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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

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

The international research network on Monitoring is organised by IEA Greenhouse Gas R&D Programme. The organisers acknowledge hospitality provided by the hosts University of Alberta.

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

Tim Dixon, IEA Greenhouse Gas R&D Programme (Chair)
Brendan Beck, IEA Greenhouse Gas R&D Programme (Co-Chair)
Kevin Dodds, BP
Hubert Fabriol, BRG/CO2GeoNet
Rick Chalaturnyk, University of Alberta
Lee Spangler, University of Montana/Big Sky RCSP
Don White, NRCan
Susan Hovorka, University of Texas/SECARB
John Kaldi, CO2CRC
Andy Chadwick, British Geological Survey

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "4th Monitoring Network Meeting, 2008/16, March and 2009".

Further information on the network activities or copies of the report can be obtained by contacting the IEA Greenhouse Gas R&D Programme at:

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FOURTH WORKSHOP OF THE IEA GHG INTERNATIONAL RESEARCH NETWORK ON MONITORING

Executive Summary

The monitoring of CO_2 injected into geological formations is a topic of great interest and importance. As CO_2 capture and storage (CCS) becomes more widely implemented regulatory bodies will require that detailed monitoring programmes are put in place to ensure that the health and safety of both operating staff and the general public are assured. In addition, if organisations wish to gain credits for the CO_2 that is injected, monitoring of the injected CO_2 will be necessary to ensure that emission reduction credits can be validated and any leakage accounted for both in the credit awards and in national inventories.

This is the 4th meeting of the IEA Greenhouse Gas R&D Programme (IEA GHG) Monitoring Network. Since the inception of the Monitoring Network a significant amount of work has been done in this field. There are now a great number of very elaborate CCS demonstration projects occurring worldwide with each one developing and testing new monitoring techniques. While this is happening there is also a great drive from many Governments to put in place the regulations needed to properly licence and supervise CCS activities. This meeting hoped to review where we are with both aspects of CCS and identify what questions still need to be answered.

The main outcomes of the workshop were:

1. An analysis of CCS monitoring and how it was dealt with in regulation. Regulation is being developed in parallel in a number of regions around the world including the US, Canada, Europe and Australia. Although regional regulation developments are not completely transferable lessons can be learnt from other regions processes which can aid development elsewhere. It was demonstrated that there are parallels that can be drawn between the acid gas injection regulation and CCS regulation however the scale of acid gas projects is significantly smaller than what is needed for CCS which reduces the applicability. It was concluded that although there is a lot of good work going on there are still some big regulatory issues to be solved, possibly the biggest and most contentious of which is when and how to hand over of the site to the national authority will occur.
2. A review and update of what is happening at a number of CCS projects around the world focusing on the different monitoring techniques that has been looked at. It was encouraging seeing the number of projects existing and planned and to see the wealth of monitoring techniques are being developed, tested and applied. As more projects are started and as current projects progress the availability of historic data will allow us to start to build monitoring standards and best practices which will improve our confidence in the technology and processes of CCS.

As well a continuing to work on some of the unresolved issues above there were a number of questions that were raised throughout the course of the meeting that will need to be addressed in the future. These include:

- How do you accurately locate and quantify the CO_2 in the reservoir?
- What do you do if a system parameter goes outside predicted values?
- What additional information can Seismic monitoring give us? When is it not applicable? Is it enough on its own and if not, what more do you need to complement it?
- How much monitoring is required for different stakeholders and can the current monitoring techniques provide what the need?
- How long do you monitor for? When and how does handover occur?

FOURTH WORKSHOP OF THE IEA GHG INTERNATIONAL RESEARCH NETWORK ON MONITORING

1. Introduction

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This is the 4th meeting of the IEA Greenhouse Gas R&D Programme (IEA GHG) Monitoring Network. Since the inception of the Monitoring Network a significant amount of work has been done in this field. There are now a great number of very elaborate CCS demonstration projects occurring worldwide with each one developing and testing new monitoring techniques. While this is happening there is also a great drive from many Governments to put in place the regulations needed to properly licence and supervise CCS activities. This meeting hoped to review where we are with both aspects of CCS and identify what questions still need to be answered.

This report provides a summary of the fourth meeting hosted by the University of Alberta in Edmonton, Canada between the 7th and 9th of November 2007.

2. Aims and Objectives of Second Workshop

The workshop aimed to provide:

- Provide an insight as to how CCS is dealt with in regulation.
- Provided a review and update of a number of CCS projects around the world focusing on the different monitoring techniques that are being applied

3. Workshop Programme

DAY 1 – Regulations and Monitoring		
07.30	**Registration/Coffee**	
08.30	**Introduction/Housekeeping:**	Brendan Beck and Rick Chalaturnyk
08.45	"**Albertans and Climate Change: Moving Forward**"	Honorable Rob Renner, Minister of Environment, Government of Alberta
09.30	**An ENGO viewpoint on CCS, Regulation and Monitoring**	Mary Griffiths, Pembina Institute
09.55	**Draft Quantification Protocol for Geological Storage Through EOR using CO_2 Injection – What Monitoring is Required?**	Brent Lakeman and Stephanie Trottier, Alberta Research Council
10.20	**Discussion/Questions**	
10.35	**Break**	
11.00	**Legal and Regulatory Guide for States and Provinces – IOGCC**	Rick Chalaturnyk, University of Alberta

11.20	**MMV : G8/CSLF and Canada-Alberta Task Force Activities**	Bill Reynen, Geological Survey of Canada
11.50	**Draft Regulatory Guidelines for Geological Storage of – CO_2ReMoVe**	Brendan Beck, IEA GHG
12.15	**Discussion/Questions**	
12.30	**Lunch**	
13.30	**Review of Acid Gas Regulations**	Stefan Bachu, Energy and Utilities Board
14.00	**Facilitated Discussion:** Are Acid Gas Regulations a suitable analogue for the development of Geological Storage Regulations?	
15.00	**Break**	
15.30	**Facilitated Discussion:** How to design and establish a suite of generic MMV protocols for CO_2 storage.	
16.00	**Facilitated Discussion:** What are the next steps to help expedite MMV arrangements and so assist in the wide scale implementation of CCS?	
18.00	**Social Event and Entertainment**	
DAY 2 – MMV Design and Reviews and Updates: CO_2 Projects		
07.30	**Registration/Coffee**	
08.15	**Welcome /Synthesis of Regulatory/Policy MMV issues from Day 1**	Rick Chalaturnyk, University of Alberta
08.30	**MMV Update on the CO2CRC's Otway Basin Pilot Project**	Kevin Dodds, BP Americas (formerly with CO2CRC)
09.00	**Nagaoka, Japan Monitoring/Verification Program Design, Deployment and Case History.**	Tsukasa Yoshimura, RITE
09.30	**MMV Efforts at the CSLF Endorsed Zama Lake Acid Gas EOR Project**	Steve Smith, EERC/PCOR
10.00	**MMV Programs at ADM Site, Illinios – Midwest Partnership**	Rob Finley, Geological Survey of Illinios
10.30	**Seismic Based MMV Programs: Frio II, Otway Basin, Permian EOR, WESTCARB/SECARB.**	Tom Daley, LBNL
11.00	**Discussion/Questions**	
11.15	**Break – POSTER SESSIONS**	
12.00	**Lunch – POSTER SESSIONS**	
13.00	**MMV in Final Phase of IEA GHG Weyburn-Midale CO_2-EOR Monitoring and Storage Project.**	Don White, Geological Survey of Canada
13.30	**Downhole Fluid Recovery System Deployment at Penn-West CO_2-EOR Monitoring Project**.	Gonzalo Zambrano, University of Alberta
14.00	**Shallow Subsurface and Atmospheric Monitoring in CO_2Geonet and CO_2ReMoVe.**	David Jones, British Geological Survey
14.30	**Discussion/Questions**	
14.45	**Break**	
15.15	**Research on Environmental Risks from Geological Carbon Dioxide Storage**	Jeremy Colls, University of Nottingham
15.45	**Baseline Survey for Evidence of Gas Microseepage Prior to a CO_2 Injection Experiment at Teapot Dome, Wyoming, USA**.	Ron Klusman, Colorado School of Mines
16.15	**Accurate Soil CO_2 Flux Meas. at High Spatial and Temporal Resolution**	Rod Madsen, LICOR Biosciences

16.45	**Discussion/Questions**	
19.00	**Dinner**	
DAY 3 – MMV Design and Reviews and Updates: CO_2 Projects		
07.30	**Registration/Coffee**	
08.00	**Welcome and Introduction to Day 3**	Rick Chalaturnyk, University of Alberta
08.15	**MMV Results from FRIO II**	Sue Hovorka, Gulf Coast Carbon Center
08.45	**Seismic Monitoring Programs at Penn-West CO_2-EOR Monitoring Project**	Don Lawton, University of Calgary
09.15	**Observation Well at Penn-West CO_2-EOR Monitoring Project**	Gonzalo Zambrano, University of Alberta
09.45	**Discussion/Questions**	
10.00	**Break**	
10.20	**Shallow Subsurface and Air Monitoring Program at Penn-West CO_2-EOR Monitoring Project.**	Bill Gunter, Alberta Research Council
10.45	**MMV Programs at the CSEMP ECBM Pilot Project**	John Faltinson, Alberta Research Council
11.10	**Role of Risk Assessment in Designing MMV Programs**	Ken Hnottavange-Telleen, Schlumberger Carbon Services
11.35	**Discussion/Questions**	
12.00	**Lunch**	
13.00	**A New Mode of Seismic Surveillance**	Leon Thomsen, BP
13.30	**Detailed CO_2 Injection and Sequestration Monitoring Through Crosswell Imaging.**	Mark McCallum, Z-Seis
14.00	**Design of Surface Seismic Programs for CO_2 Storage Monitoring**	Mark Egan, WesternGeco
14.30	**Discussion/Questions**	
14.45	**Break**	
15.00	**Passive Seismic: Listening for the Snap, Crackle, Pop!**	Marcia Couëslan, Schlumberger Carbon Services
15.30	**Employing Novel MMV Technology Integration Techniques To Increase Accuracy of Injection Monitoring.**	Eric Davies, Pinnacle
16.00	**Discussion/Questions**	
16.15	**Discussion and Wrap-up of Meeting**	Brendan Beck and Rick Chalaturnyk

4. Presentations Summaries and Discussion

4.1 Day 1 – Regulations and Monitoring

4.1.2 CCS in Alberta – Rob Renner – Alberta Minister of the Environment

The Alberta Minister of the Environment, Rob Renner, gave the opening address of the meeting and began by recognising that what the Network is doing here is critical for the going forward of regulation for CO_2 capture and storage

Alberta has been at the forefront of climate change in Canada for some time with a current target of reducing carbon intensity by 12%. This may also increase as the Canadian federal government are looking at a target of around 18% carbon intensity, with Alberta set to mirror this target in 2010. 18% is seen as a valuable contribution to climate change mitigation and achievable. With the inclusion of CCS, Alberta may even look to exceed this 18% target.

Alberta is already putting significant resources into CCS research and can be a centre of excellence in the area of CCS with good local geology and large point sources of CO_2 production in the region lending themselves to the technology. The major emissions sources in the province are from large amounts of coal fired thermal electricity and oil sands. However the places were Alberta produces CO_2 are remote from the places that they can store and utilise CO_2 so transport is an important issue that needs to be addressed. Low quality by-products of oil sands production could also be gasified to lower the environmental impact and lower strain on natural gas use. This then would provide another high concentration source of CO_2 for capture. The amount of CO_2 produced in Alberta far exceeds the requirements for CO_2 in EOR so saline storage will have to be utilised.

Like many regions around the world, the local government in Alberta will need to come up with a way of assuming liability for the stored CO_2 as the storage company can't be expected to hold the liability indefinitely. CCS needs flexible regulation and financing as it is a unique process. There are similarities with the Canadian oil sands industry. If Alberta can succeed as a market leader in CCS then it has the opportunity to be an exporter of CCS expertise and knowledge to other regions of Canada and the world.

Q) What economic incentives has Alberta looked at for CO_2 reduction?
A) Alberta is looking at a carbon trading system for the largest emitters. Alberta is also looking at ways to incentivise CO_2 reduction in areas that are not regulated under this trading system. This includes "made in Alberta offsets". Another option is to have industry invest $15/tonne into a clean development fund which could be used for investment into infrastructure or research and development.

Q) The Federal government is looking at a carbon tax because of its simplicity, has Alberta considered a carbon tax?
A) Alberta doesn't believe that a carbon tax will do anything but chase a significant amount of capital out of Alberta. Internal carbon trading is better suited to Canada's problems. A tax will just increase general revenue.
A) Alberta is the only regulated carbon trading network in Canada. Alberta already has 15 protocols to allow people to have independently verified emissions reductions that can be traded. Alberta doesn't want trading in hot air to be going on. Alberta wants to be seen as a jurisdiction that is contributing significantly to carbon reduction. Alberta's best opportunity is through CCS. Alberta wants their emissions reduction to stay in Alberta not to be sold to other places to allow them to continue emitting.

4.1.3 An ENGO viewpoint on CCS, Regulation and Monitoring – Mary Griffiths – Pembina Institute

Mary Griffiths from the Pembina Institute presented a background of their organisation and gave an overview of their stance on CCS. They also included some information about other ENGO's opinion of CCS and some of the concerns the public have about the technology.

The Pembina institute was set up in 1985 as a non-partisan, non-profit environmental organisation and have recently updated their position on CCS. Some ENGOs, such as WWF see CCS as a necessary evil or a technology that can buy us time. Others such as Greenpeace and the Sierra Club see it as an excuse to continue using fossil fuels and not to deal with the issue.

Pembina see the need for a varied portfolio of carbon management technologies and it does see CCS as a possible part of this portfolio. Pembina believe that CCS mustn't get more than their fair share of attention and investment. They do not however believe that EOR is a solution for CO_2 disposal but would rather see CCS in saline aquifers which they see as the most reliable and secure storage option.

Two of the largest concerns about CCS are those of leakage and liability. It is extremely important that a strong regulatory regime must ensure that the CO_2 is stored safely and securely. This has two parts, it is important not just to have regulation in place but also to show the public that they are being enforced. It is also important to enforce reporting guidelines for the operation of a site. To find out later that things did not go to plan is very damaging for public acceptance.

Another aspect of the public concern over leakage is the lack of colour and scent of CO_2. One solution that could be applied is using an introduced odour with stored CO_2 which could significantly improve public acceptance.

Pembina see the government as the long term holder of the CO_2 liability, but are undecided when this hand over process should take place. It is important for the tax payer that they do not foot the bill but rather a fund is generated during the operation of the storage site by the operator to fund administration and compliance inspection and liability in the long term. This cost should then ultimately be passed on to the consumer to give a price signal for CO_2 reduction. Pembina also believe that CCS should be regulated by both the national and local government.

Pembina doesn't want to see subsidies to CCS as this will upset the level playing field with energy efficiency and renewable.

Q) Do you see 25 years of liability post-closure?
A) Pembina is undecided over the length of liability.

Q) You say that you don't want to see CCS subsidised but currently renewables are subsidised so the playing field is not currently level.
A) Public would prefer renewables as they see this as a long term solution where as CCS is an end of pipe solution that doesn't decrease CO_2 generation.

Q) How do the other ENGOs accept your summary of the ENGO situation?
A) Pembina don't often present this summary in the presence of other ENGOs. Currently within Canada there is very little attention to CCS. It won't be until there are more large projects or the public calling NIMBY.

Q) Can you elaborate on Pembina's view that CO_2 EOR projects are not suitable for CO_2 storage?

A) Pembina see that there is a financial incentive already for EOR and that there is a net increase in CO_2 emissions due to the oil. It depends how you see the oil affecting the market.

Q) You talk about not wanting subsidies but EOR is the perfect step toward straight storage because it can fund itself. EOR could be the ideal platform because it doesn't require any subsidy. It can be seen that EOR projects morph into storage. This can be the case because often EOR opportunities are located with storage.
A) This is just the Pembina position for the long term. We concede that EOR is going to go ahead.

4.1.4 Draft Quantification Protocol for Geological Storage through EOR using CO_2 injection: What monitoring is required? – Brent Lakeman and Stephanie Trottier, Alberta Research Council

The Protocol document provides guidance to the operator as to what has to be done to qualify for CO_2 reduction credits. It was found that this has to be flexible and need to be adapted to the needs of the stakeholders and that they should be non-prescriptive and outcome based. It was thought that guidelines would help stimulate CO_2 mitigation action in the industry.

In the document the ARC defined the site characterization requirements for CO_2 storage and outlined a set of questions defining what they believe needs to be answered by the monitoring programme. The methodology to achieve this will change on a site by site basis.

In conclusion the protocol development process allows for integration of stakeholder / expert perspectives. In this process it is difficult to balance need for simplicity with concerns about desire for long-term CO_2 containment and risk minimization. This led to a decision to move to more streamlined system with the finalized CO_2-EOR protocol being silent on monitoring requirements.

Q) What is meant from the term reversal?
A) Reversal refers to the CO_2 exiting the storage reservoir. It in unclear how CO_2 caught in overlying traps will be dealt with?

Q) Your guidelines require no detectable leakage but this is very dangerous as it is so absolute and possibly unobtainable.
A) This is one of the more contentious areas. We didn't want to give a specific number but rather leave it to the operator to deal with any leakage.

Q) Is the quantification protocol mandatory or voluntary?
A) This would be additional to other protocols and would only be required if the firm wished to receive credits for the CO_2 storage.

Q) You said the monitoring regulations were not accepted. When are these regulations for monitoring going to be introduced?
A) There are monitoring requirements but we are still working on what a verifier will require. This protocol is like the box, we just need to fill the box with the detail.

Q) Who do you expect to be the verifier?
A) There is a separate sector in the consulting industry that could be turned to, to verify. They must show their credentials. They must also show experience in carbon reductions. This is a learning by doing process, the first couple of projects will have a lot of people working on it.

Q) Is all the information on participating in this project on the website?
A) Yes but go and see the ARC.

Q) How could the Acid gas regulations be superimposed onto the CCS industry? What are the differences?
A) We looked at what would be required in addition to what has been done for acid gas. This protocol is just for crediting. Alberta Energy and Utilities Board (EUB) already regulates any injection into the subsurface – acid gas, CO_2, other. This is guidance to create a financial benefit of the credit.

4.1.5 Storage of CO_2 in Geological Structures: A Legal and Regulatory Guide for States and Provences – The interstate oil and gas compact commission (IOGCC) – Rick Chalaturnyk, University of Alberta

Regulation exists for the capture, transport and injection but there is no long-term storage regulation which is why the IOGCC have developed a set of legal and regulatory guidelines on the storage of CO_2 in geological structures. Before commencing on the discussion of the guidelines Rick first highlighted a whole set of draft regulations and how monitoring features in the regulations. This includes pore-space ownership from a legal perspective.

The approach that the taskforce took is that CCS should be viewed as a resource management issue rather than a waste management issue. This is at odds to the Pembina Institute who views it as a waste management issue.

The IOGCC looked at how you transfer from EOR to storage as it is not obvious what functional and legal consequences this has. If you run a CO_2 EOR project and there is some residual CO_2 trapped that is fine but if you want to turn it into a "new" storage project then you may have to reapply to the surface land owner for rights to store.

Part of the conclusion is that the primary focus for monitoring and verification should occur subsurface at the primary seal rather than surface monitoring techniques. Early detection in the subsurface is the best mechanism to protect public health. The guidelines also include a leak detection and monitoring plan for all wells however some details, such as timing, have not been resolved.

A key aspect of the guidelines is the long term liability and handover of the project to a government authority. The long term liability and care-taker role is best taken on by the states rather than the national government. The operator must demonstrate an agreed level of security and confidence for the site and provide all the characteristics of the plume (Plume volume, size, location, predicted migration etc.) before hand over occurs. To finance the take over of the site, the IOGCC suggest that an operational bond is created on licensing which continues throughout the project and is release ten years after injection ceases or at a time when it is mutually agreed between the operator and the government authority. A per tonne storage bond or injection fee is paid by the operator into a government administered fund that will look after post-closure liability and administration ~$10/tonne. This fund would then pay for continued monitoring and any remediation action that is required post handover.

Q) In these kinds of documents are there provisions for the different states that CO_2 may exist in the subsurface?
A) This document says you must speak to the trapping mechanisms that are expected in the project and craft the monitoring to the type of trapping mechanism.
A) From a regulatory point of view you must account for all the CO_2 that you have injected. It doesn't matter about the state, you still have to account for it.
A) Working on this document demonstrated the importance of EOR in current EOR areas as well in new regions of the world. EOR could provide the opportunity to build infrastructure such as pipelines as well as drawing new people to the industry which is desperately required – eg reservoir engineers.

Comment) I have been to three of the four monitoring meetings and he doesn't recall ever seeing a petroleum engineer present. These are the people who are going to do CCS. We need to get the involvement of more petroleum engineers in the networks.

Q) How relevant is this document to areas outside the US and Canada.
A) Mainly US and Canada. But you have to remember that US and Canada are both based on British common law so synergies are there but perhaps not with Europe as a whole.
A) CO_2 Remove does do this.

4.1.6 MMV Components associated with G8/CSLF and Canada-Alberta Task Force Activities – Ecoenergies taskforce – Bill Reynen – Geological Survey of Canada.

Bill Reynen reported on the discussions at the CSLF, G8, IEA workshop, in particular looking at the discussion of MMV. The workshop is going to work to produce a final report of recommendations that will be submitted to the G8 member countries. In the report they will highlight MMV as a key component of the recommendations. MMV is a cross-cutting issue relevant to the 5 key overall CCS issues that are being addressed. These discussions really show that MMV is being recognised as a key issue at very high levels.

Of particular importance at the workshop were discussions about recent projects that have been cancelled such as Peterhead and the SaskPower project. It was stated that the government must be ready to respond to industry initiatives and that projects are not moving forward because of lack of regulatory certainty.

In conclusion, all the high level organisations discussed recognise the value of MMV and see it as a key component to advancing CCS. The all see that there is a pressing need for demonstration projects to enable the process of learning by doing to occur.

Q) Look into the future, how do you think the G8 will respond?
A) One of the recommendations is to hold the G8 account for implementing the recommendations. These recommendations are taken seriously by the G8. A report card will then be produced to see how well they have taken these projects forward both in G8 and non-G8 countries. The Alberta-Canada may be making public the recommendations as early as January.

Q) Can you comment of the cancelation of the SaskPower project?
A) There were a few factors involved. Firstly costs went from 1.5bn to 3.5bn. Another factor was that they were building an inefficient plant that they could live with due to the sale of CO_2. The population of Saskatewan increased more than expected which pushed them to natural gas turbines. They haven't dismissed the idea completely; they are looking to 2015 plant rather than the original 2012. So the cancellation was not a due to regulatory concern.

4.1.7 CO_2Remove licensing guidelines – Brendan Beck, IEA GHG

CO_2Remove (CO_2 Research, Monitoring, and Verification) is part of the EC 6th Framework Programme and is Funded by the EC and Industry. The IEA GHG has contributed to sub-project 4 of this project which is best practice and guidelines. As part of this subproject CO_2Remove has developed a Draft Contribution to Future Guidelines for Licensing of CO_2 Storage in Saline Reservoirs and Depleted Hydrocarbon Reservoirs.

These guidelines breakdown a CCS project into 8 separate phases:

I. Screening
II. Site Investigation
III. Well drilling & testing
IV. Site development plan
V. Construction
VI. Storage operation
VII. Closure
VIII. Post-closure

For each of these phases the guidelines provide a description of the phase, a checklist of tasks that must be completed during that phase and a final stage milestone that will be passed once the checklist is complete. The guidelines also contain a monitoring programme that is spread across all the phases which outlines the sort of data that will be required associated with each phase.

Q) I think that the burden on the company would be too much in the CO_2Remove project which doesn't hand over until the national authority is satisfied that no further monitoring is required?
A) The issue of the hand over point of the liability is a difficult one. The CO_2Remove suggests that the operator should continue monitoring until the site is secure where as IOGCC proposed that the state will continue monitoring after handover using a pool of funds collected during operation. Ultimately monitoring will continue for a similar amount of time in both cases and it is paid for by the operator in both cases it just comes down to who is running the monitoring programme. The CO_2Remove project's plans for liability transfer are inline with the general thoughts in Europe.

4.1.8 Review of Acid Gas Regulations – Stephan Bachu, Energy and Utilities Board

Acid gas injection is currently performed at a number of sites in the US and Canada. Acid gas, which is a combination of CO_2 and H_2S is naturally occurring in natural gas. This acid gas must be removed from the natural gas before the natural gas can go to market. This process of natural gas clean-up is similar to that done in Sleipner and In Salah although an order of magnitude smaller in volume.

The composition of acid gas in Canada vary from 98% CO_2 - 2%H_2S to 16% CO_2 - 84%H_2S.
Following separation from the natural gas, something must then be done with the acid gas, in particular the H_2S. Huge piles of sulphur dot the Canadian landscape from gas cleanup however this is a liability for the operator and a risk for ground water so instead the H_2S is often injected in conjunction with the CO_2 into all types of reservoirs, aquifers, oil and gas reservoir, oil reservoir, gas reservoir. The public prefers acid gas injection over other sulphur disposal methods such as stock piling or flaring. There is an injection site 10 minutes taxi ride from this conference. This was done because if the acid gas was flared it would cover the city and the suburbs all around the site.

There are currently two sites in Alberta that use acid gas for EOR. There is also a site where the acid gas is dissolved into water on the surface and the sour water is injected. Currently however the oil industry is generally using solvents and natural gas for tertiary recovery EOR because it is cheaper than CO_2.

Alberta and Texas are amongst very few jurisdictions that can deal with the regulation and licensing of CO_2 injection. At a Canadian national level CO_2 had to be classified as a toxic substance so that the government could "hit with a stick" the industry for emitting. Federal government handles CO_2 limits. What everyone is lacking is the post closure regulation. In Canada the operator is liable for the well, abandoned or not, for all of time. If the company ceases to exist then the orphaned well fund assumes liability.

Injection of CO_2 and the subsurface is the jurisdiction of the states oil and gas (energy) regulators (Alberta Energy and Utilities Board (EUB)). The EUB requires a full characterisation of the site before the commencement of injection. They also state that the maximum injection pressure in Alberta is <90% of the fracture pressure threshold of the formation however no in situ monitoring is required for acid gas. Temperature and pressure measurements of the formation are also not required.

Stephan demonstrated that there are a lot of similarities that can be drawn from the acid gas injection industry however generally the size of acid gas injection is magnitudes small than what is required for CO_2 injection.

Q) How does the EUB define 90% of the formation pressure?
A) It is a combination of the parting pressure (existing closed fractures) and the fracture pressure. If you do fracture tests then the threshold is set at 90% of that pressure, if you don't do fracture tests you have to use very conservative tables. District of Colombia uses 75%.

Q) You outlined what the current regulations are. Do you think these regulations are adequate to deal with large scale CO_2 storage?
A) I don't think they are adequate for monitoring at such a large scale, you will need in situ monitoring for large scale storage. Also in these cases you don't have any interference between sites because they are so small. No acid gas project at the moment has a plume bigger than 1km so it is very small.

Q) What is the tipping point between small and large scale?
A) Don't know, 1 million tonnes a year is definitely large scale.

Q) What are the lessons learned from acid gas injection (50 projects). Did you come across any operational problems?
A) There are some sites in the province that has been red flagged. Some have got acid gas breakthrough in wells. Under investigations these sites are still producing and they often predicted acid gas breakthrough. Another case was over pressurizing the reservoir. Interestingly the field was already over pressurised before injection. This occurred due to water injection into an adjacent reservoir and the pressure was transmitted into the reservoir. The 90% limit on injection pressure applies to aquifers, in depleted reservoirs the limit is the original formation pressure. The only case of real incident happened in BC where they injected acid gas below zero which froze the water in the reservoir which crushed the casing of the well. This lead to leakage and they had to adapt their operation.

Q) Did you find any evidence of formation damage?
A) No samples were taken so no one knows. People are very wary of going back to drill in acid gas disposal sites because drilling through acid gas is very expensive. In one case it was found that beyond a certain point the injectivity improved after the maximum displacement of the formation water. Beyond this point the CO_2 stays single phased.

Q) I noticed that one of the requirements was to show hydraulic isolation, will this apply to larger scale and both vertically and laterally?
A) Yes it will have to occur but I am not sure how to prove it. You would have to prove the absence of communication with overlying formations. Lateral isolation is not necessarily a requirement especially in anticline with a spill point or in an "infinite" aquifer.

Q) Is it just because the volumes are so small that there are no requirements for observation wells etc?
A) Yes, CO_2 storage is at a much much larger scale.

Q) If I am doing a small scale acid gas injection and I want credits for the CO_2 storage, would this be possible?

A) There is a dichotomy between the EUB which is looking to ensure public safety whereas the issuance of credits is the concern of the environmental departments. EUB will not vouch for the volumes of CO_2 stored.
A) With MMV you will be able to detect but you will not be able to quantify.
A) I do not think that there are any regulations to put in an observation well. London Convention requires a stream of overwhelmingly CO_2 so none of the acid gas sites would qualify. Before regulators can do anything the policy makers need to act.

Q) Should you discriminate about a small CO_2 storage operator?
A) Yes, because of the administration required for crediting it would be much more efficient at large scale.
A) No the small operators should get their credits. There was disagreement on how to treat small scale CO_2/acid gas storage projects.
A) From a risk basis, small projects are good because they are very low risk.
A) EUBs mandate is public safety not emissions reductions, until this mandate is changed EUB will not look to address CO_2 emissions regulation and crediting.

4.1.9 Discussion Session:

Are acid gas monitoring regulations a suitable analogue for CO_2 storage?
A) No, the lack of monitoring requirements for acid gas injection means that they are not suitable for CO_2 Storage?
A) There is an interesting catch-22 between maintaining the integrity of the storage site and drilling observation wells to increase knowledge of the formation but increase the risk of leakage.

Q) Does anyone think that seismic is enough? If no, what should be used to compliment the seismic.
A) No, seismic is not enough and the best compliment is reservoir modelling.

Q) Do we need time lapse well logging as well as modelling?
A) Yes you need calibration of the modelling with things like well logging.

Q) Do you think that the lack of monitoring for acid gas injection is inappropriate, even for acid gas?
A) No, but it is inappropriate for large scale injection. For acid gas you are limited to injection so that the plume doesn't intersect any other wells which keeps the scale down. If the CO_2 storage project was that small then perhaps the acid gas monitoring is appropriate. If there are producing wells near the acid gas injection wells then EUB can ask the operator to use the producing wells as observation wells for analysis of what is being produced.

Q) The Nagayoka project did down well temperature and pressure time-lapse monitoring but the injection amount was only 10,000 tonnes over 2 years. The down hole monitoring was very costly though. They also drilled 3 observation wells.
A) On the small sites you can't afford to do the detailed monitoring and if you do it on a risk basis then perhaps this monitoring is not required.

Q) How do monitoring requirements change with scale?
A) It is not just scale that will change the monitoring requirements but also risk, e.g. population in the vicinity.

Q) What monitoring requirements do you envisage for high risk sites?
A) EUB does not want to say for fear of being quoted.

Q) How to design and establish a suite of generic MMV protocols for CO_2 storage?

A) For accounting purposes, currently for acid gas your only knowledge of how much CO_2 is down there the only measure you have is how much you injected. For large scale projects you need more than that. I don't know how storage verification for crediting purposes will be done if it is not through the injection regulators, EUB in the case of Alberta.

A) Risk assessment should be driving the monitoring programme design. Smaller projects don't need as much monitoring as large projects.

Q) Why don't I name my large scale project 10 small scale projects?
A) It is easier to mitigate the risk of a small project rather than a large one.

Q) Who looks at the cumulative impact of the 10 individual projects?
A) If all the projects are feeding the same plume then this is true if they are multiple plumes then the cumulative risk isn't a big issue.
A) The criteria of scale is not the only criteria determining monitoring stringency. You also have to look at the number of well intrusions which wouldn't change if you split your large project into 10 small projects.

Q) Does anyone believe that if you meter CO_2 at the well head you are done?
Q) Acid gas projects are aimed at reducing H_2S emissions so deal with HSE risks rather than accounting risk.

Q) If you put it into the ground and it doesn't come out then you can say that it is still there. For acid gas can you be sure that it is all still captured? Maybe monitoring the surface and in some key subsurface areas is sufficient.
A) Right now it is not a problem but when you start getting paid for the CO_2 you store they will turn to the regulators to verify the volume of CO_2 stored.
A) The incremental costs of monitoring on a small scale is more than for a large project
A) In terms of crediting it will be hard to work out how much CO_2 is stored with just surface monitoring. With more projects a track record will be produced that will increase confidence.
A) For FutureGen with 2M tonnes injected, if you measure at the injection well and can prove that the CO_2 hasn't gone anywhere else, preferably with subsurface early warning then metering and wellbore integrity numbers should be adequate.

Q) The issue is proving it is in the ground. The ground is a big term and you are going to be licensed to store in a particular formation so leakage outside that formation is an issue. When the national authority takes over liability they will want to know where the CO_2 is. We should be looking to design monitoring techniques that can pin point the CO_2 and quantify it.

Q) Why do we care where it goes? If you lease the right to put CO_2 into the pore space and the seismic shows it is in the area and that any overlying formations don't have CO_2 increasing then it should be fine. Why is this not adequate?
A) That should be alright. This says though that seismic doesn't have the resolution to pin point the CO_2 and a well will be required.
A) We are talking about relative risk so we are limited to the best available monitoring techniques. Early projects are looking to drill a well ahead of the CO_2 plume to see if any changes can be detected. This can be used to calibrate modelling.
A) We will not be able to draft guidelines overnight, we are going to have to amend these guidelines over time as more projects get done.
A) You need to look at the risk assessment of the monitoring techniques themselves. You need to analyse the seismic to see if the risks that it generates can be fed into the greater risk assessment programme. We need to look at individual monitoring techniques to see if they are appropriate to track CO_2, find leakage or both.

A) We need to look at different approaches for EOR and for storage in aquifers. EOR can use CH_4 as a tracer and in some EOR projects can be seen in explosive quantities 5m from the surface. We could monitor methane as a precursor for CO_2 but this is not relevant for aquifers without CH_4.

Q) In terms of observation wells there are no plans to drill an observation well at Sleipner because it is too expensive. Should the requirements be different for onshore and offshore?
A) The same risk assessment method could be applied to offshore sites or isolated onshore sites but a different method may be required for populated onshore sites.
A) The problem is that these projects are being seen as an example of large scale projects

Q) If you can't verify the model then how can you be completely be sure of where the CO_2 is? So you need an observation well to verify the modelling.

Q) The oil and gas industry often find that their models are wrong. If you aren't monitoring how can you be sure your model is correct?
A) To say a simulation model is wrong is too strong, you can only say that it wasn't good enough based on the information entered. In projects that you are monitoring pressures you can use this to verify the results of the modelling. If there is no observation well above a particular plume there is no guarantee that the CO_2 hasn't gone to an overlying formation but if the pressures match then it is a good indication that it is doing what you expect.

Q) For aquifers you will probably not have too much information about the makeup of the formation. You are going to have to get all your information from limited down hole punctures and from remote sensing.
A) The lower the number of wells the lower the risk but the lower the information level. The higher the number of well the higher the risk but the increased amount of information you have from wells.

Q) Does this assume the number of wells is the major risk?
A) There are many components of risk.

Q) If you use pressure measurements to determine leakage then in a large CO_2 storage site of 1m tonne, if a fault is reactivated 5km from the injection site will you see this in the pressure measurements at the injection well?
A) If a significant amount of CO_2 leaks then you will be able to see a discrepancy between the modelling pressures and the actual pressures. If this occurs then you will have to intensify the monitoring to locate the CO_2.

Q) Looking at Sleipner, the plume is spreading out in rivulets rather than a single unit. How long do we think the plume will keep moving after injection stops?
A) Field investigations like pressure measurements are important but so is simulation. It needs to be an economical combination of the two. Simulation is getting cheaper so you can do simulations out for many years, 1000 years.

Q) Weyburn did some simulations out to 5000 years, was there still CO_2 movement?
A) Hydrodynamic CO_2 will never stop and some of this was free phase CO_2, the transient phase of other than the hydrodynamic CO_2 died off after 60 years. Weyburn showed the dissolved CO_2 went down into an underlying reservoir. An interesting point is that this underlying reservoir is up dip and continues well above the injection reservoir but is only moving at 10cm per year so in 10,000+ years may come up in Manitoba but should we be concerned with this?

Q) We should be looking at regulation and how the monitoring technology people can fit into regulation.
A) As a project operator would you draw up your package of monitoring techniques and explain them to the regulator.

A) A logical sort of criteria from multiple projects should be based on performance criteria rather than monitoring techniques.
A) There are three components. 1) If you detect a leak, 2) locating where the leak occurred, 3) quantifying how much CO_2 was lost and what should be done about it.

Q) In public consultations the questions that always comes up is "Do you know where the CO_2 is in the subsurface?" so even if this is not in regulation we should be able to answer it.
A) To what level do the public what to know?
A) They are really asking is "Is it where you think it will be?"
A) Tell me how accurately you need to know it and as a project operator we will find out.
A) The public want some confirmation that you know what is happening in the subsurface. We need to show that the integration of the monitoring and the modelling are conforming.

Q) Monitoring is not about getting more information; it is about getting the right information.

Q) I am interested to see the interest in timeframes in the crowd. Weyburn chose 5000 years, this was questioned in a recent peer review. Why would we be looking to monitor beyond timeframes of 50-100 years. Why do you model for 5000 years if you are only going to monitor for 100?
A) Phase 1 of the Weyburn monitoring and verification project was like a demonstration phase that used lots of different techniques. We chose 5000 years because we could cut it off at any time but you can look at the profile at anytime up to 5000 years. The plume moved out of the Midale formation by 500m. Reservoir simulators are usually not reliable until you history match them. You must measure and monitor to match the simulator and you are forever updating your model, you never know enough about your formation. You never know enough about you formation until the day you walk away from it. The question of 5000 years is academic you can take it out as long as you can but if you find it to be fairly confined after 5000 years then you know that the reservoir is fairly benign. Weyburn has 1000 well penetrations so then you model leakage through a leaking well you look to see if the CO_2 is then trapped somewhere else in the geosphere then it is fine. But you need to prove that your modelling is correct through some physical measuring. If nothing is changing after 500 years then why spend the money to model to 5000 years. If it is a "wild" system then you will need to do more modelling and monitoring.
A) At Nagaoka they used a Canadian reservoir simulation package. They then drilled observation wells and required breakthrough within 5 years because of budgetary constraints. They would not have known where to drill the wells if it wasn't for the simulation.
A) There are three groups of monitoring methods, 1) the reservoir, 2) the geosphere including the reservoir, and 3) the biosphere. 1 is the most important, then 2 then 3.

Q) Nagaoka did seismic and it showed where the CO_2 was, but not quantitatively. Monitoring and modelling are very important but they have their limits.

Q) What about the monitoring of the wells. Does Weyburn have a protocol for assessing and monitoring the wells?
A) Yes, they pressure test wells periodically on a rotational basis.

Q) What about large scale injection into an aquifer where it may effect wells belonging to someone else. Who is responsible for those wells?
A) All the Weyburn injection wells have a 20ft radius fibreglass hut that has detectors in them for H_2S as a pre-curser. This is the perfect place for monitoring – an enclosed space around the injection well. You can't put a hut over a producing well but the injection wells could be used as a proxy. For a saline aquifer, when the well spacing is much greater, then it would depend on the well spacing and if the plume is predicted to intersect with the well. If the modelling tells you that the plume will intersect a well you should monitor at that well.
A) Just having monitoring at the surface in not sufficient as a well failure won't necessarily show itself at the injection well.

A) About placing huts over wells, there was an incident in Germany where a well failed at 100m and the gas came to the surface along a 2km line so a hut would be ineffective.
A) There are monitoring techniques that can look at surface CO_2 over very large area such as satellite or aerial monitoring for surface deformation due to leakage.

Q) The idea of using H_2S as a tracer is a good one as you can smell H_2S.

Q) IOGCC requires you to have the property rights to all the pore space that the CO_2 will migrate to.
A) Under the Australian draft legislation for offshore CO_2 storage the proponent must demonstrate that it won't impact any other resource and the plume must be contained within the license area until closure and handover to the government which could be 20 years after injection

Q) What are the issues post-closure? Will slow CO_2 leakage result in measurable deformation at the surface?

Q) In the long term we don't really understand how abandoned wells will behave. There is still a lot of work to do in this area.

Q) Looking at Weyburn, can you break down your information to find out what the minimum number of data wells are?
A) Haven't done it for Weyburn but just a single well can make a huge difference.

Q) Focussing on wells brings us back to time scales again. There are a number of scenarios that could cause CO_2 leakage in the long term. How long do you monitor for? Should we have different regulations about the length of time different monitoring techniques should continue. For the caprock, the risk of leakage starts decreasing from the end of injection. This is not necessarily the case for wells.

Q) Has there been any physical experiments about how CO_2 reacts with brine and how that reacts with an abandoned well?
A) Questions like this are why there is the integrated Joint Network Meeting next June. Risk, well integrity and monitoring are all inherently linked. You are getting the situation that in the labs cements are dissolving quite quickly, but this is not being replicated in the field. Los Alamos labs are cutting cores in cement in a field in SACROC and taking core cuttings and doing lots of tests to see what is happening.

4.2 Day 2 & 3 – MMV Design and Reviews and Updates: CO_2 Projects

4.2.1 MMV Update in the CO2CRC's Otway Basin Pilot Project – Kevin Dodds, BP Alternative Energy/ CO2CRC

Although Kevin now works for BP Alternative Energy in the US he was a key member of the CO2CRC Pilot Project when he worked for the CO2CRC. The project was originally supposed to be injecting already however it was pushed back following regulatory delays with government and landowners. Injection is now due to start at the end of 2007. The project has three phases of operation with the transition between phases strictly governed by key performance indicators.

The CO2CRC use an integrated suite of measurements to reassure the government and the public of the integrity of the CO_2 stored. These measurements fall into two categories; storage integrity monitoring and assurance monitoring. If the storage works to plan then the assurance monitoring should never register any change.

Included in the monitoring suite were:

- Surface seismic
- Subsurface seismic
- Microseismic
- Core sampling
- Atmospheric monitoring
- Reservoir fluid sampling

The Otway project uses a new injection well and an existing well for observations and although only one observation well was used there was so many sensors that it took five 24 hour days to install all the monitoring equipment. They found an issue with the amount of sensors that you can put down the one observation well. However, it is these downhole sensors that really give the most accurate data so you want as much down there as you can.

For seismic, the reservoir has residual natural gas it which means there is very little contrast with the CO_2 in the seismic. Helping this was the fact that the subsurface seismic showed many more layers and accuracy than the surface seismic which overcame some of the contrast issues. To perform the seismic they used a bobcat for the weight drop which means the process is relatively cheap to redo.
They have included microseismic sensors as part of the assurance monitoring but they do not expect any microseismic events. The atmospheric monitoring is a challenge because the CO_2 content in the atmosphere locally has a huge variation because of the city and so trying to distinguish a signal from the background noise. They also used u-tubes to allow them to sample the reservoir fluids.

An interesting observation that they have already found is that during the wet season there was a significant difference in the character of the subsurface than during the dry season. This is very important for 4D seismic because you need to make sure that each time it is done with a similar water content in the subsurface.

Q) Your surface seismic was an orthogonal design but this is not compatible with 3DVSP which need radial sources.
A) The problem with radial design is that the further you go out the sparser the sites. Also there are problems with where the farmers would let them do it.

Q) With the u-tube, what zones were you sampling?
A) The top of the Warre C formation where the gas cap existed as well as 2 sample points below the shale break. There were questions about whether to isolate the 2 sample points from each other but this has not been resolved.

Q) Why do you not think there are benefits to simultaneous sampling?
A) The logistical benefits from doing them separately outweighed the benefits of the data.

4.2.2 Nagaoka, Japan MMV Program design, CO_2 Saturation and Movement during Post-Injection Period – Tsukasa Yoshimura – RITE/ENAA

Minami-Nagaoka gas field is one of the largest gas fields in Japan and also home to Japan's CO_2 injection pilot project. The site contains one injection well and three observation wells. The second on these observation wells is of particular interest because of the amount of observation data that was gathered from this well. The second observation well has experienced breakthrough from the CO_2 however the third and furthest observation well, which is 120m from the injection well, has not yet had breakthrough. The downhole monitoring at Nagaoka included some novel techniques such as optical borehole TV.

As well as downhole monitoring the Nagaoka project also used Seismic tomography. A number of seismic surveys were shot over the course of the project including one as a baseline before injection, then 4 times during injection and 2 times after the cessation of injection.

During the project there have been 2 earthquakes at the site however monitoring shows that there has not been any damage to either the equipment or the integrity of the storage at the site.

Q) You mention that in 2008 you are going to model the geochemistry? Which model are you using?
A) We tried to simulate it this year but we don't think it was very successful. We used an improved GEM model

Q) In one of the diagrams you showed the plume coming out in ellipses and it shows to moving up and down dip.
A) The pressure of injection has made the plume move up dip and down dip at the same rate but this will change after the end of injection

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4.2.3 MMV Efforts at the CSLF recognised Zama Lake Acid gas EOR project – Steve Smith, EERC/PCOR

The Zama field is in NW Alberta has upward of 1000 well penetrations and is being used in the Zama Lake acid gas EOR project. The main goal of the project is the EOR rather than acid gas or CO_2 disposal; therefore all the monitoring activities have to fit in with the oil production operations.

The project involves injecting acid gas into the top of the well and producing oil from the bottom of the reservoir. The reservoir is in one of 5 pinnacles that are being injected into but the monitoring is only occurring at one. The risk of injecting into the pinnacle reef is different from injecting into a laterally continuous reservoir however the local regulations for acid gas injection are very robust so Apache have already done a lot of work to prove to the regulators that it is safe to inject at this field.

From geomechanical testing it looks like this is one of the best caprocks in Alberta which is being verified with the observation well above the pinnacle showing no increase in CO_2 concentration in the reservoir water. This project will allow them to do core sample of carbonate rock that has been exposed to acid gas over time which they don't think has ever been done before.

A perflourocarbon (PFC) tracer was added to the acid gas and used for injection to see how much injected gas was being produced with the oil. PFC was used because it became very expensive to deal with carbon isotopes which can become very hard to identify where they came from. They then had trouble because no one in Canada was able to analyse the PFC so they had to send it to the US for analysis. This then became an issue itself because they couldn’t send anything across the border with H_2S present.

Q) What do you think the interaction between the PFC and the oil will be, do you think it will dissolve?
A) Yes, we think that any oil in the residual contact zone comes in contact with the acid gas some PFC might dissolve but there is enough injected to still be useful

Q) At what pressure do you expect the caprock to hydro fracture?
A) The initial pressure of the formation was about 14 – 15,000 kPa and we have run some injectivity tests and not seen any parting pressures at 26,000kPa. The project will take the reservoir to 16,000kPa

Q) If you produce all the oil will the underlying brine have any effect on the cap?
A) We are doing tests now to try and understand what will happen.

4.2.4 MMV Programs at ADM Site, Illinois - Midwest partnership, Rob Finley, Geological Survey of Illinois

The Midwest Partnership's Archer Daniels Midland (ADM) Site in Illinois is one of the 7 partnerships under the US DOE Regional Partnerships Programme. The project involves the injection of 1 million tonnes of CO_2 over 3 years however they will be drilling an oversized well so if they get more funding they can scale up the amount of CO_2 injected above this level. The sandstone formation that they are targeting for storage is the same formation that the two Illinois proposed FutureGen sites also exploit.

The region has been extensively utilised for oil and gas operations with 452 wells in the region, 150 of which are used for gas storage. This infrastructure and experience in the area has allowed a lot of data to be gathered for the project. The two closest existing wells are 30 and 50 miles away from the injection point and these wells were used to assemble a set of control data. Estimates from one of the control wells predicts that it will take between 30 and 100 years for the CO_2 to reach the primary seal cap rock through buoyancy. The project will also be drilling two observation wells 1 year and about 2.5 years after injection.

The project will utilise fluid sampling in the observation wells and well as borehole geophones for the 3D seismic. With regard to the seismic the project had trouble getting a seismic company to come to Illinois to shoot the required 6 miles of 2D seismic so could only get smallish thumper trucks. The project will also use accumulation chambers and two eddy covariance towers. This will be difficult because although the ethanol plant is injecting some CO_2 they are also releasing a significant amount into the atmosphere which will affect the atmospheric CO_2 fluxes.

Q) You have shown that pH is being monitored even though pH will be one of the last things to change, why don't you measure carbonate instead?
A) pH was an example, we are also doing carbonate monitoring.

Q) You didn't mention carbon isotopes measurements?
A) Yes we are looking at isotopes as well.

Q) Is there any flow in the Mt Simons basin?
A) We are hoping to do a full hydrological model to see if there are any discharge points that may be affected by the project.

Q) What are the regulations in the area?
A) We have had a number of discussions with regulators who have never done this permitting process before so it is a mutual learning process with the regulators.

Q) In regards to logistics and costs, will all the million tonnes be trucked?
A) No, a 4-6 inch pipeline will be build. The trucks were only used for the small EOR experiments.

4.2.5 Seismic Based MMV programs: Frio II, Otway basin, Permian EOR, WESTCARB/SECARB – Tom Daley, LBNL

Tom Daley from Lawrence Berkley National Laboratories unfortunately could not attend the network meeting but was able to give his presentation on seismic based MMV programs via the telephone. Looking at the design of borehole seismic systems discussing issues and lessons learned.

At the Frio Brine site they have looked at developing the use of seismic from conventional surface signal-surface sensors, to surface signal-downhole sensors, and finally to cross well techniques. The cross well seismic works with two wells, one providing a downhole signal and the other with the downhole sensors. The cross well development is also looking at the possibility to do continuous monitoring cross well so you could see the development of the plume as it grows, this process is known as CASSM. Part of the challenge of developing this technique was that they had to design a seismic source that could operate down the injection well during injection. The work produced very good results even when considering the small amount of CO_2 injected, only around 1500t.

Continuous Active Source Seismic Monitoring or CASSM continuously measures the changes to the cross well seismic signal as the CO_2 is injected. The travel time of the signal was seen to increase over the course of the injection until stabilising after breakthrough at the observation well. It was then seen to change only slightly after the injection ceased. This allowed the movement of the CO_2 to be monitored before reaching the observation well. Measurements at different depths could show CO_2 movement into different regions of the reservoir. The monitoring across the top of the reservoir, underneath the caprock showed that the CO_2 reached the top of the reservoir before breakthrough. This also showed that the CO_2 concentrations were at their highest at the top of the reservoir which was expected. It also showed that the concentration at the top of the reservoir decreased post-injection.

At the Otway Basin project in Australia the resolution that could be seen in the seismic images was very small because the injection is into a gas field and they were also limited in their downhole tools by a 2 3/8inch patch in the casing. In spite of this they did use a number of down hole monitoring tools including seismic, travel time monitors, Offset VSP sensors and microseismic sensors. They now have a fairly unique set of instrumentation to gather data which will enable them to accomplish all the goals they set out to achieve.

Q) Struck by the very small time delays seen in the CASSM experiment. There is remarkable stability in the system but this is explained that P waves are not very sensitive to CO_2. Did you consider measure the attenuation as well as the time?
A) Yes the system was very stable which was lucky and yes the p-waves aren't very sensitive. We are looking at attenuations and initial results do show a change in amplitude which does correlate with the time change. We do plan to look further into attenuation. Hopefully we will have some attenuation result so show in the future.

4.2.6 MMV programs for the IEA GHG Weyburn-Midale CO_2-EOR monitoring and storage Project - Don White, Geological Survey of Canada

The Weyburn project applied a wealth of monitoring techniques to the EOR project with varying results. One of the difficulties of dealing with a CO_2 EOR project is that you are dealing with a multiphase CO_2, as well as CO_2 dissolved in Oil and other complications.The project itself is very different to the other large scale CO_2 injection sites because of the number of injection wells (over 19), unlike Sleipner and In Salah which use only one large injection well. This means the project is essentially many small scale projects.

Weyburn has active and passive seismic. The active seismic benefits from the fact that the CO_2 properties are significantly different from those of the oil and brine. This greatly improves the resolution of the technique to an estimated lower limit of detection of 2500 tonnes. The passive microseismic monitors have found very little microseismic activity. During the operation of the project they have found discrepancies between the seismic and the original simulations which a good reason why you need both modelling and monitoring. The next step will be to try and take seismic to the next level to use it for quantitative monitoring of volumes and location. As well, seismic carbon isotopes are used to track the injected CO_2 as it moves through the reservoir

From here the project would like to integrate all the data they have and will be acquiring. This is seen as one of the hardest tasks that needs to be done. They also would like to install a dedicated permanent seismic array to improve the repeatability of the seismic data collection process. This decreases the near surface affects that can occur between surveys. Also you only need a source when you want to do another survey. The total error brought about through changes in survey position can become significant very quickly.

Q) Can you tell us about the design for the ERT?
A) The group from Lawrence Livermore Laboratory is doing it, and based on maps, they are determining whether to proceed with ERT field work. We also reviewed the ERT work planned for the CO2CRC project

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4.2.7 Down hole fluid recovery system deployment at the Penn-West CO_2 EOR Monitoring Project - Gonzalo Zambrano, University of Alberta

The Penn-West operations are located in the Pembina field which is the largest field in North America with 8000 wells in total. The Penn-West CO_2 EOR Monitoring Project involves a total of six production wells and two CO_2 injection wells.

The monitoring techniques used at the site include collecting pressure and temperature measurements down hole as well as the use of geophones. The eight geophones are arranged in two four phone strings. The two strings are overlapped so if one line is lost you still and a reasonable spread of sensors.

A key goal of the project is to make cheaper ways of down hole sensing including fluid sampling. The down hole monitoring at Penn-West is different from the U-tube system used elsewhere because the monitoring tools are cemented into place down hole. The cost of the U-tube system is more because you need to have the packer system custom designed. In the Penn-West CO_2 EOR Monitoring Project the observation well is cemented between 1200m and 1600m and this is where the sensors are located. From 1200m to the surface is heavy brine.

Q) Can you elaborate on the advantage of collecting samples at downhole pressure and temperature rather than using surface separator?
A) Chemical differences, pH changes when using surface separator. Geochemical purposes dictated the choice to sample at downhole pressure.

Q) If geochemical monitoring was not an objective of a project, does that mean that you would not worry about sampling at downhole pressure?
A. Not necessarily as there are advantages if you were interested in oil samples then downhole pressure and temperature would provide more accurate results about the oil.

Q) What sample size can be collected in FRS?
A) This is limited by depth of reservoir – the length of line to surface dictates the size of the sample.

Q) With all the downhole equipment that is in the well, what are the plans for abandonment?
A) We can follow the standard protocols for abandonment as we have over 1km of uncemented well that can be plugged.

4.2.8 Shallow Subsurface and atmospheric monitoring in CO_2Geonet and CO_2Remove - David Jones, British Geological Survey

This project is looking at a rapid wide area leakage detection technique. This technique could well be required given the possibility that a CO_2 leak might come from a very small area and without rapid wide area detection it will take a significant amount of time and effort to ensure you don't miss the leak. The detection system could use airborne techniques looking at variation of vegetation or through direct detection of CO_2. Another option is truck mounted laser techniques. The overall success rate for remotely detecting natural CO_2 leaks is only 36% with the most successful techniques reaching 47%

Another technique tested used a tripod mounted laser and a reflector but the instrument used proved slow and not sensitive enough. This led to a vehicle mounted laser system that fired the laser about a meter to a reflector which is also mounted on the vehicle. This was much more effective and sensitive for measuring the CO_2. This technique was also found to be very repeatable although the base CO_2 levels were found to vary significantly from day to day depending on the weather conditions. A strong wind could result in the anomaly appearing downwind from the actual anomaly site however if this result was found it would be enough to red flag an issue to go back and explore further.

Another possibility is using radon gas detection to indicate changes in the reservoir conditions. This is being used by BRGM in France. For offshore, monitoring buoys can be used. They are currently being examined and tested with the eventual aim of being deployed at a site like Sleipner. Initially it will be tested

Q) Electrochemical techniques can be unreliable and are heavily affected by changes in temperature so instead they usually use hydrodynamic measures instead.

Q) For the remote CO_2 detection system that is mounted on the vehicle do you think that the exhaust could affect readings?
A) They can, but wind direction is carefully measured so that results are not affected by vehicle monitoring the CO_2. Definite anomalies at the end of lines where vehicle turns so one solution is that we are looking at electric quad bikes for future experiments.

4.2.9 Research on Environmental Risks from Geological CO_2 storage – Jeremy Colls, University of Nottingham

At the University of Nottingham they have set up a controlled system where they can injection CO_2 up to a metre in depth below the surface and measure the presences of it at the surface. Because this is done very close to the surface the source of the leak does not matter.

The experiment uses eight adjacent 2.5 metre square plots. Four of the plots are gassed and four plots are used for control. The gas is released from a single point source in the centre of the plot. Different crops were planted to see if there was any difference in the reaction of the crop and the baseline of CO_2 for different types of crops. There was some collaboration with the BGS who came to the site and performed some specialist measurements.

The average daily gas concentrations in the soil were affected by changes in weather. CO_2 is a benefit for vegetation in the atmosphere but is detrimental to the roots because of the displacement of oxygen in the soil.

Contrary to expectations the CO_2 was found to be sinking at some point and not consistently rising from the source. In the future ASGARD is looking at using Iron goethite to chemically lock CO_2 and SO_2 as Iron carbonate. This is interesting because it can use high sulphur flue gas from coal combustion.

Q) What will be done with the sulphuric acid if it works really well?
A) They wouldn't want the sulphuric acid, they would inject and bury if it was possible, but we uncertain if it will work.

Q) What total volumes are injected and was there a mass balance on injected/ detected CO_2?
A) The injection rate was 3 litres / min to sixteen plots for six months continually. There was no mass balance but they would be interested in performing this at some point. To do this they would have constructed a flux chamber over the site, but leaks are all too common and they are very hard to fix. Also, not all the CO_2 injected will come out the same plot that it is injected into.

4.2.10 Baseline Survey for Evidence of Gas Microseepage Prior to a CO_2 Injection Experiment at the Teapot Dome, Wyoming USA – Ron Klusman, Colorado School of Mines

The original aim of the work was to measure baseline fluxes across the teapot dome field in Wyoming USA. A new fault was been discovered at the site last year and so this has added addition impetus to the work to see if there is any deep source CO_2 being released.

The project looked at soil fluxes for CO_2, CH_4 and other hydrocarbons across the teapot dome area. Areas that showed anomalous fluxes were paid more attention with trenches dug across the anomalous area where physical evidence of the flux could be seen. It was found that as the barometric pressure is dropping the CO_2 fluxes are high, where as when barometric pressure is increasing the CO_2 fluxes are notably lower. Strangely the site also showed some negative CO_2 fluxes where CO_2 was being drawn out of the atmosphere to form calcium carbonate.

The source of the measured CO_2 can be distinguished using stable isotopes. They did an isotopic analysis and compared it to measurements at other areas such as the local airport and to seawater to demonstrate the different source of the flux and the source of carbon in carbonates found. Following the analysis no evidence was found of a deep source CO_2 which suggests that the fault found is fully sealed.

Q) In the vein calcite reaction, you produce protons. Do you know what can neutralise the protons to allow the reaction to carry on?
A) The calcite base could absorb the protons which could serve as a buffer for the protons.

4.2.11 Accurate Soil CO_2 flux Measurements at High Spatial and Temporal Resolution – Rod Madsen, LICOR Biosciences

LICOR Biosciences produces instruments that can be used for CO_2 monitoring at CCS sites. They have already sold eight monitoring tools to CCS related projects around the world. Two of the instruments at LICOR of particular interest to CCS are the soil surface instruments and eddy covariance towers.

There are a number of networks existing studying the net carbon balance of CO_2 for different ecosystems. Whether an ecosystem is a net source or sink of CO_2 is important when setting up a baseline for a CO_2 storage project.

One of the surface monitoring methods are Soil flux collection chambers. For surface measurements you could set up a grid of collection chambers over suspected leakage pathways. You can also set up chambers to run continuously to see how the ecosystem reacts to different temperature and weather conditions.

There are a number of interesting issues that need to be resolved for collection chambers to provide accurate results. To keep the pressure in the chamber the same as the atmosphere continuous rotor pump are used rather than a pulsing diaphragm pump. To provide accurate results quickly you will need to have good mixing within the chamber which is why the LICOR chambers are round rather than square. You want minimal disturbance to soil moisture, temperature and radiation so the chamber must move away from the sample area between sampling.

There are then a number of factors that you must take into account when analysing the results. It must be realised that CO_2 fluxes in the chamber are not liner because if the CO_2 in the chamber is allowed to increase the flux will decrease. If you assume it is linear you will be underestimating your CO_2 flux by about 5%. There is also significant variability in CO_2 flux measurements with time and moisture for example a very small rain event can have significant effects on CO_2 fluxes because of CO_2 displacement by the water creating a puff of CO_2 into the atmosphere. This variability can however be explained. In this case there was also diurnal response in CO_2 fluxes due to the fact that the crop (corn) in the sample was still growing. However as different crops (soy beans) grow and the temperature of the soil increases and the rain increases the CO_2 flux rates increase from 1 to 8. This shows that you need a very good understanding of the background flux if you are going to detect anomalous CO_2 fluxes.

They are going to inject CO_2 at the SECARB project and use the LICOR measurements to see if there are any changes. They may even simulate a leakage event. Soil flux measurements are going to be just one component of the monitoring programme. Soil flux collection chambers can also be used in conjunction with carbon isotope analysis.

Q) What would be the cost for a full system built suit a specific project?
A) The system can range from US$15,000 US for basic system up to US$100,000 for a complete system.

Q) Rainfall will result in more than just displacement of CO_2, there will also be a microbiological activity spike that can't be ignored. Measurements from that point on are distorted due to the microbiological activity.
A) Should still be included, despite it being part of the noise that is trying to be avoided in measurements.

Q) Some companies are approaching farmers offering to purchase CO_2 credits based on continual cropping. How much back up to prove the CO_2 reductions would be available from data available from your systems?
A) Field use is part of a current intensive study that aims to find the answer to this question. We will be looking at soil carbon on a year on year basis to determine the amount of carbon stored year on year for different farming methods.

4.2.12 MMV Results from FRIO II – Sue Hovorka, University of Texas/ Gulf Coast Carbon Centre

The site was selected to be representative of the region in general. The area chosen is fault bounded but the injection volume was small and didn't come into contact with the faults and this was confirmed with no change registered at any of the faults.

The CO_2 was injected slowly because part of the project was to look specifically at the CO_2/water interface to see what is happening at this point. Down hole pressure and temperature gauges were used at the site as well as U-tubes for fluid sampling. U-tubes were used because they allow unperturbed samples to be taken regularly which in this case were used to look at the tracer responses in the reservoir. A tracer was injected before the CO_2 so it could be seen how the CO_2 spreads through the reservoir however no breakthrough of that tracer was picked up so it is thought that the CO_2 by-passed and went around the tracer. Tracers were also injected behind the CO_2 plume but this wasn't picked up at the observation well either. As well as monitoring within the reservoir the project also used above zone monitoring which is very important for assurance monitoring and early warning.

Before breakthrough you get an increase in temperature from warm waters being pushed past the observation well and you also get a pH drop and pressure increase. This all occurs before you get free phase CO_2 coming past the well.

The results of the monitoring programme showed that nothing leaked at Frio site. The media picked up on a comment that the pH was dropping and the acid could react with the rock and well seal however this was taken out of context and was an expected reaction. There was however an unexpected increase in iron and manganese dissolved in the water which they think comes from a transient very trivial amount of mineralisation.

The Frio MMV program also used an off the shelf piece of equipment designed to test for leaks in pipelines. They ran the tool over the ground to look for CO_2 and they did find evidence of some CO_2 leakage but turned out to be coming from work on the well rather than from the reservoir.

Q) A possible sources of iron could be the old casing reacting with the acid. Can you determine the source of the iron?
A) We do know that the casing was part of the source but it is not all the source because it was repeated in the laboratory with no casing present.

Q) How much CO_2 is trapped through residual gas saturation trapping?
A) In terms of residual saturation, unfortunately because the permeability of the reservoir was so high and breakthrough happened so quickly there wasn't a good amount of rock contact to analyse residual trapping. This would be an important measure to make but we didn't get the information to nail it down in this project.

4.2.13 Seismic Monitoring Programmes at Penn-West CO_2-EOR Monitoring Project – Don Lawton, University of Calgary

As was mentioned in a previous presentation, the Penn-West CO_2-EOR Monitoring Project involves two injection points, 6 production wells and one observation well.

The reservoir at this site is only 20 meters thick which is below the individual resolution of the seismic which they knew could be an issue. This meant the seismic lines had to be a lot longer than the target area as this allowed maximum resolution. They shot three 2D lines initially then added a fourth. This gave them a "poor man's" 3D image of the area which was sufficient for time lapse. The site also has an overlying coal seam about 9m think called the Ardley coals which did cause some problems in the seismic. When laying the seismic lines on the surface there were some gaps because of surface infrastructure and these gaps changed over the course of the project as different infrastructure was added at the site. In order to achieve complete repeatability between the shots the sensors that couldn't be repeated had to be stripped out of the earlier shots as well.

The difference in the time-lapse showed no differences, so the CO_2 couldn't be seen because of the resolution was not good enough. It should have showed any CO_2 above the reservoir if there was any. Subsurface seismic was looked at and it is more hopeful that it will show CO_2 in the reservoir.

VSP was added at the site which helped explain some of the problems with the surface seismic. The sensing tool was moved up in the well for different shot to try and show the reservoir further away from the well. Walk away VSPs would be the preferred way of monitoring for the site.

The Penn-West CO_2-EOR Monitoring Project also used downhole geophones however there was damage to the geophones on installation which meant that there was too much noise to use for passive seismic but they have been useful for active seismic.

Q) Has this field seen water flood and are they currently taking water from an over lying reservoir to inject?
A) There hasn't been water flood for the last 30 years. Not sure though where they are getting the water from.
A) They are getting water from another lease so it is not coming from above the reservoir.

Q) It is important to show that seismic is not always appropriate. Can you feed this into the IEA GHG monitoring selection tool because they always recommend to use seismic? Can you use your information to show when you can and can't use seismic?
A) There are two aspects of seismic, firstly is to see in the reservoir and the second is to see leakage. In our case we have found we are unable to perform the first task but we should be able to perform the second.

Q) Have you considered electromagnetic tools to look at the reservoir?
A) The wells might be too far apart to get any improved resolution.

Q) 4D seismic generally is only considered to see CO_2, could it be used to sense different attributes.
A) You can't say that the seismic hasn't been successful yet.

4.2.14 Observation Well at Penn-West CO_2-EOR Monitoring Project – Gonzalo Zambrano, University of Alberta

This presentation also looked at the Penn-West CO_2-EOR Monitoring Project. Pressure and temperature monitoring at different depths and in the injection well were used to help see the reaction of the reservoir to the injection. For the permanent installation of the instrumentation they used computer simulation to test the optimal sensor positions to enable the best contact after cementing. They are now looking as assessing how the sensors were installed and located.

Q) Could you comment on the computer visualisation in terms of creating micro annuli. Presumably the aim is to avoid micro annuli?
A) Yes this was the aim. We saw in the simulation the best position of the sensors and wires to minimise the occurrence of the micro annuli. Cementing in the sensors is cheaper.

Q) In the graph you showed on bottom hole pressure, you must be close to the minimum horizontal stress, did you see any fracture propagation?
A) No, the bottom hole pressure was kept within range to avoid any fracture. The oil field is very well known and the injection pressures that are being used are on the safe side of the fracture pressure.

Q) What would you estimate the minimum horizontal stress at the time of injection?
A) The minimum horizontal stress was about 18mPa.

Q) Have these wells been fractured previously?
A) Yes it had been fractured previously.

Q) Imagine a hypothetical situation where you were designing a pilot or commercial EOR project and you work for a practical oil company that will allow you to drill and instrument one observation well; You want the most comprehensive MMV programme but you don't want to cement. You could use geophones, or I could use fluid sampling. Fluid sampling would probably be the higher priority. But would you see difficulties in putting both fluid sampling and seismic in the one well? If so, which would you choose?
A) Depends on the question you are trying to answer e.g. reservoir sweep? misibility? credits? No one technique is going to be the answer everything but if you rank what you want to find out then this will drive the tools.
A) Fill the well from the surface to the bottom with geophones and take your samples from the production well.
A) This was a big question that came up in Otway. In demo projects you are not addressing the same questions as in a commercial project. To monitor the processes you need to go into the subsurface. For geochemistry you have to go into the reservoir, seismic can be done remotely.
A) If you are drilling a new observation well it would be a mistake to locate this just on modelling but rather use seismic and modelling to track the plume and then locate the well. For a big project you will have to do both.
A) You can do both things in the one well but there may be compromises. If these are mature wells you might not want all the fancy completions.

Q) For a pilot project you might not want to get credits. You could mount the geophones on the casing but what about doing a perforation?
A) At Penn-West the cement didn't go to the top because this will improve your ability to do remediation if necessary. There are case histories of doing perforations with casing mounted geophones.

4.2.15 Shallow Subsurface and Air Monitoring Programme at Penn-West CO_2-EOR Monitoring Project – Bill Gunter, Alberta Research Council

As well as the injection and production wells at Penn-West, there are also four ground water monitoring wells; three of which are deep and one is shallow. The important aspect of ground water sampling is to ensure you are sampling the water from where you want it.

During the operation results of monitoring showed:

- Ground water pH was relatively constant
- Water level was relatively constant
- Alkalinity variation was in spec
- Conductivity was stable with the exception of one set of values but this is still a question mark.

These results showed no sign of CO_2. Water sampling also showed that the chemistry of the water in the formation was different from that in the shallow aquifers. Looking at this you can see the change that you would expect if there was water leaking from the formation into the water in the upper aquifer. This signal might not just be CO_2 but might be more calcium and bicarbonate in the water. Carbonate isotope data would be excellent but so far these shallow aquifer waters are so dilute they can't get any carbonate isotope measurements. If the water was mixing you would see a change in the carbon isotope ratios.

It was interesting look at how the makeup of the reservoir water will change through different phases of an EOR project. The measured trends did generally follow the predicted results.

Air monitoring was also performed at the site with open path tuneable diode laser technology to detect fugitive emissions of CO_2 and CH_4. The tunable diode laser system was chosen as it averages out in homogeneities of soil gas, it is mobile, it is relatively cheap and it is efficient for the monitoring of large sites. In the future the project plans to combine the outcomes of the atmospheric monitoring with dispersion modeling to translate into quantitative results.

Q) Do you know if there is a volume change in the conversion from Ca clay to Na clay?
A) I am sure there is a volume change but I can't quote it. These programmes do look at volume change as it is very important feature in effecting permeability.

Q) Did you look at any of the minor cations?
A) No, the work on trace elements is ongoing. We do see iron increases in the water.

4.2.16 MMV Programme at the CSEMP Pilot Project – John Faltinson, Alberta Research Council

The CO_2 Storage and Enhanced Methane Production or CSEMP project is a collaboration between Suncor Energy, EnerPlus Resources Fund and the Alberta Research Council. The goals of that project are to determine baseline production of CBM from the Ardley coals at the pilot location, store CO_2 within the coal strata utilizing an injection well and measure storage effects in the coal, determine the effect of CO_2 injection and storage on CBM production from adjacent wells, and assess the economics of the collection of the CO_2 and injection into coals as a long-term storage method for the reduction of GHG emissions.

A number of monitoring techniques were used at the site including downhole gauges. The project identified a number of benefits of downhole gauges for the monitoring of store CO_2. There include:

- They enable leak detection quickly before significant injected fluid lost to the wrong zone.
- They provide better pressure monitoring and understanding of non-intuitive CO_2 pressure and phase behaviour during injection and fall-off testing.
- They give precise pressure monitoring during production testing and eliminate the need for running, setting and retrieving wire-line gauges or estimating via fluid levels.
- They allow real time 24/7 remote monitoring of down-hole pressure / temperature via the Zedi Solutions website.

The current issue facing the project is that CO_2 is leaking from Ardley coal to channel sand which has put a hold on remaining Verification & Environmental Monitoring. The CSEMP Project is now evaluating their options.

4.2.17 Role of risk assessment in designing MMV Programs – Ken Hnottavange-Telleen, Schlumberger Carbon Services

Risk assessment methods are used to decide on monitoring techniques at a site. Ideally you would use experience to provide a quantitative risk analysis however because there is only minimal experience in CCS, qualitative risk assessment utilising expert opinion is the best option.

To assist in identifying risks a CCS project can be broken into four compartments and two conduits. The compartments are; the storage reservoir, hydrocarbon reservoirs, drinking water, and the environment. The conduits are the wells and faults and fractures. Once you have identified the risks associated with the project you need a ranking system for risks. There are a number of options such as the FEPs process. You should rank the risks associated with a project and fashion the monitoring accordingly. You need to identify what monitoring methods address what risks.

In conclusion, there are a number of CCS project functions such as injectivity, capacity, containment and there are currently existing monitoring techniques for each function. Ken finished by saying that modeling is the key to verification.

Q) I would challenge you last statement and say monitoring is the key to verification.
A) They are inherently linked but it is the modelling that will provide the predictions.
A) The problem has to be properly posed in modelling. A model is only as good as the data you put into it.

Q) At Frio we did a very careful model and monitoring but there were still differences. We are being naive to think we can actually verify. We can inch up our confidence but verify is very strong concept.
A) Agreed, it is wrong to say modelling is verification. The term verification was adopted by this industry.

Q) How do you handle uncertainties in the data and how does that impact on your risk in regard to modelling?
A) Modelling is a precise combination of actual data and our understanding of how systems work.

Q) Are there stoichiastic approaches to applying risk?

A) Schlumberger is looking at how uncertainties propagate through modelling and to evaluate the results in terms of uncertainties. For the moment we haven't developed our own tools to evaluate risks but we are working on them.

Q) Models are useful for scenario analysis but ultimately they are defined by underlying data. History matching doesn't provide the unique solution; it just shows one possible option.
A) Agreed, the verification is in the measurement but it is verification of the model.

Q) A risk assessment matrix compares likelihood to probability. From experience in BP, a group of experts ranked risks and then one person came in with a different view and turned it on its head. Populating a matrix of risk is so dependent on the people in the group. How does Schlumberger build the group?
A) This is being looked at in Schlumberger. This is only one tool of many. It doesn't hurt to look at risks from different point of views.

Comment) It is not easy to develop a risk based monitoring approach and Ken was set up to demonstrate the difficulties in this method.

4.2.18 A New Mode of Seismic Surveillance – Leon Thompson, BP

Leon started by saying that his ignorance in childrearing has added to his expertise in child raising – same as CCS. He also said that looking to prove a negative result is very open to criticism from the public for doing the wrong experiment but this is what we are trying to do with CCS, we are trying to prove that there is no sign of leakage. The presentation covered a number of aspects of conventional monitoring, as well as unconventional 4D seismic and anisotropic seismic.

The subsurface permeability is highly heterogeneous. This means that measurements at a few wellbores can be seriously misleading, as they inadequately sample this heterogeneity. Hydraulic modeling is almost always based on over-simplified distributions of permeability, not confirmed by subsequent full-volume measurements. The only technology which measures the full volume with high resolution is seismic.

The benefit of seismic depends on the hardness of the rock you are trying to shoot through, he harder the rock is, the less it cares about what is in the pore space. Conventional 4D seismic assumes purely isotropic rock properties and relies on the differences in P-wave velocity and impedance caused by fluid substitution pore pressure. This is why seismic works better in soft rock than in hard rock.
There is however an entirely different way to do 4D seismic that is independent of fluids and independent of pressure. This method looks at the 4D changes in the azimuthal anisotropy of the reservoir. To do this, we need an accurate understanding of the rock physics, including their fractures.
The implication is that the permeability is augmented by fractures, with a known orientation and so future wells will be placed with this anisotropic permeability in mind, thus optimally producing the reservoir.

In conclusion CO_2 storage monitoring requires full-field measurements, not just borehole measurements, and hence seismic monitoring. Seismic provides only indirect measurements of CO_2, but there is no substitute for the high-resolution 3D coverage it supplies. Time-lapse seismic is best done with permanent sources and receivers, in order to avoid acquisition-variant artifacts, and to reduce costs. Conventional 4D seismic assumes a (heterogenous) isotropic subsurface. This may not be accurate, as it ignores the possibility of subsurface fracturing. An alternative mode of 4D seismics uses the signatures of azimuthal anisotropy, P-wave AVOAz and S-wave splitting, to detect such fractures directly

Let's not try to over simplify the complex subsurface systems.

4.2.19 Detailed CO_2 Injection and sequestration monitoring through cross well imaging – Mark McCallum, Z-Seismic

A seismic signal truck will create a signal range from 5Hz – 200Hz so it is low frequency. Cross well seismic uses a piezo electric source which is much higher frequency from 100Hz to a couple of thousand Hz. Cross well seismic with high frequency sources increases the resolution by an order of magnitude. To realise this resolution improvement you do have to do the full combination of source and receiver locations. As you sweep the field with higher frequencies you find the higher frequencies starting to drop out. This drop out or attenuation is because of rock properties and this can be analysed to generate more information and a better image of the reservoir. You can improve confidence further still through the use of cross well seismic in conjunction with 3D seismic.

The optimal well spacing for cross well seismic is a function of the rock but this technique has been applied across a kilometre in very fast rocks. Remember when doing CCS that the reservoir heterogeneity plays a huge role in where the CO_2 will end up.

Q) Can you say something about the aperture of measurements relative to reservoir thickness and geometry of wells.
A) Depth doesn’t matter. The distance of the wells is up to 800m well spacing. The depth just changes how long it takes to gather the data. On a thick reservoir it may take 2-3 days. It just comes down to if you can push a signal through it.

Q) If wells don't penetrate the reservoir can you still get a decent image?
A) Not really, you could get an overlap in the middle of the reservoir.

Q) One of the keys to CCS is showing the integrity of the seal and the fractures which are very small and hard to see.
A) If there is a fault between the two well bores with a throw of over a metre then you should be able to see that. But to get that you have to get lucky or have an idea where the faults are. Then determining if the fault is a sealing fault or a communication fault is another question. In this case if you know a fault is there you should be able to see how the fault operates by seeing if there is CO_2 moving through it or present above it.

4.2.20 Design of surface seismic programmes for CO_2 storage monitoring – Mark Egan, WesternGeco

Mark gave an excellent overview about how the seismic process works and also talked about the design of a surface seismic programme for a CCS project. The initial objective of a baseline seismic program is to establish an understanding of the structure & stratigraphy of the reservoir and overburden, find the capacity of the reservoir, and to rate the sealing properties of the reservoir. Subsequent, repeat seismic programs will then look to find out where is the CO_2 going and ultimately if it escaping. The objectives of the survey design are to meet the above objectives and meet any permitting requirements.

To meet these objectives the survey design parameters that must be considered include

- 2D vs. 3D
- Shooting direction
- Narrow azimuth vs. wide azimuth
- Aperture
- Source-receiver distances
- Sampling

Q) If seismic uses a lot of modelling, how do we know the confidence?
A) You simply model to try and find the best way to accumulate data. If you could do the seismic in ten different ways that would be the best but this is prohibitively expensive.
A) It is easier to model the wave equation than the diffuse equation. There is a large project ongoing to try and improve the quality of modelling in seismic, electromagnetic, etc.

Q) Do you think that geophysics has the ability to determine caprock integrity?
A) If you have wide azimuth seismic data you can determine the direction of the fractures. You can also guess at the density of the fracture swarms. The problem is that you don't necessarily know which ones seal and which don't.

Q) How cheap can you get this? We need to focus on changes rather than absolute parameters.

A) That's right, if we could model the types of geometries that might be present then we could estimate the risks of a particular type of error.

4.2.21 Passive Seismic Monitoring: listening for the Snap, Crackle, Pop! – Marcia Coueslan, Schlumberger Carbon Services

In this presentation Marcia looked at a number of aspects of microseismic activity including:

- What it is
- Where else is it used?
- What causes microseismic activity & what does it tell us?
- Hardware Options for sensing the activity
- Integration with geomechanical modeling

Micro Seismic refers to monitoring micro-earthquakes in a reservoir. The frequency of earthquake events increases as the event gets smaller. Passive seismic may be able to pick up small fractures in the caprock if there is an accumulation of micro events. The choice of permanent or temporary micro-seismic will depend on the project layout and options. Like conventional seismic you need to establish the baseline noise in the system to be able to interpret and identify anomalous signals. You can use geomechanical modelling to predict where the micro-events might occur. The magnitude and direction of the stress tensors in a reservoir will change as CO_2 is injected. It is ideal to come up with your optimal array size and layout before you set it up. Micro- seismic is a proven technology in other industries.

In conclusion, microseismic monitoring is an established technology in a number of other industries. Microseismic installations can effectively be deployed to monitor a range of activity at CO_2 storage sites including cap rock integrity, illumination of sub-seismic features, and re-activation or propagation of faults/fractures. Microseismic monitoring should be used in conjunction with geomechanical modeling. Feasibility studies should be completed to ensure that the microseismic monitoring system meets objectives

Q) What do you think of geomechanical modelling?
A) It is a tool in a large toolbox of options.

Q) I don't know what the role of micro-seismic will be in CCS, it is like the canary in the mine. If you start detecting something then you are too late to react. If you start to see it coming from faults it means you are reactivating the fault and you are in some trouble?
A) If your sensors are sensitive enough then you might be able to pick up micro-seismic activity before the reactivation of a fault.

Q) At the Weyburn site, it is a bit disappointing that there are only a handful of micro-seismic signals from such a large scale project?
A) The Weyburn site is EOR with water flooding with fracing having been done already which might explain the lack of activity. In an untouched reservoir you should be able to pick up more.

Q) Are there CCS case studies?
A) No, just steam injection so far.

Q) Is it not possible to do the modelling of what these stress changes are and see what level of event you are going to have to determine the required sensitivity?
A) You will still need to verify the models, at least in the first few projects. Only if the model proves to be robust can you use it.

Q) What are the trade off between surface and down hole seismic? Surface you have more options even if you can't get the same resolution. In a well you are limited to just in the well?
A) Small events a long way away from the sensors will be attenuated before reaching the sensor. Surface sensor may be able to pick these up depending on the size of the event and the noise at the surface.
A) You could have 1000 sensors on the surface and overwhelm the noise in the system however this of course would be very expensive.
A) At Weyburn they have been monitoring micro-seismic for a number of years and there is very little activity. Most of the activity is near the array which is a problem because there is very little difference between the p and s waves. Weyburn can measure events up to 300m from the well which you wouldn't pick up from the surface.

4.2.22 Employing Novel MMV Technology Integration Techniques to Increase Accuracy of Injection Monitoring – Eric Davies, Pinnacle

Eric wrapped up the workshop with a discussion of new and novel monitoring techniques. He noted that a good engineering project should solve more problems than it creates which should be the aim of any monitoring technique.

Tilt meters give a measure of surface deformation to an accuracy of +/- 0.1mm. In field experiments they have been able to measure the "tides" of solid earth effected by the moon and the sun which are more commonly associated with the ocean. Tilt meters become relevant to CCS because as fluid rises toward the surface it results in a deformation above it which you can measure at the surface. You can also measure the depth of the fluid movement by the shape of the surface distortion. There is a question about the density of meters required as there are problems with interpolation between tilt meters. However, if you know the depth of the event you want to measure you can work out the density of tilt meters required to pick it up accurately.

The InSAR process uses a satellite to measure changes in vegetation and surface deformation. Uncorrected InSAR is accurate to 1cm. however if you can correct it then you can get it accurate to 1mm. GPS could also be used to measure surface deformation and is accurate to about 1mm.

Different techniques can also be used in tandem to improve accuracy.

Q) What sort of satellite coverage do you need to get a 1mm accuracy?
A) 15 images where you can identify areas that don't move you can calibrate to 1mm

Q) Is there experience in installing tilt and microseismic in shallow wells?
A) There is no reason why not, don't know about the data though.

Q) In the long term measurements, if you had a year of data could you distinguish a 1mm displacement from noise? Also what would the effect of a 2 degree temperature change would affect it?
A) 1mm is at the limit of the detection near the GPS, if you are further away 1mm will be hard to achieve. With temperature it is important to get the tools to a place where the temperature is stable.

Q) Looking at surface expression and relate it to strain in subsurface, what does that mean for distribution of fluids?
A. It could be taken further, but they have pretty much just expressed the fact without taking any inference from it. It would need taking a step further and building the best possible geo-mechanical model and figuring it out from that.

5. Outcomes and Next Steps

Day 1 looked at CCS monitoring and how it was dealt with in regulation. Regulation is being developed in parallel in a number of regions around the world including the US, Canada, Europe and Australia. Although regional regulation developments are not completely transferable lessons can be learnt from other regions processes which can aid development elsewhere. It was demonstrated that there are parallels that can be drawn between the acid gas injection regulation and CCS regulation however the scale of acid gas projects is significantly smaller than what is needed for CCS which reduces the applicability. It was concluded that although there is a lot of good work going on there are still some big regulatory issues to be solved, possibly the biggest and most contentious of which is when and how to hand over of the site to the national authority will occur.

Days 2 & 3 provided a review and update of what is happening at a number of CCS projects around the world focusing on the different monitoring techniques that has been looked at. It was encouraging to see the number of projects existing and planned and to see the wealth of monitoring techniques are being developed, tested and applied. As more projects are started and as current projects progress the availability of historic data will allow us to start to build monitoring standards and best practices which will improve our confidence in the technology and processes of CCS.

Finally there were a number of questions that were raised throughout the course of the meeting that will need to be addressed:

- How do you accurately locate and quantify the CO_2 in the reservoir?
- What do you do if a system parameter goes outside predicted values?
- What additional information can Seismic monitoring give us? When is it not applicable? Is it enough on its own and if not, what more do you need to complement it?
- How much monitoring is required for different stakeholders and can the current monitoring techniques provide what the need?
- How long do you monitor for? When and how does handover occur?

The next meeting involving the Monitoring Network will be the Joint Network meeting New York in June 2008. Following this, the next dedicated Monitoring Network meeting will be in Kyoto, Japan in early 2009.

Attendees at the 4th Monitoring Network Meeting, Edmonton Canada,
7th-9th November 2007

Martin Fasola	Repsol YPF
Greg Leamon	Geoscience Australia
Pat McLellan	Advanced Geotechnology/Weatherford
Isabelle Fillion	Air Liquide Canada
Dave Podgurny	Air Liquide Canada
Kristine Haug	Alberta Energy and Utilities Board
Christeen Finzel	Alberta Environment
Francisco Moreno	Alberta Geological Survey
John Faltinson	Alberta Research Council
Brent Lakeman	Alberta Research Council
Guillermo Ordorica-Garcia	Alberta Research Council
Dan Palombi	Alberta Research Council
Stephanie Trottier	Alberta Research Council
William Sawchuk	ARC Resources Ltd.
Frank Perrino	ATCO Midstream Ltd.
Alf Hartling	BC Ministry of Energy Mines and Petroleum Resources
Rob Lavoie	CalPetra Research and Consulting Inc.
Richard Luhning	Enbridge
Chuck Szmurlo	Enbridge
Waleed Jazrawi	EnCana Corporation
Bob Nichol	Alberta Government, Department of Energy
Don White	Geological Survey of Canada
Bill Reynen	Geological Survey of Canada
Darren Koon	Linde
Dave Ryan	Natural Resources Canada
Ahmed Shafeen	Natural Resources Canada
Andrew Hewitt	Ontario Ministry of Natural Resources
Doug Heaton	Pyecombe Consulting Services
Marcia Coueslan	Schlumberger Carbon Services
David Mercer	Schlumberger Water Services
Dayle Chadbourne	SemCAMS
Timo Makinen	Shell Canada Oil Sands
Mary Griffiths	The Pembina Institiute
Tayfun Babadagli	University of Alberta
Abdullah Alshuhail	University of Clagary
Susan Hovorka	University of Texas
Rick Chalaturnyuk	University of Alberta
Surrindar Singh	Alberta ReseAlberta Energy Research Institute
Philip Shum	Alberta Energy
Gareth Johnson	University of Clagary
Don Lawton	University of Clagary
Jason McCrank	University of Clagary
Maurice Shevalier	University of Clagary
Gal Frederick	BRGM
Franz Lahaie	INERIS
Guillemette picard	Schlumberger
Michel Verliac	Schlumberger
Claudia Vivalda	Schlumberger Carbon Services
Franz May	BGR/CO2GeoNet
Stefano Picotti	OGS
Toshiyuki Tosha	AIST/GSJ
Kenji Kubota	Central Research institute of Electric Power Industry
Tsukasa Yoshimura	ENAA
Koji Kano	Engineering Advancement Association of Japan
Jiro Watanabe	Geophysical Surveying Co. Ltd.
Daiji Tanase	J-Power
Toshifumi Matsuoka	Kyoto university
Nobukazu Soma	AIST
Hiroyuki Azuma	Oyo Corporation
Keigo Kitamura	RITE
Modesto Montoto	Cuidad de la Energia Foundation
David Jones	British Geological Survey
Toby Aiken	IEA GHG
Brendan Beck	IEA GHG
Jeremy Colls	University of Nottingham
Mark Kelley	Battelle Memorial Instituite
Leon Thomsen	BP
Kevin Dodds	BP Alternatienergy
Ron Klusman	Colorado School of Mines
Steve Smith	Energy & Environmental Research Centre
Scott Anderson	Environmental Defense
Robert Finley	Illinois State Geological Survey
Rod Masden	LI-COR Biosciences
Eric Davis	Pinnacle Technologies
Glenn McColpin	Pinnacle Technologies
Ken Hnottavange-Telleen	Schlumberger Carbon Services
Sandra Locke	Alberta Energy

Edmonton, Canada

4th Monitoring Network Meeting

7th –9th November 2007

Fantasyland Hotel, West Edmonton Mall, Edmonton, Canada

Organised by

IEA Greenhouse Gas R&D
Programme and
University of Alberta

7th November 2007 Day 1

07.30 to 08.20 Registration
08.20 to 08.45 Introduction/Housekeeping: Rick Chalaturnyk/Brendan Beck

Session 1 Opening Address/Welcome — Introduction by Andy Ridge

08.45 to 09.30 — Albertans and Climate Change: Moving Forward: Honorable Rob Renner, Minister of Environment, Govt. of Alberta

Minister Renner will open the Network Meeting and speak to new climate change regulations, effective July 1, 2007, that require Alberta facilities that emit more than 100,000 tonnes of greenhouse gases a year to reduce emissions intensity by 12 per cent. Part of the regulations include guidance and verification documentation and approved quantification protocols for the for the Alberta-based credit system.

Session 2 Keynotes: Chair Andy Ridge

09.30 to 09.55 — An ENGO viewpoint on CCS, Regulation and Monitoring: Mary Griffiths, Pembina Insitute

09.55 to 10.20 — Draft Quantification Protocol for Geological Storage Through Enhanced Oil Recovery using CO_2 Injection – What Monitoring is Required? Brent Lakeman, Alberta Research Council

10.20 to 10.35 — Discussion/Questions

10.35 to 11.00 Break

Session 3 Keynotes: Chair Brent Lakeman

11.00 to 11.20 — Storage of Carbon Dioxide in Geologic Structures: A Legal and Regulatory Guide for States and Provinces;Rick Chalaturnyk, University of Alberta

11.20 to 11.50 — MMV Components associated with G8/CSLF and Canada-Alberta Task Force Activities:Bill Reynen, Geological Survey of Canada

11.50 to 12.15 — Draft Regulatory Guidelines for Geological Storage of CO2 – CO2ReMoVe: Brendan Beck, IEA GHG

12.15 to 12.30 — Discussions/Questions

12.30 to 13.30 Lunch

Session 3 Acid Gas Regulations for Storage Projects: Chair Bill Gunter

13.30 to 14.00 — Review of Acid Gas Regulations: Stefan Bachu, Energy and Utilities Board

14.00 to 15.00 — Facilitated Discussion:
Are Acid Gas Regulations a suitable analogue for the development of Geological Storage Regulations:
- Pre-Injection Phase MMV?
- Injection Phase MMV?
- Post-Injection Phase MMV?

What's missing?, what would work? What wouldn't work? Applicability to saline aquifer storage?

15.00 to 15.30 Break

Session 4 Facilitated Discussion: Design of MMV Protocols:

15.30 to 16.00 — THEME: - How to design and establish a suite of generic MMV protocols for CO_2 storage
- for accounting purposes within national emission inventories;
- protect health, safety and environment (HSE) - existing or new regulations?
- recognition within emissions trading schemes (accounting for capture, transport and injection);
- assurance that sites perform effectively (frequency);
- verify CO_2 remains trapped in short term; and
- provide a basis for predictions about behaviour in the very long term basis.

Session 5 Facilitated Discussion: Path Forward

16.00 to 17.30 — THEME: What are the next steps to help expedite MMV arrangements and so assist in the widescale implementation of CCS:
- managing MMV arrangements within a CCS
integrated system (pre injection (3-5 yrs); injection (5-50 years); post injection (50-200 years); and
- post closure (>200 years)
- MMV arrangements for RD&D today (what are the minimum regulatory arrangements for pilot projects; pre-commercial);
- MMV arrangements for commercial scale projects, onshore & offshore storage;
- MMV arrangements for allowing realistic market expectations (insurers/reinsurance/financiers - risk premiums); and
- how to strike a balance between regulator; technology and market.

Close Day 1
19.00 Social Event and entertainment

8th November 2007 Day 2

0815 to 8.30 Welcome and Synthesis of Regulatory/Policy MMV issues from Day 1 and their relationship to MMV Case Histories: Rick Chalaturnyk, University of Alberta

Session 1 MMV Design and Reviews and Updates: CO_2 Projects

08.30 to 09.00	MMV Update on the CO2CRC's Otway Basin Pilot Project: Kevin Dodds, BP Americas (formerly with CO2CRC)
09.00 to 09.30	Nagaoka, Japan Monitoring/Verification Program Design, Deployment and Case History:Tsukasa Yoshimura, RITE
09.30 to 10.00	MMV Efforts at the CSLF Endorsed Zama Lake Acid Gas EOR Project; Steve Smith, EERC/PCOR
10.00 to 10.30	MMV Programs at ADM Site, Illinios – Midwest Partnership; Rob Finley, Geological Survey of Illinios
10.30 to 10.45	Discussion/Questions

10.45 to 12.00 Break Poster Sessions

12.00 to 13.00 Lunch

13.00 to 13.30	MMV Programs in Final Phase of IEA GHG Weyburn-Midale CO2-EOR Monitoring and Storage Project: Don White, Geological Survey of Canada
13.00 to 14.00	Downhole Fluid Recovery System Deployment at Penn West CO_2-EOR Monitoring Project; Gonzalo Zambrano, University of Alberta
14.00 to 14.30	Shallow Subsurface and Atmospheric Monitoring in CO2Geonet and CO2ReMoVe: David Jones, British Geological Survey
14.30 to 14.45	Discussion/Questions

14.45 to 15.15 Break

15.15 to 15.45	Research on Environmental Risks from Geological Carbon Dioxide Storage: Jeremy Colls, University of Nottingham
15.45 to 16.15	Baseline Survey for Evidence of Gas Microseepage Prior to a CO_2 Injection Experiment at Teapot Dome, Wyoming, USA: Ron Klusman, Colorado School of Mines
16.15 to 16.45	Accurate Soil CO_2 Flux Measurement at High Spatial and Temporal Resolution: Rod Madsen, LICOR Biosciences
16.45 to 17.00	Discussion/Questions

Close Day 2

19.00 Dinner - Edmonton's historical Fort Edmonton Park

Buses will depart from Fantasyland Hotel parking lot at 18.45.

Join us for dinner at Edmonton's historical Fort Edmonton Park. The Fort showcases the pioneer spirit with which Edmonton was established. Nestled in the heart of the original Fort, the Clerk's Quarters are heated by wood-burning stoves and offer patrons an opportunity to have an authentic pioneer experience combined with the modern luxury of fine dining.

9th November 2007 Day 3

08.00 to 08.15 Welcome and Organization of Day 3 Rick Chalaturnyk, University of Alberta

Session 1 Reviews and Updates: CO_2 Projects

08.15 to 08.45 MMV Results from FRIO II: Sue Hovorka, Gulf Coast Carbon Center

08.45 to 09.15 Seismic Monitoring Programs at Penn West CO2-EOR Monitoring Project: Don Lawton, University of Calgary

09.15 to 09.45 Monitoring Results from Permanent Instrumentation Systems Deployed in Observation Well: Gonzalo Zambrano, University of Alberta

09.45 to 10.00 Discussion/Questions

10.00 to 10.20 Break

10.20to 10.45 Shallow Subsurface and Air Monitoring Program at Penn West CO2-EOR Monitoring Project: Bill Gunter, Alberta Research Council

10.45 to 11.10 MMV Programs at the CSEMP ECBM Pilot Project: John Faltinson, Albert Research Council

11.10 to 11.35 Role of Risk Assessment in Designing MMV Programs: Ken Hnottavange-Telleen, Schlumberger Carbon Services

11.35 to 12.00 Discussion/Questions

11.45 to 13.00 Lunch

Session 2 CO2 Monitoring Using Seismic Chair: Marcia Coueslan

13.00 to 13.30 A New Mode of Seismic Surveillance: Leon Thomsen, BP

13.30 to 14.00 Detailed CO_2 injection and Sequestration Monitoring Through Crosswell Imaging: Mark McCallum, Z-Seis.

14.00 to 14.30 Design of Surface Seismic Programs for CO_2 Storage Monitoring Jeff Thompson, WesternGeco

14.30 to 14.45 Discussion/Questions

14.30 to 15.00 Break

15.00 to 15.30 Passive Seismic Monitoring: Listening for the Snap, Crackle, Pop: Marcia Couëslan, Schlumberger Carbon Services

15.30 to 16.00 Employing Novel MMV Technology Integration Techniques To Increase Accuracy of Injection Monitoring: Eric Davies, Pinnacle

16.00 to 16.15 Discussion/Questions

Session 4 Summary Discussion Chair: Brendan Beck

16.00 to 16.285 REVIEW OF FIELD TRIPS
Summary and Location of Next Meeting

Close Day 3

Evening to Explore Edmonton and West Edmonton Mall
Field Trips to Penn West CO2-EOR Projects will depart from the Fantasyland Hotel at 07.30 am

Western Economic Diversification Canada

Diversification de l'économie de l'Ouest Canada

4th IEA Monitoring Network Meeting

Edmonton, Alberta, Canada

November 7th – 9th , 2007

International Energy Agency Greenhouse Gas Programme

IEA GHG

- 20 contracting parties, 18 multinationals sponsors
- Evaluation of technologies aimed at reducing GHG emissions
- Promotion and dissemination of results and data from its evaluation studies
- Technical and policy publications, issue specific workshops

IEA Greenhouse Gas R&D Programme (IEA GHG): Networks

Unique position to facilitate co-operation between the leading research groups on greenhouse gas (GHG) mitigation. IEA GHG therefore coordinates several international research networks. The networks bring together the expertise and experience of organizations at the forefront of research, development and demonstration into GHG mitigation technologies. The networks currently operated by the IEA GHG include:

- **International Network for CO2 Capture**
- **International Network on Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae**
- **Oxy-Fuel Combustion Network**
- **Risk Assessment Network**
- **Well Bore Integrity Network**
- **Monitoring Network**
  - Established on 8th November 2004, the first meeting of the Monitoring Network demonstrated that there was a large tool box of monitoring techniques that could be applied for both surface and sub surface monitoring of CO2. It was clear that no single technique would be sufficient to meet all the different monitoring needs. Therefore, the aim of the network has been, to focus more on monitoring programs rather than individual techniques.

http://www.co2captureandstorage.info/networks

IEA Monitoring Network Meetings

Inaugural Meeting of the Monitoring Network

November 8 - 9, 2004

Seymour Centre, University of California Santa Cruz, USA

2nd Monitoring Network Meeting

October 4-6, 2005

INGV Offices, Rome, Italy

3rd Monitoring Network Meeting

October 30 - November 2, 2006

Melbourne, Australia,

4th Monitoring Network Meeting

November 7th - 9th 2007

Edmonton, Canada

Agenda – Wednesday, Nov. 7

07.30 to 08.30	Registration/Coffee
08.30 to 08.45	Introduction/Housekeeping: Brendan Beck/Rick Chalaturnyk
08.45 to 09.30	**Honorable Rob Renner, Minister of Environment,** Government of Alberta **"Albertans and Climate Change: Moving Forward"**
09.30 to 09.55	**An ENGO viewpoint on CCS, Regulation and Monitoring** Mary Griffiths, Pembina Institute
09.55 to 10.20	**Draft Quantification Protocol for Geological Storage Through EOR using CO2 Injection – What Monitoring is Required?** Brent Lakeman and Stephanie Trottier, Alberta Research Council
10.20 to 10.35	**Discussion/Questions**
10.35 to 11.00	**Break**
11.00 to 11.20	**Legal and Regulatory Guide for States and Provinces – IOGCC** Rick Chalaturnyk, U of A
11.20 to 11.50	**MMV : G8/CSLF and Canada-Alberta Task Force Activities** Bill Reynen, Geological Survey of Canada
11.50 to 12.15	**Draft Regulatory Guidelines for Geological Storage of CO2 – CO2ReMoVe** Brendan Beck, IEA GHG
12.15 to 12.30	**Discussion/Questions**
12.30 to 13.30	**Lunch**
13.30 to 14.00	**Review of Acid Gas Regulations** Stefan Bachu, Energy and Utilities Board
14.00 to 15.00	**Facilitated Discussion:** **Are Acid Gas Regulations a suitable analogue for the development of Geological Storage Regulations**
15.00 to 15.30	**Break**
15.30 to 16.00	**THEME: How to design and establish a suite of generic MMV protocols for CO_2 storage**
16.00 to 17.30	**THEME: What are the next steps to help expedite MMV arrangements and so assist in the widescale implementation of CCS**
18.00 – 20.00	**Social Event and Entertainment**

Agenda – Thursday, Nov. 8

07.30 to 08.15 Registration/Coffee
08.15 to 08.30 **Welcome /Synthesis of Regulatory/Policy MMV issues from Day 1**
Rick Chalaturnyk, University of Alberta
08.30 to 09.00 **MMV Update on the CO2CRC's Otway Basin Pilot Project**
Kevin Dodds, BP Americas (formerly with CO2CRC)
09.00 to 09.30 **Nagaoka, Japan Monitoring/Verification Program Design, Deployment and Case History**
Tsukasa Yoshimura, RITE
09.30 to 10.00 **MMV Efforts at the CSLF Endorsed Zama Lake Acid Gas EOR Project**
Steve Smith, EERC/PCOR
10.00 to 10.30 **MMV Programs at ADM Site, Illinios – Midwest Partnership**
Rob Finley, Geological Survey of Illinios
10.30 to 10.45 Discussion/Questions
10.45 to 12.00 Break – POSTER SESSIONS
12.00 to 13.00 Lunch
13.00 to 13.30 **MMV in Final Phase of IEA GHG Weyburn-Midale CO2-EOR Monitoring and Storage Project**
Don White, Geological Survey of Canada
13.30 to 14.00 **Downhole Flu id Recovery System Deployment at Penn West CO2-EOR Monitoring Project**
Gonzalo Zambrano, University of Alberta
14.00 to 14.30 **Shallow Subsurface and Atmospheric Monitoring in CO2Geonet and CO2ReMoVe**
David Jones, British Geological Survey
14.30 to 14.45 Discussion/Questions
14.45 to 15.15 Break
15.15 to 15.45 **Research on Environmental Risks from Geological Carbon Dioxide Storage**
Jeremy Colls, University of Nottingham
15.45 to 16.15 **Baseline Survey for Evidence of Gas Microseepage Prior to a CO2 Injection Experiment at Teapot Dome, Wyoming, USA**
Ron Klusman, Colorado School of Mines
16.15 to 16.45 **Accurate Soil CO2 Flux Meas. at High Spatial and Temporal Resolution**
Rod Madsen, LICOR Biosciences
16.45 to 17.00 Discussion/Questions

19.00 Dinner : Ft. Edmonton Park - Sponsored by Schlumberger Carbon Services
Buses will be departing from the Fantasyland Hotel parking lot at 6:45 pm and 7:15 pm for the short drive to the Fort

Agenda – Friday, Nov. 9 Morning

07.30 to 0.800 Registration/Coffee

08.00 to 08.15 Welcome and Introduction to Day 3

Rick Chalaturnyk, University of Alberta

08.15 to 08.45 **MMV Results from FRIO II**

Sue Hovorka, Gulf Coast Carbon Center

08.45 to 09.15 **Seismic Monitoring Programs at Penn West CO2-EOR Monitoring Project**

Don Lawton, University of Calgary

09.15 to 09.45 **Observation Well at Penn West CO2-EOR Monitoring Project**

Rick Chalaturnyk, University of Alberta

09.45 to 10.00 Discussion/Questions

10.00 to 10.20 Break

10.20 to 10.45 **Shallow Subsurface and Air Monitoring Program at Penn West CO2-EOR Monitoring Project**

Bill Gunter, Alberta Research Council

10.45 to 11.10 **MMV Programs at the CSEMP ECBM Pilot Project**

John Faltinson, Alberta Research Council

11.10 to 11.35 **Role of Risk Assessment in Designing MMV Programs**

Ken Hnottavange-Telleen, Schlumberger Carbon Services

11.35 – 12.00 Discussion/Questions

12.00 to 13.00 Lunch

Agenda – Friday, Nov. 9 Afternoon

12.00 to 13.00 Lunch

13.00 to 13.30 **A New Mode of Seismic Surveillance**

Leon Thomsen, BP

13.30 to 14.00 **Detailed CO2 Injection and Sequestration Monitoring Through Crosswell Imaging**

Mark McCallum, Z-Seis

14.00 to 14.30 **Design of Surface Seismic Programs for CO2 Storage Monitoring**

Jeff Thompson, WesternGeco

14.30 to 14.45 Discussion/Questions

14.45 to 15.00 Break

15.00 to 15.30 **Passive Seismic: Listening fo r the Snap, Crackle, Pop!**

Marcia Couëslan, Schlumberger Carbon Services

15.30 to 16.00 **Employing Novel MMV Technology Integration Techniques To Increase Accuracy of Injection Monitoring**

Eric Davies, Pinnacle

16.00 to 16.15 Discussion/Questions

16.15 to 16.25 Discussion and Wrap-up of Meeting

Location of Next Network Meetings

16.25 to 16.30 **REVIEW OF FIELD TRIPS** the PEMBINA institute

Sustainable Energy Solutions

An ENGO viewpont on CCS, Regulation and Monitoring

Dr. Mary Griffiths

IEA GHG Monitoring Network 4th Meeting

November 7, 2007

the PEMBINA institute Sustainable Energy Solutions

The Pembina Institute

"To advance sustainable energy solutions through research, education, consulting and advocacy."

- Founded 1985
- Non-partisan, non-profit environmental organization
- Primer and initial position on CCS published 2005
  - *CO_2 capture and storage: An arrow in the quiver or a silver bullet to combat climate change?*
- Position on CCS recently updated

Wind Power by Pembina

Overview

- Perception of CCS by environmental community
- The Pembina Institute perspective
- Environmental non-governmental organizations (ENGOs) & public perception
- Essential elements for regulation and monitoring
- Liability – who pays?
- Public engagement

ENGO perspectives

- Various ENGO views on CCS – geologic storage
  - Some accept CCS, as a 'necessary evil'
    - to combat climate change and avoid nuclear power
    - to win time for an economy fully-powered by renewable energy
  - Some sceptical and see CCS as "entrenching technology"
  - All concerned that CCS will divert resources from conservation, low-impact renewable energy, etc.
- ENGOs help inform wider public debate
  - Important to consider and address ENGO concerns

ENGO concerns

- CCS is a waste management strategy
  - Does not reduce CO_2 emissions at source
- Perpetuates use of fossil fuels
  - Diverts public and private resources from energy conservation, energy efficiency and low-impact renewable energy
- Can only be used for large point sources
  - Reduces overall plant efficiency so increases total CO_2 production
- Risk of leakage
- Long-term storage management and liability issues

The Pembina Institute's position on CCS

- Urgent need to reduce GHG emissions
- Need wide portfolio of measures
- CCS should be conditional on:
  - Massive scale-up of energy efficiency and low-impact renewable energy
  - Regional context (esp. availability of more sustainable options)
  - Geological context of CO_2 disposal
  - Fair distribution of investment between taxpayers and polluters

Pembina position (continued)

- CCS should focus on permanent, secure disposal
  - Deep saline aquifers - most reliable and secure
  - Use of CO_2 for EOR is not a disposal solution (thus should not be priority)
- Strong regulatory framework must ensure:
  - Public safety
  - Adequate monitoring
  - Clear attribution of liabilities
  - Transparent accounting and net reduction in GHG emissions, etc.

ENGO and public concern – risk

- Technical risk = Probability of hazard **X** impact of the hazard
- Hazard includes leaks from:
  - Equipment
  - Pipelines
  - Storage
    - Leak via faults, fissures, abandoned wells
- Risk – relates to potential impact on soil, water, air, life
  - Severity depends on proximity of humans, animals, etc.
- To minimize risk:
  - Limit storage to the least hazardous applications (the safest possible geological reservoirs)
  - Strict regulatory requirements

Regulations for CO_2 transportation

- Stringent standards for CO_2 pipelines to minimize corrosion risk
- Leak detection systems in pipeline & block valves
- Set backs in built-up areas
  - Avoidance of low-lying areas
- Introduce odour (mercaptans) so leaks from pipelines can be detected
- Monitoring requirements for leak detection

Regulatory framework for storage

- Distinguish between less secure and more secure storage
  - e.g., EOR and deep saline aquifers
- Address ownership of pore-space
- Establish regional selection criteria for storage
  - Identify areas/formations most suited to storage
  - Must be safe for many 1,000's of years
- Undertake site-specific risk assessment
  - Risk of leaks to surface
  - Potential impact of leaks
- Require protocols for injection
- Ensure strict monitoring
  - Short and long-term (underground and on surface)
  - Identify best techniques to monitor how CO_2 moves underground
  - Off-site monitoring near settlements?
- Establish independent verification process

Site selection

- Site screening
- Site-specific checklist
  - e.g., CO_2ReMoVe draft CO_2 Storage Guidelines and IOGCC
- Site investigation
  - Baseline monitoring
  - Potential migration pathways – surface characteristics (local ecosystems, human settlements)
  - Groundwater flows
- Provide local ENGOs & public with information on what has been done to verify suitability of site, minimize risk:
  - cap rock integrity
  - identification of existing wells and other potential routes to surface
  - inspection and remediation of existing wells
  - evaluation of potential impact on groundwater, surface, etc.

Risk assessment

- Risk assessment should include:
  - CO_2 storage risk assessment
  - Predictive modelling for future CO_2 behaviour and migration
  - Information on baseline monitoring and future monitoring plans
  - Plan to manage risk:
    - Emergency response plan for injection facility and surroundings Remediation if leaks occur
- Need formal process (EIA or equivalent) to provide for public input on risks for health, safety and local environment and opportunity for a public hearing
    - e.g., CO_2ReMoVe draft CO_2 Storage Guidelines – proposes amending legislation to require EIA, if not already required

Storage operations

- Regulations must stipulate frequency and scale of monitoring operations
- Monitor CO_2 movement in formation, etc.
- Monitor abandoned wells in vicinity of plume
- Compare data with predictive models
- Adjust predictive models, as needed
- Immediate reporting to public on any leaks to groundwater, soil, air

Site-closure

- Clear injection well abandonment and reclamation procedures
- Detailed monitoring and reporting requirements
  - Public reporting
- Determine what body is responsible for monitoring, verification and remediation
  - In near future – company
  - In long-term – government
    - Industry-funded, provincial or state-based trust fund

Compensation and liability

- Compensation to landowners for injection wells (comparable to oil and gas well system)
- Liability
  - Need clear rules as to who is liable for leaks
  - Who pays if humans, livestock, land are affected
    - During operations
    - Post-closure
  - Need clear, speedy process to help those affected
  - Rules and process must be clearly set out in regulations, so public can understand
- Levy or tax on operators, to cover costs for administration and compliance inspections during operations and for monitoring and liability post-closure (e.g. IOGCC proposal)

the PEMBINA institute Sustainable Energy Solutions

Where should burden of cost lie?

- Within Canada, Pembina believes:
  - Emissions reductions should be based on both polluter pays and ability-to-pay principles
  - Large industrial facilities in highly profitable sectors should be required to shoulder full costs of eliminating GHGs as cost of doing business a.s.a.p.
  - Some government involvement acceptable, due to scale of investment required in CCS and urgency for deep reductions in Canada's GHG emissions
    - Taxpayers must be ensured of fair financial return on their investment
  - CCS must not lead to diversion of scarce resources needed for higher priority approaches (conservation and low-impact renewable energy)
  - In long term: CCS must not be a liability for taxpayers in future generations

Associated regulatory issues

- Need additional regulations for:
  - CO_2 emissions trading
  - Accreditation
  - Adjustments for leaks
    - Global issue of smaller GHG reductions if CO_2 leaks back to surface
- Must ensure transparency for public credibility

Which level of government?

- International criteria for GHG emission reduction reporting
- National regulation for overall minimum standards
  - For pipelines, transportation
- State or provincial level for site specific activities, “cradle to grave” reporting, etc.

Public engagement

- Involve key ENGOS and other informed public in review of regulatory requirements
- Find out the issues that are likely to be stumbling blocks and address them
- Provide funding for ENGO/public input
- Timing critical – start a.s.a.p., so that good, transparent regulations in place BEFORE develop major projects

Any questions?

The Pembina Institute is a non-profit organization engaged in advocacy and education

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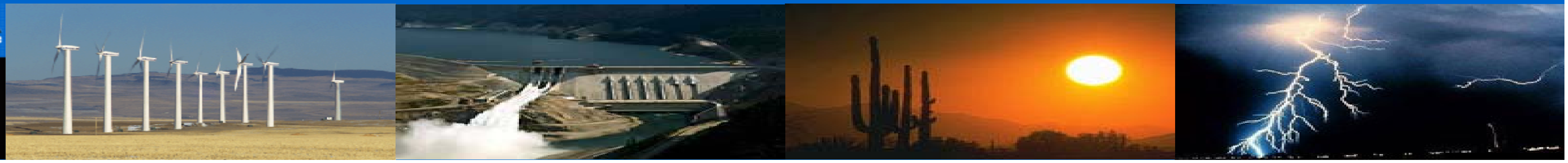

Quantification Protocols and GHG Monitoring for CO_2-EOR Operations

Brent Lakeman and Stephanie Trottier

Presentation to IEA GHG Monitoring Network
November 7, 2007
Edmonton, Alberta

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Outline

ALBERTA RESEARCH COUNCIL

- Setting the Context
- Approach
- What is a Quantification Protocol
- Stakeholder Perspectives
- Expert Group Discussion Findings
- Suggested Approach to Monitoring
- Application of Protocol
- Conclusions

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Setting the Context (1)

- 2005 -- Emission reduction credits recognized as key part of regulatory structure for *Large Final Emitters* (LFEs)
- GHG Quantification Protocols as mechanism to facilitate GHG reduction activities
- Suite of initial protocols to support key areas of strategic importance to Canada
  - Including CO_2-EOR

Setting the Context (2)

- Early 2005 -- Alberta Environment, on behalf of National GHG Offset team, asked Canada's Energy Innovation Network (EnergyINet) and ARC to develop draft quantification protocol for CO_2-EOR projects
  - Guidance document prepared by Environment Canada for all protocols to follow
  - Recognition that protocol could inform other geological storage applications being considered
    - E.g. acid gas injection

What is a Quantification Protocol (1)

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- Outlines methodology, data and information needs to demonstrate the amount of reductions that will occur
  - Quantifies the difference between emissions with project and baseline, and how this is determined (measured, estimated, etc.)
  - Also outlines how reductions will be verified to generate credits
- Can represent a significant cost of credit creation
- While ‘technical’ in nature, protocols can require a range of policy decisions
  - Start-date, location of emission sources, baselines (e.g. what is considered ‘business as usual’)

What is a Quantification Protocol (2)

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- Main elements of protocols
  - Define project scope / boundary
  - Define baseline scenario
  - Detail sources and sinks to be considered
  - Describe how to quantify sources and sinks and credit quantification methodology

    Emission Reduction = Baseline Emission –Project Emission

  - Provide Monitoring, and QA/QC guidance

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Approach

ALBERTA RESEARCH COUNCIL

Preparation of scoping document to facilitate stakeholder discussion

↓

Expert Group discussions

↓

Document areas of discussion, agreement, and areas where agreement not reached

↓

Preparation of draft protocol

↓

Revisions to Protocol based on stakeholder input

↓

Submission to Alberta Environment for inclusion in an Offset System

↓

Finalization of Protocols

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Perspectives of Expert Group (1)

- Expert Group
  - Alberta Geological Survey
  - Alberta Research Council
  - Climate Change Central
  - Duke Energy
  - Encana
  - EnergyINet
  - University of Alberta

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Perspectives of Expert Group (2)

- Key areas of discussion
  - Level of Detail for Protocol
  - Project Boundaries
  - Monitoring and Performance Assessment

Experts Group Discussion

Level of Detail for Protocol

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- Protocols provide detailed guidance to proponent
- Level of flexibility needed for large range of possible projects
- Need of balance between:
  - Manageability for proponent and system administration
  - Ensuring accuracy of credits claimed

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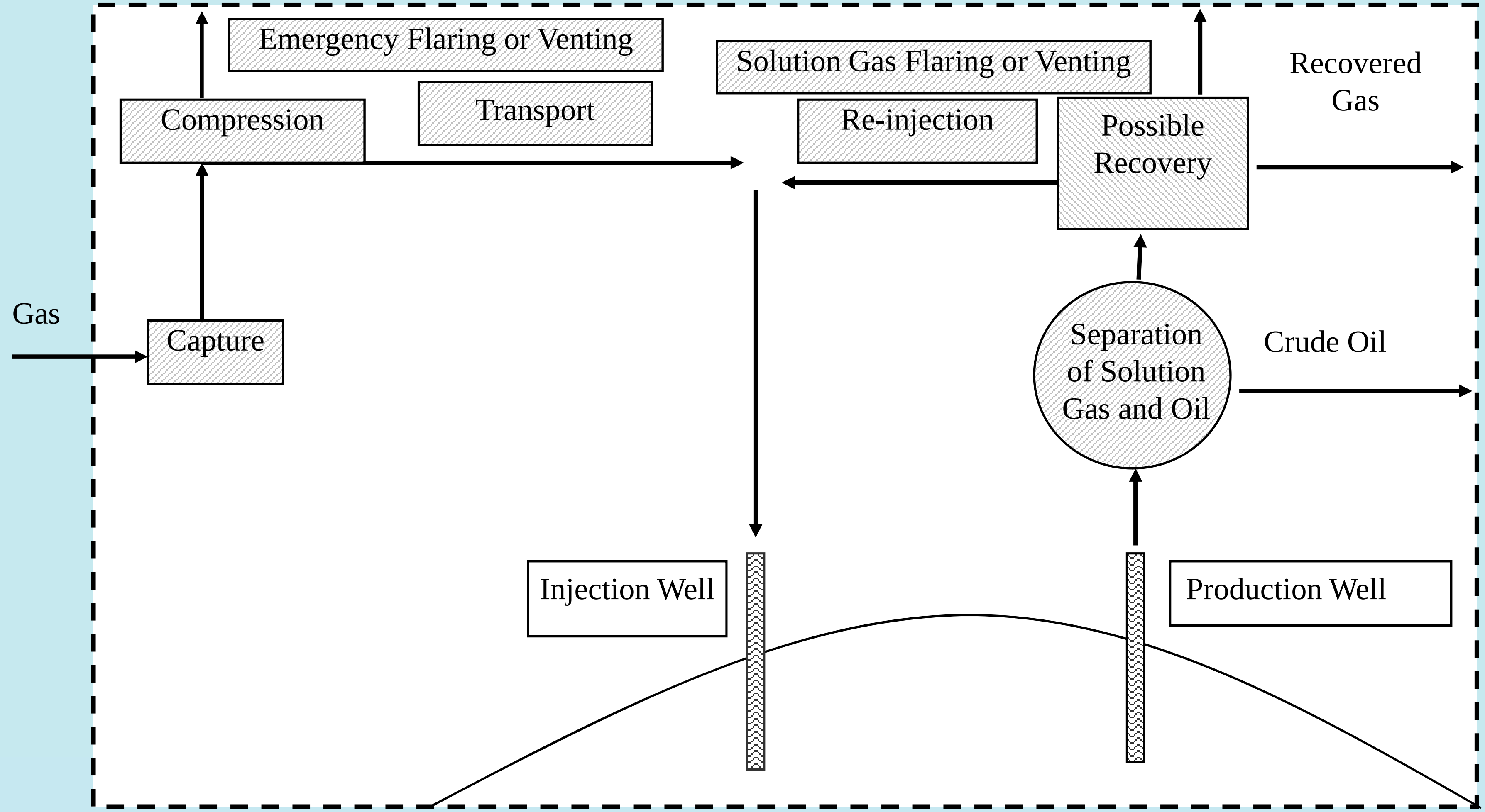
Experts Group Discussion

Project Boundaries

ALBERTA RESEARCH COUNCIL



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Experts Group Discussion

Monitoring and Performance Assessment

- Performance assessment determines level of risk associated with the project
- Monitoring requirements based on performance assessment for each project
- Protocol indicates what the monitoring is expected to achieve
  – The questions it should answer

Suggested Approach to Monitoring (1)

- Elaborating Monitoring Program
  - **Outlining project**
  - Predicting mechanisms that control behavior
  - Answering technical questions related to monitoring requirements
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - Determining the magnitude of expected change in parameters
  - Selecting instrument or monitoring locations
  - Determining timeframes and the depth of monitoring

Suggested Approach to Monitoring (2)

ALBERTA RESEARCH COUNCIL

- Proponents demonstrate that site is an adequate reservoir for CO_2 Storage?
  - Adequate seal
  - Volume of reservoir is sufficient to accommodate desired volumes of CO_2
  - Adequate injectivity
  - CO_2 will not damage seal as a result of geomechanical deformation or geochemical interactions
  - Potential impact of impurities

Suggested Approach to Monitoring (3)

ALBERTA RESEARCH COUNCIL

- Site characterization
  - Geology / hydrogeology of reservoir
  - Geology / hydrogeology of region surrounding the reservoir
  - CO_2 storage capacity estimate
  - Assessment of cap rock integrity
  - Assessment of condition of the wells that penetrate reservoir
  - Fluid samples collection - assess mineral species and chemical reactions of reservoir fluid with CO_2
  - Baseline seismic data, if available
  - Baseline data from injection and observation wells (i.e. logs, pressure, temperature and fluids)
  - Baseline for the relevant environmental monitoring (atmospheric CO_2 fluxes, etc.)

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Suggested Approach to Monitoring (4)

ALBERTA RESEARCH COUNCIL

- Elaborating Monitoring Program
  - Outlining project
  - **Predicting mechanisms that control behavior**
  - Answering technical questions related to monitoring requirements
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - Determining the magnitude of expected change in parameters
  - Selecting instrument or monitoring locations
  - Determining timeframes and the depth of monitoring

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Suggested Approach to Monitoring (5)

- Elaborating Monitoring Program
  - Outlining project
  - Predicting mechanisms that control behavior
  - **Answering technical questions related to monitoring requirements**
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - Determining the magnitude of expected change in parameters
  - Selecting instrument or monitoring locations
  - Determining timeframes and the depth of monitoring

Suggested Approach to Monitoring (6)

ALBERTA RESEARCH COUNCIL

- What the monitoring should demonstrate
  - No detectable seepage/leakage of CO_2 from the reservoir to the atmosphere or potable water zones
  - No migration/leakage out of the reservoir either laterally or vertically
  - Fracture pressure is not being exceeded
  - Mass of CO_2 within the reservoir corresponds to amount injected
  - Integrity of reservoir is intact

Suggested Approach to Monitoring (7)

ALBERTA RESEARCH COUNCIL

- Elaborating Monitoring Program
  - Outlining project
  - Predicting mechanisms that control behavior
  - Answering technical questions related to monitoring requirements
  - **Selecting parameters to be measured and identifying their role in answering technical questions**
  - Determining the magnitude of expected change in parameters
  - Selecting instrument or monitoring locations
  - Determining timeframes and the depth of monitoring

Suggested Approach to Monitoring (8)

- Elaborating Monitoring Program
  - Outlining project
  - Predicting mechanisms that control behavior
  - Answering technical questions related to monitoring requirements
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - **Determining the magnitude of expected change in parameters**
  - Selecting instrument or monitoring locations
  - Determining timeframes and the depth of monitoring

Suggested Approach to Monitoring (9)

ALBERTA RESEARCH COUNCIL

- Elaborating Monitoring Program
  - Outlining project
  - Predicting mechanisms that control behavior
  - Answering technical questions related to monitoring requirements
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - Determining the magnitude of expected change in parameters
  - **Selecting instrument or monitoring locations**
  - Determining timeframes and the depth of monitoring

Suggested Approach to Monitoring (10)

ALBERTA RESEARCH COUNCIL

- Elaborating Monitoring Program
  - Outlining project
  - Predicting mechanisms that control behavior
  - Answering technical questions related to monitoring requirements
  - Selecting parameters to be measured and identifying their role in answering technical questions
  - Determining the magnitude of expected change in parameters
  - Selecting instrument or monitoring locations
  - **Determining timeframes and the depth of monitoring**

Suggested Approach to Monitoring (11)

ALBERTA RESEARCH COUNCIL

- Provide assurance that any reversal will be detected through the monitoring process.
  - Monitoring tools and frequency associated with the level of risk expected
  - Based on the site characterization
  - Based on specific EOR injection/production strategies
- Monitoring plan elaborated on a site-by-site basis
- Ensures flexibility and manageability

Suggested Approach to Monitoring (12)

ALBERTA RESEARCH COUNCIL

- Program will have to address three phases:
  - Operational
  - Verification
  - Environmental
- Monitoring kept in place for the duration of the registration period
- Following end of injection, proponent provides assurance that emissions are still stored

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Outstanding Issues

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- Burden of elaborating monitoring program rests on proponent
- Regulatory framework
  - Define what constitutes containment
  - Post crediting period monitoring requirements
  - Establishment of a liability period
  - Define expectations if reversal does occur

Application of Protocol (1)

ALBERTA RESEARCH COUNCIL

- Protocol submitted to Alberta Environment
- All protocols underwent refinement and further stakeholder discussions
  - Process led by Climate Change Central
- Draft protocols modified and simplified
  - Adapted to Alberta Offset System

Application of Protocol (2)

ALBERTA RESEARCH COUNCIL

- Modified CO_2-EOR protocol officially approved and released in October 2007 as part of the Alberta Offset System

  www.carbonoffsetsolutions.ca

- Modified protocol silent on site characterization and monitoring requirements
- Requirements primarily regulation based
  - Ensure injection well monitoring
  - Ensure good production practice for enhanced hydrocarbon recovery projects

Conclusions

ALBERTA RESEARCH COUNCIL

- Protocol development process allows for integration of stakeholder / expert perspectives
- Difficult to balance need for simplicity with concerns about desire for long-term CO_2 containment and risk minimization
- Decision to move to more streamlined system
  - Finalized CO_2-EOR protocol is silent on monitoring requirements
- CO_2-EOR (and other storage projects) significantly larger than other types of offsets contemplated. May ultimately involve additional processes

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Acknowledgement

ARC acknowledges the funding provided by Alberta Environment for the development of the draft CO2-EOR protocol and its championing of the Alberta offset system

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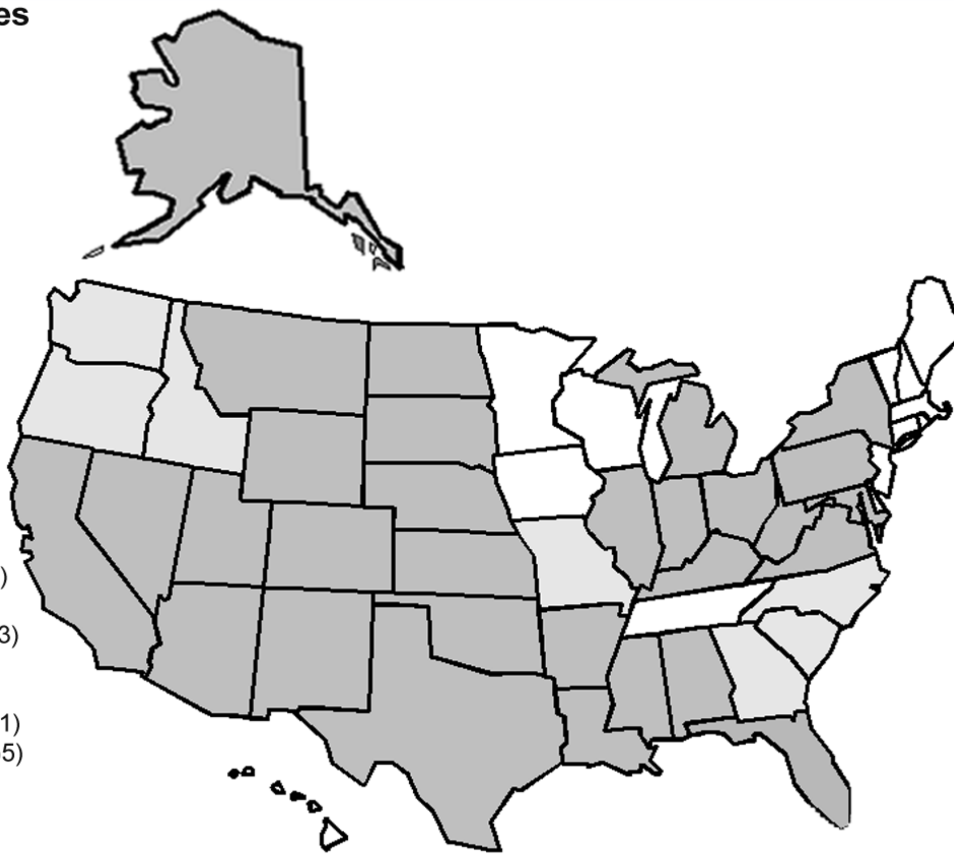
Overview of the IOGCC Phase II Carbon Capture and Geological Storage Regulatory Task Force

The Interstate Oil and Gas Compact Commission

Member States
Alabama (1945)
Alaska (1957)
Arizona (1955)
Arkansas (1941)
California (1974)
Colorado (1935)
Florida (1945)
Illinois (1935)
Indiana (1947)
Kansas (1935)
Kentucky (1942)
Louisiana (1941)
Maryland (1959)
Michigan (1939)
Mississippi (1948)
Montana (1945)
Nebraska (1953)
Nevada (1955)
New Mexico (1935)
New York (1941)
North Dakota (1953)
Ohio (1943)
Oklahoma (1935)
Pennsylvania (1941)
South Dakota (1955)
Texas (1935)
Utah (1957)
Virginia (1982)
West Virginia (1945)
Wyoming (1955)



Associate States
Georgia (1946)
Idaho (1960)
Missouri (1995)
North Carolina (1971)
Oregon (1954)
South Carolina (1972)
Washington (1967)

International Affiliates
Alberta (1996)
British Columbia (2002)
Egypt (1999)
Republic of Georgia (2001)
Newfoundland and
Labrador (1997)
Nova Scotia (1997)
Venezuela (1997)

REDUCING ANTHROPOGENIC SOURCES OF GREENHOUSE GASES

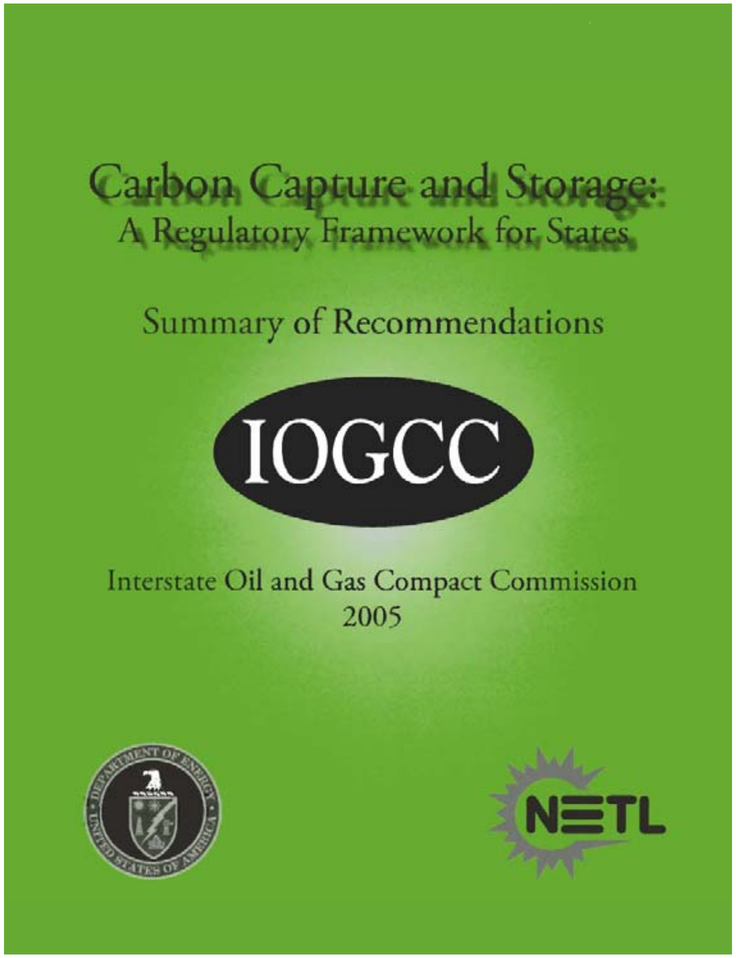
- ENERGY CONSERVATION
- INCREASING ENERGY EFFICIENCIES
- USE OF RENEWABLE ENERGY SOURCES
- USE OF NON-FOSSIL FUEL ENERGY SOURCES,SUCH AS NUCLEAR, HYDROGEN AND OTHER DEVELOPING TECNOLOGIES
- SEQUESTRATION THROUGH NATURAL PROCESSES OR PHYSICAL STORAGE

Overview Statements

- Following conservation, geologic storage of CO_2 is among the most immediate and viable strategies for mitigating the release of CO_2 into the atmosphere.
- Envision that the report will result in a substantially consistent system for the geological storage of CO_2 regulated at the state and provincial level in conformance with national and international law.
- Given the proposed long-term care-taker role of the states, they are likely to be the best positioned to provide the necessary cradle to grave regulatory oversight of CO_2 storage."

Lawrence Bengal, Chairman of the IOGCC Task Force

Brief Summary of Phase I Work and Recommendations



- Industry and states have 30 years experience in the production, transport and injection of CO.

- States have necessary regulatory analogues in place to facilitate development of a comprehensive CCGS regulatory framework.

- CO_2 should be regulated as a commodity to allow the application of oil and gas conservation laws which will facilitate development of storage projects.

- Involve all stakeholders including general public in the development of regulatory frameworks.

Phase II Task Force Objectives

1. Creation of a nationwide guidance document, approved by the IOGCC, which is specific enough to enable each state to develop its own statutes and regulations while at the same time helping to lay the essential groundwork for a state-regulated, but nationally consistent, “cradle to grave” system for the capture and geologic storage of CO_2.

2. Provide assistance to Regional Partnership Pilot Projects in (a) understanding and complying with regulatory requirements for field testing and injection; and (b) work with member state in implementing draft model laws and regulations and assessing adequacy of those laws and regulations.

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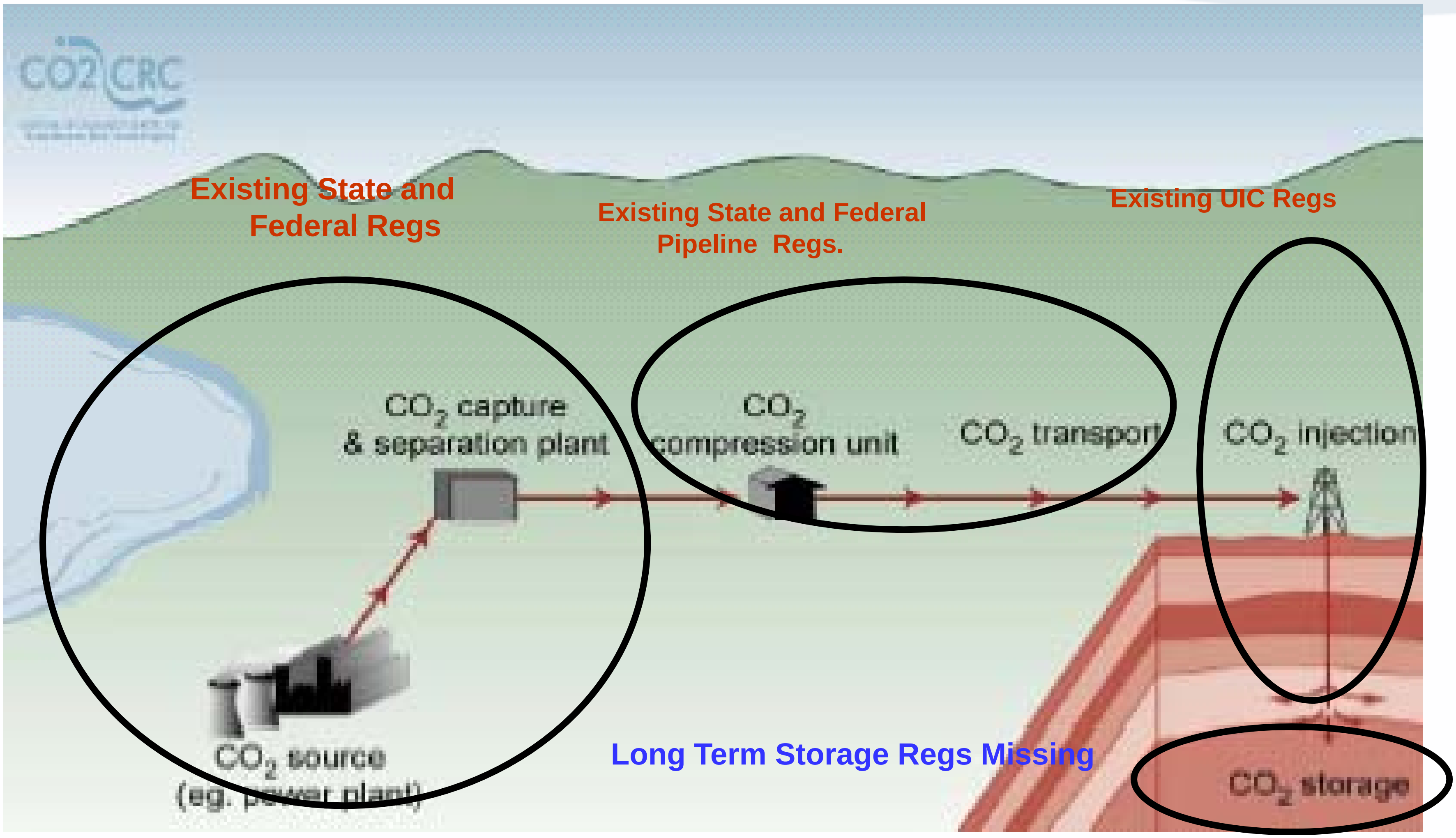
  State Oil and Gas Board of Alabama
Williams, Michael L.
  Chairman
  Texas Railroad Commission

***** Observer

Appropriate Regulatory Framework

The Task Force strongly believes that treatment of geologically stored CO_2 as waste using waste disposal frameworks rather than resource management frameworks will diminish significantly the potential to meaningfully mitigate the impact of CO_2 emissions on the global climate through geologic storage.

