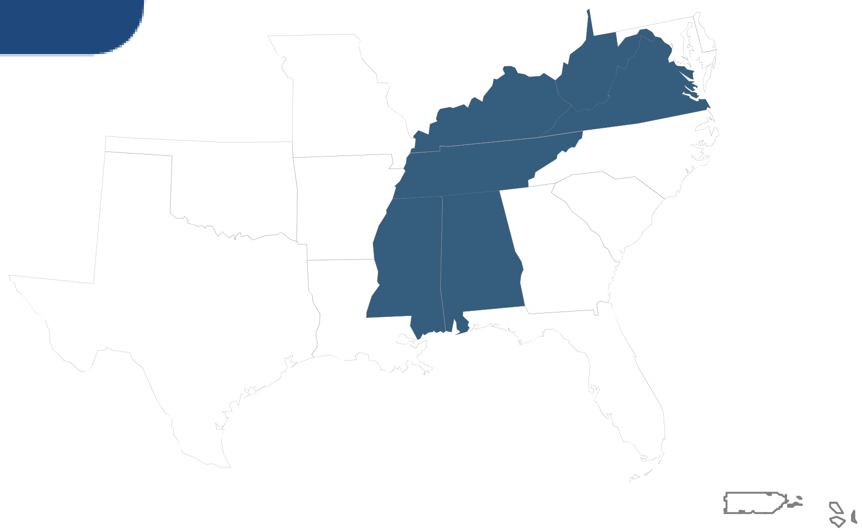


CCS Topics by Partner

Virginia Tech &

Geological Survey of Alabama

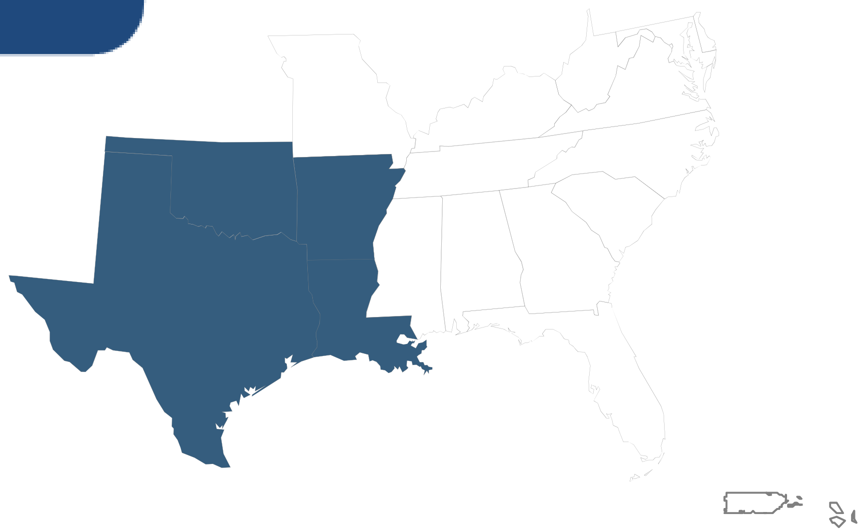
Coal & Shale	Coalbed Methane	Related MVA



CCS Topics by Partner

The University of Texas, Bureau of Economic Geology

Saline	Oil & Gas	Related MVA



CCS Topics by Partner

EnTech Strategies

"Research Experience in Carbon Sequestration" in the Southeast

Coming Soon…

www.SECARB-Ed.org

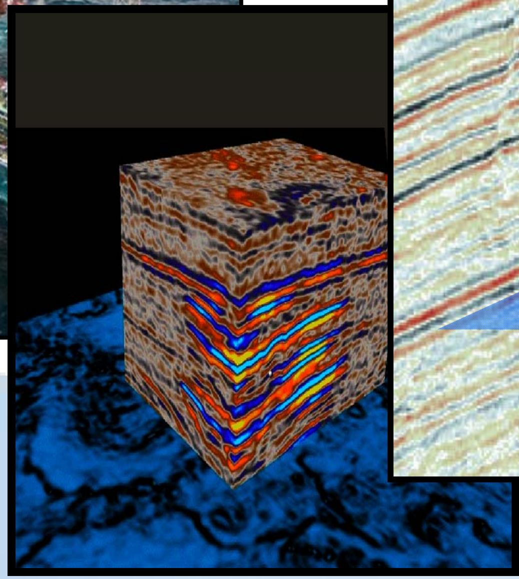
Kimberly Sams
Assistant Director, Geoscience Programs
Southern States Energy Board
6325 Amherst Court
Norcross, Georgia 30092 USA
Phone: (770) 242-7712
Fax: (770) 242-0421
sams@sseb.org
www.sseb.org

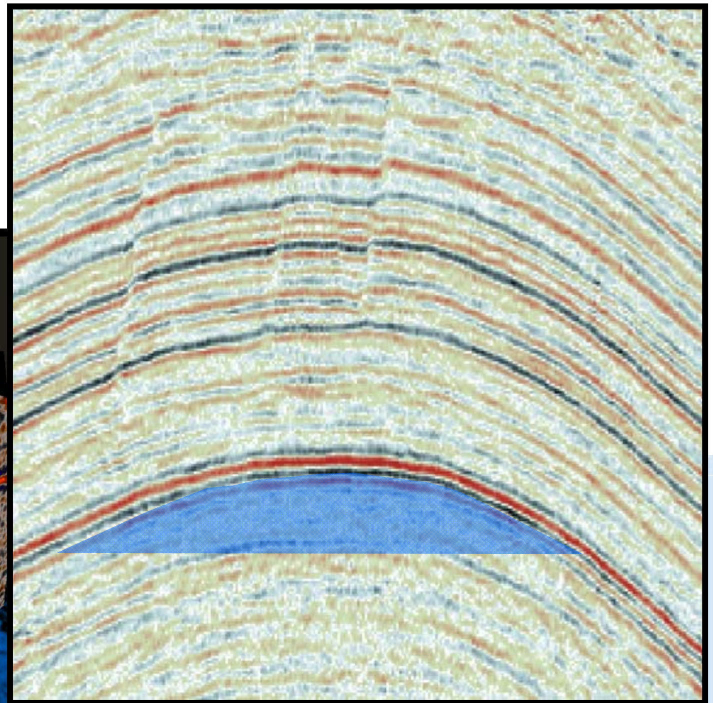
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Some remarks on uncertainty

Andy Chadwick (British Geological Survey)

6th IEAGHG Monitoring Network Meeting Natchez 6 – 7 May 2010





EU Storage Directive: performance monitoring philosophy

Predict **pre - injection**

Monitor
Verify / Modify model

Predict
Monitor
Verify / Modify model (remediate / terminate) **injection**

Predict
Monitor
Verify / Modify model

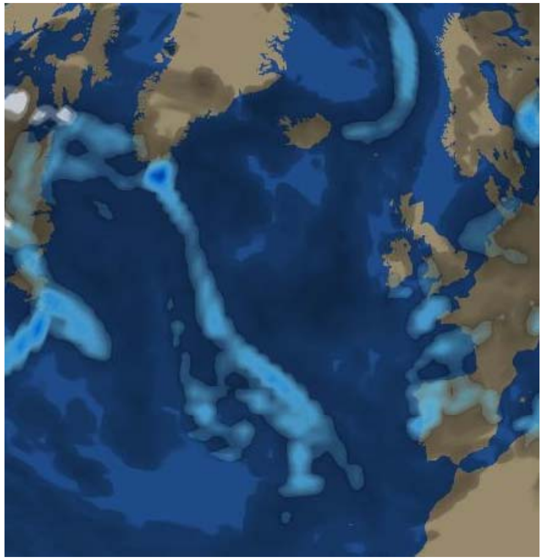
Predict
Monitor

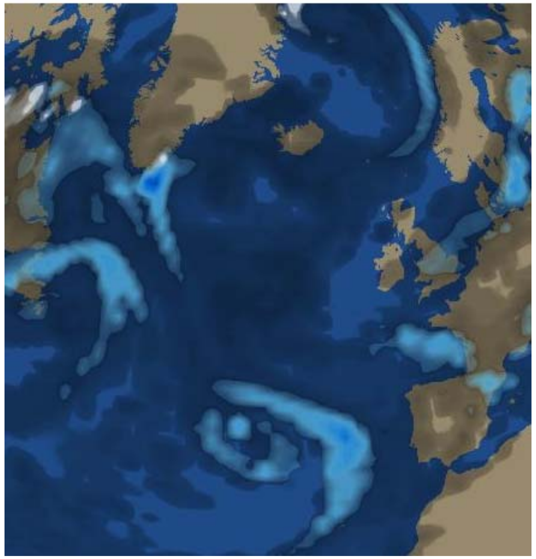
post - injection

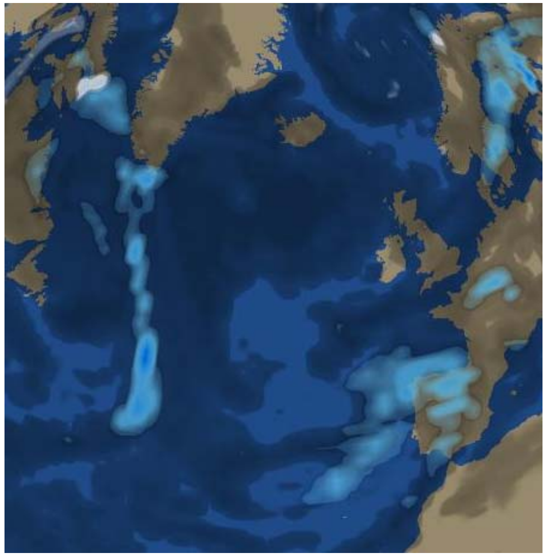
Verify model
Long-term robust prediction

transfer of liability

Predictive modelling



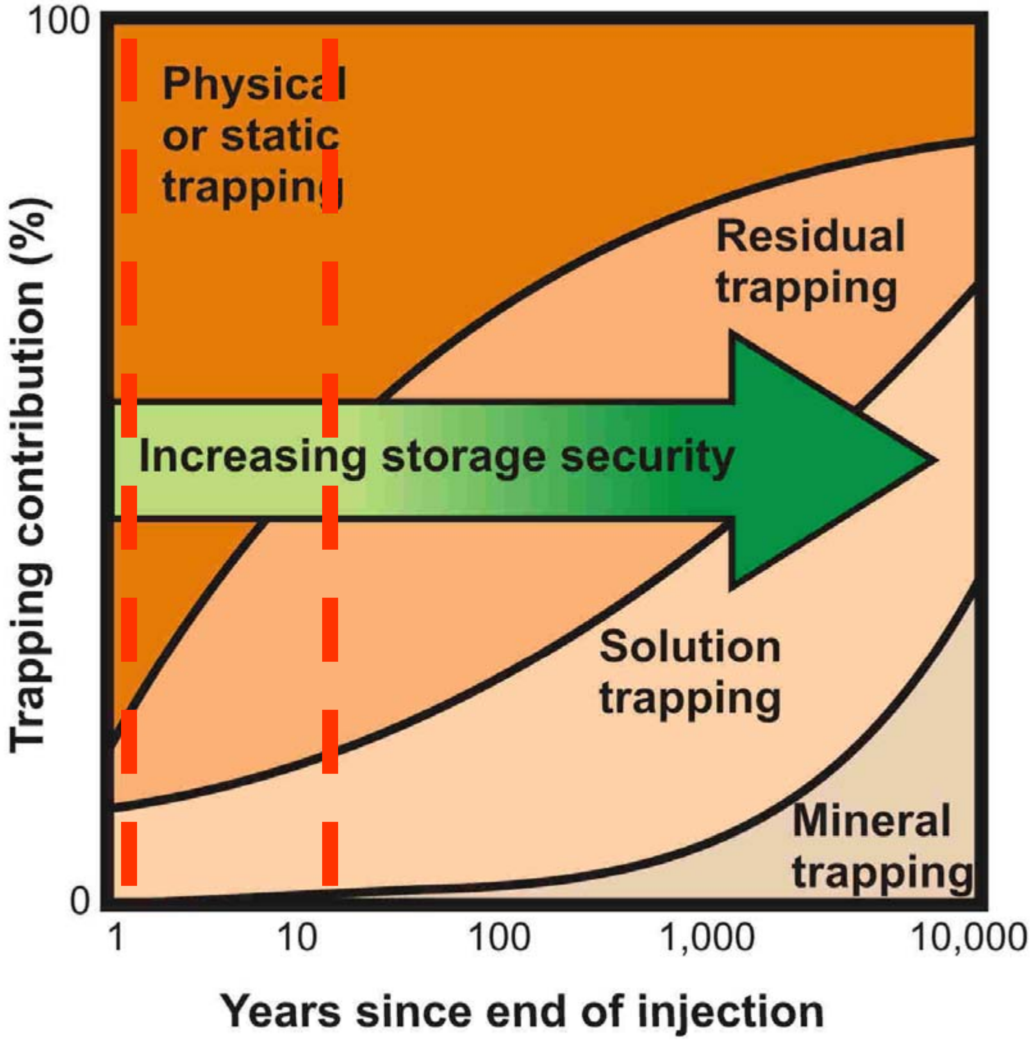




today

Instantaneous uncertainty remains roughly constant
…… but leads to divergent long-term outcomes

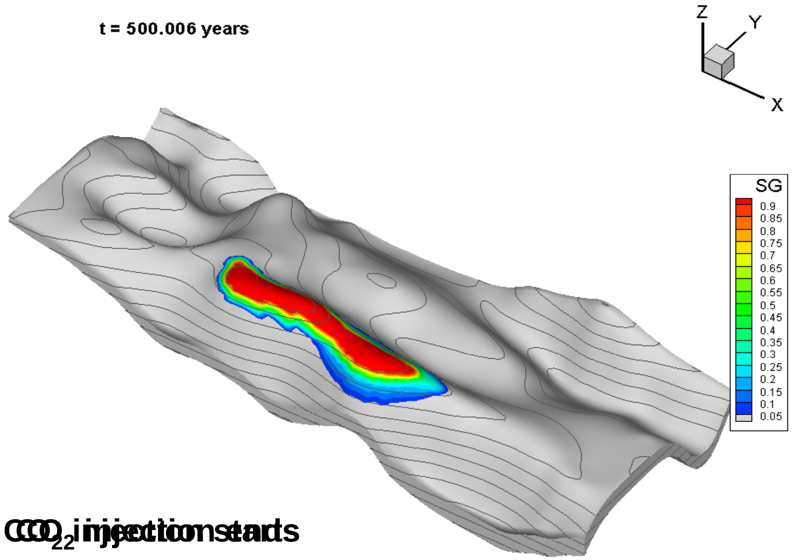
‘Instantaneous’ uncertainty decreases with time …..



Behaviour ‘converges’ on stability

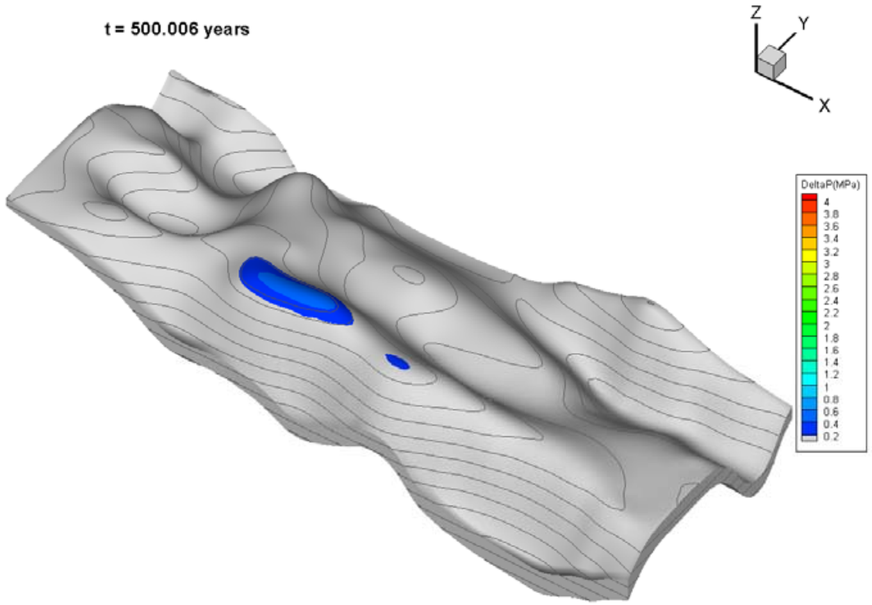
Predicted behaviour:
A ‘convergent’ site

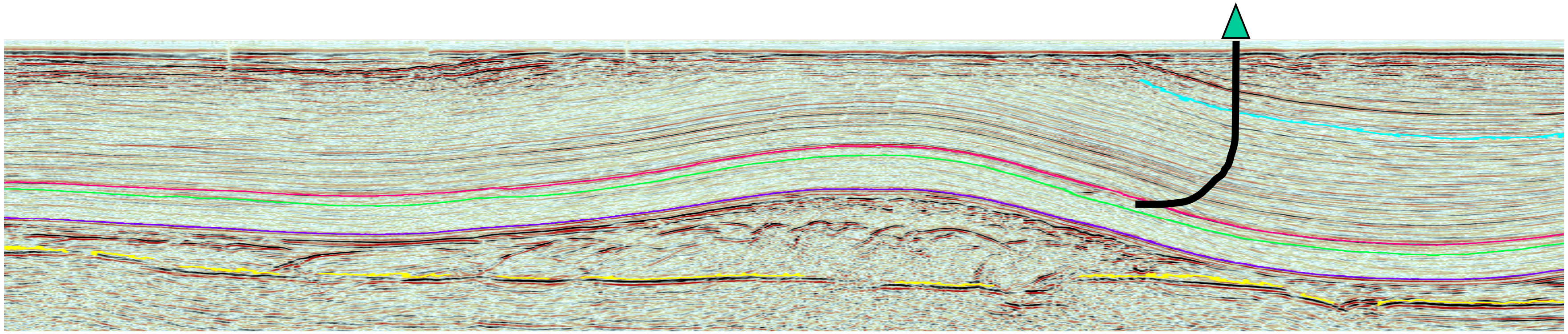
Free CO_2



CO_2 injection starts
CO_2 injection ends

Formation pressure





Monitoring systems

Non-invasive	Invasive
Surface TL seismic	Downhole P, T
Seabed imaging	VSP (VHRTT)
Gravimetry	Crosshole seismics
Surface CSEM	Crosshole ERT / EM
Wellhead pressure	Fluid sampling
Surface flux	Saturation logging
InSAR	Dissolution logging
[SPATIAL]	[PROCESS CALIBRATION]

EU Storage Directive: Minimum conditions for transfer….

1. Actual behaviour of the injected CO_2 conforms with the modelled behaviour

2. No detectable leakage

3. Storage site is evolving towards a situation of long-term stability

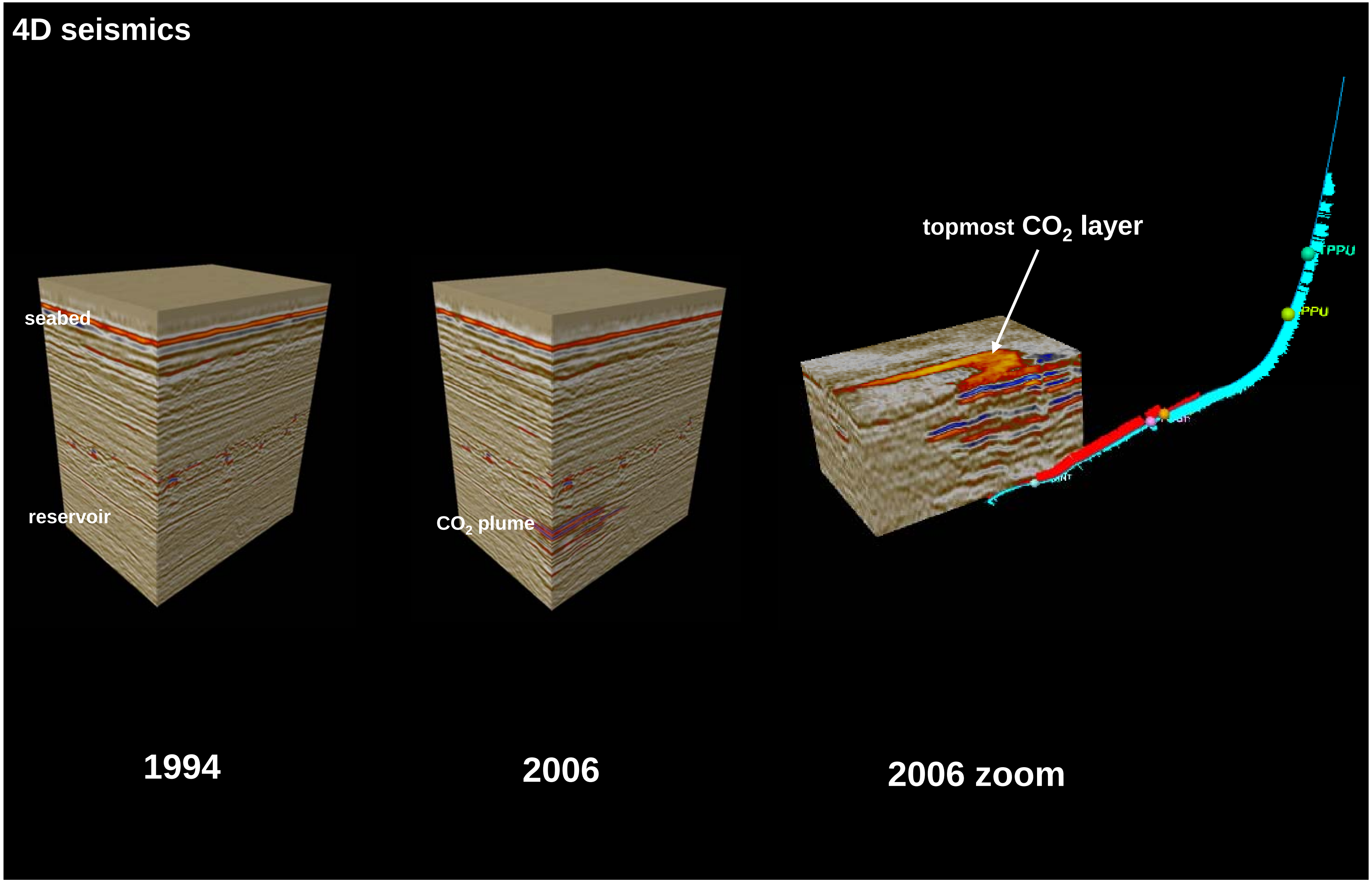
EU Storage Directive: Minimum conditions for closure….

1. Actual behaviour of the injected CO_2 conforms with the modelled behaviour

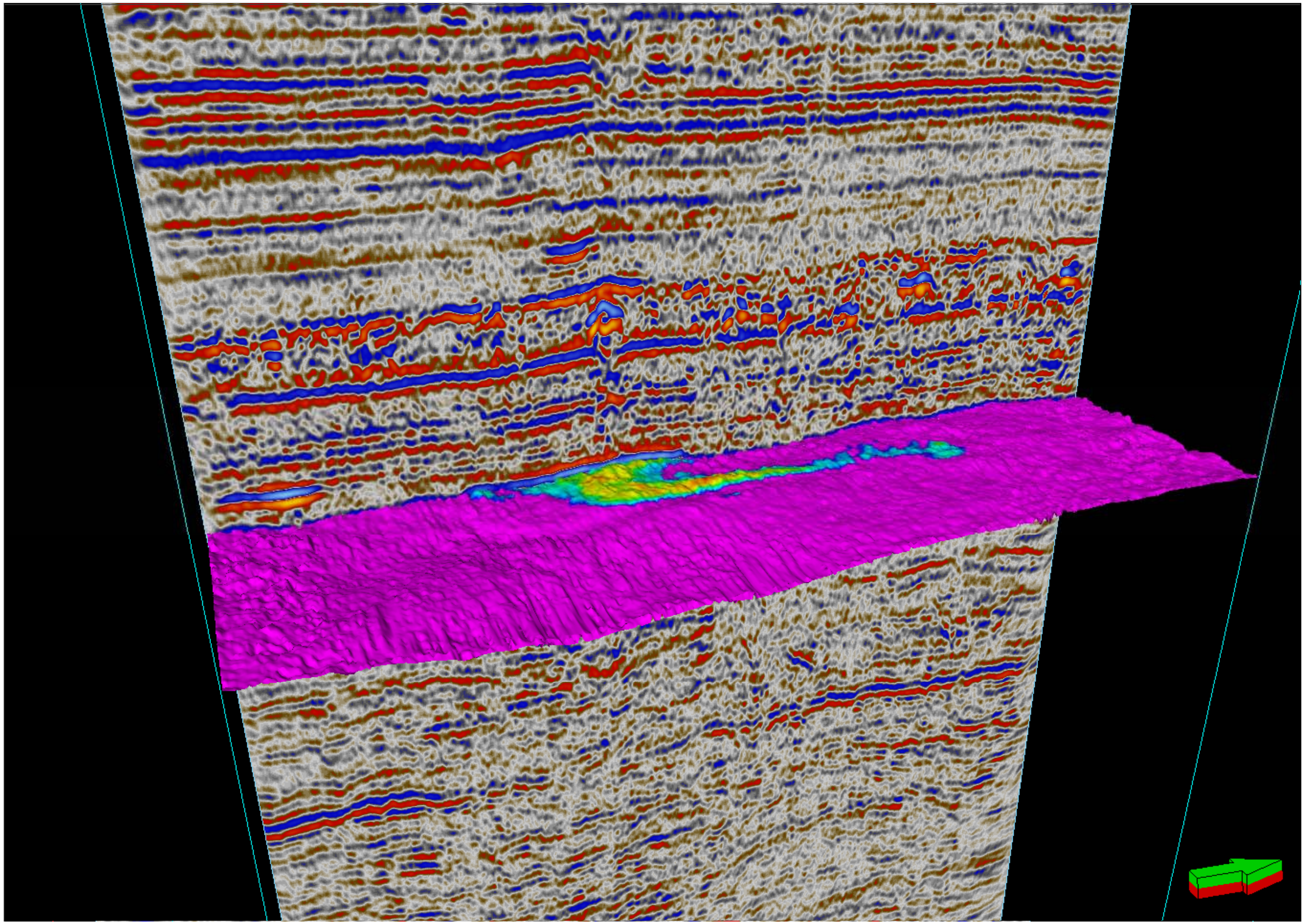
2. No detectable leakage

3. Storage site is evolving towards a situation of long-term stability

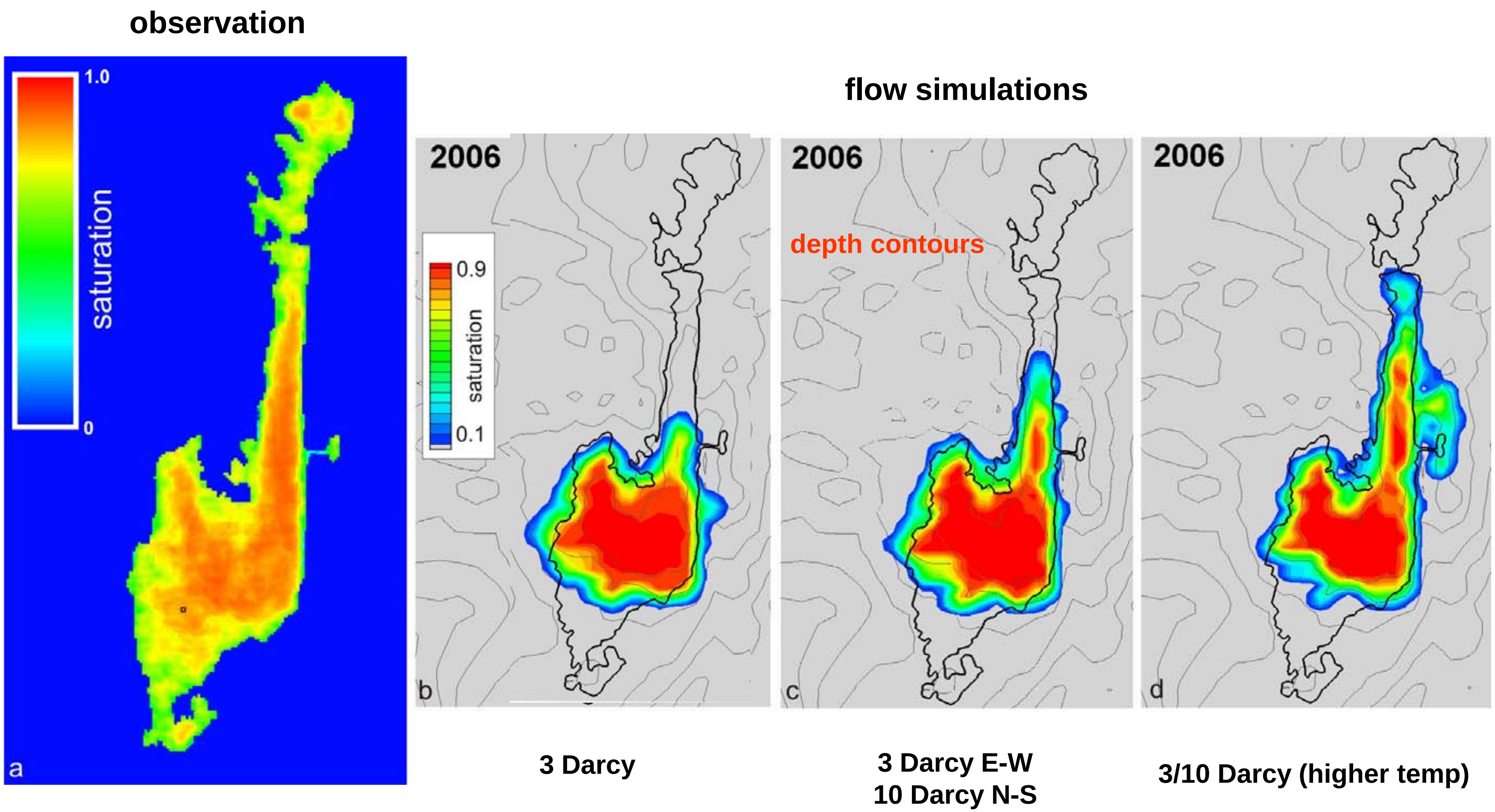
Non-invasive monitoring: Actual behaviour at Sleipner



Sleipner: actual behaviour 2001 - 2006



Sleipner: actual vs modelled behaviour 2001 - 2006

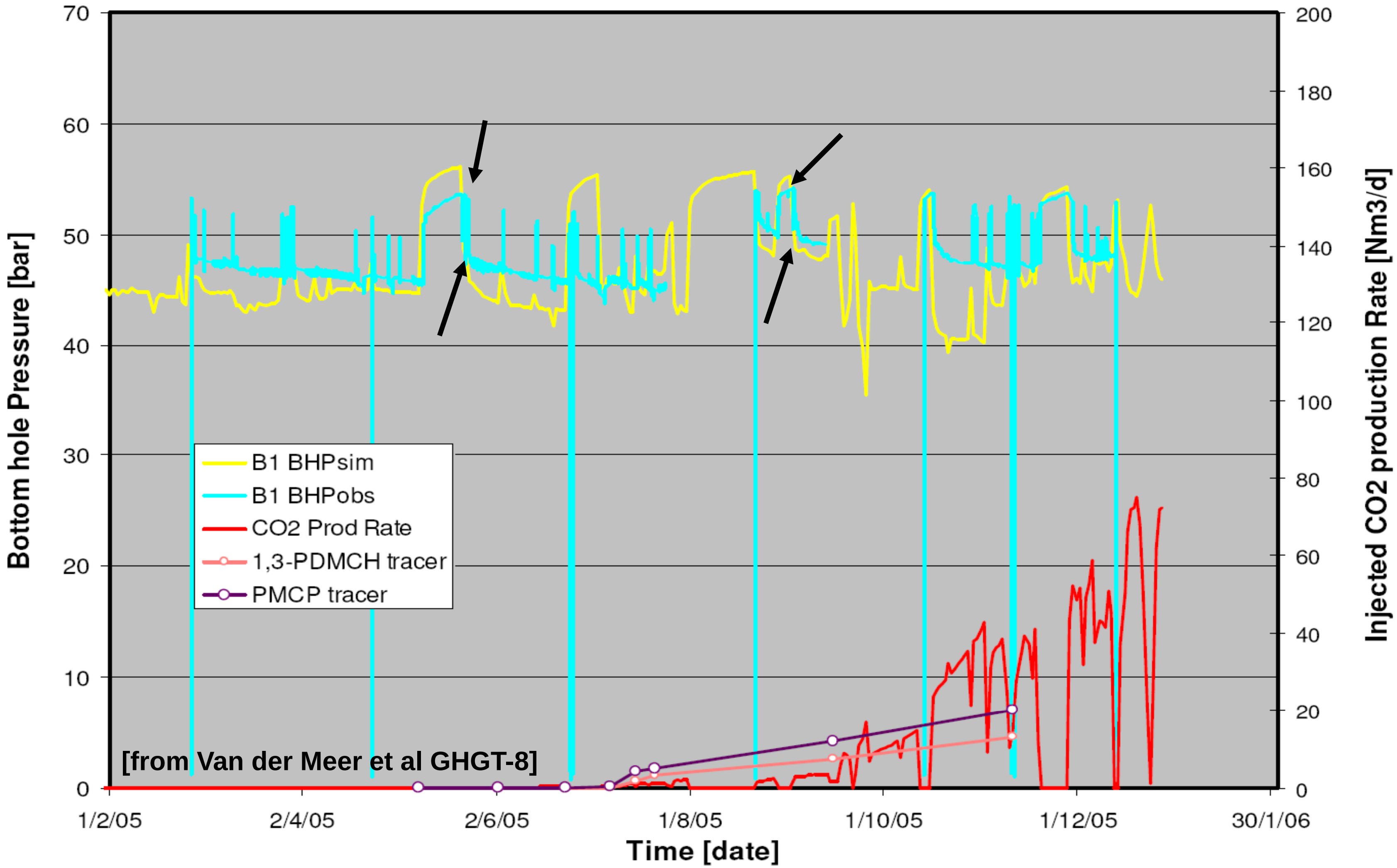


Core permeabilities 2 - 3 Darcy
Well permeabilities 1 - 8 Darcy

Perfect history-match challenging
Well within known uncertainties
Overall process understanding OK
Is mismatch significant?

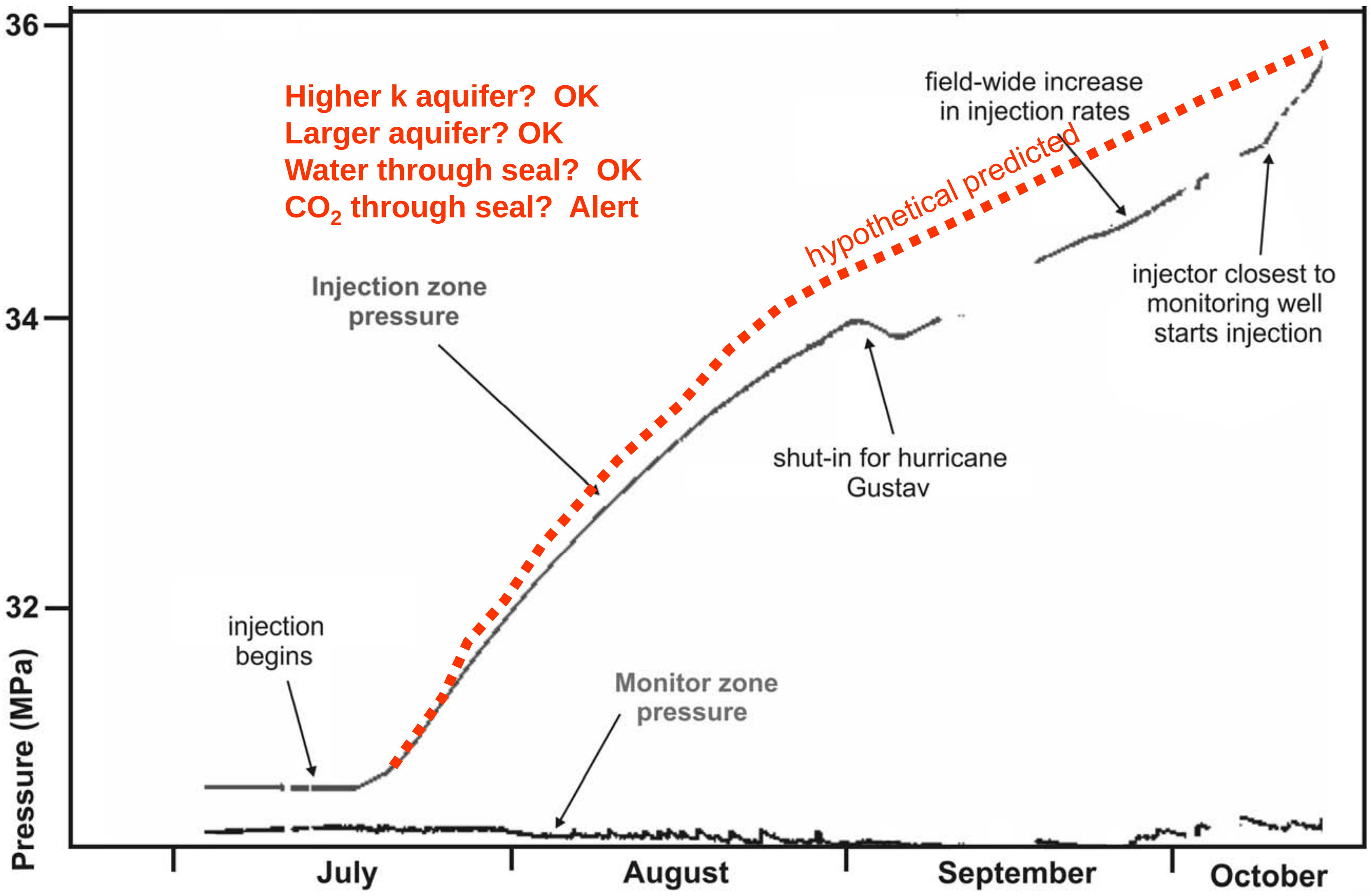
Invasive Monitoring: actual vs modelled behaviour at K12-B

Pressure and plume velocity



Mismatch probably not significant?

Invasive monitoring: actual behaviour at Cranfield



Potentially divergent consequences?

[from Meckel et al. 2009]

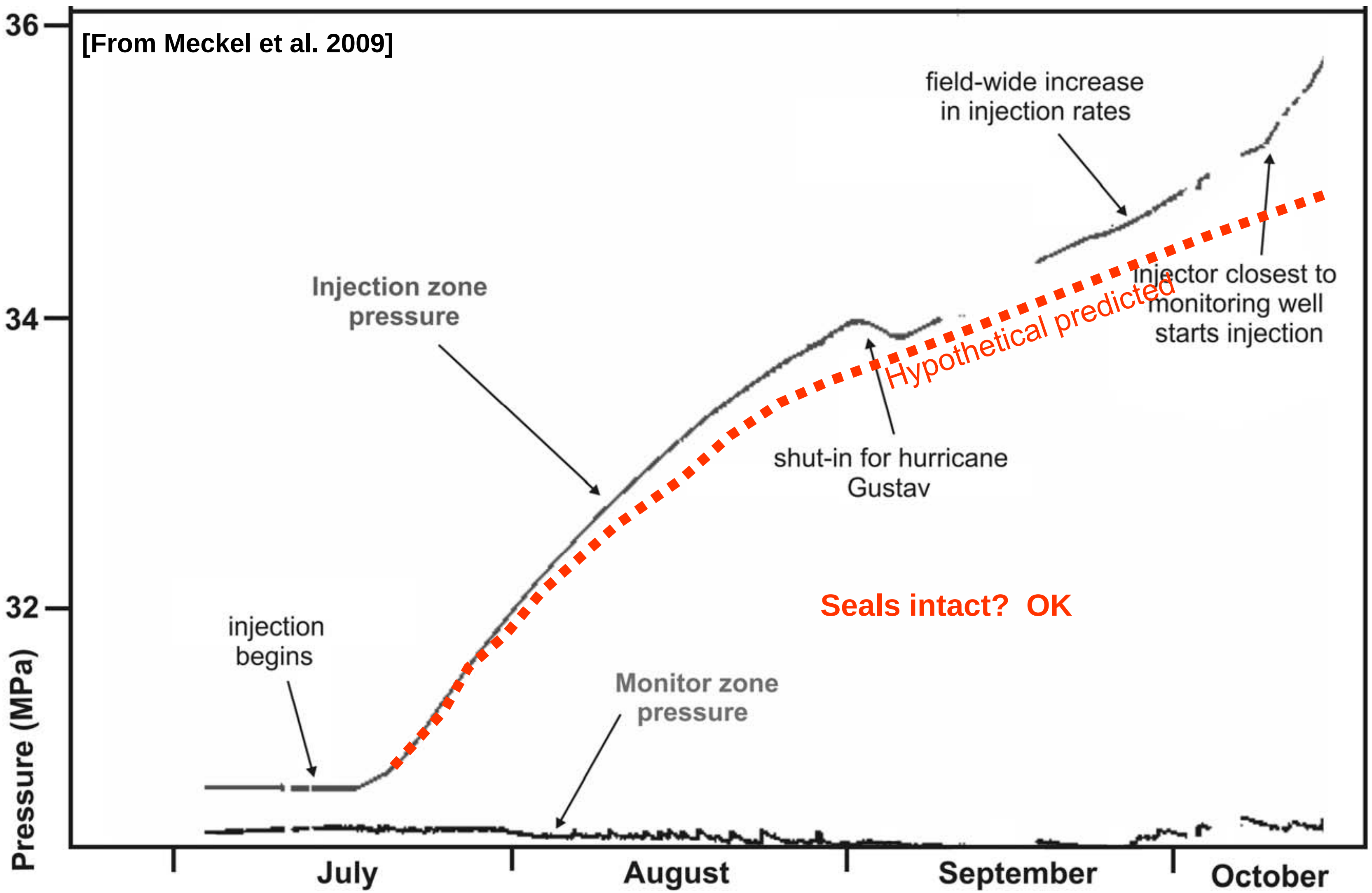
EU Storage Directive: Minimum conditions for closure….

1. Actual behaviour of the injected CO_2 conforms with the modelled behaviour

2. No detectable leakage

3. Storage site is evolving towards a situation of long-term stability

Invasive monitoring: actual behaviour at Cranfield

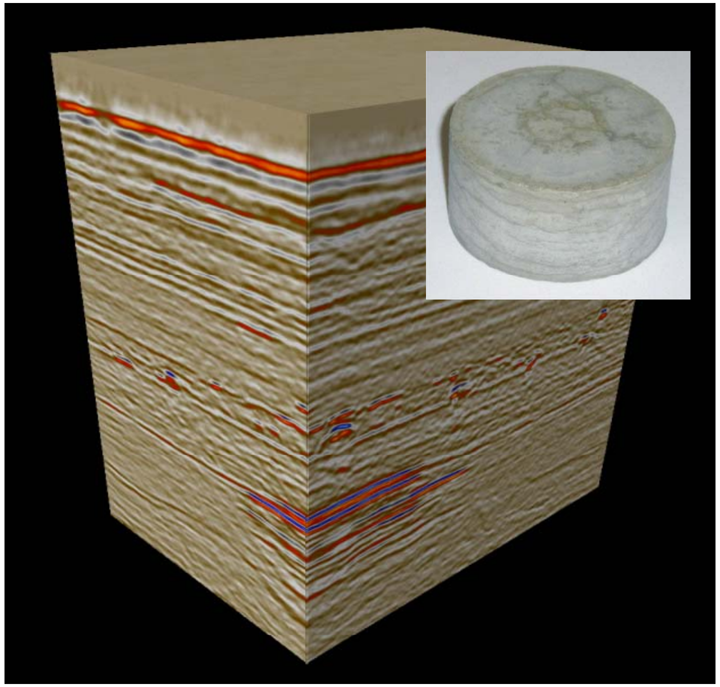


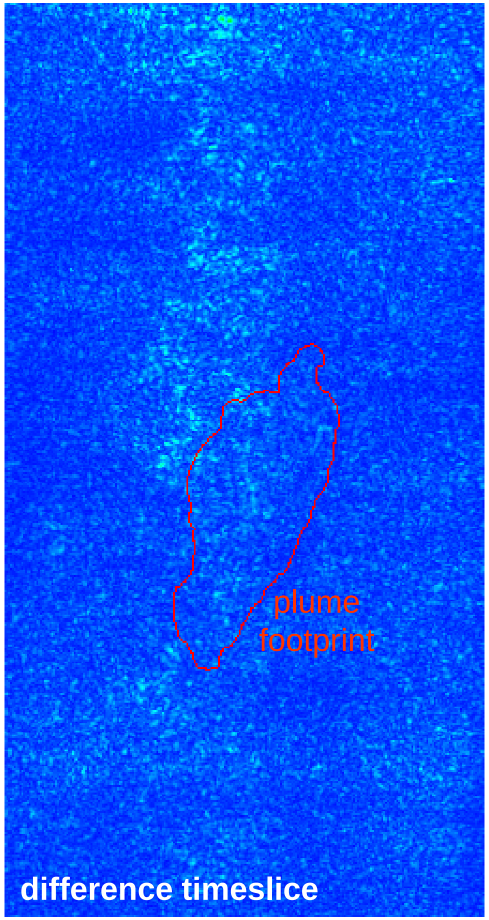
No Leakage ……. OK

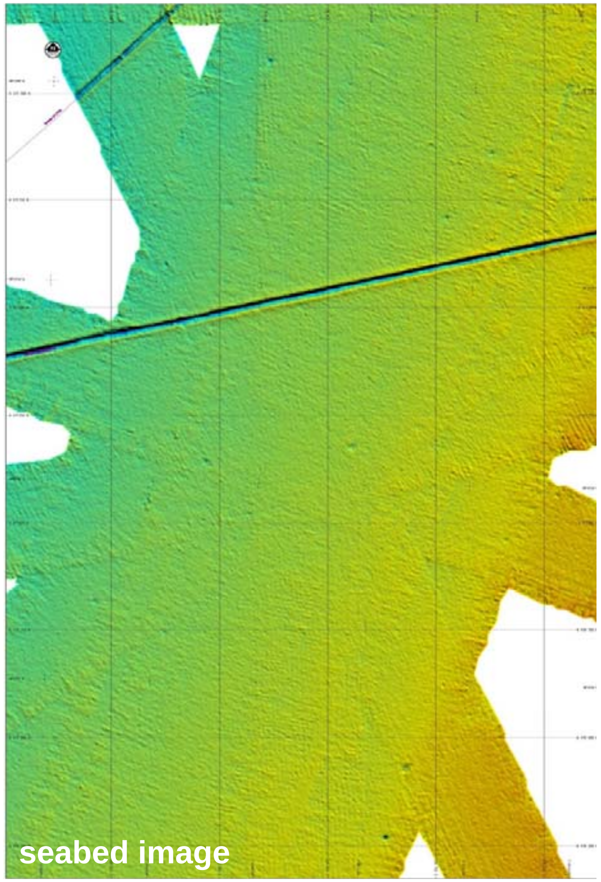
Sleipner leakage performance:

no detected migration out of reservoir

no detected leakage at surface







4D seismic: continuous uniform coverage of reservoir and overburden but <u>finite detection threshold</u>

No leakage ……. OK

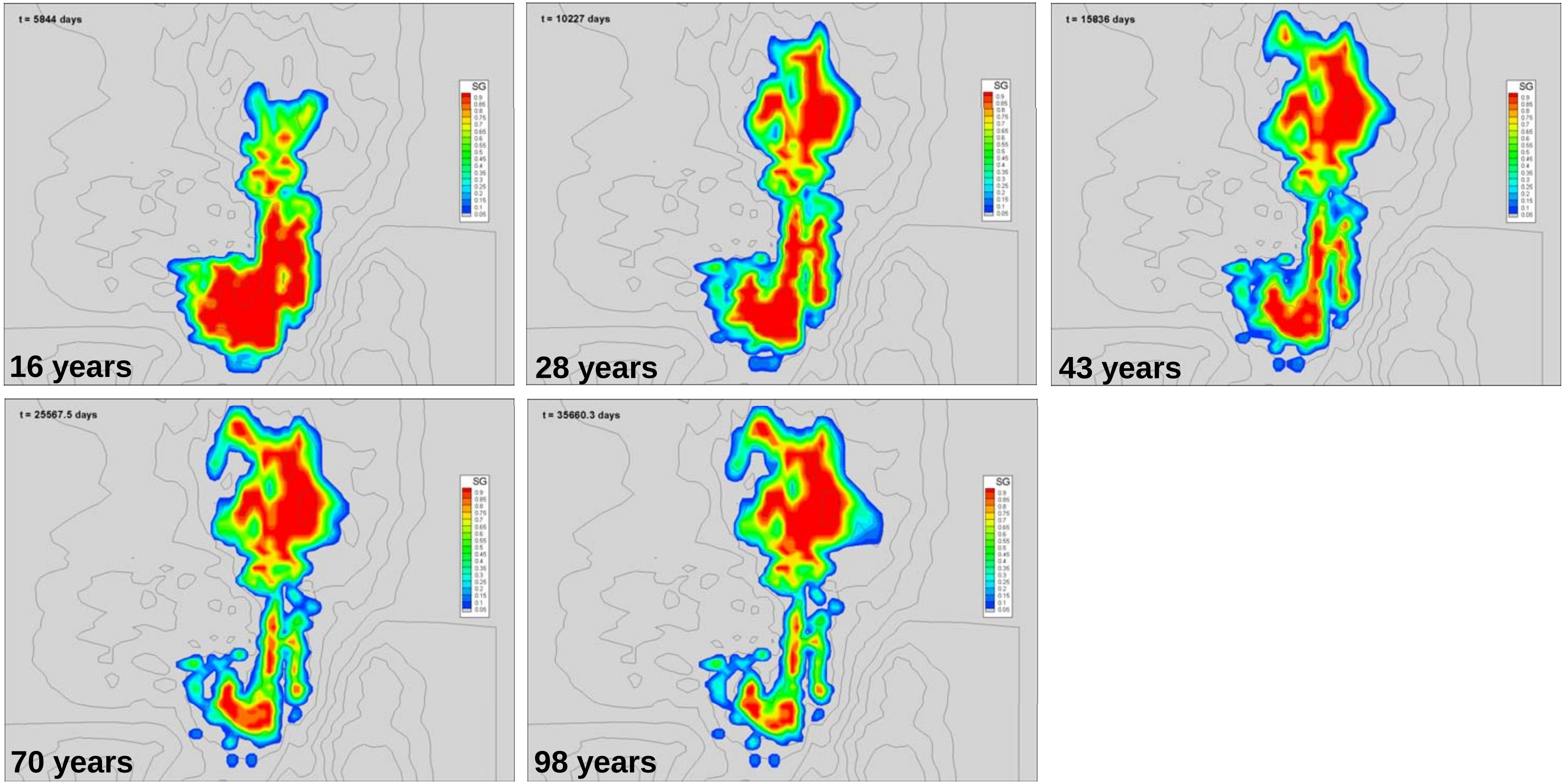
EU Storage Directive: Minimum conditions for closure….

1. Actual behaviour of the injected CO_2 conforms with the modelled behaviour

2. No detectable leakage

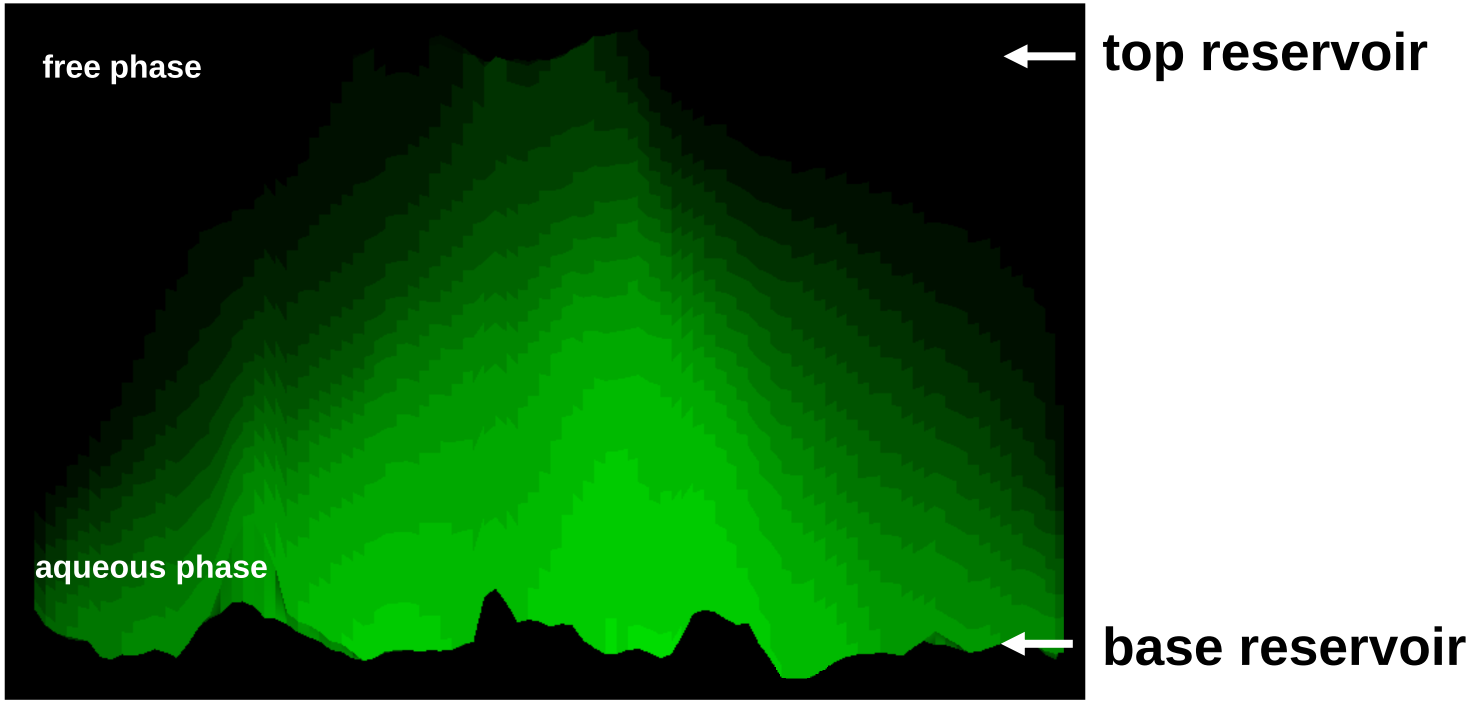
3. Storage site is evolving towards a situation of long-term stability

Sleipner – initial post-injection spatial stabilisation



Need to show that the closure relief not compromised by topographic uncertainty
[N.B. Hypothetical assumed injection ceased in 2006!]

Sleipner – Long-term stabilisation



Year 7020

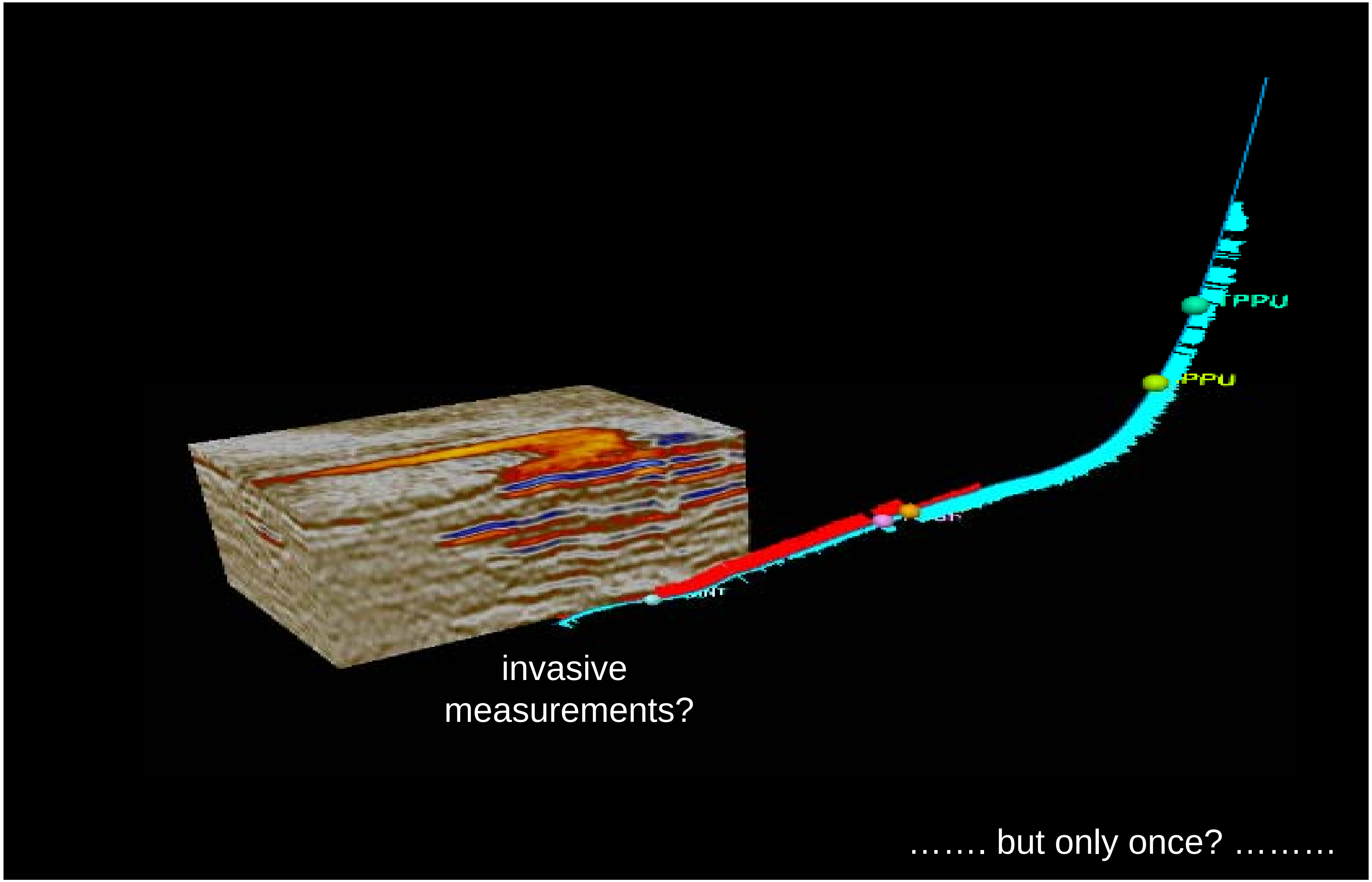
0 to 160 years: free CO_2 spreads laterally at top reservoir

> 160 years: CO_2 in aqueous phase sinks in reservoir

BUT how do we demonstrate dissolution and convection is reasonable?

[simulation courtesy of Erik Lindeberg SINTEF)

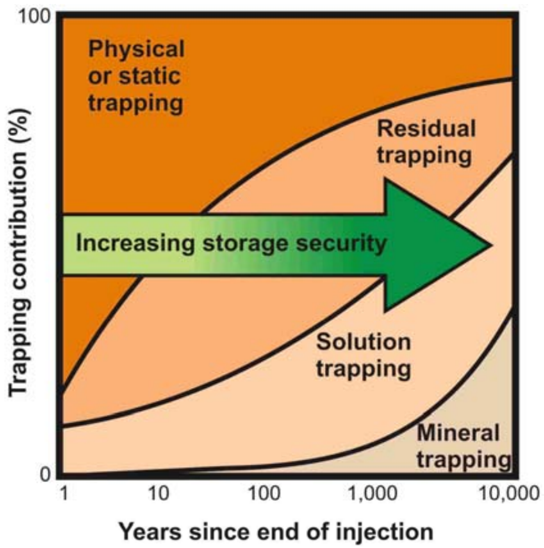
Post-injection monitoring for convection



Managing uncertainty

Actual behaviour of the injected CO_2 conforms with the modelled behaviour

- Need demonstrate basic understanding
- Uncertainty will not lead to future divergence



No detectable leakage

- Monitoring tools have finite detection thresholds
- Need to accept site characterisation i.e. ‘innocent until proven guilty’

Storage site is evolving towards a situation of long-term stability

- Need to demonstrate onset of key stabilisation process
- Analogue data from pilot-scale or similar sites

Legal aspects

OSPAR mentions ‘permanent containment’

Even with the most ambitious geochemical trapping scenarios this is difficult to prove ……

The Risks of Monitoring

Charles Jenkins
CSIRO and CO2CRC

+ data and insights from Chris Boreham, Patrice de Caritat, Matthew Jones, Se Gong, Ulrike Schacht, Linda Stalker

Overview

- What is monitoring for?
- What do different stakeholders want?
- How can things go awry?
- What happens then?
- Morals of the story

What is monitoring for?

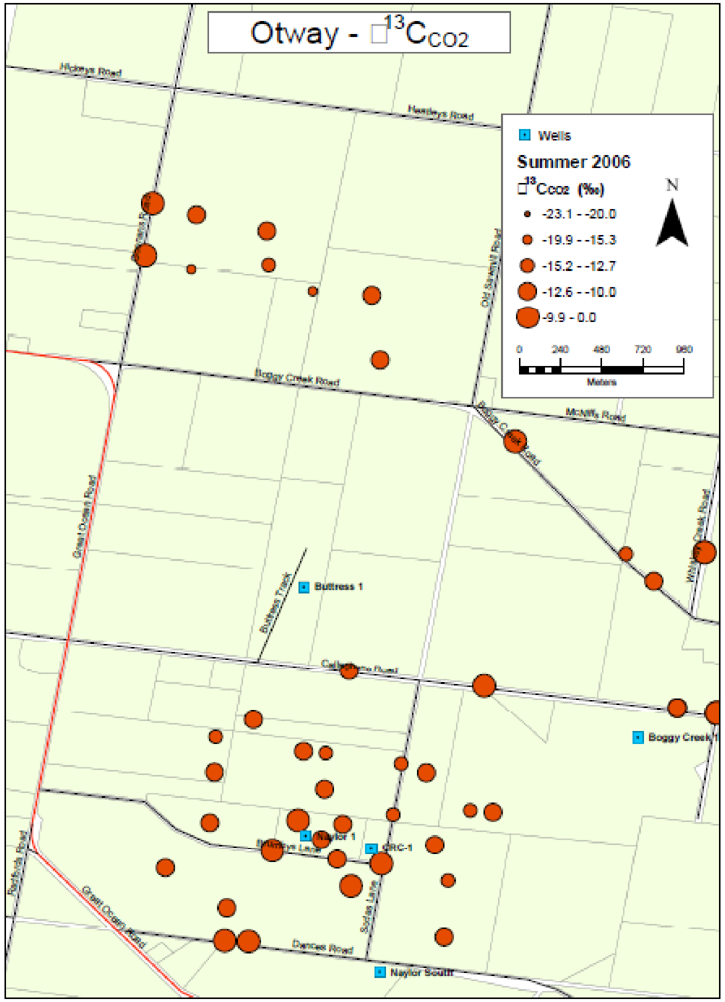
- Assurance
  - No leaks, ie required to measure "nothing"
  - Audience likely to be concerned when we measure "something"
  - Addressed to most influential / decisive stakeholder community
- Quantification
  - About $
  - To a large extent, a "by agreement" situation
  - Can / will be resolved in private
- Climate
  - Toughest to meet requirements
  - Hardest to measure
  - No negotiation!

Dealing with Assurance

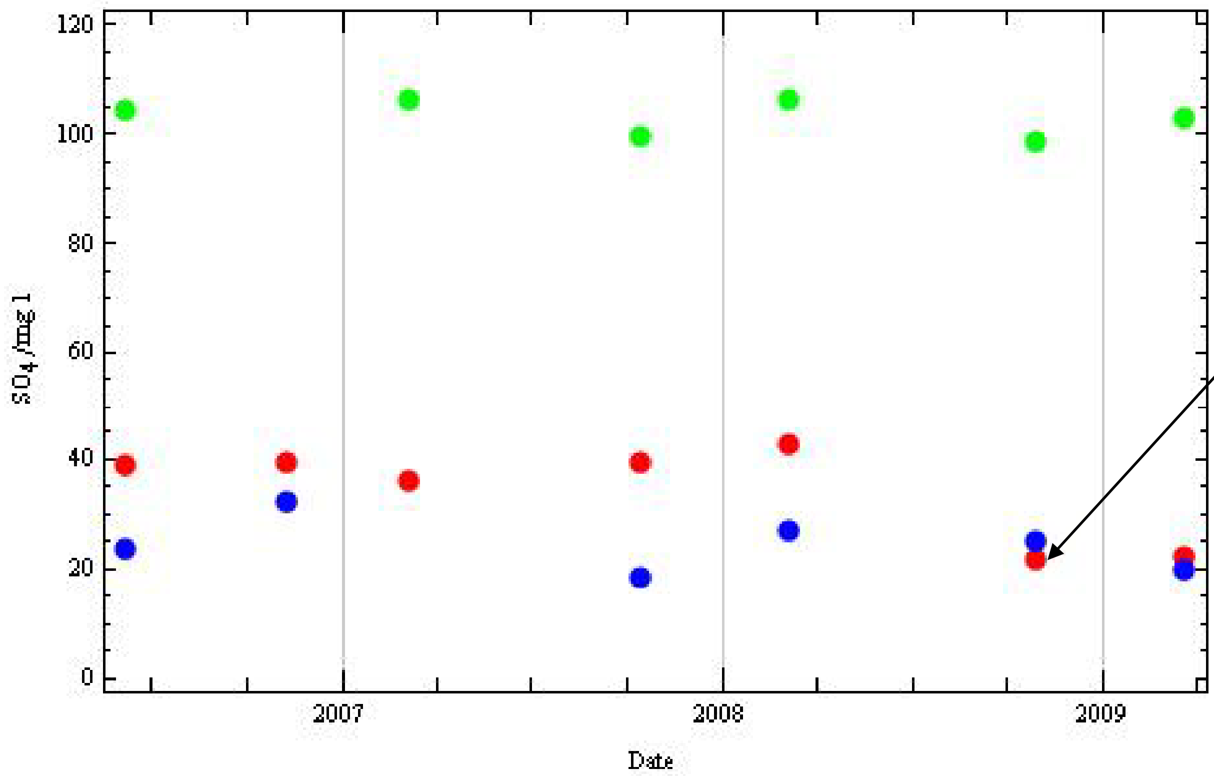
- What kind of "nothing" do we measure?
  - Before = after   ie   before-after=0
  - Example: tracers in groundwater
- Or, before = after = 0
  - Example: what we expected from seismics at reservoir level
  - Example: what we hoped from seismics above reservoir level

Assurance at Otway

- Ground water
- Soil gas
- Headspace gas
- Atmospheric

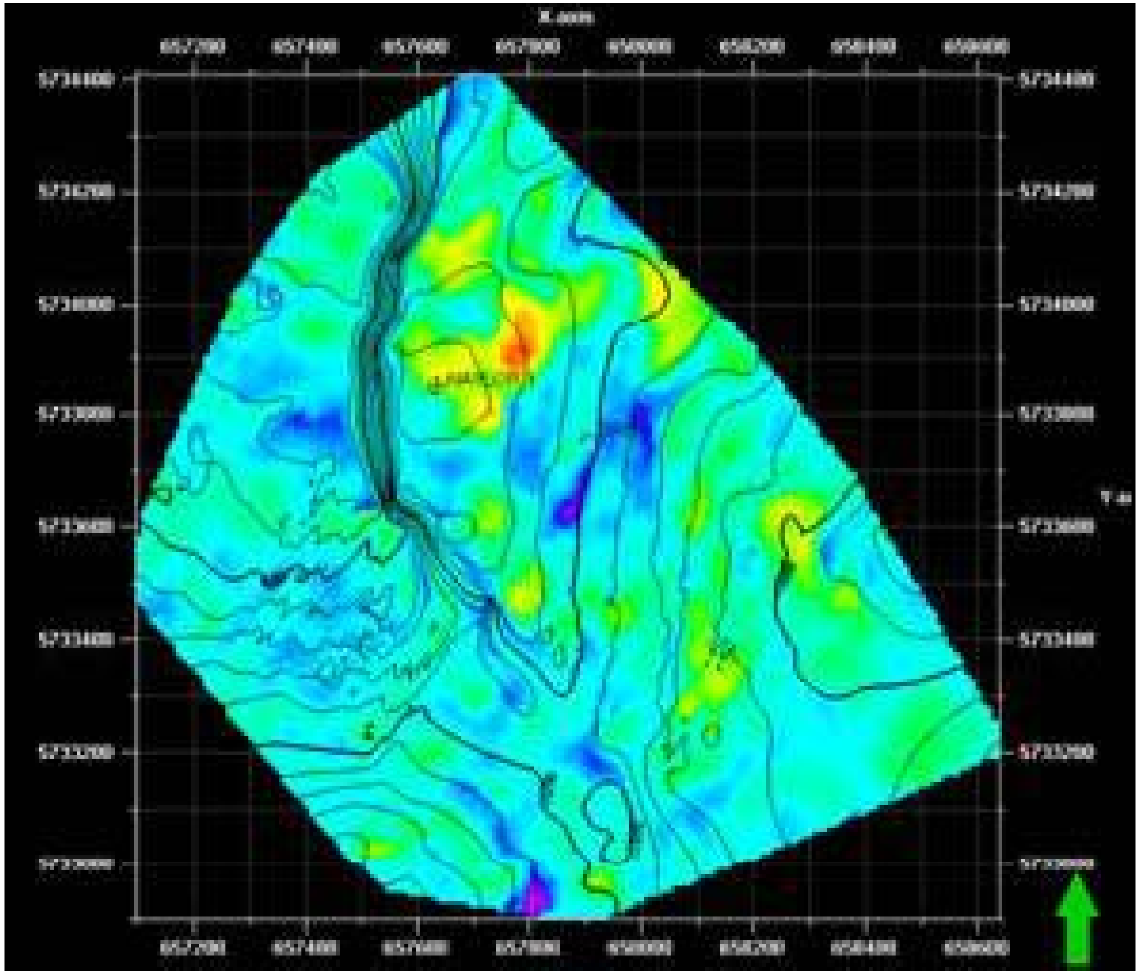


Example groundwater data



3 s.d. jump post-injection!

Example seismic image



Two kinds of issues

- We see something when we shouldn't
- We don't see something when we should

- The *statistics* of the measurements are critical

- "Type I error" – the truth is zero but every now and then, because of noise, we measure something.
- "Type II error" – there is something there, but we can't see it because the data are too noisy.