CO2 CAPTURE TRANSPORTATION AND GEOLOGIC STORAGE PROCESS



Task Force Guiding Principles

- **MUST BE SEAMLESS – maximize economic and environmental benefits, establish "cradle to grave" framework to provide for fully integrated regulatory oversight and clearly identify risk parameters for industry.**

- **KEEP IT SIMPLE – do not over-regulate for the exotic, initially address what will most likely occur, amend regulations with experience.**

- **BE FLEXIBLE AND RESPONSIVE – modify as gain knowledge with easy projects, respond to constantly changing technologies, which is a certainty, "one size" will not fit all projects.**

- **"DOABLE" - implement regulations which can be fielded now, problems will occur, but most are solvable, can not be focused on resolving every conceivable issue before initiating regulations.**

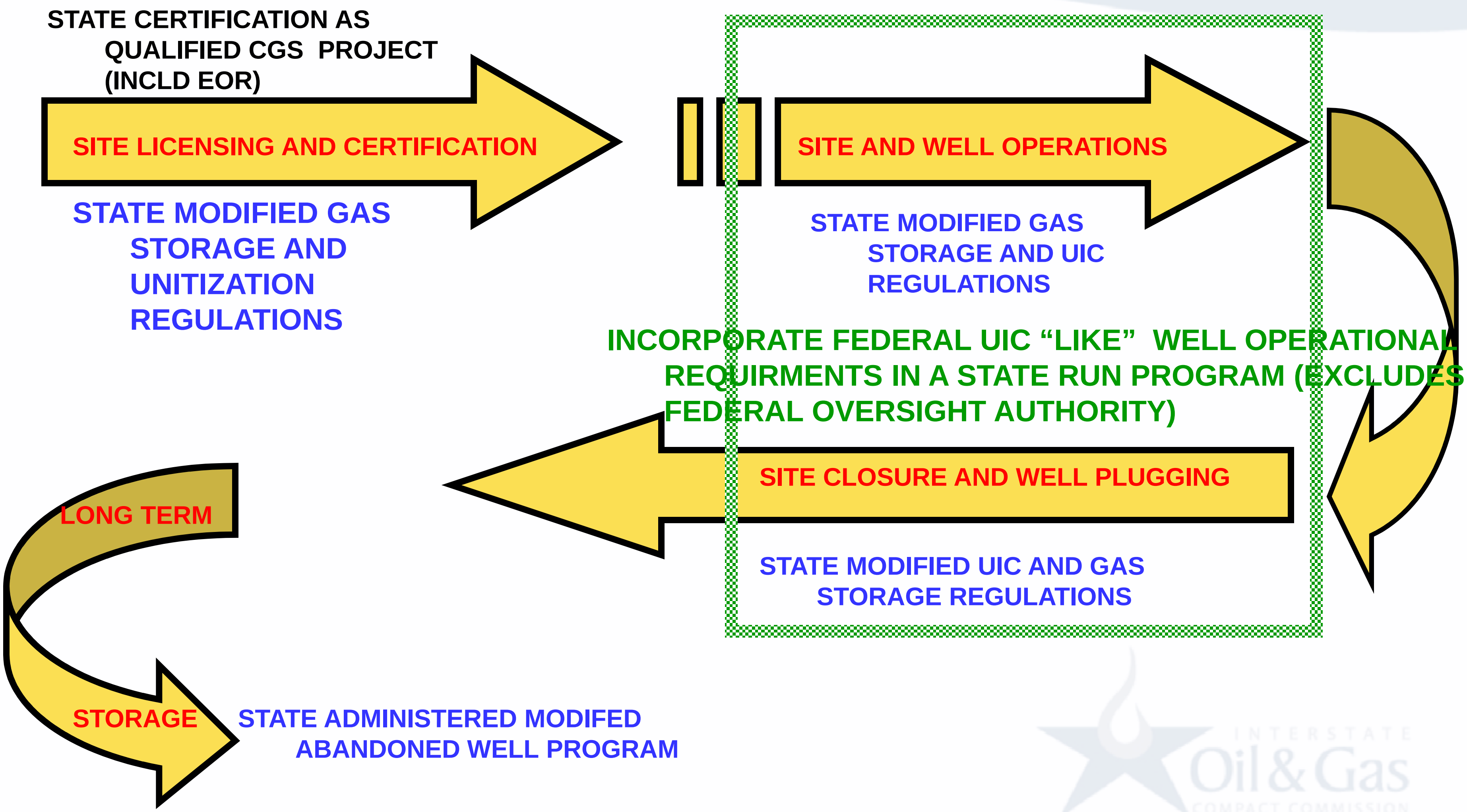
- **MAINTAIN POSITIVE PUBLIC PRESENTATION – CGS is <u>part</u> of a <u>solution with economic and environmental benefits</u> and not a waste problem waiting for a regulatory protection solution.**

Guidance Document Components:

- Analysis of Property Rights Issues Related to Underground Space Used for Geologic Storage of Carbon Dioxide
- Overview and Explanation of the Model General Rules and Regulations
- Model Statute for Geologic Storage of Carbon Dioxide
- Model General Rules and Regulations

Table of Contents

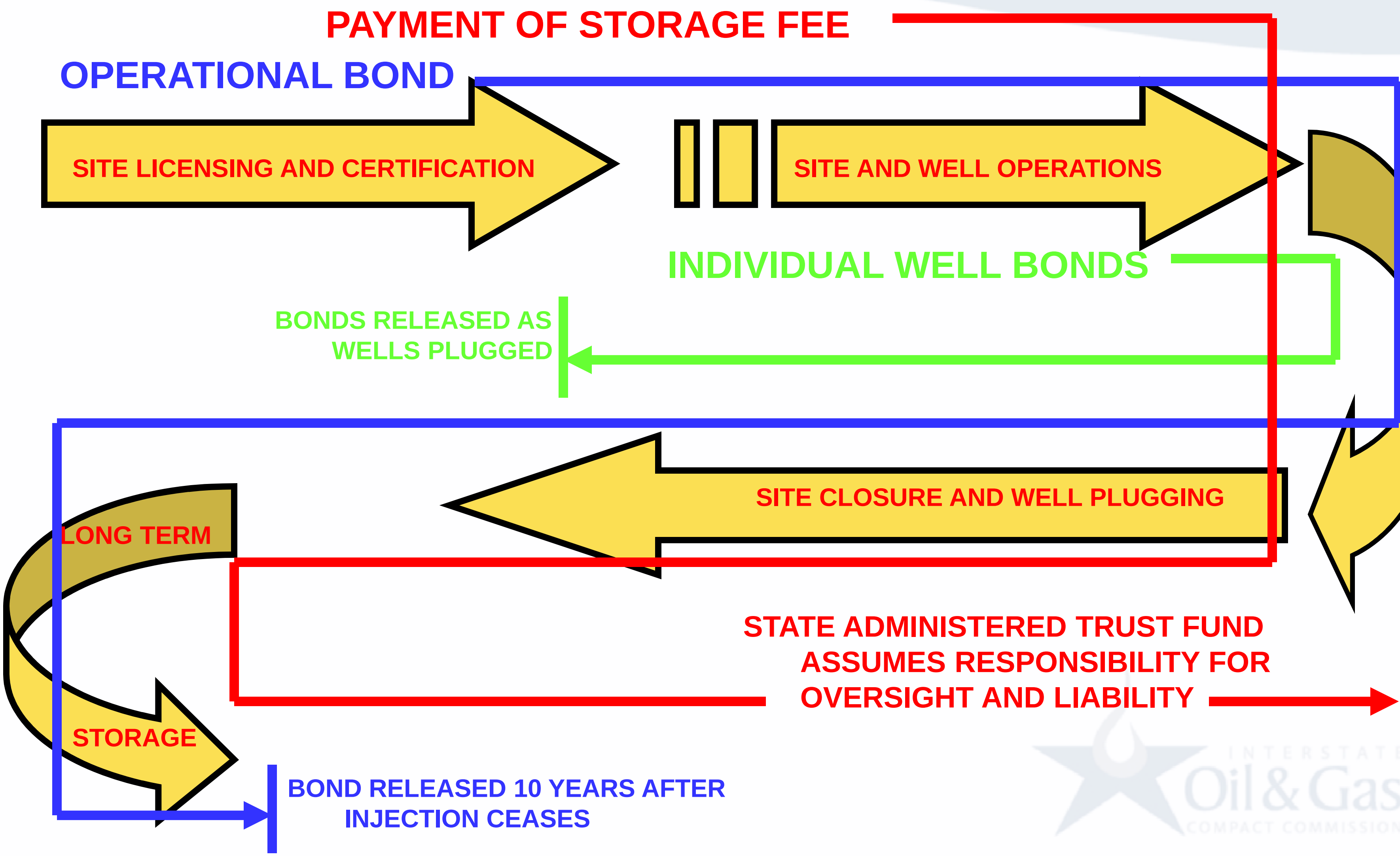
STATE ADMINISTERED “CRADLE TO GRAVE” CGS REGULATORY FRAMEWORK



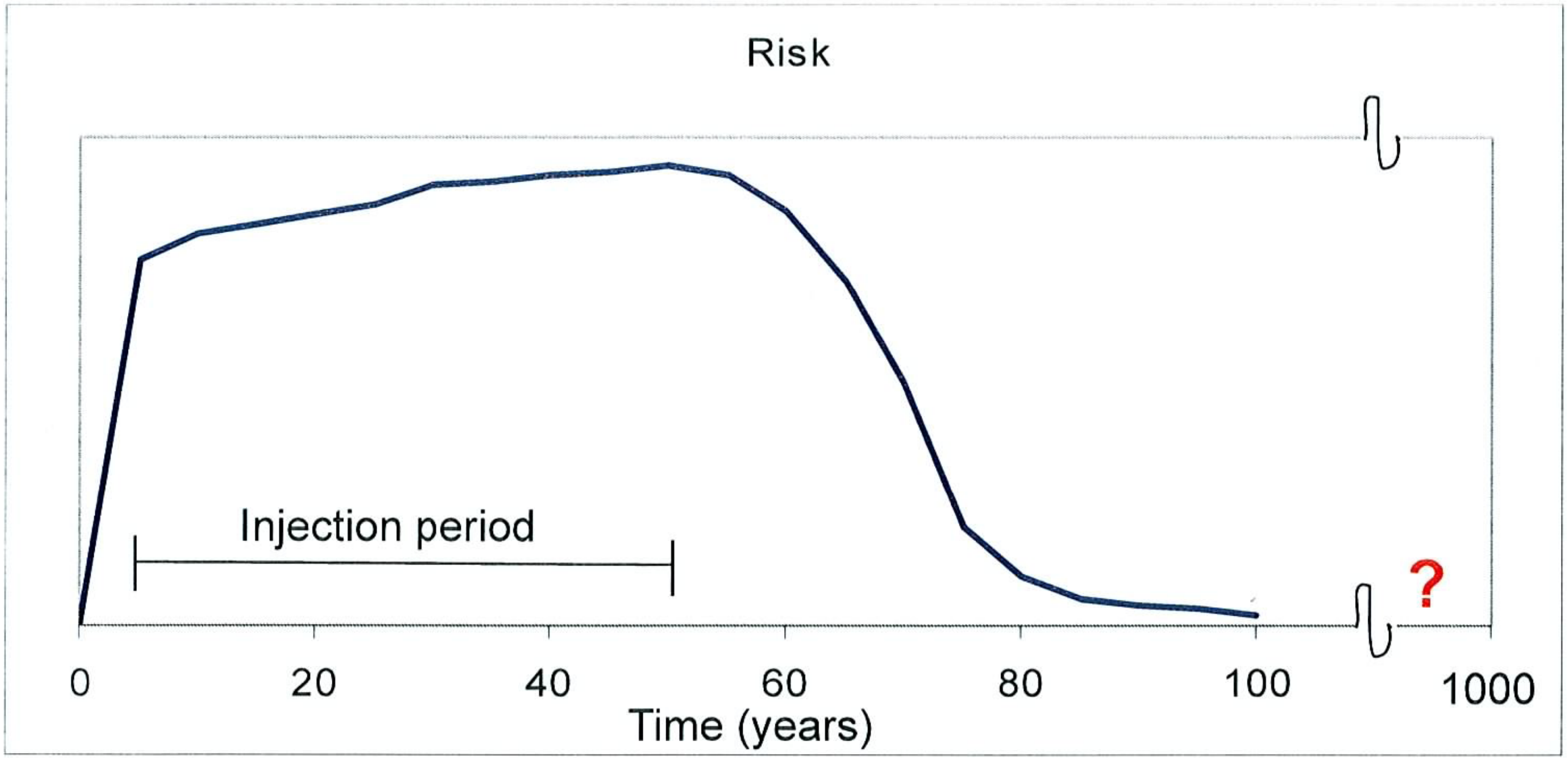
Analysis of Property Rights Issues Related to Underground Storage

- Control of the reservoir and associated pore space used for CO2 storage is necessary to allow for orderly development
- The right to use reservoirs and associated pore space is considered a private property right in the United States, and must be acquired from the owner.
- Control of the necessary storage rights should be required as part of the initial storage site licensing to maximize utilization of the storage reservoir.
- In the U.S., with the exception of federal lands, the acquisition of these storage rights, which are considered property rights, generally are functions of state law.

STATE ADMINISTERED FRAMEWORK "CRADLE TO GRAVE" CGS REGULATORY



The risk timeline for leakage is heavily-laden in early times.



Why does it look like this?

Pressure driver during and post injection

Most "changes" occur in early phase

Long-term effects trap larger quantities of CO_2

Seals may be affected over long-term

NETL

2K-2571

STATES CURRENTLY DEVELOPING REGULATIONS USING DRAFT VERSIONS OF MODEL REGULATIONS

- **New Mexico**
- **California**
- **North Dakota**
- **Texas**
- **At least 5 other states beginning work**

MMV Components of Draft Regulations

- Task Force has proposed a two-stage Closure Period and Post-Closure Period to deal with long-term monitoring and liability issues.
- Operator of the storage site would be liable for a period of ten years after the injection site is plugged, unless otherwise designated by the state regulatory agency.
- At the end of the Closure Period, the liability for ensuring that the site remains a secure storage site during the Post-Closure Period would transfer to the state.
- A trust fund that is industry-funded and state administered would provide the necessary oversight during the Post-Closure Period. The trust fund would be funded by an injection fee assessed to the Carbon Storage Project operator and calculated on a per ton basis.

Framework – 4 Analogues

1) naturally occurring CO_2 contained in geologic reservoirs, including natural gas reservoirs;

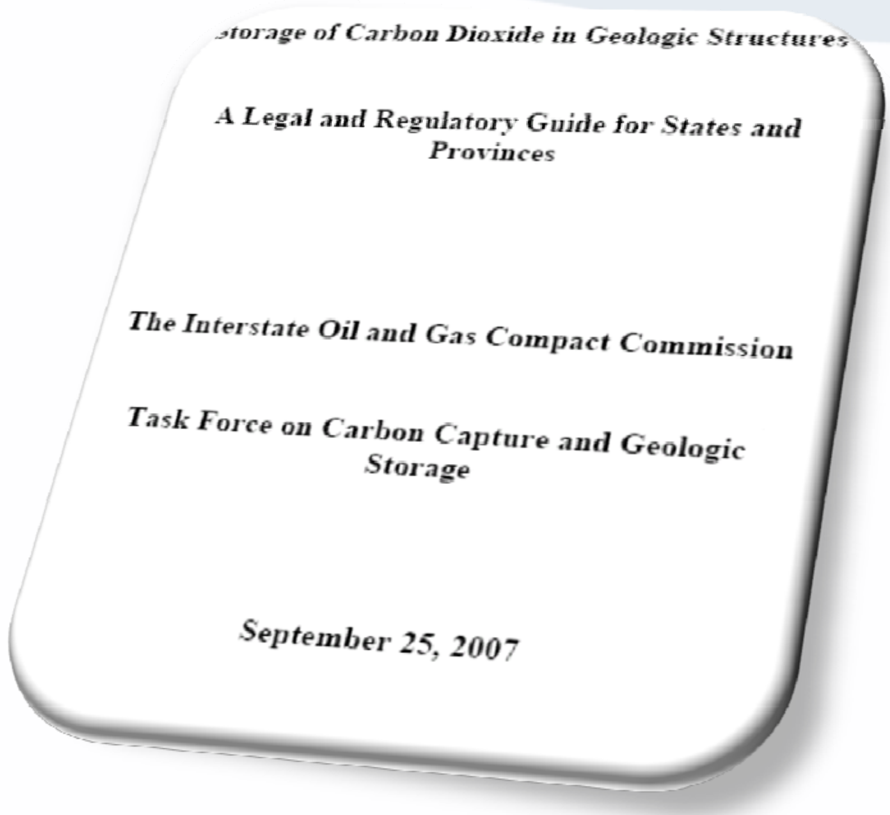
2) the large number of projects where CO_2 has been injected into underground formations for EOR operations;

3) storage of natural gas in geologic reservoirs; and

4) injection of acid gas (a combination of H_2S and CO_2), into underground formations, with its long history of safe operations.

- Together the EOR, natural gas storage, and acid gas injection models provide a technical, economic, and regulatory pathway for long-term CO_2 storage.
- However, owing to the scarcity of post-injection CO_2 EOR projects and abandoned natural gas storage fields, inadequate guidance for a long-term CO_2 storage regulatory framework exists.
- Consequently, a regulatory framework needs to be established to determine long-term liability and to address long-term **monitoring and verification** of the reservoir and mechanical integrity of wellbores penetrating formations in which CO_2 has been emplaced.

Draft Regulations



Storage of Carbon Dioxide in Geologic Structures

A Legal and Regulatory Guide for States and Provinces

The Interstate Oil and Gas Compact Commission

Task Force on Carbon Capture and Geologic Storage

September 25, 2007

The full report can be found at:
http://www.iogcc.state.ok.us/

CO2REMOVE

Draft Contribution to Future Guidelines for Licensing of CO2 Storage in Saline Reservoirs and Depleted Hydrocarbon Reservoirs

Brendan Beck, IEA GHG, Monitoring Network Meeting,

November 7-9, Edmonton, Canada

CO2ReMoVe

- **CO2 Re**search, **Mo**nitoring, and **Ve**rification
- EU 6th Framework Programme
- Funded by the EU and Industry
- Research based on datasets from real CO2 injection sites
- Partners: TNO (co-ordinator), BGR, BGS, BP, BRGM, ConocoPhillips, ExxonMobil, CMI, DNV, ECN, GEUS, GFZ, IEA-GHG, IFP, Imperial College, MEERI PAS, Quintessa, OGS, URS, Schlumberger, SINTEF, Statoil, Total, Vattenfall, Vector, Wintershall, Westerngeco.

CO2ReMoVe: 5 Sub - projects

- **SP1:** Provision of Site Monitoring Datasets
- **SP2:** Performance Assessment (PA)
- **SP3:** Monitoring Interpretation and tool development
- **SP4:** Best Practice and Guidelines
- **SP5:** Dissemination and Training

CO2ReMoVe: 5 Sub - projects

- SP1: Provision of Site Monitoring Datasets
- SP2: Performance Assessment (PA)
- SP3: Monitoring Interpretation and tool development
- **SP4: Best Practice and Guidelines**
- SP5: Dissemination and Training

IEA Greenhouse Gas R&D Programme

Overview

LEGAL:	Non Exclusive	Exclusive License Operations						National Authority
PHASES:	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
ACTIVITIES:	**Screening** Site screening & ranking with available data + new acquisition.	**Site Investigation** Data Acquisition. Well planning. Start baseline monitoring.	**Well testing** Test Well. Coring. Pressure/temperature.	**Site Development Plan** Risk Assessment. EIA. Safety Case for Long Term storage	**Construction** Build site infrastructure. Set-up of operation organization.	**Storage operation** Injection Surface + sub-surface monitoring. History matching.	**Closure** Stop injection. Monitoring. Relinquishment of license.	**Post-closure** Transfer of liability to national authority.

MILESTONES	Site Investigation Licence	Drilling Licence	Declare site commercial	Storage Licence	Begin Storage Injection	End Storage Injection	Relinquish Storage Licence
APPROX. TIMEFRAME	+1 year	+2 years	+3 years	+4 years		+5 to 40 years	+5 years

Structure

- CO2REMOVE guideline made up of 8 Phases
    I. Screening
    II. Site Investigation
    III. Well drilling & testing
    IV. Site development plan
    V. Construction
    VI. Storage operation
    VII. Closure
    VIII. Post-closure
- Each phase contains:
    - Description
    - Task check list
    - Milestone

Phase I; Screening

- *Aim: Evaluate the practically and potential of storing CO2 in an appropriate region by identifying, assessing and comparing possible candidate sites.*
- *This phase is non-exclusive.*
- Checklist (7 of 19)
  - Identify candidate CO2 sources
  - Identify candidate storage sites and pipeline routes
  - Compile available information on the properties of the reservoir formation
  - Compile industry history of candidate storage sites
  - Perform preliminary capacity estimate of storage sites
  - Define extend of license area
  - Assemble documentation
- Milestone I: Apply for exclusive Site Investigation Licence

Phase II; Site Investigation

- *Aim: Refine preliminary storage capacity estimates and to provide the geological information necessary to show that the site will perform effectively and safely.*
- *All phases from now on are exclusive*
- Checklist (6 of 13)
  - Refine the available information on the properties of the reservoir formation
  - Refinement of storage capacity estimate
  - Identify potential leakage pathways
  - Predictive flow modelling that includes reservoir, overburden and potential leakage pathways
  - Plan for drilling programme
  - Base line monitoring commences*
- Milestone II: Apply for exclusive Drilling Licence

*Baseline monitoring

- *Needs to be initiated in good time prior to injection, exact timing (Phase II, III, IV) will be the responsibility of the licensee.*
- *Should include characterisation of the following systems over timescales that take into account seasonal and annual variation.*
  - Geosphere;
    - Reservoir, underlying geology, and overburden.
    - Might include seismic data and drilling
  - Biosphere and local ecosystems;
    - Target species should be identified and monitored,
    - Potential for migration pathways to groundwater or local ecosystems should be identified.
  - Background fluxes;
    - CO_2, and CH_4 if appropriate, should be monitored at the storage site and any other relevant location,
    - Hydrological context should be understood.
    - Isotopic analysis of any background fluxes may be preferred as this is likely to help distinguish between background and injected CO_2.

Phase III; Drilling and Well Testing

- *Aim: To confirm and refine the site investigation and to provide basic data for predictive fluid flow modelling and capacity estimates.*
- Checklist (5 of 8)
  - The drilling of test well(s)
  - Core extraction from test wells and analysis
  - Down hole logging of the test well
  - Pressure testing of the formation
  - The refinement of the reservoir models based on well data
- Milestone III: Declare the site commercial

Phase IV; Site Development Plan

- *Aim: Plan operation and closure of the CO2 injection site in detail.*
- *This phase also includes the completion of an environmental impact assessment.*
- Checklist (6 of 13)
  - A CO2 storage risk assessment
  - Delivery of a catalogue of all the geological data obtained to the authorities
  - Design of injection facilities including number and location of wells
  - Development of site monitoring plan
  - Development of remediation plan
  - Development of well abandonment plan
- Milestone IV: granting of an exclusive Site Storage Licence

Phase V; Construction

- *Aim: Construct the pipeline, injection facility and distribution system, and CO2 injection well(s).*
- Checklist (4 of 4)
  - Baseline monitoring
  - Storage operation planning and personnel training
  - Construction work tendering and the selection of sub-contractors
  - Monitoring of the impacts associated with construction activities
- Milestone V: Start of injection of CO2 into the storage reservoir

Phase VI; Storage Operation with Injection of CO2

- *Aim: Injection of the CO2, evaluate how the site is performing compared to predictive models through Performance Assessment and evaluate the evolving risks through ongoing Risk Assessment.*
- Checklist (4 if 6)
  - Injection of CO2 according to the volumes and rates specified in the Site Development Plan
  - Execution of the monitoring programme* laid out in the Site Development Plan
  - Regular history matching of the data acquired through monitoring against the predictive models
  - Regular reporting to licensing authorities, local authorities and general public
- Milestone VI: End of injection of CO2 into the storage reservoir

*Monitoring Programme

- *Monitoring will be used to provide input into ongoing Risk Assessments and Performance assessments that will be carried out during the operational closure phases.*

*Monitoring Programme

- *The following measurements should be history matched against the predictive flow modelling.*
  - *Injected CO2:*
    - Mass, temperature and pressure of injected CO2 should be measured continuously at each well throughout the injection period.
  - *CO2 inside the storage reservoir:*
    - Temperature and Pressure.
    - Time-lapse imaging of the migration of CO2 within the storage reservoir.
  - *CO2 outside of the storage reservoir;*
    - *S*hould detect any migration from the storage reservoir.
  - *Surface fluxes of CO2;*
    - Periodic investigations of the site, and any area below which monitoring and modelling suggests CO2 is distributed
  - *Groundwater;*
    - Contamination of potable water should be detected
  - *Well Integrity;*
    - Abandoned wells in the vicinity of the plume should be monitored

*Monitoring Programme

- The monitoring program should also contain descriptions of the following:
  - *Timing of surveys during Storage Operation phase;*
    - Time-lapse surveys will need to be performed. Frequency of surveys should be described and justified.
  - *Timing of surveys during Site Closure phase;*
    - Monitoring will need to demonstrate the site is in agreement with predictive models.
    - Depending on the success of the history matching the frequency of monitoring surveys may be reduced.
  - *Layout of surveys;*
    - Taking into account land or marine use around the site, the geological nature and depth of the reservoir, location of faults, wells and other surface infrastructure.

*Monitoring Programme

- The monitoring program should also contain descriptions of the following:
  - *Permanent monitoring installations;*
    - eg. geophone arrays, pressure and temperature sensors or fluid sampling systems.
    - Pads for gravity surveys, or markers for other key surveys may be installed.
  - *Monitoring and modelling techniques;*
    - A description of how monitoring techniques will be continuously reviewed to reflect the most recent best practice guidelines.
  - *Detection limits and uncertainty;*
    - The sensitivity of the monitoring techniques to detecting CO2 migration and leakage.

Phase VII; Site Closure

- *Aim: Review and finalise the Safety Case for Long Term Storage Containment based on the results of the ongoing monitoring.*
- *This phase occurs between the cessation of injection and the transfer of liability from the licensee to the relevant national authority.*
- Checklist (5 of 10)
  - Continued monitoring and history matching with simulation data
  - The compilation of an operational log that documents the history of the storage site
  - The compilation of a monitoring log that documents the history of the monitoring at the storage site
  - The removal of the surface infrastructure
  - The abandonment of the wells
- Milestone VII: Relinquishment of Site Storage Licence with transfer of liability to the relevant national authority

Phase VIII; Post Closure

- The post closure phase lasts an indefinite length of time and responsibility for a storage site and the trapped CO2 resides with the designated national authority
- Safety in the Post Closure Phase should not be based on the prerequisite need for a monitoring regime since this may be construed as placing an unethical burden on future generations to continue monitoring.

IEA Greenhouse Gas R&D Programme

Thank You

ALSTOM BG GROUP bp Chevron EniTecnologie e-on EPRI
ExxonMobil REPSOL YPF RWE Schlumberger STATOIL TOTAL VATTENFALL

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Regulatory Framework for Acid Gas Disposal in Western Canada

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Senior Advisor

EUB Alberta Energy and Utilities Board
Alberta Geological Survey AGS

Associate Editor (Storage)

What is Acid Gas?

Acid gas is a mixture of H_2S and CO_2 with a minor fraction of hydrocarbon gases separated from sour gas to meet pipeline and market specifications for natural gas

Acid gas disposal is a commercial-scale analogue to CO_2 geological storage!

Why Inject the Acid Gas?

- Natural gas containing H_2S and CO_2 (sour gas), is being produced in increasing quantities in the Alberta basin
- Acid gas (H_2S & CO_2) is stripped off the sour gas
- By regulation, gas producers are allowed to emit (flare) <1 t/d sulphur into the atmosphere
- Sulphur is recovered at surface (Claus process) at high cost, which is uneconomic on the market; or
- The acid gas is injected close to the gas plant into deep depleted hydrocarbon reservoirs and saline aquifers, at a lesser cost than sulphur recovery

Aerial View of the Zama Gas Plant

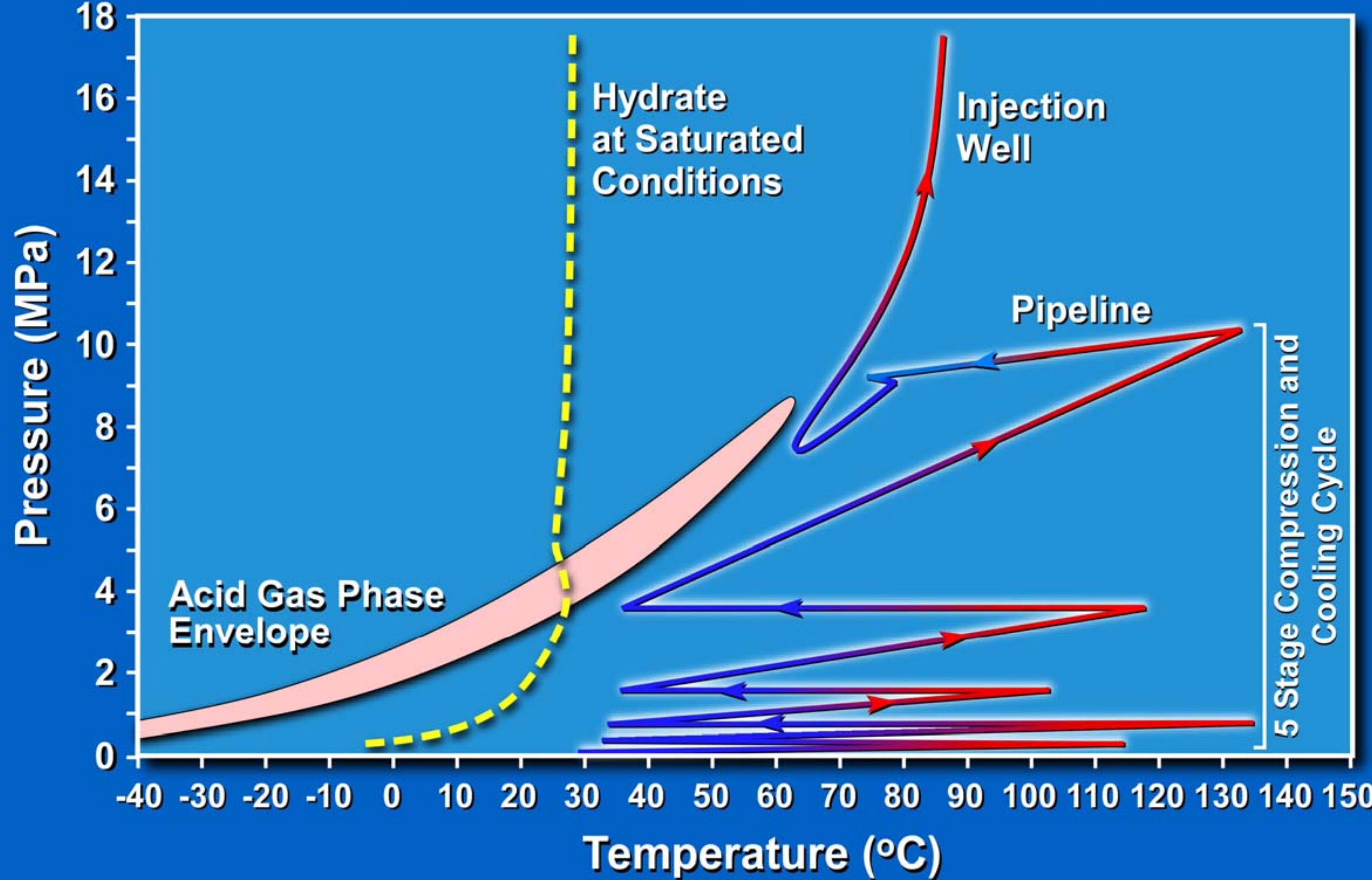
Sulphur recovered from Sour Hydrocarbons at Zama, Northwestern Alberta

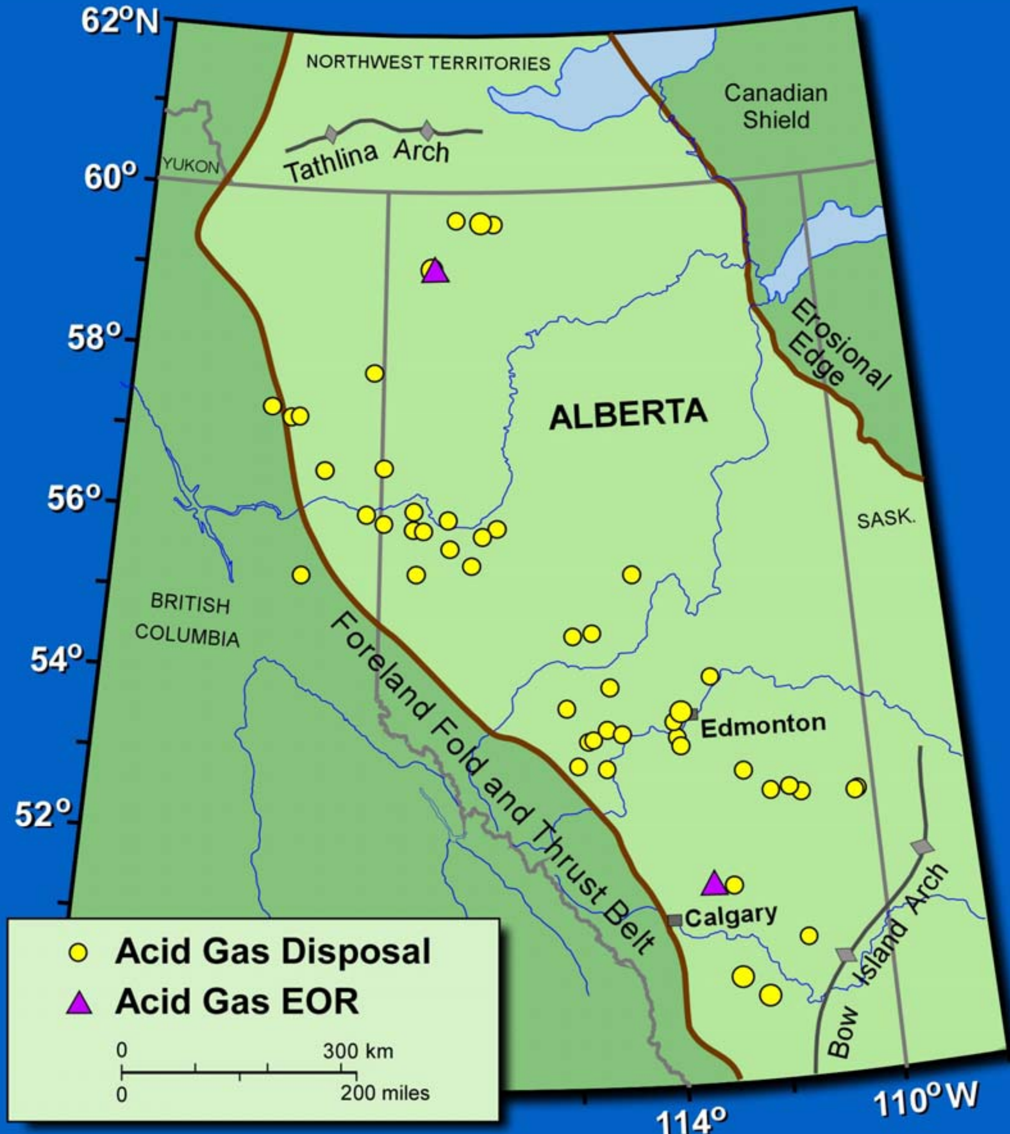
Alberta Energy and Utilities Board

Current Acid Gas and CO_2 Injection Operations in Canada

Alberta Geological Survey AGS

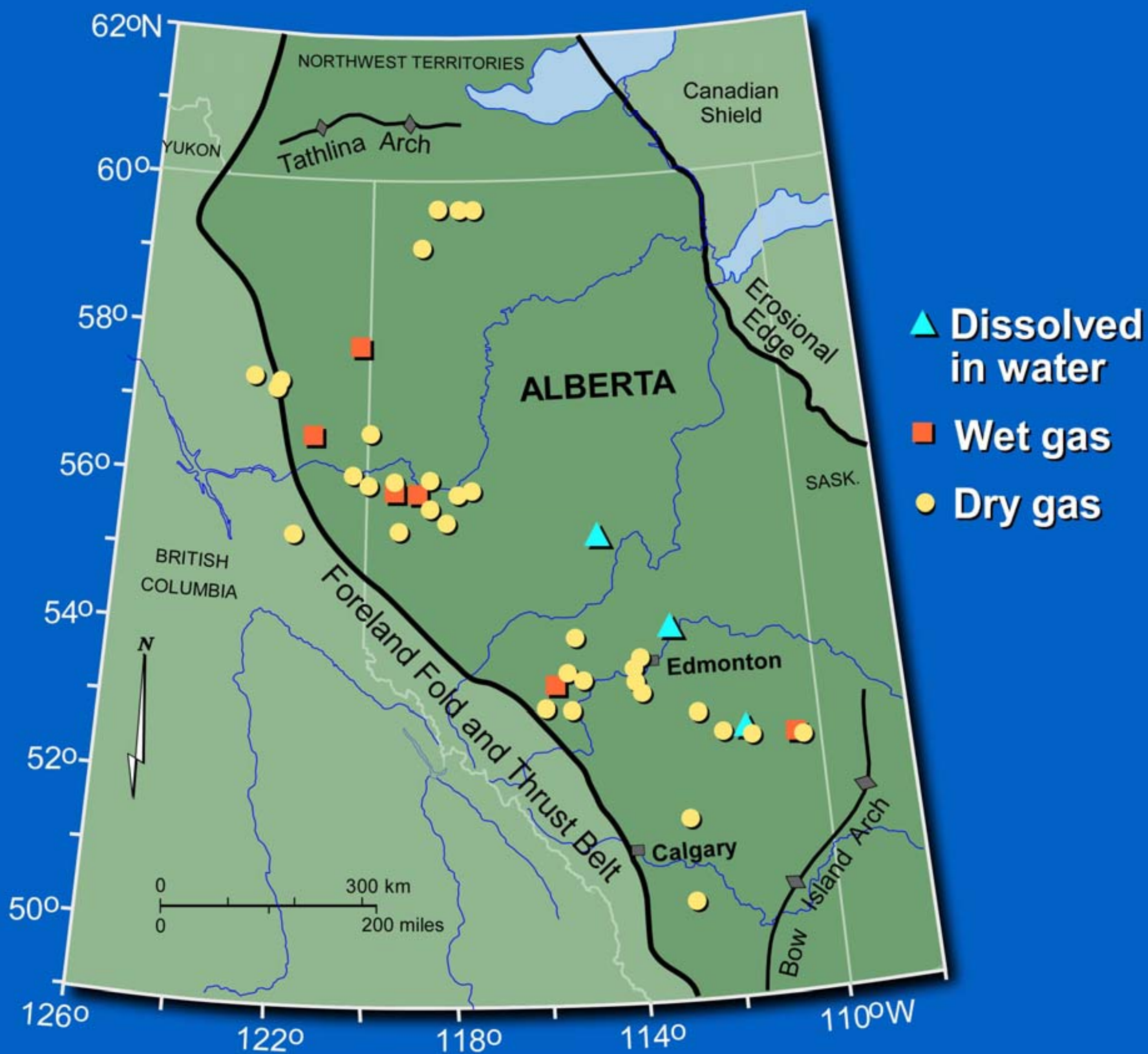
Typical Compression Cycle and Injection for Acid Gas





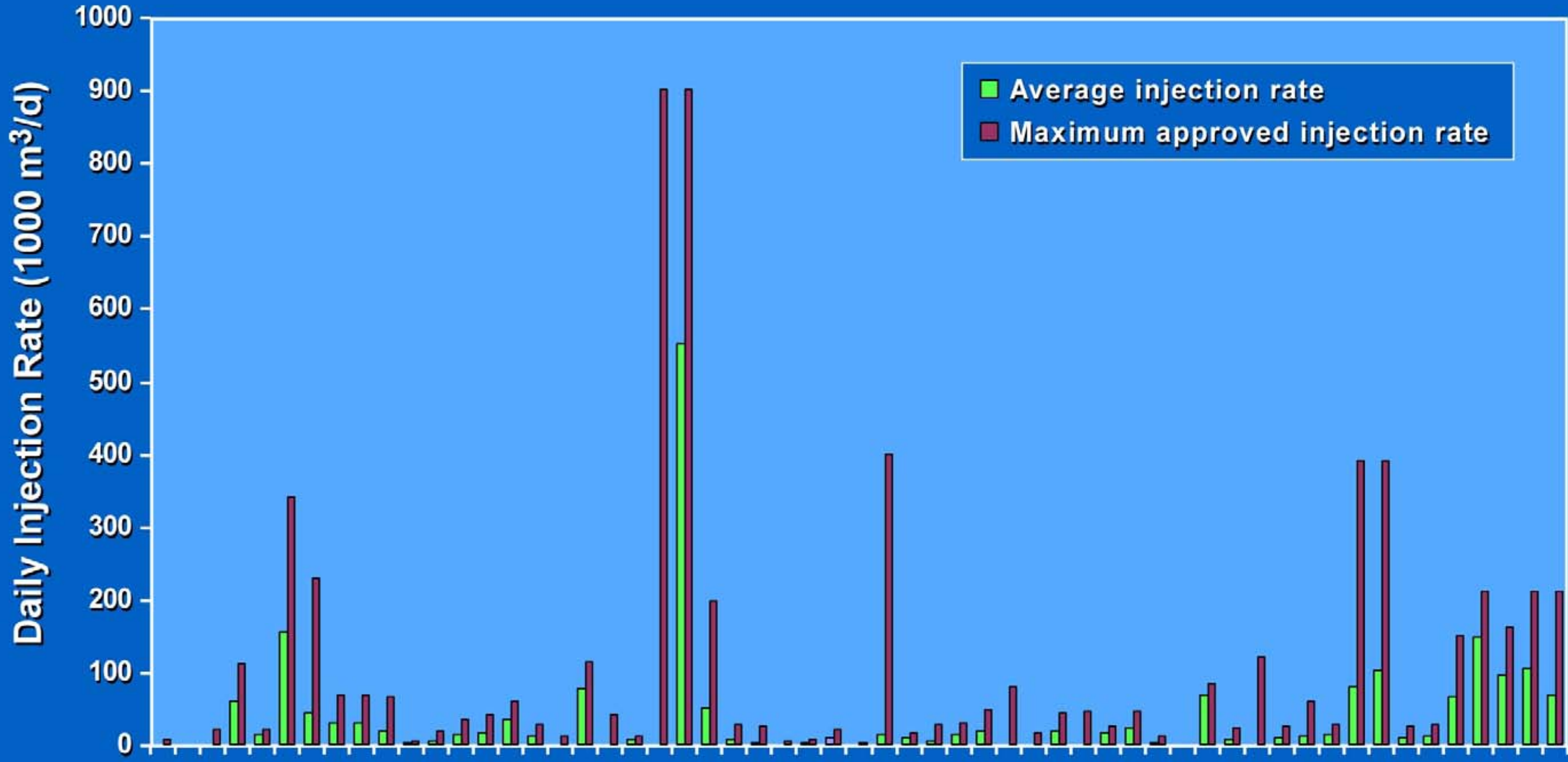
Location of Acid Gas Injection Operations in Western Canada

Type of the Injected Stream at Acid-Gas Injection Sites in Western Canada

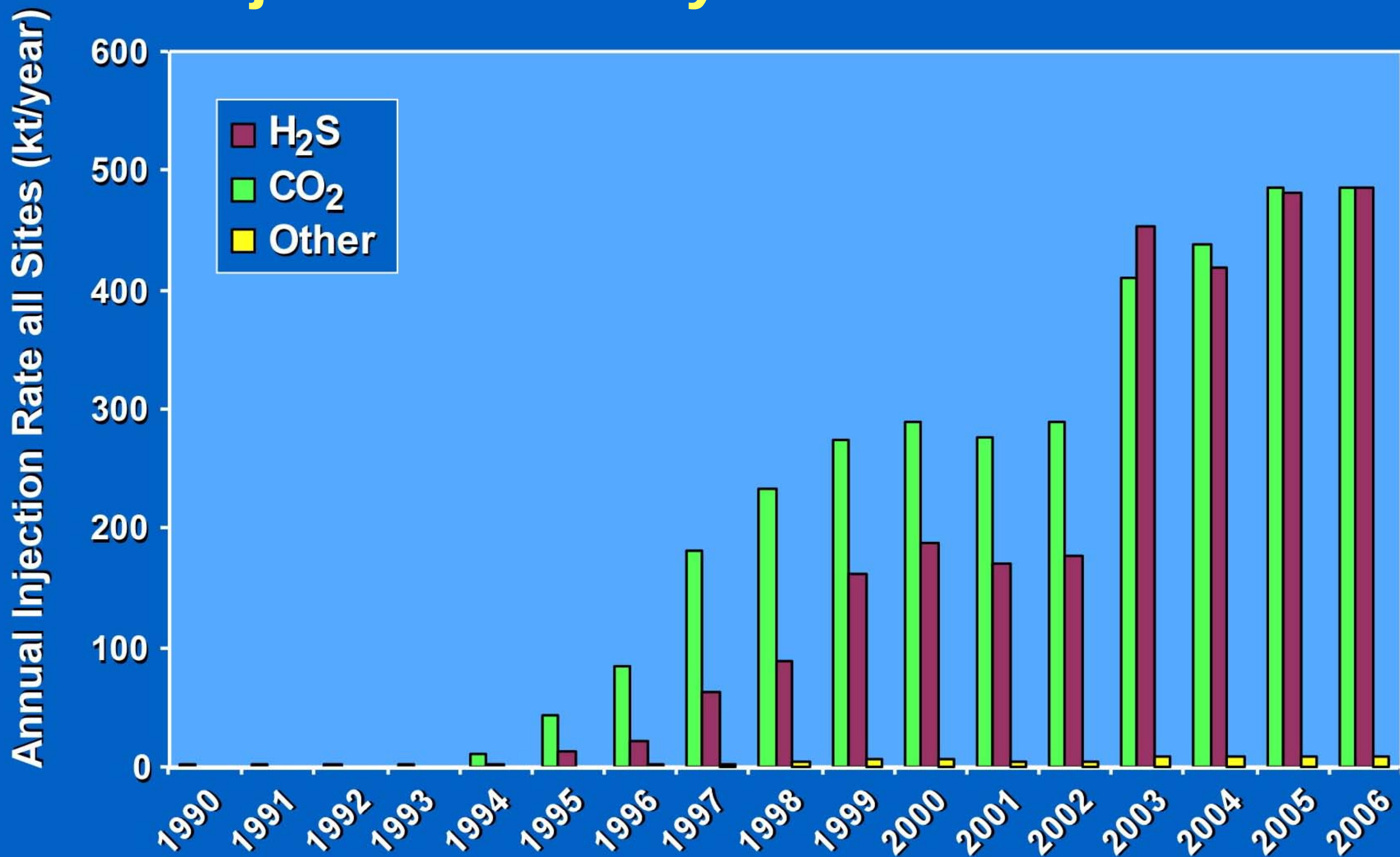


Average Composition of Acid Gas Injected In Western Canada

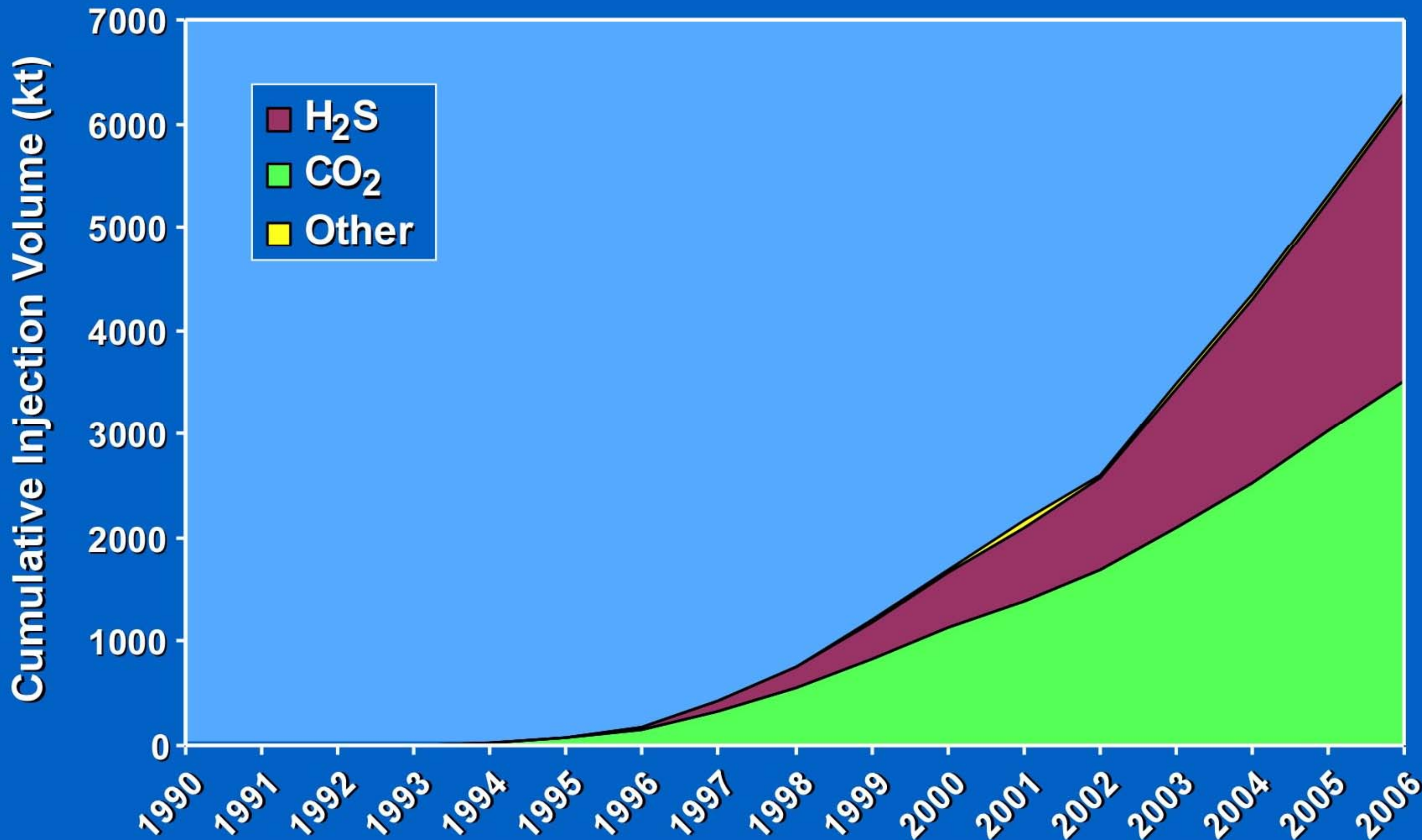
Average and Maximum Approved Injection Rates for Acid Gas Injected in Western Canada



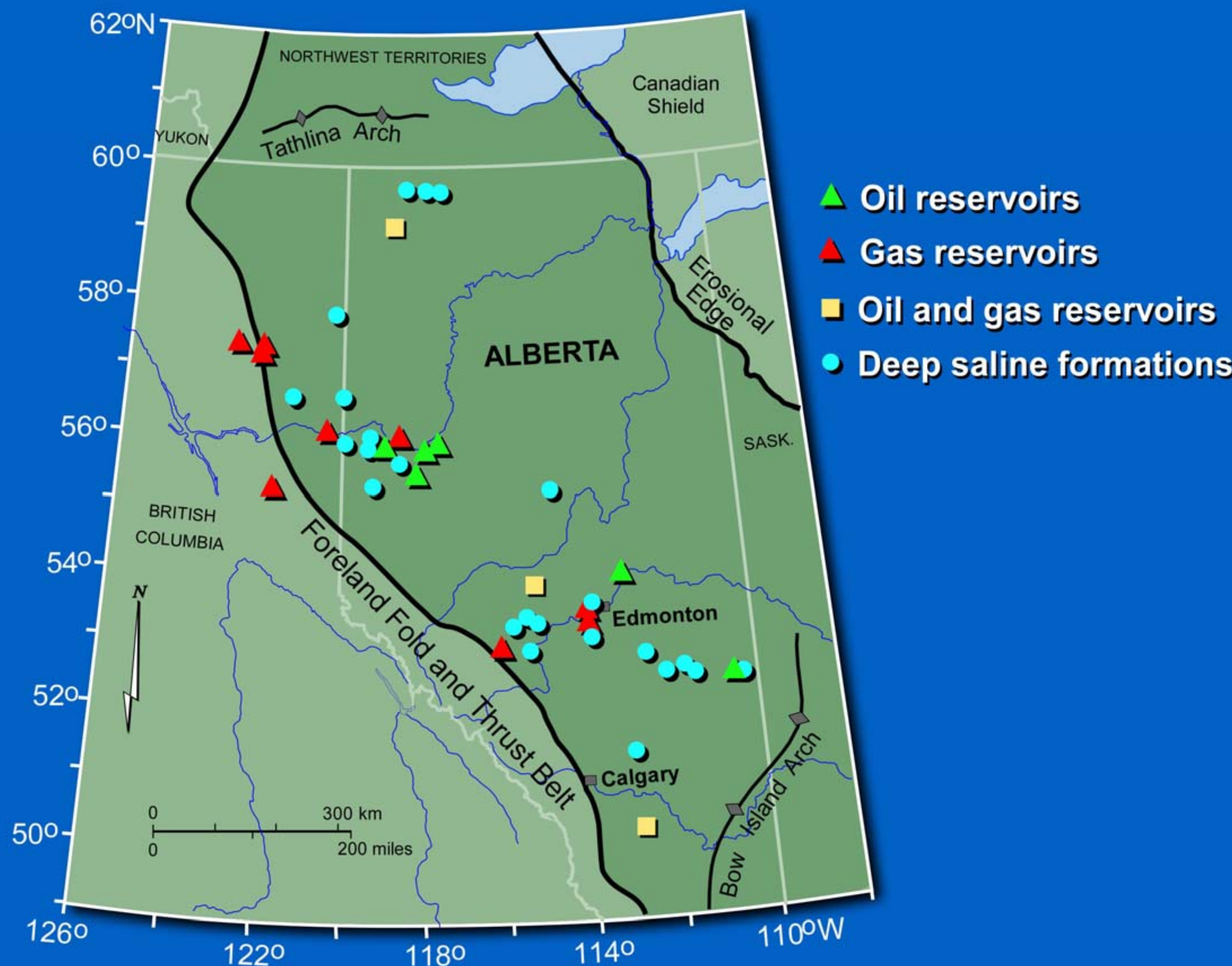
Cumulative Amounts of Acid Gas Injected Annually in Western Canada



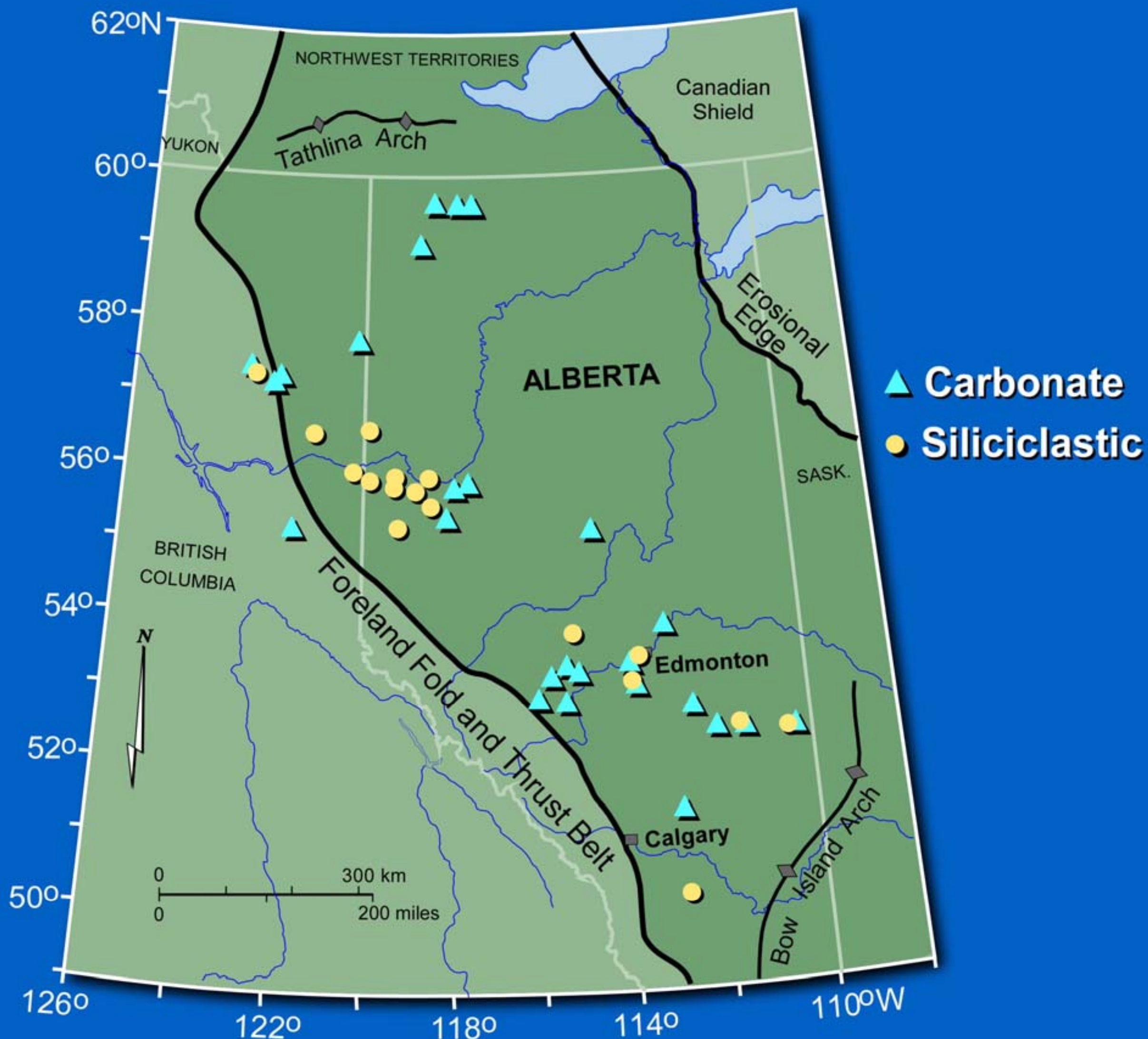
Cumulative Amount of Acid Gas Injected in Western Canada



Host Unit
at Acid-Gas Injection Sites in Western Canada



Rock Type
at Acid-Gas Injection Sites in Western Canada



Operating Ranges of Acid-Gas Injection Schemes in Western Canada

Characteristic	Minimum	Maximum
Licensed H_2S (mol fraction)	0.05	0.97
Actual injected H_2S (mol fraction)	0.02	0.83
Actual injected CO_2 (mol fraction)	0.14	0.95
In-situ acid gas density (kg/m^3)	204.8	728.3
In-situ acid gas viscosity (mPa·s)	0.02	0.09
Maximum well head pressure (kPa)	3,750	19,000
Maximum injection rate (10^3 m^3/day)	4.2	900
Actual average injection rate (10^3 m^3/day)	1.0	500
Maximum injection volume (10^6 m^3)	6	1,876

Characteristics of the Aquifers and Oil or Gas Reservoirs Used for Acid-Gas Injection in Western Canada

Characteristic	Minimum Value	Maximum Value
Average injection depth (m)	824	3432
Formation thickness (m)	4	276
Net pay (m)	3	100
Porosity (%)	4	30
Permeability (mD)	5	4,250
Formation pressure (kPa)	5,915	35,860
Formation temperature (^oC)	34	110
Water salinity (mg/l)	19,740	341,430
Brine density (kg/m^3)	998	1273
Brine viscosity (mPa·s)	0.36	1.32
Oil gravity (^{o}API)	16	68
Gas specific gravity	0.573	1.121

Alberta's Regulatory Agencies

- Alberta Department of Environment is in charge of groundwater protection (establishes the depth of protected groundwater: TDS<4000 ppm; licenses water wells)

- Alberta Energy and Utilities Board (EUB) has jurisdiction over oil and gas production, and deep well injection and disposal (licenses all deep wells), including well construction and abandonment

Directive 65 for Application for Disposal Operations,
Directive 51 for Well Construction for Acid Gas Injection, and
Directive 20 for Well Abandonment

http://www.eub.ca/docs/documents/directives/Directive020.pdf
http://www.eub.ca/docs/documents/directives/Directive051.pdf
http://www.eub.ca/docs/documents/directives/Directive065.pdf

Main Regulatory Objective in Deep Well Injection

Ensure that there is no migration and/or leakage out of the injection target that would:

- Contaminate energy and mineral resources
- Contaminate potable groundwater resources
- Endanger life and property

Regulatory attention focuses on:

- Wellbore integrity
- Formation suitability to ensure confinement
- Suitability of the injected stream in regard to the nature of the fluid and well and formation integrity
- Reporting
- Early detection and mitigation of potential problems

EUB Information Requirements Regarding Acid Gas Disposal Zone

- Aquifer/reservoir conditions (P,T) and characteristics (fluids, ϕ, k)
- Capacity of disposal zone
- Thickness, integrity and extent of caprock
- Location & extent of bottom and lateral bounding formations
- History of neighboring wells
- Effect on resources in disposal zone

Injection Well Classification in Alberta

In decreasing order of monitoring and surveillance requirements

- *Class Ia:* oilfield or industrial waste fluids
- *Class Ib:* produced water and common oilfield waste streams
- *Class II:* brine and brine-equivalent fluids
- *Class III:* hydrocarbons, inert and sour/acid gases
- *Class IV:* potable water or steam

Class III Injection Wells in Alberta

Injection of hydrocarbons, or inert or other gases, for the purpose of storage or enhanced hydrocarbon recovery

- Solvent or other HC products for enhanced recovery
- Sweet natural gas for storage
- CO_2, N_2, O_2, air, other gases for storage or enhanced recovery
- Sour or acid gases for disposal, storage or cycling operations

Requirements for Class III Injection Wells in Alberta

- Hydraulic isolation of the host zone and of hydrocarbon-producing zones
- Injection through tubing
- Annulus filling with corrosion-inhibiting fluid
- Installation of safety devices above ground and in the wellbore
- Cementing across protected groundwater
- Logging for cement top, hydraulic isolation and casing inspection
- Initial annulus pressure test
- Annual packer isolation test
- Wellhead pressure limitation at <90% of rock fracturing threshold
- Area of review based on reservoir modelling
- Hydraulic isolation of offset wells that penetrate the same zone within the area of review

Monitoring and Reporting Requirements for Acid Gas Disposal Schemes

- Well head pressure and temperature
- Gas composition
- Wellhead flow rate
- Maintenance and special well workovers
- Annual or bi-annual reporting

Public Concerns

- Preference by public for acid gas injection rather than flaring or other forms of sulphur recovery
- Potential for flaring and/or atmospheric emissions in the event that the injection facility is shut down for whatever reason
- Potential for contamination of groundwater resources
- Whether other operators now and in the future will know about the existence, location and extent of an acid gas disposal scheme (hence, by extension, of a CCGS scheme)

Conclusion

Deep injection of acid gases is a mature technology that can be used for the large-scale implementation of greenhouse gas capture and sequestration in geological media

IEA R&D 4th M&V Network Workshop

Otway Basin Pilot Project Update

Kevin Dodds*,

On behalf of

Cooperative Research Centre

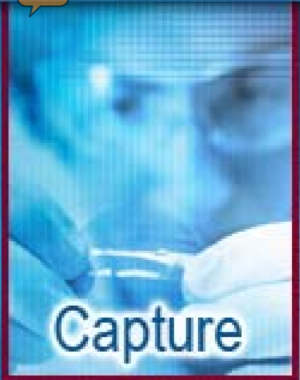
for Greenhouse Gas Technologies (CO2CRC)

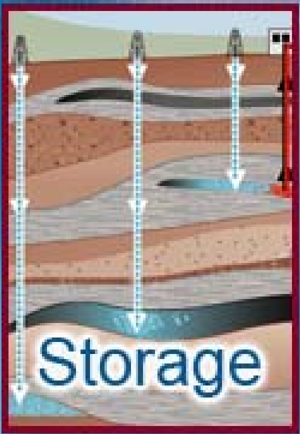
Don Sherlock, Jim Underschultz, Sandeep Sharma

Milovan Urosevic and Anton Kepic

David Etheridge and Don de Vries

Tom Daley and Barry Friefeld LBNL





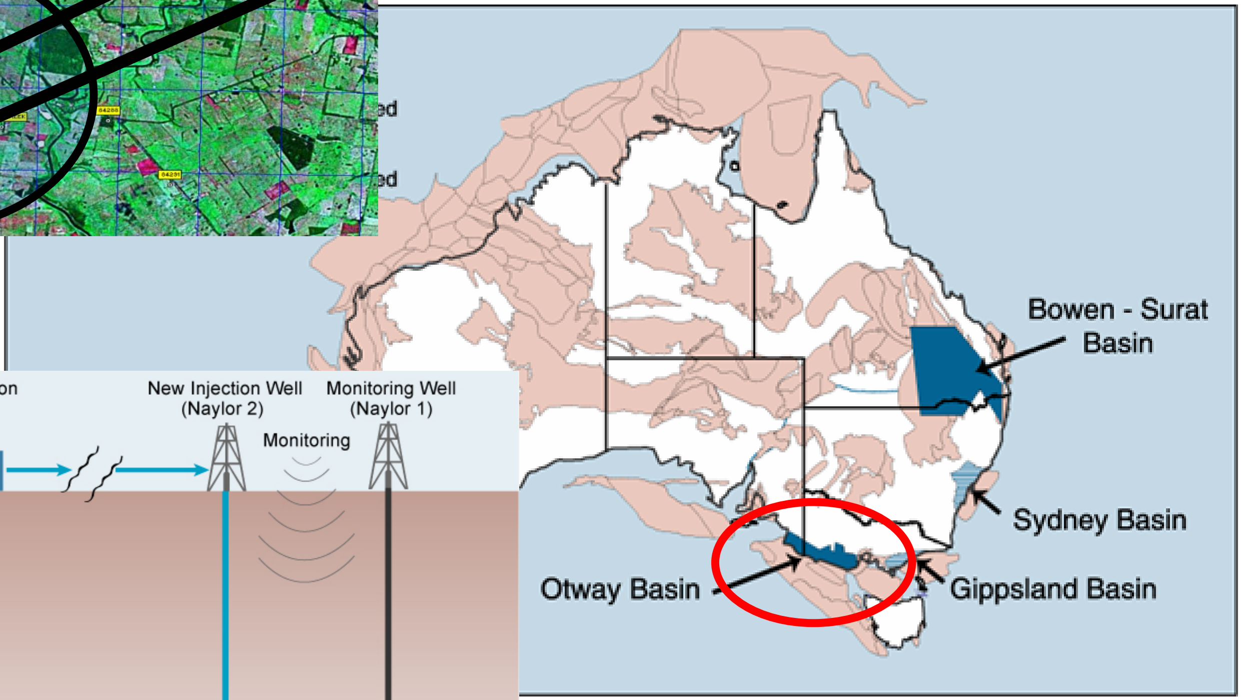
CO2CRC Participants

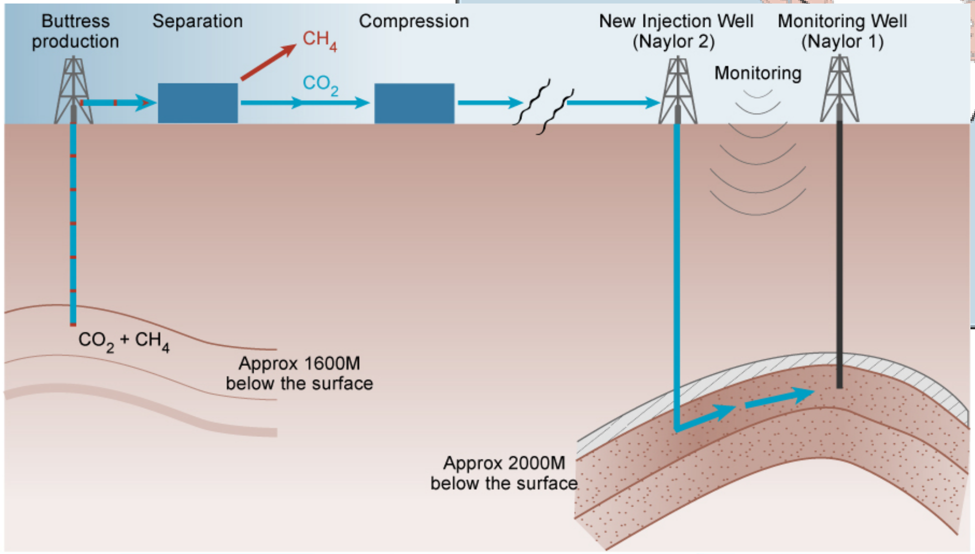
bp | xstrata coal | RIO TINTO
THE UNIVERSITY OF ADELAIDE AUSTRALIA | CRC AUSTRALIA | Australian Government Geoscience Australia | CSIRO | Shell | Chevron
MONASH University | THE UNIVERSITY OF MELBOURNE | bhpbilliton | NZ RESOURCE CONSORTIUM
Schlumberger | SOLID ENERGY Coals of New Zealand | ANGLO AMERICA | Origin energy
UNSW | Curtin University of Technology | WOODSIDE | NSW DEPARTMENT OF PRIMARY INDUSTRIES | Victoria The Place To Be
FOUNDATION FOR RESEARCH SCIENCE & TECHNOLOGY Tūāpapa Rangahau Pūtaiao | ACARP Australian Coal Association Research Program | ConocoPhillips | STANWELL CORPORATION LIMITED

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

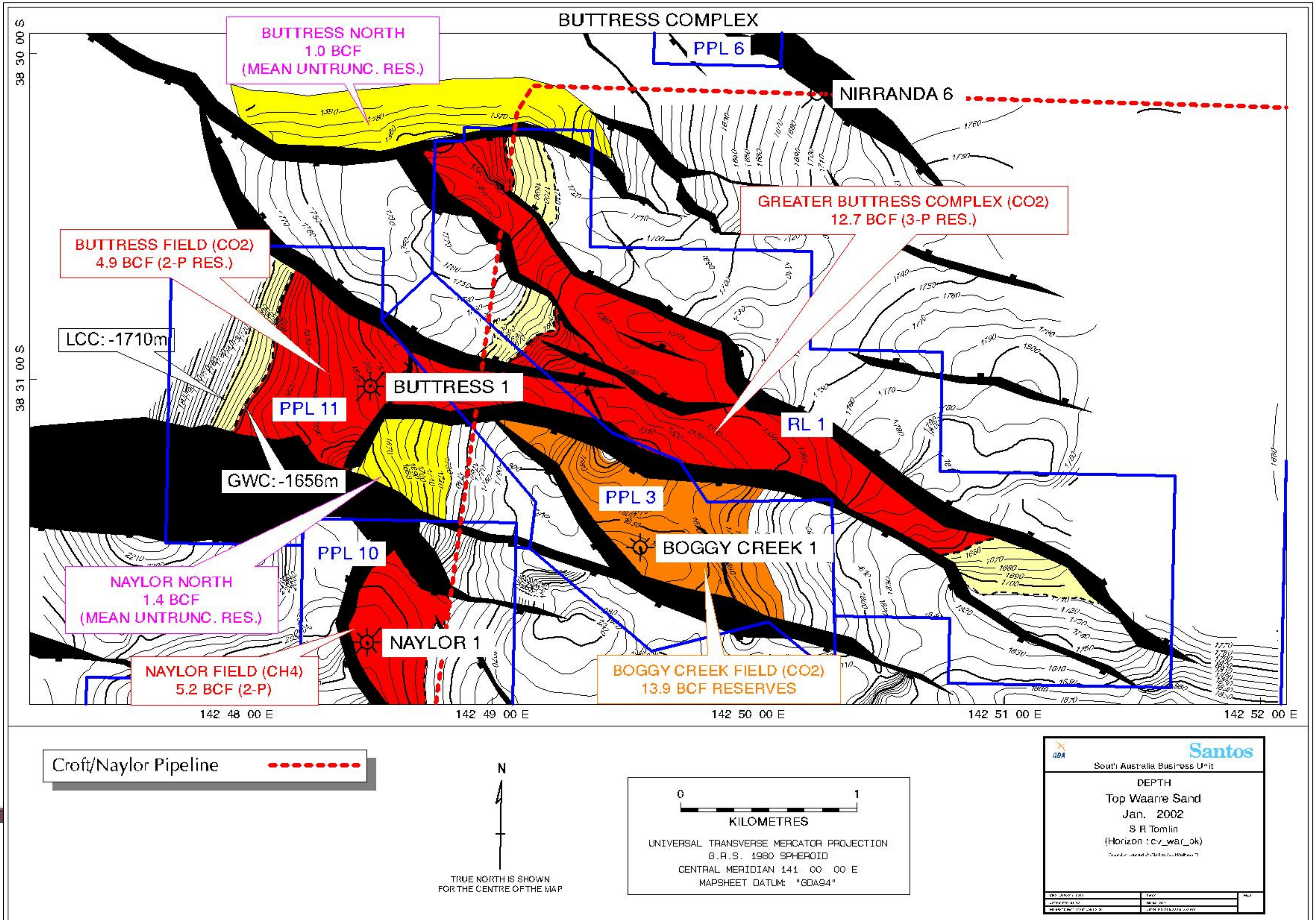
CO2CRC

Otway Basin Pilot Project - OBPP





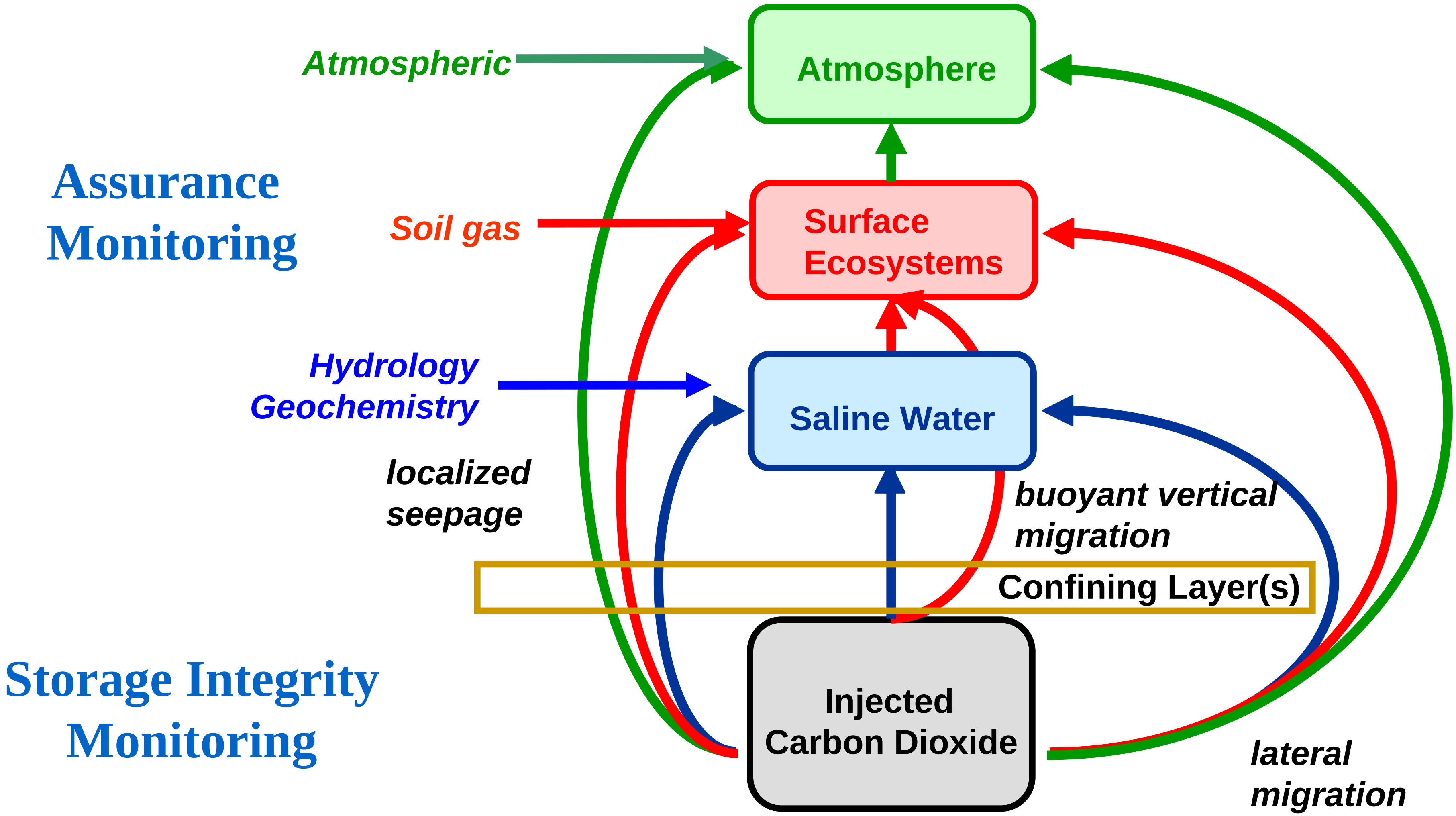
Structure Map - OBPP Fault Distribution



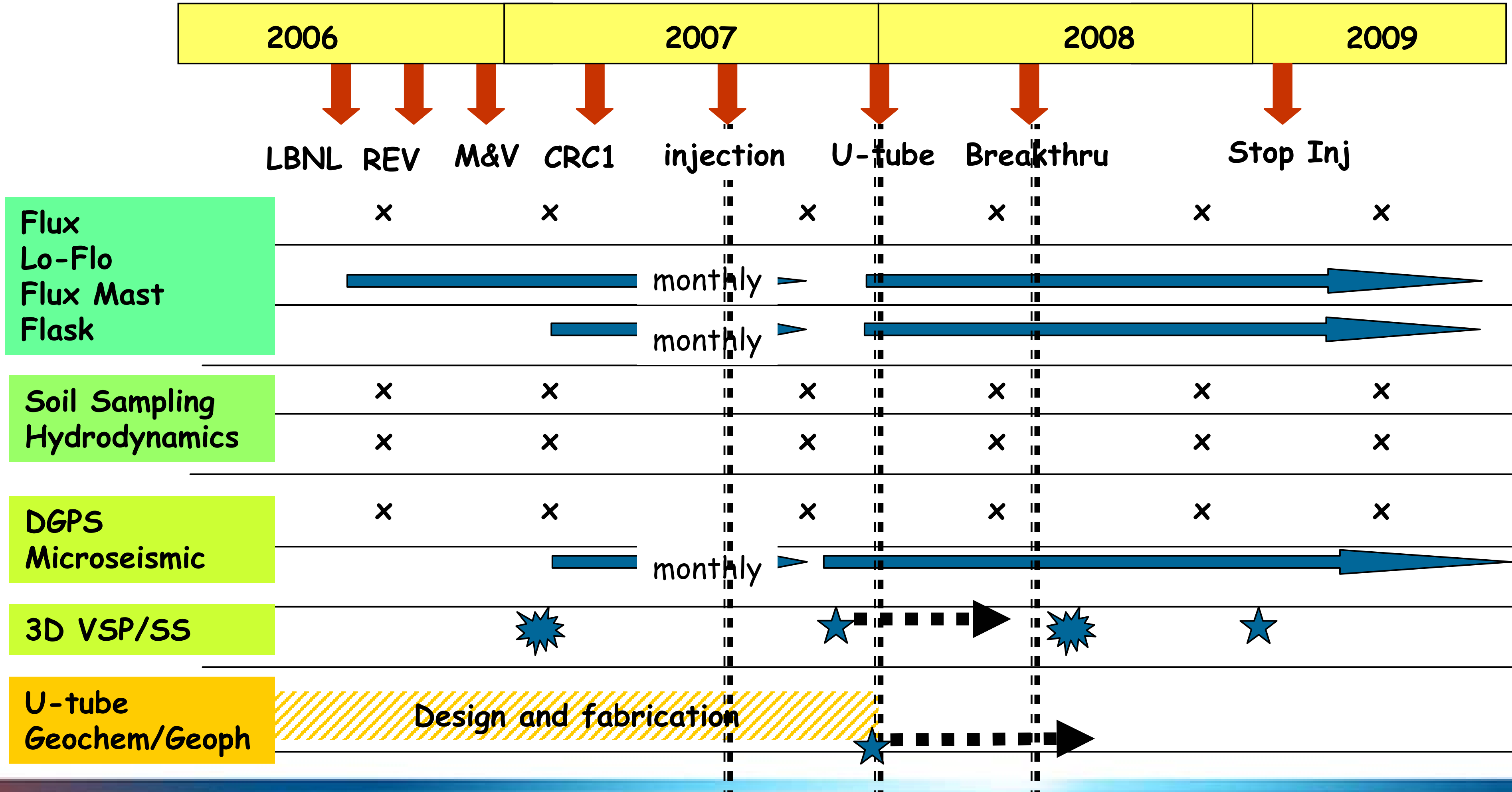
OBPP Implementation Phases
EPA Transition Criteria

- **Phase 1 (Pre-injection and Injection):**
  - Site characterisation and risk assessment
  - Project approvals, regulatory, landowner and community activities
  - **Baseline monitoring preparation for confirmation and assurance**
  - Plant design, fabrication and commissioning
  - Drill new injection well.
  - Production, transportation and Injection
  - **Confirmation M&V activities** **KPI**
- **Phase 2 (Post Injection Monitoring and Closure):**
  - **Confirmation monitoring of CO2 plume and validation of models**.
  - Safe closure of all wells as per regulation and site restoration **KPI**
- **Phase 3 (Post Closure)**
  - **Monitoring for public assurance** **KPI**
- **Phase 4 (Long Term)**
  - **Monitoring for public assurance** **KPI**

Monitoring Domains



OBPP M&V Schedule

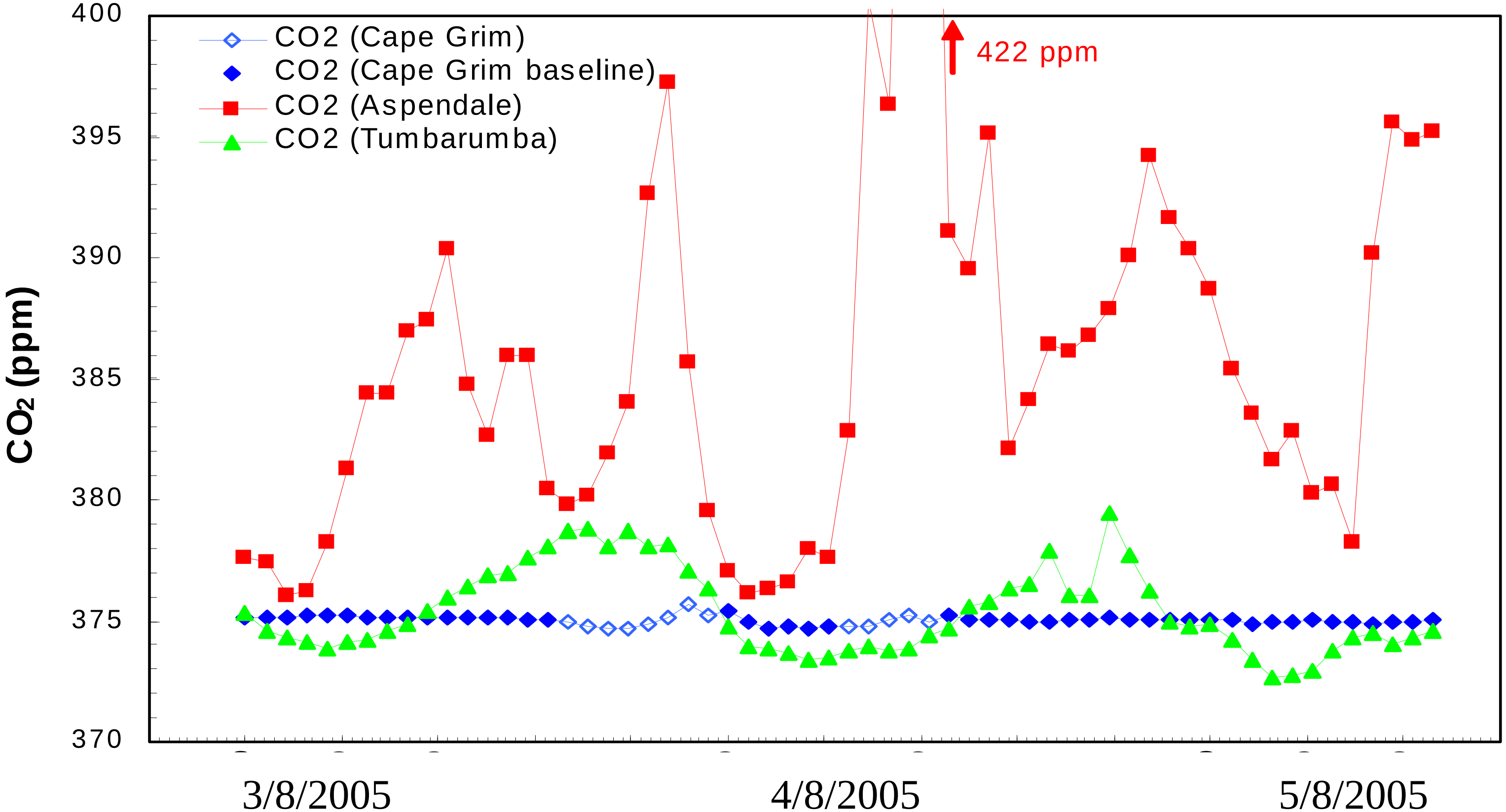


Atmospheric Conclusions

- CCS can provide long term climate benefit if leakage rates are small (<0.1% per year average)
- Atmospheric monitoring can potentially provide independent verification
- Requires continuous high precision measurements of CO_2, tracers and CO_2 fluxes
- and transport/dispersion models to determine fluxes and back trajectories
- May be able to detect and quantify leaks of the order of 1000 t CO_2/year (Otway)
- The environmental setting (ecosystem and other emissions, winds) will strongly affect the sensitivity of detection

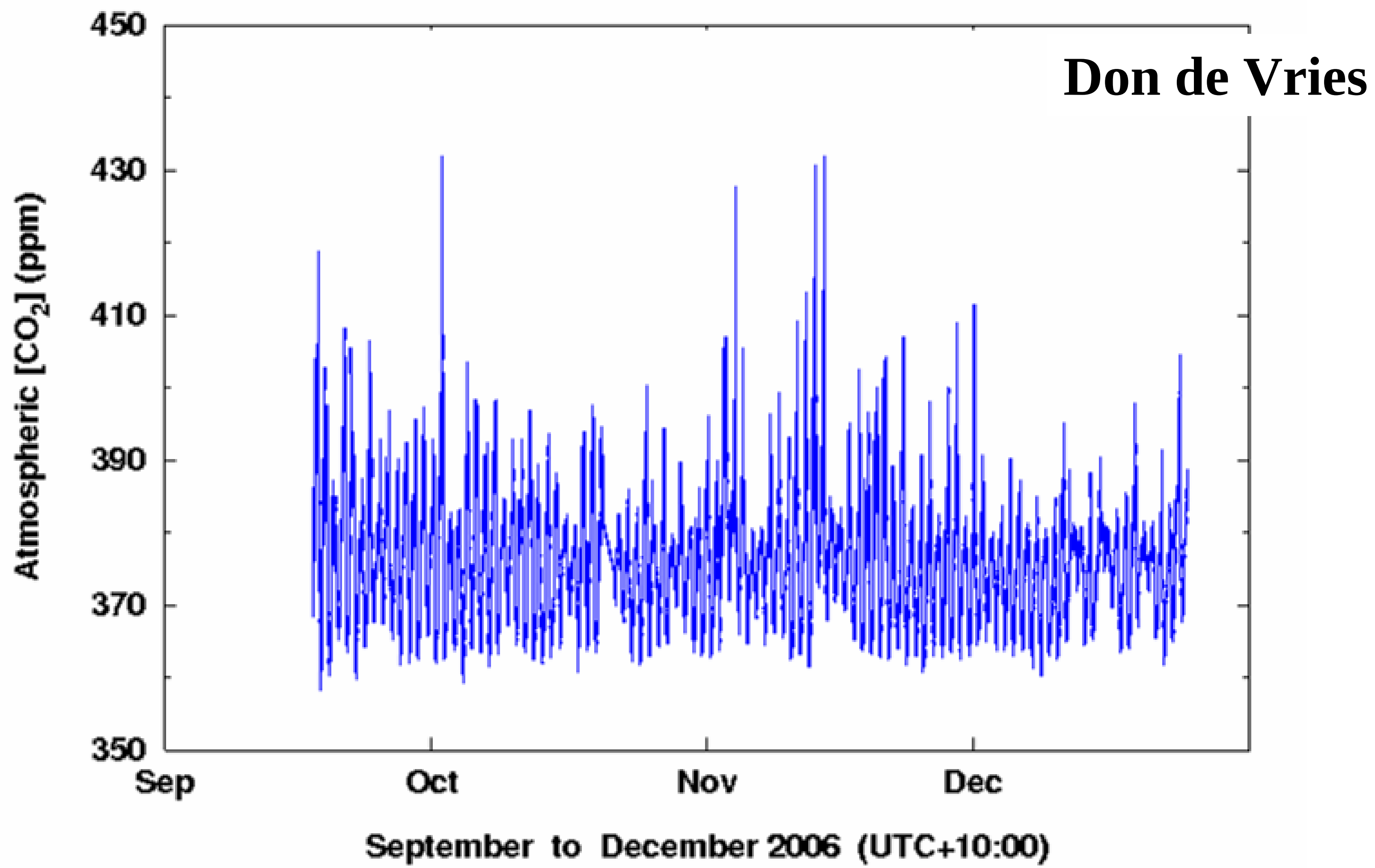
Background CO_2 variations – THE challenge

David Etheridge



CO_2 hour means LoFlo TM
CSIRO Marine and Atmospheric Research

Concept demonstrator – Atmospheric CO_2

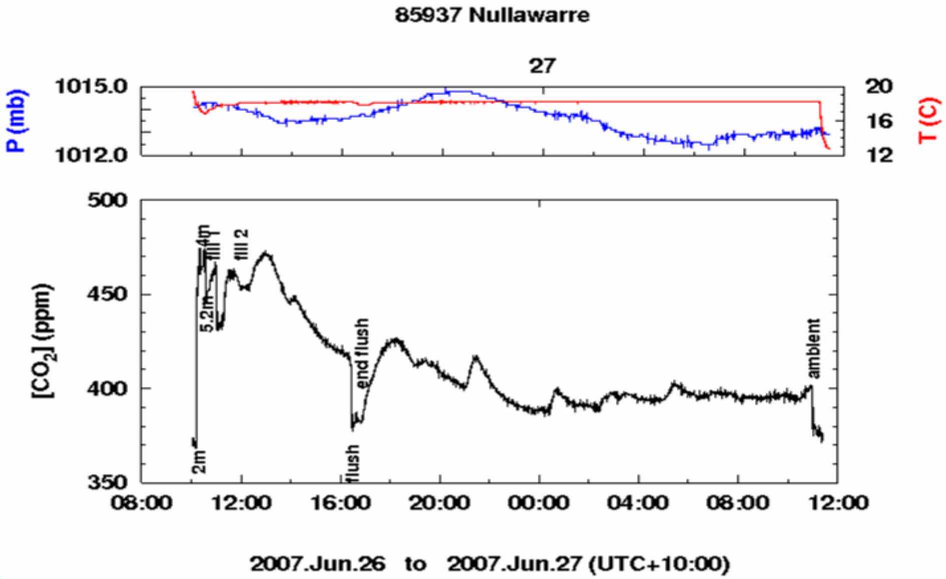


CO_2 headspace gas sensor

First Otway headspace gas survey

Instrument package

- CO_2 sensors (2 ranges covering 0 .. 10%)
- Pressure
- Temperature
- Flask sampling

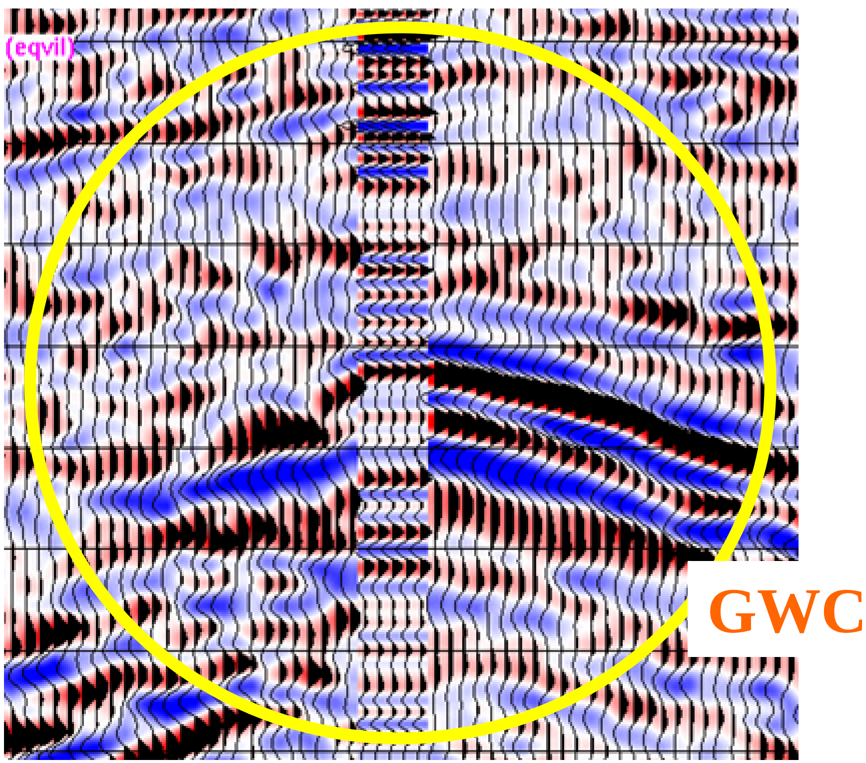


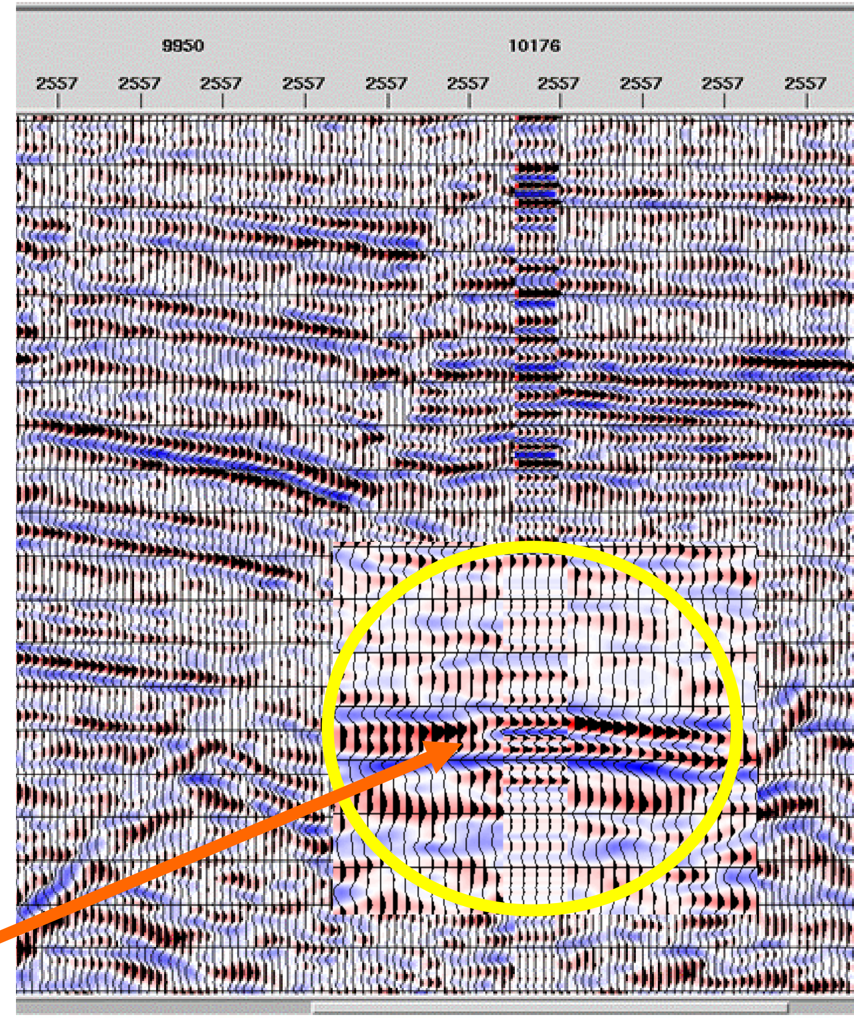
- **CO_2 sensors give an immediate indication of CO_2 levels in the headspace and help plan the laboratory CO_2 analysis**

- **Flask sampling allows the precise laboratory analysis of other trace gases**

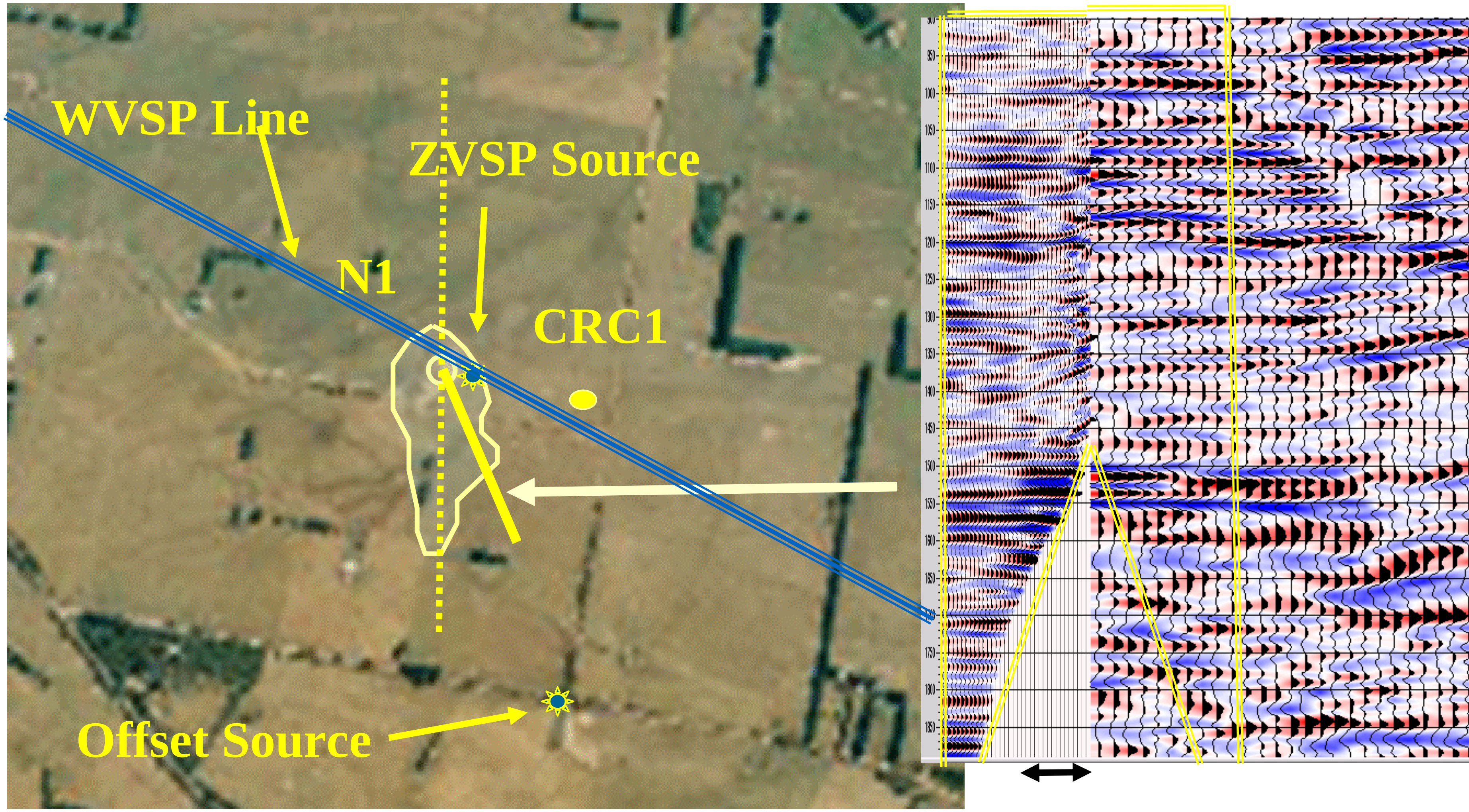
Integrity Monitoring :
Surface & Borehole Geophysics

Fast Shear





OVSP and Original Interpreted GWC



Subsurface Monitoring

Key Requirements

- Breakthrough : Positive confirmation of CO_2 arrival using geochemical means.
- CO_2 plume position and size measured through geophysical methods

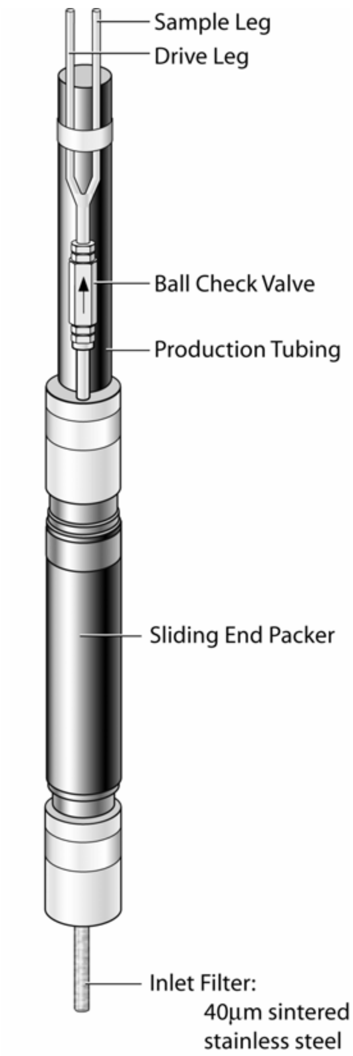
Challenges:

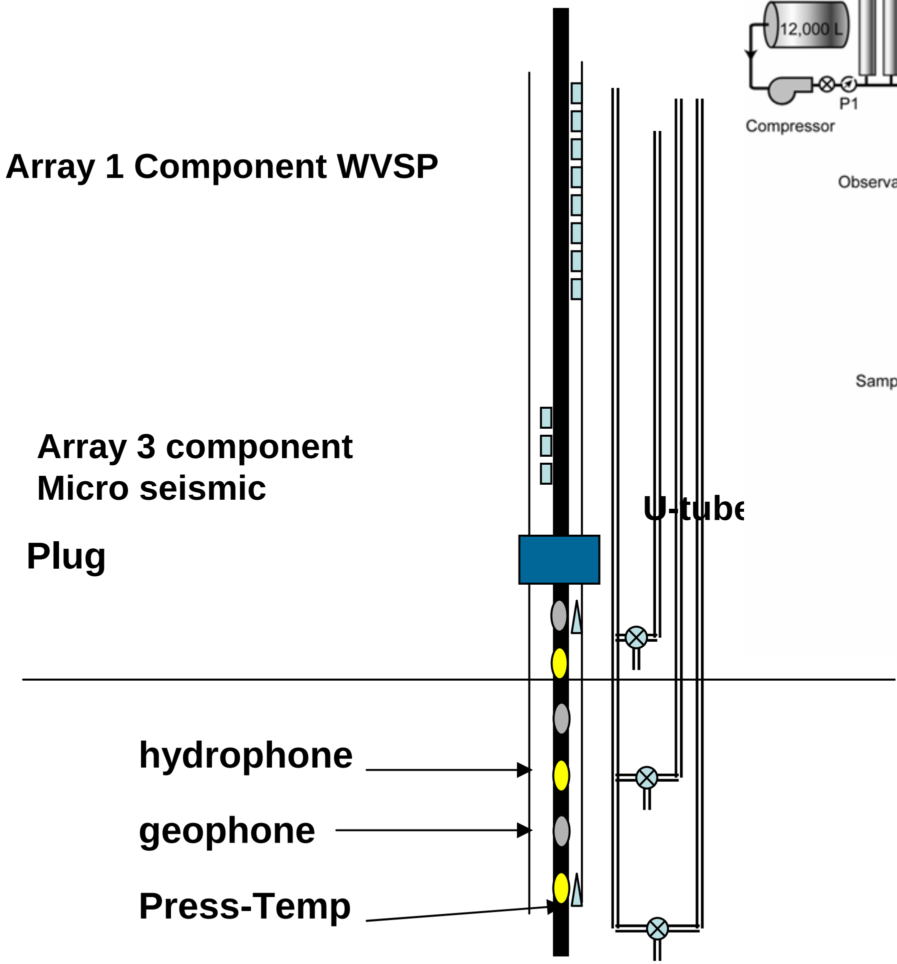
- Geophysically monitoring CO_2 under a gas cap
- Bundling geochemical and geophysics sensors
  - ⇨ Engineering
  - ⇨ Surface terminations
- Deployment:
  - ⇨ Running and installing
  - ⇨ Retrieval

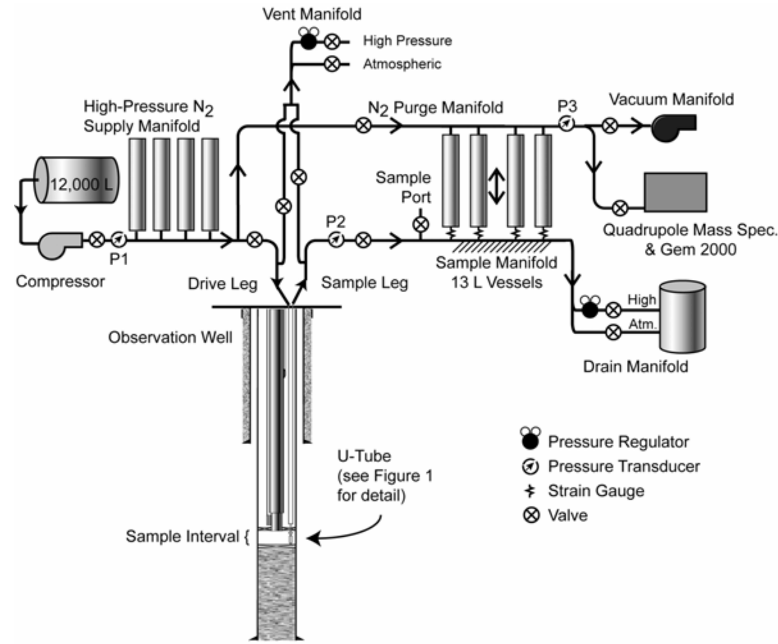
Well Monitoring Plans – Wish List

- Chemical/gas sampling via u-tube ✓
- Passive micro-seismic monitoring ✓
- Pressure and temperature monitoring ✓
- Surface to well seismic (VSP) ✓
- Acoustic source in well for high resolution acoustic monitoring ✗
- Possible cross-well seismic ✗
- Tilt sensors ✗

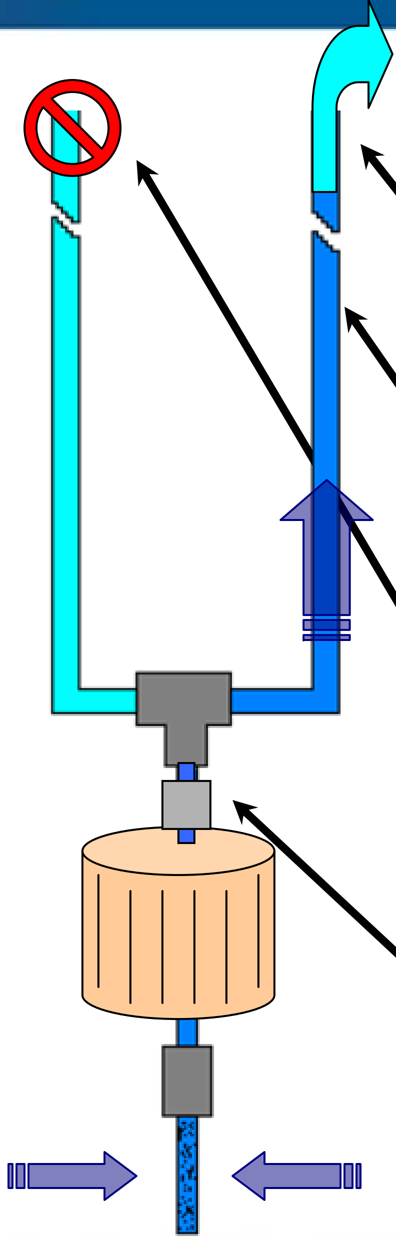
Integrated Completion







Naylor 1 Completion



U-tube Sampler

Sample to Tube

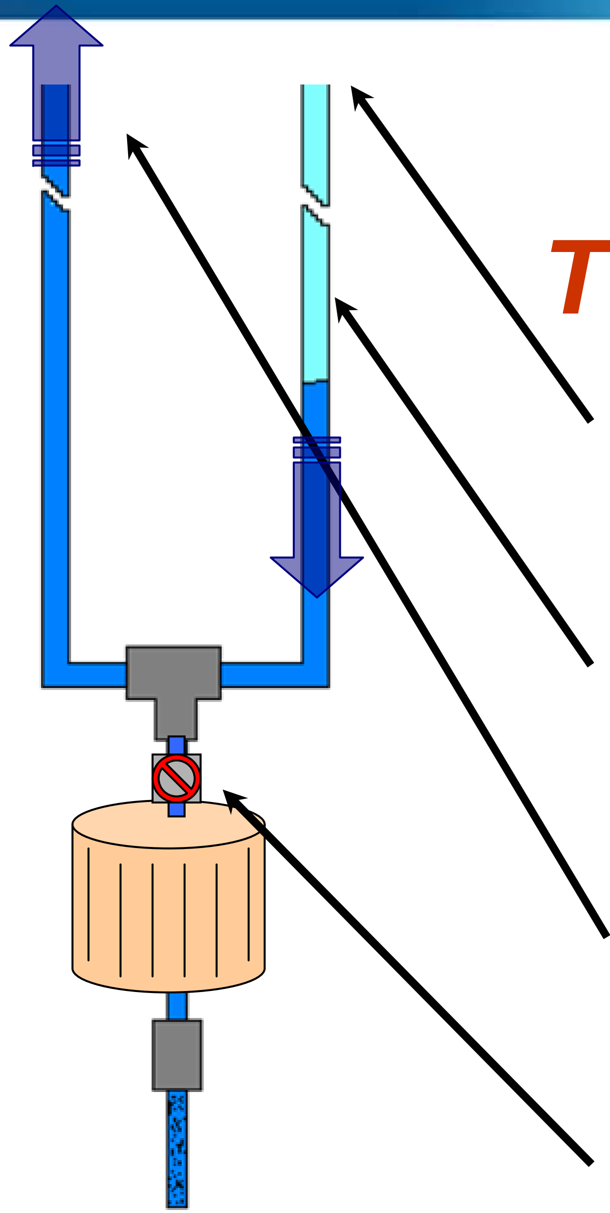
(Not to scale)

Upstream surface value open, pumping at surface to create > +3 psi differential at check value.

Formation water – tube water interface. Degassing/contamination will mostly occur here.

Downstream surface valve closed

Check valve open due to > +3 psi differential (higher P on reservoir side)

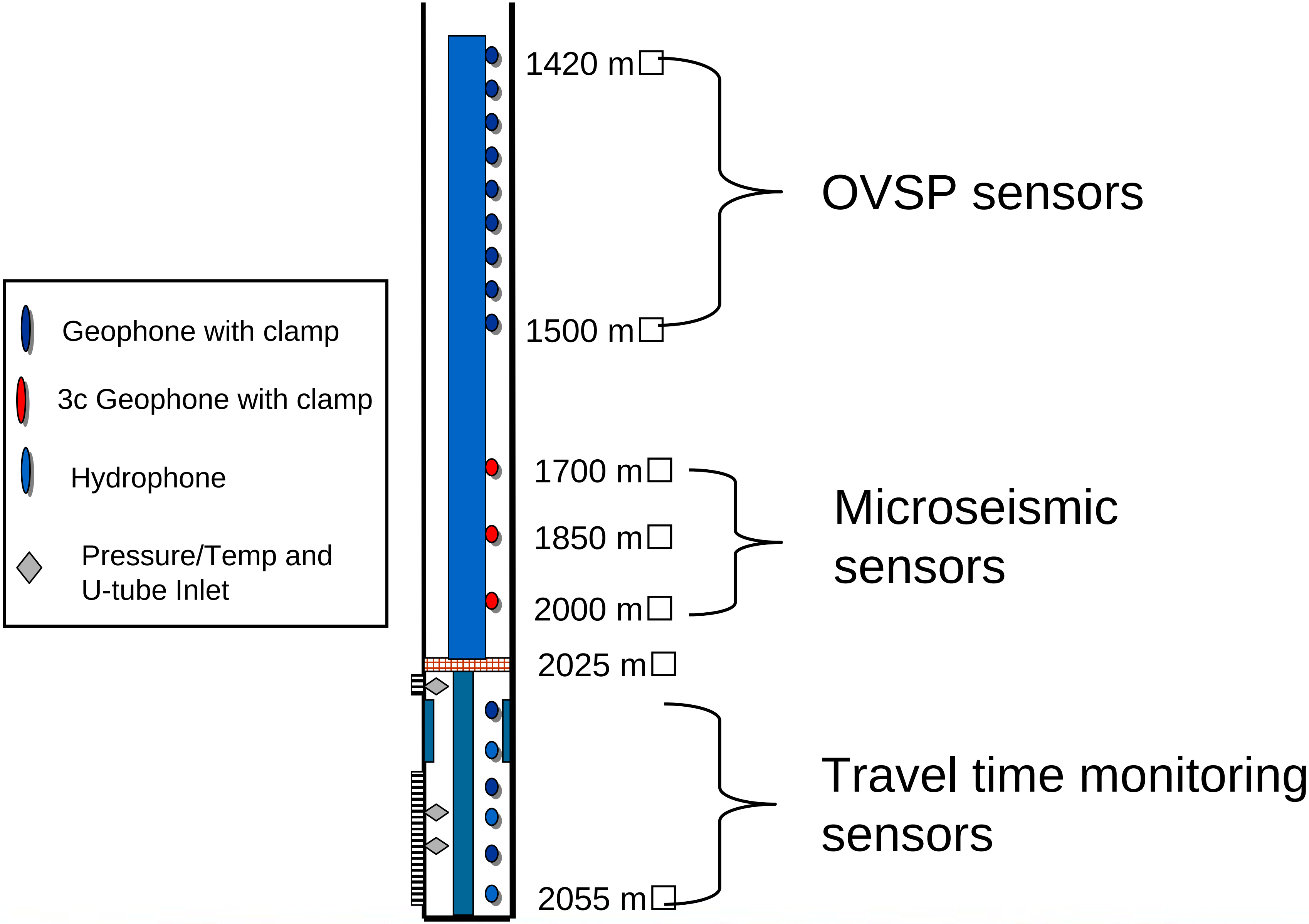


U-tube Sampler

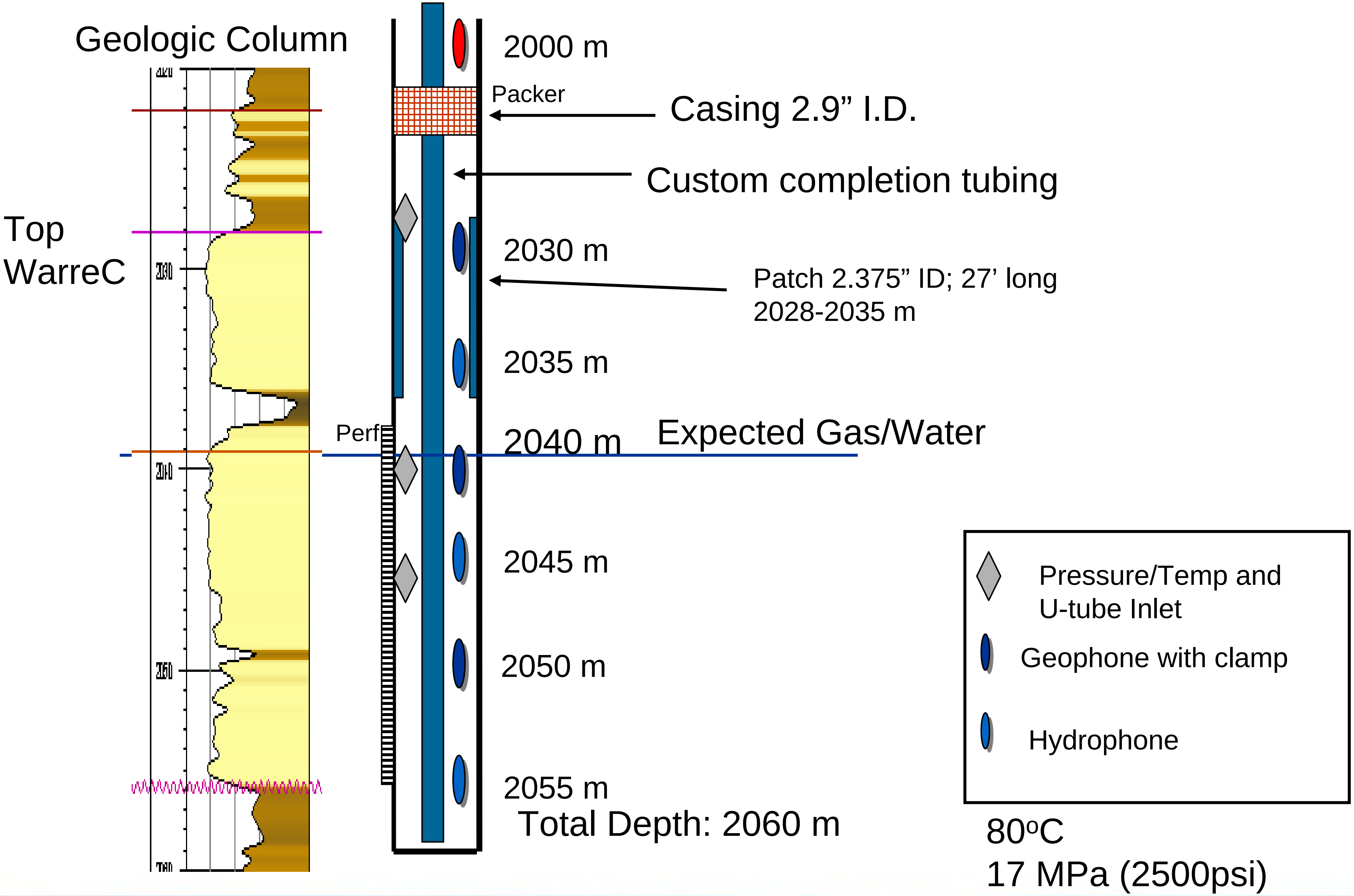
Tube Sample to Surface

(Not to scale)

- Upstream surface value open, pumping at surface to create < +3 psi differential at check value.
- Formation water – Tube water interface. Minor sample contamination occurs.
- Downstream surface valve open; to sampling vessels (multiple samples taken, first & last may be contaminated).
- Check valve closed due to < +3 psi differential (higher P on surface side)



Total Depth: 2060 m


Geologic Column
Top
WarreC
2000 m
Packer
Casing 2.9” I.D.
Custom completion tubing
2030 m
Patch 2.375” ID; 27’ long
2028-2035 m
2035 m
Perf
2040 m
Expected Gas/Water
2045 m
2050 m
2055 m
Total Depth: 2060 m
Pressure/Temp and
U-tube Inlet
Geophone with clamp
Hydrophone
80ºC
17 MPa (2500psi)

Otway Project
Monitoring Well Instrumentation

- Combined Seismic and Hydrologic Sampling
- Sucker Rod deployment in 7 cm (3 inch) casing
- Bottom Hole Assembly (BHA) Packer + instrumentation:
  - 3 U-tubes for sampling
  - 6 seismic sensors
  - 2 P/T gauges
  - ~35 m long, 5 cm tube in ~1.5 m sections
- Surface Assembly (horizontal): 2 days
- Vertical BHA lift: 3 cranes (incl. 48 m crane) and 1 man-lift
- 5 24-hour days to install
  - ➢ ~ 260 sucker rods each with 5 bands and 1 coupling protector
  - ➢ 12 Geophones above packer attached to sucker rod
  - ➢ 9 stainless steel tubes

It’s In …. Now What?

- Regular Fluid sampling through the three U-tube ports for:
  - Breakthrough
  - Isotope Geochemistry
- Microseismic monitoring (24 hr with automated event logging)

- Regular High Resolution Travel-time measurements
- Frequent ZVSP and WVSP surveys for 4D imaging

CO2CRC Core Participants:

CRC AUSTRALIA

Australian Government
Geoscience Australia

bp

RIO TINTO

xstrata coal

CSIRO

ANGLO AMERICAN

Chevron

Schlumberger

STANWELL CORPORATION LIMITED

Origin energy

SOLID ENERGY Coals of New Zealand

NZ RESOURCE CONSORTIUM

Victoria The Place To Be

curtin University of Technology Western Australia

WOODSIDE AUSTRALIAN ENERGY

THE UNIVERSITY OF ADELAIDE AUSTRALIA

ACARP Australian Coal Association Research Program

UNSW

THE UNIVERSITY OF MELBOURNE

MONASH University

bhpbilliton

CO_2 Saturation and Movement during Post-Injection Period

Nagaoka Project , Japan

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2: Geophysical Surveying Co., Ltd.

3: Oyo Corporation

4: J-Power

5: RITE (Present:Kyoto University)

6: RITE

4th MEETING of the MONITORING NETWORK

November 7-9, 2007

Discussion Points

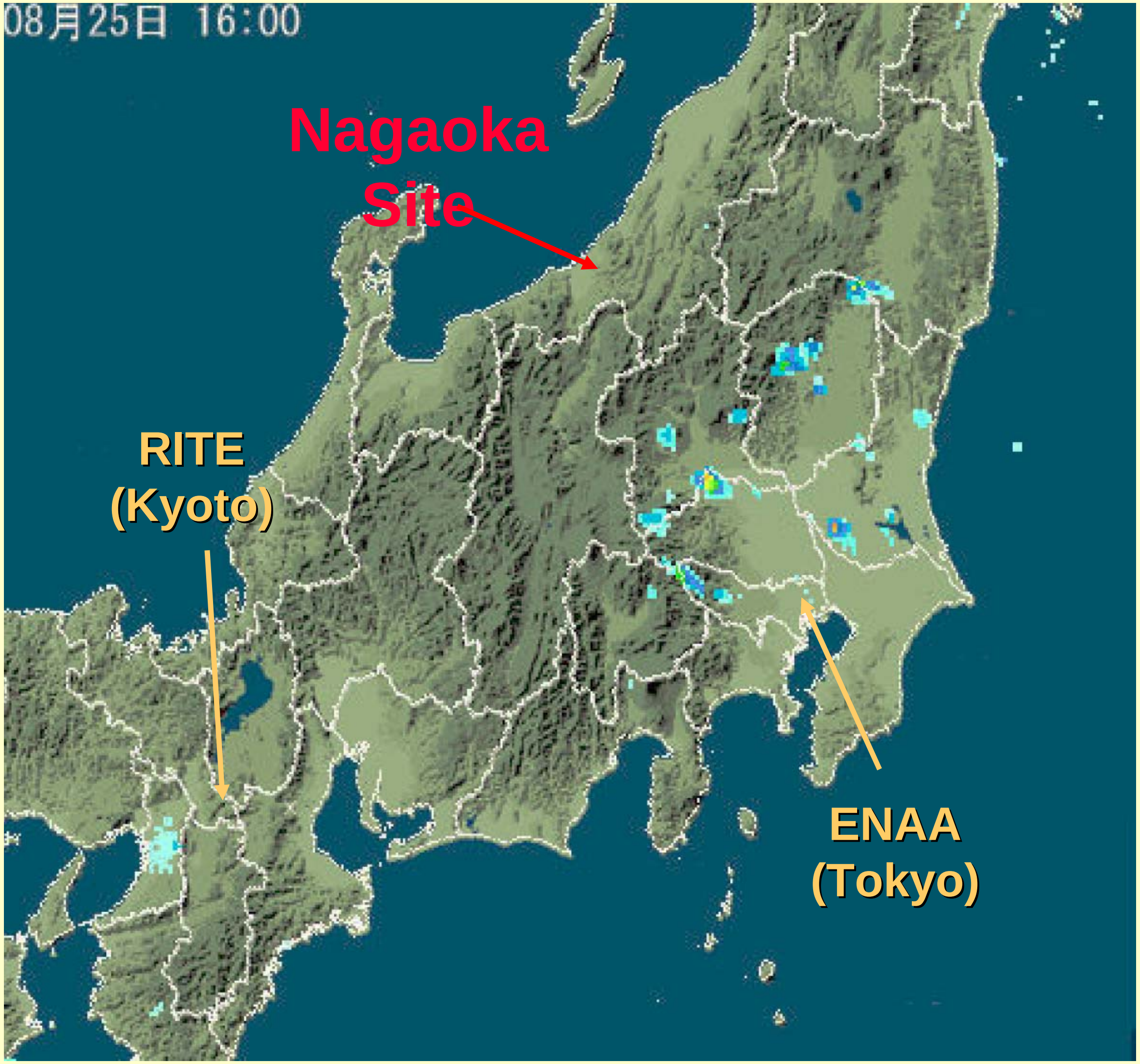
- CO_2 saturation occurred at Patchy condition?
- Resistively and Porosity become decreasing one year after stopping injection of CO_2, not velocity. Why and How?

Contents

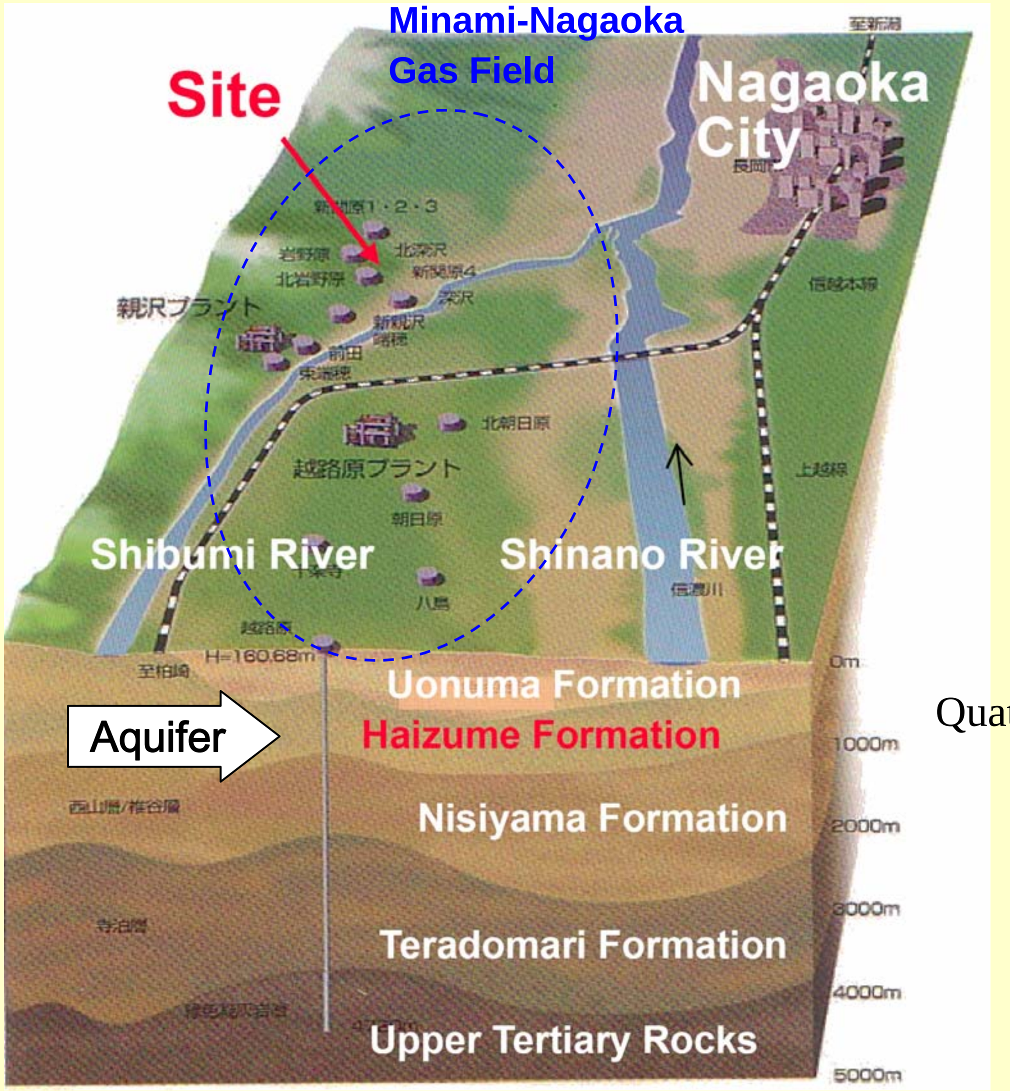
- Review of Nagaoka Project and New Findings
- CO_2 saturation
- Movement of CO_2
- Summary

Nagaoka General Information

Location Central Japan



Nagaoka Site Cross Section



Quaternary

Project General Information

Chronicle of Nagaoka Project

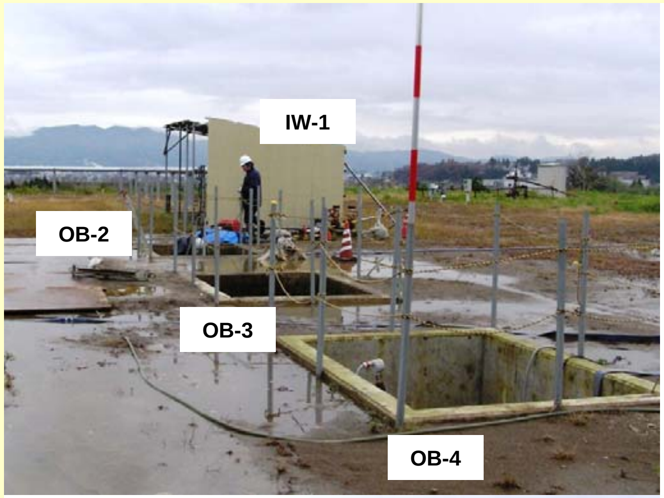
- **FY2000 : Site Selection ・・・South Nagaoka Gas Field**
- **Drilling of Wells, Well logging and Test of Core Sample**
  - ✧ FY 2000-2001 : Injection well (IW-1)

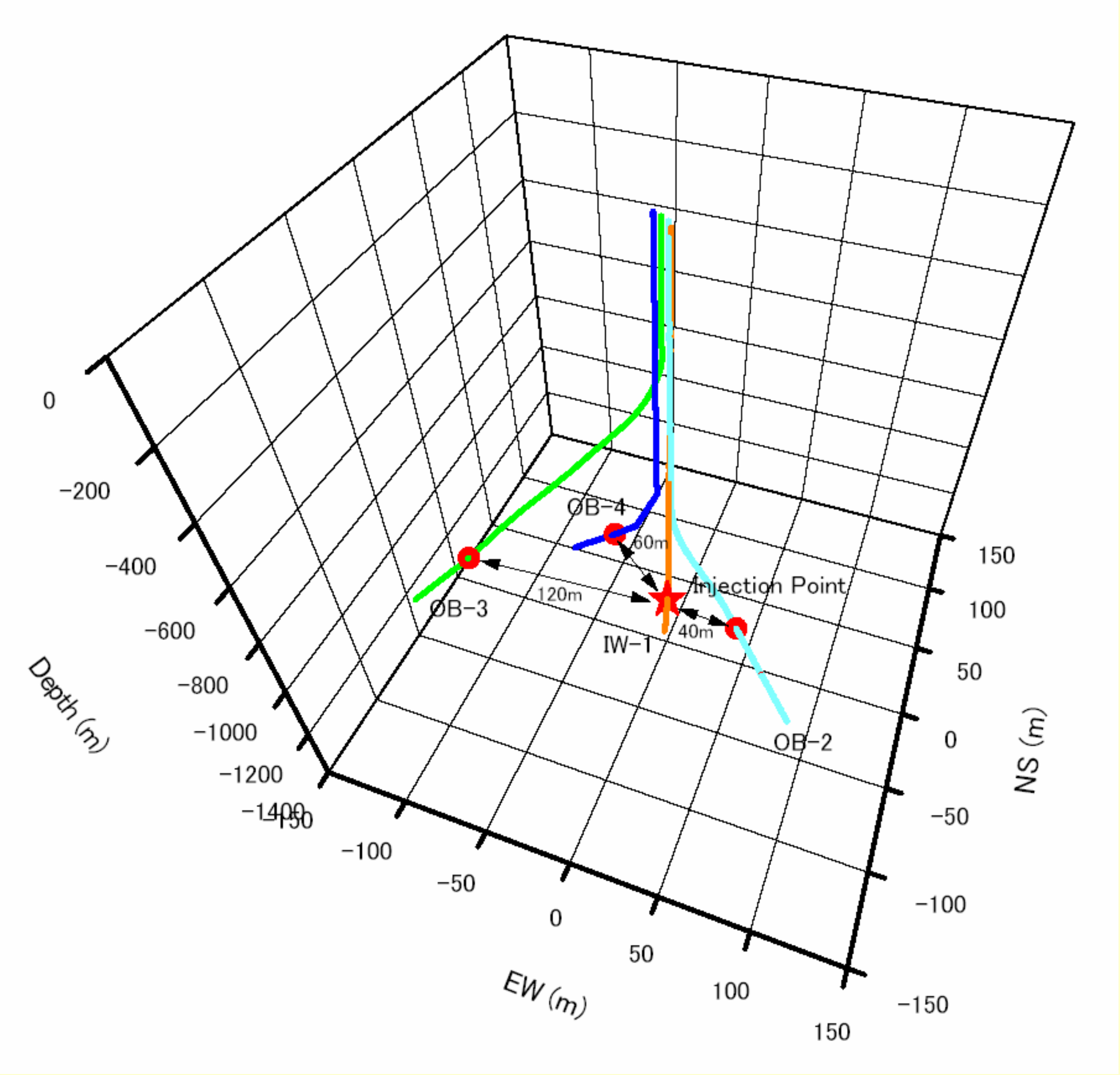
    and Three observation wells (OB-2, OB-3, OB-4) drilled
- **FY 2002 – 2003 : Construction of the Facilities**
- **FY 2003 – 2004 : Injection of CO_2 ・・・10,405t**
- **FY 2002 – present : Monitoring of CO_2 for 5 years**
- **FY 2000 – present : Simulation Study (now on progressing)**
  - ✧ FY 2000 – 2002 : Simulation prior to the injection start
  - ✧ FY 2003 - present : History matching simulation after the injection start
  - ✧ Future prediction for 1000 years
- **FY 2007 – RST, CBL and No Blockage of Wells, End of Project**

Well Configuration

Injection well : IW-1

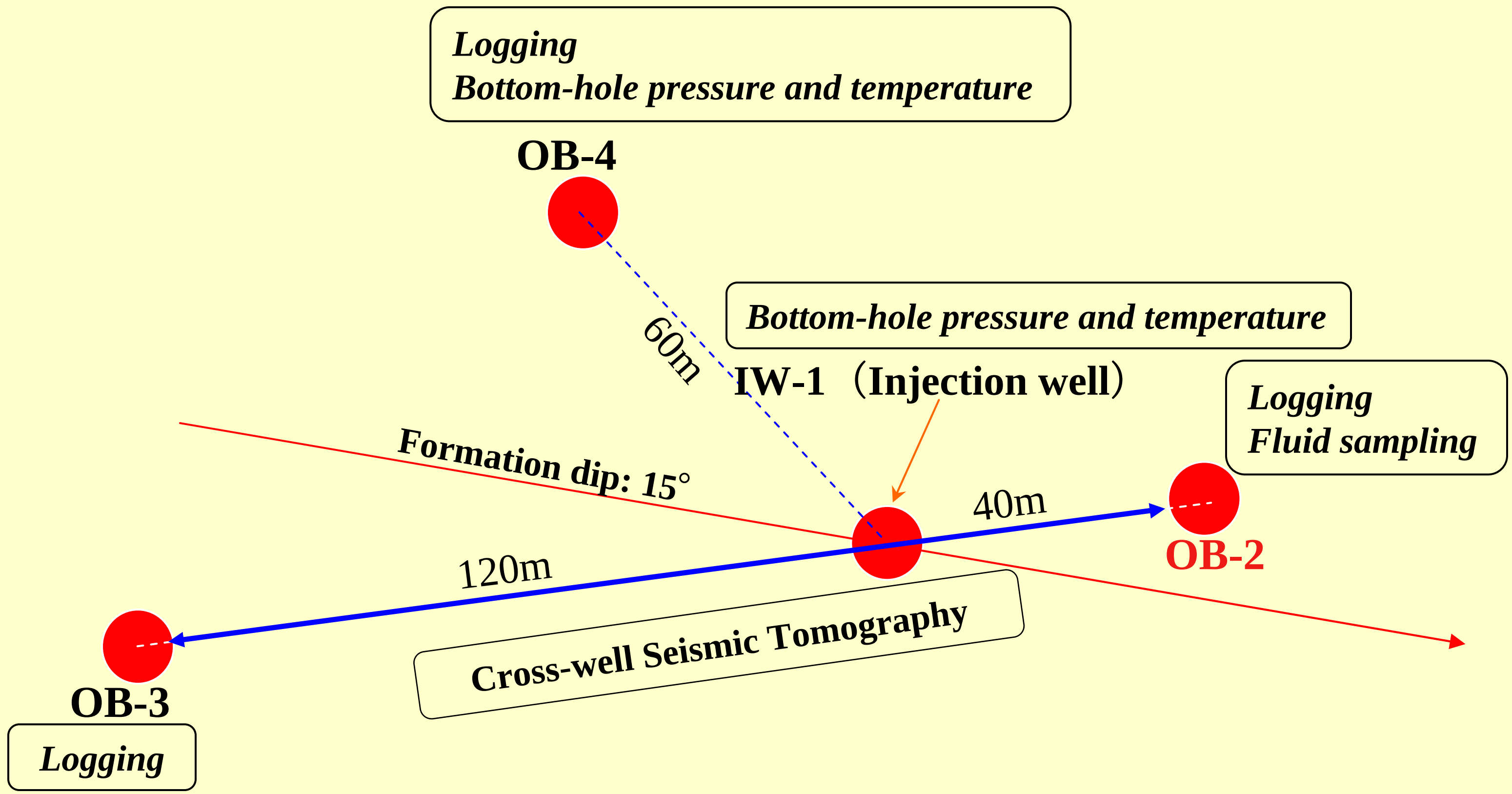
Observation well :OB-2, OB-3, OB-4





Well Configuration

Arrangement of Wells at Reservoir Level

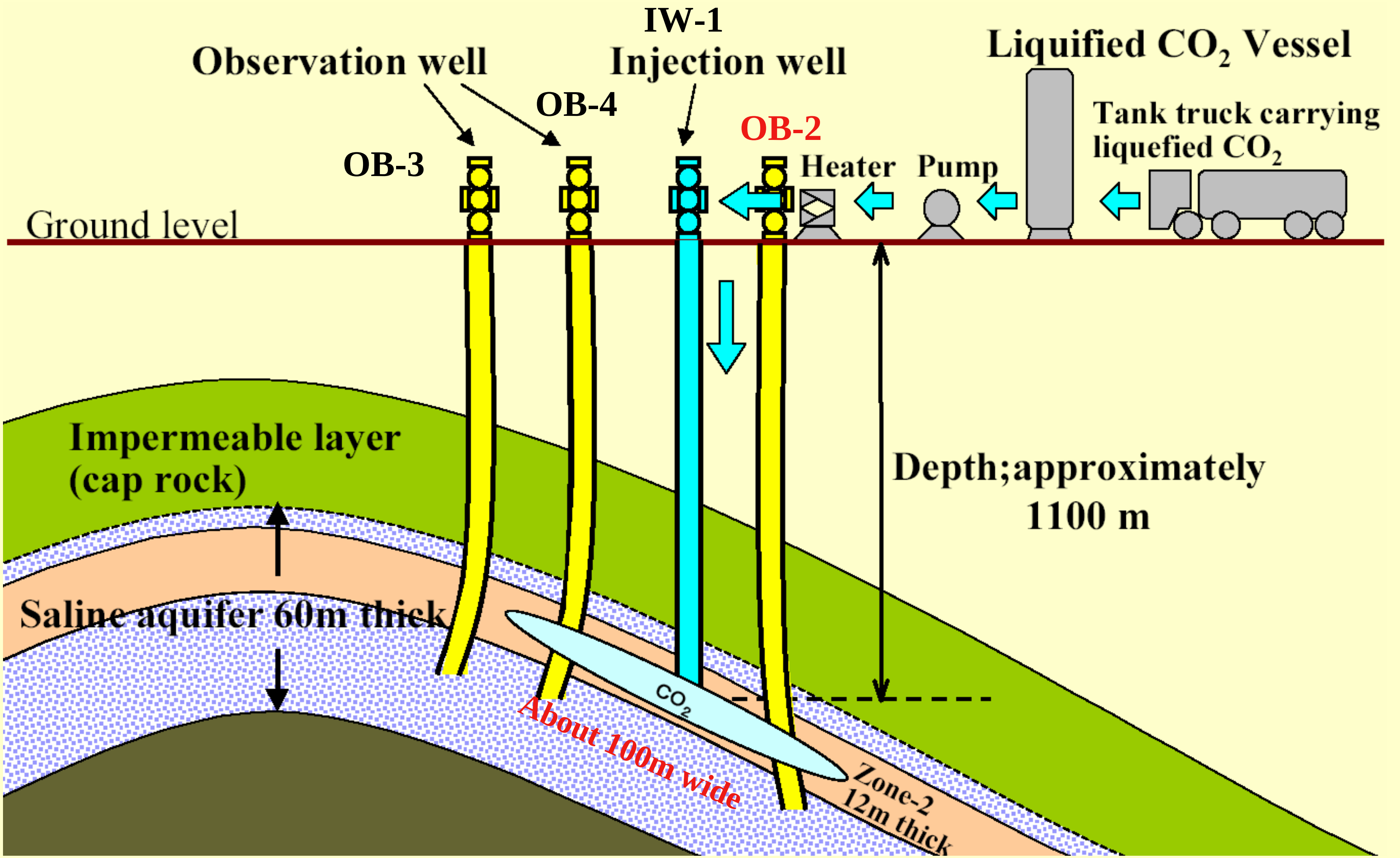


Injection well : Perforated at Zone-2 (12m)
Observation wells : FRP Casing at reservoir interval

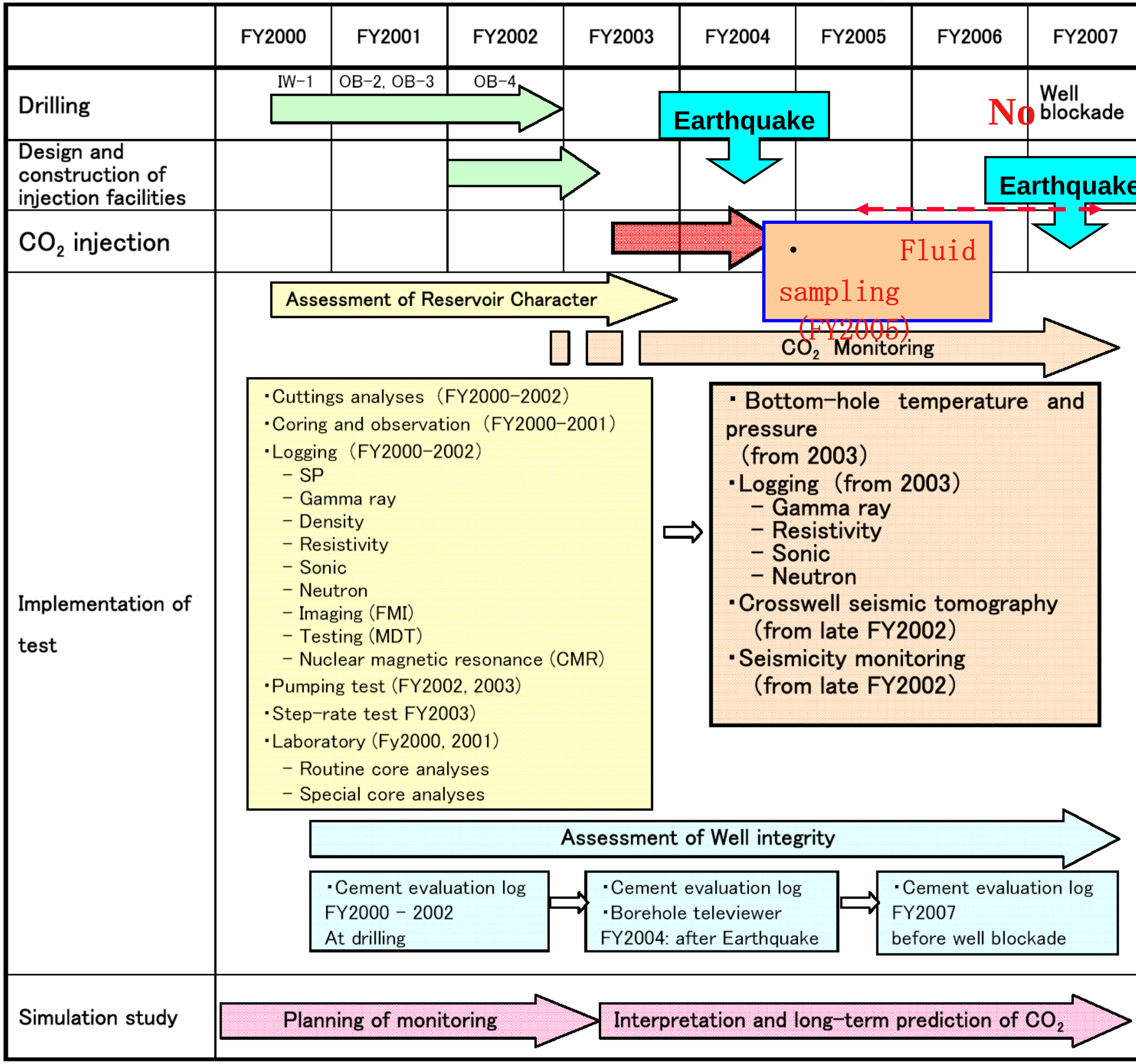
Main Features of CO_2 Injection

- Reservoir: Aquifer of 1,100m deep
- Duration of Injection: About 18 months
- Injection started on 7 July 2003, ended 11 January 2005
- Total Amount of CO2 : 10,405 t
- Injection Rate: 20 - 40t /day
- CO_2 Phase: kept to be Supercritical
- Injection Pressure
  - Well Head 6.6 - 7.4 MPa
  - Well Bottom 11.9 - 12.6 MPa
- Temperature of CO_2
  - Well Head 32.0 - 35.5 ℃
  - Well Bottom 45.0 - 48.6 ℃
- CO_2 Phase: kept to be Supercritical Phase (at Well Bottom)

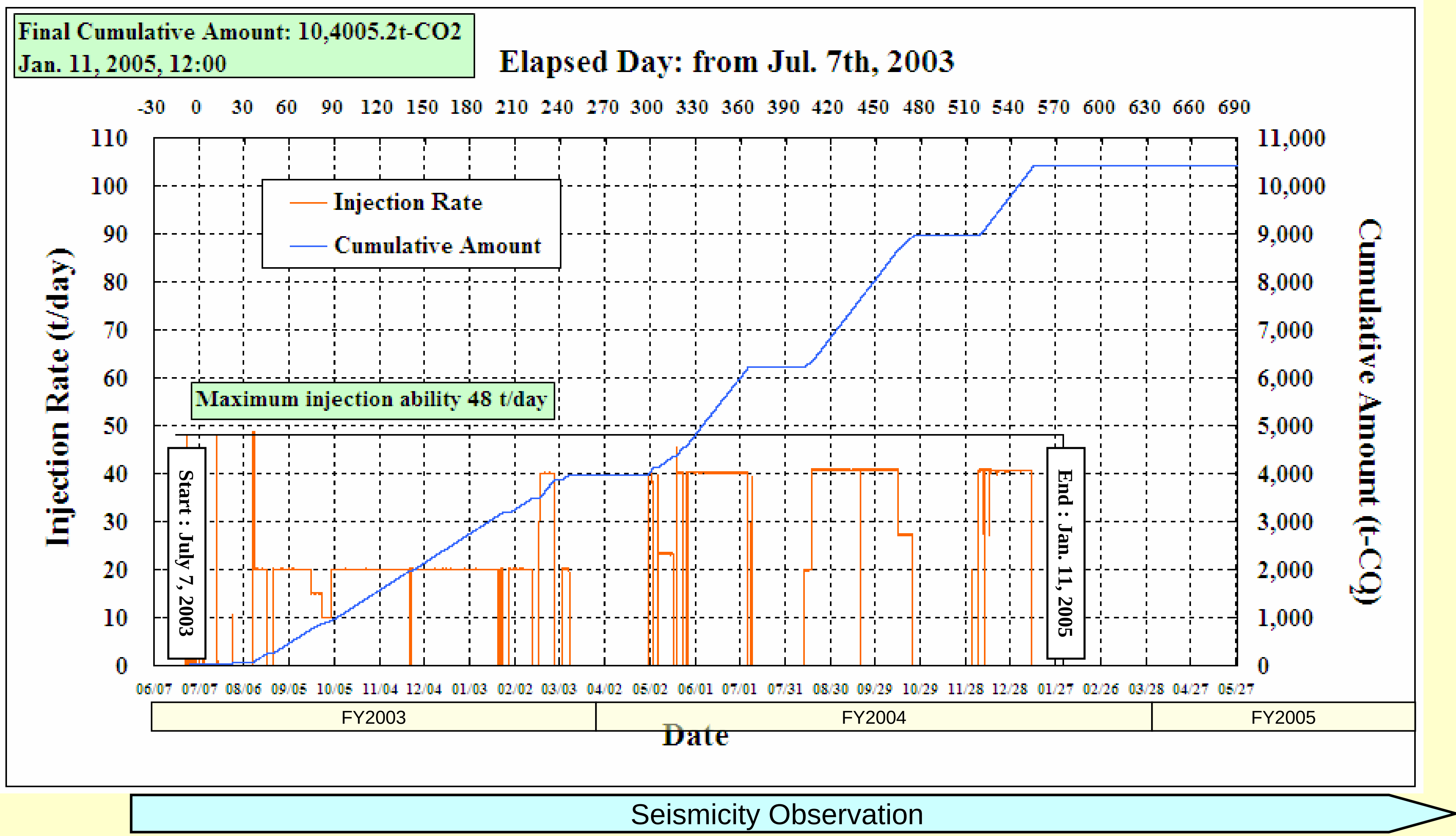
Sketch of Injection



Flow of Investigation & Monitoring



Progress of Injection and Monitoring

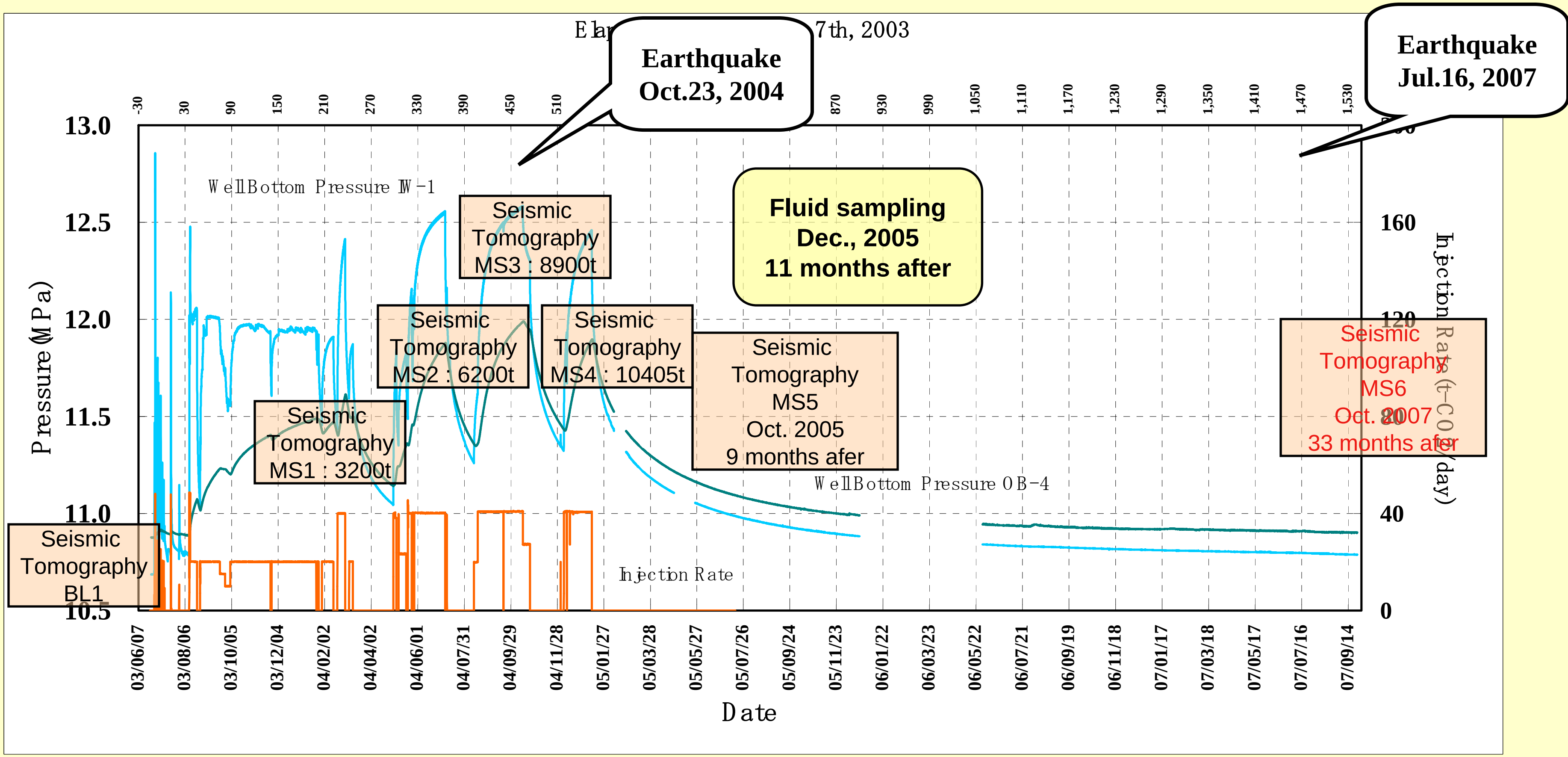


- **Pressure & Temperature Measurement**
  - Continuously at well bottom and well head)
- **Time-lapse Logging**

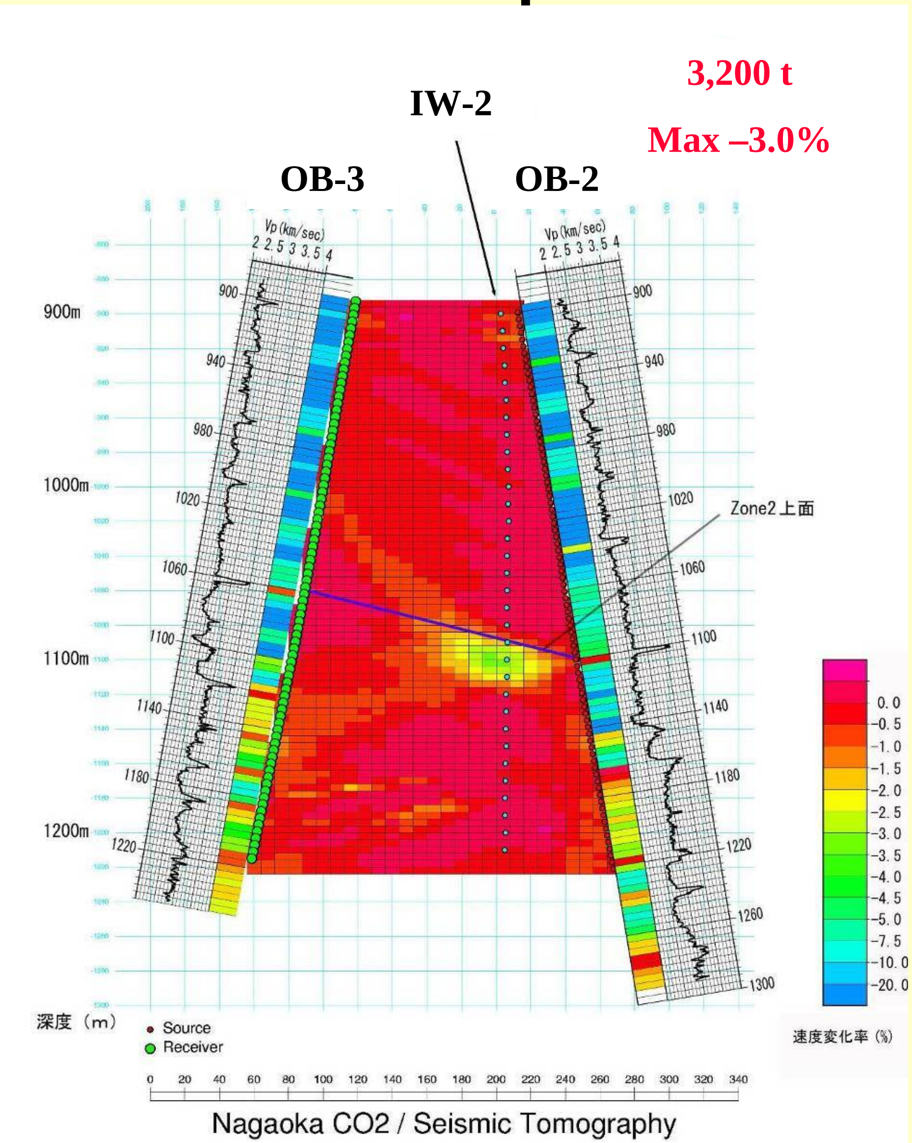
  (Baseline + 22 times during injection +14 times after the end of injection)
  - Induction Log
  - Neutron Log
  - Acoustic Log
- **Time-lapse Cross-well Seismic Tomography**
  - Seven times : Before the injection – After the injection
- **Seismicity observation** (during and after injection)
  - Micro earthquake (3years)
- **Fluid Sampling**
  - 11 months after the end of injection (CHDT)
  - Borehole optical TV

Seismic Tomography

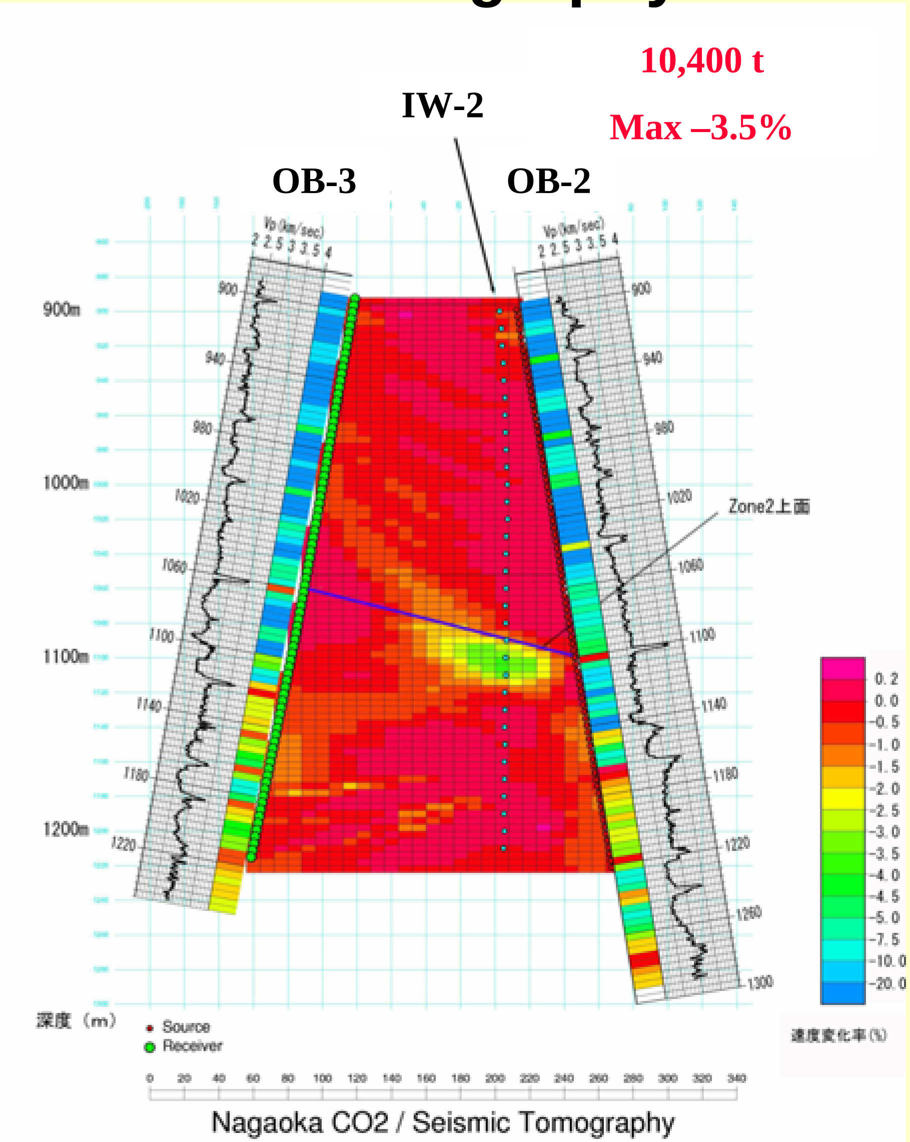
Pressure Measurement & Seismic Tomography



Time-lapse Crosswell Seismic Tomography



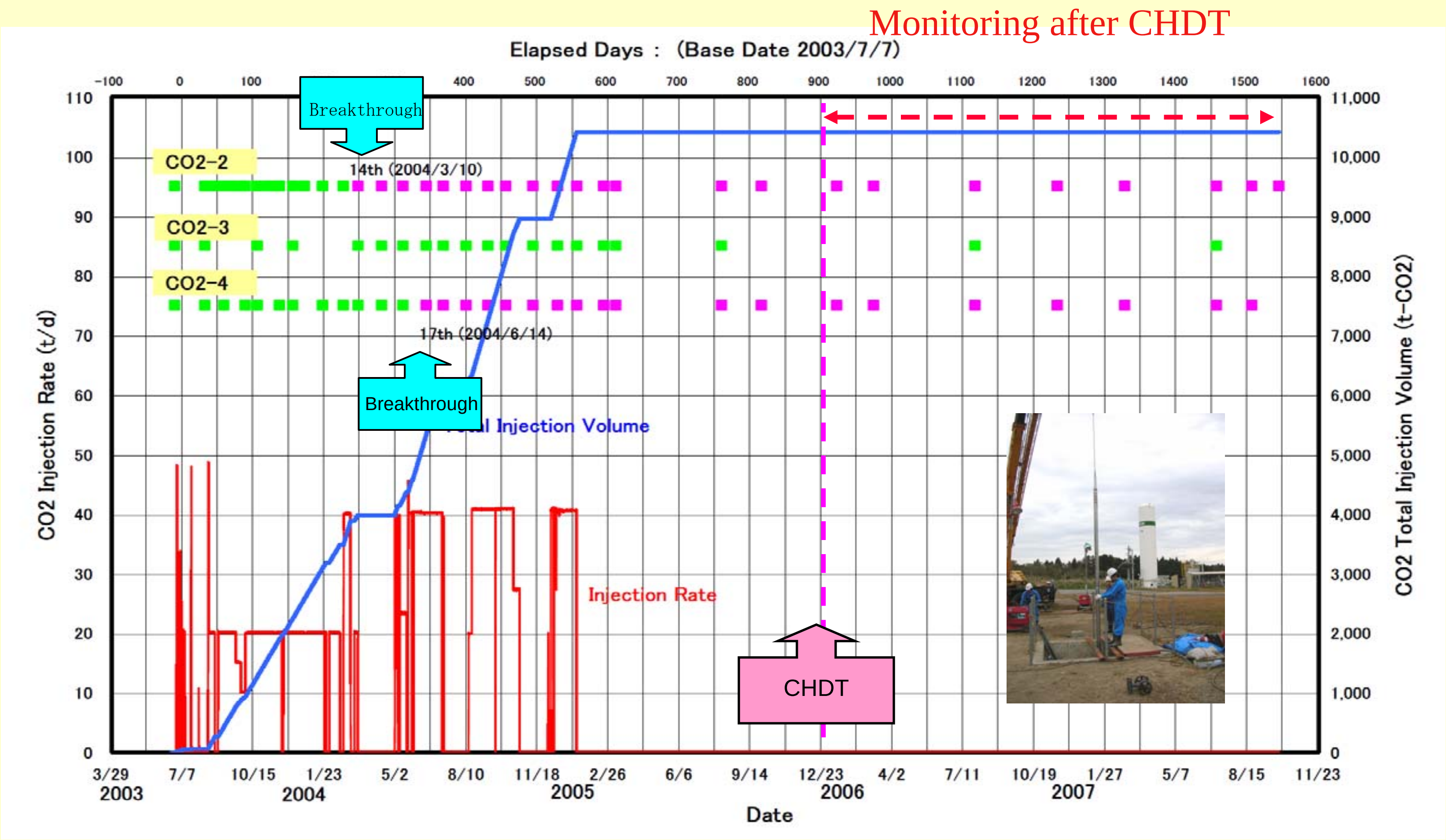
MS1/BLS



MS4/BLS

Time-lapse Well Logging

Time-lapse Well Logging



CO_2 Breakthrough at OB-2,3,4

13th logging on Feb. 12 (3,500t-CO_2)
No Change

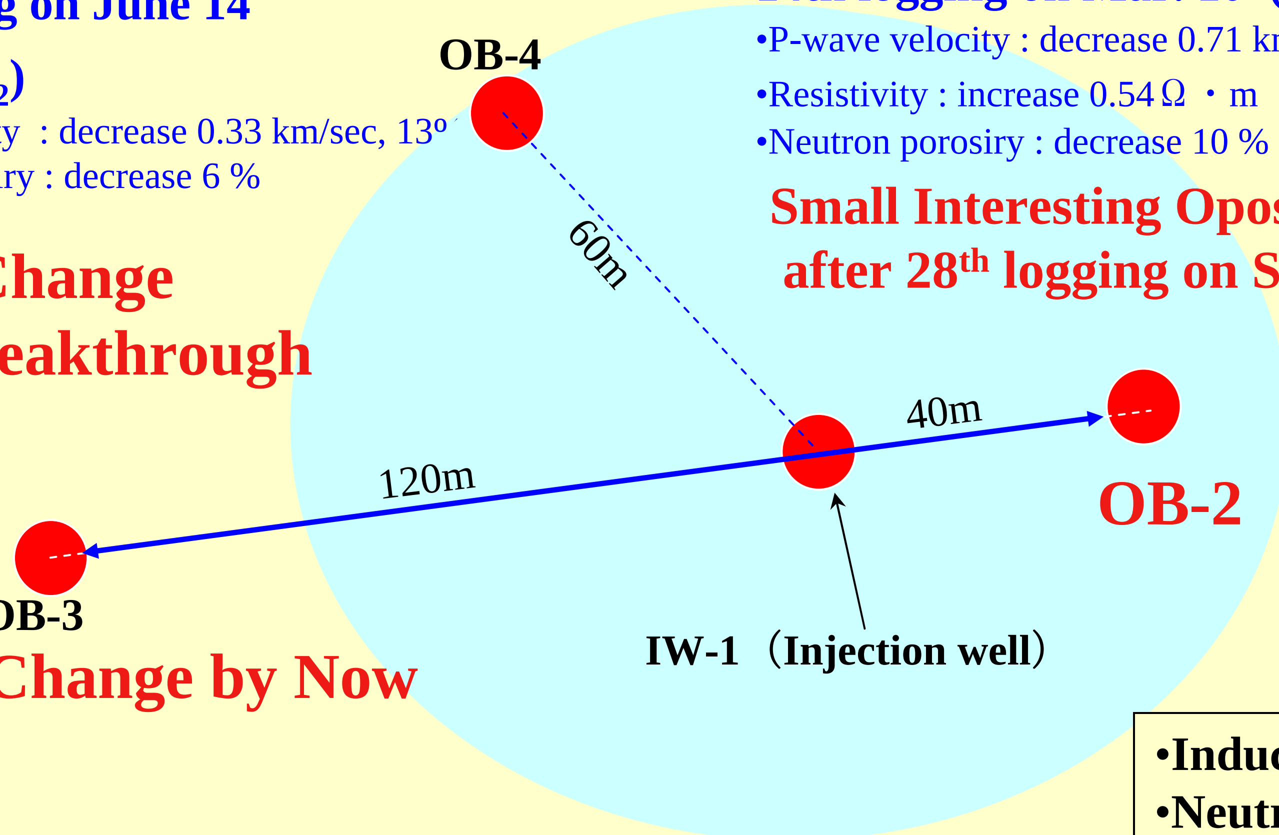
16th logging on May 12 (4,300t-CO_2)
No Change

14th logging on Mar. 10 (4,000t-CO_2)
- P-wave velocity : decrease 0.71 km/sec, 28%
- Resistivity : increase 0.54 Ω・m
- Neutron porosiry : decrease 10 %

17th logging on June 14 (5,400t-CO_2)
- P-wave velocity : decrease 0.33 km/sec, 13º
- Neutron porosiry : decrease 6 %

Small Interesting Opossite Change after 28th logging on Sept. 24, 2004

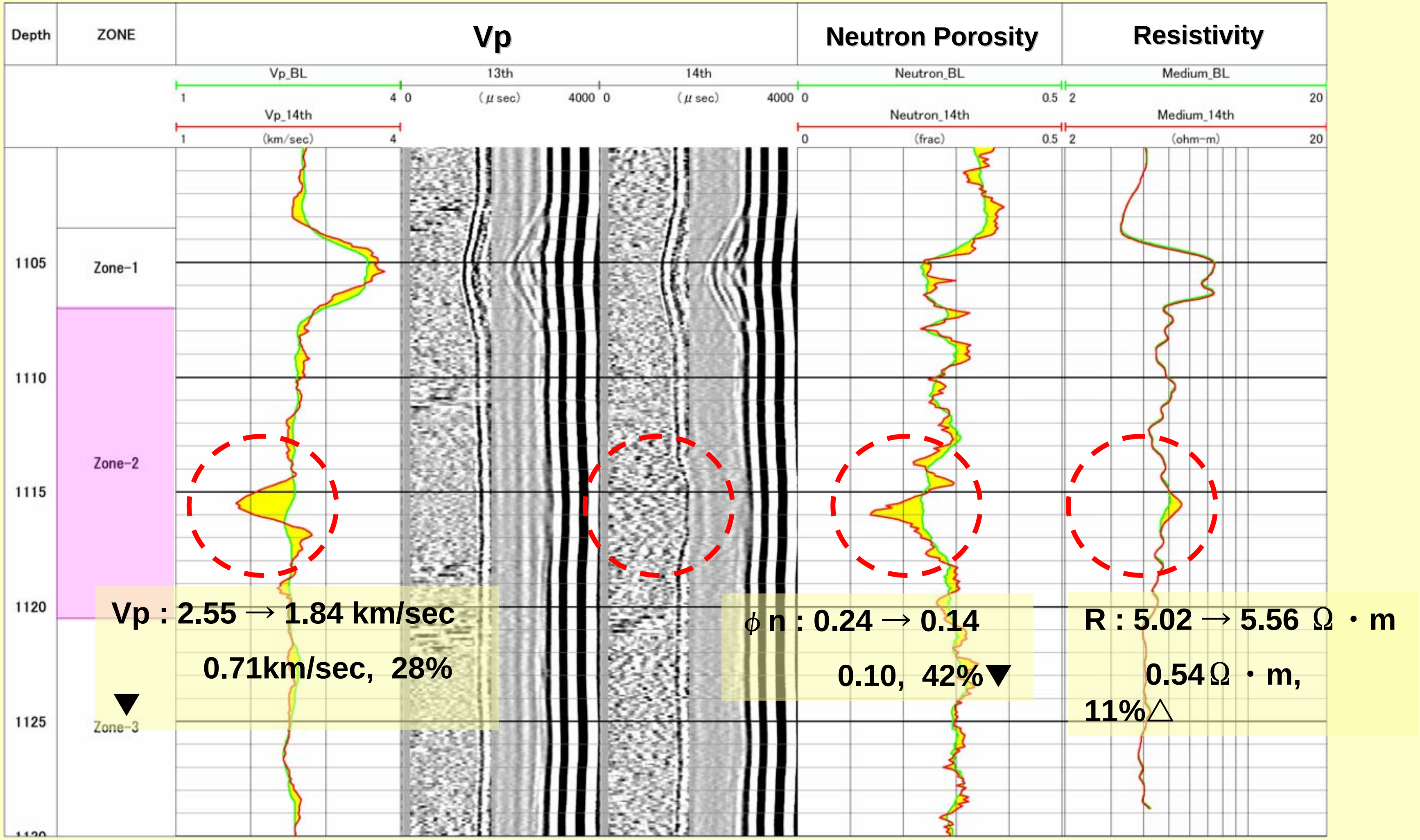
No Big Change after Breakthrough



No Change by Now

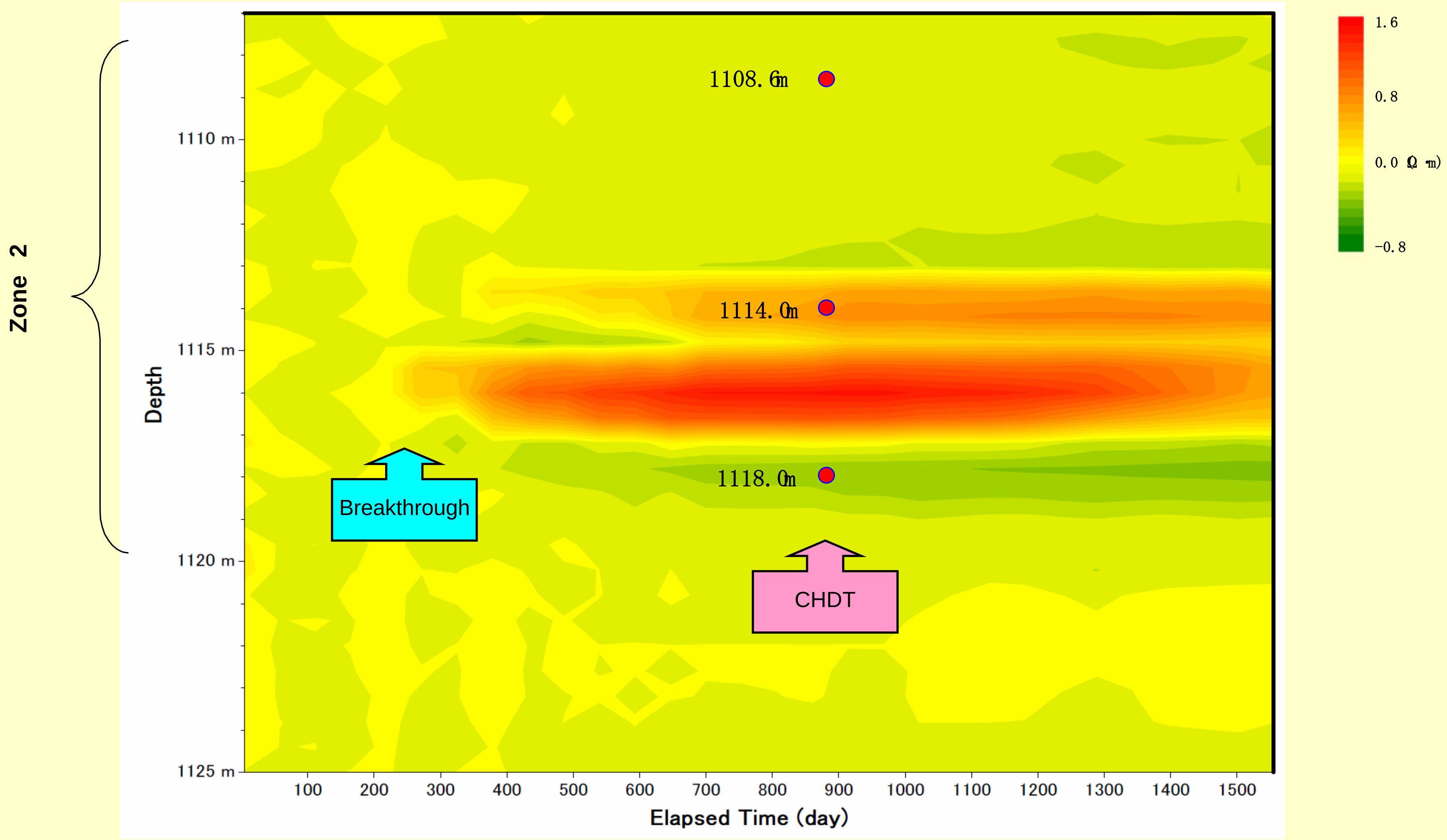
- **Induction Log**
- **Neutron Log**
- **Acoustic Log**
- **Gamma Ray Log**

CO_2 Breakthrough at OB-2

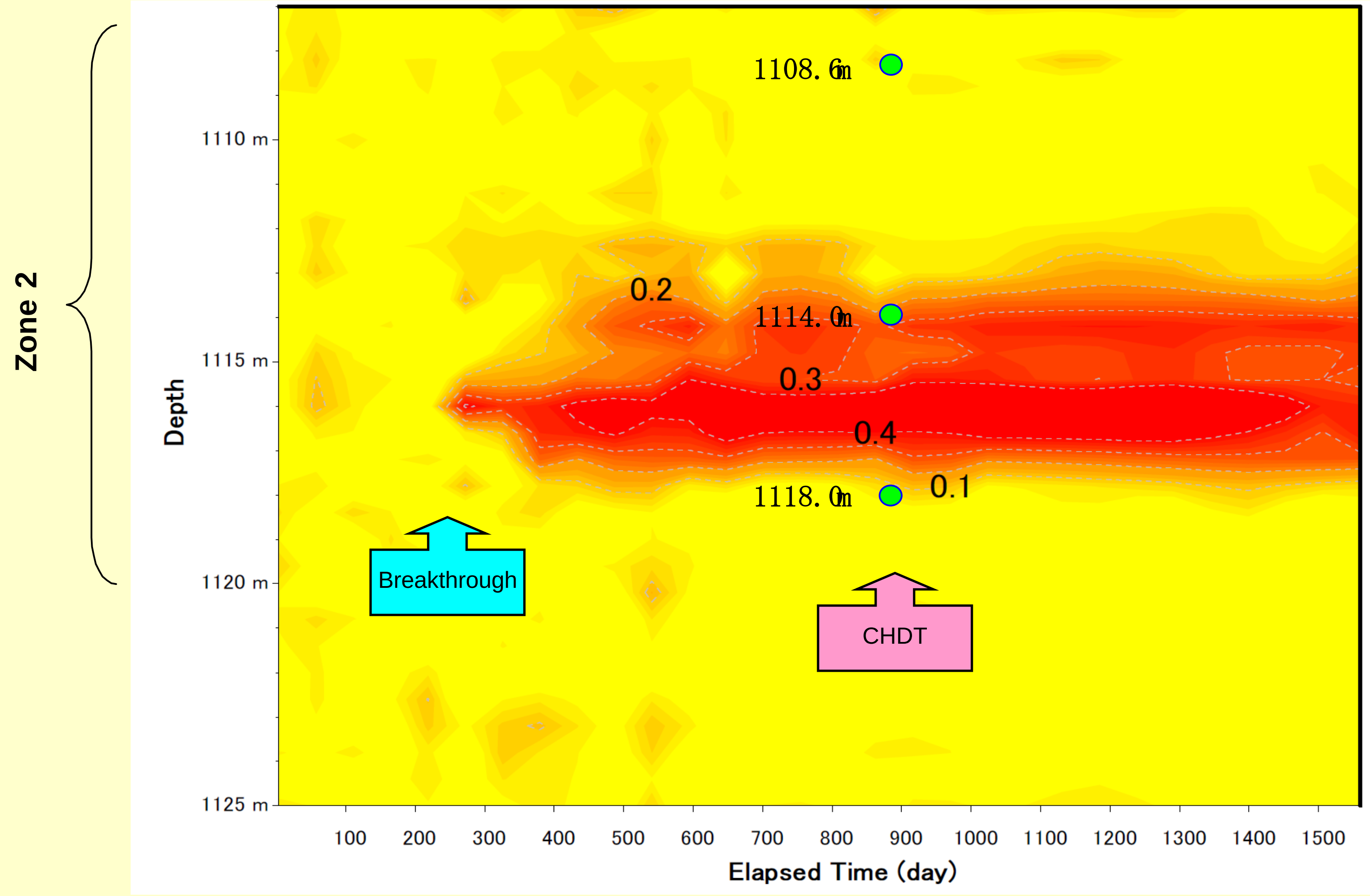


Feb. 12. 2004 ⇨ Mar. 10. 2004

Change of Resistivity at OB-2 and Sampling Points



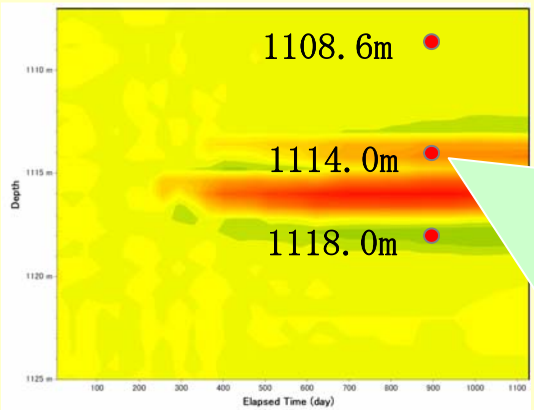
History of CO_2 Saturation at OB-2 and Sampling Points



CHDT Result

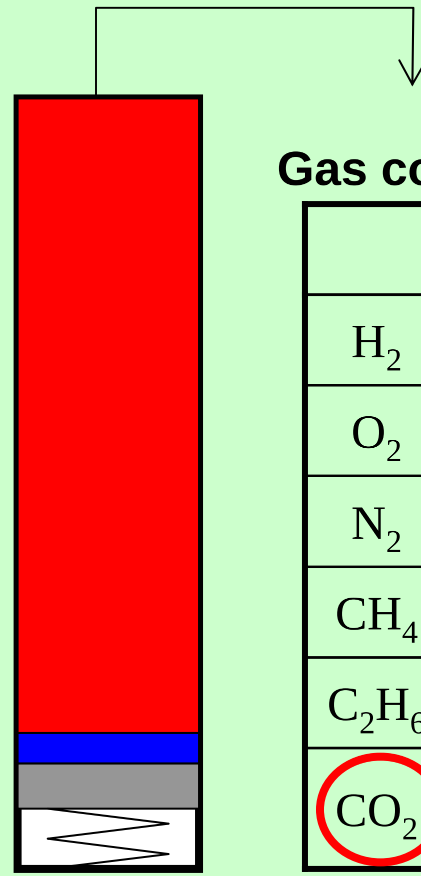
Fluid sampling

OB-2 1114m ： Mostly free CO_2



Gas:
≒3,500ml

Water:
50ml - 280ml
(Contamination 96%)



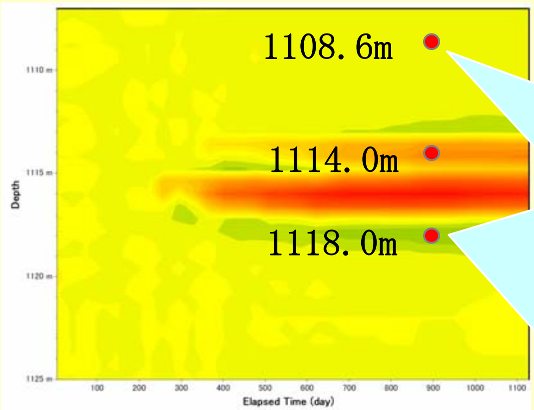
Gas composition

	mol%
H_2	0.00
O_2	0.20
N_2	0.75
CH_4	0.27
C_2H_6	0.00
CO_2	**98.78**

Sample Chamber
(volume 3,786ml)

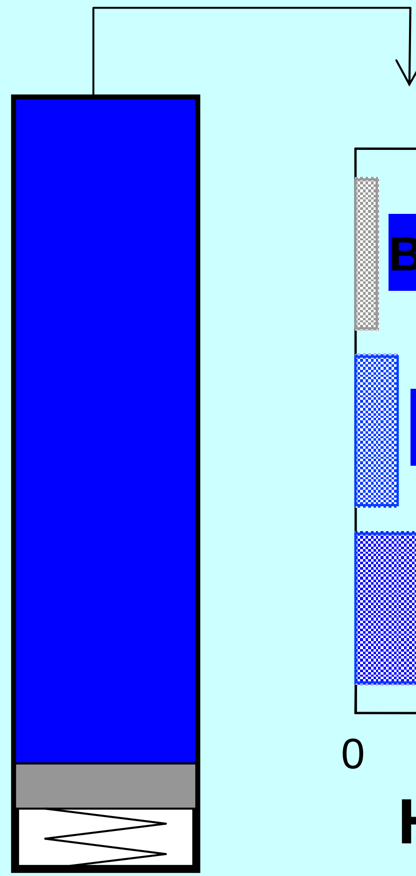
Fluid sampling

OB-2 1108.6m & 1118m : Water

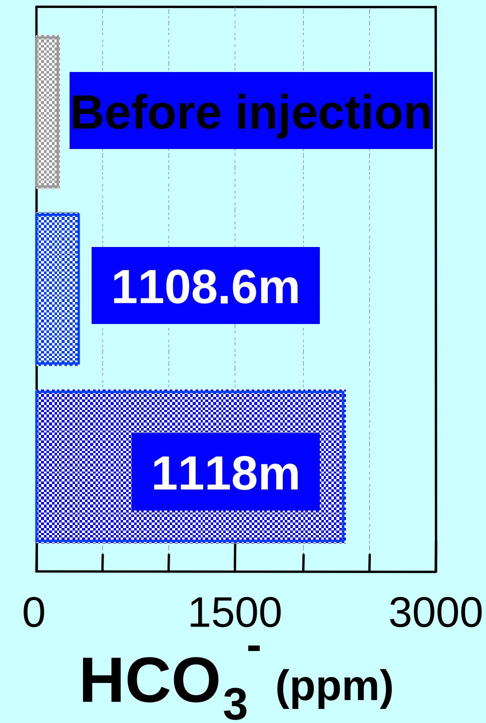


Gas:
None

Water:
3430ml
-3540ml
(Contamination <1%)



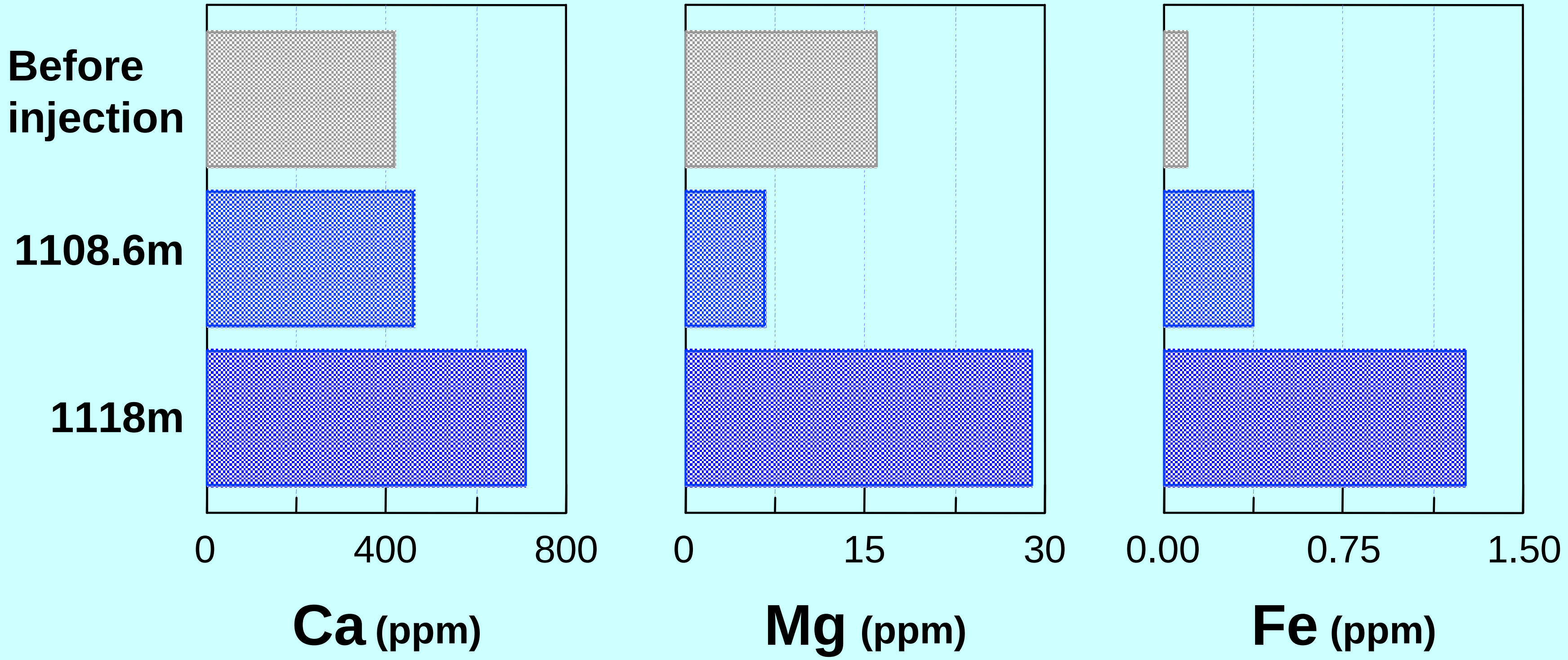
Sample Chamber
(volume 3,786ml)



At 1118m, formation water rich in dissolved CO_2.

Fluid sampling

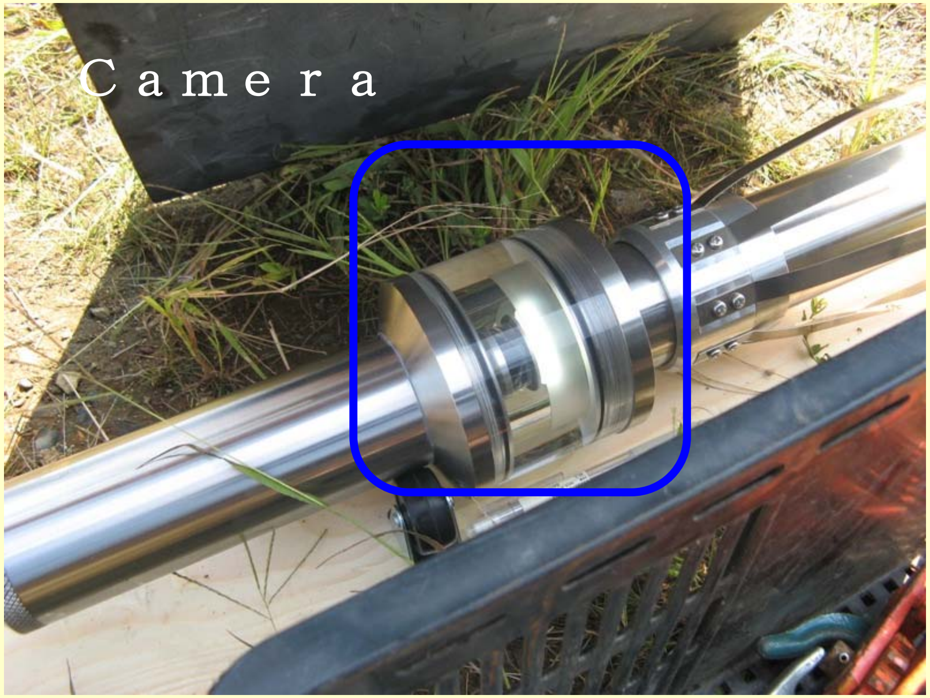
OB-2 1108.6m & 1118m : Ca, Mg & Fe



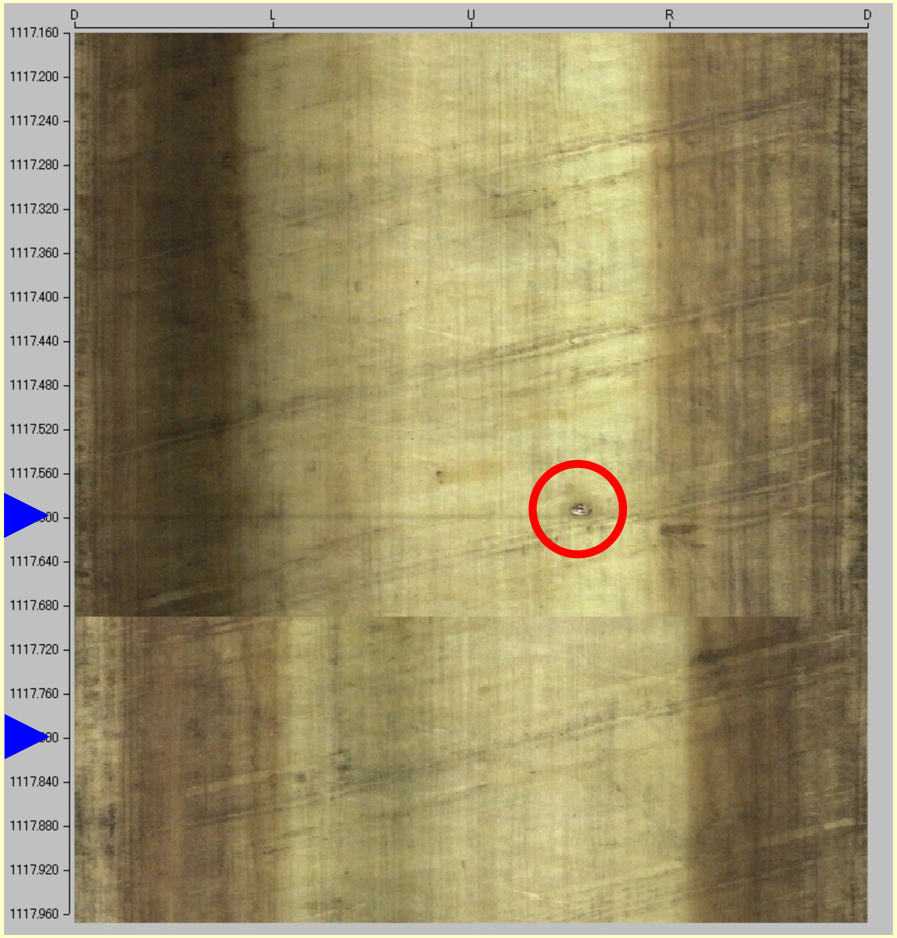
At the depth of 1118m (HCO_3^- conc. increased), concentrations of Ca, Mg and Fe also increased.

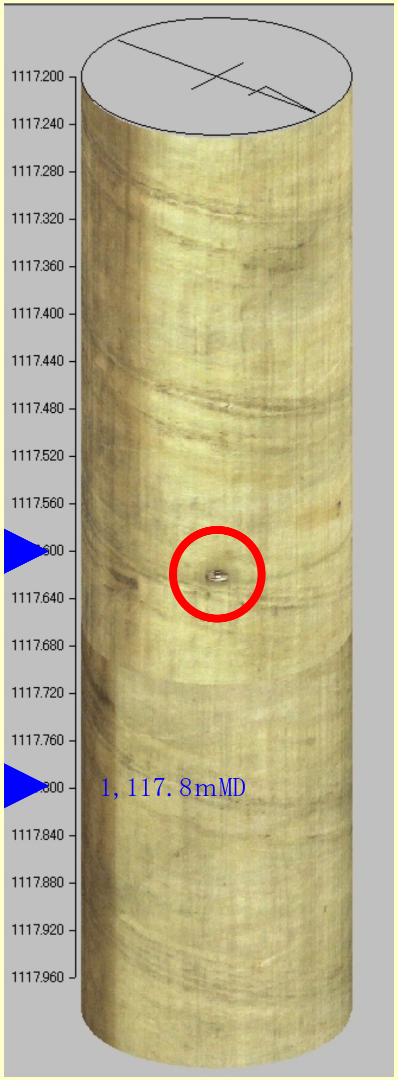
BHTV Result

ＢＨＴＶ（Optical)



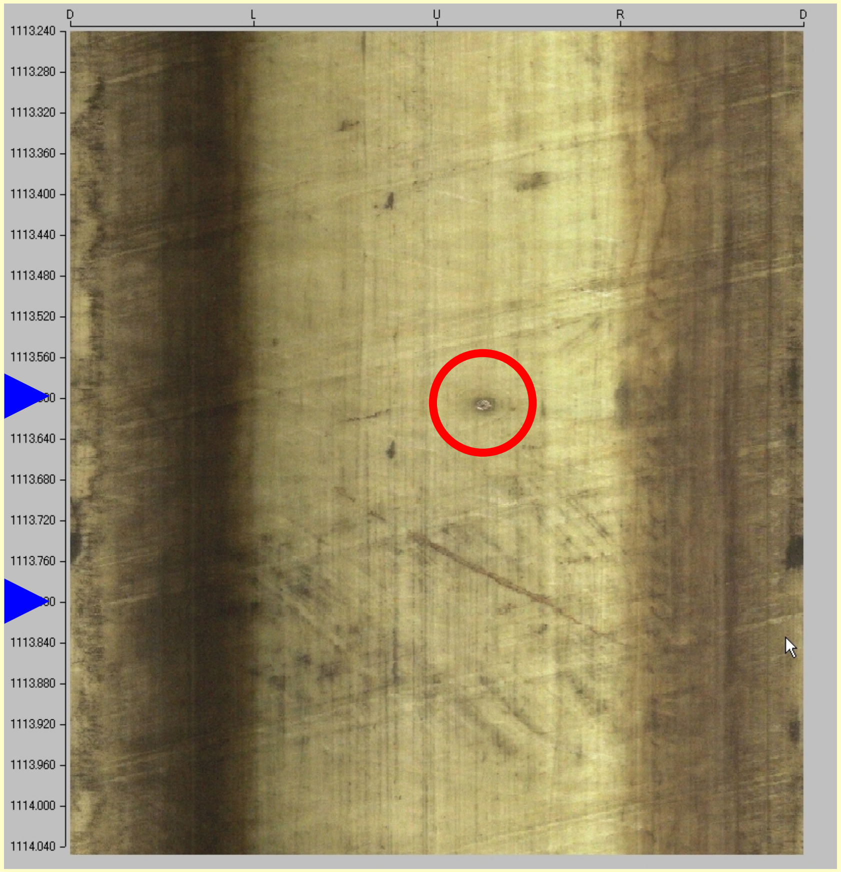
ＢＨＴＶ（**Optical) at depth of CHDT 1**

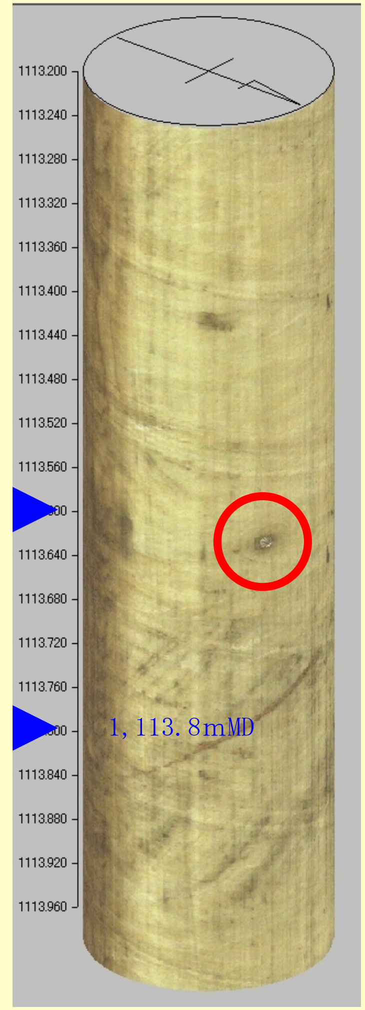




1118m

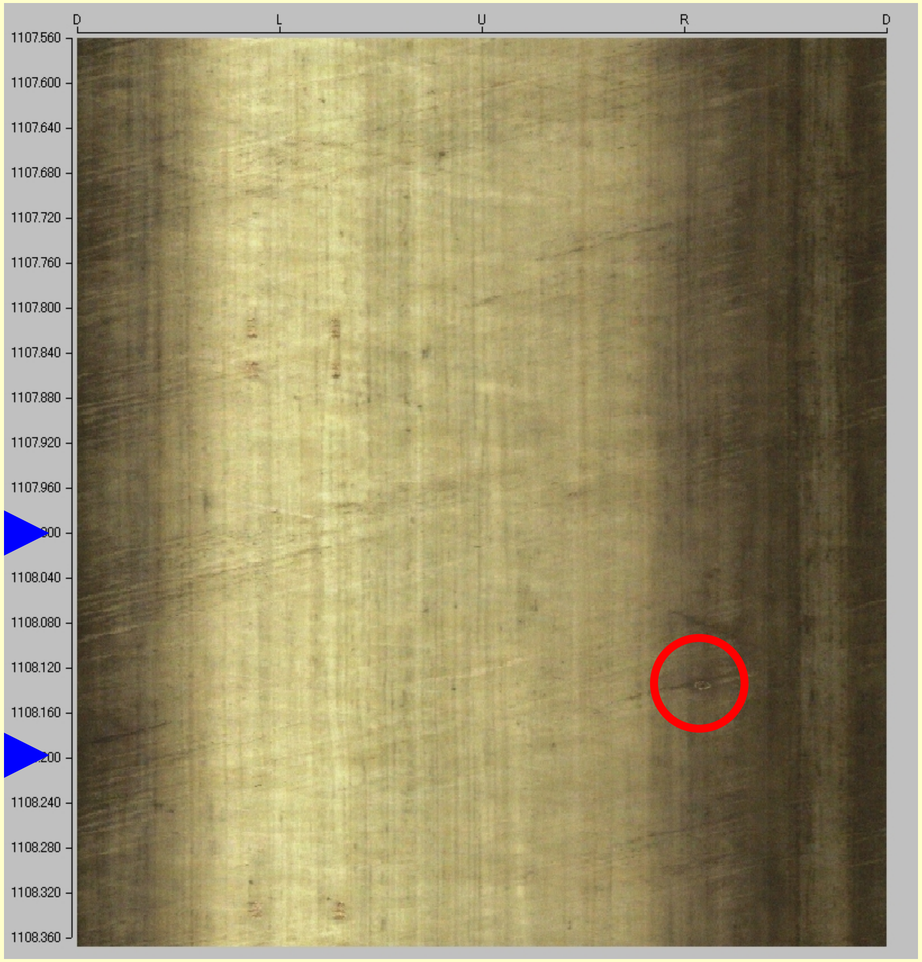
ＢＨＴＶ（Optical) at depth of CHDT 2

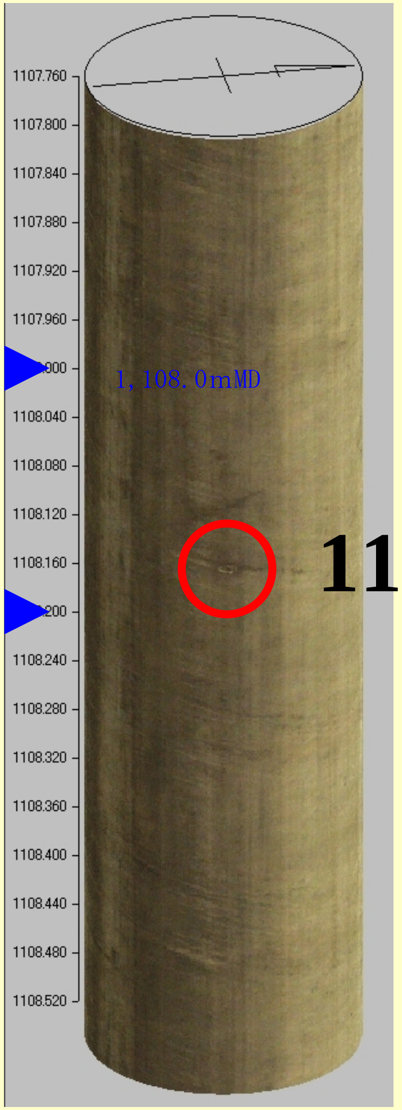




1114m

ＢＨＴＶ（Optical) at depth of CHDT 3

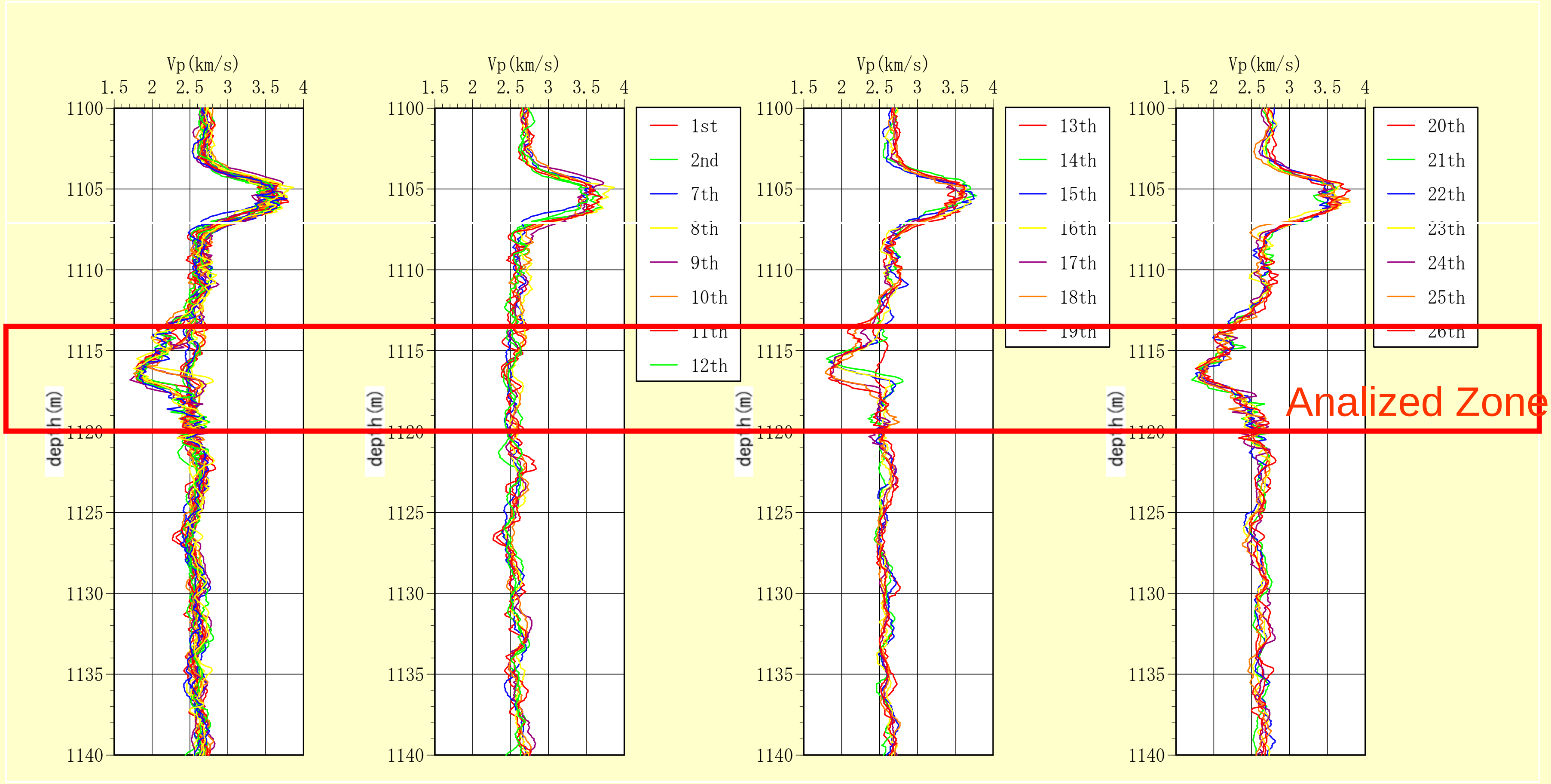




1108.6m

CO_2 saturation

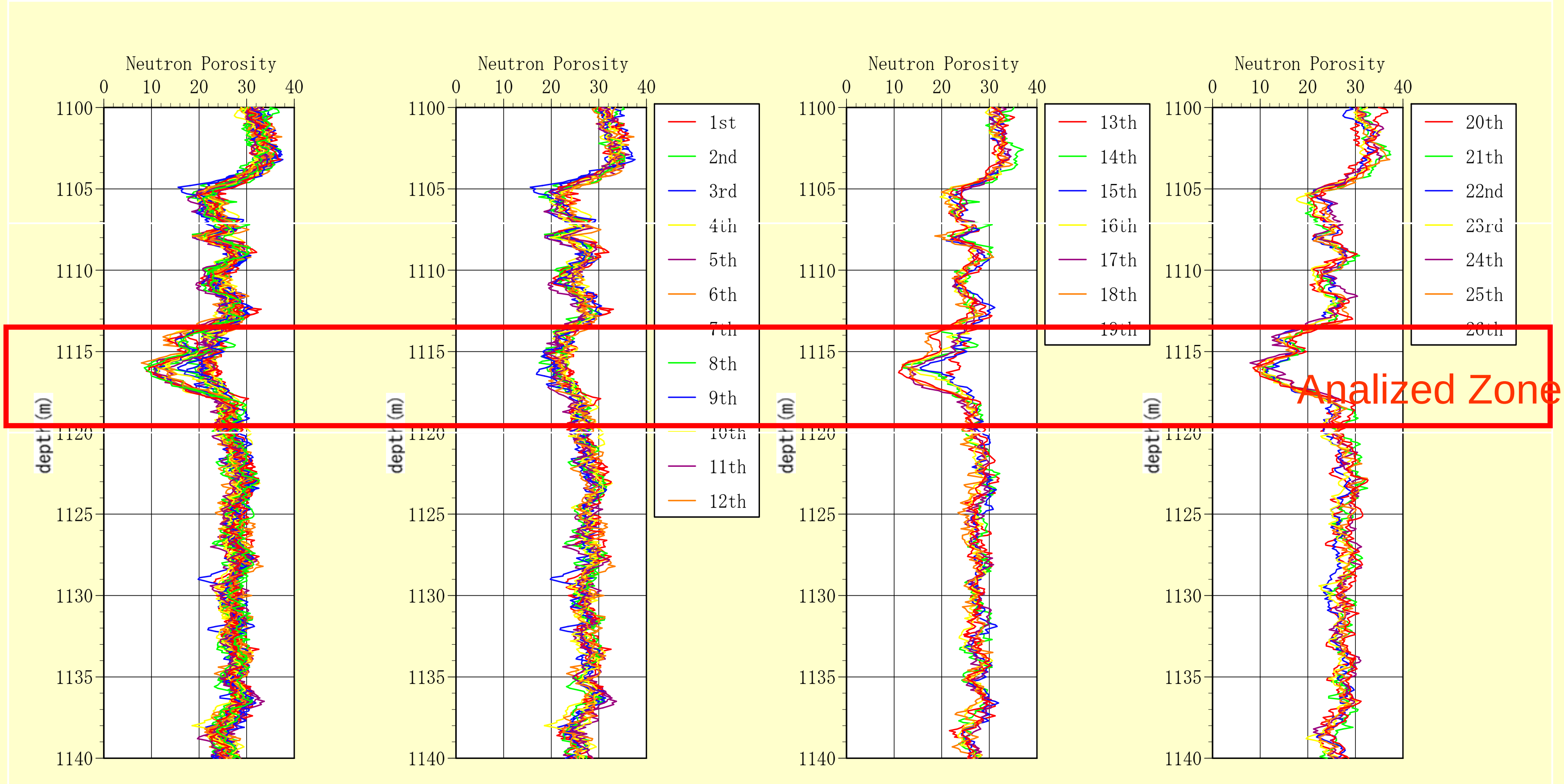
Sonic Velocity（OB-2）



All data | 1-12th data | 13-19th data | 20-26th data

<u>At 14th ,observed for CO2 arrival</u>

Neutron Porosity (OB-2)



All data

1-12th data

13-19th data

20-26th data

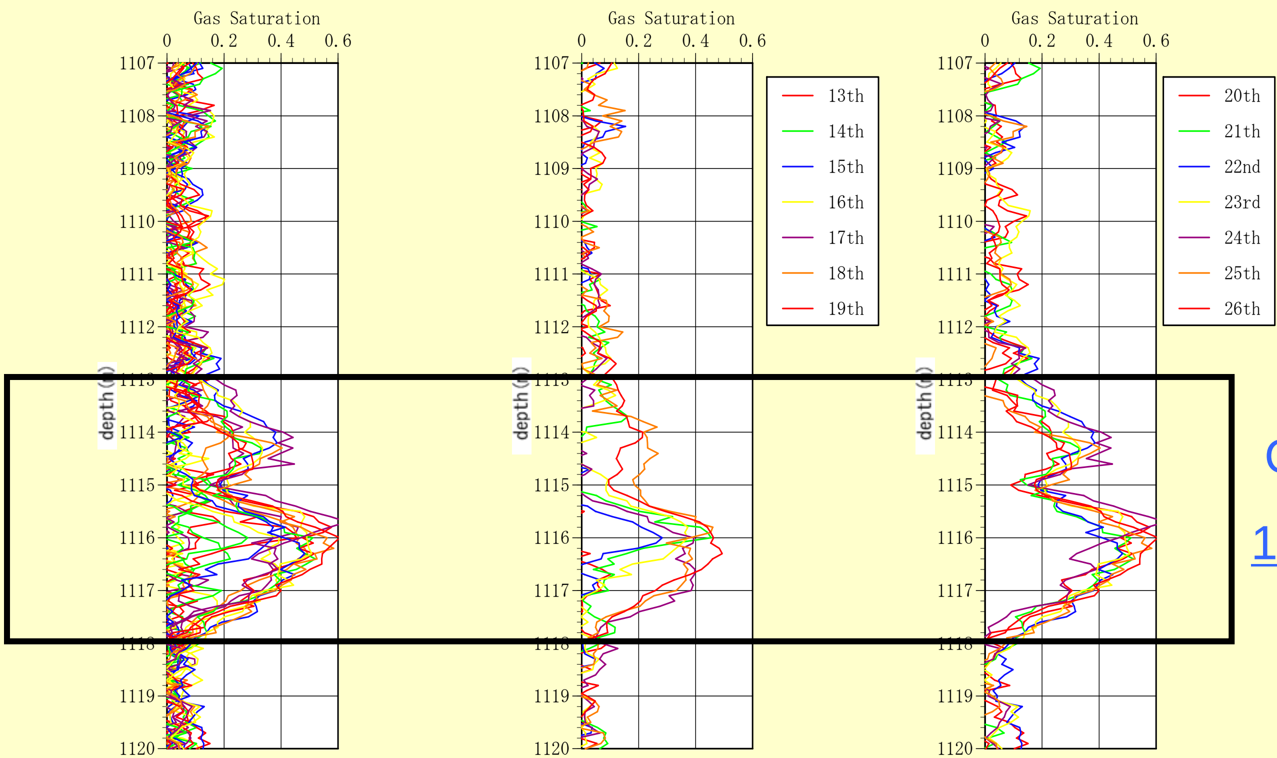
At 14th ,observed for CO2 arrival

CO2 Saturation from Neutron log

Porosity at base line log : ϕ_b

Porosity after CO2 injection : ϕ_m

CO2 Saturation : $S_{CO2} = \dfrac{\phi_b - \phi_m}{\phi_b}$



Changed Zone

1113～1118m

All data | 13-19th data | 20-26th data

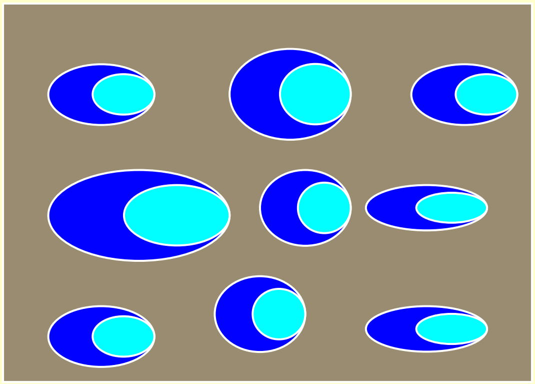
Modeling and Calculation

- Determining Skeleton rock modulus from Rock physics model
  - friable-sand model (Dvorkin and Nur(1996))
- Substitution fluid for Gassmann theory

<Gassmann formula>

$$\frac{K_{sat}}{K_{mineral} - K_{sat}} = \frac{K_{dry}}{K_{mineral} - K_{dry}} + \frac{K_{fluid}}{\phi\left(K_{mineral} - K_{fluid}\right)}$$

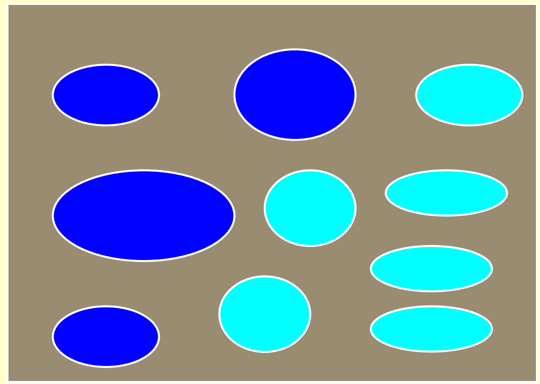
Three state of CO2 saturation



Uniform saturation

All pores have same saturation

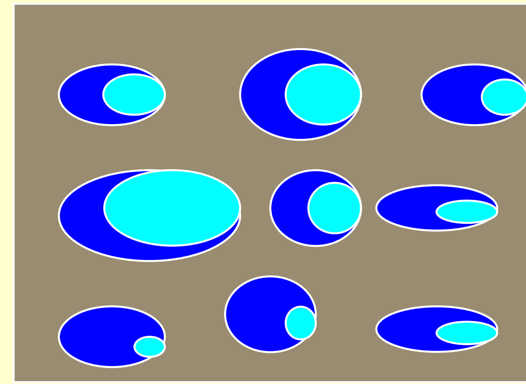
$$\frac{1}{K_{fl}} = \frac{S_{gas}}{K_{gas}} + \frac{S_{water}}{K_{water}}$$



Patchy saturation

Partially saturation

$$\frac{1}{K} = \frac{V_{water}}{Kpart_{water}} + \frac{V_{gas}}{Kpart_{gas}}$$



Patchy (fluid) saturation

Several pores have different saturation

$$K_{fl} = S_{gas} K_{gas} + S_{water} K_{water}$$

Brie empirical fluid mixing equation

$$K_{fl} = S_{water}^{e} K_{water} + (1 - S_{water}^{e}) K_{gas}$$

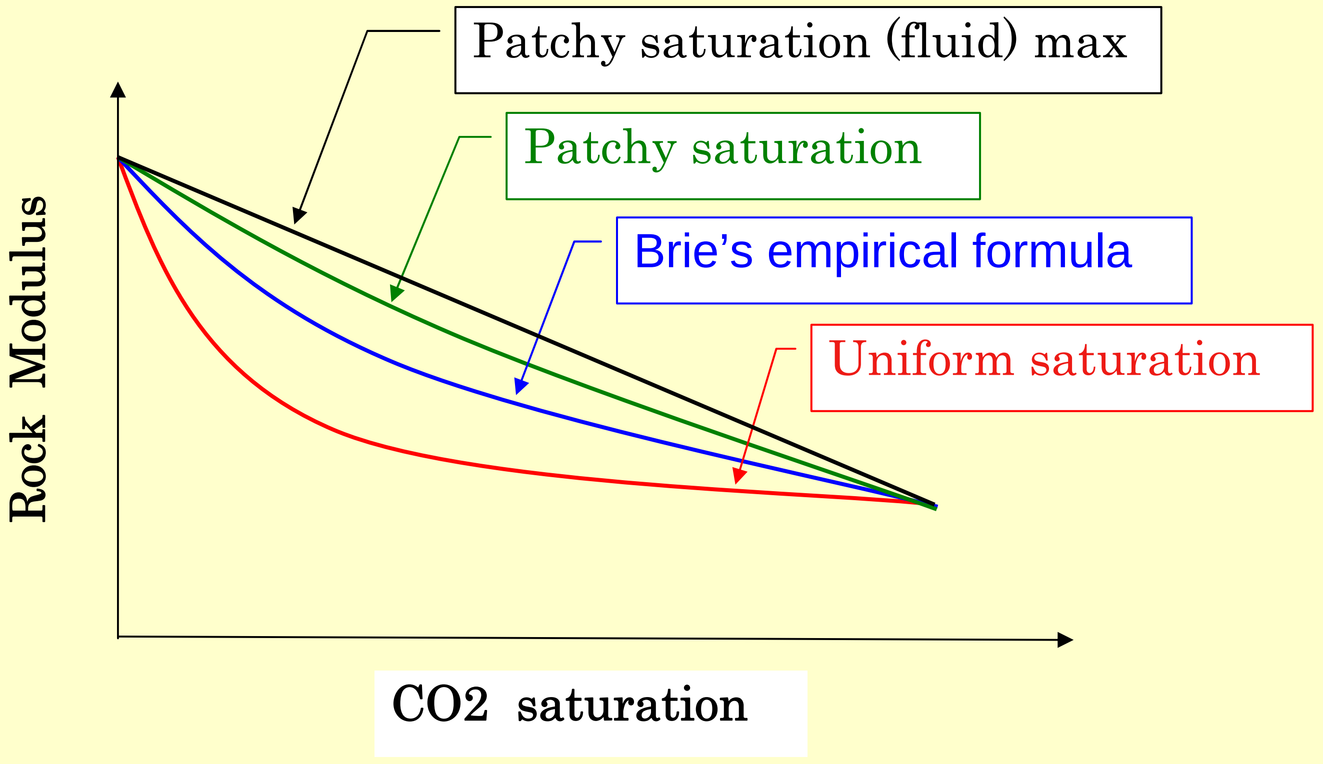
The e is empirical coefficient.

$$K_{fl} = S_{gas} K_{gas} + S_{water} K_{water} \qquad (e=1)$$

$$1/K_{fl} = V_{water}/K_{water} + V_{gas}/K_{gas} \qquad (e=\infty)$$

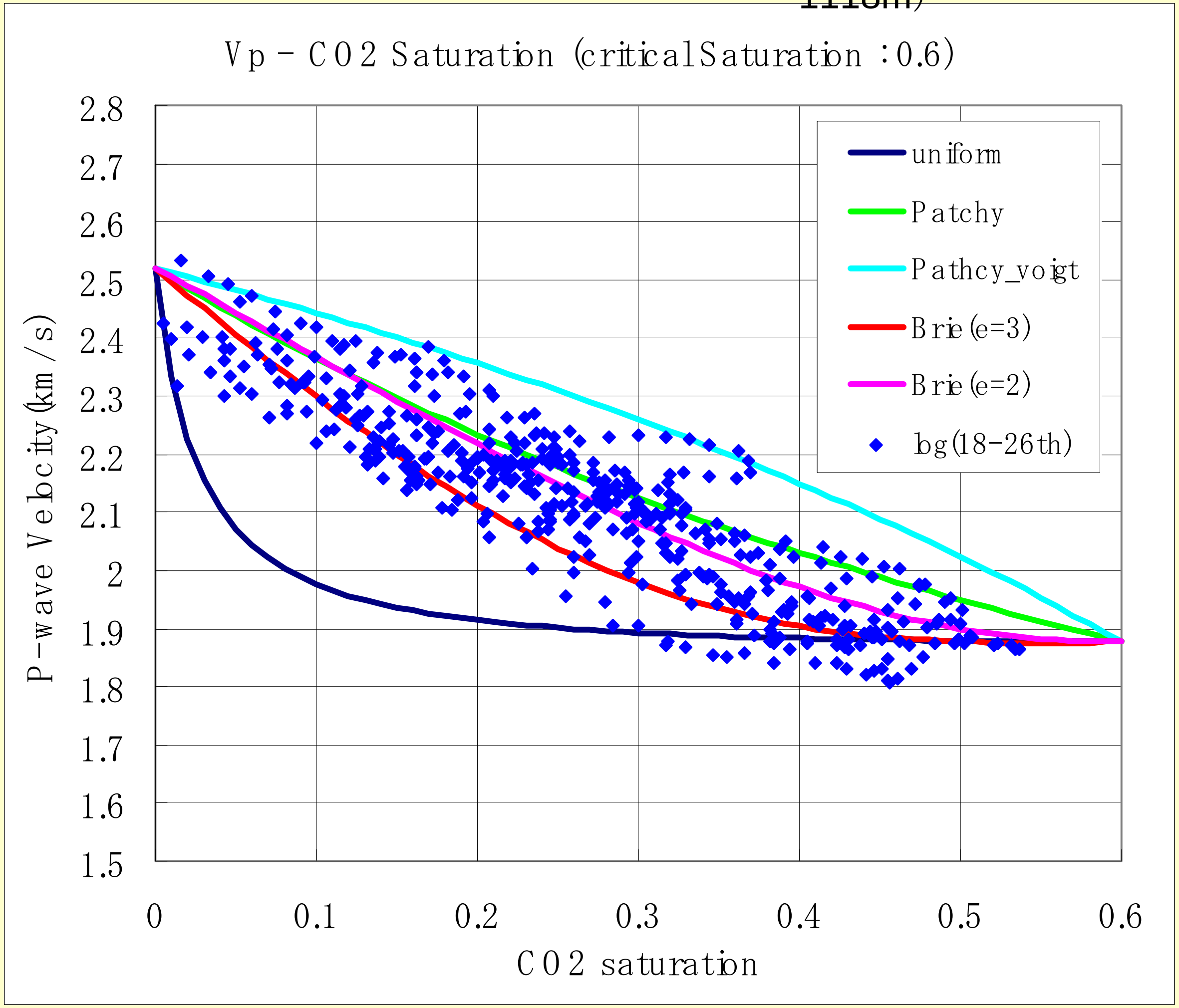
Brie .et.(1995):Shear sonic interpretation in gas bearing sands, Proc,SPE

Schematic diagram of three state saturation



Comparison model calculation and observed data

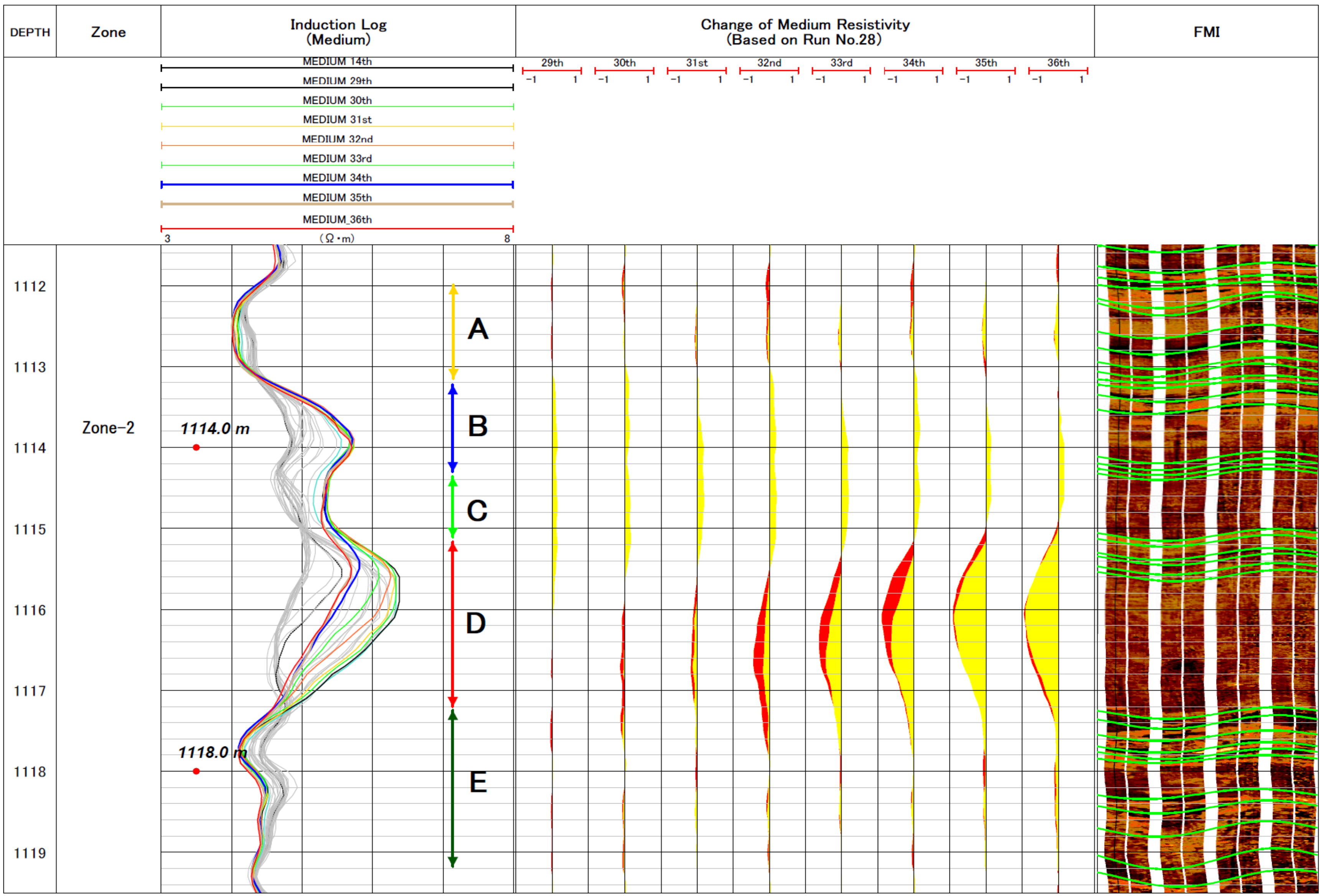
（from Friable-Sand model、1113－1118m）



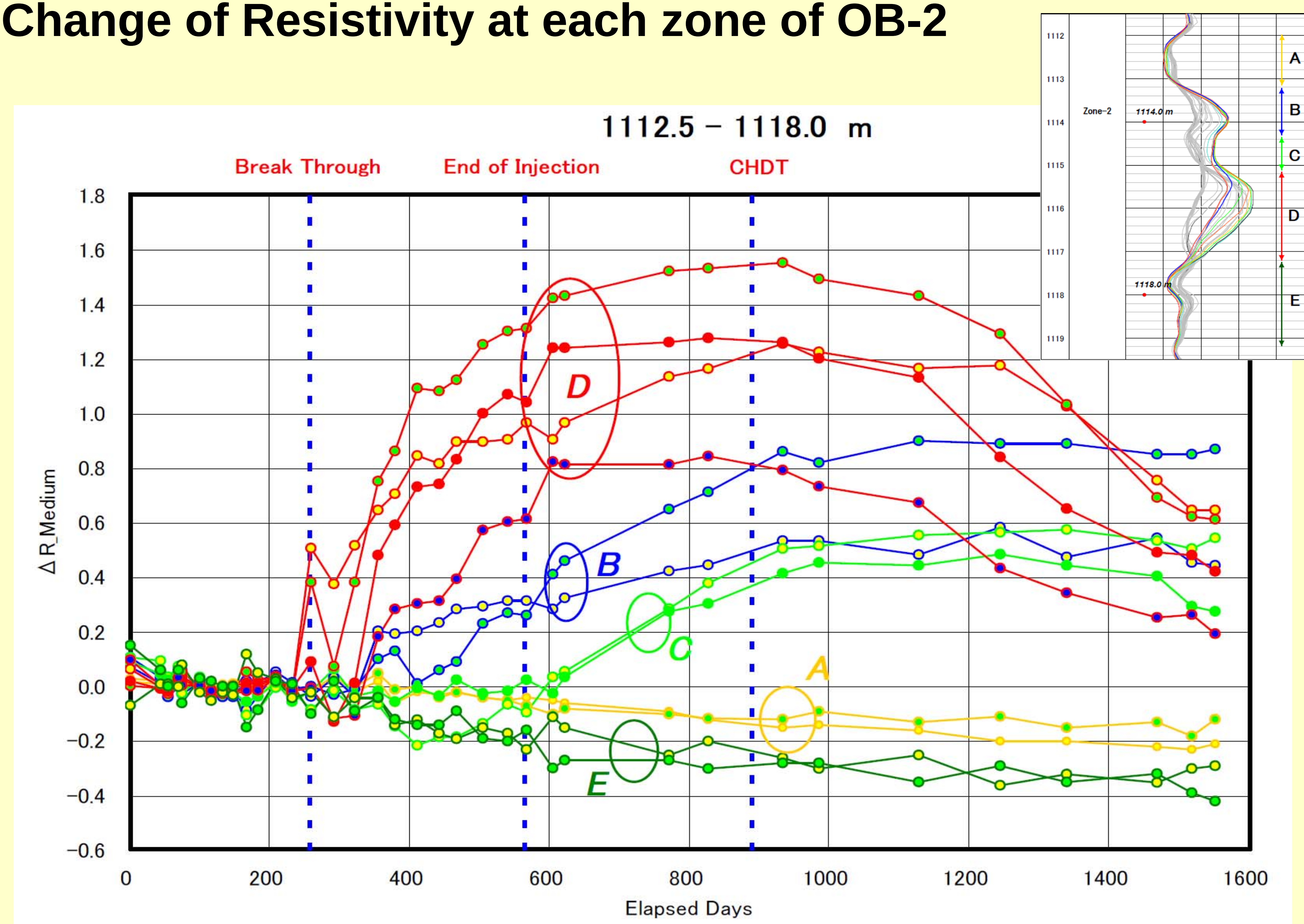
Good agreement with Patchy and Brie model

Movement of CO2 after CHDT

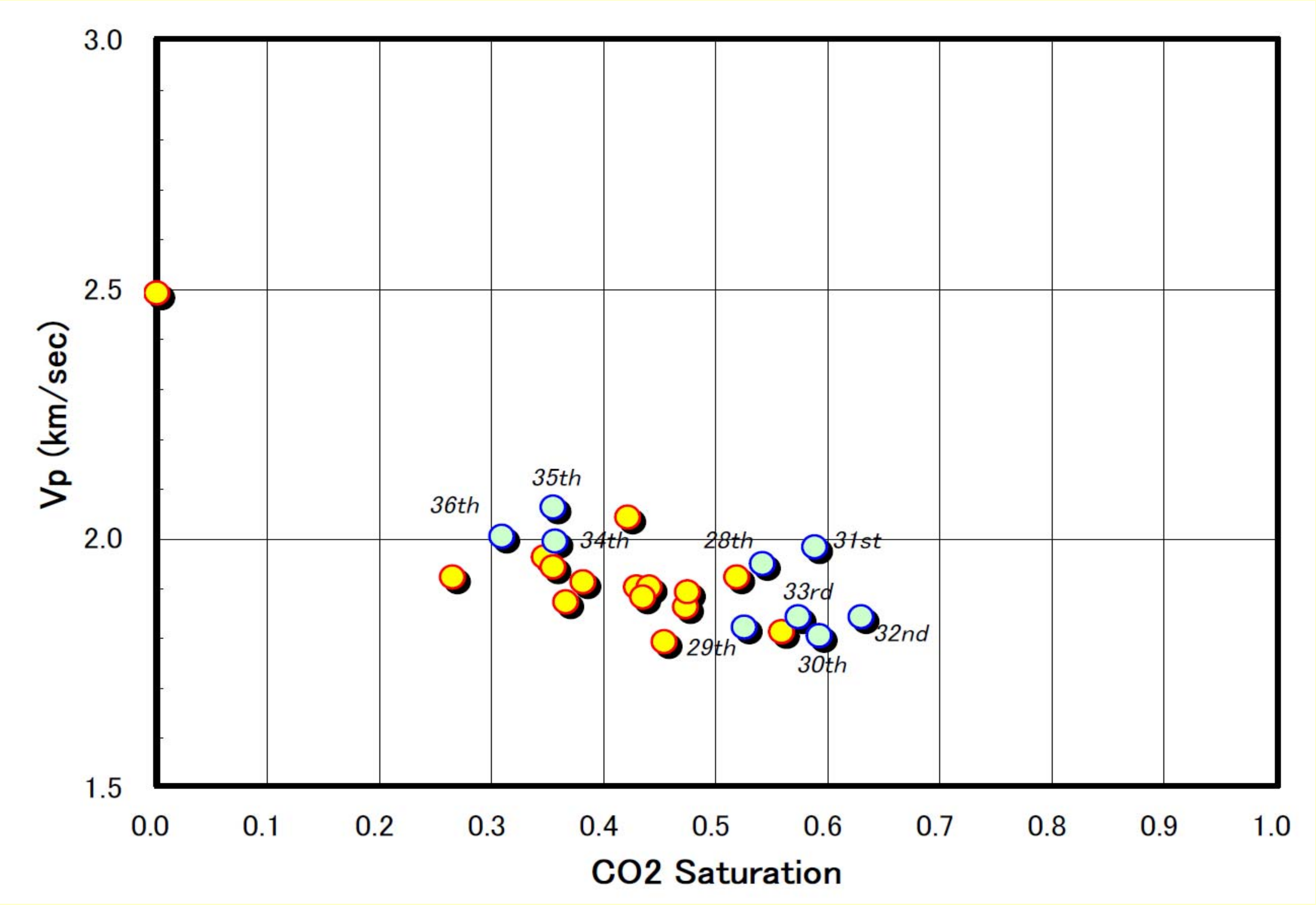
Change of Resistivity at OB-2 between 29th-36th



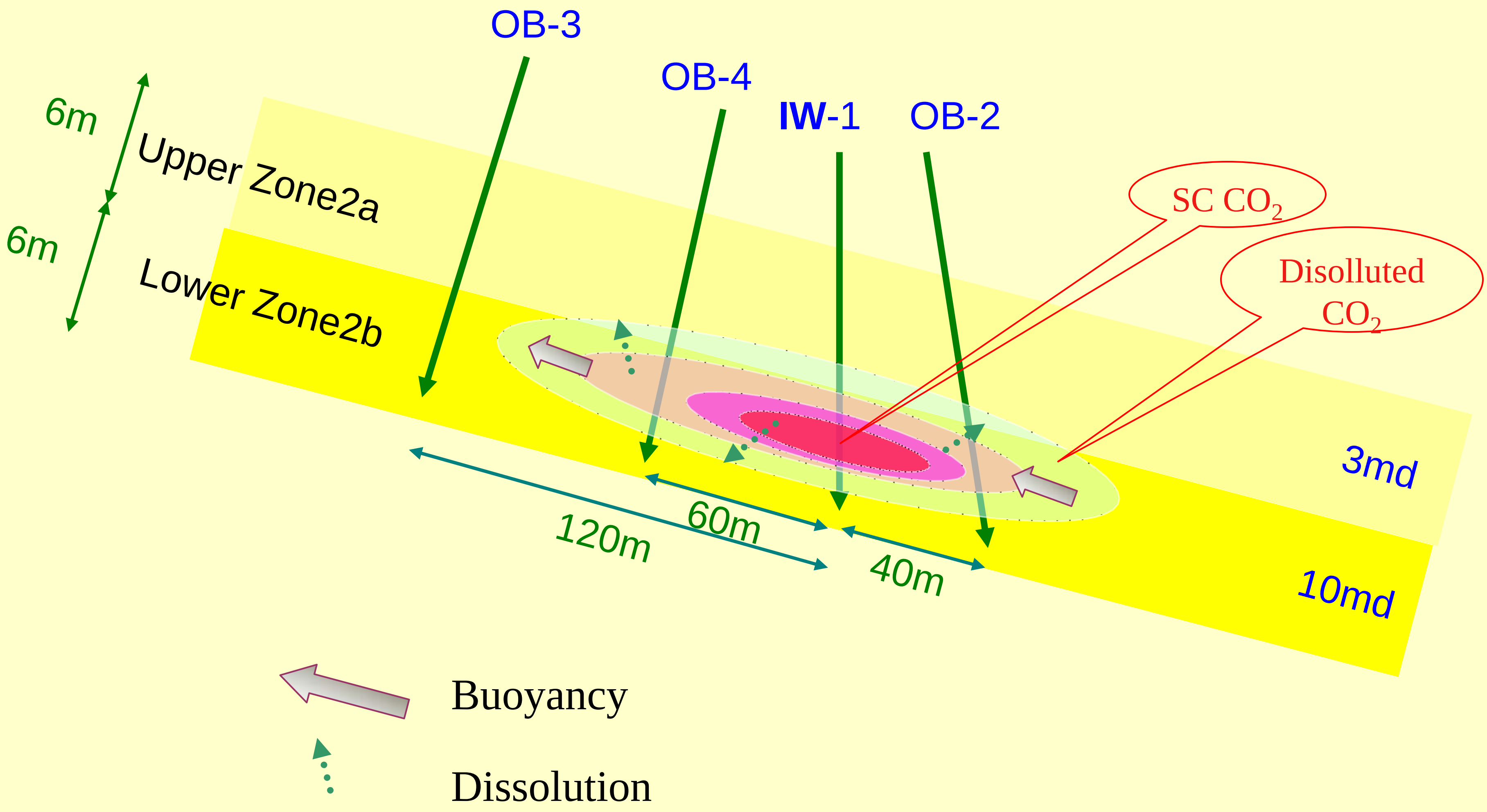
Change of Resistivity at each zone of OB-2



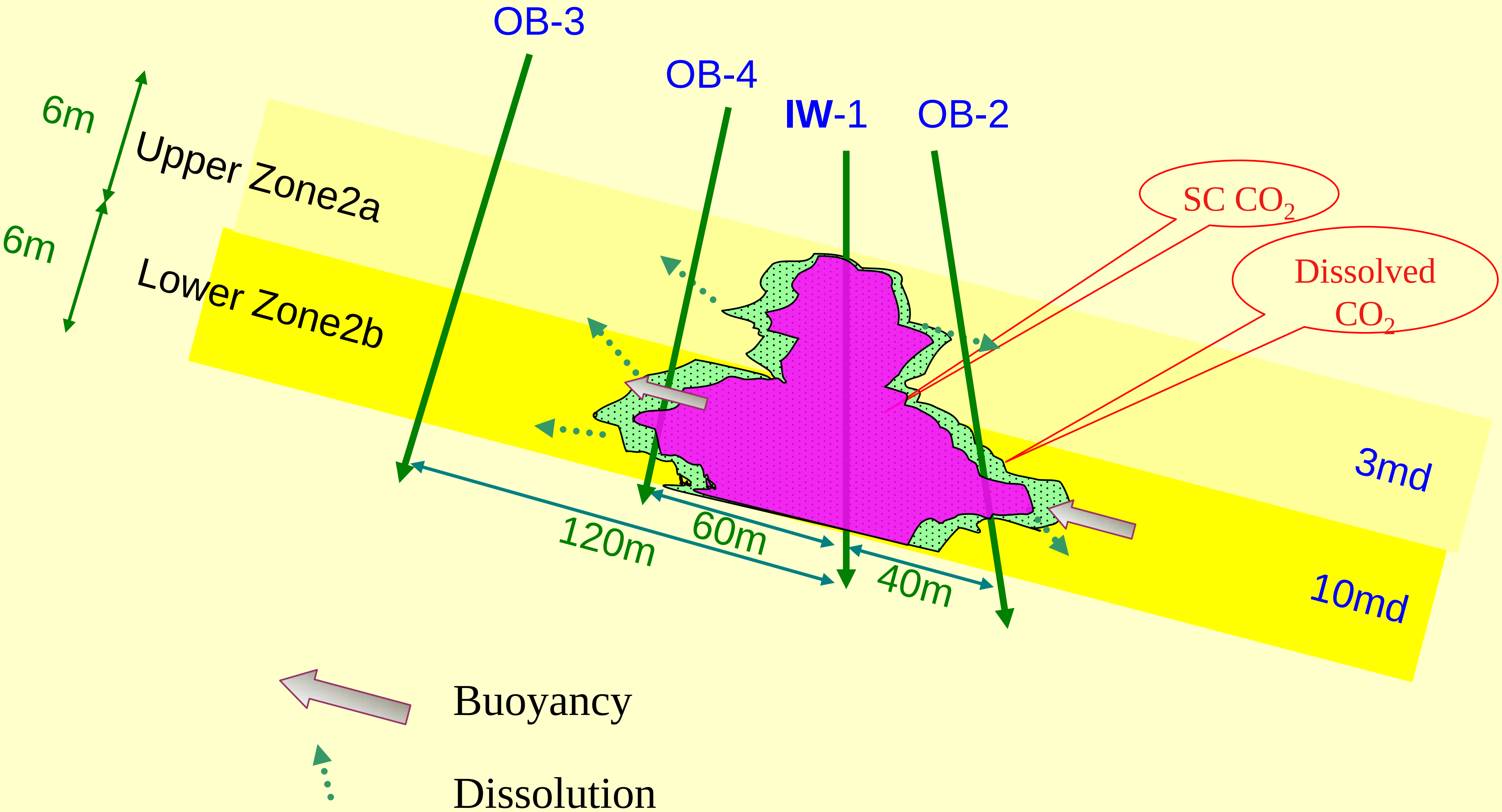
Vp- CO2 Saturation at OB-2 (1116m depth)



CO_2 Movement Model(1)



CO_2 Movement Model(2)



Dissolution and Mineral trapping of CO_2 in saline aquifers

Host rock

Gas trapping

$CO_2(sc)$

Clay minerals

Feldspar

Formation water

Dissolution

$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3$

$\rightleftharpoons$

$H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$

+ Cation (Ca^{2+}, Mg^{2+}, Fe^{2+} etc.) + H_4SiO_4

Solubility trapping

Ionic trapping

Mineral trapping

Carbonate ($CaCO_3$, $MgCO_3$, $FeCO_3$, etc.)

Additional Study Plan in 2007

- **Additional data acquisition:**
  - **Logging at the injection well IW-1 (RST and NL)**
  - **Logging at the observation well OB-2,3,4 (usual logging and CBL)**
- **History-match simulation incorporating these additional data is expected to improve our understanding of CO_2 movement and distribution.**

Summary(1)

- **Patchy Saturation**

From the relation between the velocity and CO_2 saturation rate calculated by neutron log, we concluded that the state of CO_2 saturation during CO_2 injection might be almost Patchy saturation not uniform at Nagaoka Site.

Summary(2)

- **CO_2 Movement**

  The resistivity and porosity have become decreasing one year after stopping injection of CO_2 while velocity does not increase. The reason of the decrease which was detected by time-lapse well loggings is that the distribution area of CO_2 might be shrinking by dissolution of CO_2 and moving upward because of buoyancy.

ACKNOWLEDGMENTS

The authors would like to express their most sincere gratitude to the continuous advice provided by Professor K. Sato. The project “Research and Development of Underground Storage for Carbon Dioxide” is funded by Ministry Economy, Trade and Industry (METI) of Japan under the contract of between RITE and METI. ENAA, in the process of conducting the field test of CO2 injection as a branch office of RITE, owed much to RITE staff members for their enthusiastic involvement and assistance.

MMV Experience and Preparations for Deep Saline Reservoir Injection in the Illinois Basin

prepared by
Robert J. Finley
and the MGSC Project Team
Illinois State Geological Survey

IEA Monitoring Network
Edmonton, Alberta
8 November 2007

Midwest Geological Sequestration Consortium

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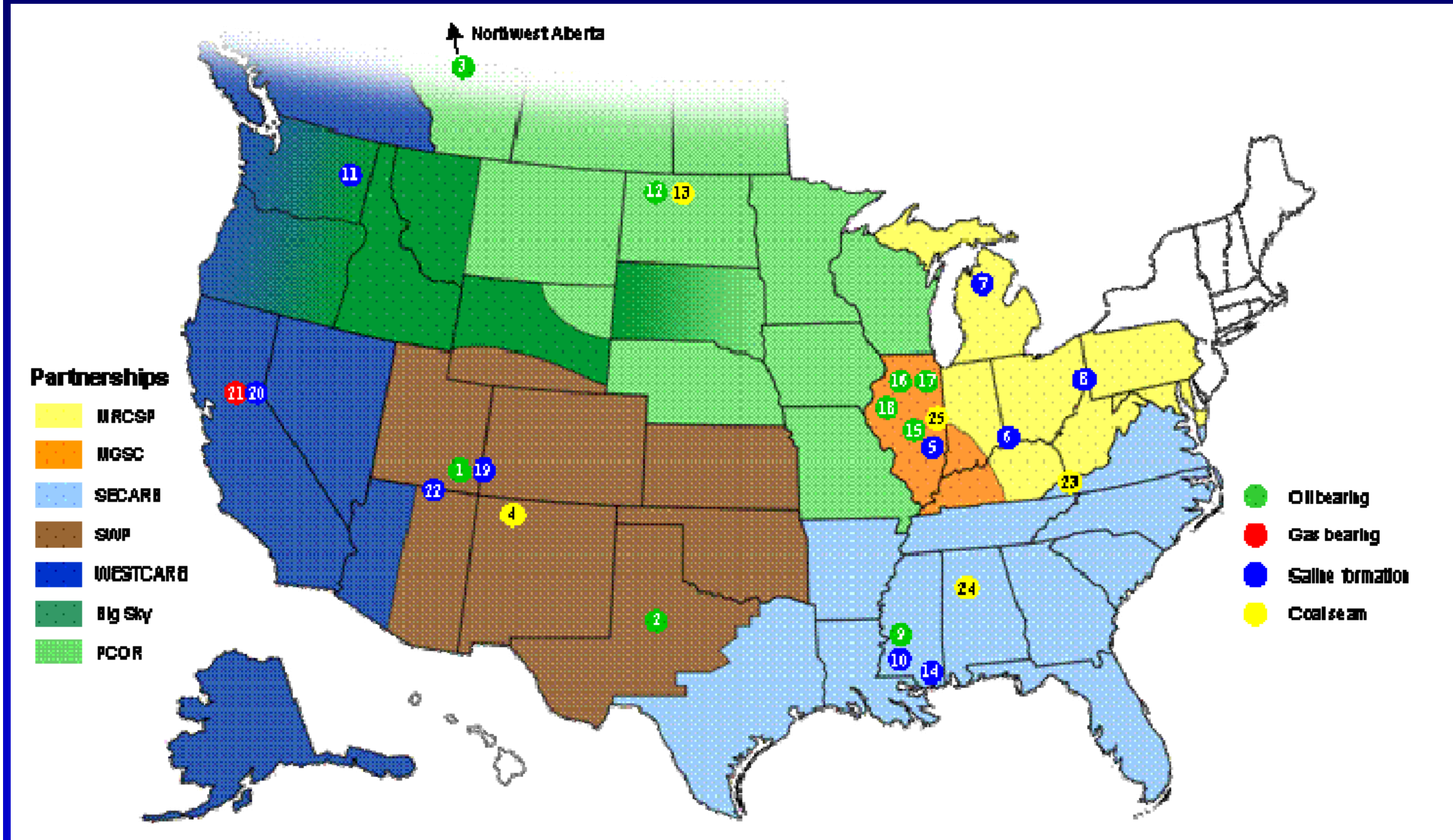
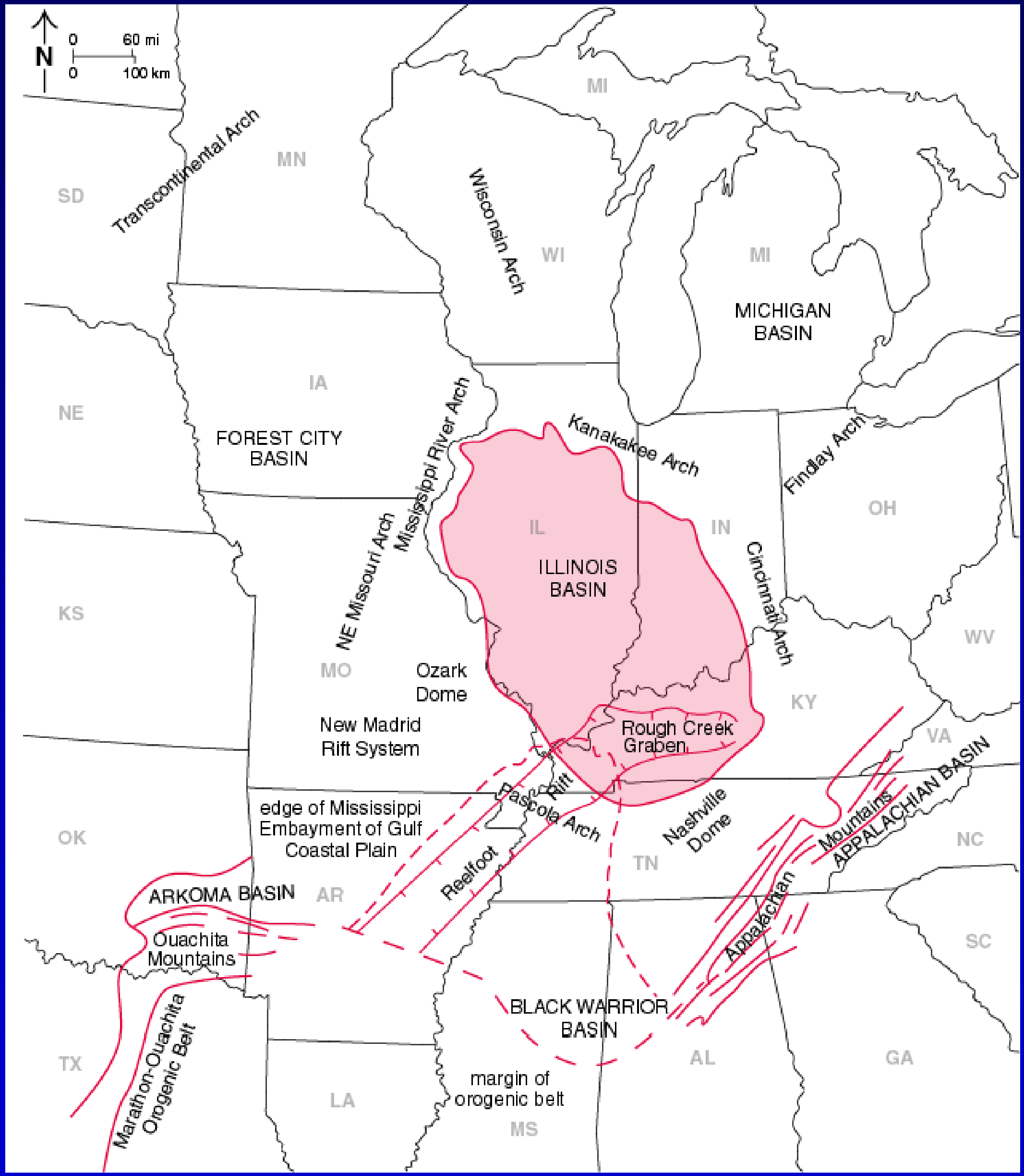
- The MGSC is a collaboration led by the geological surveys of Illinois, Indiana, and Kentucky

Validation Phase Field Tests

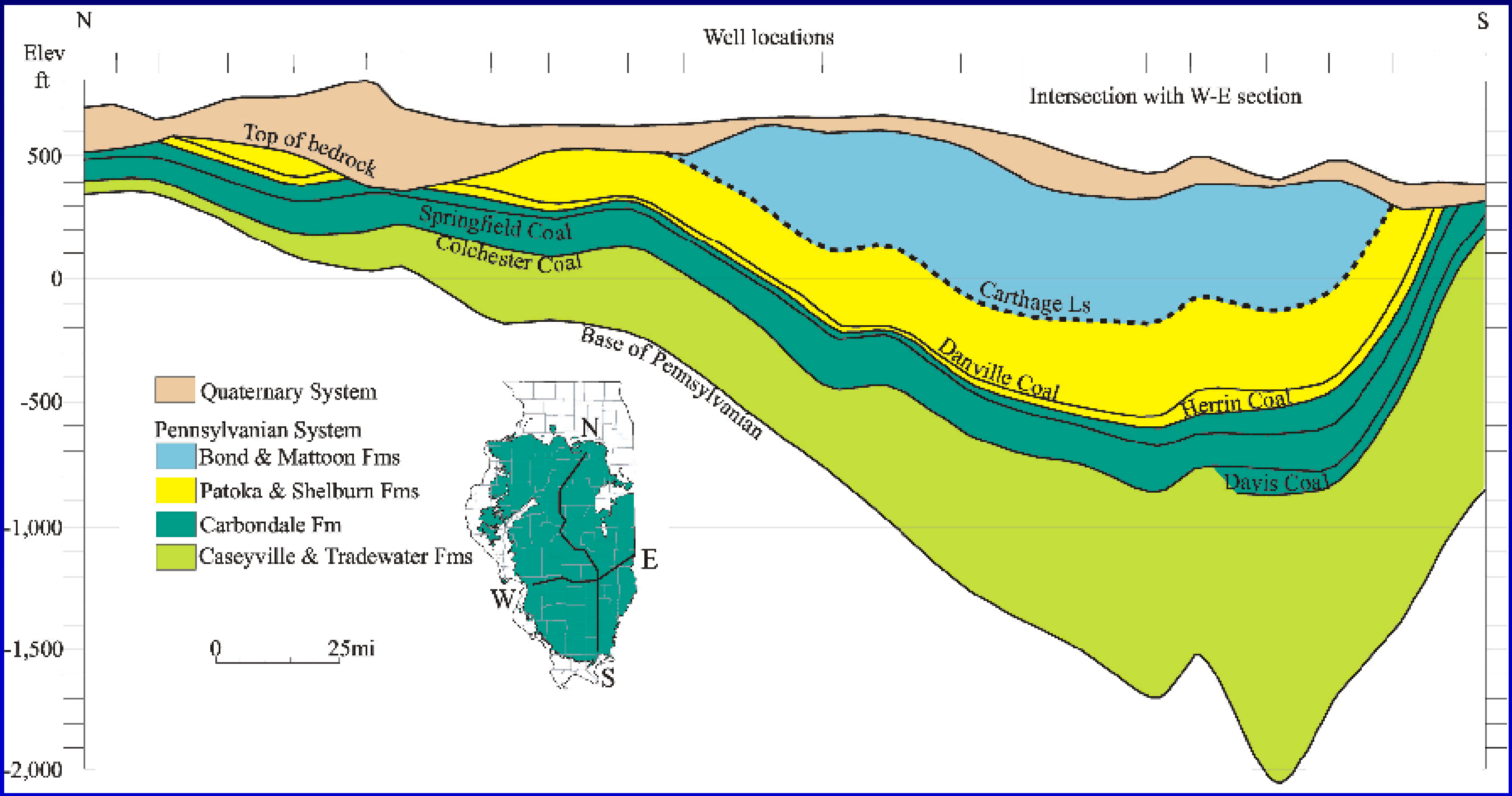
Geologic Field Test Sites



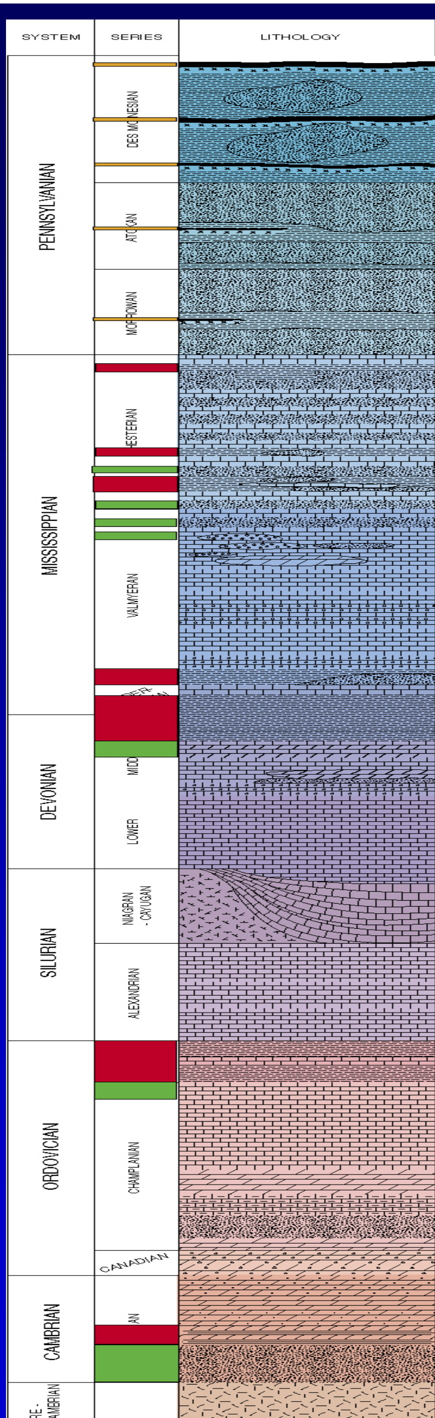
Illinois Basin



N-S Cross Section of Coal-bearing Strata in Illinois



By Christopher Korose, Jamie McBeth, and Colin Treworgy, ISGS



Pennsylvanian coal seams

Mississippian sandstone and carbonate oil reservoirs

New Albany Shale

Illinois Basin Stratigraphic Column

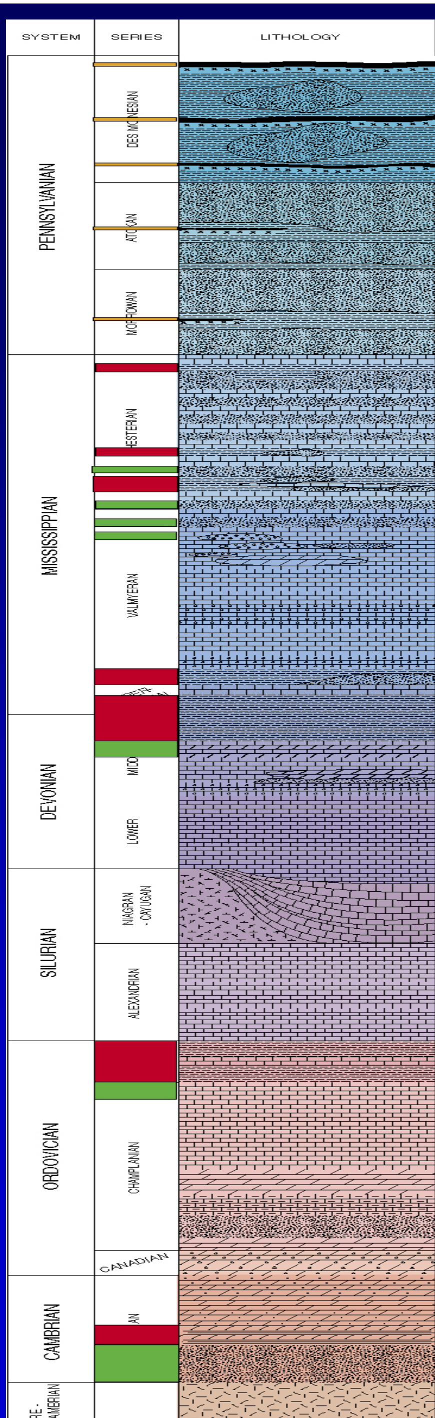
Maquoketa Shale

St. Peter Sandstone

Eau Claire Shale

Mt. Simon Sandstone

from Leetaru, 2004



Pennsylvanian coal seams

adsorption on coal

Mississippian sandstone and carbonate oil reservoirs

CO_2 EOR in mature fields

New Albany Shale

adsorption on shale

Potential Seal

Potential Sink

Coal Bed Potential Sink and Seal

Maquoketa Shale

St. Peter Sandstone

major saline reservoirs

Eau Claire Shale

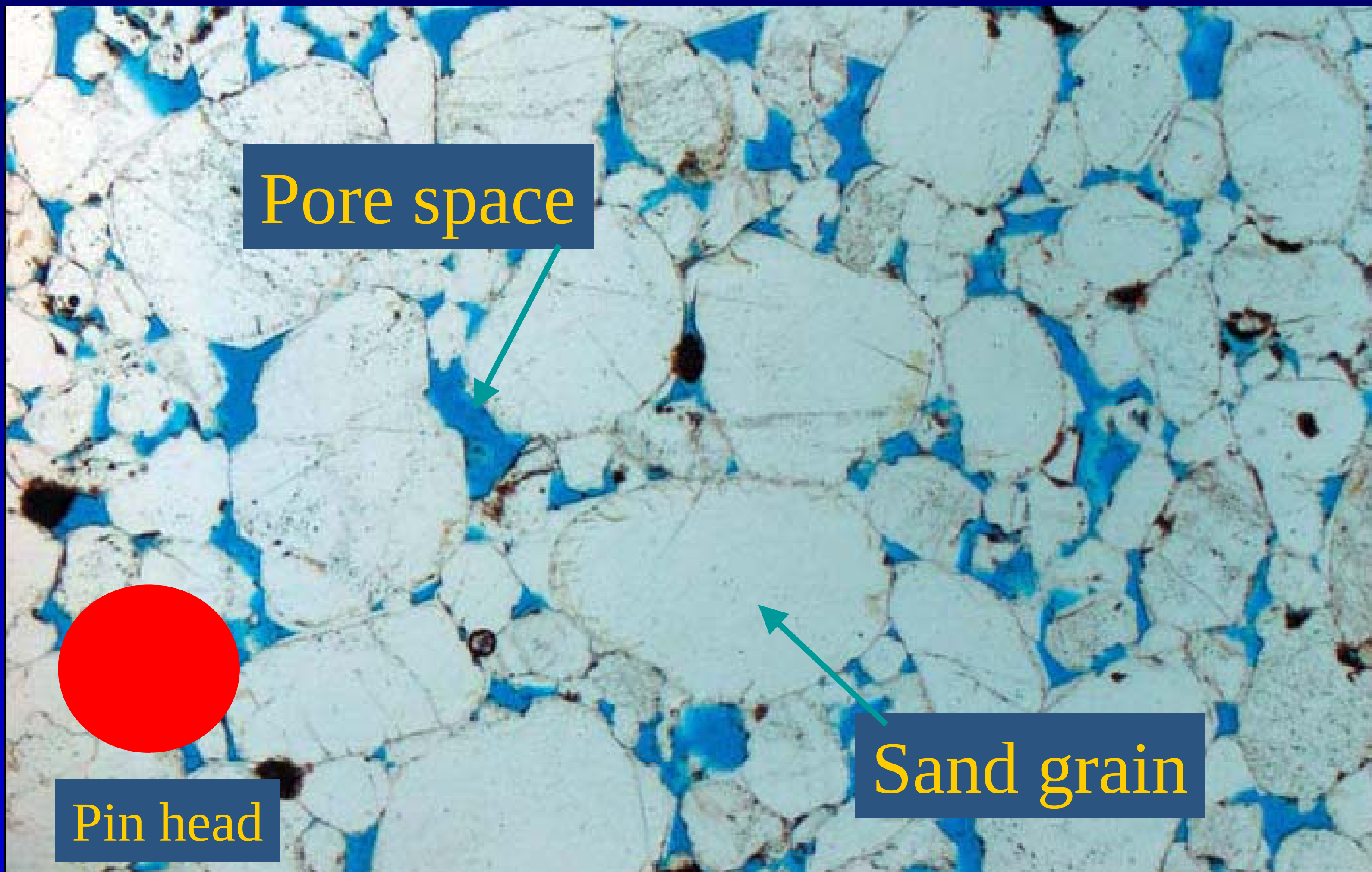
Mt. Simon Sandstone

from Leetaru, 2004

Mt. Simon Sandstone Reservoir

- Mt. Simon Sandstone is used for natural gas storage in Champaign County, IL at 4,000 to 4,200 ft
- Mt. Simon core has been recovered from a few deep exploration wells

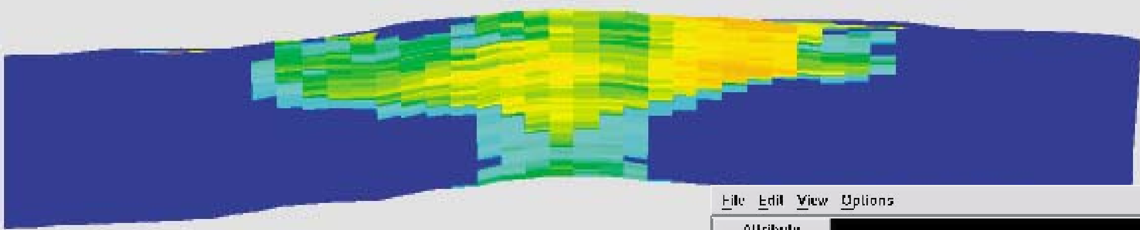
CO_2 Storage in Sandstone Reservoir Pore Space



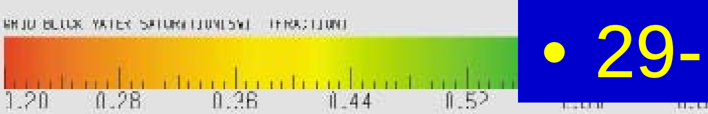
Midwest Geological Sequestration Consortium, A DOE Regional Carbon Sequestration Partnership: Seeking Optimal Sinks

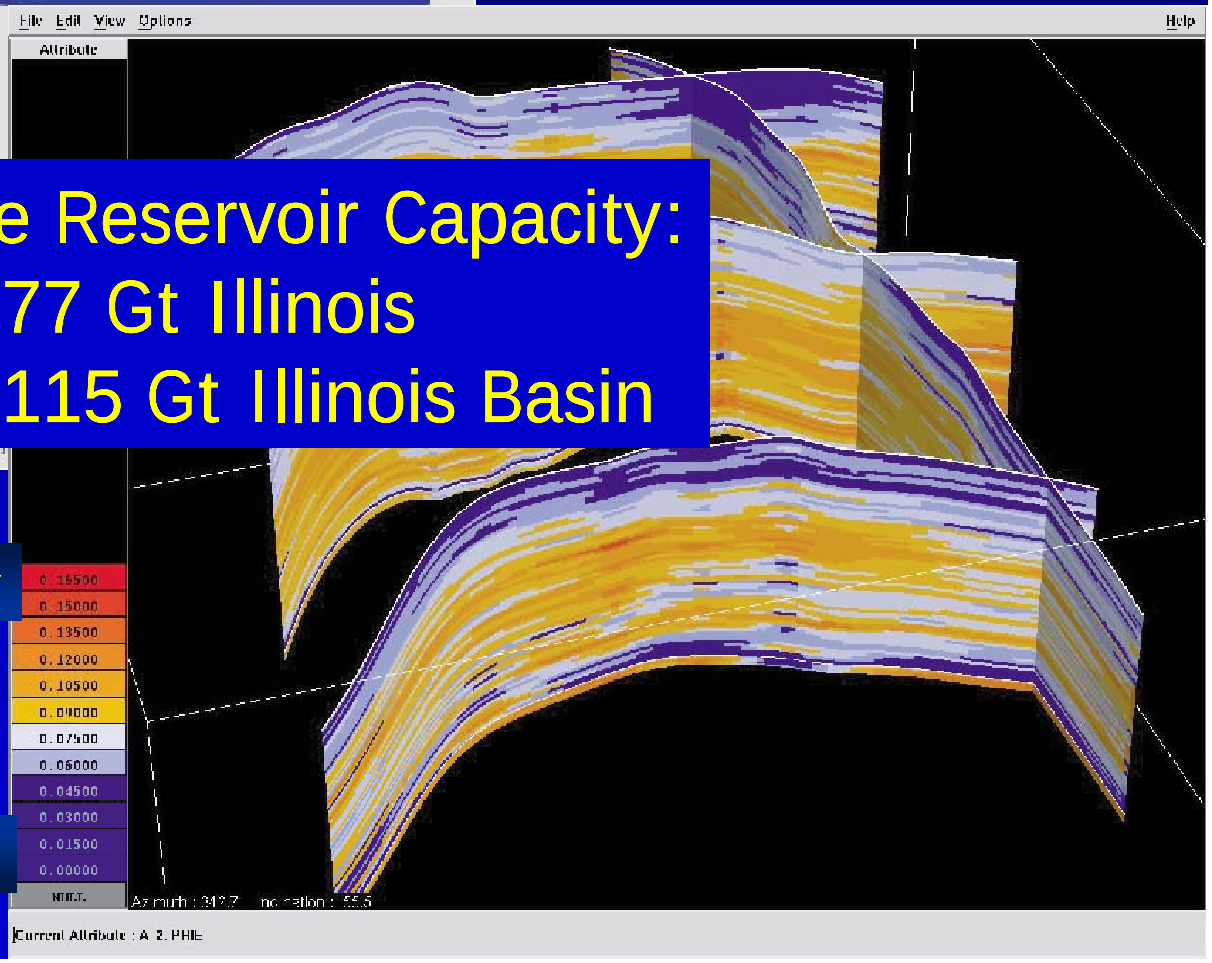
- High CO_2 storage capacity
- High CO_2 injection rate
- Storage mechanism assessment
- Major focus on reservoir characterization for coal seams, mature oil reservoirs, and deep saline reservoirs
- Structural characterization
- Outreach and web site enhancement
  - www.sequestration.org

Mt. Simon Assessed from Gas Storage Facilities



80 years of injection
40 years shut-in

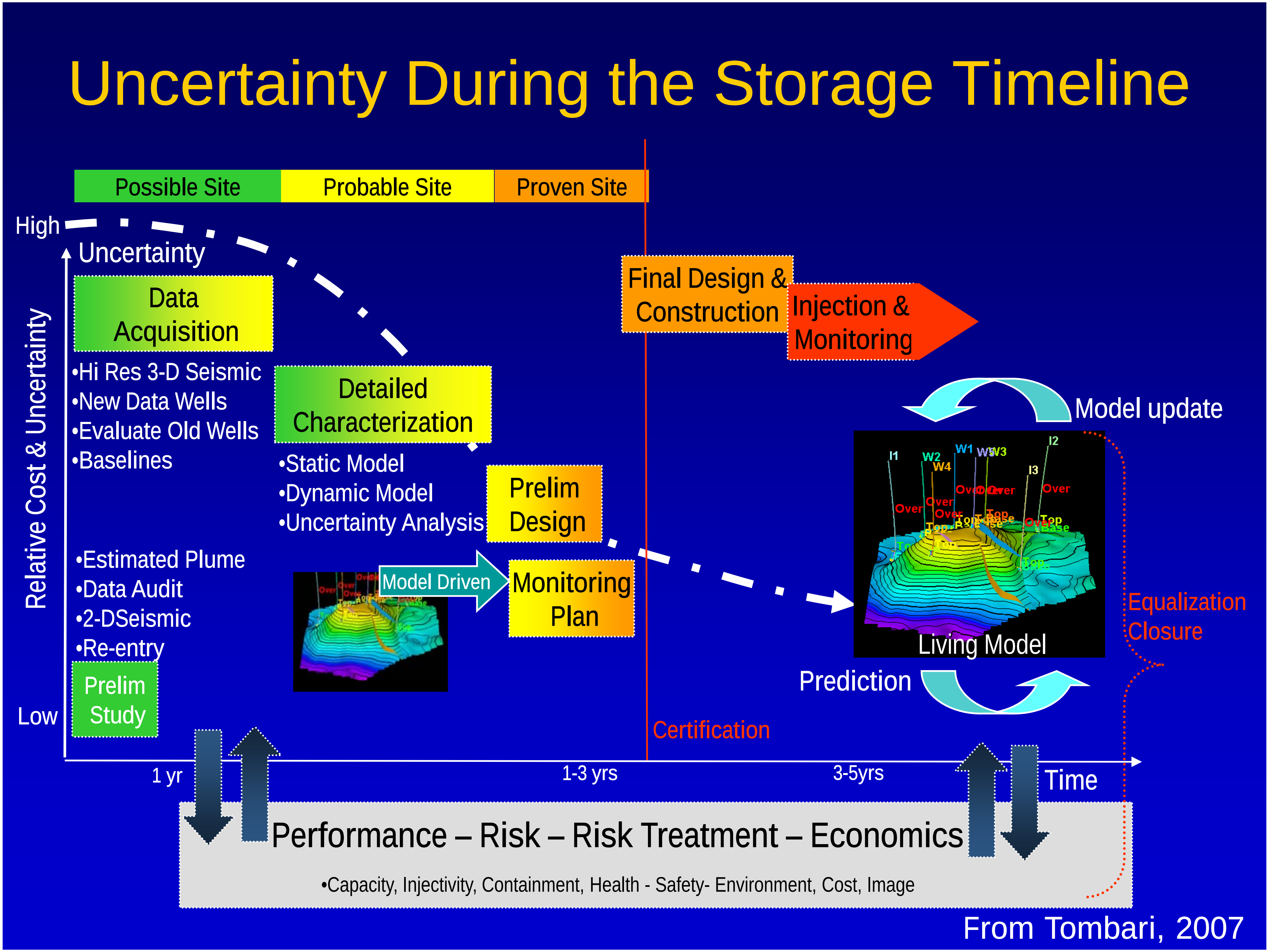




Saline Reservoir Capacity:
- 19-77 Gt Illinois
- 29-115 Gt Illinois Basin

High Porosity

Low Porosity



Uncertainty During the Storage Timeline
Possible Site
Probable Site
Proven Site
High
Uncertainty
Relative Cost & Uncertainty
Data Acquisition
•Hi Res 3-D Seismic
•New Data Wells
•Evaluate Old Wells
•Baselines
Detailed Characterization
•Static Model
•Dynamic Model
•Uncertainty Analysis
Prelim Design
Final Design & Construction
Injection & Monitoring
Model update
Living Model
Prediction
Equalization Closure
•Estimated Plume
•Data Audit
•2-DSeismic
•Re-entry
Prelim Study
Low
Model Driven
Monitoring Plan
Certification
1 yr
1-3 yrs
3-5yrs
Time
Performance – Risk – Risk Treatment – Economics
•Capacity, Injectivity, Containment, Health - Safety- Environment, Cost, Image
From Tombari, 2007

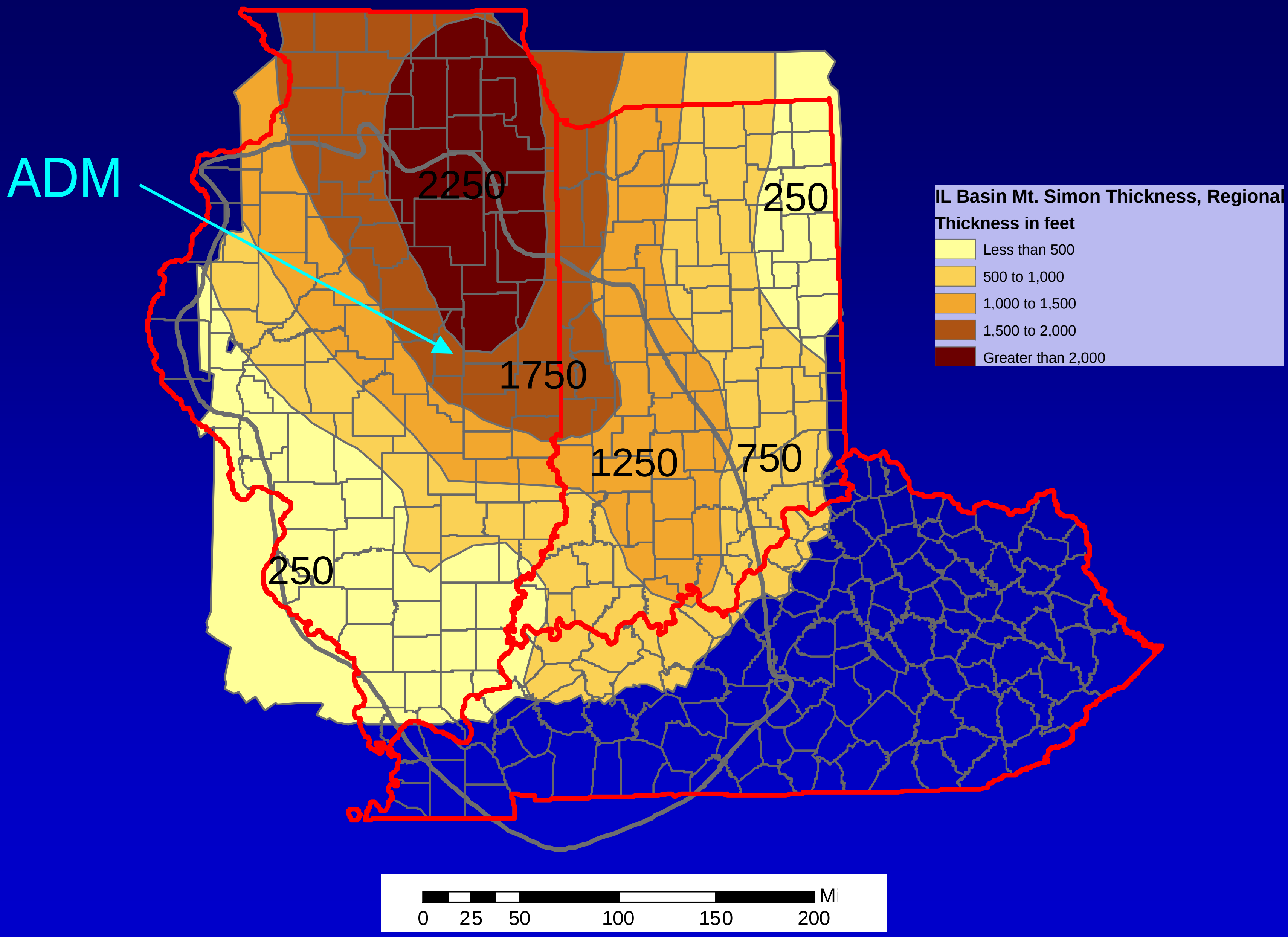
Concept for MGSC Phase III

- Inject 1,000 tons/day of supercritical CO_2 into a saline reservoir over a period of three years to achieve a large-scale test injection of 1 million tons
- The test is to take place in Decatur, Illinois, injecting into the Mt. Simon Sandstone at a depth of about 6,500-7,200 ft accompanied by extensive MMV
- The CO_2 is to be provided by the Archer Daniels Midland Company from an ethanol facility and injected on a site owned by ADM adjacent to their plant
- The Mt. Simon Sandstone is the major saline reservoir under evaluation for geological sequestration in the Illinois Basin and has an assessed capacity of 27.1-108.6 Gtonnes

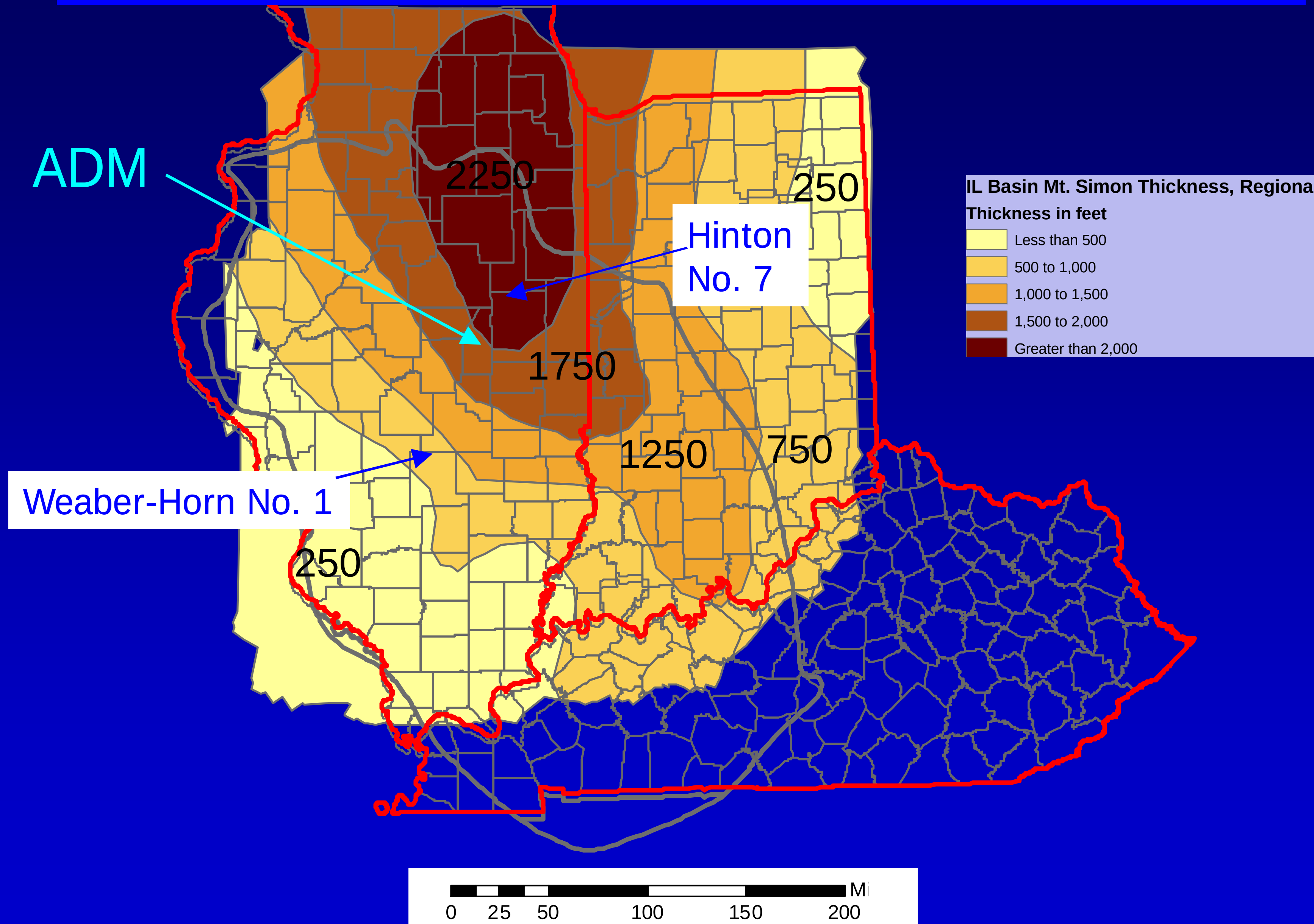
MMV Components

1. Site Assessment
2. Atmospheric monitoring
3. Remote sensing
4. Vadose zone monitoring
5. Shallow geophysical monitoring
6. Shallow groundwater monitoring
7. Injection well monitoring
8. CO_2 monitoring
9. Injection formation monitoring
10. Mitigation plans should CO_2 leakage occur
11. Validation using geochemical, reservoir integrity/gas migration, groundwater flow/contaminant transport, and CO_2 flux model predictions.