Consequences

- Type I error rate is sometimes called the “false alarm rate”
  - We would like this to be small, but
  - we also want to detect anomalies, so
- we want the *power* (1-Type II error rate) to be large.
- Invariably you have to trade off the power against false alarm rate

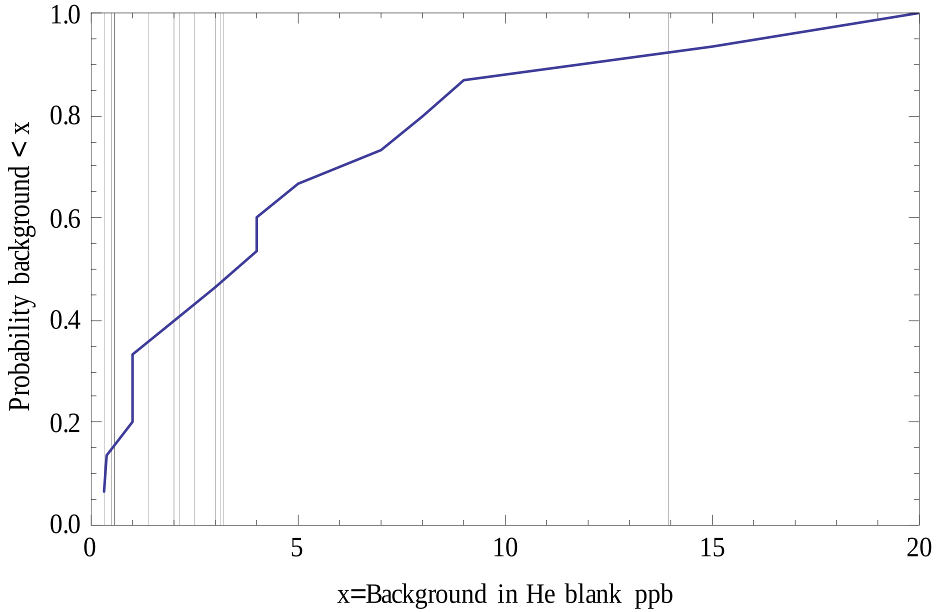
Another example: SF_6

Volume (uL)	File name	Sample name	SF_6	SF_6 (ppm)
150	OP715_SF6	OP715	4.1222815E+06	**0.014**
150	OP712_SF6	OP712	8.6585617E+04	0.000
150	OP719_SF6	OP719	1.3743603E+05	0.000
150	OP713_SF6	OP713	1.6011663E+05	0.001
150	OP702_SF6	OP702	1.6255653E+05	0.001
150	OP710_SF6	OP710	1.6625491E+05	0.001
150	OP704_SF6	OP704	3.9998855E+05	0.001

But…

150	HEBLK_160409_SF6	Helium blank	2.8278581E+05	0.001
150	HEBLK_170409_SF6	Helium blank	5.1210745E+06	0.017
150	HEBLK_170409_SF62	Helium blank	1.0542016E+06	0.004

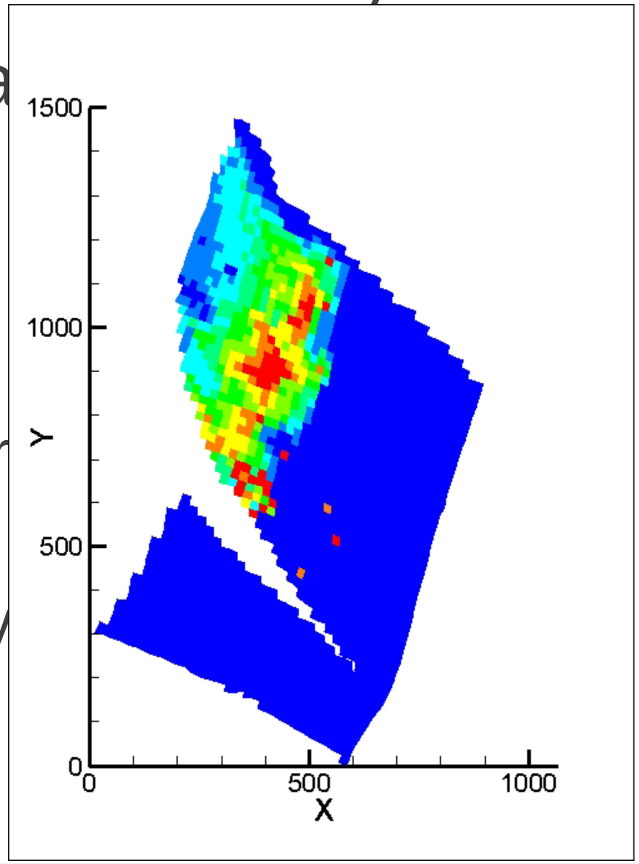
In detail



- A good understanding of the statistics is needed: these are not Gaussian, for instance
- Problem was resolved but it was not satisfactory to decide on an acceptable Type I error rate after the fact.
- Power of this measurement is unknown.

The other examples

- Considerable campaign to understand seismic data by forward modelling and noise analysis
- The rest of the groundwater da challenge
  - Every bore is different
  - Not much data
  - Simple-minded analysis yields or too many “3 s.d.” measurements
  - Non-gaussian statistics will apply



Measured in groundwater…

Eh	Na	K	Ca	Mg	Cl	HCO3
SO4	PO4	I	Br	F	CO3	CO2
NO3	NO2	Ag	Al	As	Au	B
Ba	Be	Bi	Cd	Ce	Co	Cr
Cs	Cu	Dy	Er	Eu	Fe	Fe(2)
Fe(3)	Ga	Gd	Ge	H2S	Hf	Hg
Ho	In	La	Li	Lu	Mn	Mo
Nb	Nd	NH4	Ni	Pb	Pd	Pr
Rb	Rh	Ru	Sb	Sc	Se	SiO2
Sm	Sn	Sr	Ta	Tb	Te	Th
Ti	Tl	U	V	W	Yt	Yb
Zn	Zr	dD(H2O)		d18O(H2O)		

This may be too many measurements – the chance of a false alarm is increased but without compensating diagnostic usefulness.

Less is more!

Conclusions

- You need to understand, ahead of time, how you will draw conclusions from monitoring
- This will involve some heavy-duty statistical work if techniques are being pushed to the limits
- Failure to do this means you will have a tiger by the tail.
- In any case – you need a plan to let go of the tiger!

CSIRO CO2CRC

CO2CRC Participants

Supporting participants: Department of Resources, Energy and Tourism | CANSYD | Meiji University | Process Group | University of Queensland | Newcastle University | U.S. Department of Energy | URS

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

Post-Injection Monitoring at the Nagaoka Site

Saeko Mito* & Ziqiu Xue

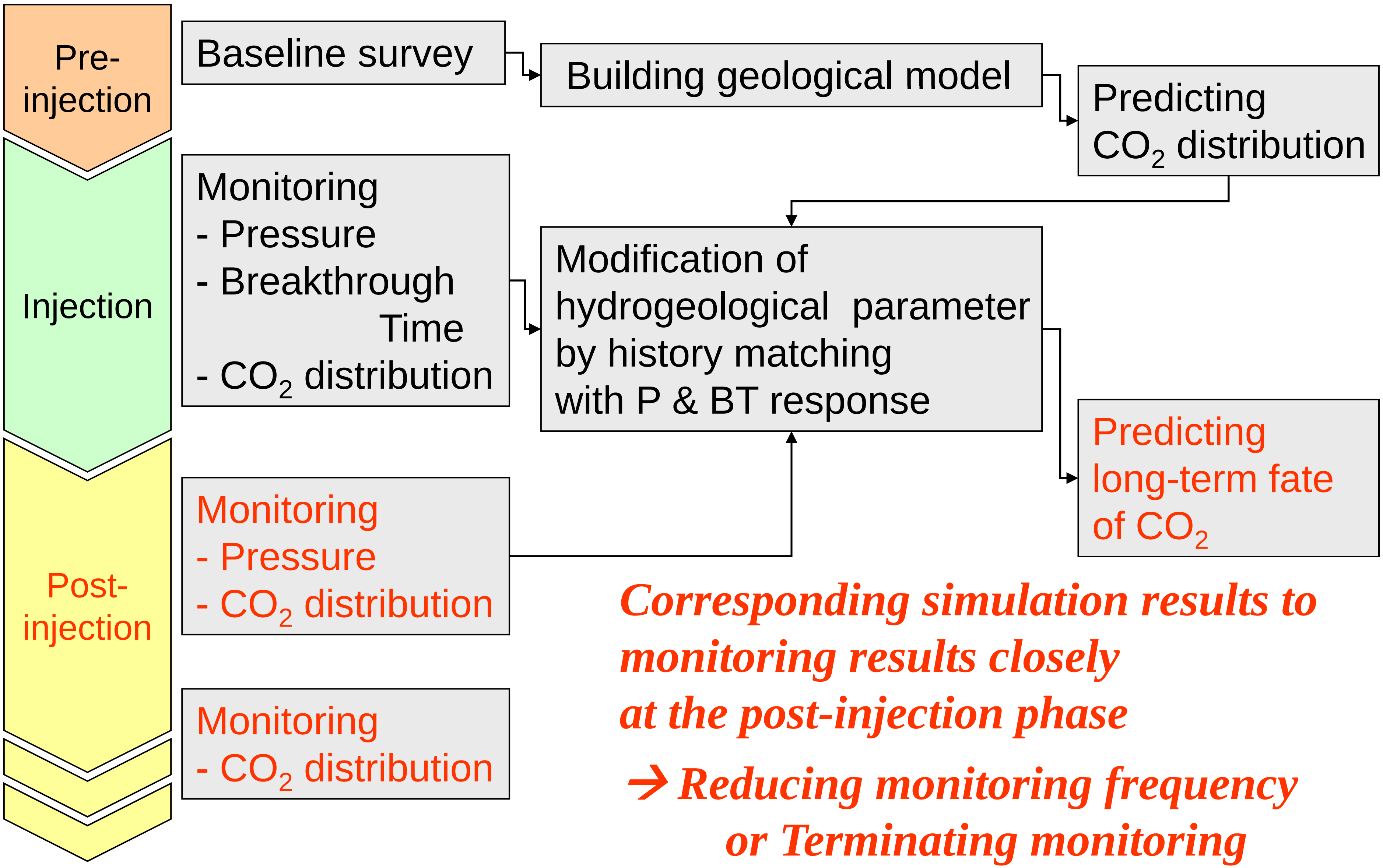
Research institute of Innovative Technology for the Earth (RITE)

NAGAOKA Project

6th IEA GHG Monitoring Network Meeting, 7 May 2010

RITE
Research Institute of Innovative Technology for the Earth

How long should we monitor at Nagaoka?



Corresponding simulation results to monitoring results closely at the post-injection phase

→ Reducing monitoring frequency or Terminating monitoring

Outline

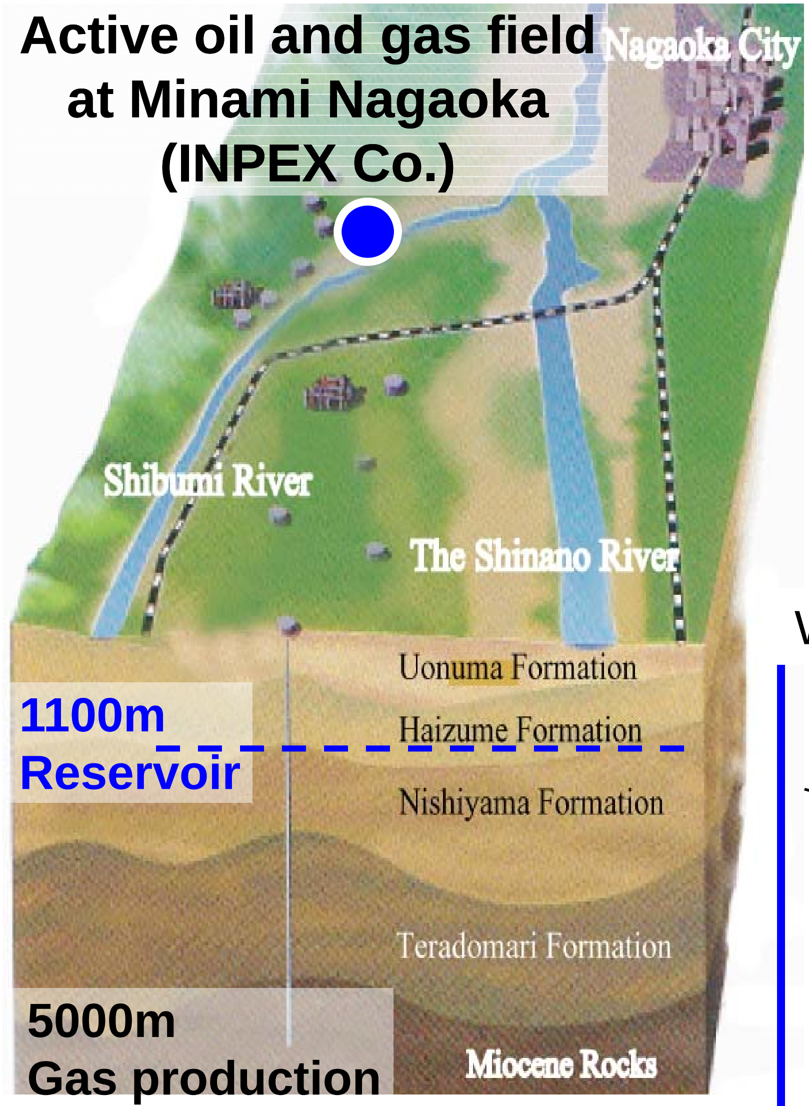
1. Overview of the Nagaoka pilot CO_2 injection project

2. Implementation of short-term prediction
   (History matching with CO_2 monitoring results using TOUGH2 during the injection phase)

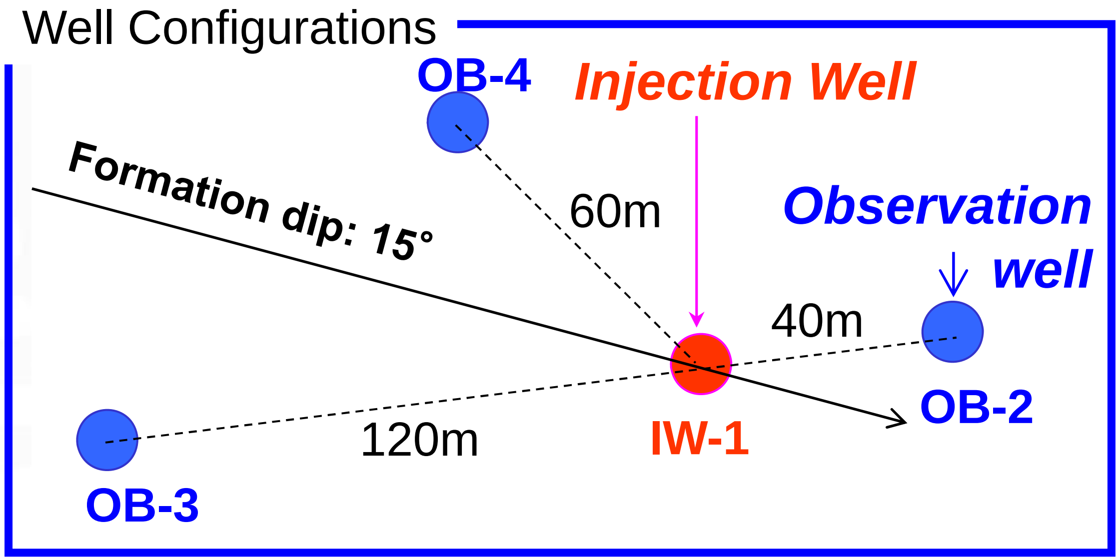
3. Implementation of long-term prediction
   (Trapping of CO_2 stored in the reservoir at the post-injection Phase)

4. Future Monitoring Plan and Summary

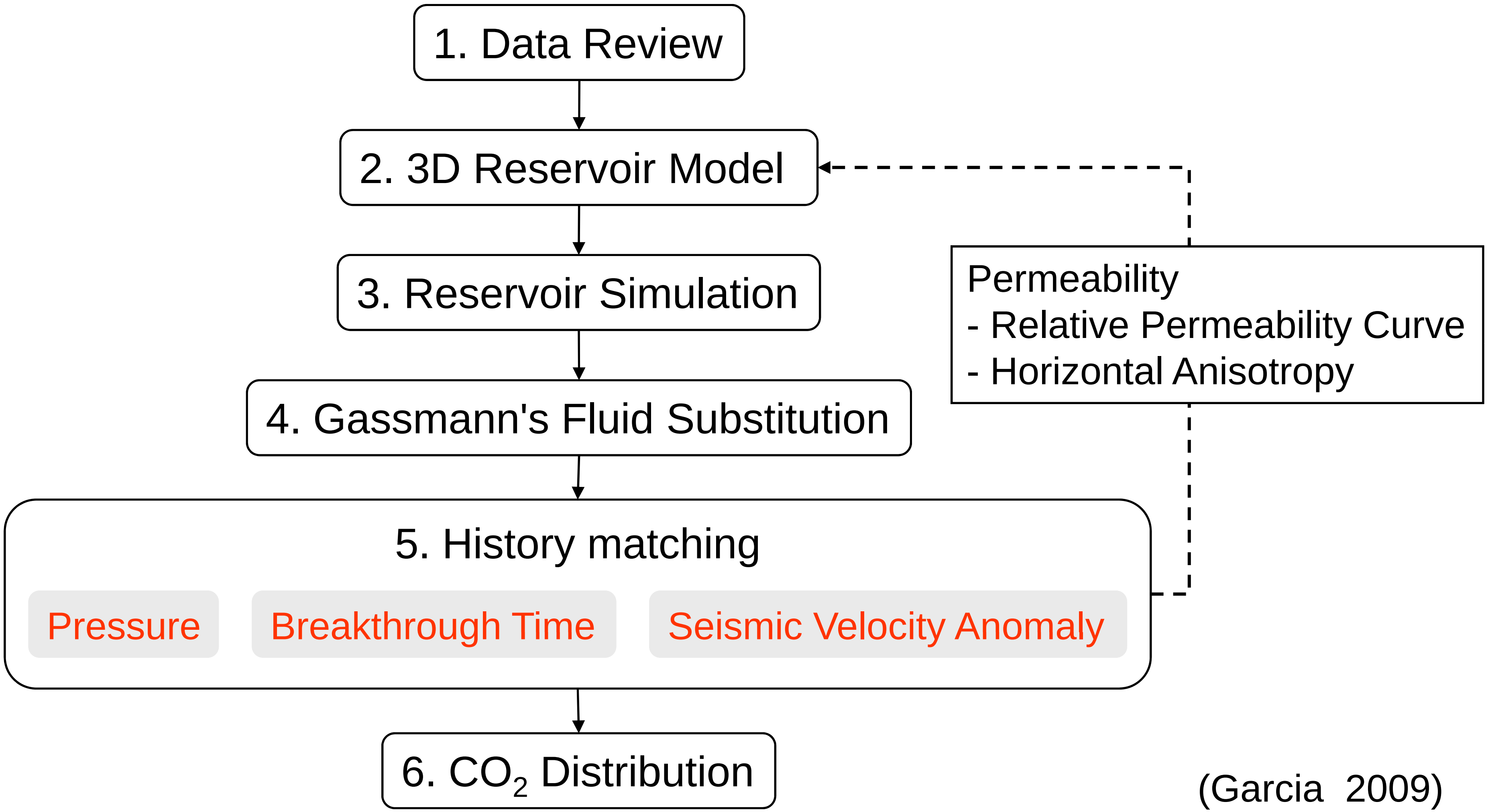
Overview of the Nagaoka Pilot CO_2 Injection Test



- *Duration; FY2000-2007 funded by METI, Japan*
- *Total amount of the injected CO_2;* ***10,400 ton***
- *Reservoir; Pleistocene sandstone*
  Haizume Formation, ***60m thick***
- *Target injection layer; Zone 2,* ***12m thick***
- *Porosity;* ***23%***
- *Permeability; ave.* ***7mD*** *(pumping test)*
- *Reservoir Conditions;* ***48°C****,* ***11MPa***

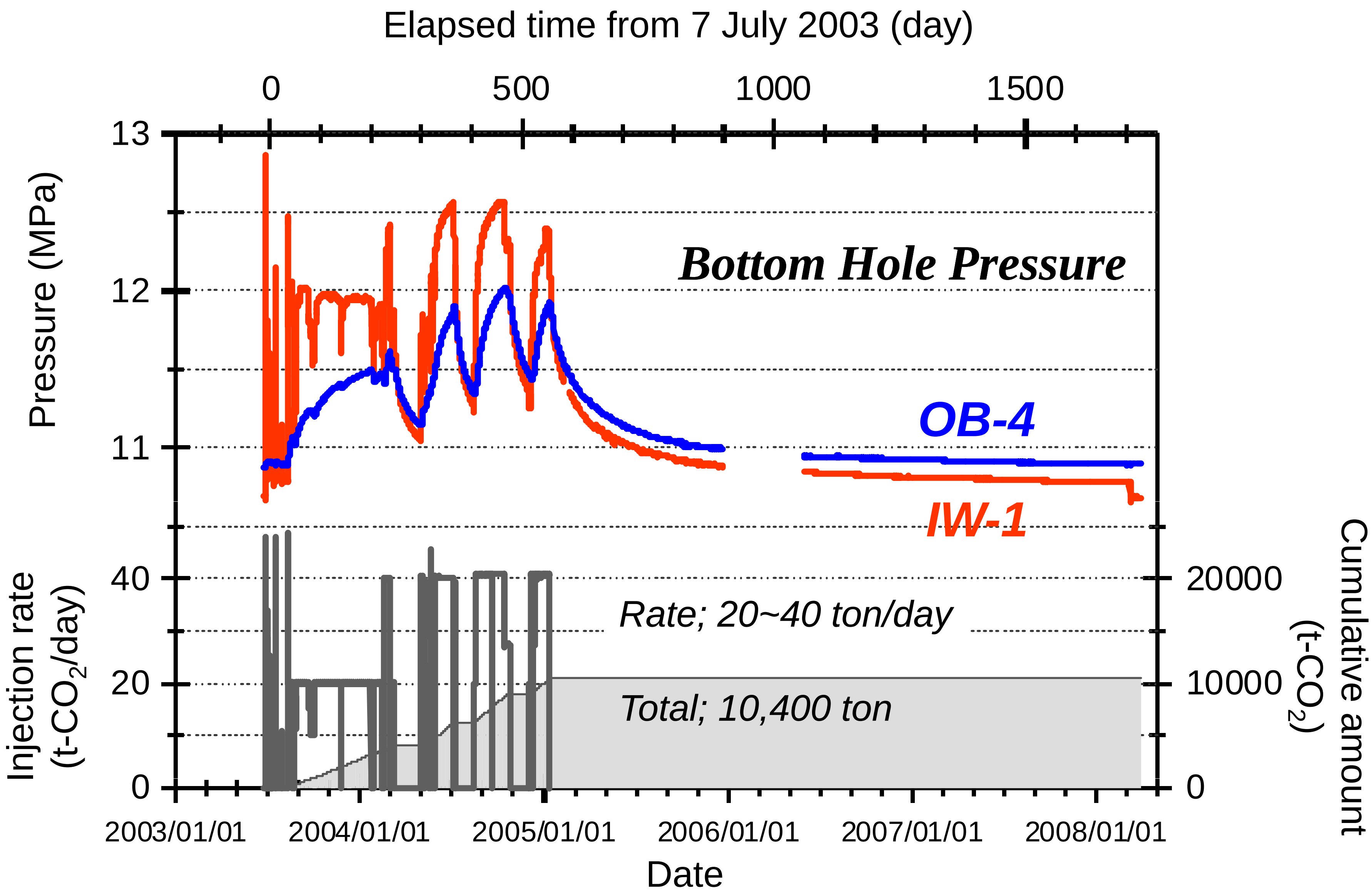


Implementation of Short-term Prediction (History Matching Methodology)

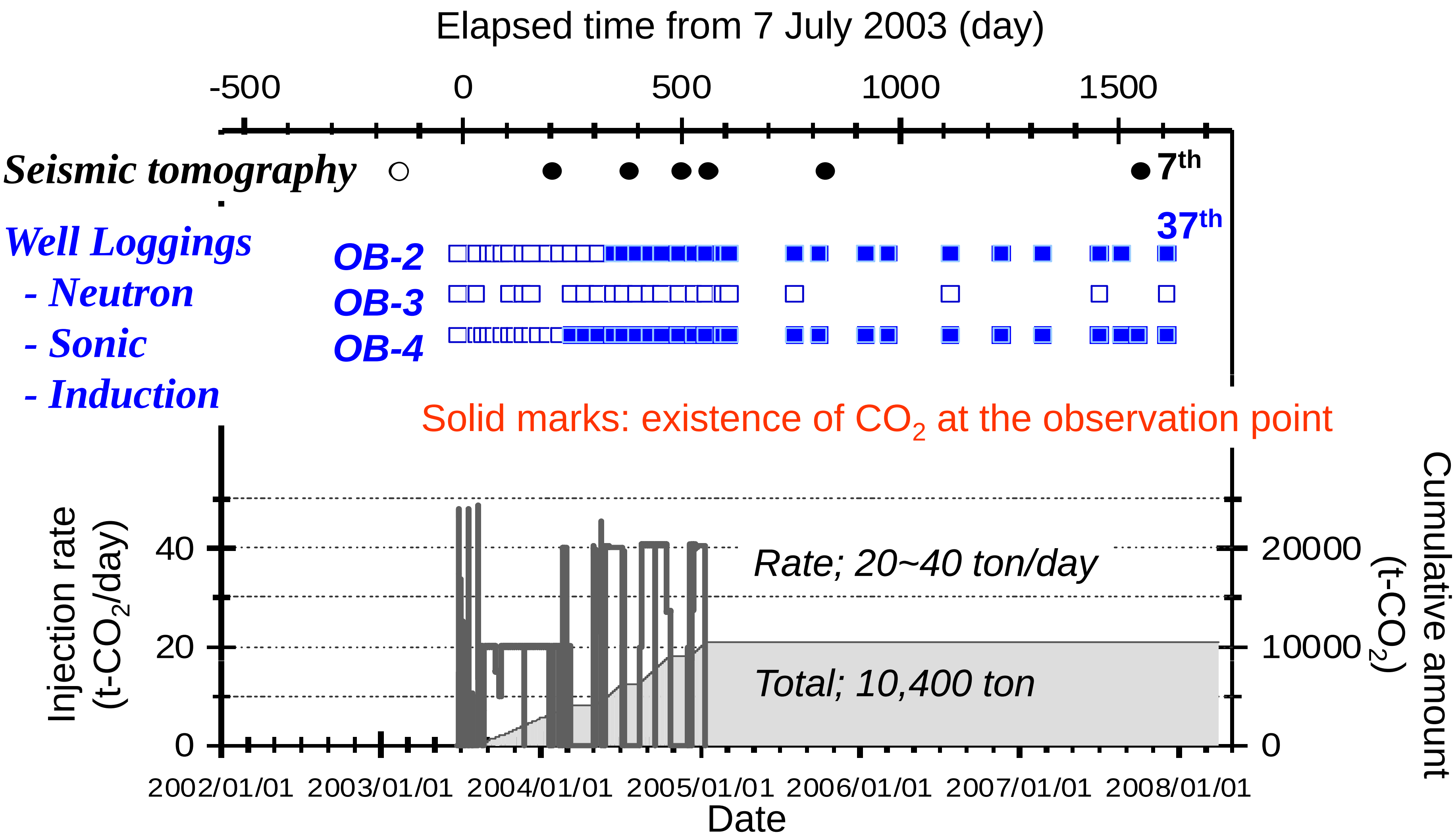


(Garcia 2009)

Dataset for History Matching 1: Bottom Hole Pressures



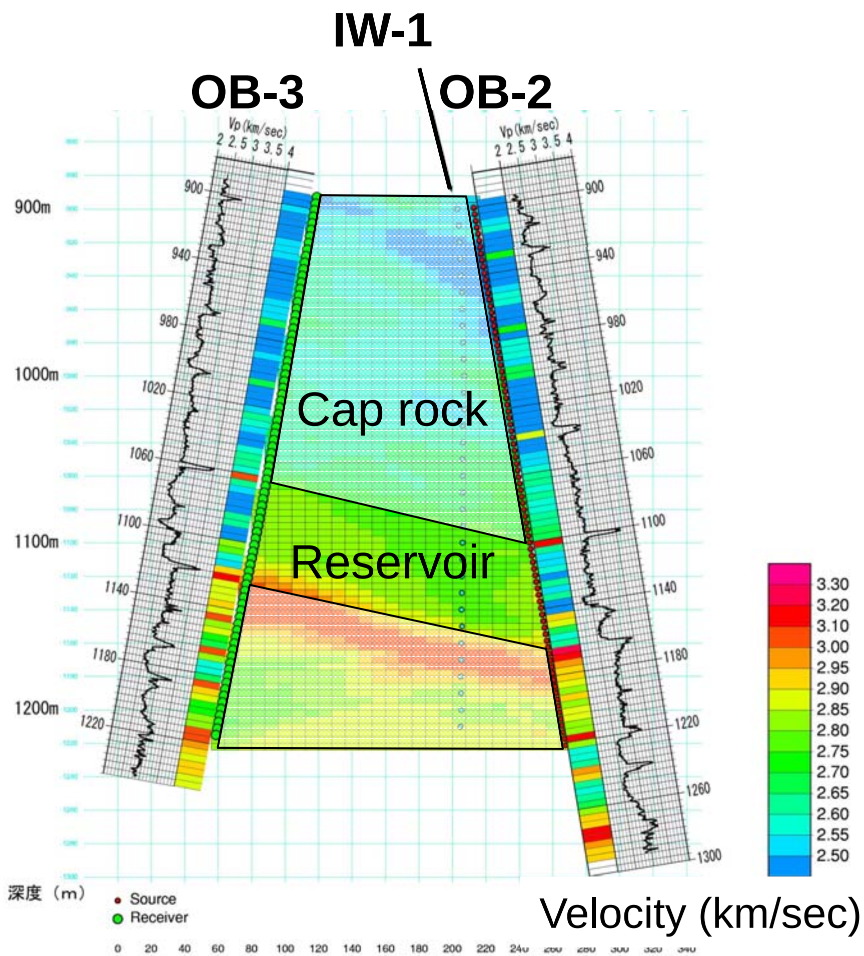
Dataset for History Matching 2: Breakthrough Timing at the Observation wells



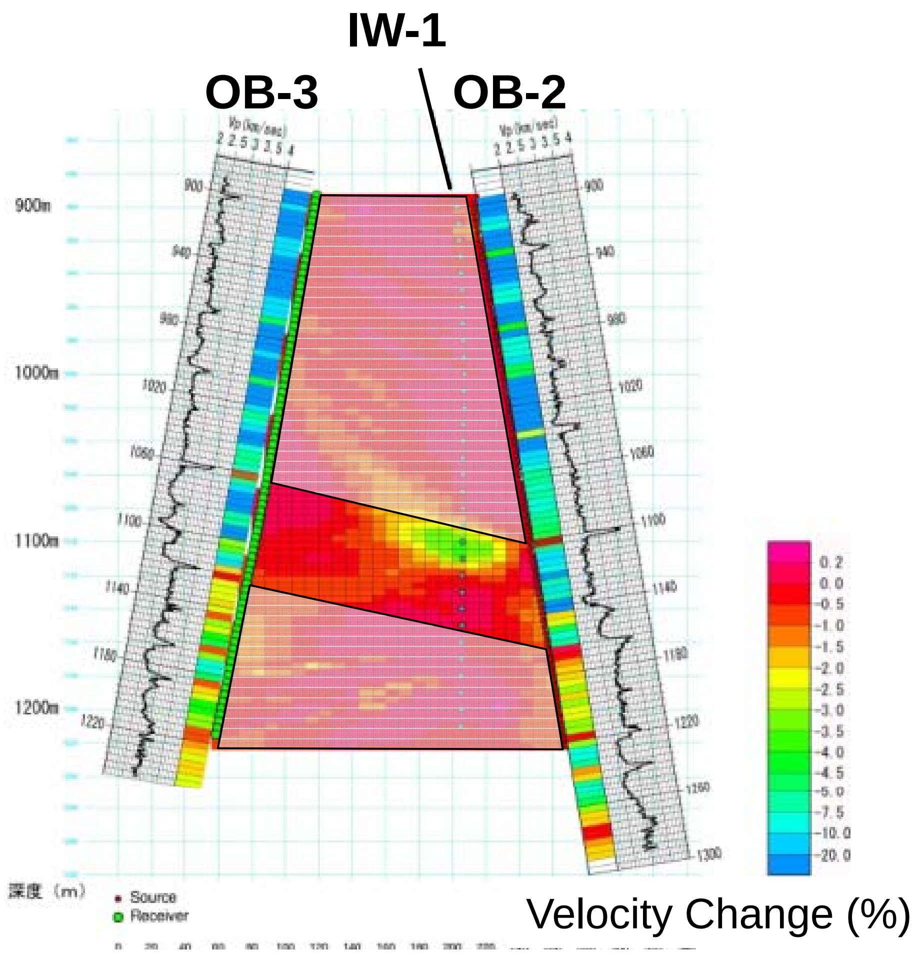
For detail: Mito and Xue (2008)
5th Monitoring Network Meeting, Tokyo

Dataset for History Matching 3: Results of Seismic Tomography

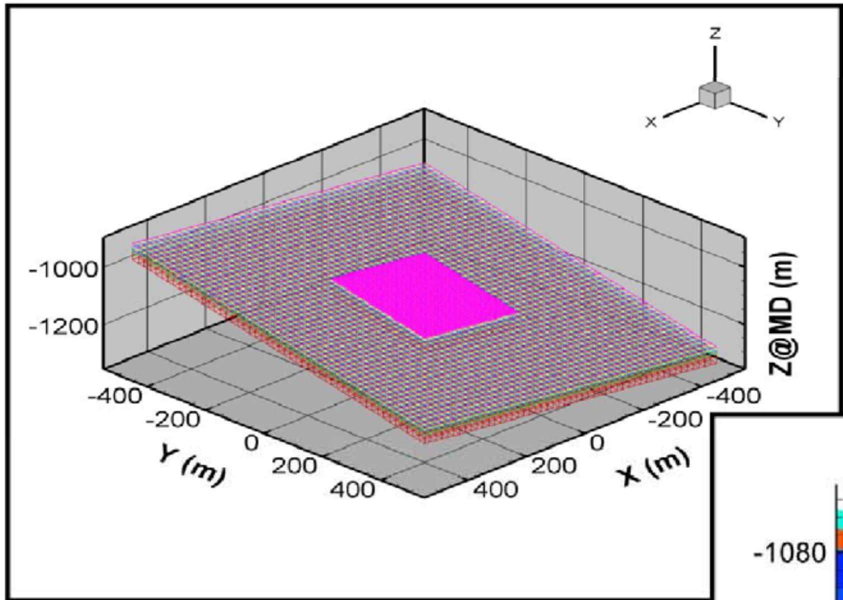
Base Line Survey



Changes between MS4(10400tonCO_2) and BLS



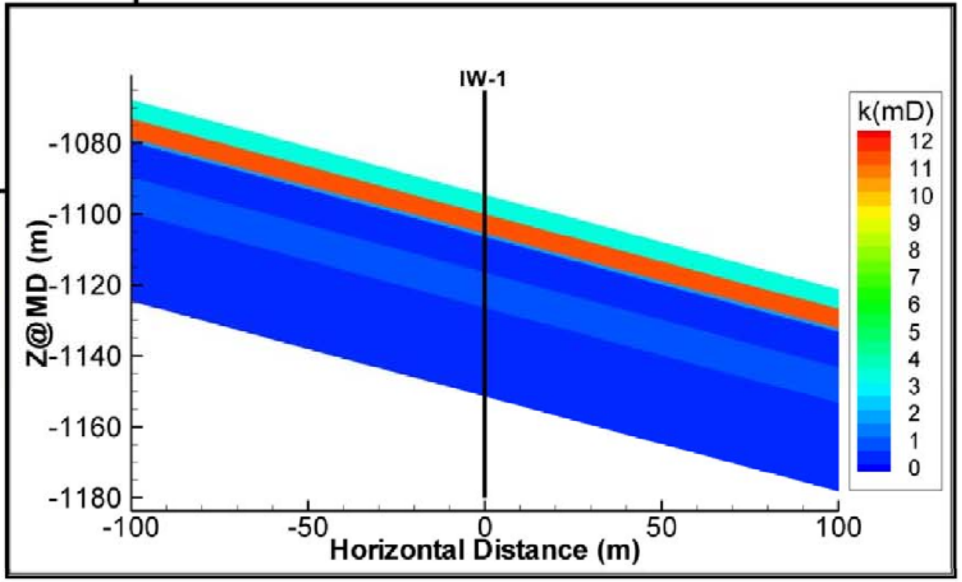
3D Reservoir Model



Area Name	Area Size (m^2)	Gridblock Size (m^2)
Outer Area	1000x1000	20x20
Inner Area	320x320	5x5

Layer	ϕ	Thick. (m)	Kh (mD)	kv/kh	β (1/Mpa)
Zone 2 U.	0.225	5.5	3.19	0.25	2.9×10^{-3}
Zone 2 M.	0.225	5.5	11.15	0.25	2.9×10^{-3}
Zone 2 L.	0.225	1.0	1.59	0.25	2.9×10^{-3}
Zone 3 U.	0.204	10.0	0.330	0.25	2.9×10^{-3}
Zone 3 L.	0.204	10.0	0.660	0.25	2.9×10^{-3}
Zone 4&5	0.234	25.0	0.460	0.25	2.9×10^{-3}

Ohkuma, H. (2008)



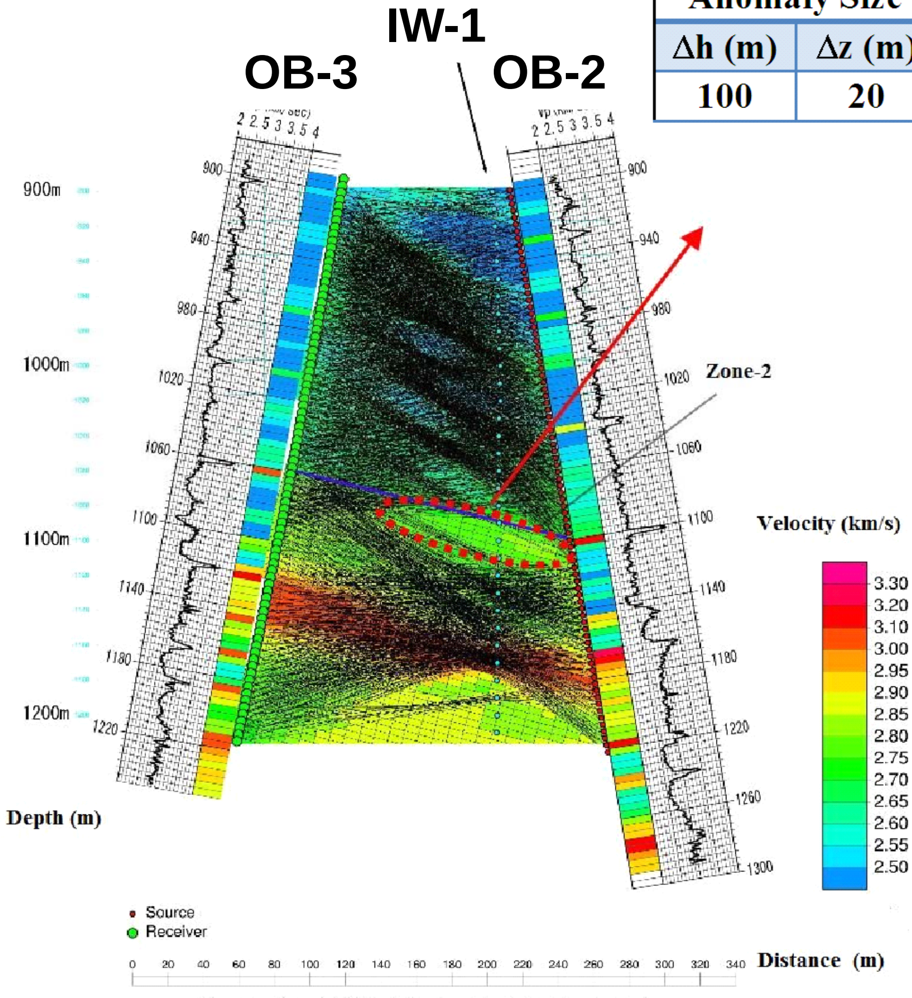
$$k_h = (k_x \cdot k_y)^{-0.5},\ k_y/k_x = 1.2$$

(Garcia 2009)

History Matching Result (Anomaly size)

Observation

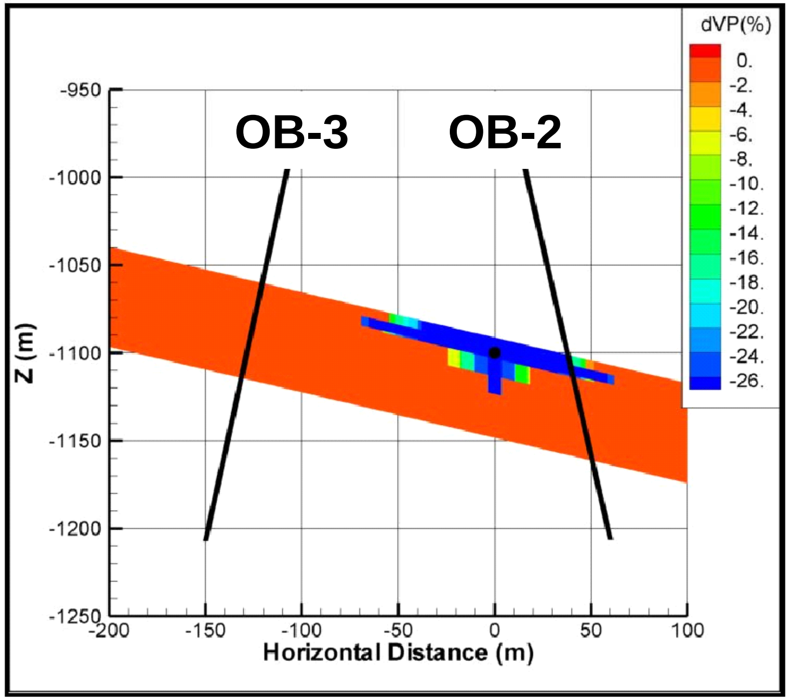
Anomaly Size	
Δh (m)	Δz (m)
100	20



Nagaoka CO2 / Seismic Tomography

Simulation

Anomaly Size	
Δh (m)	Δz (m)
105	22



For detail: Mito and Xue (2009)
2nd Modelling Network Meeting, Utah

Implementation of Long-term Prediction (Key parameters)

Relative permeability curve

Residual CO_2 saturation

Dissolution of CO_2

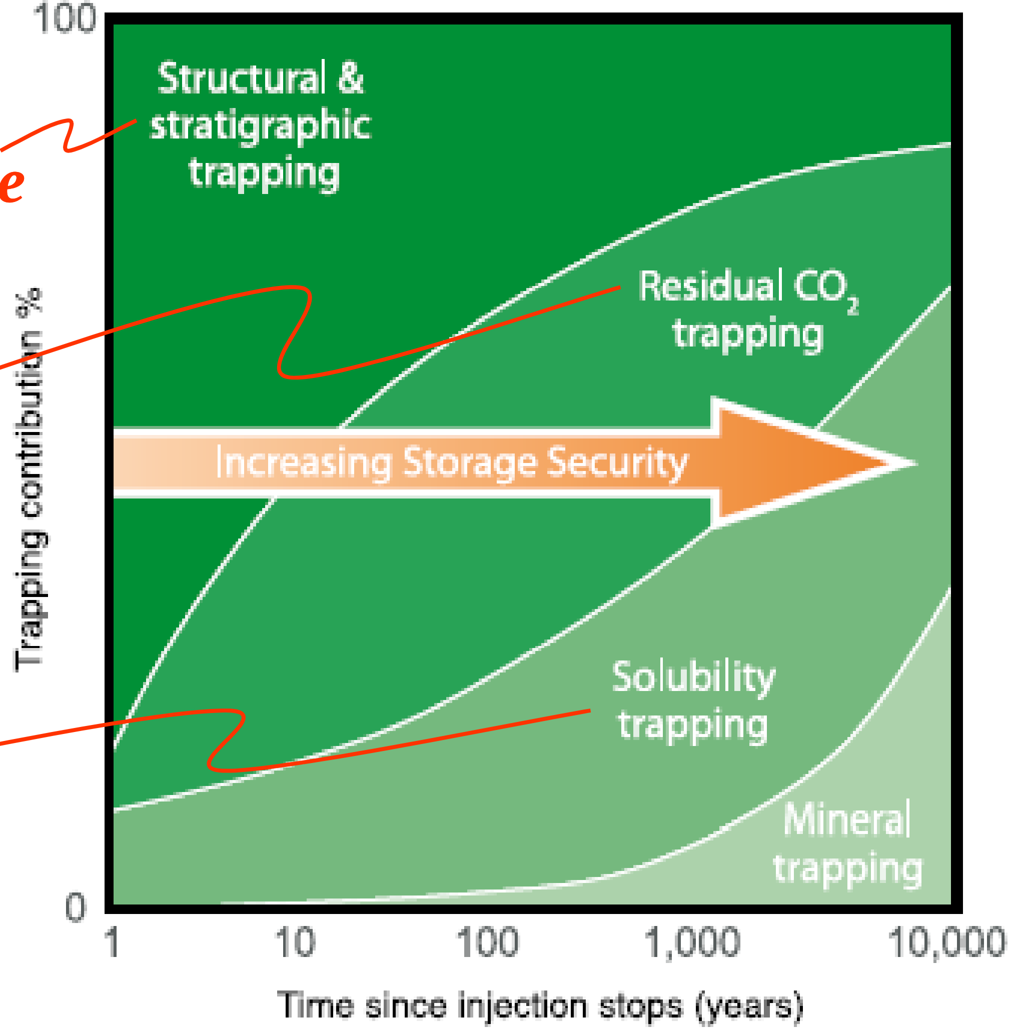
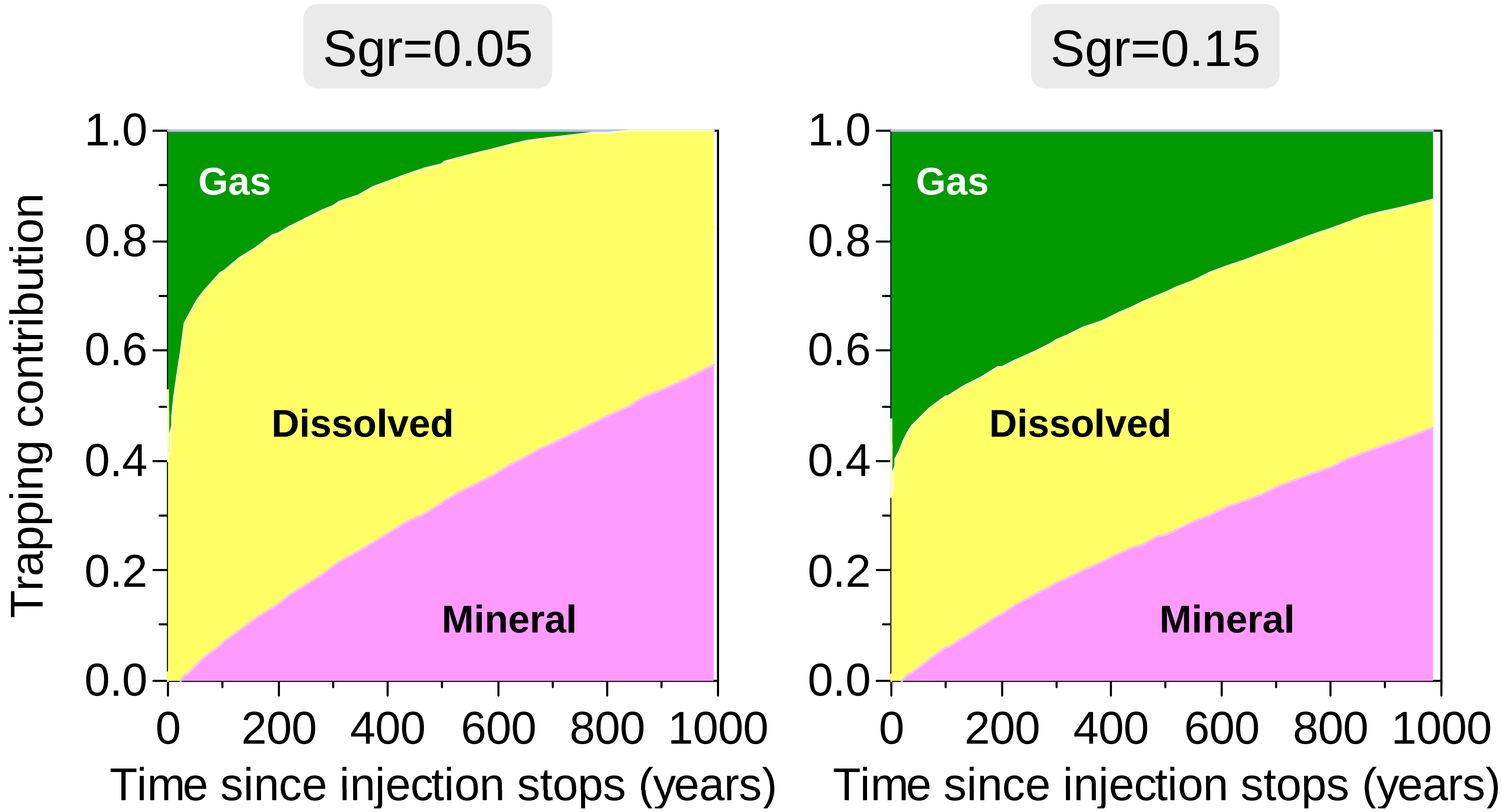
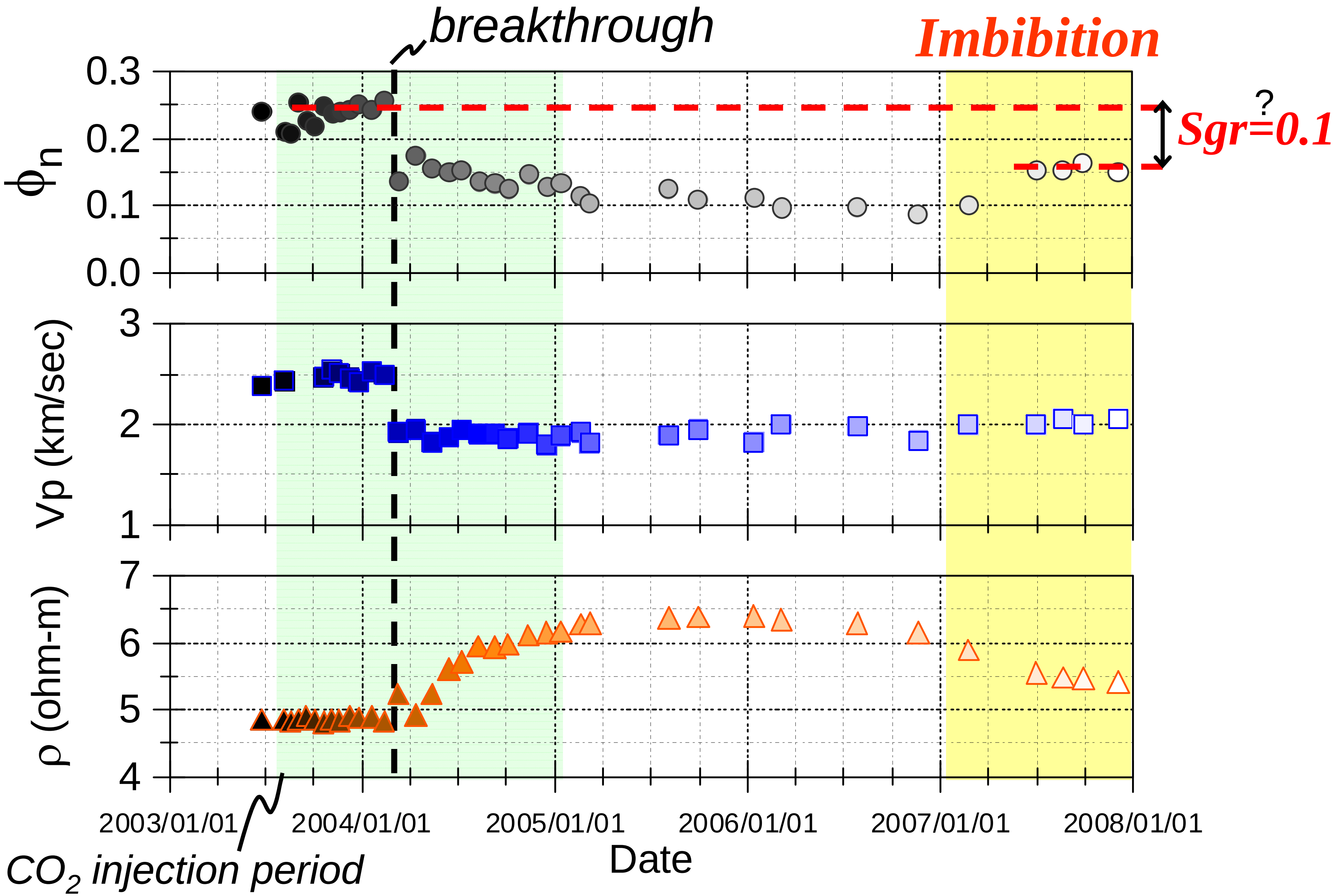


Image of trapping processes over time (IPCC 2005)

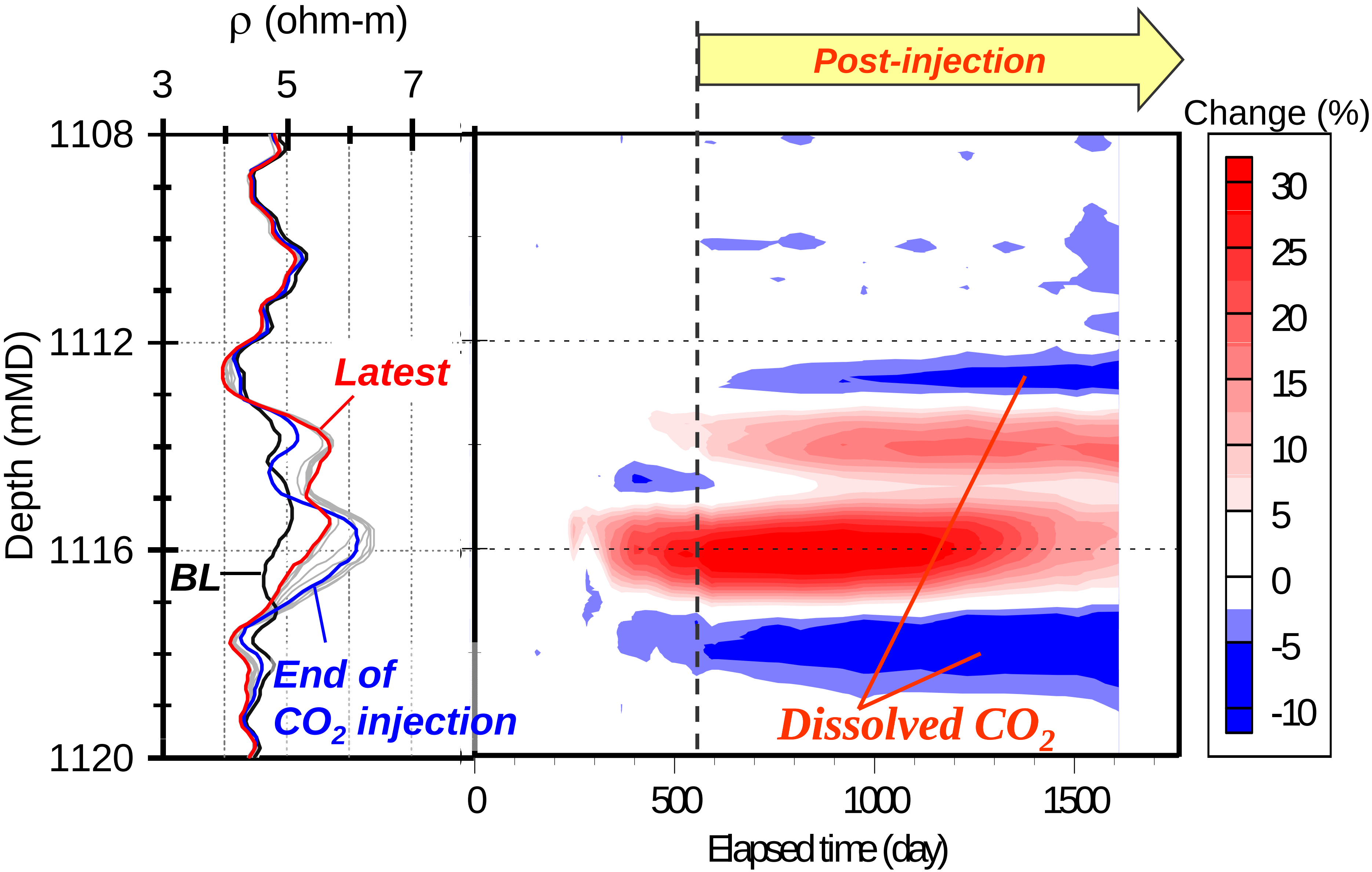
Preliminary Results of Trapping Process at the Nagaoka Site



Residual CO_2 Saturation in the Reservoir (1116.0m @ OB-2)

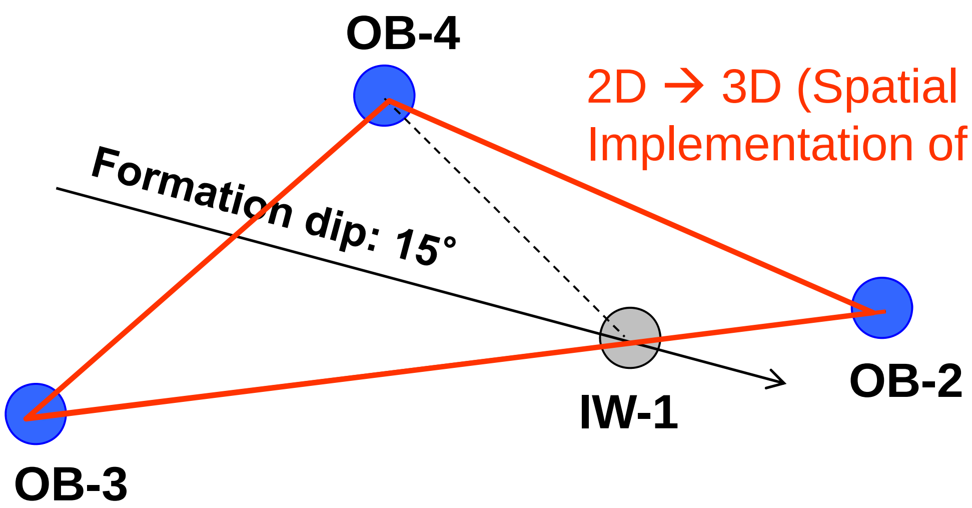


Dissolved CO_2 @ OB-2



Future Monitoring Plan at the Nagaoka site

FY	~2008	2010	2011	2012	2013	2014
Well logging	38 times	●	●	●	●	●
Seismic Tomography	7 times	●		●		●
VSP	0		●			
CHDT/ U-tube	1/0		●		●	



2D → 3D (Spatial distribution)
Implementation of 3D seismic survey

Summary

- Post -injection monitoring is valuable to improve understanding of CO_2 distribution and trapping processes.

- Resistivity is sensitive to dissolved CO_2 from the induction logging. Exactly solubility trapping is confirmed at the Nagaoka site. It may enhance geochemical process and contribute to long-term safety of storage.

- A geological model could be verified with monitoring data sets. History matching is vital to build confidence of long-term prediction.

Acknowledgements

- This project is funded by Ministry of Economy, Trade and Industry (METI) of Japan.

- We appreciate staff of ENAA, INPEX Co., Geophysical Surveying Co. Ltd., OYO Co., GERD, Kyoto University (Henry Garcia) and RITE involved in Nagaoka pilot CO_2 injection project.

Thank you for your attention!

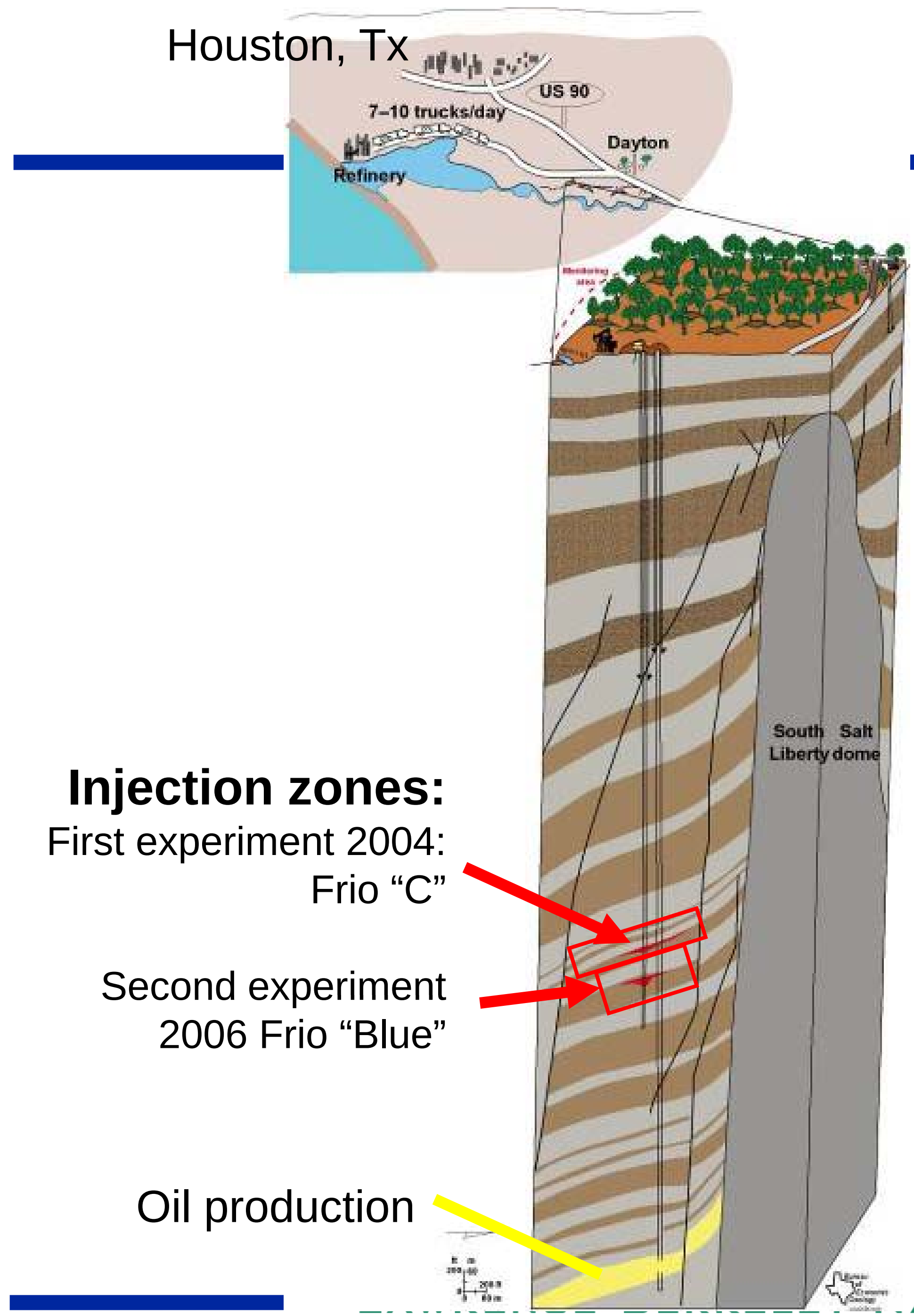
NAGAOKA Project

RITE
Research Institute of Innovative Technology for the Earth

Frio Vertical Seismic Profile (VSP)

- Initial pre and post injection surveys for 1600 ton injection in 2004 at ~1500 m
- Second injection in 2006 of ~300 ton at ~1650 m
- Third VSP before plug and abandon (P&A) in 2009

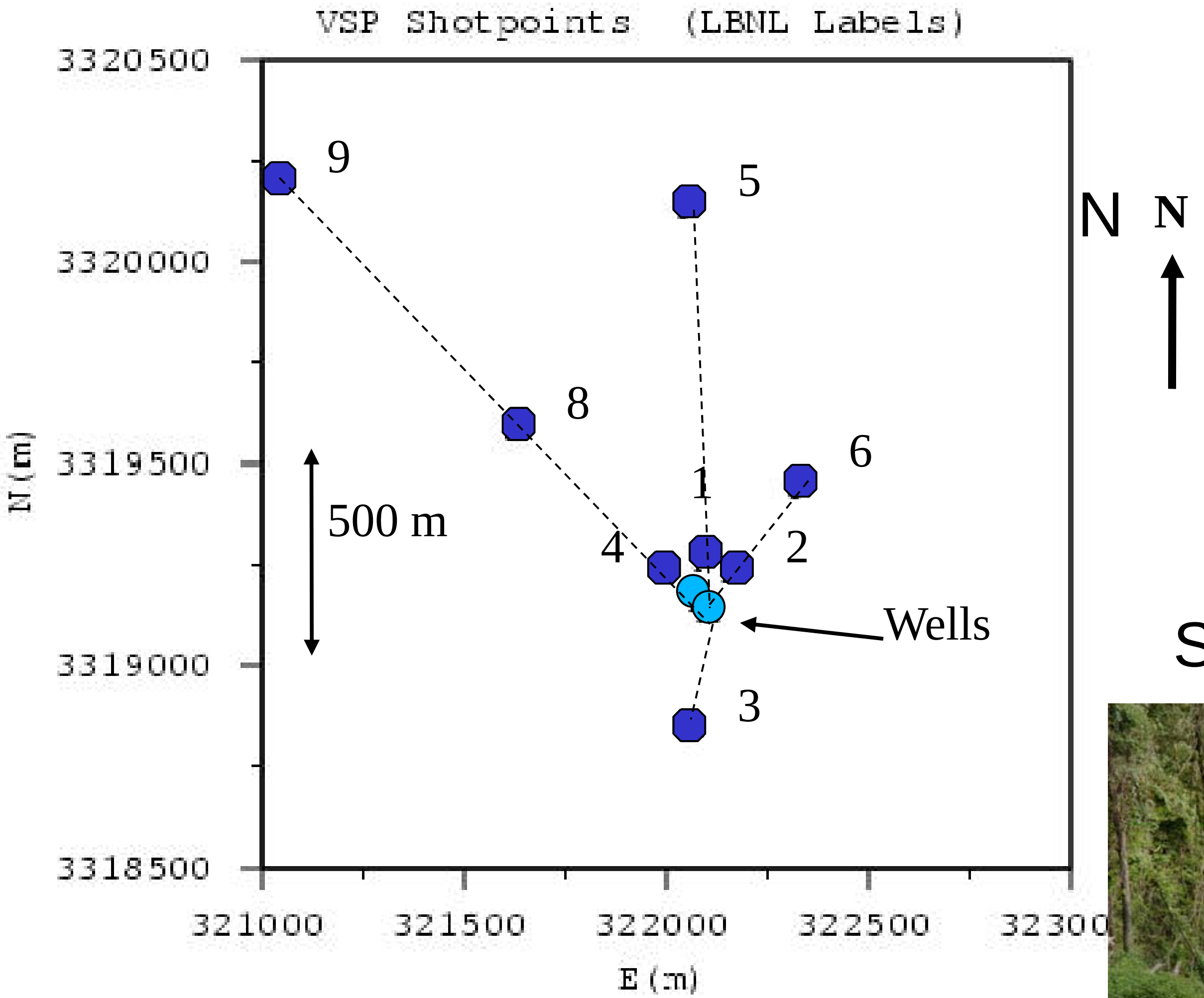
Frio Brine Pilot Site: 30 m well spacing Two test intervals



- Injection intervals: mineralogically complex reworked fluvial sandstones, porosity 24%, permeability 4.4 to 2.5 Darcys
- Steeply dipping 11 to 16 degrees
- Seals – numerous thick shales, small fault block
- Depth 1,500 and 1657 m
- Brine-rock system, no hydrocarbons
- 150 and 165 bar, 53 -60 degrees C, supercritical CO_2

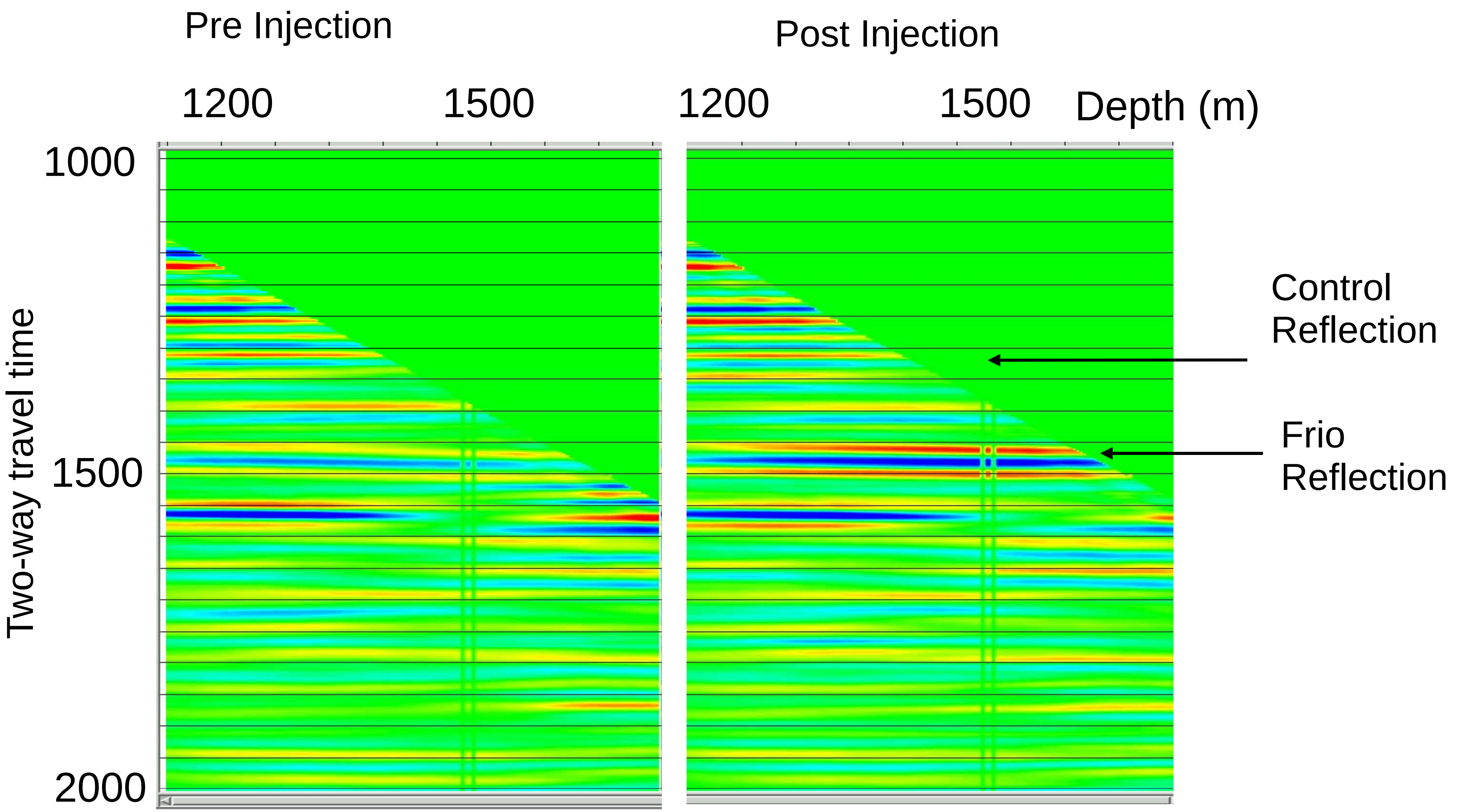
Hovorka, et al, 2006.