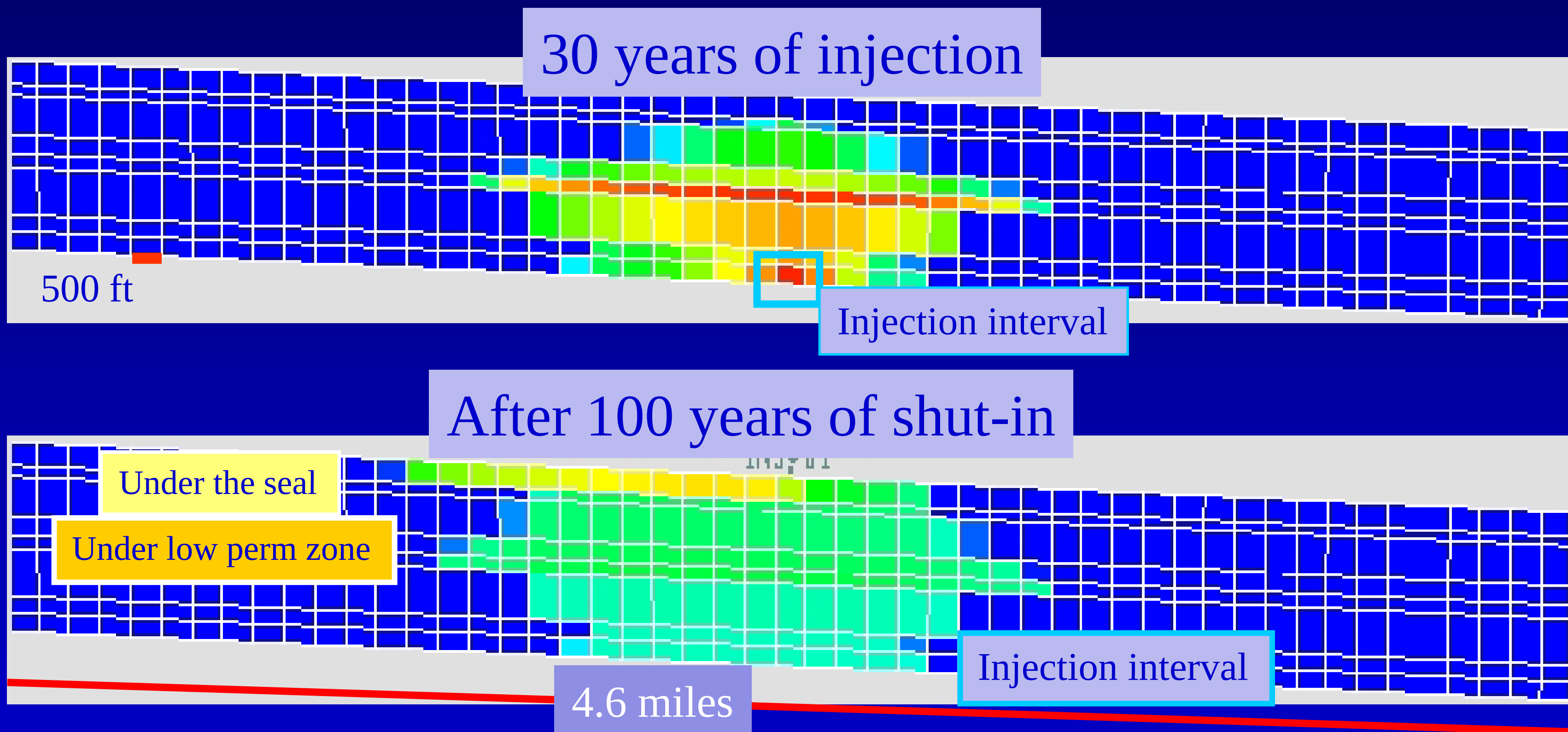
Mt. Simon Thickness



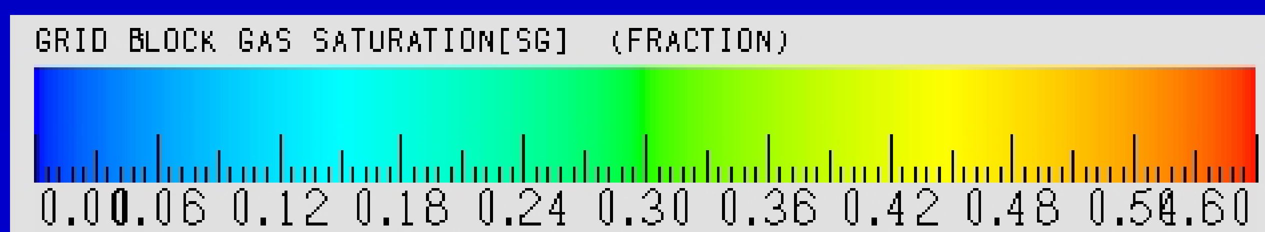
Phase III Deep Saline Reservoir Test



Injection into the Weaber-Horn
1 degree dipping beds



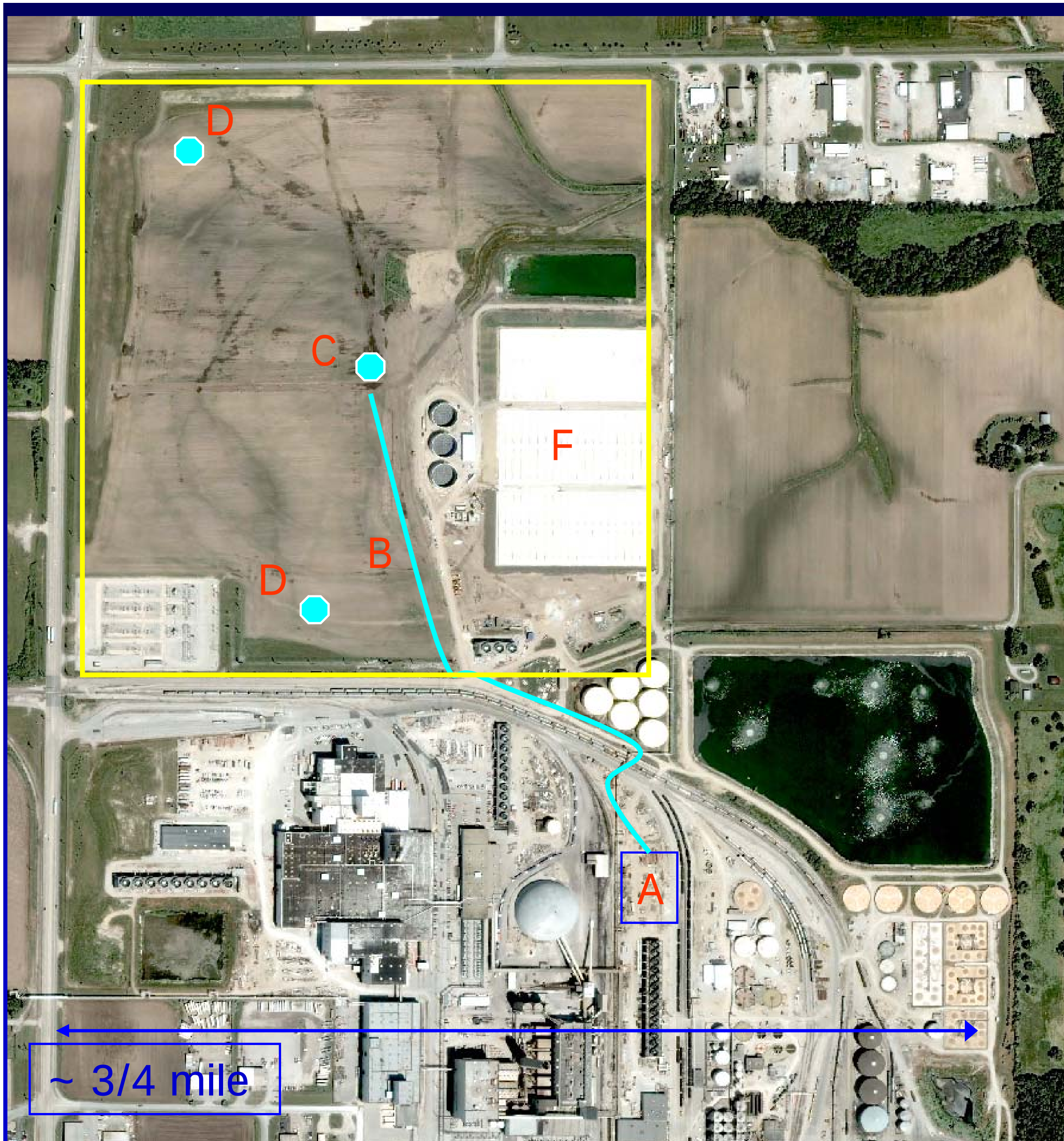
1 million tons/yr



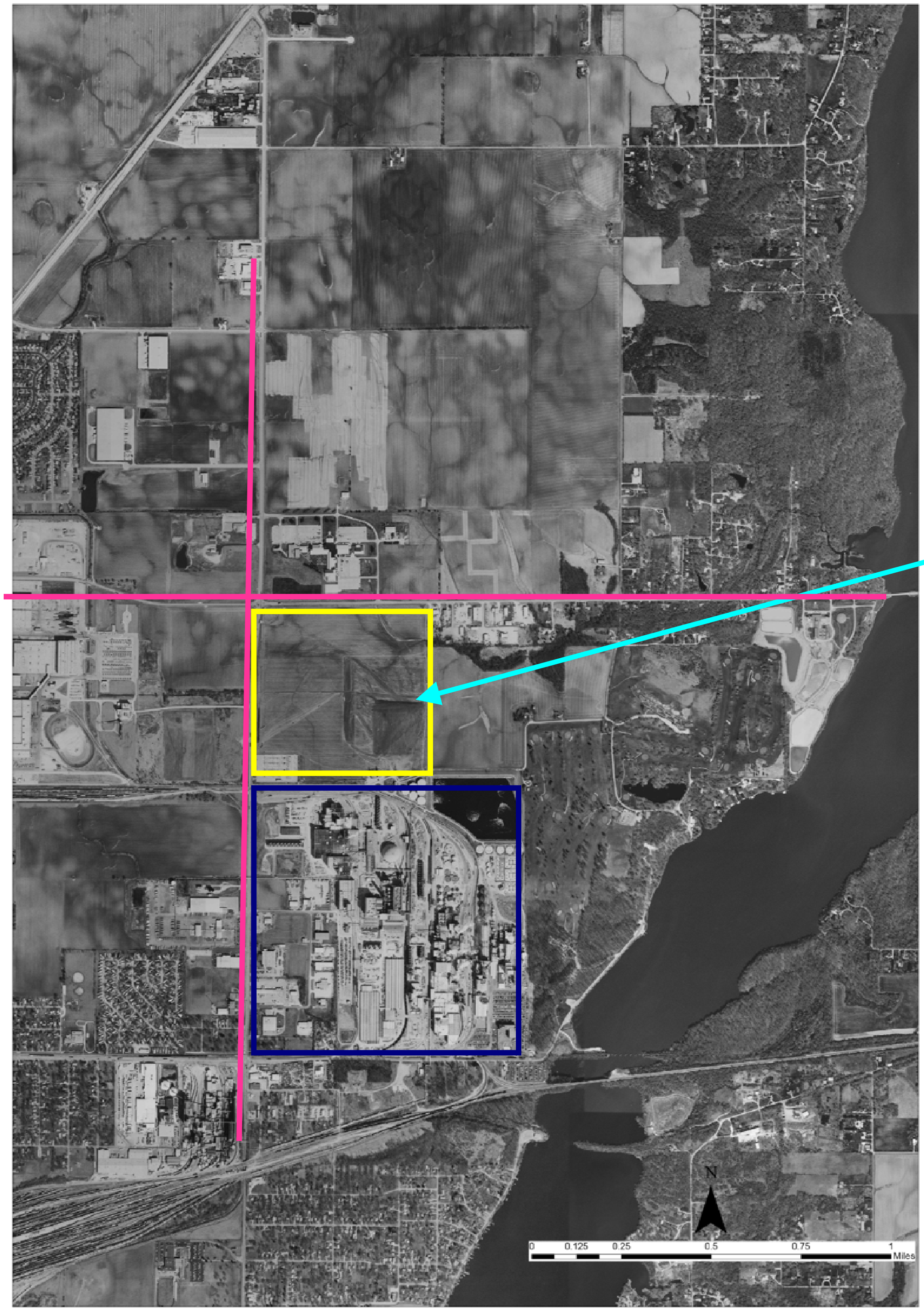
Monitoring, Mitigation and Verification

- Develop integrated geochemical/geomechanical model to guide MMV program using extensive data collection from injection well and initial geophysical surveys for site characterization
- Utilize Phase II techniques for testing ambient air, soil vadose zone, groundwater, and observation of vegetation
- Two verification wells to enhance geophysical observations of plume boundaries, confirm those boundaries by subsurface sampling, and sample within Mt. Simon and formations above the primary seal
- Continue MMV for two years after I million tons injected

ADM Test Site



- A Dehydration/ compression facility location
- B Pipeline route
- C Injection well site
- D Potential verification well sites
- F Anaerobic wastewater treatment facility

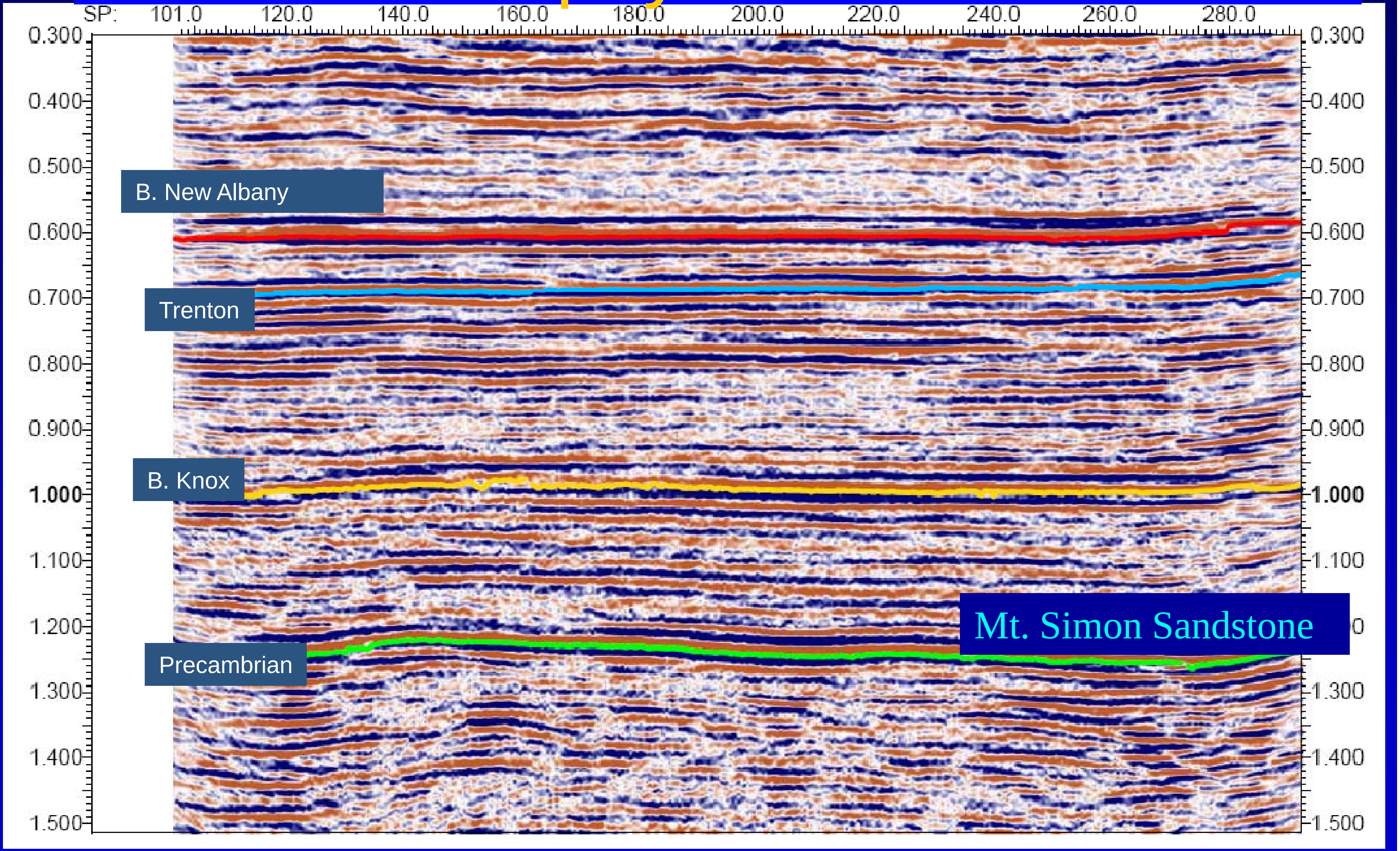


Archer Daniels Midland Company Site

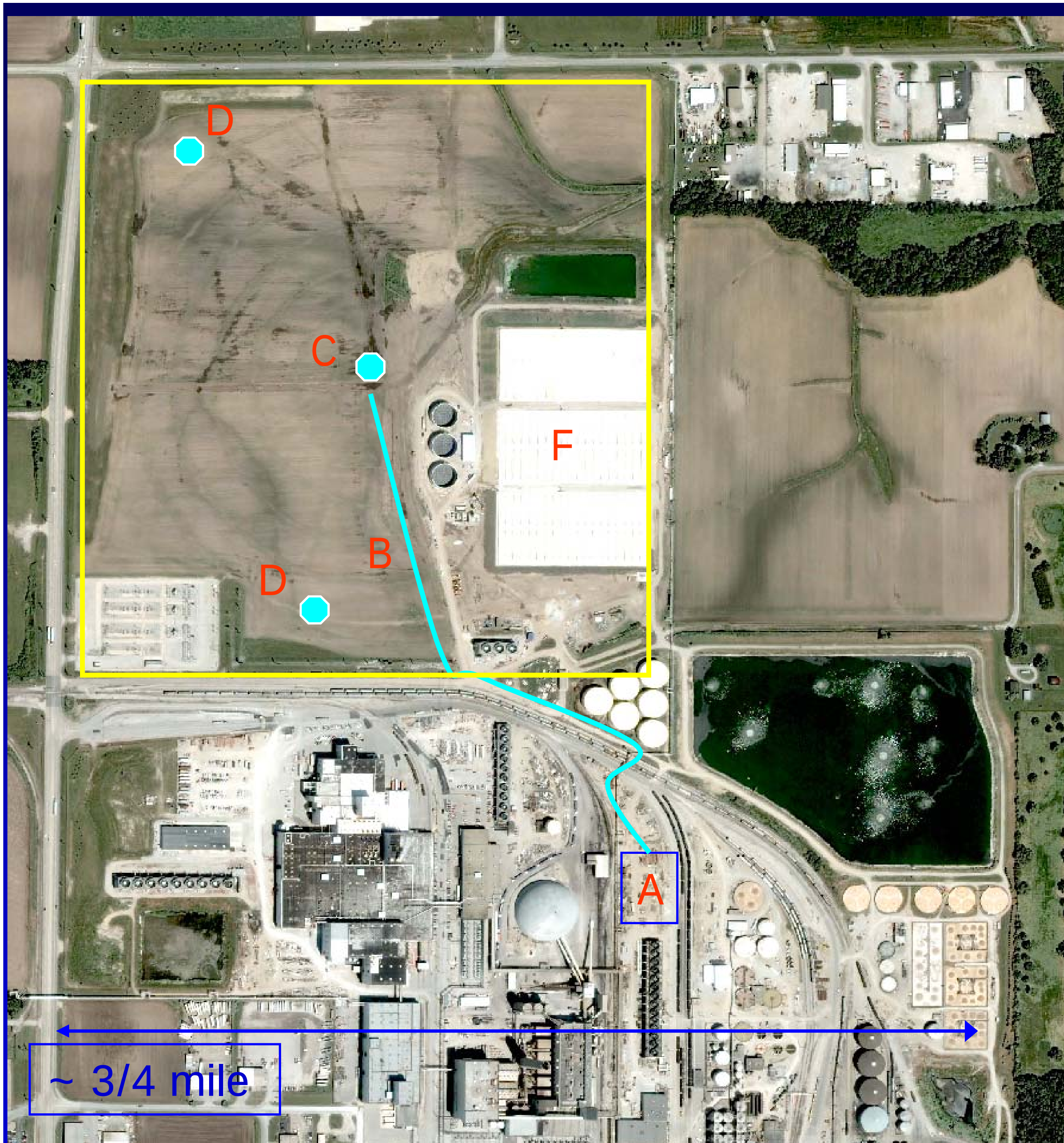
- Injection tract
- North-south and east-west 2D seismic lines acquired in October 2007
- Qualify site for drilling in April 08

VibroSeis Trucks at ADM Site

Mid-Illinois Basin 2D Geophysical Data

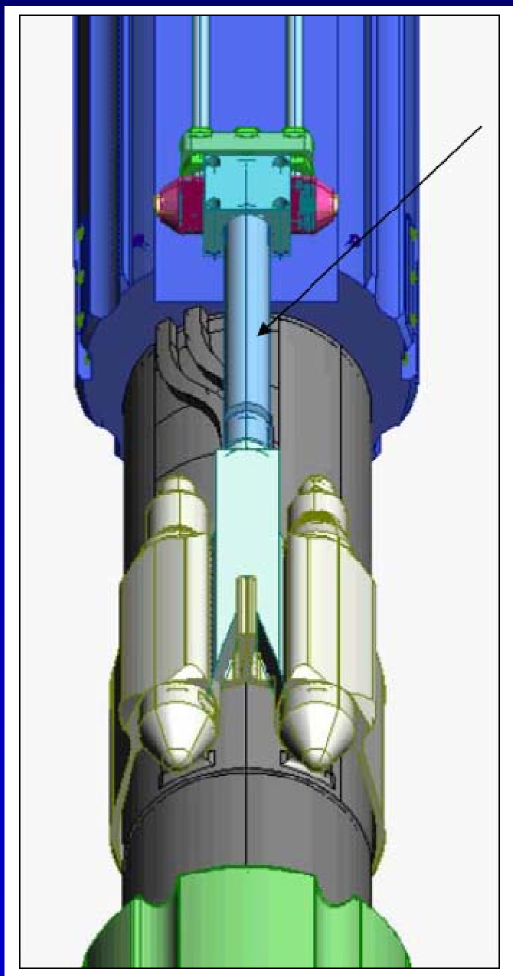


ADM Test Site

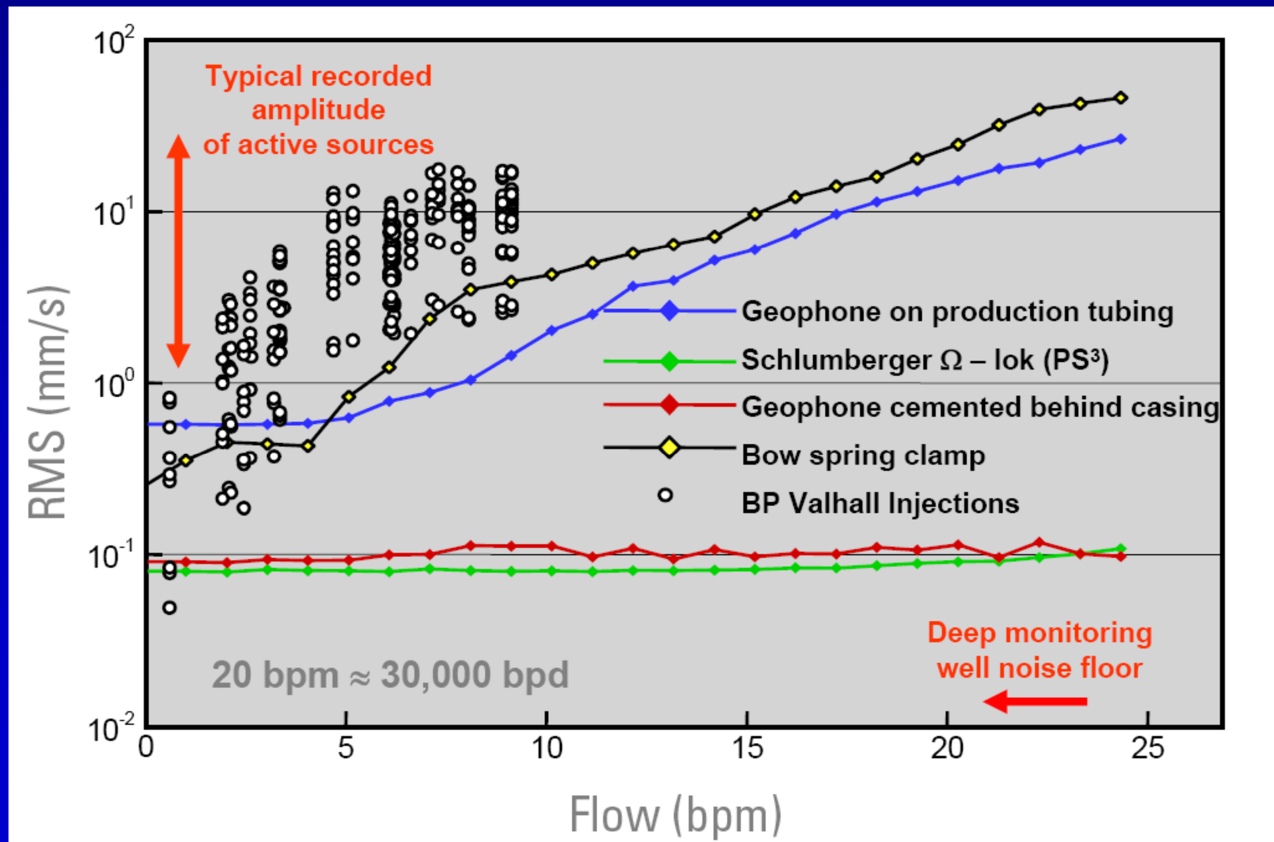


- A Dehydration/ compression facility location
- B Pipeline route
- C Injection well site
- D Potential verification well sites
- F Anaerobic wastewater treatment facility

Matrix Monitoring Strategies

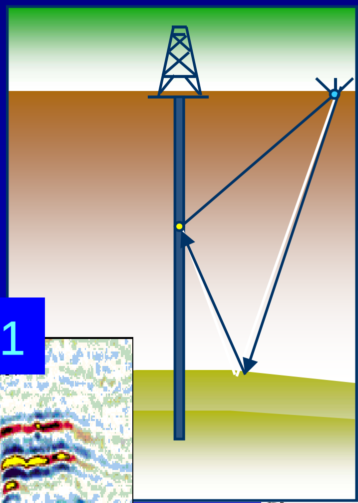


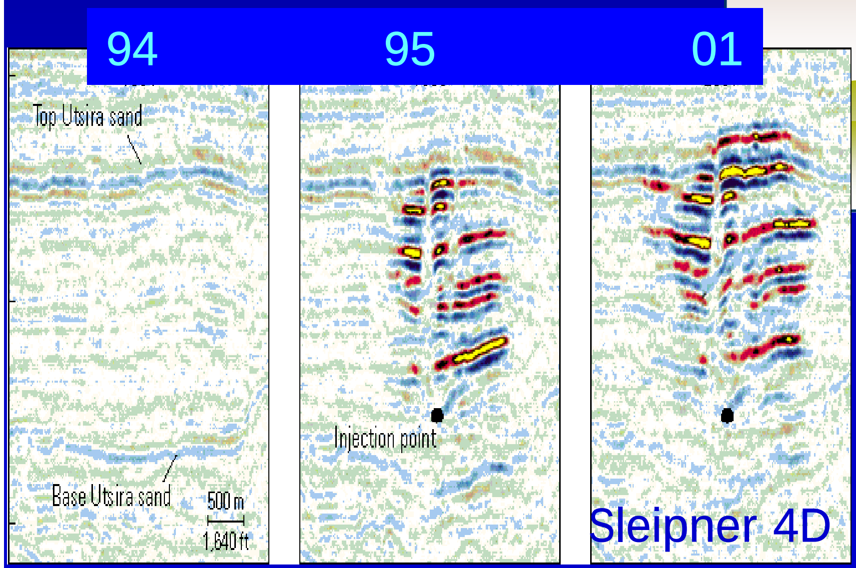
- Geophones run in on tubing, deployed to casing, avoids cement integrity problems, recoverable as needed



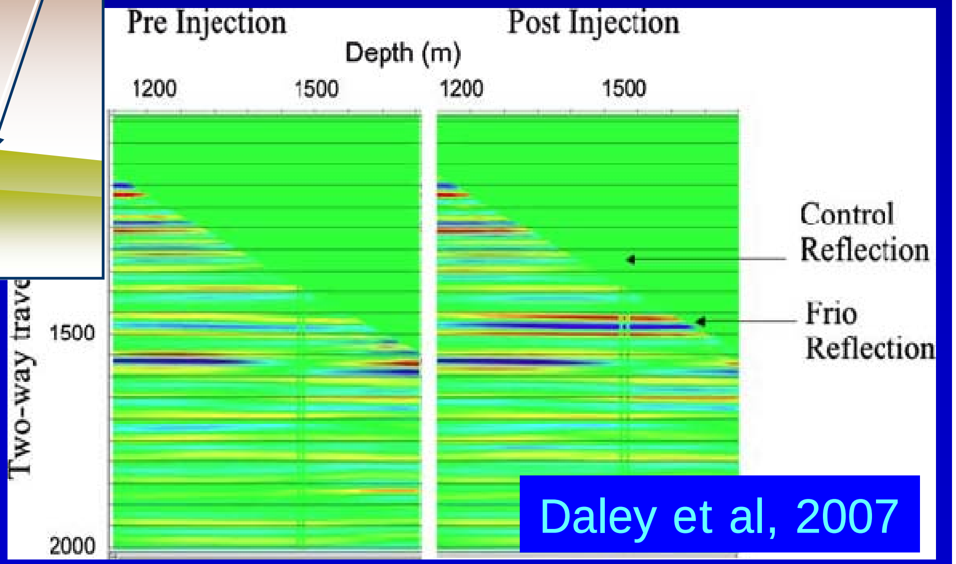
Plume Monitoring Strategies

- Seismic response of plume based on repeat surface 3D ("4D") similar to Sleipner project and offset or walkaway Vertical Seismic Profile (VSP) using geophone array



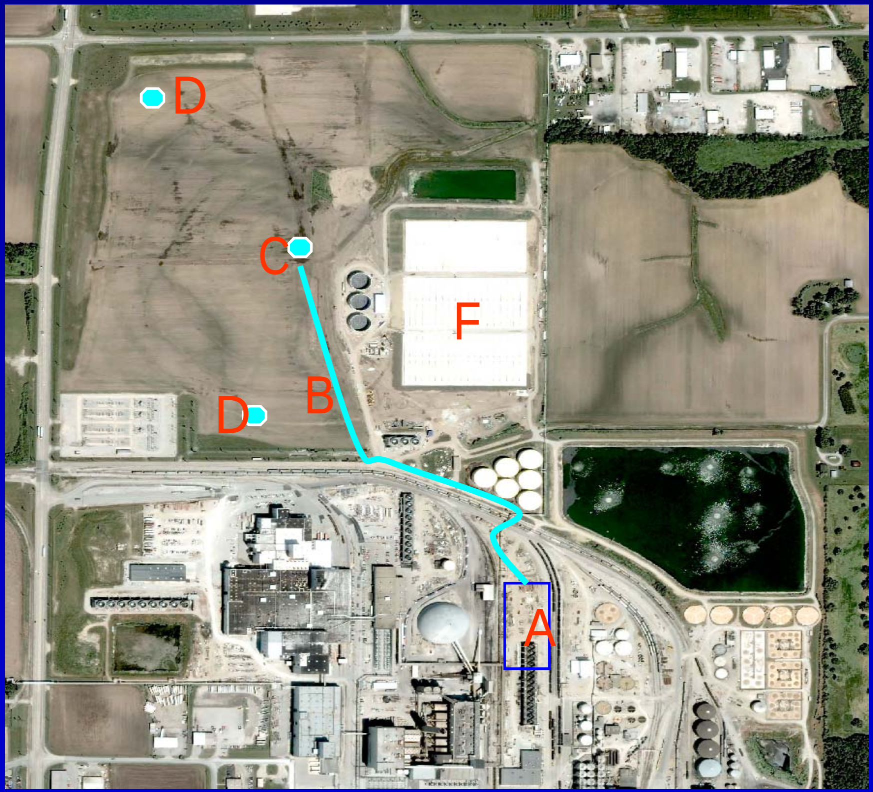


Frio Brine Pilot

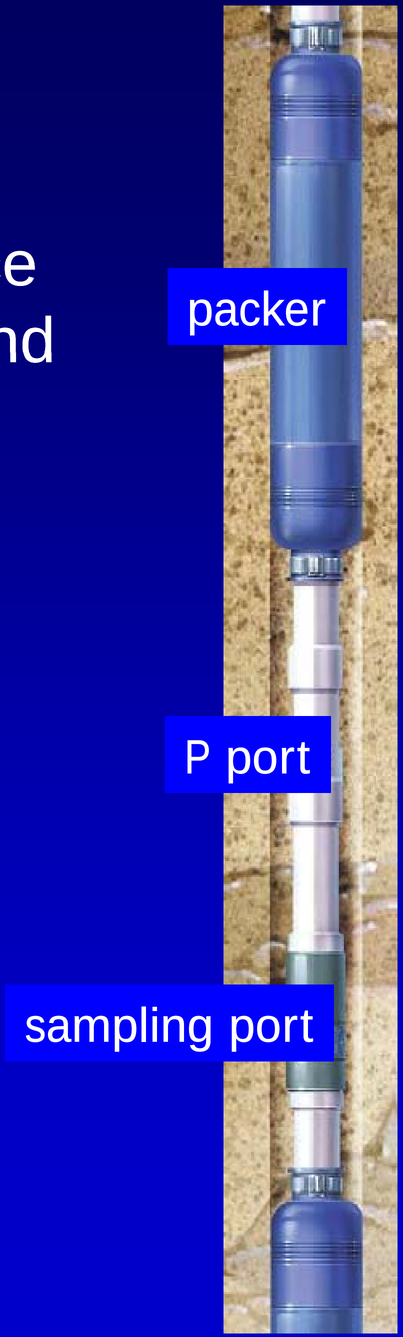


Plume Monitoring Strategies

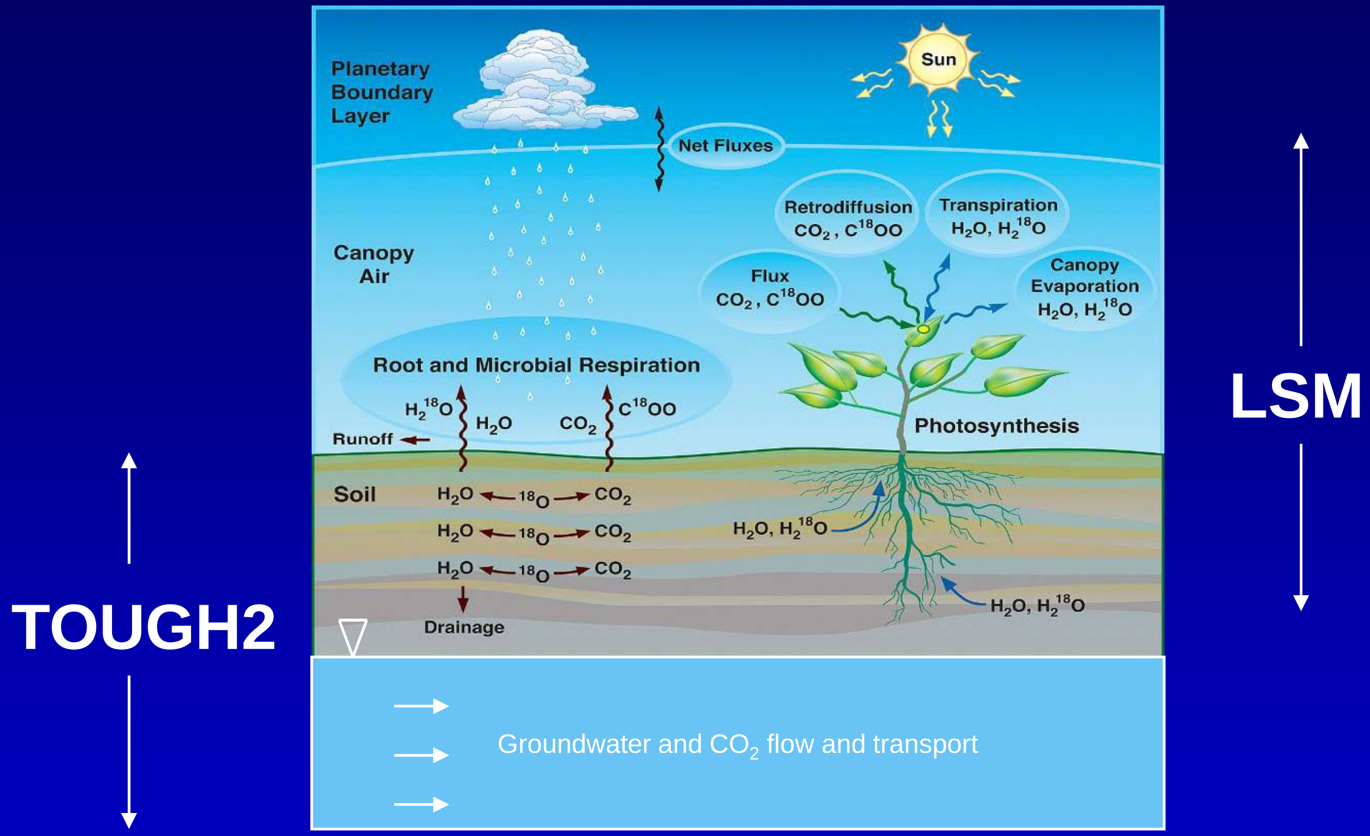
- Drill two verification wells (D) based on surface seismic and VSP data, generally one updip and one downdip, or placed based on VSP plume boundary imaging



- Open-hole logging and flexible (Westbay) fluid sampling strategy
- Pressure/temp. monitoring
- Cased-hole logging



Model Domains and Processes



MMV for CO_2 storage is complicated by natural processes involving carbon.

from Oldenburg, LBNL

Surface flux measurements, modeling, and advanced data analysis may be needed to discern seepage signal from background variation (e.g., Lewicki, Hilley, and Oldenburg, 2005).

Accumulation Chamber (AC) and Eddy Covariance (EC) Instruments

Accumulation Chamber:
- **Local surface CO_2 flux**
- **Scale ~ cm^2**
- **Measurement time ~ minute**

from Oldenburg, LBNL

Eddy Covariance:
- **Average net surface CO_2 flux**
- **Scale ~ m^2- km^2 (scales with height)**
- **Requires time-averaging**
- **Steady-state, homogeneous, flat, horizontal surface**

Shallow Groundwater Monitoring

Use existing wells & install monitoring wells to:

- Determine shallow (< 60m) groundwater flow regime.
- Determine water quality with emphasis on carbonate chemistry.

ISGS installing downhole bladder pump

ISGS installing monitoring wells

MMV in the Field

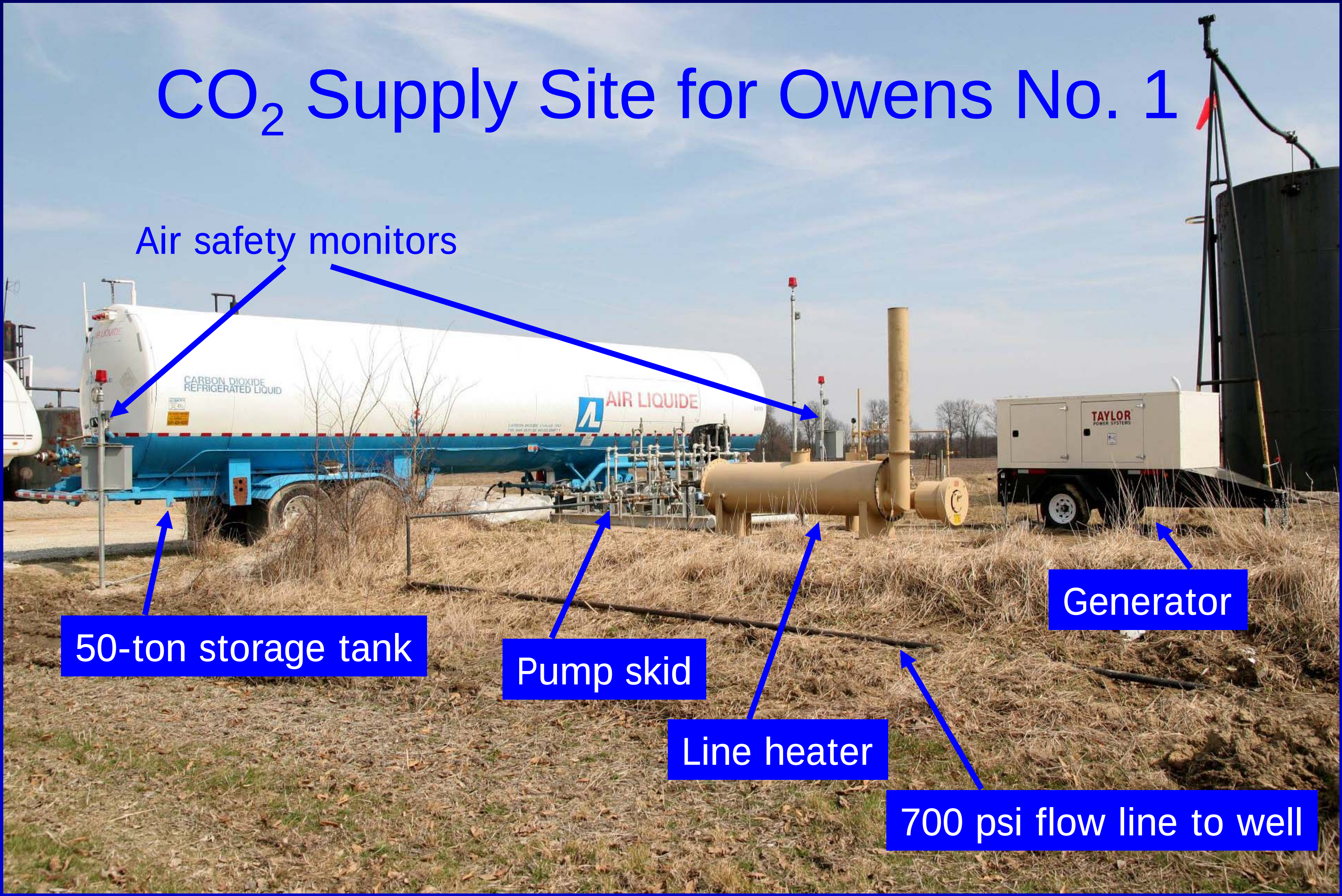
- Installing monitoring wells
- Installing vadose zone samplers
- Collecting background samples

Monitoring well nest

Formation brine sampling

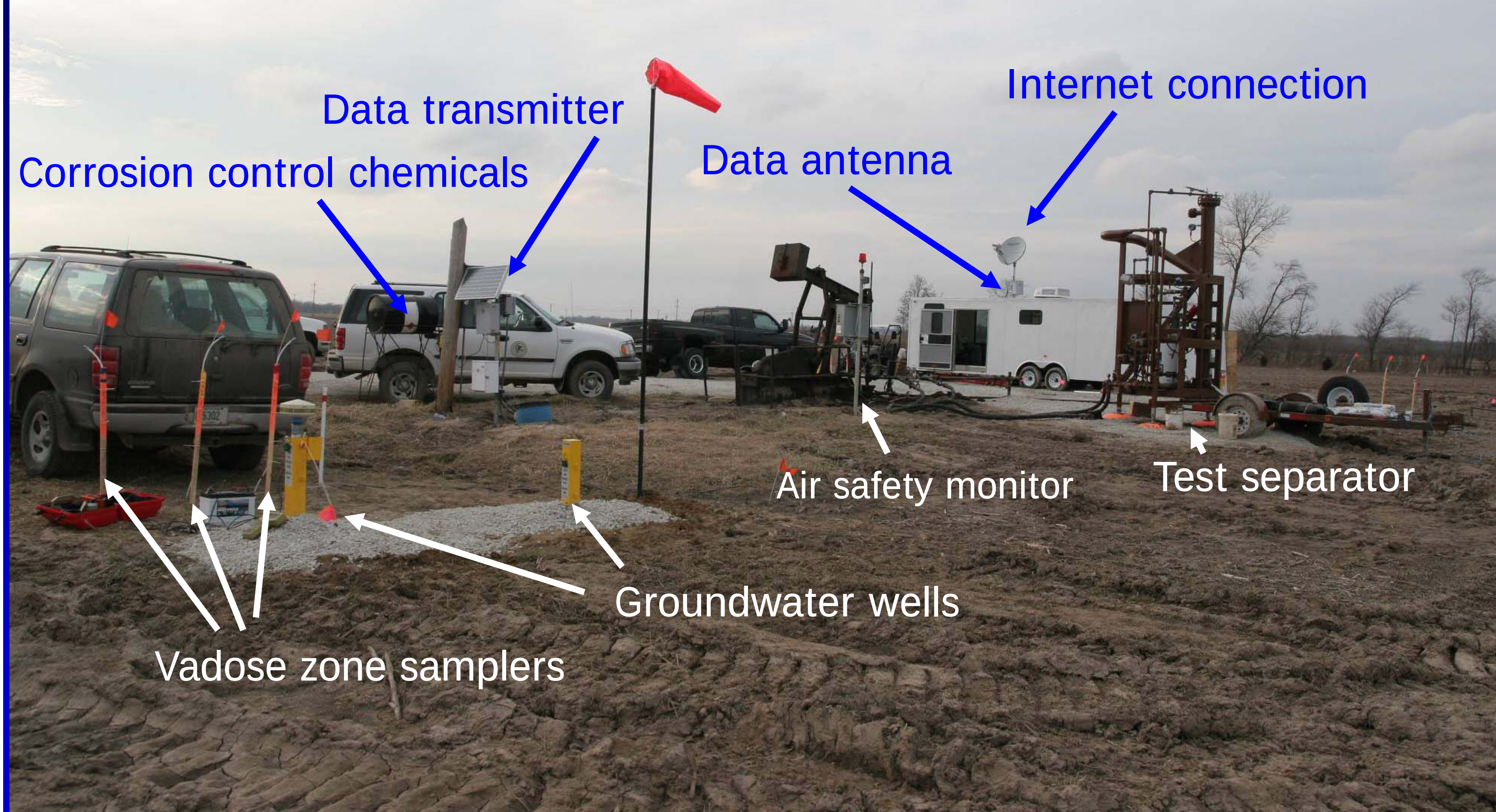
Groundwater sampling

CO_2 Supply Site for Owens No. 1



Owens No. 1 Well Site

Single Well EOR Test
Owens No. 1, Loudon Field

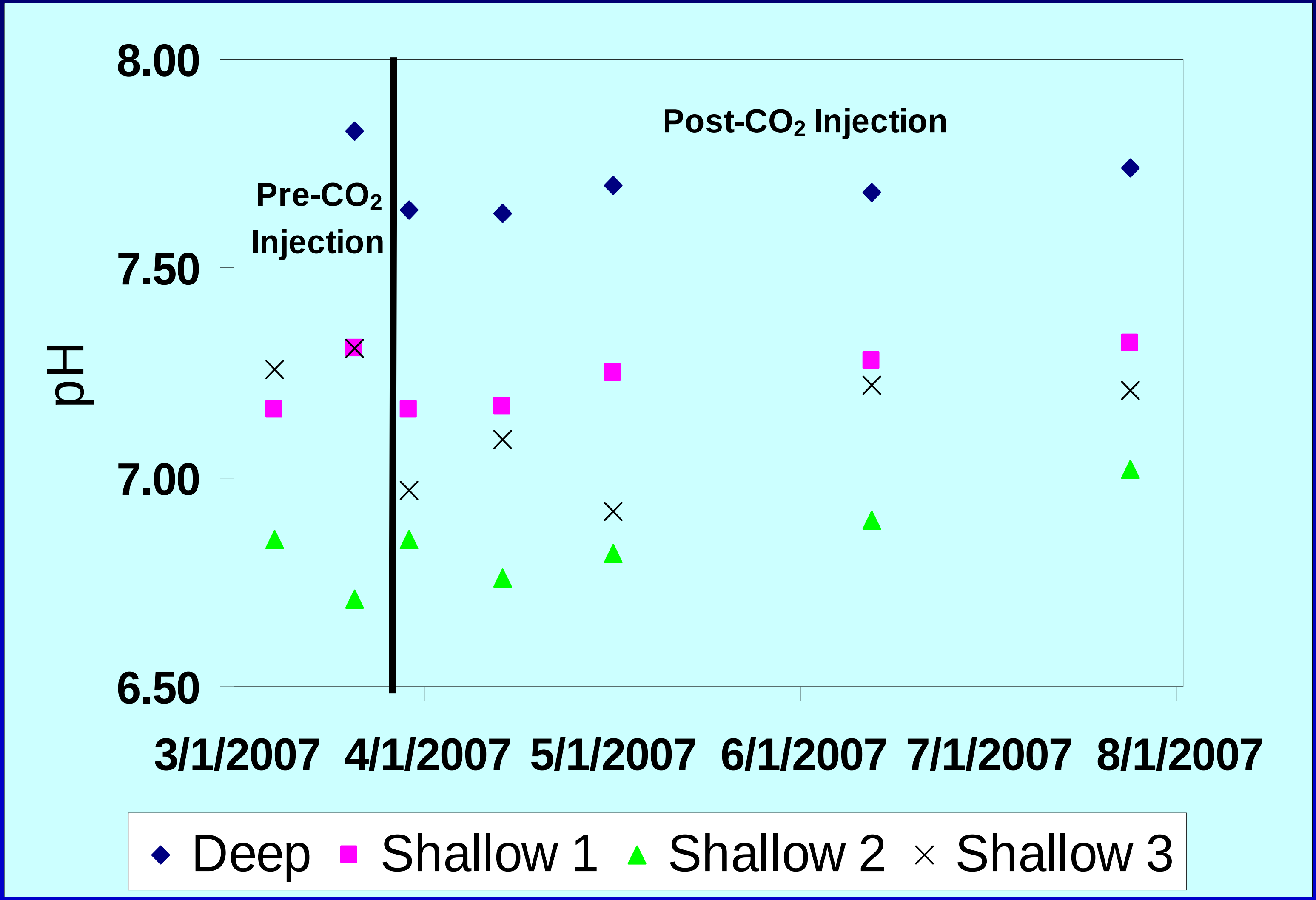


Vadose Zone Monitoring

Soil gas collected at 0.5, 1.2, 2.4 m depths

Field- CO_2, CH_4
Lab- CO_2, Hydrocarbons

pH of Monitoring Wells



ADM Groundwater Modeling

- Modeling Objectives
  - Estimate the flow and transport of a potential CO_2 leak from the injection well. Focus on leakage into shallow groundwater which is used as a local water resource (municipal water is supplied by surface reservoir)
  - Design a groundwater monitoring network to detect any CO_2 leakage into shallow groundwater

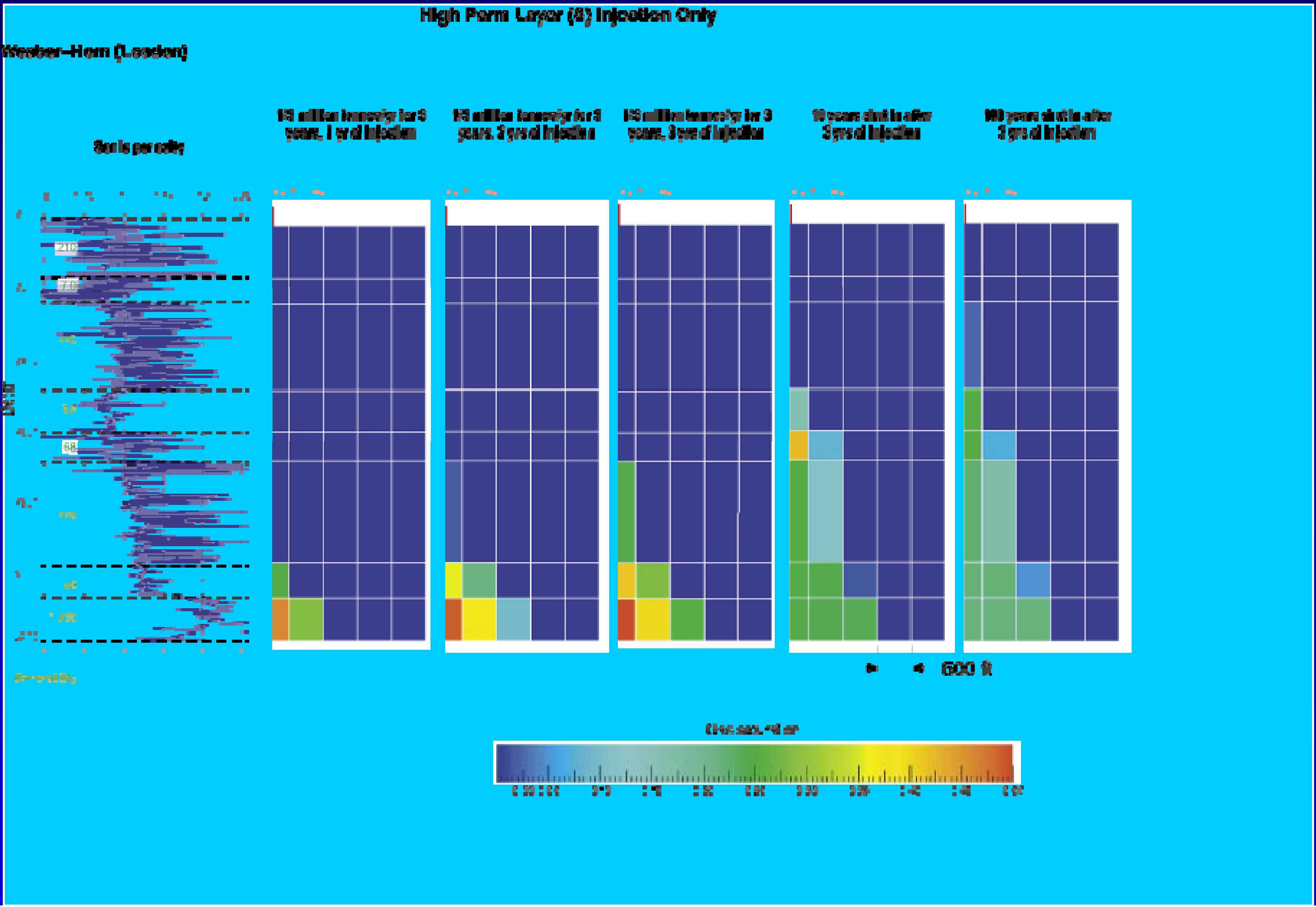
ADM Geochemical Modeling

- Used to help understand changes in chemical composition of groundwater that could be a result of CO_2
- Determine cation/anion balance, solute speciation, solid-phase equilibria
- Use multiple equilibrium chemistry models such as PhreeqeCi and Geochemist’s Workbench

Phase III Outcomes

- A large-scale injection of 1 million tons of CO_2 successfully demonstrated and associated safety, efficiency, and effectiveness requirements met
- Volume sufficient to monitor geophysically, dehydration/compression equipment scalable to an IGCC comparable to FutureGen
- A process model established for equipment, permitting, injection, MMV, and outcome assessment that will support energy facility development with integrated carbon sequestration in the Illinois Basin and elsewhere

Simulation of CO_2 injection into Mt. Simon at ADM Site



Phase III Schedule

- Gantt chart developed showing 14 Tasks and 77 Subtasks
- Project begins October 07— merges with Phase II saline test
- Baseline MMV activities begin October 07
- UIC permit planned for February 08
- The injection well will be drilled in April-May 08
- Final functional testing of compression, pipeline, and wellhead initiated in July 09
- Injection would occur from October 09-September 12
- Verification wells would be drilled April-May 2010 and April-May 2012
- MMV carried out through December 2015

Illinois Seeking FutureGen and Facilitating IGCC, Carbon Sequestration, and CO_2 EOR

- Illinois Office of Coal Development leading Illinois' FutureGen team; IN and PA formally endorse Illinois sites
- IL SB 1704 provides liability protection for the Alliance and establishes monitoring responsibility at ISGS
- Illinois Office of Coal Development supporting IGCC projects with grants, bonding, and cofunding Midwest Geological Sequestration Consortium
- Illinois working across state agencies to attract more IGCC projects that use Illinois coal and are optimized for carbon sequestration
- Illinois seeking public-private partnership to develop a CO_2 pipeline backbone to deliver CO_2 from these projects to Illinois oil fields

Midwest Geological
Sequestration Consortium
www.sequestration.org

MMV Programs in the Final Phase of the IEA GHG Weyburn-Midale CO_2-EOR Monitoring & Storage Project

Don White
Geological Survey of Canada

Weyburn Field

Weyburn Unit:

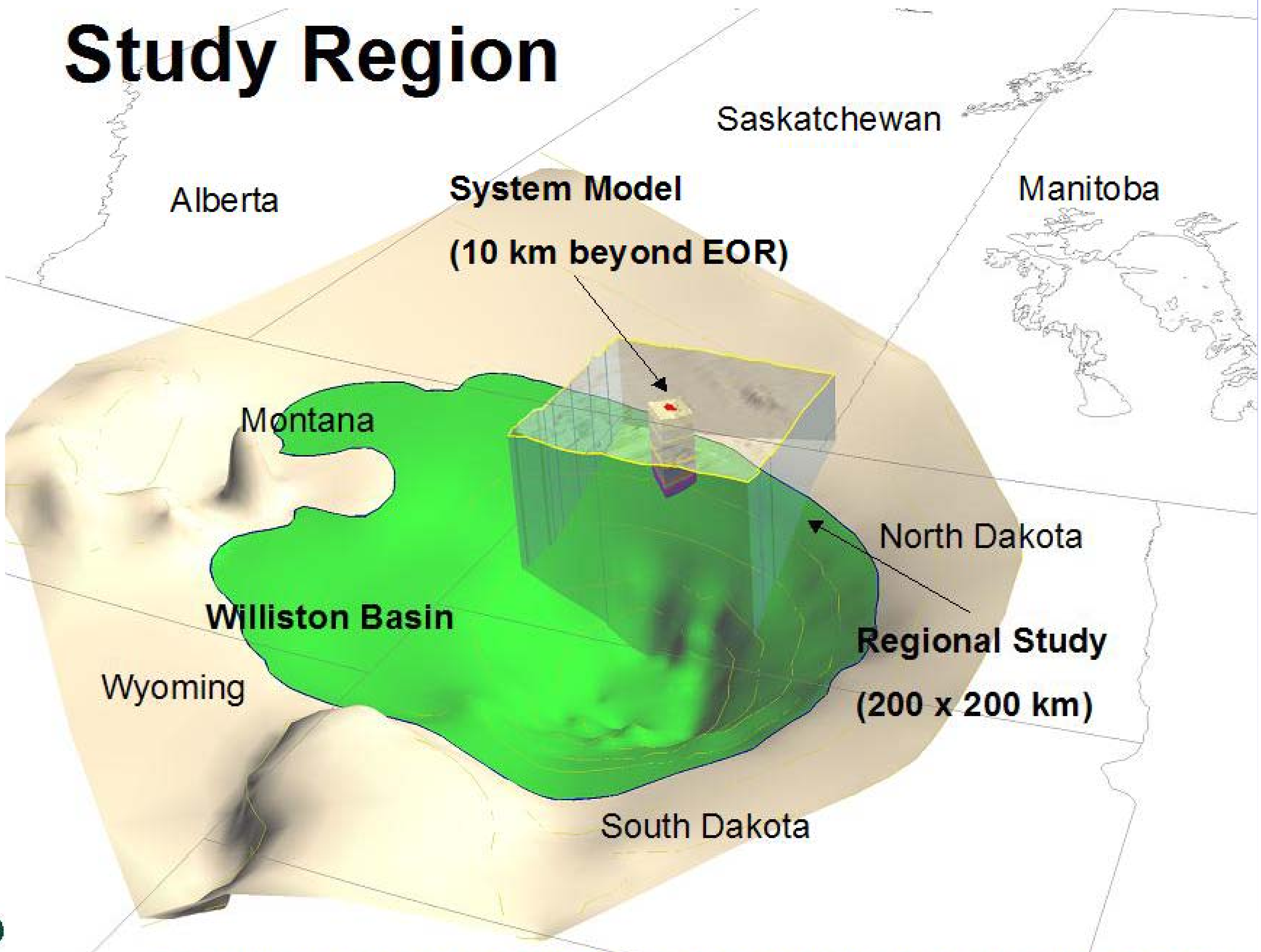
Field Size: 70 sq. miles

Oil Recovered: 370 million bbls

OOIP: 1.4 billion bbls

CO2 IR: 130 million bbls

Study Region

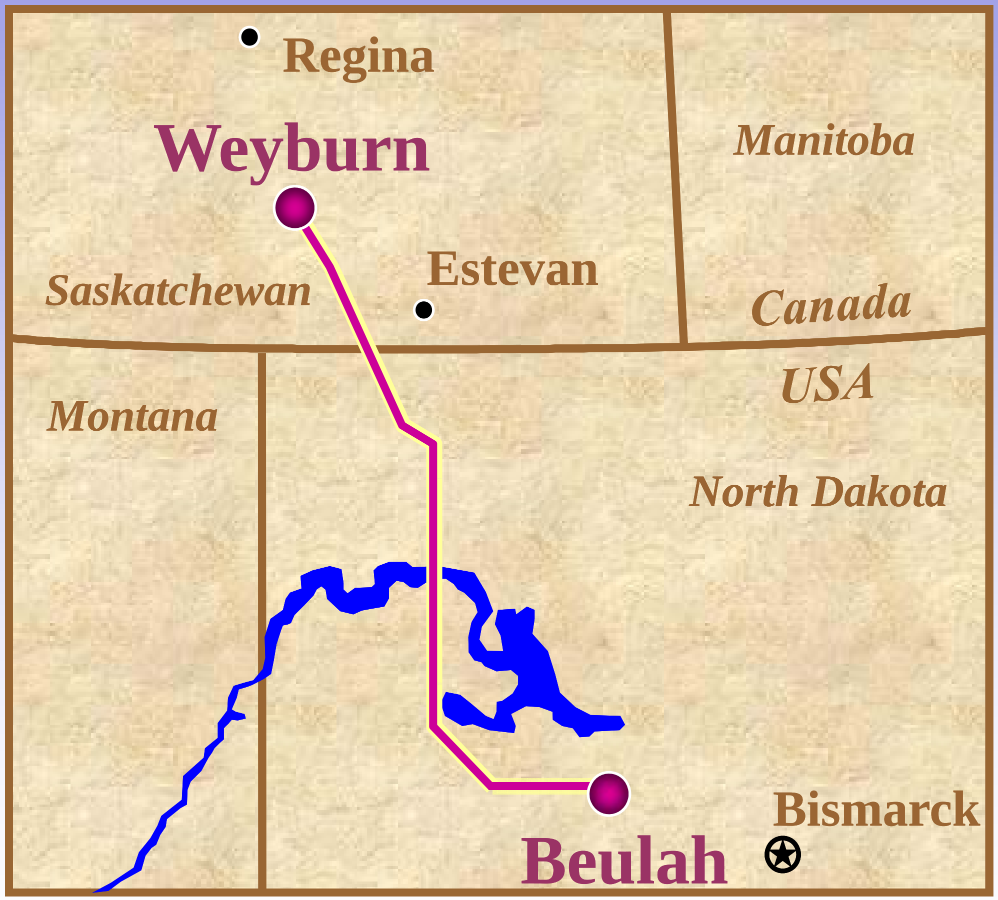


Petroleum Technology Research Centre

IEA WEYBURN CO_2 MONITORING AND STORAGE PROJECT

The Source of CO_2

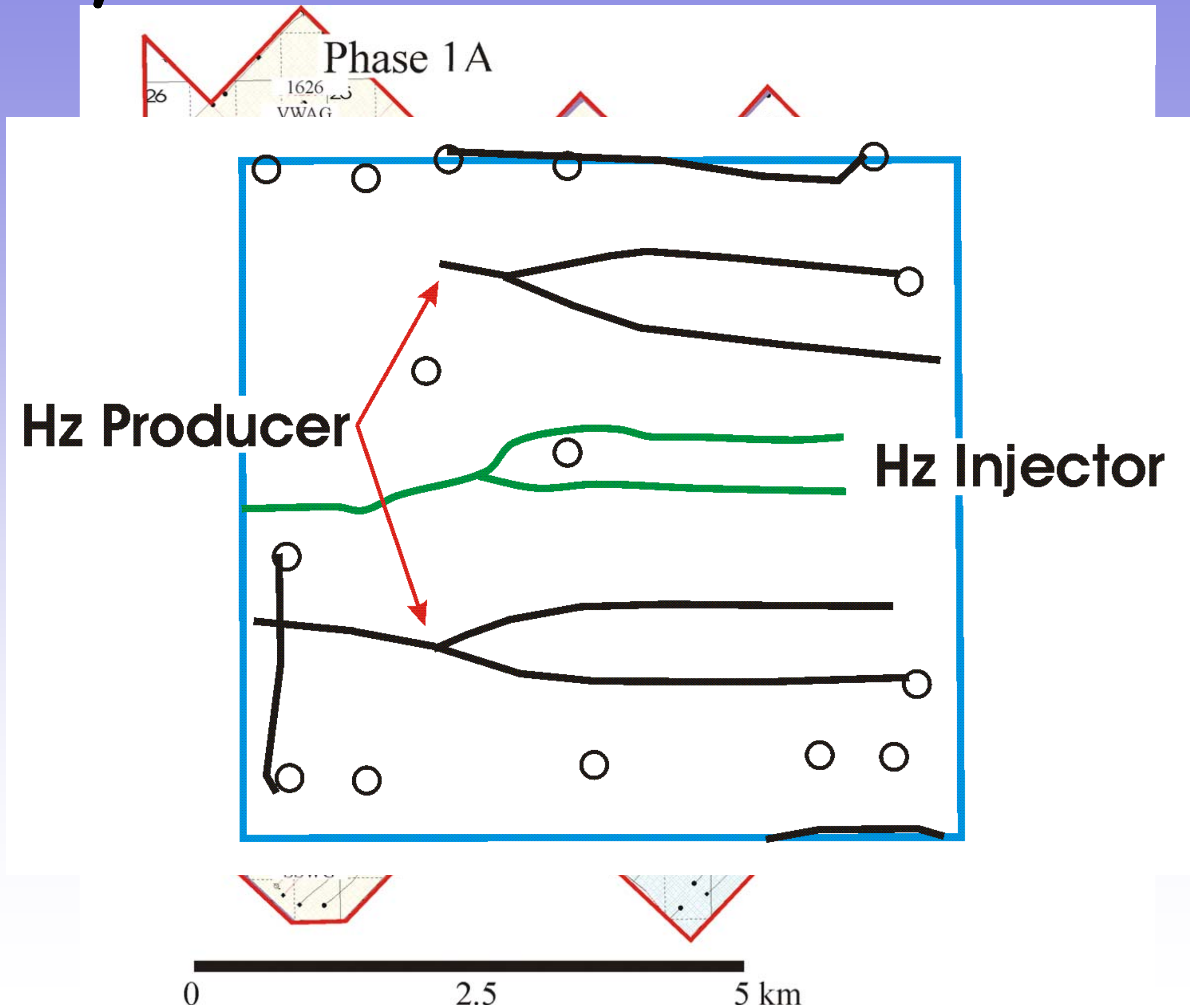
- **Dakota Gasification Company**
- **250 mmscfd CO_2 by-product of coal (lignite) gasification**
- **CO_2 purity 95%**
- **EnCana currently injects ~6000 tonnes (21% recycle)**



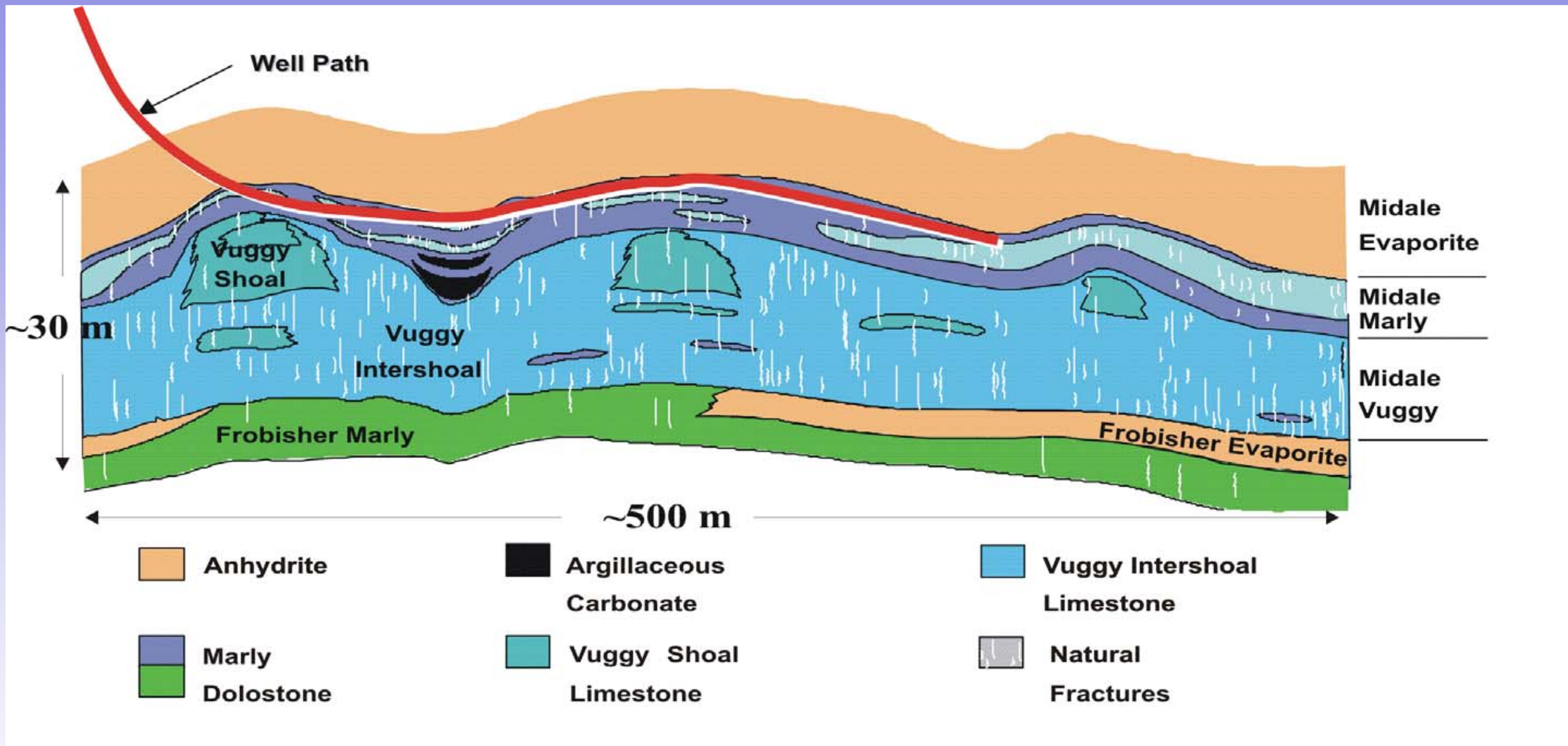
Operations Update (to Sept 1st, 2007)

- **Total CO_2 injection: 268 BCF (14 Mt)**
- **Source CO_2 injected: 205 BCF (10.9 Mt)**
- **Current CO_2 purchase is: 125 MMscfd (6600 tonnes/d)**
- **CO_2 and associated gas being recycled 60 MMscfd (3200 tonnes/d)**
- **2007 infill drilling, 56 wells**
- **Of the 395 producing wells in the EOR area:**
  - **275 producers experienced operational response (CO_2 detected in casing gas)**
  - **150 producers experienced incremental production response**
- **Current Unit production 27,600 bbl/day**

Weyburn Field: Phase 1A EOR Area



The Reservoir (Fractured Carbonate)



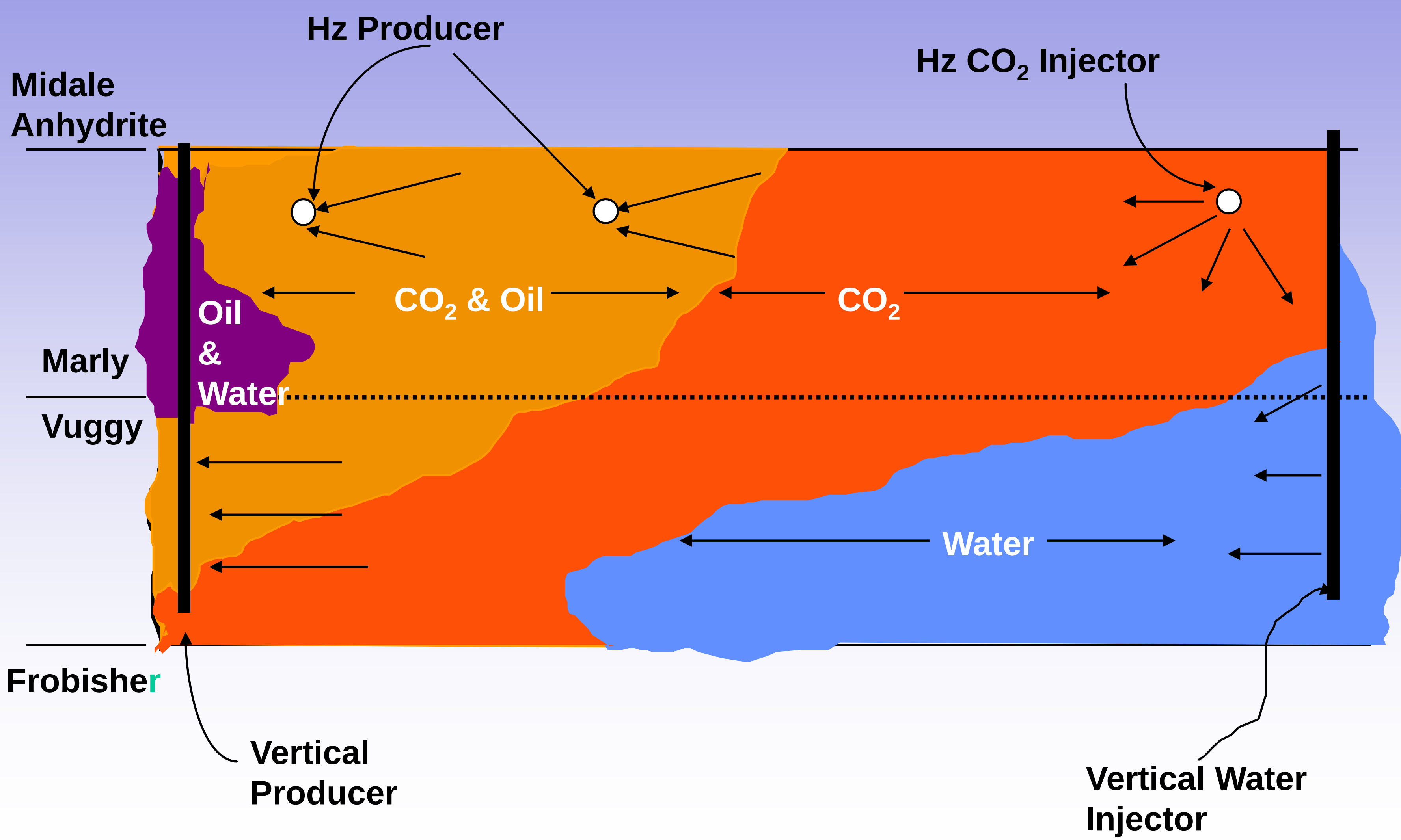
Reservoir: 1450 m depth, <30 m thick, T=63^{o} C, P=14 MPa

Anhydrite seal

Marly Dolostone: 6 m thick, 16-38% porosity, 1-50 mD perm

Vuggy Limestone: 17 m thick, porosity 8-20%, 10-300 mD perm

The CO_2 (Miscible) Flood



Properties of CO_2

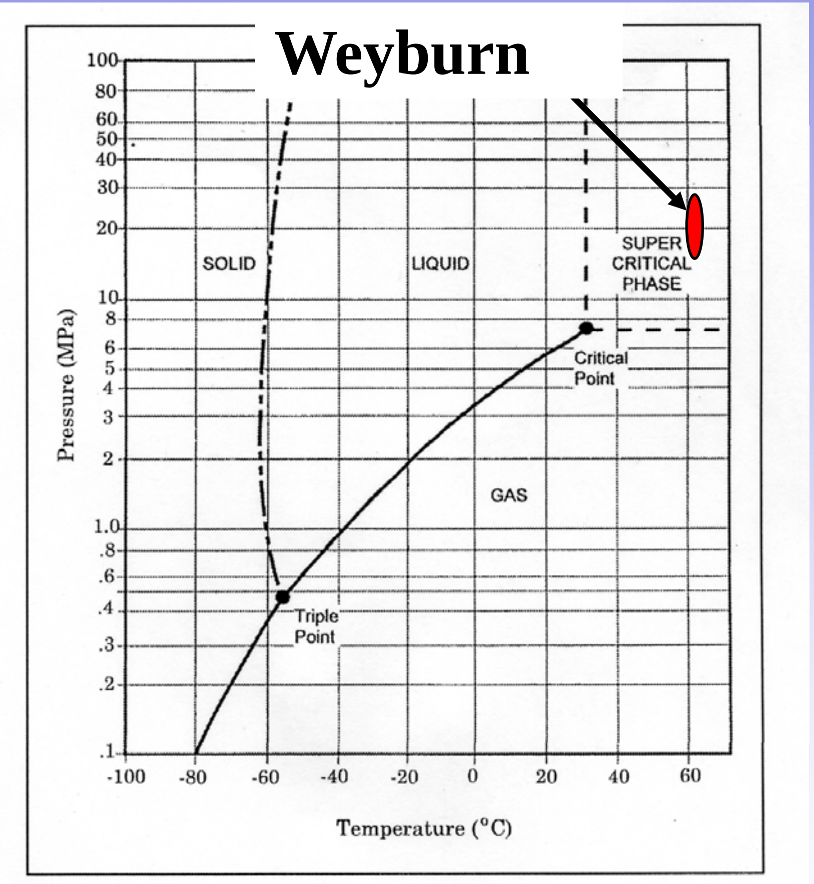
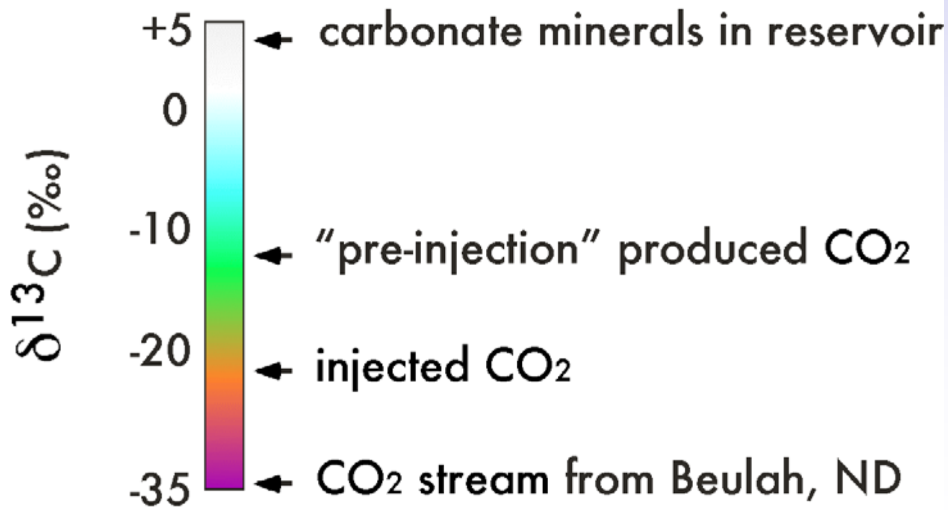


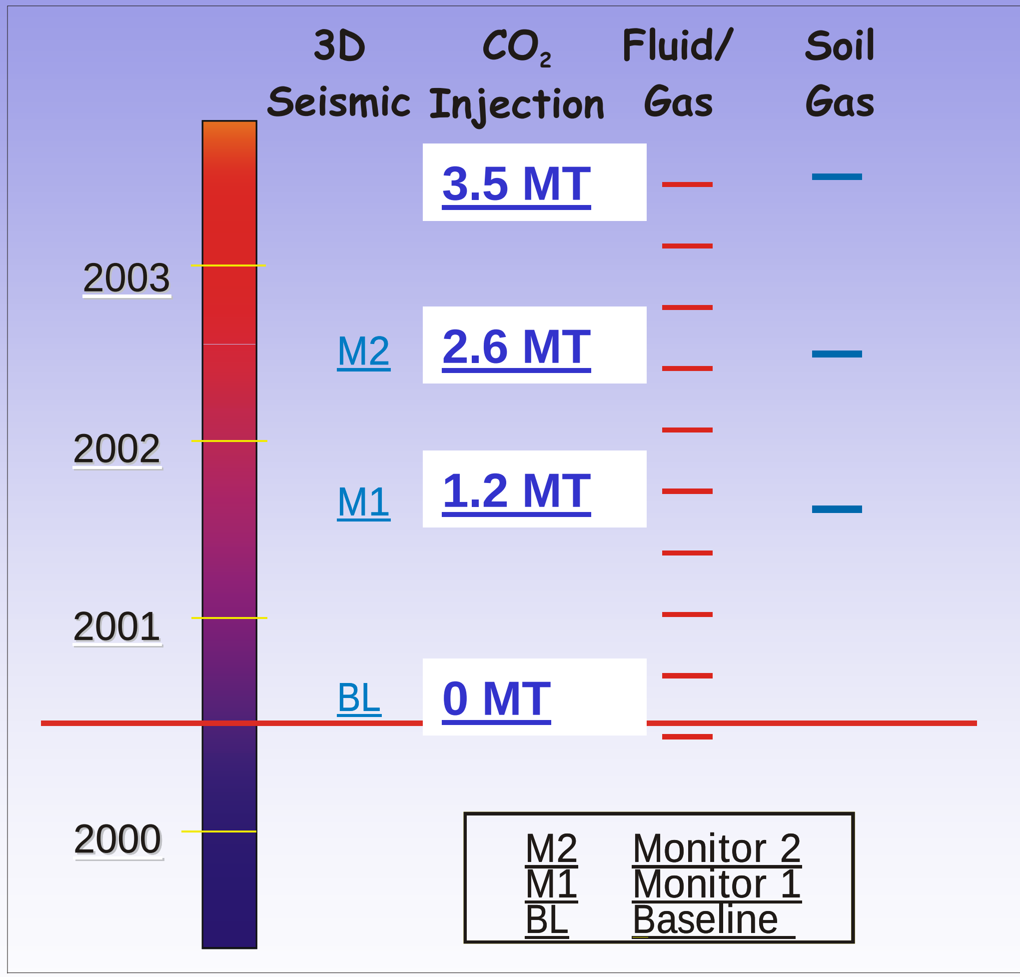
Fig. 4. Phase diagram for carbon dioxide.

Reservoir fluid properties (for P=15-25 MPa; T=63 deg C) summarized from Brown (2002).

Fluid	**Bulk Modulus** (GPa)	**Density** (gm/cc)	**Viscosity** (relative to oil)	**Solubility of CO2** (molar %)
Oil	1.2-1.7	0.80-0.88	1	66
Brine	2.7-3.2	1.02-1.08	~1/10	1-2
CO_2	**0.05-0.18**	0.58-0.76	1/70	100



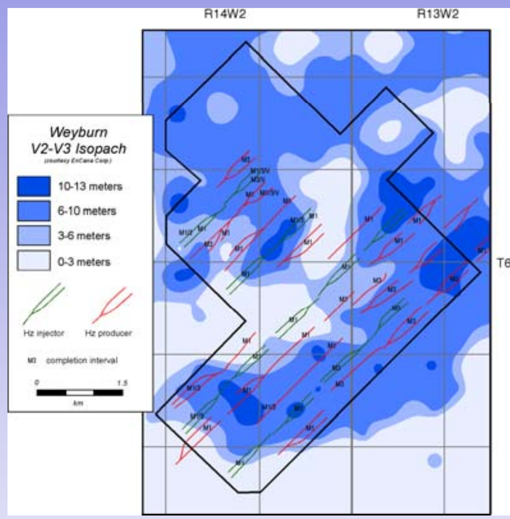
Monitoring Schedule



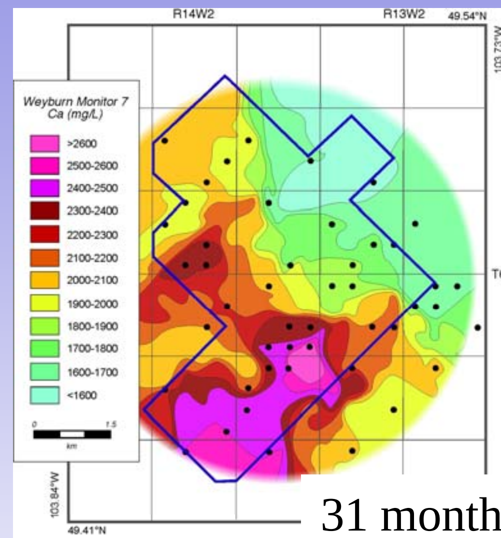
Phase I Monitoring Techniques

- Production Data
- Geochemistry of Production Fluids/Gases
- 3D Multi-component Time-Lapse Seismic
  - PP, PS, SS
- Passive Microseismic Monitoring
- Horizontal X-well tomography
- VSP & Vertical X-well tomography
- Magnetotellurics
- Soil Gas Sampling

Injected CO_2 and Reservoir Reaction Follow the Vuggy



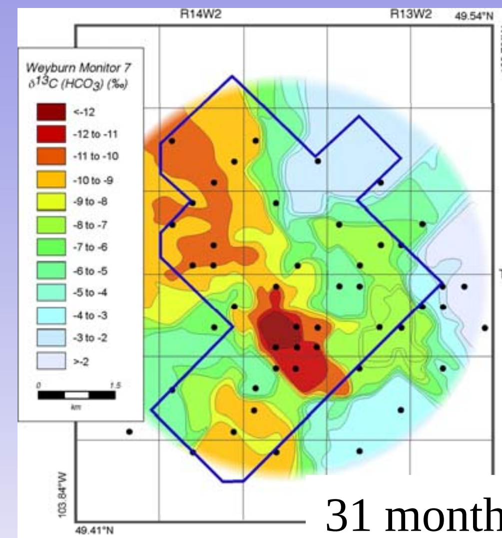
V2+V3
Vuggy Shoal



31 months

Ca Distribution

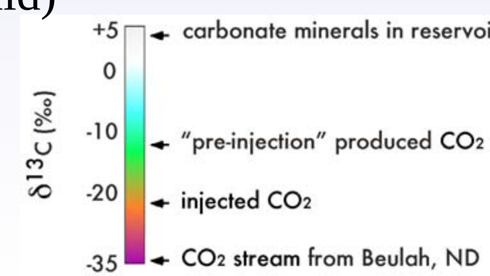
Calcite and dolomite dissolution increases the Ca^{2+} and Mg^{2+} concentrations in produced fluids.



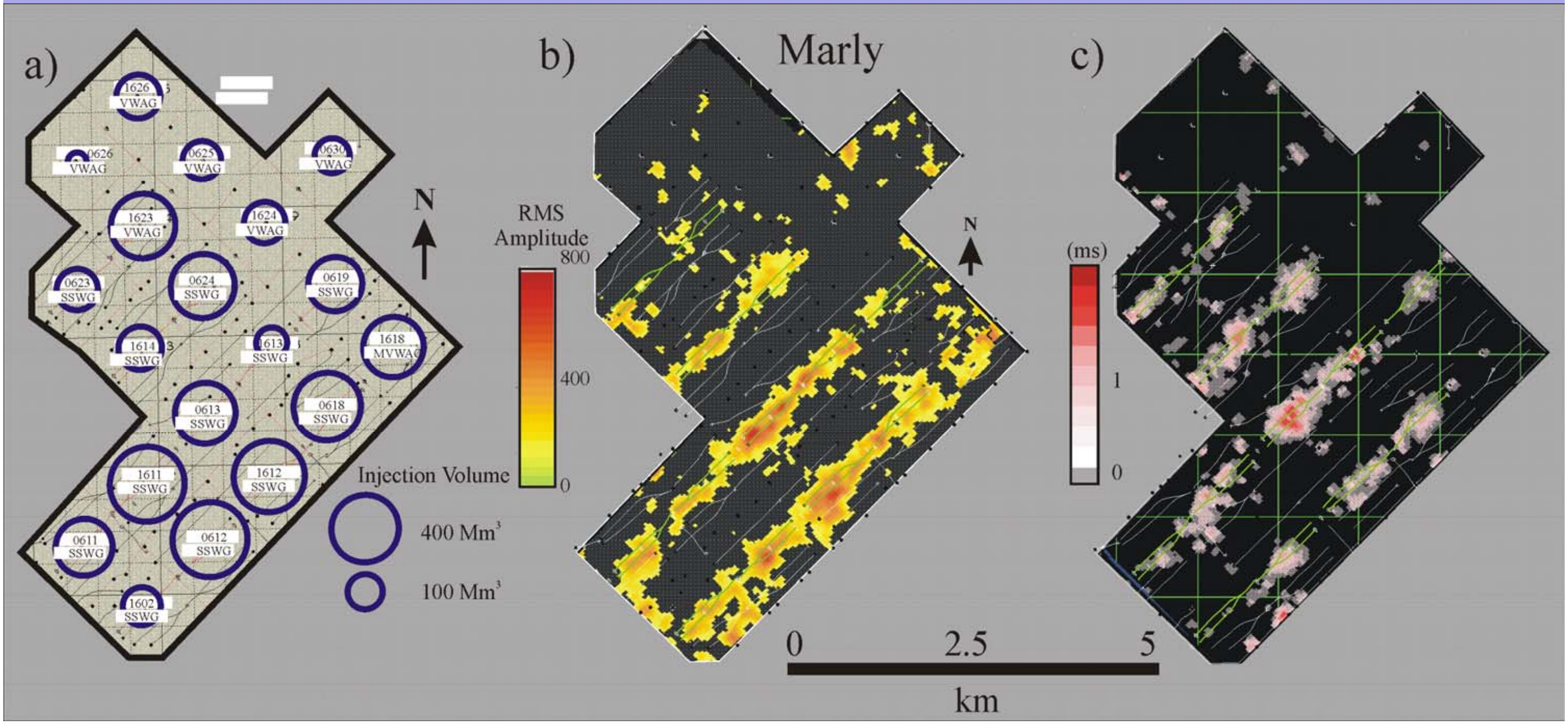
31 months

$\delta\ ^{13}C$ Distribution

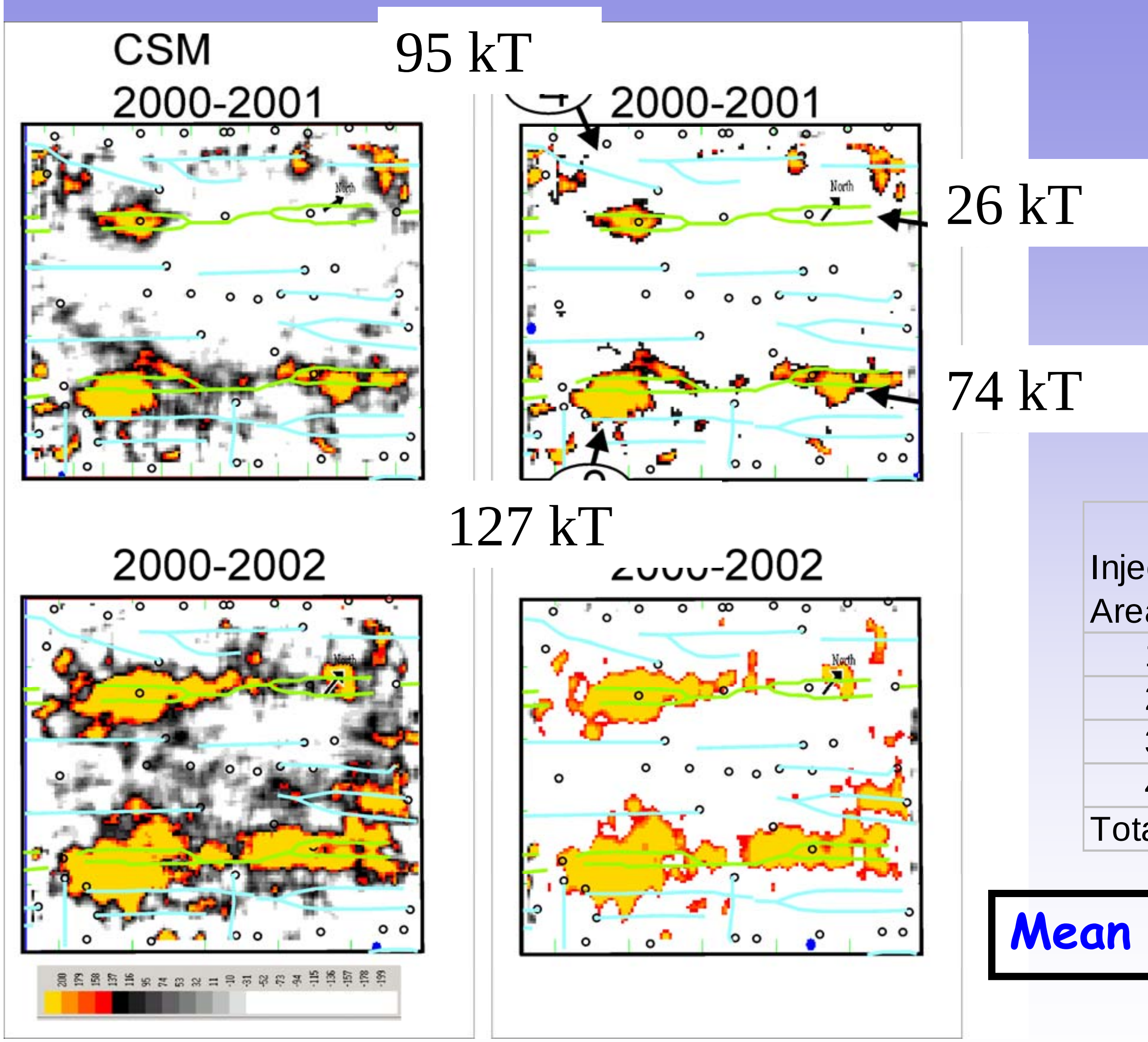
Injected CO_2 dissolution (decreasing $\delta^{13}C$ in produced fluid)



Monitor 2 Production-Seismic Comparison



First-Order Volumetrics



<u>Reservoir Properties:</u>

T=63 deg C

P= 15 MPa

Porosity=0.13

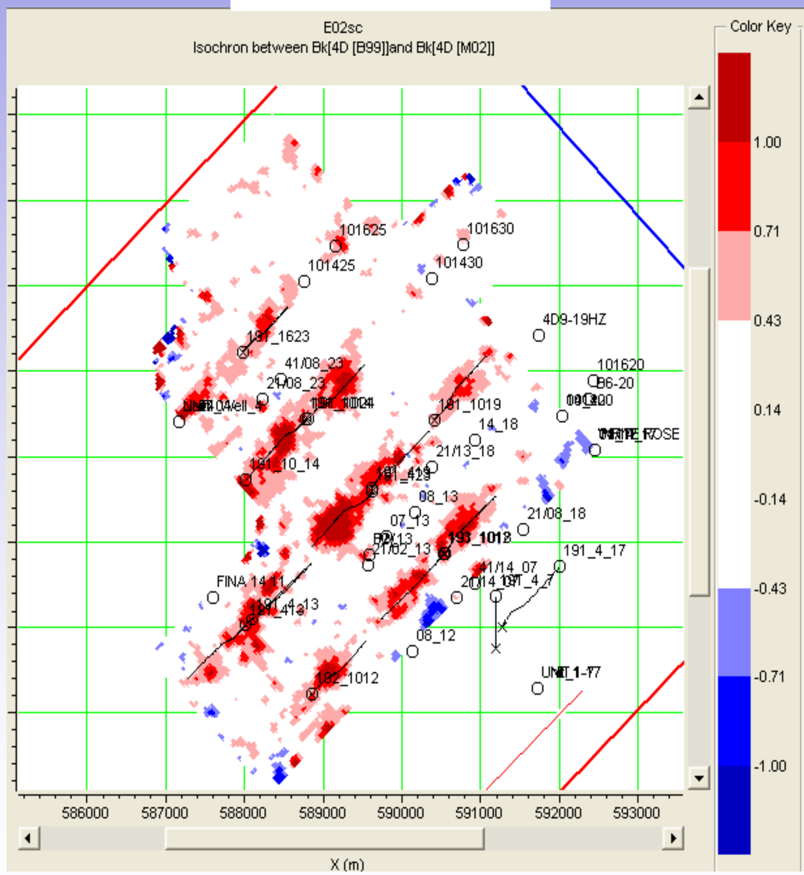
Thickness=23 m

Injector Area	2001 Seismic vol./CO2 vol. Ratio	2002 Seismic vol./CO2 vol. Ratio
1	5.3	6.3
2	8.6	12.6
3	5.4	6.2
4	3.1	4.0
Total	4.6	5.5

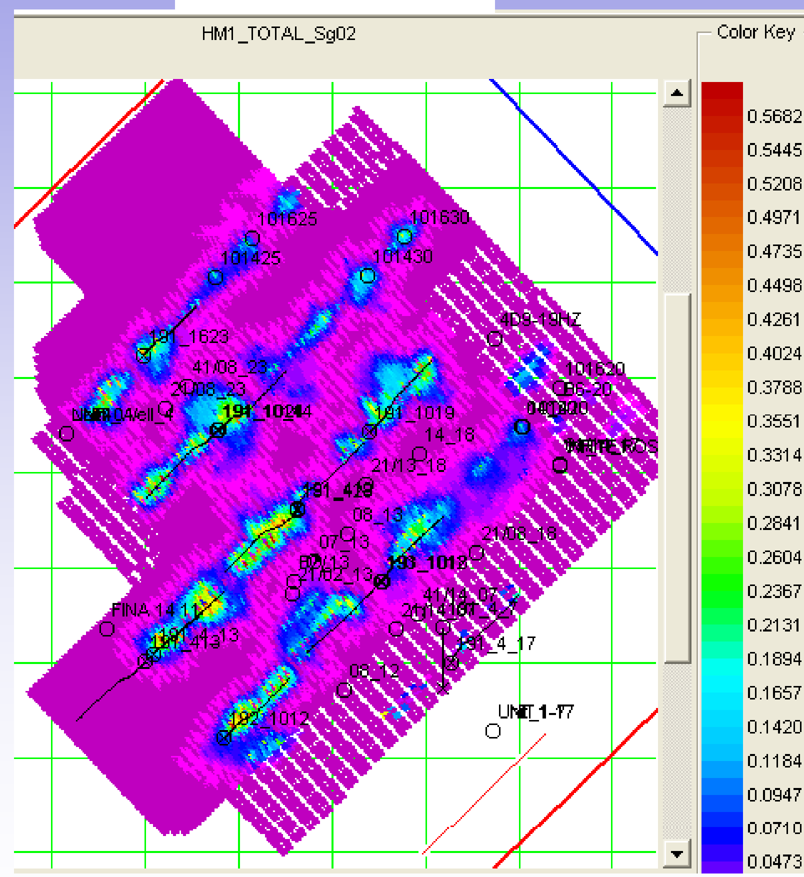
Mean Saturation=0.19-0.23

CO2 distributions from Seismic and Simulator, 1st iteration (Monitor 2 Survey)

Seismic



Simulator



0.5

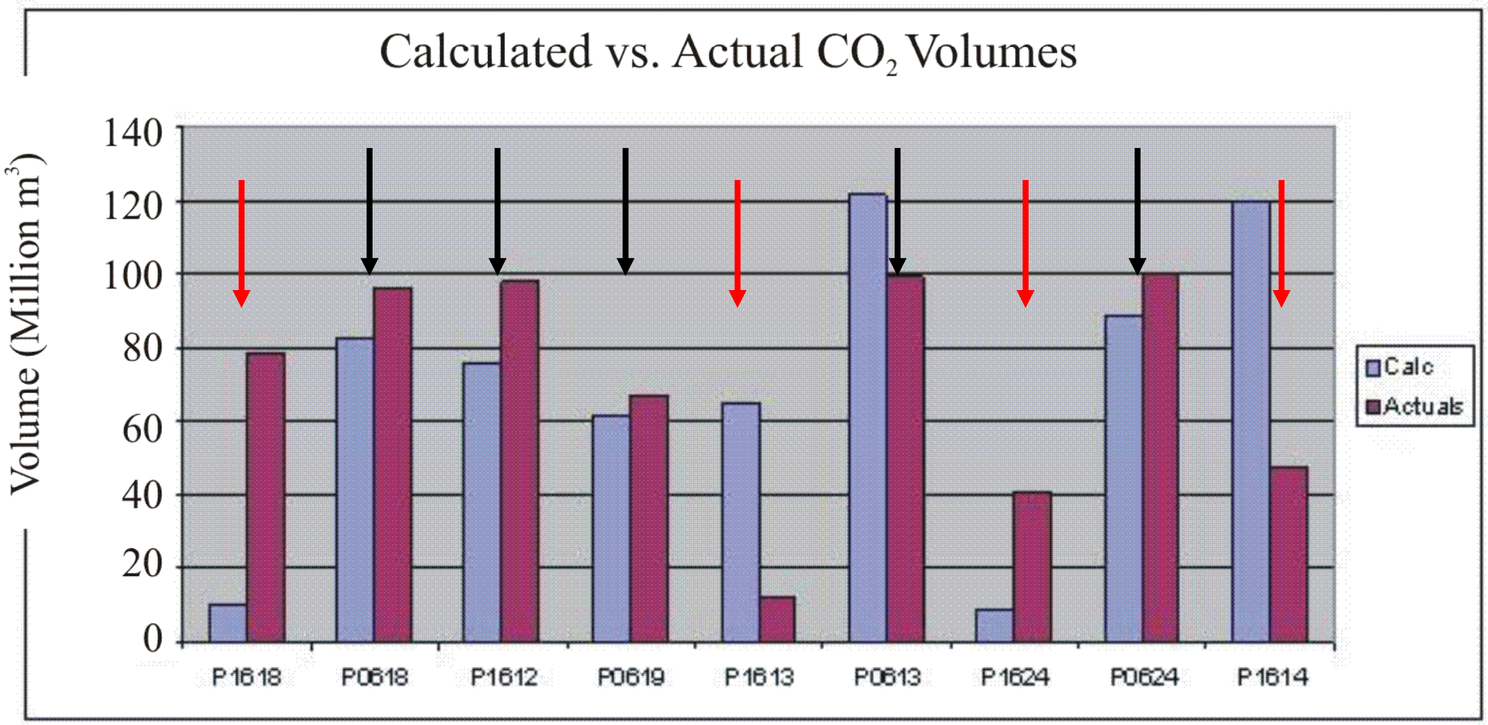
0.4

0.3

0.2

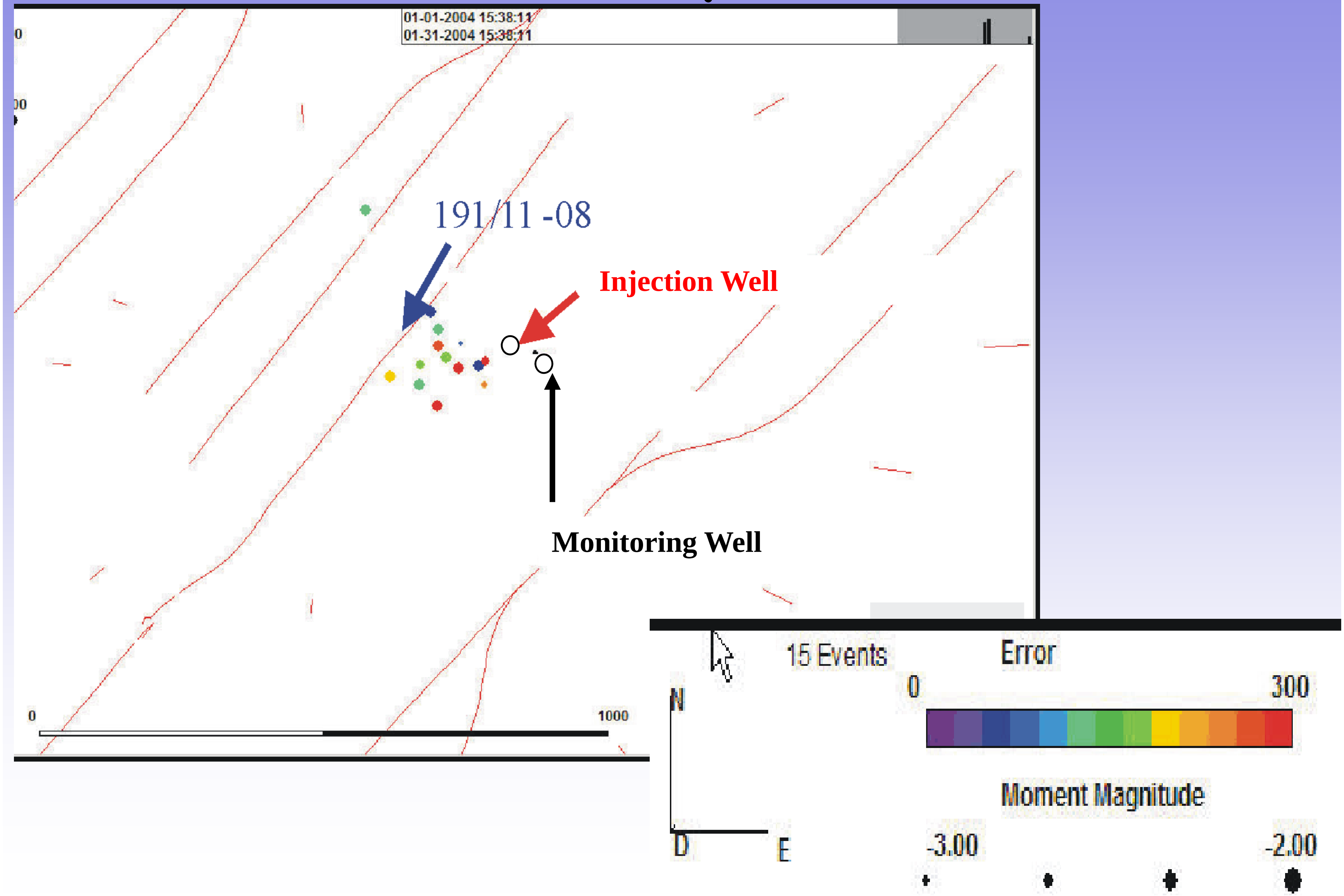
0.1

Net CO_2 injected vs seismic estimate



Assumes average Sg of 0.20

Microseismicity: Plan View



Phase I Results (in a nutshell)

- Monitoring methods clearly show **physical and chemical effects** associated with CO_2 injection.
- Map pattern **distribution of CO_2** at the reservoir.
- Seismic anomalies $\Rightarrow$ **mean S_{CO2} ~20%.**
- Seismic response is highly sensitive to **low S_{CO2} (5-10%)**; good for detection, but makes volume estimation difficult.
- ΔVp: **Sg <12%, P=2-3%**.
- Areas of **CO_2 channelling** (fracture systems?).
- Detection limit: **1.4 million m^3** (2500 tonnes) of CO_2 using time-lapse surface seismic.
- **No evidence of CO_2 escaping** from the reservoir from surface seismic .
- **Microseismicity is low**: 60 microseismic events at the reservoir level with M=-3 to -1 during 6-months.
- **Improved history-match** using seismic-constrained reservoir model.

Outstanding Questions from Phase I

- Role of fracture systems in controlling distribution of injected CO_2?
  - Verify by downhole measurements.
- Need for dual-porosity models to account for fracture permeability?
  - Compare single/dual porosity simulations.
- Can seismic estimates of CO_2 concentrations be improved?
  - Likely by:
    - Better saturation vs. pressure discrimination (in situ measurements; varying operating pressures)
    - Validated rock physics/fluid model (in situ measurements)
    - Accounting for reservoir heterogeneity (z, porosity, multi-phase fluid distribution)
    - Seismic-constrained reservoir simulation
- Can predictive capabilities of reservoir model be improved?
  - Likely, by continued time-lapse monitoring

Weyburn-Midale Timeline

- 2000-2004 Phase I
- 2005-2006 The Lost Years
- 2007-2010 Final Phase

Final Phase Program Guidance

- Knowledge gaps from Phase I
- Recommendations from an IEA Expert Review Panel
- IPCC Special Report on CCS

Final Phase Technical Research Program

IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project

IEA GHG
WEYBURN-MIDALE
CO_2 MONITORING
AND STORAGE PROJECT

Final Phase Program Themes

- Geological Integrity
- Wellbore Integrity
- **Storage Monitoring Methods**
- Risk Assessment; Storage Trapping Mechanisms; Remediation Measures; Environment, Health, and Safety

Final Phase Monitoring Objectives

- Monitor **CO_2 volume, distribution, concentration and leakage** from the reservoir.
- Monitor levels of **induced microseismicity** due to CO_2 injection.
- Assess the **economy, accuracy and applicability** of monitoring methods.
- Determine the need for monitoring technologies as a **function of time** and **estimated risk level**.

Final Phase Monitoring Workplan (Geochemistry)

- Shallow groundwater sampling
- Soil gas sampling
- Fluid sampling
- Hydrocarbon sampling
- In situ fluid sampling
- Integrated expt/model studies on reservoir core:
  - Study 1: fracture perm & two-phase flow
  - Study 2: fracture perm/alteration, process scaling
  - Study 3: fluid-rock interactions (batch/PFR)
  - Study 4: pore-scale mineral alteration
- Reactive transport modeling

Final Phase Monitoring Workplan (Geophysics)

3.1 New data acquisition

3.2 Data processing, analysis, inversion and modelling

3.3 Assessment of monitoring techniques and strategies

3.4 Integration of monitoring results

Final Phase Workplan: 3.1

3.1 NEW DATA ACQUISITION

3.1.1 3D-3C time-lapse seismic data acquisition

3.1.2 Passive seismic monitoring

3.1.3 Time-lapse well-logging

3.1.4 Downhole spinner surveys

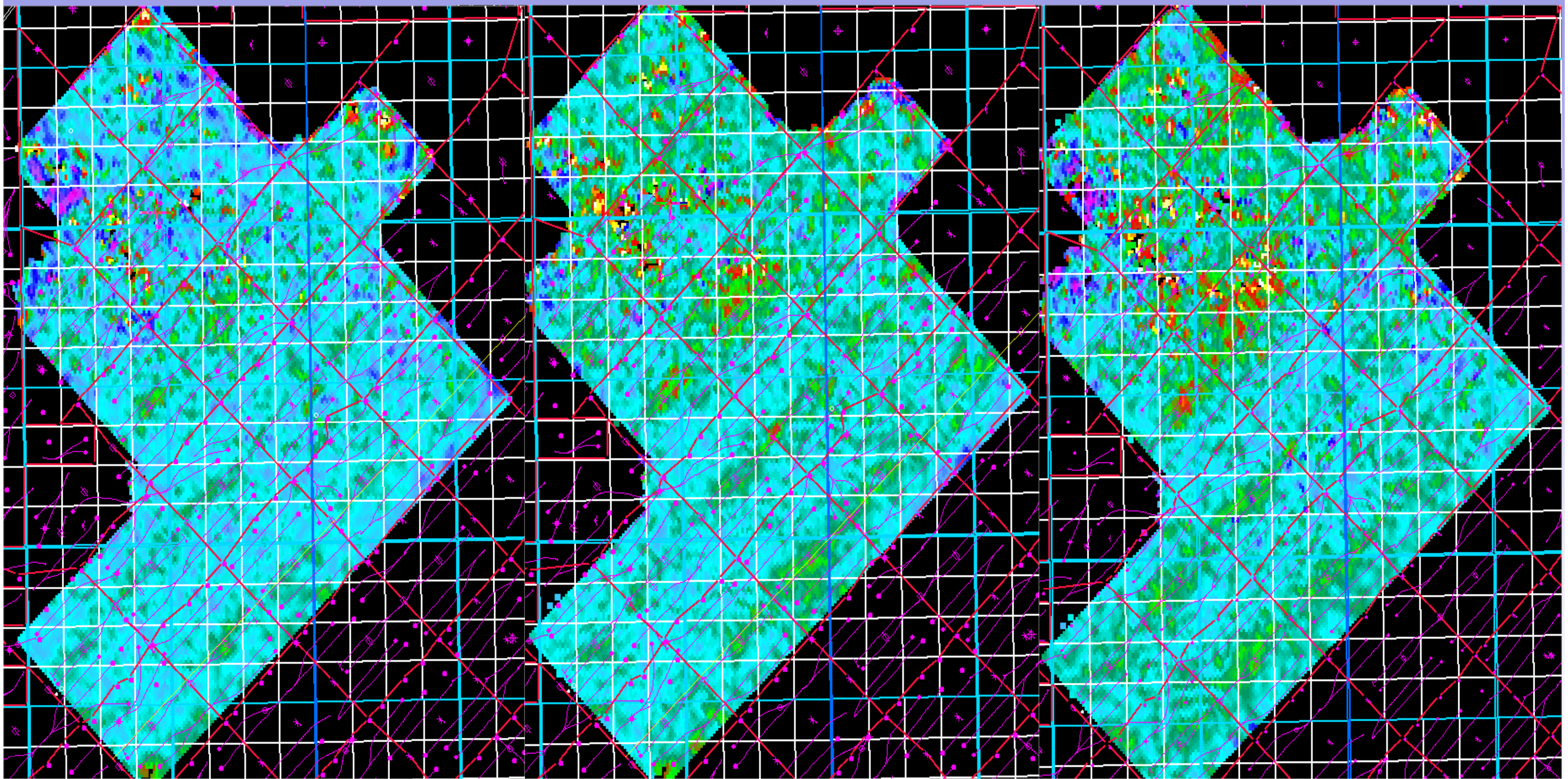
3.1.5 Well pressure measurements

3.1.6 Dedicated Seismic Monitoring System

3.1.7 Dedicated monitoring well

3.1.8 Electrical Resistance Tomography

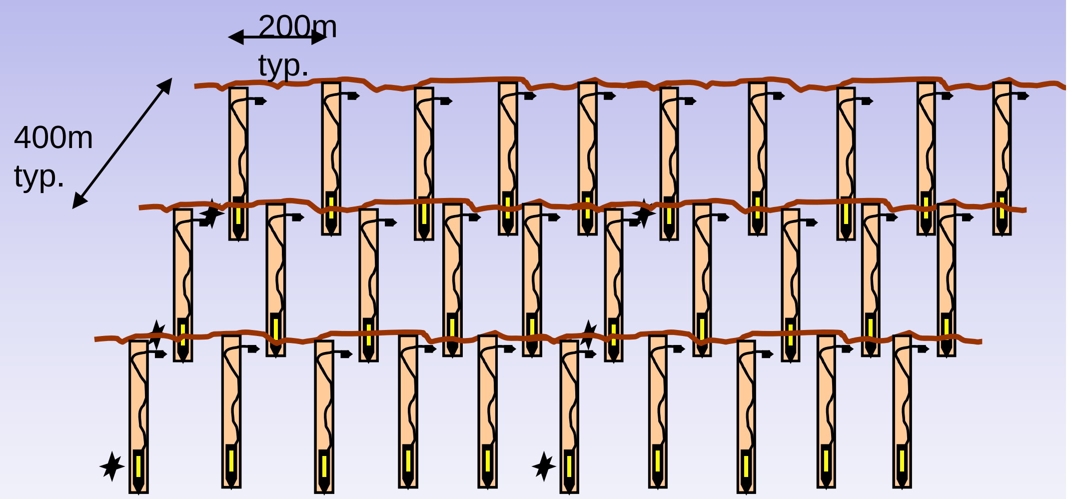
Tracking CO_2 Movement: Seismic Surveys (Baseline to 2004)- Phase 1



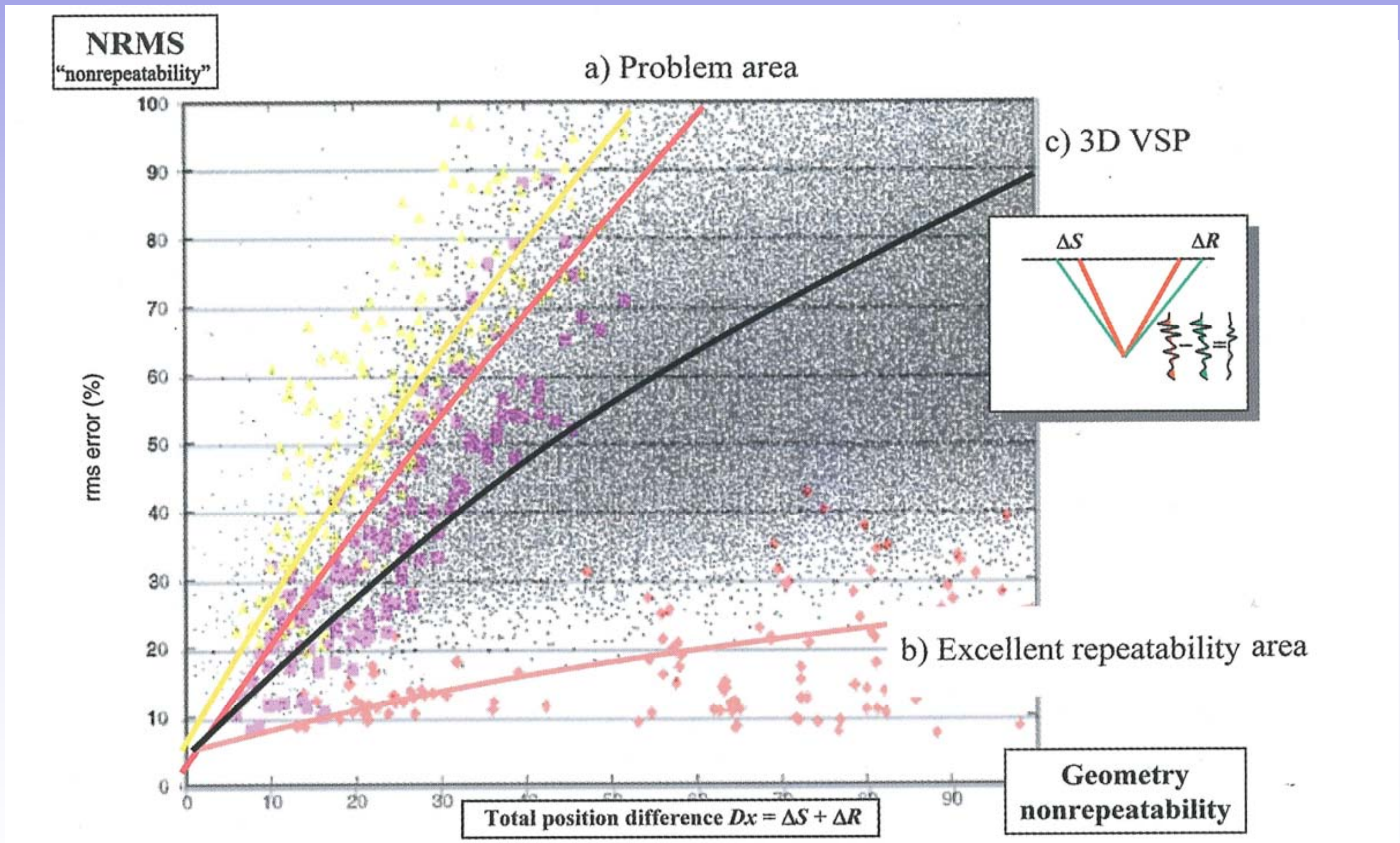
Baseline - 2001 Baseline - 2002 Baseline - 2004

Permanent/Semi Land 3C System

- REPEATABILITY!!
- Minimize near-surface coupling variations
- Eliminate positioning errors
- Repeatability allows sparse array
- Cost effective for long-term monitoring
- On-demand spot surveys

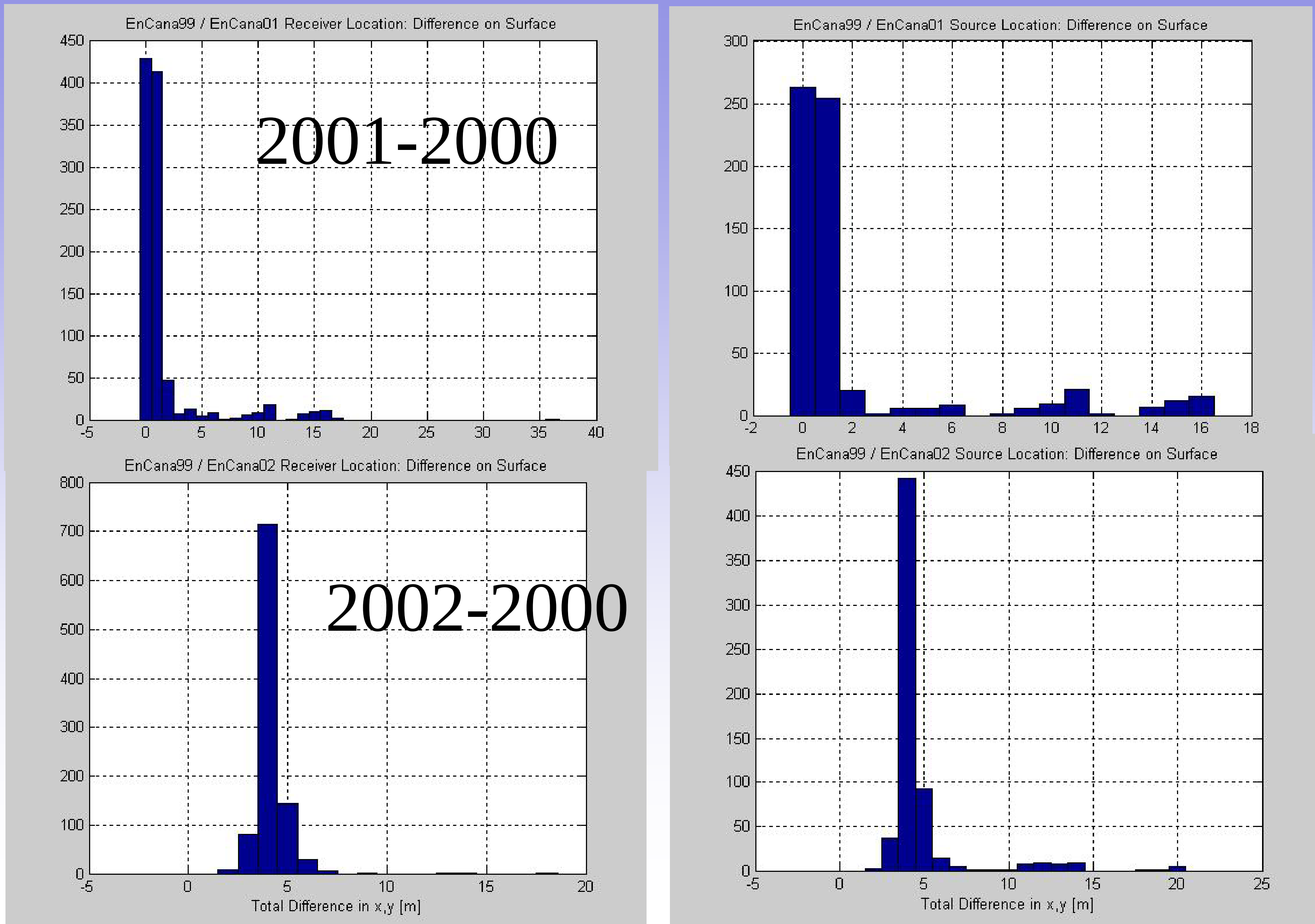


- **VSP Variogram**
  - **NRMS increases with Sum{shot + receiver separation}**



From Rodney Calvert, DISC No.8, 2005

Receiver/Source Location Differences



Final Phase Workplan: 3.2

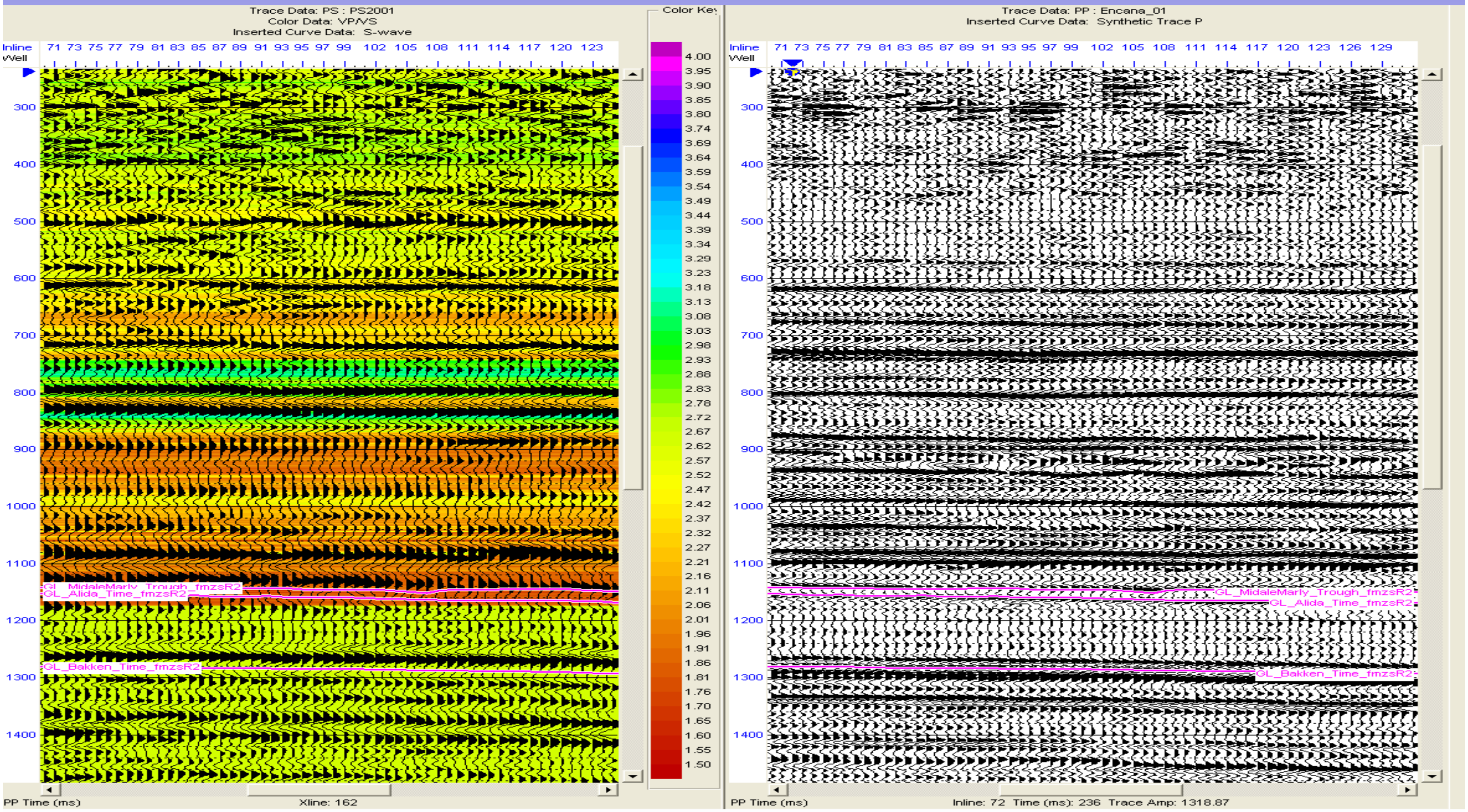
3.2 DATA PROCESSING, ANALYSIS, INVERSION AND MODELLING

3.2.1 Data reprocessing

3.2.2 Seismic modelling and inversion

3.2.3 Seismic-constrained reservoir simulation (see 3.4 Integration)

PS PP


Trace Data: PS : PS2001
Color Data: VP/VS
Inserted Curve Data: S-wave
Color Key
PP Time (ms)
Xline: 162
GL_MidaleMarly_Trough_fmzsR2
GL_Alida_Time_fmzsR2
GL_Bakken_Time_fmzsR2
Trace Data: PP : Encana_01
Inserted Curve Data: Synthetic Trace P
Inline: 72 Time (ms): 236 Trace Amp: 1318.87

Final Phase Workplan: 3.3

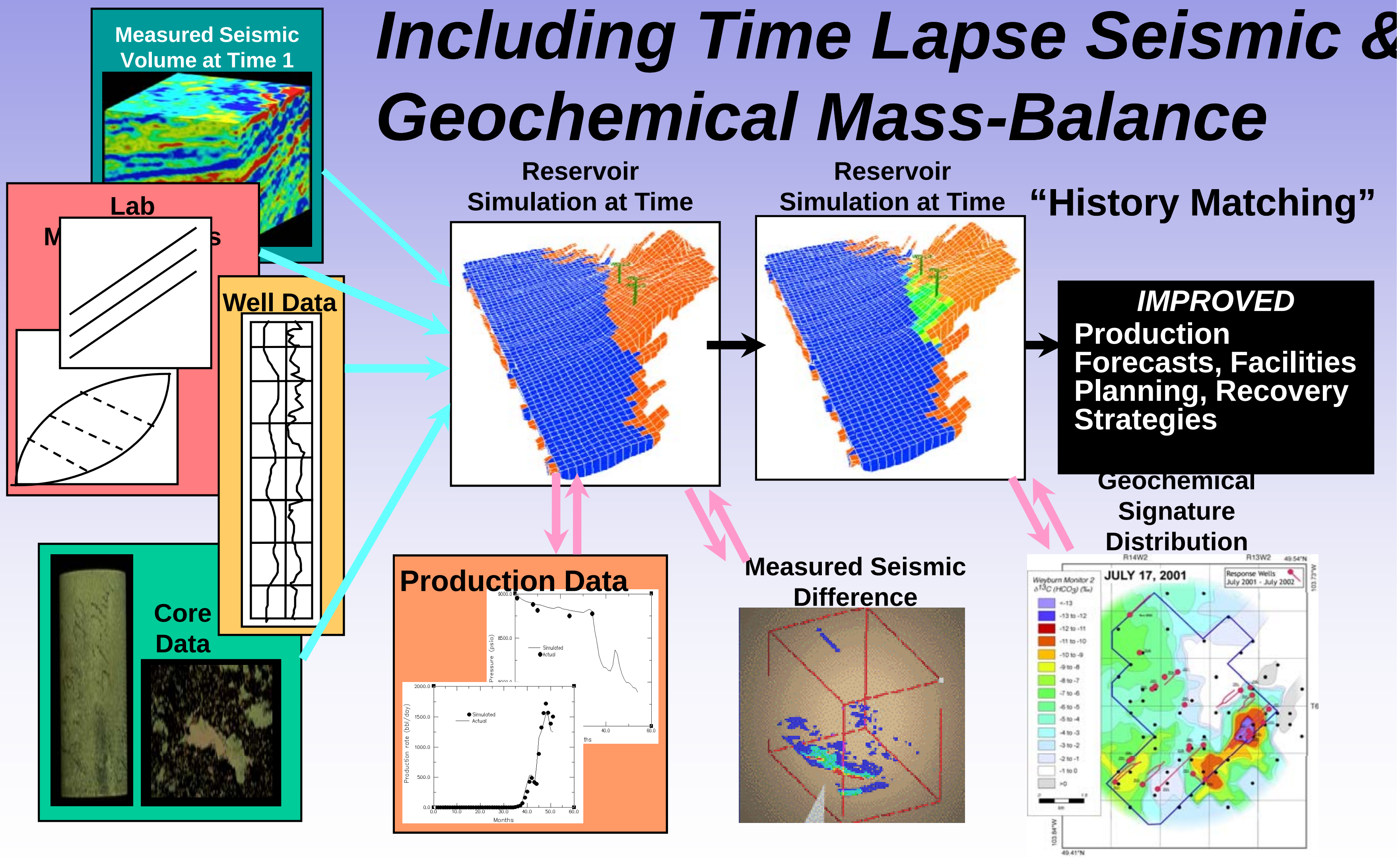
3.3 Assessment of Monitoring Techniques and Strategies

- **Evaluate applicability, effectiveness and limitations** of different surface and subsurface monitoring techniques.
- **Characterize the accuracy** of monitoring technologies.
- Identify the parameters and conditions that control accuracy of **predictive and quantitative capability**.
- Determine appropriate monitoring technologies needed as a **function of time and risk**.

Final Phase Workplan: 3.4

Reservoir Modeling and Flow Simulation

Including Time Lapse Seismic & Geochemical Mass-Balance



IEA Weyburn CO_2 Monitoring and Storage Project

An International Collaborative Research Program Led by the PTRC Based in Regina, Saskatchewan, Canada

ptrc
Petroleum Technology Research Centre

QUESTIONS ?

SPONSORED BY:

Natural Resources Canada **Ressources naturelles Canada**

Department of Energy, United States of America

NETL

EnCana

Saskatchewan Industry and Resources

AERI

European Commission

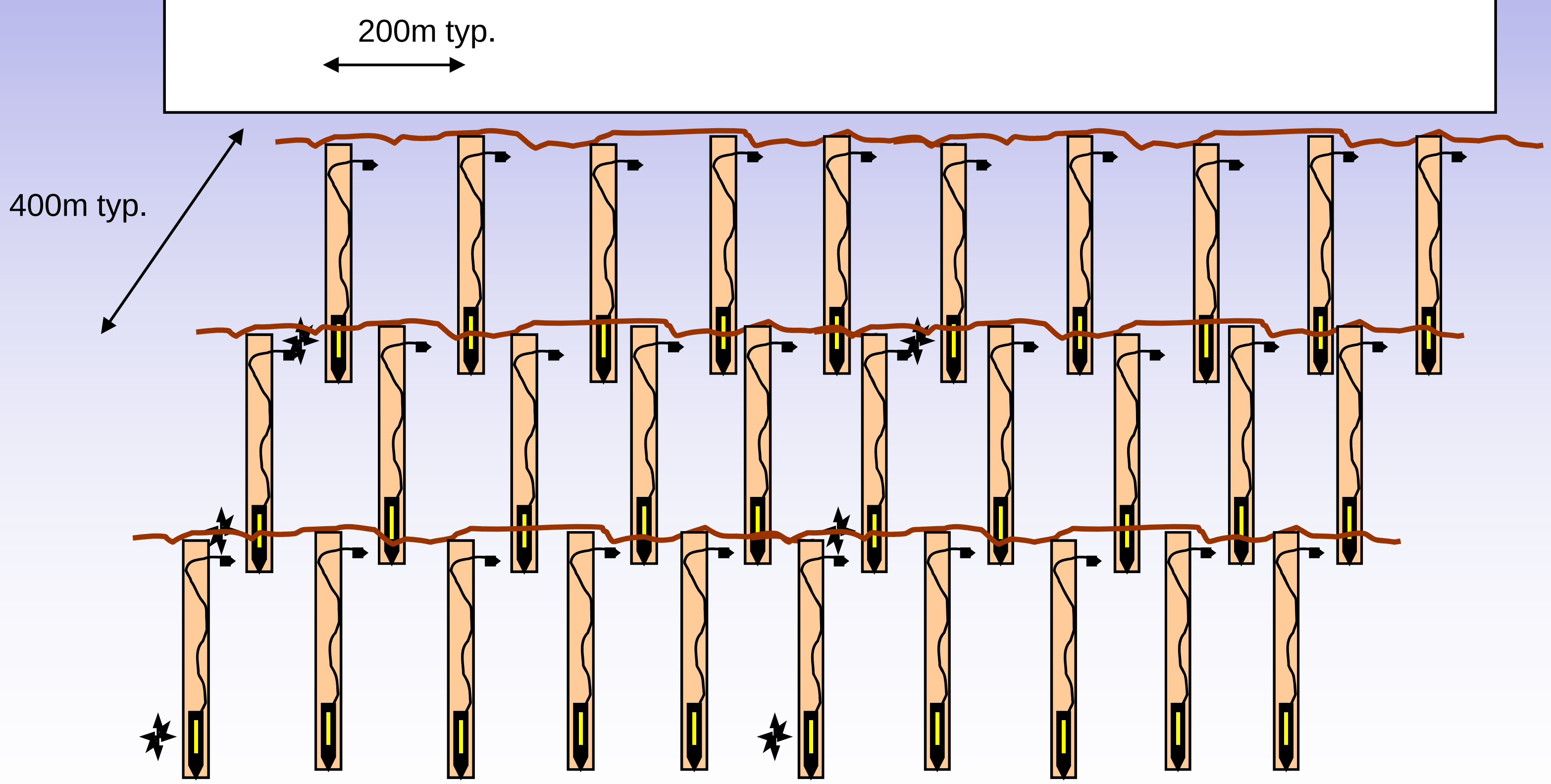
IEA Greenhouse Gas R&D Programme

As well as 8 Industry Sponsors:

BP, ChevronTexaco, Dakota Gasification Co, Engineering Advancement Association of Japan, Nexen Canada, SaskPower, Total and TransAlta Utilities Corp.

Buried 3C Digital Modules (example)

Oriented X-Comp in line of profile,
Z- vertical wrt hole



Acknowledgements (Phase I)

- Tom Davis, Colorado School of Mines
- Keith Hirsche, Hampson-Russell Software
- Ernie Majer, Lawrence Berkeley National Laboratory
- Shawn Maxwell, Engineering Seismic Group
- Hubert Fabriol, BRGM
- Geoff Burrowes, Sandy Graham, Ryan Adair, David Cooper, David Hassan, Guoping Li, EnCana
- Ernie Perkins, David Law, ARC
- Ian Hutcheon, Maurice Shevalier, U. Calgary

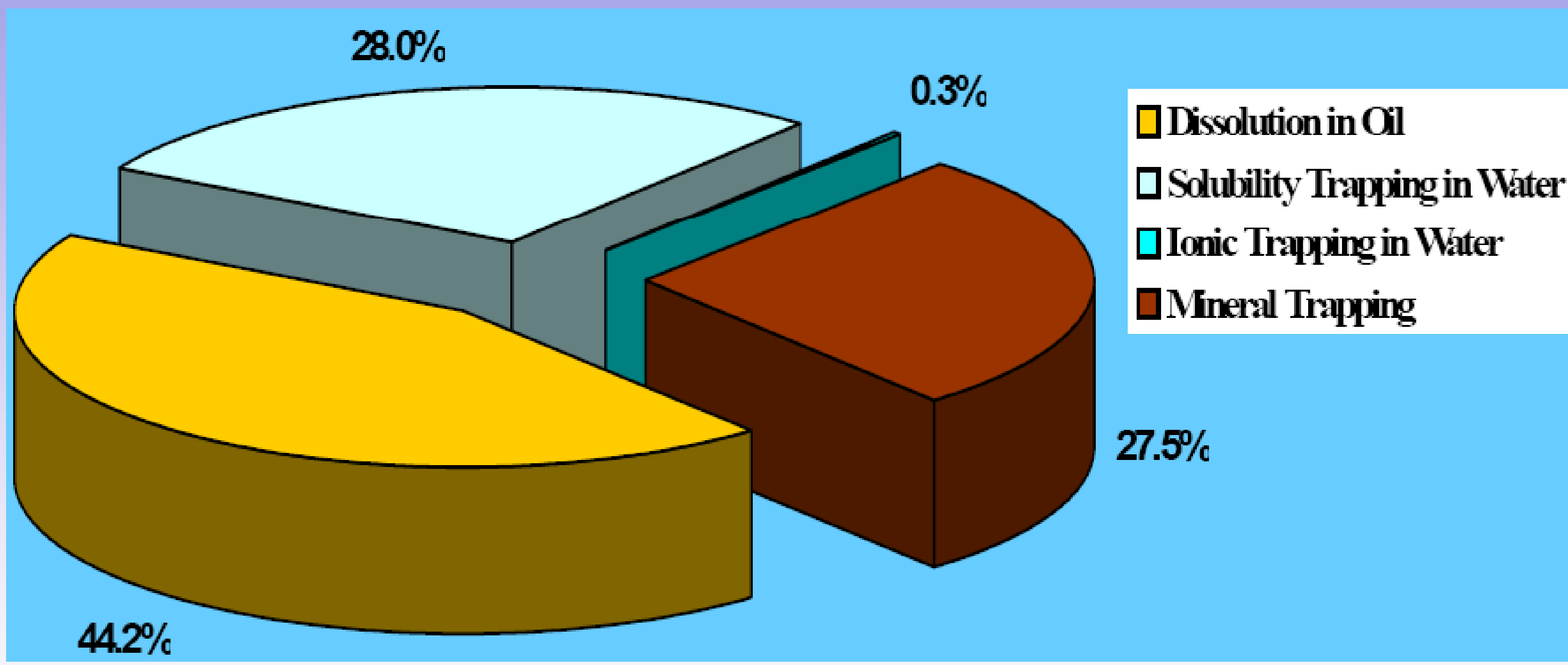
Further Research: Refinement of Techniques

- **In situ measurements for verification of seismic responses.**
- **Improved link between seismic properties, reservoir conditions & reservoir simulation.**
  - Baseline reservoir characterization for improved CO2 volumetrics
  - Beyond thresholding; Quantitative use of seismic anomalies. Requires appropriate rock-fluid physics model.
  - Seismic-based dual porosity reservoir simulation
  - Testing reservoir simulations by seismic response modelling
- **New time-lapse seismic monitoring:** Repeatable, efficient, flexible, economic, and continuous 3D multicomponent monitoring. A dedicated seismic array.
- **New analysis of existing data.**
  - Scenario testing by sub-sampling data sets
  - Reprocessing of converted wave (P-S, S-P) and pure-S data
  - Revisiting saturation-pressure using prestack analysis

4. Budget

Task	Cost (US K$)
3.1 New Data Acquisition	
3.1.1 3D-3D Time-Lapse Seismic Monitoring	2500
3.1.2 Passive Seismic Monitoring	350
3.1.3 Time-lapse well logging	200
3.1.4 Spinner surveys	200
3.1.5 Pressure measurements	100
3.1.6 Dedicated seismic array	500
3.1.7 Electrical Resistive Tomography	350
3.2 Data Processing, Analysis, Inversion and Modelling	
3.2.1 Data Reprocessing	300
3.2.2 Seismic modelling and inversion	400
3.2.3 Seismic constrained reservoir simulation	250
3.3 Technique Assessment	0 (cost assumed under 3.4 Integration)
3.4 Monitoring Integration	300
3.5 Total	**5450**

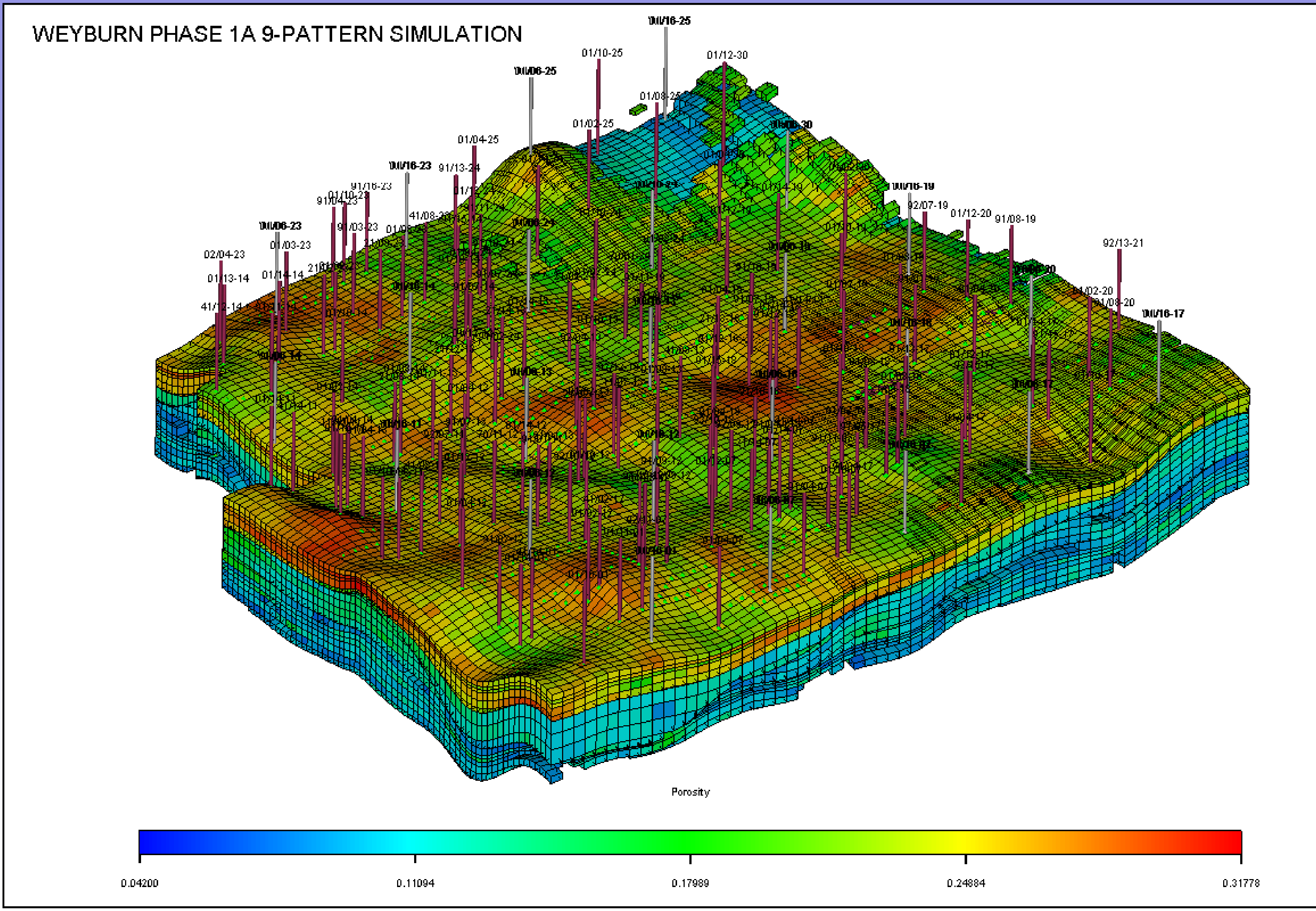
Trapping Mechanisms



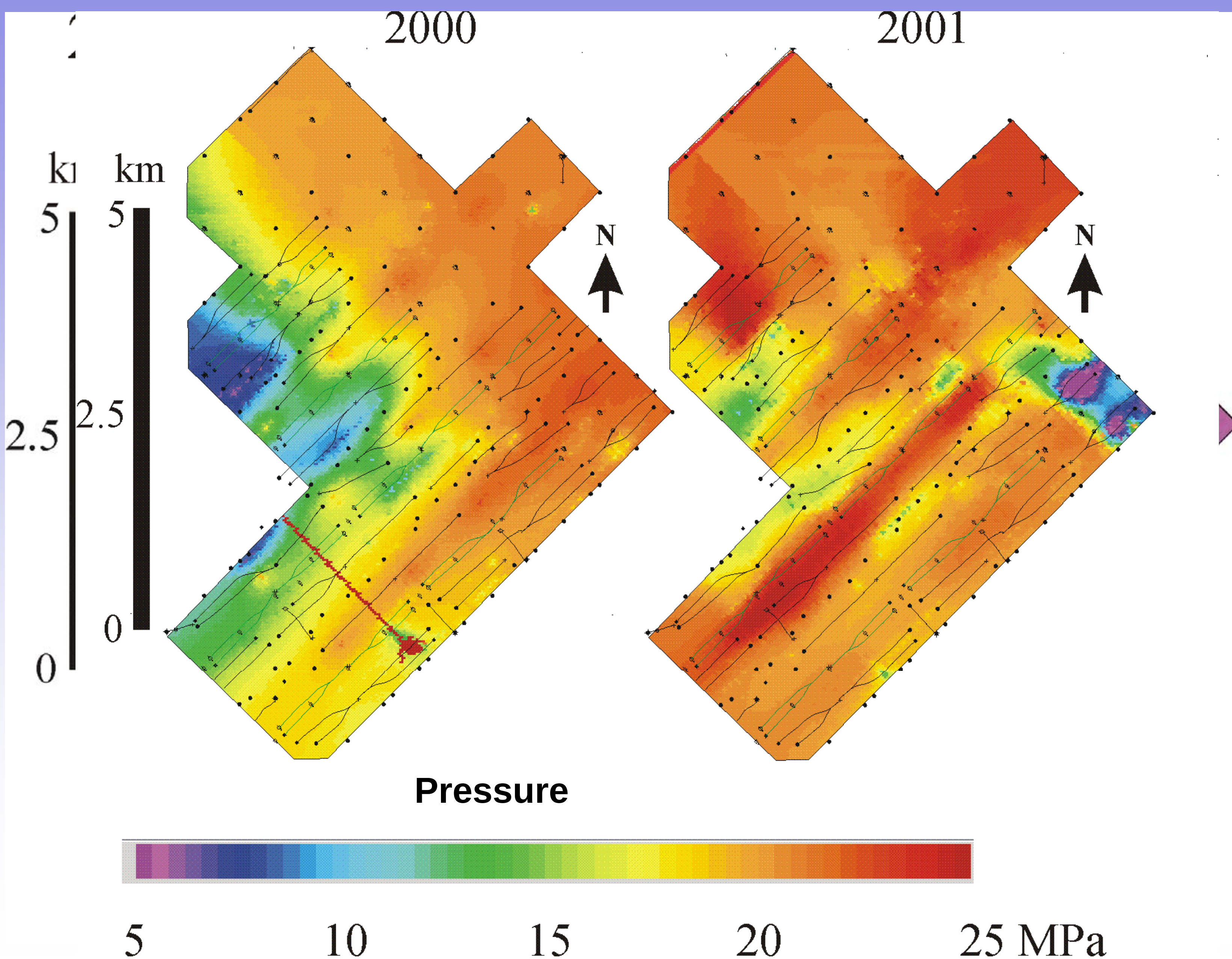
Role of Seismic Monitoring

- Reservoir Characterization for Injection Suitability
  - Structure and properties
  - Reservoir properties required to interpret time-lapse results.
- Long-Term Monitoring
  - Justified for EOR, but is it for long-term CO2 injection?
  - Yes. Costs of infrastructure justify reservoir management.
  - Suitable for assessing significant reservoir leakage.