Frio VSP Shot Points



Shot hole drilling

Frio VSP Reflection Amplitude Site 1
F-K Filter for Enhancement

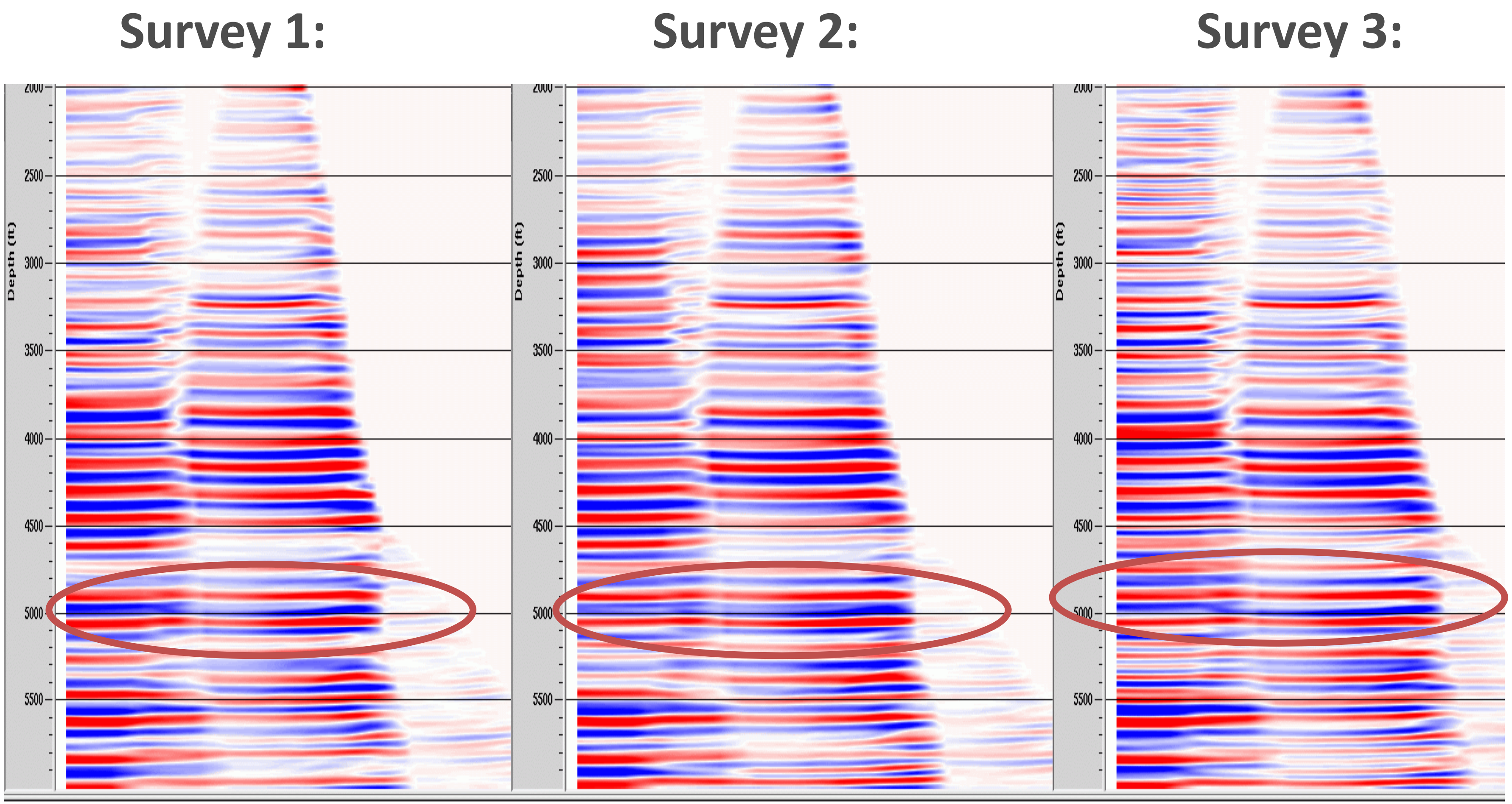


Daley et al, 2007/8

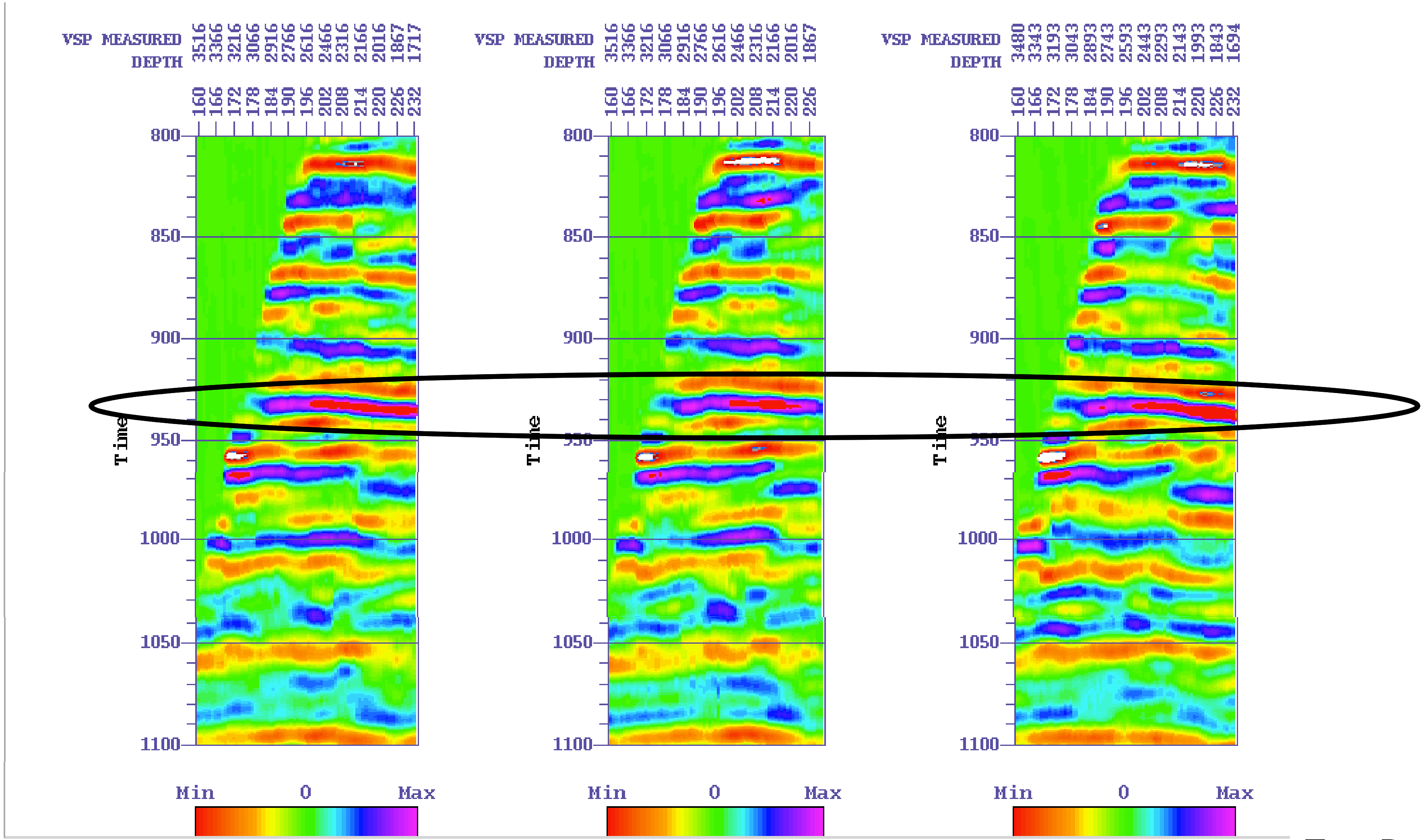
Frio VSP Reprocessing

- Three VSPs processed together (reprocess two) by contractor (SeismicReservoir2020)
- Processing:
  - Static shifts to shots (explosive source)
  - Three component sensor rotation
  - First break picking
  - Downgoing deconvolution (10-100Hz, 800 ms)
  - Wavefield Separation of Upgoing Energy (11 trace median filter) - Current Analysis/Interpretation
  - *Prestack Kirchhoff Depth Migration*
  - *VSP-CDP transfrom*

PreStack Depth Migration South-North
SR2020 Processing

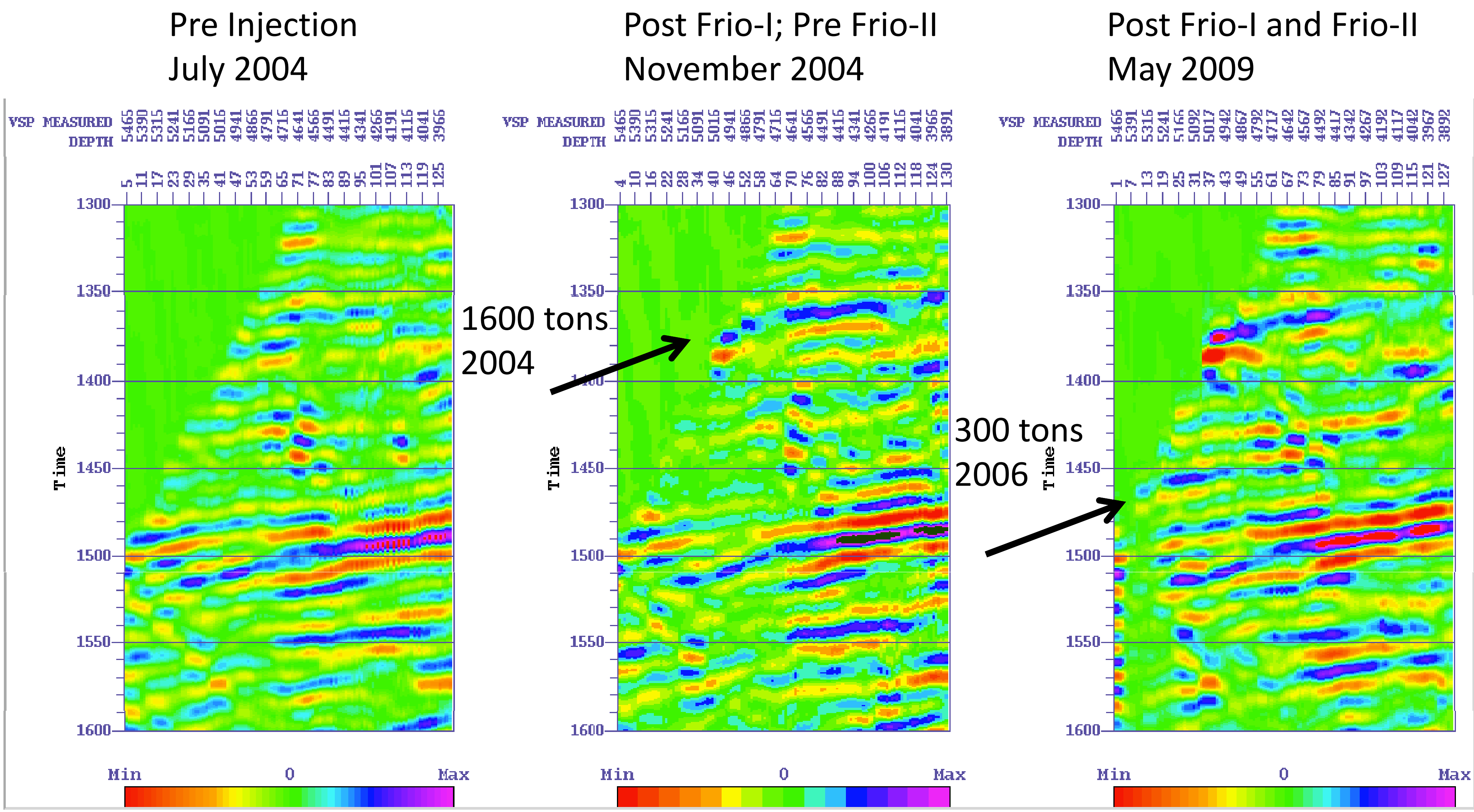


Reflector for Normalization ~ 1 km Depth

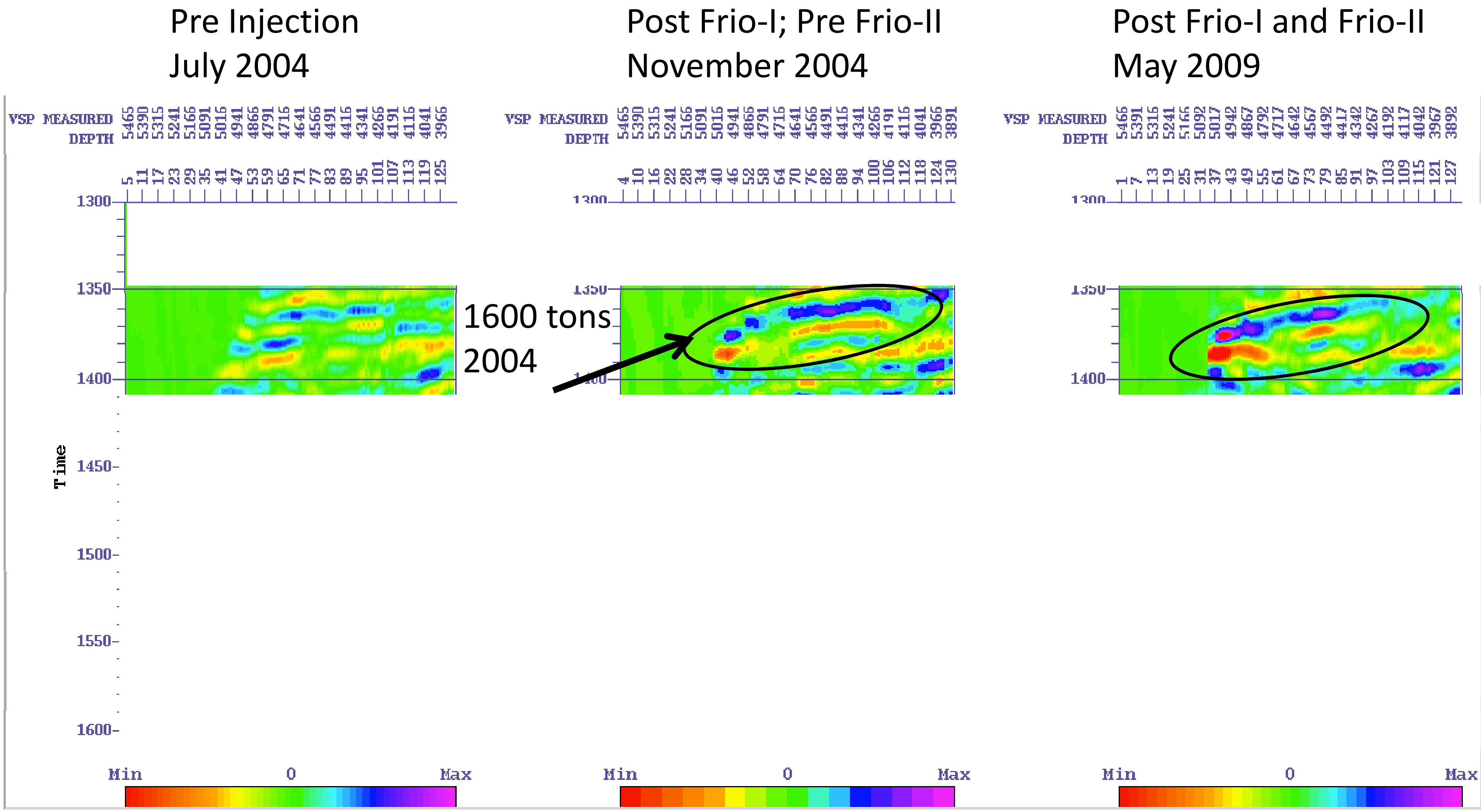


Tom Daley

Frio Time Lapse VSP: Upgoing



Frio Time Lapse VSP: Reflection



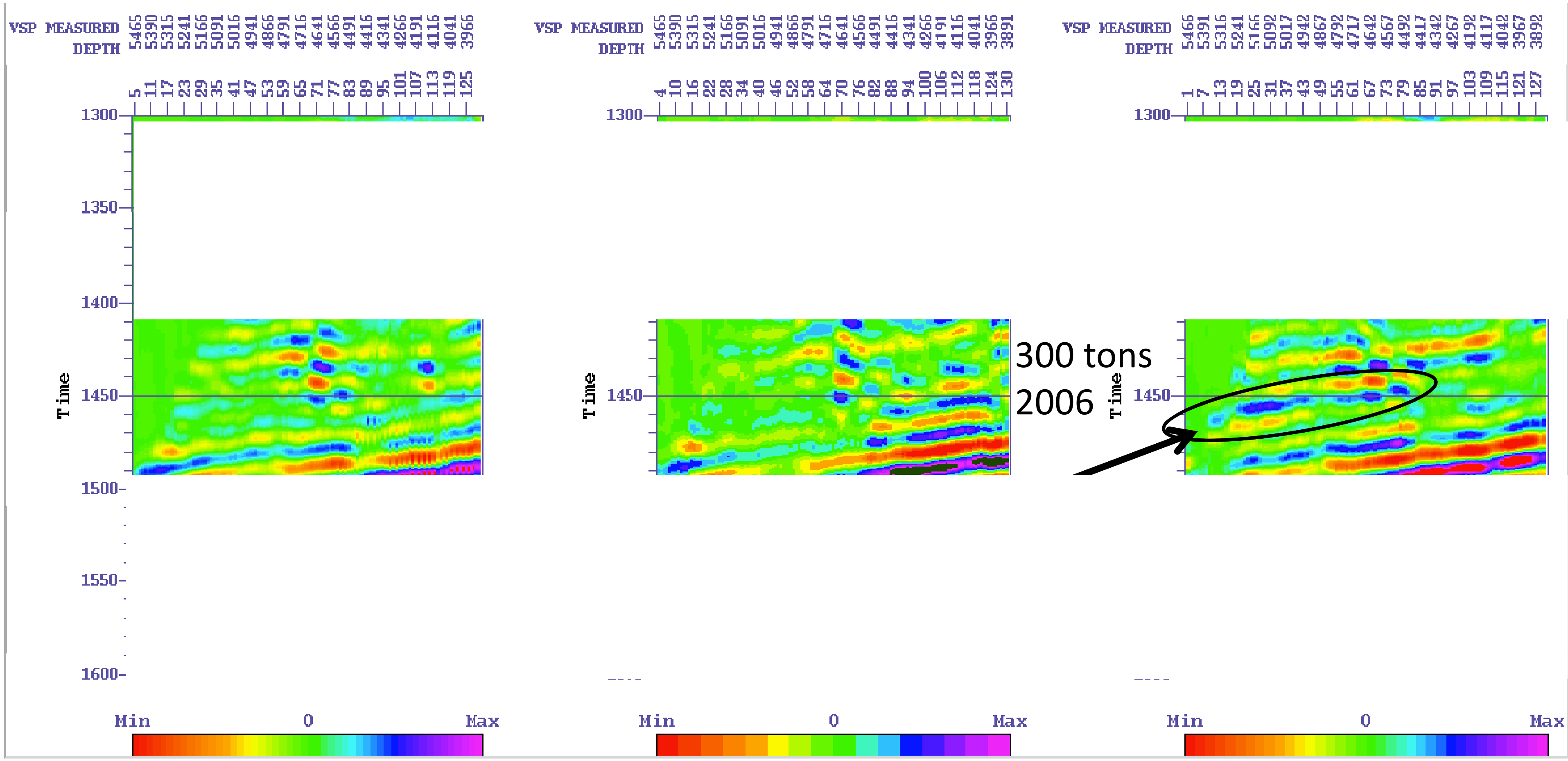
Tom Daley

Frio Time Lapse VSP: Reflection

Pre Injection
July 2004

Post Frio-I; Pre Frio-II
November 2004

Post Frio-I and Frio-II
May 2009



Tom Daley

Status/Conclusions

- Post injection VSP shows response from both 1600 ton (after ~5 years) and 300 ton (after ~3 years) plumes
- Two known plume amounts monitored by same data
- Implications for minimum quantity detectable with VSP
- Current analysis using 'raw' upgoing, with limited source points the imaging methods (VSP-CDP and migration) are less clear, probably due to velocity heterogeneity
- Data will be used to study repeatability, quantification, permanence

Update Five Years Post Injection Frio Brine Pilot

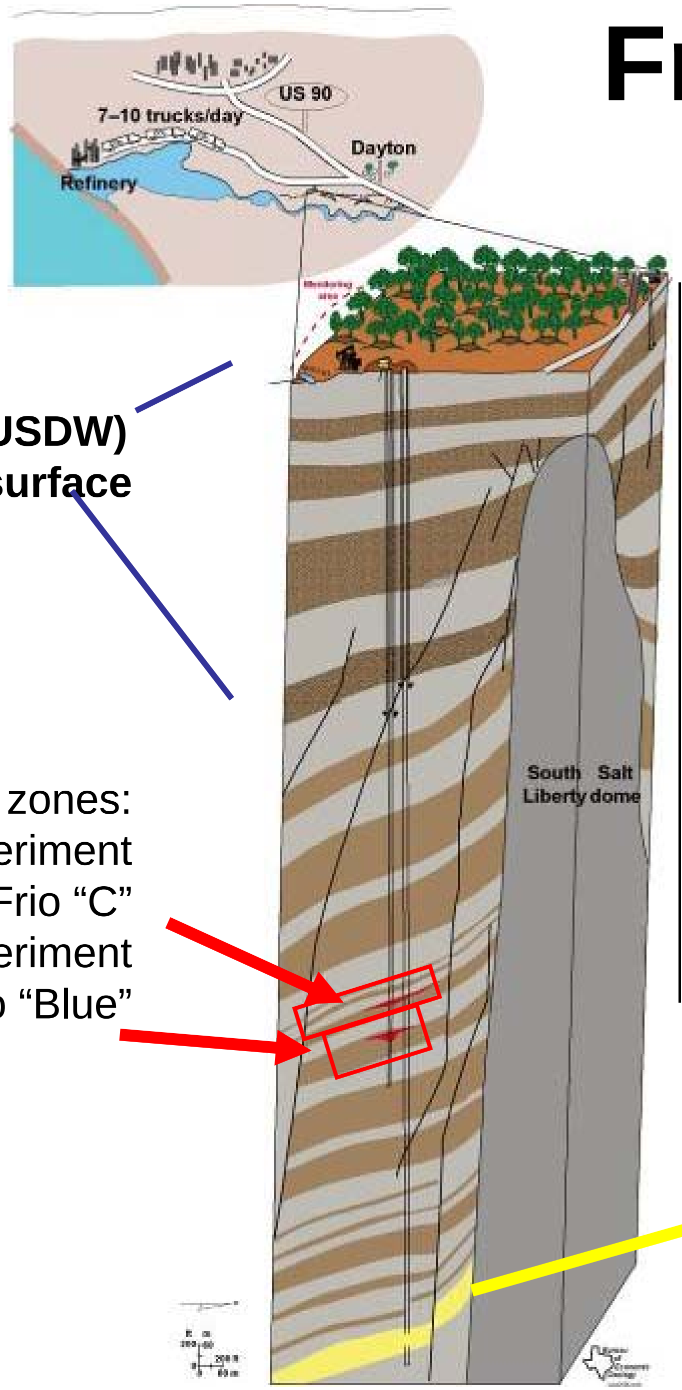
Susan D. Hovorka
Thomas Daley

Frio Brine Pilot Test

Food grade CO_2
Shipped by truck

Fresh water (USDW) protected by surface casing

Injection zones:
First experiment 2004: Frio “C”
Second experiment 2006 Frio “Blue”



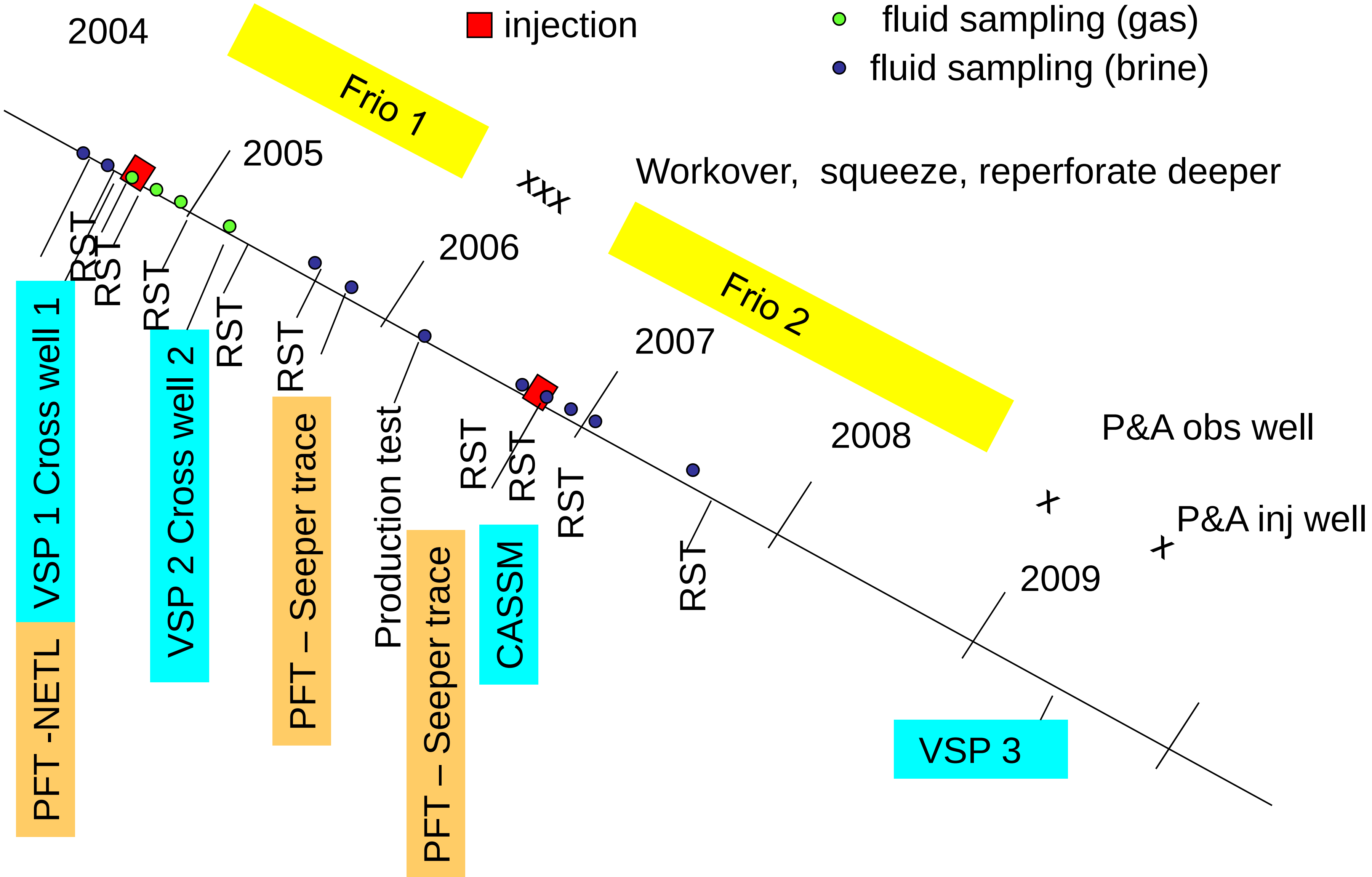
Depth 5034 and 5450 ft

Steeply dipping- high permeability sandstone

Fluid is brine 100 ppt NaCl
100 -110 degrees F

Oil production

Timeline


injection
fluid sampling (gas)
fluid sampling (brine)
2004
2005
2006
2007
2008
2009
Frio 1
Frio 2
xxx
Workover, squeeze, reperforate deeper
P&A obs well
P&A inj well
RST
RST
RST
RST
RST
RST
RST
RST
RST
VSP 1 Cross well 1
PFT -NETL
VSP 2 Cross well 2
PFT – Seeper trace
Production test
PFT – Seeper trace
CASSM
VSP 3

Frio Brine Pilot Research Team

- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, Jeff Kane, Andrew Tachovsky, Abhijit Mukarjee, Tip Meckel; Mark Holtz, Shinichi Sakurai, Seay Nance, Joseph Yeh, Paul Knox, Khaled Faoud, Jeff Paine
- Lawrence Berkeley National Lab, (Geo-Seq): Larry Myer, Tom Daley, Jonathan Ajo-Franklin Barry Freifeld, Rob Trautz, Christine Doughty, Sally Benson, Karsten Pruess, Curt Oldenburg, Jennifer Lewicki, Ernie Majer, Mike Hoversten, Mac Kennedy, Paul Cook, Duo Wang, Ray Solbau
- Schlumberger: T. S. Ramakrishna, Nadja Mueller, Austin Boyd, Mike Wilt
- Oak Ridge National Lab: Dave Cole, Tommy Phelps, David Riestberg, Phil Szymcek
- Lawrence Livermore National Lab: Kevin Knauss, Jim Johnson
- Alberta Research Council: Bill Gunter, John Robinson, Bernice Kadatz
- Texas American Resources: Don Charbula, David Hargiss
- Sandia Technologies: Dan Collins, “Spud” Miller, David Freeman; Phil Papadeas
- BP: Charles Christopher, Mike Chambers
- SEQURE – National Energy Technology Lab: Curt White, Rod Diehl, Grant Bromhall, Brian Stratizar, Art Wells
- Paulsson Geophysical – Bjorn Paulsson
- University of West Virginia: Henry Rausch
- USGS: Yousif Kharaka, Bill Evans, Evangelos Kakauros, Jim Thordsen
- Praxair: Glen Thompson, Joe Shine, Dan Dalton,
- Australian CO2CRC (CSIRO): Jim Underschultz, Kevin Dodds, Don Sherlock
- Core Labs: Paul Martin and others

Gulf Coast Carbon Center

NETL

An Evolving Experiment

Frio 1 October 2004 – January 2006

- Conservative "early success"
- Key issues – tool performance and model validation through history match
- Inject in 10 ft thick Frio upper "C" sand
- Multi-tool testing
- VSP and time laps seismic cross well tomography two months after injection

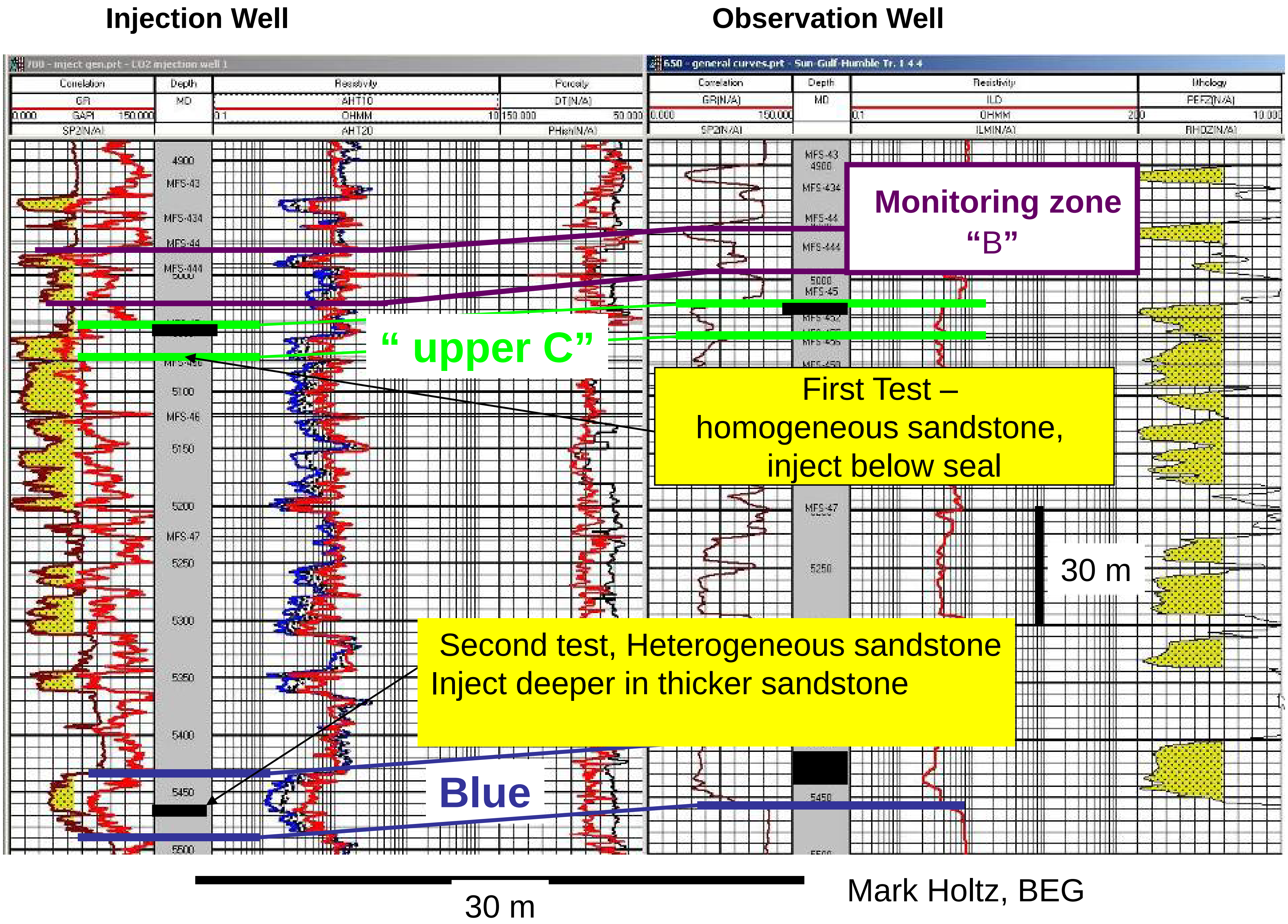
Frio 2 September 2006 – July 2008

- Storage permanence – quantifying residual saturation and dissolution
- Post- injection monitoring under stable conditions just completed July 2007
- Buoyancy in Frio "Blue" sand
    - Inject "deep": 6 feet perforation in base 32 ft thick sandstone
    - inject slowly: 50T/day x 5days
    - Rock-water reaction, tracer fractionation as a result of dissolution
    - Novel tool – tubing-conveyed seismic array

Post injection Conclusions

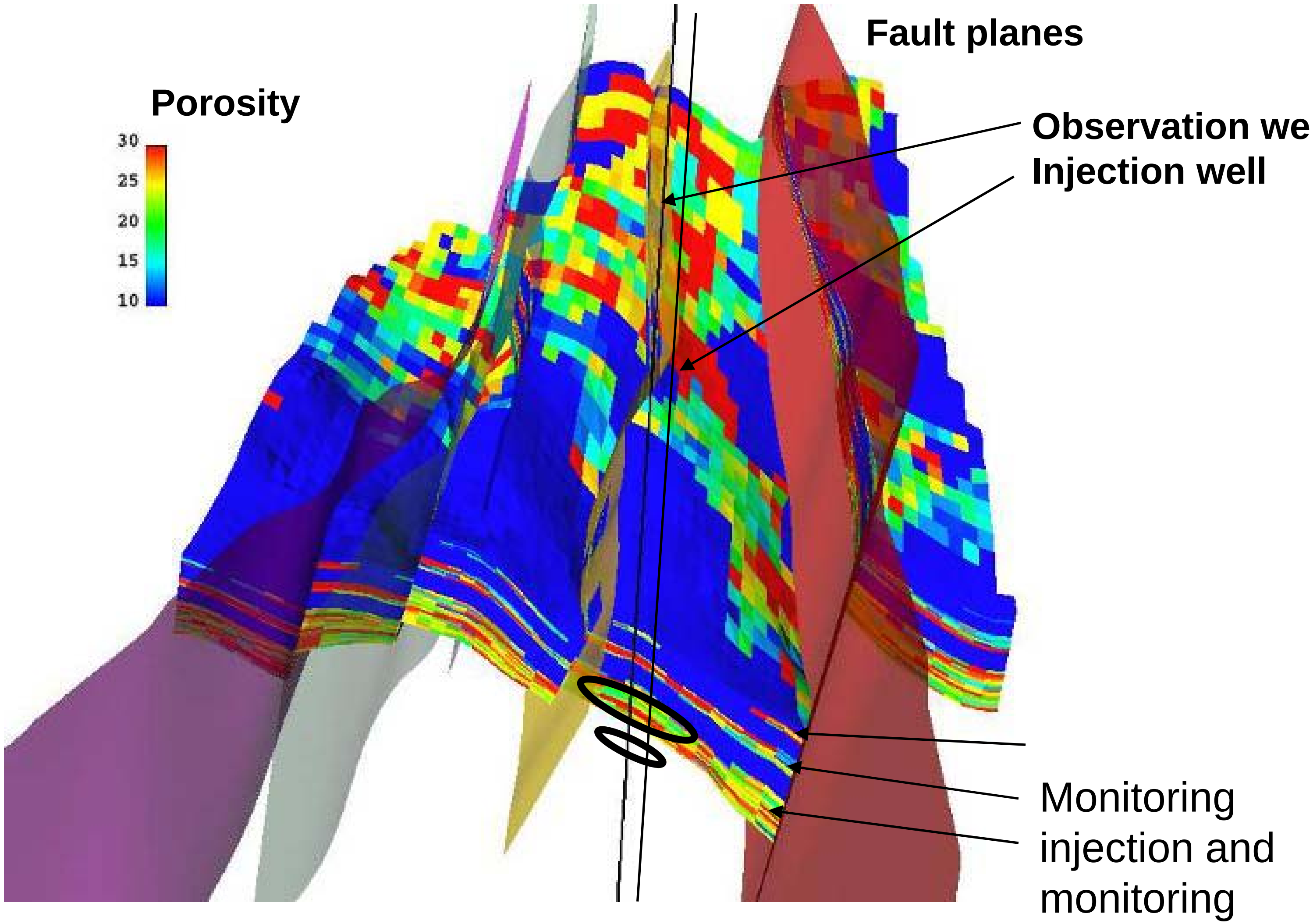
- Provide data to confirm long term models
  - Saturation and fluid mobility
  - Dissolution

- A short test scales to long term post injection faster than a long test… is this true?



Mark Holtz, BEG

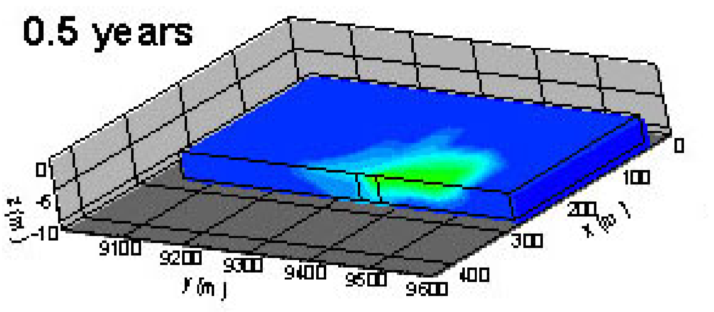
Steep dip, high permeability – CO2 will migrate rapidly



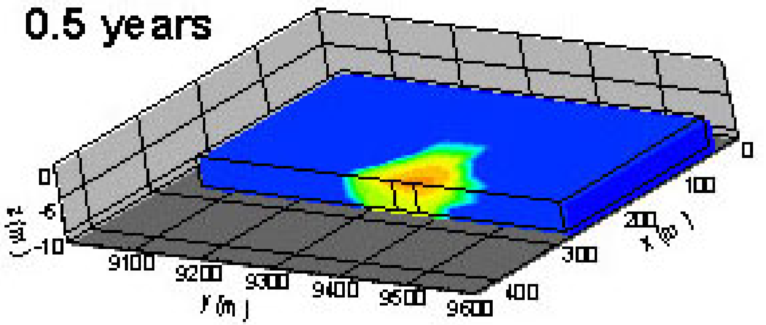
Knox, Fouad, Yeh, BEG

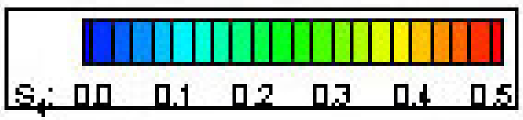
Modeling and Monitoring Demonstrate Permanence

Residual gas saturation of 5%



Residual gas saturation of 30%

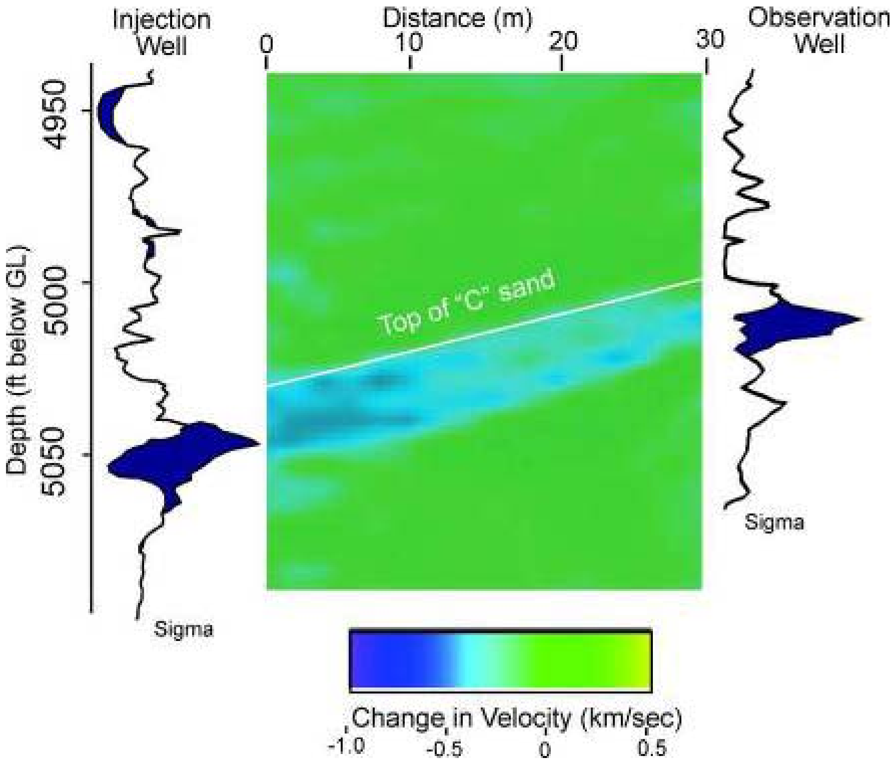


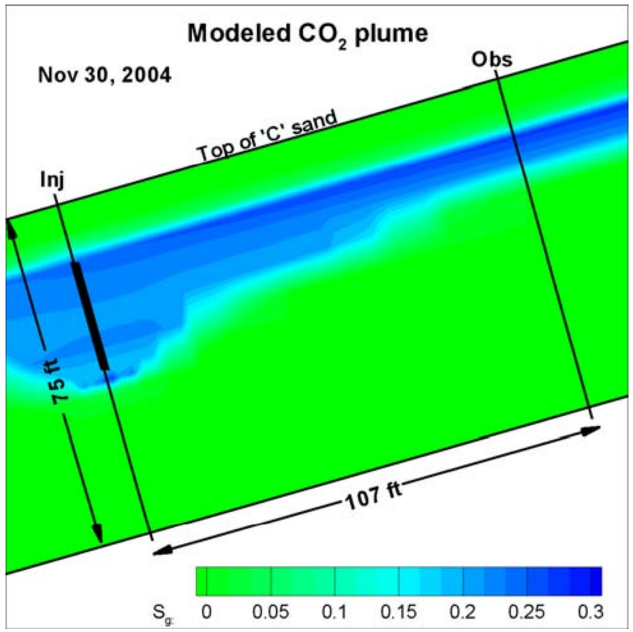


- **Modeling has identified variables which appear to control CO_2 injection and post injection migration.**
- **Measurements made over a short time frame and small distance confirm the correct value for these variables**
- **Better conceptualized and calibrated models will now be used to develop larger scale longer time frame injections**

TOUGH2 simulations
C. Doughty LBNL

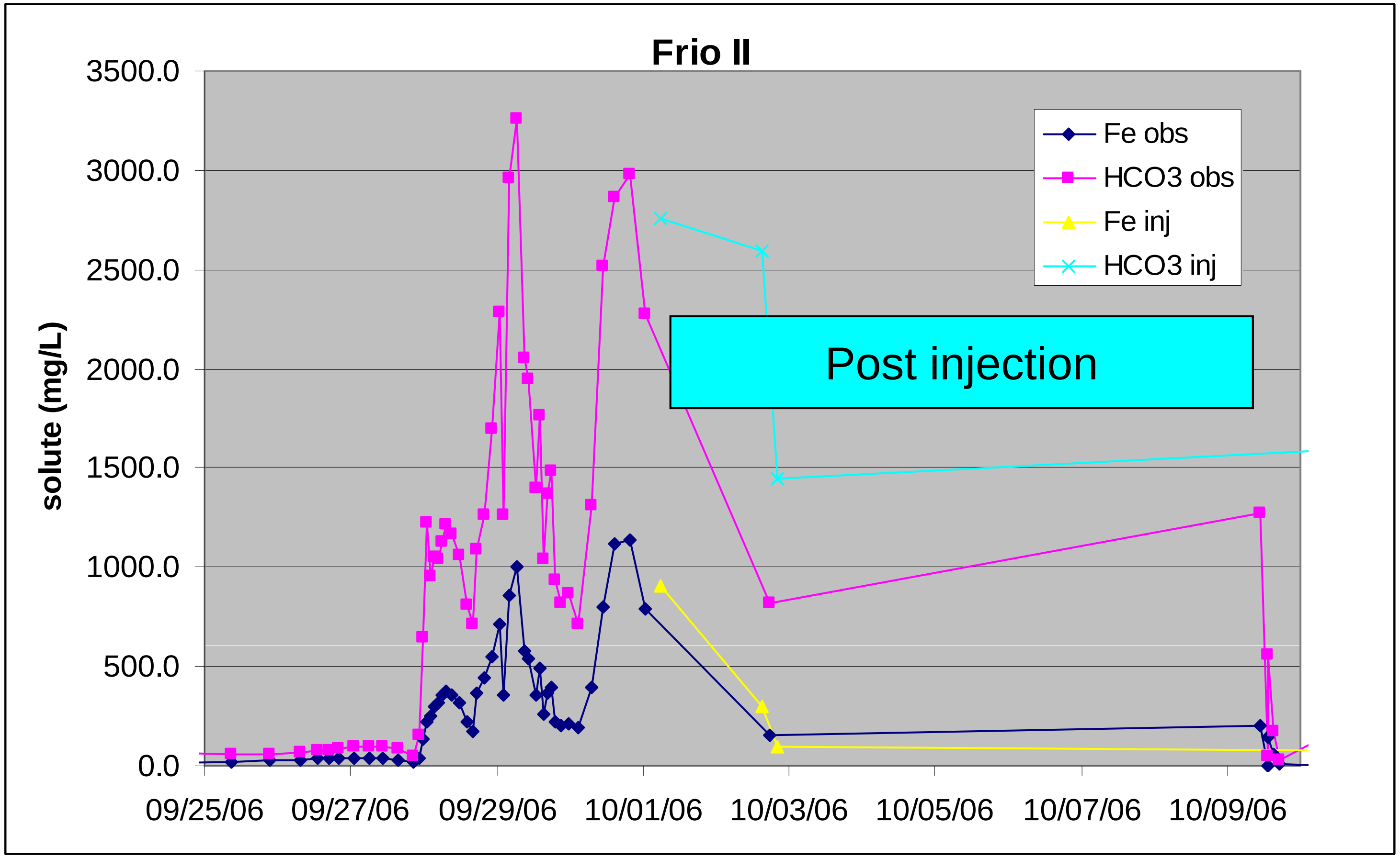
First test: Post injection CO_2 Saturation Observed with Cross-well Seismic Tomography vs. Modeled





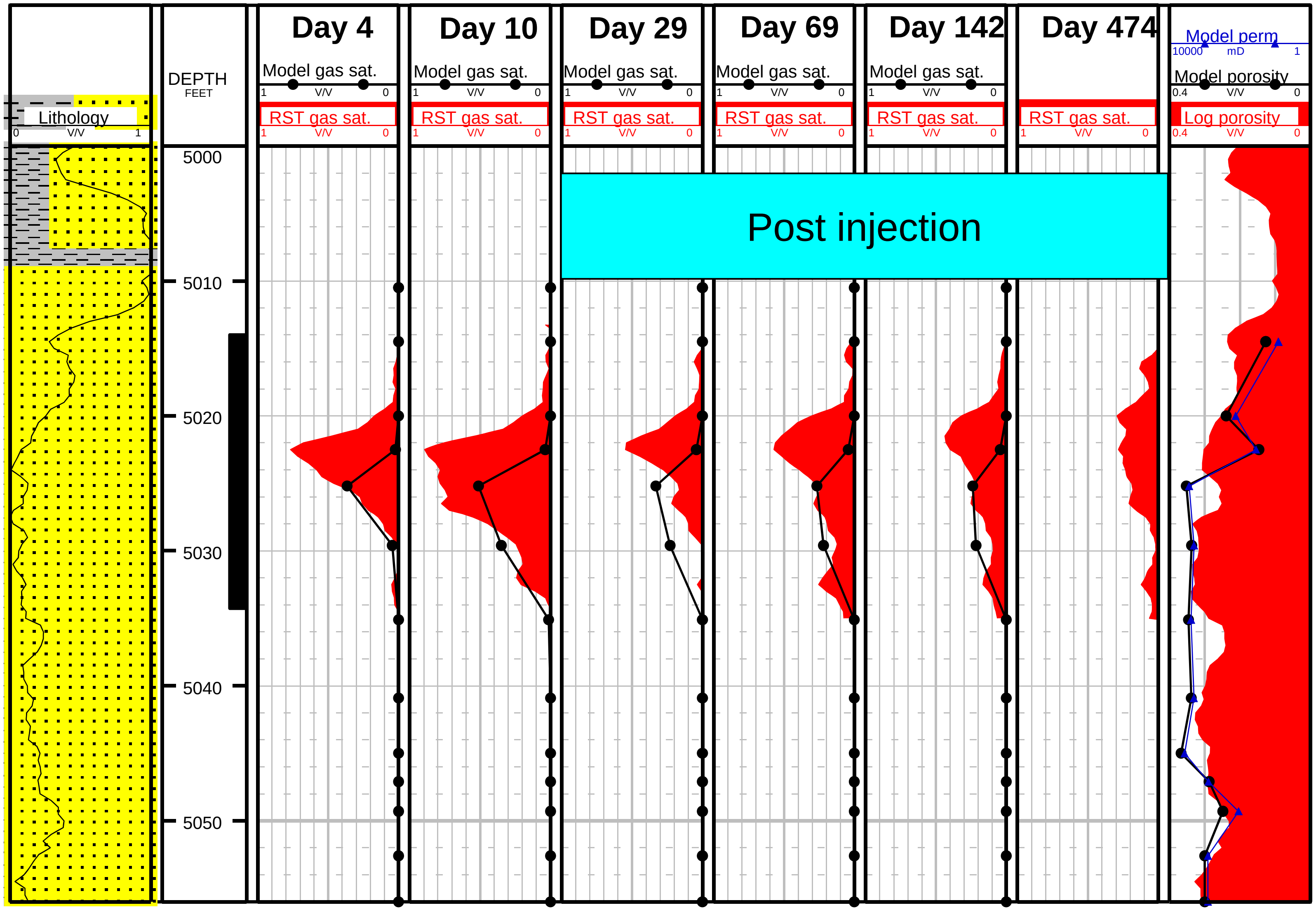
Tom Daley and Christine Doughty LBNL

Geochemical Evidence of CO_2-Rock Interaction



Yousif Kharaka, USGS

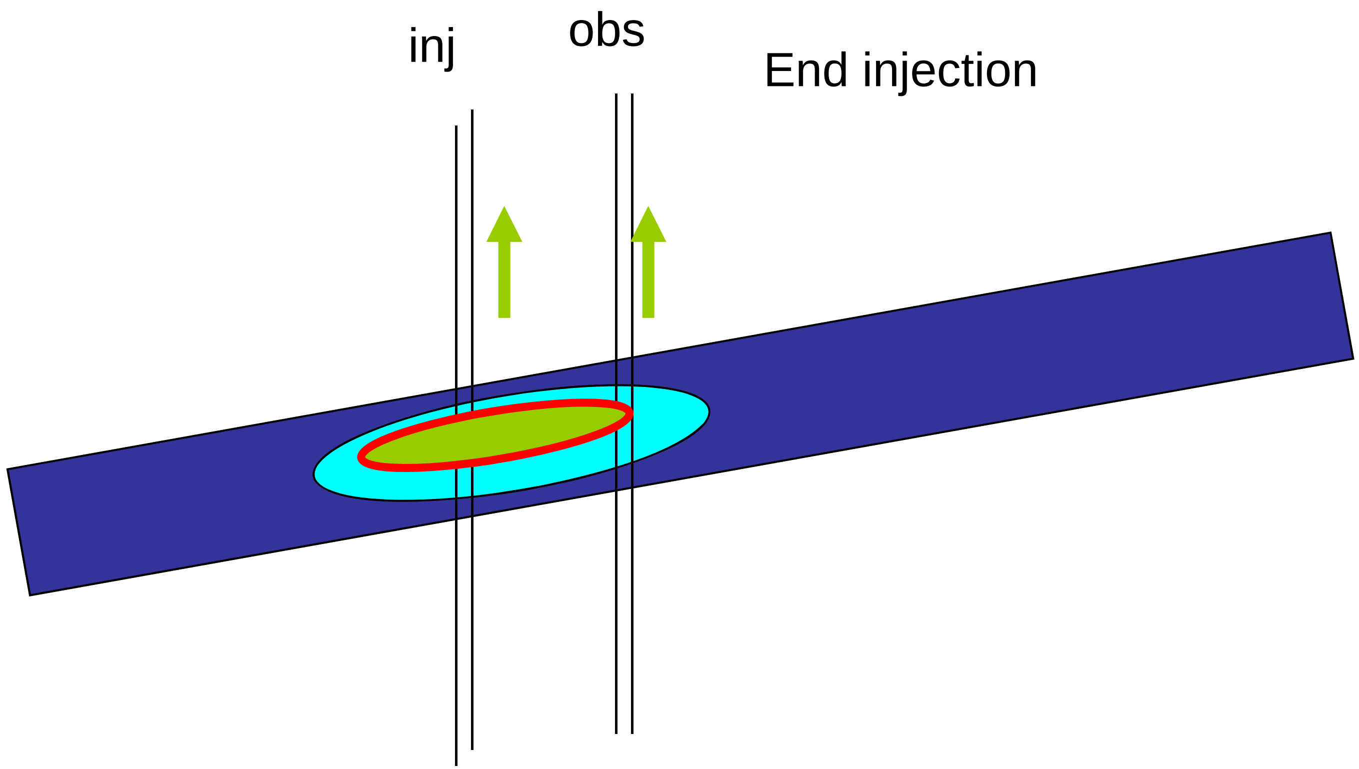
Measurement at a Well:
Saturation logging (RST) Observation well to measure changes in CO_2 saturation – match to model



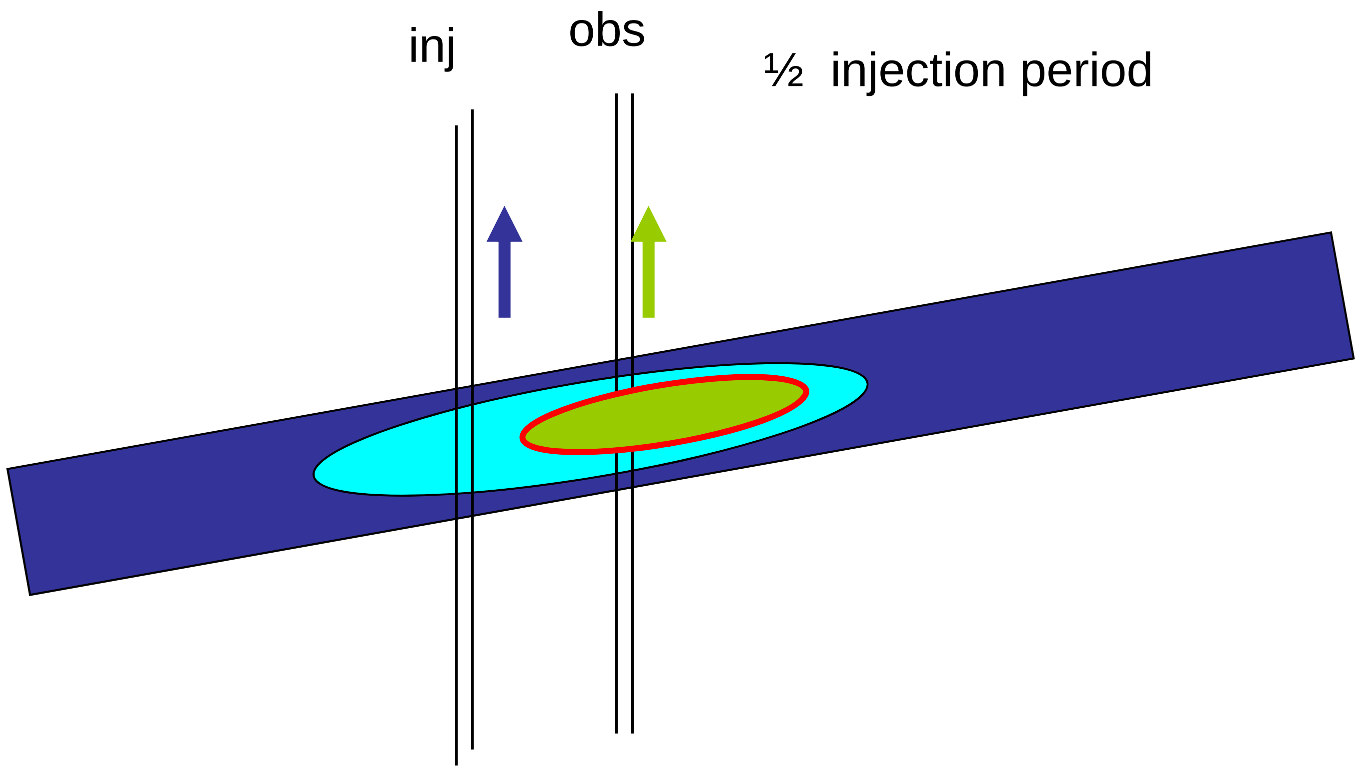
Shinichi Sakurai, Jeff Kane, Christine Doughty

January 2006, attempting to produce the CO_2 back – no success. CO_2 is underground but cannot be produced

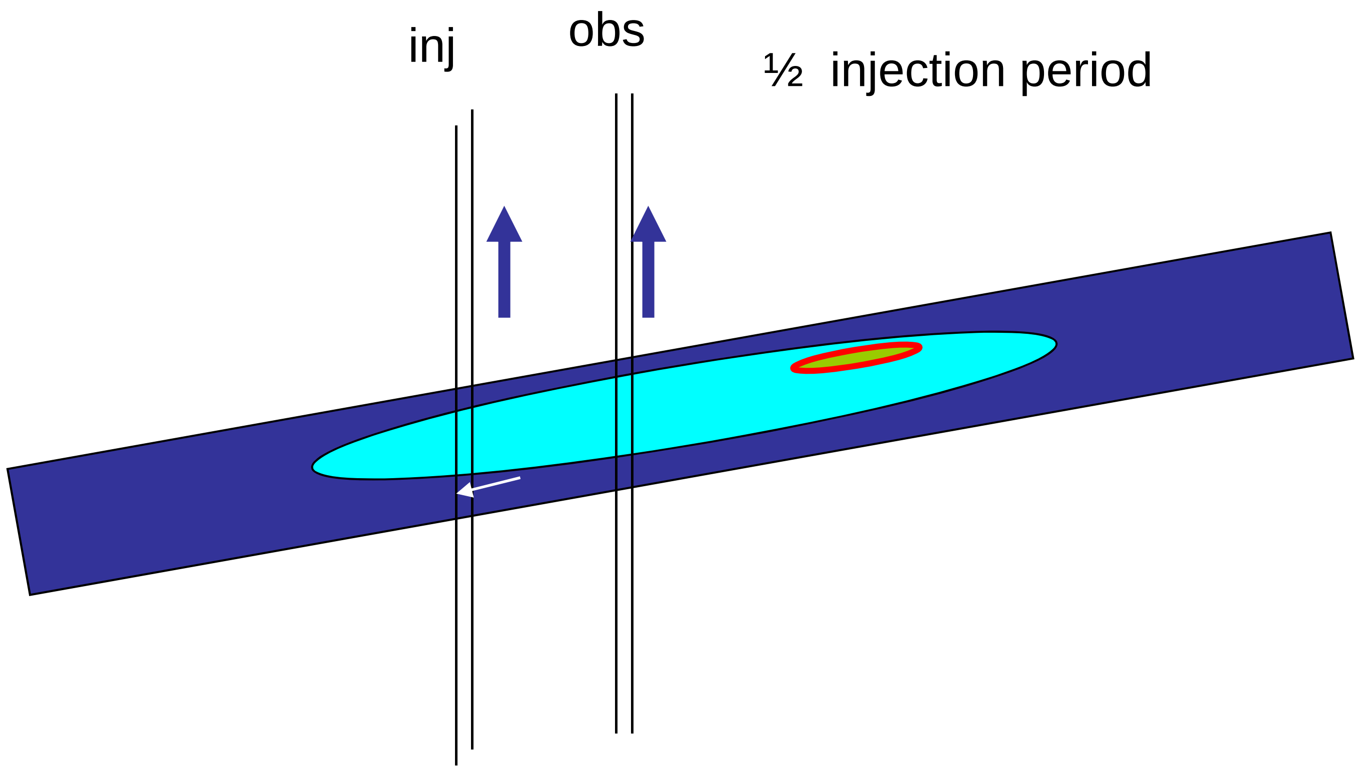
Post injection fluid mobility



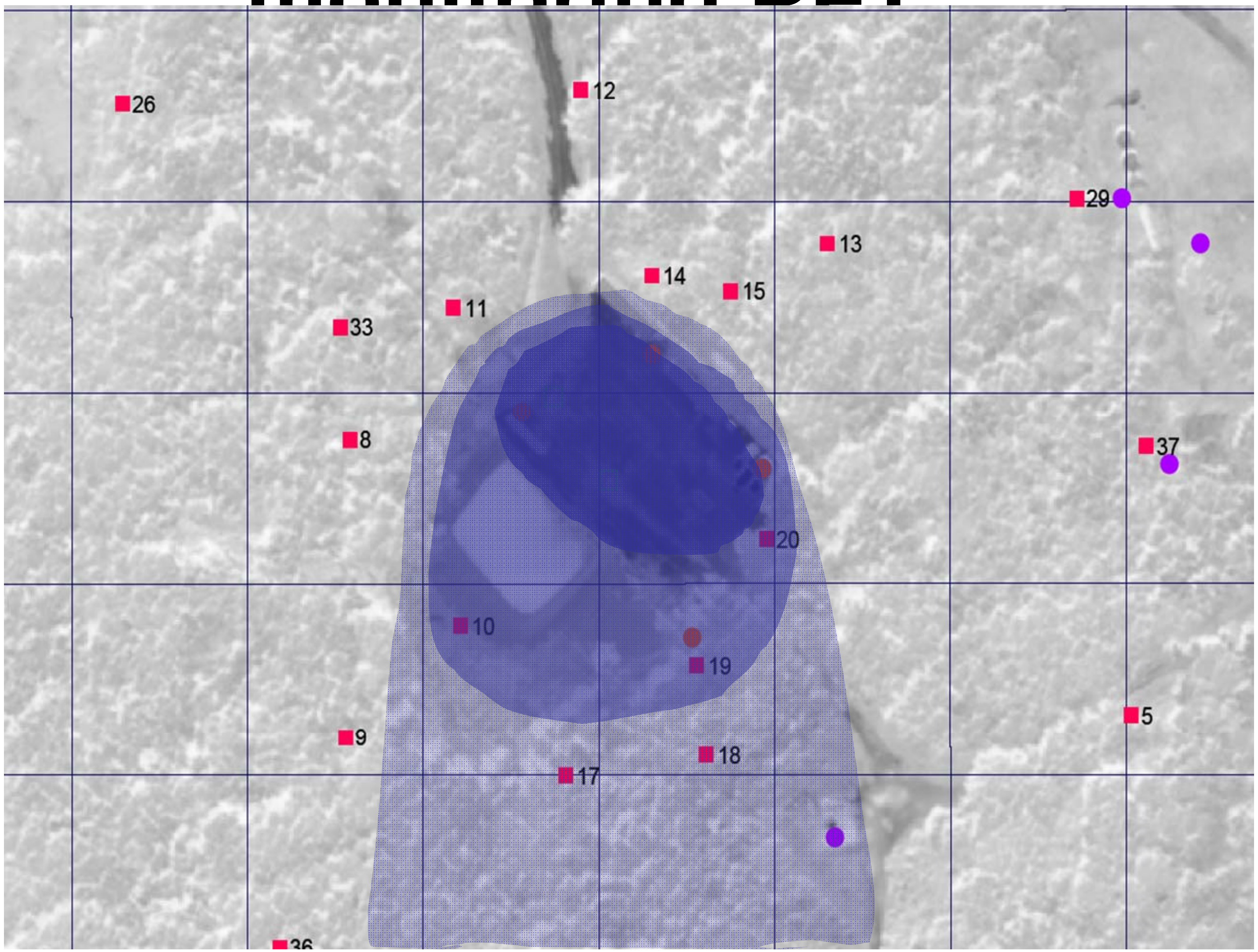
Post injection fluid mobility



Post injection fluid mobility



During injection surface monitoring PFT



From Art Wells et al, 2005


I year post injection PFT
survey Seeper Trace

Seeper Trace equipment

In Salah Gas Stockage de CO_2

Surface deformation forward modelling cf InSar data In Salah

Kevin Dodds BP from material derived from :

CO_2 JIP Technical Review 2010 February 2nd and 3rd, Cambridge, UK

The Interpretation of InSAR Range Change Observations in Terms of Reservoir Volume Change and Fault/Fracture Aperture Change D. W. Vasco, LBNL A. Ferretti, F. Novali, and A. Rucci, TRE R. C. Bissell, A. S. Mathieson, I. W. Wright, BP P. S. Ringrose, StatOil

Field Scale Geomechanics: Hydromechanical Simulations of Surface Uplift due to CO_2 Injection at In Salah Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

Coupled Thermal, Hydraulic and Geomechanical Numerical Modeling for Interpretation of Ground Surface Deformations and Potential of Injection-Induced Micro-Earthquakes J. Rutqvist, Don Vasco, Ernie Majer, HH Liu, Karl Kappler, Lehau Pan LBNL

Monitoring CO2 sequestration with a network inversion InSAR method Bruce Macdonald, MDA

bp Statoil sonatrach

Introduction

In Salah Gas
Stockage de CO_2

Goal

- Cost effective monitoring of the geological storage of carbon dioxide

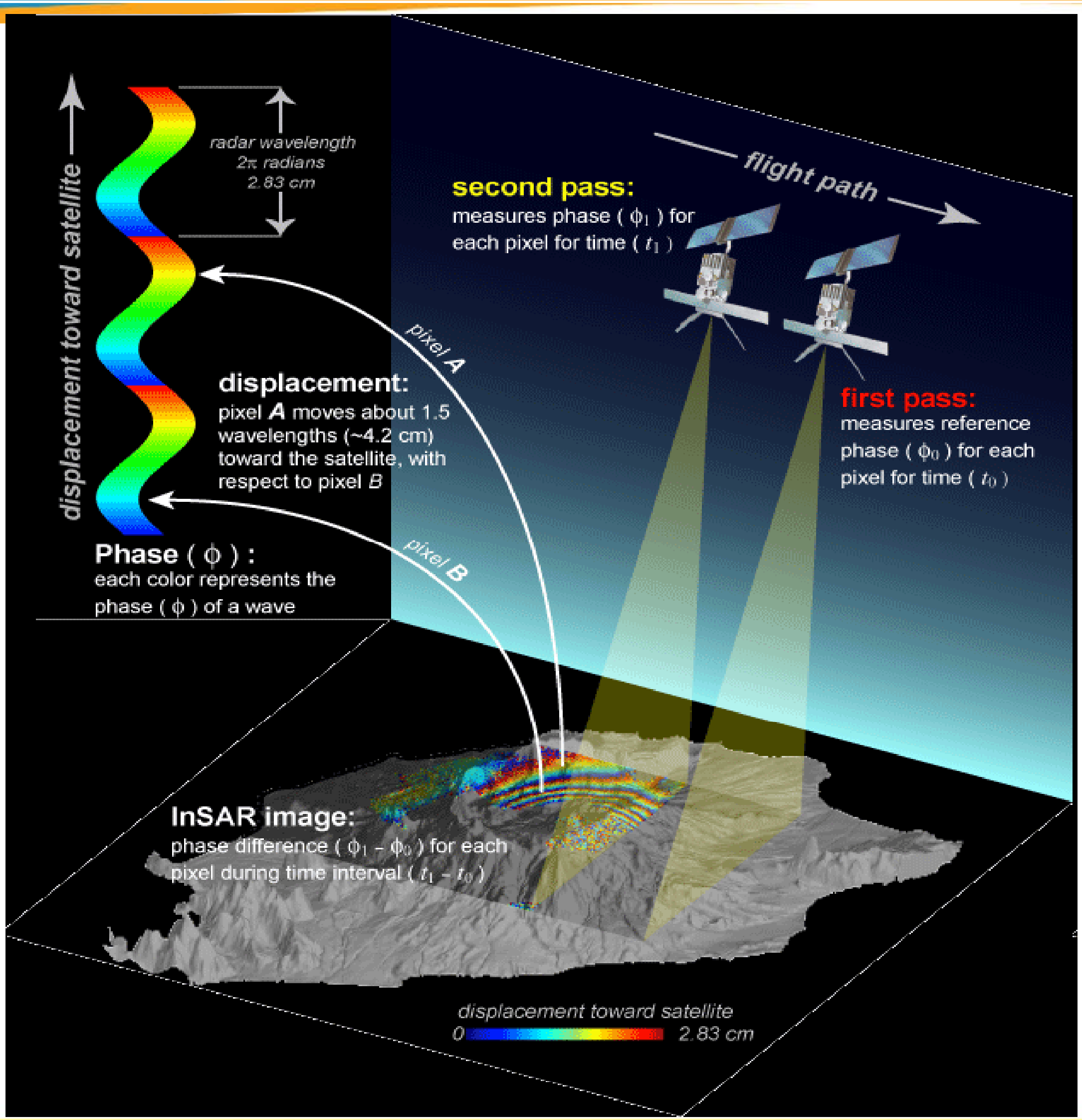
Approach

- Satellite monitoring of surface deformation
- Use surface deformation to infer the flow associated with the injection of CO_2

Outline

- The In Salah CO_2 storage project and satellite monitoring
- The importance of an accurate elastic Earth model for calculating surface deformation
- Fault/Fracture opening and reservoir volume change due to CO_2 injection

What is InSAR (SAR Interferometry)?



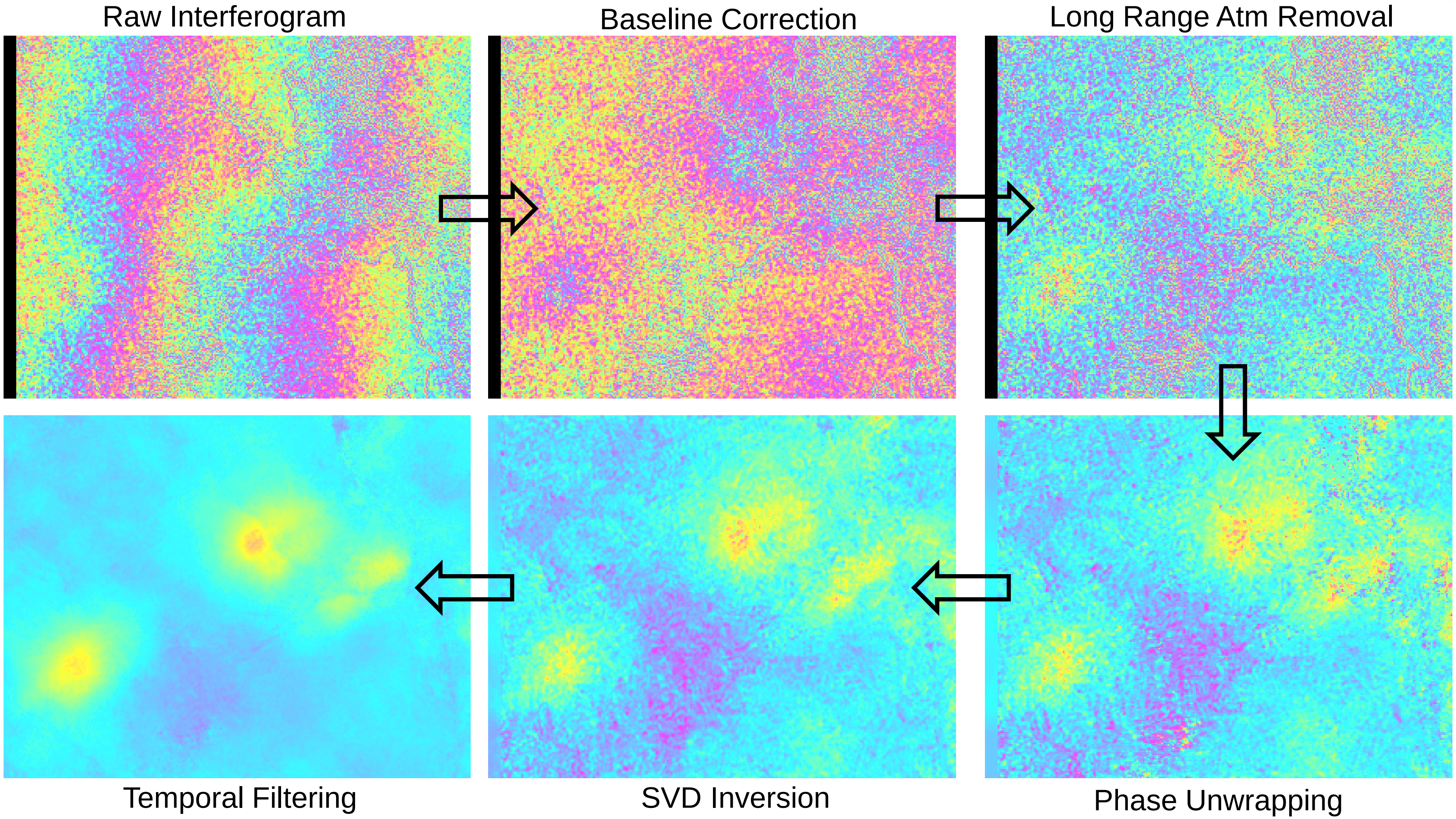
Interferometric repeat pass phase sensitive to:

- **Surface displacement (in look direction)**
- **Topography (proportional to look perpendicular orbit separation)**
- **Atmospheric water vapor changes**
- **Ionospheric changes**
- **Soil parameter changes**

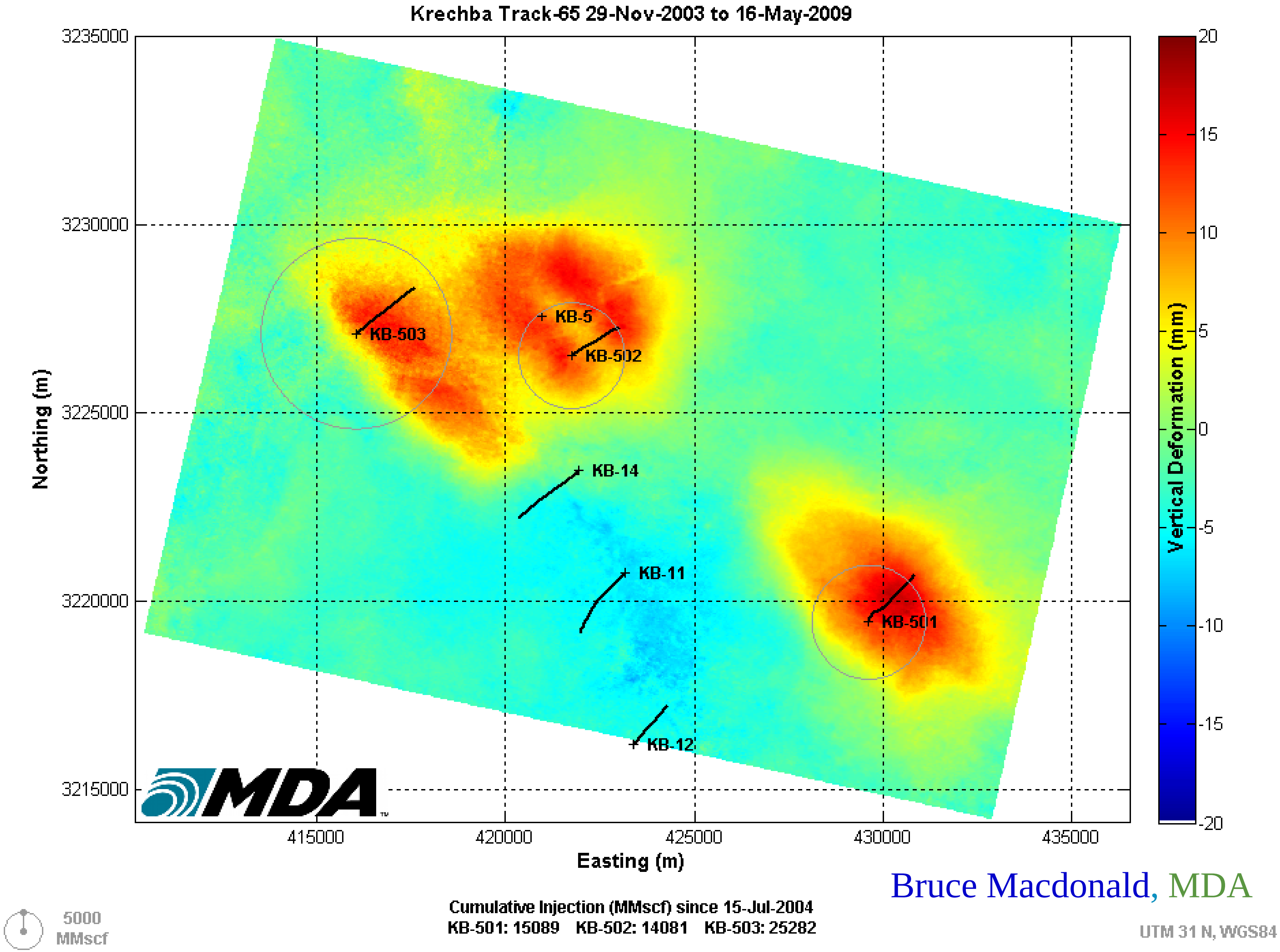
Bruce Macdonald, MDA

Example: 20031129_20060701 Bruce Macdonald, MDA

In Salah Gas Stockage de CO_2



Spectral decorrelation, small pock-mark type atmospheric bubbles, and deformation

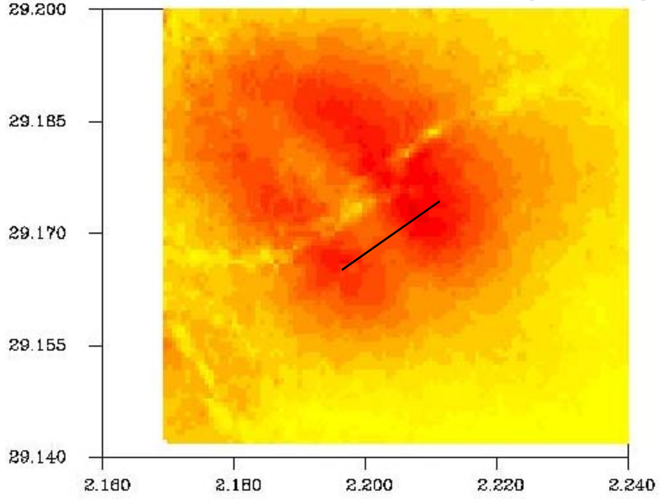


Bruce Macdonald, MDA

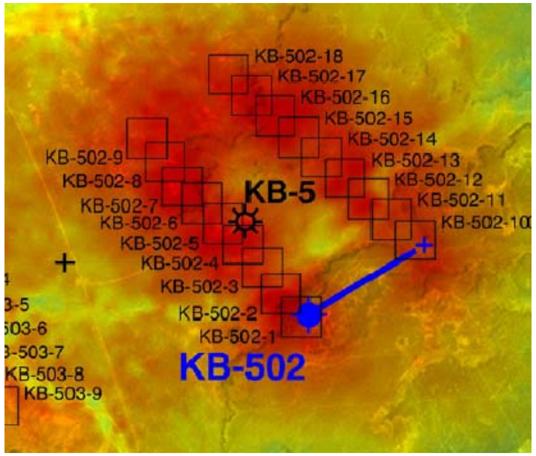
Fault Opening and Double-Lobe Uplift at KB502

Three independent InSAR analyses of KB502 uplift:

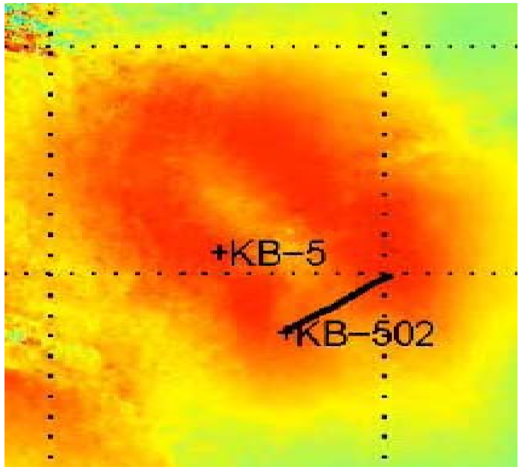
TRE and Vasco et al., (2010)



Onuma, JGI (GHGT-9)



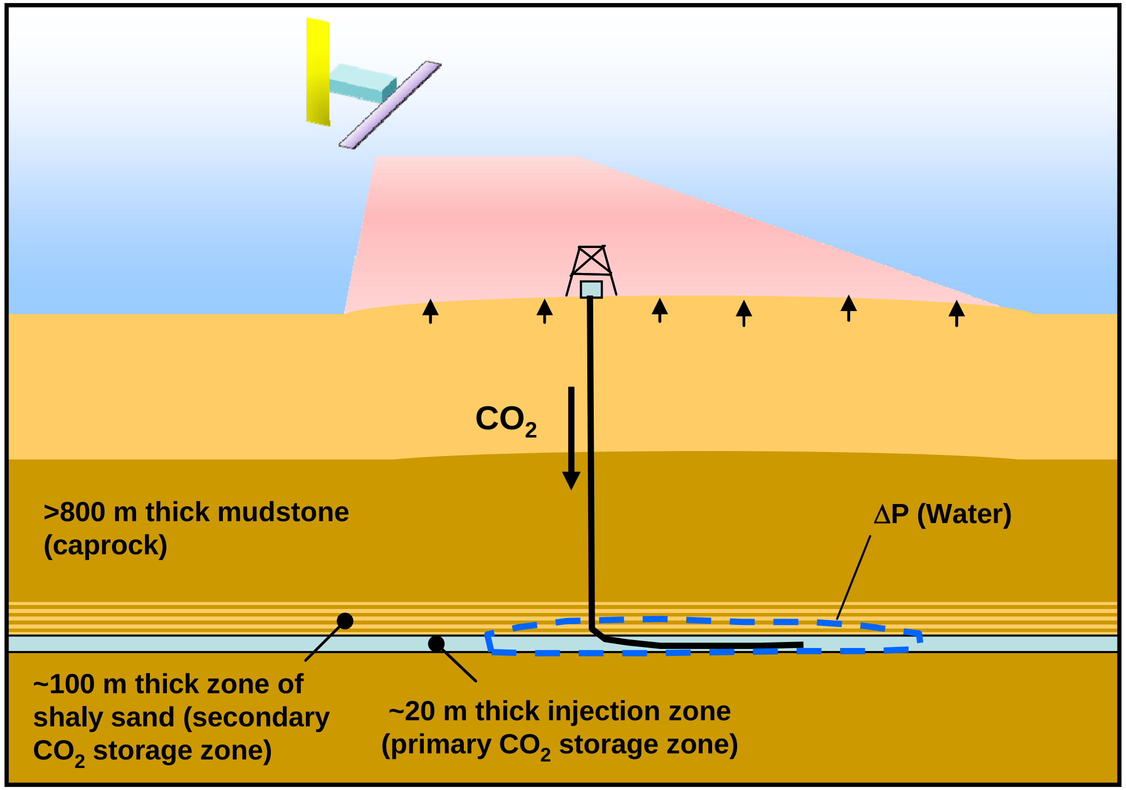
MDA, Pinnacle



- Vasco et al. (2010) has interpreted this to be a tensile opening feature extending about 80 m above and below the injection zone and having an “aperture change” of about 6 cm.

- Here it is considered a jointed zone with anisotropic elastic properties being pressure inflated by the injection.

The Mechanism of Surface Uplift

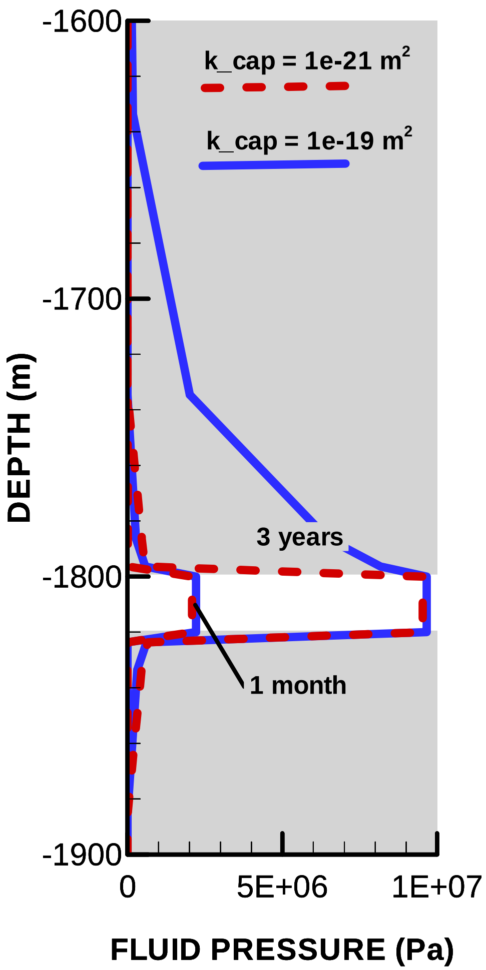


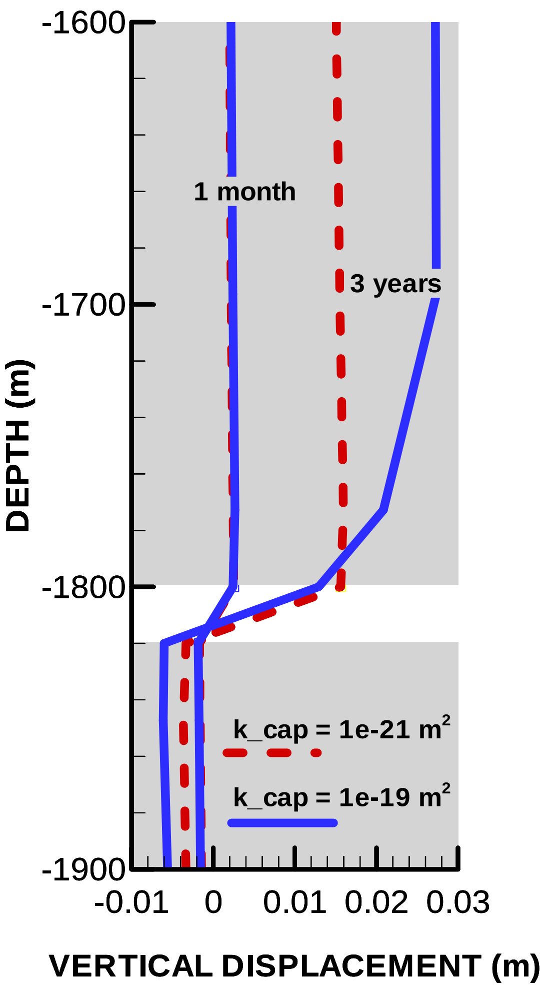
J. Rutqvist, Don Vasco, Ernie Majer, HH Liu, Karl Kappler, Lehau Pan
LBNL

- Consistent with pressure-induced volumetric expansion of reservoir rocks within the 20 m thick injection zone and perhaps within the 100 m thick zone of shaly sands just above the injection zone ⇒ indicates that CO_2 and brine is confined at depth below the caprock.

Effects of Caprock Permeability

J. Rutqvist, Don Vasco, Ernie Majer, HH Liu,
Karl Kappler, Lehau Pan LBNL

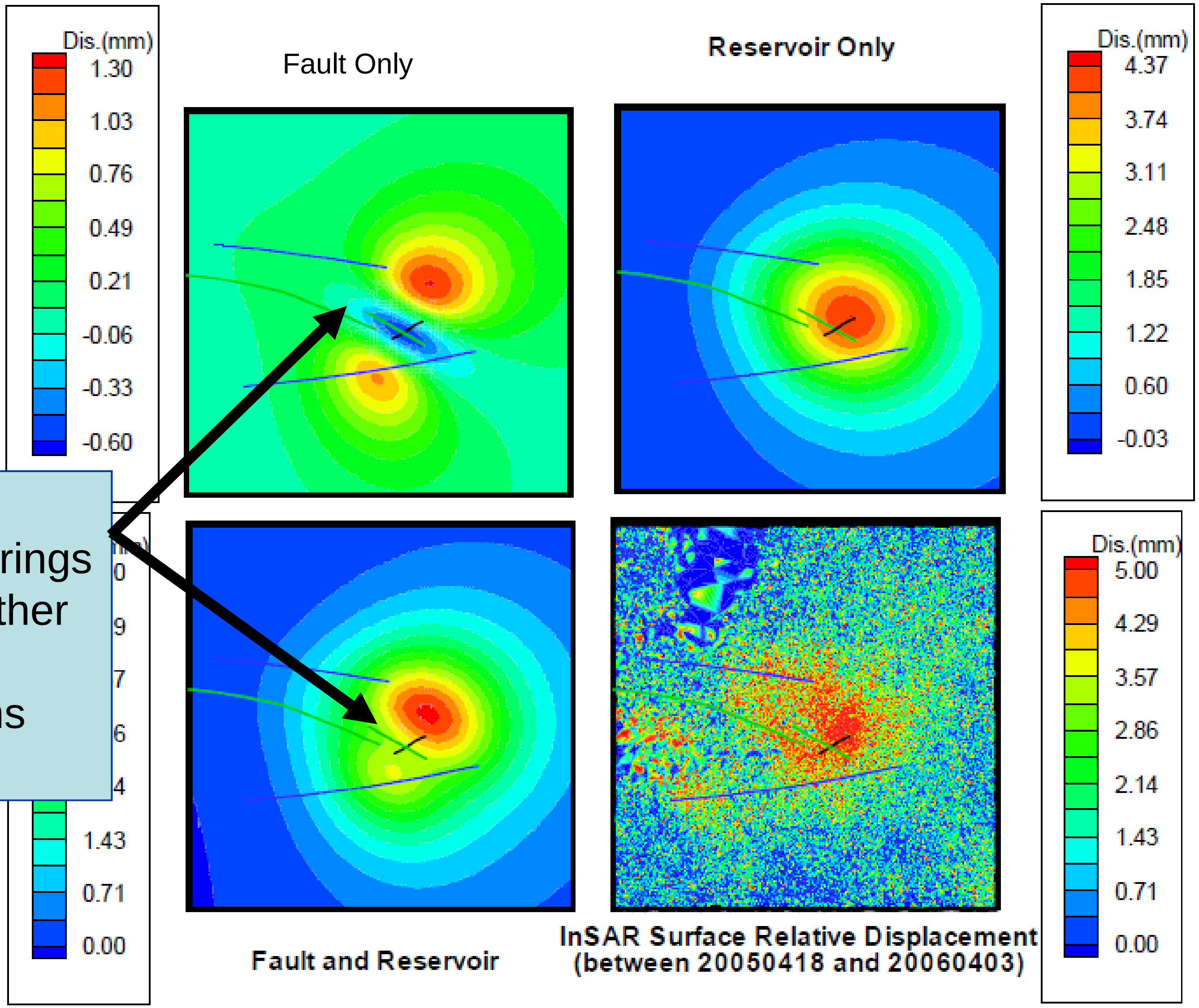




- A small amount of fluid migrates into the caprock (1 % effective porosity) causing a pressure change and vertical expansion that contributes to the ground uplift

Hydromechanical effect of the fault leads to morphology consistent with the InSAR data

In Salah Gas
Stockage de CO_2



Addition of reservoir brings lobes together and overwhelms "trough"

Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

bp Statoil sonatrach

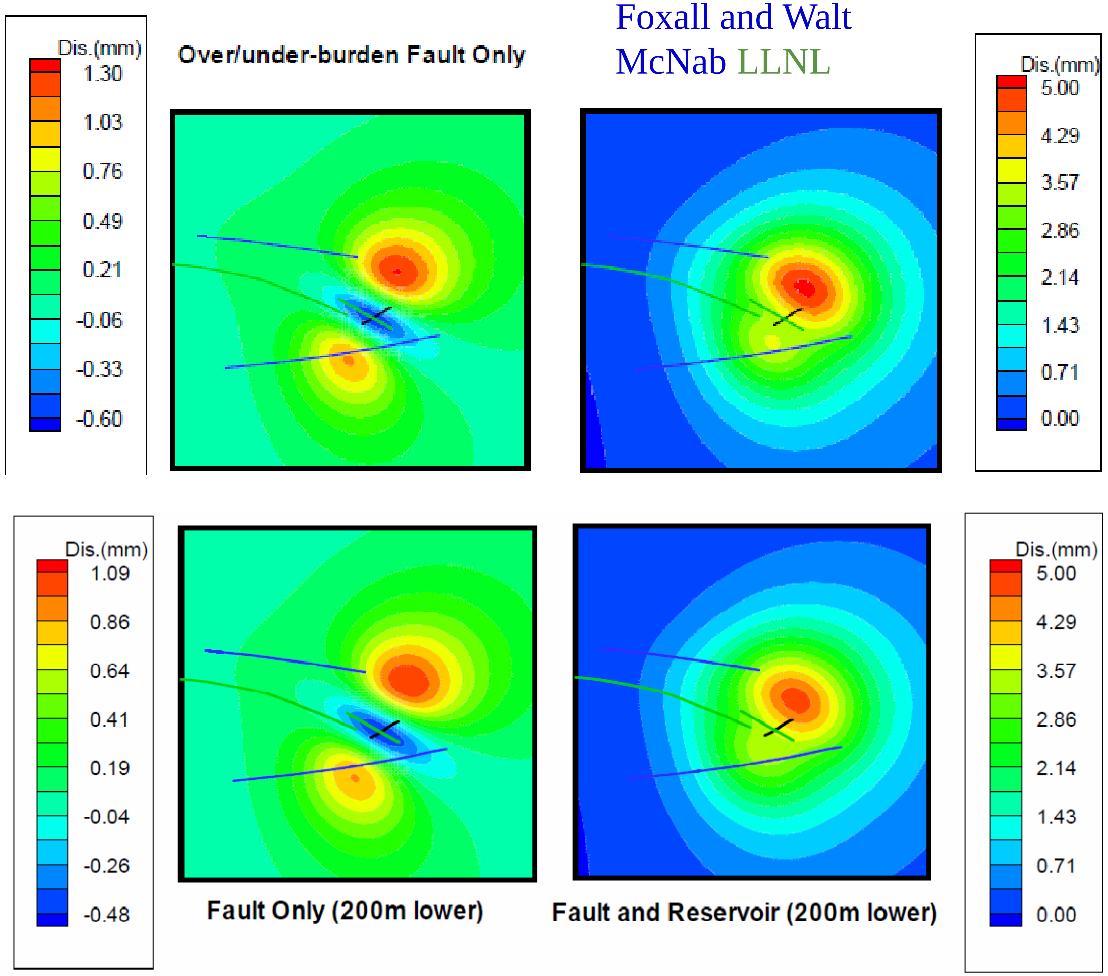
A key question: How sensitive are we to the vertical location of the fault?

Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

The answer: Not very

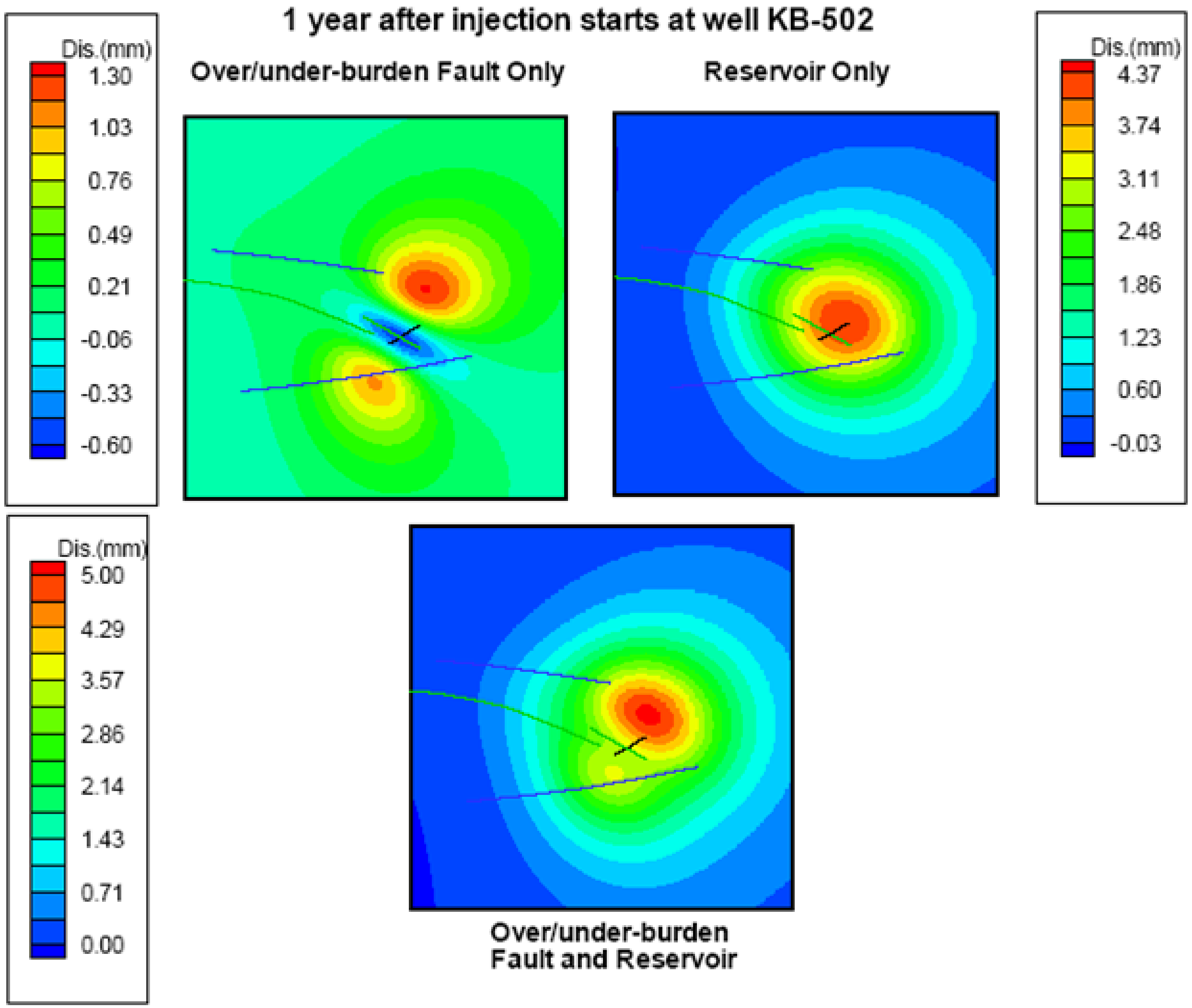
There are small differences between the baseline and case of fault *lowered* 200m

I.e.: It is difficult to discern whether fault is in overburden or only underburden



3 Year Analysis: Includes shut-in of KB-502

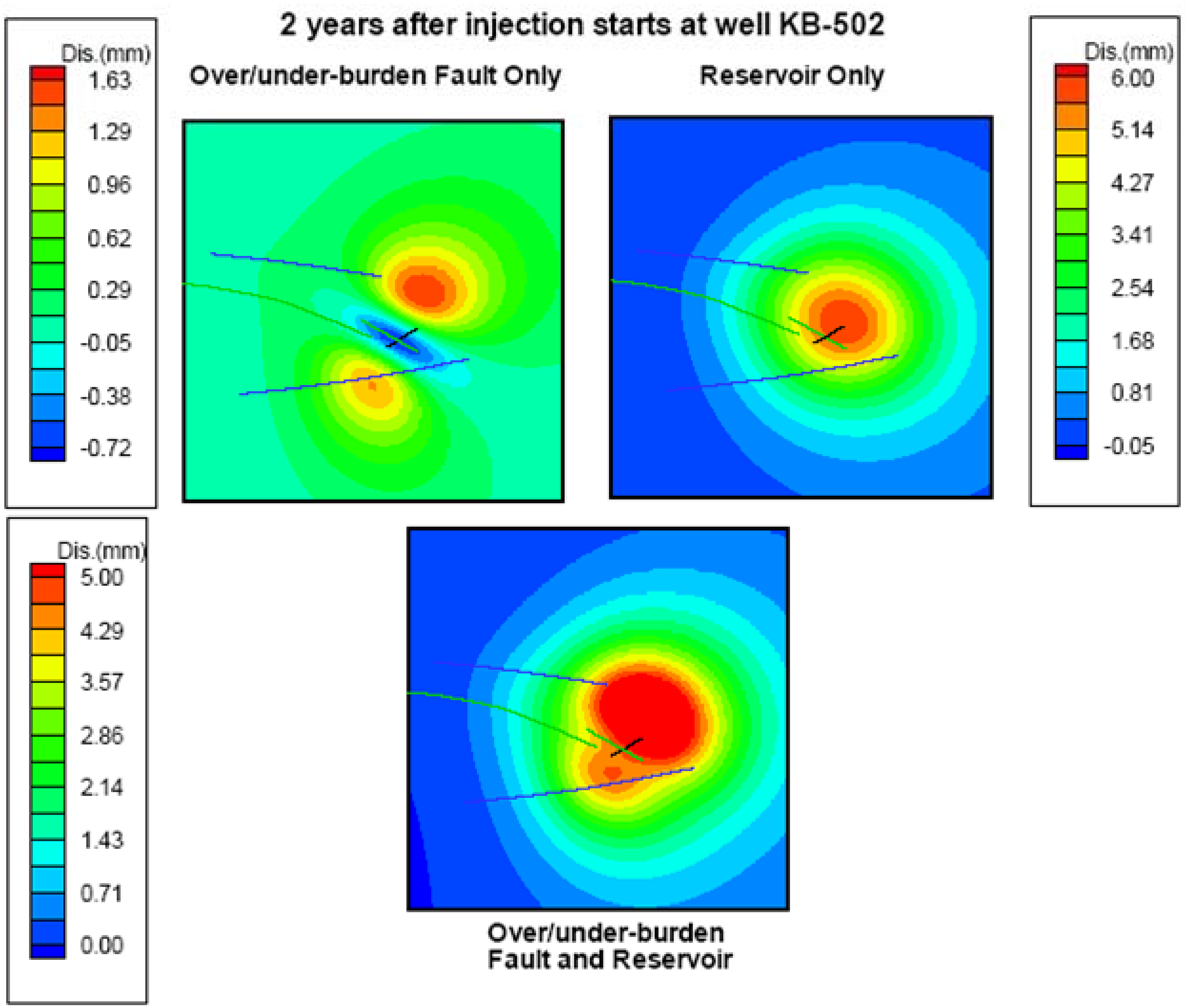
In Salah Gas
Stockage de CO_2



Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

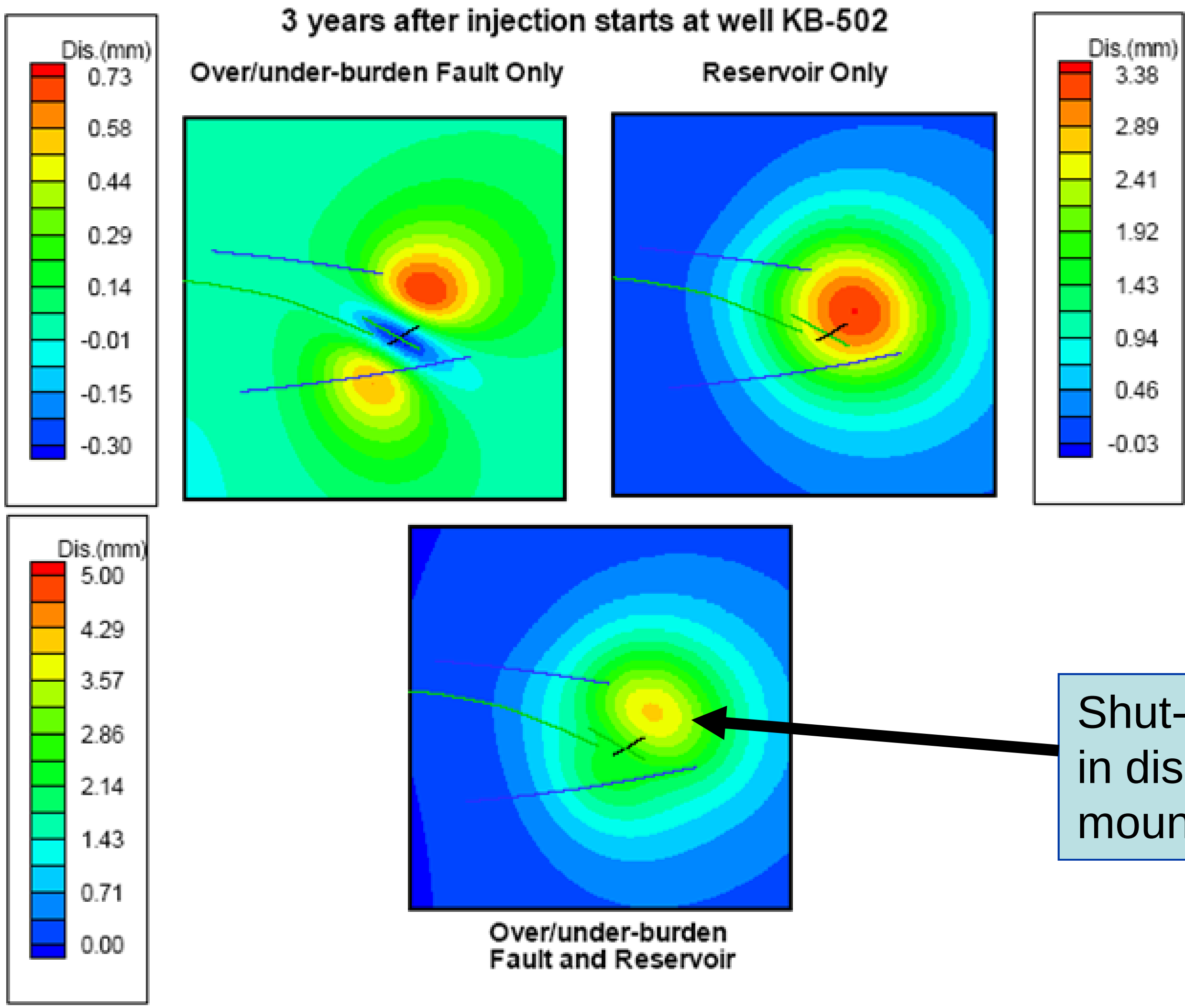
bp Statoil sonatrach

3 Year Analysis: Includes shut-in of KB-502



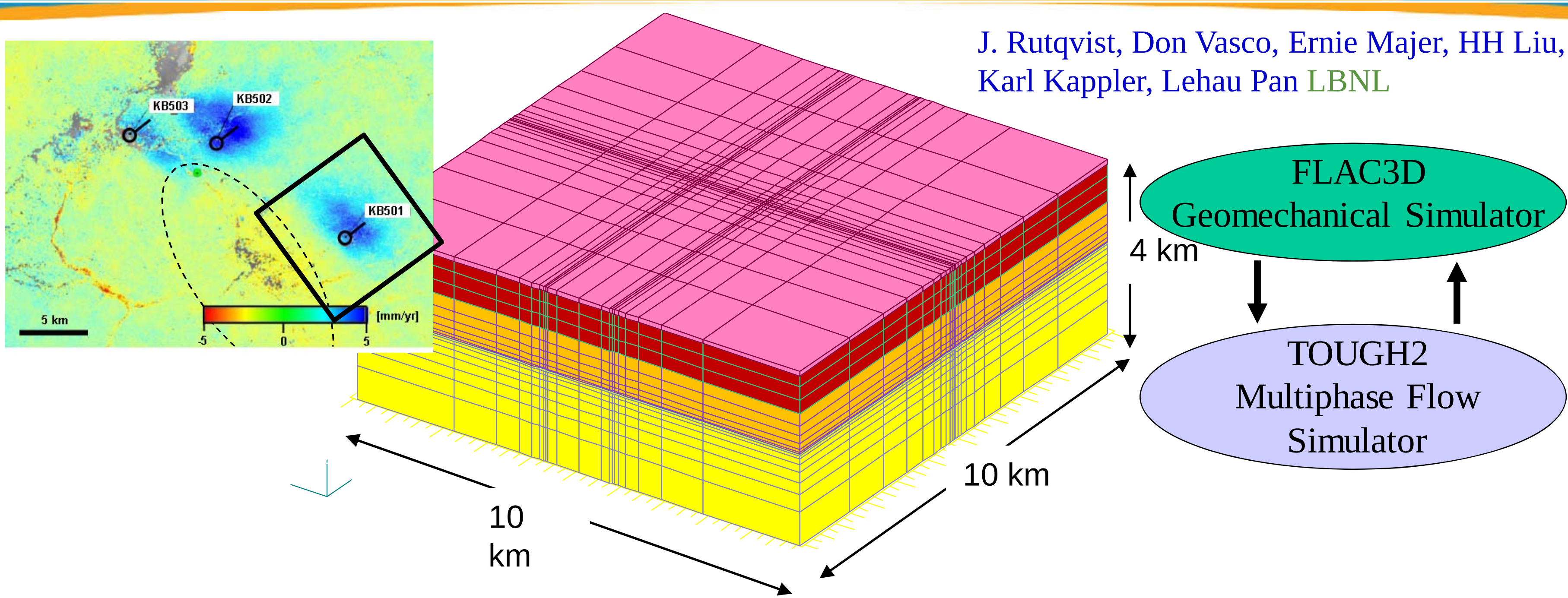
Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

3 Year Analysis: Includes shut-in of KB-502



Joseph P. Morris, Yue Hao, William Foxall and Walt McNab LLNL

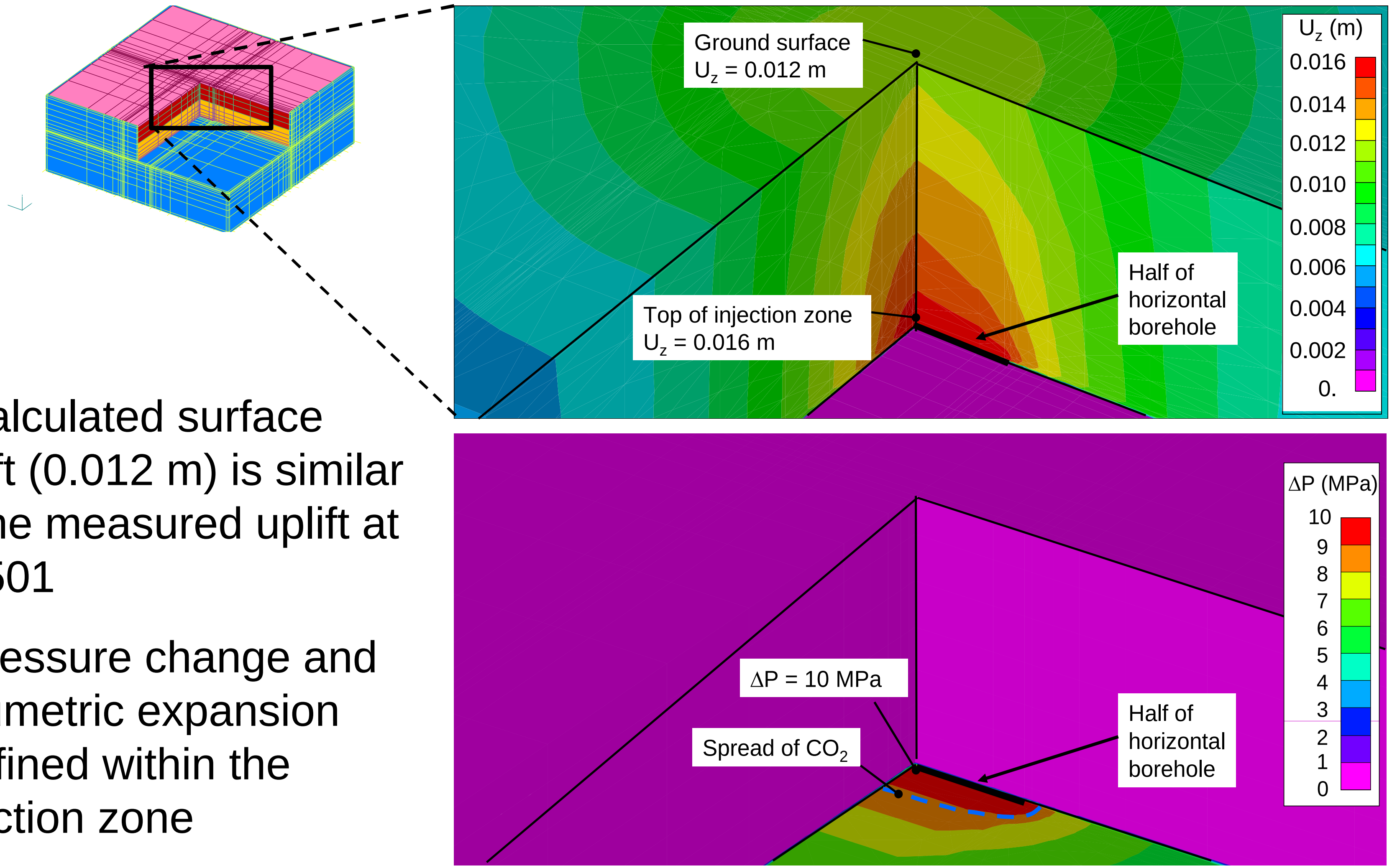
Shut-in results in dissipation of mound



- Elastic properties of C10.2 sandstone consistent with laboratory measurements conducted by University of Liverpool (Faulkner and Mitchell) at relevant confining stress level.

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

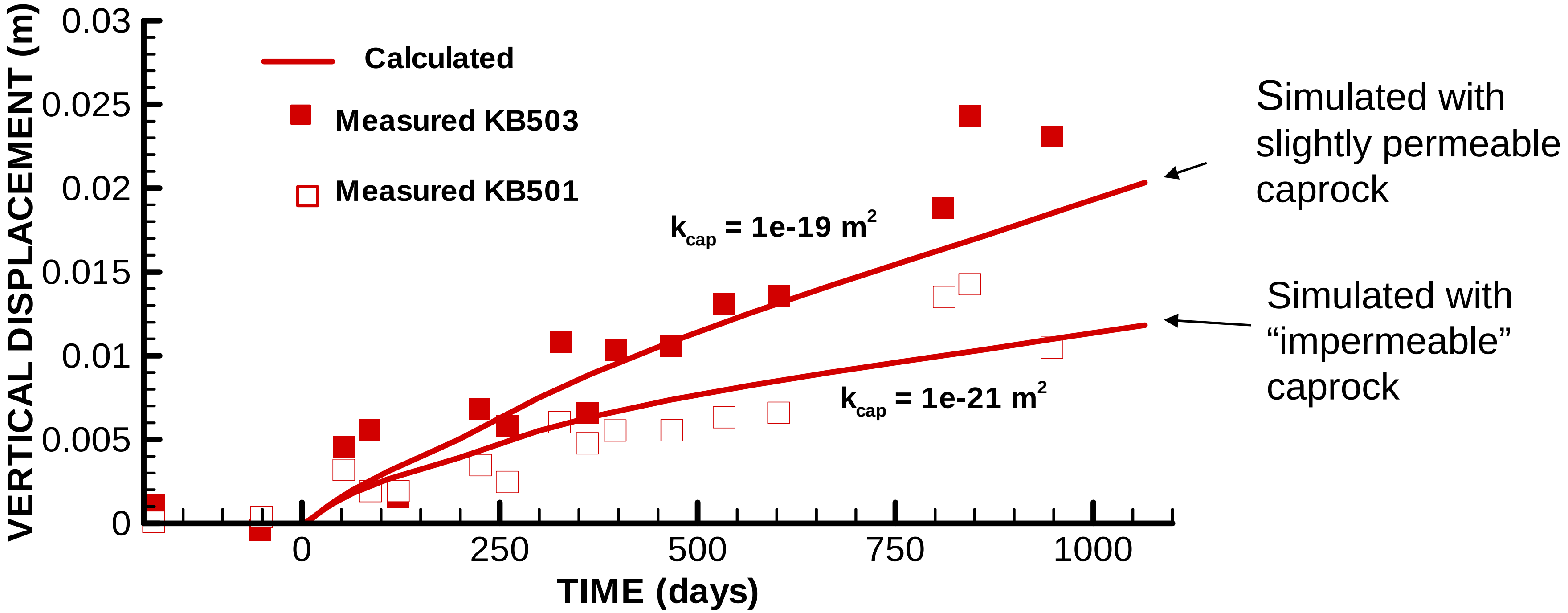
Simulated Displacement and Pressure at 3 Years



- Calculated surface uplift (0.012 m) is similar to the measured uplift at KB501
- Pressure change and volumetric expansion confined within the injection zone

Comparison of Simulated and Measured Uplift

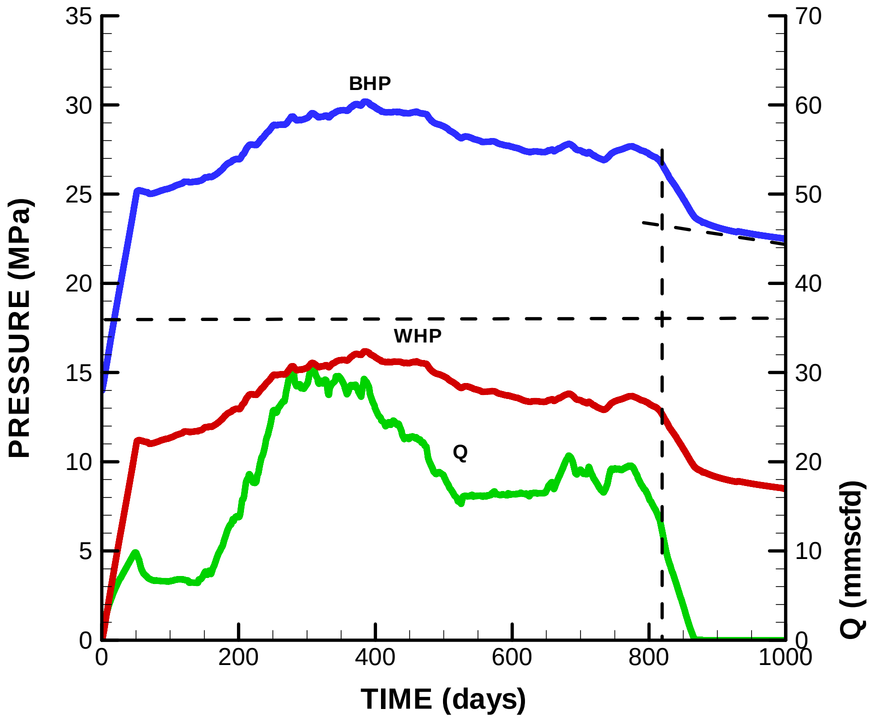
J. Rutqvist, Don Vasco, Ernie Majer, HH Liu,
Karl Kappler, Lehau Pan LBNL



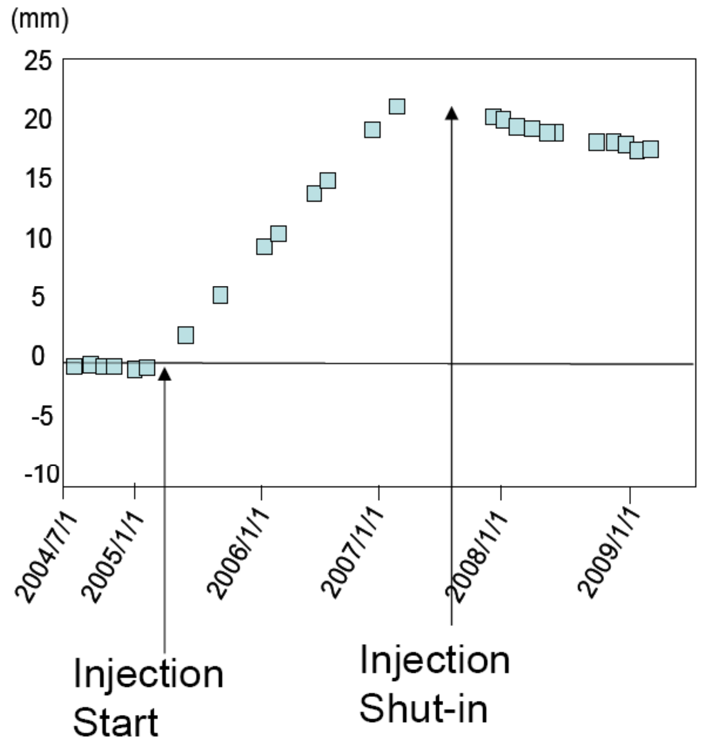
Uplift and Subsidence During Shut-In of KB502

In Salah Gas Stockage de CO_2

Injection data with BHP estimated with LBNL's T2 Well Simulator (data until spring 2008):



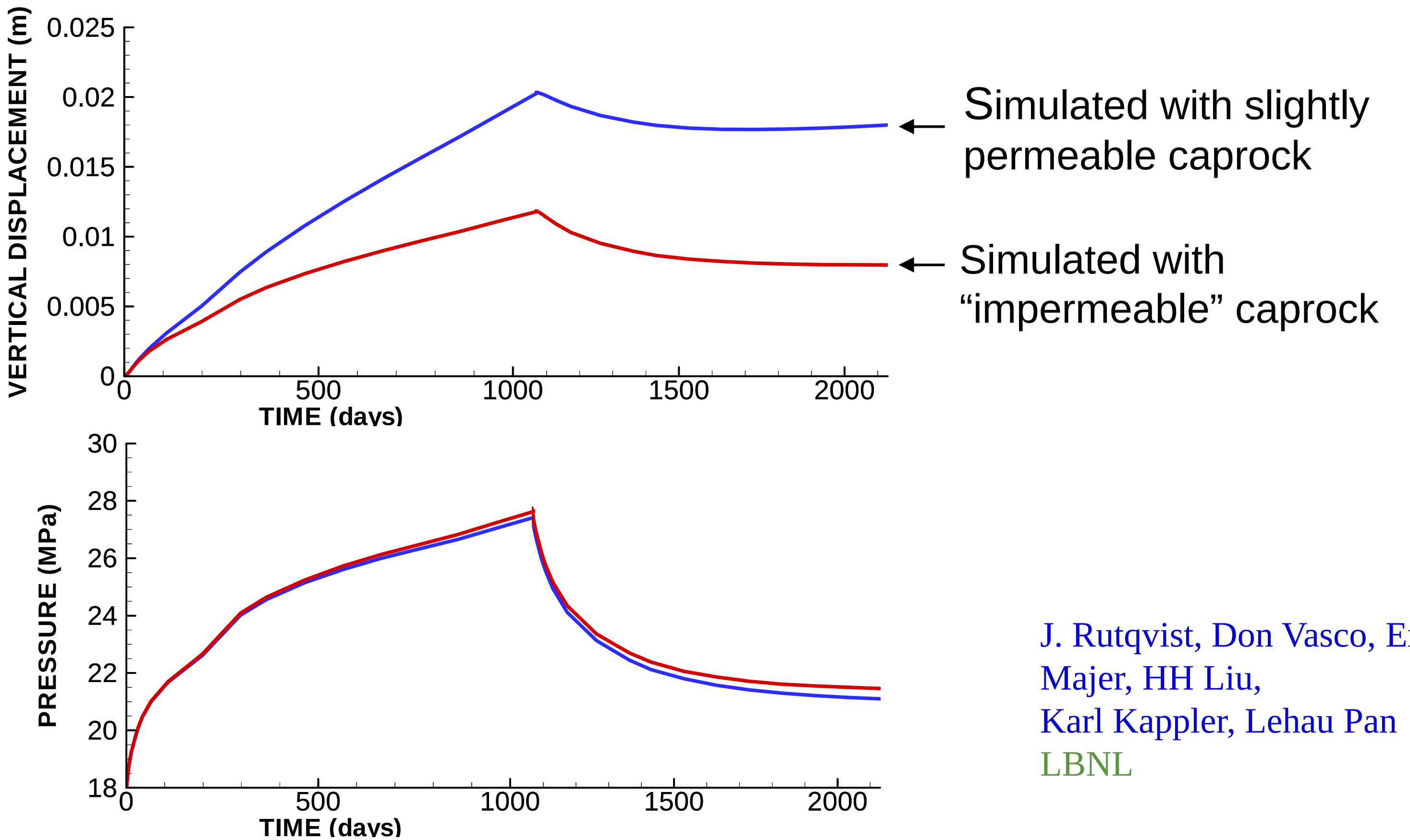
Transient evolution of uplift and subsidence (from T. Onuma, JGI, IEA CO_2 Monitoring WS, 2009):



- Field data show partial pressure drop and slow subsidence

bp Statoil sonatrach

Uplift and Subsidence During Shut-In of KB502



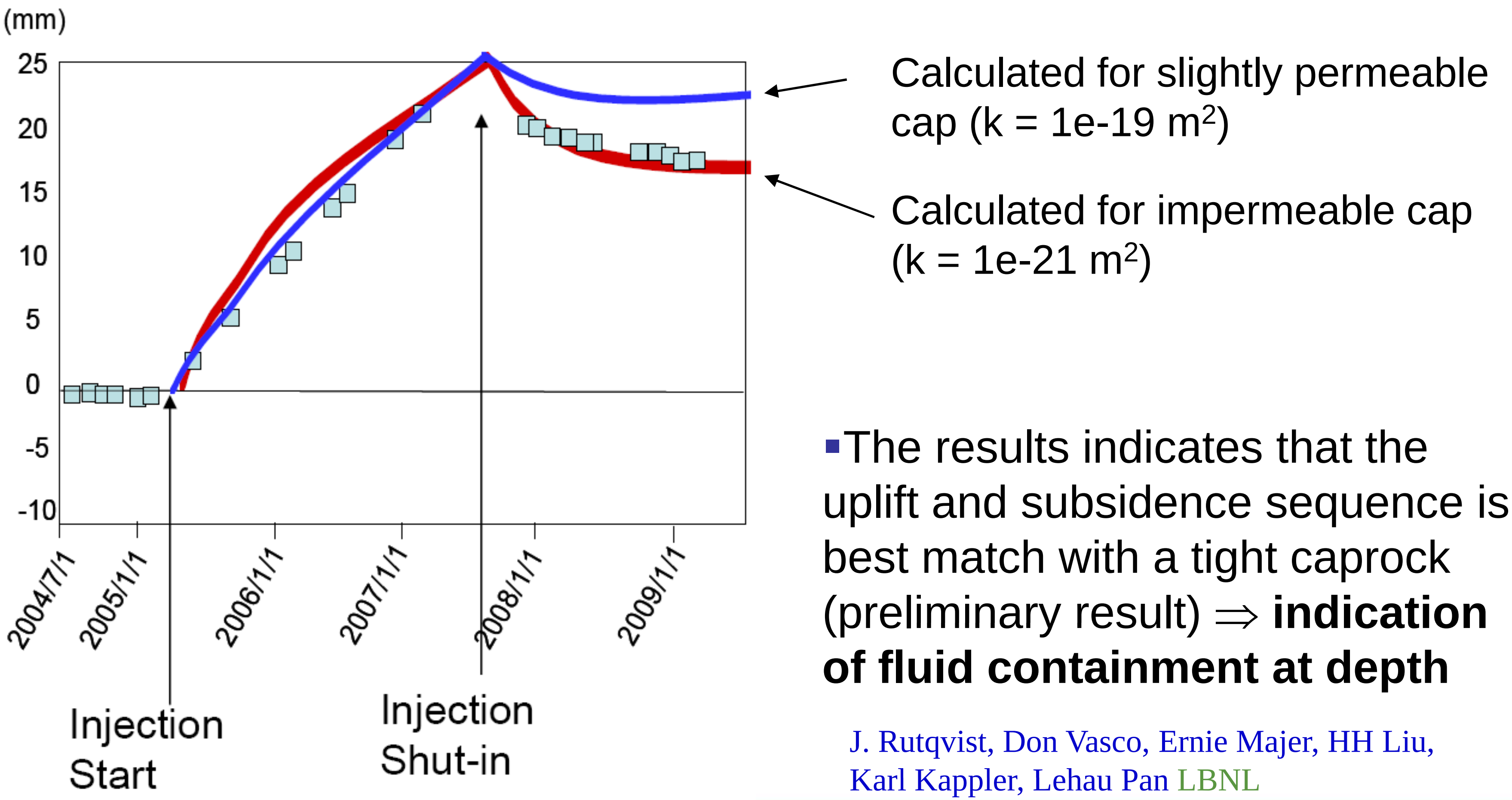
J. Rutqvist, Don Vasco, Ernie Majer, HH Liu,
Karl Kappler, Lehau Pan
LBNL

- The slow subsidence and partial pressure drop is captured in the coupled simulation $\Rightarrow$ the apparent irreversible mechanical response is modeled as an elastic response

Uplift and Subsidence During Shut-In of KB502

In Salah Gas Stockage de CO_2

InSAR field data by Onuma (2009) compared to calculated uplift “normalized” to the maximum uplift to study the relative uplift/subsidence evolution:



- The results indicates that the uplift and subsidence sequence is best match with a tight caprock (preliminary result) ⇒ **indication of fluid containment at depth**

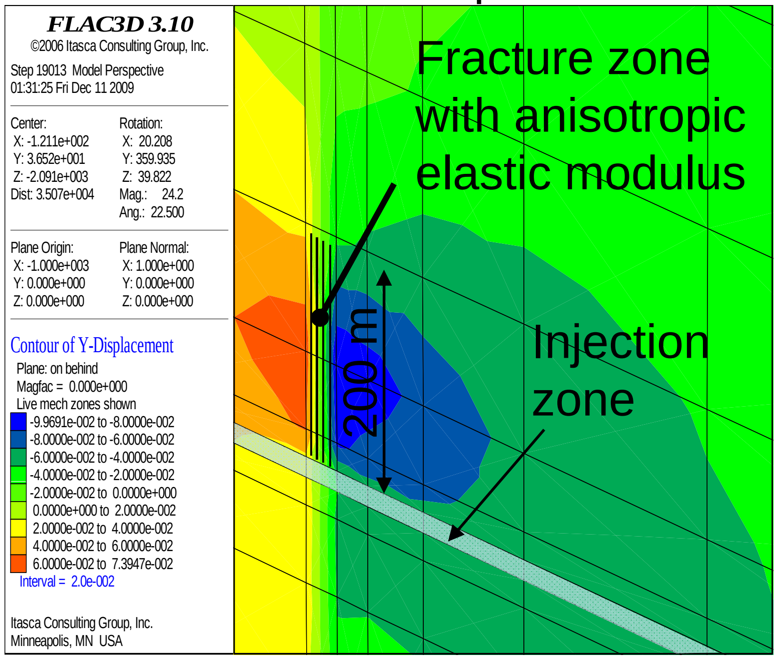
J. Rutqvist, Don Vasco, Ernie Majer, HH Liu, Karl Kappler, Lehau Pan LBNL

bp Statoil

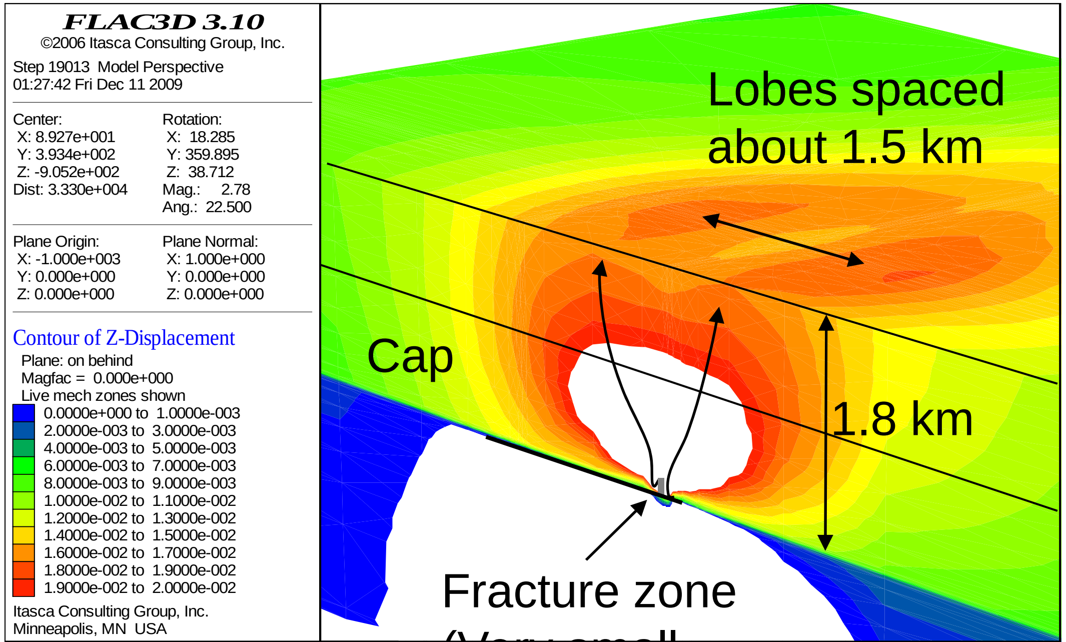
Fault Opening and Double-Lobe Uplift at KB502

In Salah Gas
Stockage de CO_2

Horizontal Displacement



Vertical Displacement



Fracture zone (Very small compared to overburden)

"Opening" 8 cm on each side ⇒ horizontal strain 0.32% if inflated zone 50 m wide

- Fracture zone with poro-elastic reversible strain (no failure!) can explain the double uplift lobe pattern.
- Other modeling attempts (e.g. two permeable zones) were not successful.

bp Statoil sonatrach

Concluding Remarks

The coupled geomechanical analysis indicates that:

- The uplift is consistent with pressure-induced volumetric expansion of reservoir rocks within the 20 m thick injection zone and perhaps within the 100 m thick zone of shaly sands just above the injection zone.
- The partial pressure drop and slow subsidence after shut-in of KB502 is consistent with pressure-induced elastic volumetric changes in the reservoir rock.
- The double uplift lobe is consistent with lateral expansion of a jointed zone extending about 200 m up from the reservoir (i.e. to below 1600 m).
- The highest potential for injection-induced MEQ is along the horizontal wells due to the combined effect of fluid pressurization and cooling.

A refined model will be developed and final results will be presented at GHGT-10

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

Monitoring ecosystem impacts of CO_2 storage – the RISCS project

Sarah Hannis on behalf of
Dave Jones & Julie West
and the RISCS project team

SEVENTH FRAMEWORK PROGRAMME

IEA GHG 6th Monitoring Network Meeting, Natchez, 6-8th May 2010

Research into Impacts and Safety in CO_2 Storage

- Significant leakage from CO_2 storage is not expected
- If it occurred there could be adverse environmental effects
- These effects are not well constrained

RISCS aims to carry out research on impacts arising from known CO_2 fluxes (observed and modelled)

- In both marine and terrestrial environments
- Through experiments and natural field observations

Project overview

RISCS will provide information to underpin

- Evaluation of safety of storage sites
- Environmental Impact Assessments
- Safe design of sites to minimise impacts
- Design of near surface monitoring strategies
- Refining of storage licence applications/conditions
- Frameworks to communicate safety of storage

Ultimate output is 'Guide for Impact Assessment'

Project overview

- **4 year project**, fully funded, started January 2010
- **24 participants** (UK, Greece, Netherlands, Italy, Norway, Sweden, France, Germany) + Australia, Canada, USA
- **6 industrial** (Enel, Statoil, Vattenfall, EoN, PPC, RWE) providing funding (c €200k each), research input, advice
- **4 non-European** (CO_2CRC & Montana State, Regina, Stanford universities) in advisory role
- **1 NGO** (ZERO)
- **CO_2GeoNet** (Primarily represented by NIVA, BRGM in addition to 5 participants)
- **IEA-GHG** – advice and help with dissemination

Project organisation

- WP1 **Description of reference environments and scenarios**
- WP2 **Assessing impacts in marine environments**
- WP3 **Assessing impacts in terrestrial environments**
- WP4 **Assessing impacts - numerical simulations**
- WP5 Integration and dissemination
- WP6 Coordination/management

Experiments and field observations

WP1 Description of reference environments and scenarios

- Develop a comprehensive set of credible CO_2 impact scenarios for varied near-surface reference environments
- The scenario analysis process will explore:
  - CCS systems main features, events & processes (FEPs)
  - How CCS systems are likely to evolve with time
  - Potential failure/leakage mechanisms
  - Potential human/ecological impact mechanisms
- The scenarios will be a basis for the experiments, field studies and models investigating impacts
- The overall purpose of the scenarios is to provide a sound basis for the regulation and monitoring of CO_2 storage sites.