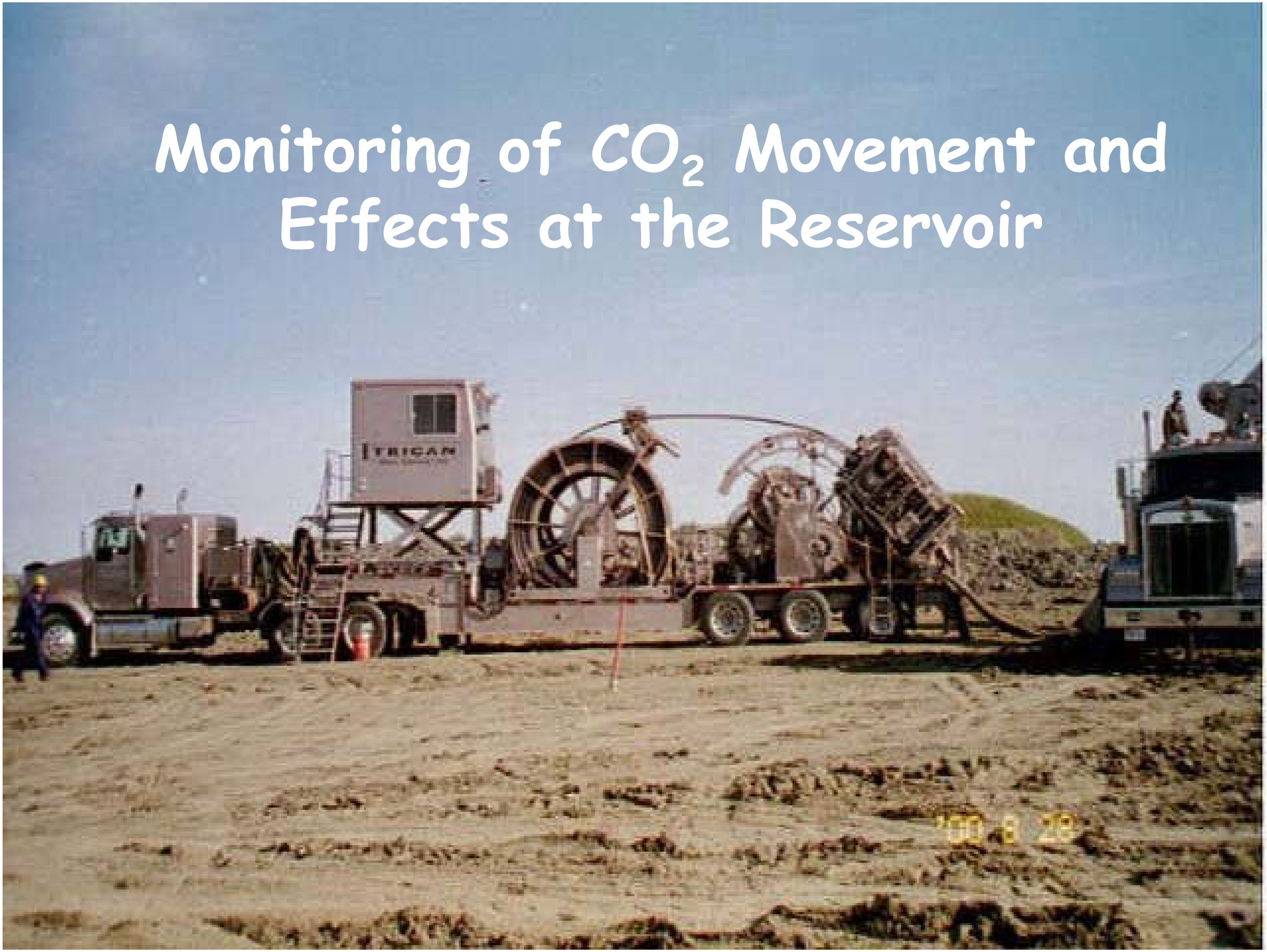
Pre-injection Prediction



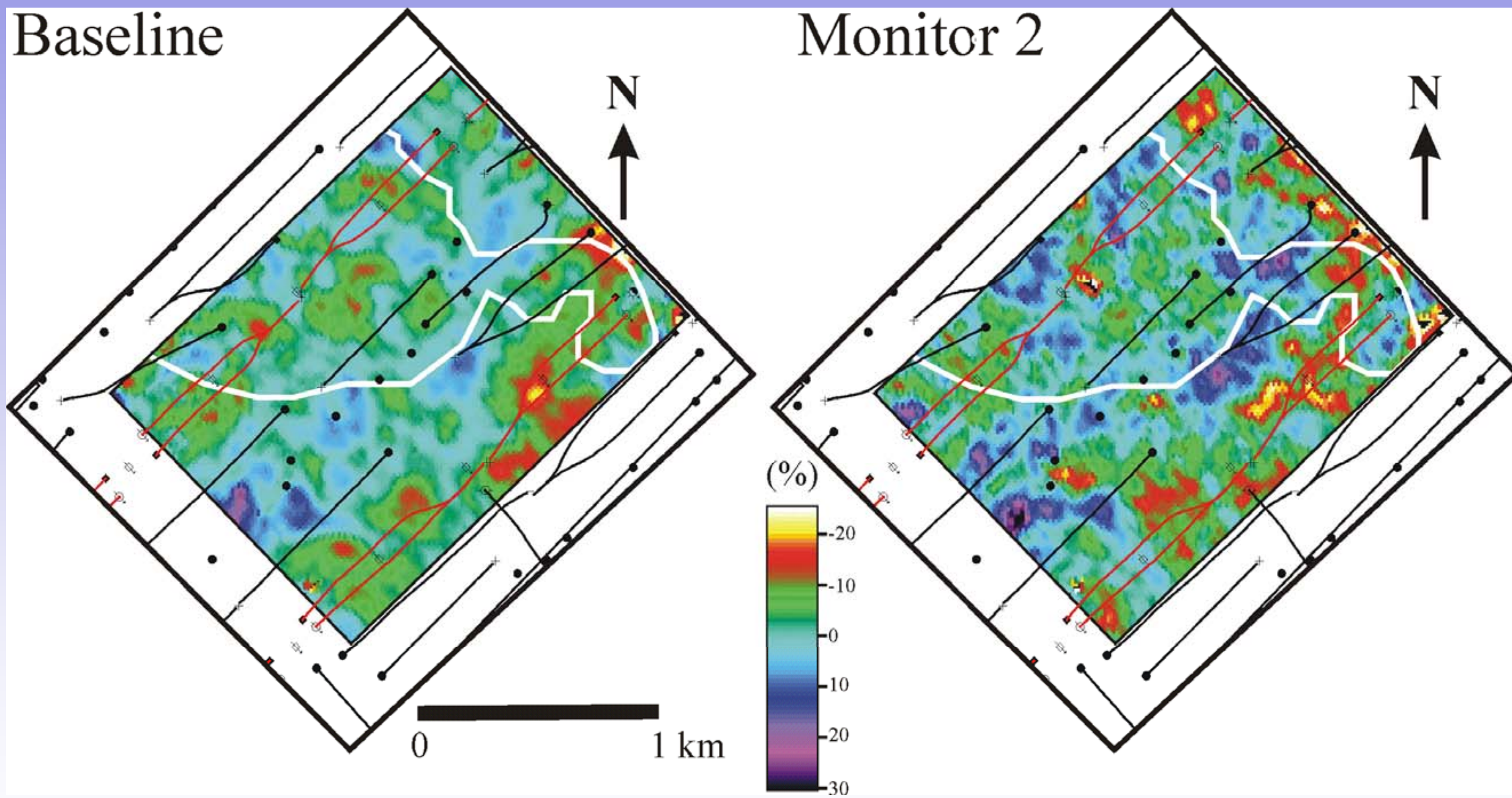
Pre-injection Prediction



Monitoring of CO_2 Movement and Effects at the Reservoir

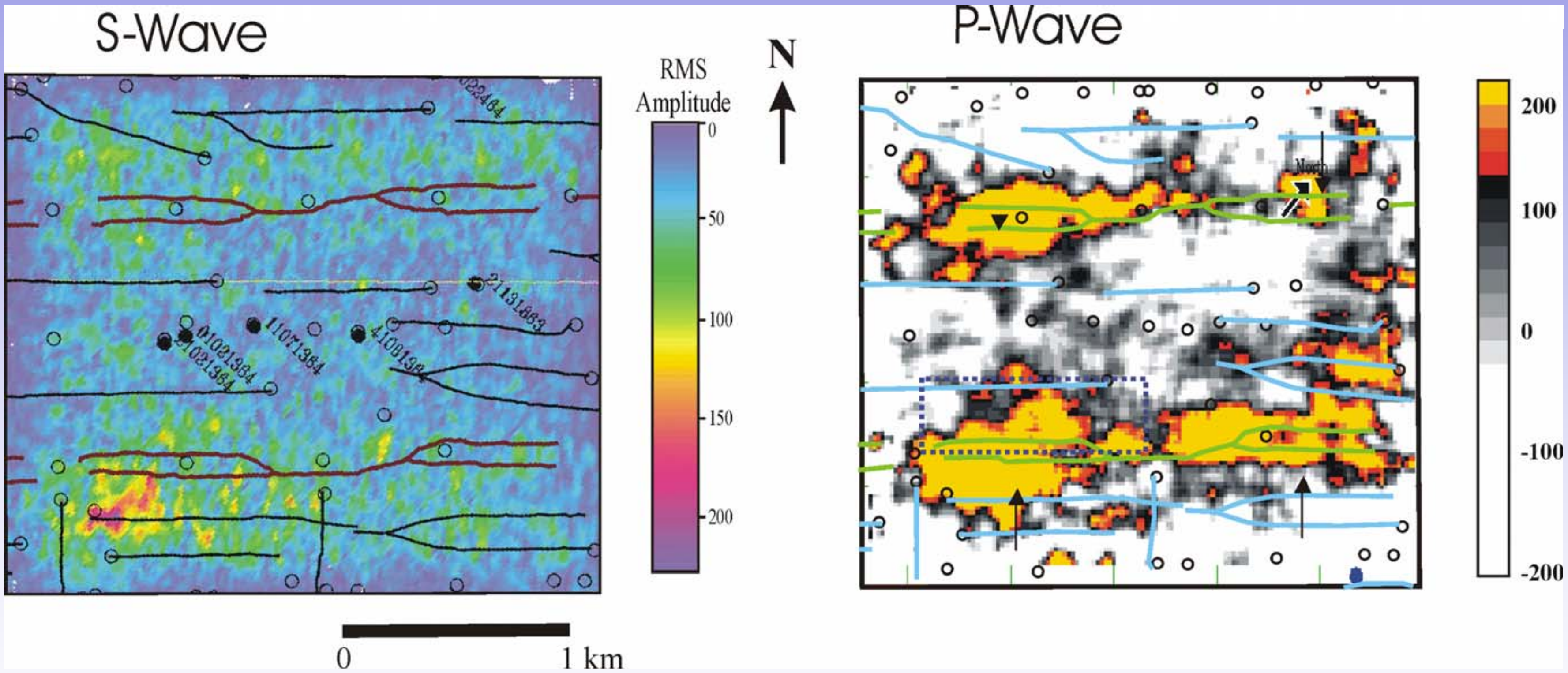


S-Wave Splitting



Saturation/Pressure Discrimination

S-wave vs. P-wave Amplitude Difference Anomalies



Phase I Objectives

- Test and **improve geological-based simulator predictions** of how the CO_2 flood will progress
- **Assess the chemical reactions** that form the predicted mechanisms for long-term storage of CO_2 within the reservoir
- Observe the **dynamic response of the reservoir** to CO_2 flooding
- Develop and demonstrate robust **methodologies for monitoring the CO_2 flood**
- Determine the **distribution and security of the CO_2** within the reservoir

Weyburn Phase I Research Themes

- Geological Characterization
- **Prediction, Monitoring & Verification of CO_2 Movement**
- CO_2 Storage Capacity, Distribution & Economics
- Long-Term Risk Assessment

Time-Lapse Seismic

- P- and S-Wave
  - pressure vs. saturation
  - fractures (S-wave splitting)
- Time delays & Amplitude differences
  - vertical discrimination

Downhole Fluid Recovery System (FRS) Deployment at PennWest CO_2-EOR Monitoring Project

Groundwater monitoring technologies for CCS projects

By
Gonzalo Zambrano
Geological Storage Research Group, University of Alberta

Outline

- Surface monitoring
- Downhole monitoring
- Downhole Fluid Recovery System Application at PennWest CO_2-EOR

Surface Monitoring

- Reservoir fluid sampling at ground level: Geochemestry of production fluid and gases (Weyburn)

CONSIDERATIONS

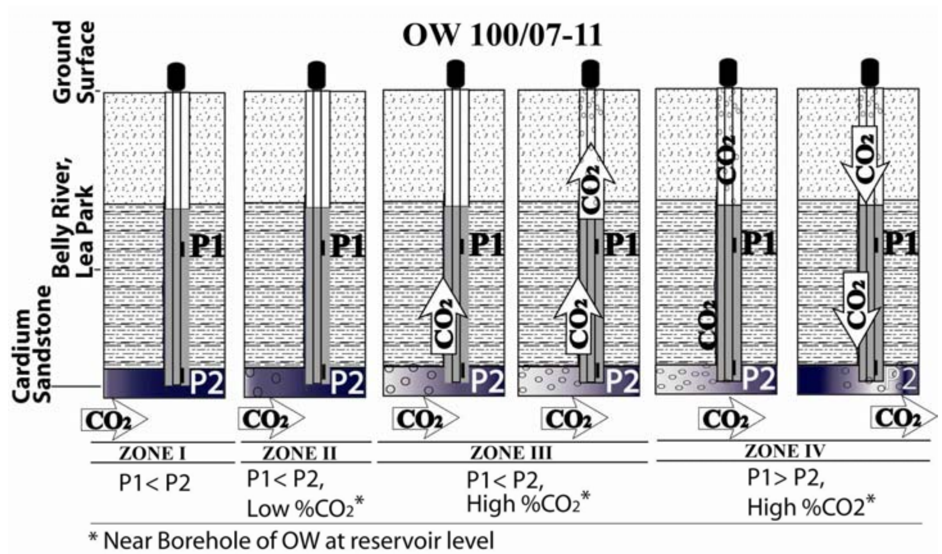
- Economic
- Portable laboratory equipment
- Depressurization effects and chemistry change

Downhole monitoring

Downhole sample ports

-Permanent Installation System

-Packer System



Zambrano, G. and Chalaturnyk, R. 2007

CONSIDERATIONS

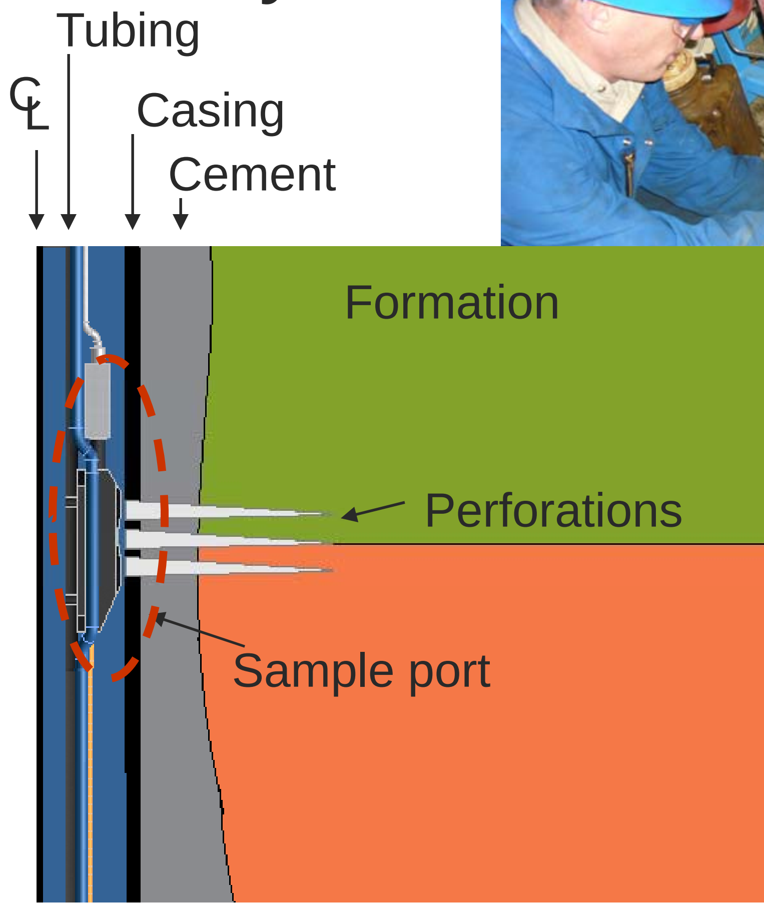
- High initial cost
- Well dedicated for monitoring
- Expertise in downhole installation

ADDED VALUE

- Sample at multiple horizons
  - @ reservoir level
  - @ Cap rock (seal) level
- Samples at in-situ conditions

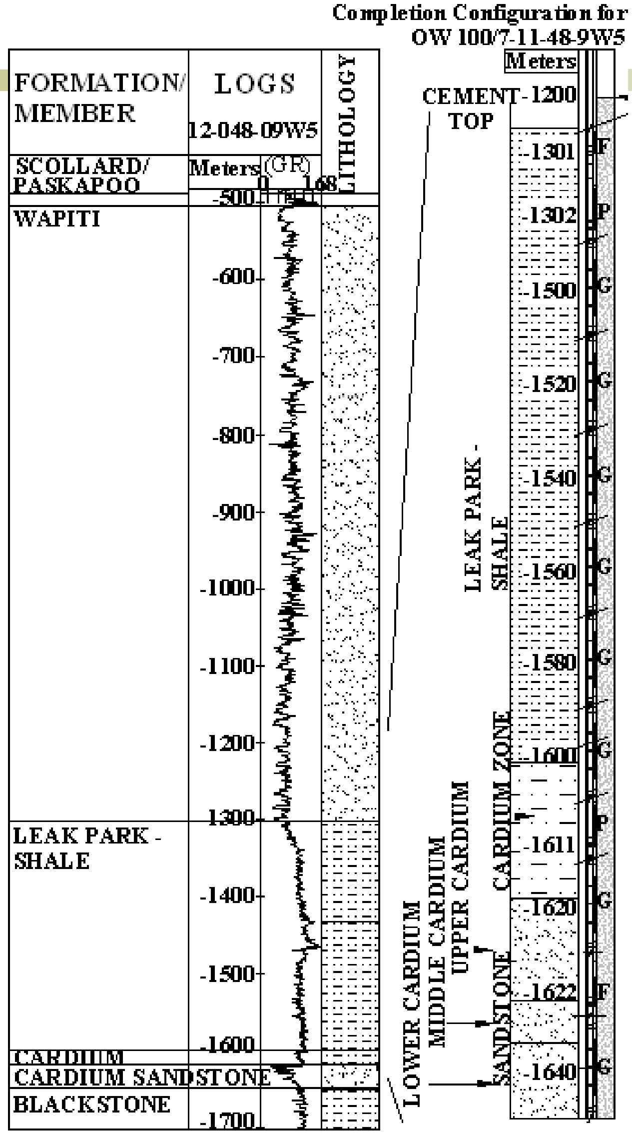
Downhole Monitoring Technology

- Permanent installation system

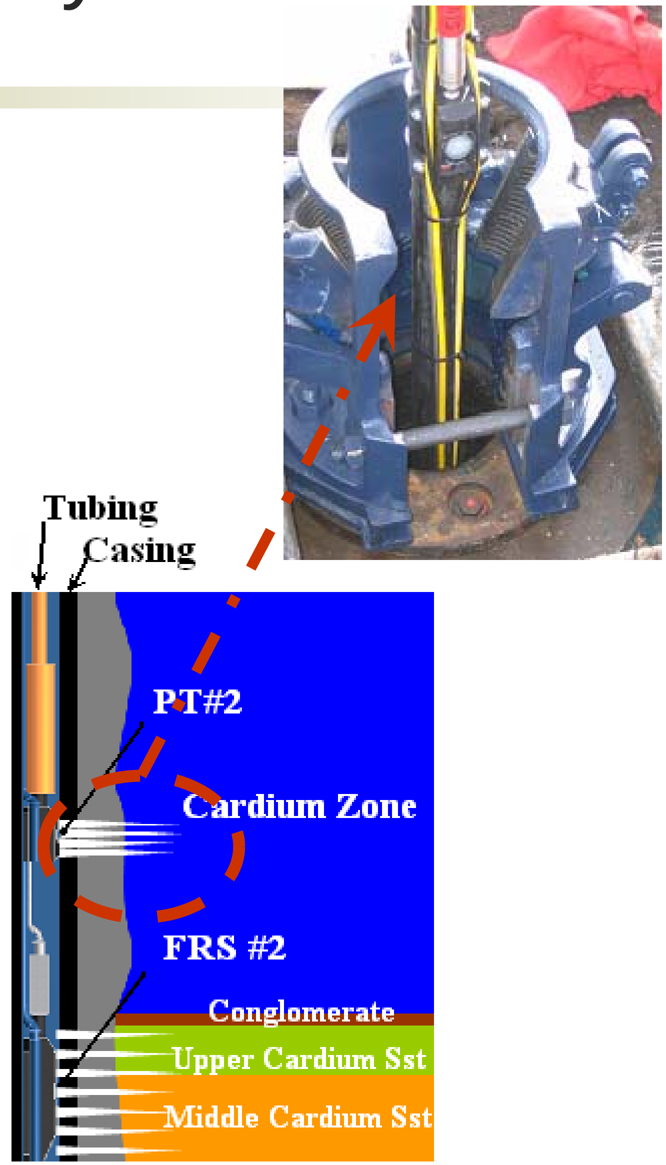


Zambrano, G. and Chalaturnyk, R., 2007

Permanent Installation of Multi-instrument System



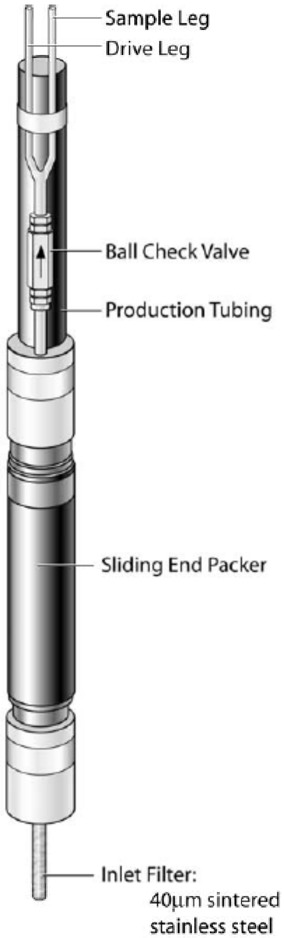
F: FRS sample port P: Pressure/temp. gauge
G: Geophone



Zambrano, G. and Chalaturnyk, R., 2007

Options for Openhole Completions – U-Tube

- Packer system



Freifeld, B. et al, 2005

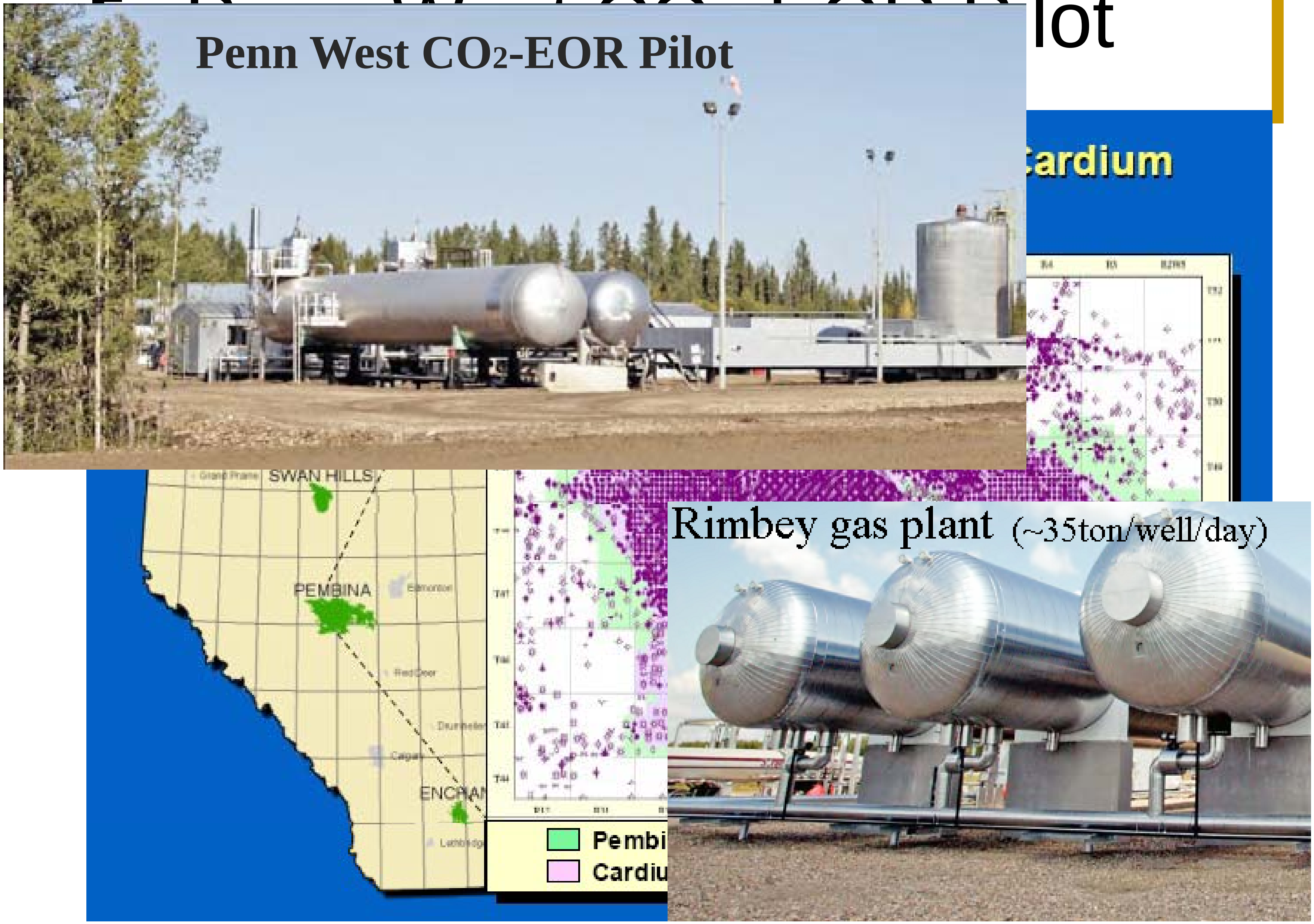
Application of Multi-instrument String in CCS projects

Considerations

- Gas Seal System
- Multi-instrument's Geometry
- Well Integrity Monitoring
- Completion Issues :

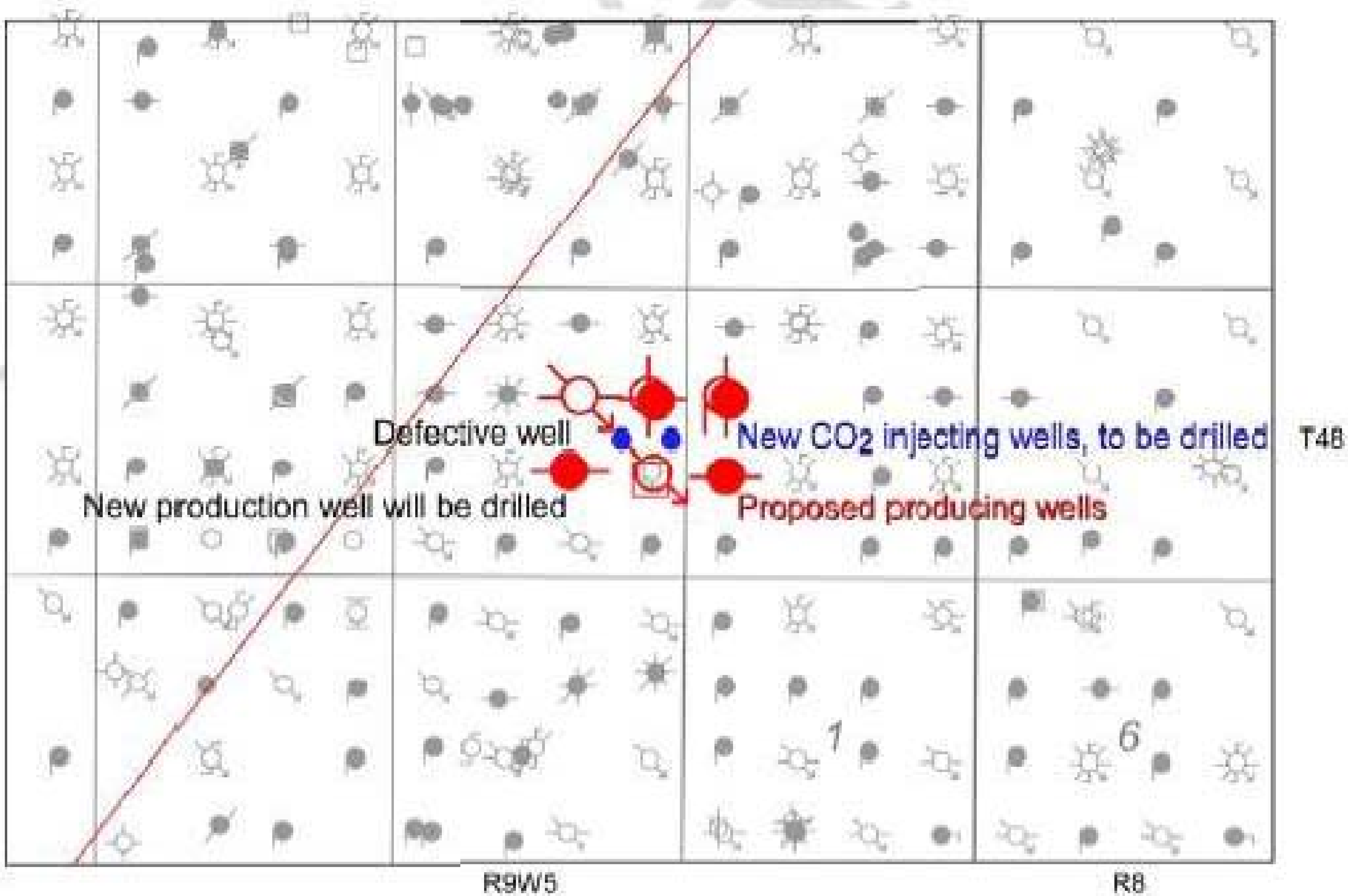
  Borehole Stability

  Cement Job

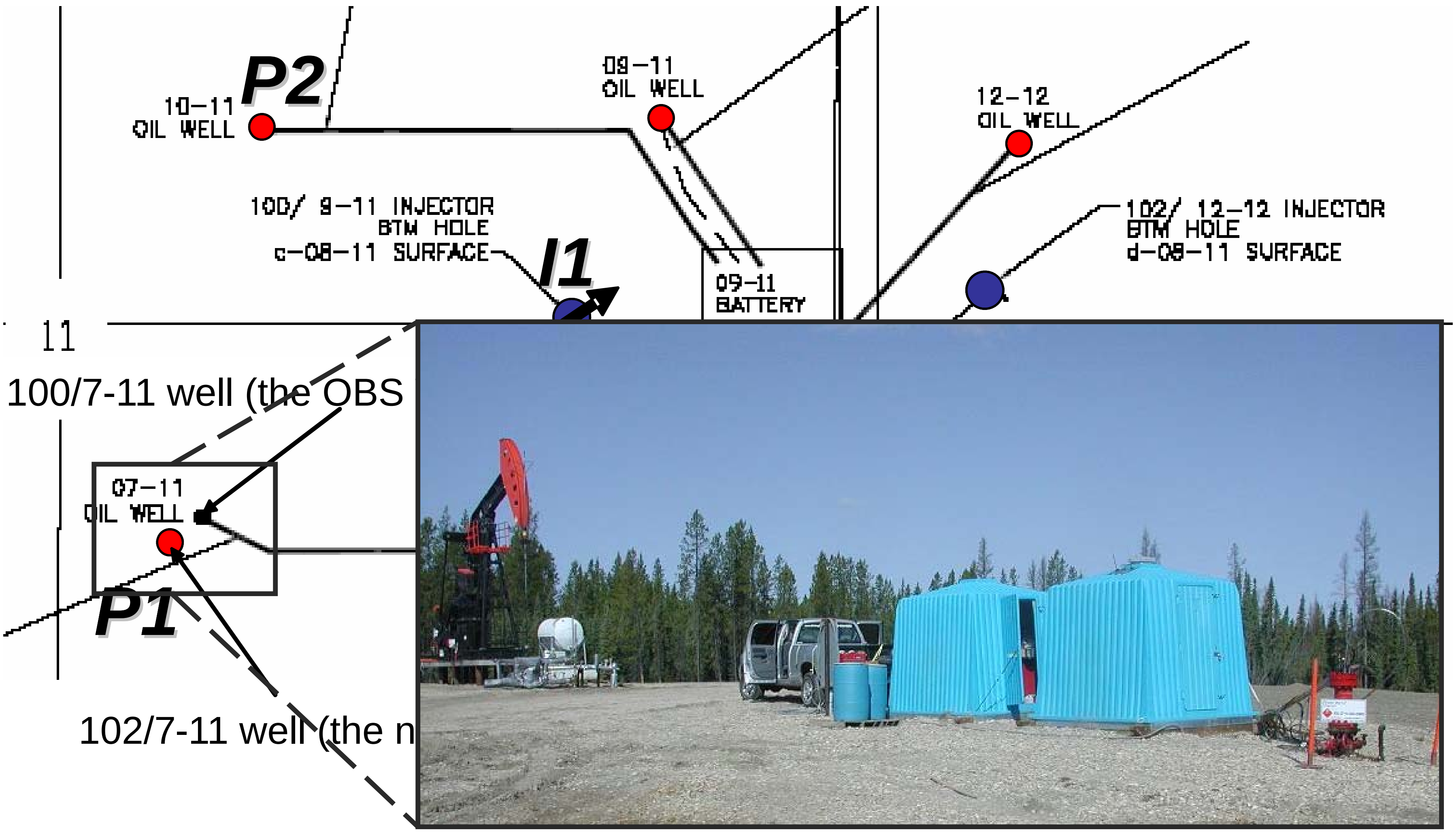


Penn West CO2-EOR Pilot
Cardium
SWAN HILLS
PEMBINA
Edmonton
Red Deer
Calgary
Lethbridge
ENCHAN
Pembi
Cardiu
Rimbey gas plant (~35ton/well/day)

Pennwest CO_2-EOR Pilot



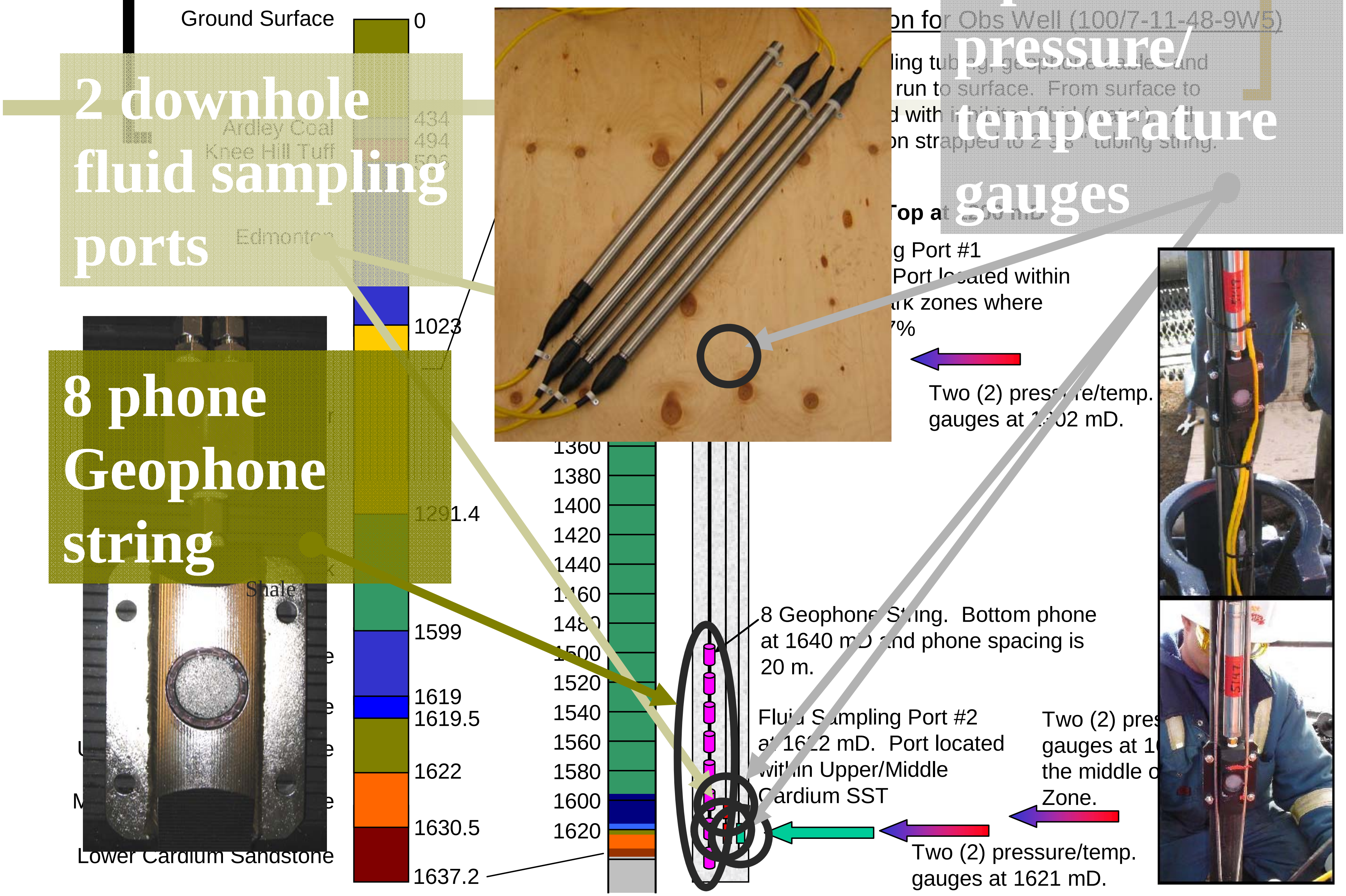
Pennwest CO_2-EOR Pilot
6 Producers, and 2 injectors



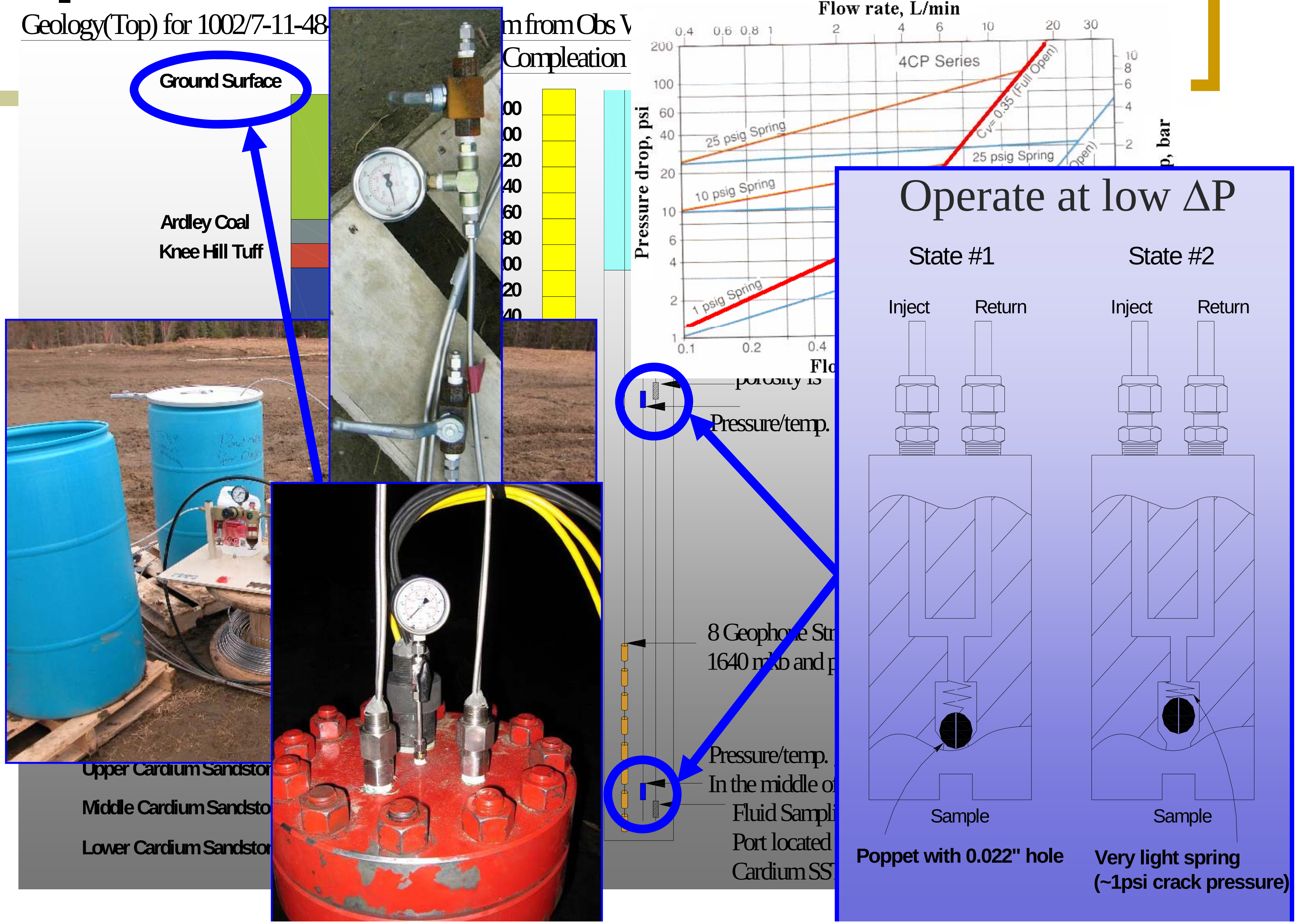
Observation Well Specifications

Well depth:	1600 m (5250 ft)
Casing:	139.7 mm (5.5 in) @ 25.3 kg/m
BHP:	approximately 19 MPa (2700 psi)
BHT:	approximately 50°C (122 °F)
Deviation:	none (vertical well)
Other:	well is sweet

Geology and Design Completion

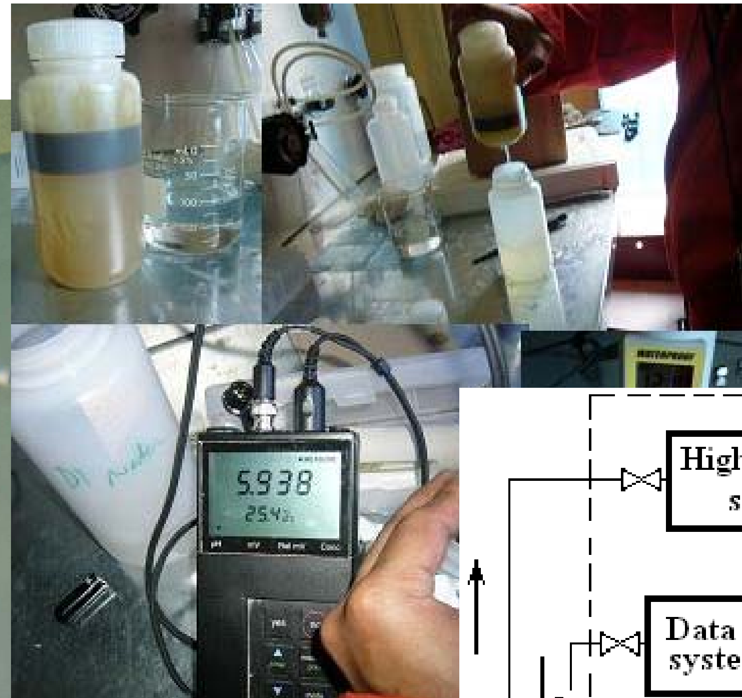


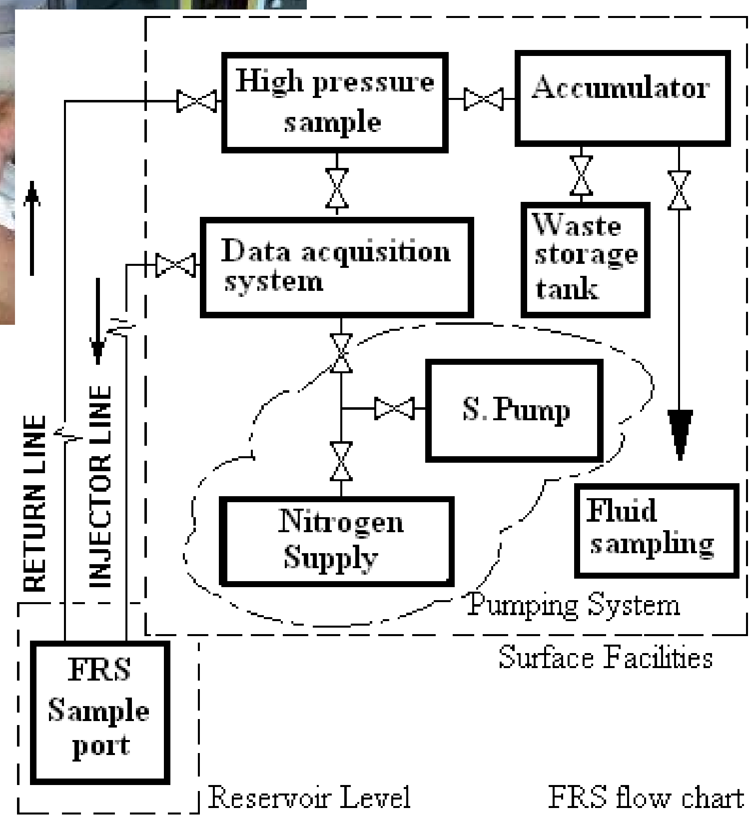
FRS



Geology(Top) for 1002/7-11-48-
m from Obs W
Compleation
Ground Surface
Ardley Coal
Knee Hill Tuff
Upper Cardium Sandston
Middle Cardium Sandsto
Lower Cardium Sandston
Pressure/temp.
8 Geophone Str
1640 mkb and p
Pressure/temp.
In the middle o
Fluid Sampli
Port located
Cardium SS
Flow rate, L/min
4CP Series
Pressure drop, psi
25 psig Spring
10 psig Spring
1 psig Spring
Cv= 0.35 (Full Open)
Operate at low ΔP
State #1
State #2
Inject
Return
Inject
Return
Sample
Sample
Poppet with 0.022" hole
Very light spring
(~1psi crack pressure)

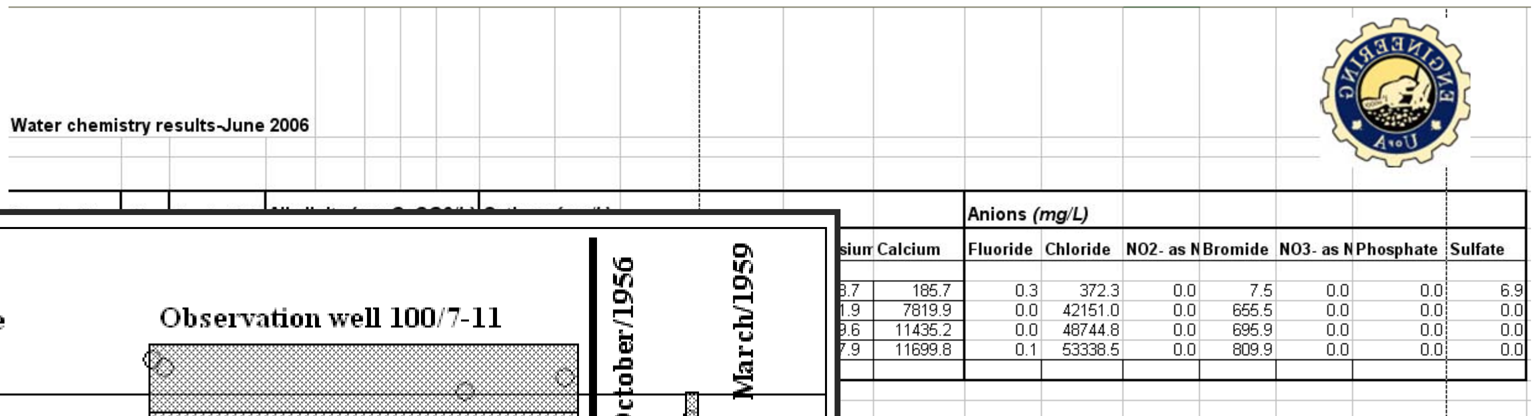
Fluid Recovery System (FRS)





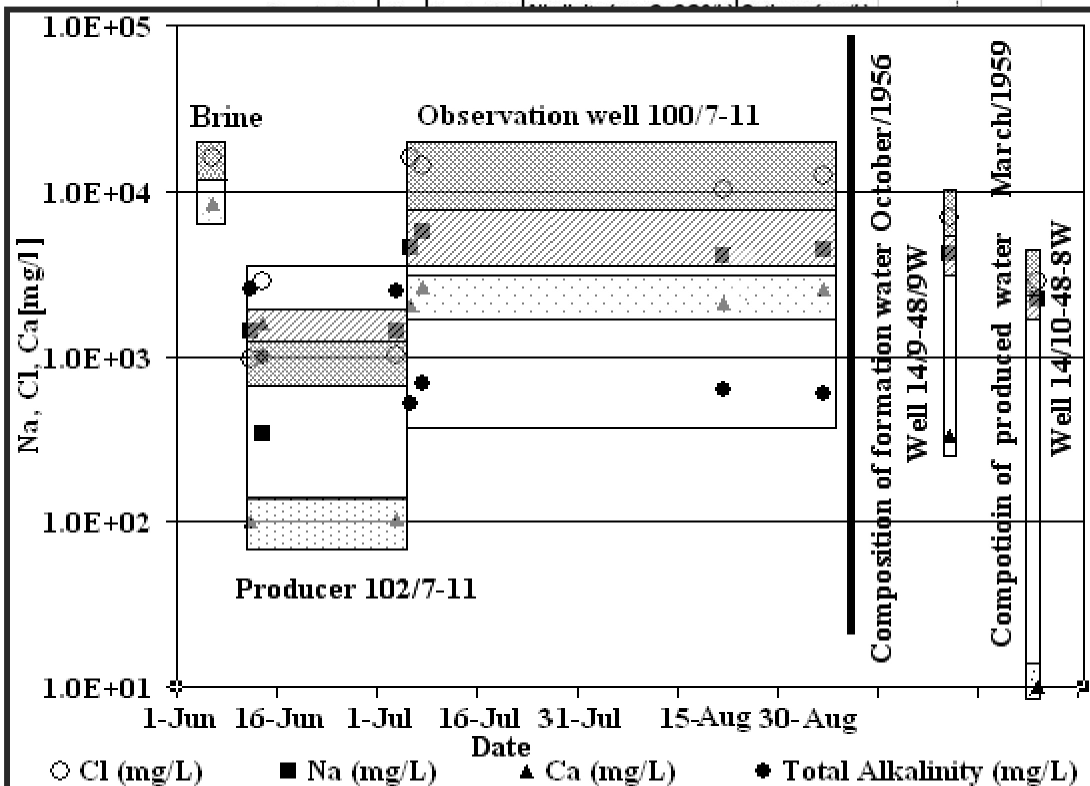
Zambrano, G. and Chalaturnyk, R. 2007

FRS 2006 Preliminary results



Water chemistry results-June 2006

		Anions (mg/L)						
sium	Calcium	Fluoride	Chloride	NO2- as N	Bromide	NO3- as N	Phosphate	Sulfate
.7	185.7	0.3	372.3	0.0	7.5	0.0	0.0	6.9
1.9	7819.9	0.0	42151.0	0.0	655.5	0.0	0.0	0.0
.6	11435.2	0.0	48744.8	0.0	695.9	0.0	0.0	0.0
7.9	11699.8	0.1	53338.5	0.0	809.9	0.0	0.0	0.0



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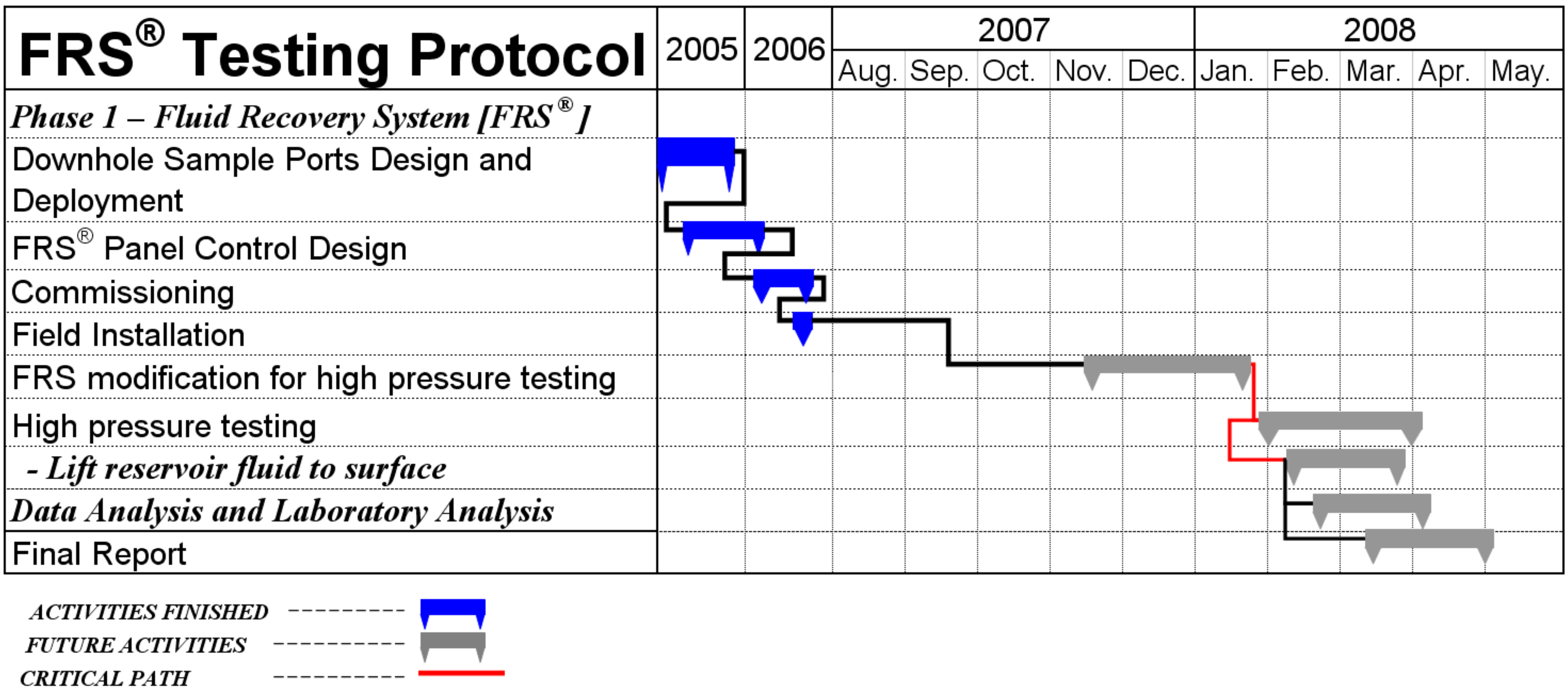
Work Plan 2007 - 2008



QUESTIONS ?

Downhole Fluid Recovery System (FRS) Deployment at PennWest CO_2-EOR Monitoring Project

Groundwater monitoring technologies for CCS projects

By
Gonzalo Zambrano
Geological Storage Research Group, University of Alberta

Shallow surface, atmospheric and offshore gas monitoring in CO_2Geonet and CO_2ReMoVe

David Jones

British Geological Survey

Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG
Tel 0115 936 3100

Organisations involved in these aspects

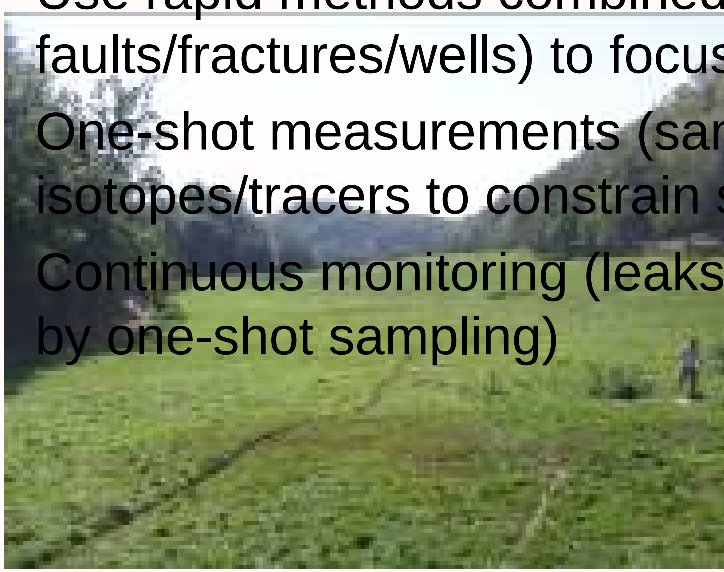
- British Geological Survey (D Jones, T Barlow, B Lister, R Shaw, J Pearce, L Bateson, C Fleming)
- Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, Germany) (F May, I Möller, N Rann)
- Bureau de Recherche Géologique et Minière (K Le Pierres, F Gal, G Braibant, A Gadalia)
- Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (M Vellico)
- Università di Roma “La Sapienza” (S Beaubien, G Ciotoli, A Annunziatellis, S Lombardi)

Outline

- Basis of approach
- Methods for rapid surveying
- Continuous monitoring techniques
- Offshore methods
- Summary and future research

Basis of approach

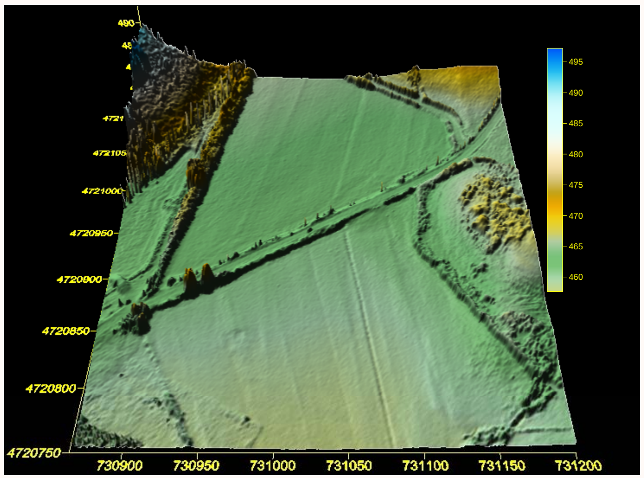
- Need to cover large areas rapidly – storage sites can cover many km^2
- Targets (leaks) may be very small (c.f. natural CO_2 vents) and displaced from original source (e.g. well)
- Conventional survey techniques take time and may miss sites
- Use rapid methods combined with local knowledge (e.g. of faults/fractures/wells) to focus detailed investigations
- One-shot measurements (samples to laboratory) – isotopes/tracers to constrain source(s) of gas
- Continuous monitoring (leaks may be transient and so missed by one-shot sampling)



Rapid methods

- Remote sensing of vegetation effects
- Direct airborne CO_2 detection
- Surface methods (vehicle-mounted laser analyser)
- Test on natural analogue sites
- Deploy on demonstration CO_2 storage projects

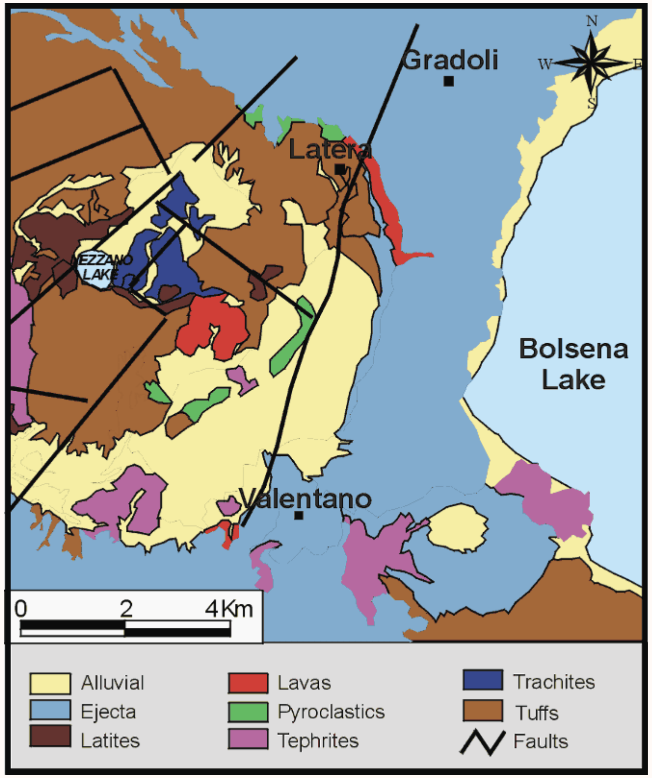
Using natural analogues

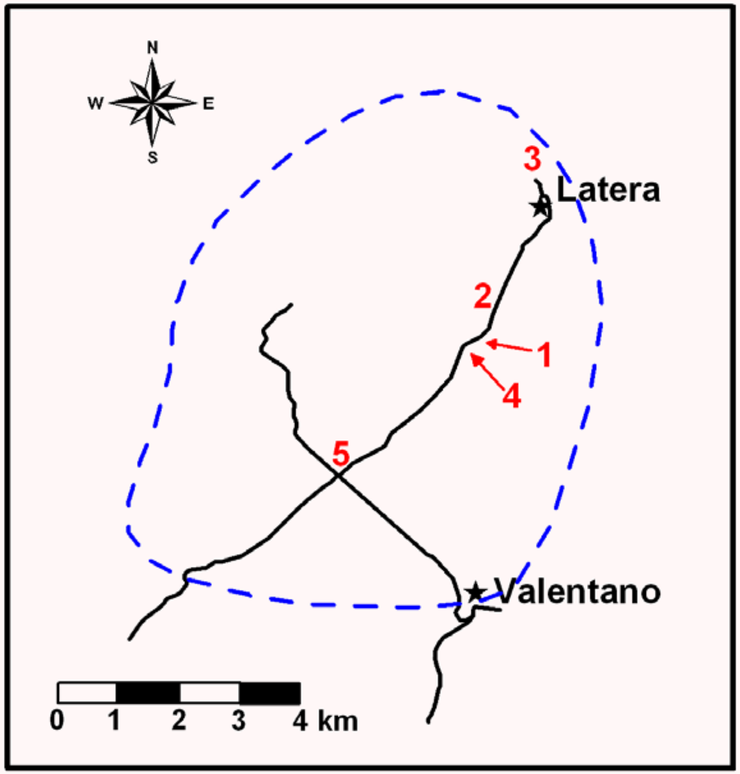


- Industrial-scale demonstration projects should not leak significantly.
- We can test near-surface monitoring techniques in areas of natural CO_2 seeps.

- Latera in Latium, Central Italy, is a caldera with many CO_2 seeps to surface.
- Extensively studied in CO_2GeoNet and previously in FP5 Nascent project.
- Joint research by BGS with NERC ARSF, Universita la Sapienza Roma and OGS

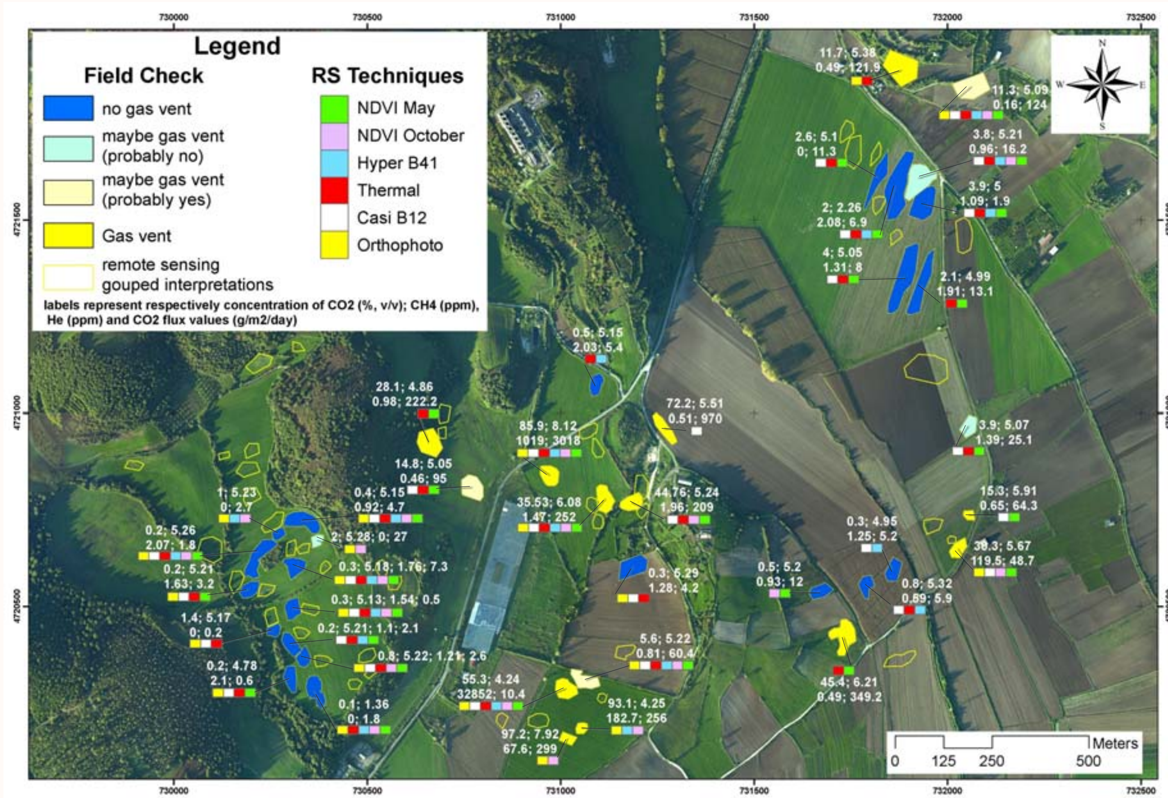
Latera caldera: central Italy



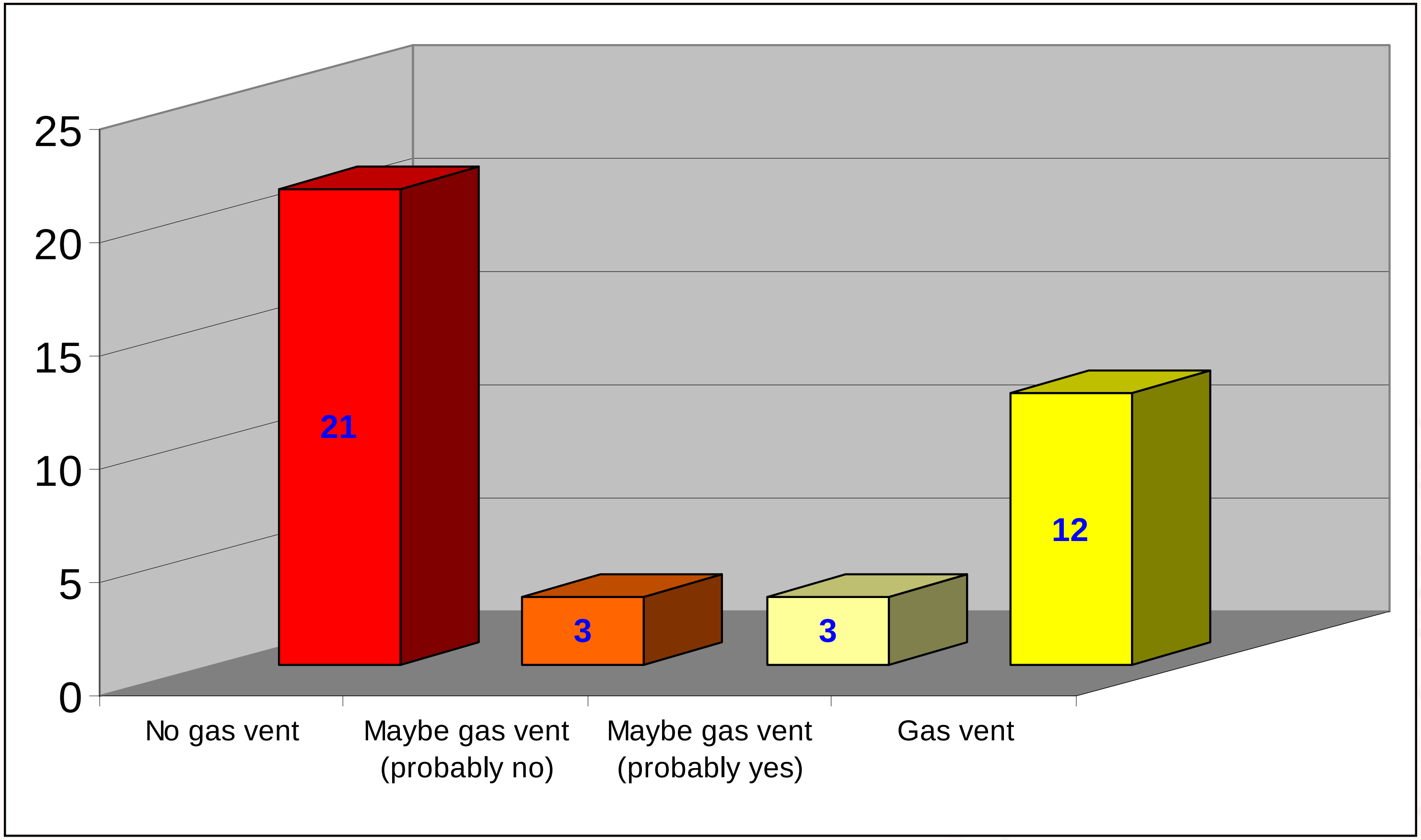


Indirect remote sensing

- Assessing impacts of leakage on vegetation or in bare soil by applying well-tested, mature techniques in novel manner.
  - Seasonal variations
  - Best practice recommendations
- Principal techniques are:
  - Relative chlorophyll content (NDVI)
  - Thermal (ATM) and multispectral (CASI) in bare soil
- Supported by extensive groundtruthing
  - Soil gas measurements
  - Botanical assessments

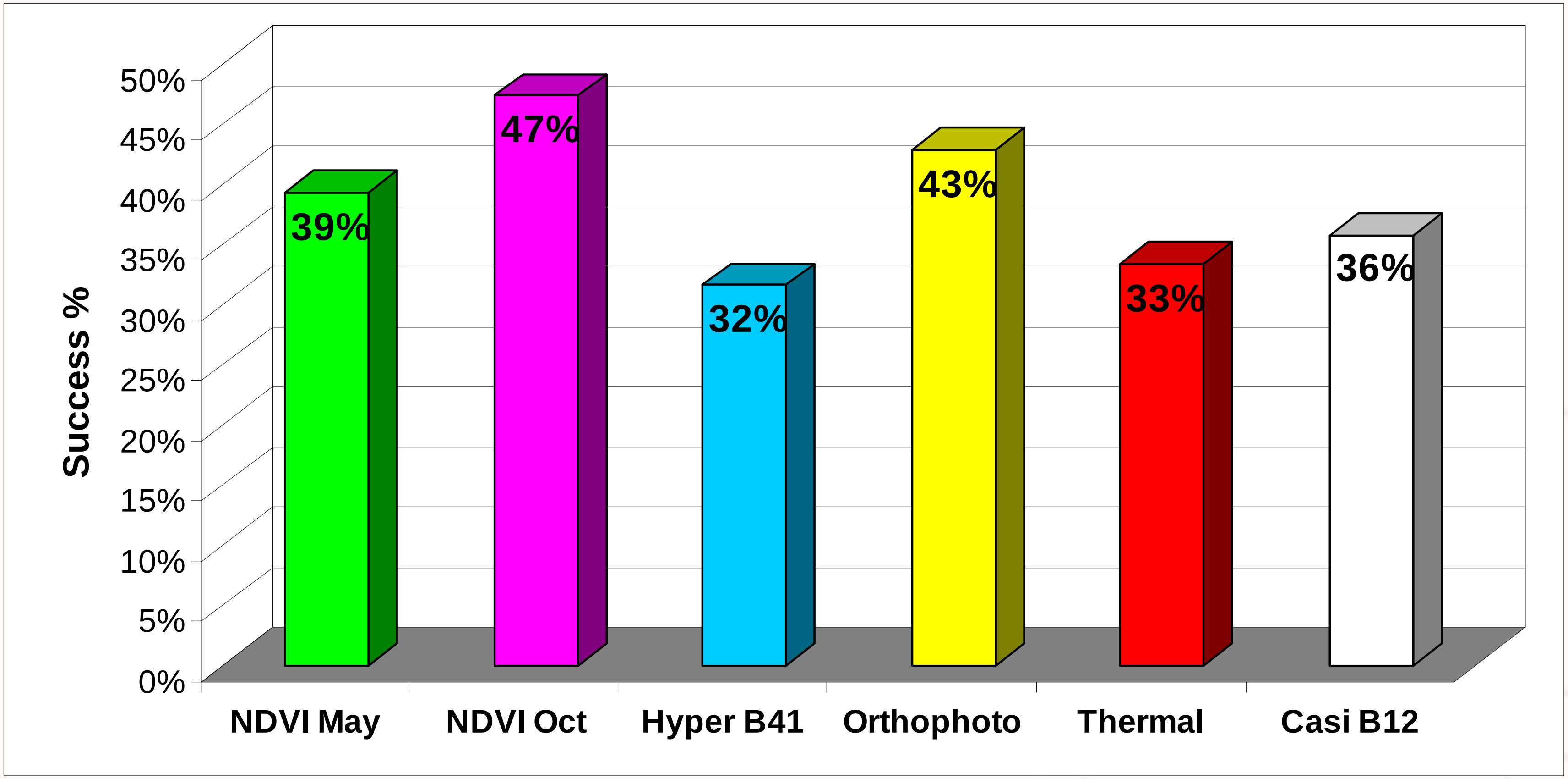


Total Success Rate



- Of 39 areas tested, 24 are probably not vents while 15 probably are gas vents. (39% total success rate)

Success Rate of Each Method



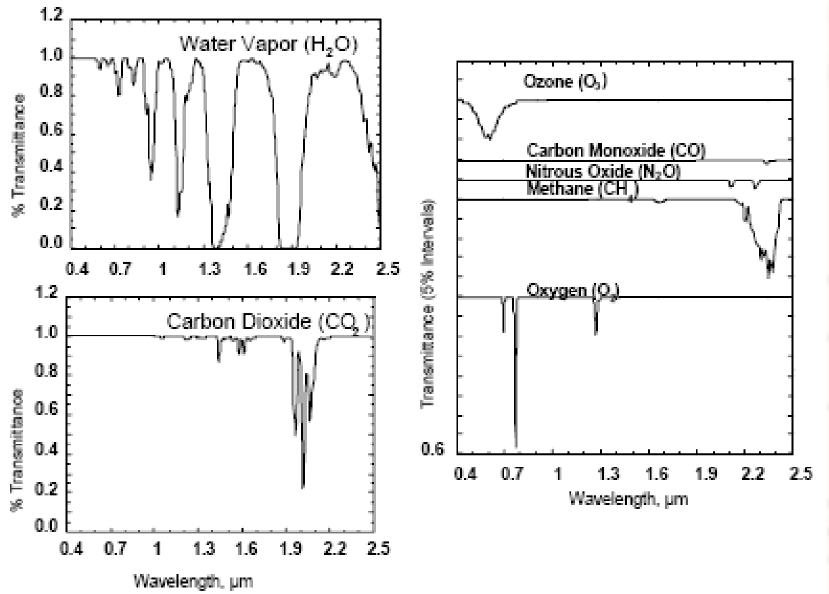
- Comparison of the individual methods shows that the NDVI October data had the highest success rate, while Hyper B41 had the lowest

Direct CO_2 detection – test of concept

- ARSF commissioning of AISA Hawk potentially allows direct atmospheric CO_2 detection.

- Joint test by ARSF and BGS at Keyworth in June 2007
  - Dry run with large baths, lined by tarpaulins of known reflectance, filled with CO_2
  - Data currently being interpreted

- This new application now tested (September 2007) over natural seeps at Latera.
  - Results awaited

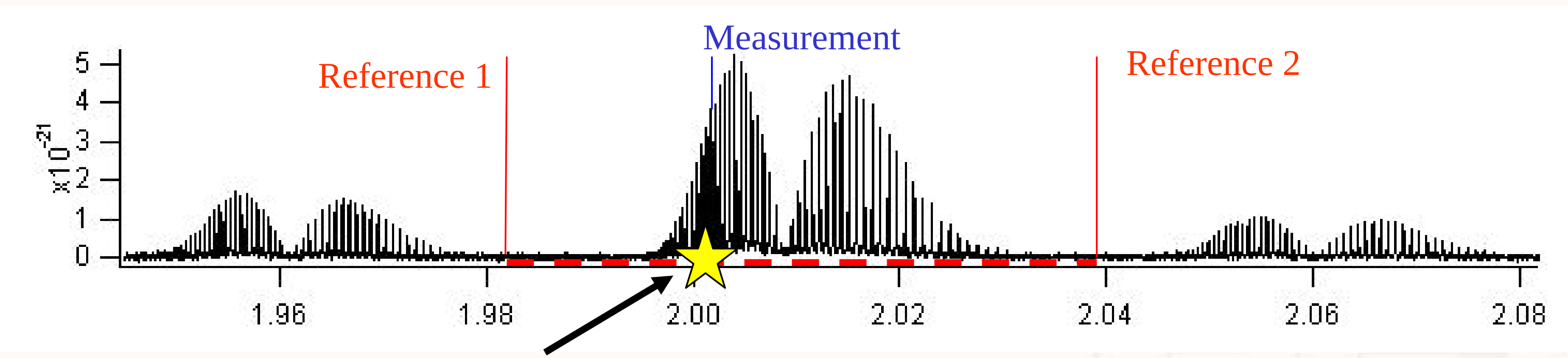


Continuum Interpolated Band Ratio **(CIBR)**

- Use two reference bands, with appropriate weighting, to interpolate what the reflectance value would be in the measurement band if no CO_2 absorption was occurring.
  - This interpolated value becomes the denominator in the Band ratio equation:

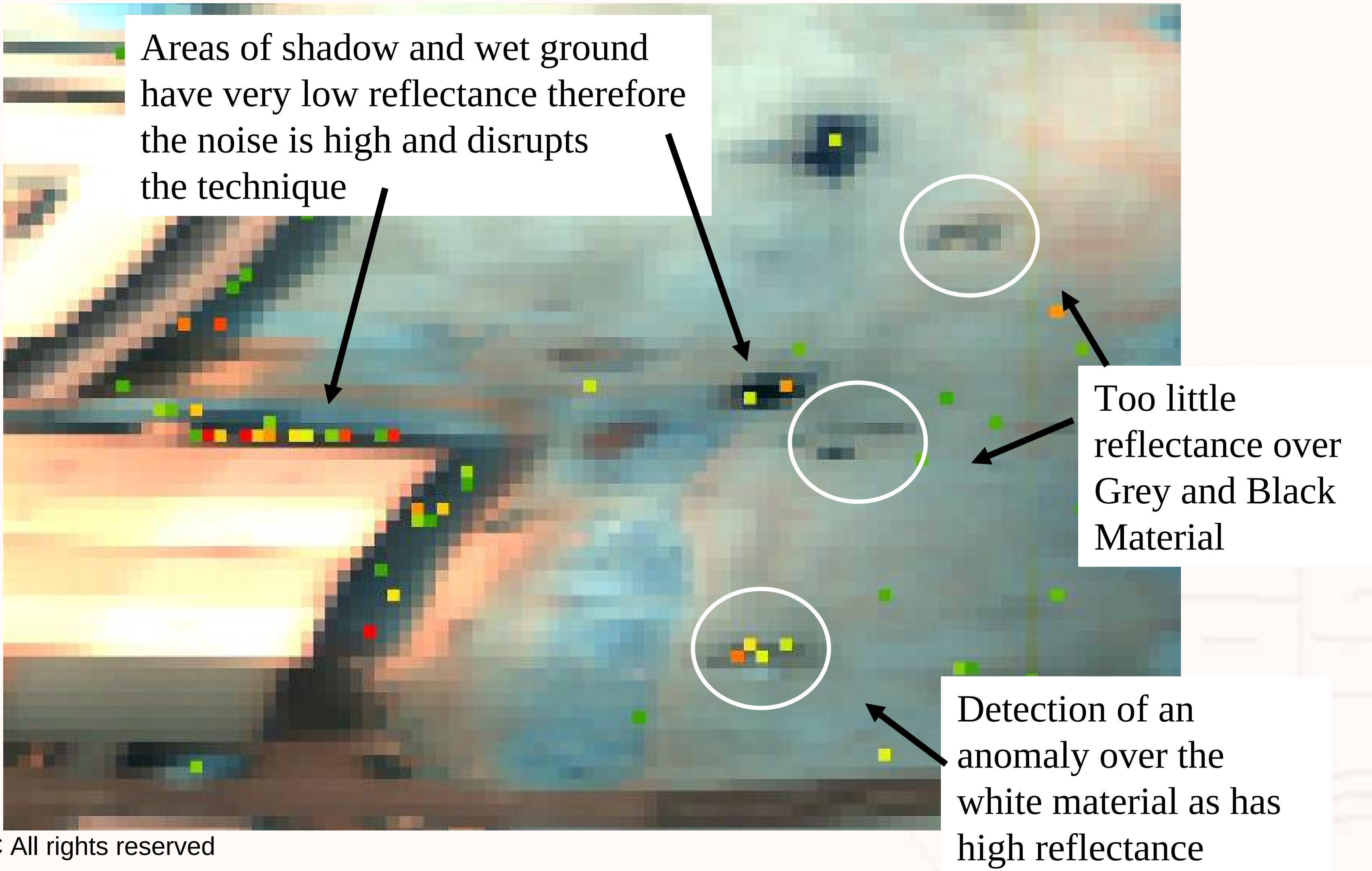
$$CIBR = \frac{R(\lambda m)}{Interpolated\_R(\lambda m)}$$

Continuum Interpolated Band Ratio **(CIBR)**



Interpolated value for the measurement band; it's value if no CO_2 absorption was occurring

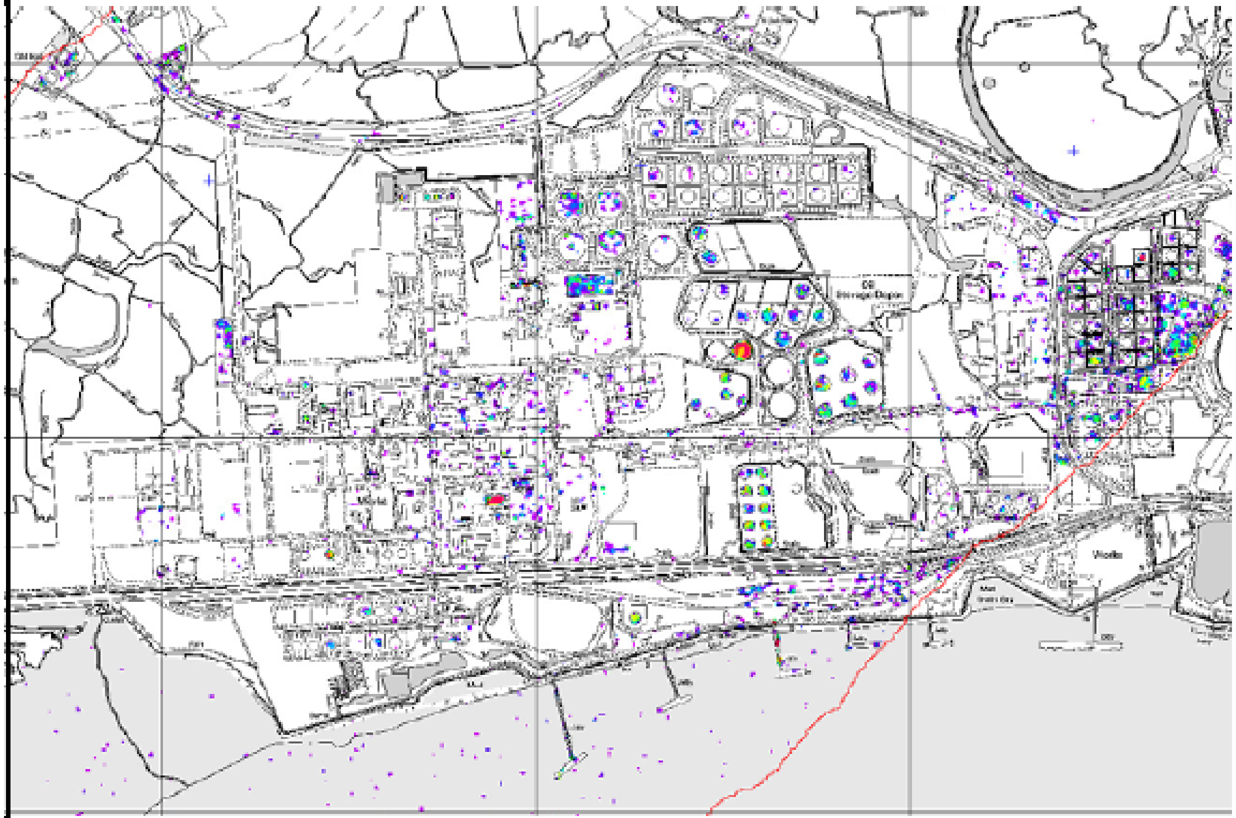
CIBR Processing for a Smaller Area



Continuum Interpolated Band Ratio

- In the case of the BGS test the CIBR technique may work to an extent.
- However there is too much noise in the data to be sure.
  - Illumination effects
  - Poorly known sensor calibration
  - **Very poor** weather conditions
- It has worked in the past over an oil refinery
  - This was under perfect weather conditions!
  - And using a sensor with well known calibration

Hymap Detection of CO_2



Carbon dioxide Anomalous pixels over 80th percentile

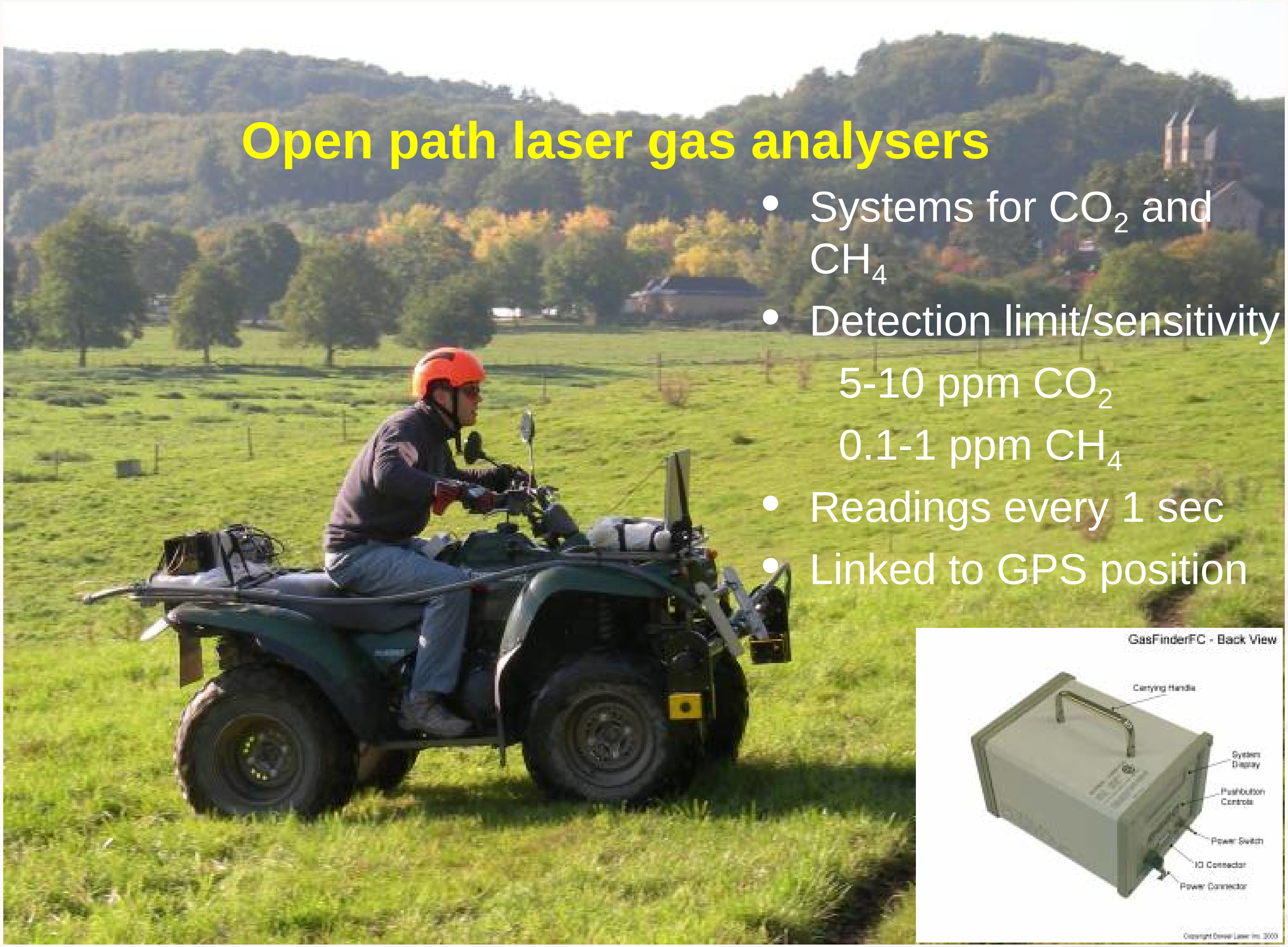
Courtesy of Andrew Wilson

Open path laser analysers

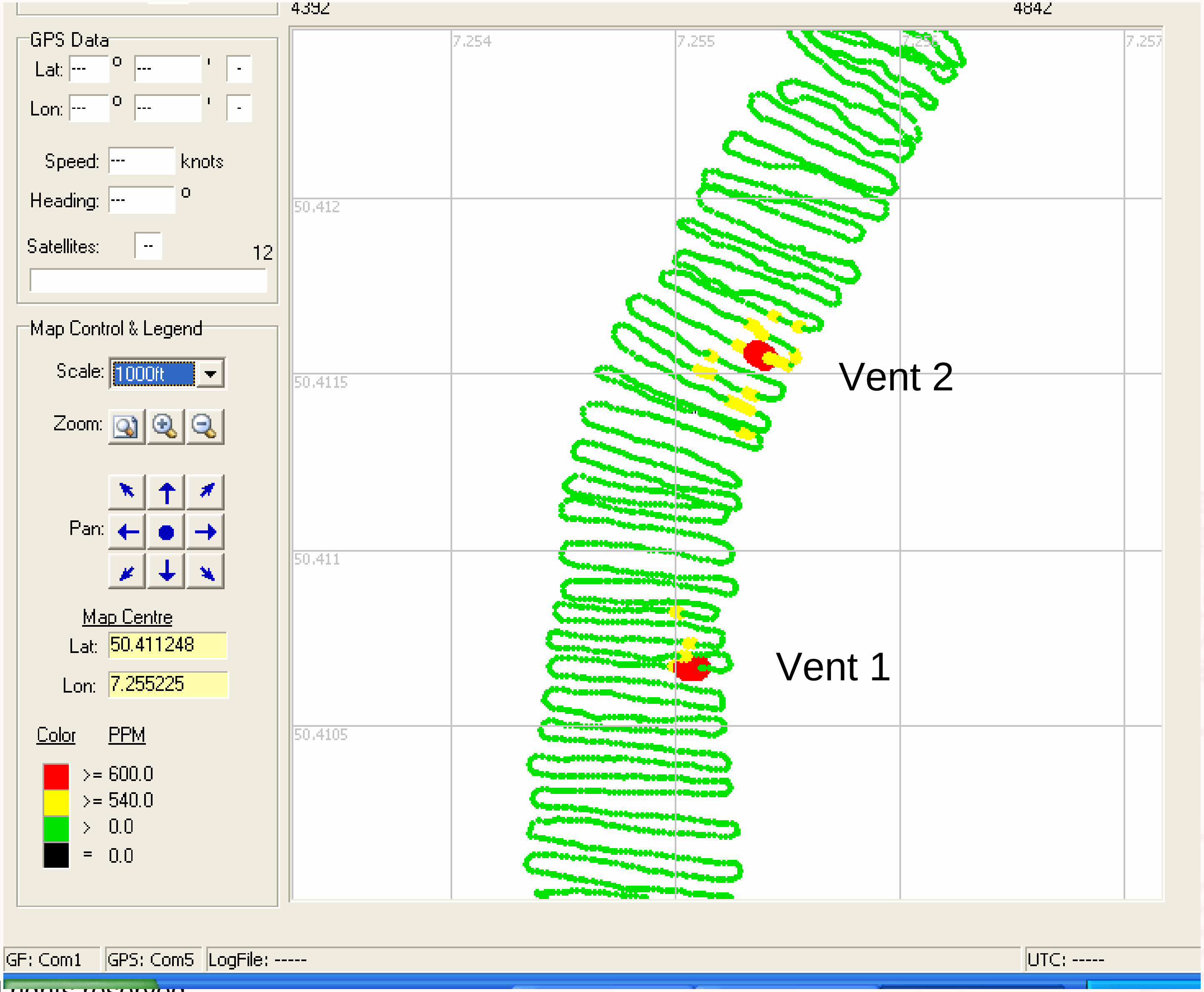
- Tested open path CO_2 laser in conventional mode at Latera
- Sensitivity c. 100 ppm
- Background values when path length > 100 m
- Conclusion – probably too low sensitivity and too slow as a rapid mapping technique

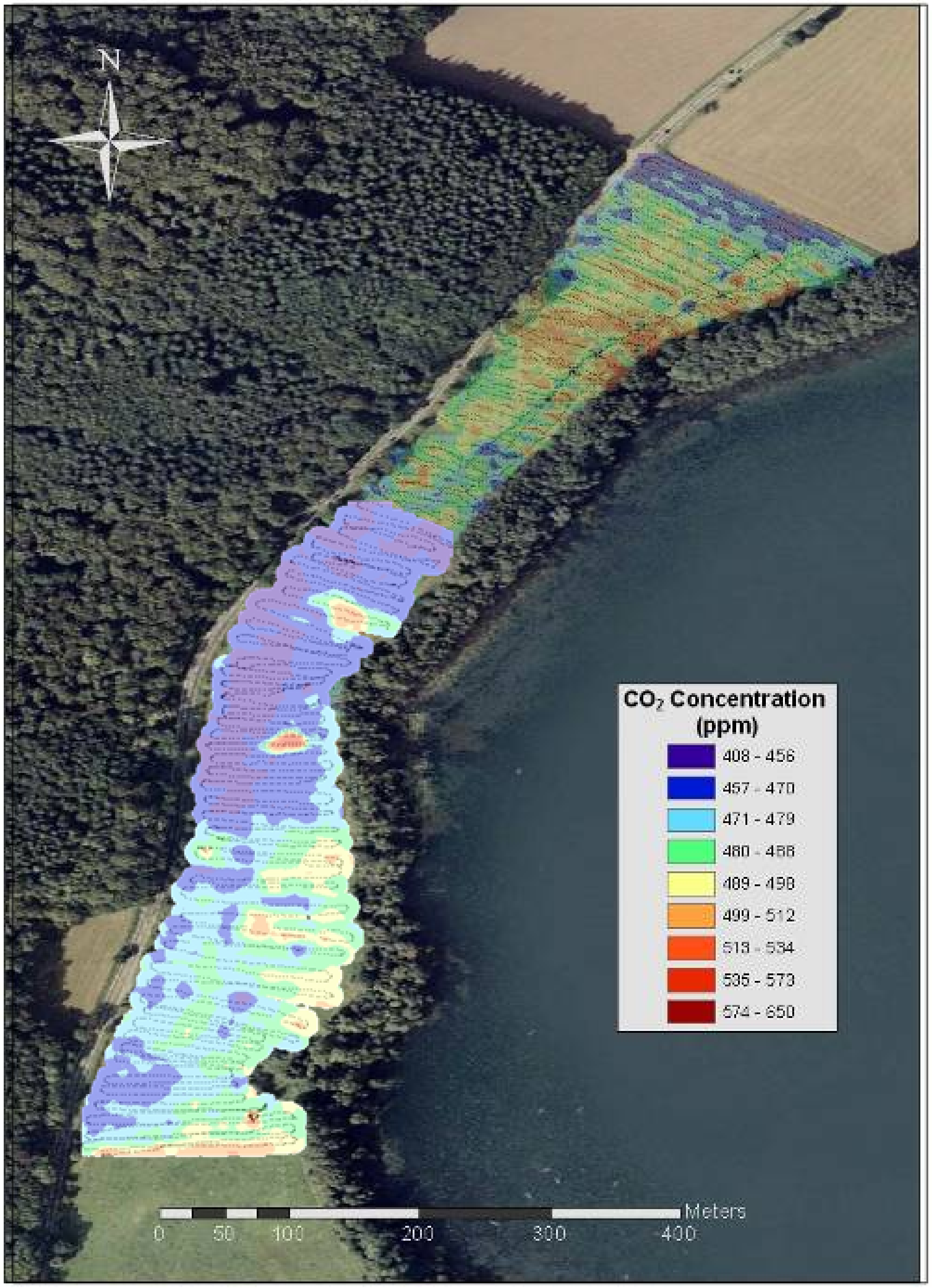
Open path laser gas analysers

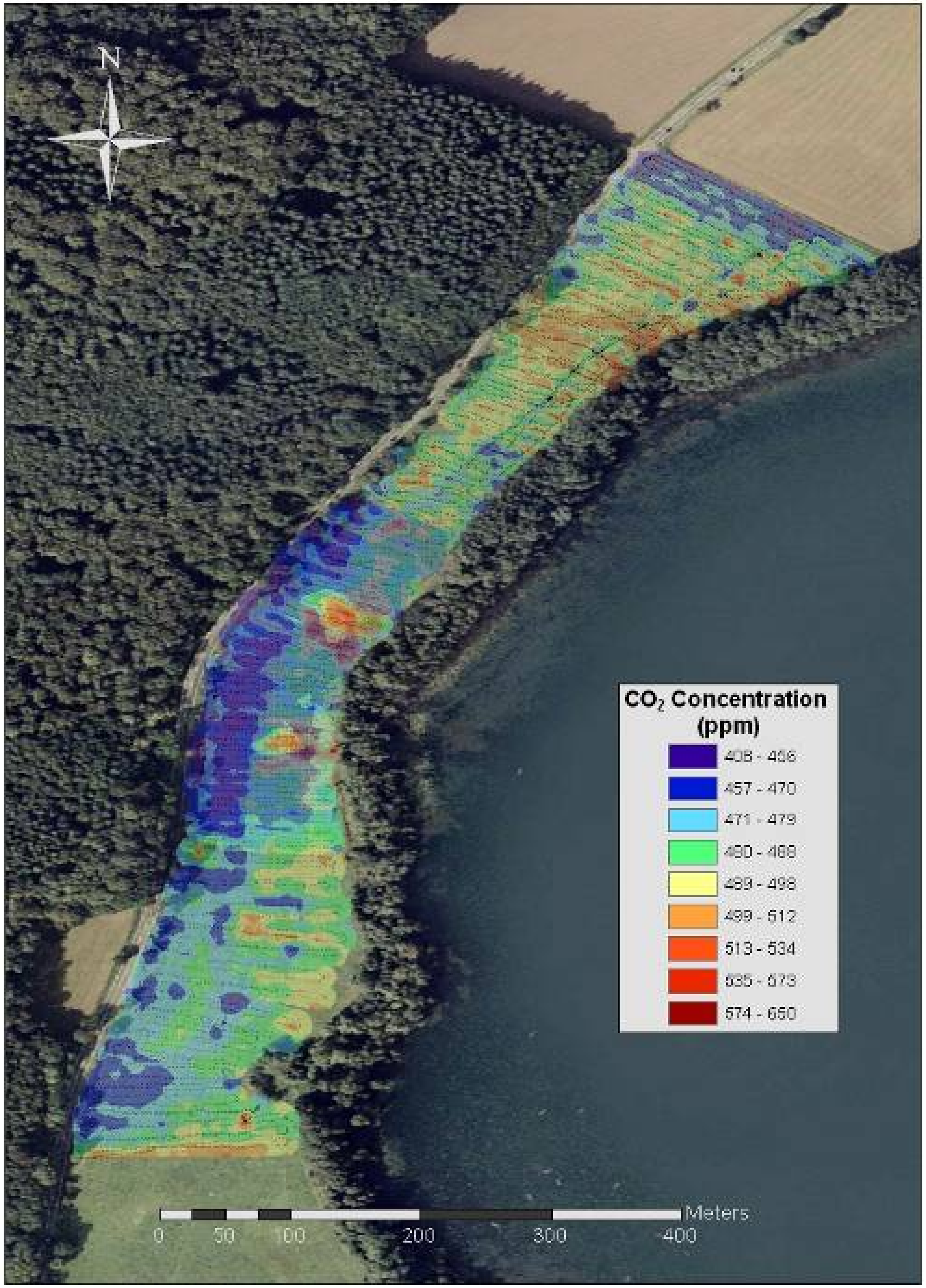
- Systems for CO_2 and CH_4
- Detection limit/sensitivity
  5-10 ppm CO_2
  0.1-1 ppm CH_4
- Readings every 1 sec
- Linked to GPS position




Oberzissen
alenberg
Buchholz
Glees
Wassenach
Wehr
Laacher See
Naturschutzgebiet
Nickenich
Maria Laach
A61 E31
412
Bell
Kretz
256
Plaidt
Kruft
Die
Ober
Nieder
MLST-B
MLST-C3
MLST-C1
MLST-C2
North Sea
Baltic Sea
DEN.
Kiel
Rostock
Lübeck
Bremerhaven
Hamburg
Emden
Bremen
BERLIN
POL.
NETH.
Hannover
Magdeburg
Duisburg
Essen
Düsseldorf
Cologne
Bonn
Leipzig
Dresden
Elbe
BEL.
Frankfurt am Main
Wiesbaden
Rhine
Mannheim
CZECH REPUBLIC
LUX.
Karlsruhe
Nürnberg
Stuttgart
Danube
FRANCE
Munich
AUSTRIA
Zugspitze
SWITZ.
LIECH.
0 50 100 km
0 50 100 mi


GPS Data
Lat:
Lon:
Speed: knots
Heading:
Satellites:
12
Map Control & Legend
Scale: 1000ft
Zoom:
Pan:
Map Centre
Lat: 50.411248
Lon: 7.255225
Color PPM
>= 600.0
>= 540.0
> 0.0
= 0.0
4392
4842
7.254
7.255
7.257
50.412
50.4115
50.411
50.4105
Vent 2
Vent 1
GF: Com1
GPS: Com5
LogFile: -----
UTC: -----


N
CO₂ Concentration (ppm)
408 - 456
457 - 470
471 - 479
480 - 488
489 - 498
499 - 512
513 - 534
535 - 573
574 - 650
Meters
0
50
100
200
300
400


N
CO_2 Concentration (ppm)
408 - 456
457 - 470
471 - 479
480 - 488
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513 - 534
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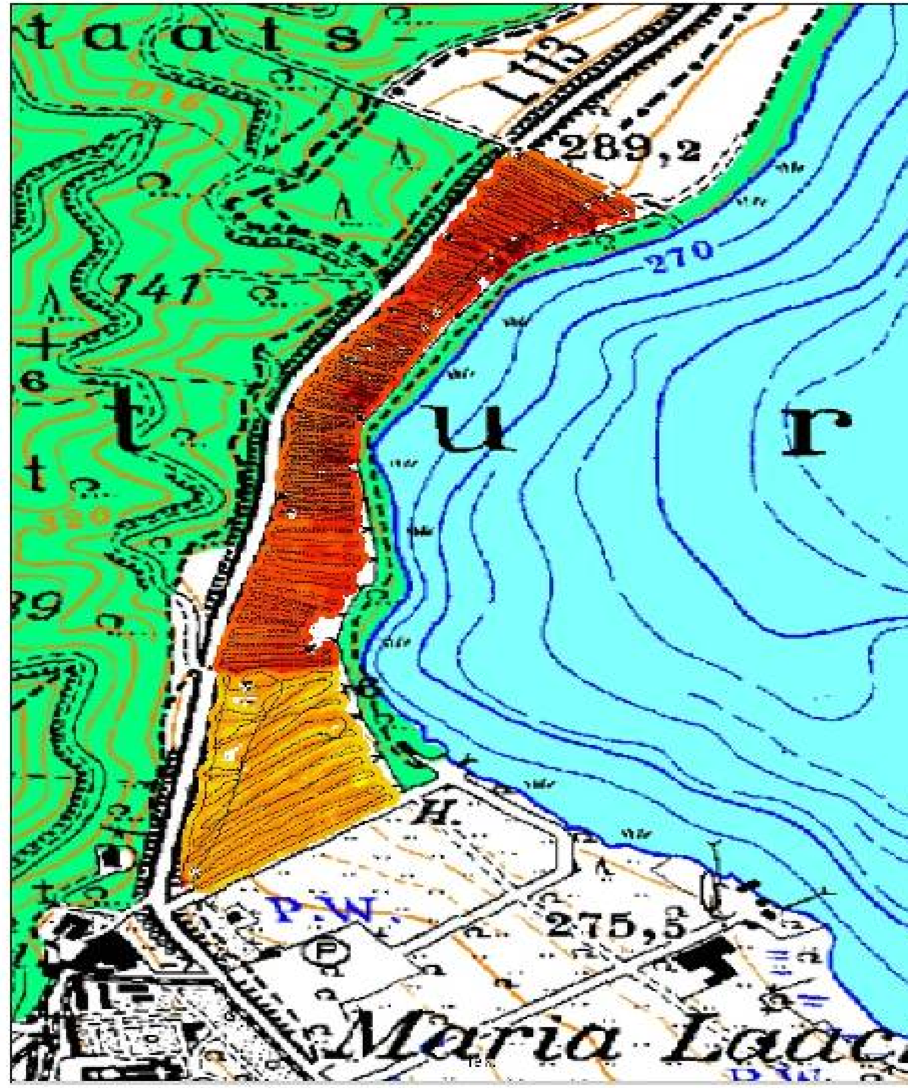
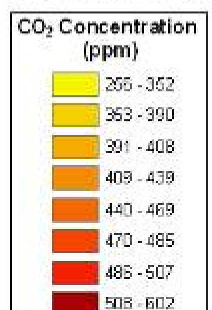
574 - 650
Meters
0
50
100
200
300
400

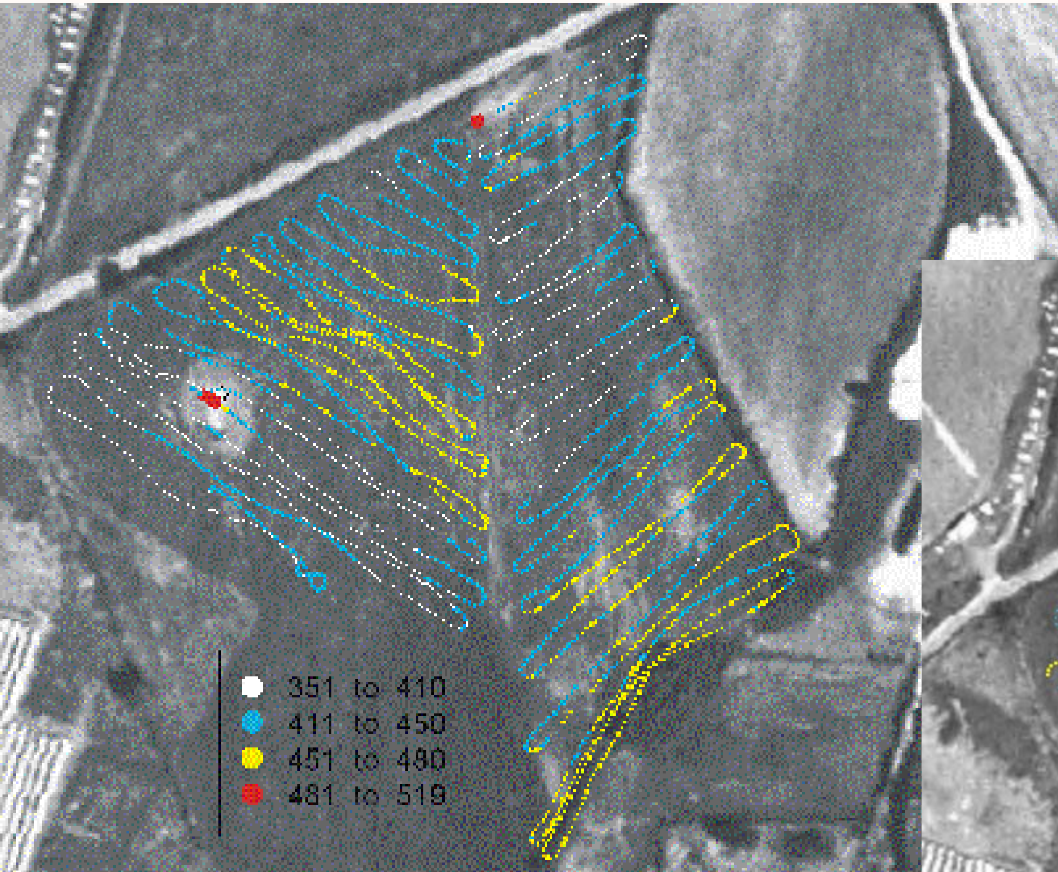
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

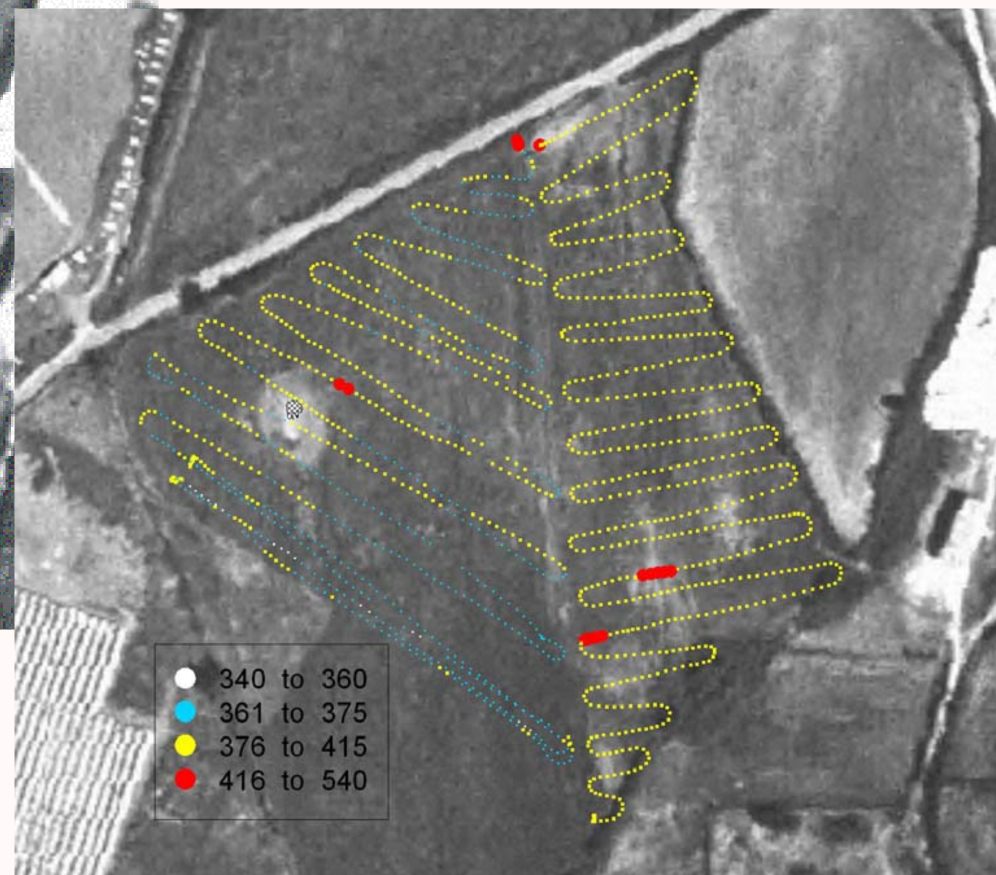




Quad-mounted CO_2 laser
All data for 3 days plotted
using same scale

N


351 to 410
411 to 450
451 to 480
481 to 519


340 to 360
361 to 375
376 to 415
416 to 540

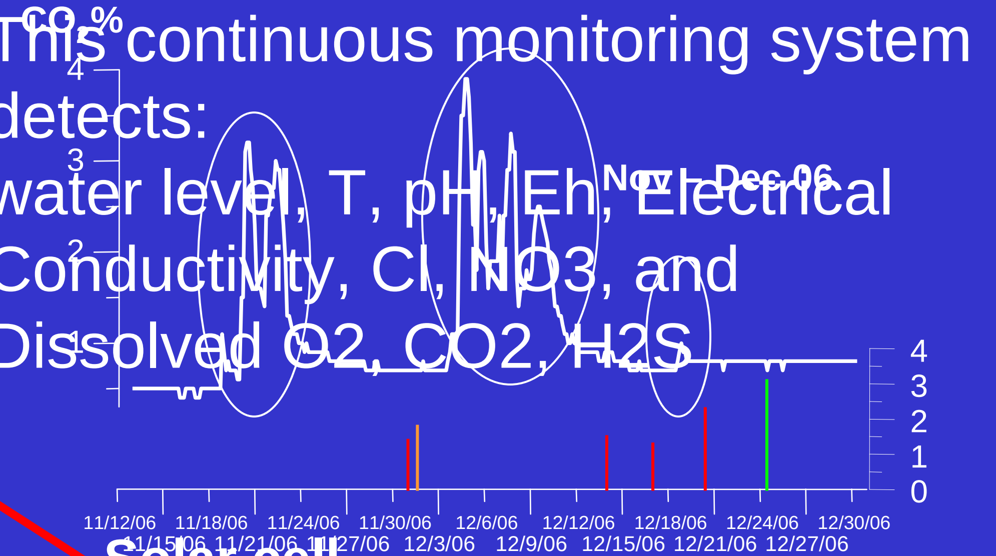
Onshore monitoring system (URS)

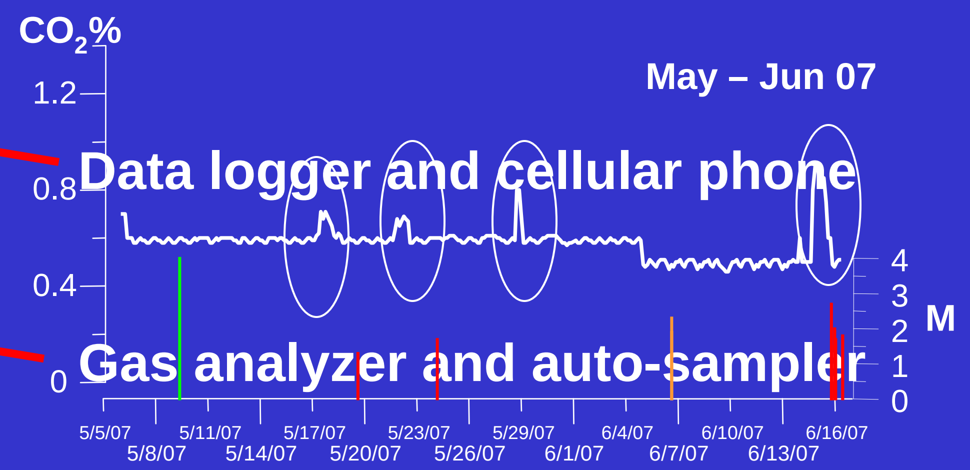
This continuous monitoring system detects:
water level, T, pH, Eh, Electrical Conductivity, Cl, NO3, and Dissolved O2, CO2, H2S

Solar cell

Data logger and cellular phone

Gas analyzer and auto-sampler





Variation of CO2 dissolved in water possibly induced by local earthquakes M< 3

Modelling of the soil gas flux by the means of a long term monitoring of ^{222}Rn : BARASOL (Algade) method

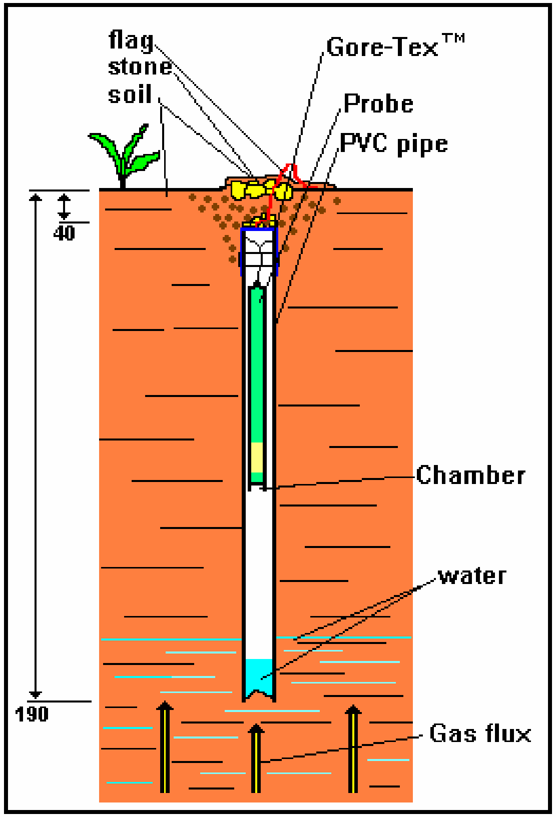
Introduction of rigid probes (including inner memory) on the strongest anomalies of He (deep gas tracer) and ^{222}Rn (gas rate tracer) displaying supposed CO_2 leaks.

Tube length: 1.5 m

Diameter : 11 cm

Volume: 11.4 l

Surface: 0.0095 m^2



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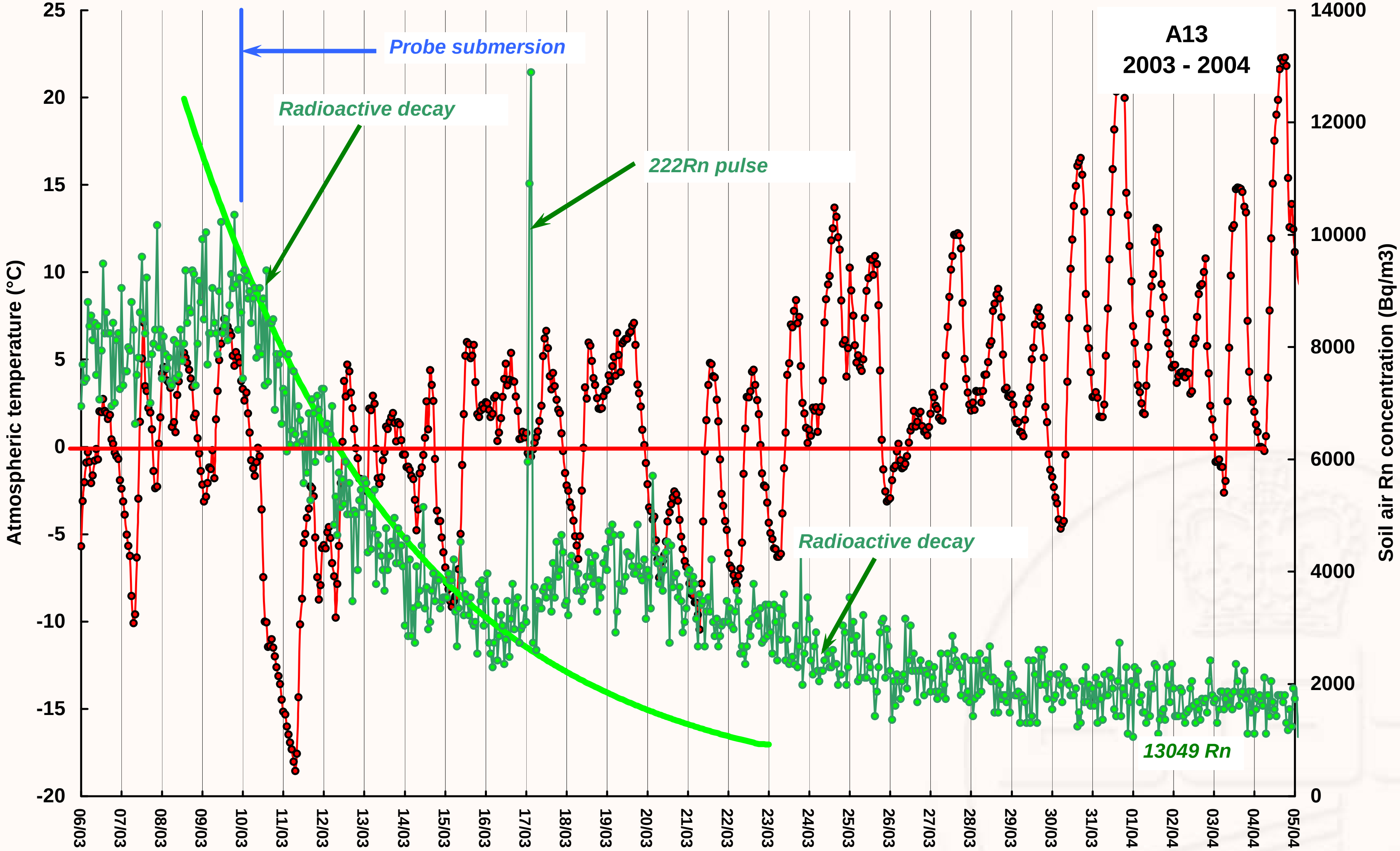


Other approaches

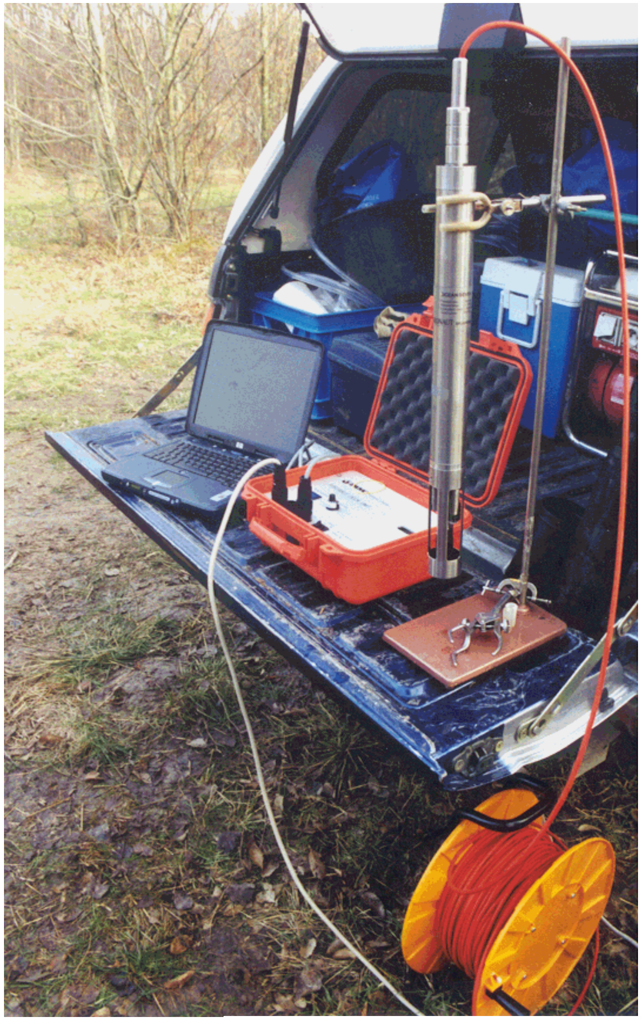
Eddy covariance equipment

- Measuring CO_2 flux at fixed sites continuously
- Footprint > 100 x sensor height

BRGM geochemical approach – CO_2

Multi-parameter probe (Idronaut Ocean Seven 316Plus) for vertical logging (up to 1500m depth) and continuous monitoring:

- **basic: pH, T°, pressure**
- **optional: Eh, Electrical conductivity, Cl, NO_3 and pCO_2**



Direct pCO_2 measurement consists in:

- ➢ **pH glass electrode**
- ➢ **Combined reference Ag/AgCl electrode**
- ➢ **In contact with an electrolyte behind a gas permeable membrane**

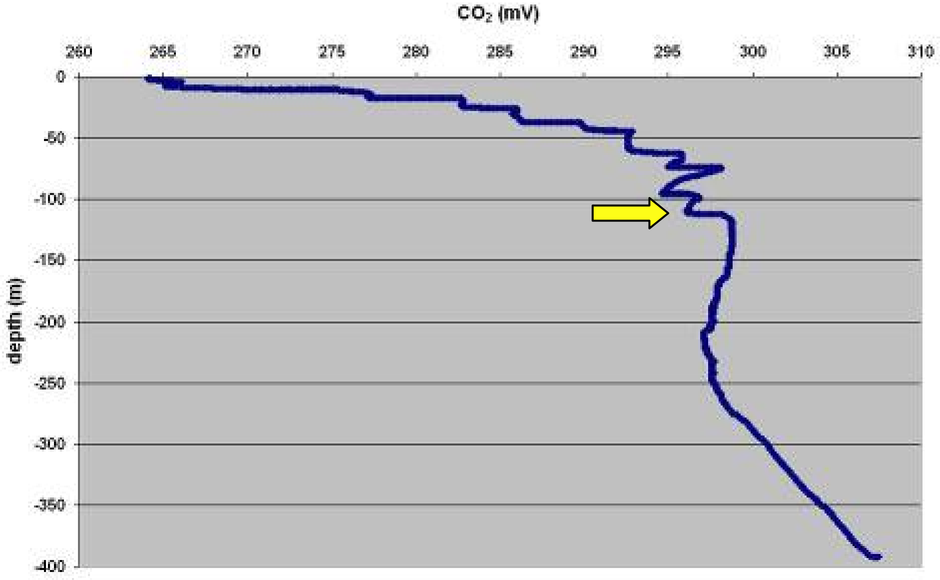
So that a ten fold increase in pCO_2 is nearly equivalent to a decrease of 1 pH unit

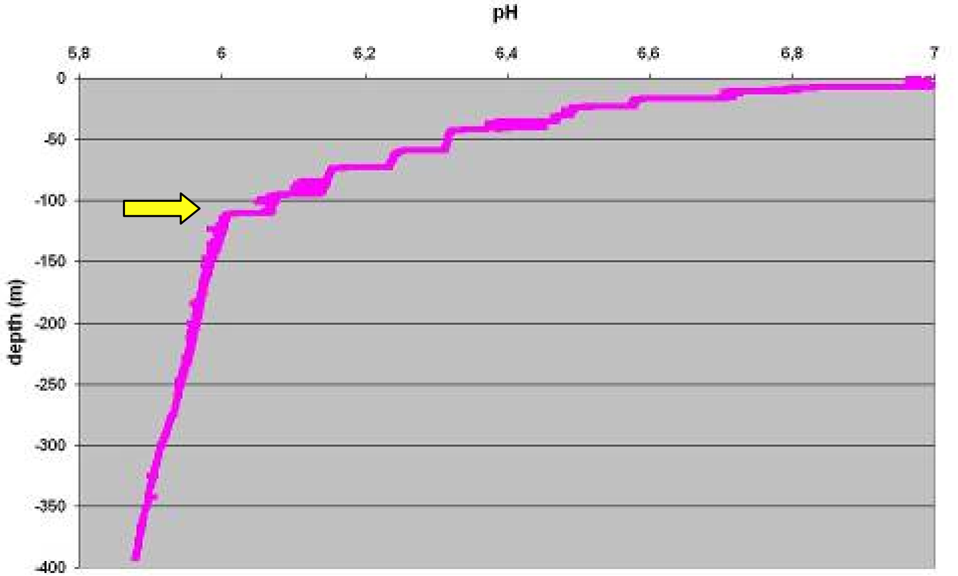
Géosciences pour une Terre durable

brgm

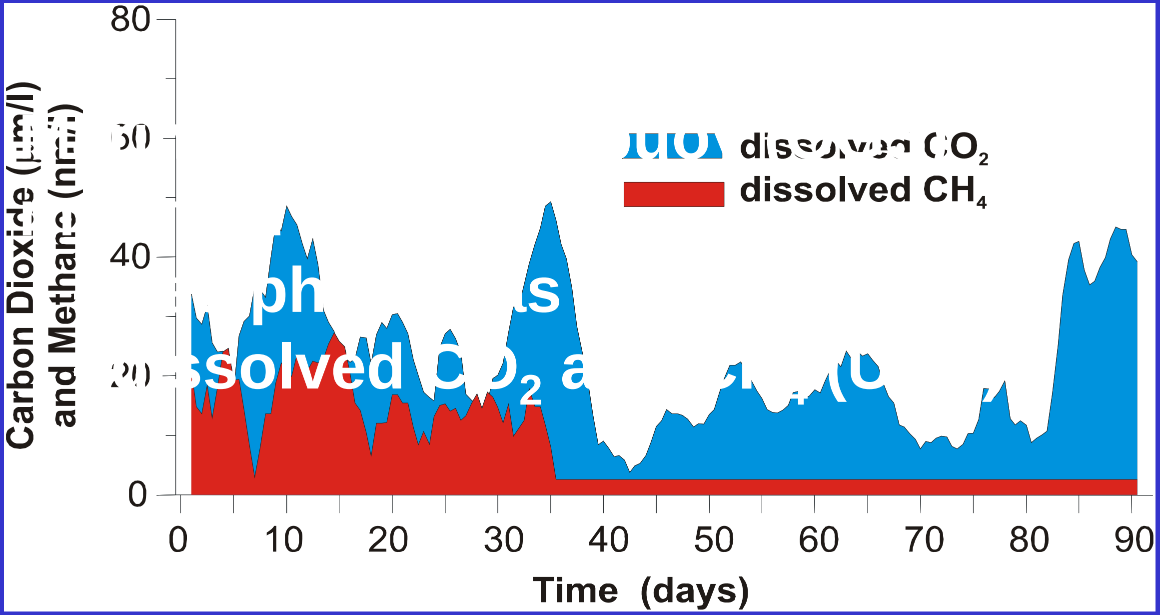
BRGM geochemical approach – CO_2

- First results:
  - in lab.: calibration of the sensor under both gaseous and water (CO_2 added) fluxes ⇒ logarithmic-linear behavior, with response times around 2 minutes (> 80% of the injected gas quantity).
  - field deployment : 400m depth diving in a 500m depth mineral water (CO_2-rich) borehole ⇒ increase in the dissolved CO_2 content from surface to bottom ; well identification of bubbling point ( ).