WP2 Assessing impacts in marine environments

Field observations

Panarea field site, Italy

Experiments in artificial enclosures

<10 L

1000 L

4500 L

+ Benthic chamber lander

WP2.1 Experiments in artificial enclosures

- Response & recovery of individual species
  - Growth, survival, reproduction
- Response & recovery of benthic communities
  - Microbial, meiofauna and macrofauna

Including:
  - Speed and scale of impacts
  - Speed of lateral recolonisation
  - Speed of larval recruitment

- **Benthic chamber** – 3 exposure experiments at 3 exposure rates in 400m water for 10 days (in Norway)

WP2.1 Experiments in artificial enclosures

Taxa
Crustaceans
Mollusks
Polychaetes
Plankton community
Micro-organisms
Macro-meiofauna

Chemical/physical parameters
pH
Temperature
Salinity
Dissolved oxygen
Nutrients
DOC
DIC
Alkalinity
Pressure
Nutrient fluxes
Mixing

Biological parameters
Haemolymphe parameters
Growth
Survival
Reproduction

WP2.2 Field observations

- At Panarea, southern Italy, CO_2 is naturally leaking to the water column (~20 m water depth)
- Diffuse and localised leaks, gas vents with a range of flow intensity
- To address: system complexity, **spatial-temporal variability**
- To extrapolate the experiments into **real-world** situations

WP2.2 Field observations

An integrated study will be performed:

- **Chemical** – Conductivity-temperature-depth (CTD) transects, water sampling (Niskin bottle and multi-parameter probe) & continuous monitoring station
- **Biological** – virus & prokaryote abundances, prokaryote community structure, in-situ benthic flux measurements
- **Physical** – Acoustic Doppler Current Profiler (ADCP) to determine circulation, vertical and horizontal structure components of the current during seasonal sampling

WP3 Assessing impacts in terrestrial environments

Field experiments

Northern Europe

- Norwegian experiments
- UK (ASGARD) experiments

Field observations

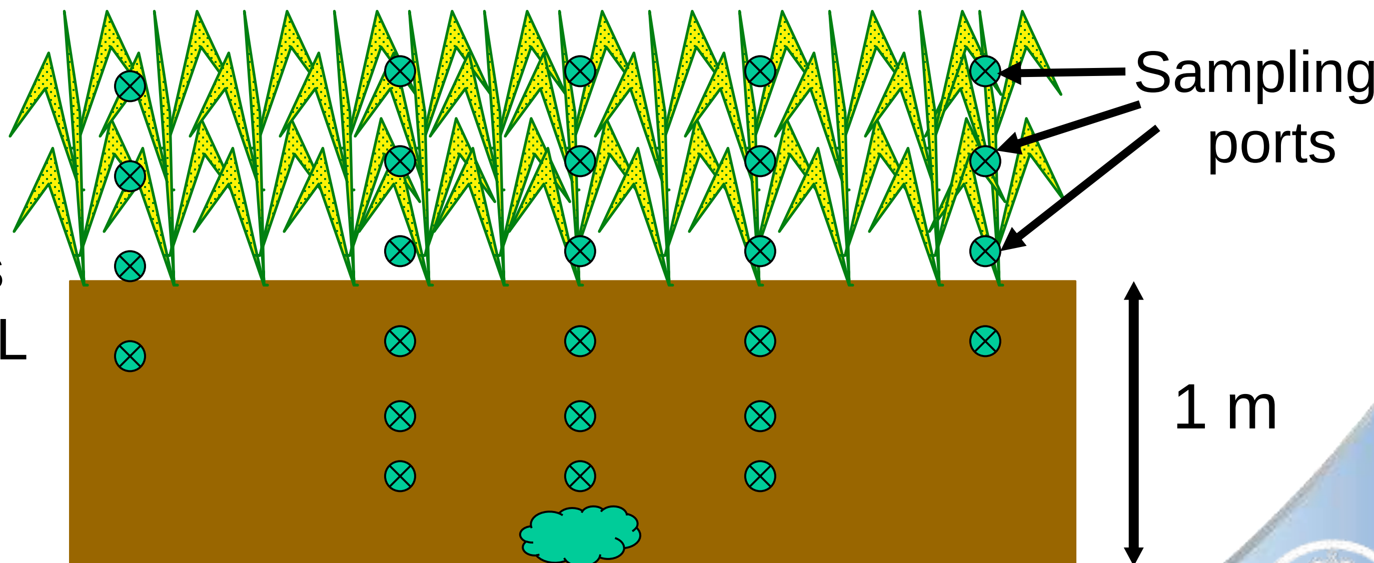
Southern Europe

- Italy, Greece, France

WP3.1 Norwegian experiments

- **Effects (greenhouse experiments)**

- **Exposure (simulated CO_2 leak)**

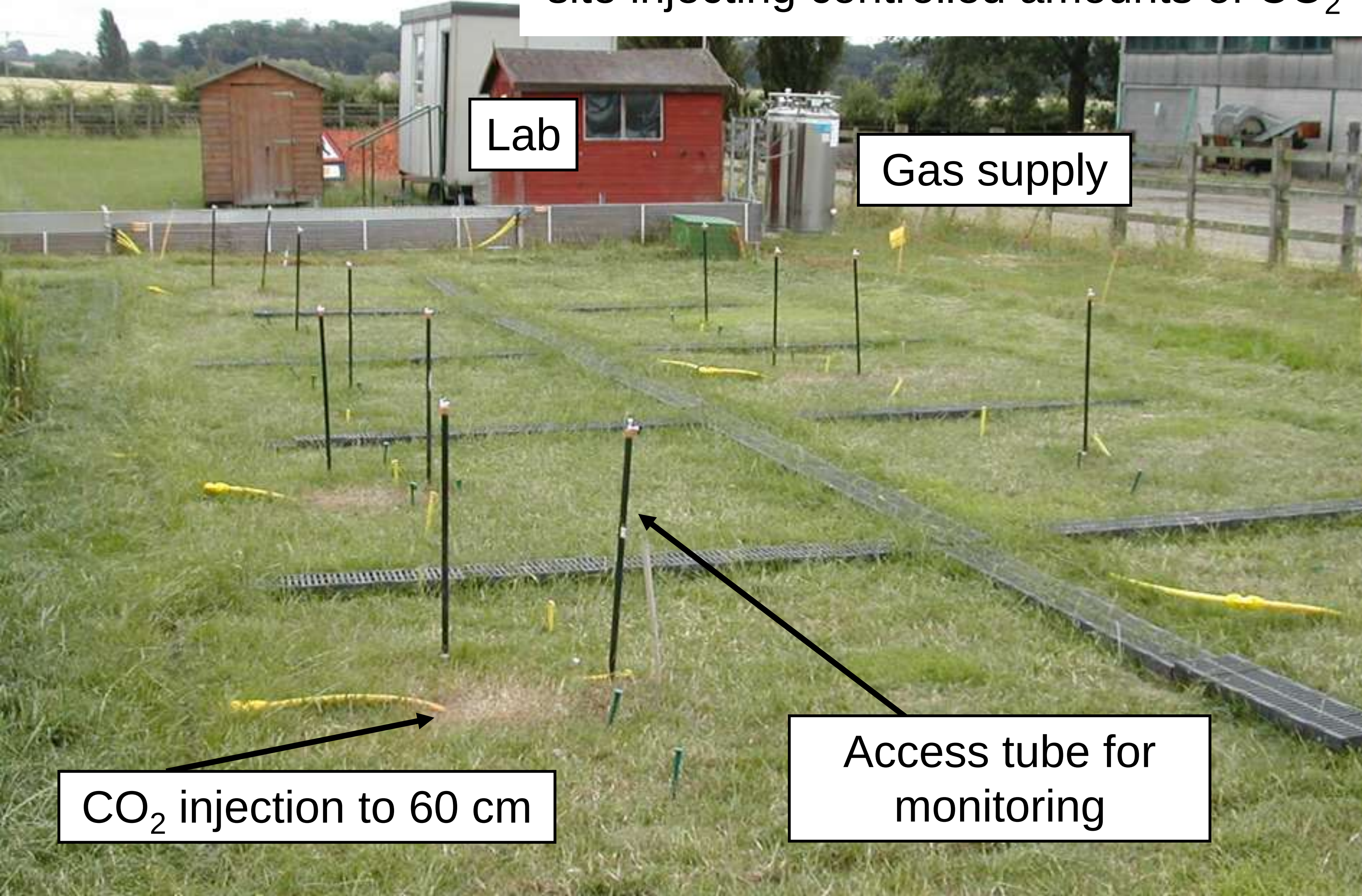


Measurements with $^{13}C/^{12}C$ TDL (tunable diode laser spectrometer)

Injection CO_2 / $\delta^{13}C$

WP3.2 ASGARD

University of Nottingham experimental site injecting controlled amounts of CO_2



WP3.2 ASGARD

- Test detection techniques
  - Remote sensing
  - Isotope analysis
  - Continuous monitoring
- Monitor changes in plant and soil conditions (chemistry, microbiology)
- Test sensitivity to soil and plant types and gas concentration (impact thresholds, effects on roots, ecosystem recovery)

WP3.3 Naturally leaking sites in southern Europe

- Florina well site, Latera, San Vittorino & Montmiral sites
- Variety of flux rates, time scales and gas compositions
- Impact of leaking gas on:
  - **Vegetation** (spatially and through time)
  - **Potable groundwater quality** (water origin, mixing and water-rock-gas interaction)
- Impact of using CO_2-impacted groundwater for crop irrigation

WP4 Assessing impacts – numerical simulations

- **Synthesise** information from WPs 1, 2 & 3
- Quantify CO_2 **transport** onshore and offshore in space/time and the associated chemical **perturbation**
- Develop a:
  - **Marine systems model** describing the key biogeochemical and ecological components relevant to CO_2 and its impacts in shallow sediment layer and overlying water column *(varying depth, mixing, temperatures and fauna)*
  - **Terrestrial systems model** representing the important processes in the transport of CO_2 to and in the near-surface terrestrial environment, and its impacts *(e.g. pH evolution and groundwater quality)*

Guide for Impact Assessment

Inform key stakeholder groups on specific issues:

- What to consider when appraising potential impacts in the event of leakage from a storage site
- How to evaluate the potential impacts of storage project development: design stage, construction, operation, post-injection and to enable transfer of site liability to the competent authority
- Options for directly assessing the potential scales (temporal and aerial, realistic leakage ranges (fluxes, masses)) and ecosystem responses
- Options for identifying, predicting and verifying the nature of impacts

Project coordinator:

Dave G Jones

Email: dgj@bgs.ac.uk

Tel: +44 115 936 3576

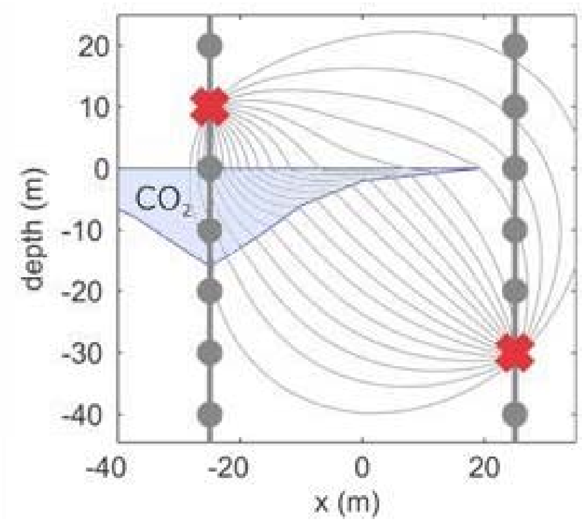
Presented by Sarah Hannis, s.hannis@bgs.ac.uk

Evaluation of **Geoelectrical Crosshole** and **Surface-Downhole** Measurements

presented by

Conny Schmidt-Hattenberger for the Ketzin ERT group

Outline



I. Our Motivation

II. Site specifics

III. Work-Flow & Results

Crosshole Measurements

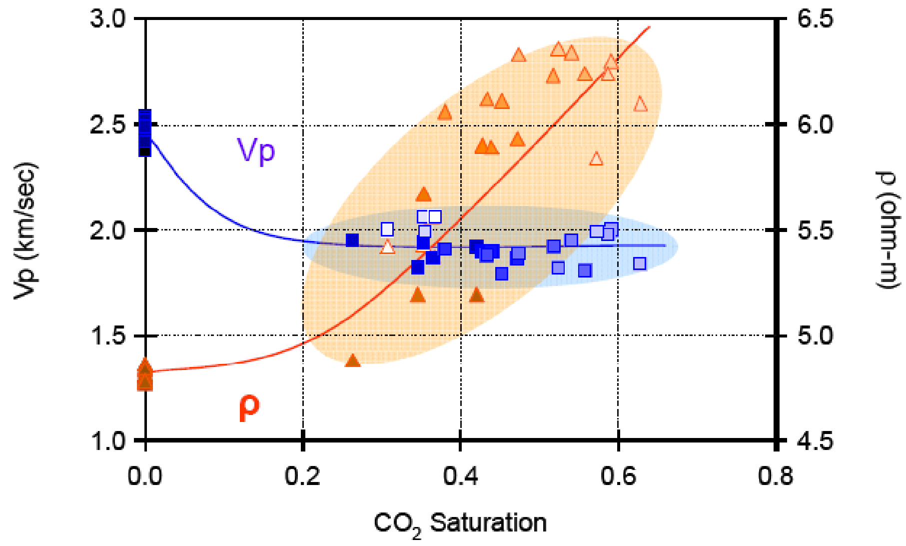
Surface-Downhole Measurements

IV. Summary & Lessons learned

I. Motivation

Geophysical monitoring of the migration of injected CO_2 by using **seismic** and **geoelectrical** **measurements**

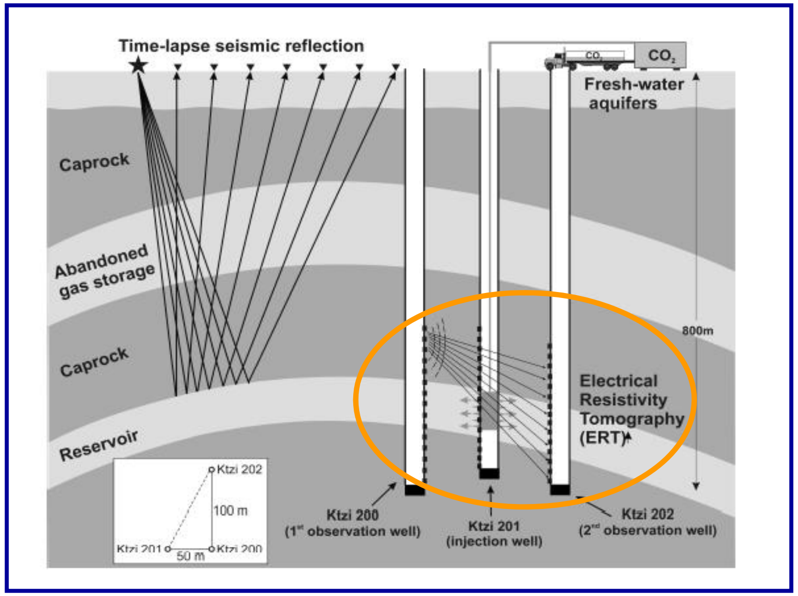
- at intermediate and high gas saturation (above 20 %) geoelectrical methods are more sensitive than seismic methods
- geoelectrical measurements are relatively easy to deploy
- higher repetition rates and cost-efficiency,
  but: lower structural resolution

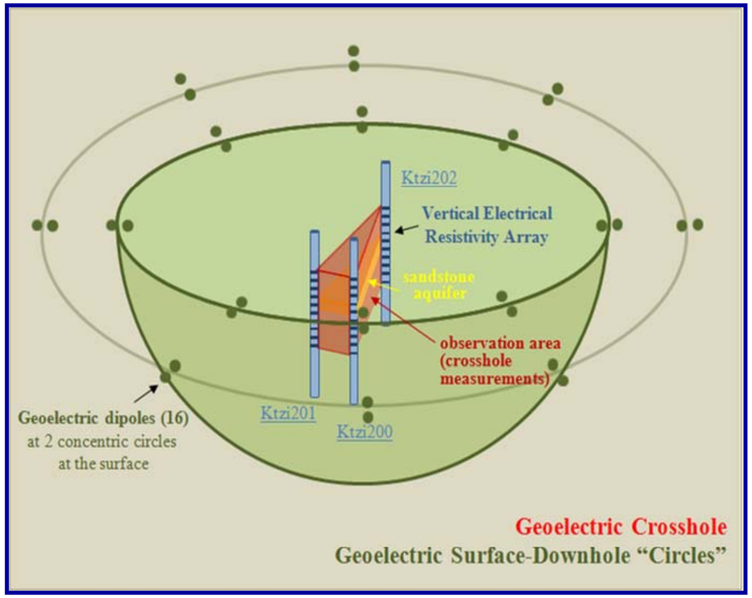


P-wave velocity and **resistivity** versus CO_2 saturation - measured at Nagaoka test site (Japan),
X. Zue et al,. SPE 126885, Nov. 2009,
- theoretical derived in: Wilt & Alumbaugh, 2006

→ investigation of the ***feasibility*** of the geoelectrical monitoring of the CO_2 migration into the saline aquifer in Ketzin

II. Site specifics – measurement concept





VERA

June 21, 2008 baseline | daily | twice a week until December 2008 | weekly further on

Pre-Injection Phase	Start Injection Phase		Regular Injection Phase
Operational Work Facility Testing	**June 30, 2008** Start of Injection	**July 15, 2008** Arrival of CO_2 at Ktzi200 **530 t CO_2**	**March 20, 2009** Arrival of CO_2 at Ktzi202 **11,200 t CO_2**

S-S / S-D

10/ 2007 1st baseline | 04/2008 2nd baseline | 07/2008 – 1st repeat *600 t CO_2* | 11/2008 – 2nd repeat *4500 t CO_2* | 04/2009 – 3rd repeat *13700 t CO_2*

III. Work-Flow and Results

Major phases:

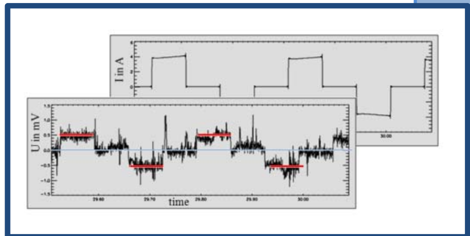
(1) Operational Phase

- Design of VERA (modeling, expertise for technical layout)
- Borehole installation, organizing data recording and handling
- Development of suitable large-scale surface-downhole measurement concept

(2) Start Injection Phase

- Preliminary results (instable states based on the small amount of CO_2)
- Tool optimization (Software, Data-readout, Pre-Processing demands)

(3) Regular Injection Phase



Ensuring of data-quality
Consistency of models and parameters
Alternative or improved evaluation schemes

(4) Start of data integration and joint interpretation

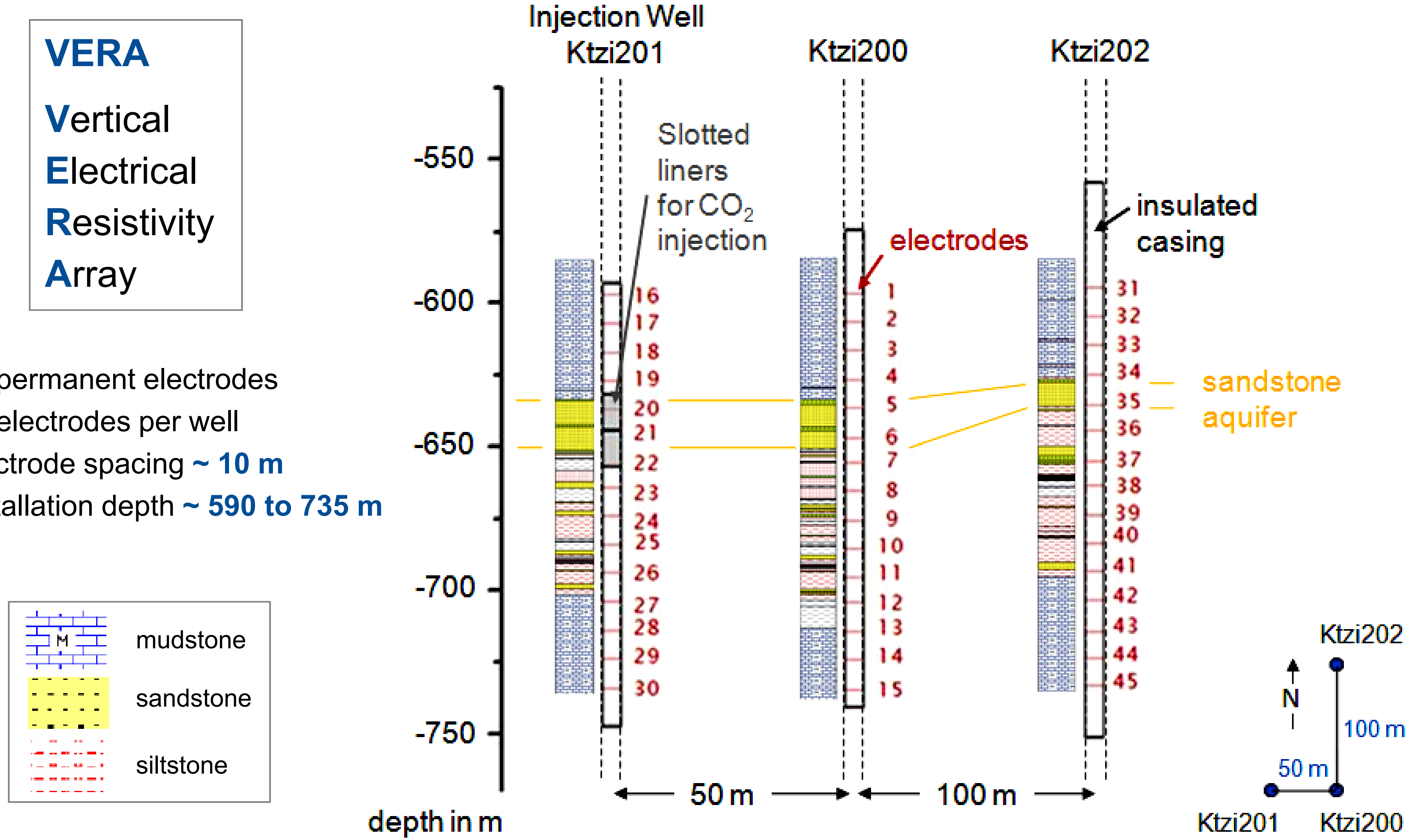
still in process…

Design of Crosshole Measurements

VERA

Vertical
Electrical
Resistivity
Array

45 permanent electrodes
15 electrodes per well
electrode spacing **~ 10 m**
installation depth **~ 590 to 735 m**



Technical Layout Cross-hole ERT

VERA - **V**ertical **E**lectrical **R**esistivity **A**rray

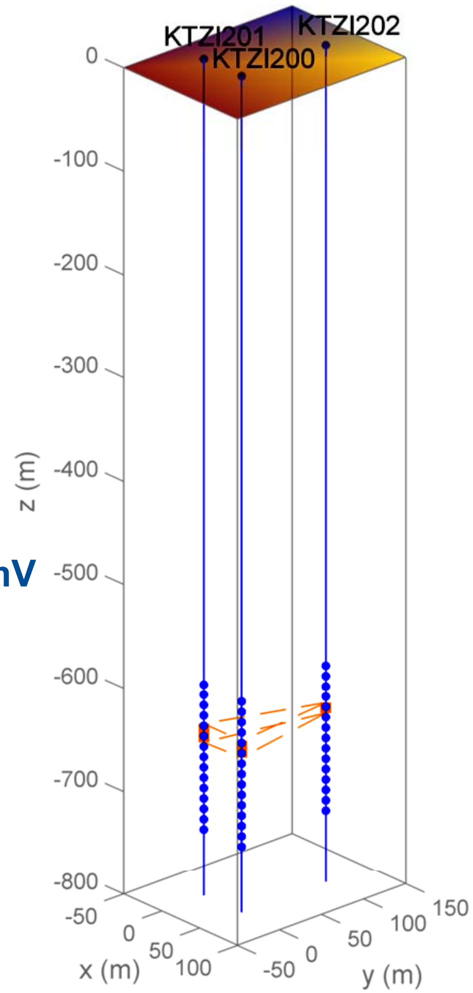
Steel electrode

Taper pin

Insulated casing

Electrical cable

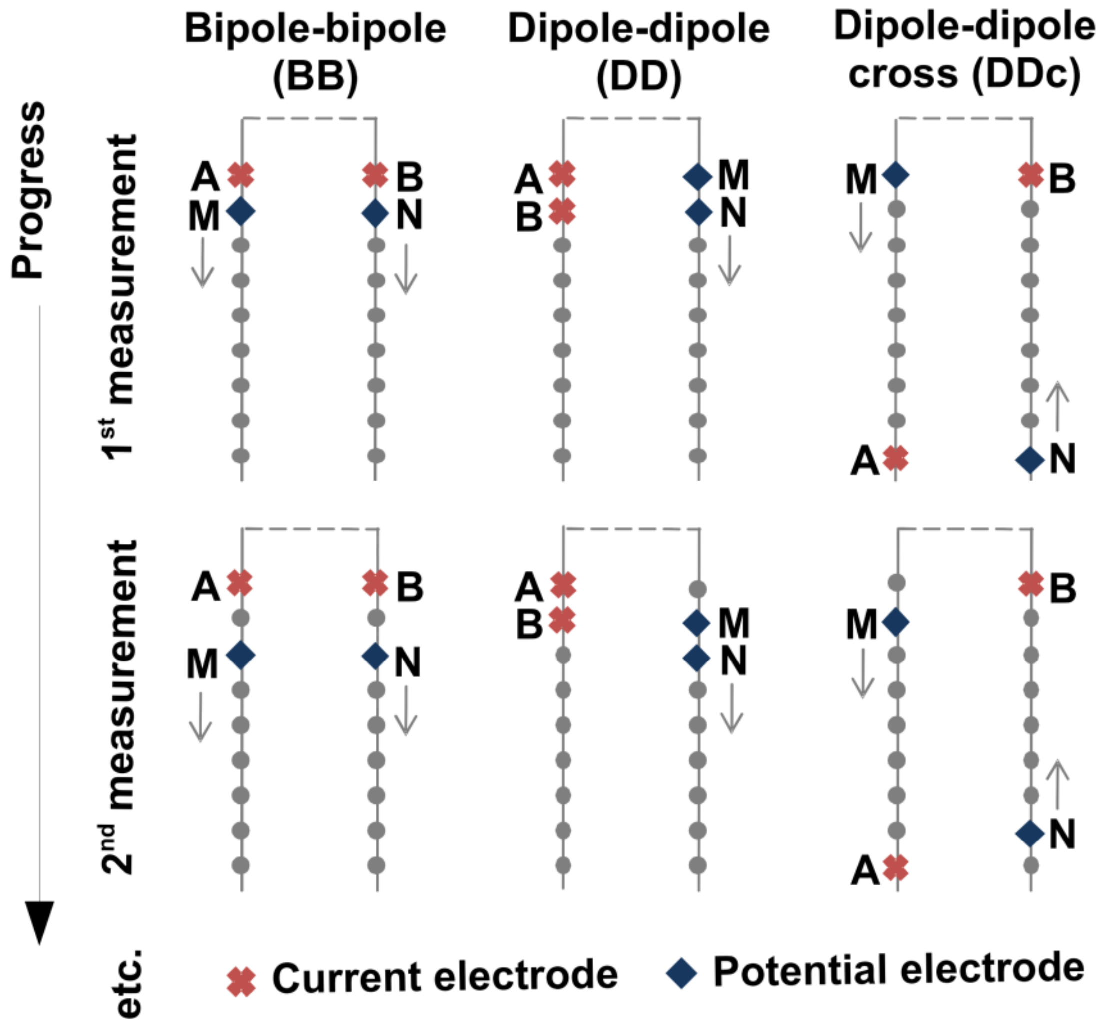
- used current: **2.5 A** max.
- used channels: **15**
  (for potential registration)
- measured voltage: **50 µV** to **100 mV**



ZONGE measurement equipment

Electrode Configurations

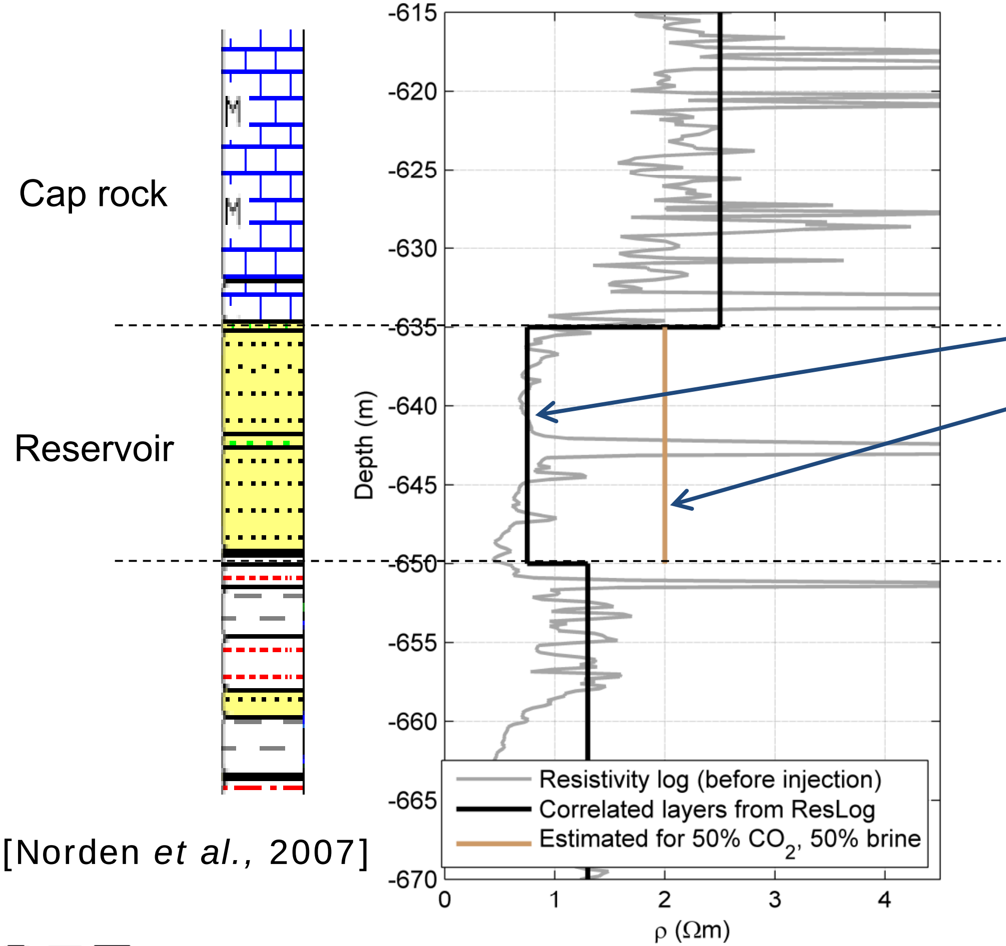
Selection of the electrode configurations of the main VERA acquisition schemes



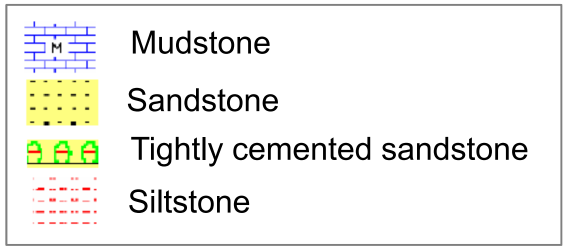
[Bergmann *et al*., 2009]

Resistivity Logging

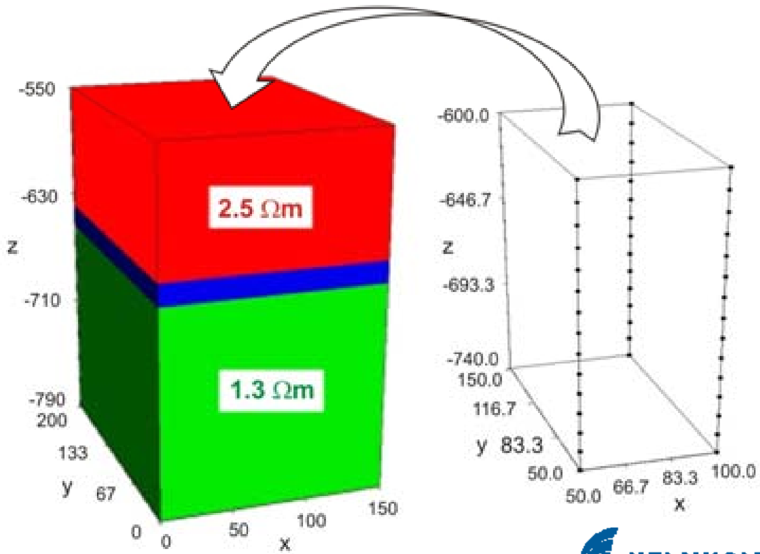
Logging results at
injection well Ktzi201



[Norden *et al.*, 2007]

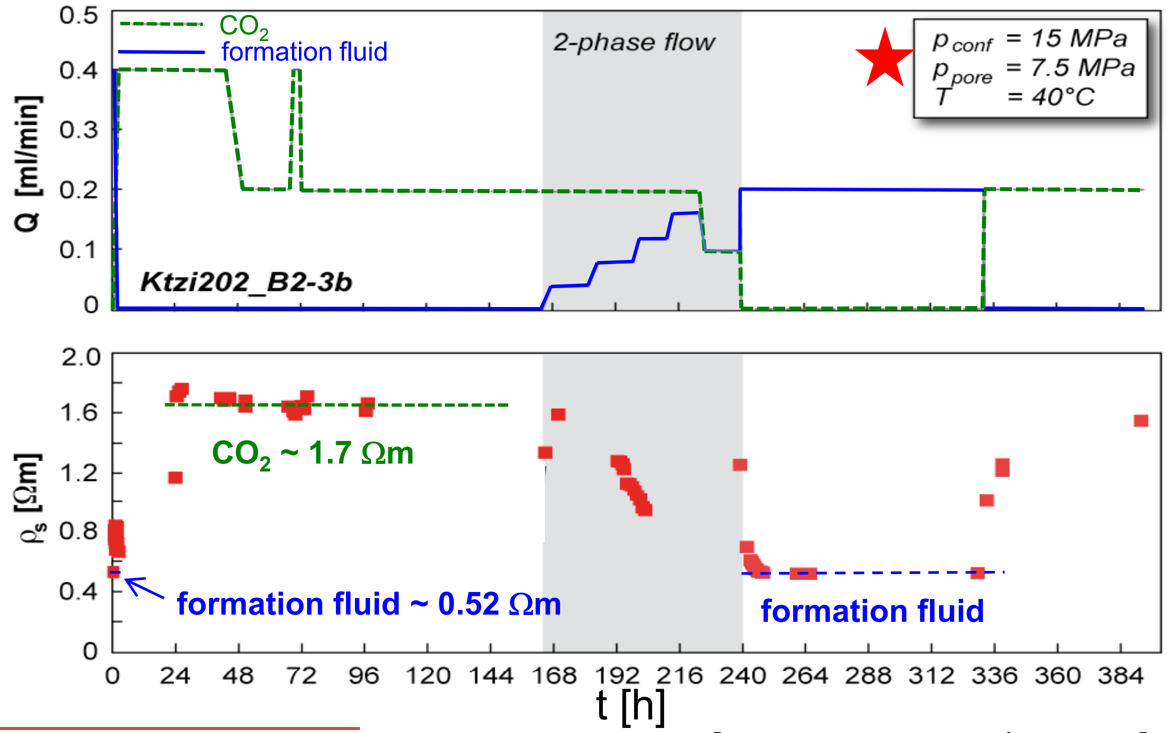


100 % brine: 0.75 Ωm
50 % brine, 50 % CO_2: 2.0 Ωm



Laboratory Experiments

Results from laboratory flow-through experiments of WP3.1



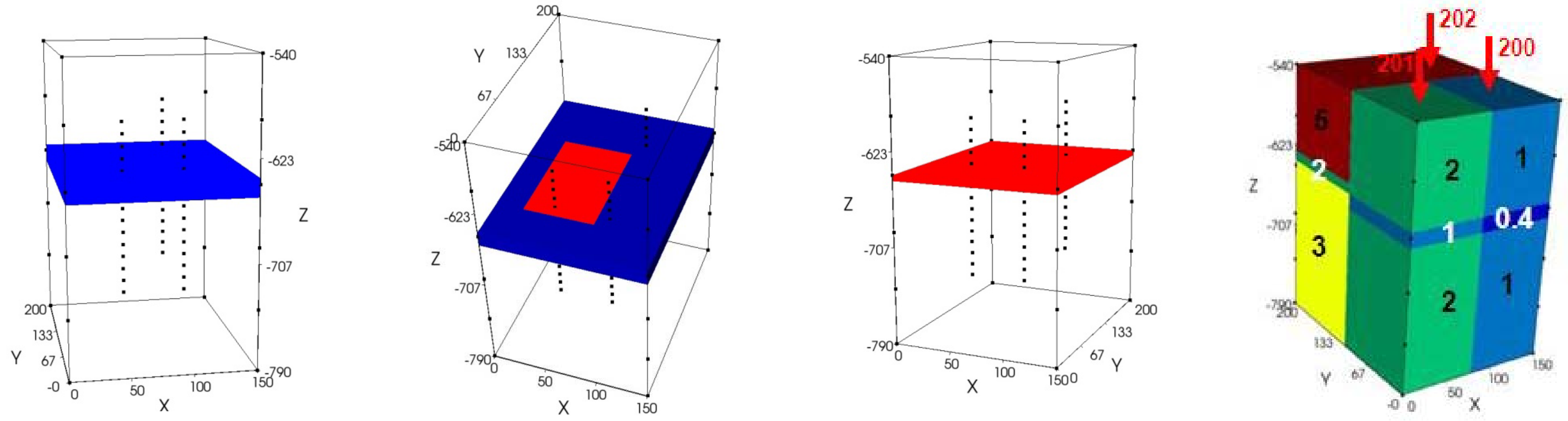
[Kummerow *et al.*, 2008]

	Lab data before CO_2	Lab data after CO_2	difference
Ktzi202_B2-3b			
★ ρ [Ωm]	0.53	1.71	+223%
Ktzi202_B3-1b			
★ ρ [Ωm]	0.46	1.26	+174%

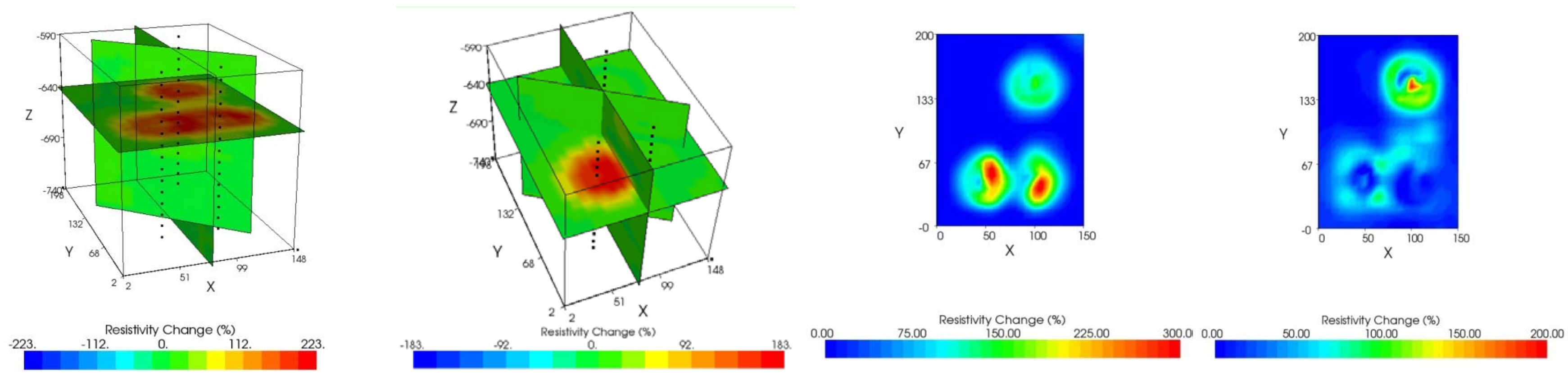
Available lab data indicate a bulk CO_2 saturation of 50% which corresponds to a resistivity increase of about 200%

Forward Modeling

Synthetic resistivity models and corresponding time-lapse results

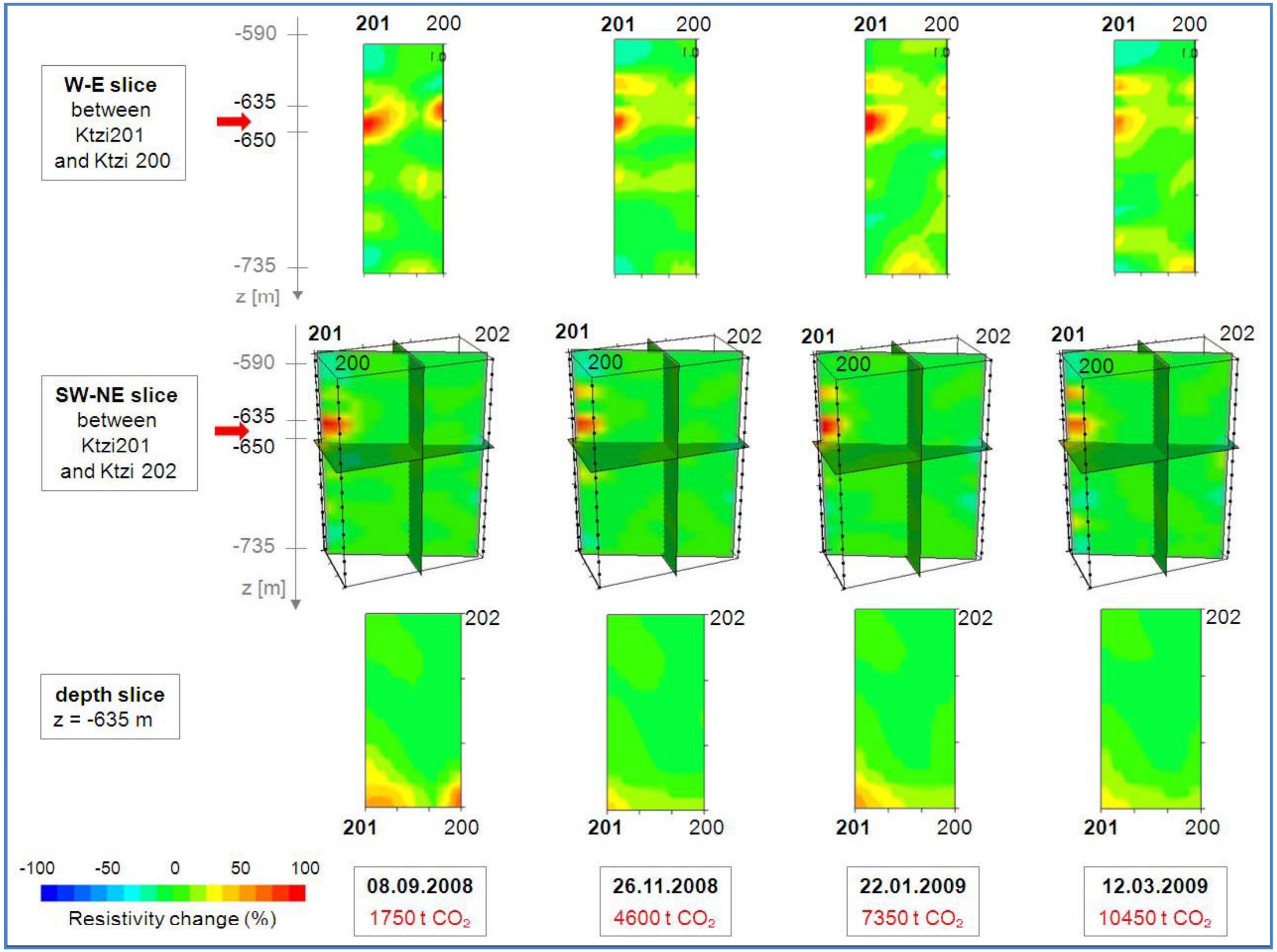


homogeneous CO_2 distribution | **small CO_2 plume** | **very thin layer with CO_2** | **composite model**



[H. Schütt, 2008]

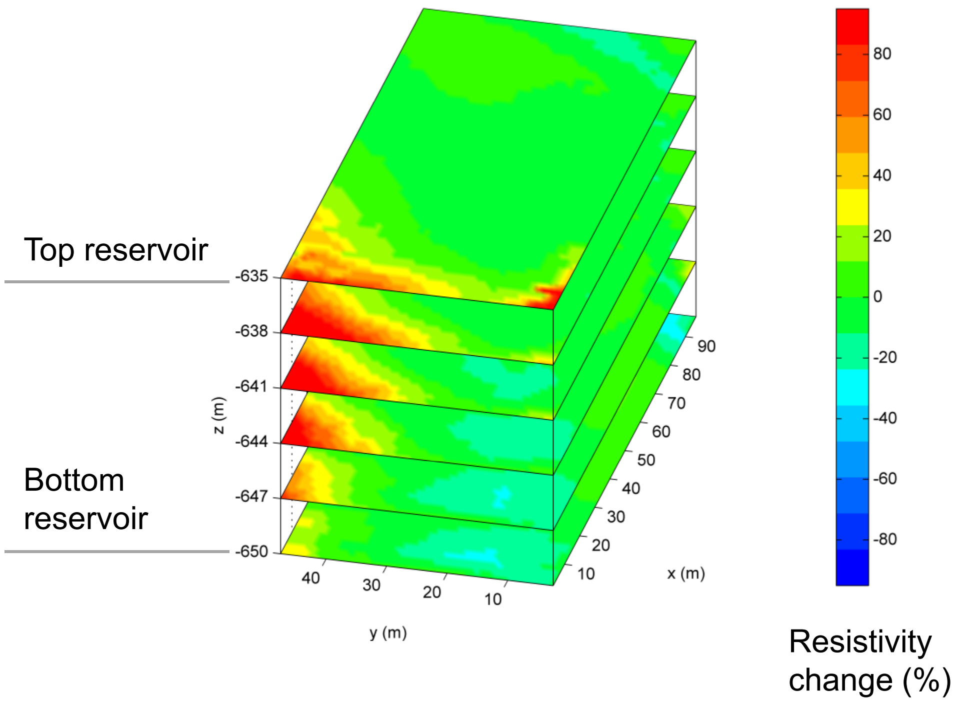
First Results of Time-Lapse Difference Inversion



[Kießling *et al.*, IJGGC, accepted 2010]

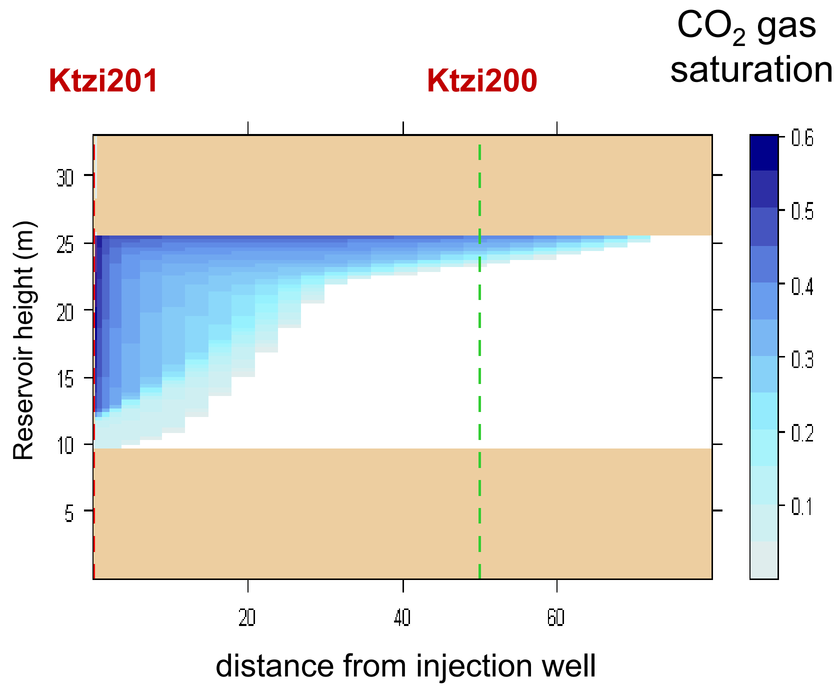
First Results from Field Data

Difference inversion:
(3D-EarthImager, AGI / USA)



08.09.2008: 1750 t CO_2

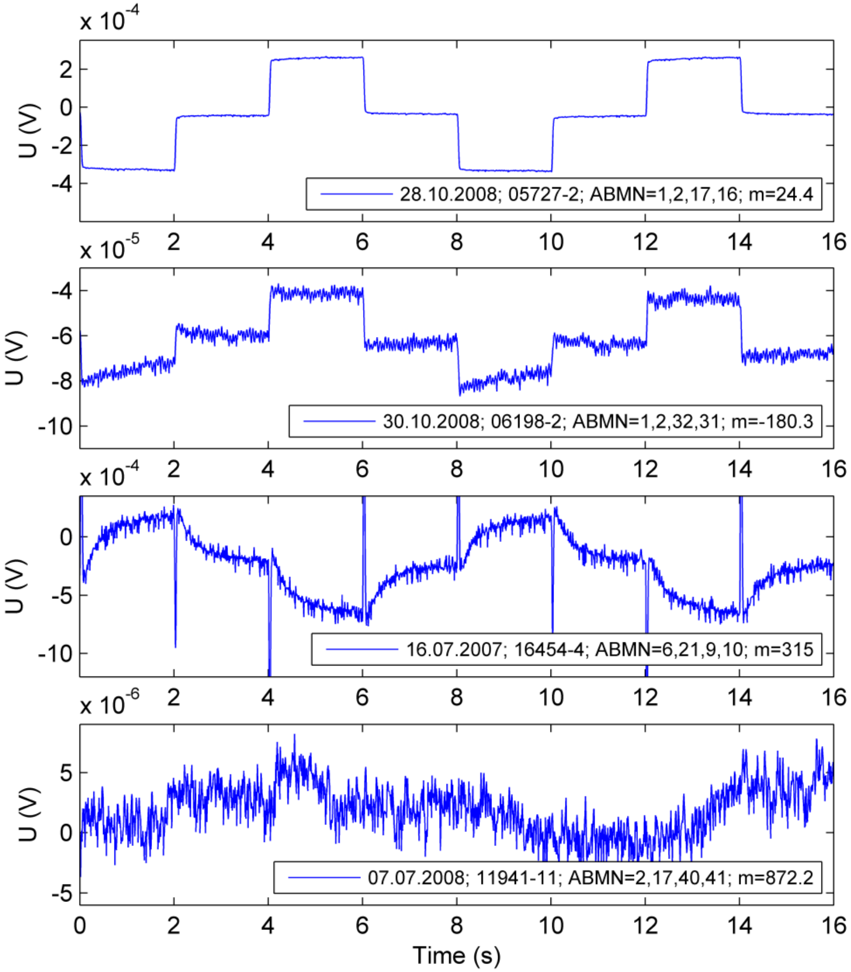
THOUGH2, V2: homogeneous aquifer,
homogeneous permeability,
circular migration

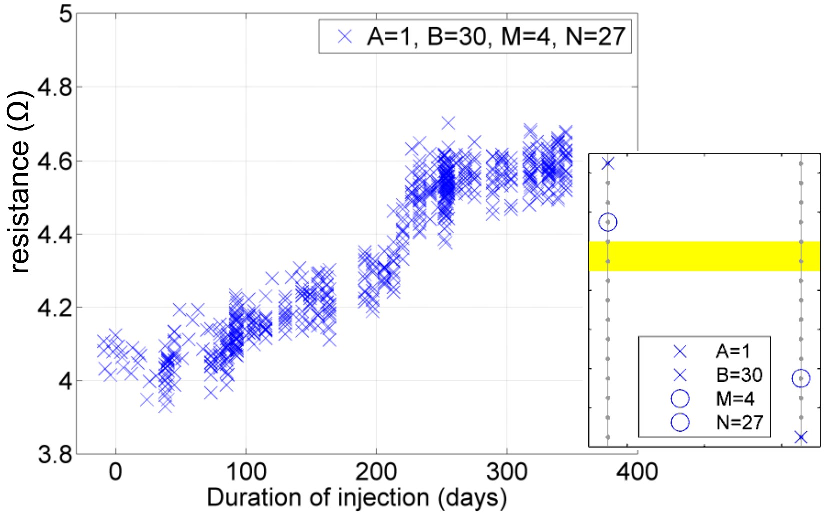


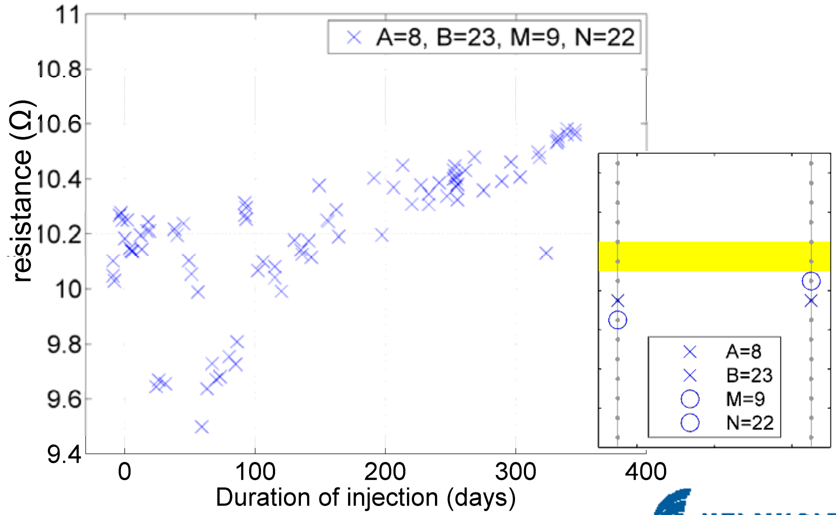
[Lengler, 2008]

Quality Control of Field Data

Examples



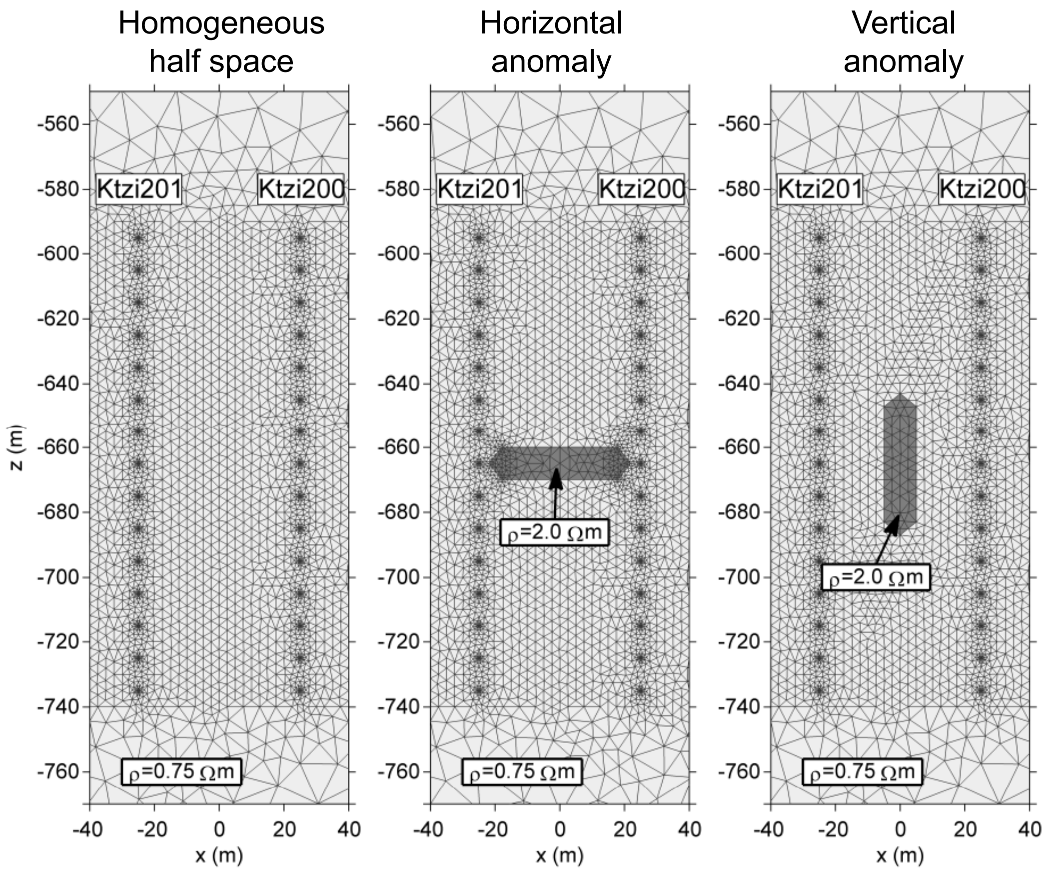




[Bergmann, 2009]

Sensitivity Studies

Resistivity models used for forward modeling

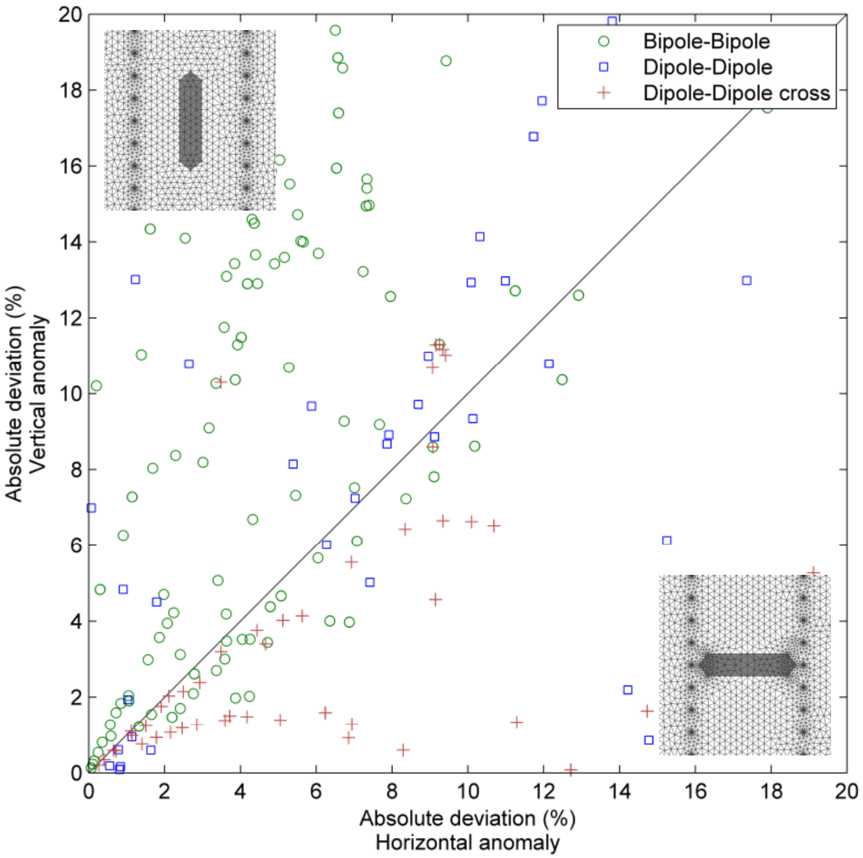


[Bergmann *et al.*, 2009]

- Forward modeling with BERT [Rücker *et al.*, 2006]
- 2D models with electrode geometry (6 km x 4 km)

Sensitivity Studies

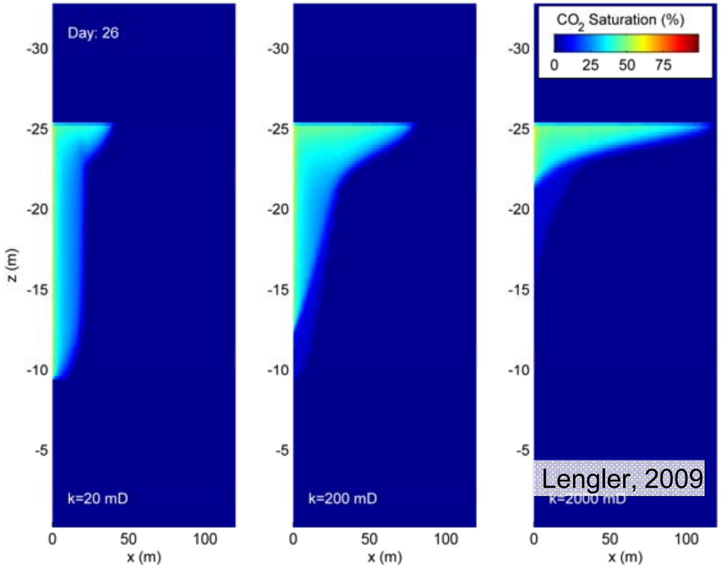
Evaluation of the crosshole measurement configurations



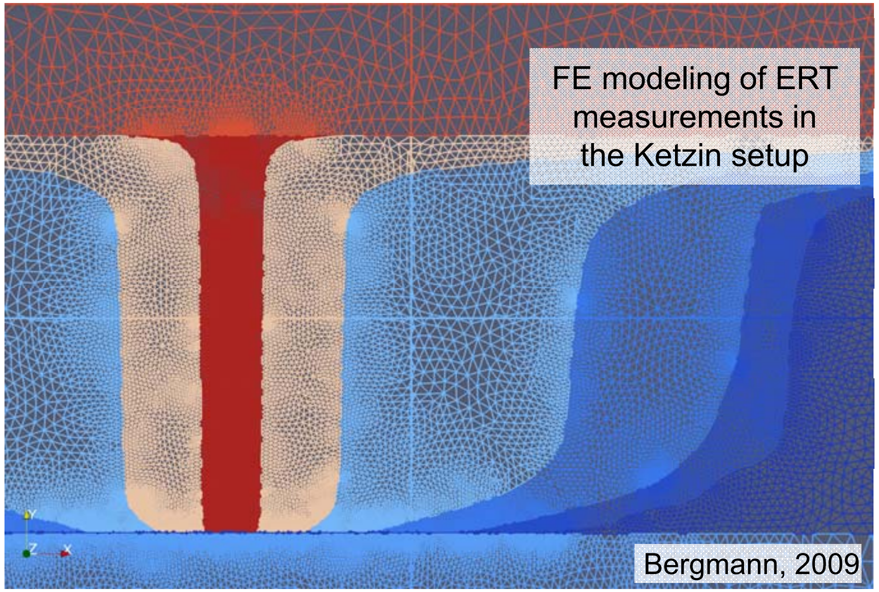
- The **Bipole-Bipole** configuration shows most significant alteration for vertical shaped anomalies
- The **Dipole-Dipole cross** configuration shows most significant alteration for horizontal shaped anomalies
- The **Dipole-Dipole** configuration does not show a distinct preference towards the shape of anomalies
- For Bipole-Bipole and Dipole-Dipole cross data, magnitudes of synthetic and field data match

[Bergmann, 2009]

Relating Resistivity and CO_2 Saturation

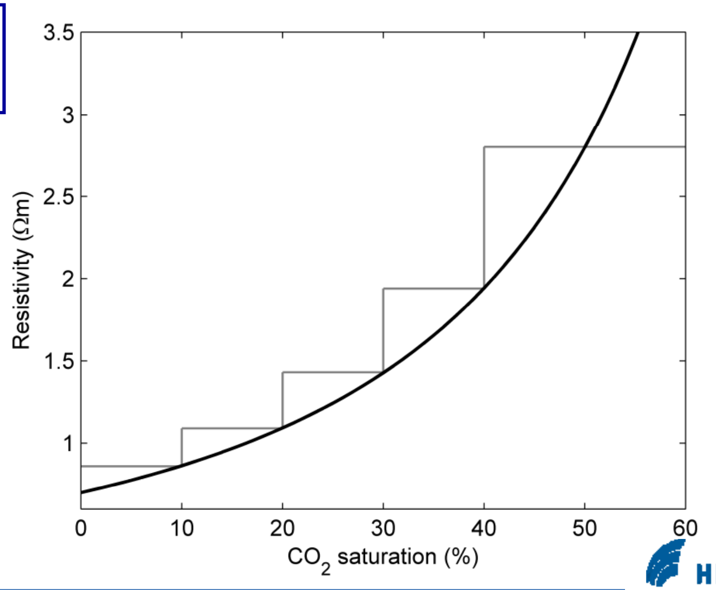


Step 1:



Multiphase fluid flow modeling of migration scenarios in the simplified injection formation model with varying reservoir permeability

$$\rho(S_{CO2}) = \frac{A\rho_w}{\phi^m(1 - S_{CO2})^n}$$



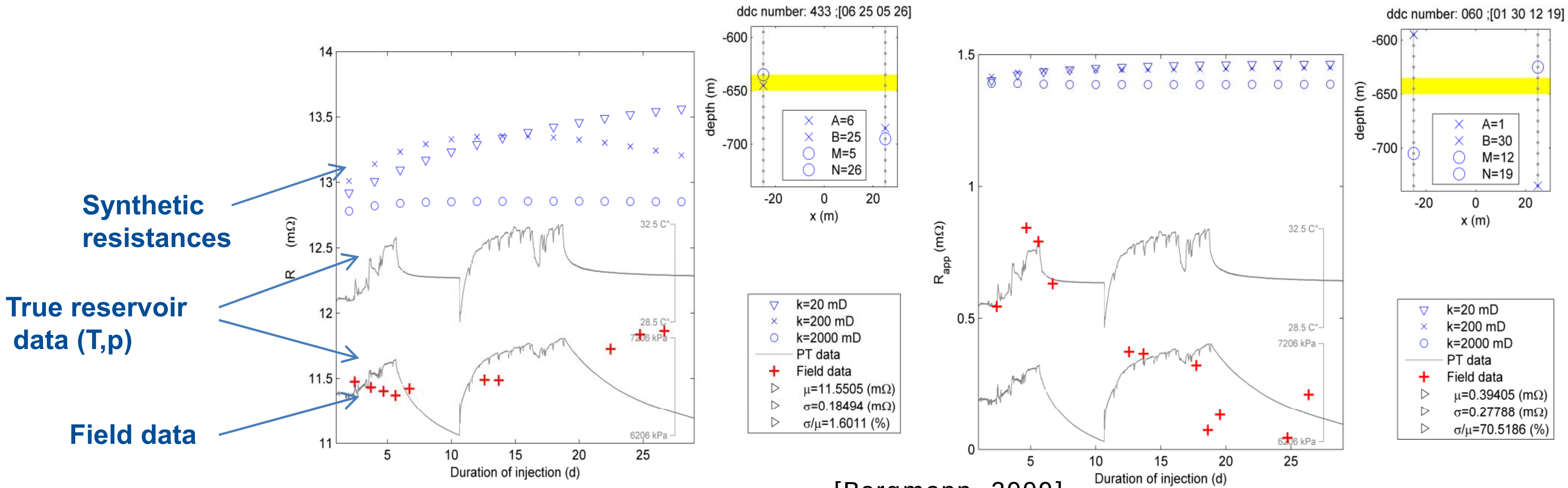
Resistivity saturation relation derived from Archie's equation (black line) for ρw=0.037 Ωm, A=1, m=n=2, Φ=23 %. The grey line depicts the discretized resistivity saturation relation utilized in forward modelling.

Relating Resistivity and CO_2 Saturation

Step 2:

Comparison with field data

Examples of electrode configurations



[Bergmann, 2009]

Conclusion:

Comparison of field data and modeled data allows analysis of potential CO_2 induced alterations and noise sources in the pre-inversion domain.

But the reservoir model needs to be refined to improve the fitting of both datasets.

Error Analysis and Dataset Optimization

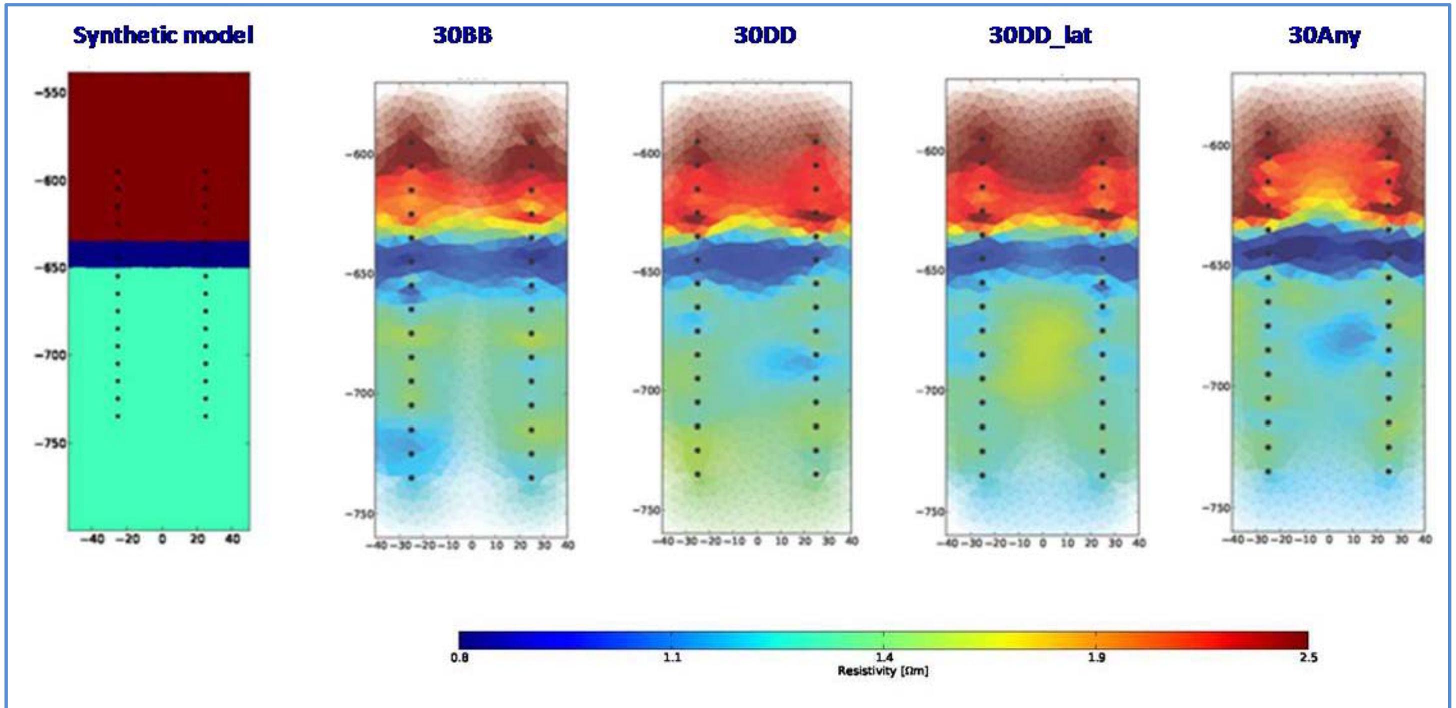
Synthetic three-layer model with noise ~3% + 50µV/1A

Removal of data with noise > 30%

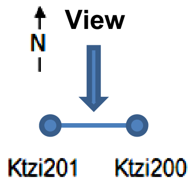
$$\frac{\delta \rho_i^a}{\rho_i^a} = p\% + \left(\frac{\delta U}{U_i}\right) \times 100\%$$

Processed with BERT – Boundless Electrical Resistivity Tomography

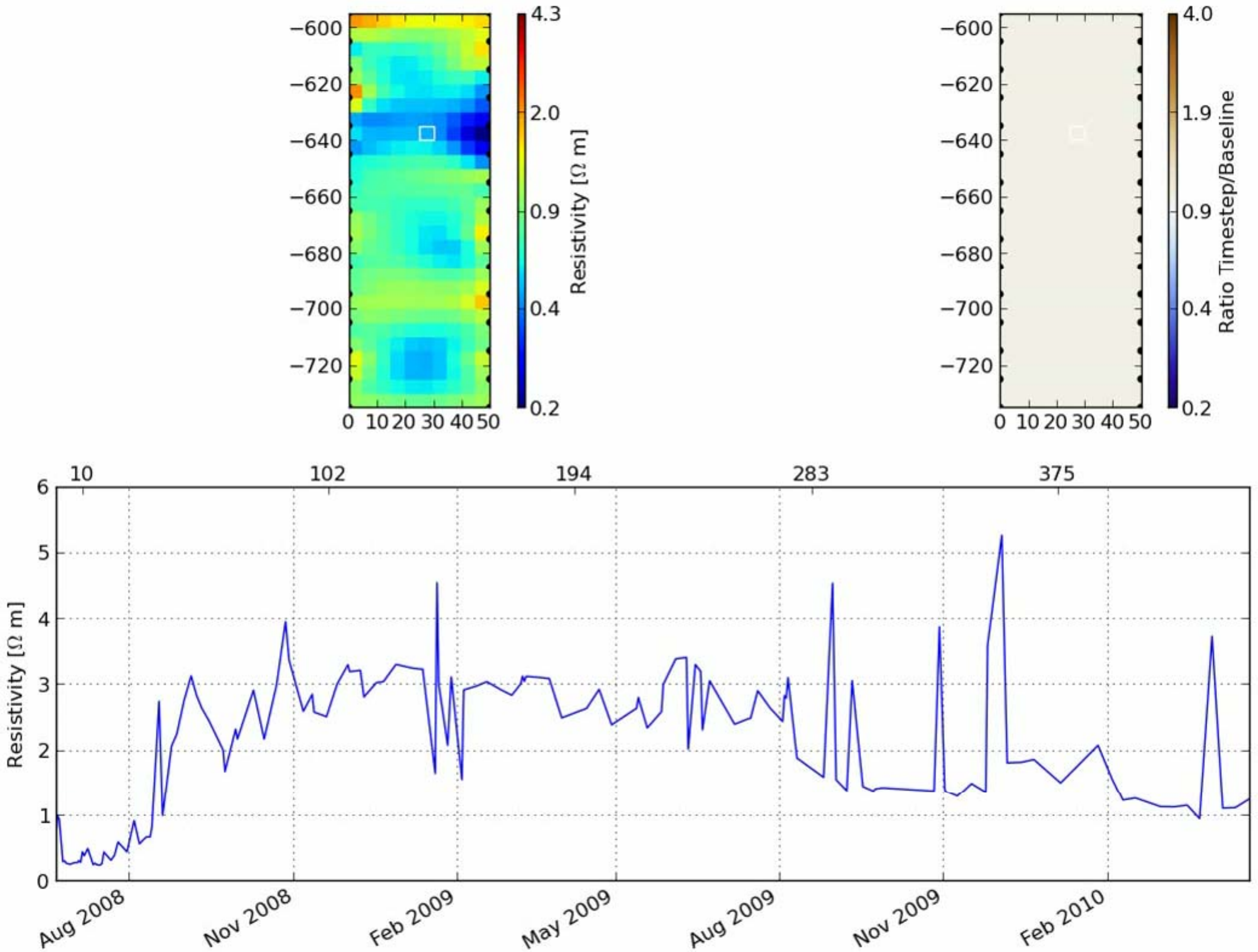
[Rücker, 2009]



Measurement configuration	BB	DD	DD_lateral	Any= all data (BB+DD+DDc+user defined)
Data of sufficient quality	100%	20%	60%	57%



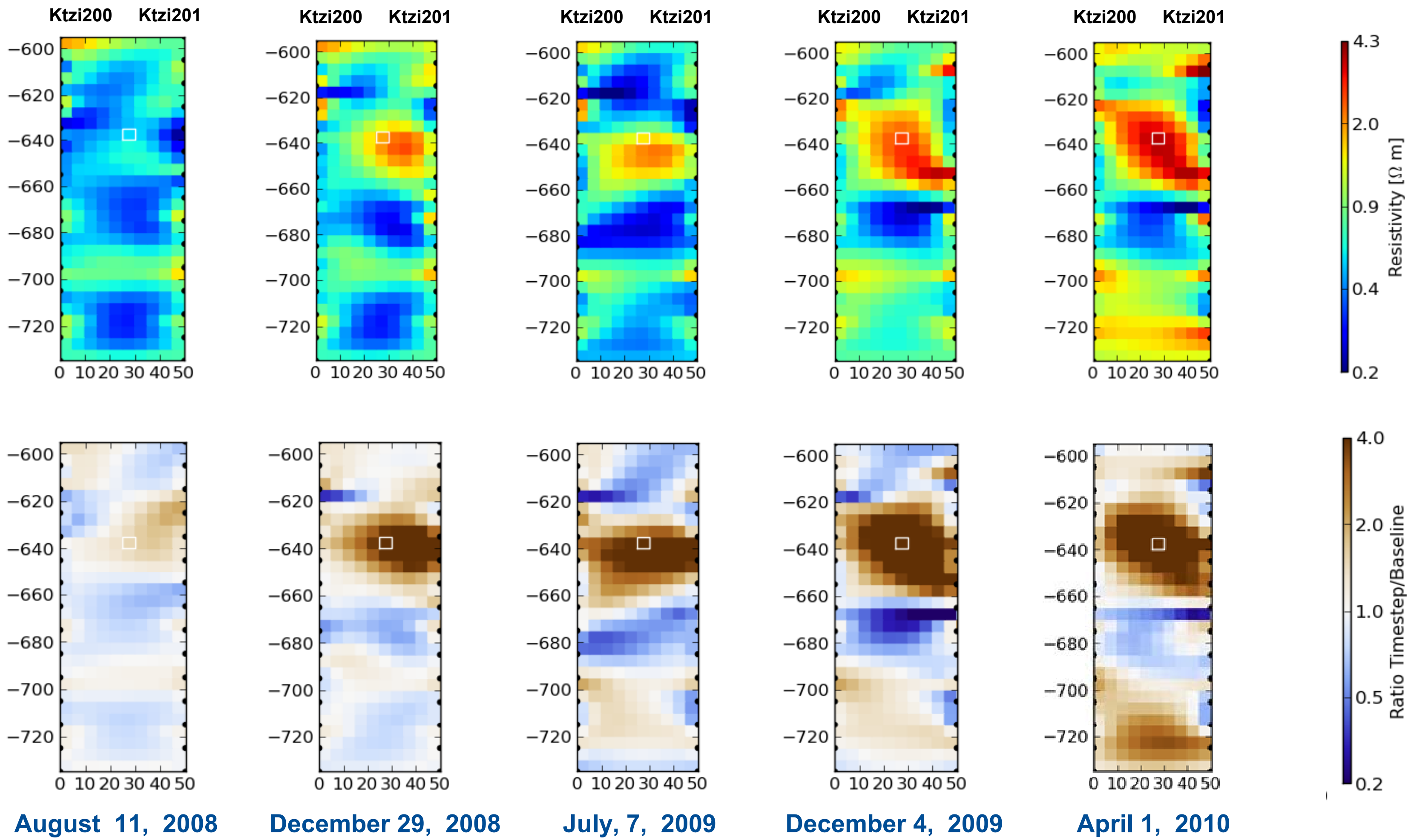
Crosshole-ERT Inversion Results



[C. Rücker, 2010]

Crosshole-ERT Inversion Results

[ERT Team]



2D Inversion with BERT / cross section Ktzi200-Ktzi201: λ = 100 (regularization strength), ρ^a_{min}=0.05 Ωm, ρ^a_{max} =3 Ωm, error approximation: 3% + 50 µV/ 1 A, amount of model cells: 702 (grid-model), **distribution of inverted resistivity (above), distribution of resistivity ratio (below)**

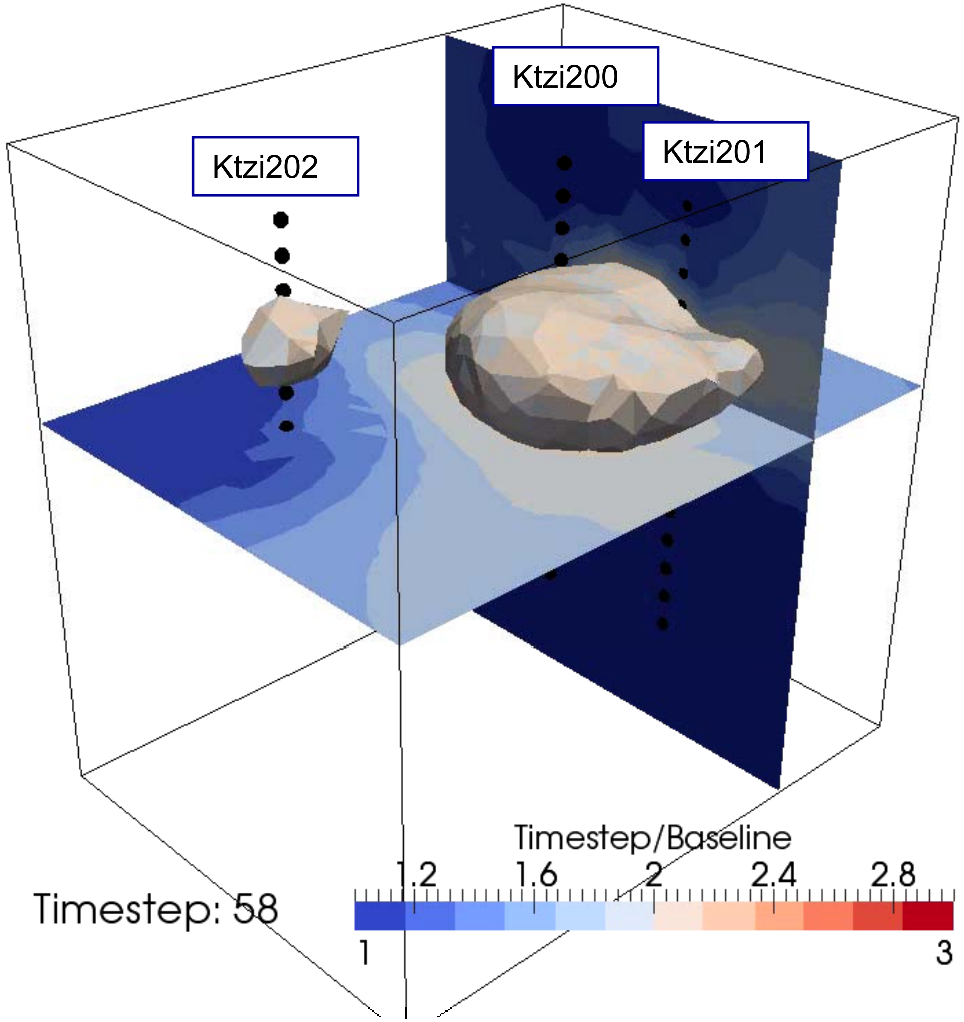
3D-Inversion

Field data:
June 4, 2009

3D Inversion with BERT :
λ = 100 (regularization strength),
ρ^a_{min}=0.05 Ωm,
ρ^a_{max} =3 Ωm,
error approximation:
3% + 50 μV/ 1 A

Isosurfaces with resistivity ratios >2

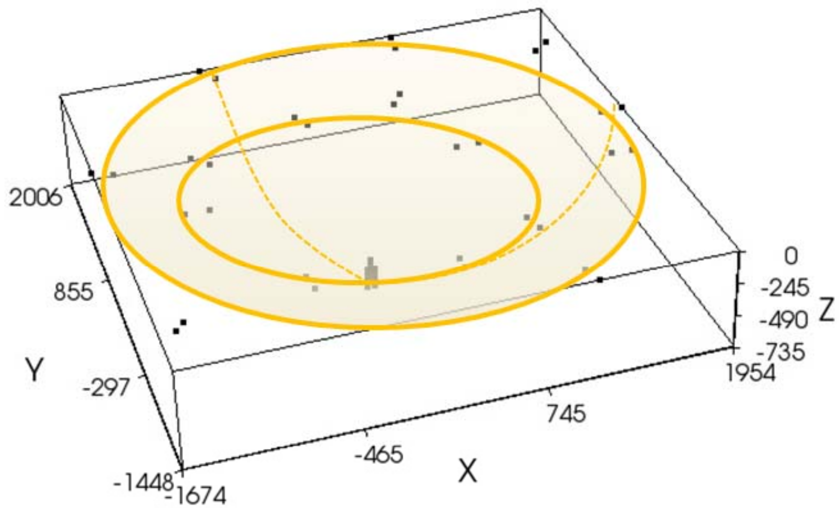
→ arrival of CO_2 @ Ktzi202 appears in the inverted data

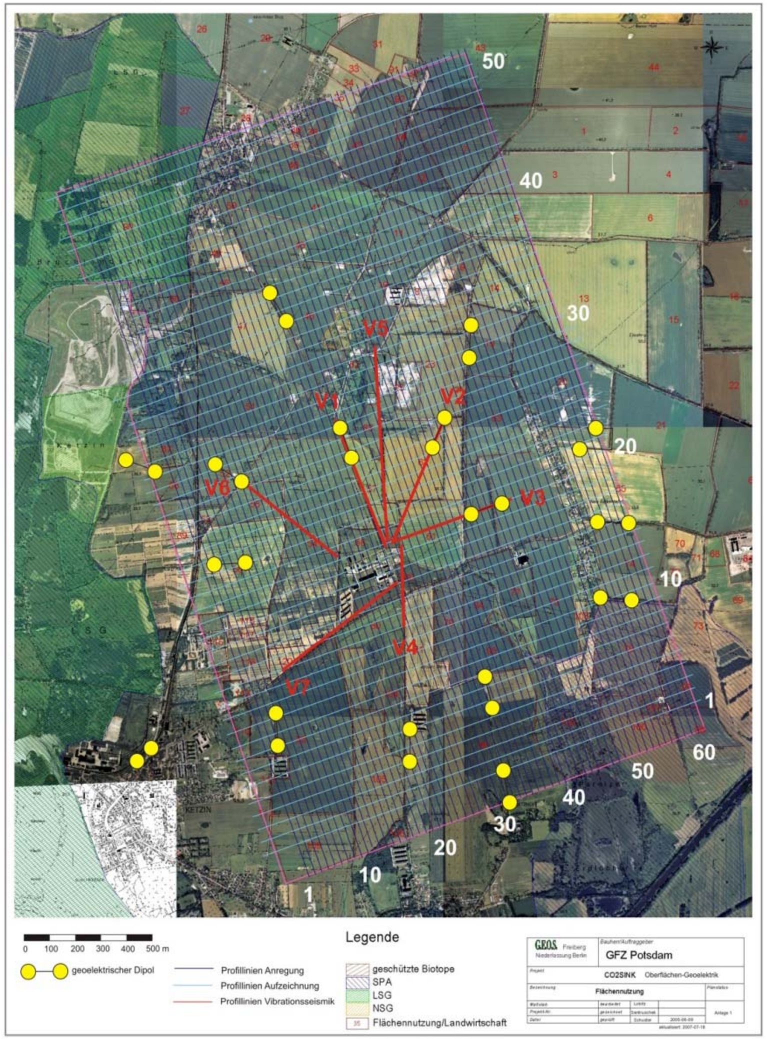


[C. Rücker, 2010]

Large-scale geoelectrical measurements

Site map with **geoelectrical surface dipoles** (yellow dots) and **3D seismic survey at the surface** (light blue grid within the yellow quadrangle)





500 m

Surface-Downhole Data Acquisition & Pre-Processing

Data Recording

16 surface dipoles for current injection (15-20 min at each surface dipole)

potential registration at (14+3) dipoles at each well and 15 dipoles at surface

= 1056 single potential time-series per survey

Data Readout

Data files from Texan in own data format

Formatting

Conversion in SEGY-Format

Protocol

Assignment of Data and Dipol positions

Pre-Processing & Data quality control

Filtering and Fourier-Transformation: calculation of electrical resistance R(Ω) from ratios of the amplitudes (spectra)

Including k - geometric factor

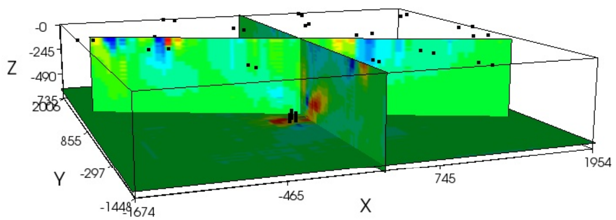
$$k = 4\pi \cdot \left(\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2} \right)^{-1}$$

Calculation of apparent resistivities ρ_a in Ωm

$$\rho_a = k \cdot R = k \cdot \frac{\Delta V}{I}$$

3D Inversion

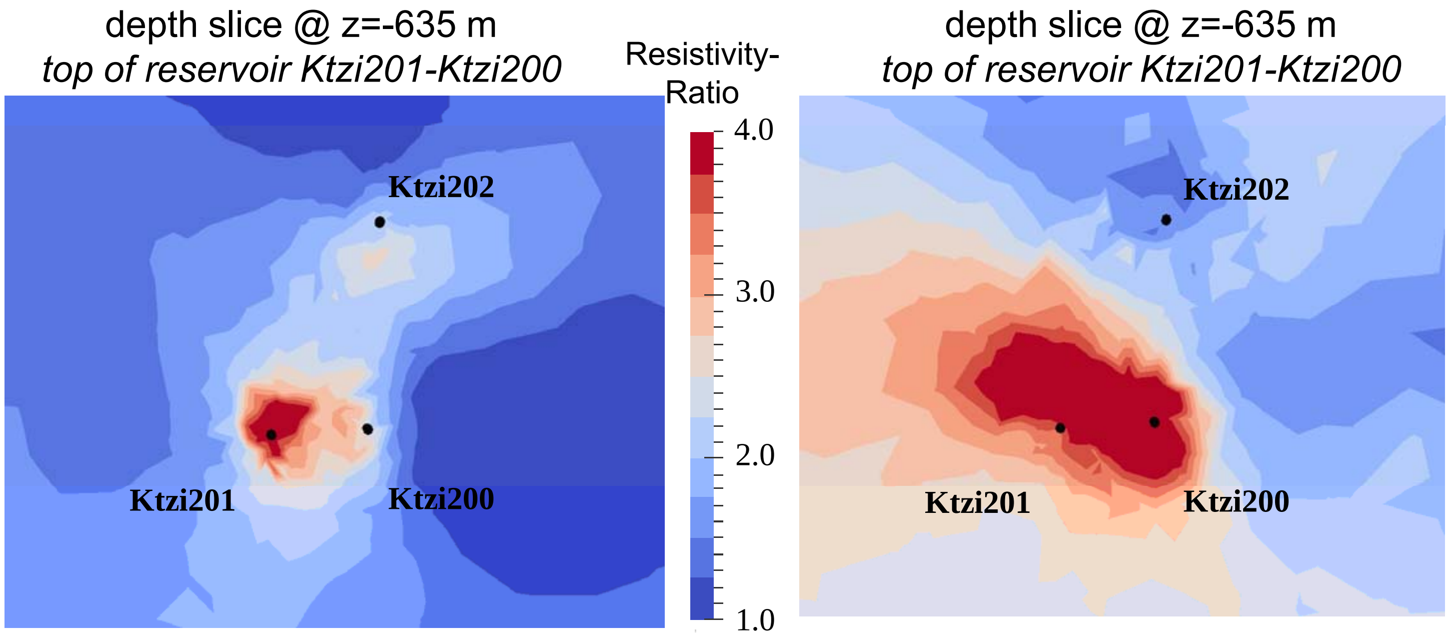
Resistivity changes and anisotropic effects caused by CO_2 migration



Surface-Downhole Inversion Results

Resistivity-Ratios:
2^{nd} Repeat vs.
2^{nd} Baseline

Resistivity-Ratios:
3^{rd} Repeat vs.
2^{nd} Baseline



[Kießling & Rücker, 2010]

2^{nd} Baseline:
- 04/2008

2^{nd} Repeat:
- 11/2008
- 4,500 t CO_2
- Arrival of CO_2 at Ktzi200 (07/2008)

3^{rd} Repeat:
- 04/2009
- 13,500 t CO_2
- Arrival of CO_2 at Ktzi200 (07/2008)
- Arrival of CO_2 at Ktzi202 (03/2009)

surface-downhole and surface-surface data:
2^{nd} Baseline: 1025 data points, 3^{rd} Repeat: 966 data points; calculation of R (Ω) from spectral analysis, 3D Inversion with BERT: $\lambda = 100$ (regularization strength), topography, range 10^2 to 10^5 Ωm, error approximation: 1% + 10 µV/ 4 A, amount of model cells: 19050 (tetrahedral)

GFZ Helmholtz Centre Potsdam

HELMHOLTZ ASSOCIATION

Results and Discussion

Preliminary Inversion Result: using 3D inversion software BERT (Rücker & Günther, 2006)

Resistivity-Ratios:
3rd Repeat vs.
2nd Baseline

2nd Baseline:
- 04/2008

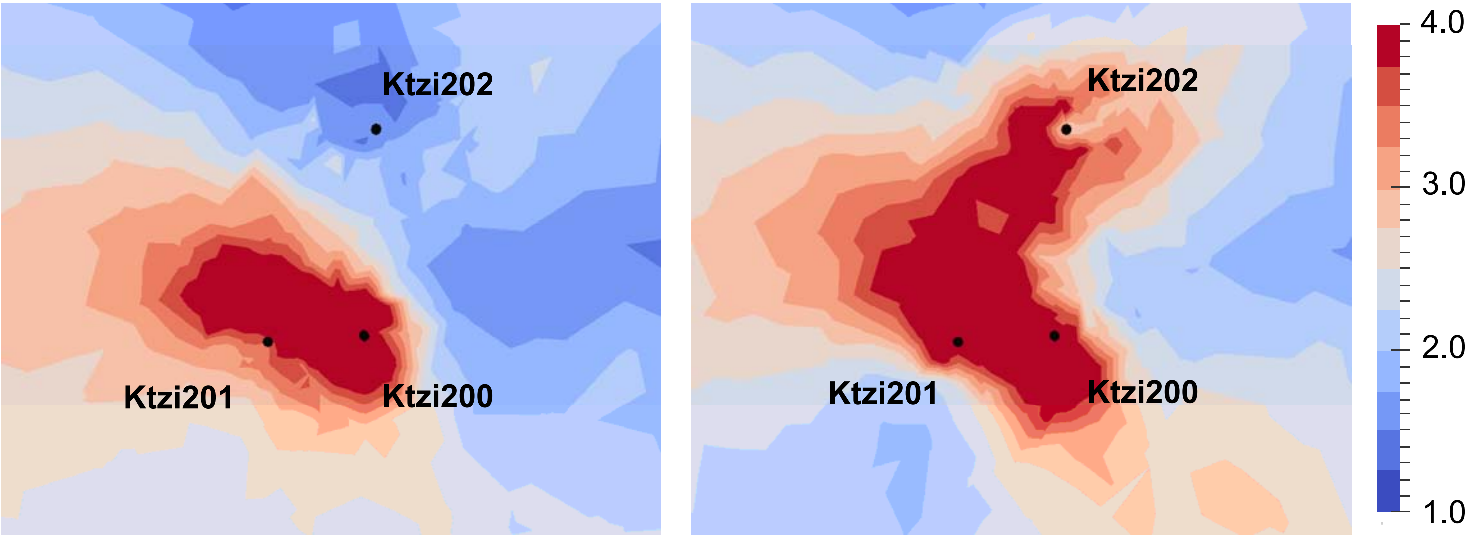
3rd Repeat:
- 04/2009
- 13,500 t CO_2
- Arrival of CO_2 at Ktzi200 (07/2008)
- Arrival of CO_2 at Ktzi202 (03/2009)

depth slice (z = **- 635 m**)

top of reservoir Ktzi200–Ktzi201

depth slice (z = **- 620 m**)

top of reservoir Ktzi202



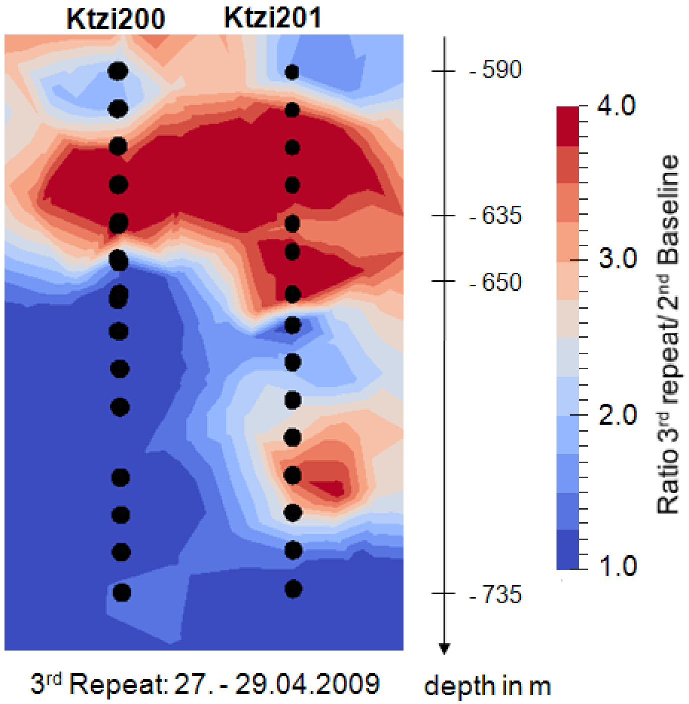
[Kießling & Rücker, 2010 (unpublished)]

surface-downhole and surface-surface data;
2nd Baseline: 1025 data points, 2nd Repeat: 1023 data points;
calculation of electrical resistance from spectral analysis;
3D Inversion with BERT: calculation: λ = 100 (regularization strength), topography, range 10^2 to 10^5 Ωm, error approximation: 1% + 10 μV/ 4 A, amount of model cells: 19050 (tetrahedral);
plotted depth slice; distribution of resistivity ratios

Results and Discussion

Geoelectrical Surface-Downhole and Crosshole data: **Comparison**

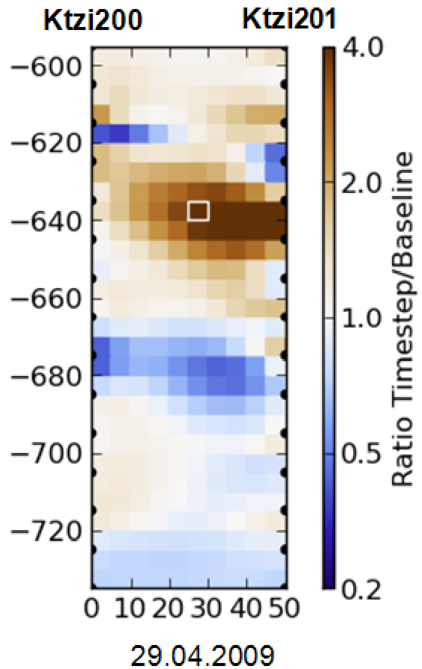
Geoelectrical Surface-Downhole



[Kießling & Rücker, 2010 (unpublished)]

surface-downhole and surface-surface data;
2nd Baseline: 1025 data points, 2nd Repeat: 1023 data points;
calculation of electrical resistance from spectral analysis;
3D Inversion with BERT: calculation: λ = 100 (regularization strength), topography, range 10^2 to 10^5 Ωm, error approximation: 1% + 10 μV/ 4 A, amount of model cells: 19050 (tetrahedral); plotted depth slice; distribution of resistivity ratios

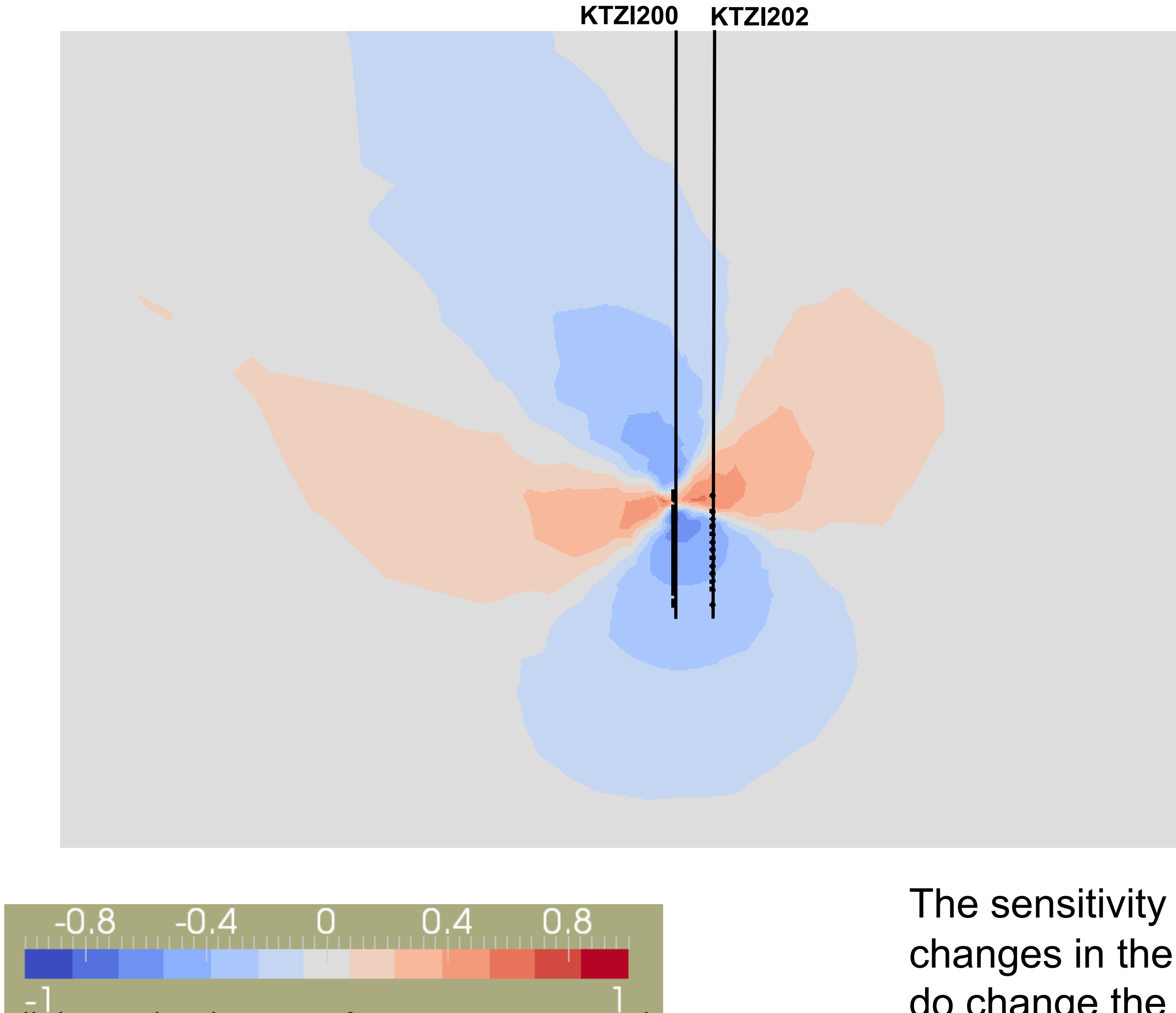
Geoelectrical Crosshole



[Rücker, 2010 (unpublished)]

data: any; 29.04.09 (time step 87); 2D inversion with BERT: λ = 100 (regularization strength), range 0.05 to 3 Ωm, error approximation: 3% + 50 μV/ 1 A, amount of model cells: 702 (grid-model); cross section Ktzi200-Ktzi201 with depth; distribution of resistivity ratios

Sensitivity Considerations



[Rücker, 2010]

$$S_{ij}(\mathbf{m}) = \frac{\partial f_i(\mathbf{m})}{\partial m_j}$$

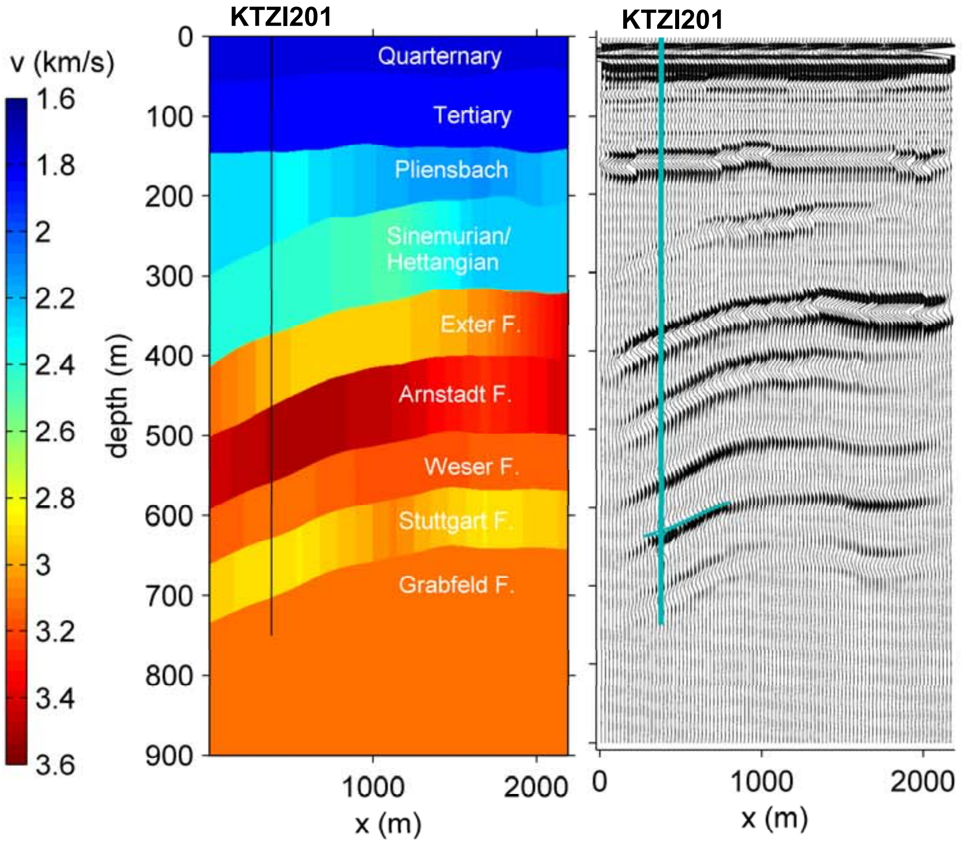
$$\mathbf{S} = \begin{pmatrix} \frac{\partial f_1}{\partial m_1} & \cdots & \frac{\partial f_1}{\partial m_M} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_N}{\partial m_1} & \cdots & \frac{\partial f_N}{\partial m_M} \end{pmatrix}$$

The sensitivity matrix $\boldsymbol{S_{ij}}$ indicates how changes in the model domain element $\boldsymbol{m_j}$ do change the data domain element $\boldsymbol{f_i}$

Intended Combination of Seismic and Geoelectric Measurements

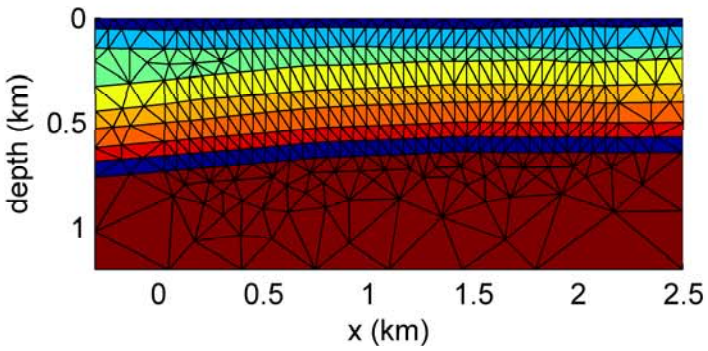
Velocity model

Stacked section from FD-forward modelling



[Bergmann, 2010]

Triangular mesh parametrization with structural constraints

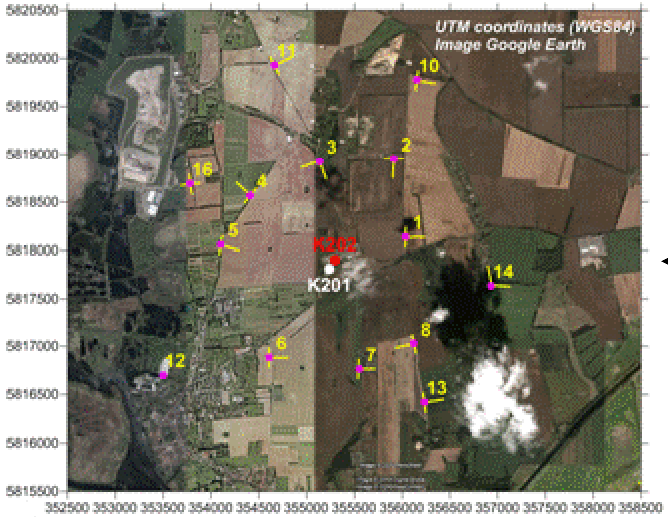


Future studies are intended to incorporate structural constraints (e.g. from seismics) and error-weighted inversion schemes

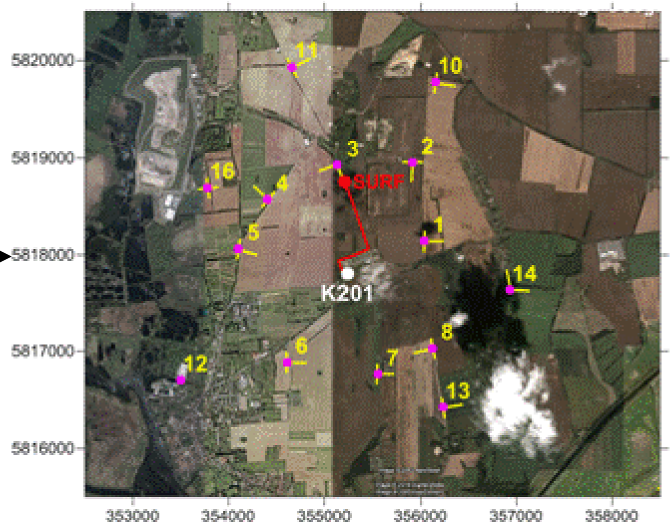
CSEM monitoring of CO_2 injection at Ketzin pilot site
2008-2009 surveys, preliminary results

- Hole to surface CSEM
  - A complementary approach to crosshole tomography
    - Lower resolution but larger zone of detectability
  - Receiver stations in surface do no need electrodes array at the reservoir depth, one point of injection is enough
  - The metallic casing itself may be used to inject electrical current at depth

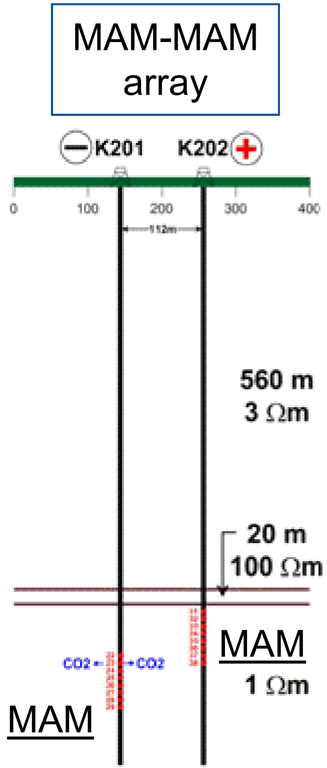
    ⇒ LEMAM – Long Electrode Mise-a-la-Masse

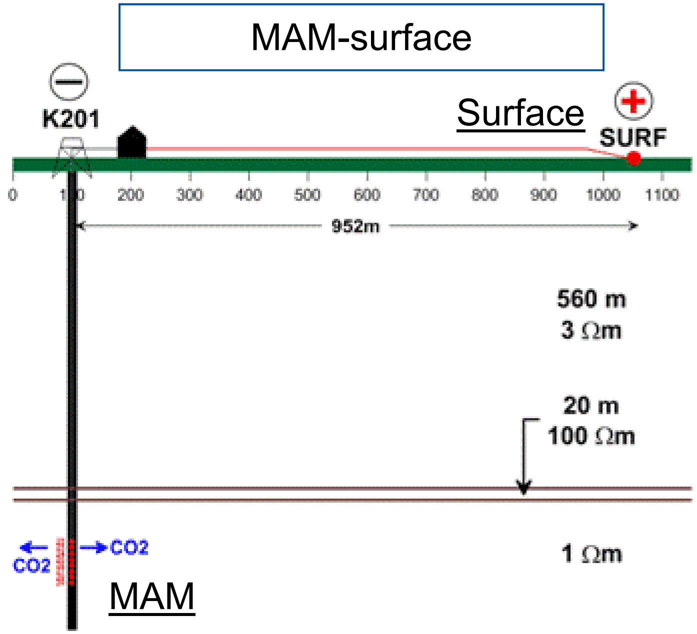


Receiver stations at the surface, around the boreholes



Two CSEM arrays are used at Ketzin pilot injection

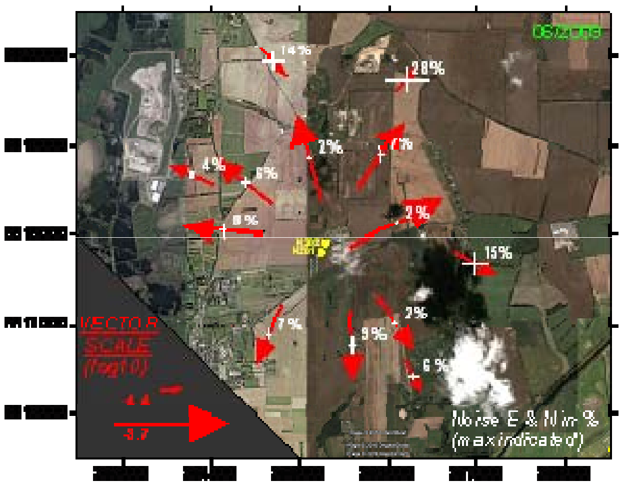




Different current injection but same receiver stations at the surface.
Surveys :

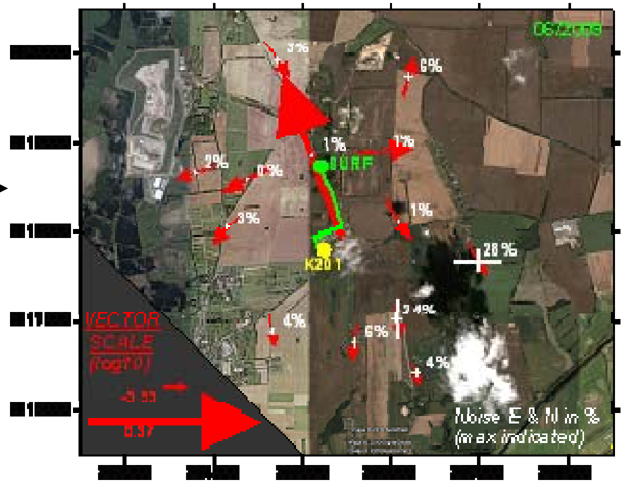
- baseline in 2008 (before start of CO_2 injection)
- 1rst repeat in 2009 (~18.000 t of CO_2)
- 2nd repeat in 2010 → scheduled in 2010

MAM-MAM measurements



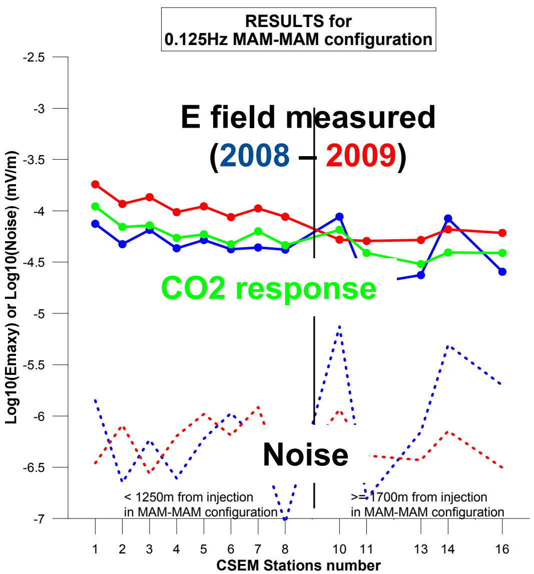
Electric field distribution

MAM-Surface measurements



Electric field distribution

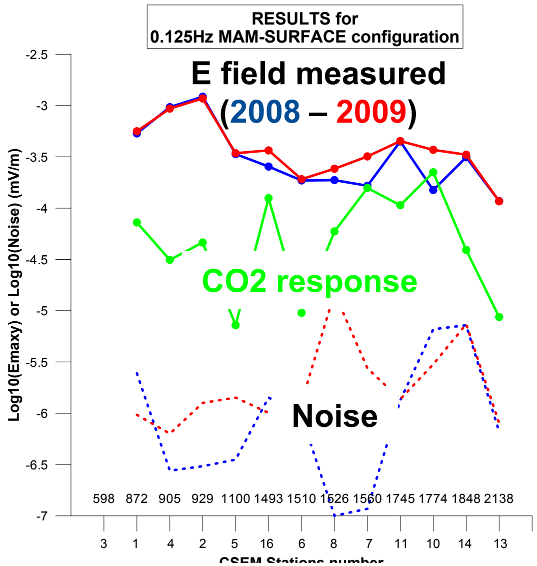
Each array shows a very contrasted response in surface



Amplitude of signal at all stations

Detectability of injected CO_2 by surface receivers proven

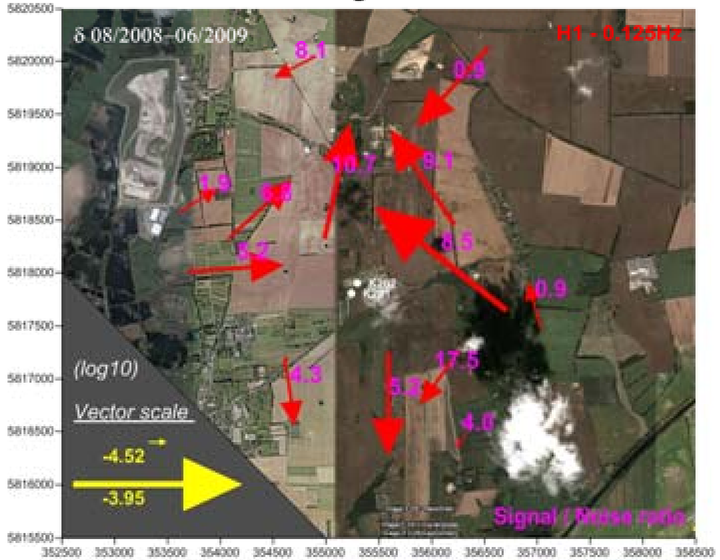
The two arrays show clear responses, but current injection at depth (left) shows a better detectability.



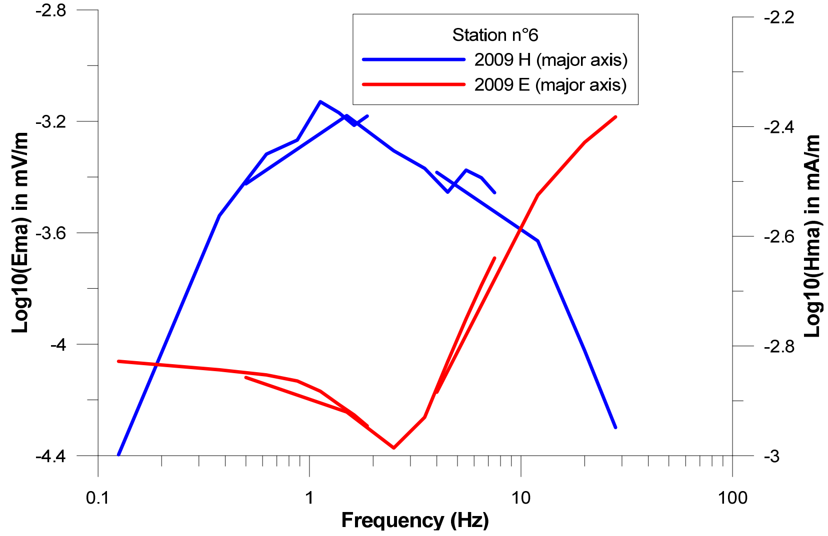
Amplitude of signal at all stations

Time lapse response of CO2 injection in surface (MAM-MAM)

δE major axis



Frequency variation of E and H total fields measured at surface (2009)



Station n°6 (MAM-MAM array)

On-going:

- Performance assessment of exploiting vectorial nature (left) and frequency behaviour (right) of H & E fields measured in surface, to map resistivity changes at depth and link it to the CO2 saturation in the reservoir

Next field survey in Summer 2010 :

- Second field repeat to prove ability to detect slight changes in CO2 saturation (contrast weaker than between survey 09 / baseline 08)

VI. Summary

- VERA system has been successfully installed and is operating since three years
- Resistivity logging and laboratory experiments are available and support geoelectric monitoring with structural and petrophysical information
- Pre-injection resistivity model was built based on site-specific data relating Archie's law with standard sandstone parameters
  - *low-resistivity environment (few Ωm to below 1 Ωm)*
  - *thin reservoir layer (max. 20 m)*
  - *small resistivity contrasts → max. increase ~300% due to partial CO_2 saturation*
- Studies incorporating multi-phase fluid flow modelling were performed indicating a significant dependency of apparent resistivity alteration to hydraulic conductivity within the reservoir (due to time-dependent CO_2 distribution)
- Inversion results are in good correspondence with current information from other monitoring systems (seismic, gas monitoring, RST and DTS) → contribute to the "big picture", but more detailed investigations have to be conducted

VI. Lessons learned

- Necessity of improved degree of automization as well as a standard workflow for data acquisition, processing and evaluation

→helps to overcome time-consuming manually data handling and avoids delay in delivering results to site operators / regulators

- Demand for unified models, synchronized parameters and coordinates

→supports efficient data integration and corresponding joint interpretation

Thanks to all involved persons

CO2SINK

CO2 REMOVE research monitoring verification

GeoEn

COSMOS

GEOTECHNOLOGIEN

GFZ Helmholtz Centre Potsdam

Federal Ministry of Education and Research

Federal Ministry of Economics and Technology

HELMHOLTZ ASSOCIATION

Some aspects of seismic monitoring at Otway

Towards the end of phase I monitoring program…

M. Urosevic[1,3], R. Pevzner[1,3], V. Shulakova[2,3] and A. Kepic[1,3]

1- Curtin University, 2 - CSIRO, 3 - CO2CRC

With contributions from

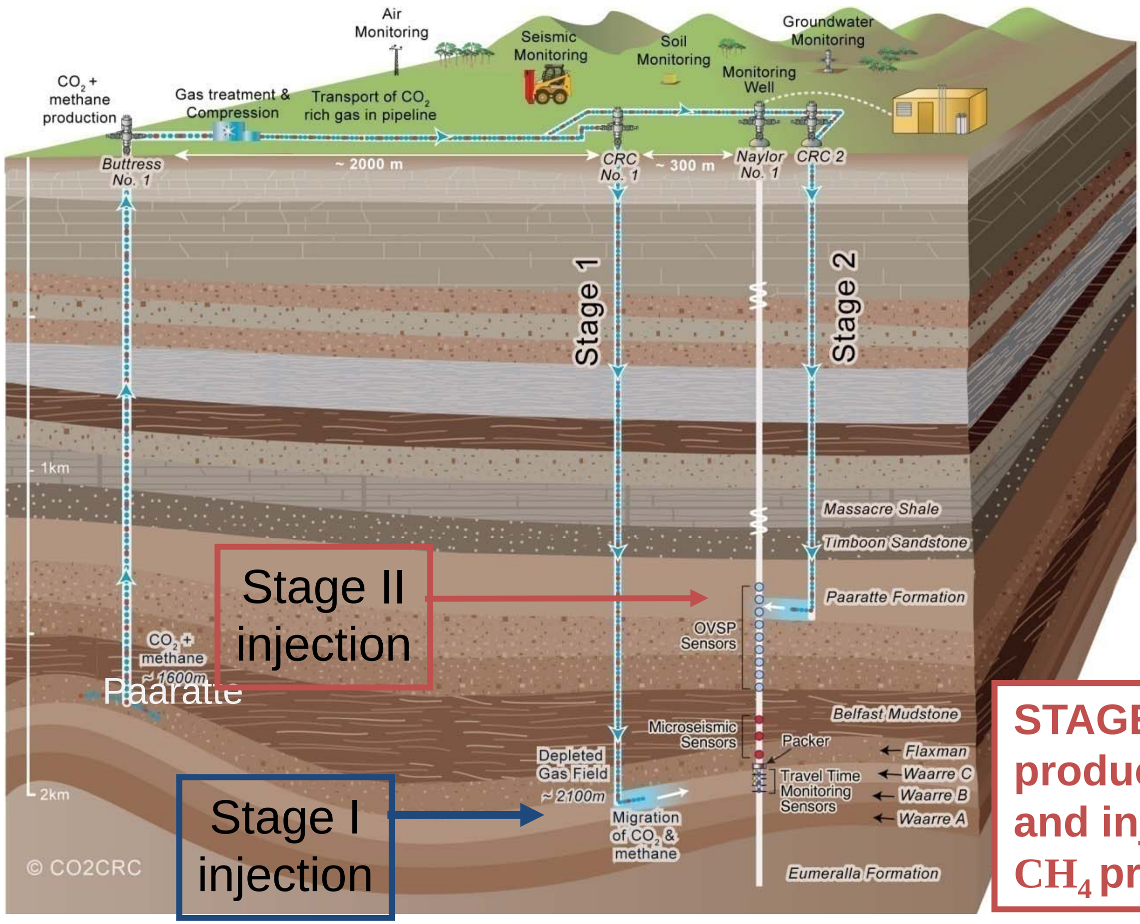
C. Jenkins, S. Sharma, K. Dodds, D. Sherlock, R. Li, T. Dense, T. Daley, P. Wisman, B. Gurevich

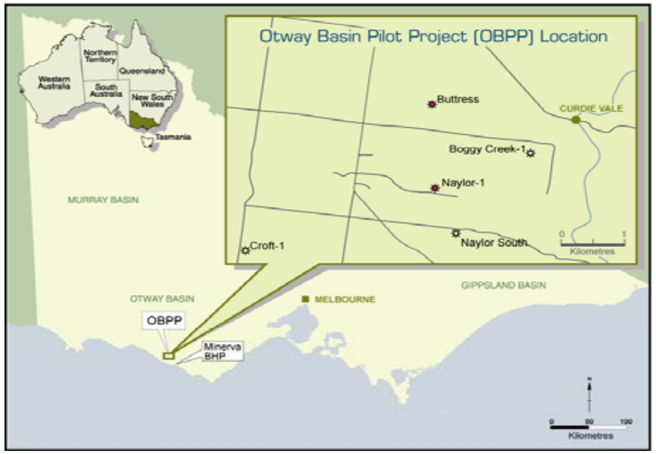
Schlumberger CO2 research crew

M. Verliac, A. J. Campbell, W. S. Leaney, L. Dahlhaus,

Curtin University of Technology CSIRO CO2CRC

Otway Basin Pilot Project (Victoria, Australia)





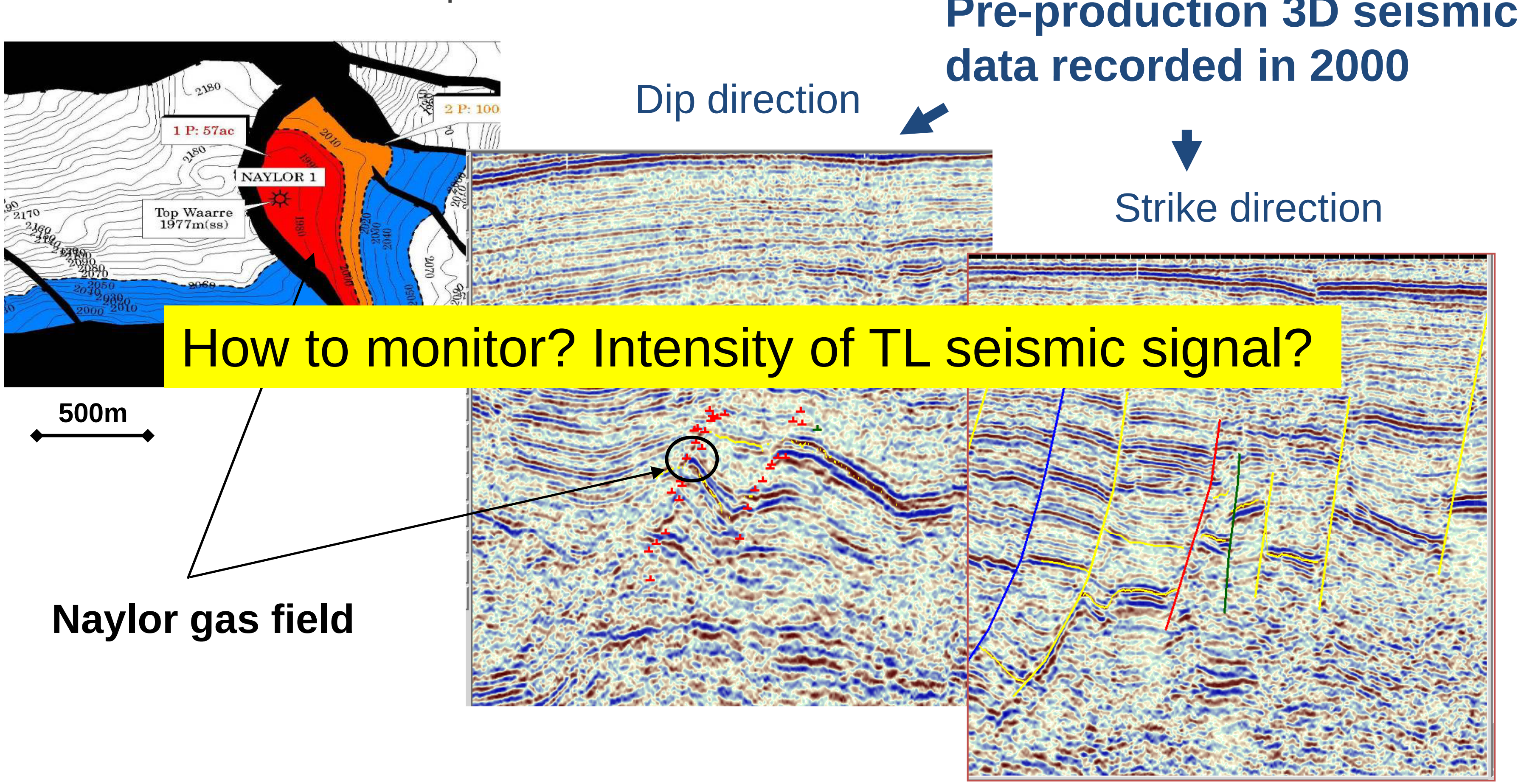
STAGE I: An 80/20 % of CO_2/CH_4 stream produced from Buttress, transported and injected into CRC-1 well (previous CH_4 production well) -65 Kt.

STAGE II: CO_2/CH_4 stream injected into CRC-2well(huff-and-puff) – up to 10 Kt.

Curtin University of Technology CSIRO CO2CRC

Naylor reservoir

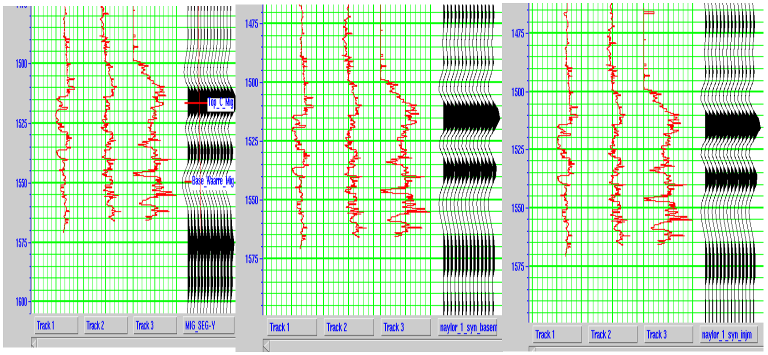
- Small, thin, heterogeneous and relatively deep depleted gas reservoir, surrounded by complex faulting, 80-20% mix injected, excludes the application of most of the geophysical methods that might be used for CO2 monitoring, except the most sensitive seismic techniques

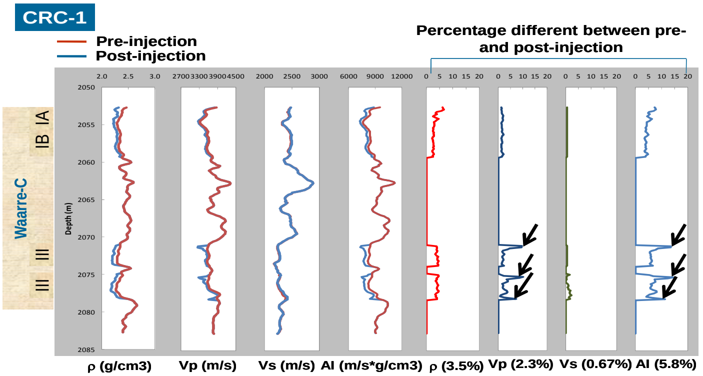


De-motivation for the study - Modelling CO_2 related TL effect

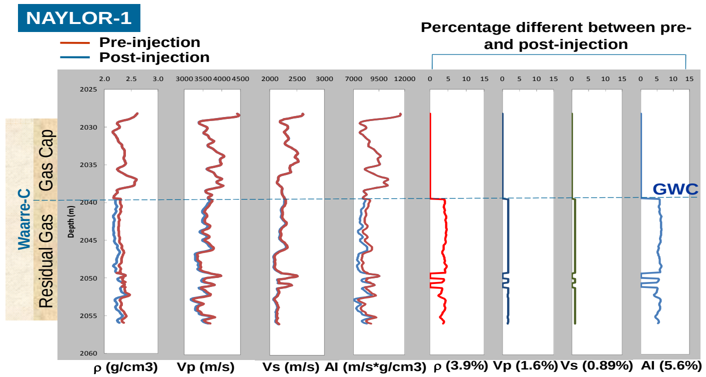
Naylor-1 monitoring well -initial modelling

Pre-production Post-production After CO_2 injection





ΔAI ~3-6%



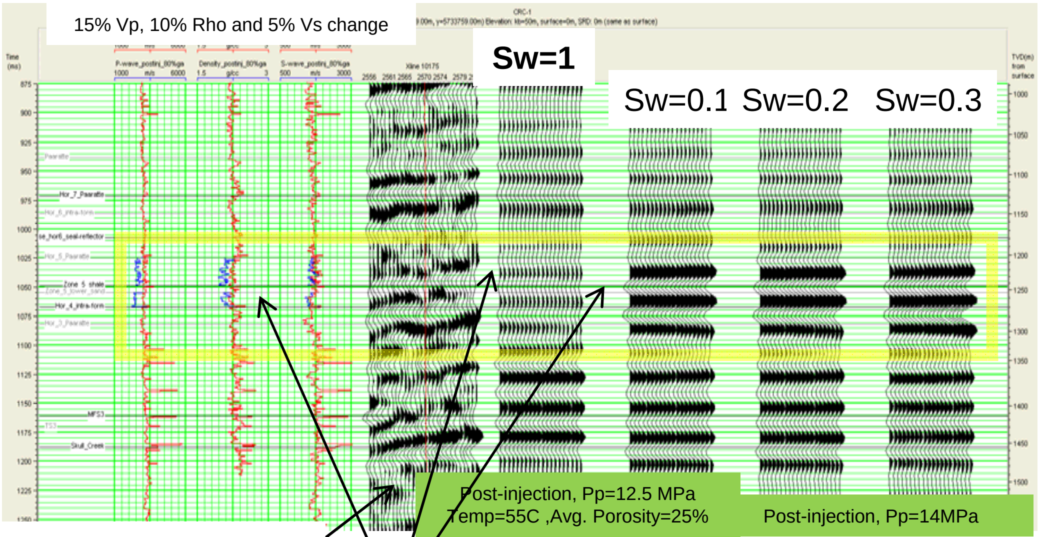
Computed changes in elastic properties including acoustic impedance for two wells. In both cases impedance changes up to 6%; density dominated;
Detectable TL effect for NRMS level < 20% (?) **Δ AI>6%, ΔR>15%**

1D Modelling of CO_2 “leak” scenario

Upward migration of CO_2 into overlain strata (Paaratte saline aquifer 500 m above Naylor) will produce very strong 4D seismic response

Assurance monitoring

Depth
~ 1100 m

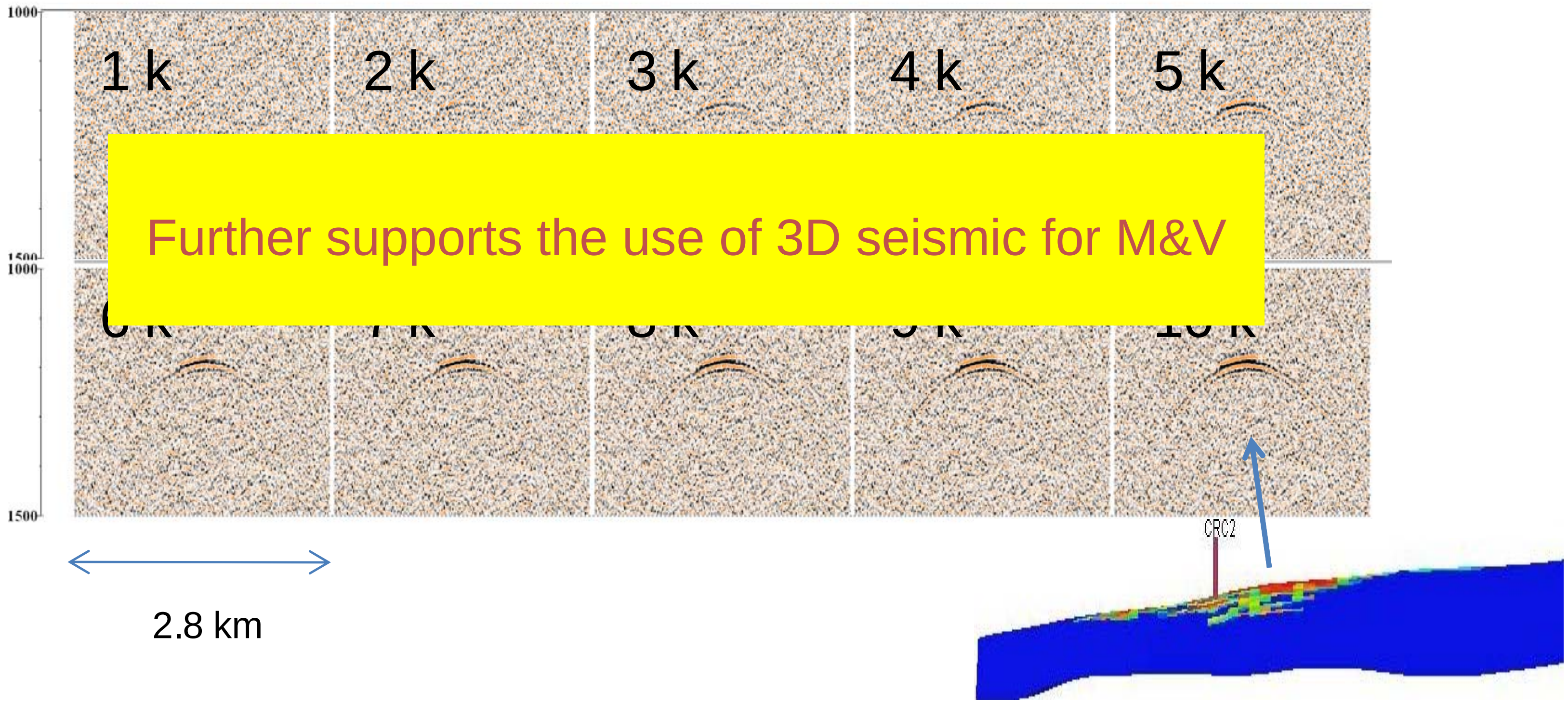


Pre-production seismic

Paaratte

Very strong 4D effect in Paaratte!

2D sensitivity modelling of a CO_2 "leak" into the Paaratte saline formation - model from reservoir simulation



Further supports the use of 3D seismic for M&V

The CO_2 quantities shown in thousand tonnes. CO_2 occupies thin layer, with small areal extent (less then Fresnel radius) - diffracted energy is roughly proportional to CO_2 volume; 30% of background noise.

Designing the monitoring program...

Small target, small 4D effect, potentially poor repeatability (land seismic)

other limitations: accessibility, environmental and other restrictions, cost…

Need surveys that can achieve:

- High resolution
- High sensitivity
- High data density
- Very good repeatability

Seismic monitoring – Final program

- Time lapse 3D surface seismic
  - Least sensitive and repeatable but provides coverage of entire reservoir and beyond
  - Necessary for ‘assurance monitoring’ to detect loss of primary containment
  - No 4D effect expected
- Time lapse borehole seismic
  - CRC-1: 3DVSP with 3C geophones (Schlumberger’s VSI)
    - Improved sensitivity and resolution relative to surface data, improved repeatability
    - More chance for direct CO_2 monitoring, limited coverage
  - Naylor-1: 2D with permanent sensors (LBNL)
    - Potentially most sensitive and repeatable

TL : Simultaneous acquisition of 3D surface and 3D VSP

- 750 kg,
m – 2008
-vibe 2009

3D TL seismic data acquired – Phase I

Surface seismic:

- Baseline 2007/8
- 1st repeat 2009 (33Kt)
- 2nd repeat 2010 (65Kt, post injection)

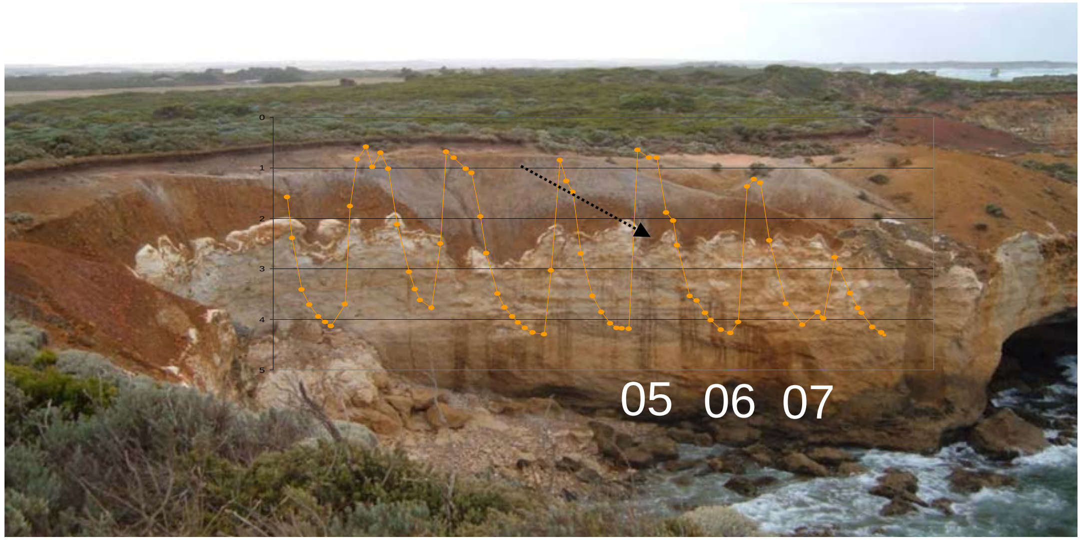
VSP

- Baseline 2007
- Post injection 2010

Key question: repeatability vs TL effects

Weathering conditions: top soil (farming zone) + weathered clay-rich zone on top of corrugated limestone

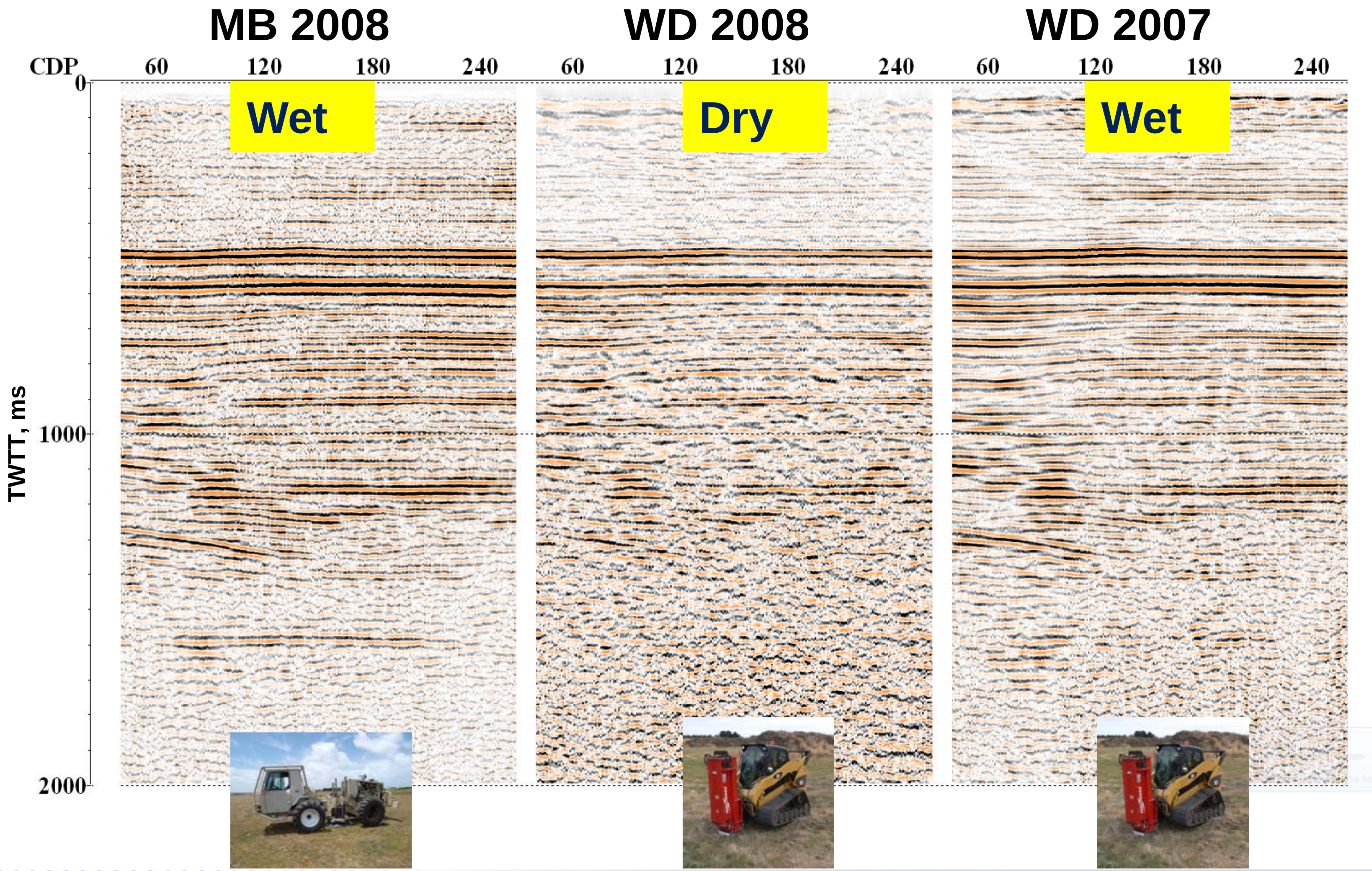
Seasonal variation of Water Table



Variable scattering with WT variation

Soda's Rd tests
2Dseismic test line
Dry/wet conditions
Different sources
7 repeats

Processed and cross-equalized 2D stacked sections (Soda's Rd)



Curtin University of Technology
CSIRO
CO2CRC

Repeatability via NRMS

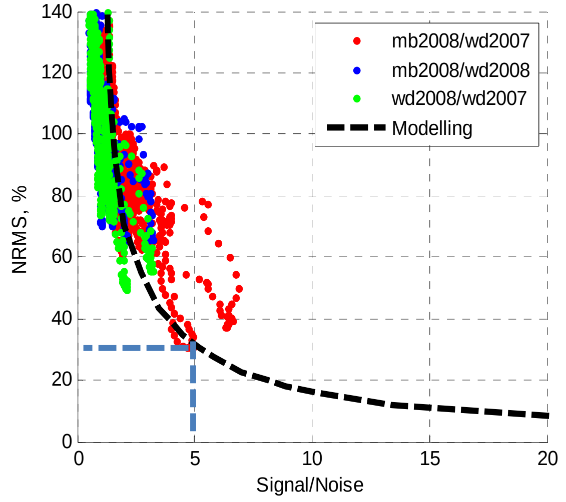
$$NRMS = 200\% \frac{RMS(a-b)}{RMS(a)+RMS(b)}$$

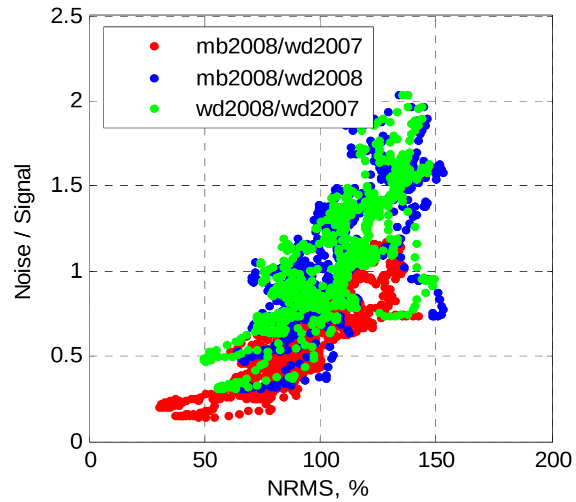
where *a* and *b* are two surveys being compared [Kragh and Christie, 2002]

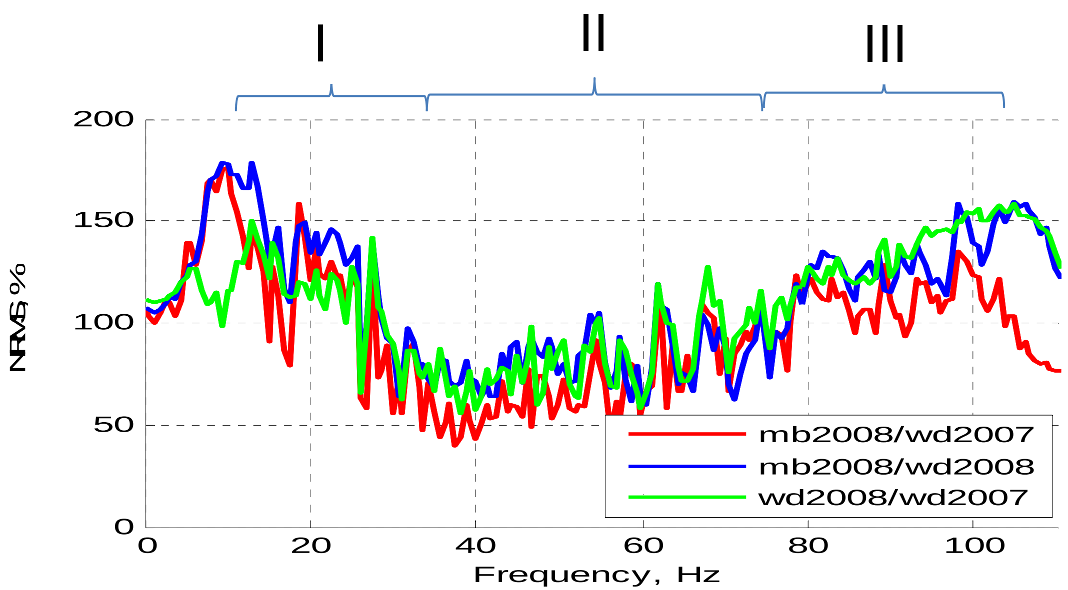
$$SN_i = \sqrt{\frac{[g_{i,i+1}]_{MAX}}{1-[g_{i,i+1}]_{MAX}}}$$

where *i* is trace number, $g_{i,i+1}$ is normalized cross-correlation function between *i* and *i+1* traces and $[g_{i,i+1}]_{MAX}$ is its maximum value

What is non-repeatability?