Offshore monitoring system (URS, BGR, OGS)



Preliminary results for dissolved phase CO_2 and CH_4

Summary

- Trying to develop a suite of techniques
- Rapid coverage of large areas
- Focus on detailed study areas
- Use rapid results and local knowledge to target possible sites of gas migration
- Continuous monitoring and discrete measurements

Future research

- Improve detection efficiency and reduce ‘false positives’ for airborne vegetation effects
- Develop direct airborne gas detection
- Gain further experience of vehicle-mounted laser systems (background and weaker gas emissions)
- Technique development through deployment at existing and other test sites
  - Norwegian CO_2 field lab
  - Other natural systems e.g. Panarea, Italy
  - Demonstration projects e.g. In Salah

The University of Nottingham

IEA Greenhouse Gas Monitoring Network Workshop
Edmonton Nov 2007

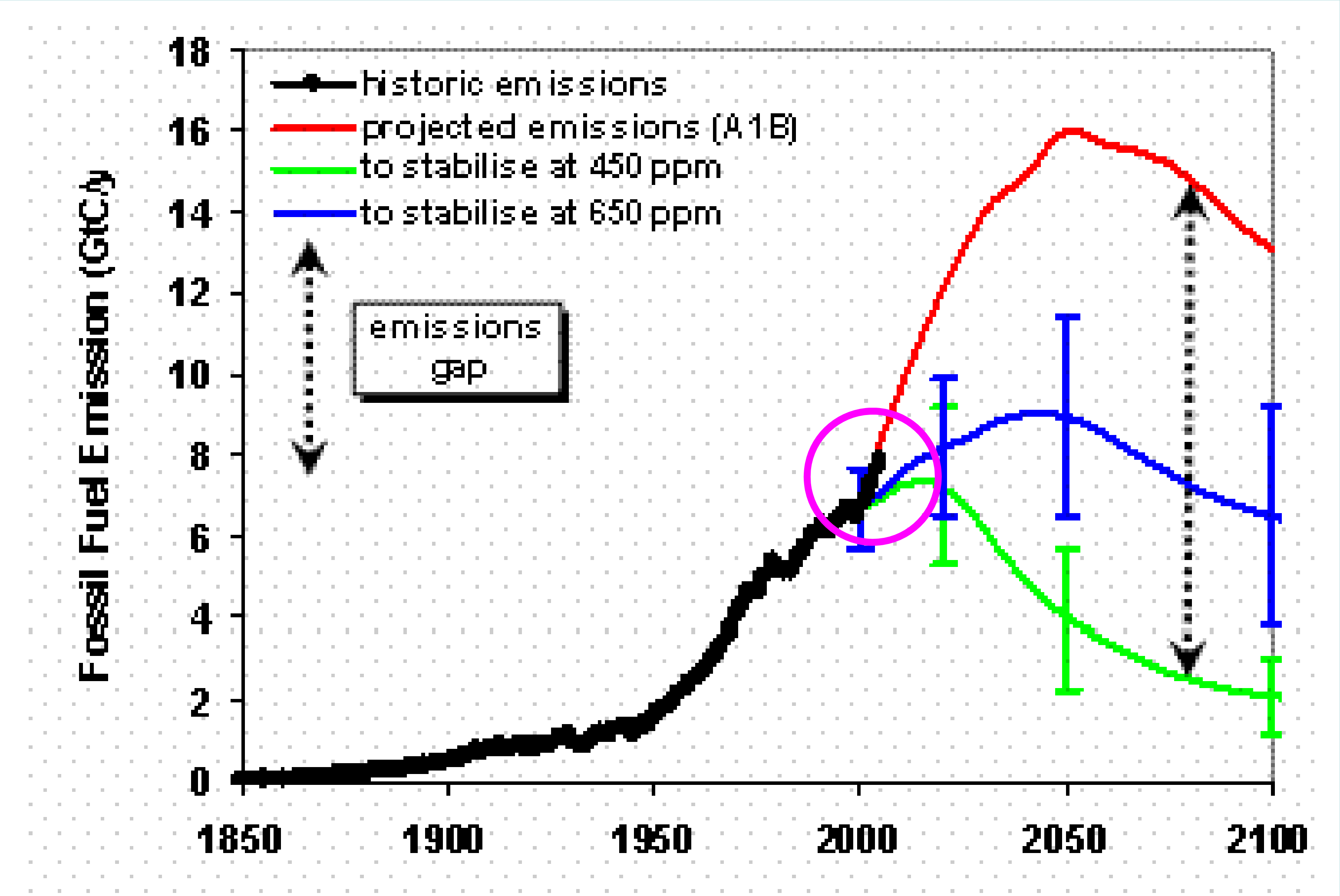
Research on Environmental Risks from Geological Carbon Dioxide Storage

Jeremy Colls

University of Nottingham, UK


Hogwarts
SCOTLAND
Aberdeen
Dundee
Stirling
Edinburgh
Glasgow
Newcastle
UNITED KINGDOM
IRELAND
York
Hull
Liverpool
Sheffield
Bangor
Nottingham
Norwich
WALES
ENGLAND
Cambridge
Oxford
Cardiff
London
Bristol
Plymouth


Context 1



historic emissions
projected emissions (A1B)
to stabilise at 450 ppm
to stabilise at 650 ppm
emissions gap
Fossil Fuel Emission (GtC/y)
0
2
4
6
8
10
12
14
16
18
1850
1900
1950
2000
2050
2100

Context 2

- With no action, peak Global CO_2 Emissions in 2050 will be ~ 60 Gt /year
- Need to reduce this by 50 Gt/year to ~ 10 Gt/year
- If GCS is going to make a worthwhile difference, need it to account for say 20% of this reduction
- ie > 10 Gt CO_2/year
- Hence need > 10 000 Sleipner-sized injection schemes

ASGARD
(Artificial Soil Gassing and Response Detection)

We have set up ASGARD to:

- inject CO_2 into the soil at controlled rates, simulating a leak from any underground source
- measure changes in plant and soil conditions
- test detection techniques such as remote sensing and isotope analysis

ASGARD
Experimental site

- Total 34 plots, each 2.5 x 2.5 m.
  - 8 plots original pasture
  - 8 plots planted with barley (2006) and fallow (2007)
  - 8 plots planted with linseed (2006)
  - 6 test plots for additional experiments
  - 4 pasture plots away from the main site to act as "remote controls"

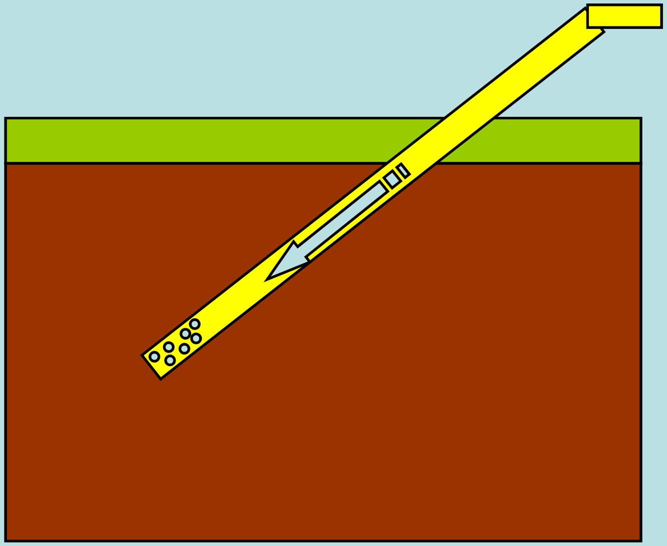
ASGARD Equipment

CO_2 stored in 2 x 200 L cryogenic cylinders

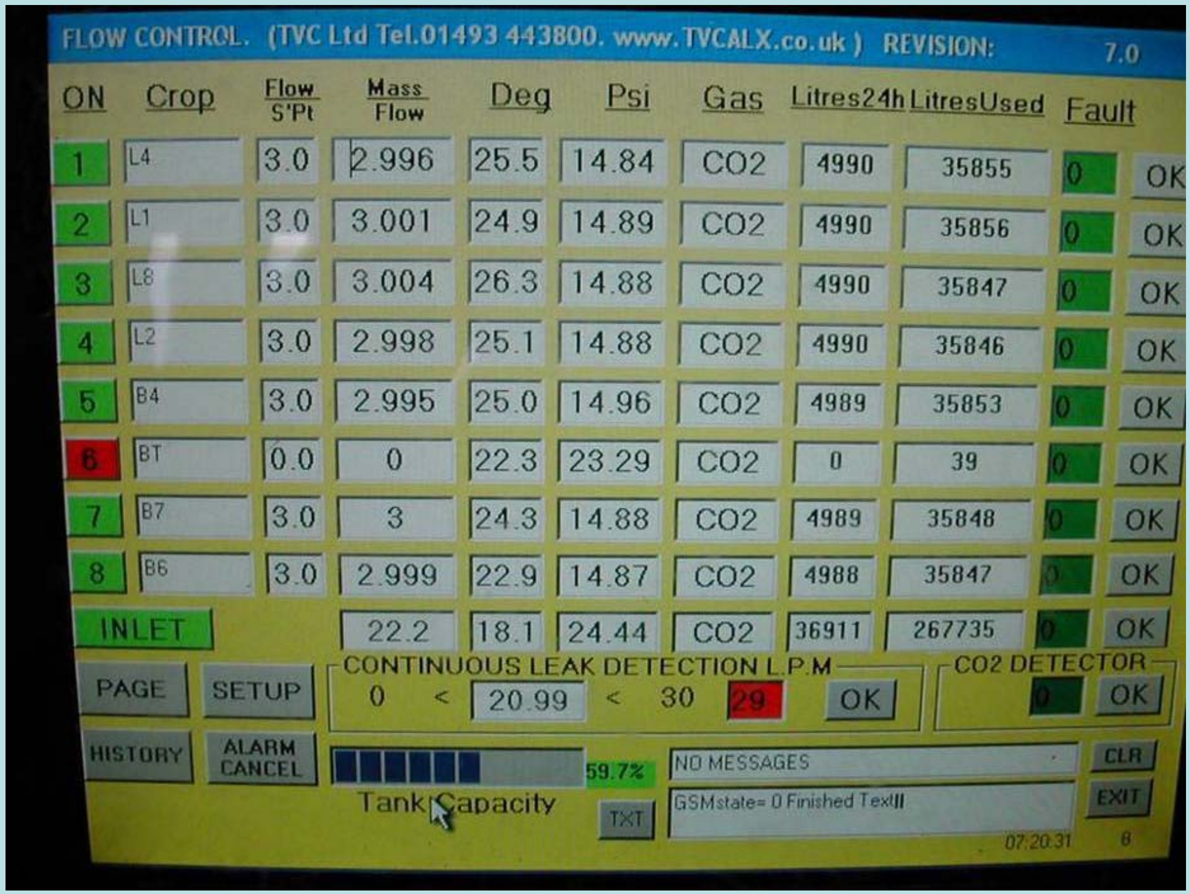
Gas delivery rate controlled with individual mass flow controllers for each plot

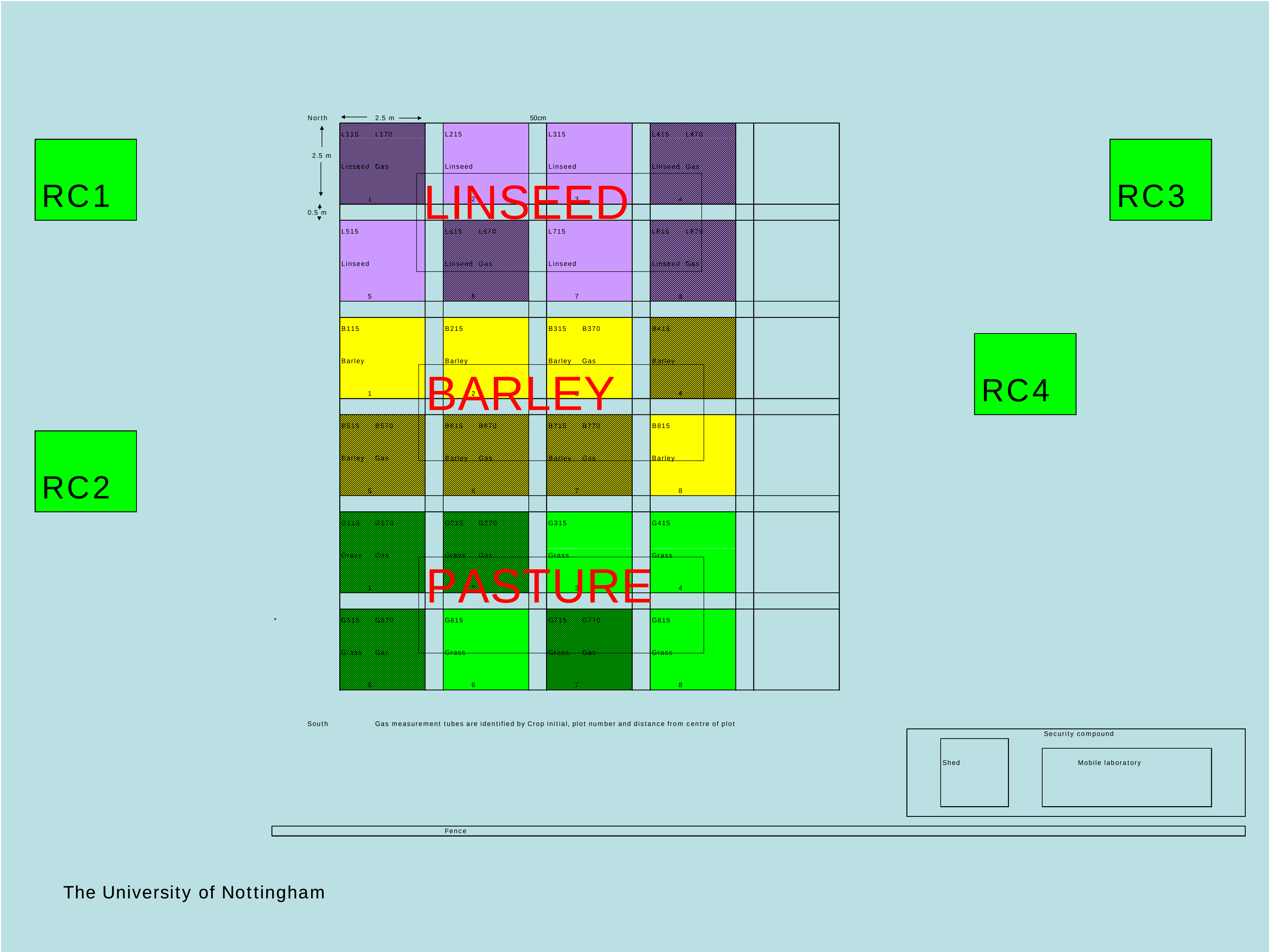
CO_2 piped out to the plots

and injected into the soil of 4 plots in each crop at a depth of 60 cm



CO_2 injection data display





RC1
RC2
RC3
RC4
North
2.5 m
2.5 m
0.5 m
50cm
LINSEED
BARLEY
PASTURE
L215
Linseed
L315
Linseed
L515
Linseed
L715
Linseed
B115
Barley
B215
Barley
B315 B370
Barley Gas
B815
Barley
G315
Grass
G415
Grass
G615
Grass
G815
Grass
South
Gas measurement tubes are identified by Crop initial, plot number and distance from centre of plot
Security compound
Shed
Mobile laboratory
Fence
The University of Nottingham

UoN Measurements

- Daily measurements of soil gas concentration in each plot
- Soil gas distribution across plots (barholing)
- Canopy CO_2 concentration (Draeger tubes)
- Spectral changes in plant shoots (ASD Spectroradiometer)
- Isotopic changes in soil CO_2

BGS Involvement

Baseline characterisation

- Local and site geology (March 2006)
- Soil gas, botany, microbiology, mineralogy, soil geochemistry (March & May 2006)

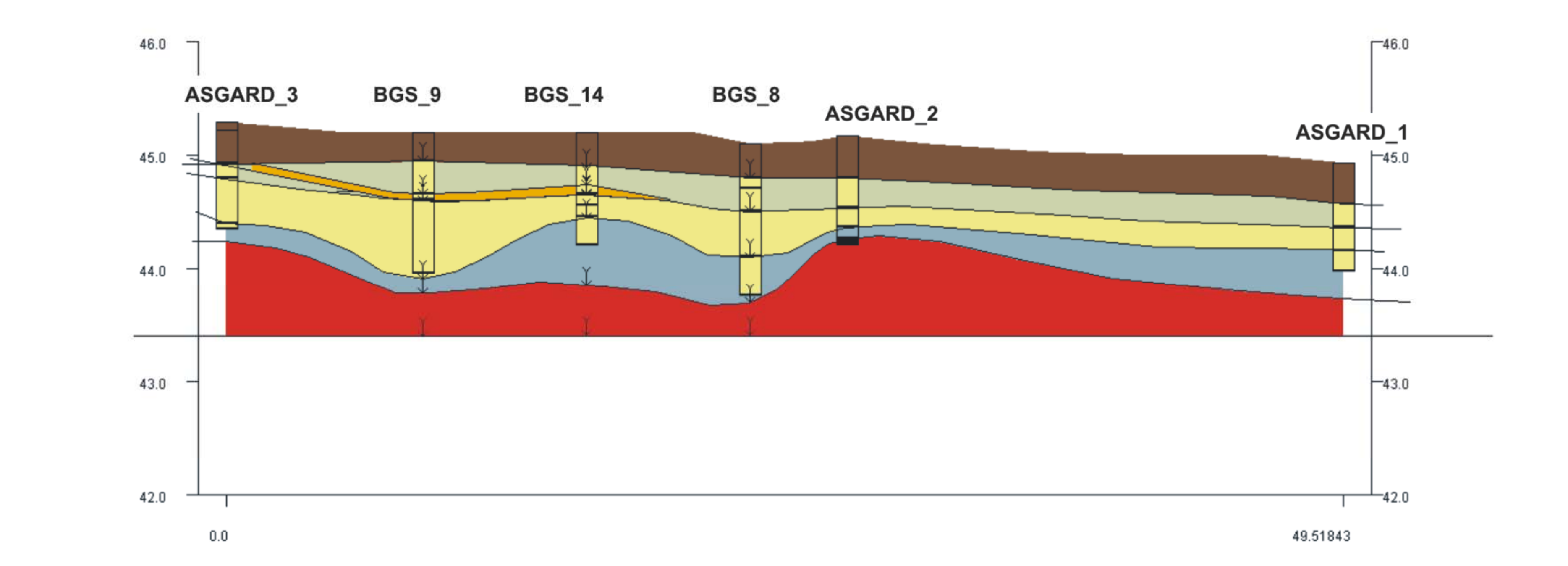
During injection

- Soil CO_2 concentrations & CO_2 flux (August06)

End of injection(September 2006)

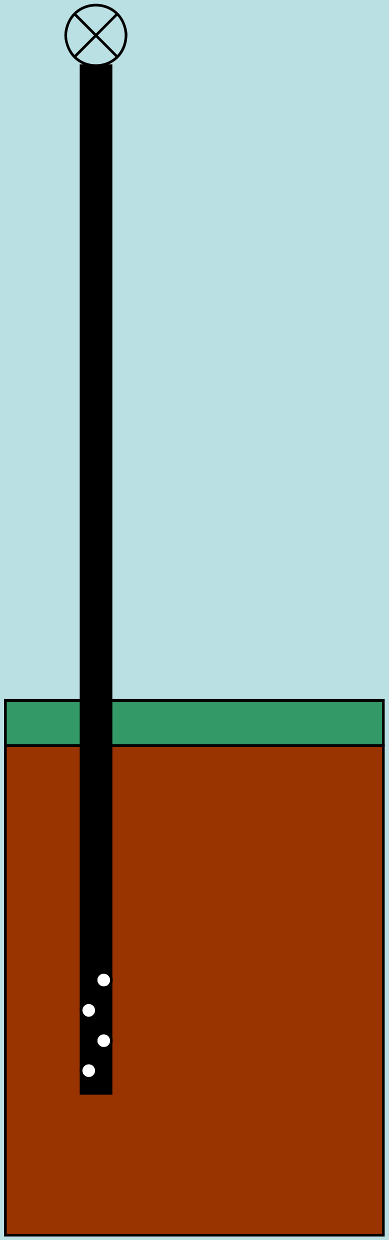
- Soil CO_2 concentrations and CO_2 flux
- Botany, microbiology, mineralogy, geochemistry

Variability of the sub-soil

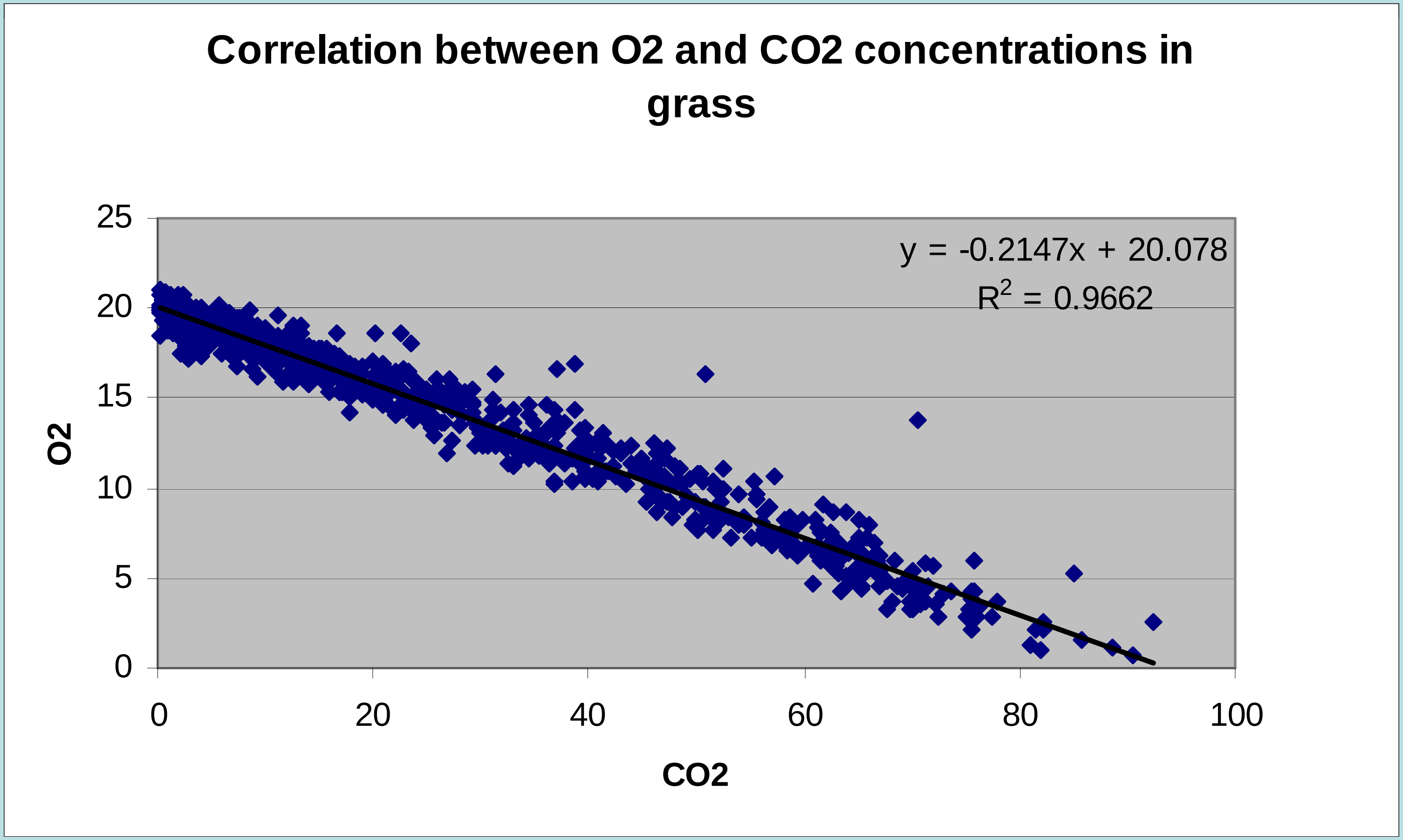


Gas concentrations

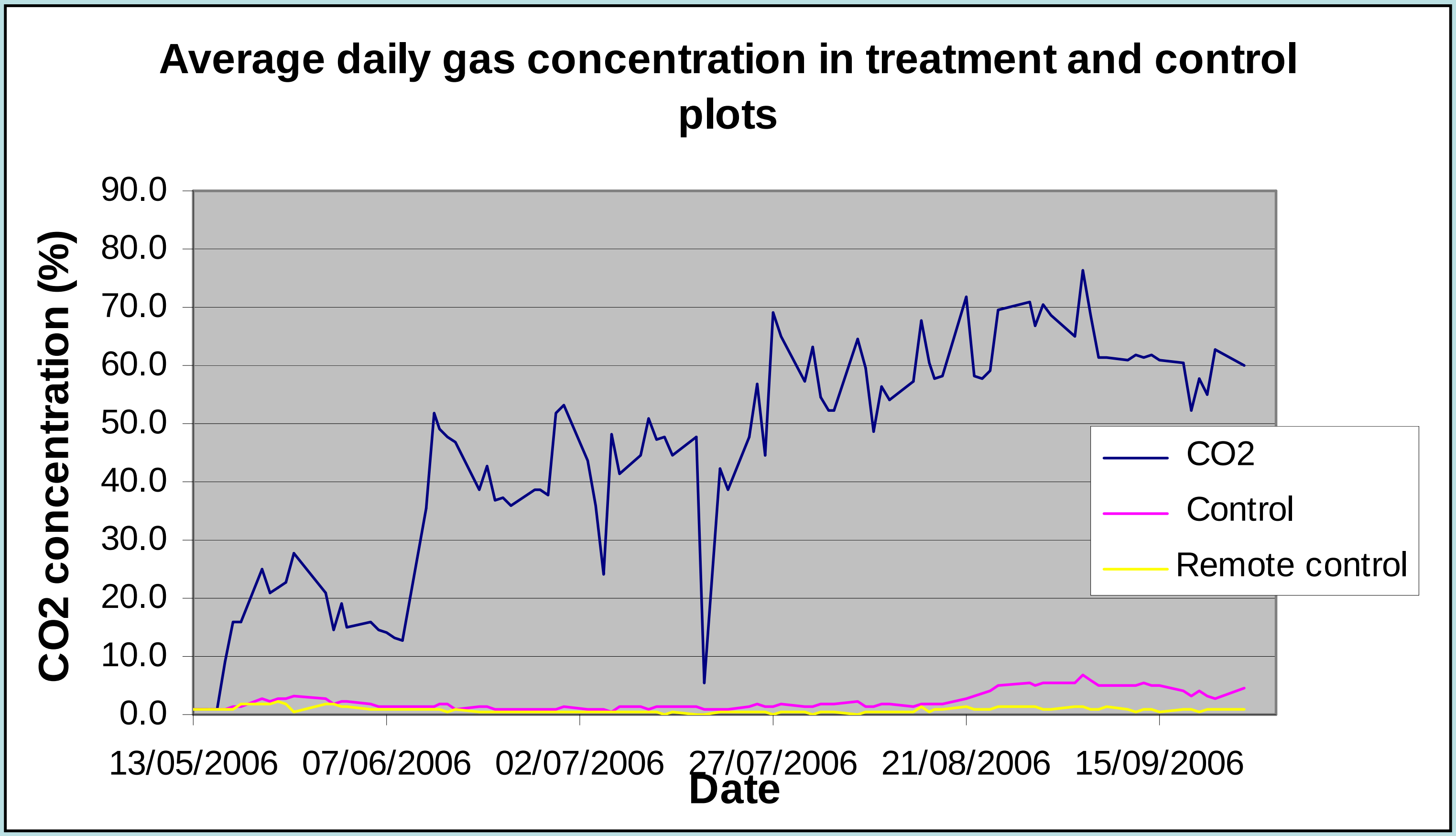
Soil gas concentration (CO_2, O_2 and CH_4) was measured on a daily basis using permanently installed sampling tubes.



Simple displacement of oxygen



Stabilisation of soil CO_2 concentration



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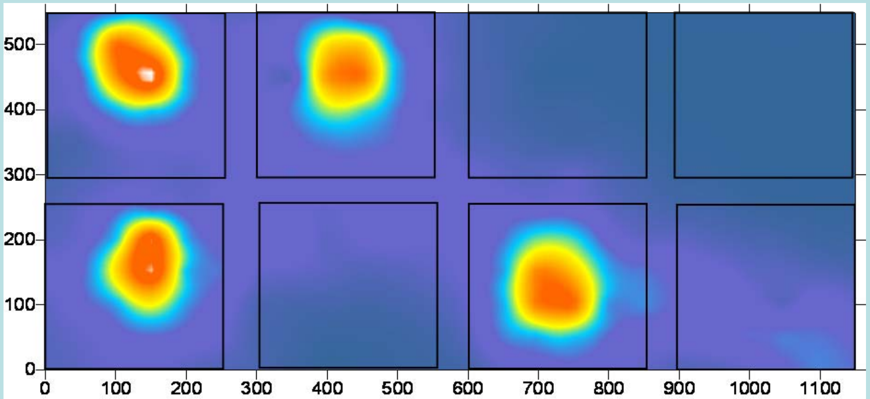
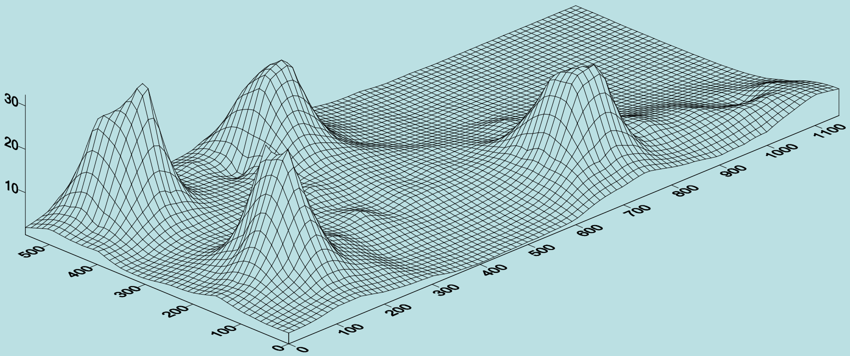
Soil CO_2 concentration distribution across pasture plots

Barholes, 30 cm deep, were made at 50 cm intervals over each plot. CO_2 measurements were taken using the GA2000 gas detector



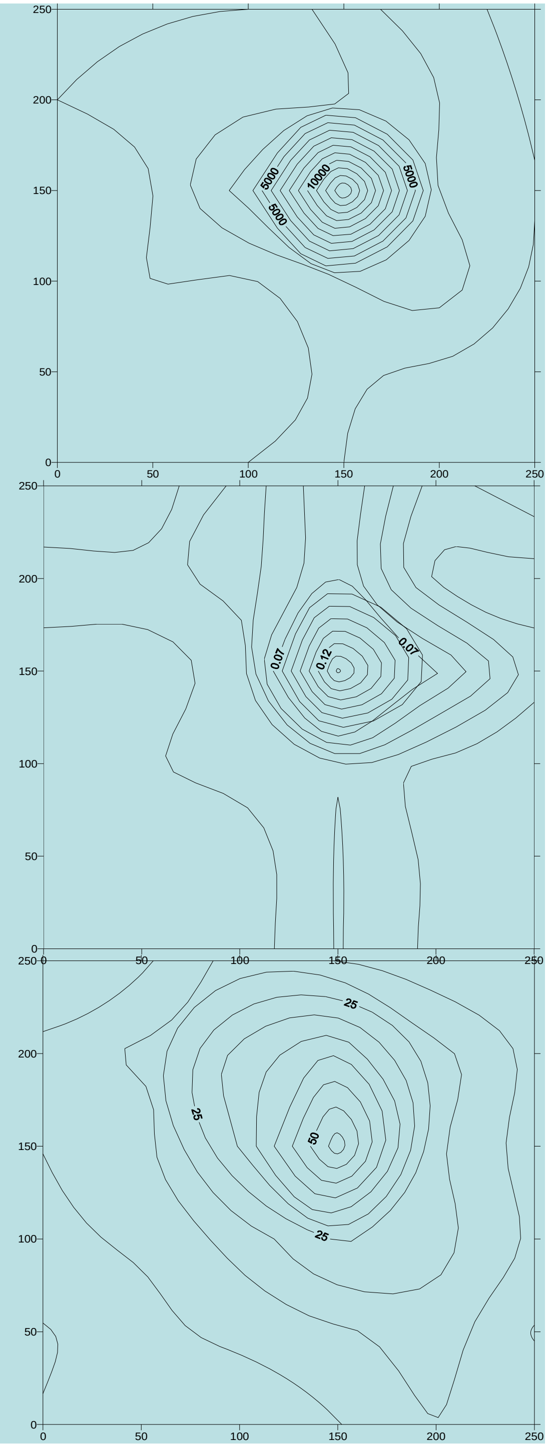


Canopy concentration

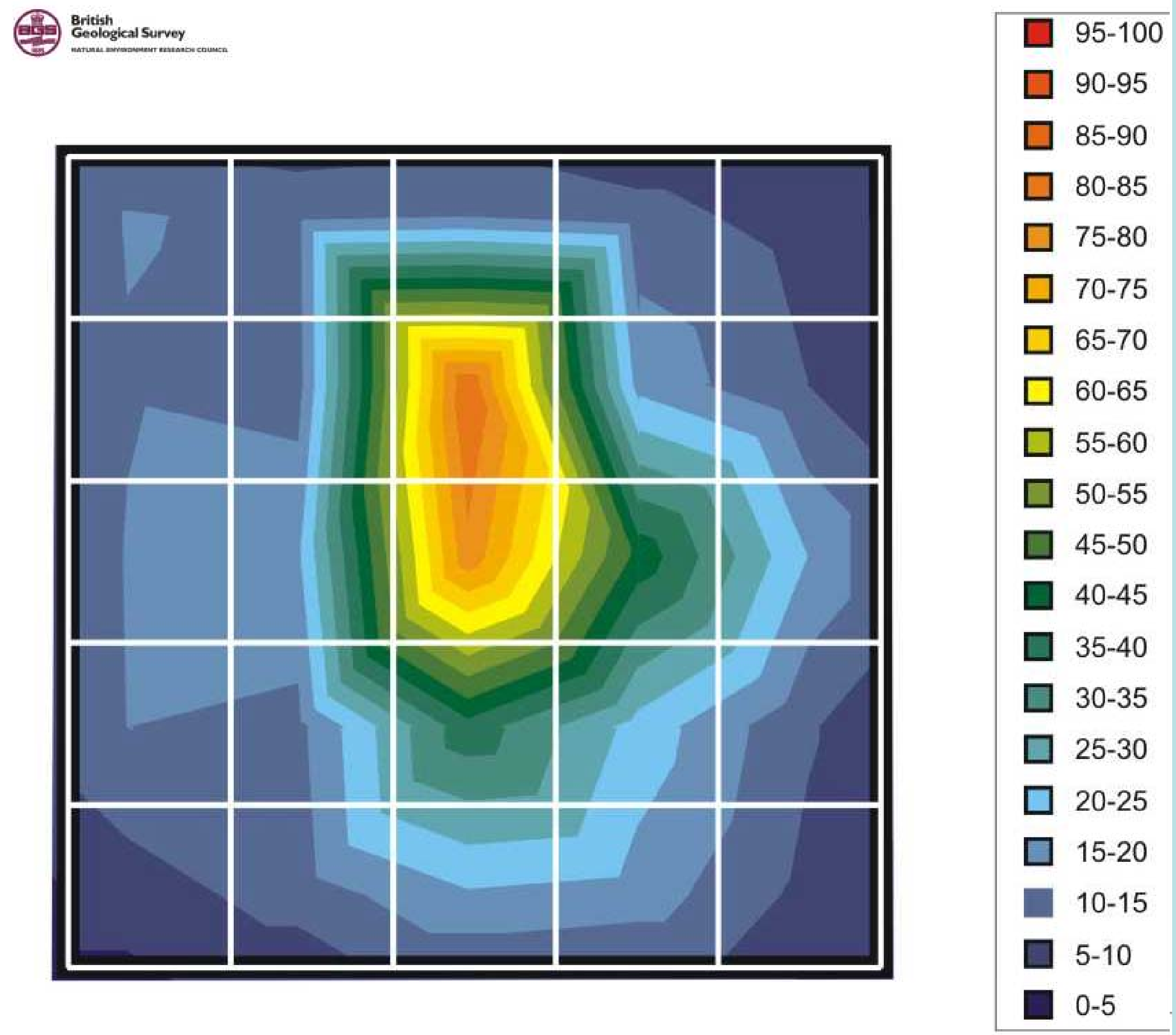
Flux through surface

Soil CO_2 concentration

The University of Nottingham

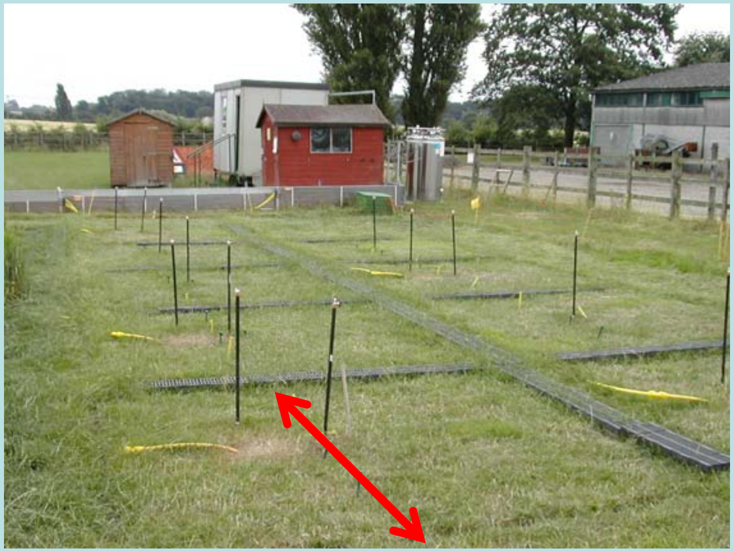


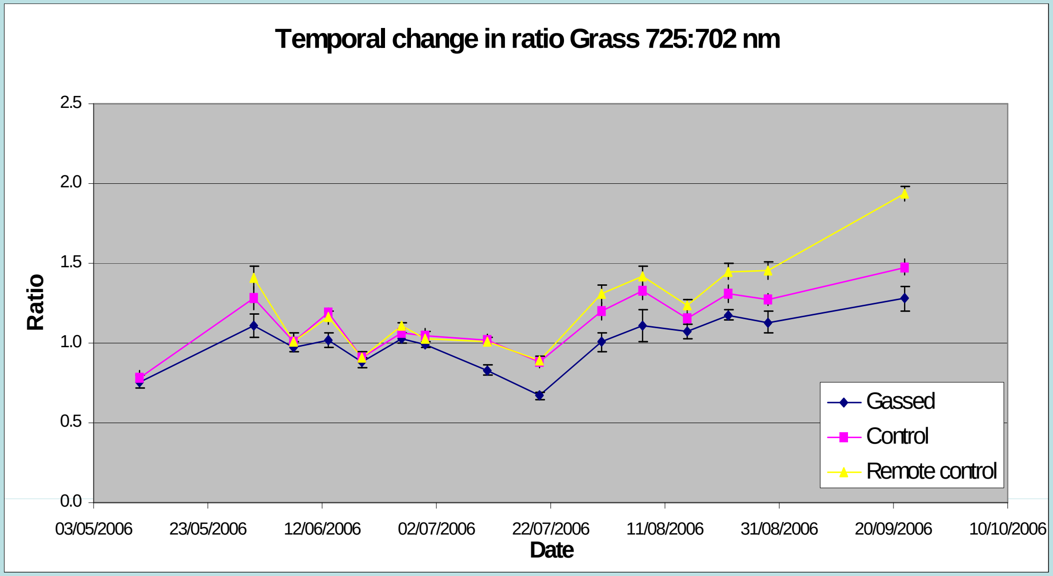
Plot G8 September 2006
CO_2 concentration (%) at 20 cm

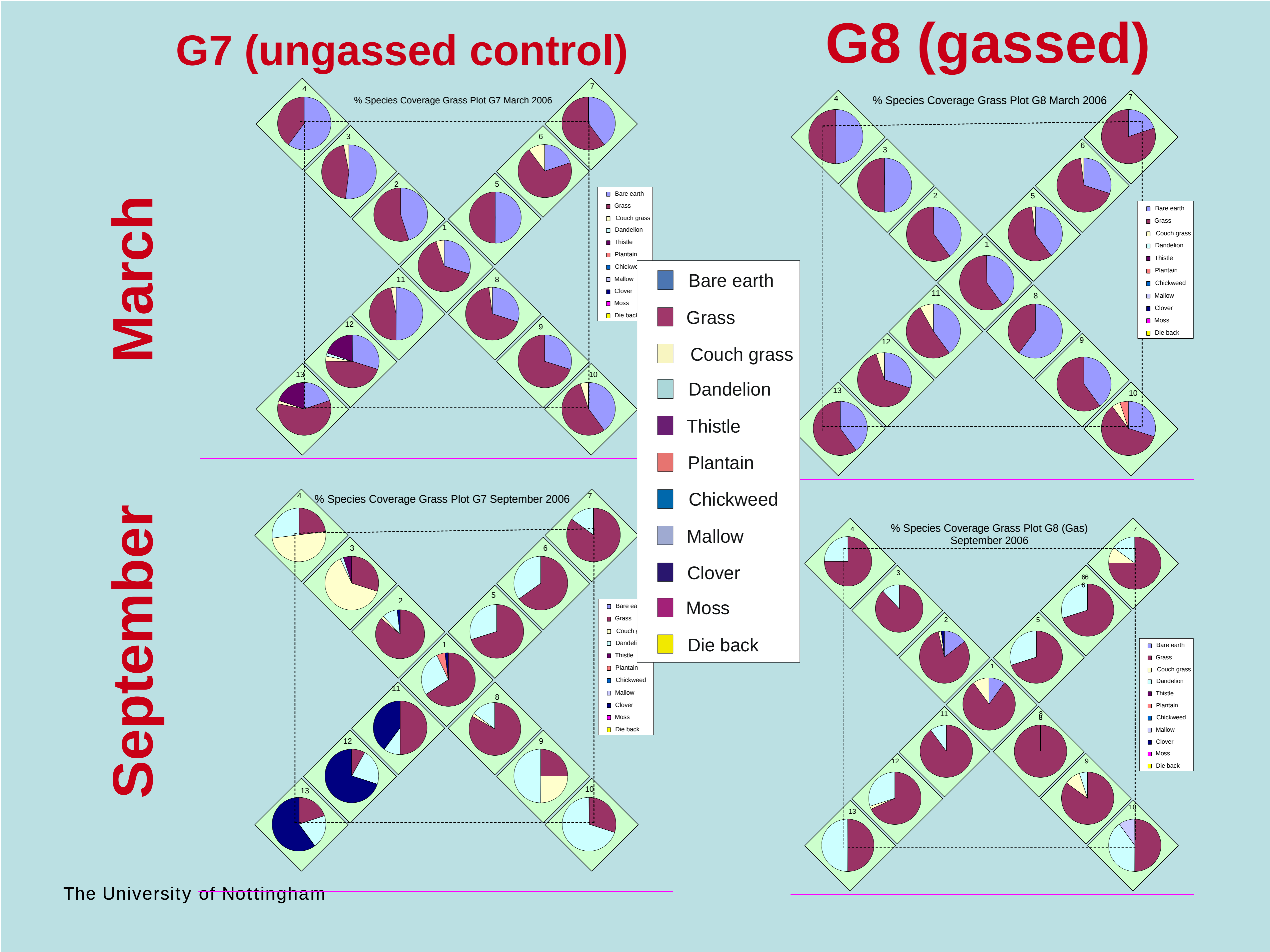


Vegetation stress

Spectral measurements were taken at 50 cm intervals along a transect across each plot.

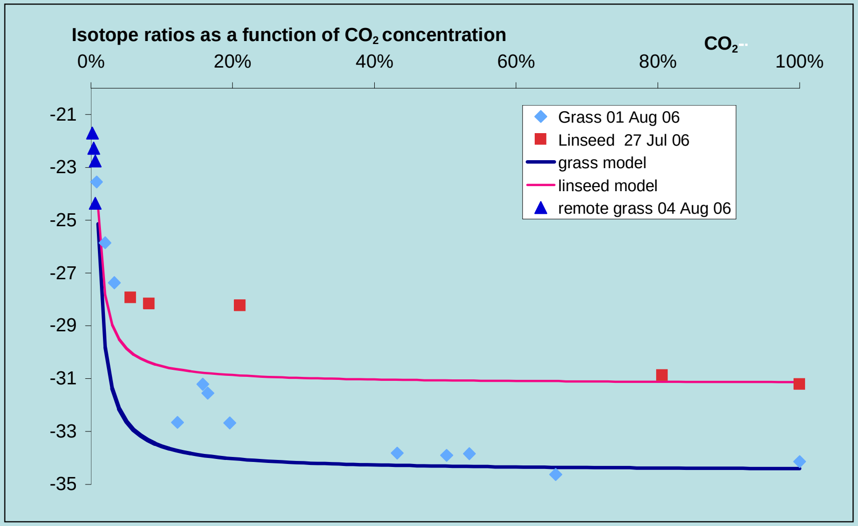






G7 (ungassed control)
G8 (gassed)
March
September
% Species Coverage Grass Plot G7 March 2006
% Species Coverage Grass Plot G8 March 2006
% Species Coverage Grass Plot G7 September 2006
% Species Coverage Grass Plot G8 (Gas) September 2006
Bare earth
Grass
Couch grass
Dandelion
Thistle
Plantain
Chickweed
Mallow
Clover
Moss
Die back
The University of Nottingham

Isotope measurements



Ongoing Activities

- Dr Ravi Patil; Royal Society India Fellowship; Responses of pasture and fallow plots to injected CO_2
- Manal Al-Traboulsi; PhD on root responses to soil CO_2, using a Bartz rhizoscope system
- Waleed Hassan; PhD on gas fluxes and concentrations, using a WestSystems flux measurement system
- Xuan Li; part-PhD on soil elemental composition

New ASGARD Project on CO_2/SO_2, starting Jan 2008

- Nottingham School of Engineering project on geochemical sequestration of CO_2/SO_2 mixtures in ferric-iron bearing sediment storage sites

- Eg **2FeOOH (goethite) + 2 CO_2 + SO_2 $\leftrightarrow$ 2 $FeCO_3$ (siderite) + H_2SO_4**

- ASGARD will be used to investigate leaks of CO_2/SO_2 mixtures

- **We will use flue gas ratio (~ 0.1-0.5% SO_2), not the stoichiometric ratio**

- **Even at this low SO_2 proportion, surface terrestrial impacts will be determined by the SO_2, not by the CO_2**

Future work

The ASGARD Facility is available to the GCS industry

- to generate data on the consequences of leaks, to support environmental permitting and EIA
- to increase capability on the detection of leaks, for monitoring and verification of storage integrity

Baseline Survey for Evidence of Gas Microseepage Prior to a CO_2 Injection Experiment at Teapot Dome, Wyoming, USA

Ronald W. Klusman

Colorado School of Mines

and

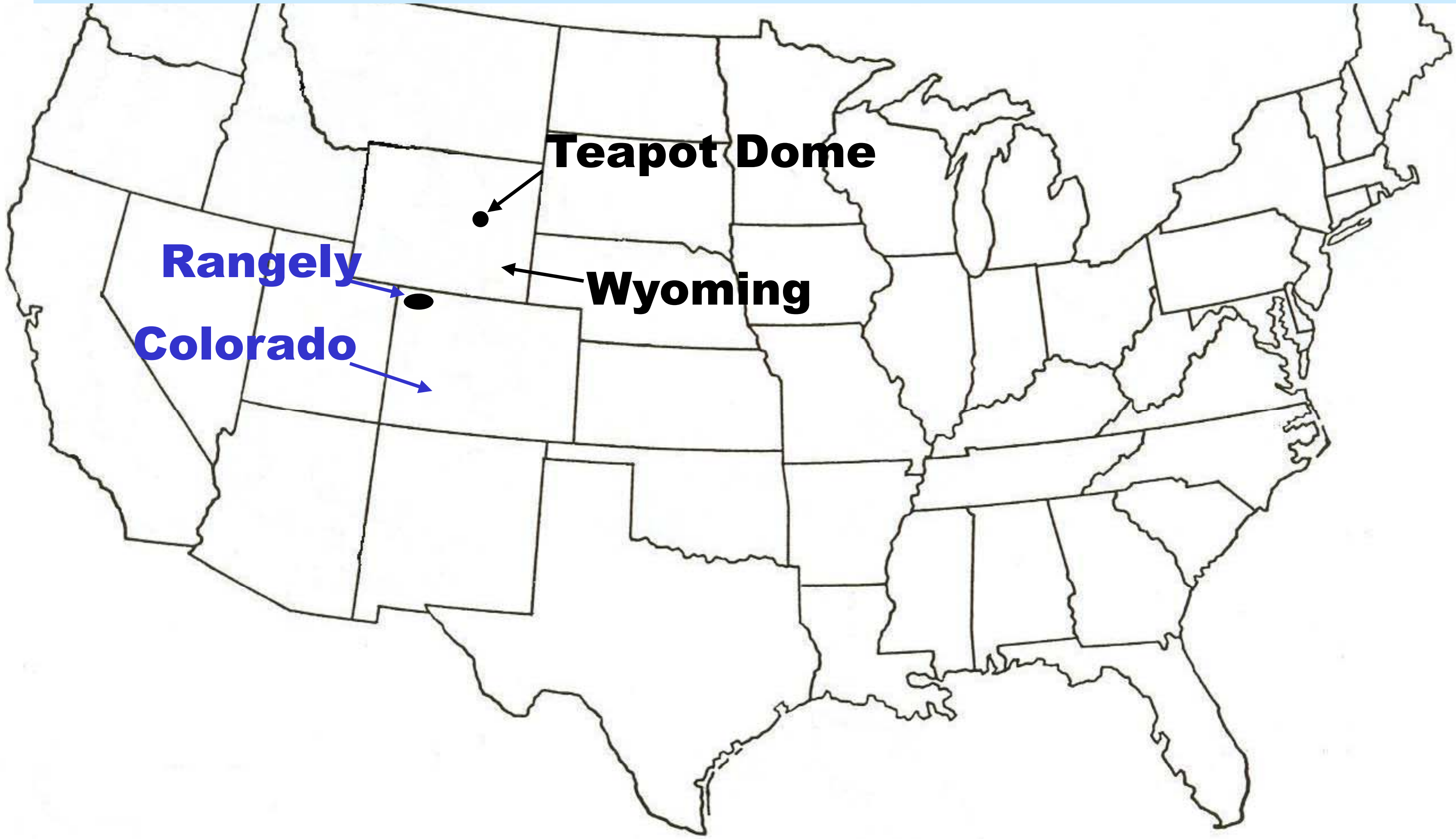
Mark Milliken and Vicki Stamp

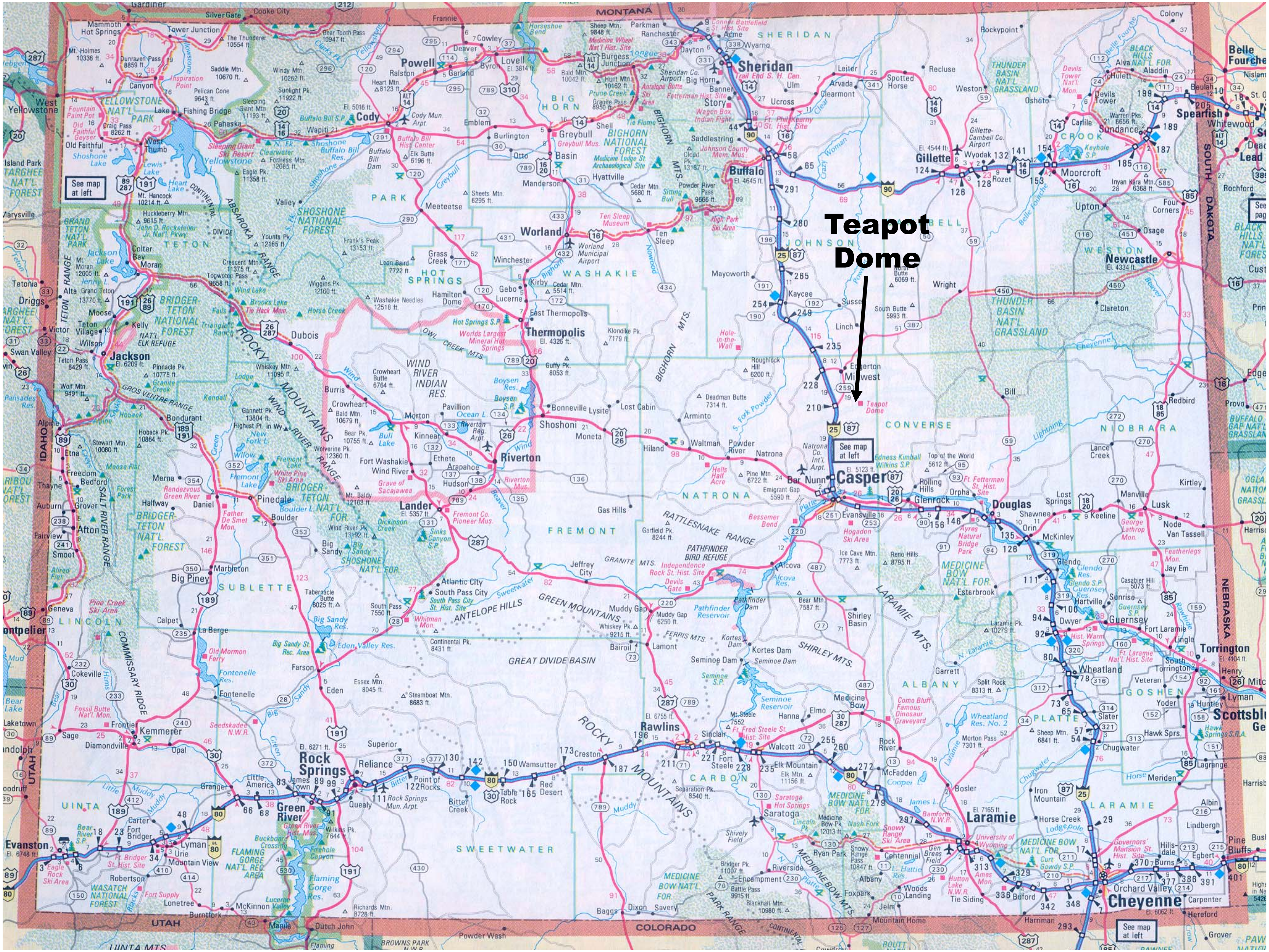
Rocky Mountain Oilfield Testing Center

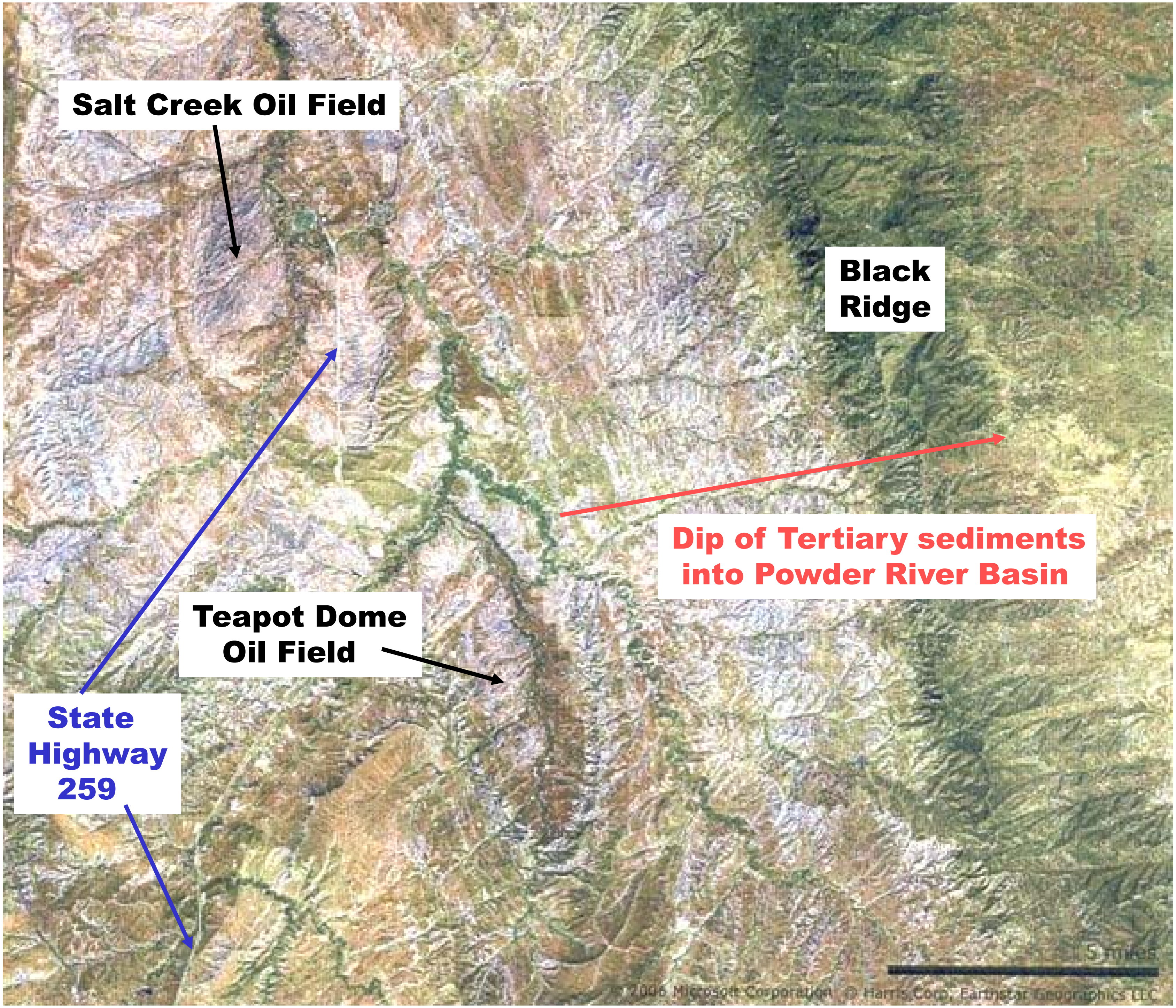
OBJECTIVES OF RESEARCH

- **Look for evidence of gas microseepage in a 1 km^2 area around a proposed CO_2 injection well,**
- **Look for evidence of gas microseepage along and across the newly discovered 87-10 Fault,**
- **Use stable isotope measurements to determine the genesis of the $CaCO_3$ phases in the 87-10 Fault.**

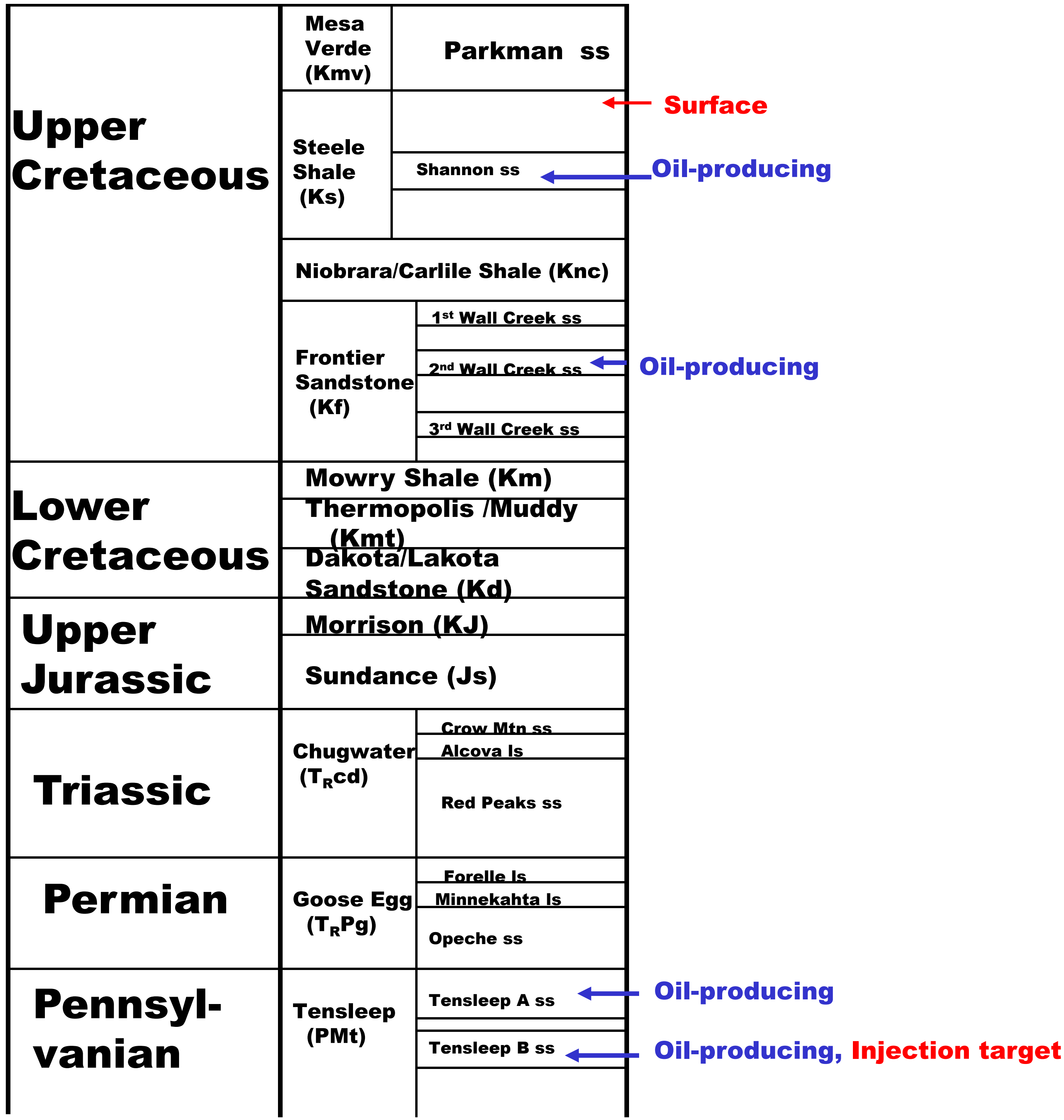
MICROSEEPAGE DETECTION AND MEASUREMENT LOCATIONS WITH REFEREED PUBLICATIONS




Teapot
Dome
MONTANA
SOUTH DAKOTA
NEBRASKA
COLORADO
UTAH
IDAHO
Sheridan
Buffalo
Gillette
Casper
Douglas
Cheyenne
Laramie
Rawlins
Rock Springs
Green River
Evanston
Riverton
Lander
Thermopolis
Worland
Cody
Powell
Jackson
Newcastle
Torrington
Wheatland
Teapot Dome
Midwest
NATRONA
CONVERSE
FREMONT
SWEETWATER
CARBON

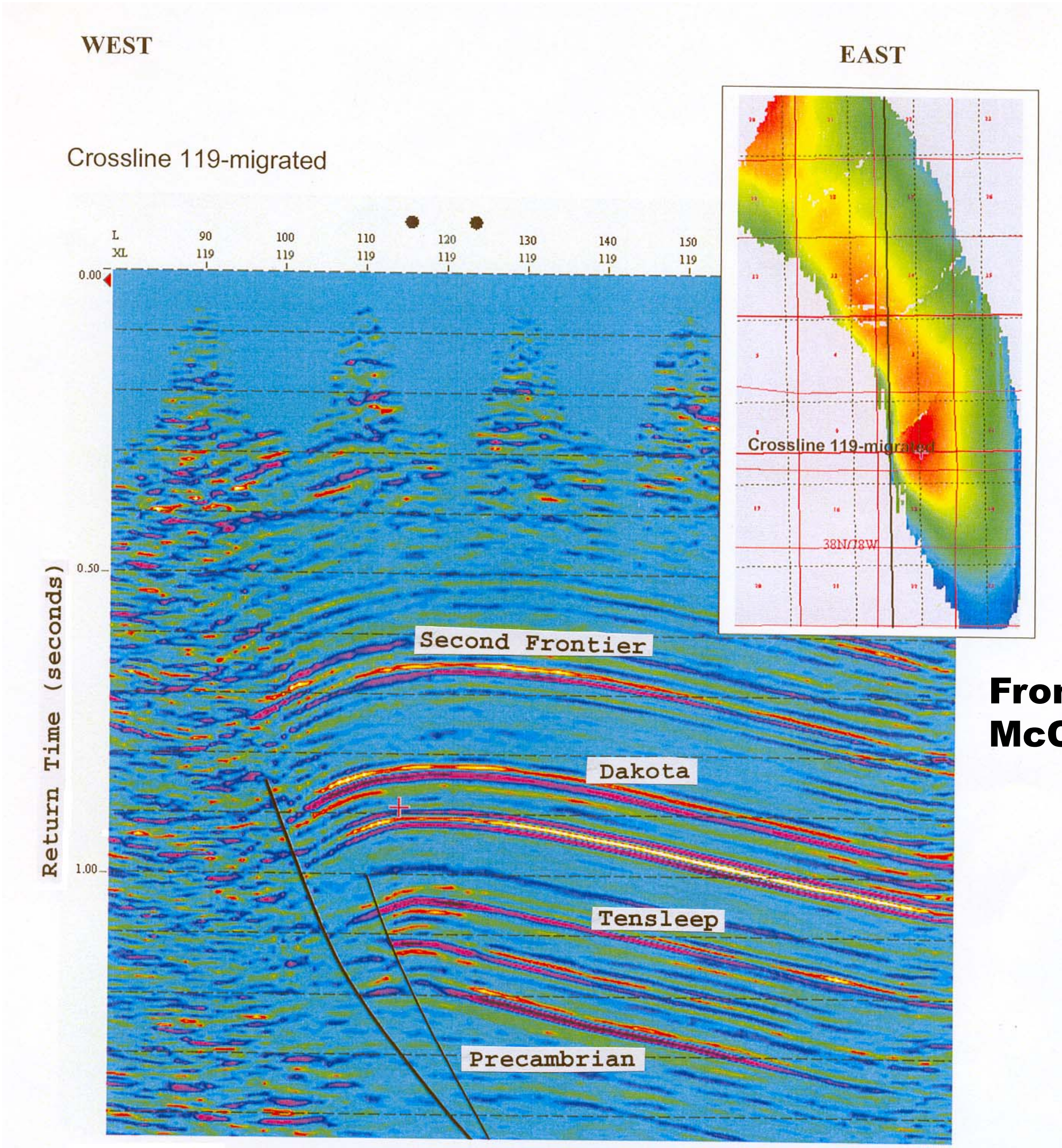


Salt Creek Oil Field
Black Ridge
Dip of Tertiary sediments into Powder River Basin
Teapot Dome Oil Field
State Highway 259
5 miles
© 2006 Microsoft Corporation © Harris Corp, Earthstar Geographics LLC

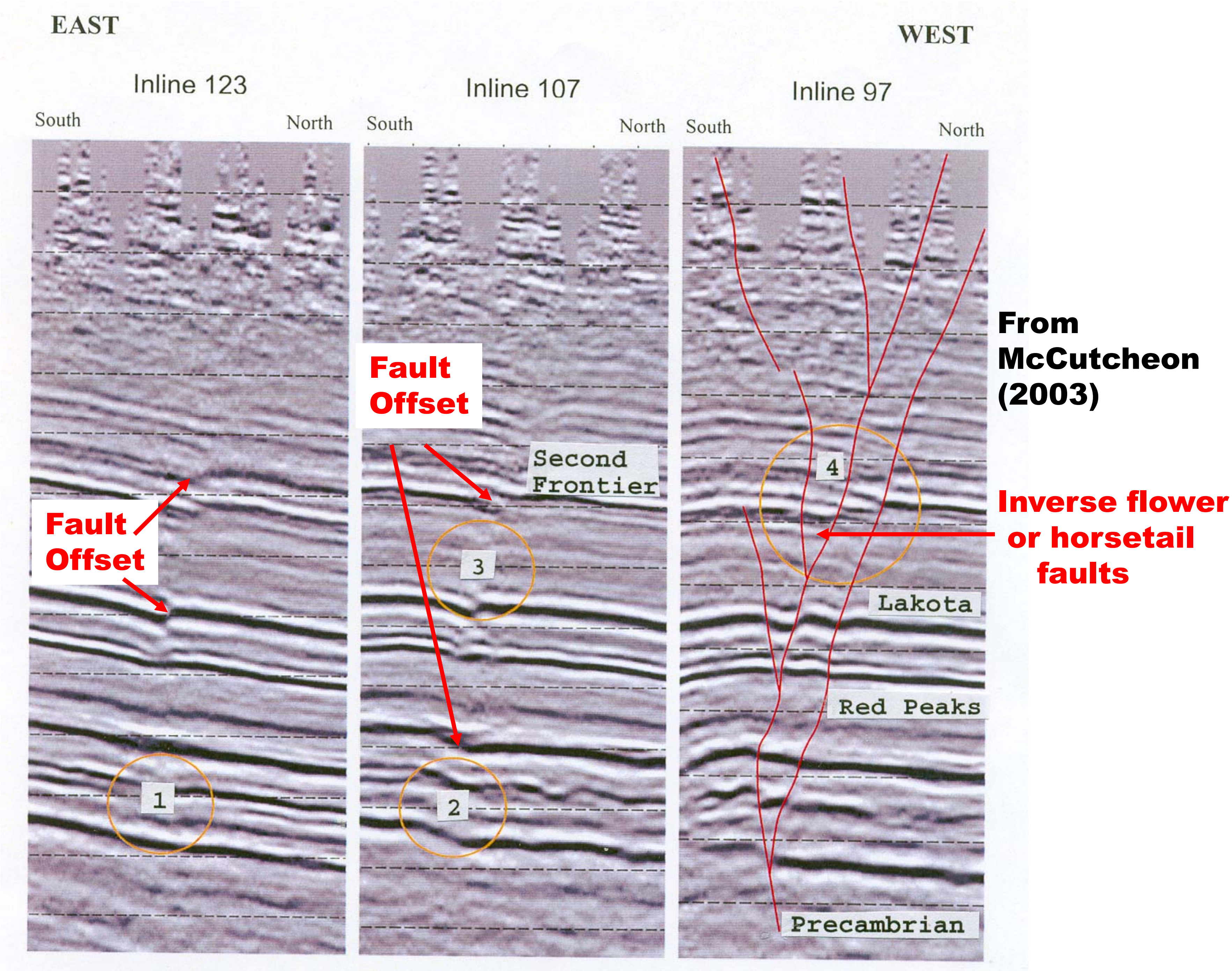

Upper Cretaceous
Mesa Verde (Kmv)
Parkman ss
Surface
Steele Shale (Ks)
Shannon ss
Oil-producing
Niobrara/Carlile Shale (Knc)
Frontier Sandstone (Kf)
1st Wall Creek ss
2nd Wall Creek ss
Oil-producing
3rd Wall Creek ss
Lower Cretaceous
Mowry Shale (Km)
Thermopolis /Muddy (Kmt)
Dakota/Lakota Sandstone (Kd)
Upper Jurassic
Morrison (KJ)
Sundance (Js)
Triassic
Chugwater ($T_R$cd)
Crow Mtn ss
Alcova ls
Red Peaks ss
Permian
Goose Egg (T_RPg)
Forelle ls
Minnekahta ls
Opeche ss
Pennsyl-vanian
Tensleep (PMt)
Tensleep A ss
Oil-producing
Tensleep B ss
Oil-producing, Injection target

TEAPOT DOME CHARACTERISTICS

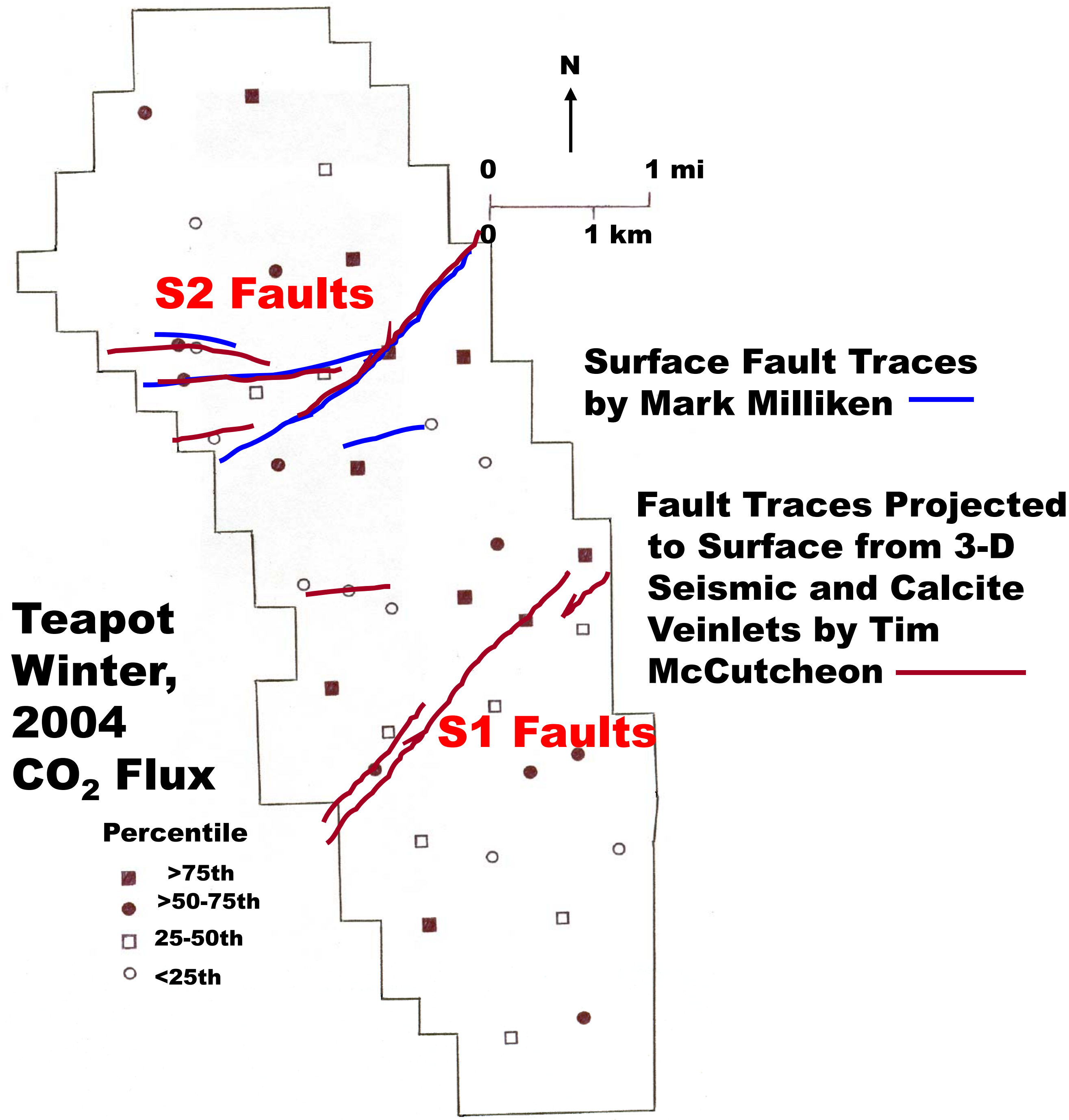
- **Approximately 18 mi^2 (42 km^2),**
- **Completely depleted, with production approximately 300 bbl day^{-1}, from three stacked horizons,**
- **2nd Wall Creek (2nd Frontier) and Shannon are underpressured,**
- **Deepest horizon (Tensleep B at 1700 m, 5500 ft), is normally pressured, and proposed for CO_2 sequestration experimentation.**



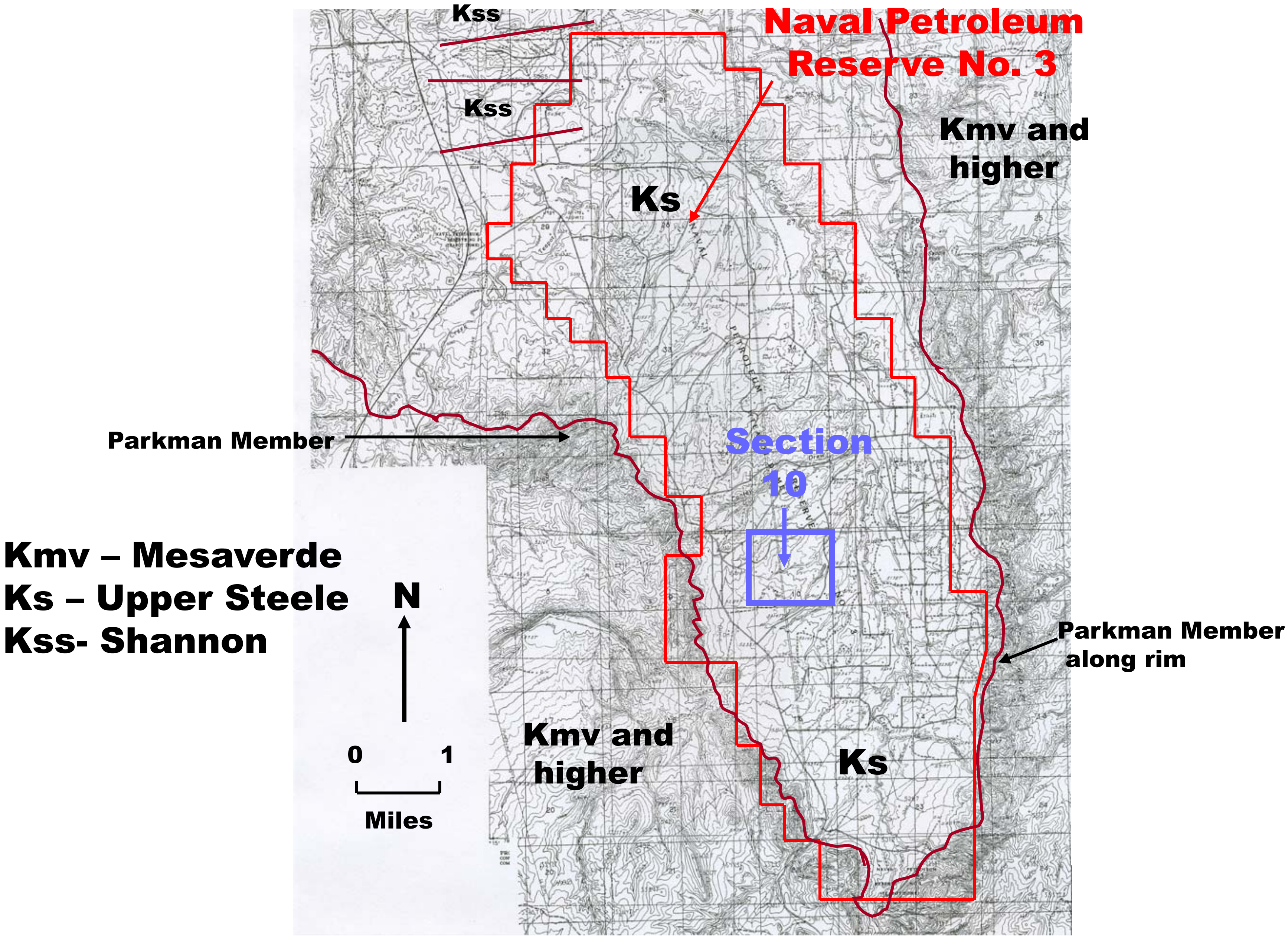
From McCutcheon (2003)



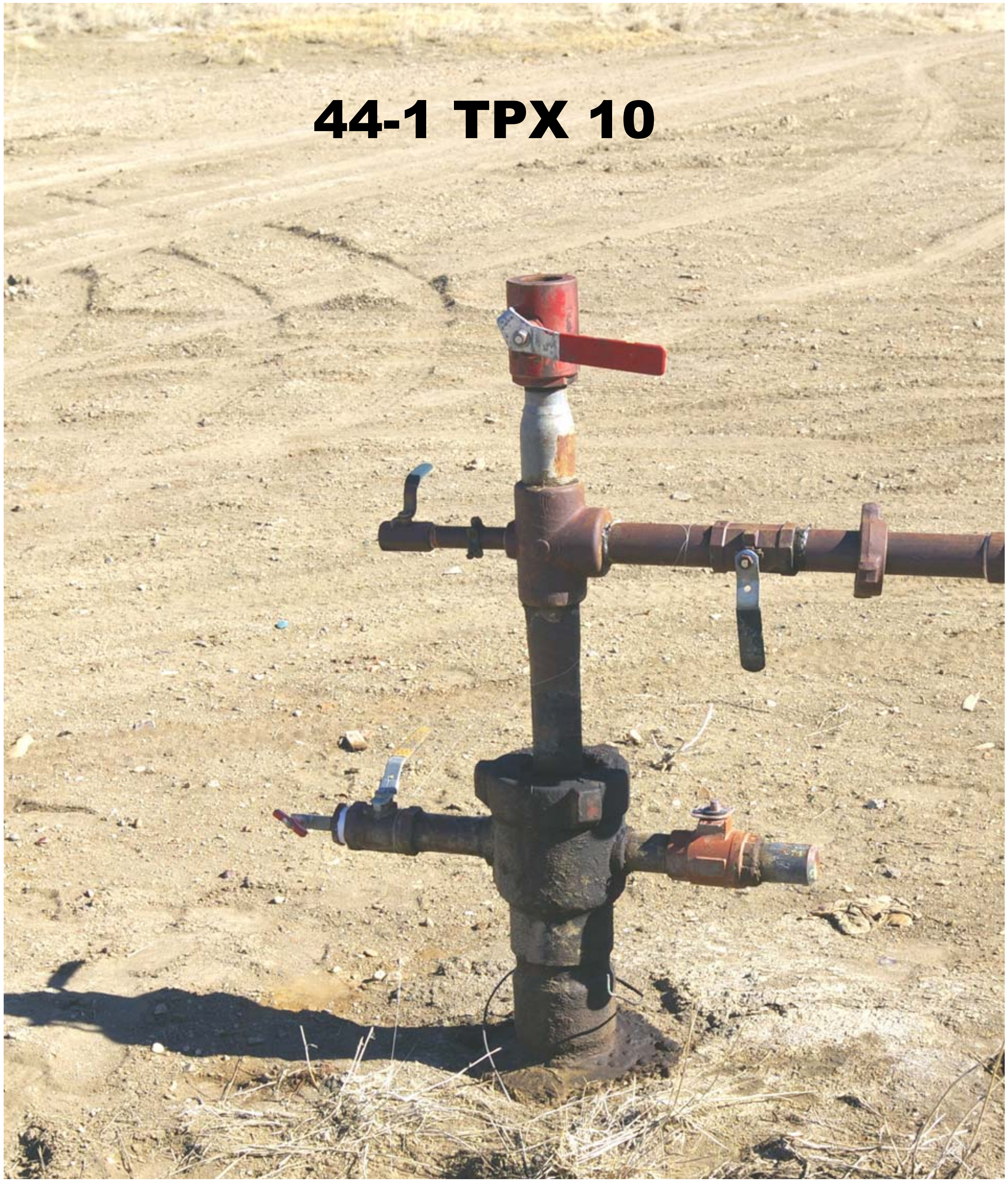
From McCutcheon (2003)



N
0
1 mi
0
1 km
S2 Faults
Surface Fault Traces by Mark Milliken
Fault Traces Projected to Surface from 3-D Seismic and Calcite Veinlets by Tim McCutcheon
S1 Faults
Teapot Winter, 2004 CO_2 Flux
Percentile
>75th
>50-75th
25-50th
<25th


Naval Petroleum Reserve No. 3
Kss
Kss
Ks
Kmv and higher
Parkman Member
Section 10
Kmv – Mesaverde
Ks – Upper Steele
Kss- Shannon
N
0
1
Miles
Kmv and higher
Ks
Parkman Member along rim


U. S. DEPT. OF ENERGY
NPR #3
44-1TPX 10
2477' FSL, 2416' FWL
Sec. 10, T 38 N, R 78 W


44-1 TPX 10

DEFINITIONS (Klusman)

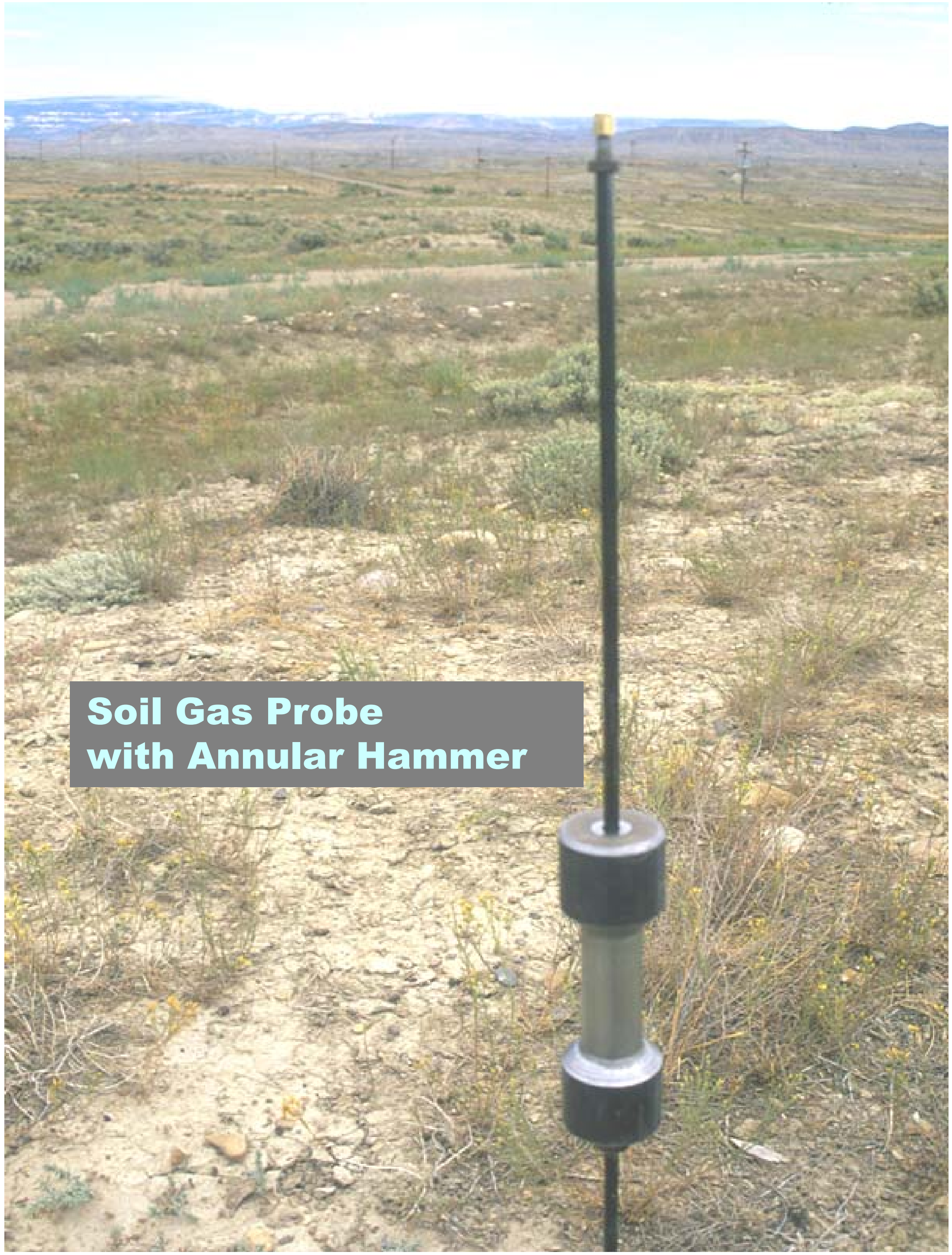
- **Macroseepage** (leakage)- strong odors, wet bubbly ground, abnormal snowmelt patterns, temperature anomalies at 1 meter depth,
- **Miniseepage** – stressed or dying vegetation in patches without evidence of disease because of flooding of soil with gas, temperature anomalies at 10 meters, blue-gray haze during winter inversions, saline water seepage,
- **Microseepage** – detection of gases at surface requires sampling and laboratory analysis or sensitive optical (IR) measurements in long open path, common over large areas in sedimentary basins and oil/gas fields,
- **Secondary effects** – may be present in many cases at all three levels of intensity; includes secondary carbonate from oxidizing carbon, horizontal gradient magnetic effects, abnormal bacterial consortium present, sulfate depleted shallow ground water, radiometric anomalies, vegetation restricted to shallow-rooted grasses.

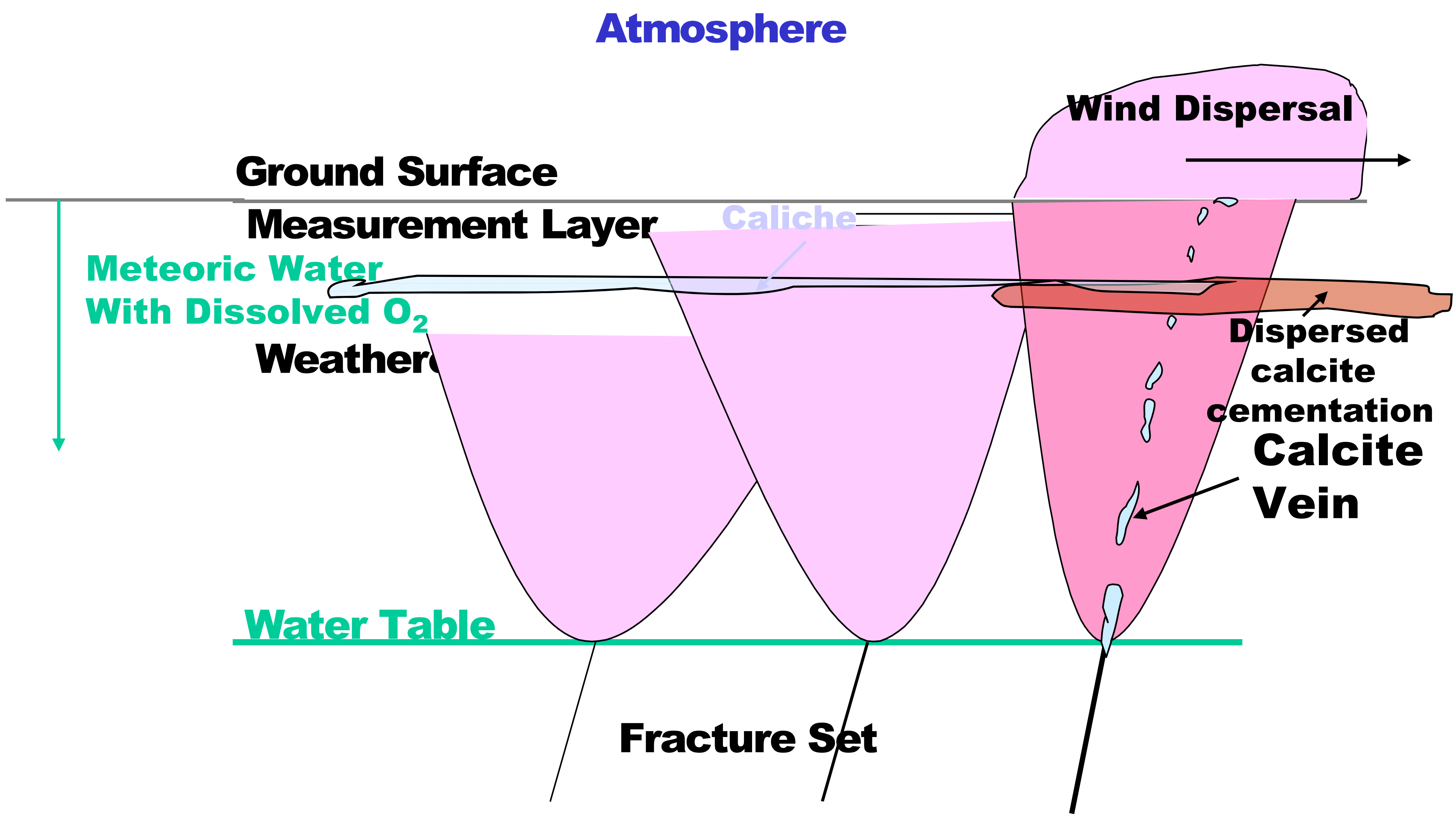
IMPORTANCE OF CO_2 AND CH_4 IN A MMV PROGRAM

- **CO_2 soluble in, and reactive with water which attenuates migration,**
- **CH_4 is not soluble, nor reactive, being relatively stable in the subsurface environment,**
- **CH_4 likely ubiquitous in early sequestration options in spent oil/gas fields,**
- **CH_4 is a more mobile molecule when overpressured,**
- **CH_4 has a greater GWP if it reaches the atmosphere,**
- **CH_4 is explosive.**

SUMMER VS WINTER MEASUREMENTS

- **Searching for a subtle signal in the presence of substantial surface noise,**
- **Microbial oxidation of soil organic matter to CO_2, and root respiration producing CO_2 is lower in winter,**
- **Methanotrophic oxidation rate of CH_4 in unsaturated zone is lower in winter,**
- **Therefore, the best chance of detecting a deep-sourced signal for either CO_2 or CH_4 is in the winter or dry season.**


Soil Gas Probe
with Annular Hammer



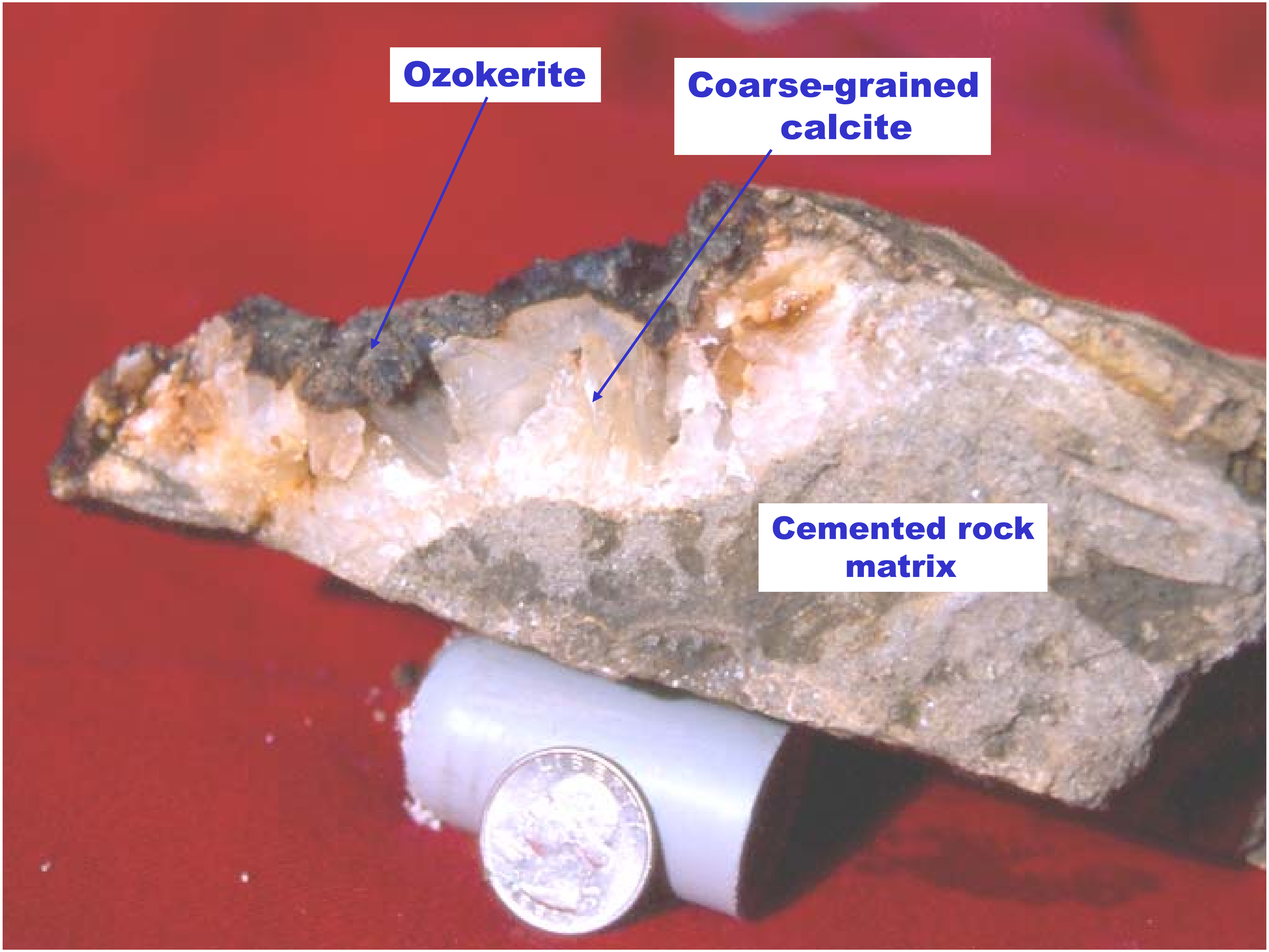
Atmosphere
Wind Dispersal
Ground Surface
Measurement Layer
Caliche
Meteoric Water
With Dissolved O_2
Weathere
Dispersed calcite cementation
Calcite Vein
Water Table
Fracture Set

SOURCES OF CARBON DIOXIDE

- **Three sources are always present; 1)Atmosphere, 2) Near-surface inorganic, 3) Biological,**
- **4th) Methanotrophic oxidation of CH_4 to CO_2,**
- **5th) Injected CO_2.**
- **Measurement of stable isotopes critical in assessing source(s) of CO_2.**

Calcite vein in Section 3

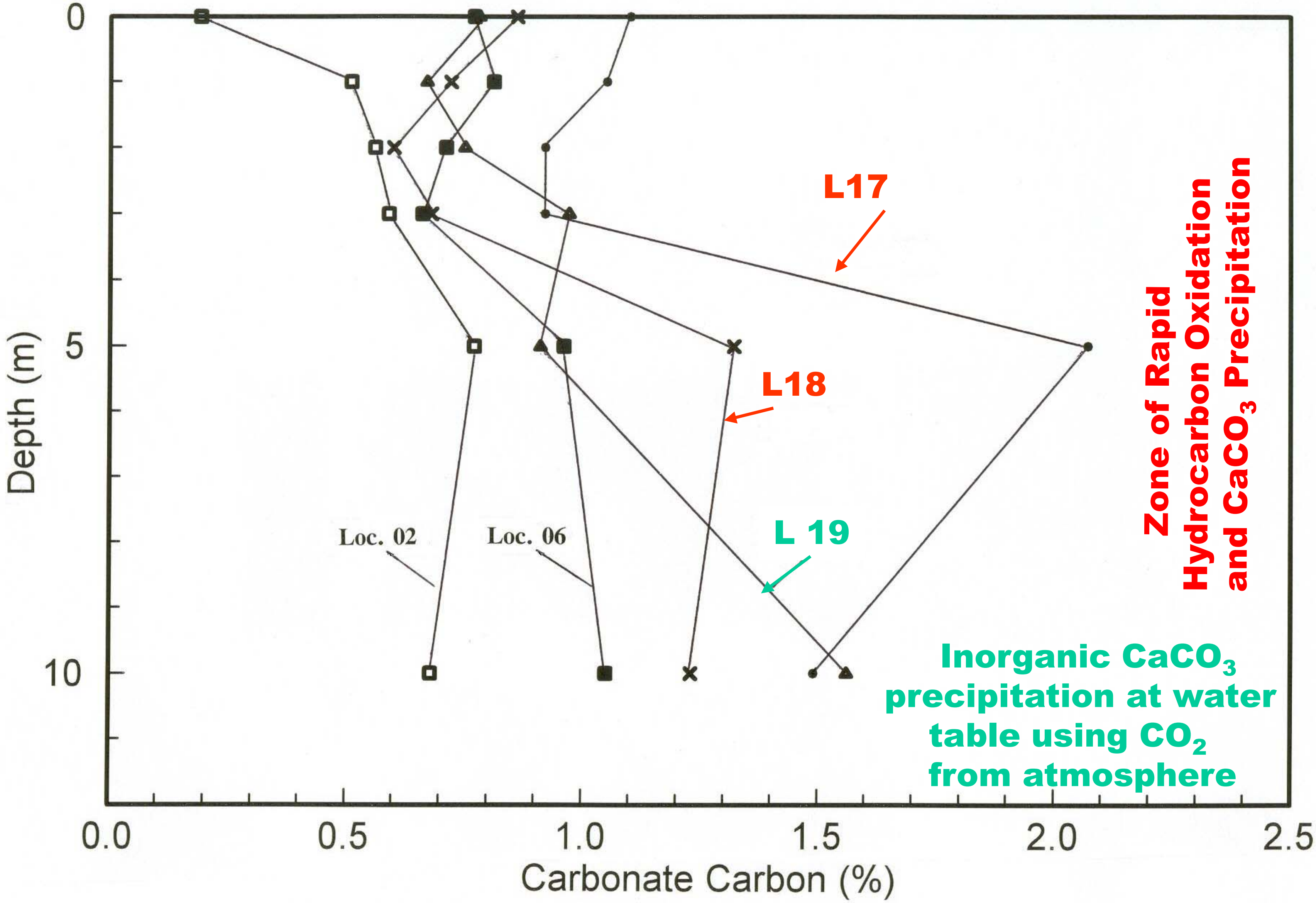

Coarse-grained calcite
with and without voids


Ozokerite
Coarse-grained calcite
Cemented rock matrix

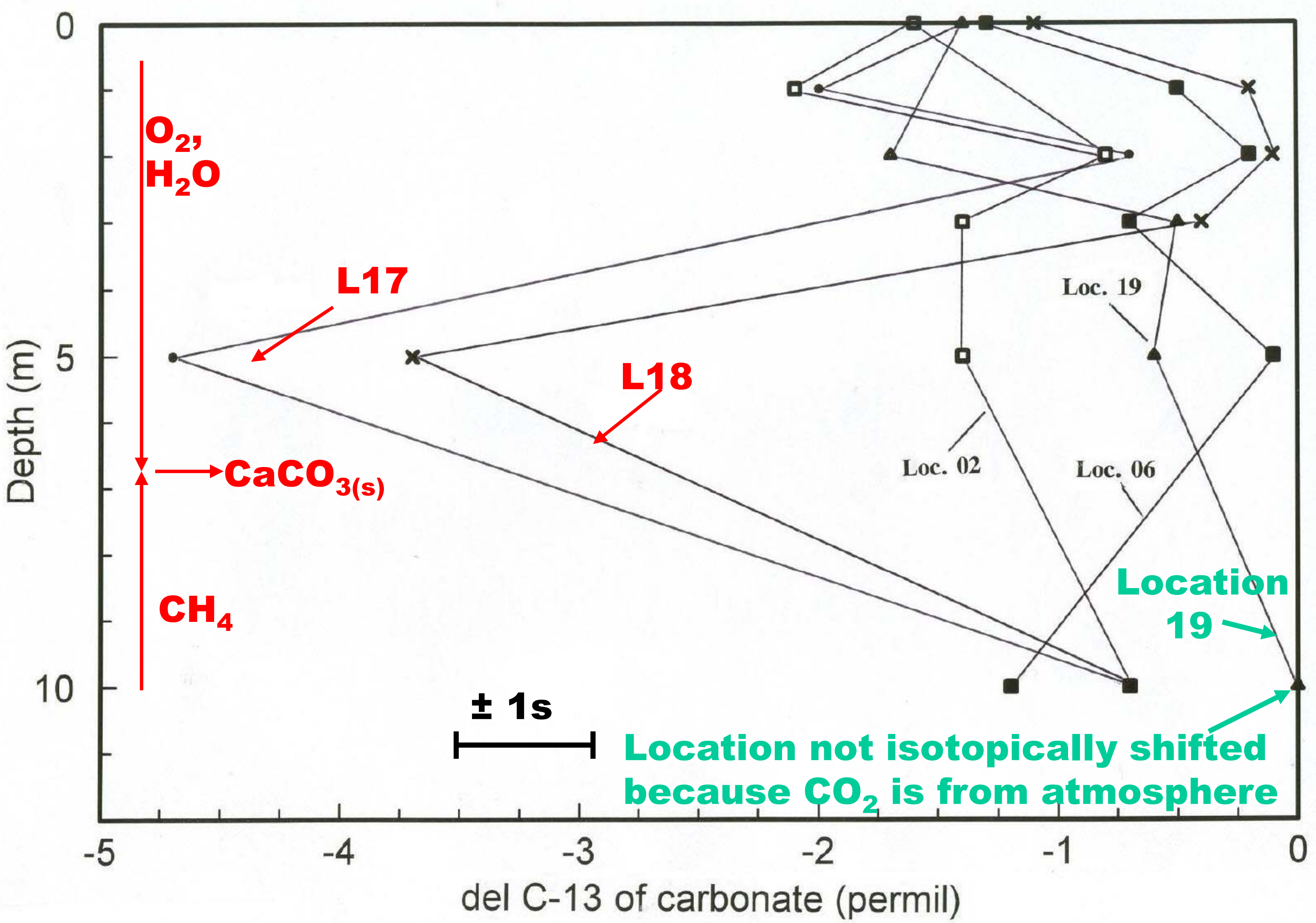
SELECTION OF “INTERESTING” LOCATIONS FOR 10-m HOLES TO COMPARE AND CONTRAST CHARACTERISTICS

- **Initial baseline survey of fluxes and soil gas in January, 2004,**
- **Magnitude and direction of both CO_2 and CH_4 fluxes,**
- **Magnitude and gradient of both CO_2 and CH_4 in soil gas profiles,**
- **Isotopic shift in 60-, and 100 cm soil gas CO_2 , relative to the atmosphere,**
- **Select locations for drilling “anomalous” and “non-anomalous” 10-m holes for nested gas sampling.**

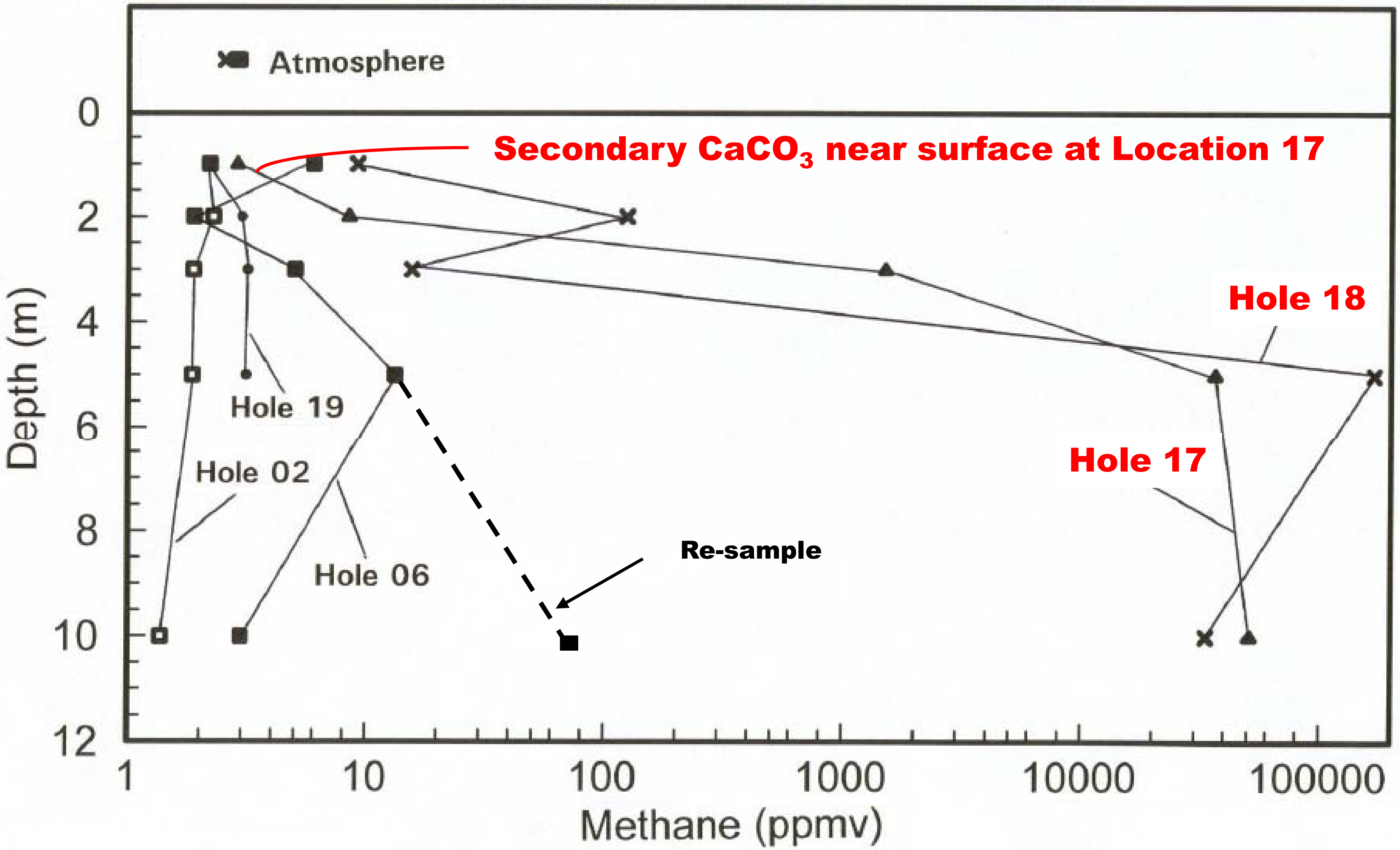
TEAPOT, INORGANIC CARBON IN CUTTINGS (%)



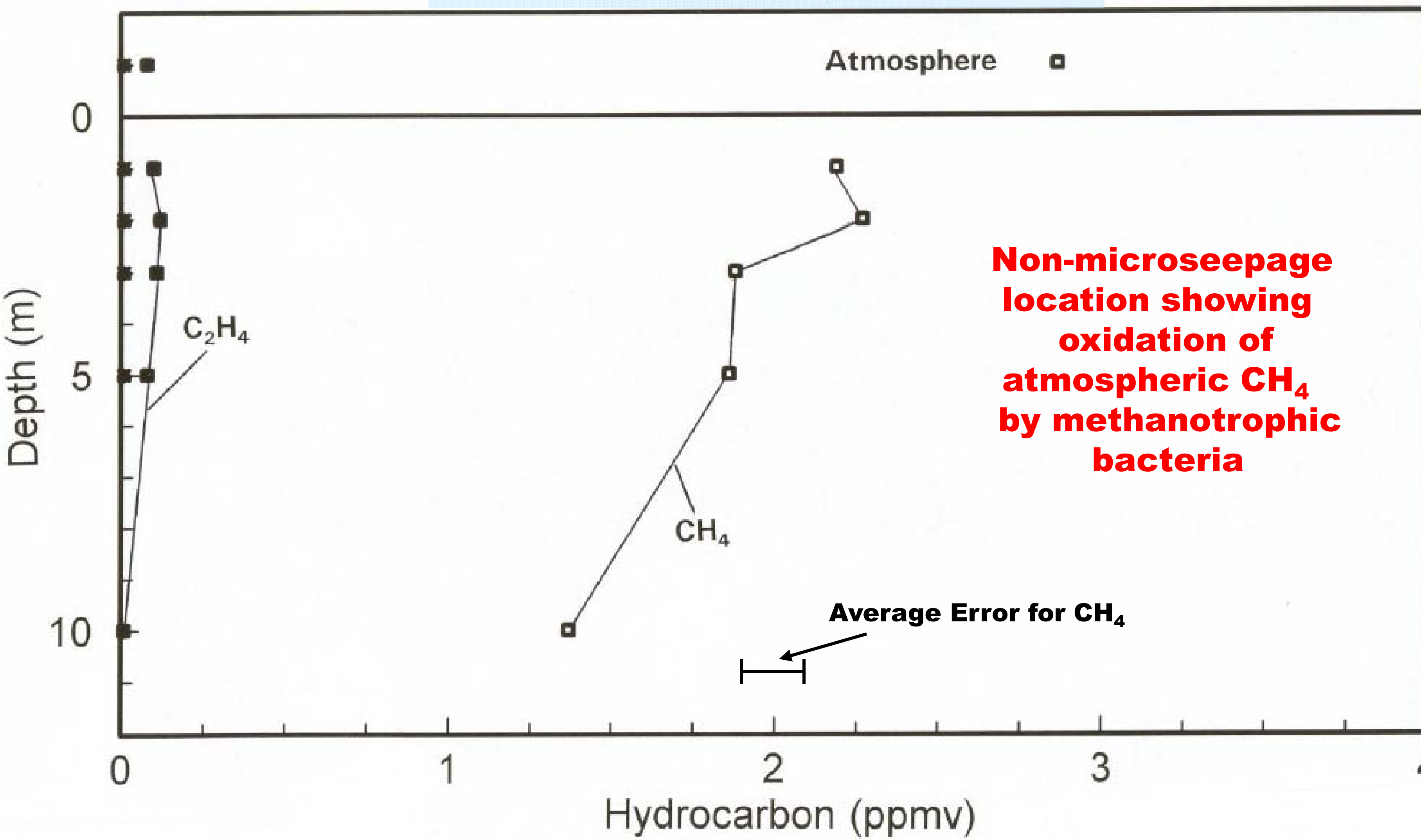
TEAPOT - $\delta^{13}C$ OF INORGANIC CARBON (‰)



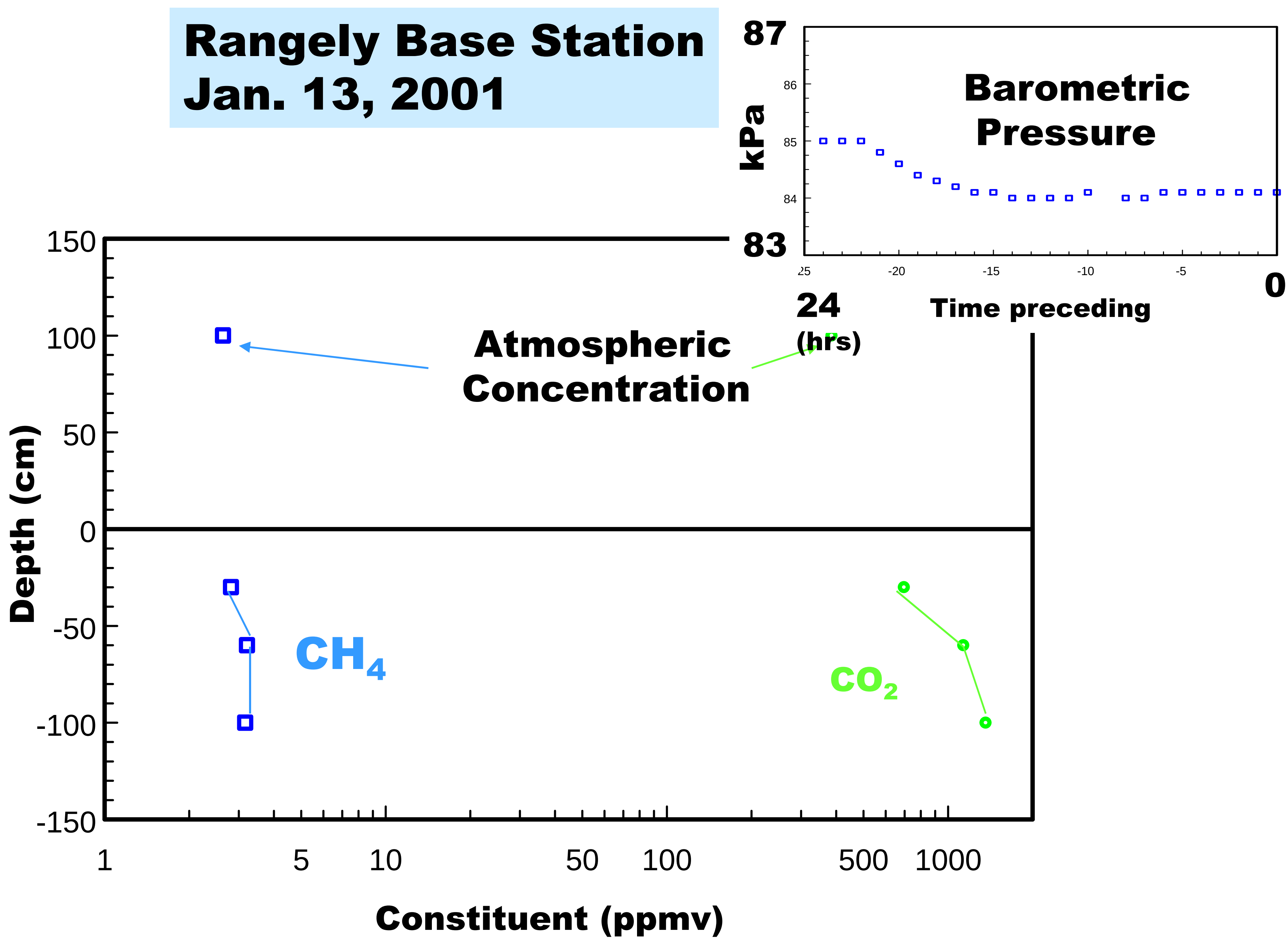
Teapot - Winter, 2005
Methane in 10-m Holes



Teapot - Winter, 2005
10-m Hole 02

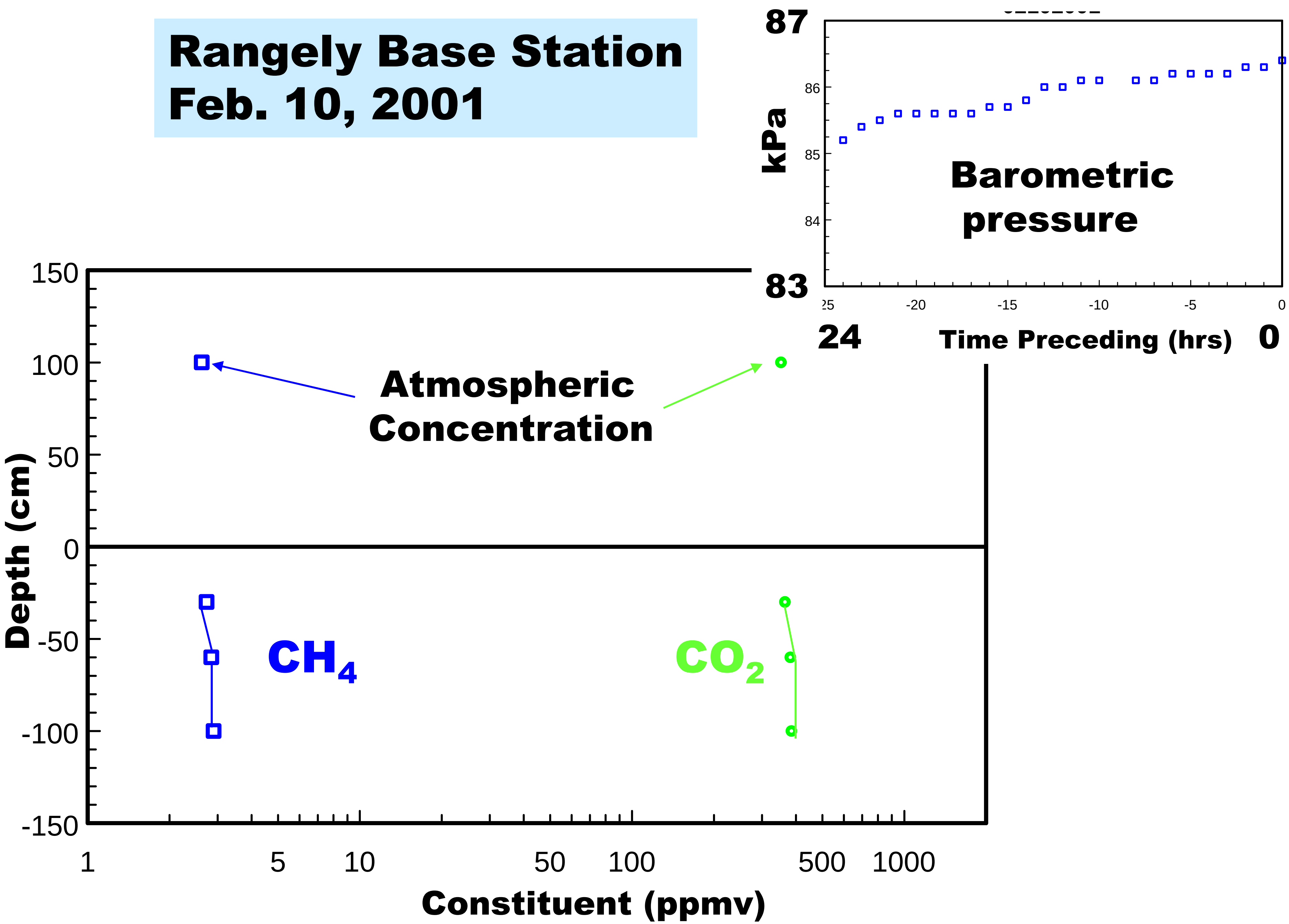


Non-microseepage location showing oxidation of atmospheric CH_4 by methanotrophic bacteria

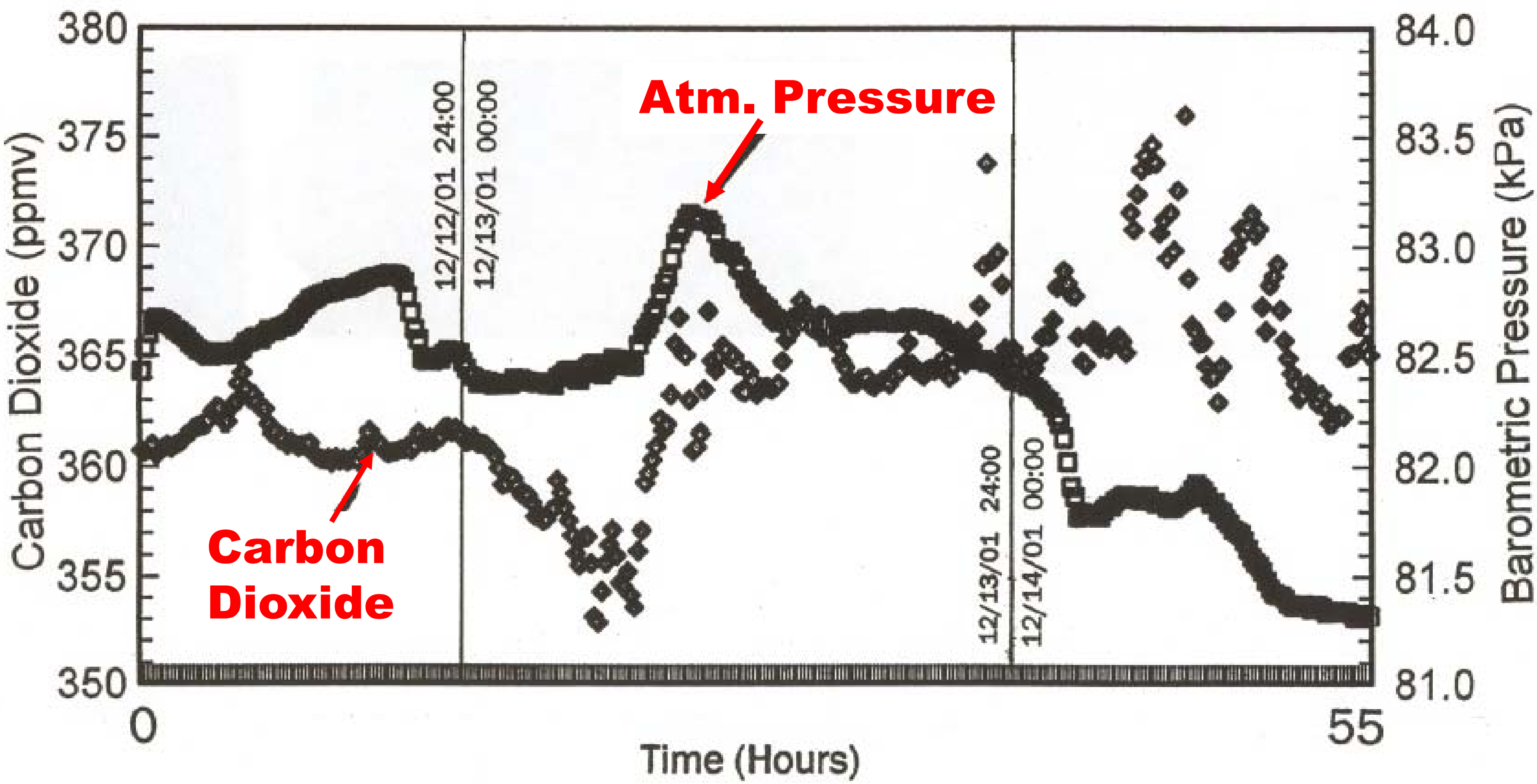


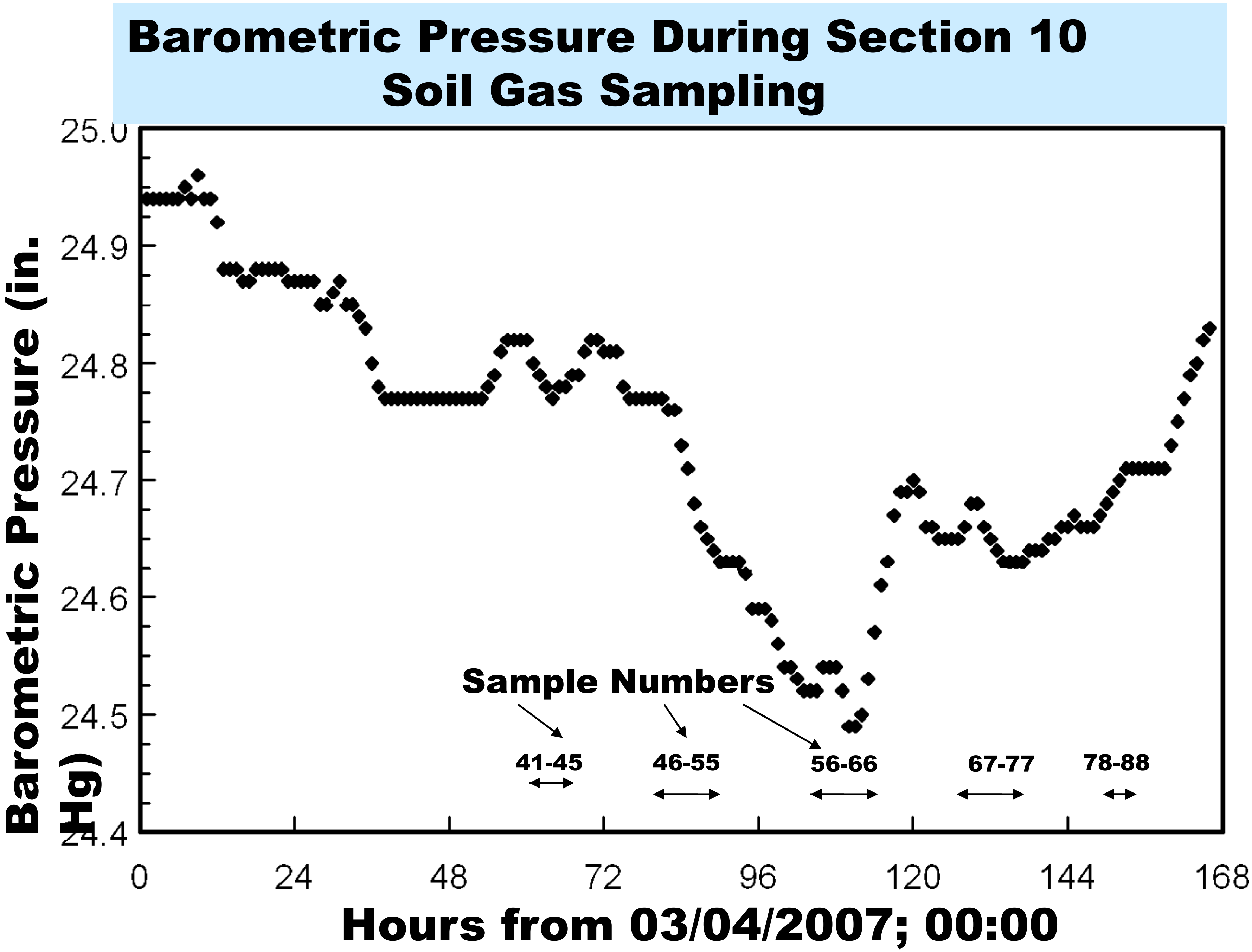
Rangely Base Station
Jan. 13, 2001
Barometric Pressure
kPa
87
86
85
84
83
25
-20
-15
-10
-5
0
24
(hrs)
Time preceding
Atmospheric Concentration
CH4
CO2
Depth (cm)
150
100
50
0
-50
-100
-150
1
5
10
50
100
500
1000
Constituent (ppmv)

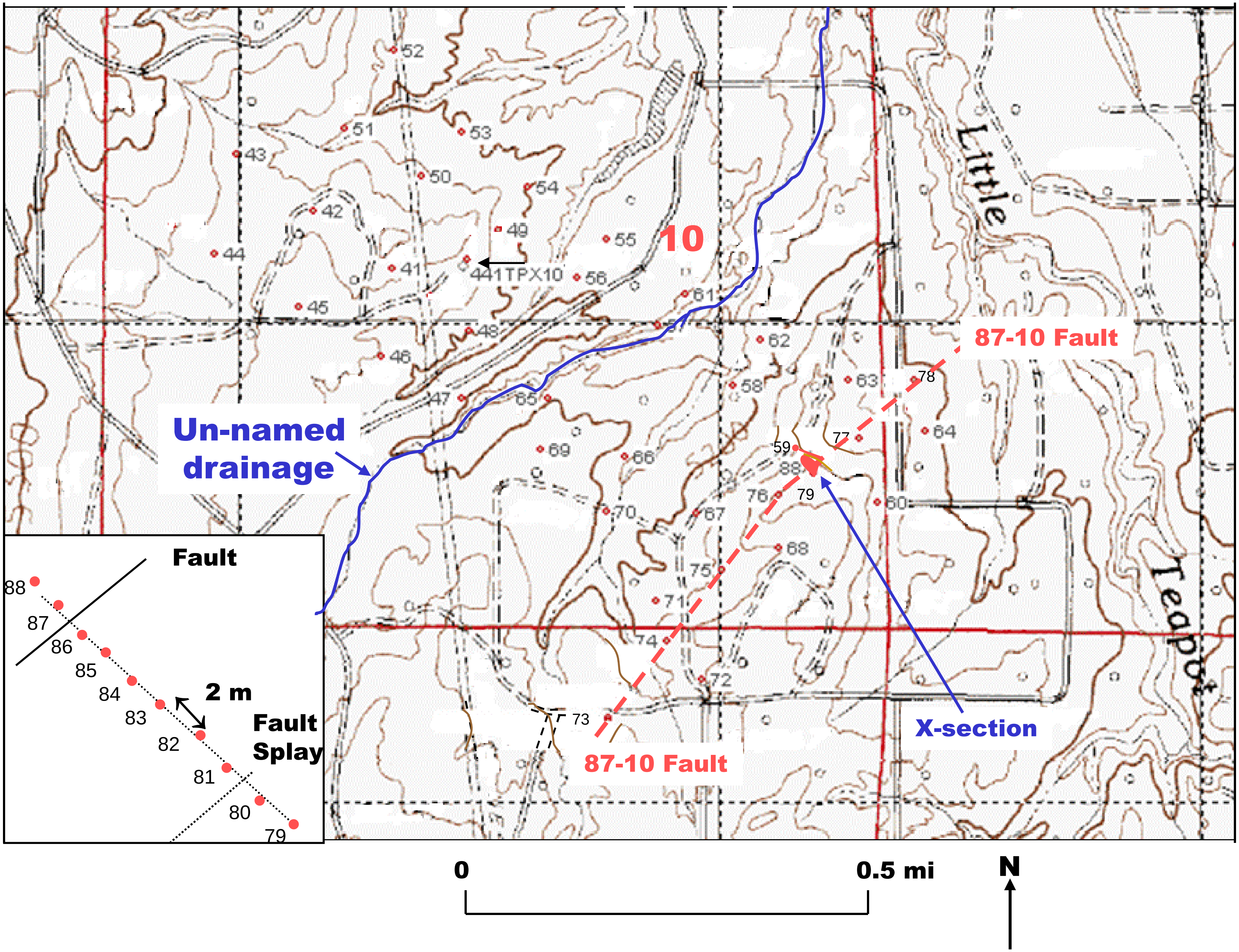
Rangely Base Station
Feb. 10, 2001



Atmospheric Carbon Dioxide/Pressure
12-12 to 12-14-2001

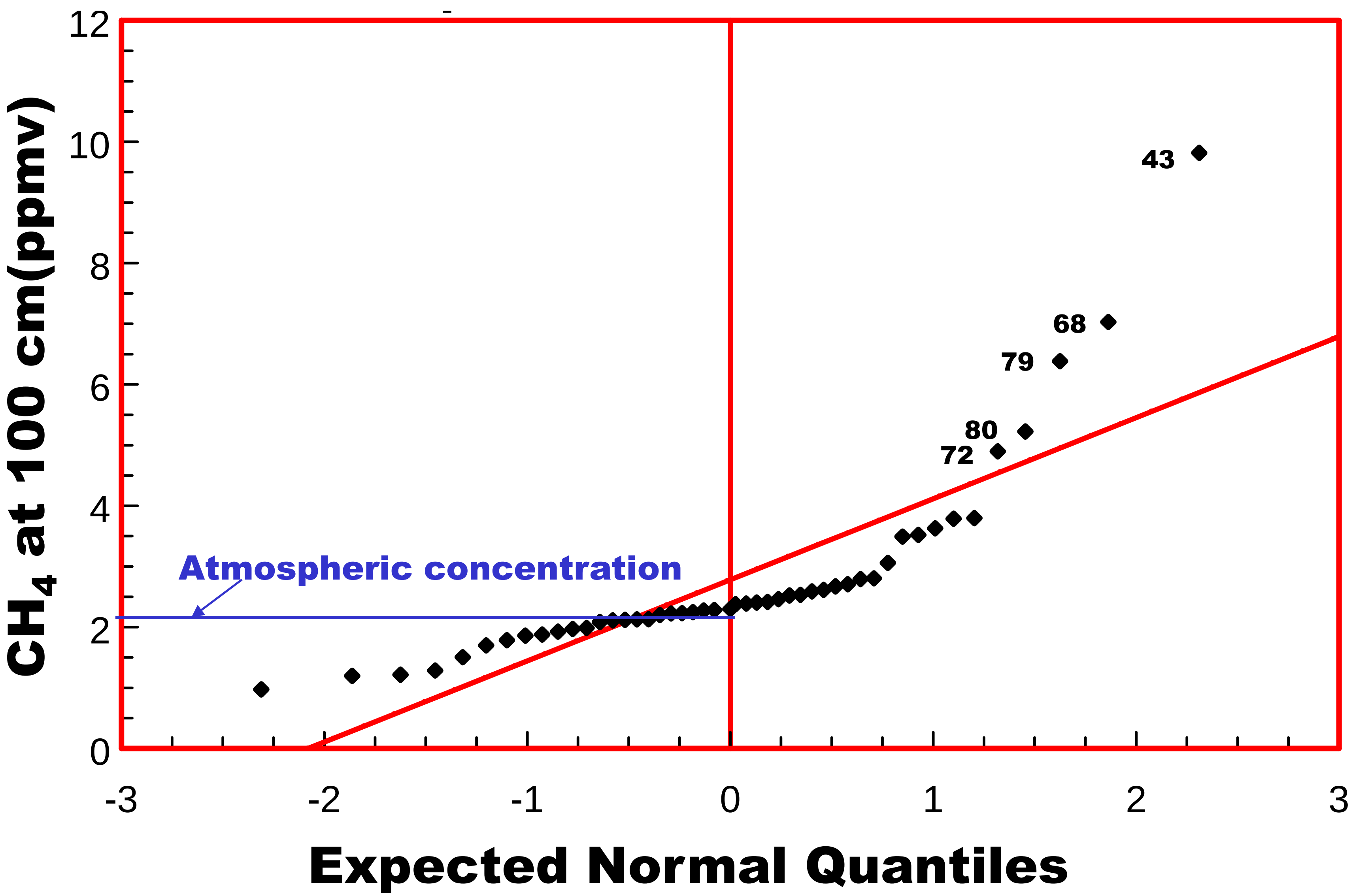



Barometric Pressure During Section 10
Soil Gas Sampling
Barometric Pressure (in. Hg)
25.0
24.9
24.8
24.7
24.6
24.5
24.4
0
24
48
72
96
120
144
168
Hours from 03/04/2007; 00:00
Sample Numbers
41-45
46-55
56-66
67-77
78-88

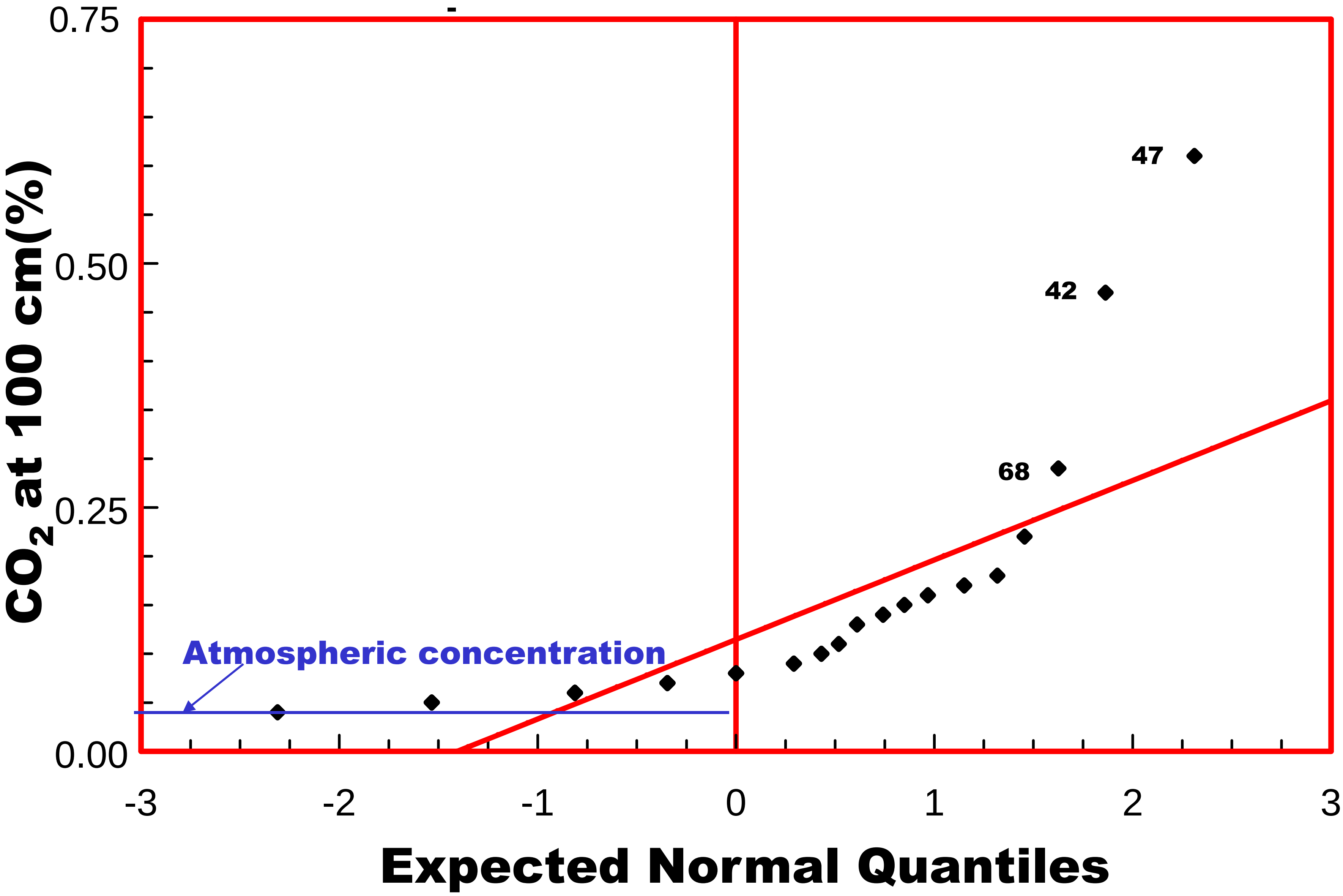


52
51
53
43
50
54
42
49
44
41
441TPX10
55
56
10
61
45
48
46
62
87-10 Fault
Little
58
63
78
47
65
Un-named
drainage
77
64
69
59
66
88
79
76
60
70
67
68
75
71
74
72
73
87-10 Fault
X-section
Teapot
Fault
88
87
86
85
84
83
82
81
80
79
2 m
Fault
Splay
0
0.5 mi
N