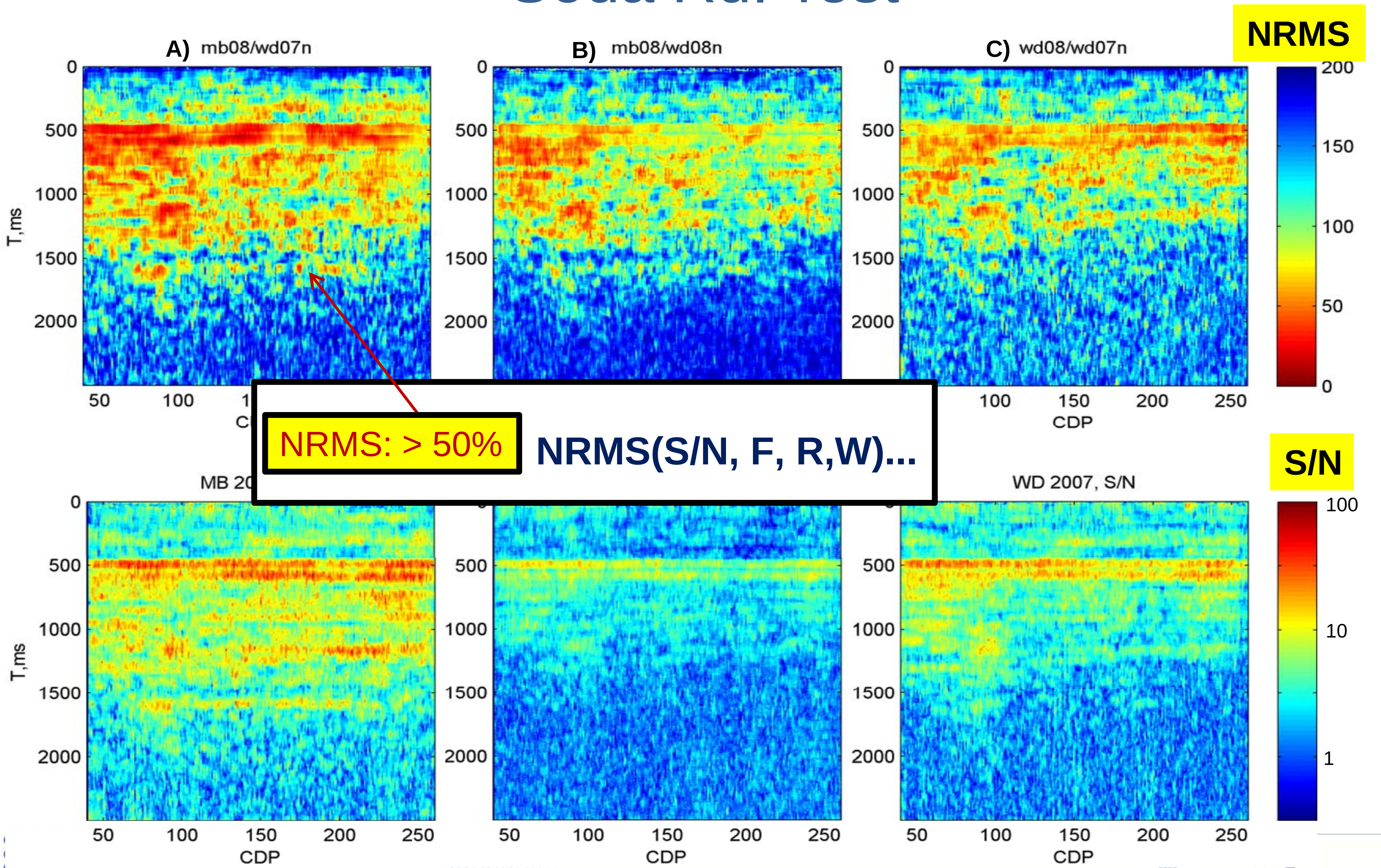
2D

University of Technology

CSIRO

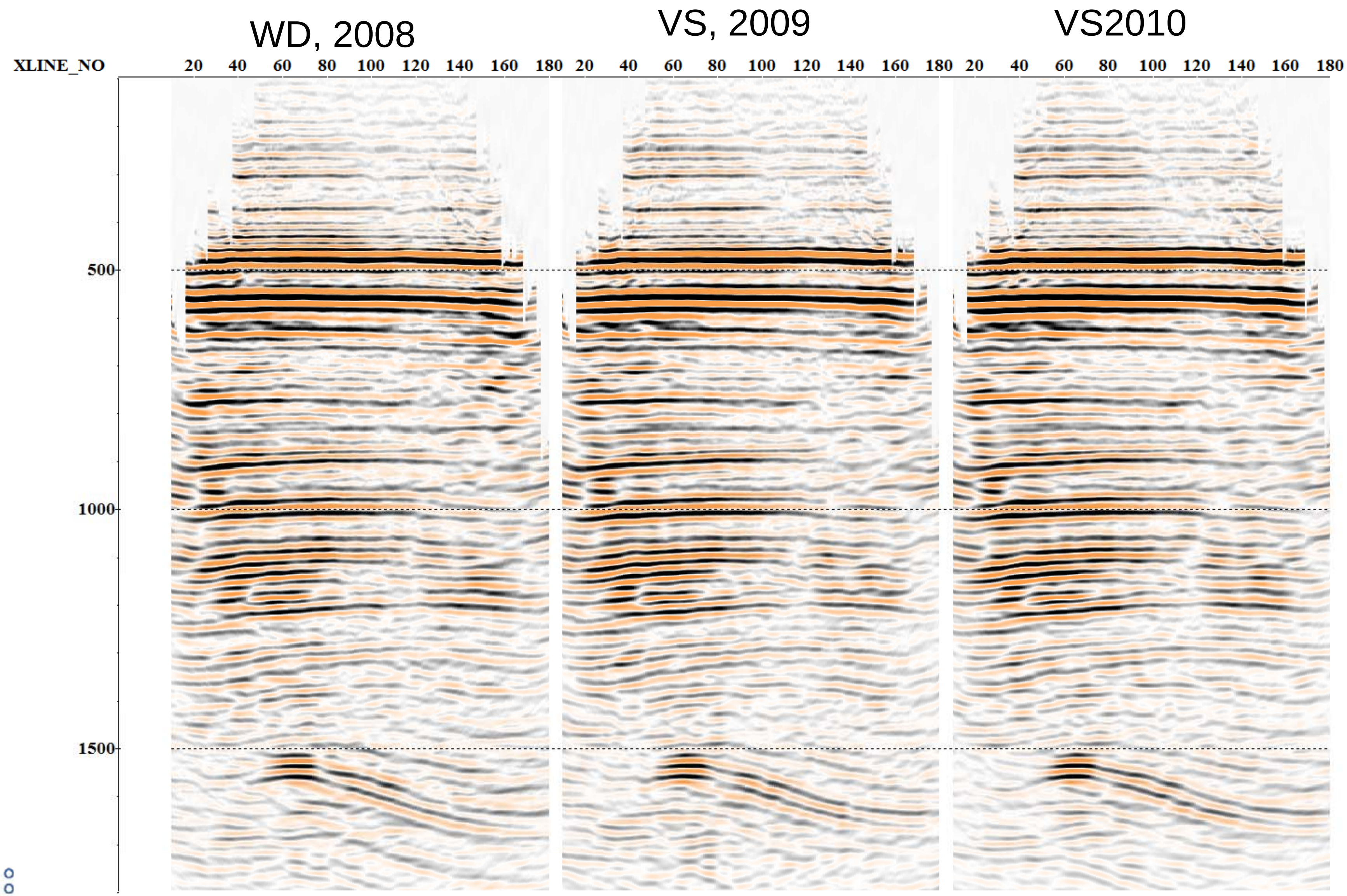
CO2CRC

Soda Rd. Test

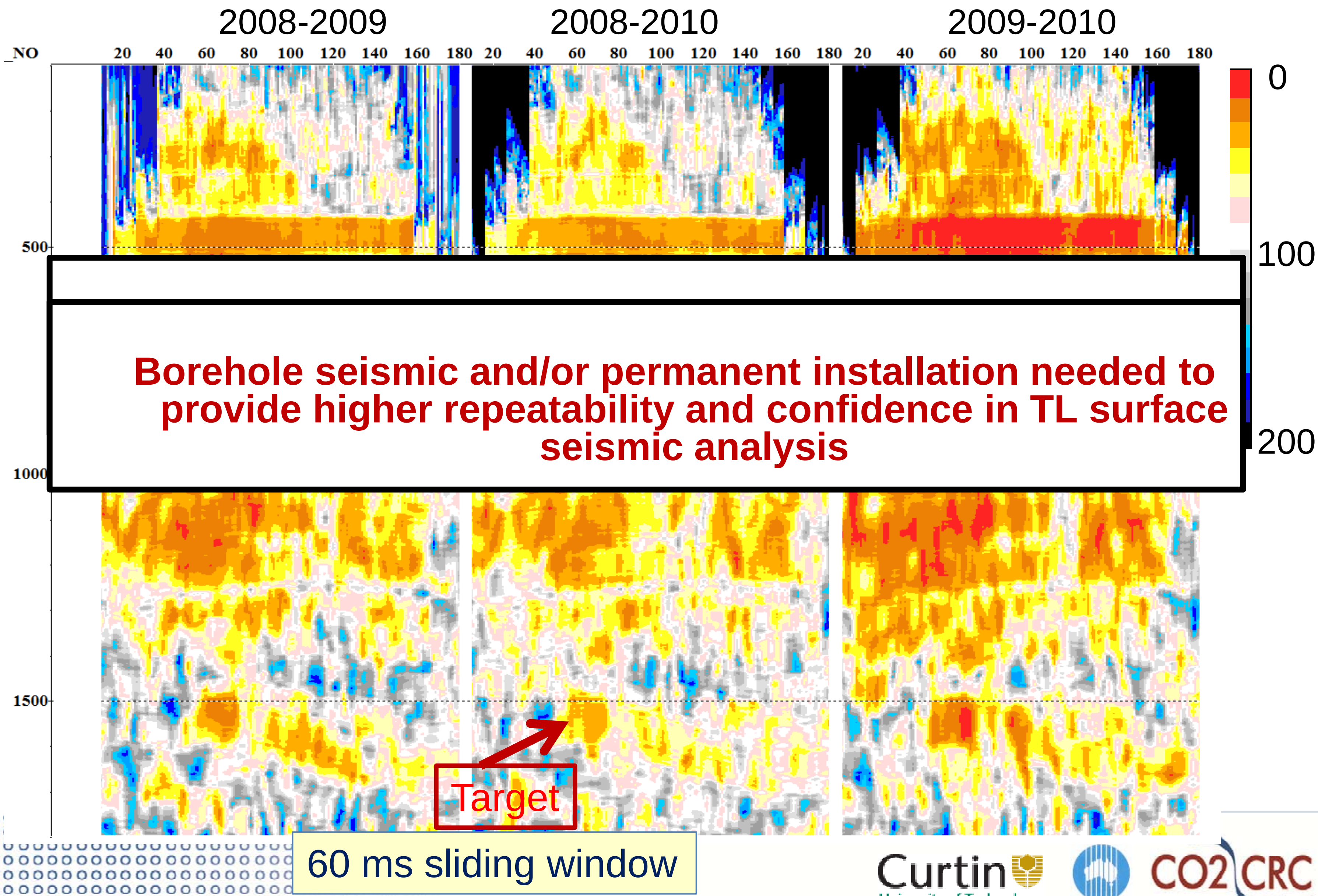


NRMS
A) mb08/wd07n
B) mb08/wd08n
C) wd08/wd07n
T,ms
CDP
NRMS: > 50%
NRMS(S/N, F, R,W)...
S/N
WD 2007, S/N

3D Baseline 2008, repeat I (2009) and II (2010): cross-equalised



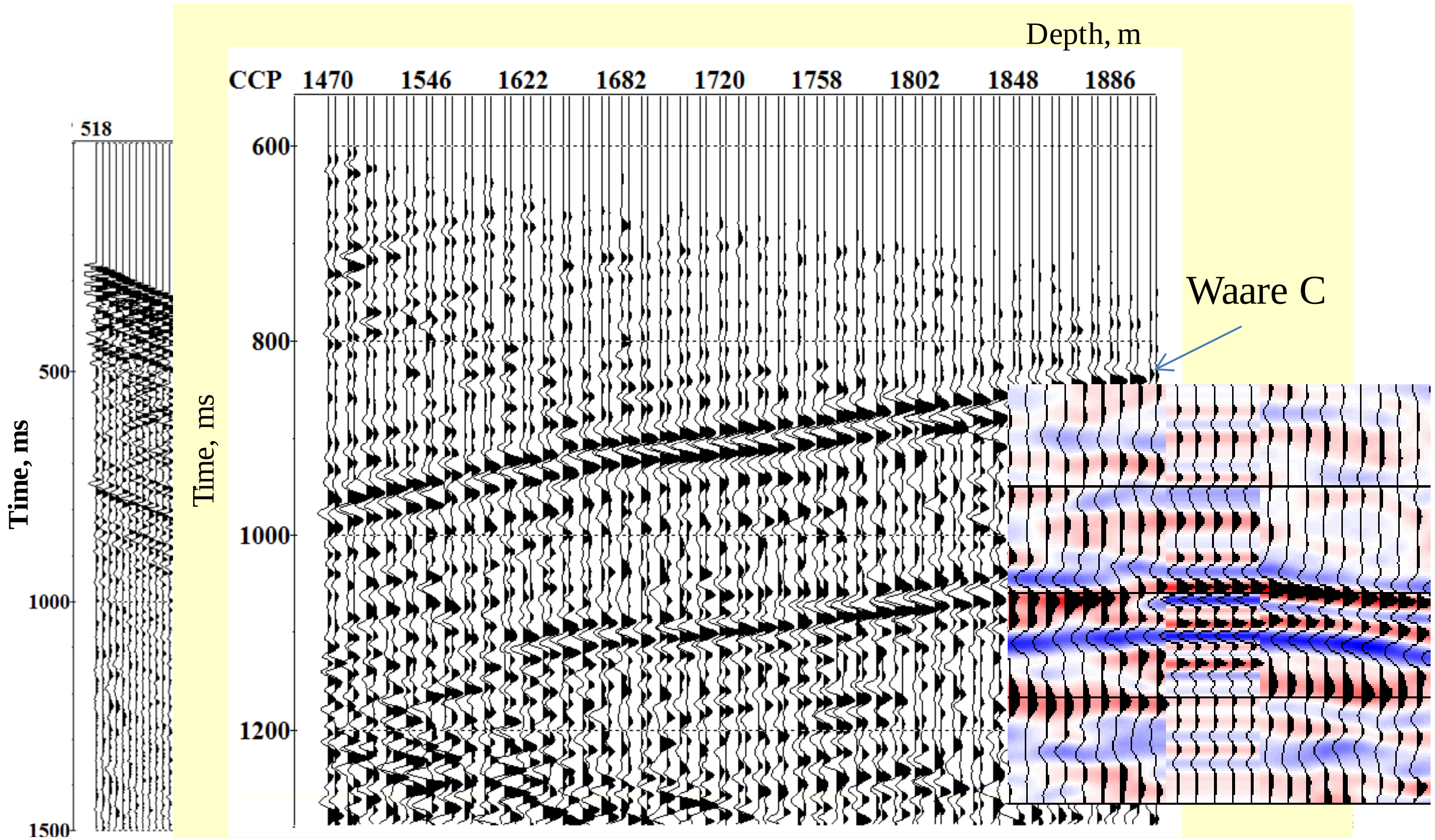
2D lines extracted from NRMS cubes



Borehole seismic and/or permanent installation needed to provide higher repeatability and confidence in TL surface seismic analysis

Curtin University of Technology CSIRO CO2CRC

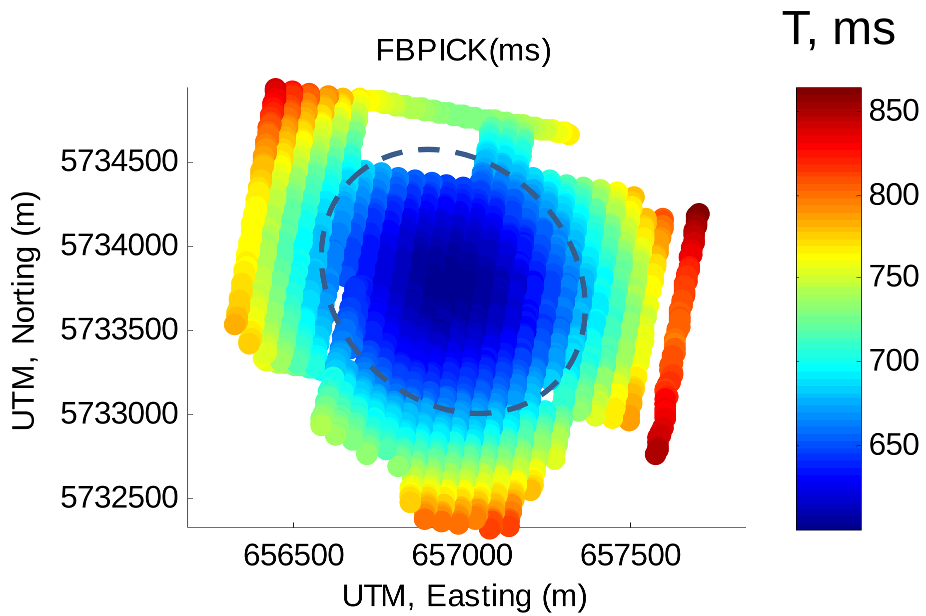
TL ZVSP repeatability (2007-2010)

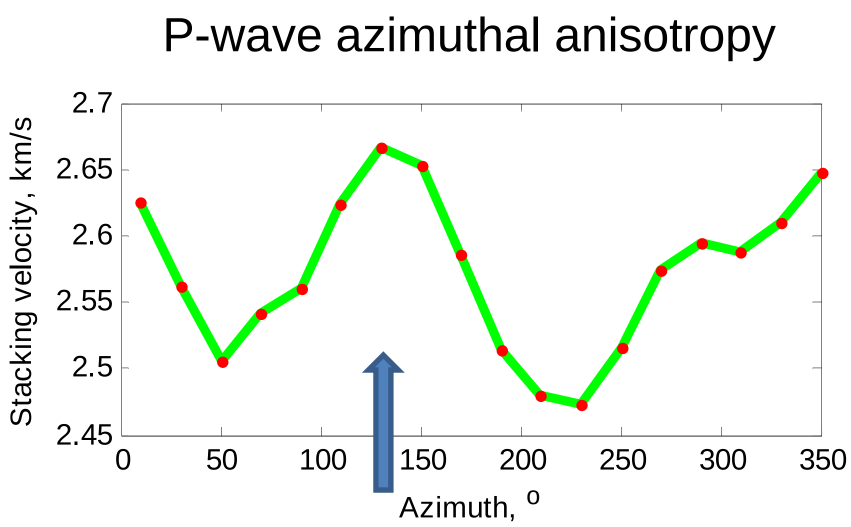


Very high S/N for Waarre-C; NRMS< 10%

3D TL VSP studies

Schlumberger – TL 3D imaging; Curtin – full wavefield analysis



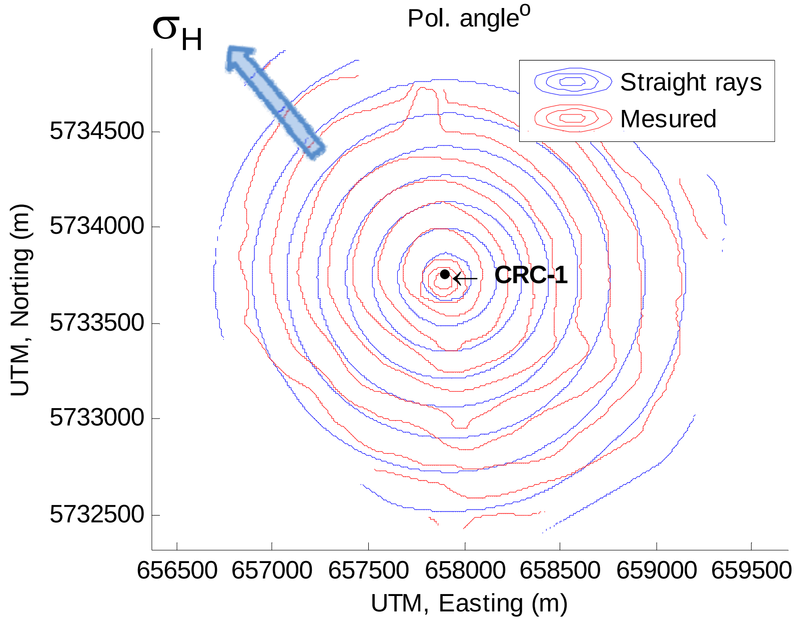


"Stacking" velocity analysis

Fast direction

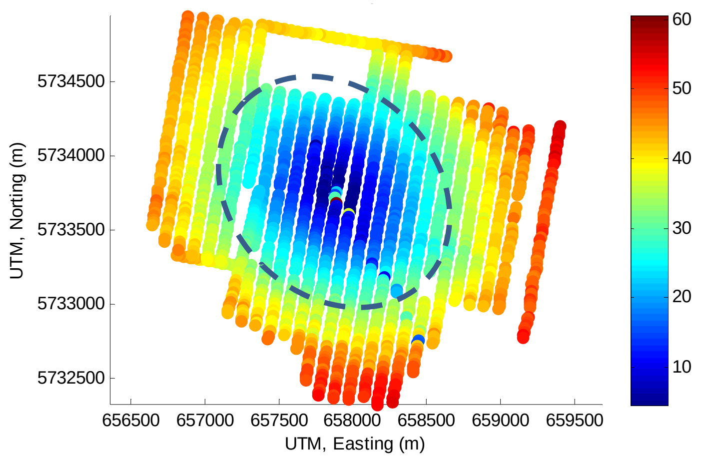
-Elevation statics
-First breaks average hyperbola
for azimuthal segment using 15° increment

P-wave anisotropy



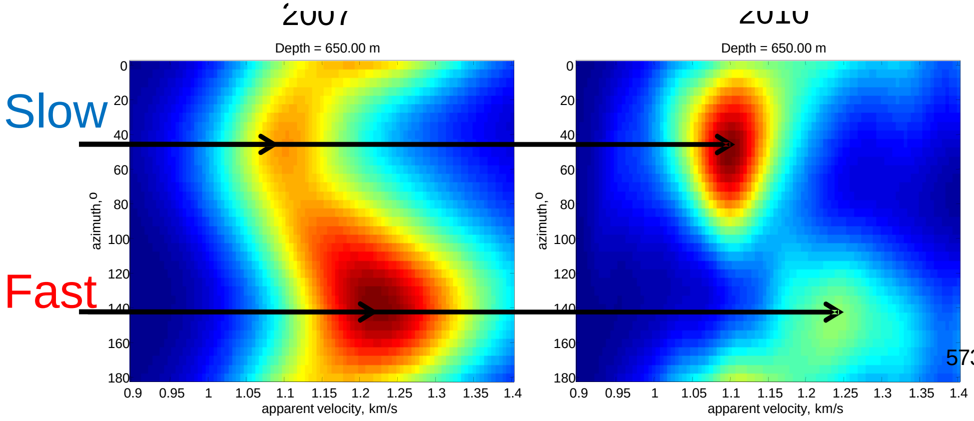
σ_H =140-145^0

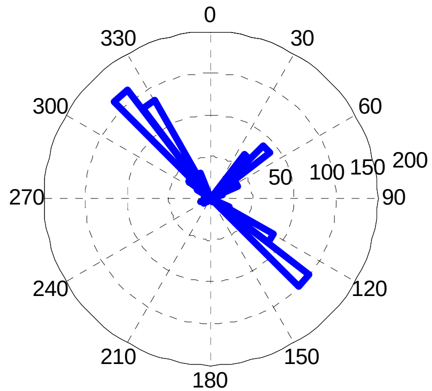
Inclination angle

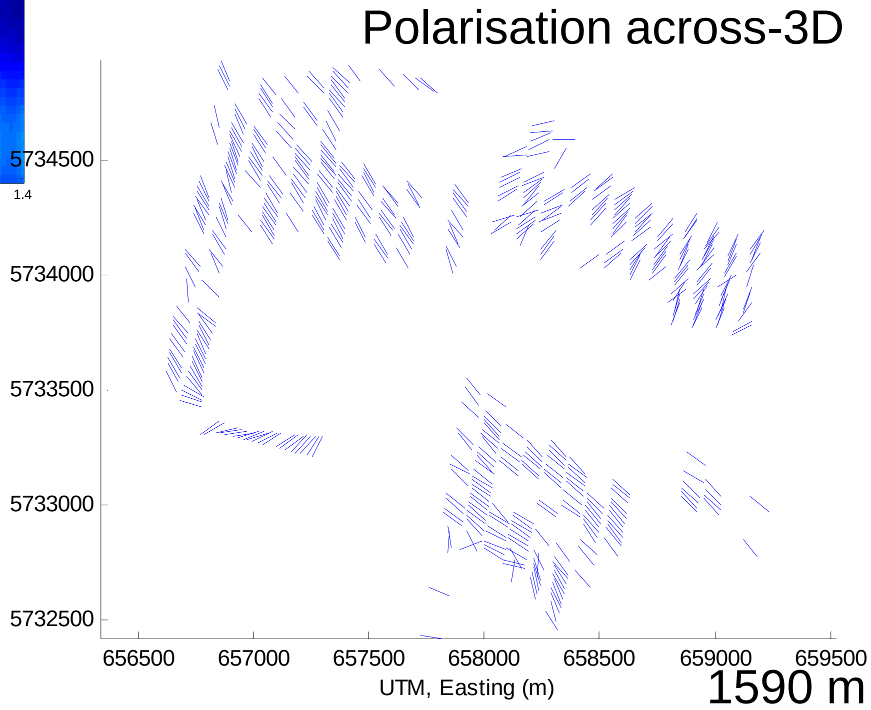


Converted S-wave anisotropy: CO_2-induced stress changes?

TL seismic anisotropy for M&V?

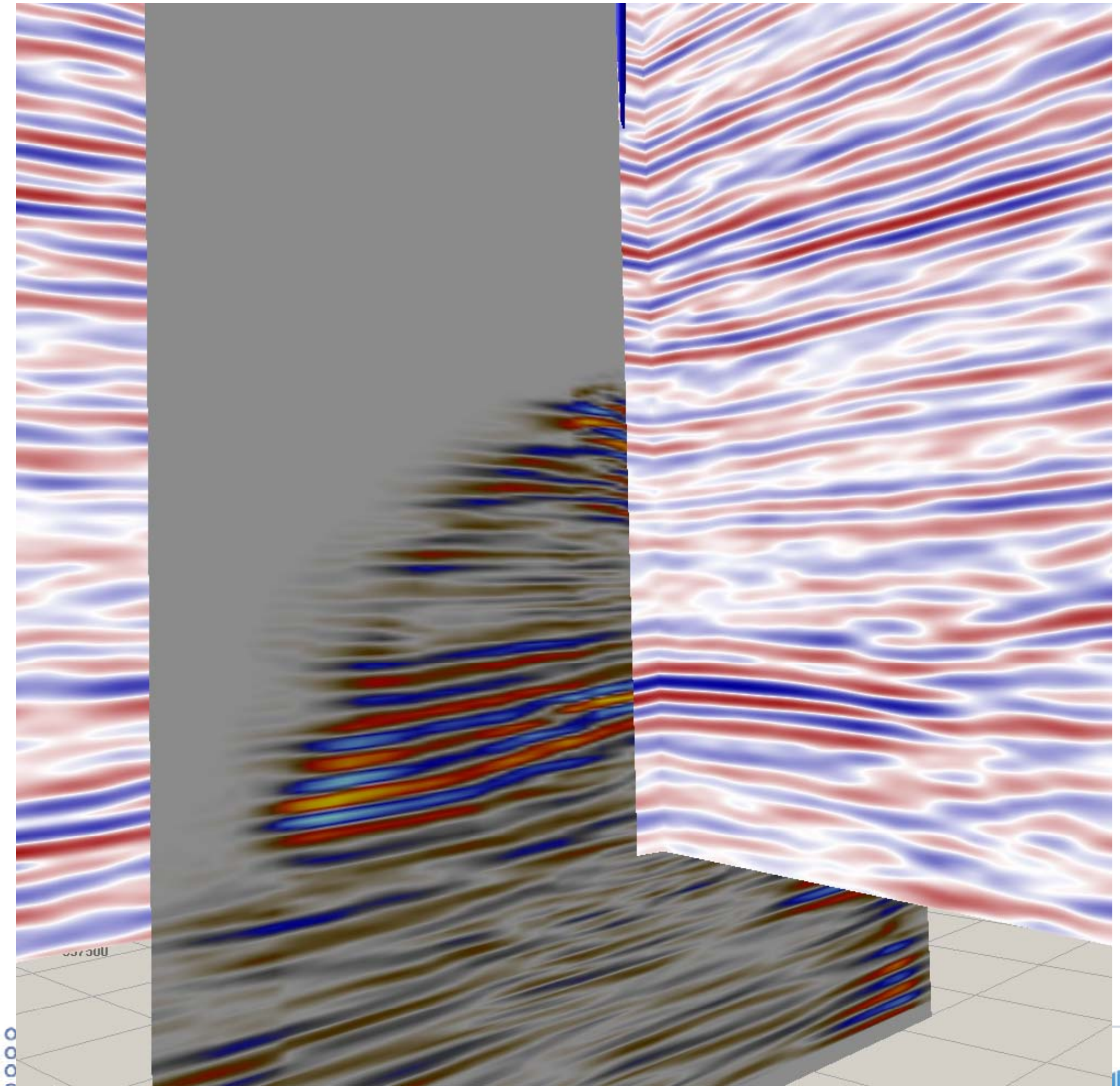






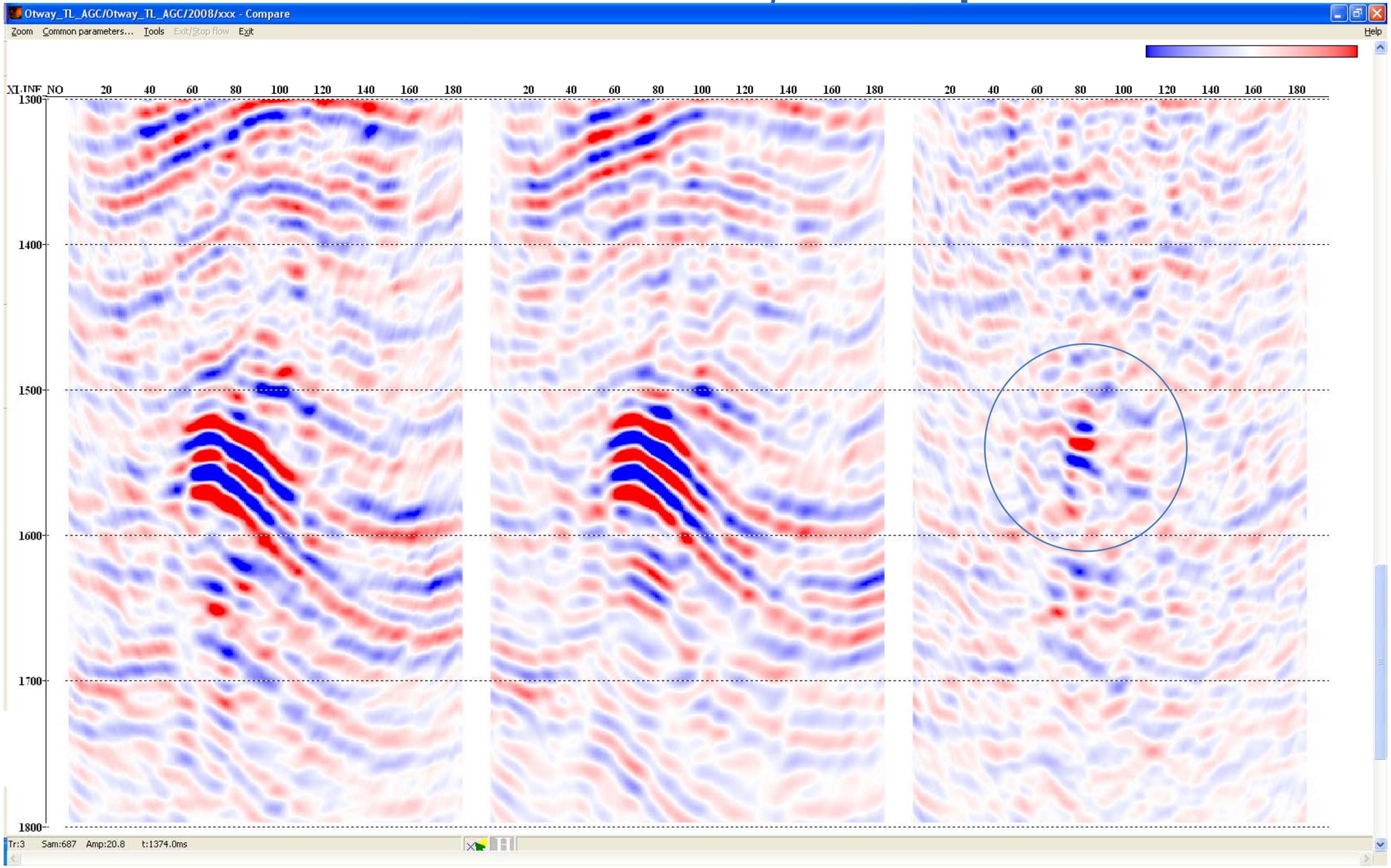
Curtin University of Technology
CSIRO
CO2CRC

3D VSP and surface seismic (baseline)



A. Campbell
Schlumberger

Difference 08-09, First pass



Conclusions and & way forward

- Good quality TL 3D surface data were acquired with Uni-crew
- Base line seismic data recorded with free fall WD source, next two repeats with MB; very good (post-stack) repeatability achieved!
- Changes in soil saturation produce kinematic effects and different ground roll patterns
- CO_2 upward migration (“Leak”) readily detectable with 3D TL seismic
- 3D repeatability much higher than 2D repeatability
- Low S/N low NRMS can improve with either strong source or high-fold
- M&V of CO_2 storage in depleted gas fields could be achievable with high resolution 3D TL seismic, analysis ongoing
- Repeatability important, may need to be determined ahead of TL seismic (NRMS-function of S/N which is dependent on several variables)

Current processing activities

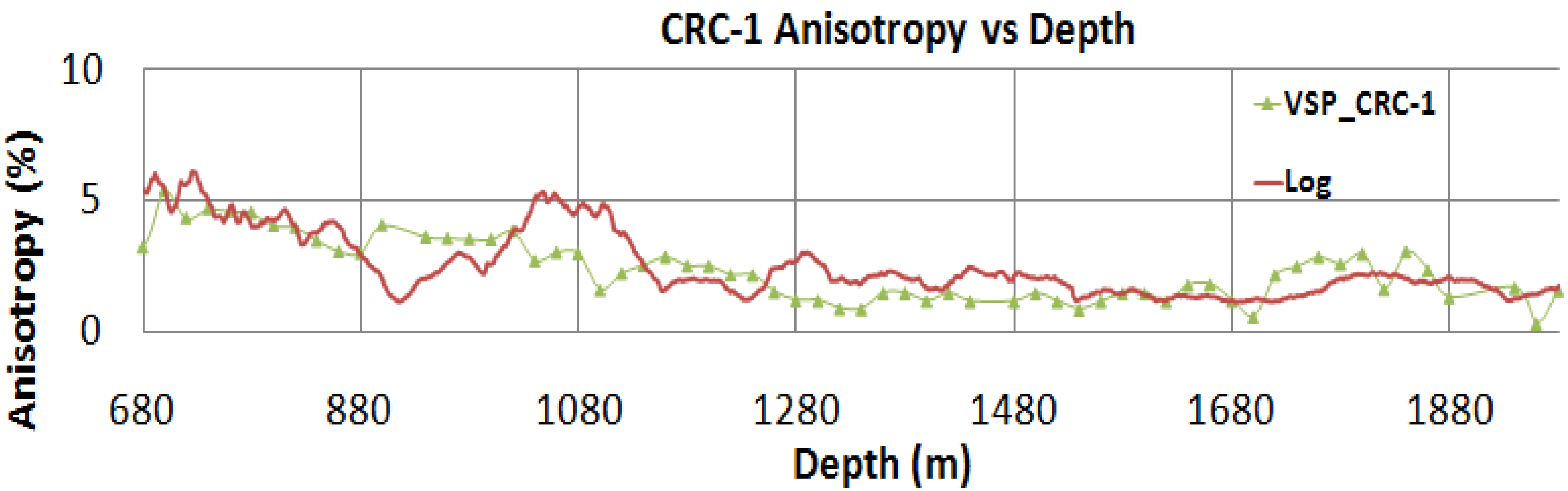
SURFACE SEISMIC

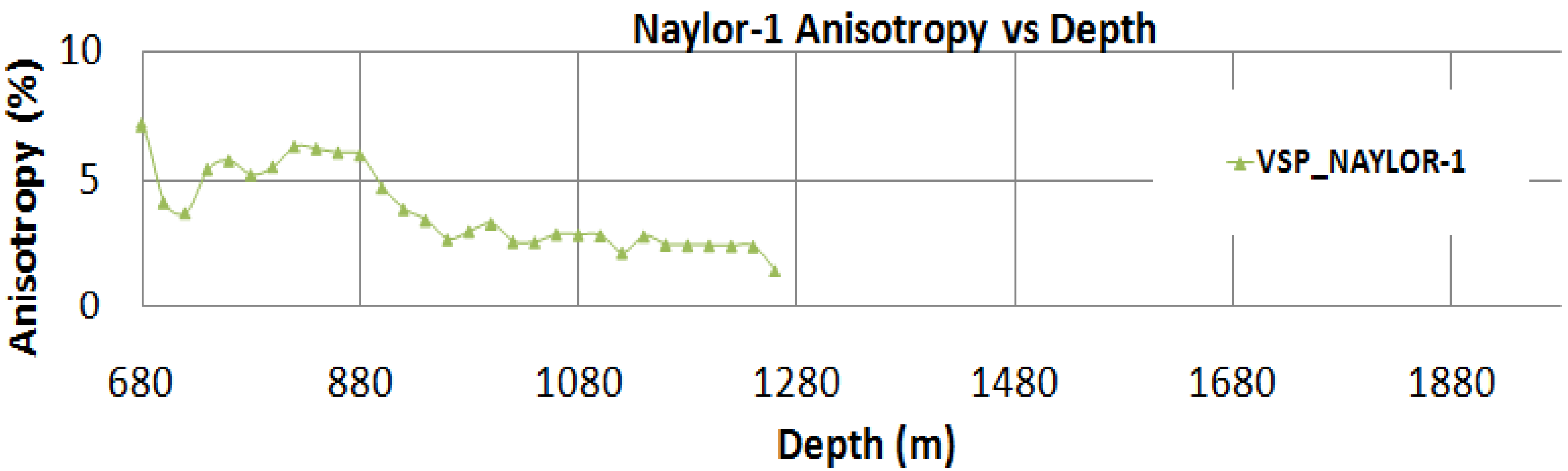
- Reprocessing 3*3D along two different streams
- Reprocessing (3D 09/10 using full number of channels)
- Diffraction processing (leak studies)
- Inversion (AI, EI, AVO)
- Differences in TL attribute maps

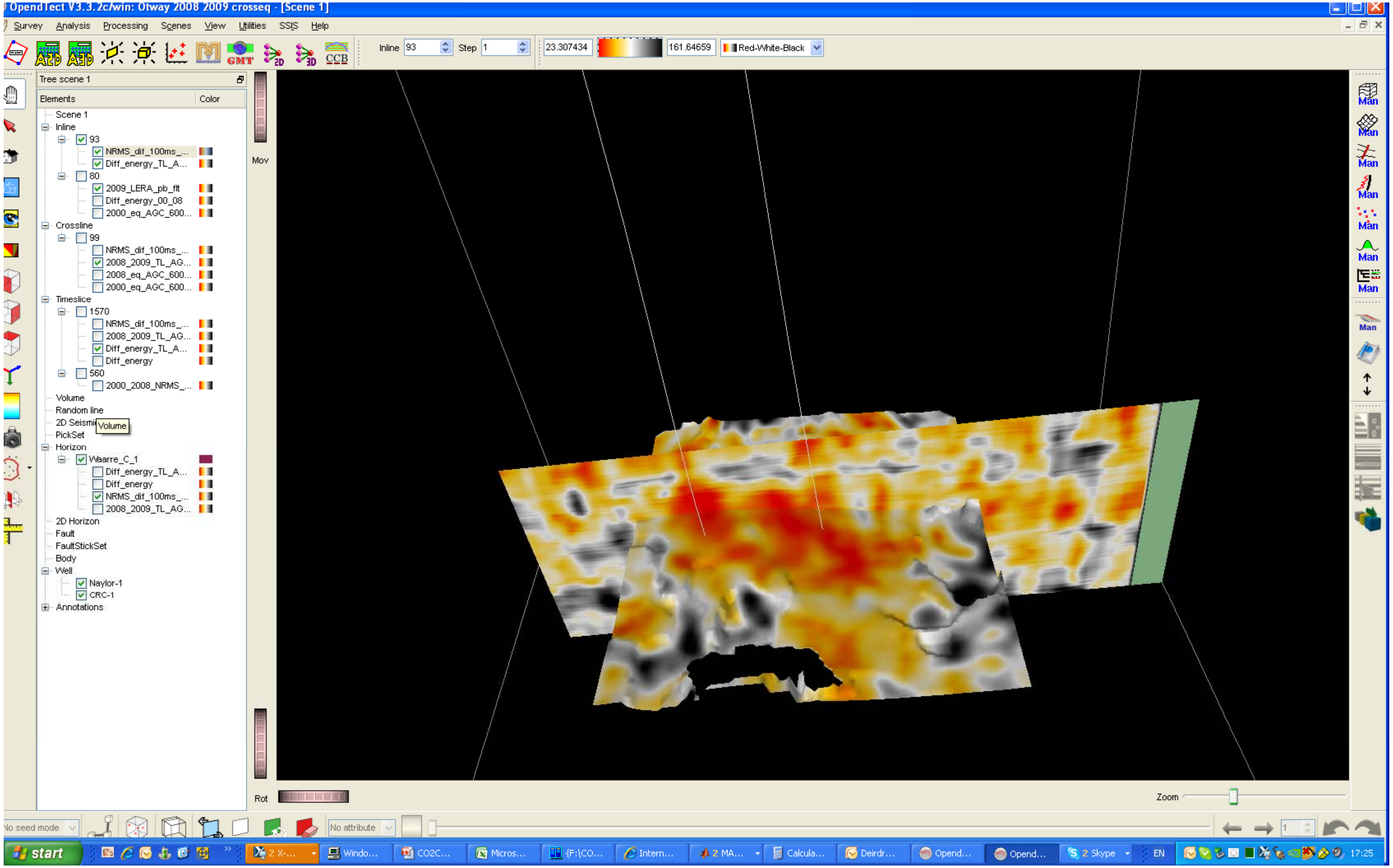
- Reprocessing of pre-production 3D (2000)
- TL analysis (2000,08,09 and 10)

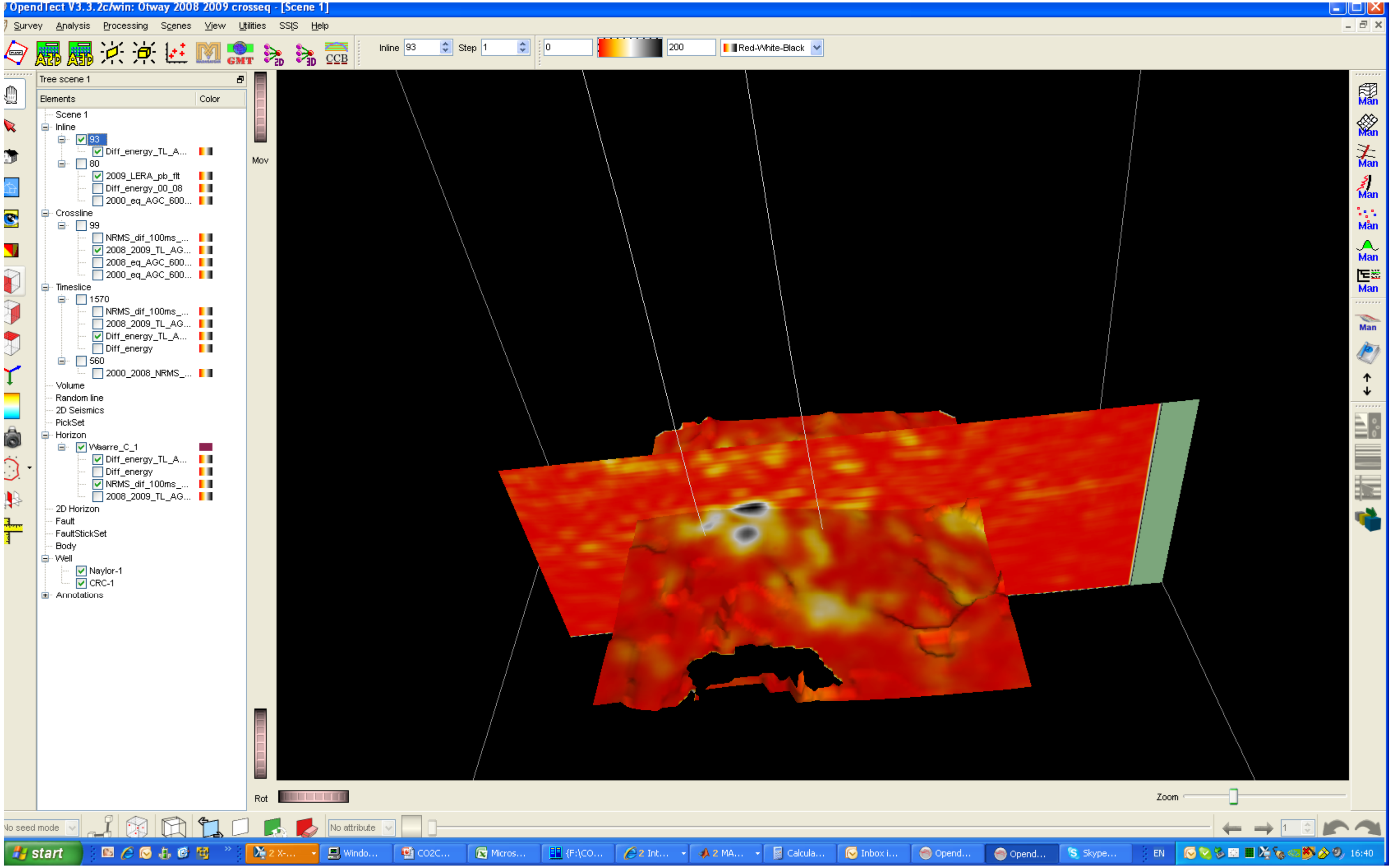
VSP

- Full wavefield analysis (TL 2D and 3D VSP)
- TL VSP image analysis and TL seismic anisotropy (P,S)


CRC-1 Anisotropy vs Depth
Anisotropy (%)
10
5
0
680
880
1080
1280
1480
1680
1880
Depth (m)
VSP_CRC-1
Log


Naylor-1 Anisotropy vs Depth
Anisotropy (%)
10
5
0
680
880
1080
1280
1480
1680
1880
Depth (m)
VSP_NAYLOR-1


OpendTect V3.3.2c/win: Otway 2008 2009 crosseq - [Scene 1]
Survey Analysis Processing Scenes View Utilities SSIS Help
Inline 93 Step 1
23.307434
161.64659
Red-White-Black
Tree scene 1
Elements
Color
Scene 1
Inline
93
NRMS_dif_100ms_...
Diff_energy_TL_A...
80
2009_LERA_pb_flt
Diff_energy_00_08
2000_eq_AGC_600...
Crossline
99
NRMS_dif_100ms_...
2008_2009_TL_AG...
2008_eq_AGC_600...
2000_eq_AGC_600...
Timeslice
1570
NRMS_dif_100ms_...
2008_2009_TL_AG...
Diff_energy_TL_A...
Diff_energy
560
2000_2008_NRMS_...
Volume
Random line
2D Seismic
PickSet
Horizon
Waarre_C_1
Diff_energy_TL_A...
Diff_energy
NRMS_dif_100ms_...
2008_2009_TL_AG...
2D Horizon
Fault
FaultStickSet
Body
Well
Naylor-1
CRC-1
Annotations
Mov
Rot
Zoom
No seed mode
No attribute
start
17:25

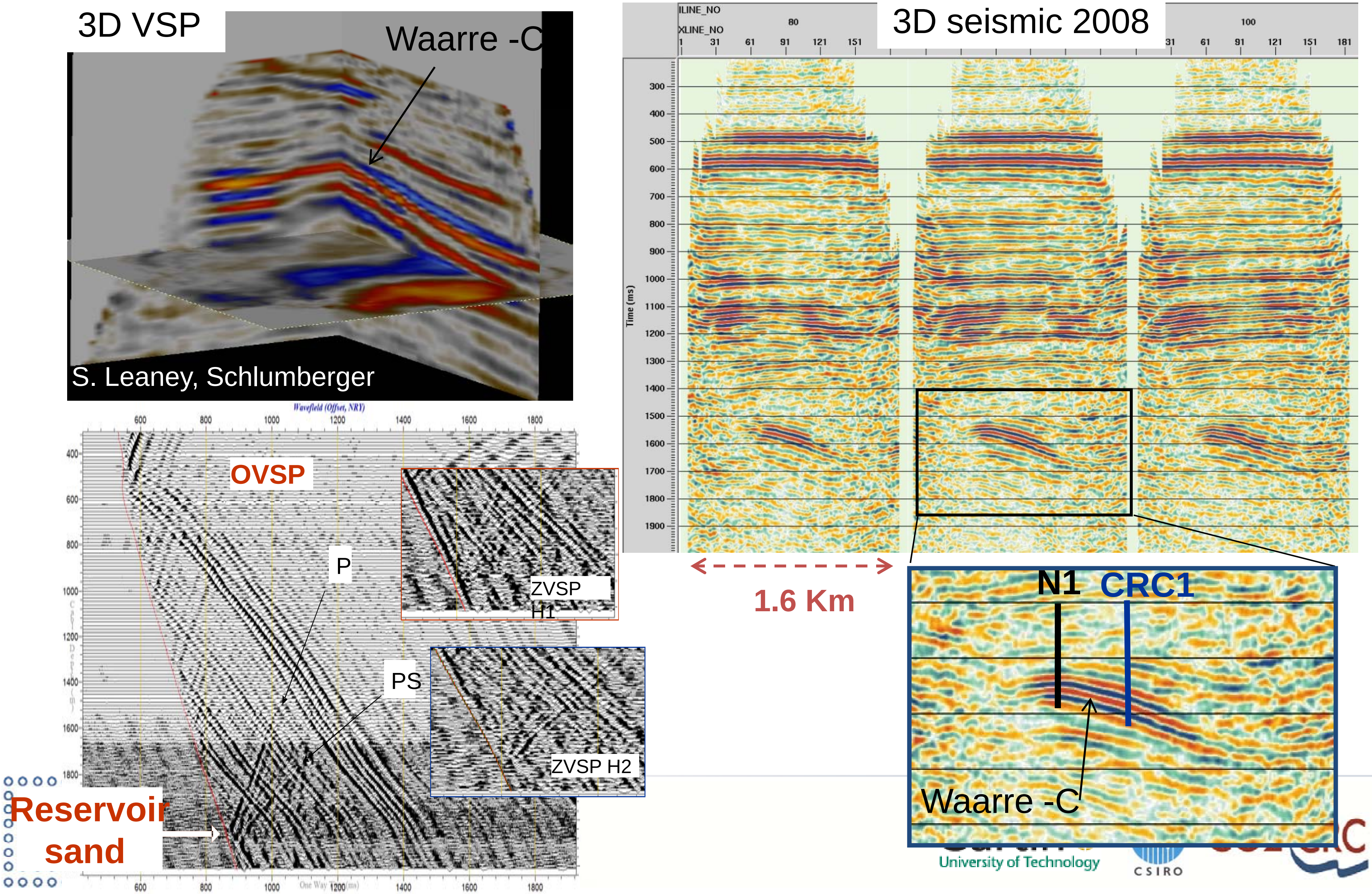


Curtin University of Technology

CSIRO

CO2CRC

BASELINE 3D VSP and 3D surface seismic results



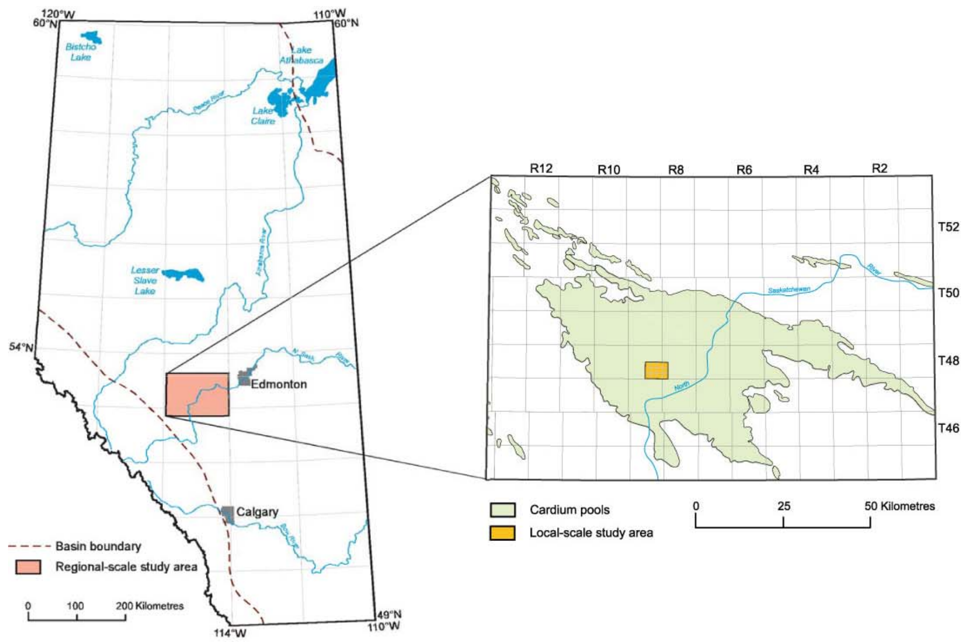
Alberta Innovates Technology Futures

Effects of CO_2 Injection on Mineralogy

Ernie Perkins,
ernie.perkins@albertainnovates.ca

Alberta
Freedom To Create. Spirit To Achieve.

Penn West Monitoring Program



- Geology
- Geophysics
- Geochemical Monitoring
- Reservoir Modelling
- Geomechanics
- Groundwater Monitoring
- Soil Gas and Flux Monitoring
- Atmospheric Monitoring
- Technology Development

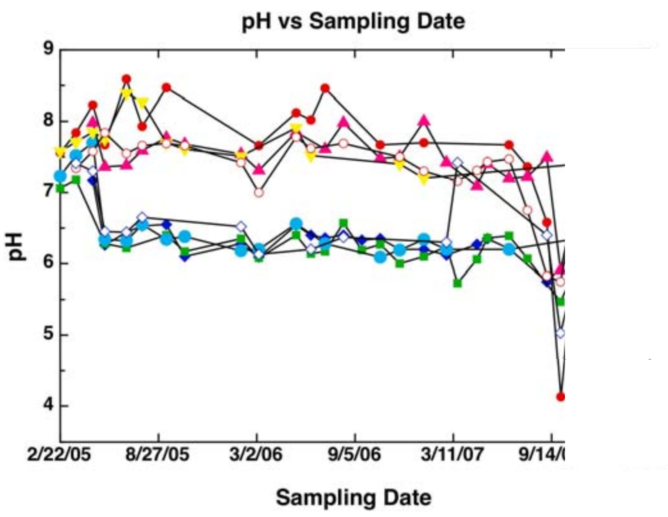
Project completed in 2008.

Geochemical monitoring program is ongoing.

Alberta Innovates Technology Futures

Penn West Monitoring Program

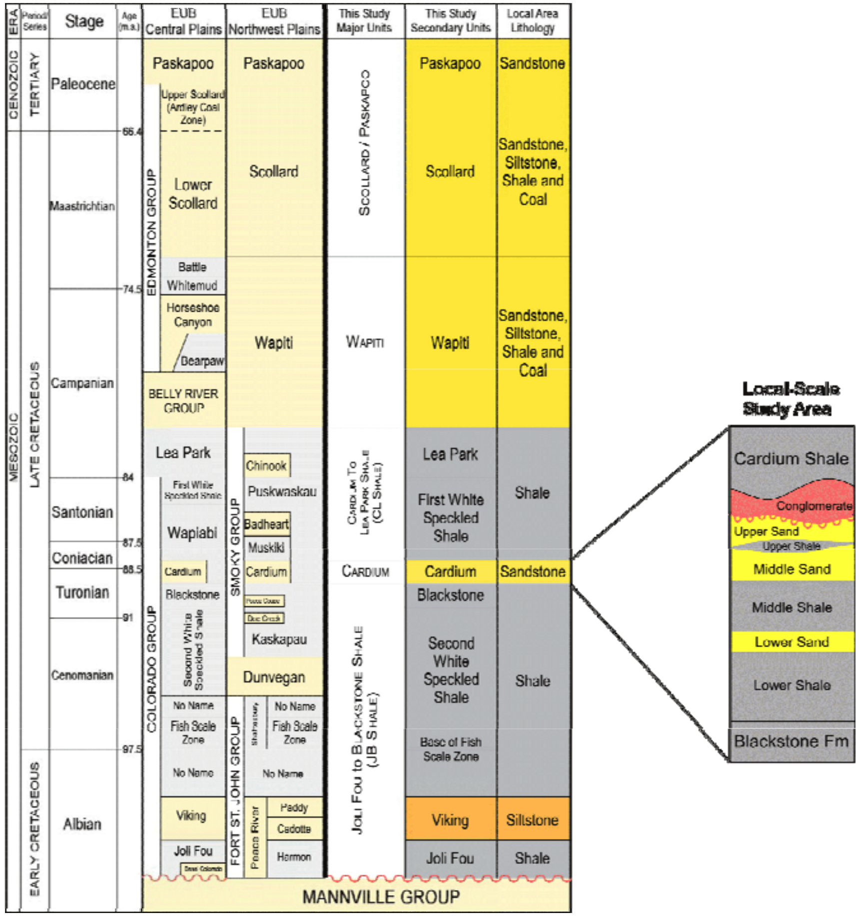
Evaluation of Mineral Reactions



- Direct observation
  - Core
- Prediction
  - Modelling
- Interpretation
  - Fluid Samples

Mineralogy

- Numerous samples were selected from the Cardium from pre-production, post water flood and during CO_2 flood cores.
- Mineralogy of each was established through detailed analytical work.



Alberta Innovates Technology Futures

Mineralogical Results Baseline

Mineral Phases	Cardium Shale wt%	Conglomerate wt%	Upper Sandstone wt%	Middle Sandstone wt%	Lower Sandstone wt%	Cemented Sandstone wt%	Interstitial Shale wt%	Siderite Nodule wt%
Quartz	46.0	85.6	86.4	86.2	86.8	45.3	43.5	4.7
Kaolinite	6.3	1.9	2.3	2.6	2.1	1.5	4.4	0.9
Chlorite	3.3	1.0	0.8	1.0	1.0	0.0	2.2	0.1
Albite	2.7	0.3	0.5	0.6	1.3	0.8	2.3	1.5
Smectite	0.9	0.0	0.0	0.0	0.0	0.0	2.2	0.0
Calcite	0.2	1.7	0.2	0.2	0.1	12.5	0.2	4.0
Muscovite	15.5	1.8	2.6	2.1	2.3	1.6	17.1	4.1
Illite	14.0	2.1	1.7	1.4	1.5	1.1	14.1	3.3
Anatase	0.7	0.1	0.1	0.1	0.2	0.1	0.7	0.2
Apatite	0.4	0.5	0.3	0.3	0.3	0.0	0.7	1.2
Pyrolusite	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2
Siderite	0.5	0.5	1.1	0.7	0.4	32.3	1.1	75.5
Pyrite	1.6	0.2	0.5	0.4	0.2	0.4	1.4	0.1
K-feldspar	3.7	1.1	0.9	1.2	1.1	1.0	3.1	0.7

Alberta Innovates Technology Futures

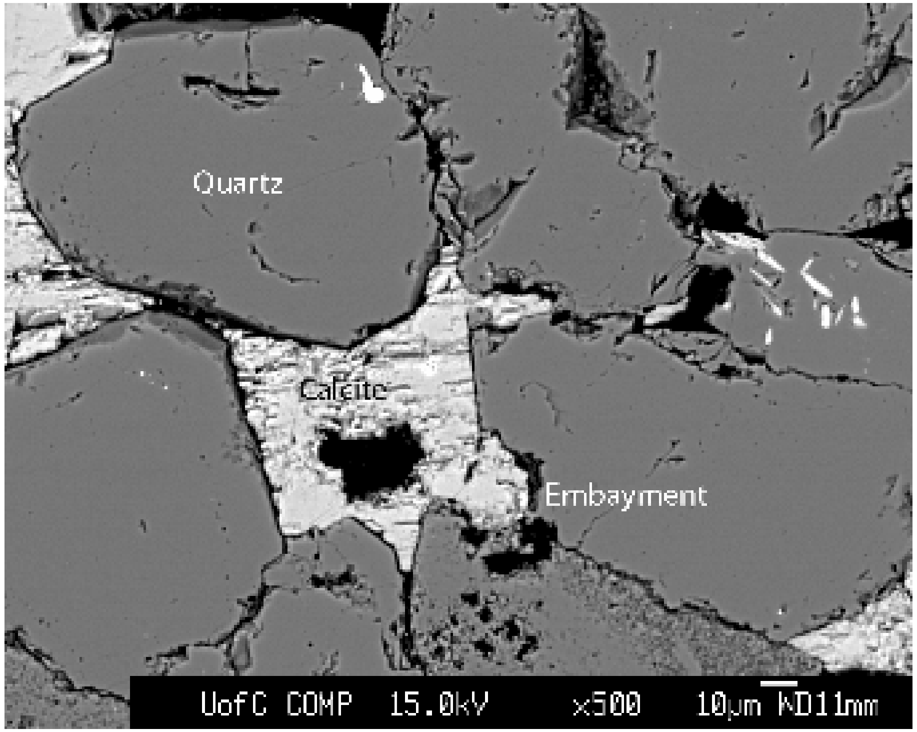
Observed Mineralogical Changes

- Post Water Flood
  - Dissolution of quartz, feldspar, carbonates.
  - Dissolution features (etching, pitting, etc).
  - No precipitation of new phases observed.
- During CO2 Flood
  - Exactly the same mineralogical and textural features!

Any changes due to CO_2 flood could not be distinguished from the changes due to the water flood.

Alberta Innovates Technology Futures

Why were there no observed changes in core due to the CO_2 Flood?



Hypotheses?

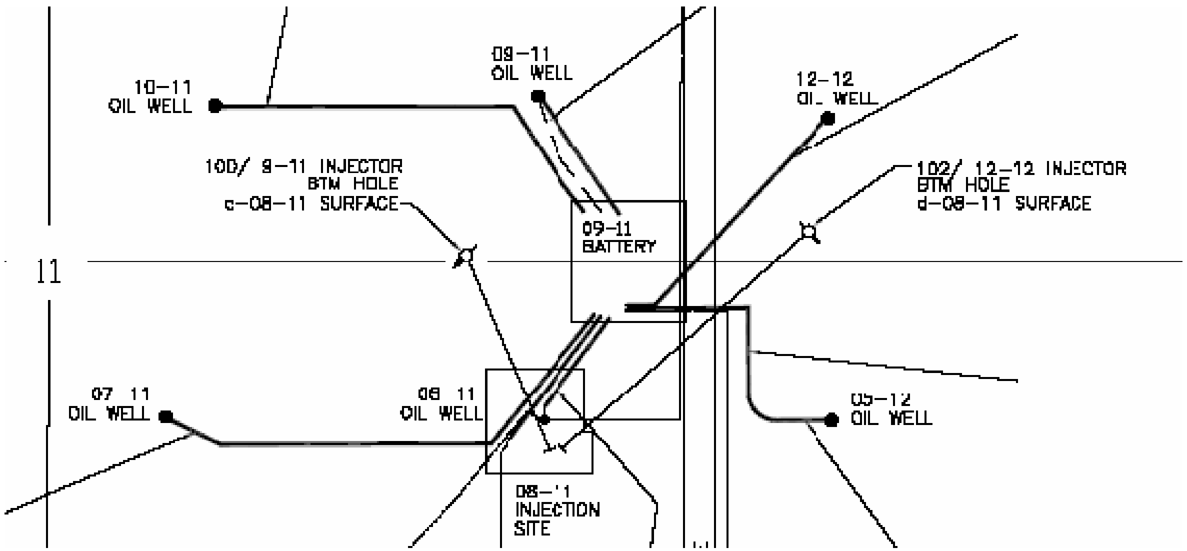
- ? Core was tight.
- ? CO_2 did not sweep this area of the reservoir.
- ? Reactive mineralogy / surface sites gone – reacted out due to water flood.
- ? Fluids are in equilibrium by the time they reach this area of the reservoir

None of these hypotheses are really satisfactory.

Alberta Innovates Technology Futures

Processes included in Models

- Fluid (CO_2, H_2O, Oil) transport
- Fluid Mixing
- CO_2 dissolution into/out of aqueous phase
- CO_2 dissolution into/out of oil
- Ion exchange
- Mineral dissolution
- Mineral precipitation
- Residual trapping



Alberta Innovates Technology Futures

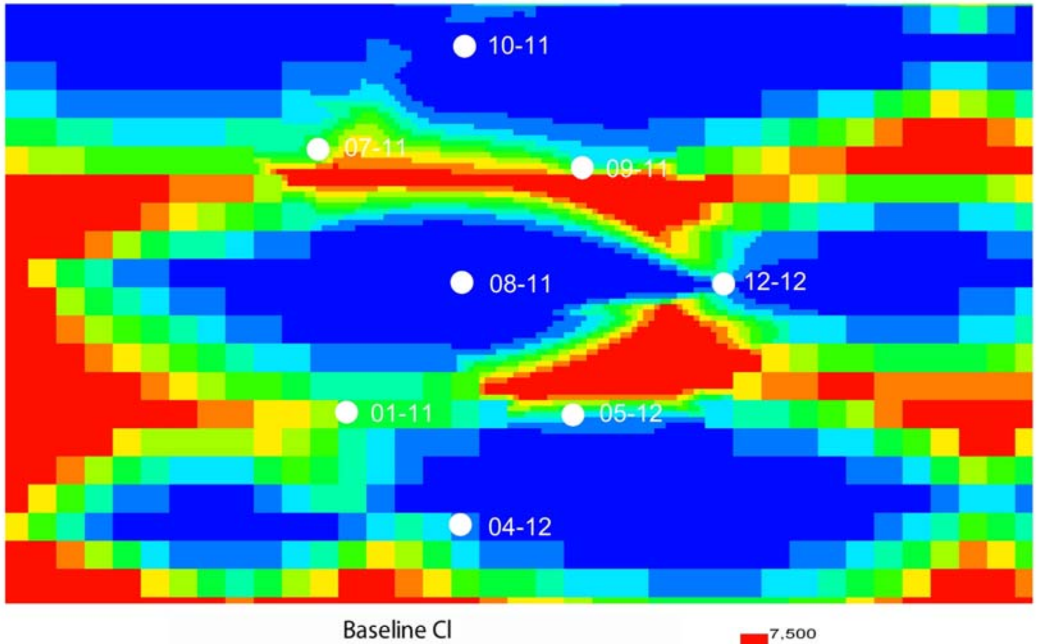
Geochemical Reservoir Modelling

Using CMG GEM reservoir simulator

Model history matched to oil and water production

Modelled mineral dissolution is very small, resulting in insignificant changes to porosity (<0.01%) and permeability

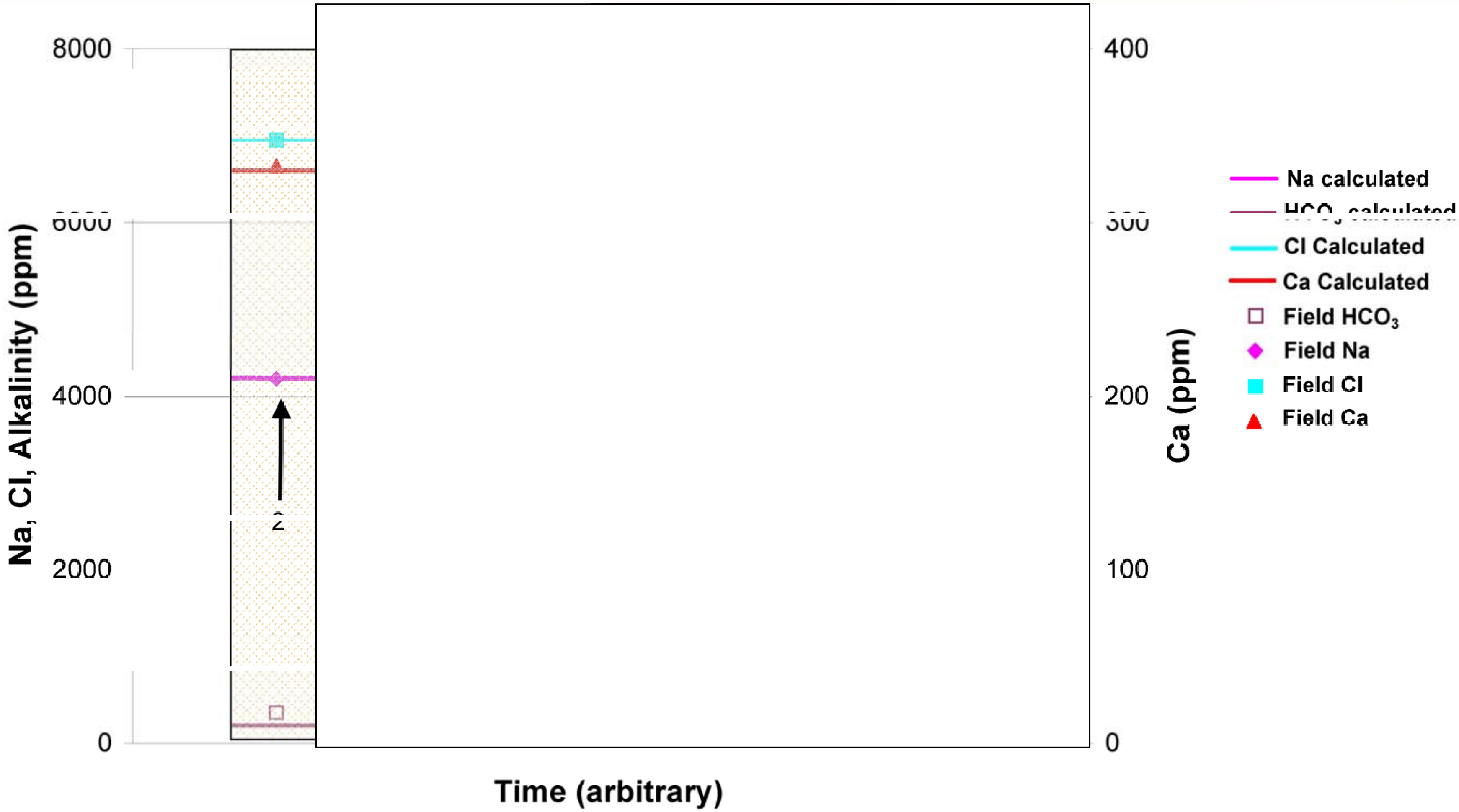
Chloride distribution at end of water flood



Flow in the reservoir is controlled by fractures

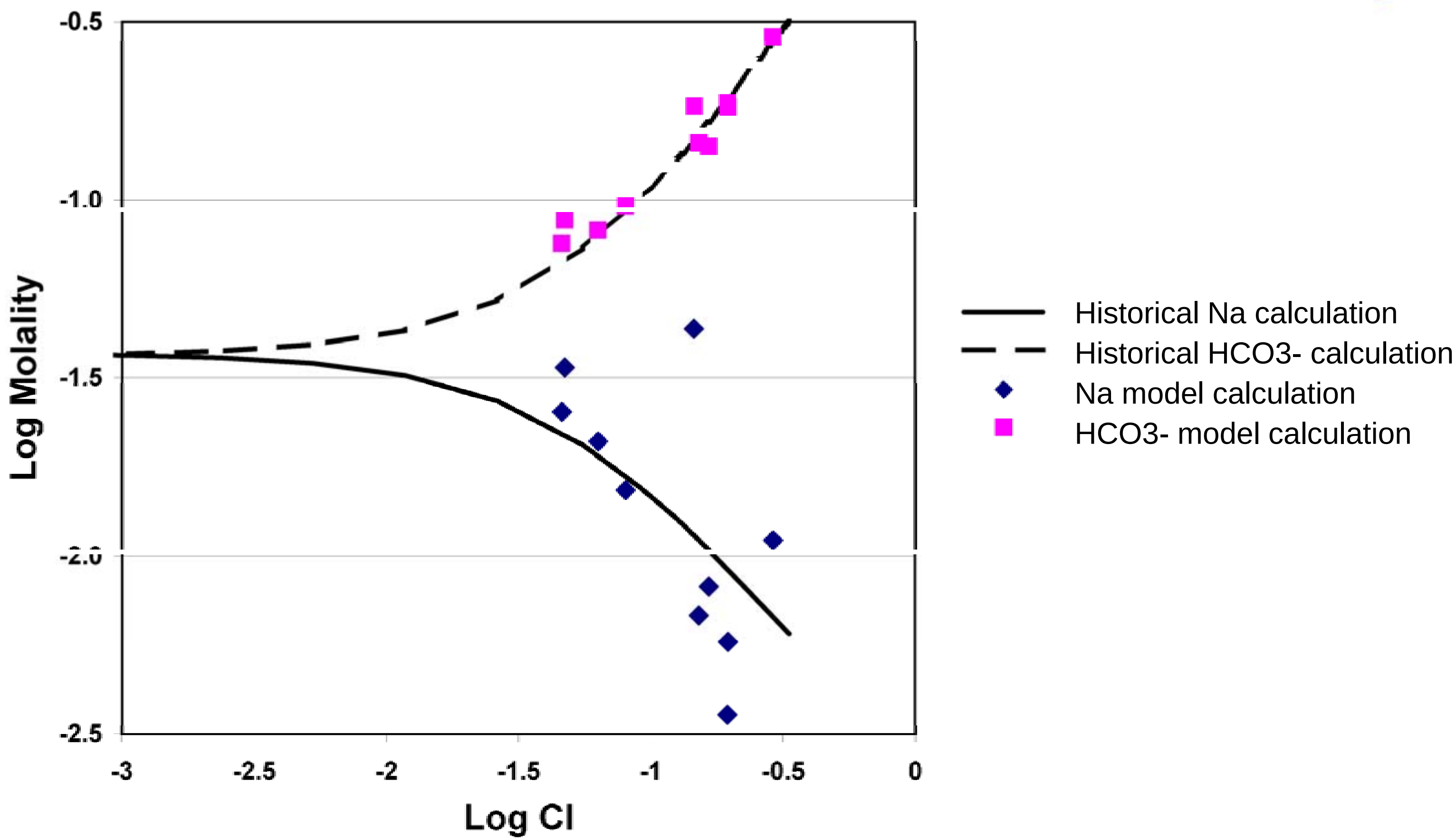
Alberta Innovates Technology Futures

1-D slice – concentrations



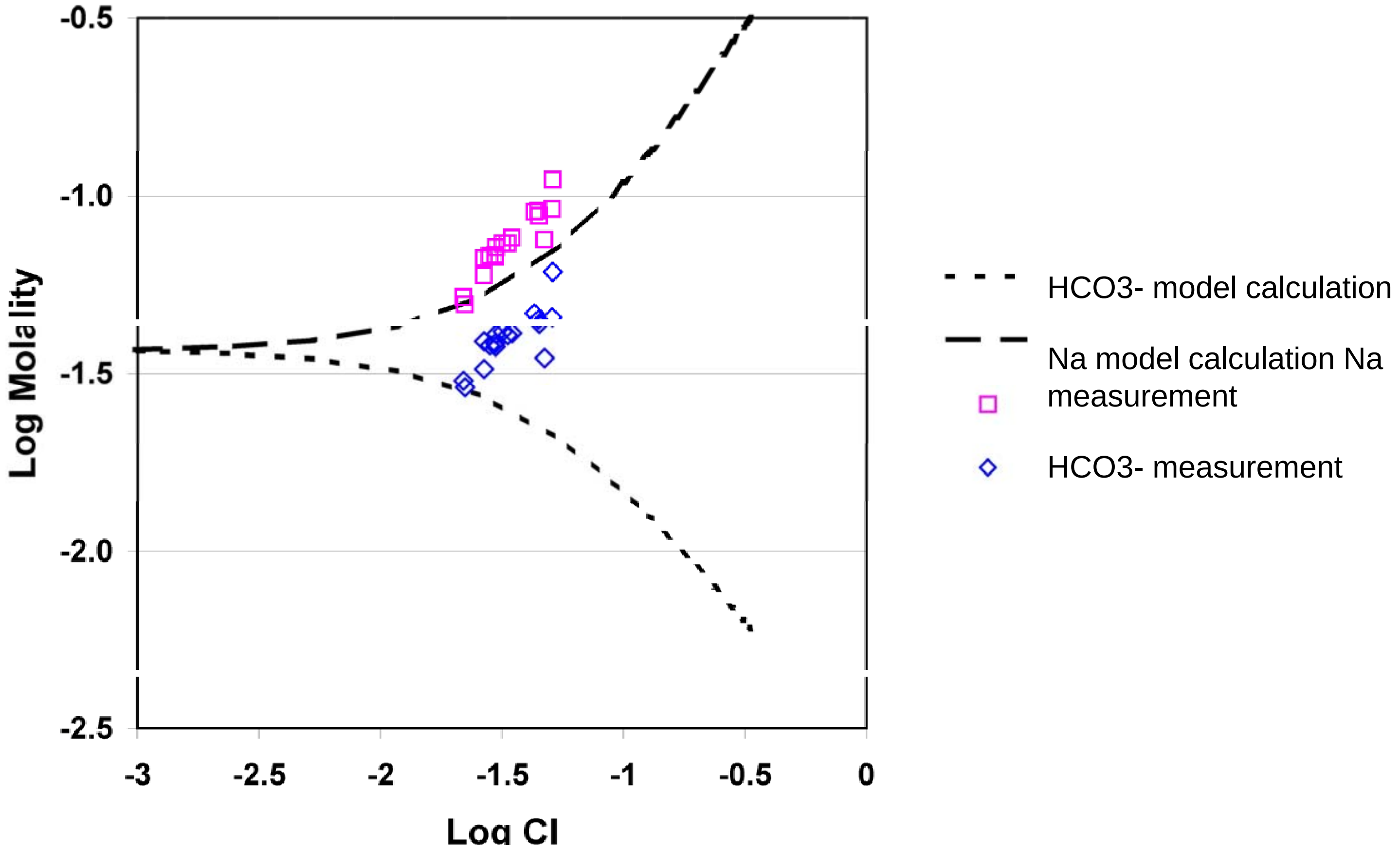
Technology Futures

Measured and modelled concentrations during the water flood



Alberta Innovates Technology Futures

Measured and modelled concentrations during the CO_2 flood



Alberta Innovates Technology Futures

Why the differences?

- Geological model not accurate (faults not properly implemented, porosity/permeability variations/issues, etc).
- Numerical issues (grid size, convergence problems, model simplified too much, etc).
- Computational ability (faster, bigger … more power).

Detailed evaluation has shown all of the above are true to *some* extent.

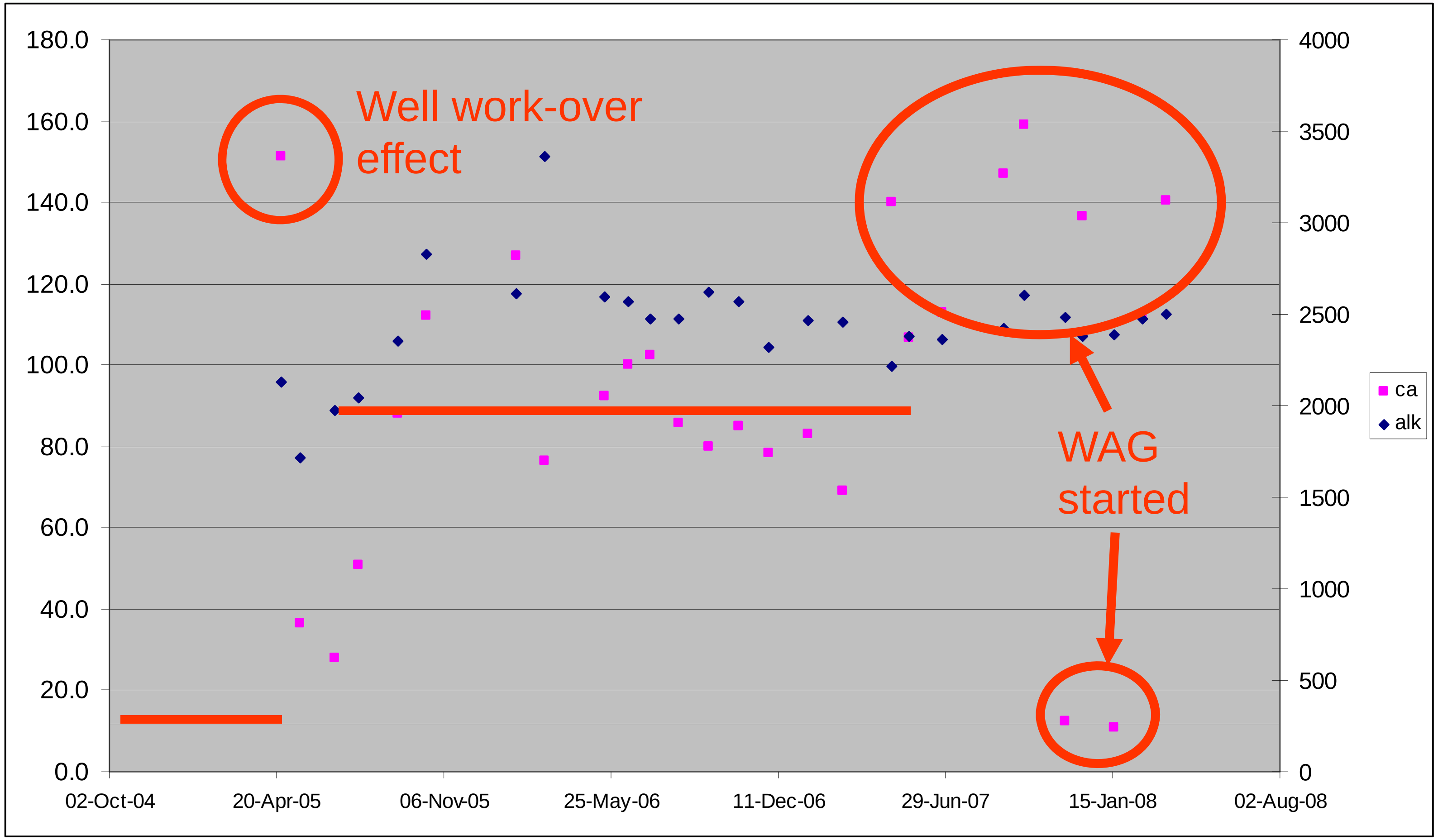
Alberta Innovates Technology Futures

Mass balance Considerations Water flood

- Using Cl concentration in formation and injection fluid, sodium concentration was estimated.
- Observed concentration approximately 300 mg/l higher than expected (based on conservative mixing).
- Calcite dissolution displaces Na from Clay surface
- 250 mg/l Ca released by calcite dissolution

Alberta Innovates Technology Futures

Field Ca and alkalinity versus time
(just at/after breakthrough)



Well 7-11

Mass balance Considerations CO_2 Flood

- Based on calcium and bicarbonate concentration changes, calcite dissolution results in approximately 80 mg/l dissolved Ca.
- Less Ca is released (less calcite/carbonates dissolved) during the CO_2 flood than the water flood.

Alberta Innovates Technology Futures

Geochemical Fantasy

Over 30 years of EOR (with lots of assumptions),

- Assuming 100 % sweep (contact with “reactive reservoir”),
  - only ~8 grams of calcite is dissolved per ton of reservoir.
- Assuming 0.1 % sweep (contact with “reactive reservoir”),
  - only ~8 kilogram of calcite is dissolved per ton of reservoir.

Alberta Innovates Technology Futures

General Geochemical Conclusions

- Significant amount of mineral reaction will only be observed in limited areas

.

- Field chemical / operational history may interfere / hide mineralogical (and fluid) changes.

Alberta Innovates Technology Futures

Penn West Conclusions

In the Penn West reservoir,

- Core studies, geochemical modelling predictions and interpretation of monitoring date indicate that **mineralogical changes** are small.
- The impact of **mineralogical changes** on flow is minimal.
- Formation water chemistry is very a sensitive monitoring tool to monitor **mineralogical changes**.

Alberta Innovates Technology Futures

This work was carried out with the strategic guidance and financial support of:

AERI Alberta Energy Research Institute

Western Economic Diversification Canada / Diversification de l'économie de l'Ouest Canada

Penn West Energy Trust

Alberta Government

Natural Resources Canada / Ressources naturelles Canada

Alberta Innovates Technology Futures

Lawrence Livermore National Laboratory

SECARB
Cranfield Electric Resistance Tomography (ERT) Observations
(1 Dec 2009 – 1 Mar 2010)

C. Carrigan (LLNL)
D. La Brecque (MPT)
D. Larsen (Promore-Corelab)
A. Ramirez (LLNL)
W. Daily (MPT)
D. Freeman (Sandia Tech.)
J. Friedmann (LLNL)
S. Hovorka (BEG – UT)



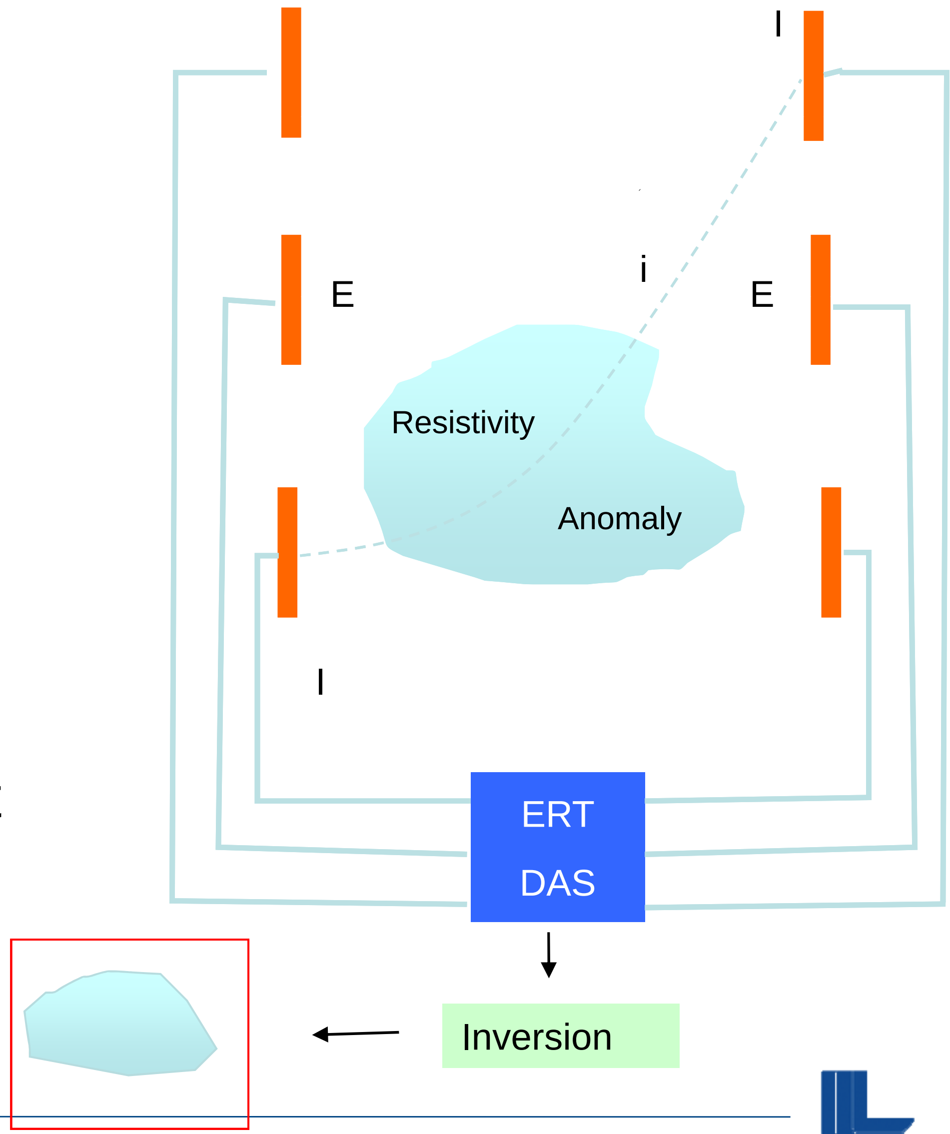

(photos courtesy of David Freeman)

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

This work performed under the auspices of the U.S. Department of Energy by
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

“ERT 101-- add history”

- Initial development for geophysical use (1980’s) -- US, Japan, Canada
- Switched DC, 4 electrode measurement approach
- Measurements provide E and I pairs for many electrode combinations and current pathways
- Electrical data inverted to find resistivity model that best fits E and I data subject to imposed constraints



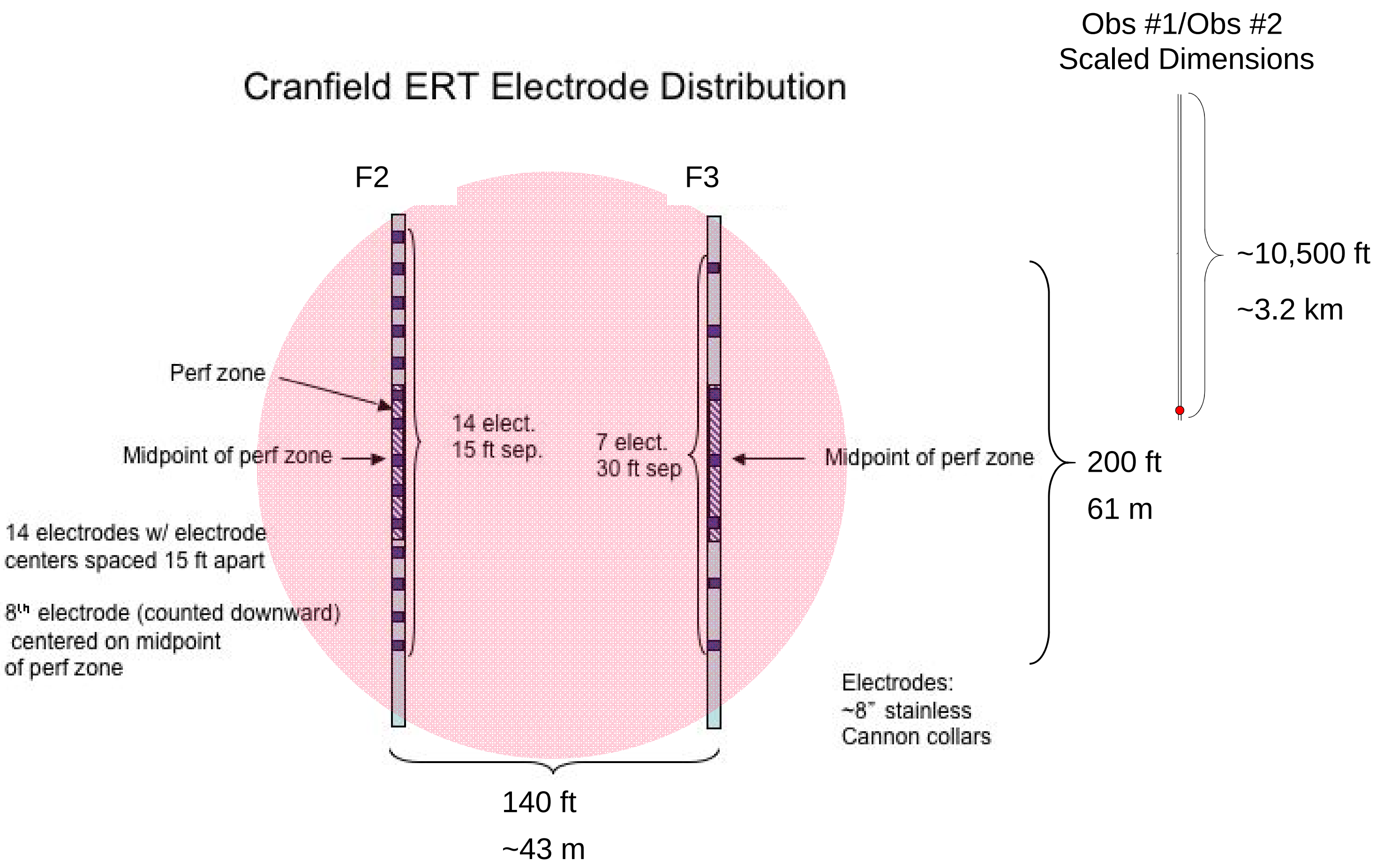
Advantages of ERT Imaging Approach

- Robust System – no moving parts
- Outside-the-casing installation
- Relatively low cost to install
- Very low cost for continuous, autonomous operation
- Can be operated remotely with internet control

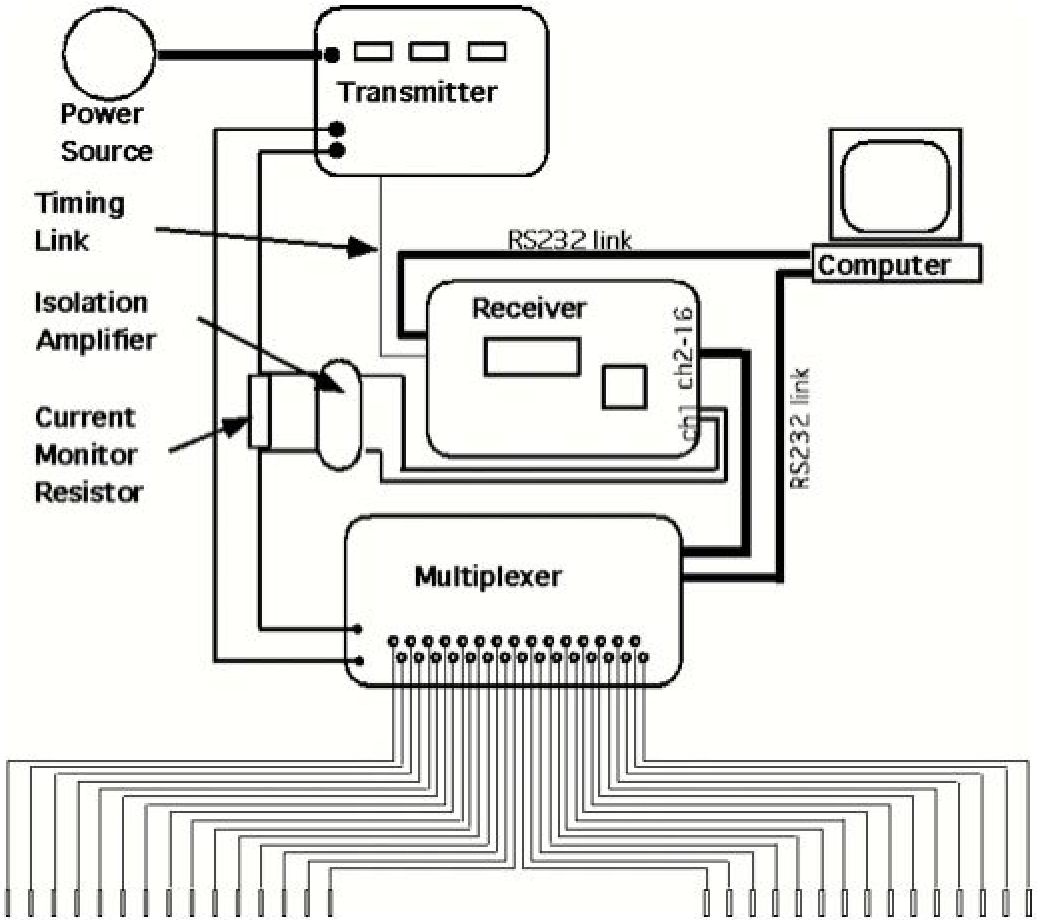
Cranfield ERT Array

- World's deepest ERT arrays (~10,500 ft, 3200 m)
- Two vertical cross-well electrode arrays ~130 ft (~41 m) apart
- All components mounted external to casing
- 21 electrodes (14 and 7 arrangement)
- 220,000 ft (~67 km) of insulated wiring
- 35,000 ft (~10.7 km) of cable armoring
- Full remote internet operation using *Multi-Phase Technol.* data acquisition system (*DAS-1*)
- 4 different electrode sampling schedules
- ~10,000 measurements/day

Cross-Well ERT In The Lower Tuscaloosa Formation (>10^4 ft)



Basic data acquisition system – autonomous, 24/7 operation



ERT Array Construction: Electrodes

- Electrode collars are 316-L stainless
- Collars mount on fiberglass-reinforced well casing
- Filled-resin centralizers protect electrodes & cables
- In use for 8 months

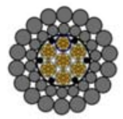
ERT Array Construction: Individual Elect. Cables

- #16 AWG TEC cables attach to individual electrodes
- Encapsulated in stainless tubing and polypropylene
- TEC cables attach to "splitter" via insulated Swagelock connectors

ERT Array Construction: Cable “Splitter”

- 7 connectors attach cables to bottom of splitter
- Single connector off top feeds into double-armored 7-conductor wireline cable
- Wireline cable terminates at surface

Manufacturer:	Rochester Cable Corp.
Conductors:	7 (16 AWG)
Insulation Type:	Teflon (FEP)
Armor Material:	Galvanized Carbon Steel
Overall Size:	0.420 inch OD
Temperature Rating:	400 Fahrenheit
Breaking Strength:	>18,000 lbf
Crush Resistance:	Up to 13,000 lbf



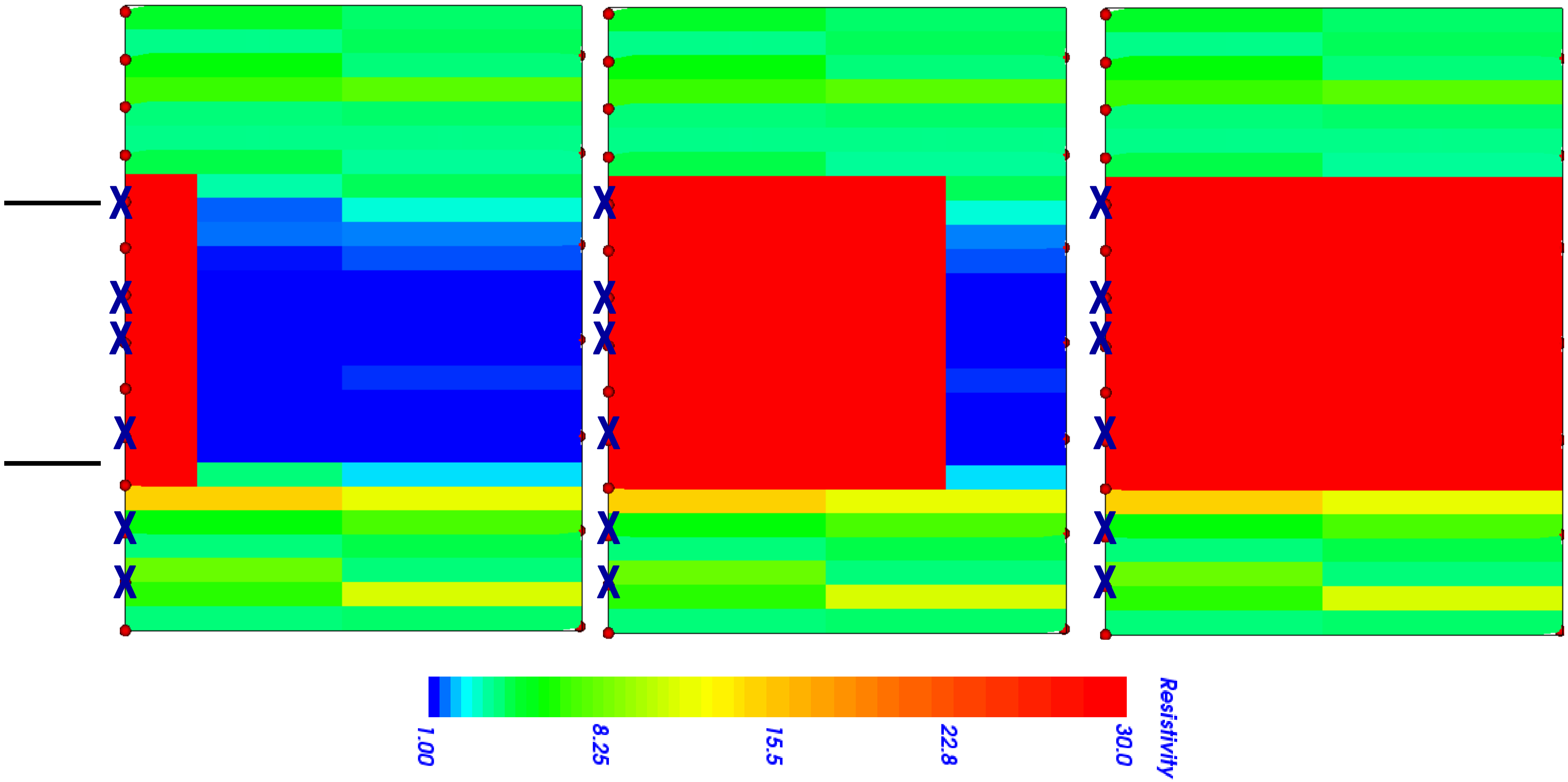
Cross Section

Synthetic Model Study

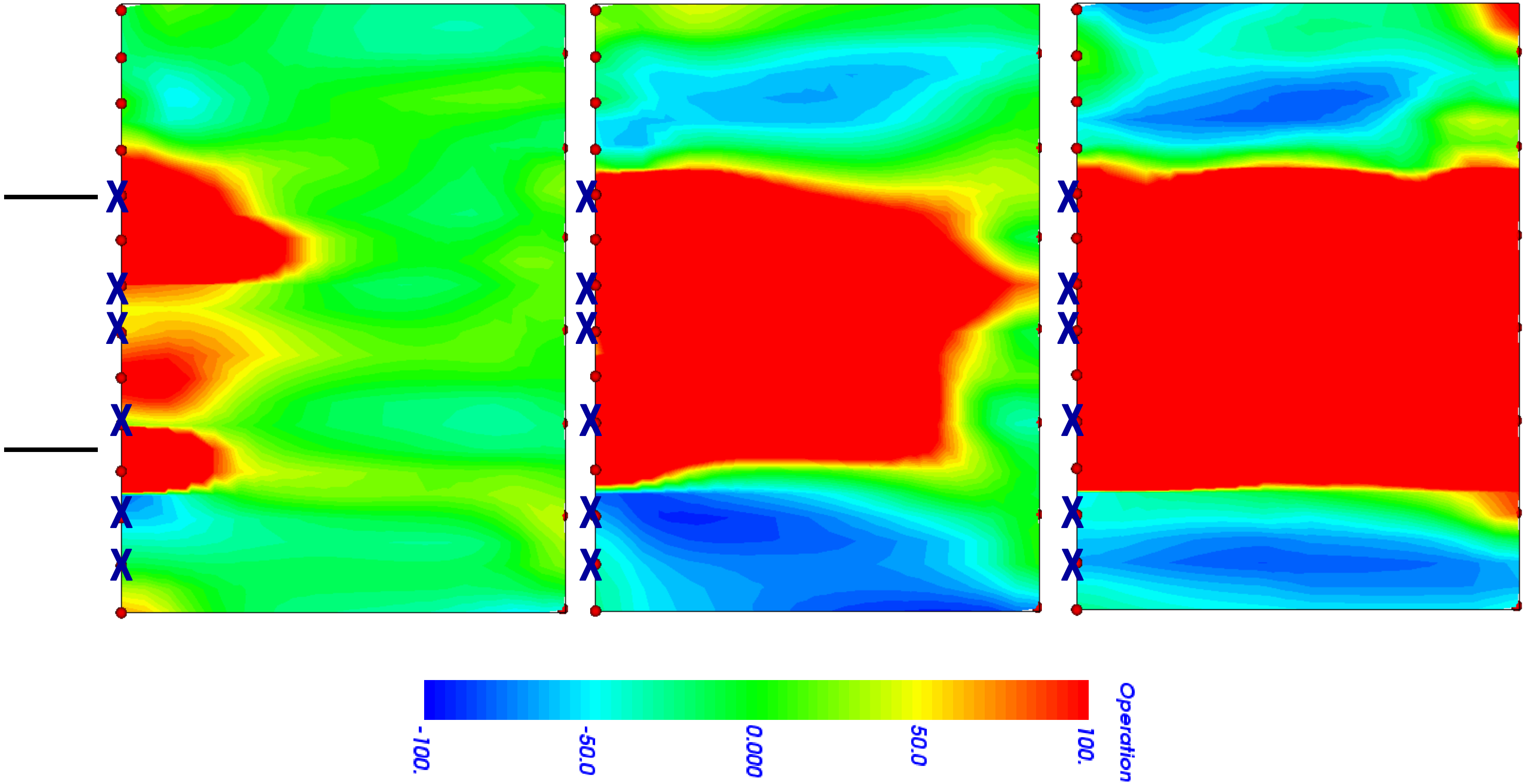
Multi-Phase Technologies, LLC

- Layered background created by simple averaging of well logs
- Introduced 100 Ohm-m anomaly from 2180 to 3210 m depth
- Anomalies centered on injector and extend +/- 75m, 100m and 125 m from injector
- Boreholes used for imaging are 69 m and 112 m from injector
- Data inverted using robust inversion, assumed 3% noise.

Model of CO_2 anomaly invading the reservoir



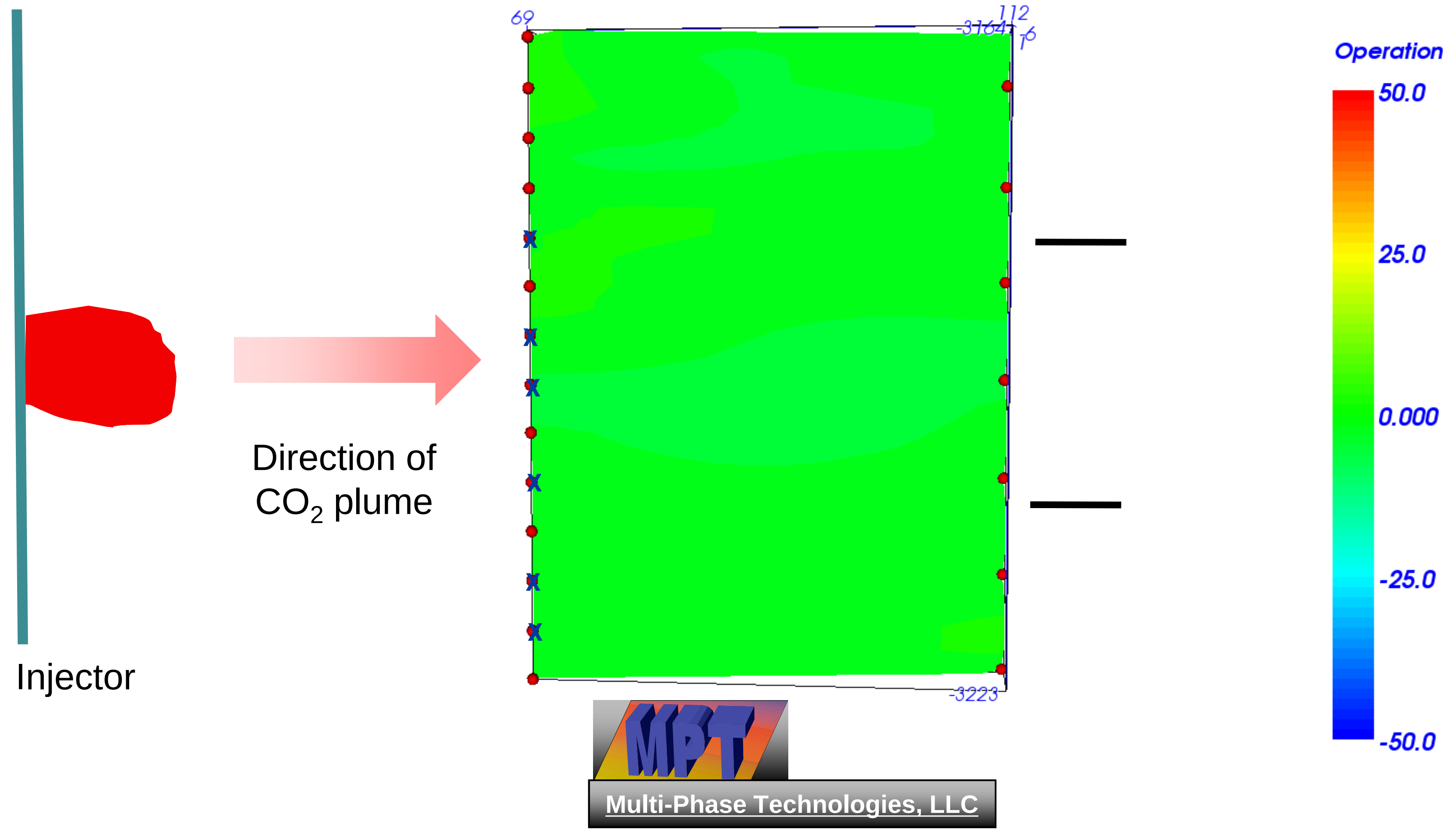
ERT reconstructions of synthetic CO_2 model, percent resistivity change



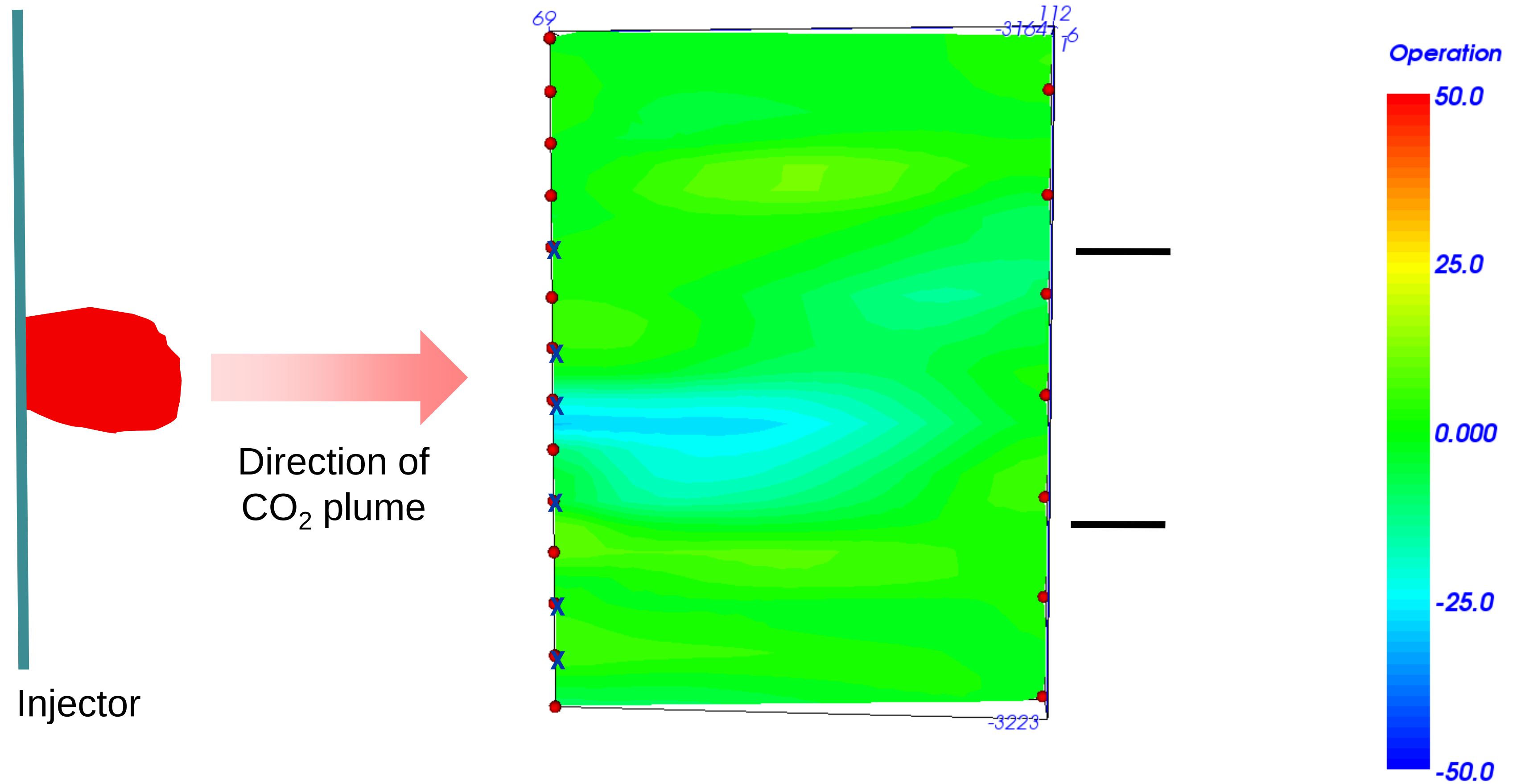
Modeling study conclusions

- The imaging routine tends to expand the size of the anomalous zone by 1 voxel width.
- The coarse resolution of these images is due primarily to the relatively few electrodes available.
- Some images show fairly strong “overshoot effects” shown as blue colored zones above and below the anomalies
- Some artifacts below the bottom of the Tuscaloosa
- The good news is that despite these issues it should be possible to follow the approximate progress of the CO_2.

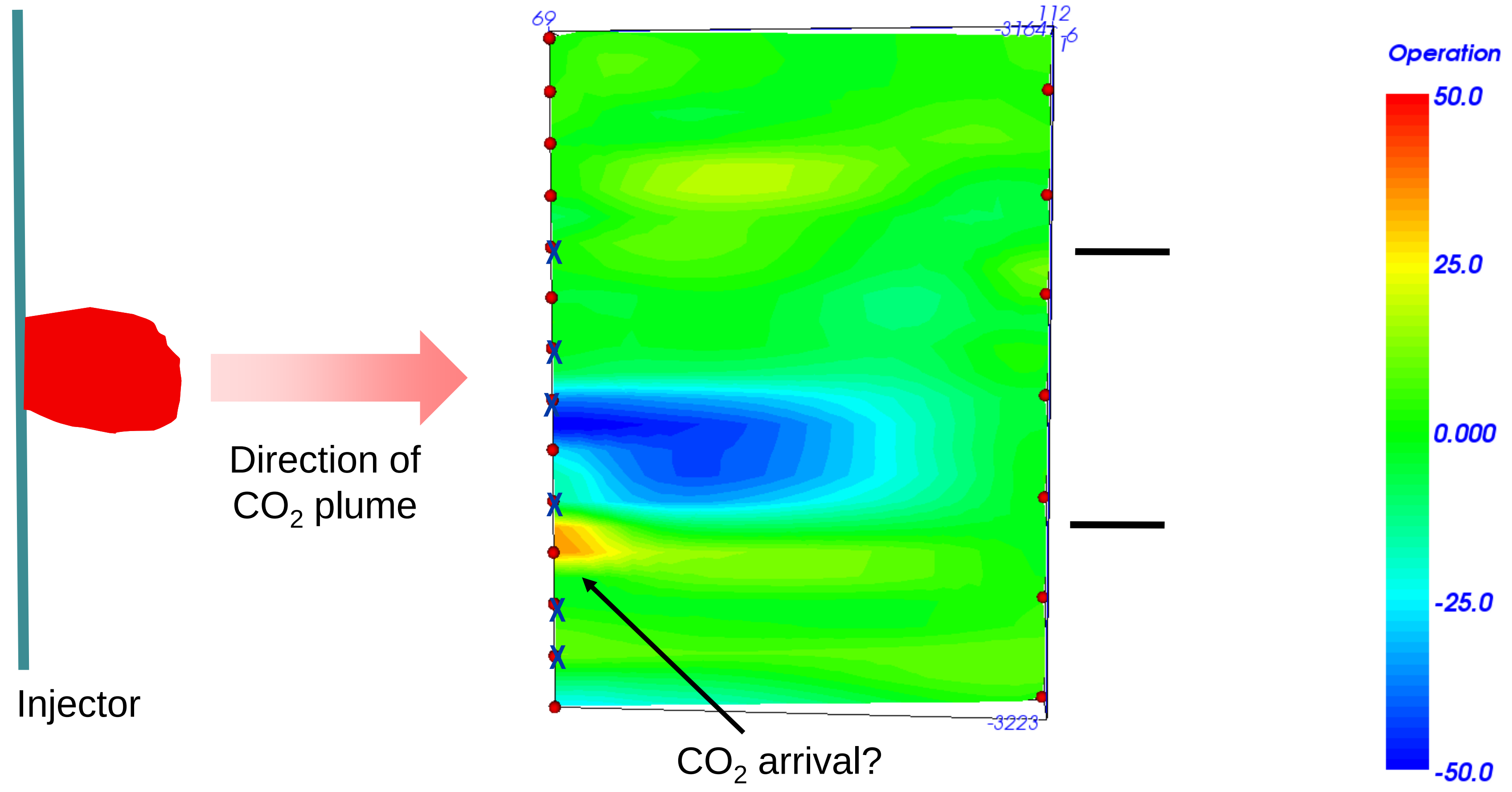
Nulled Background At Initiation Of Injection (1 Dec 2009)



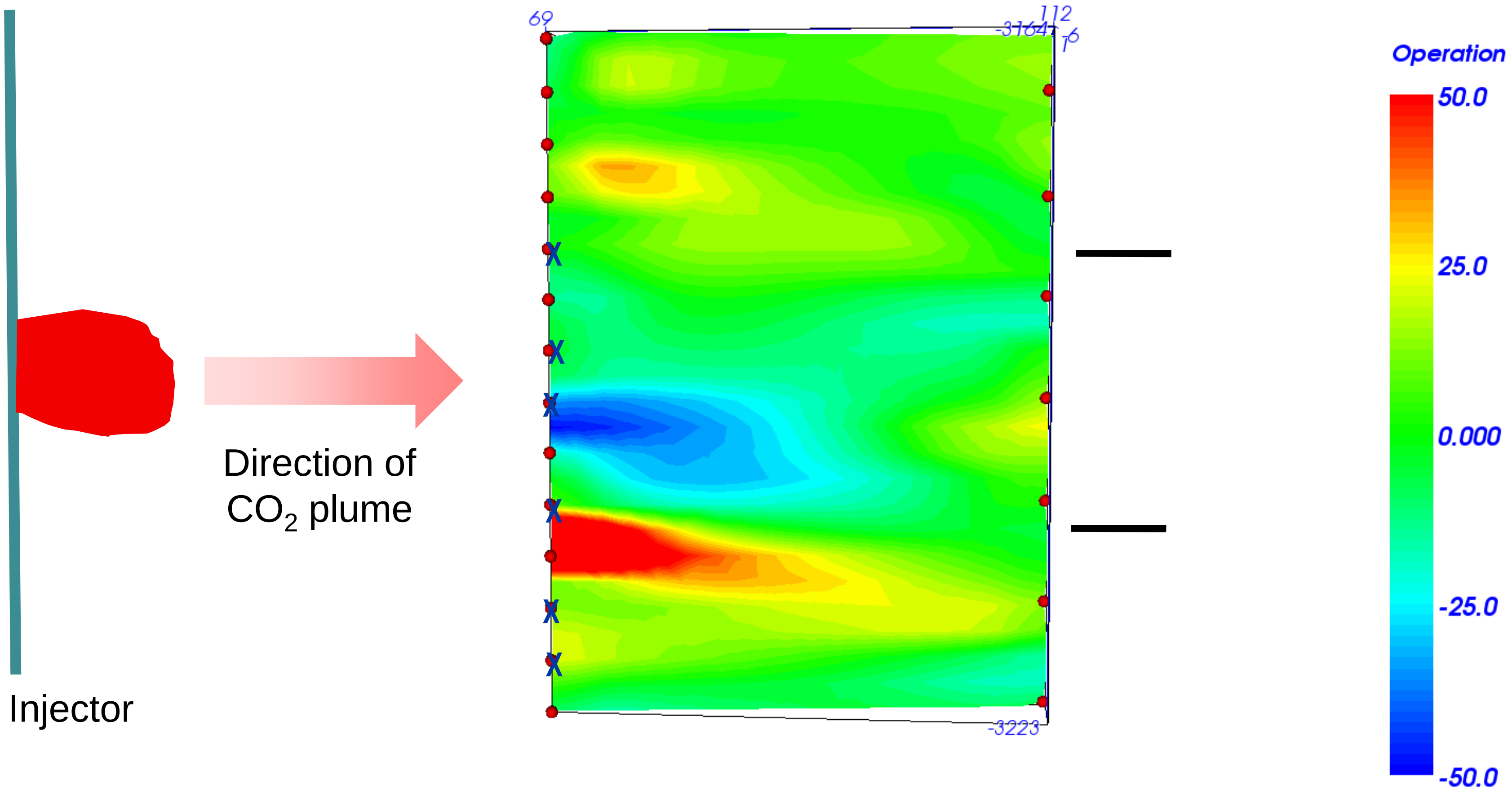
Injector Overworking Fluids?
(4 Dec 2009)



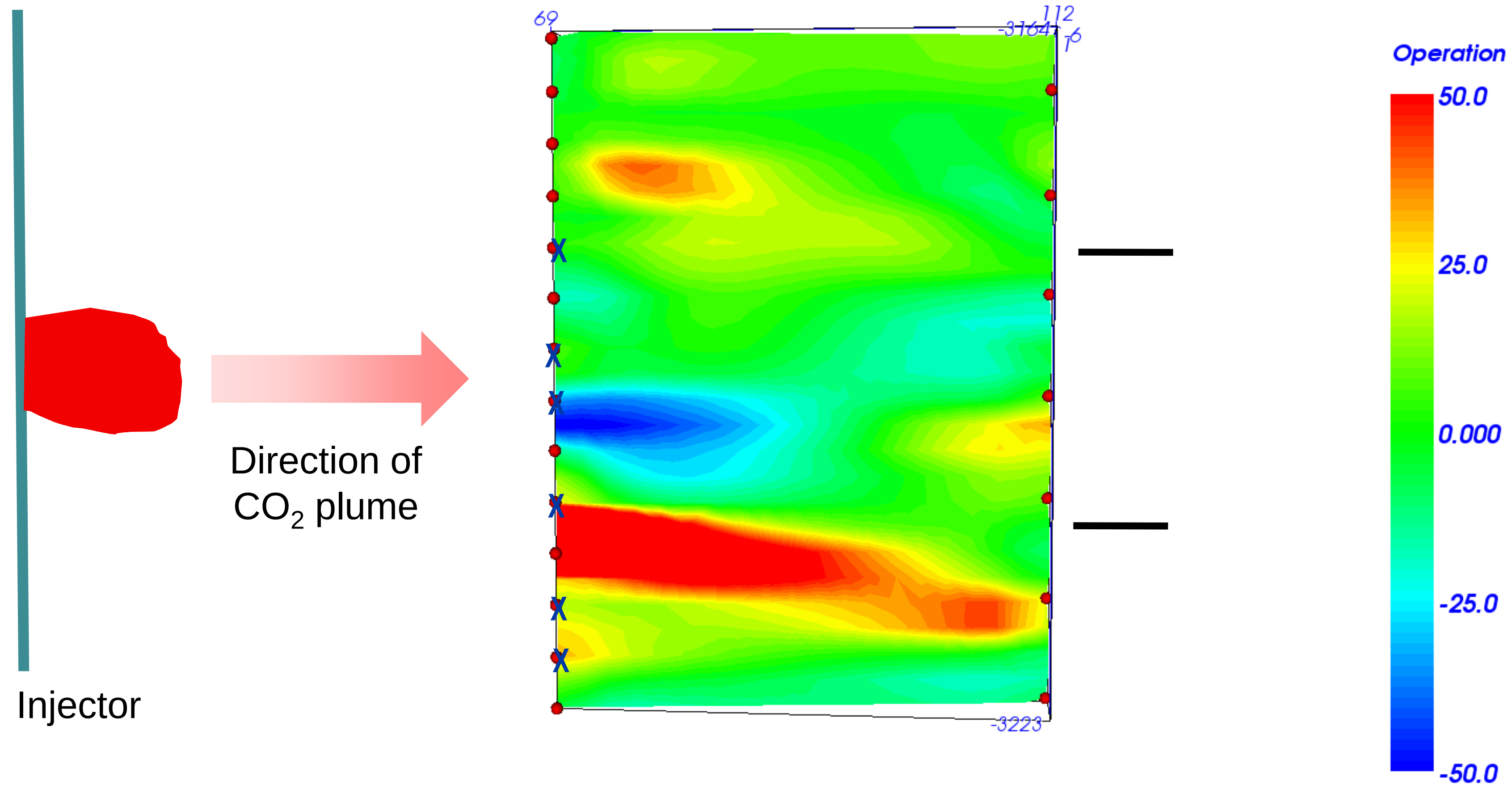
Arrival of CO_2 Plume? (9 Dec 2009)



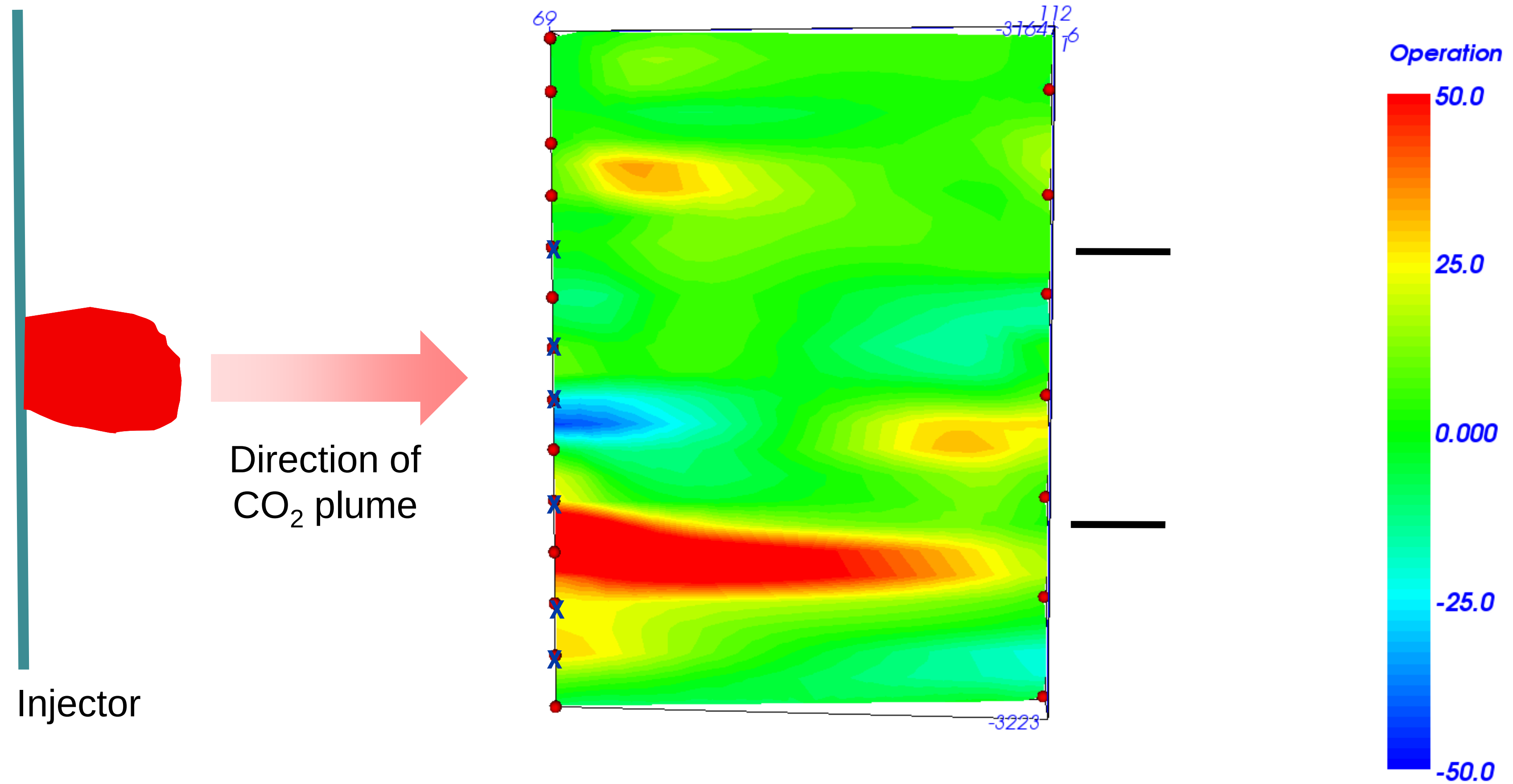
Growth Of CO_2 Plume?
(21 Dec 2009)



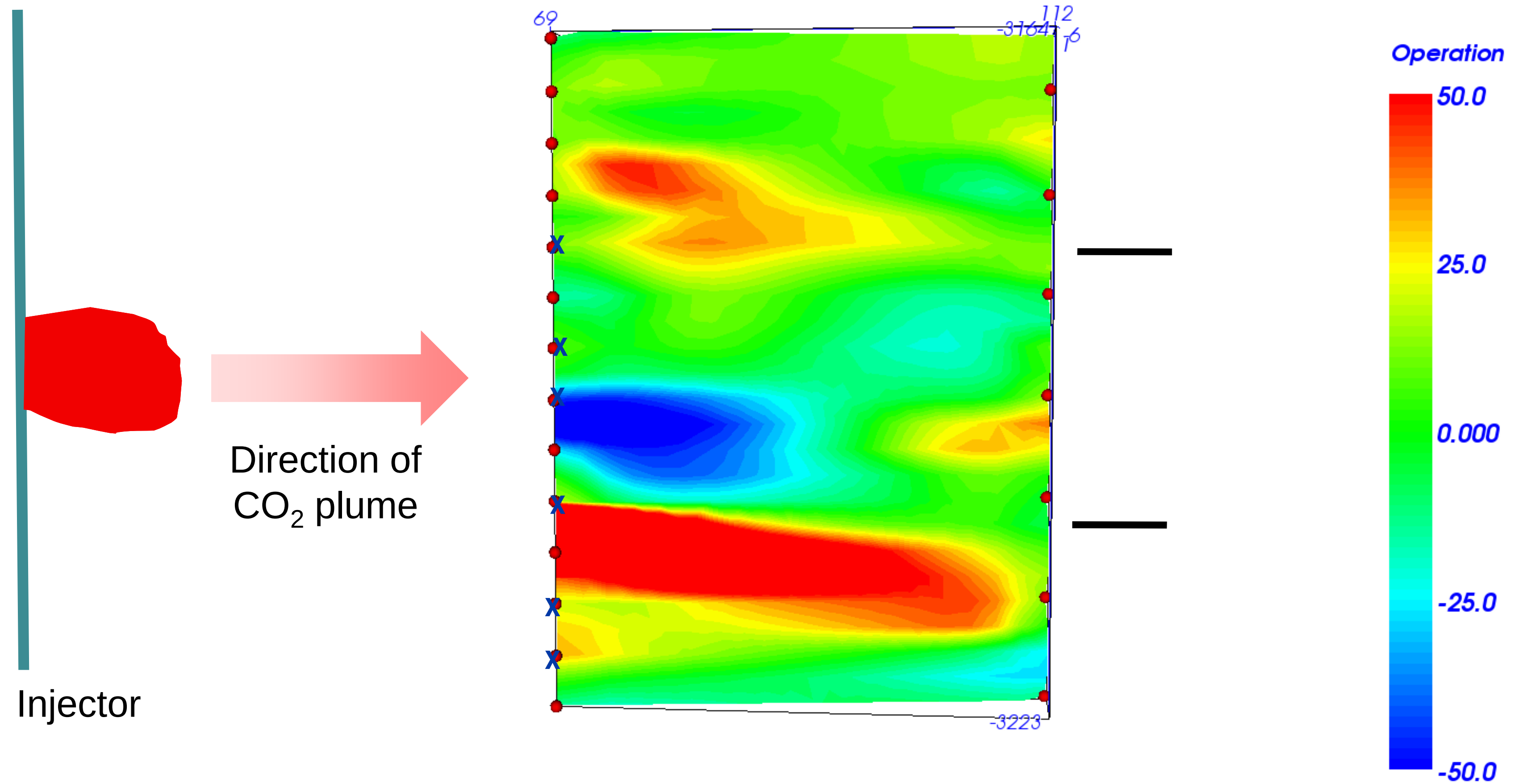
Growth Of CO_2 Plume?
(11 Jan 2010)



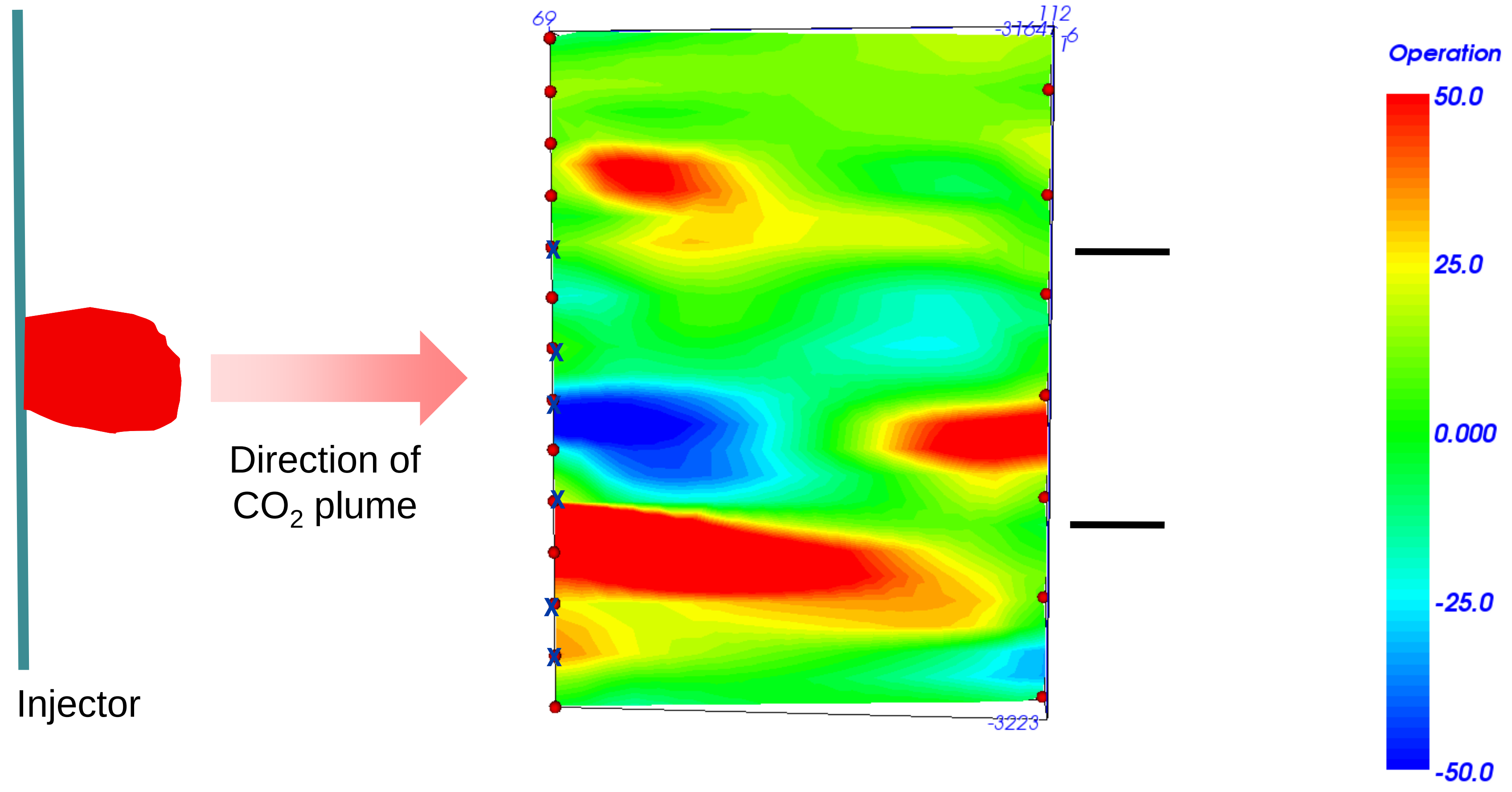
Growth Of CO_2 Plume?
(13 Jan 2010)



Growth Of CO_2 Plume?
(5 Feb 2010)



Growth Of CO_2 Plume?
(23 Feb 2010)



Current Conclusions / Interpretations

- CO_2 produces strong signal
- ERT reconstructs basic plume details
  - ✓ Coarse resolution
- Resistive anomaly appears associated with CO_2 movement in Lower Tuscaloosa formation with Dec 9 arrival at F2
- Significant positioning and resolution loss due to electrode damage in F2, analysis continues
- Conductive anomaly apparently due to work over fluids appears just after start of injection
- System continues to remotely log ~10,000 ERT measurements/day (May 2010)

Lessons learned

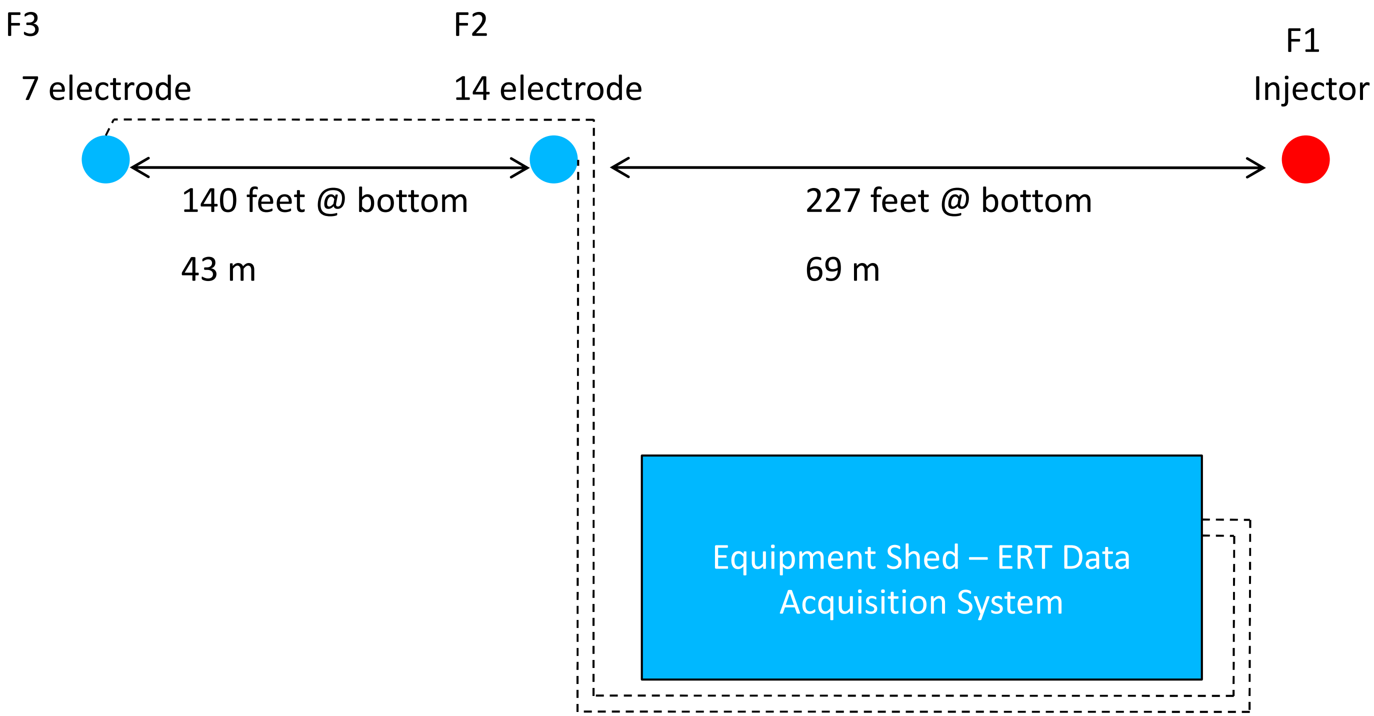
- Robustness of electrode centralizers need improvement
- Time required for cabling installation needs to be shortened while maintaining array robustness
  - ✓ Choice of electrical connectors may be very important
- May need more well centralizers to protect wiring and electrodes

Thank you

- Any questions ?

- I brought electronic/hard copies of publications:
  - ✓ Ramirez, A., R. Newmark, and W. Daily, 2003, Monitoring carbon dioxide floods using electrical resistance tomography (ERT): Sensitivity studies, *Journal of Enviromental. and Eng. Geophysics* ,vol. 8, no. 3, pp. 187 - 208.
  - ✓ Daily, W., A. Ramirez, A. Binley and D. LaBrecque, 2005, Electrical Resistance Tomography--Practice and Theory, *Soc. Exploration Geophysics: Near Surface Geophysics*, ed. Dwaine Butler

SECARB Cranfield ERT Site



Cranfield Phase III Study Area