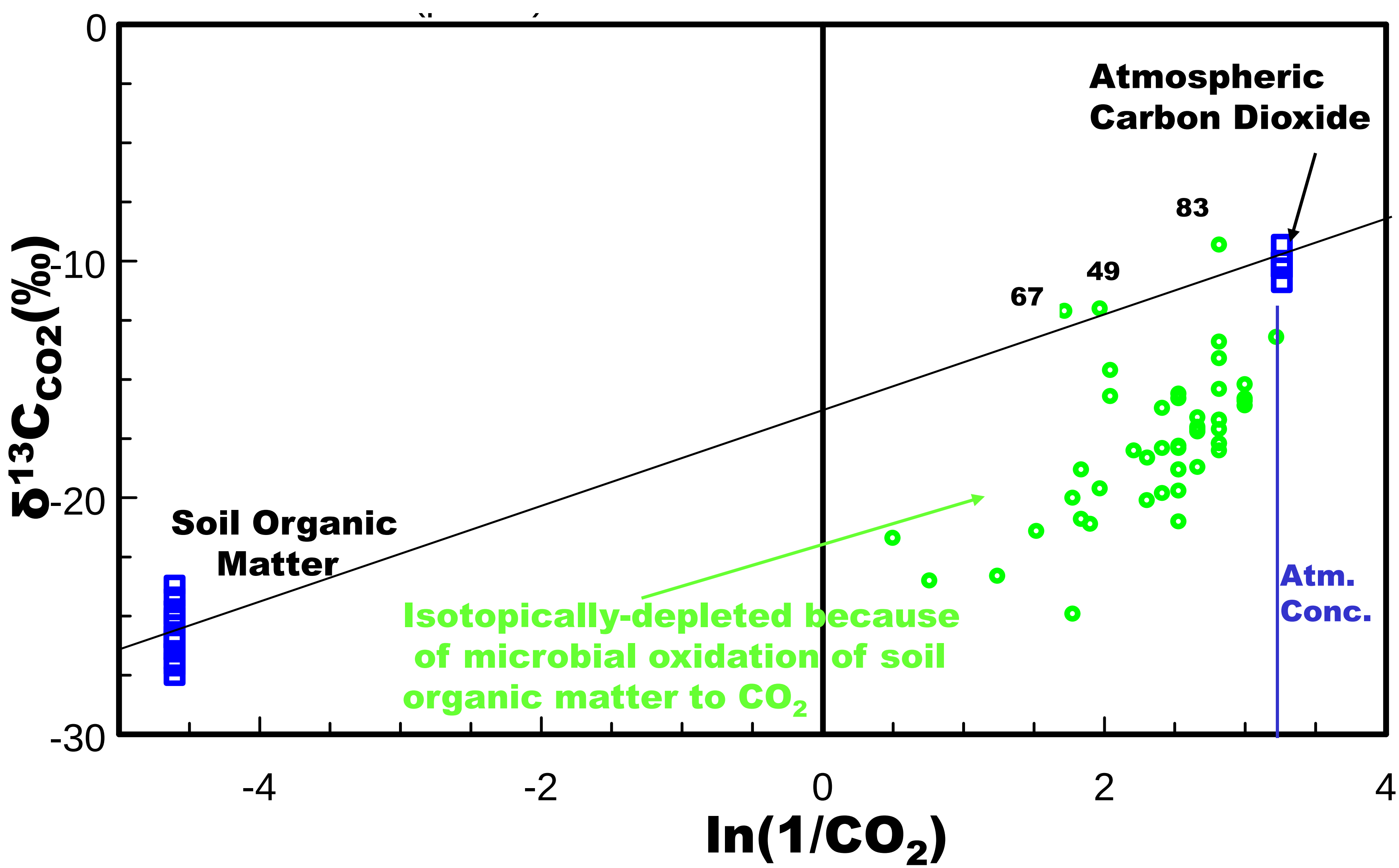
SECTION 10 SAMPLING



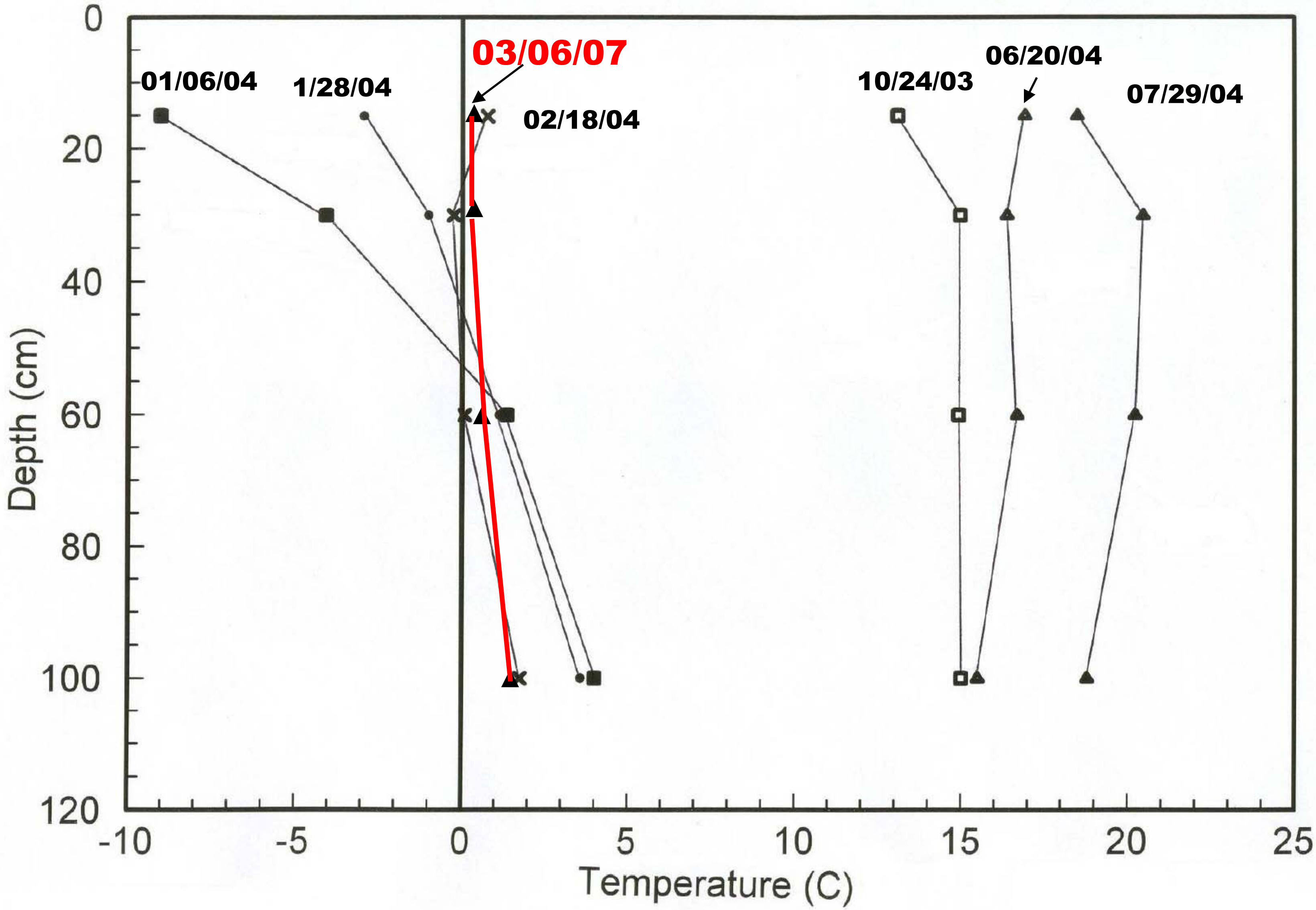
SECTION 10 SAMPLING



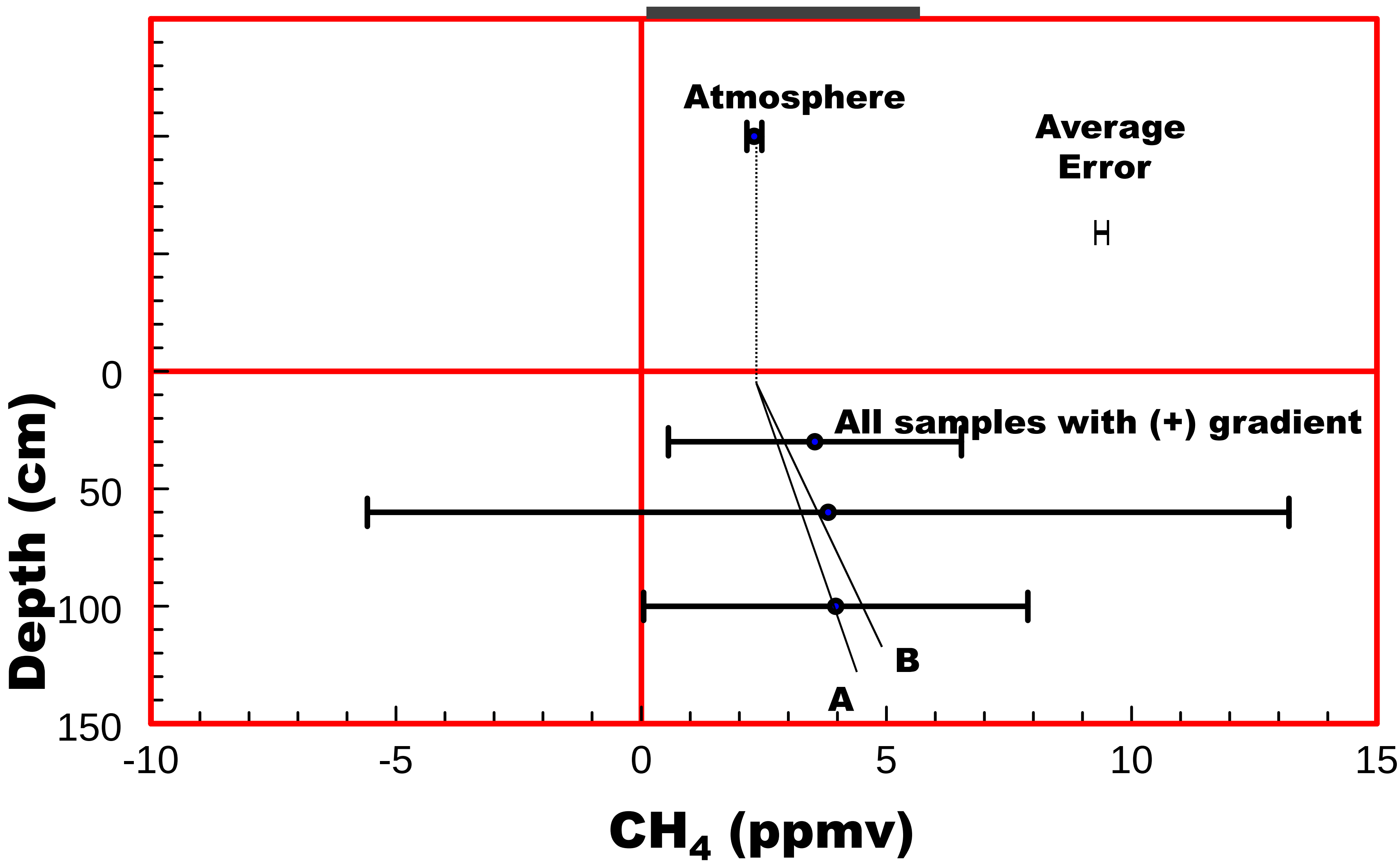
SECTION 10 SAMPLING



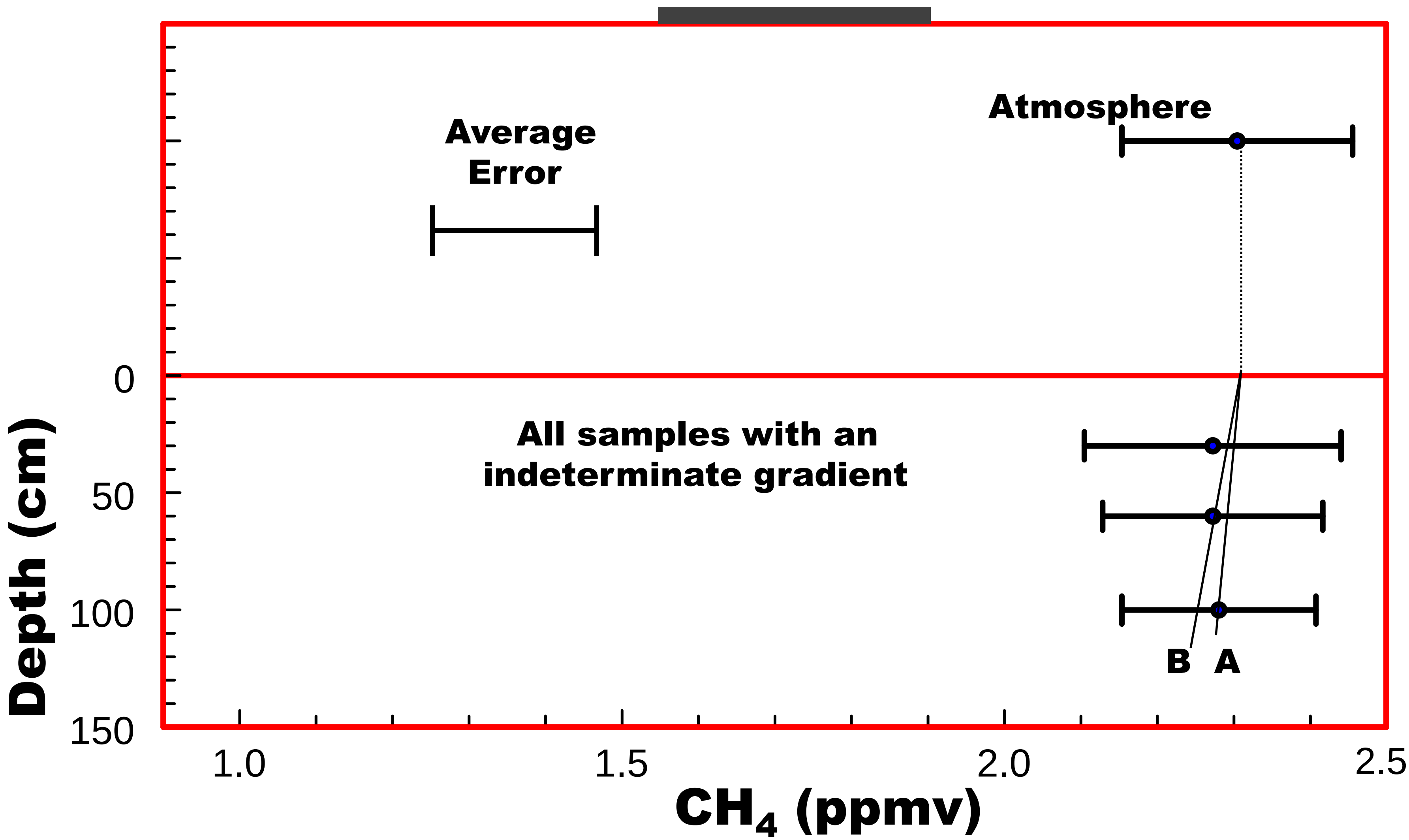
SOIL TEMPERATURE PROFILES AT NPR-3



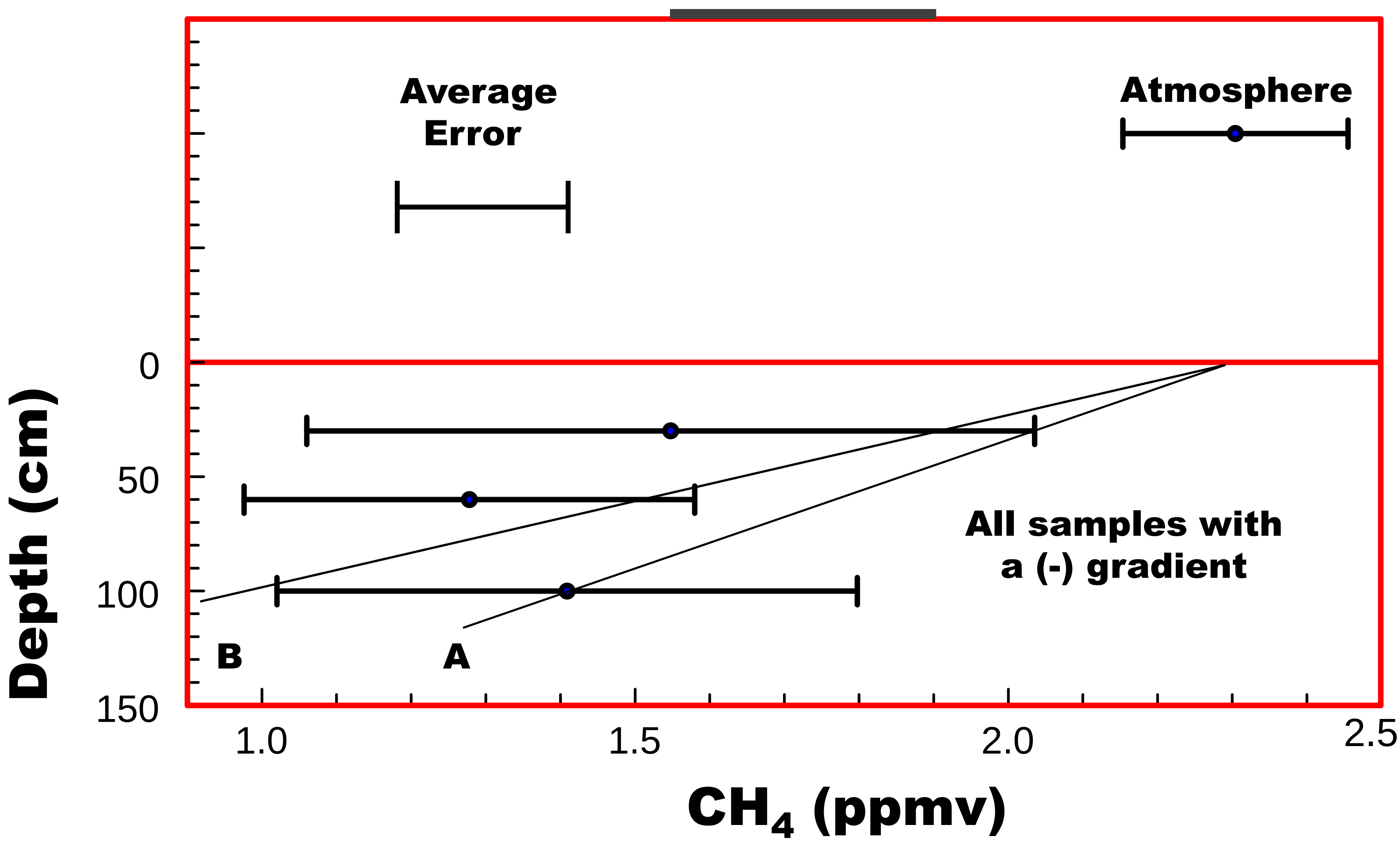
POSITIVE METHANE GRADIENT

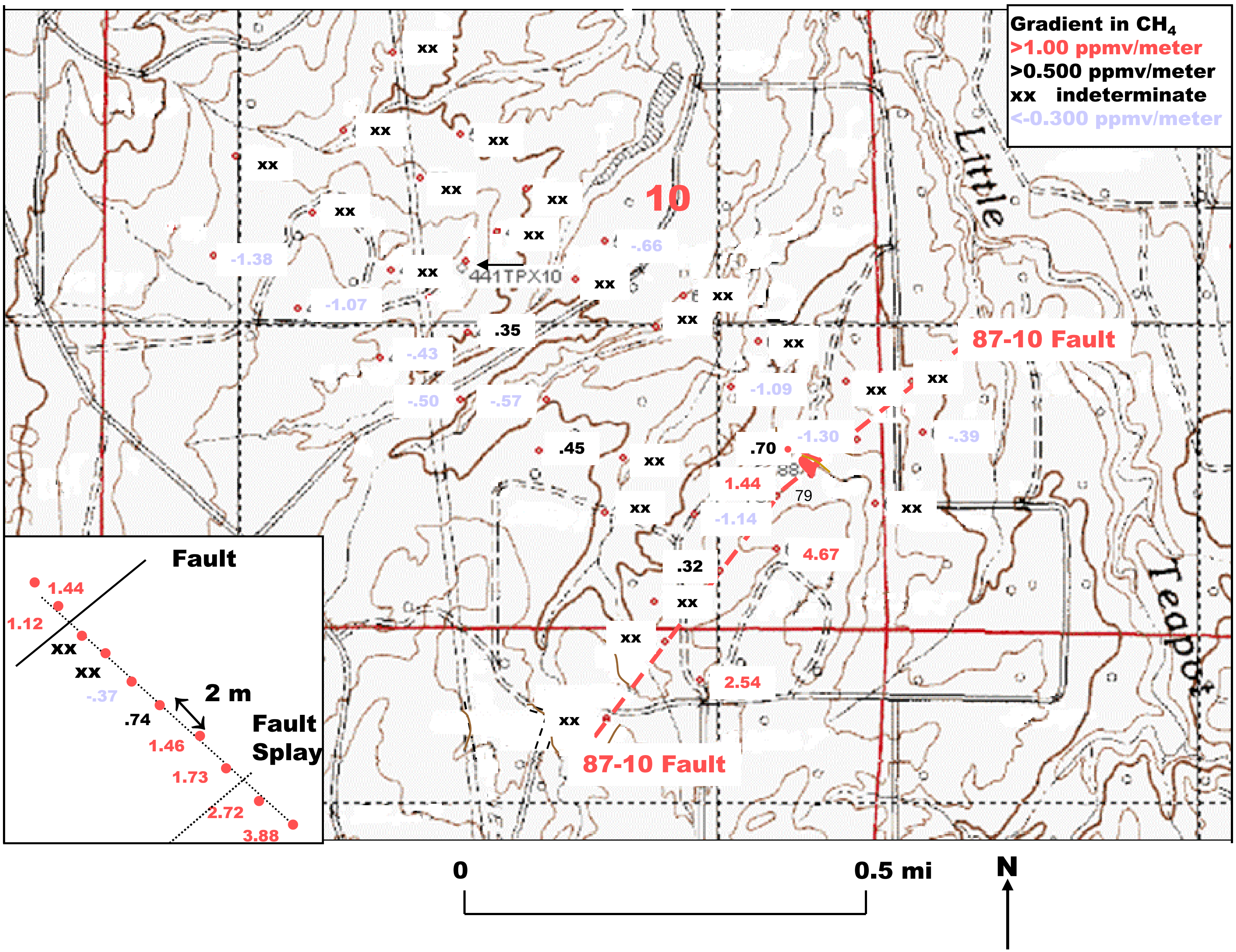


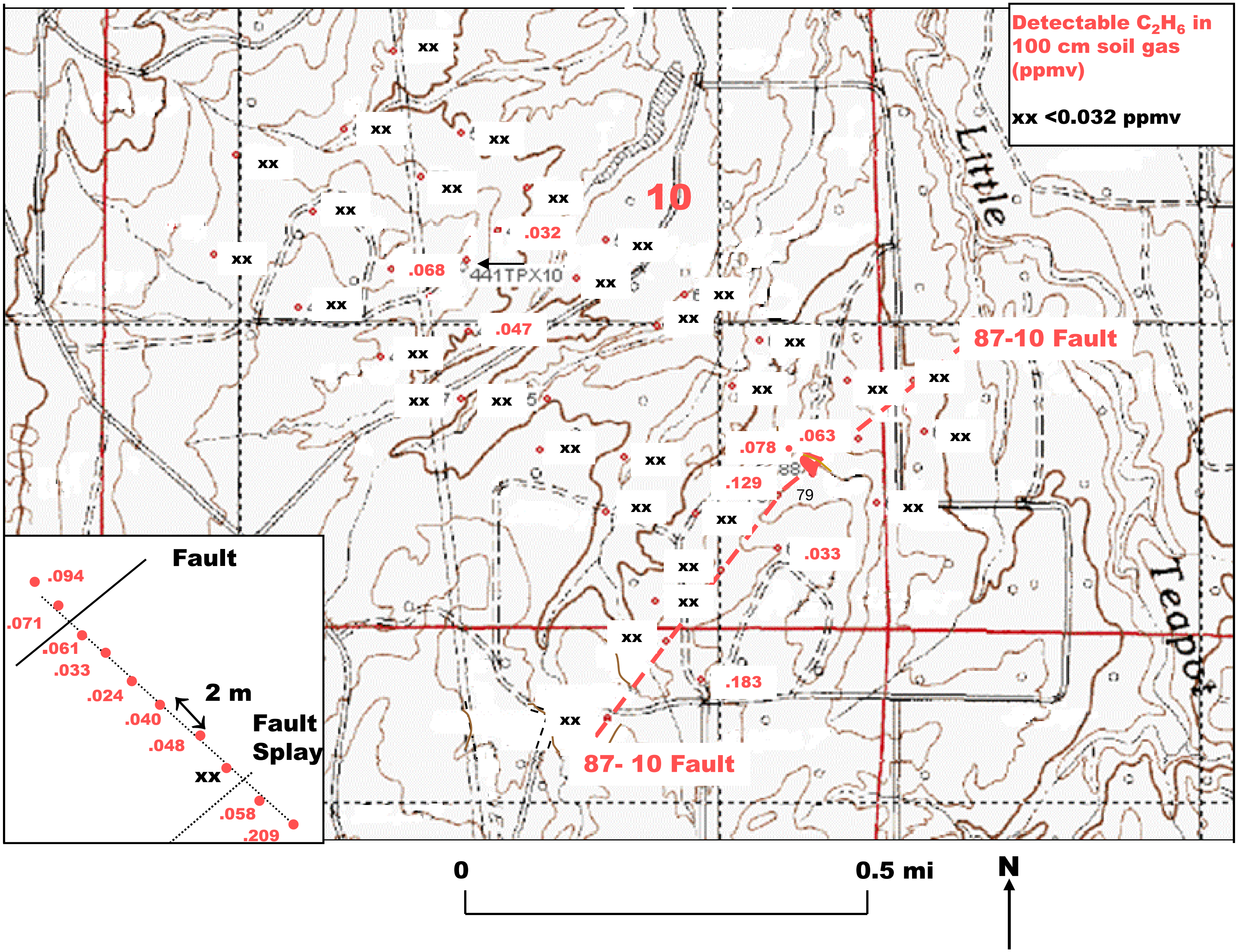
INDETERMINATE METHANE GRADIENT



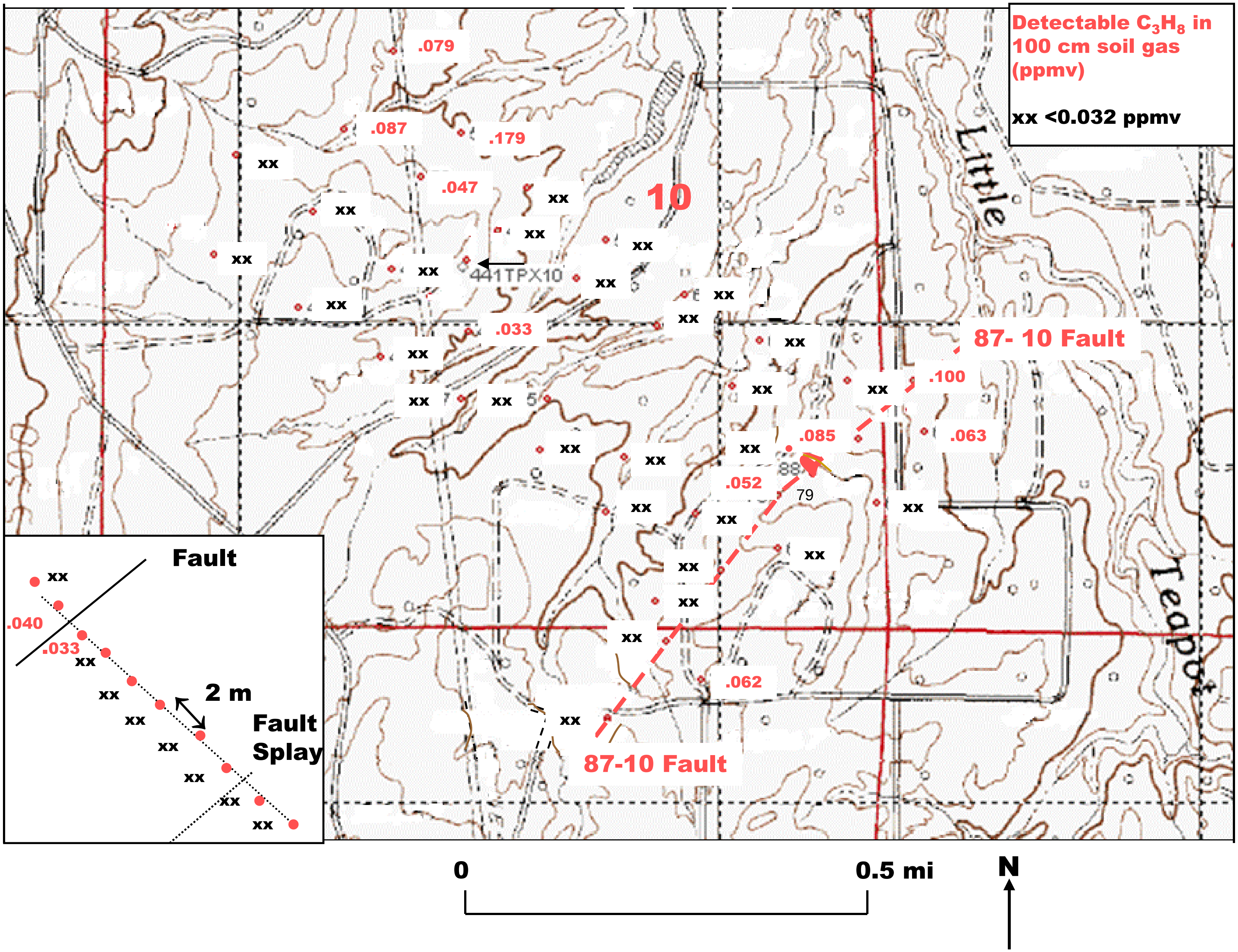
NEGATIVE METHANE GRADIENT



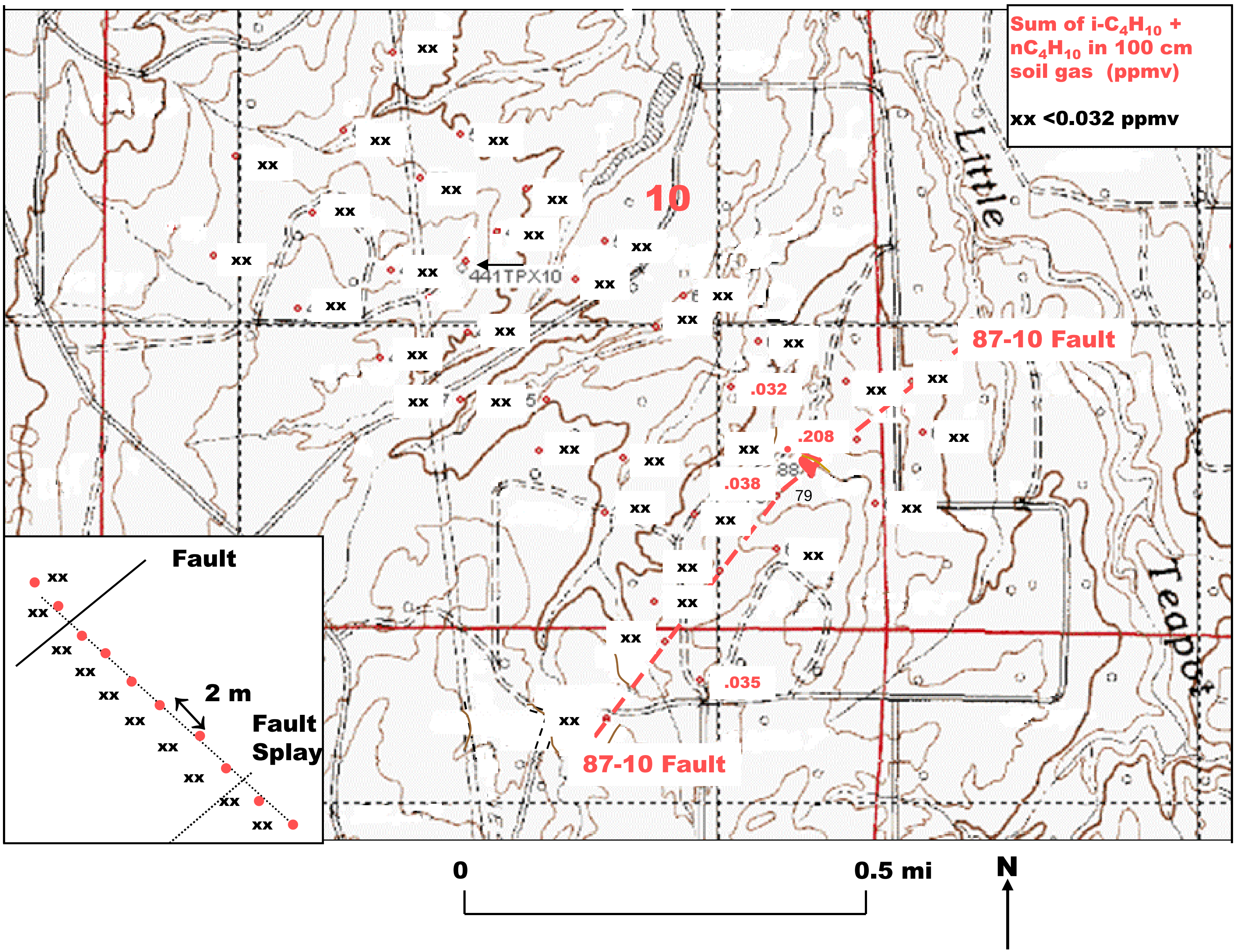

Gradient in CH_4
>1.00 ppmv/meter
>0.500 ppmv/meter
xx indeterminate
<-0.300 ppmv/meter
10
Little
Teapot
441TPX10
87-10 Fault
87-10 Fault
-1.38
-1.07
-.66
.35
-.43
-.50
-.57
.45
-1.09
.70
-1.30
-.39
1.44
-1.14
4.67
.32
2.54
79
Fault
1.44
1.12
xx
xx
-.37
.74
2 m
1.46
1.73
2.72
3.88
Fault
Splay
0
0.5 mi
N



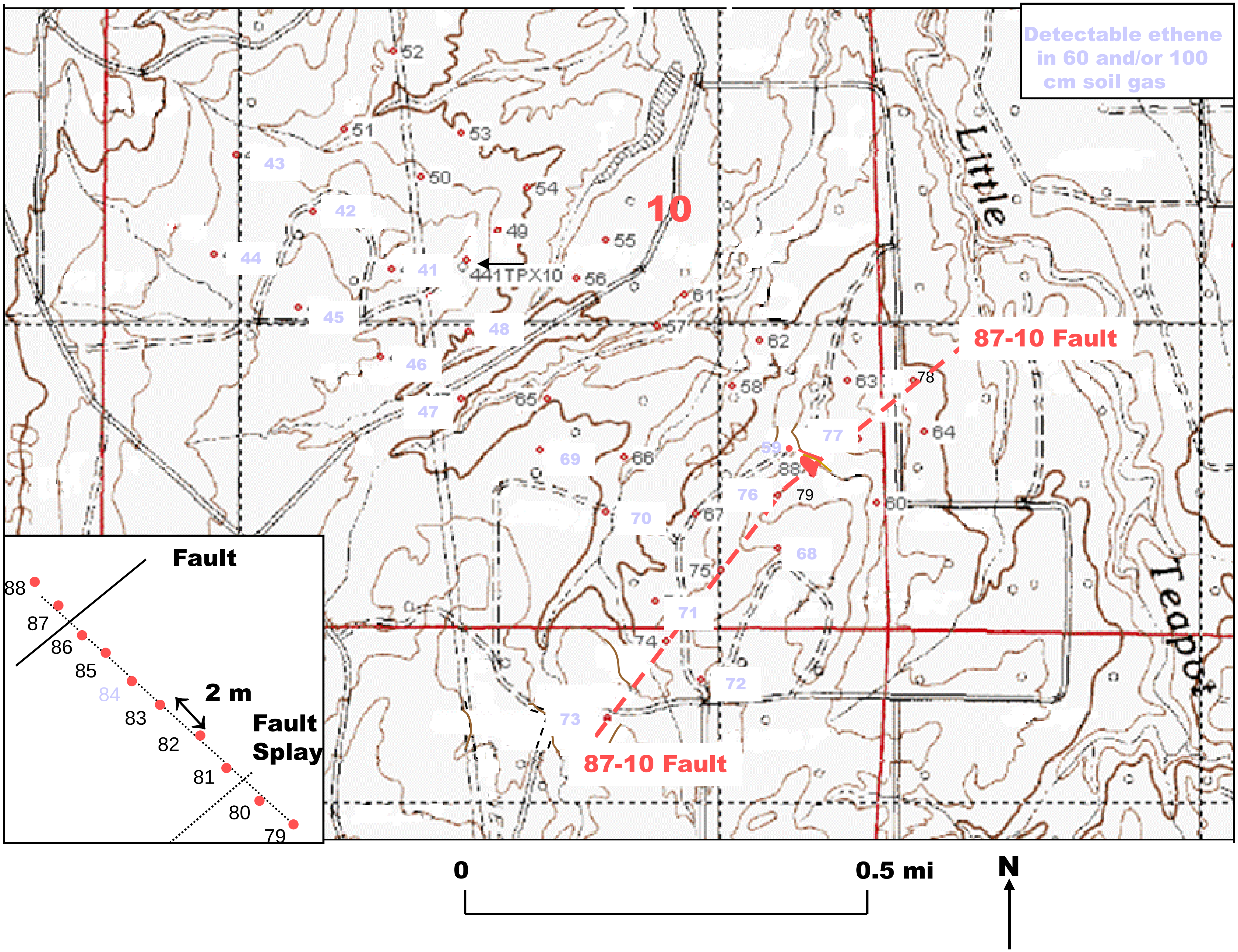
Detectable C_2H_6 in 100 cm soil gas (ppmv)
xx <0.032 ppmv
10
.032
.068
441TPX10
.047
87-10 Fault
.078
.063
.129
79
.033
.183
87- 10 Fault
Little
Teapot
Fault
.094
.071
.061
.033
.024
.040
.048
2 m
Fault Splay
.058
.209
0
0.5 mi
N



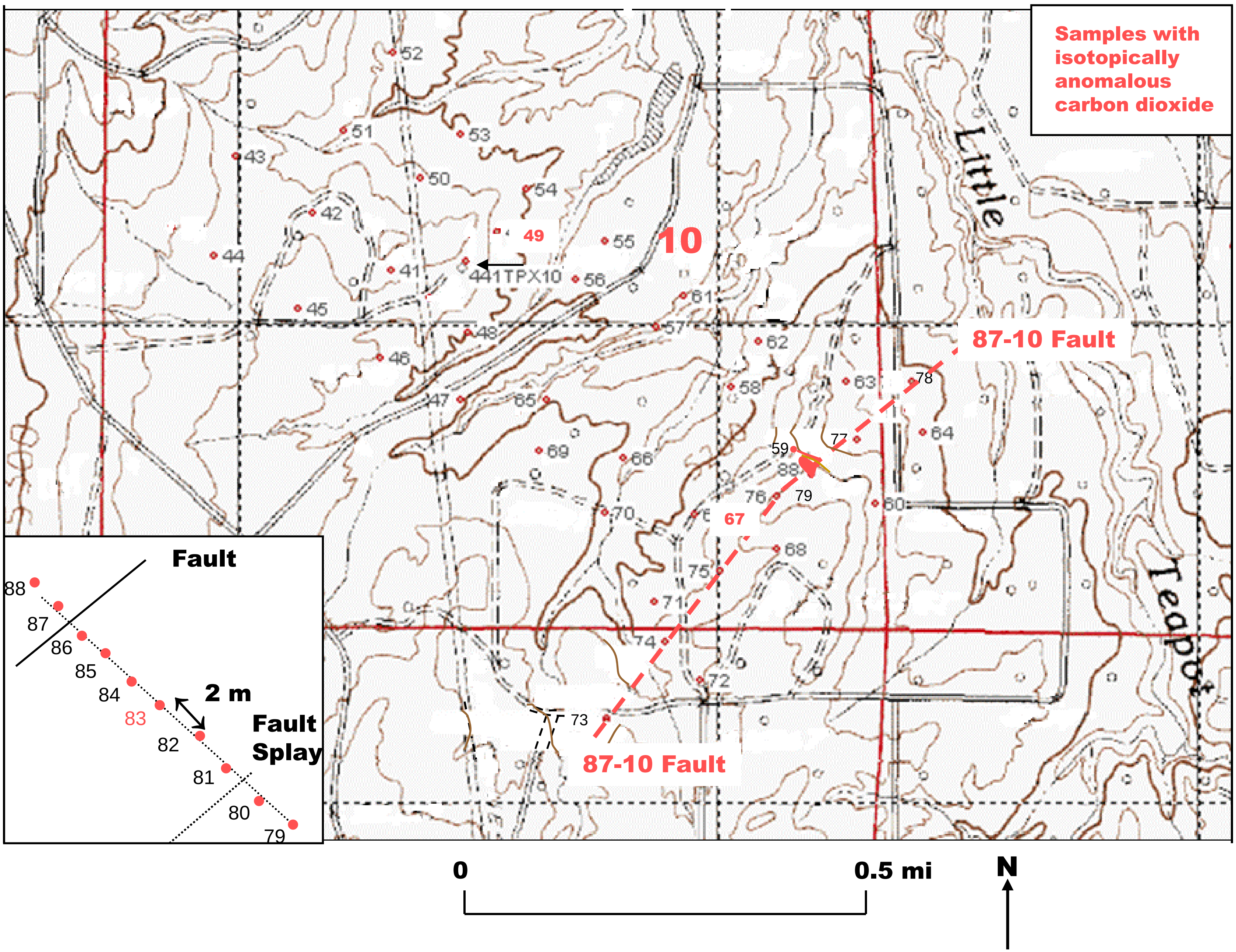
Detectable C_3H_8 in 100 cm soil gas (ppmv)
xx <0.032 ppmv
.079
.087
.179
.047
.033
.100
.085
.063
.052
.062
10
441TPX10
Little
Teapot
87- 10 Fault
87-10 Fault
Fault
Fault Splay
2 m
.040
.033
0
0.5 mi
N



Sum of i-C_4H_{10} + nC_4H_{10} in 100 cm soil gas (ppmv)
xx <0.032 ppmv
10
441TPX10
Little
Teapot
87-10 Fault
.032
.208
.038
.035
88
79
87-10 Fault
Fault
2 m
Fault Splay
0
0.5 mi
N



Detectable ethene in 60 and/or 100 cm soil gas
10
Little
Teapot
441TPX10
87-10 Fault
87-10 Fault
Fault
Fault Splay
2 m
88
87
86
85
84
83
82
81
80
79
0
0.5 mi
N



Samples with isotopically anomalous carbon dioxide
10
87-10 Fault
87-10 Fault
441TPX10
Little
Teapot
Fault
Fault Splay
2 m
0
0.5 mi
N

ALONG STRIKE OF 87-10 FAULT

Calcite float	+	-	-	+	+	-
CO_2	-	-	-	-	-	-
C_2H_4	+	-	-	+	+	-
C_4H_{10}	-	-	-	0.038	0.208	-
C_3H_8	-	-	-	0.052	-	-
C_2H_6	-	-	-	0.129	0.063	-
CH_4 Grad.	-	-	0.32	1.44	-1.30	-
Sample Nos.	73	74	75	76	77	78

Location of trench?

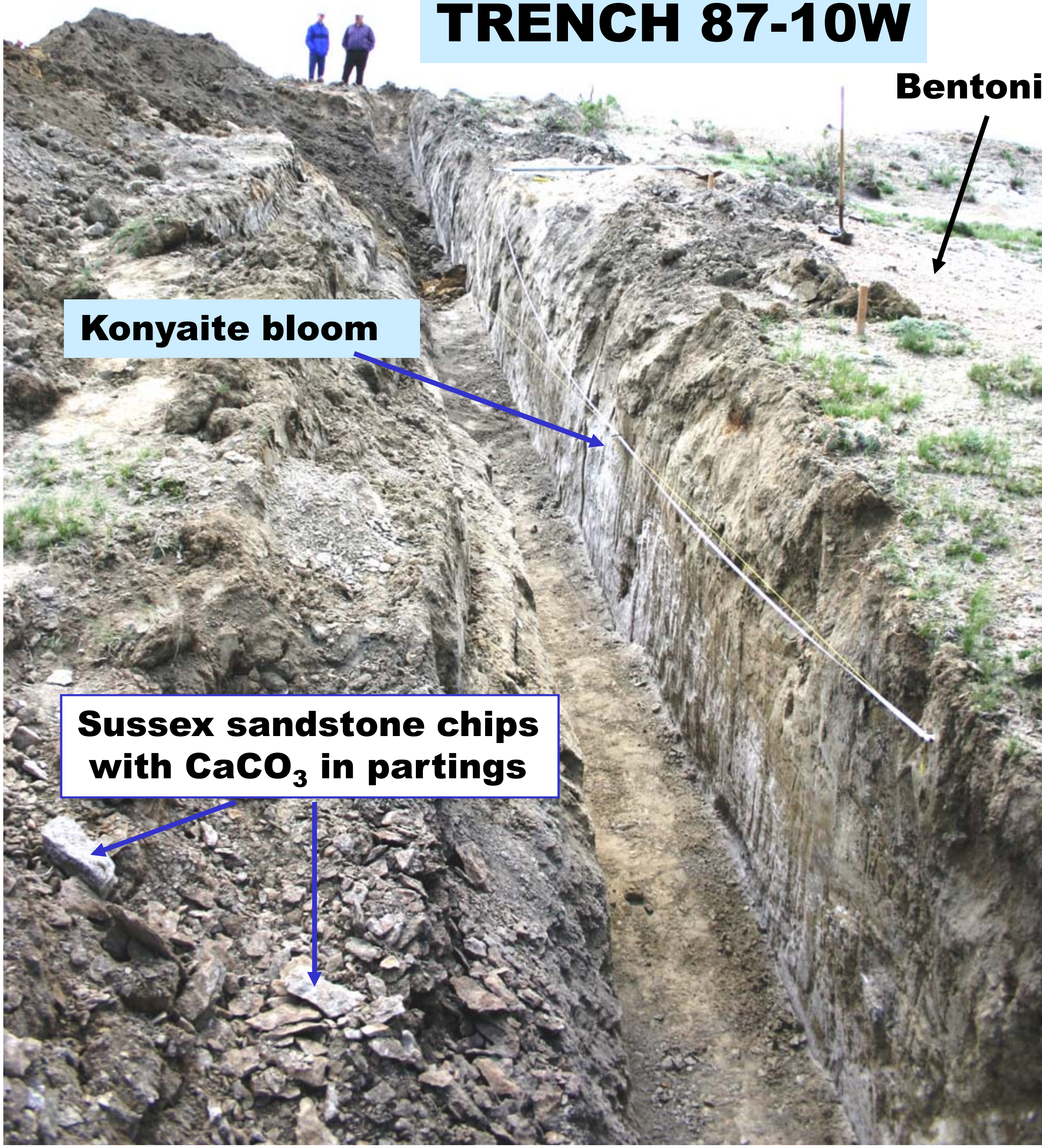
SW ← 1000 m → NE

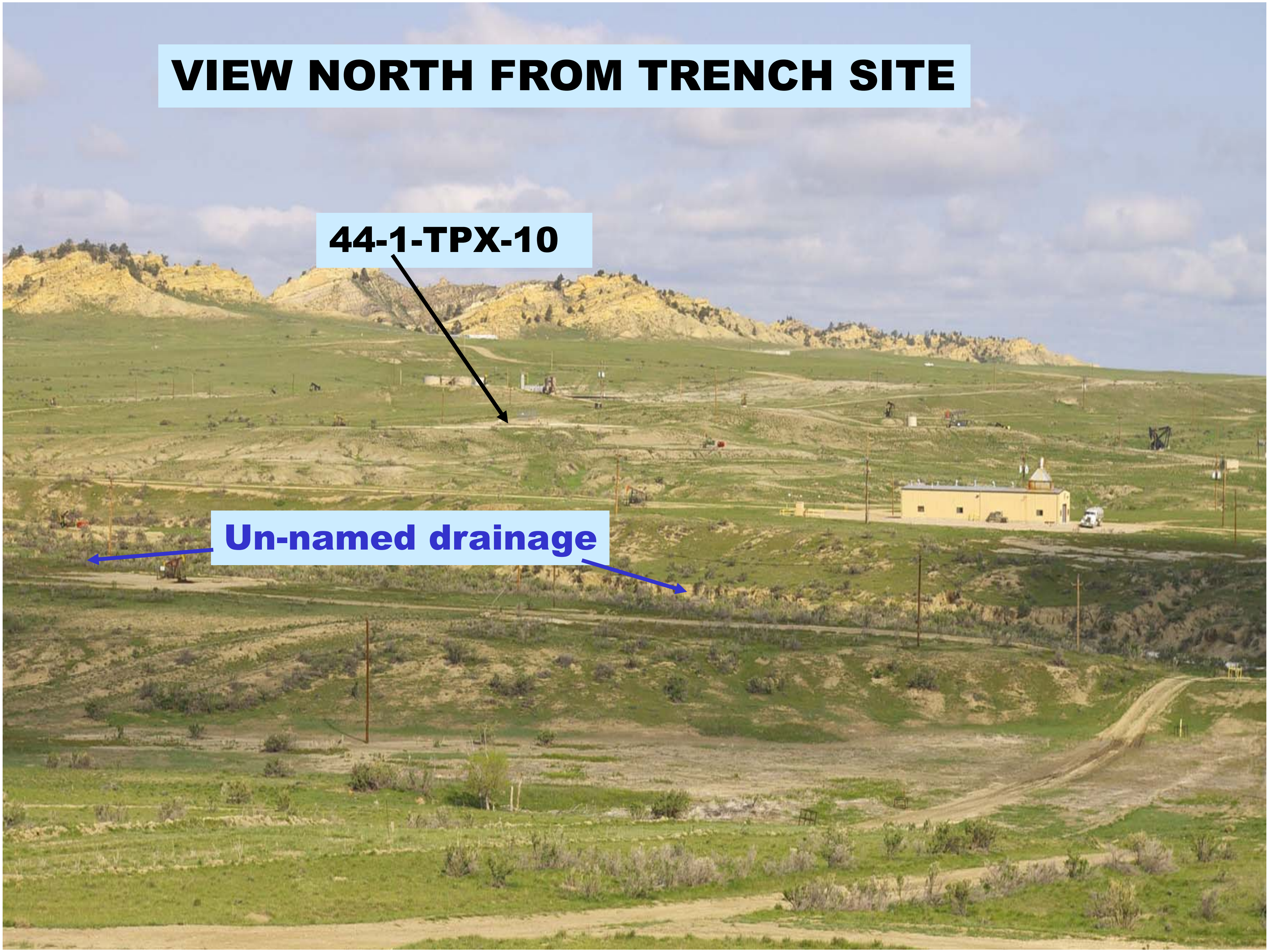
CROSS-SECTION ON 87-10 FAULT

	79	80	81	82	83	84	85	86	87	88
Calcite float	+	+	+	+	+	+	+	+	+	+
CO_2	-	-	-	-	+	-	-	-	-	-
C_2H_4	-	-	-	-	-	+	-	-	-	-
C_4H_{10}	-	-	-	-	-	-	-	-	-	-
C_3H_8	-	-	-	-	-	-	-	.033	.040	-
C_2H_6	.209	.058	-	.048	.040	.024	.033	.061	.071	.094
CH_4 Grad.	3.88	2.72	1.73	1.48	0.74	-0.37	-	-	1.12	1.44
Sample Nos.	79	80	81	82	83	84	85	86	87	88

S ← 18 m → N

TRENCH 87-10W

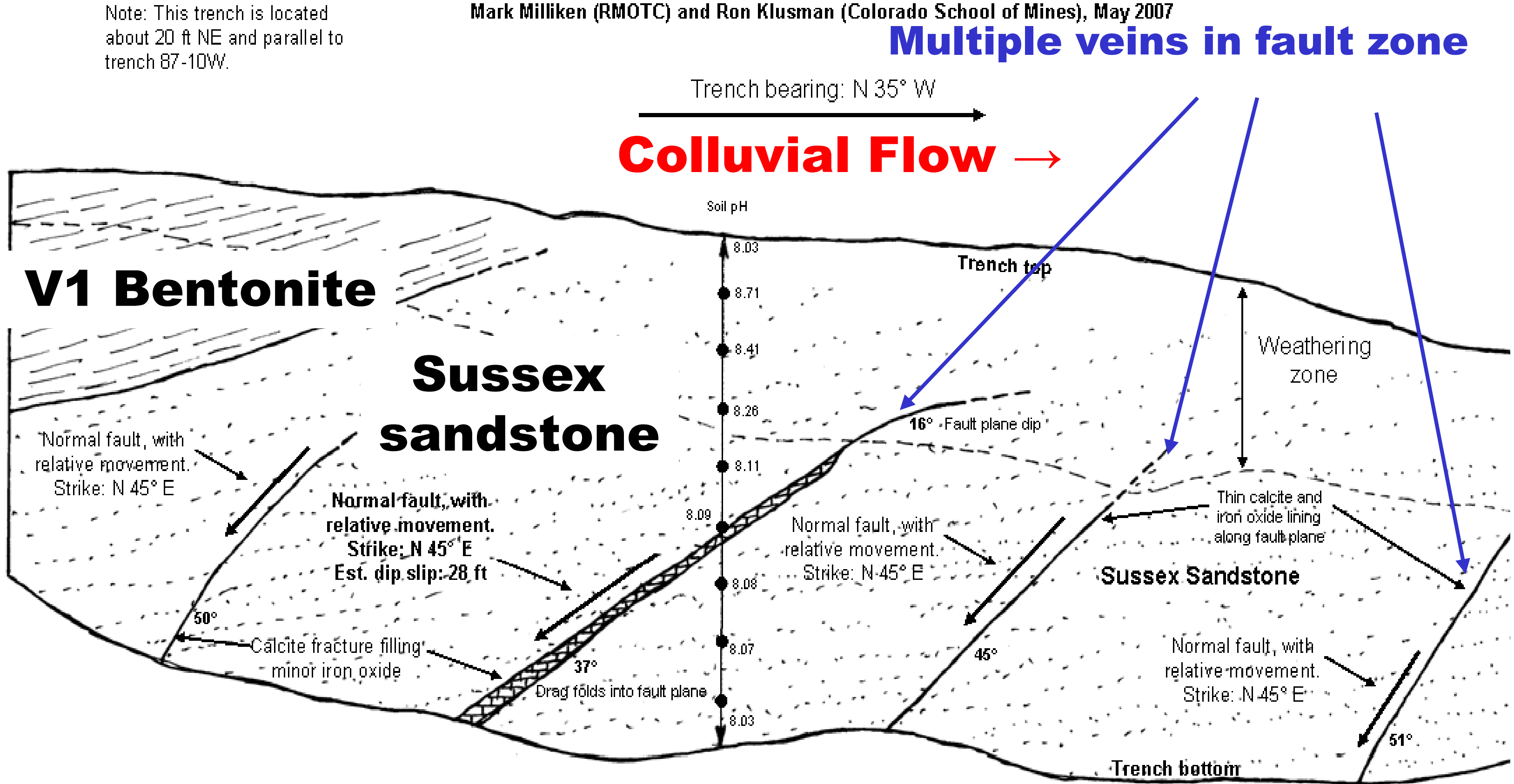



VIEW NORTH FROM TRENCH SITE
44-1-TPX-10
Un-named drainage

NPR-3 GEOLOGY TRENCH 87-10E

Mark Milliken (RMOTC) and Ron Klusman (Colorado School of Mines), May 2007

Note: This trench is located about 20 ft NE and parallel to trench 87-10W.



Weathering zone: A weak "A" soil horizon is typified by rooting, iron oxides, calcite, and colluvial materials. The underlying "B" horizon features increased soil pH values. The B horizon is typified by calcite precipitation along older root paths due to illuviation. Soil pH values are courtesy of Ron Klusman.

Sussex Sandstone Member of the Steele Shale Formation (Upper Cretaceous): Tan to dark brown in color. Generally unconsolidated thin-bedded marine sandstone interbedded with silty shale. Includes occasional well-cemented sandstone zones.

Calcite fracture filling: Secondary calcite, white to buff color, abundant well developed crystalline facets. Thickness ranges from 0.1 in. to 4 inches and may include multiple emplacement events.

V1 Bentonite: Oxidized bentonite, yellowish orange in color. The lowest in a series of at least nine bentonite beds above the Sussex Sandstone. The base of

Scale

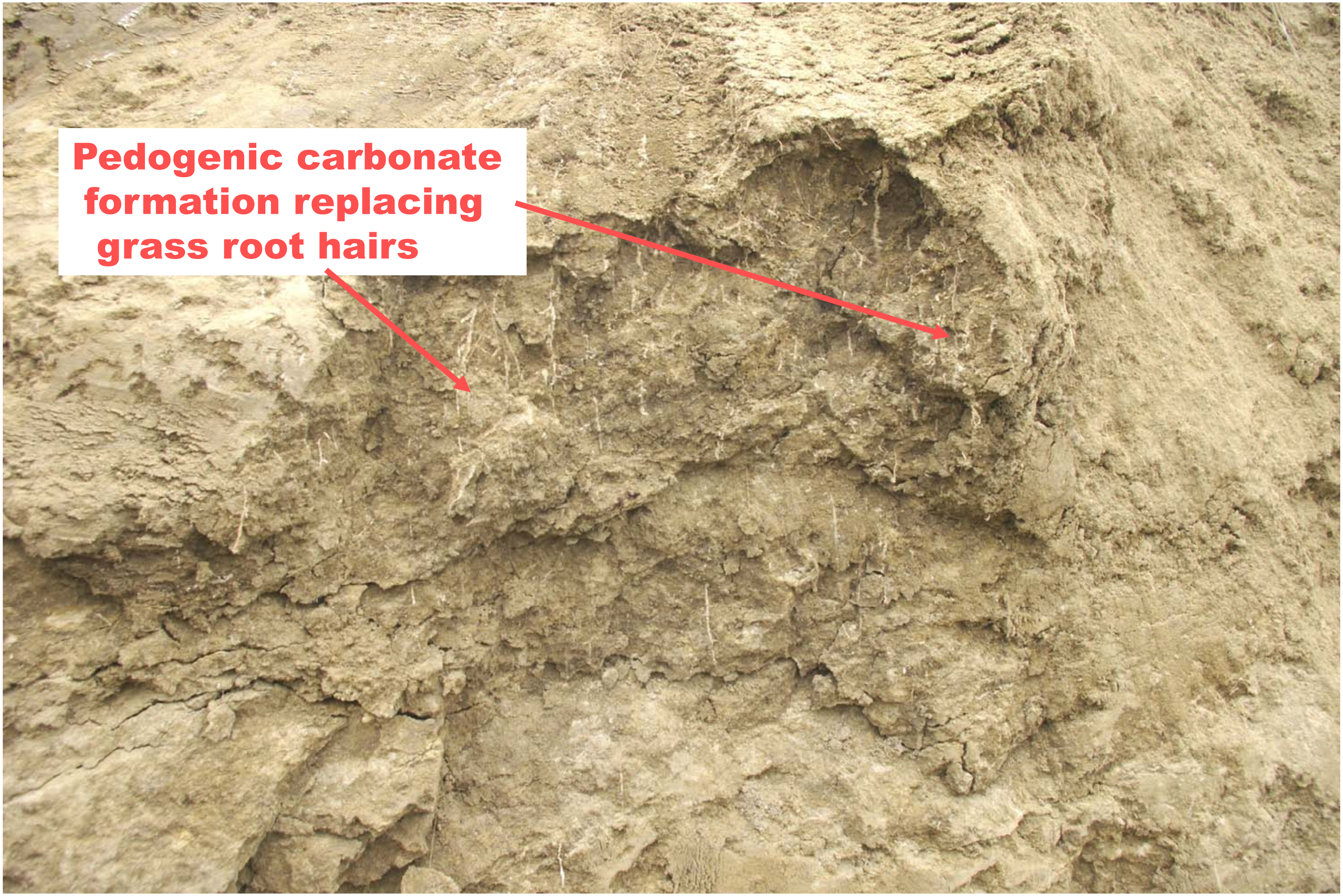
Horizontal = Vertical

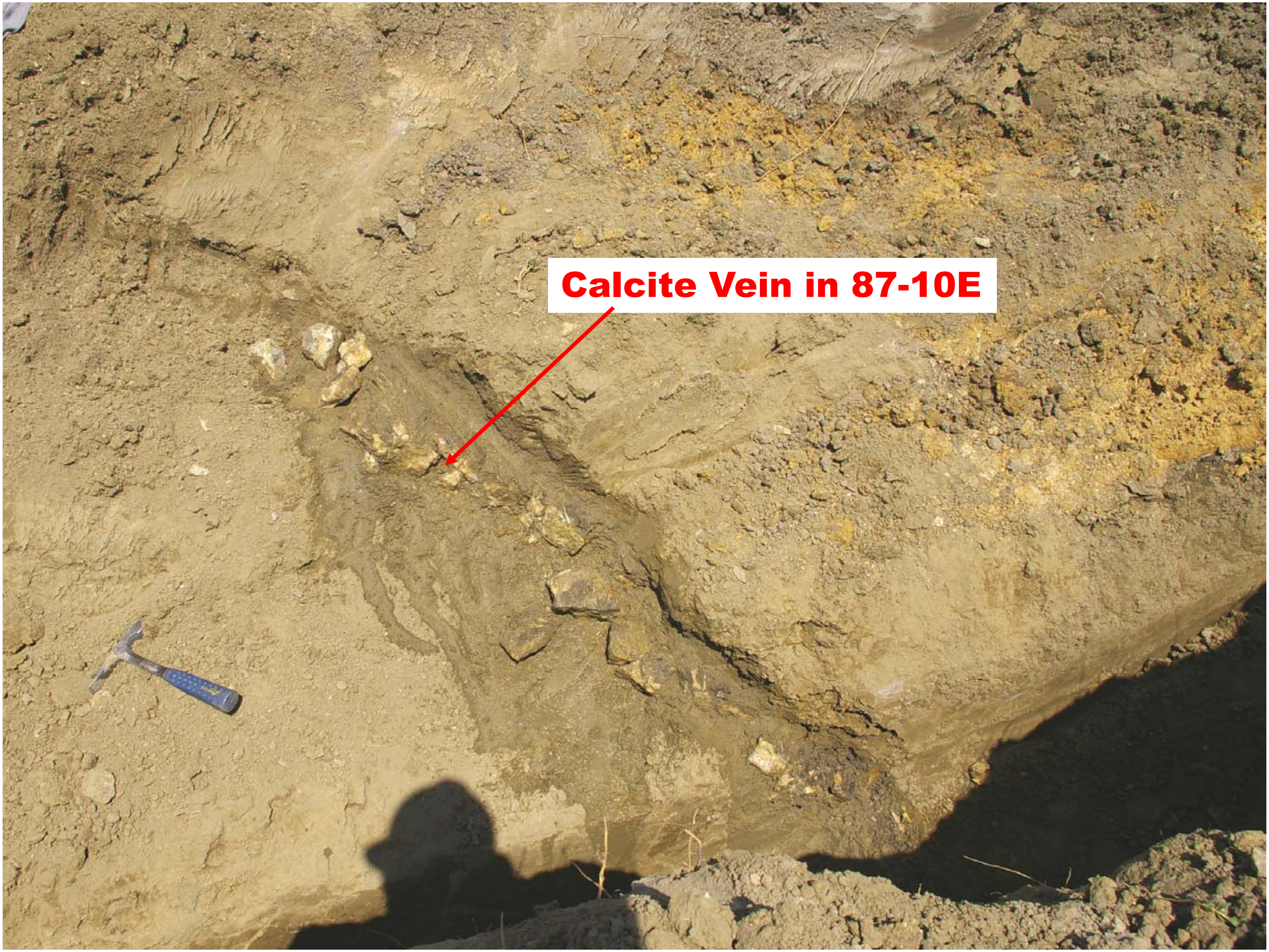
One foot

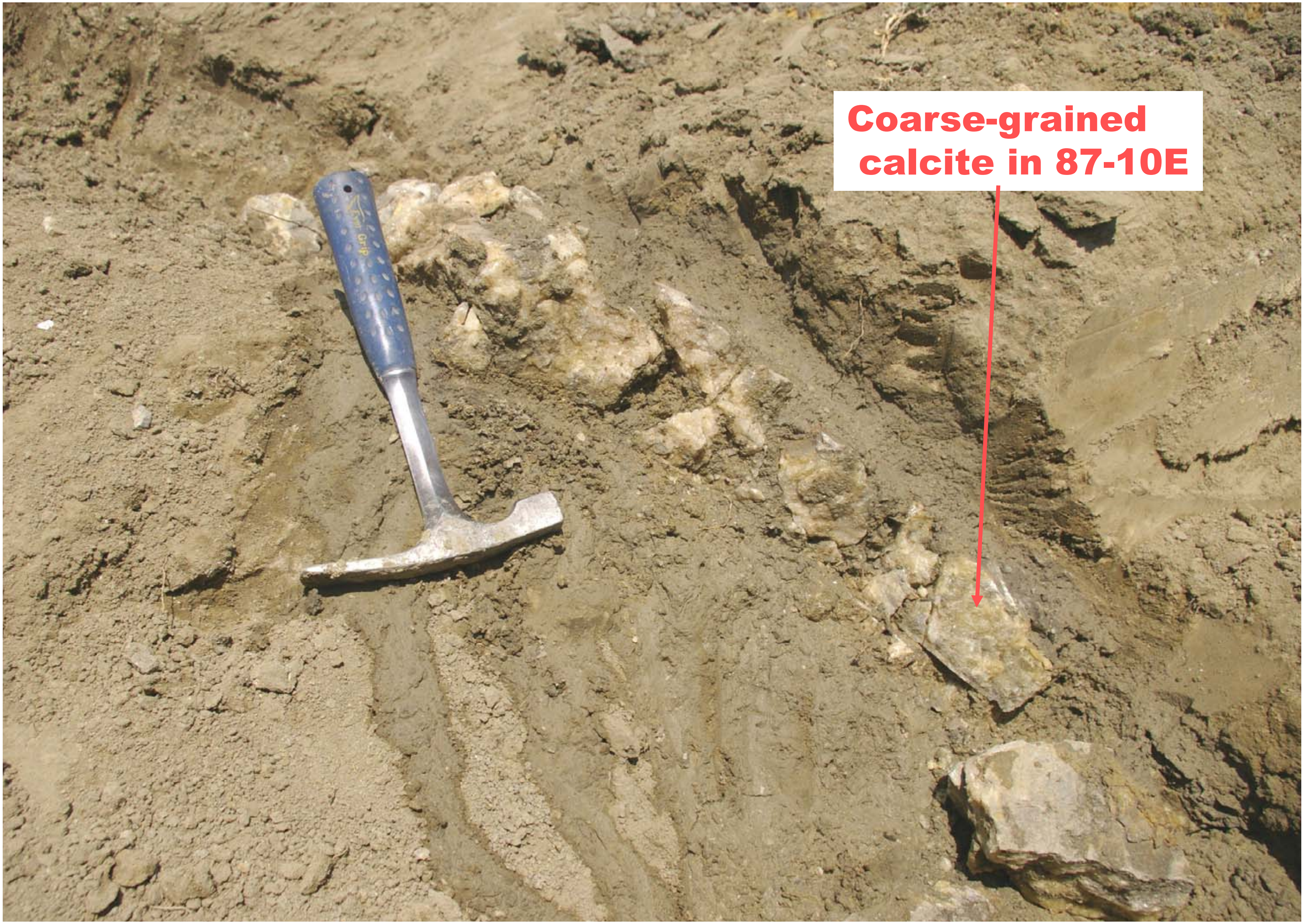
One meter

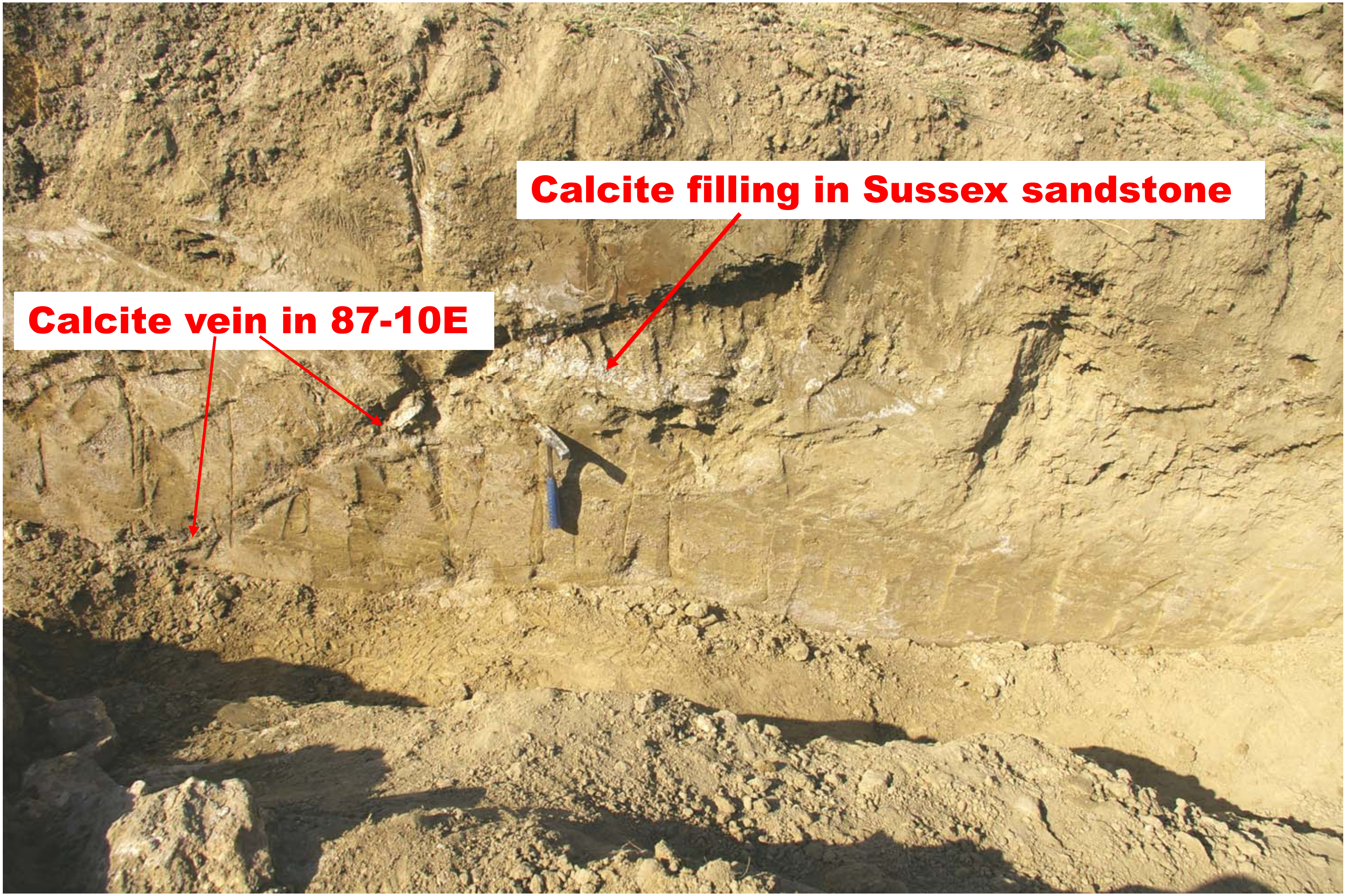
Location
NPR-3
SE/4 SE/4 Sec. 10
T. 38 N., R. 78 W.
Natrona Co., WY
43.27369558 -106.19379242


Oxidizing processes
extending from surface
into weathering zone

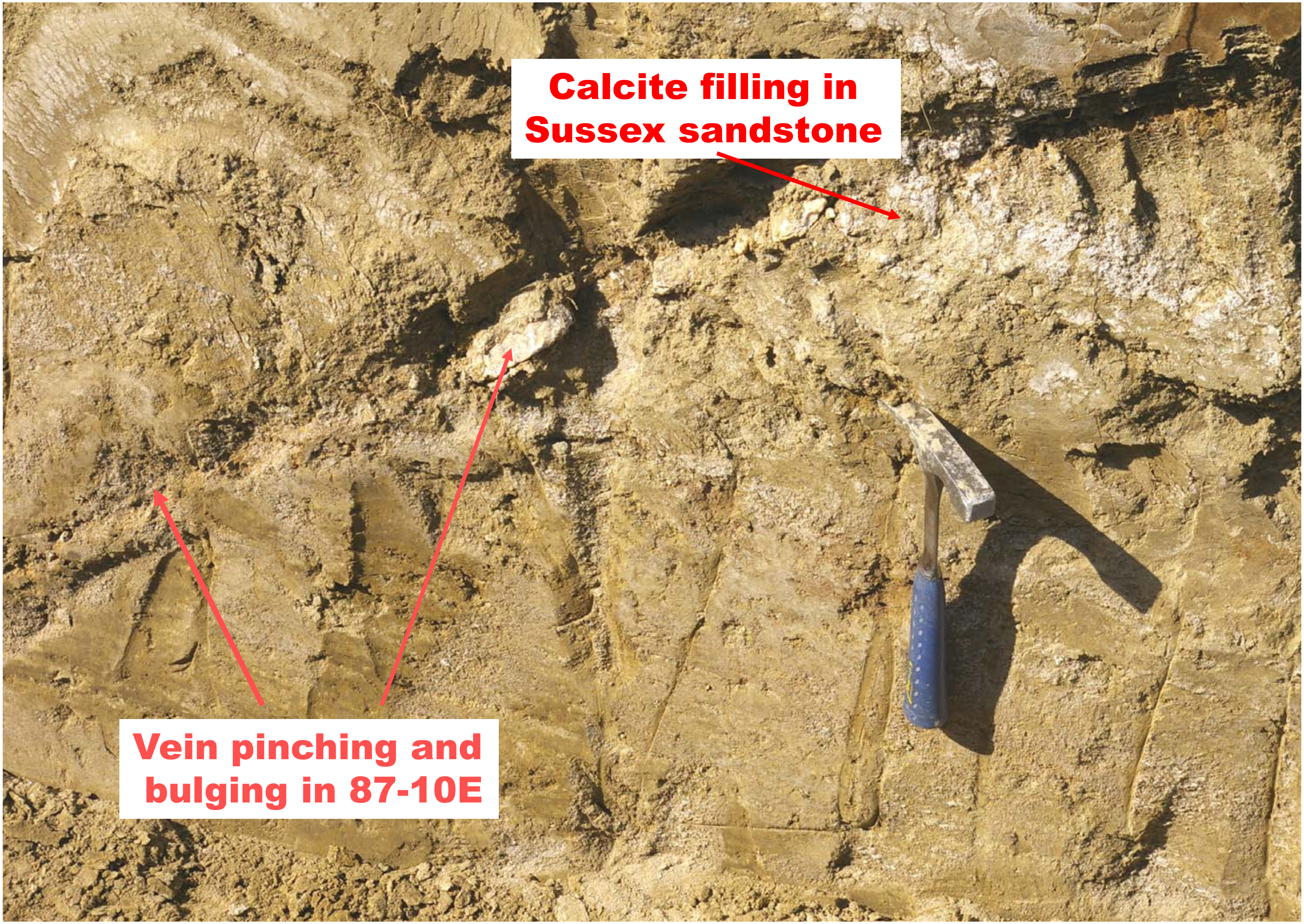

Pedogenic carbonate
formation replacing
grass root hairs

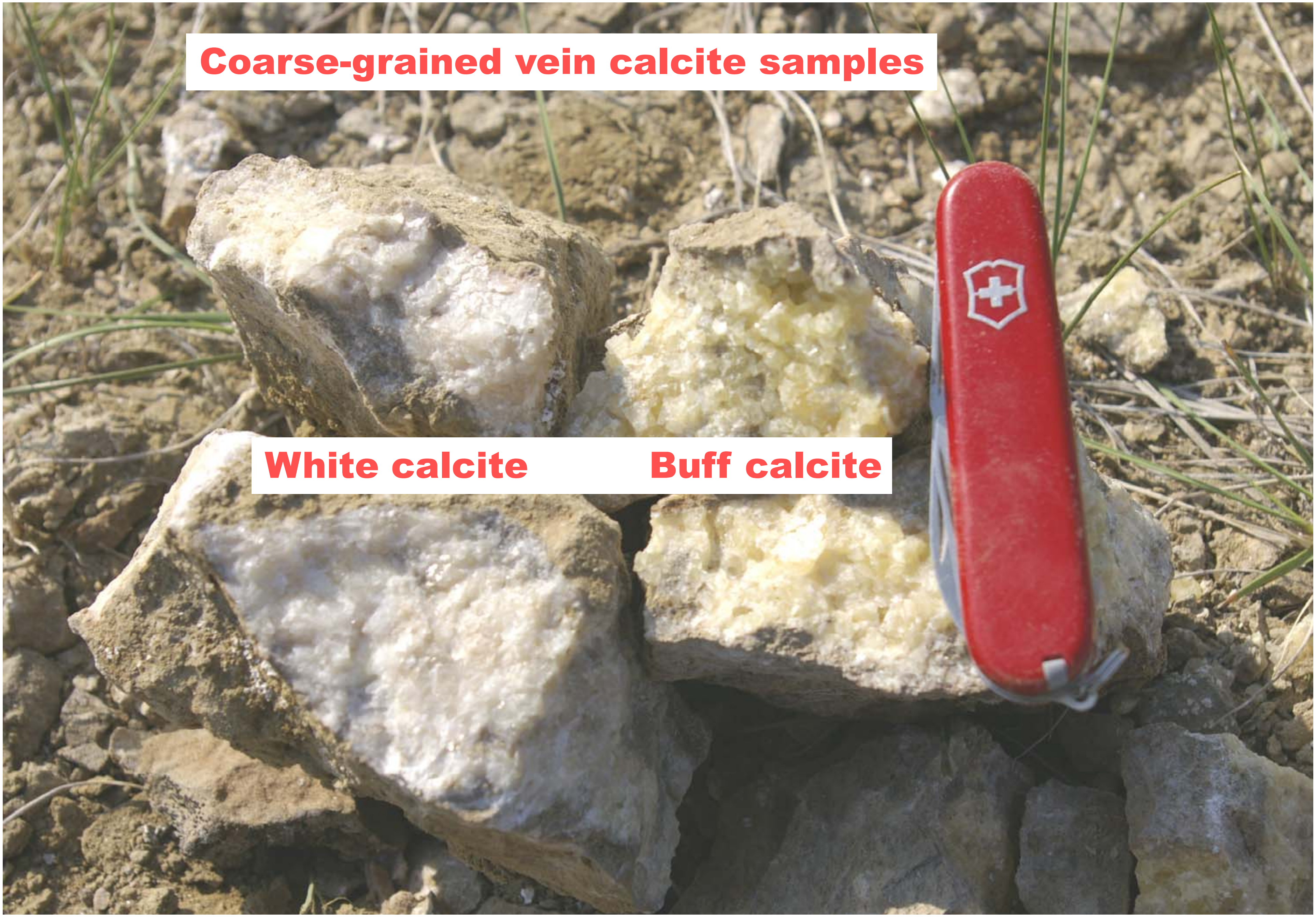

Calcite Vein in 87-10E


Coarse-grained
calcite in 87-10E



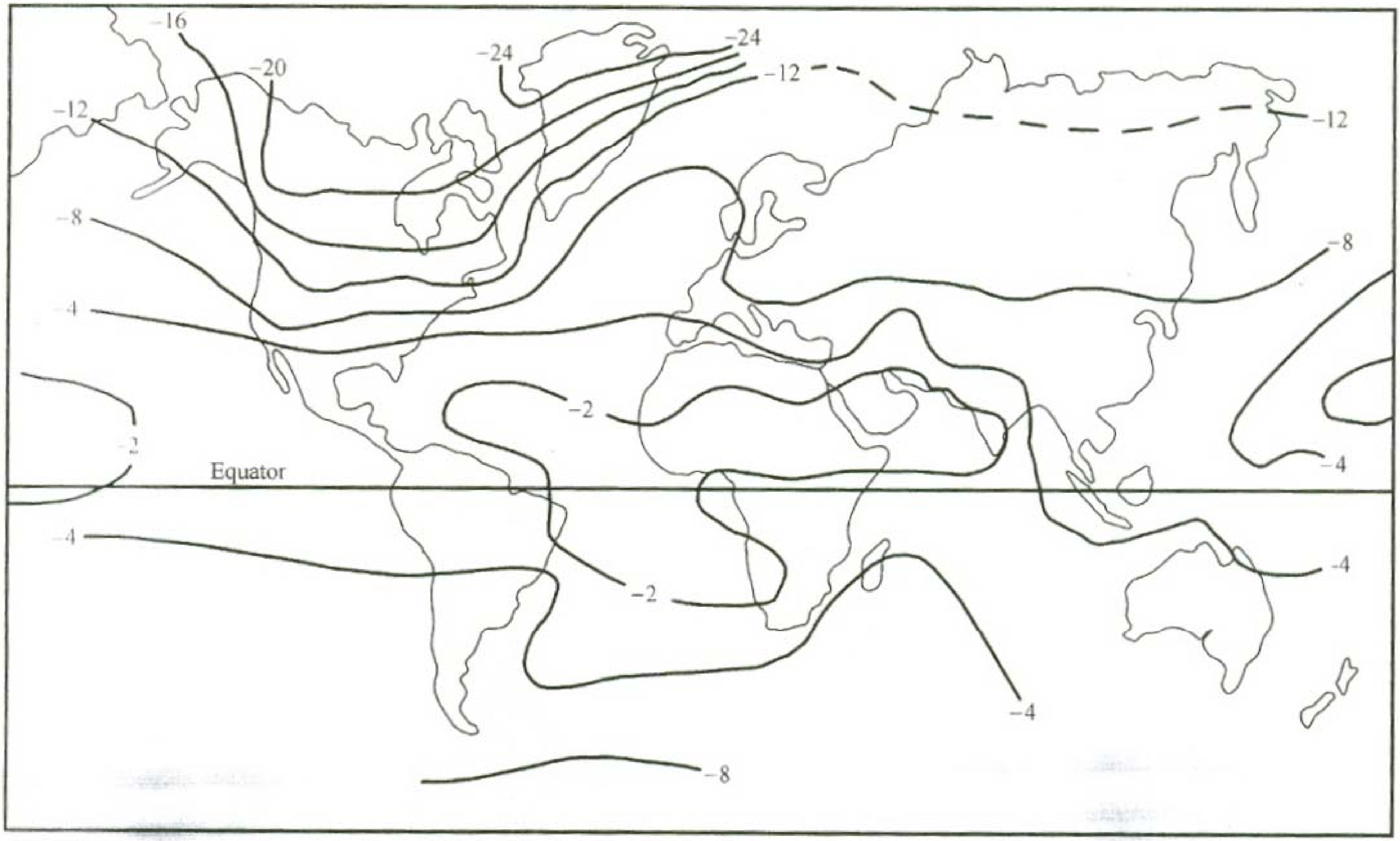
Calcite filling in Sussex sandstone
Calcite vein in 87-10E


Calcite filling in
Sussex sandstone
Vein pinching and
bulging in 87-10E


Coarse-grained vein calcite samples
White calcite
Buff calcite

AVERAGE ANNUAL δ¹⁸O OF PRECIPITATION

from Gat (1981) based on IAEA data (Yurtsever, 1975)



$$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \leftrightarrow CaCO_3 + 2H^+$$

$$\uparrow\downarrow$$

$$Ca^{2+}$$

Pedogenic processes - CO_2 from atmosphere
- H_2O from atmosphere
- Ca^{2+} from weathering in soils

Vein calcite – CO_2 from gas and oxidation of hydrocarbons
H_2O from connate water (seawater)
Ca^{2+} from connate water

$CO_2 + H_2O$ rapidly equilibrates with HCO_3^- , both chemically and isotopically.
$CO_{2\,(atm)}$ $\delta^{13}C$ = -9.52‰ (Klusman, 2007)
$\delta^{18}O$ of H_2O – f(temperature, latitude, elevation, precipitation)
$H_2O_{(atm,\ Casper)}$ $\delta^{18}O$ = -8.08‰ (Dansgaard, 1964)
$H_2O_{(atm,\ Casper)}$ $\delta^{18}O$ = -7.565‰ (Gat and Gonfiantini (1981)
$H_2O_{(Seawater)}$ $\delta^{18}O$ ~ 0.00‰ (Faure and Mensing, 2006)

$$2CH_4 + SO_4^{2-} + 2H^+ \leftrightarrow 2CO_2 + H_2S \text{ (sulfate reduction)}$$

$$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \leftrightarrow CaCO_3 + 2H^+$$

$$\uparrow\downarrow$$

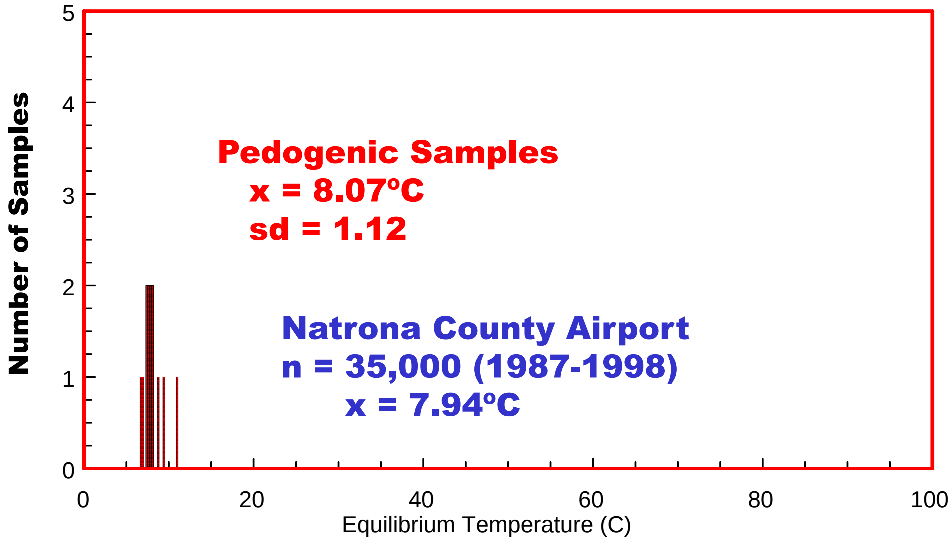
$$Ca^{2+}$$

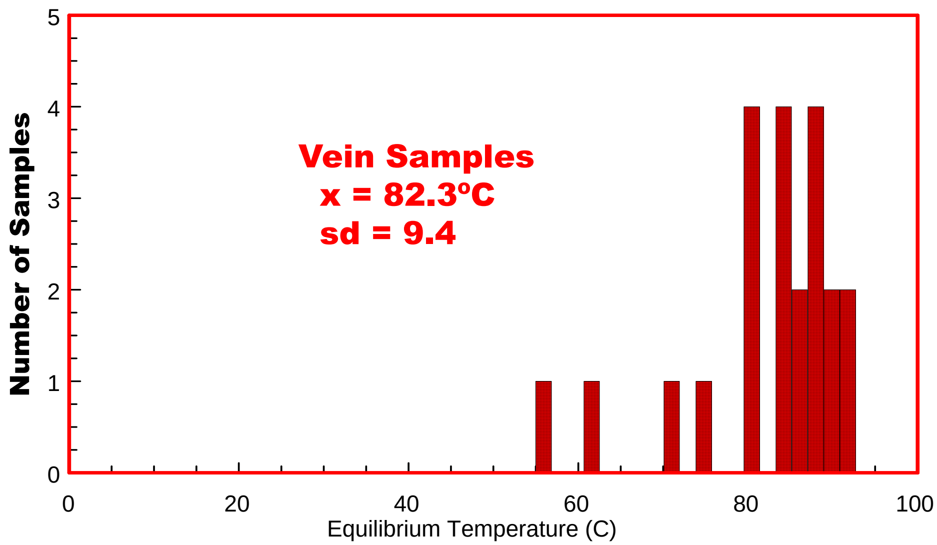
Vein calcite – CO_2 from gas and oxidation of hydrocarbons
H_2O from connate water (seawater)
Ca^{2+} from connate water

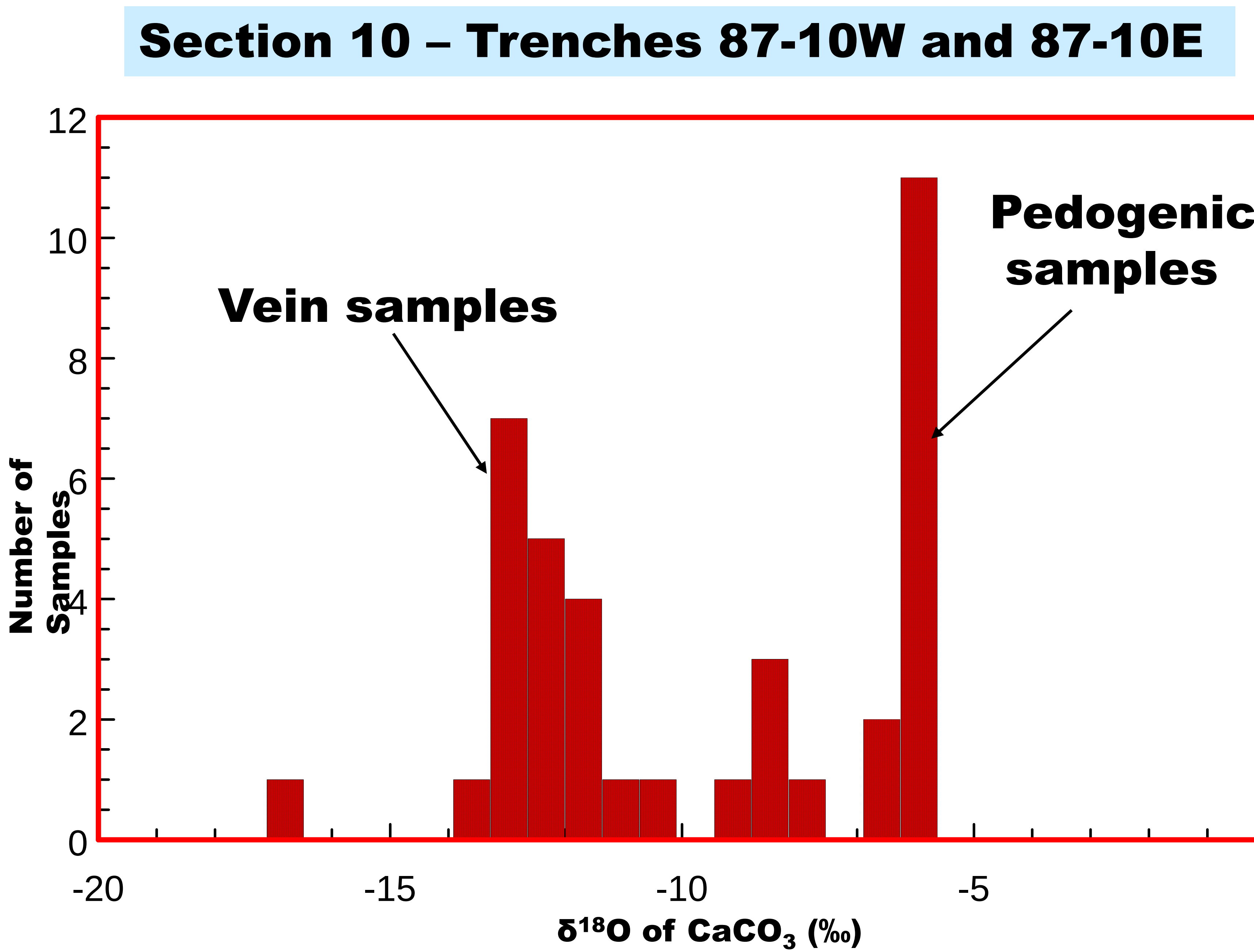
$CO_2 + H_2O$ rapidly equilibrates with HCO_3^-, both chemically and isotopically.

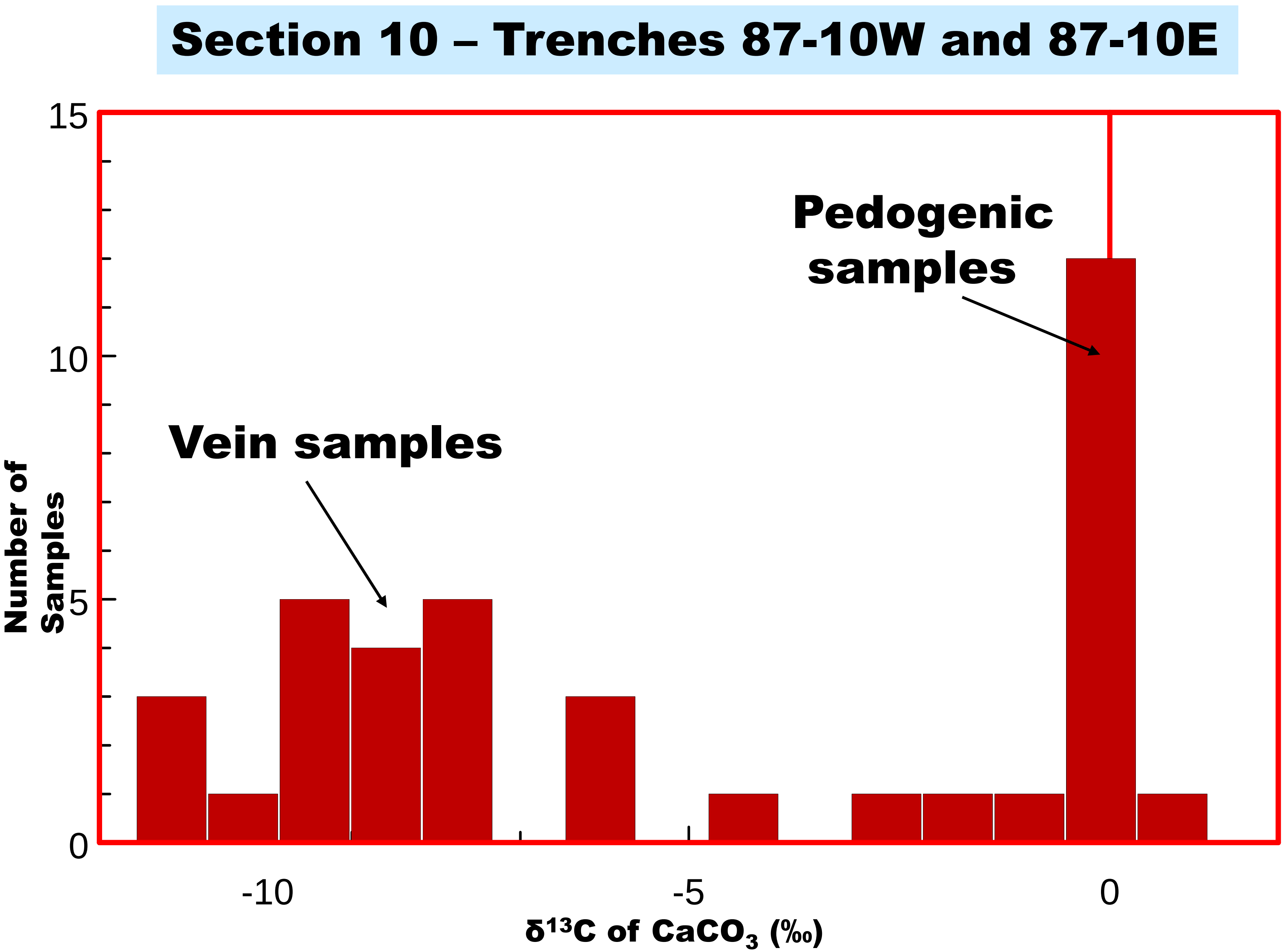
$HCO_{3\,(Tensleep)}^-$ $\delta^{13}C$ = +0.06‰ (Klusman, 2004)
$CO_{2\,(gas\ plant)}$ $\delta^{13}C$ = +7.6‰ (Klusman, 2005)
$CH_{4(gas\ plant)}$ $\delta^{13}C$ = -50.37‰ (Klusman, 2005)
$CH_{4(gas\ plant)}$ $\delta^{13}C$ = -50.29‰ (Dennen et al. 2005)
$C_2H_{6(gas\ plant)}$ $\delta^{13}C$ = -34.64‰ (Dennen et al. 2005)
$C_3H_{8(gas\ plant)}$ $\delta^{13}C$ = -31.55‰ (Dennen et al. 2005)
Ozokerite $\delta^{13}C$ = -30.4‰ (Klusman, 2004)
$CaCO_{3(unaltered\ Steele\ Shale)}$ $\delta^{13}C$ = -0.73‰ (Klusman, 2004)

EQUILIBRIUM TEMPERATURE (ºC) BASED ON $\delta^{18}O$



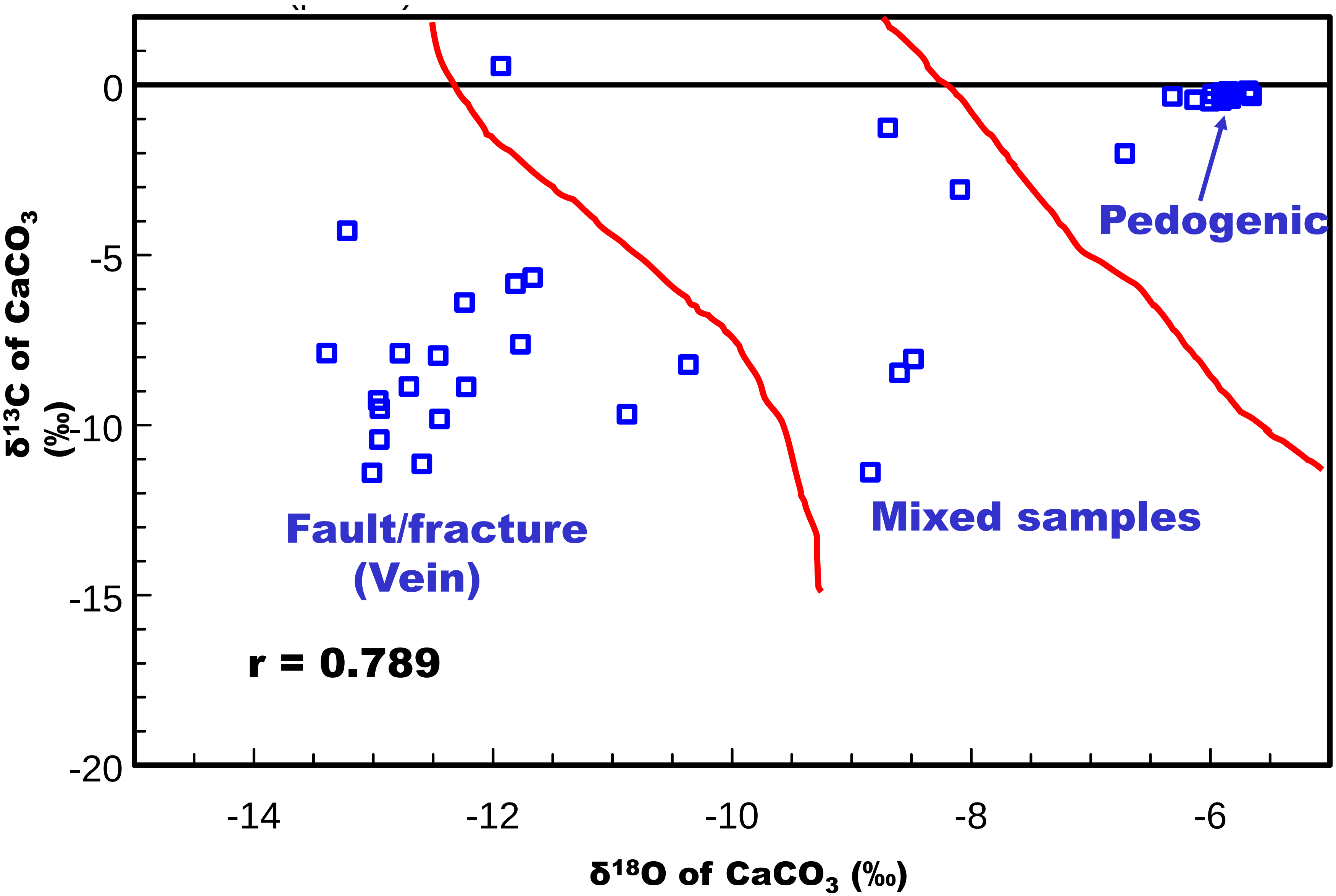



Section 10 – Trenches 87-10W and 87-10E
Vein samples
Pedogenic samples
Number of Samples
δ18O of CaCO3 (‰)
0
2
4
6
8
10
12
-20
-15
-10
-5
0

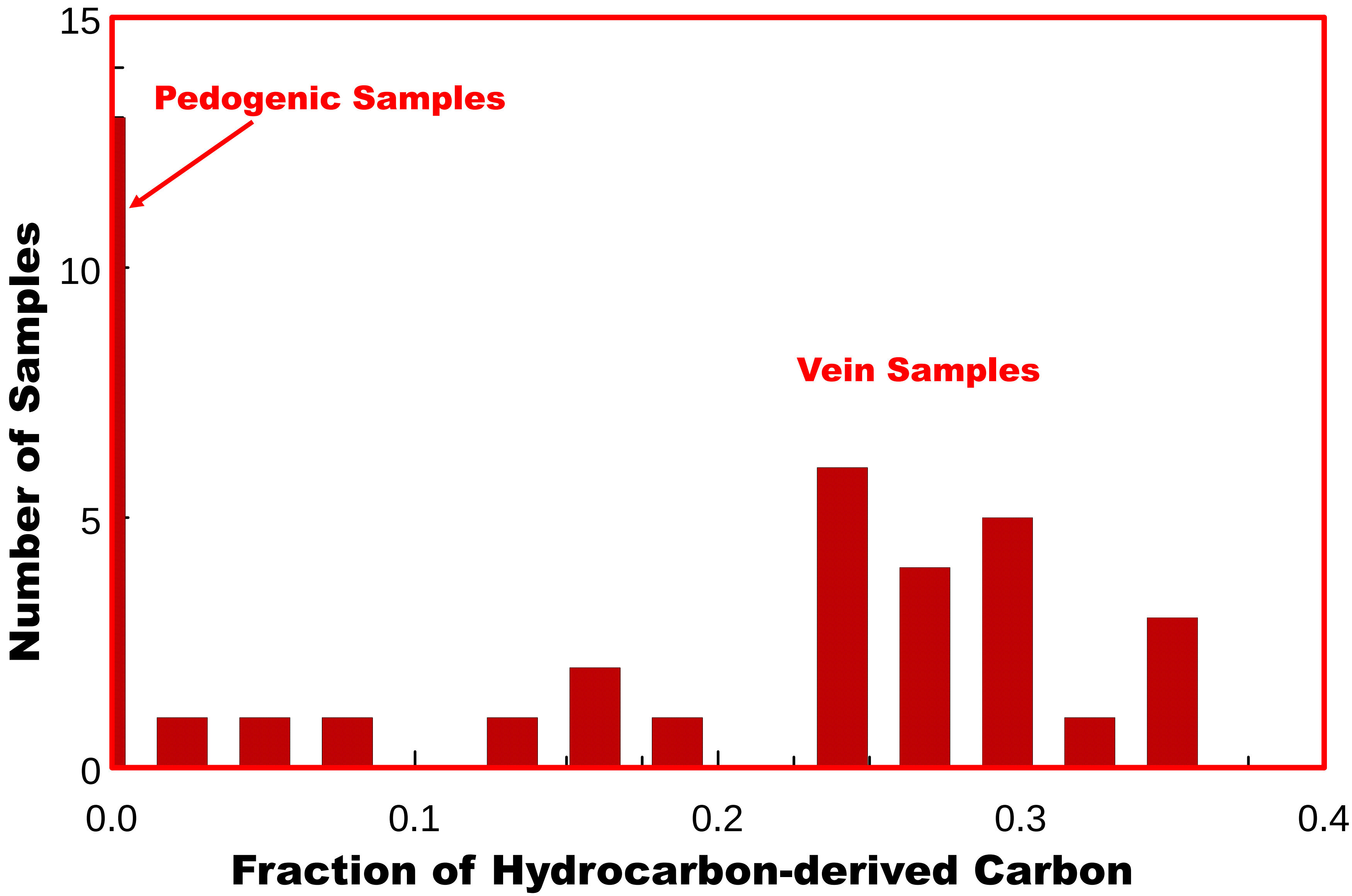


Section 10 – Trenches 87-10W and 87-10E
Pedogenic samples
Vein samples
Number of Samples
15
10
5
0
-10
-5
0
δ13C of CaCO3 (‰)

Section 10 – Trenches 87-10W and 87-10E



SOURCE OF CARBON IN $CaCO_3$



CONCLUSIONS

- **Microseepage of CH_4 and light alkanes is occurring at the present time primarily south of the un-named drainage and along a section of the 87-10 Fault,**
- **Evidence for the beginning step of hydrocarbon oxidation,**
- **No evidence of a deep-sourced CO_2 found,**
- **Helium isotopes support presence of microseepage in 10-m holes ~ 1 km north of Section 10 (Mackintosh and Ballentine (2007),**
- **Vein calcite emplaced at 2-2.5 km depth based on equilibrium temperature,**
- **Injection experiment can proceed.**

SUPPORT AND CONCERNS ABOUT CONCLUSIONS

- Dennen et al (2005) USGS-OFR 2005-1275- Cretaceous oils have mixed marine and terrestrial source, biodegraded, methanogenesis occurring, Tensleep oils have a marine source, more mature and less biodegraded. Episodic gas migration may be occurring.
- Brennan et al (2006) USGS-OFR 2006-1214- Fluid inclusion microthermometry indicated ozokerite was emplaced at ≥66ºC, Shannon achieved a maximum T of 76ºC (Hansley and Nuccio, 1992), ~10-12 Ma during uplift in SW Powder River basin. "The fractures in this study have no active connection to any deeper oil-bearing strata."
- Milliken (2007) Numerous bentonite beds in the Upper Steele Shale should seal small displacement faults, preventing seepage,
- Mackintosh and Ballentine (2007) have measured helium isotopes in 10-meter holes of Klusman (2004, 2005, 2006) which supports the existence of deep-sourced microseepage.

CONCLUSIONS ABOUT CH_4

- **CH_4 is as important as CO_2 for monitoring programs,**
- **CH_4 is more likely to seep to the near-surface than CO_2 in overpressured conditions,**
- **Methanotrophic oxidation of CH_4 will be critical for attenuation of microseepage.**

HOW TO DETECT AND CONFIRM PRESENCE OF MICROSEEPAGE

- Measure in "winter" or "dry" season,
- GC measurements of CH_4 must be better than routine,
- Liberal application of stable isotopic ratios,
- Use flux magnitudes, soil gas concentration gradients, isotopic shifts to find "interesting" locations,
- Correct 8 out of 8 at Rangely and Teapot in selecting locations for 10-m holes (2001-04),
- Then, thorough characterization with "nested" soil gas sampling to at least 5 meters depth, preferably 10 meters, which is less sensitive to season,
- Additional confirmation of thermogenic source with stable isotopes and carbon-14.

HOW TO MISS PRESENCE OF MICROSEEPAGE

- Measure in "wrong" season,
- Skip search for CH_4,
- Poor precision in GC measurement of CH_4 so that determination of direction and magnitude of flux is lost in sampling and analytical noise,
- No replication to allow assessment of sampling and analytical error,
- Minimal use of stable isotopes,
- Problems Increasing Difficulty with MMV
- Coal-derived CO_2 isotopically similar to near-surface biological CO_2,
- Warm, wet climates will be more difficult for MMV, even with good methodology.

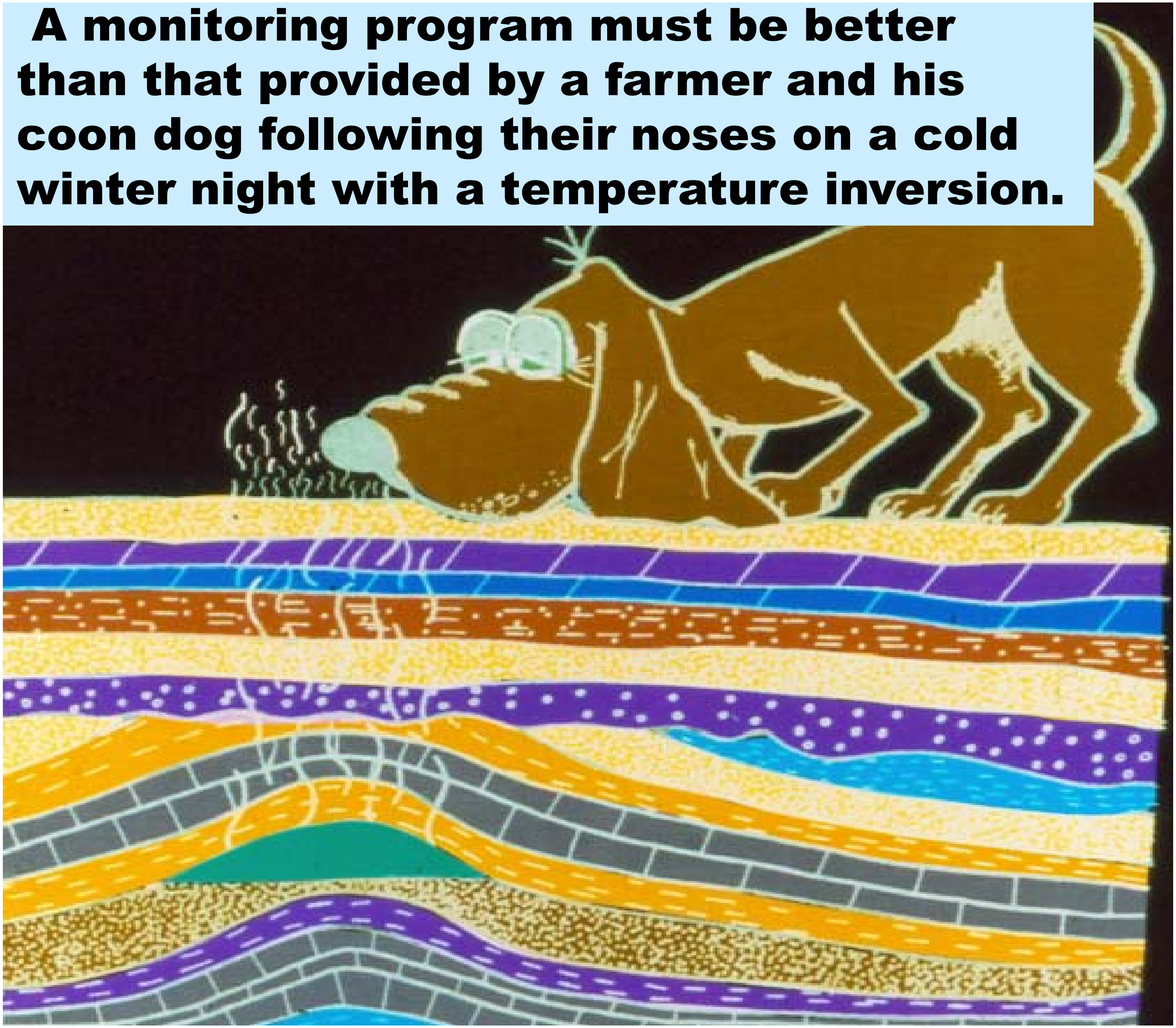
RECOMMENDATIONS FOR FURTHER STUDY AT TEAPOT

- **Repeat soil gas portion of survey in winter season 3-12 months after CO_2 injection,**
- **Monitor formation water quality in Tensleep and underpressured 2nd Wall Creek reservoirs, HCO_3^- will change first,**
- **Rare gas isotopes (S. Mackintosh, C. Ballentine-University of Manchester, UK),**
- **Open-path optical measurements.**

OTHER METHODOLOGIES TO DETECT MICROSEEPAGE

- **Side-scan sonar for off-shore determination of bubble column density (Quigley et al. 1999); complemented with composition and isotopic measurements on samples,**
- **Open-path spectroscopic measurement of CH_4 in the atmosphere (Etiope, INGV,2005),**
- **Rare gas isotopes (S. Mackintosh, C. Ballentine-University of Manchester, UK),**
- **Eddy covariance mainly applied in pristine environments; practical problems in oil-field environments(?)**

A monitoring program must be better than that provided by a farmer and his coon dog following their noses on a cold winter night with a temperature inversion.

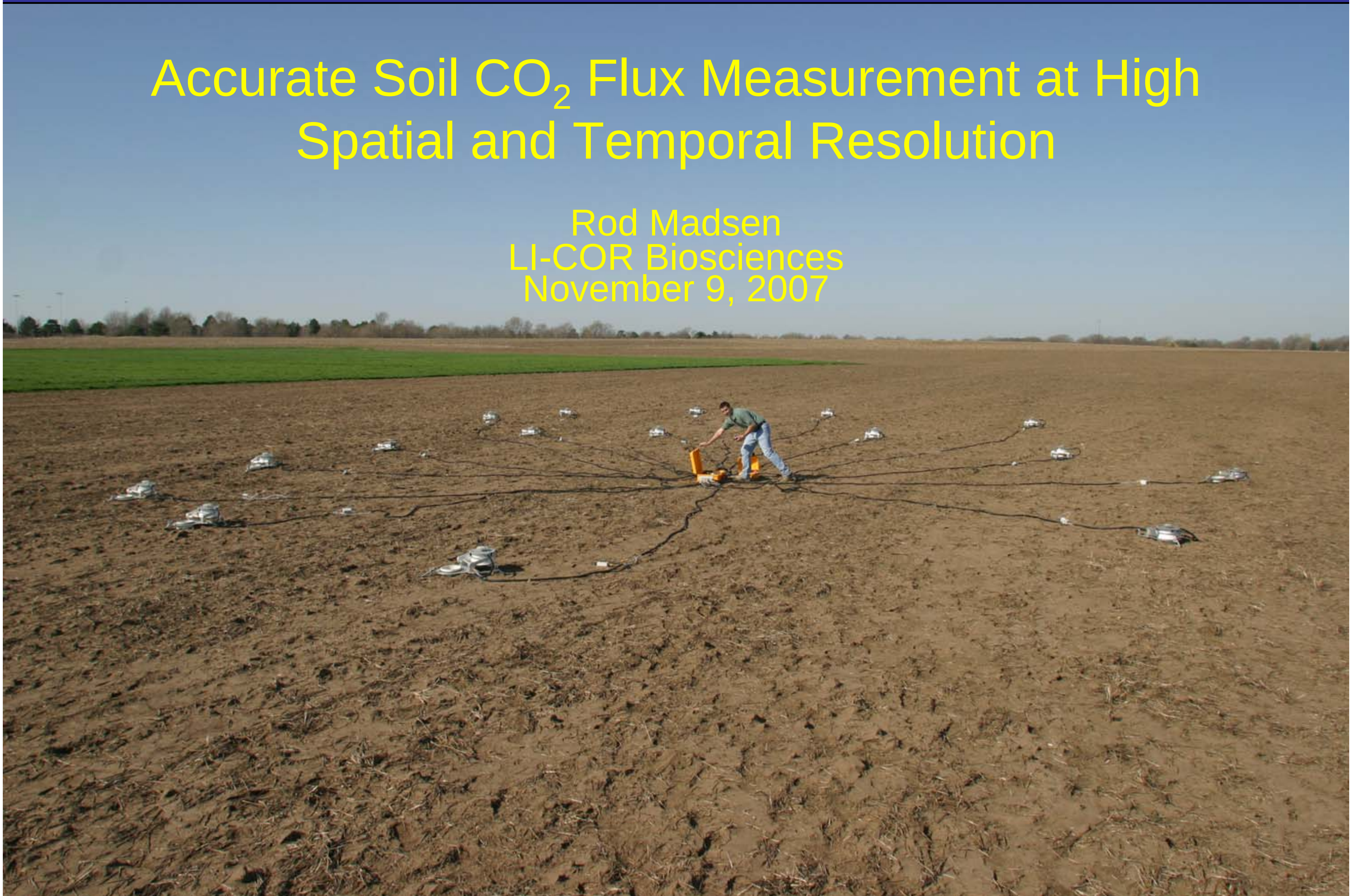


ACKNOWLEDGEMENTS

- The Department of Energy-Rocky Mountain Oilfield Testing Center (RMOTC) supported the Teapot Dome research; Vicki Stamp (Engineering) and Mark Milliken (Geology) are the Project Managers,
- Several individuals at the Colorado School of Mines, and Naval Petroleum Reserve No. 3.

Accurate Soil CO_2 Flux Measurement at High Spatial and Temporal Resolution

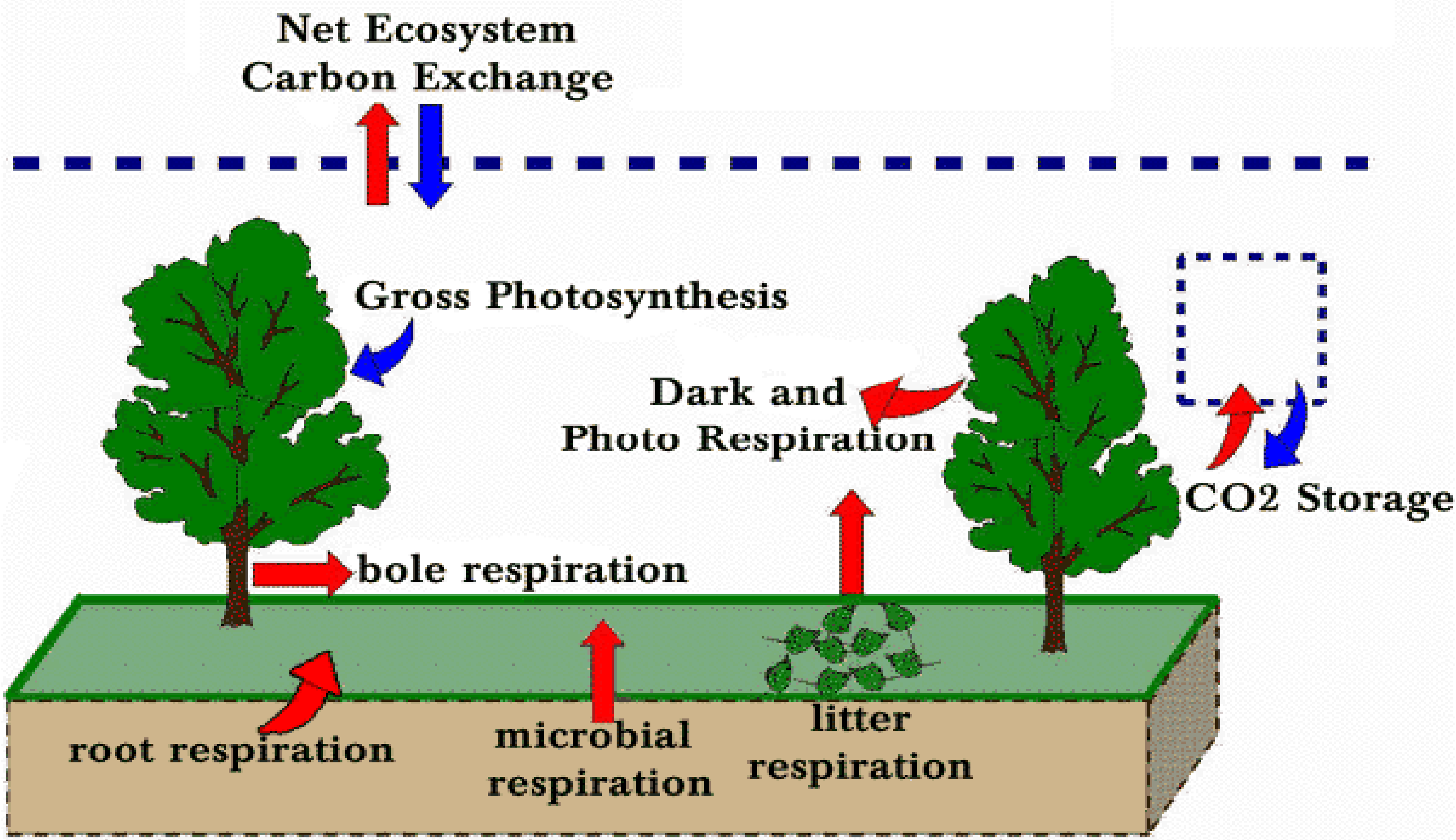
Rod Madsen
LI-COR Biosciences
November 9, 2007



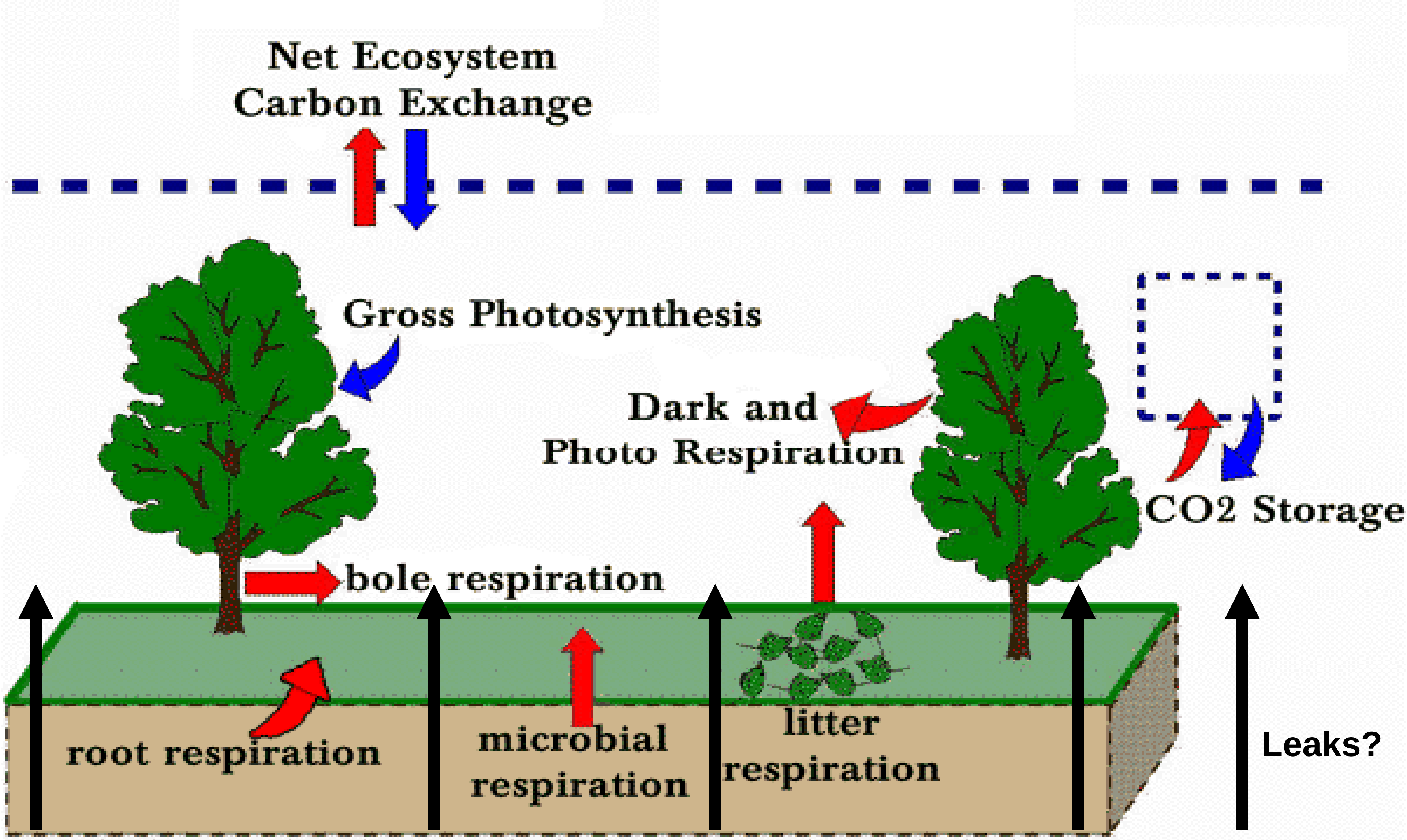
Outline

- Canopy Carbon Balance
- Surface Monitoring Instrumentation
- Requirements for a good measurement
- Field Data
- MMV Example

Canopy Carbon Balance



Canopy Carbon Balance



Why Surface Monitoring?

- To demonstrate that storage is a permanent sequestration option
- Help refine the field deployment technologies for large scale injections
- Track migration over time for validation and calibration of model predictions and monitoring tools
- Assure the public that human health and the environment are high priorities
  - Establish baseline conditions
  - Refine early warning tools of storage leaks and diagnosis of why storage may leak

Instrumentation

Soil Surface

Atmospheric

Fly-over CO_2 measurements

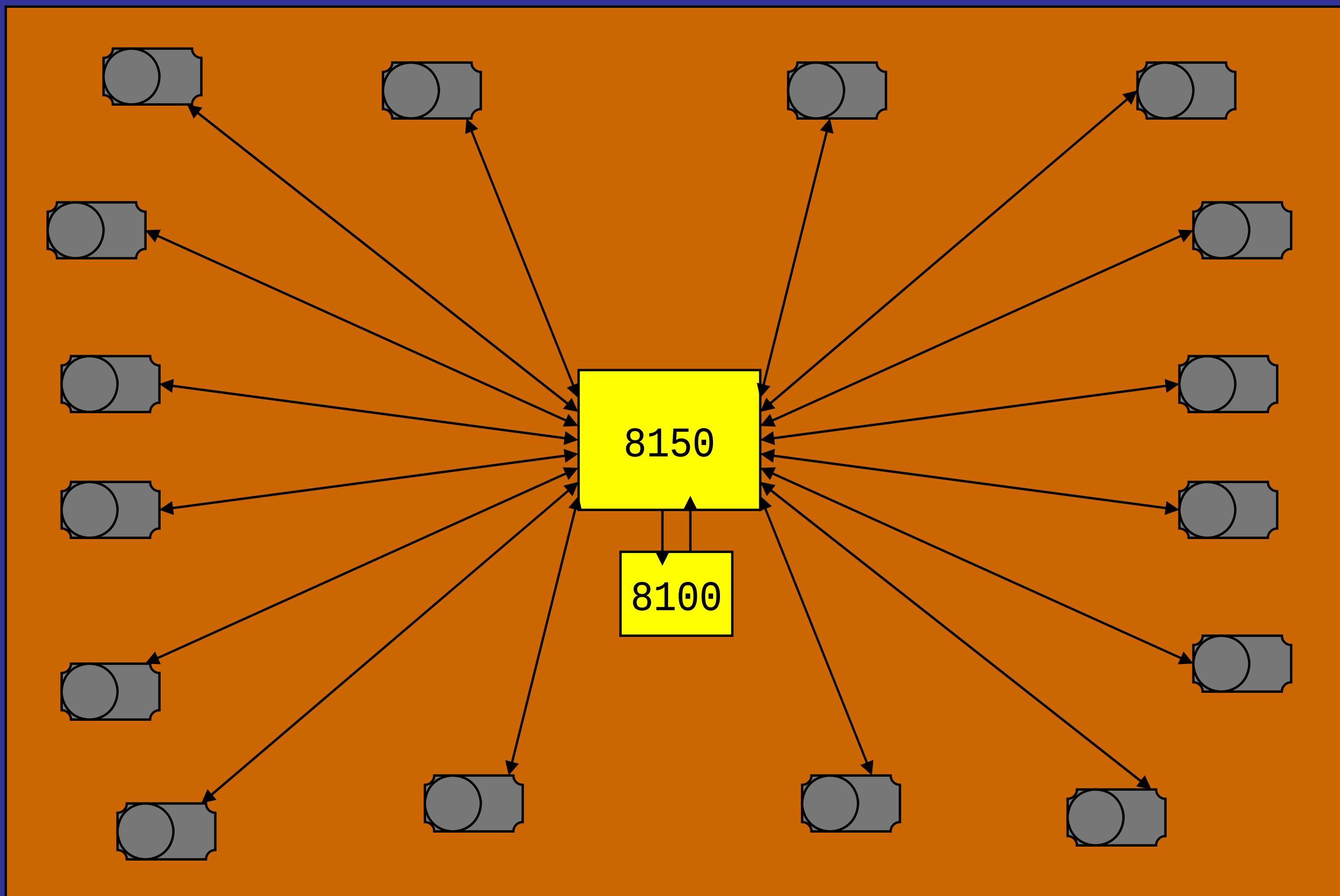
Eddy Covariance measurements from Helicopters (Roni Avissar, Duke Univ)

Spatial Sampling
Survey Measurements

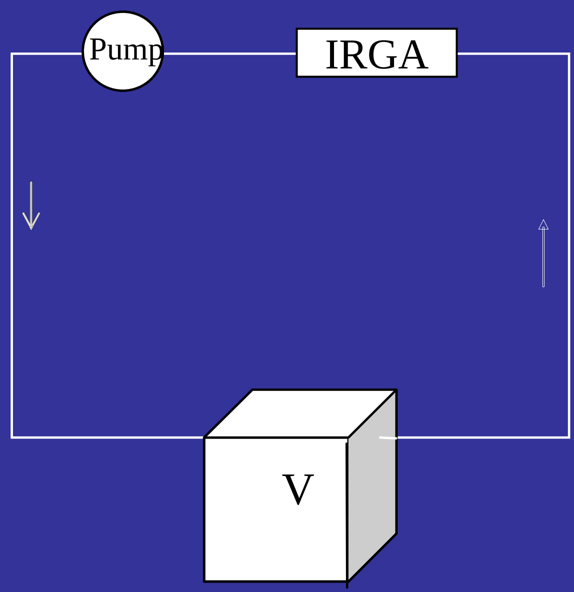
Temporal Sampling
Long-term Measurements

Both Spatial and Temporal

LI-8100/8150 Multiplexer



Requirements for a good measurement



$$F_{CO2} \approx \frac{V}{S}\frac{dC}{dt}$$

$\boldsymbol{F_{CO2} \propto (CO_2^{soil} - CO_2^{chamber})}$ **+ mass flow**

1. CO_2^{soil} not disturbed
2. $P_{bench} \sim P_{ambient}$
3. $CO_2^{chamber} = CO_2^{air}$
4. $P_{chamber} = P_{ambient}$
5. Good mixing
6. No disturbance to soil moisture, temperature or radiation

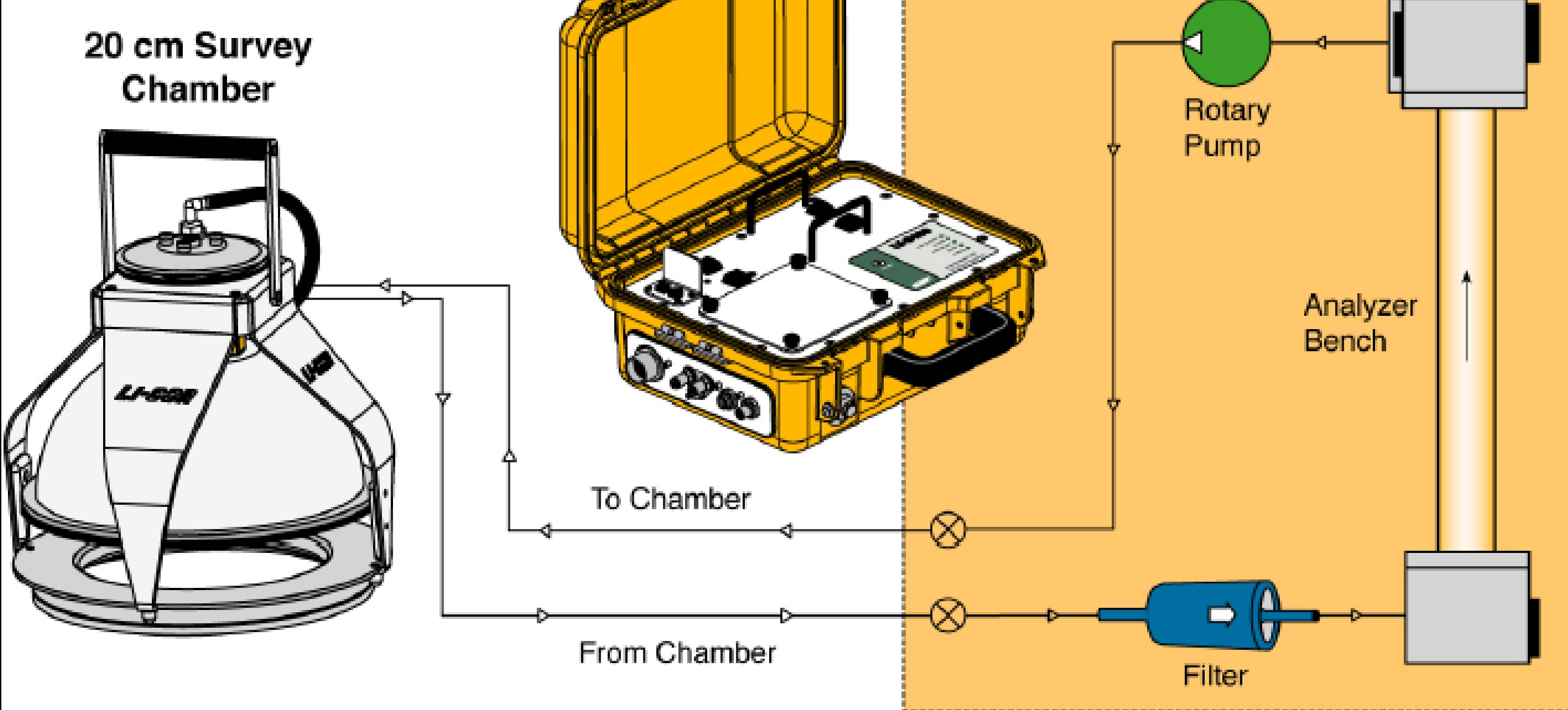
Requirement: CO_2^{soil} not disturbed

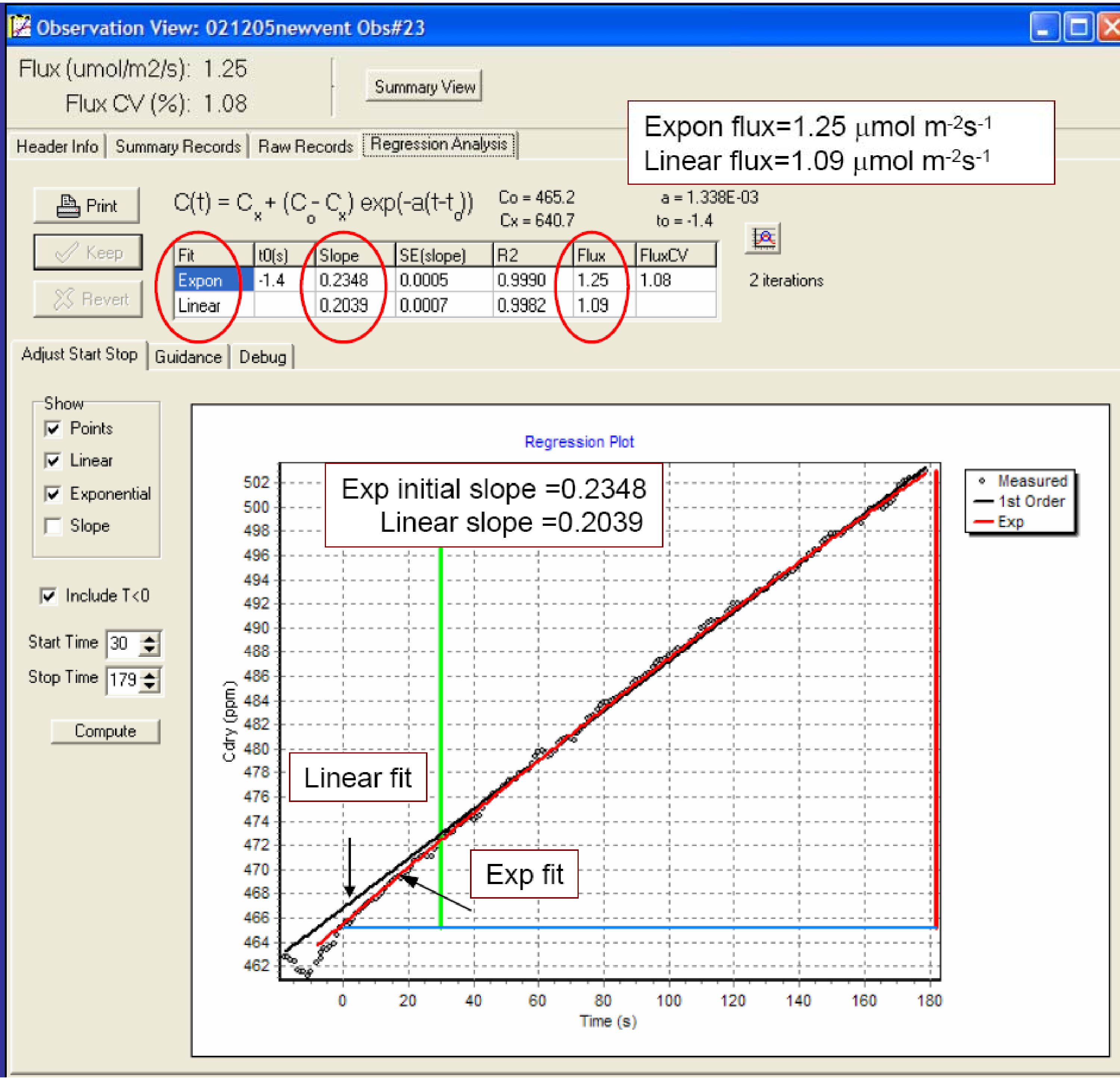
- Slowly close & open the chamber

LI-8100

Requirement: $P_{bench} \sim P_{ambient}$

Flow Control




Observation View: 021205newvent Obs#23
Flux (umol/m2/s): 1.25
Flux CV (%): 1.08
Summary View
Expon flux=1.25 μmol m-2s-1
Linear flux=1.09 μmol m-2s-1
Header Info
Summary Records
Raw Records
Regression Analysis
Print
Keep
Revert
C(t) = Cx + (Co - Cx) exp(-a(t-to))
Co = 465.2
Cx = 640.7
a = 1.338E-03
to = -1.4
Fit | t0(s) | Slope | SE(slope) | R2 | Flux | FluxCV
Expon | -1.4 | 0.2348 | 0.0005 | 0.9990 | 1.25 | 1.08
Linear | | 0.2039 | 0.0007 | 0.9982 | 1.09 |
2 iterations
Adjust Start Stop
Guidance
Debug
Show
Points
Linear
Exponential
Slope
Include T<0
Start Time 30
Stop Time 179
Compute
Regression Plot
Exp initial slope =0.2348
Linear slope =0.2039
Measured
1st Order
Exp
Linear fit
Exp fit
Cdry (ppm)
Time (s)

Key features: New pressure vent design

Pcham=Pambient

XU ET AL.: CHAMBER PRESSURE EQUILIBRIUM

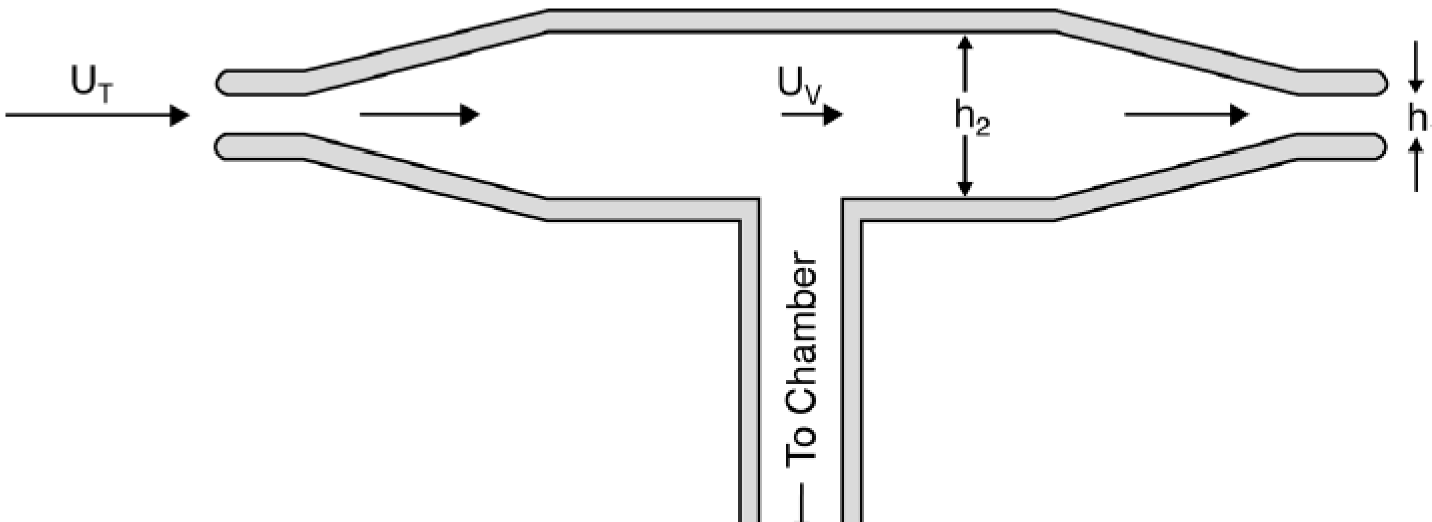
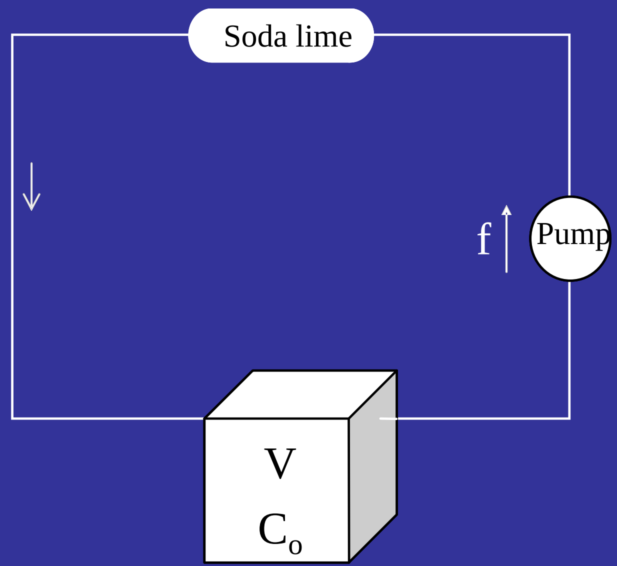
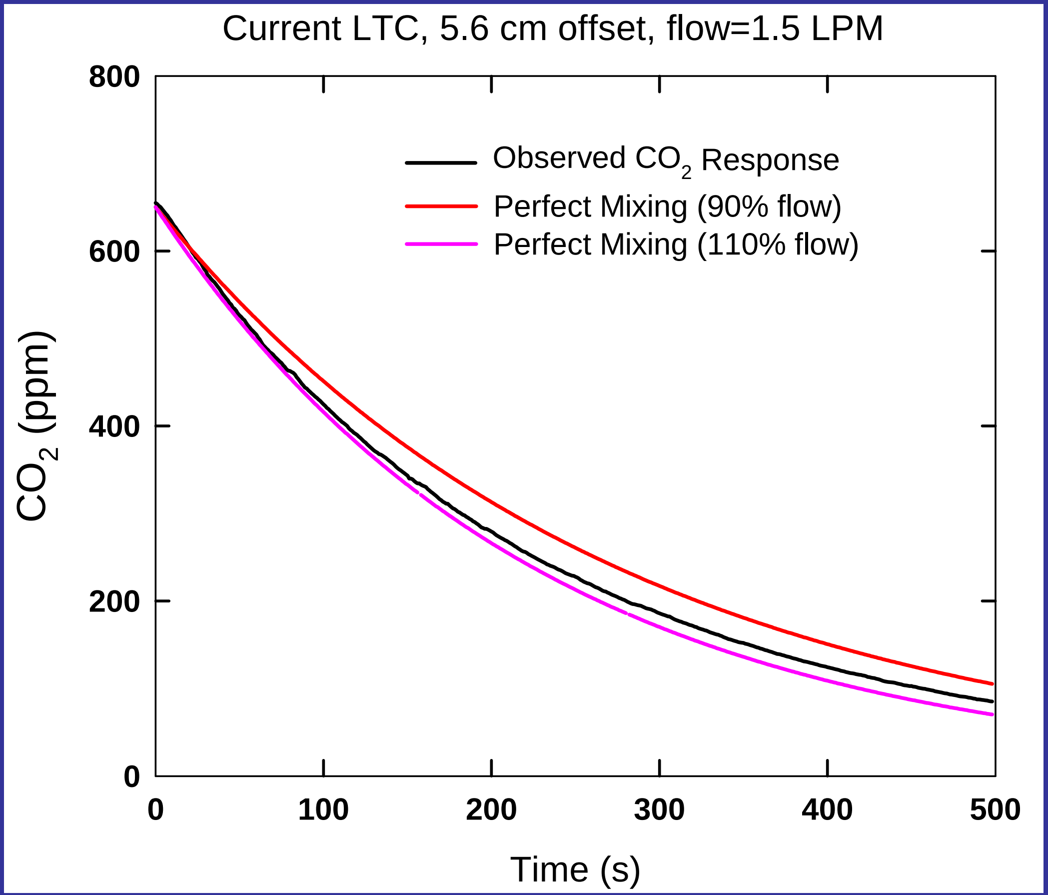


Figure 1. Cr ... peed at the height of the v ... ne edge and the central dis ...

Key features: Good mixing



$$C_t = C_o e^{-\frac{f}{V}t}$$

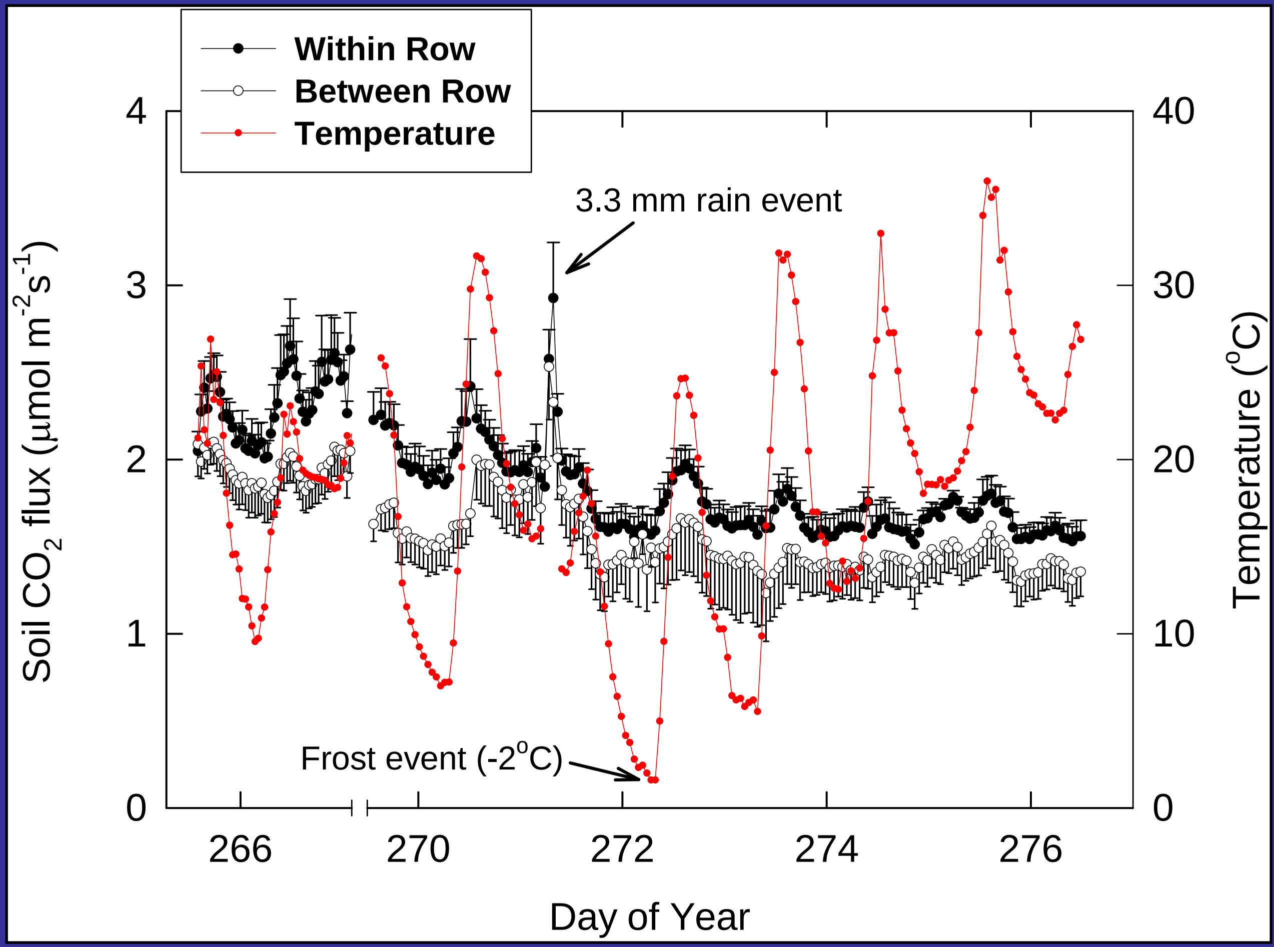


Requirement: No disturbance to soil moisture, temperature or radiation

Key features: Move the chamber away when not in measurement mode

Mead corn
field testing
2005

Results: 2005 Mead corn field



a. F_{CO2} higher within row than between rows

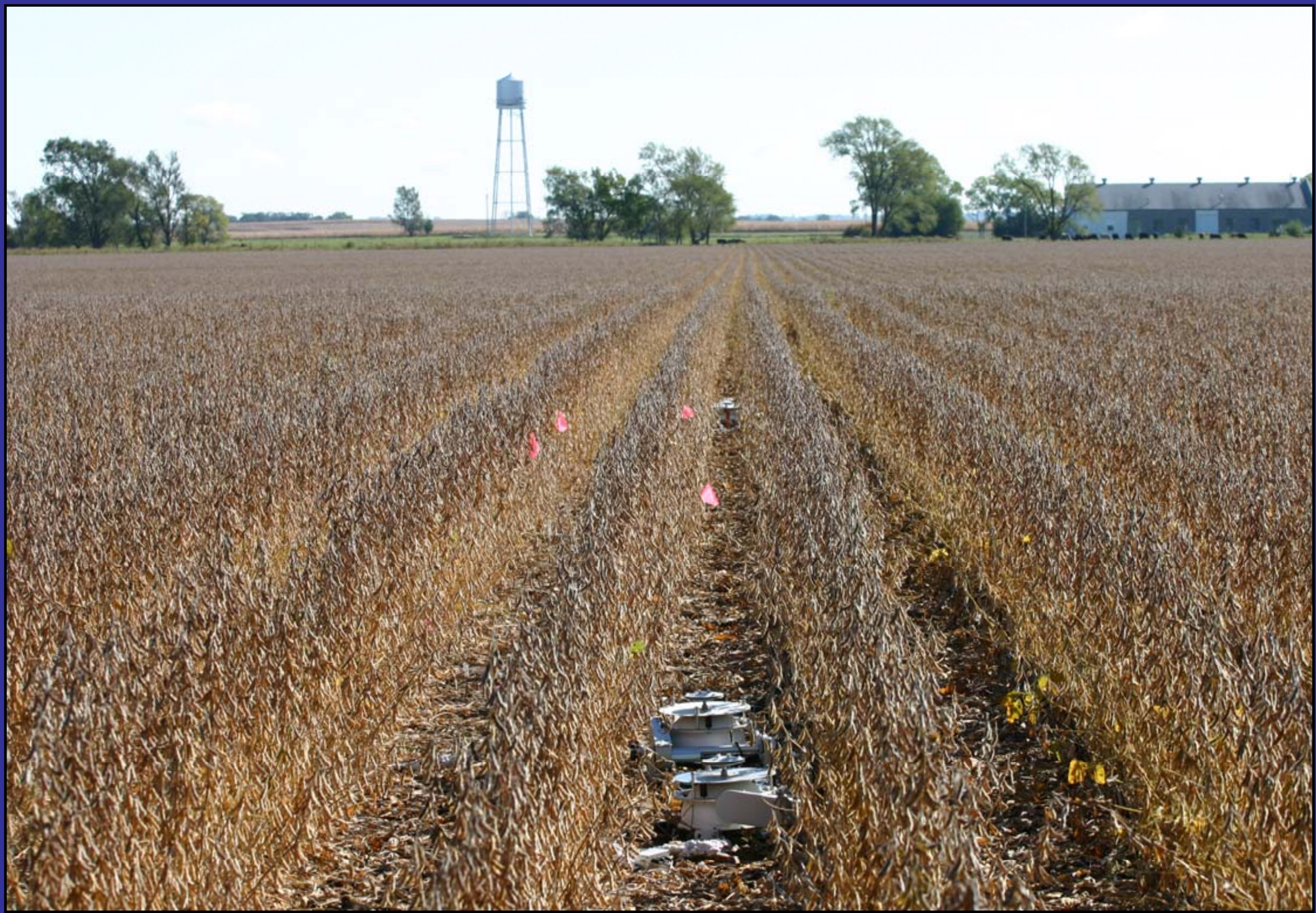
b. Rain event enhanced F_{CO2}

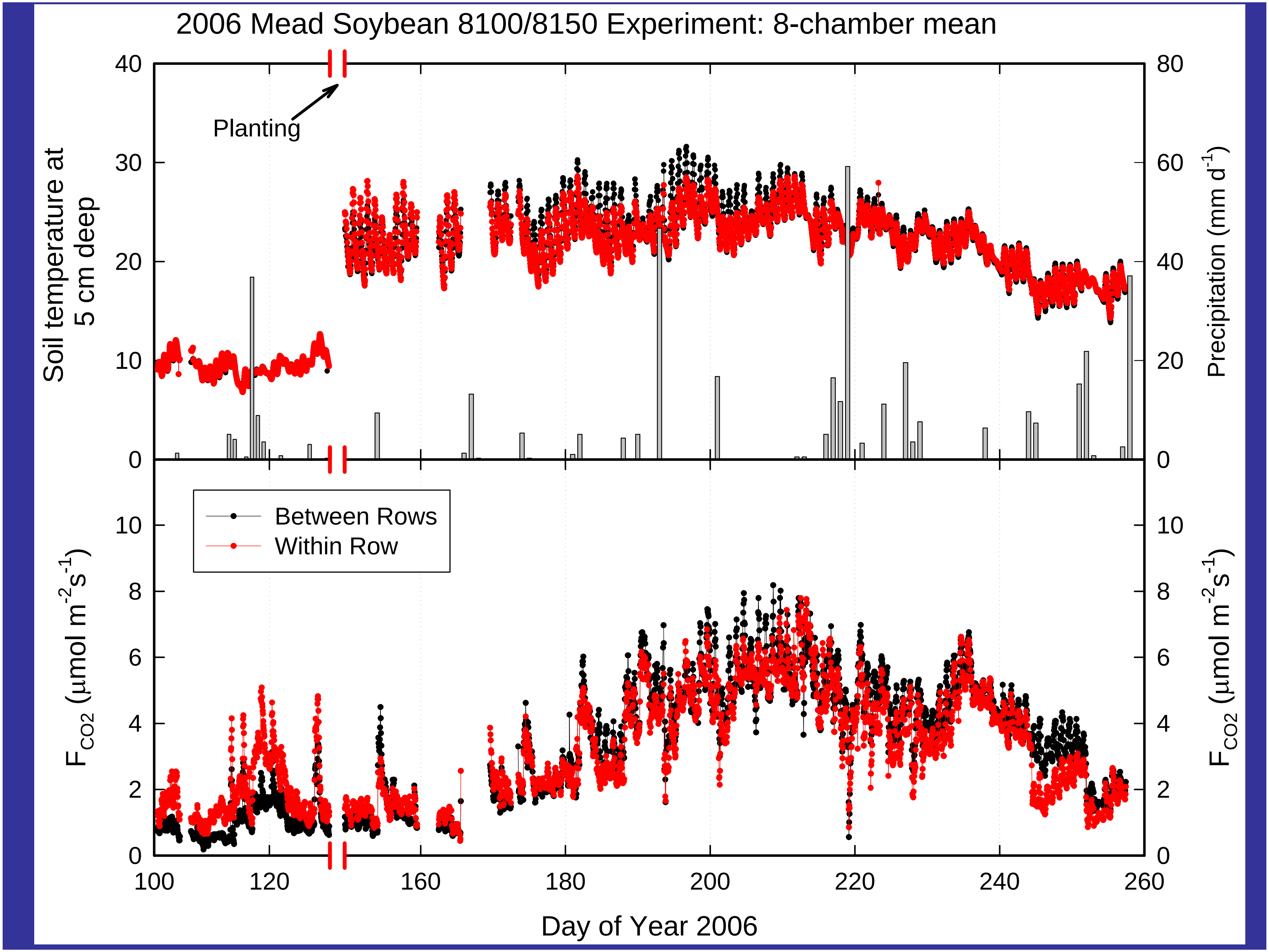
c. Diurnal variation in F_{CO2} became smaller after a frost

Mead Field 2006 (June)

Between rows & within row comparison

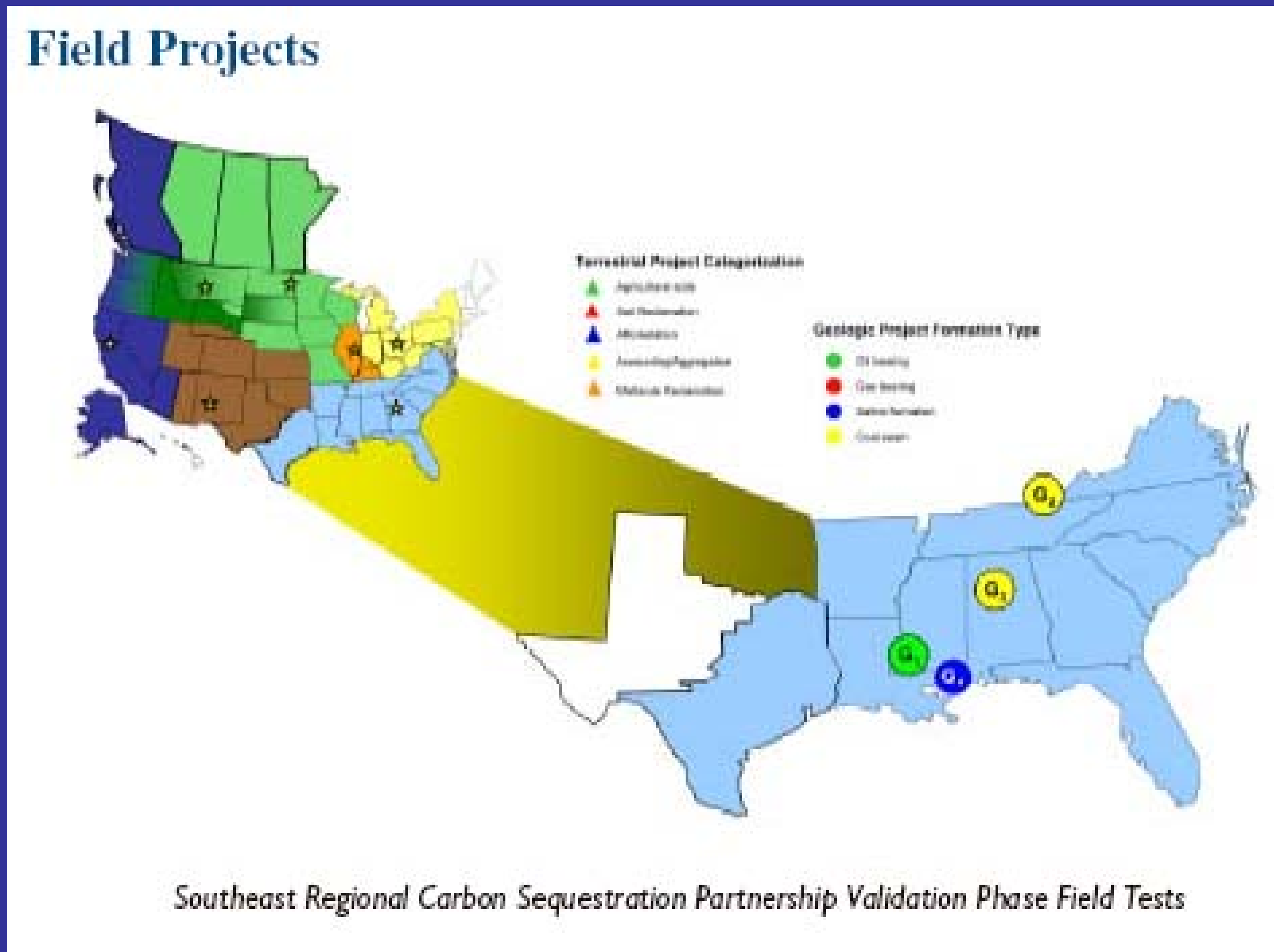
Mead Field 2006 (Sept)





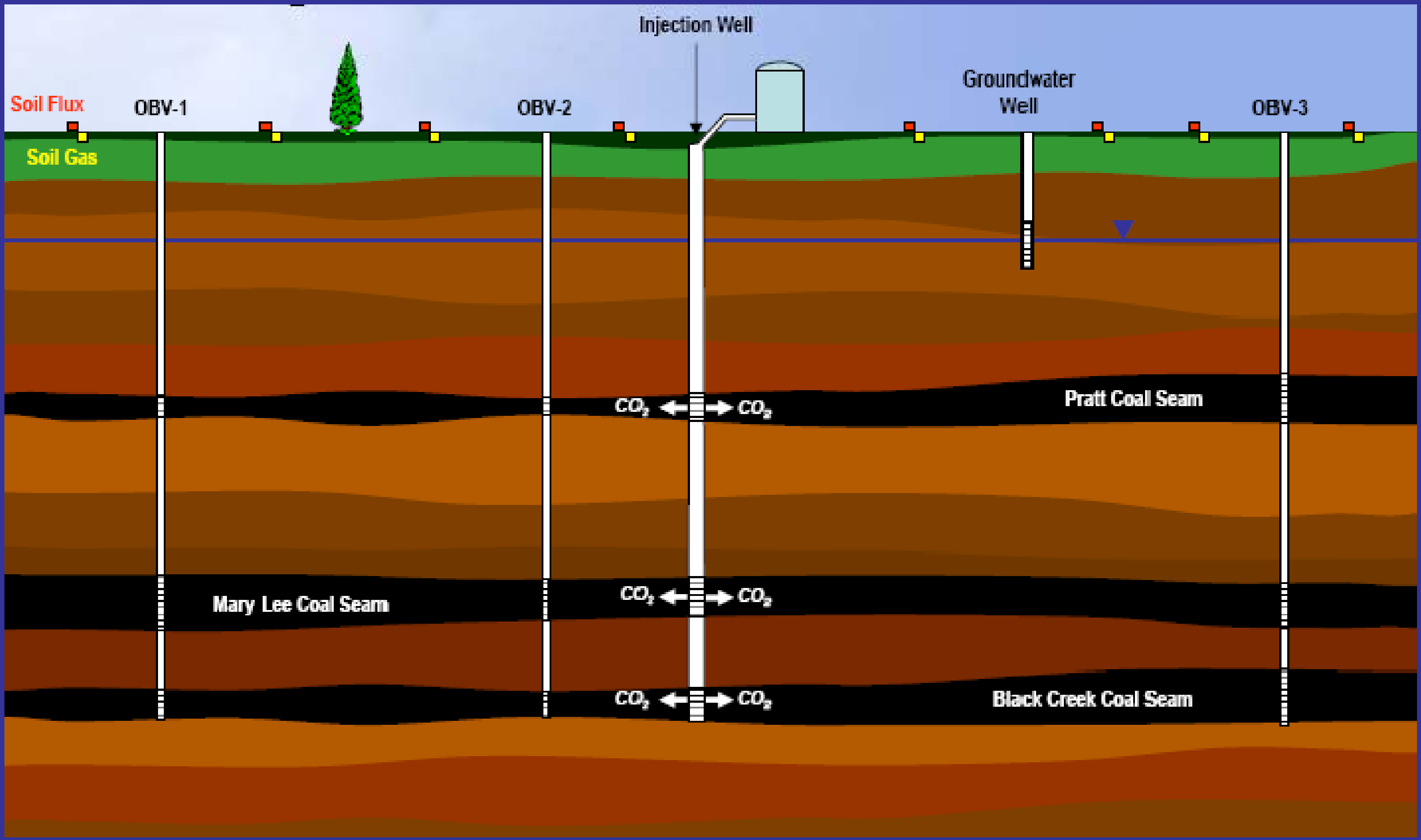
2006 Mead Soybean 8100/8150 Experiment: 8-chamber mean
Planting
Soil temperature at 5 cm deep
Precipitation (mm d-1)
Between Rows
Within Row
FCO2 (µmol m-2s-1)
0
10
20
30
40
60
80
2
4
6
8
100
120
160
180
200
220
240
260
Day of Year 2006

SECARB Project



Site Monitoring Activity
SECARB

MMV Conceptual



Monitoring Table

Technique	Equipment	Parameters	Application
Reservoir Pressure and Fluid Composition	Pressure dataloggers and sample bombs in both injection and deep monitoring wells	Formation and injection pressure CO_2, TDS, ph	Injectivity and heterogeneity Tracking CO_2 migration and leakage through formations
Surface Vegetation	Visual Monitoring	Vegetation Stress	Surface Seepage
Soil Gas	**LI-8100 Automated Soil CO_2 Flux System (LI-COR Biosciences)**	**Soil CO_2 Flux**	**Surface Seepage**
Carbon Isotopes	Modified LI-8100 sampling with off site analysis or NETL portable Cavity Ring Down Spectrometer (CRDS)	Indentify source of CO_2	Surface Seepage
Groundwater Quality	Well sampling with peristaltic pumps for both purge and sample with off site analysis	Ph, TOC/TIC, soluble metals	Shallow Groundwater
UIC Integrity Testing	Hydrostatic pressure gauge Wire line tool (acoustic log)	Hydrostatic Pressure Test (HPT) Cement Bond Log (CBL)	Internal integrity of well casing External integrity of casing cement and borehole

Conclusions

- Soil CO_2 flux measurements can be an important part of a MMV protocol
- A baseline understanding of the ecosystem CO_2 flux is essential for any type of leak detection
- A combination of diurnal and spatial measurements can answer the background questions fast and effectively
- Public perception is key

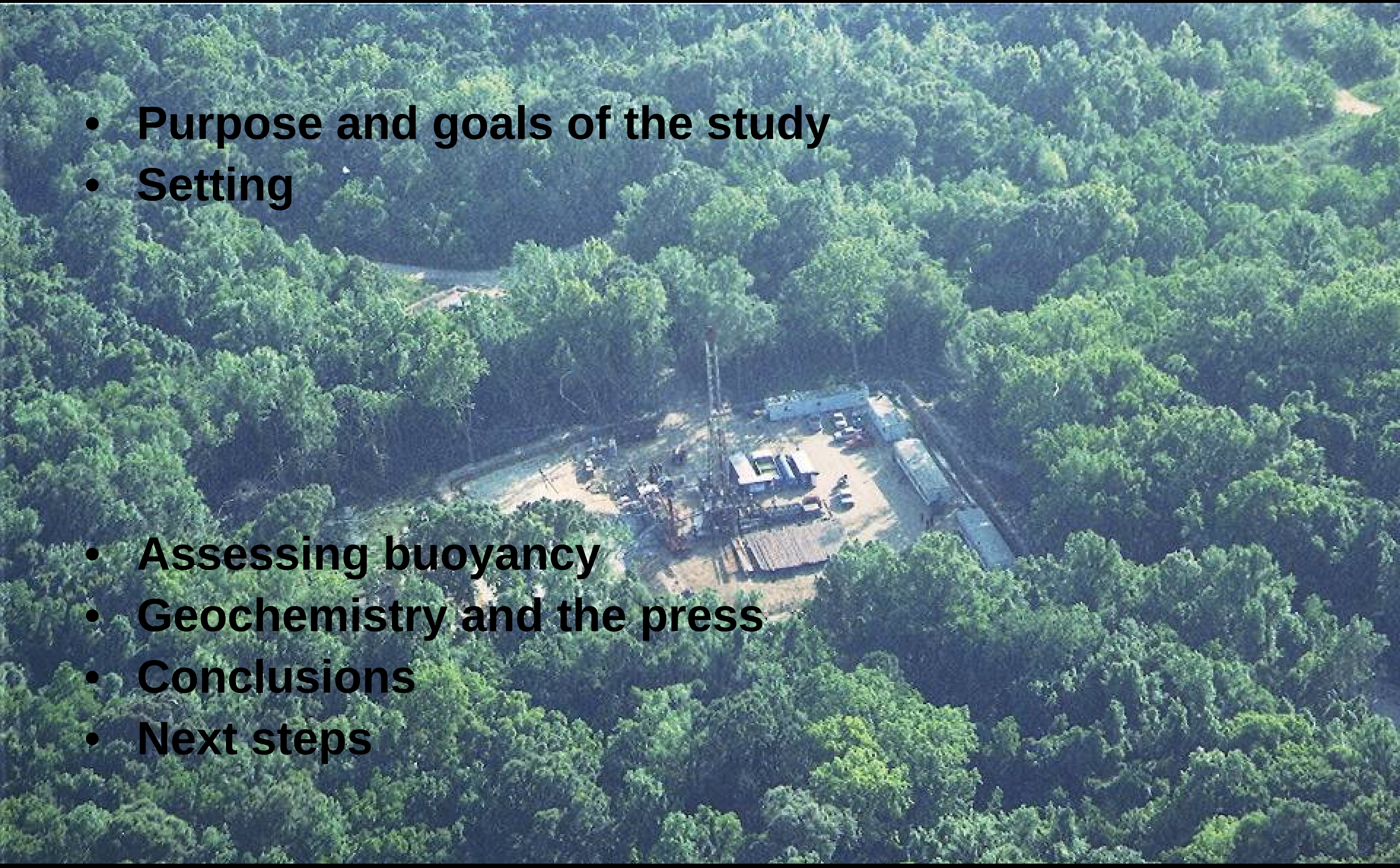
Monitoring at Frio project

Susan Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School Of Geosciences
The University of Texas at Austin

Funded by
US Department of Energy
National Energy Technology Lab

IEA GHG R&D Programme
Monitoring Network, Edmonton, AB
November 9, 2007

Talk Overview



- Purpose and goals of the study
- Setting
- Assessing buoyancy
- Geochemistry and the press
- Conclusions
- Next steps

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 – June 2007

- 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

Frio Brine Pilot Research Team

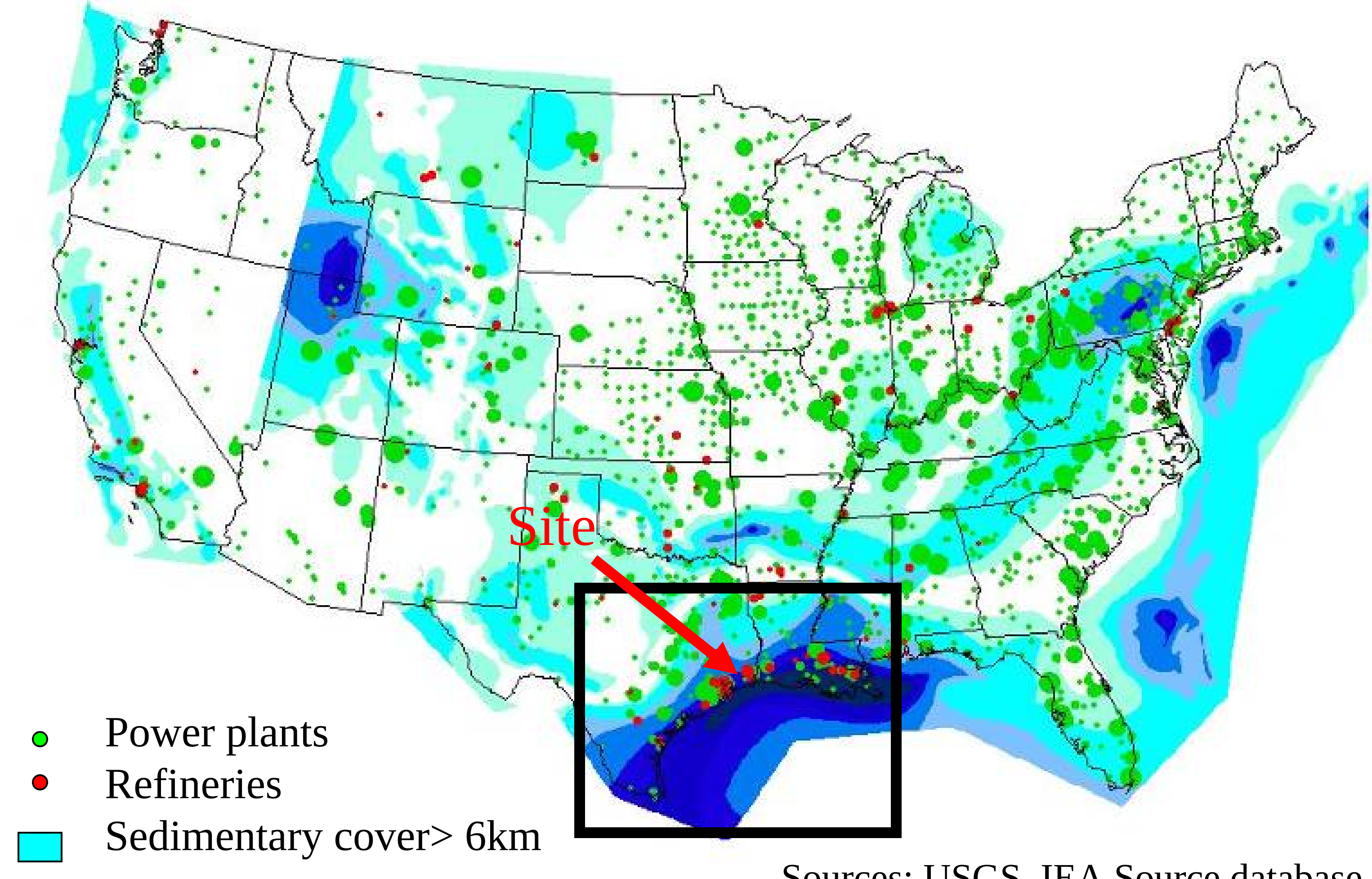
- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, Jeff Kane, Andrew Tachovsky, Abhijit Mukarjee, Tip Meckel; Mark Holtz, Shinichi Sakurai, Seay Nance, Joseph Yeh, Paul Knox, Khaled Faoud, Jeff Paine
- Lawrence Berkeley National Lab, (Geo-Seq): Larry Myer, Tom Daley, 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
- MIT/ NBNL Jonathan Ajo-Franklin

Gulf Coast Carbon Center

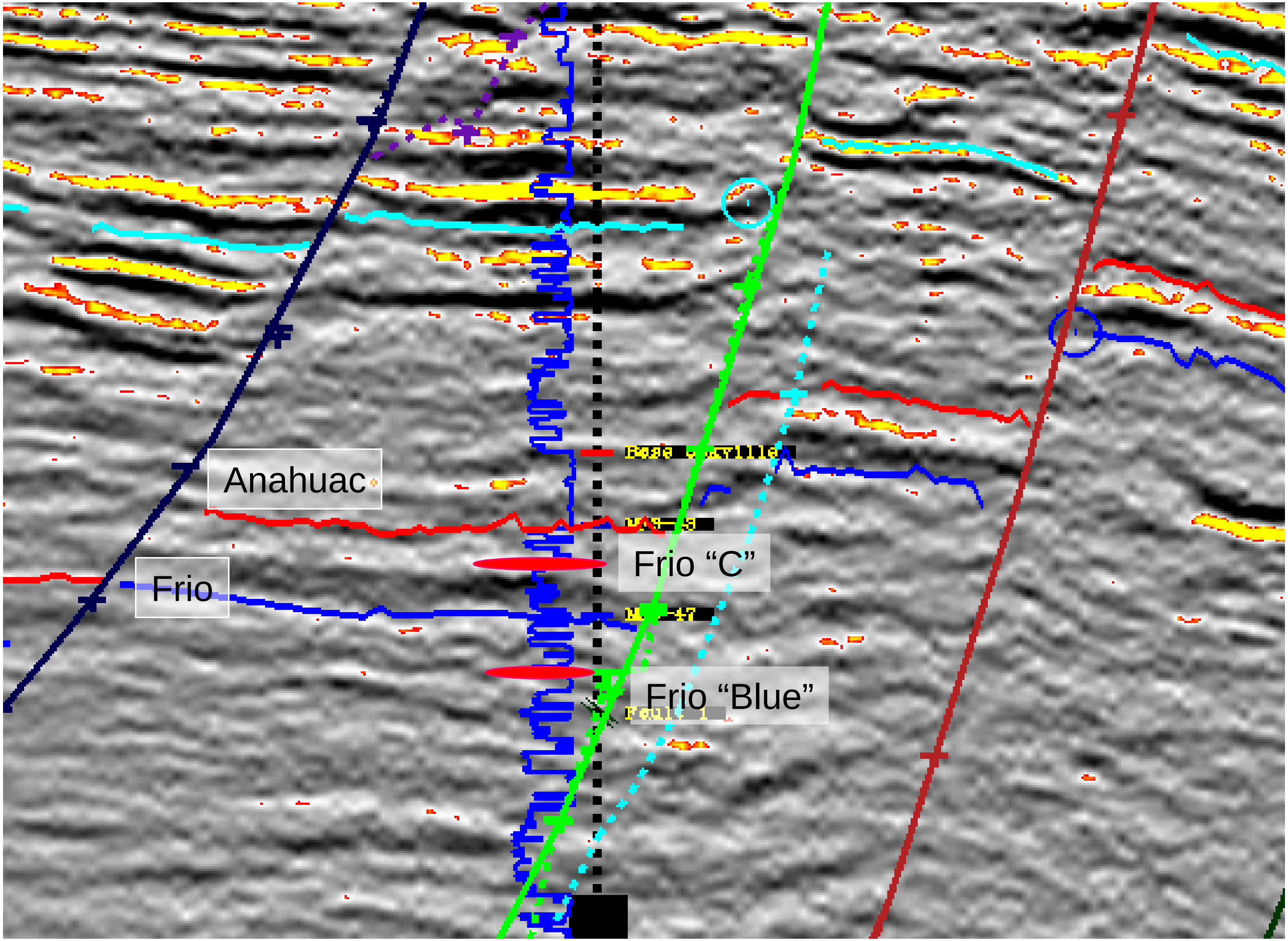
NETL

Geologic Storage "Sequestration" of CO_2

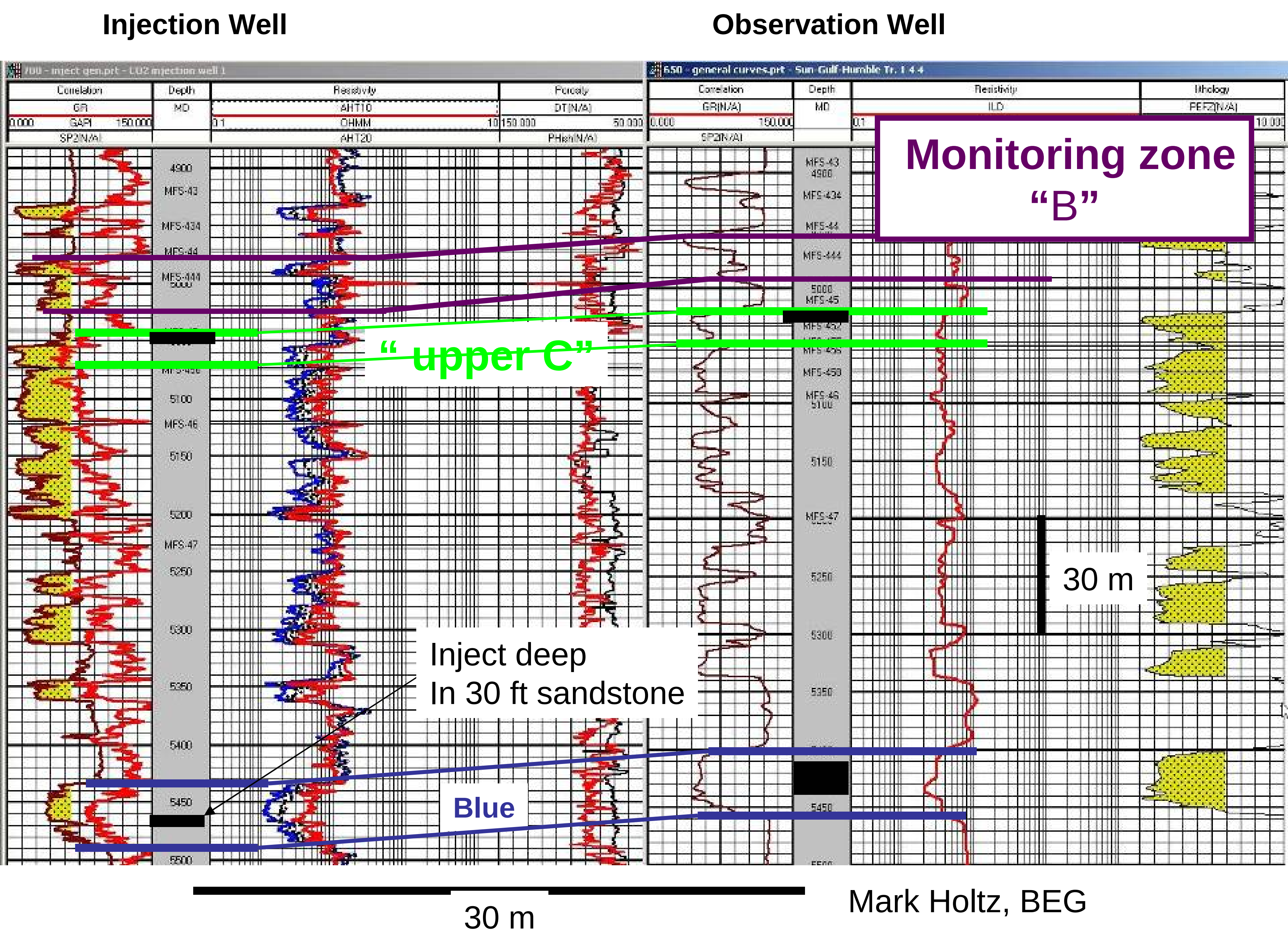
Testing the feasibility of establishing a "closed loop" to limit atmospheric emissions of carbon from fossil fuels



Sources: USGS, IEA Source database

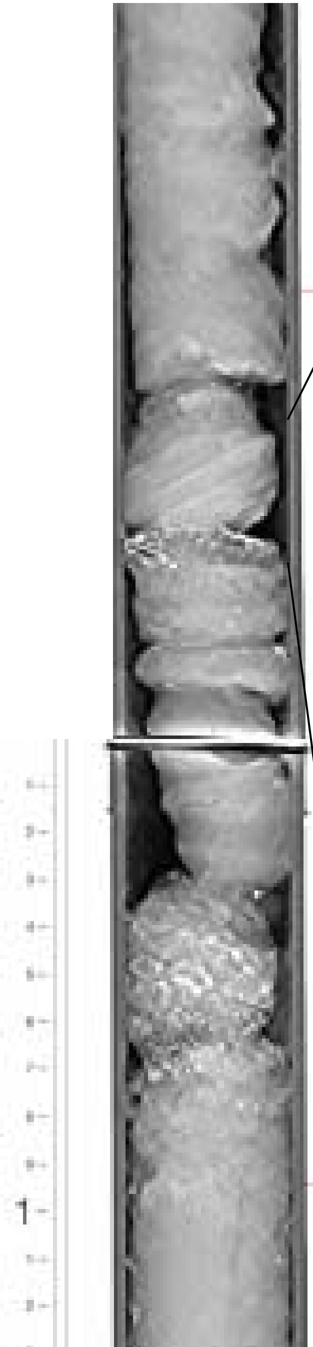


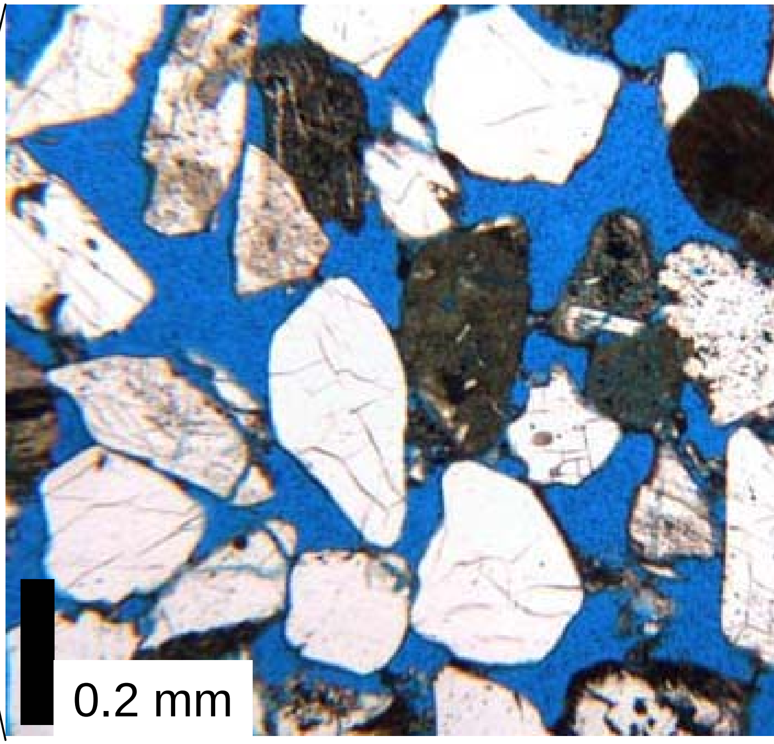
Khaled Faoud, BEG


Injection Well
Observation Well
Monitoring zone "B"
" upper C"
Inject deep
In 30 ft sandstone
Blue
30 m
30 m
Mark Holtz, BEG

Heterogeneous Frio "Blue" Sandstone

CT Scan





Uncertainty in predicting interwell permeability

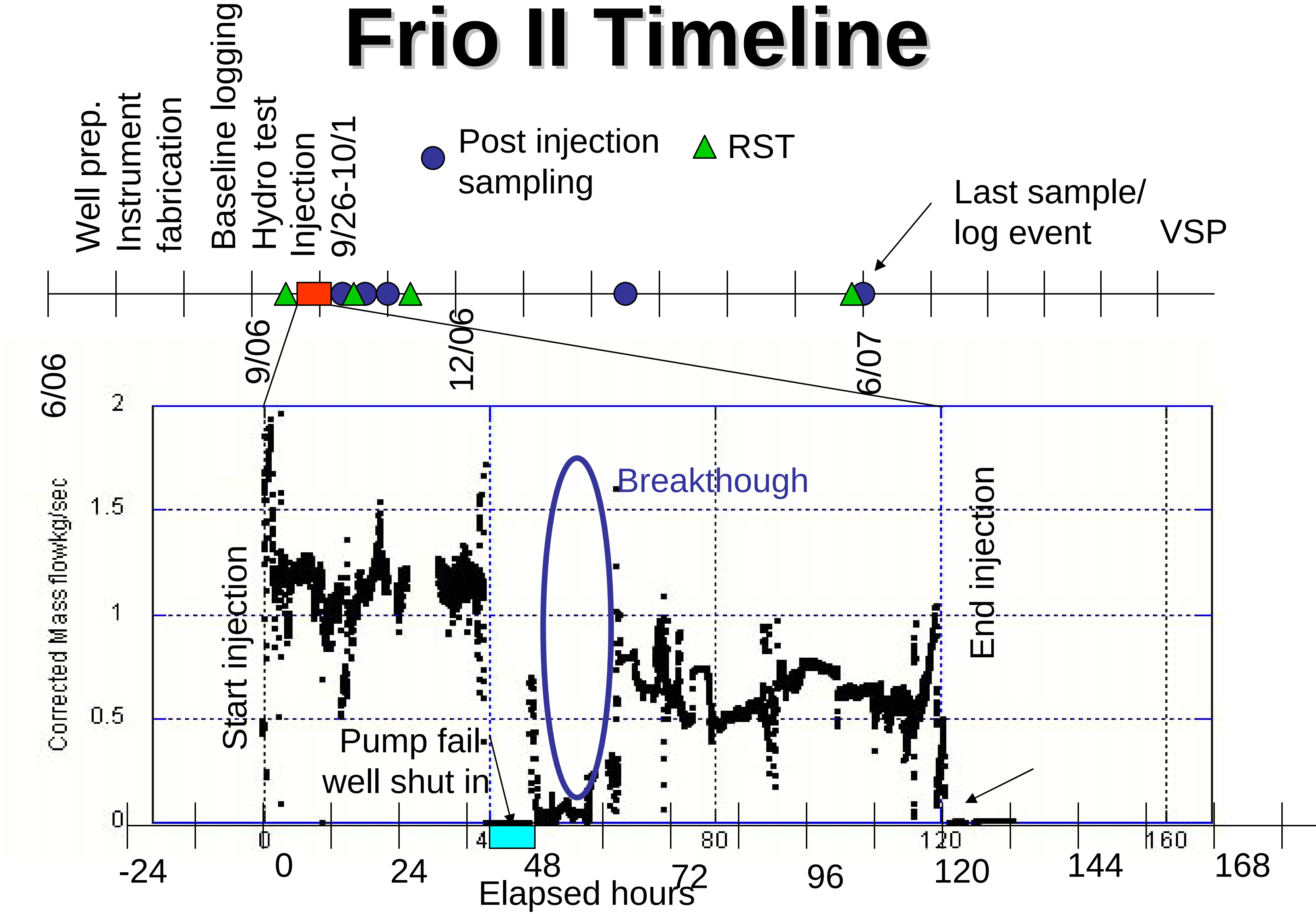

Injection well
Observation well

Frio 2 Monitoring Techniques Selected

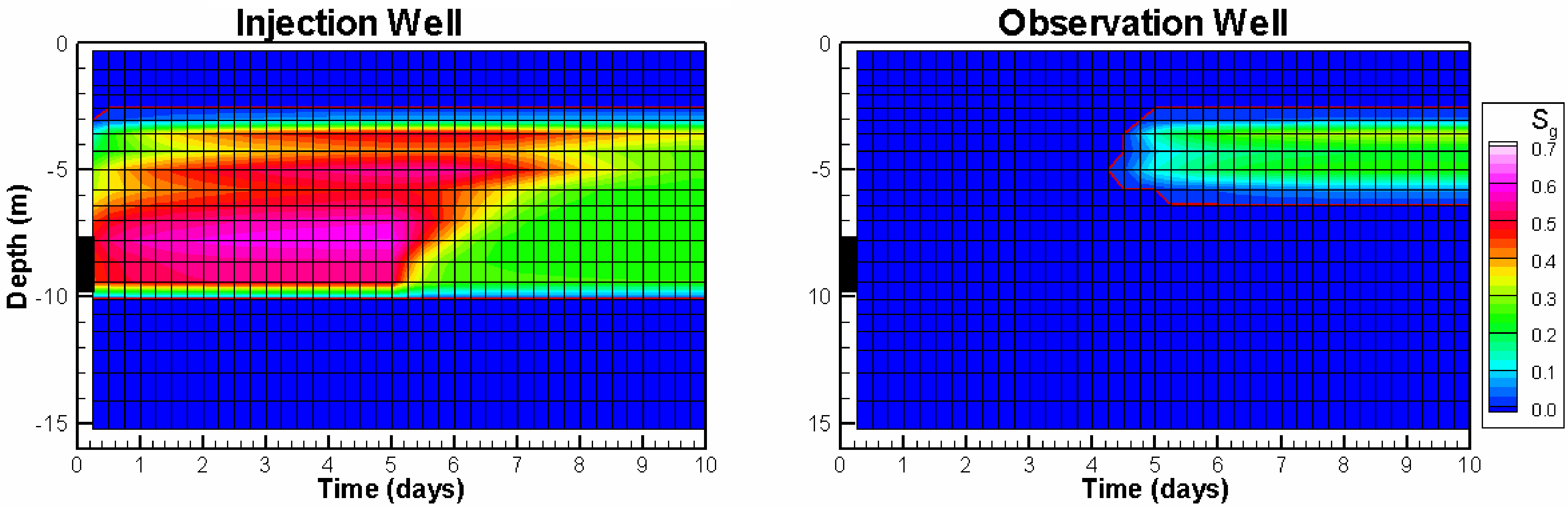
- Injection zone characterization – core analysis, open and cased hole logs, single phase hydrologic testing
- Downhole Panex gages: pressure and temperature
- RST logs: CO_2 saturation change with time – pressure and temperature change with depth
- U-tubes – gas soluble tracers and aqueous transport and gas and aqueous chemistry
- Continuous Active Source Seismic Monitoring (CASSM) cross-well array
- PFT tracers to show engineering adequacy

Gulf Coast Carbon Center

Frio II Timeline



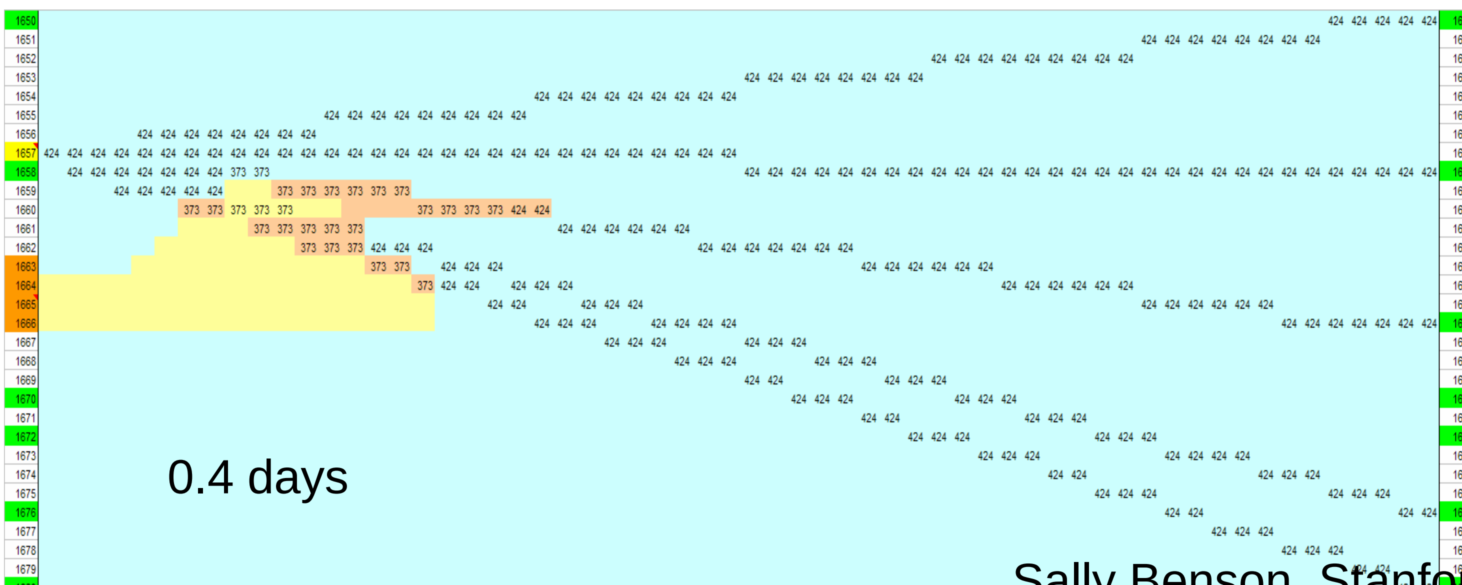
Pre-Injection Modeled Saturation in Both Wells



Slow injection 100 T/day planned,
Injection low in thick high permeability sand
= Slow break though, good resolution on tracers and chemistry

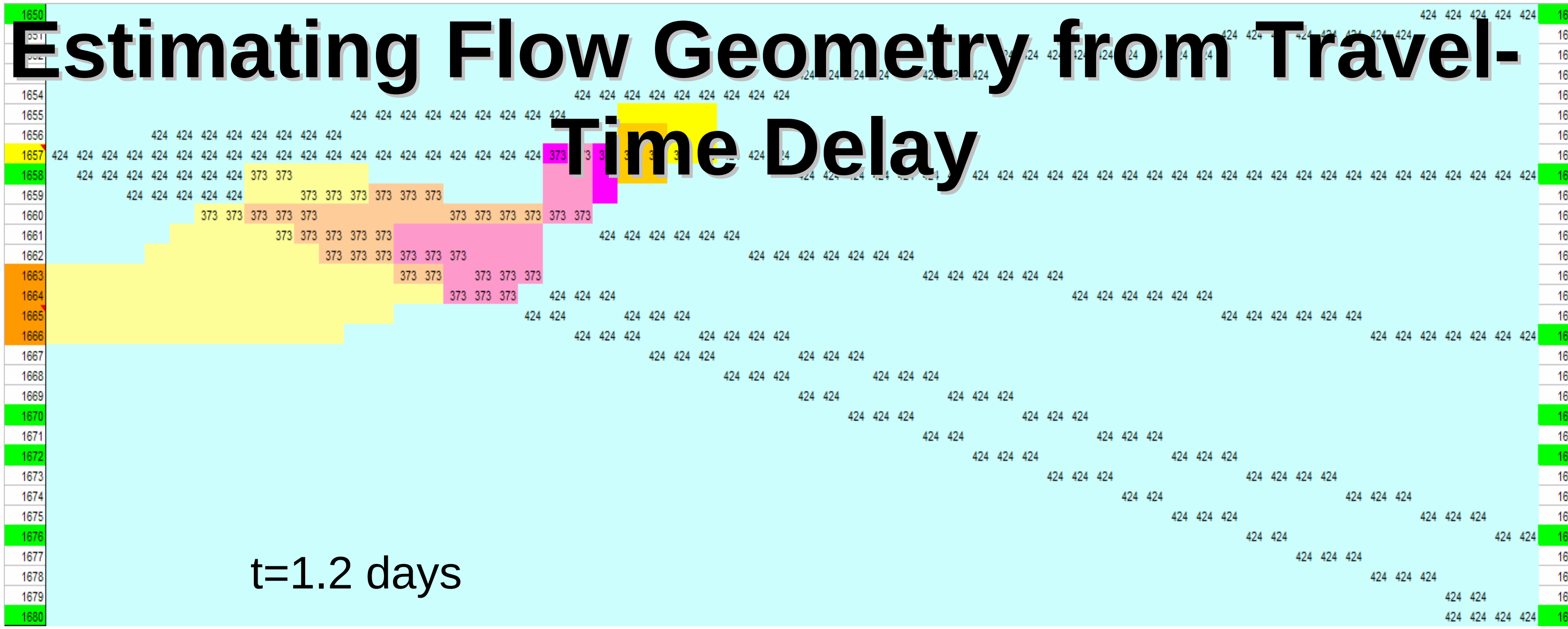
Christine Doughty LBNL

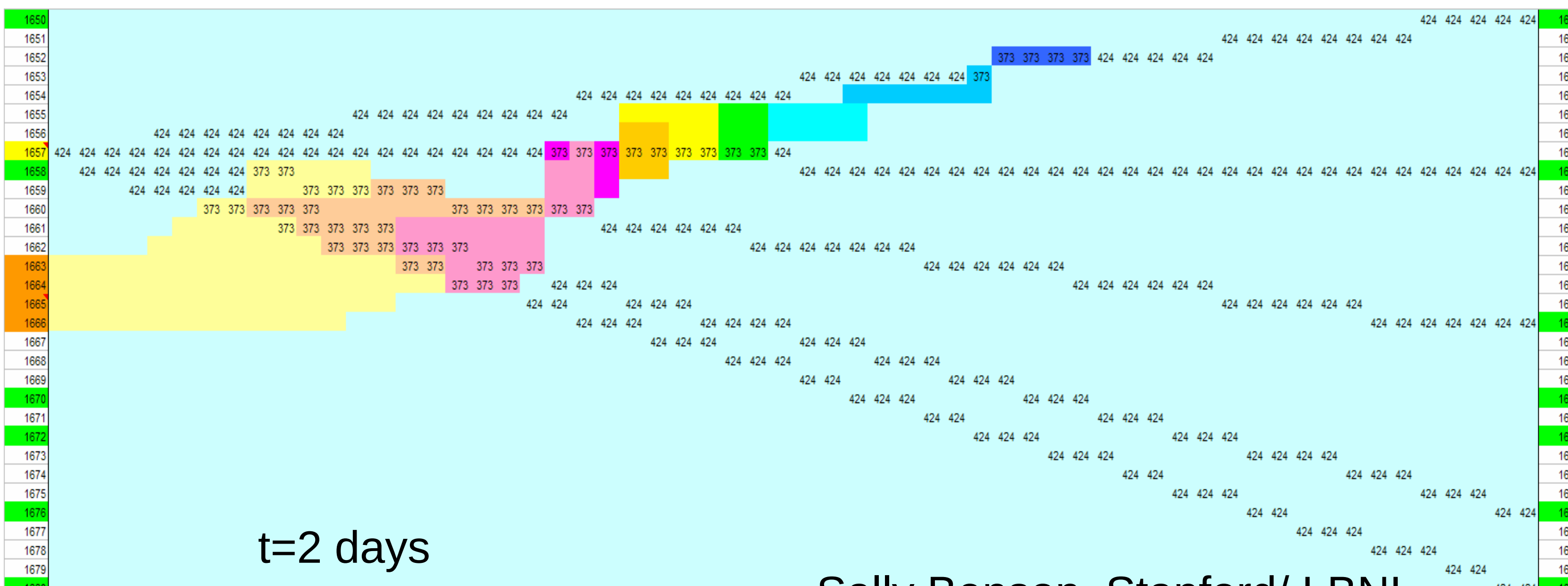
Estimating Flow Geometry from Travel-Time Delay



Sally Benson, Stanford/ LBNL

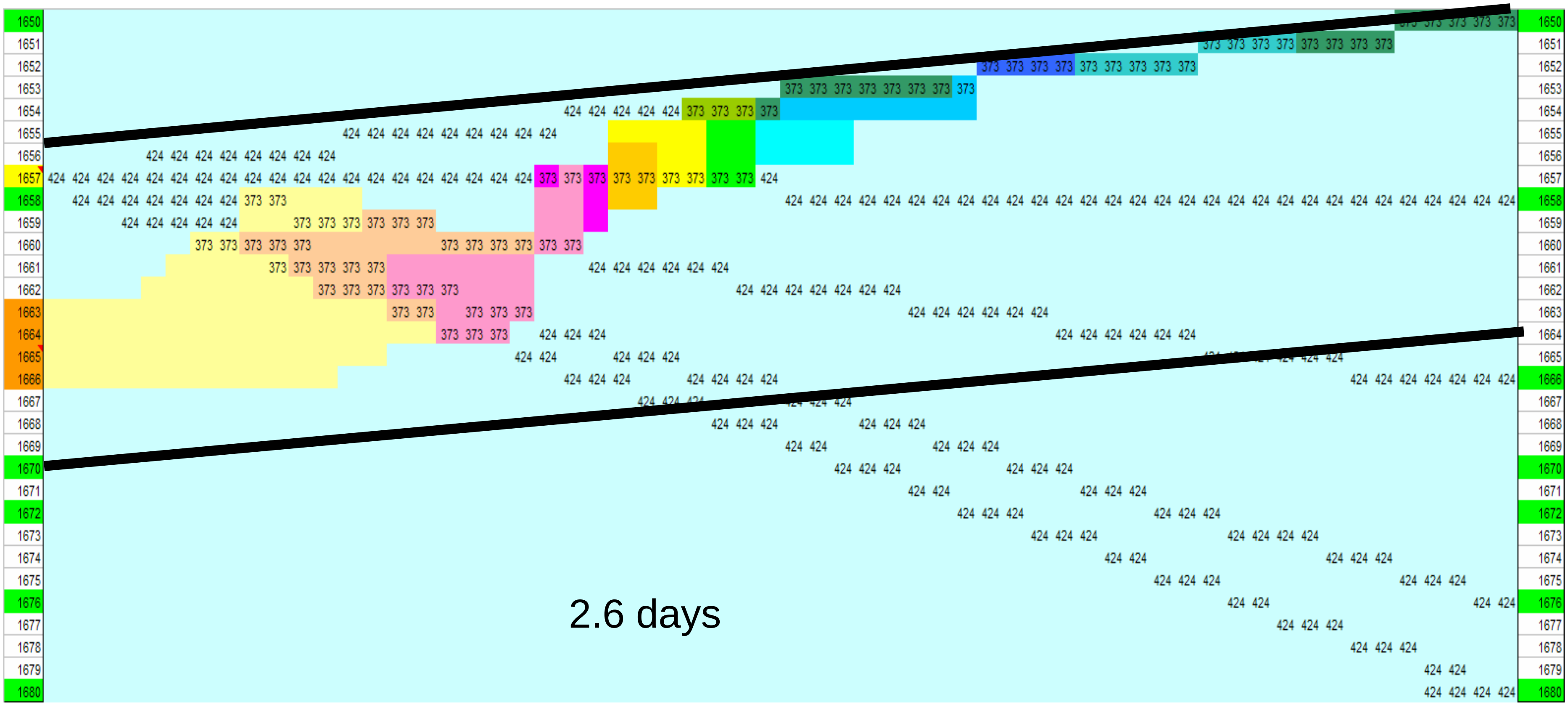
Estimating Flow Geometry from Travel-Time Delay





Sally Benson, Stanford/ LBNL

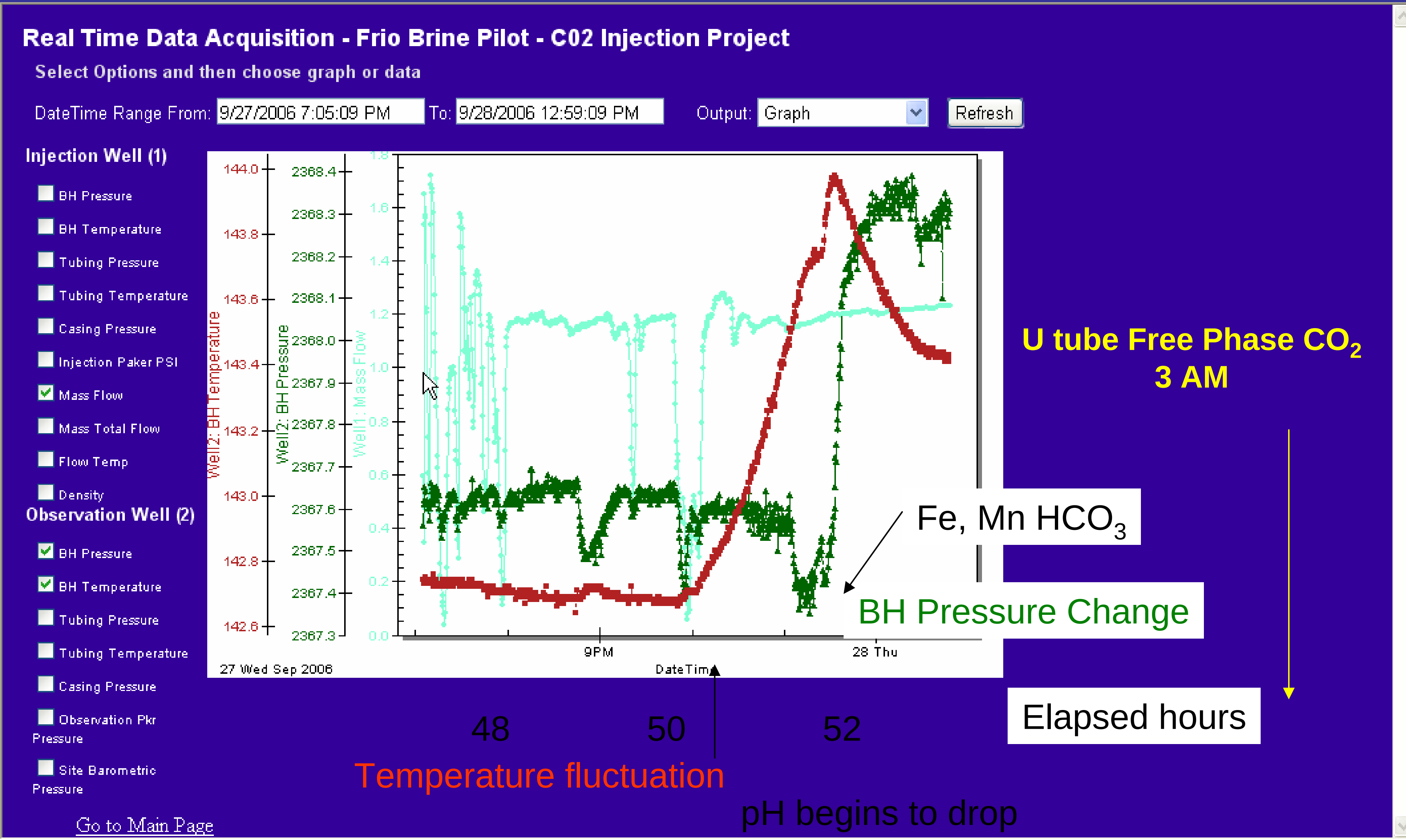
Estimating Flow Geometry from Travel-Time Delay



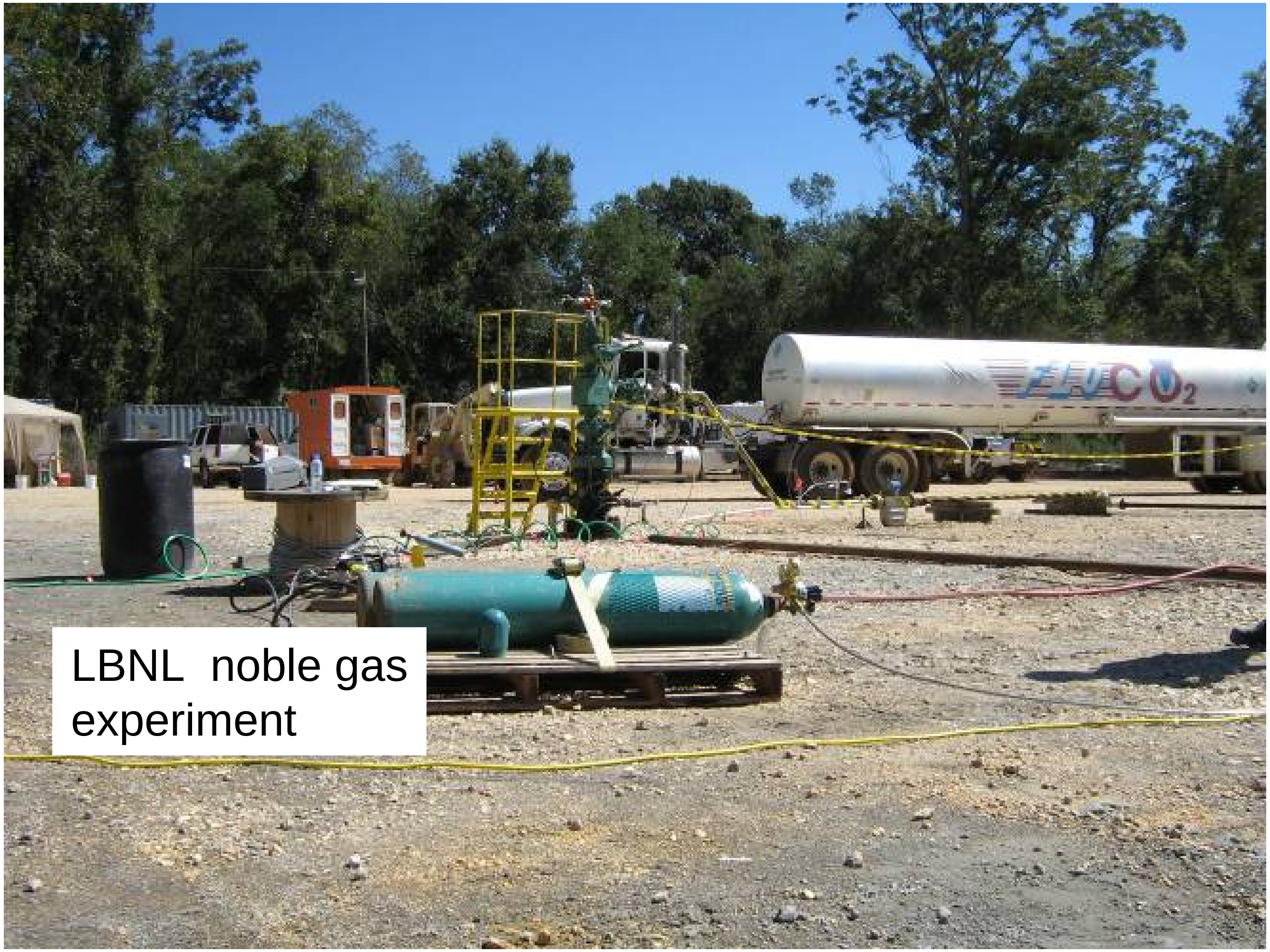
Sally Benson, Stanford/ LBNL

30 m

Rapid Breakthrough



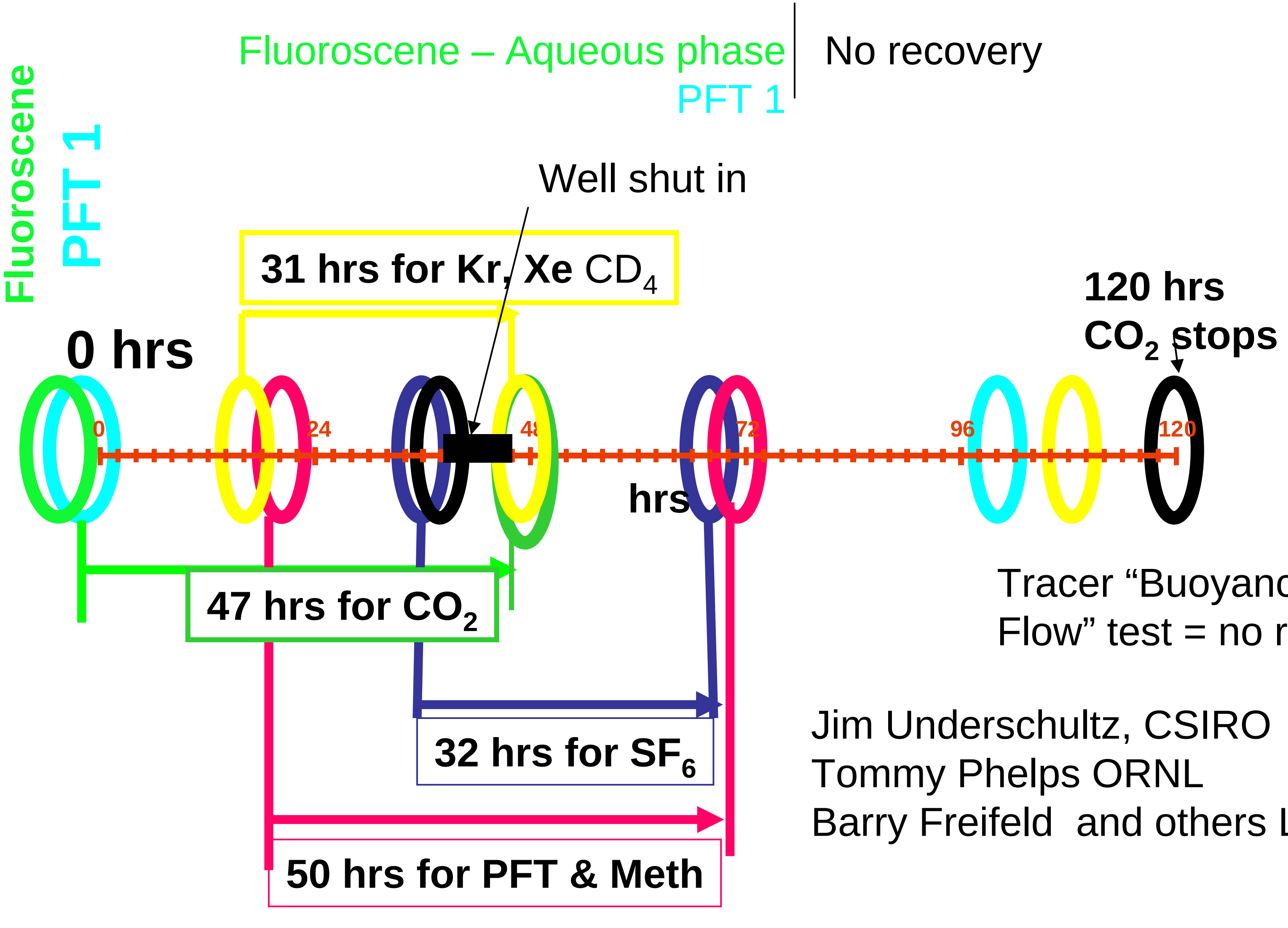
FRIO II CD_4 Tracer Injection Experiment



J. Underschultz[1], Linda Stalker, C. Boreham[2], and Ernie Perkins[3]

[1]CSIRO Petroleum, [2]Geoscience Australia, [3]Alberta Research Council.

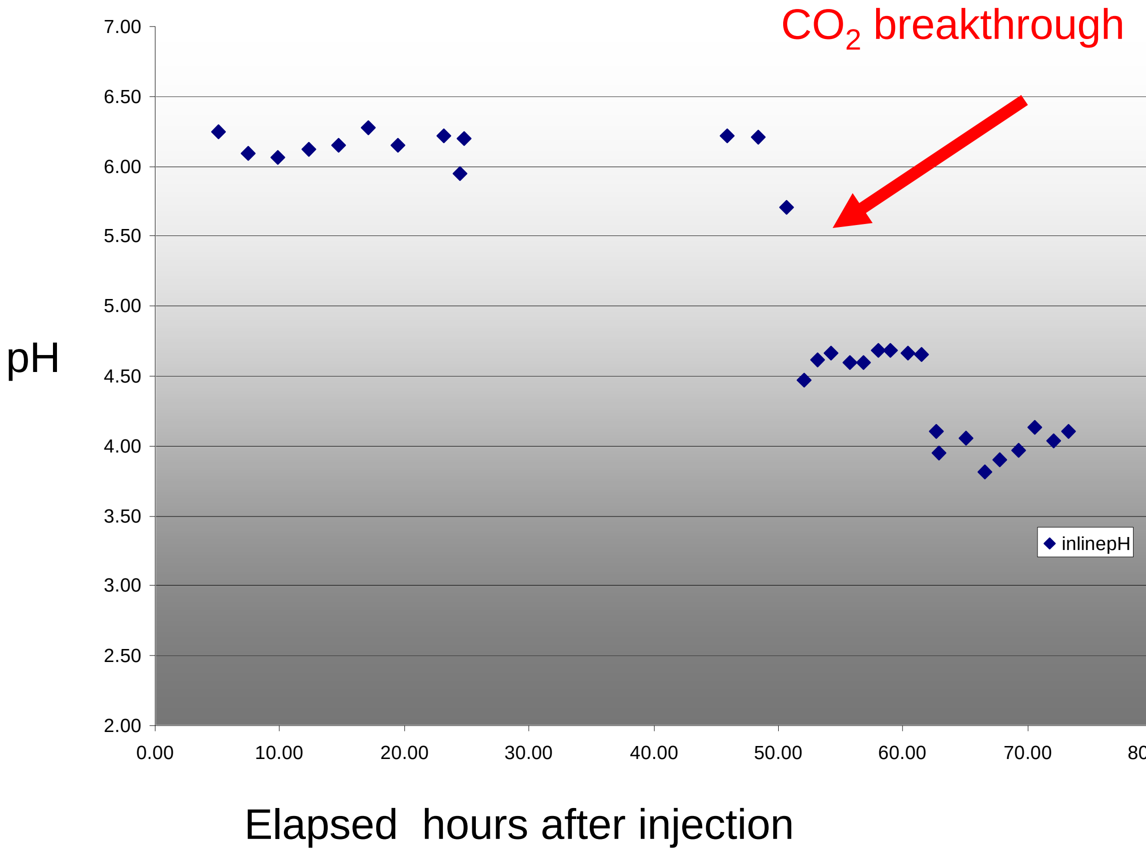
Frio II Tracer Timeline - Evidence of Complex Flow Processes



Tracer “Buoyancy Flow” test = no result

Jim Underschultz, CSIRO
Tommy Phelps ORNL
Barry Freifeld and others LBNL

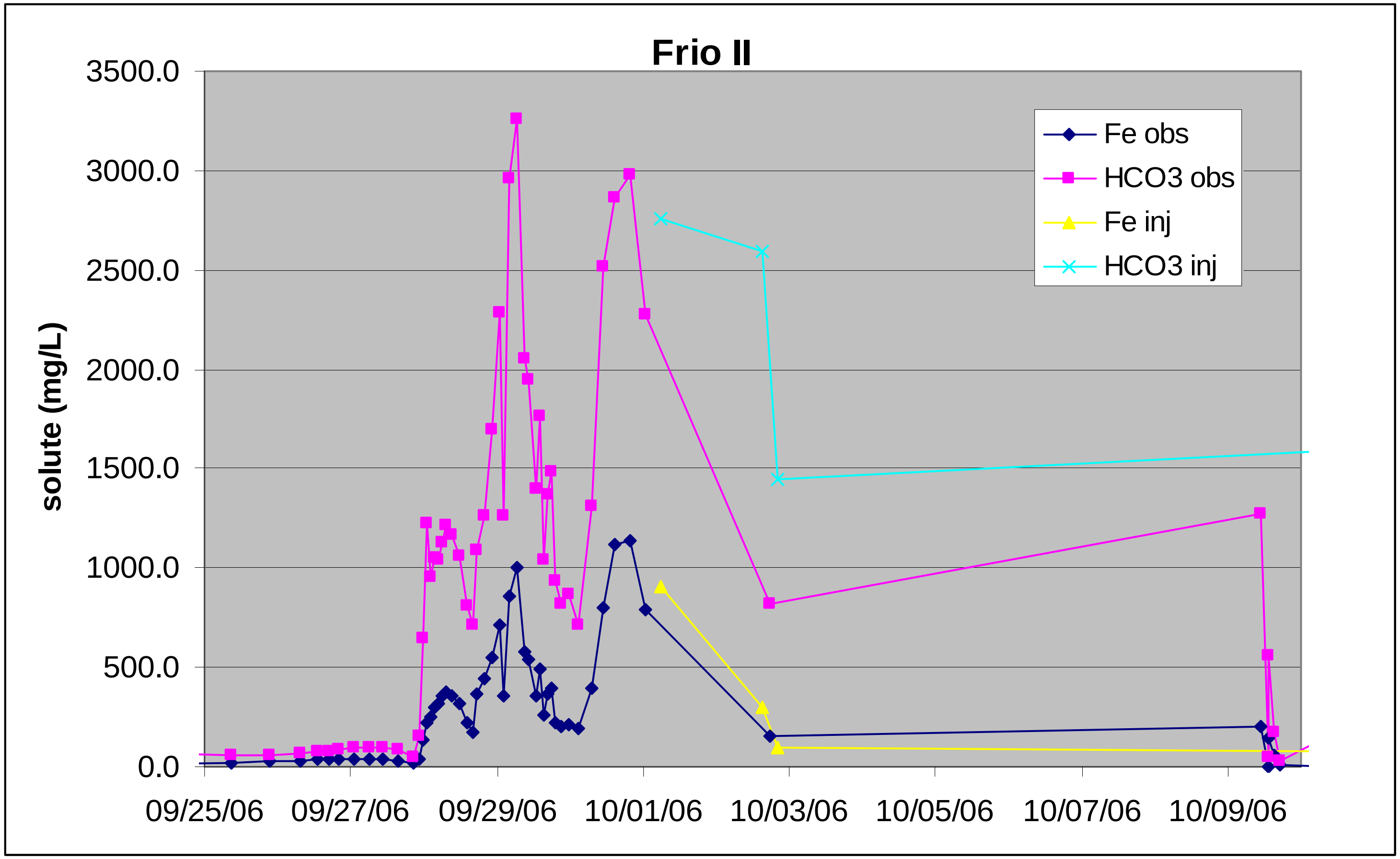
Geochemistry and the Press Fluid Evolution During Injection-Dissolution of CO_2 and Rock-Water interaction



Analysis underway by USGS
Alkalinity, metals, DOC, DIC, VOC

U-tube and onsite labs for brine and gas analysis with QMS and GC

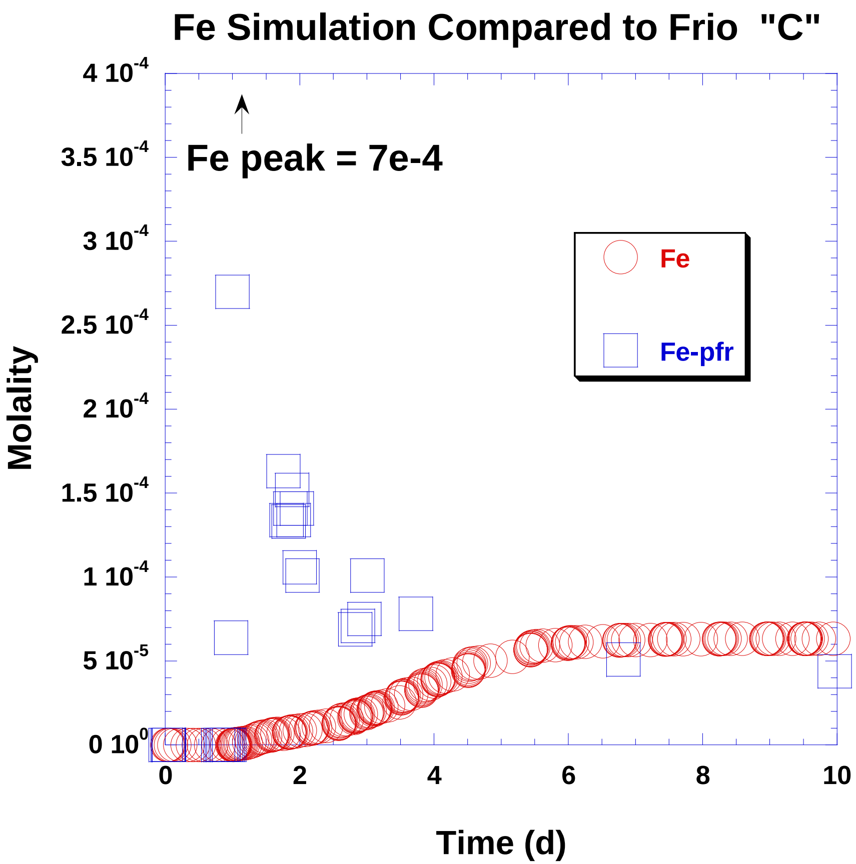
Geochemical Evidence of CO_2-Rock Interaction

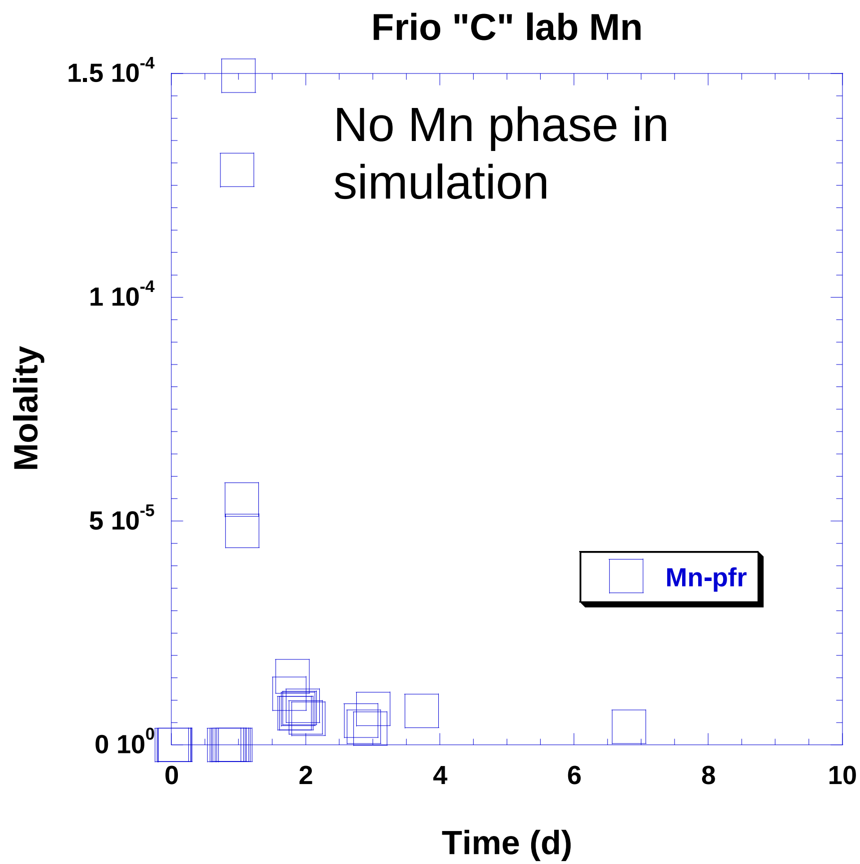


Yousif Kharaka, USGS

High iron – Fe &Mg

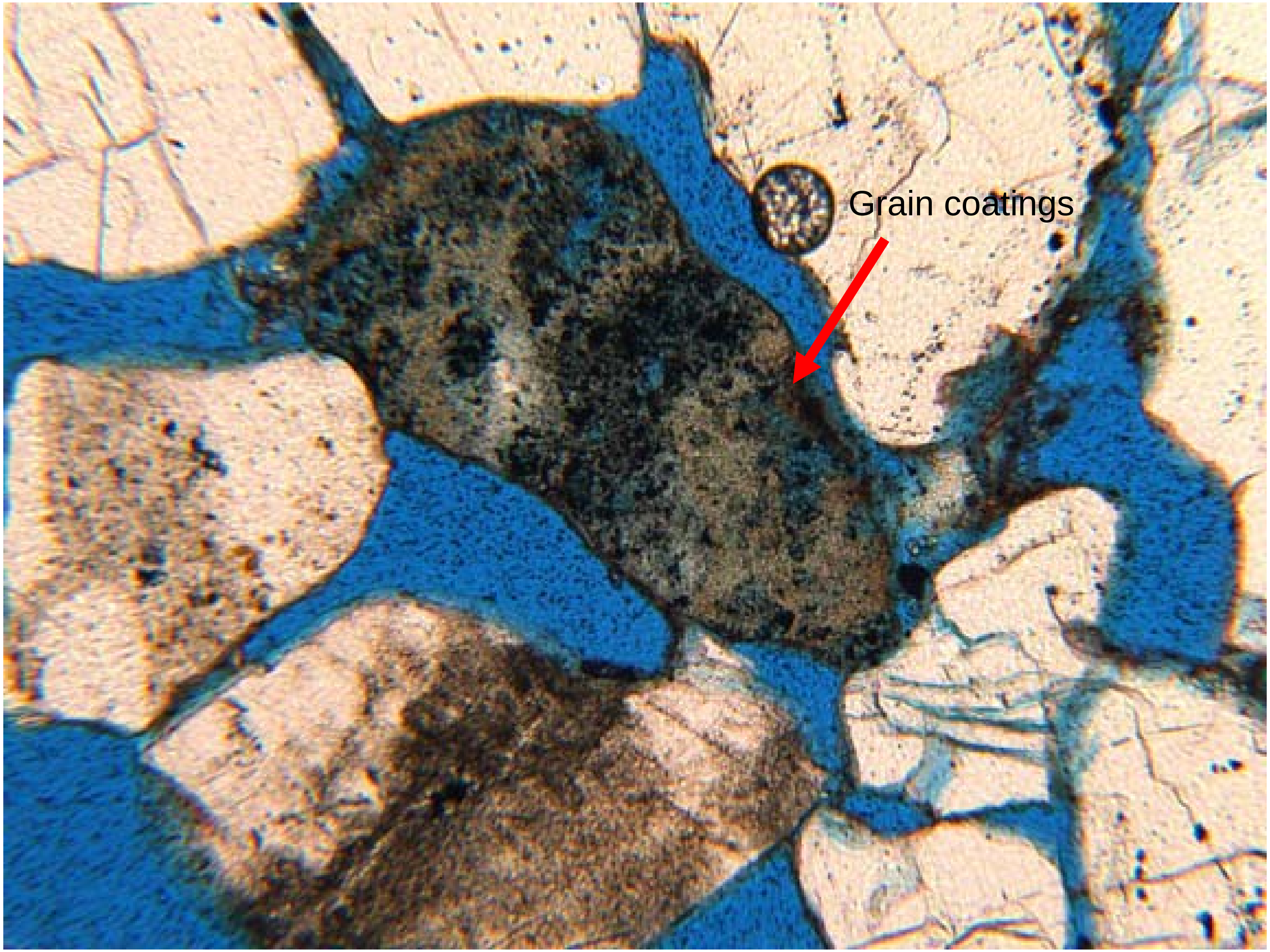
Geochemical Simulation vs. Lab data





Kevin Knauss, LLNL

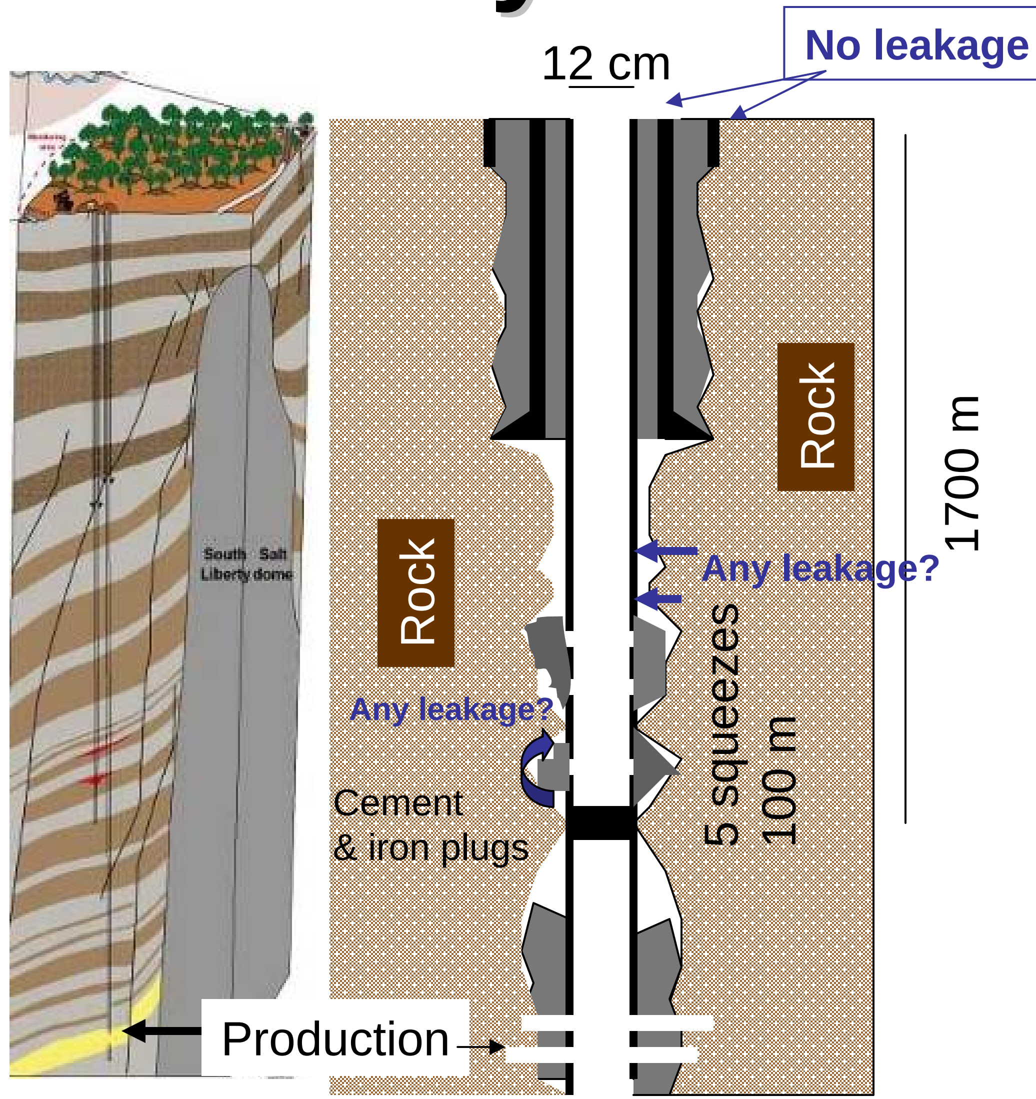
Grain coatings – early actors in geochemistry



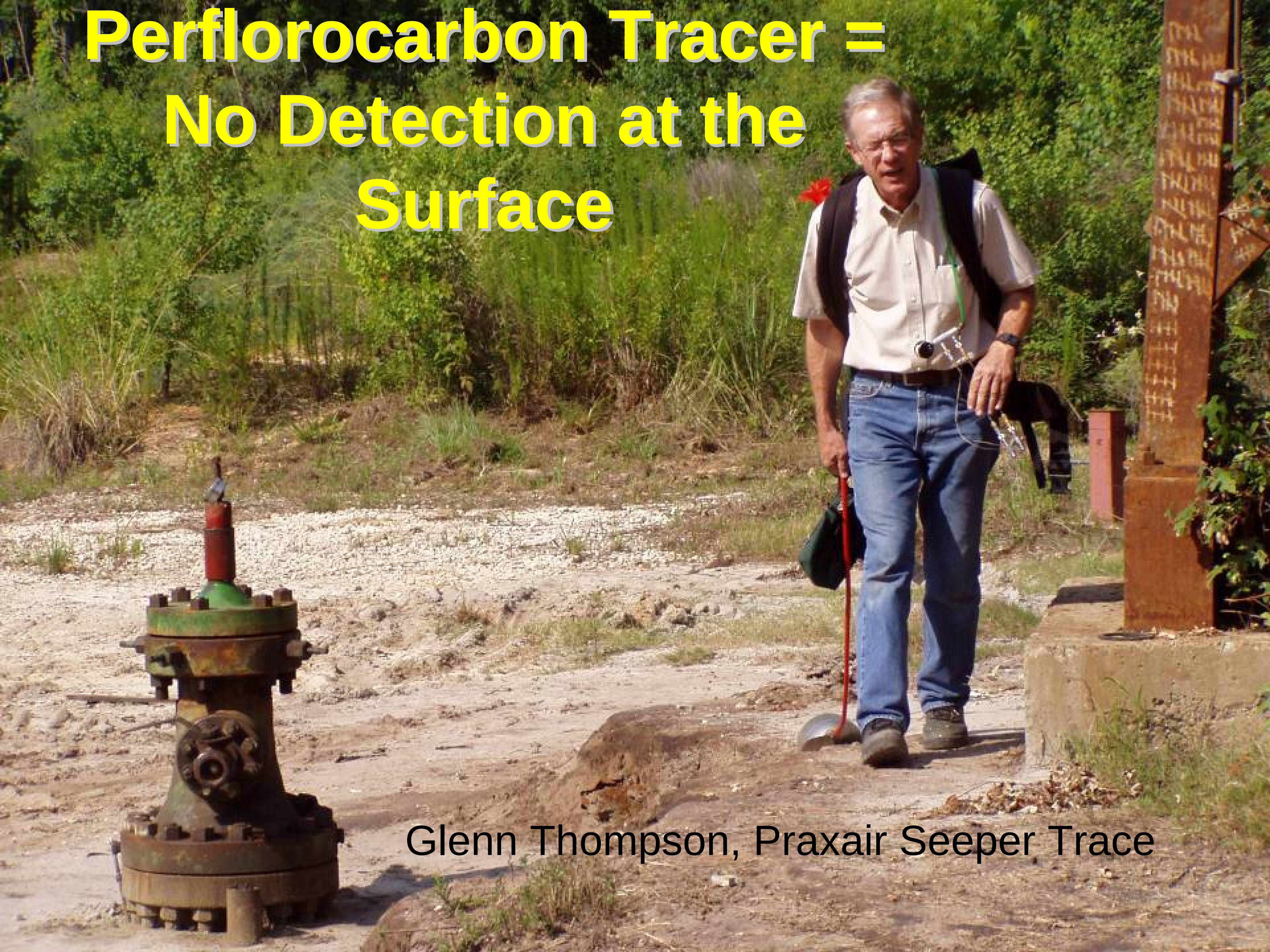
5mm

Testing wells – likely flaws

1952 oil production well was retrofit as an observation well



Well construction


Perflorocarbon Tracer =
No Detection at the
Surface
Glenn Thompson, Praxair Seeper Trace

Seeper Trace equipment

Conclusions

- Interaction of buoyancy and reservoir heterogeneity lead to complex CO_2 plume development
- High surface area important in early rock-water interactions – mineral trapping
- Geochemical evidence – no well leakage
- Experiments moving to next larger scale

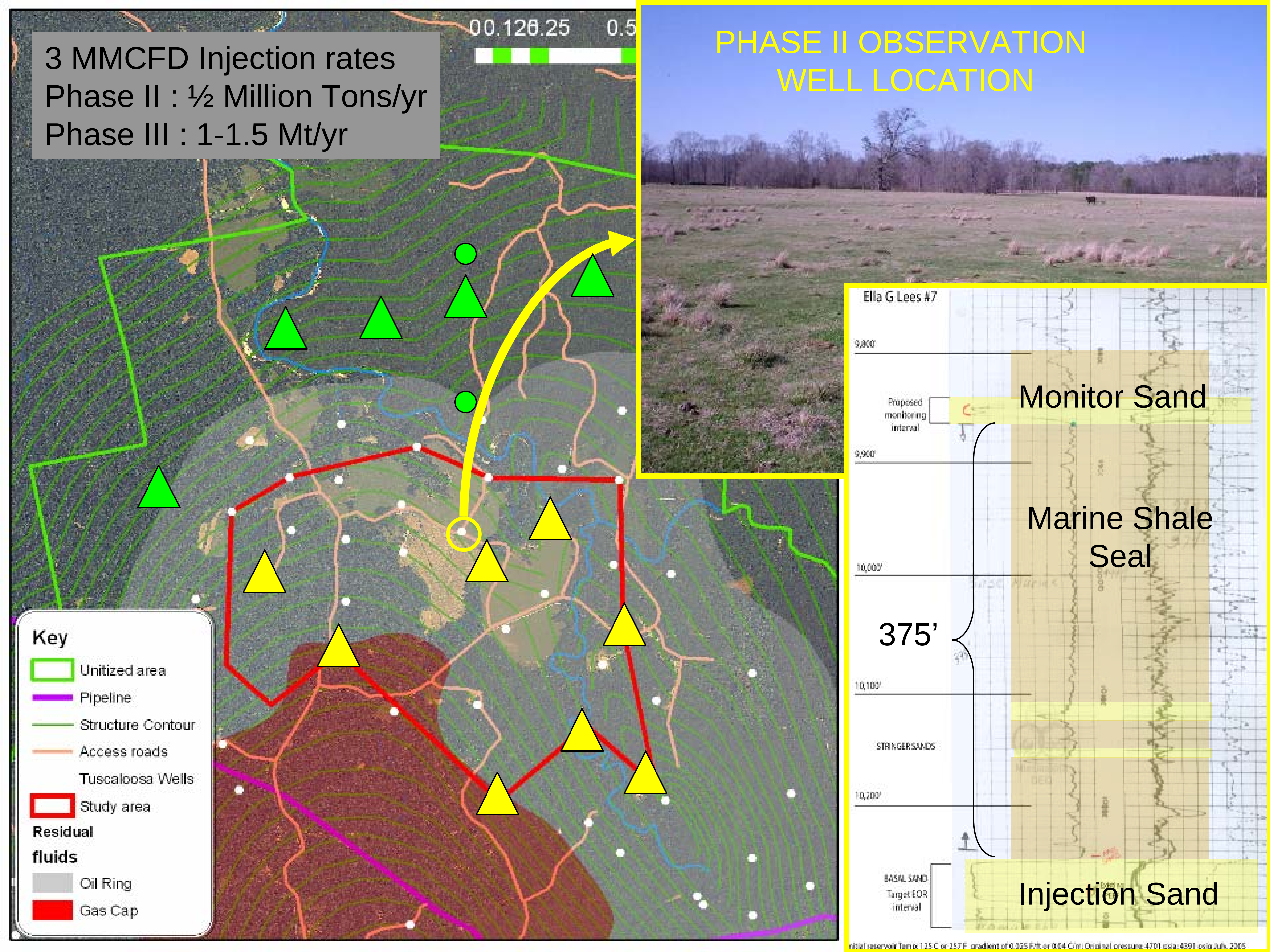
Next test: Stacked storage

US DOE Phase III – Cranfield Mississippi (Denbury Resources)

(1) Sweep efficiency – how effectively are pore volumes contacted by CO_2?
- Important in recovery efficiency in EOR
- For storage – what is capacity of subsurface? Prediction of plume size

(2) Injection volume is sum of fluid displacement, dilatancy, dissolution, and rock+fluid compression
- Tilt to start to understand magnitude of dilatancy
- Bottom hole pressure mapping to estimate fluid displacement

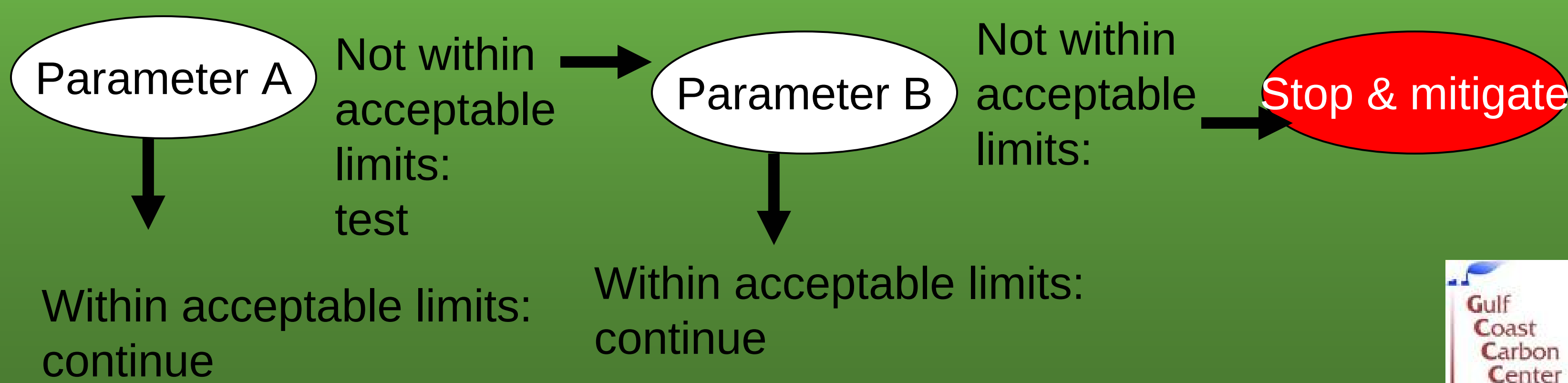
(3) Effectiveness of Mississippi well completions regulations in retaining CO_2 in GHG context
- Above zone monitoring



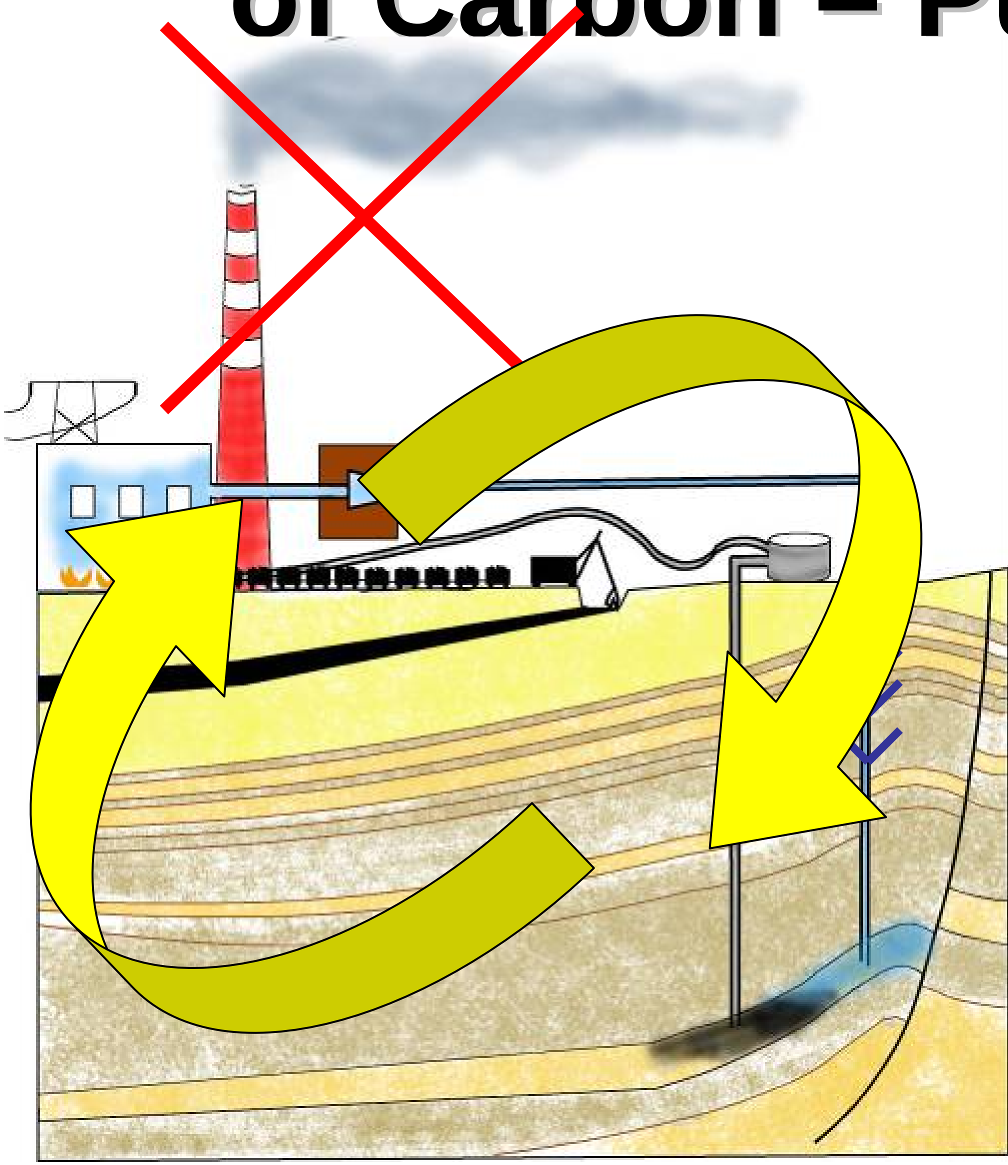
3 MMCFD Injection rates
Phase II : ½ Million Tons/yr
Phase III : 1-1.5 Mt/yr
0 0.125 0.25 0.5
Key
Unitized area
Pipeline
Structure Contour
Access roads
Tuscaloosa Wells
Study area
Residual fluids
Oil Ring
Gas Cap
PHASE II OBSERVATION
WELL LOCATION
Ella G Lees #7
9,800'
Proposed monitoring interval
9,900'
10,000'
10,100'
STRINGER SANDS
10,200'
BASAL SAND
Target EOR interval
Monitor Sand
Marine Shale Seal
375'
Injection Sand

Need for Parsimonious Monitoring Program in a Mature Industry

- **Standardized, dependable, durable instrumentation, reportable measurements**
- **Possibility of above-background detection:**
  - **Need for a follow-up testing program to assure both public acceptance and safe operation**
- **Hierarchical approach:**



Geologic Sequestration of Carbon – Put it back



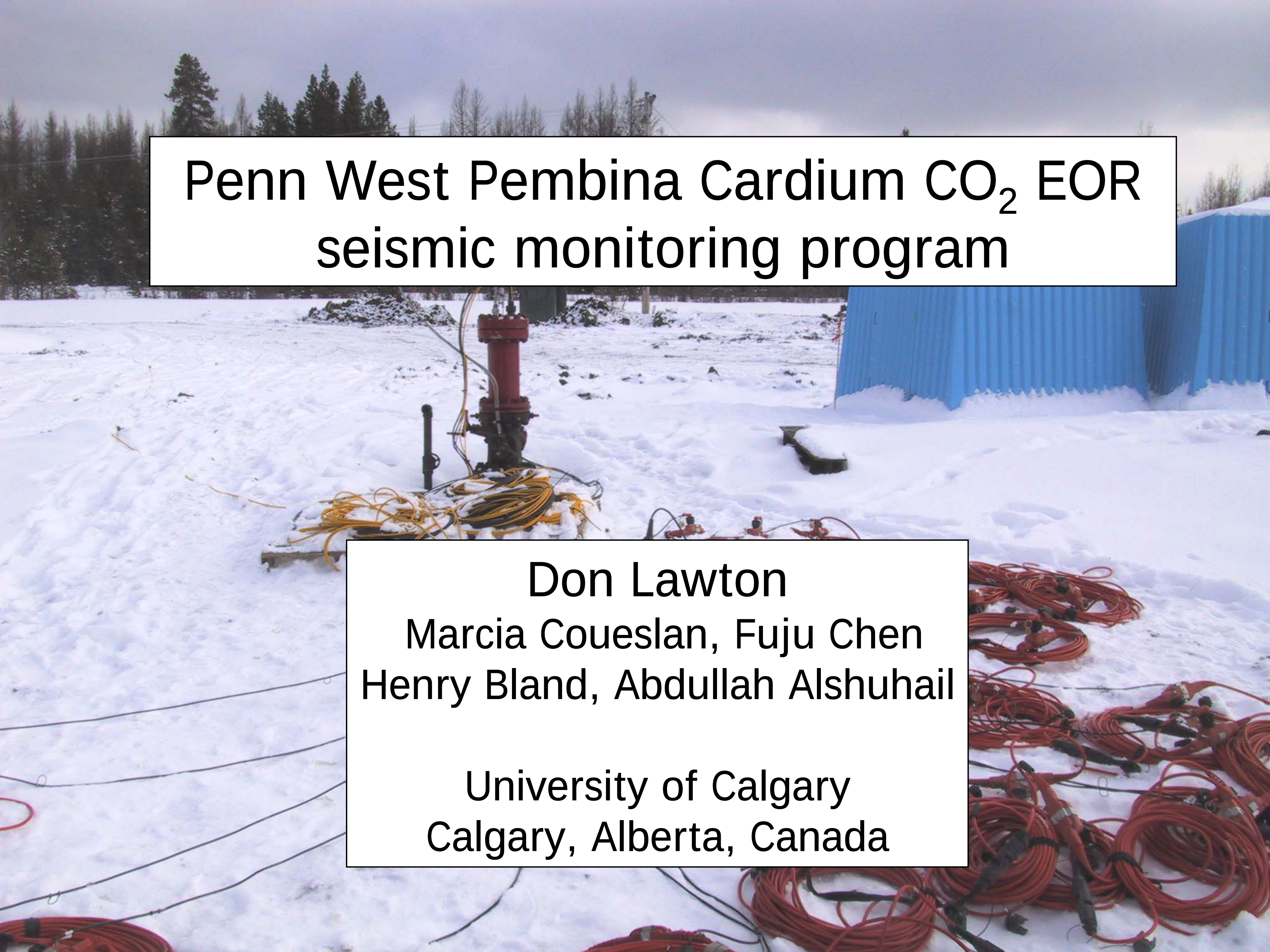
Carbon extracted from coal or other fossil fuel…

Returned into the earth where it came from

www.gulfcoastcarbon.org

susan.hovorka@beg.utexas.edu

Gulf Coast Carbon Center



Penn West Pembina Cardium CO_2 EOR seismic monitoring program

Don Lawton

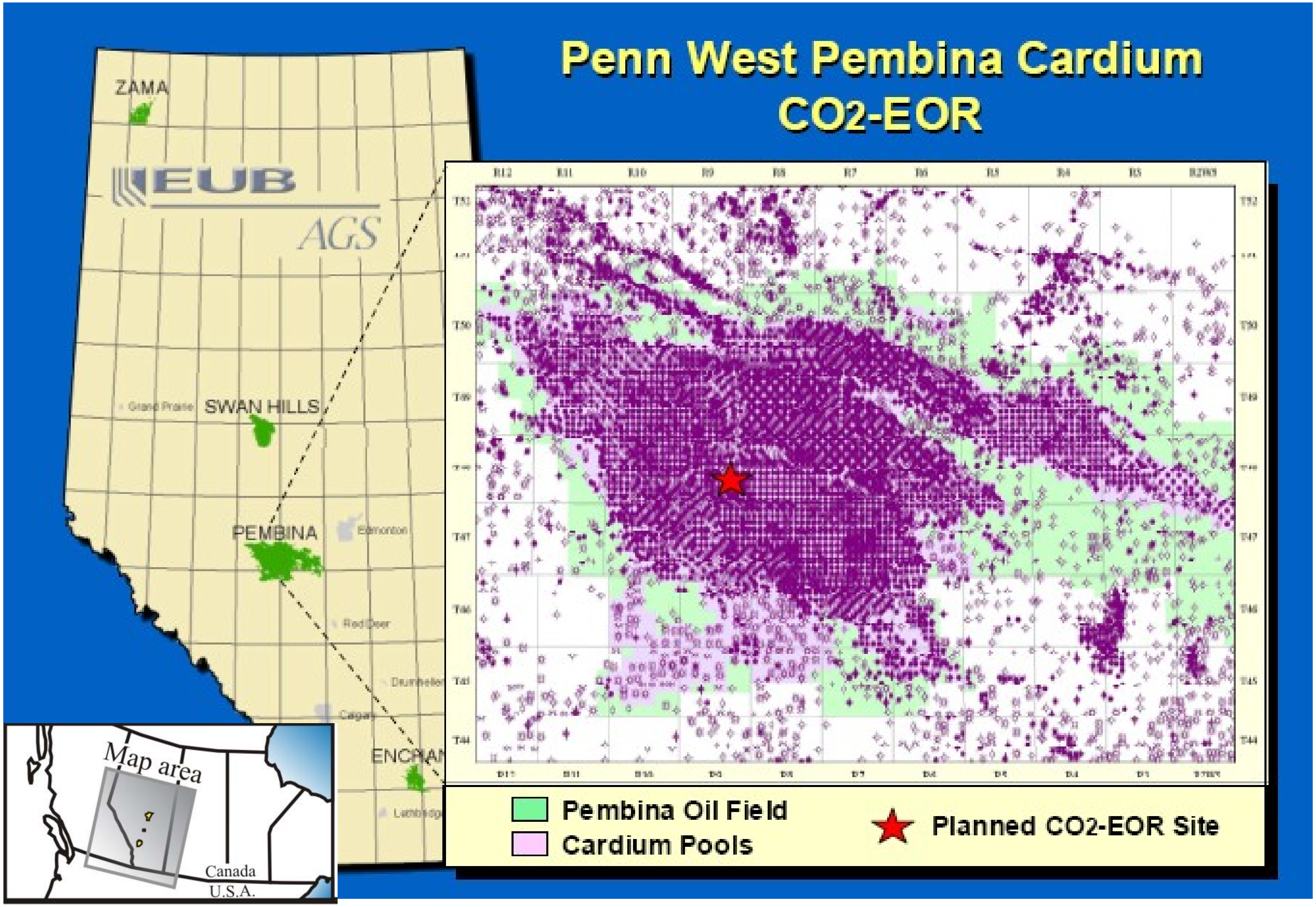
Marcia Coueslan, Fuju Chen

Henry Bland, Abdullah Alshuhail

University of Calgary

Calgary, Alberta, Canada

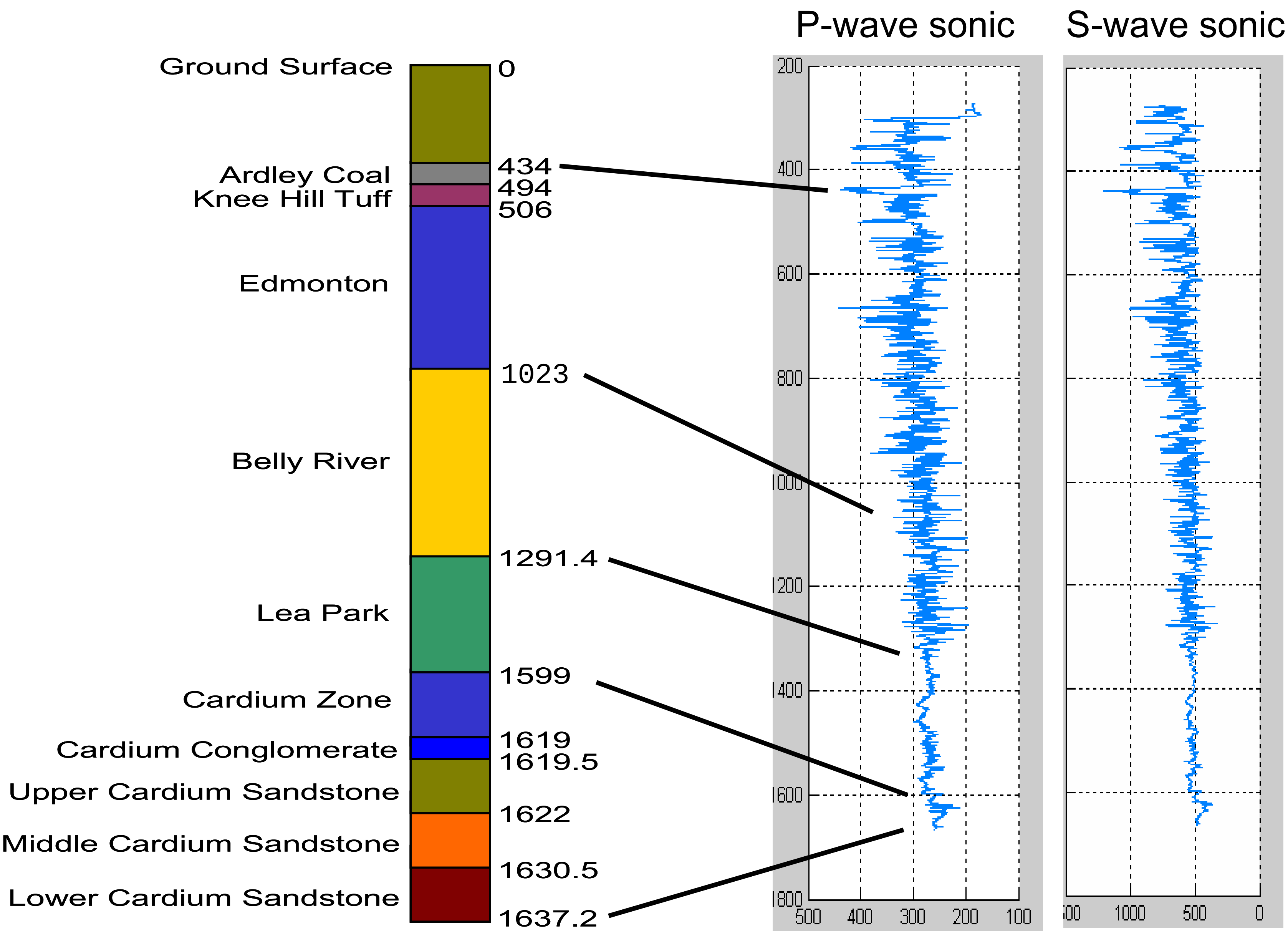
Penn West Petroleum CO_2-EOR Pilot



Penn West monitoring program (2005-2008) (ARC, AGS, UofA, UofC)

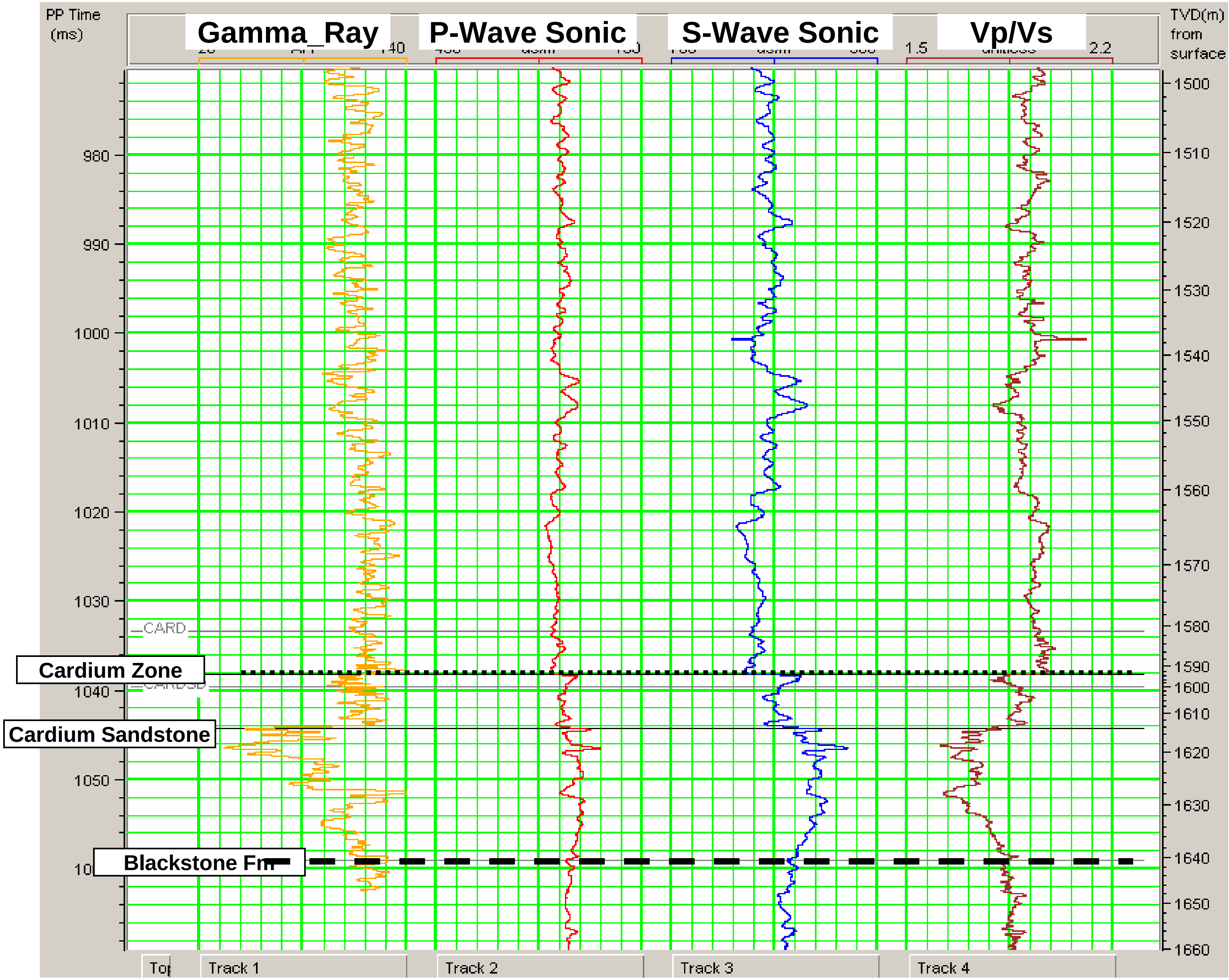
- Regional, local & reservoir geology
- Hydrogeology
- Well analysis, well integrity
- Observation well instrumentation
- Timelapse seismic program
- Passive seismic program
- Timelapse geochemistry program
- Monitoring wells (groundwater)
- Soil and casing gas
- Core & reservoir fluids analysis
- Rock physics & well log suites

Stratigraphy and sonic log response

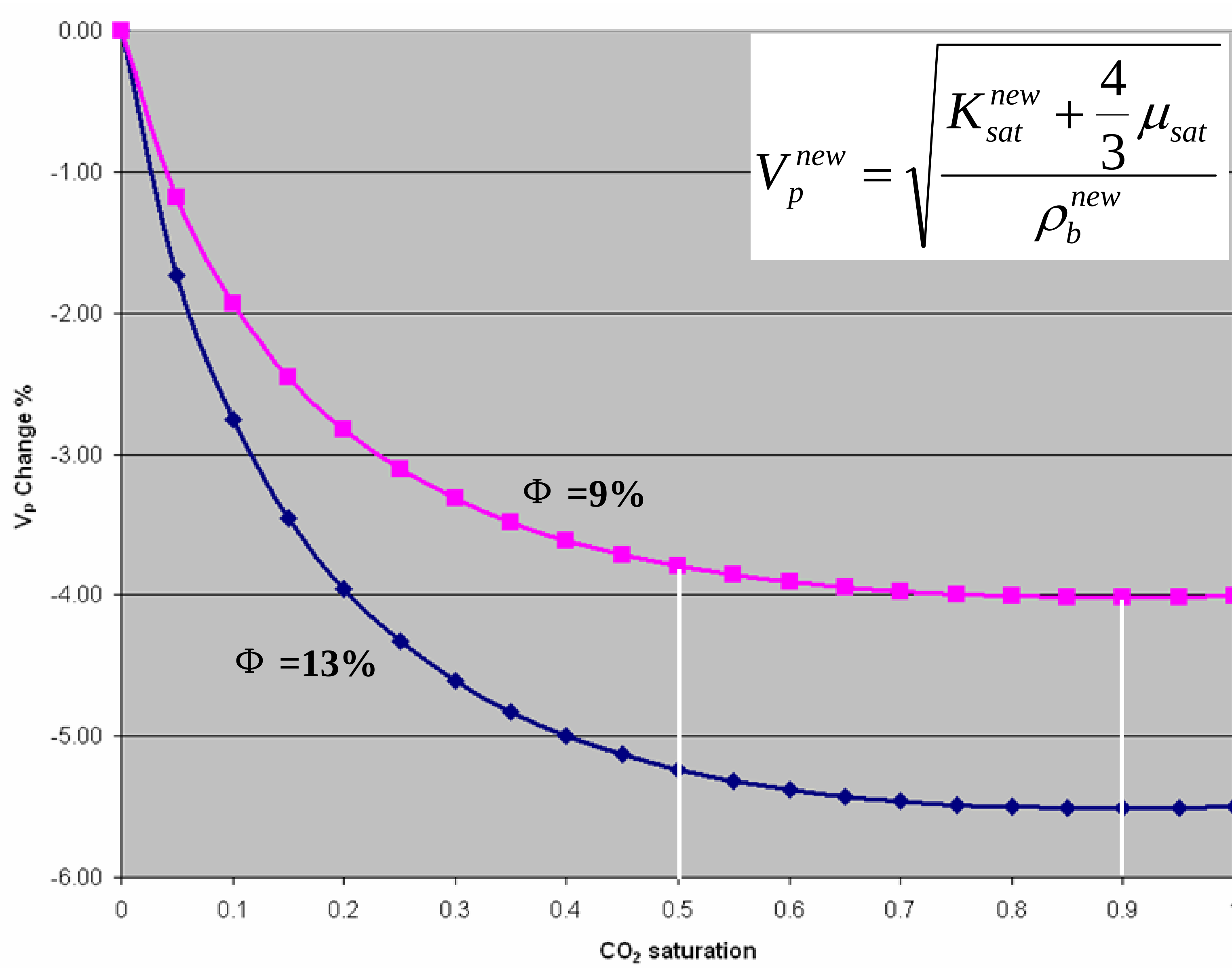


Courtesy Rick Chalaturnyk

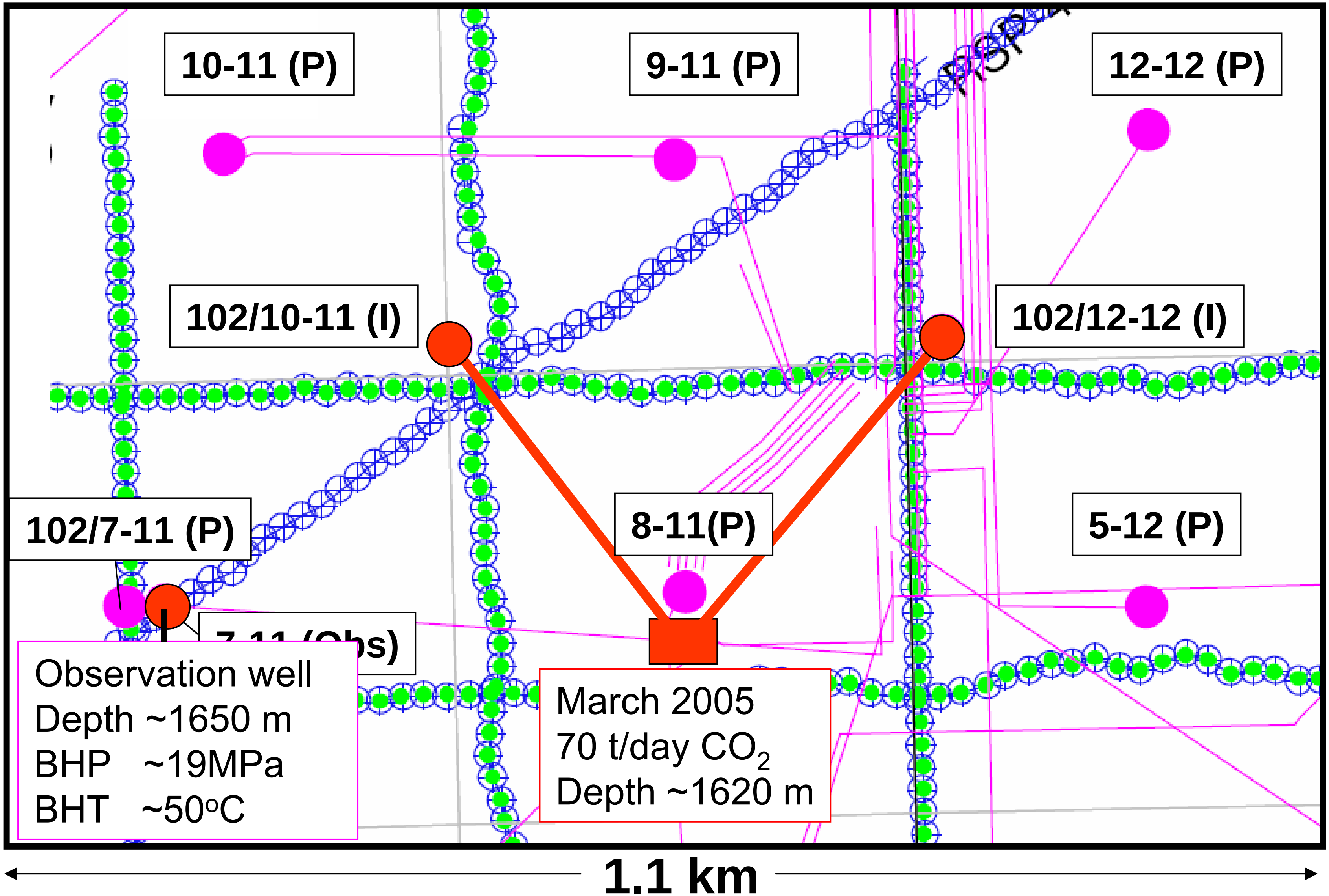
102/07-11-48-9W5/0



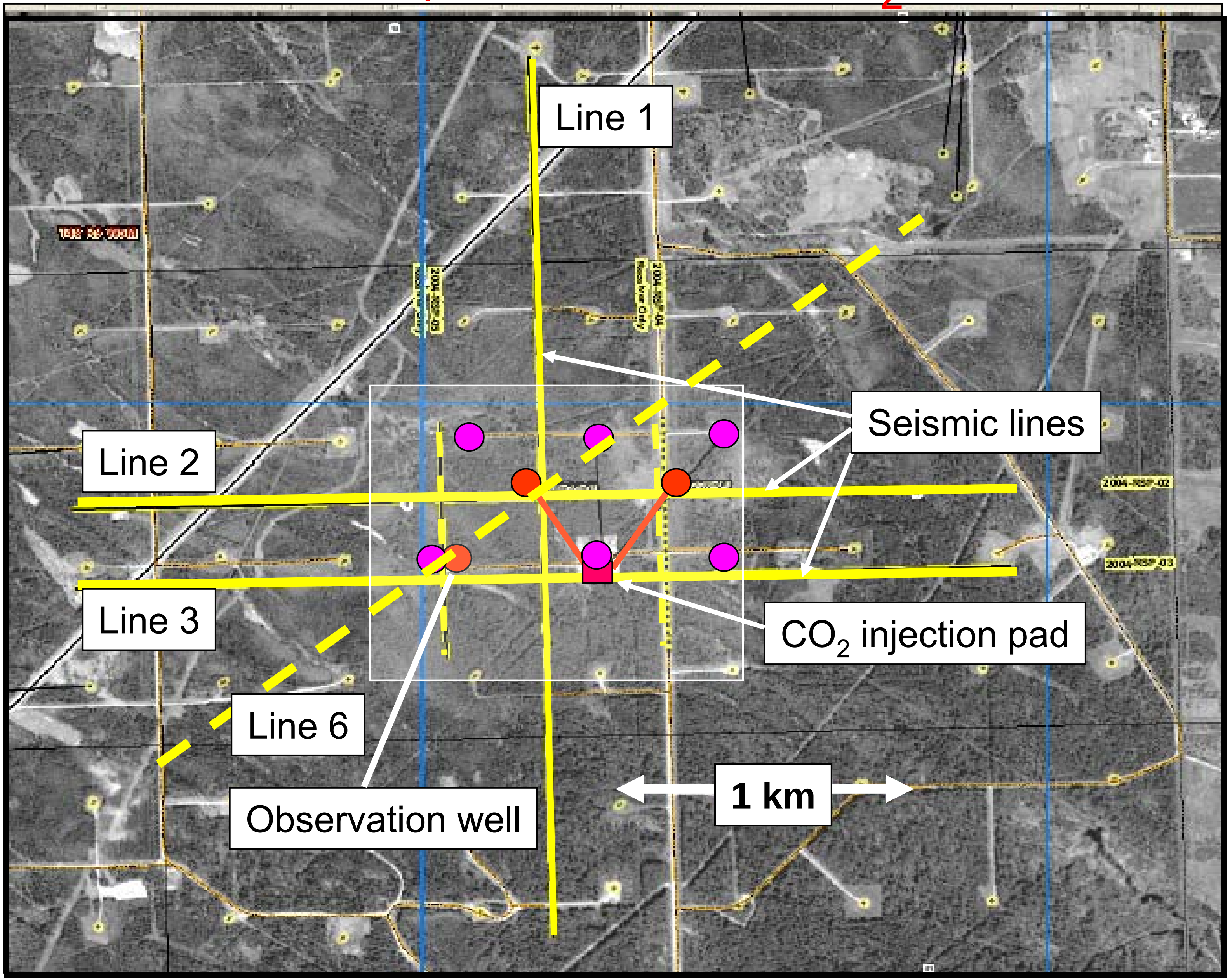
V_p change versus CO_2 saturation



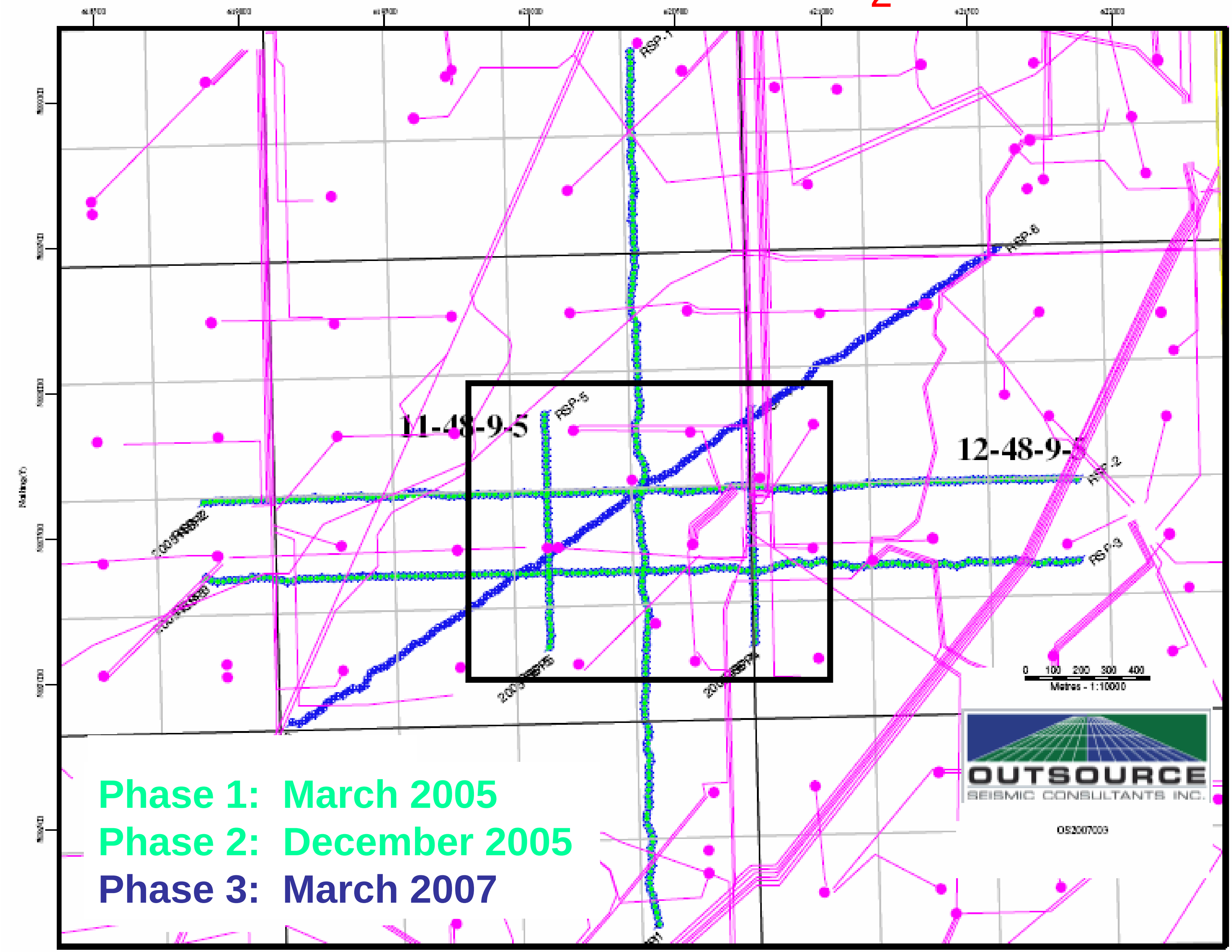
PennWest Pembina Cardium CO_2 Pilot



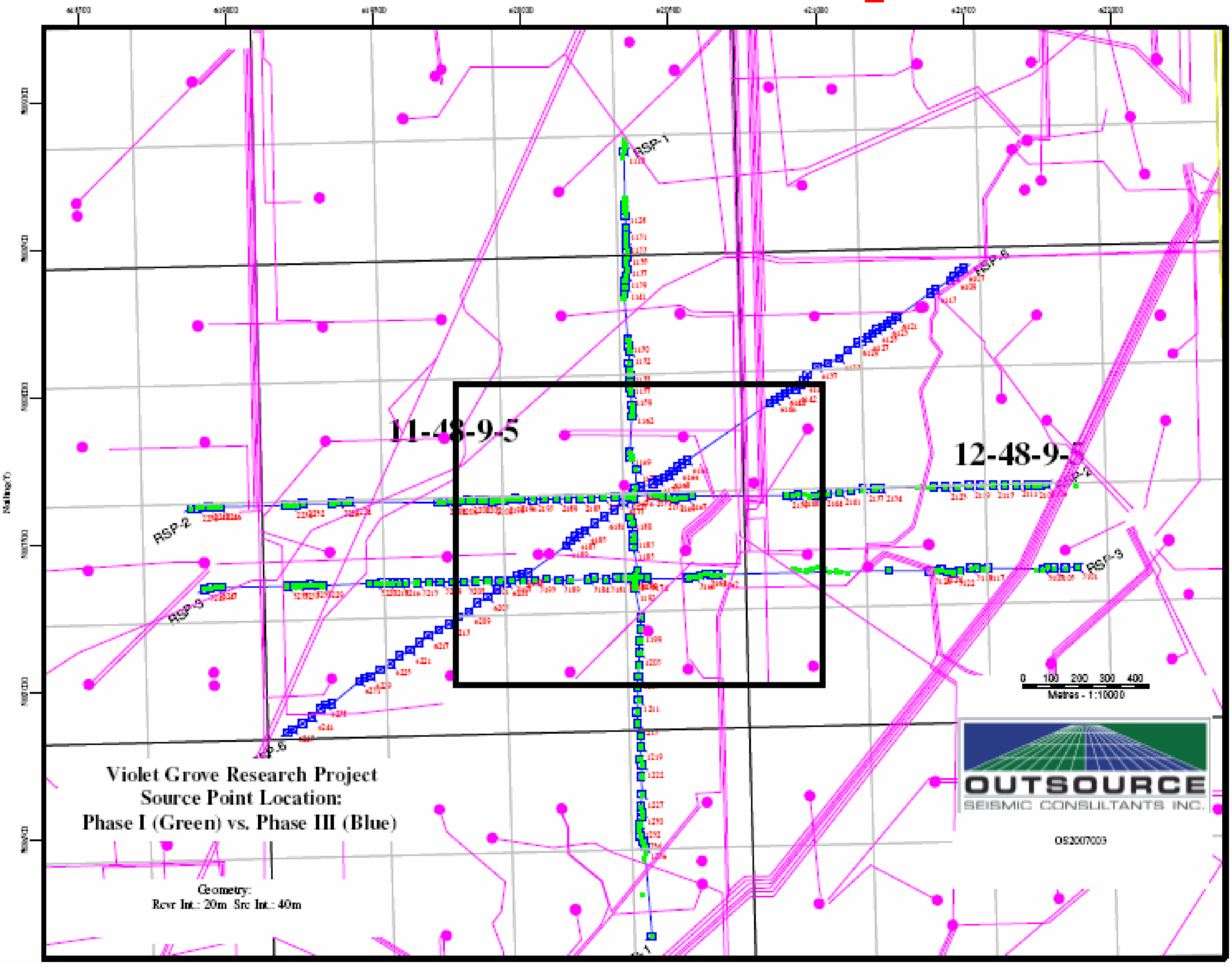
Seismic lines, Penn West CO_2 EOR Pilot



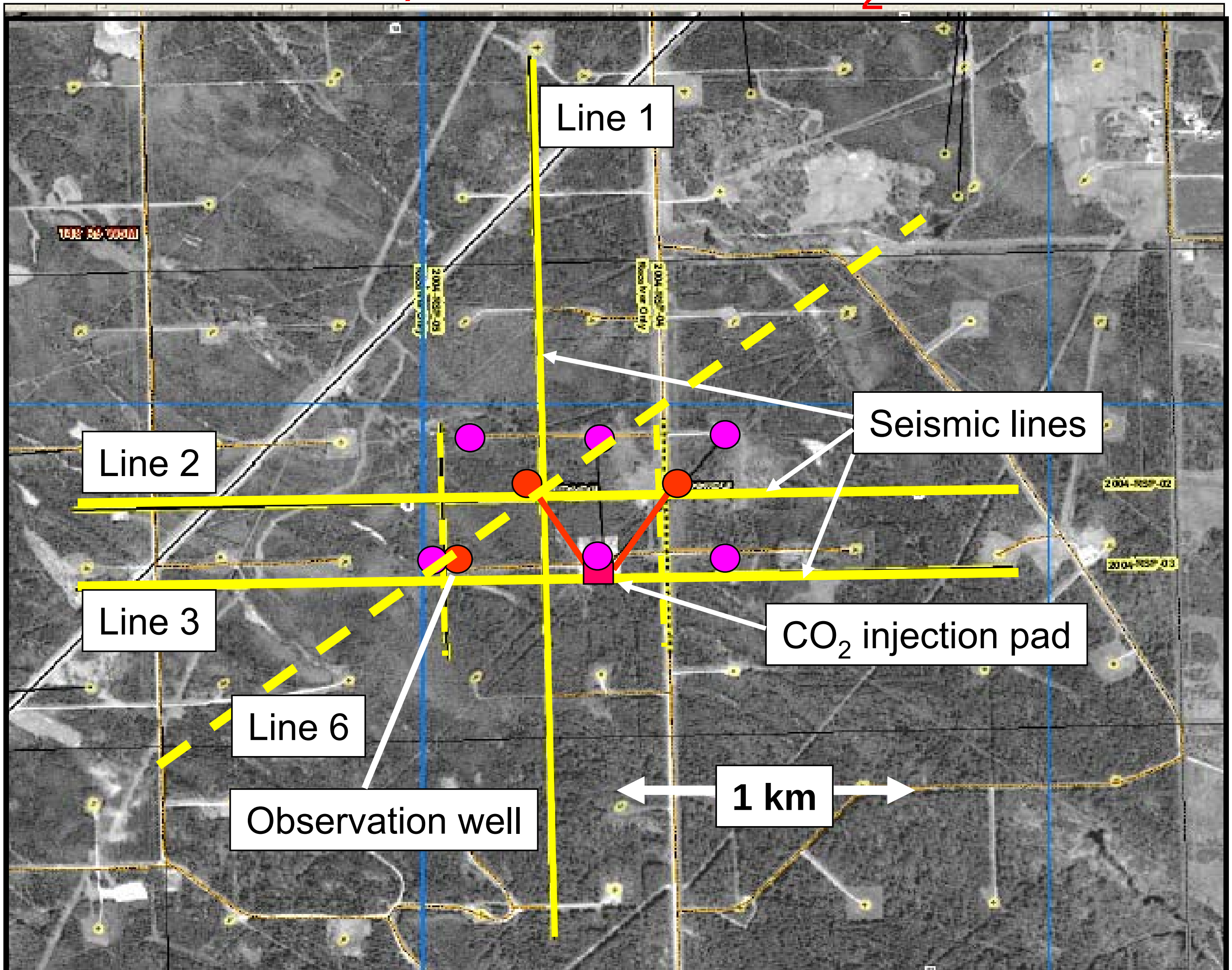
Seismic lines, Penn West CO_2 EOR Pilot



Seismic lines, Penn West CO_2 EOR Pilot



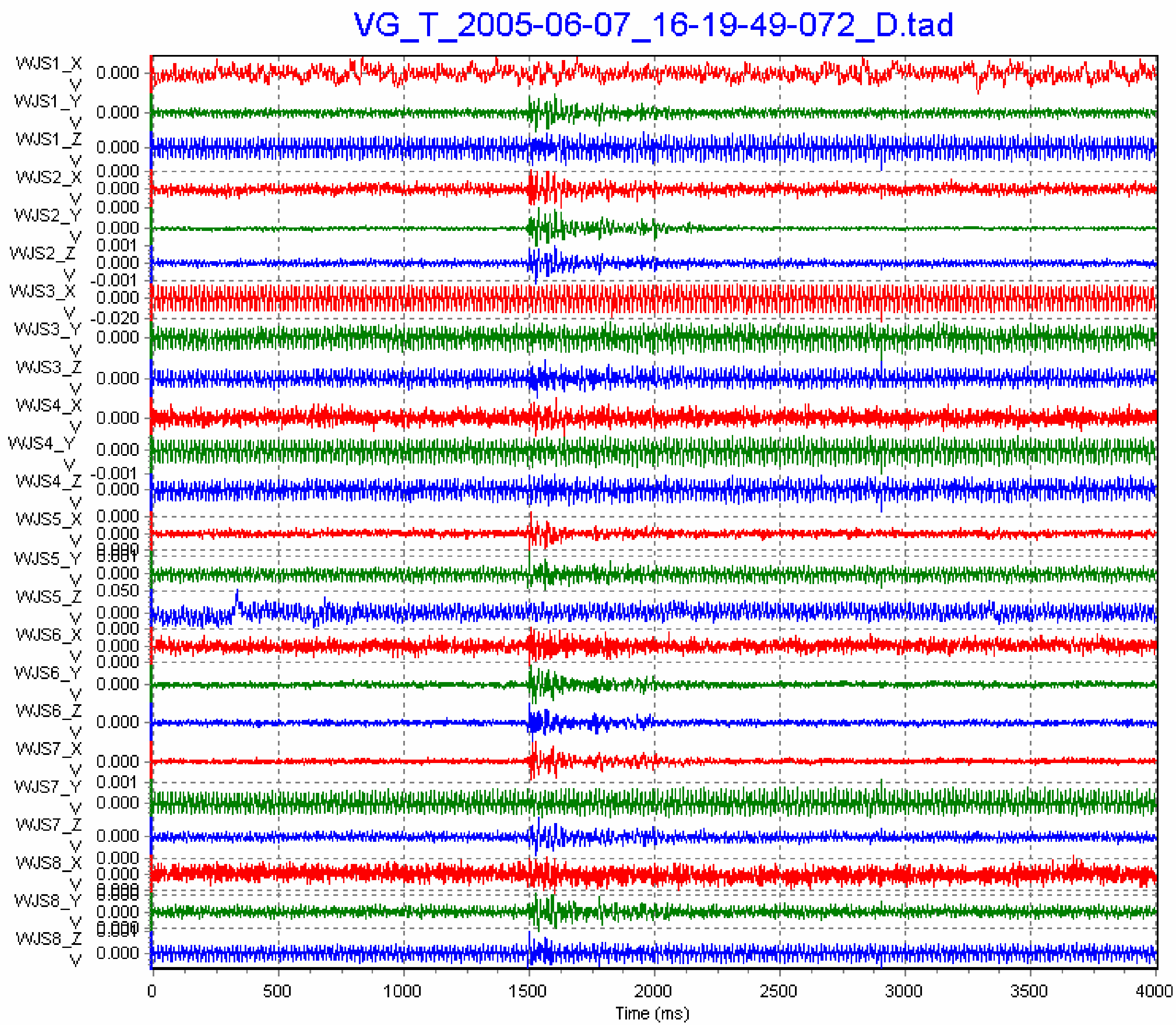
Seismic lines, Penn West CO_2 EOR Pilot



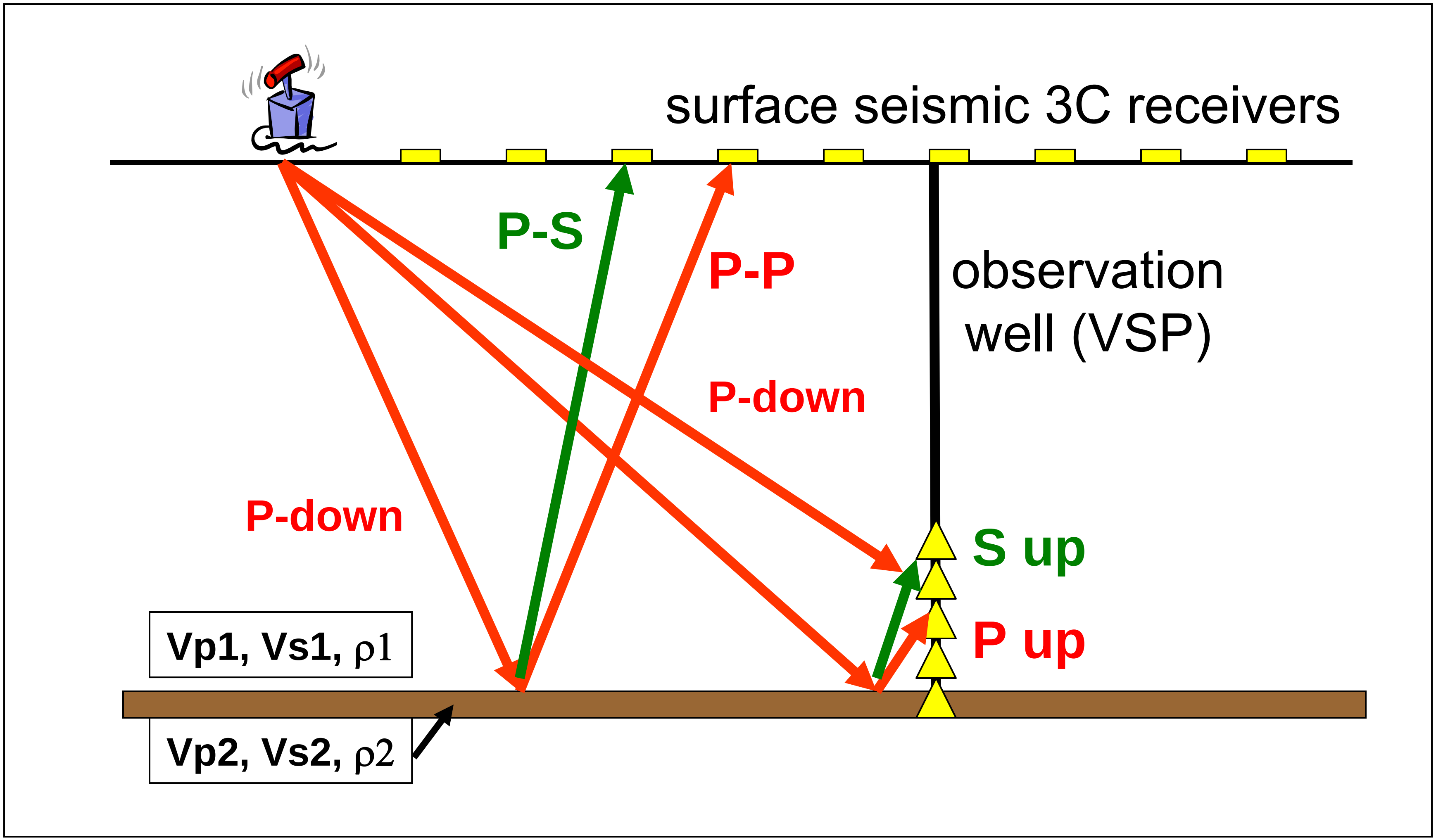

BRANDETTE
RIG #19


BRANDETTE

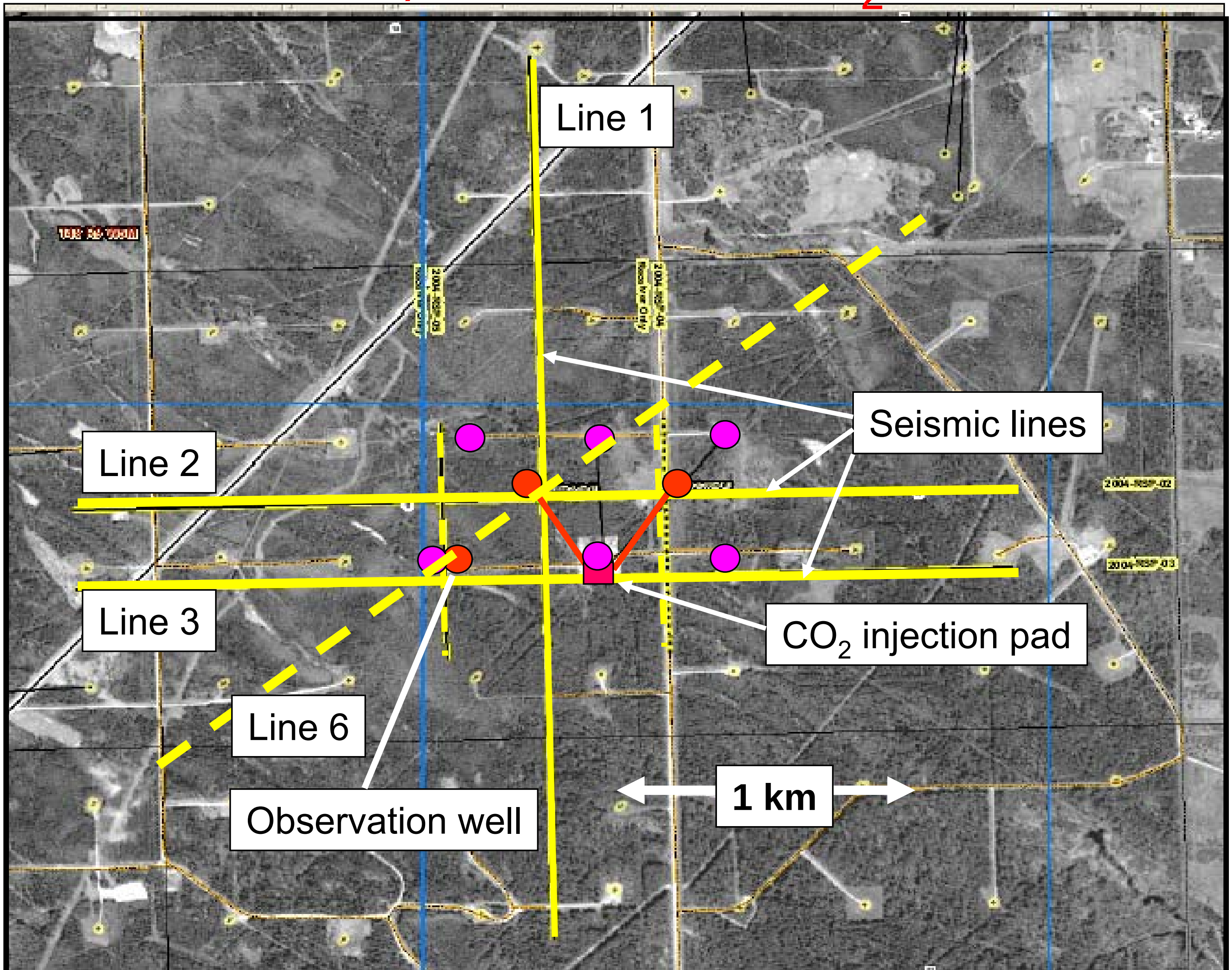
Passive seismic record



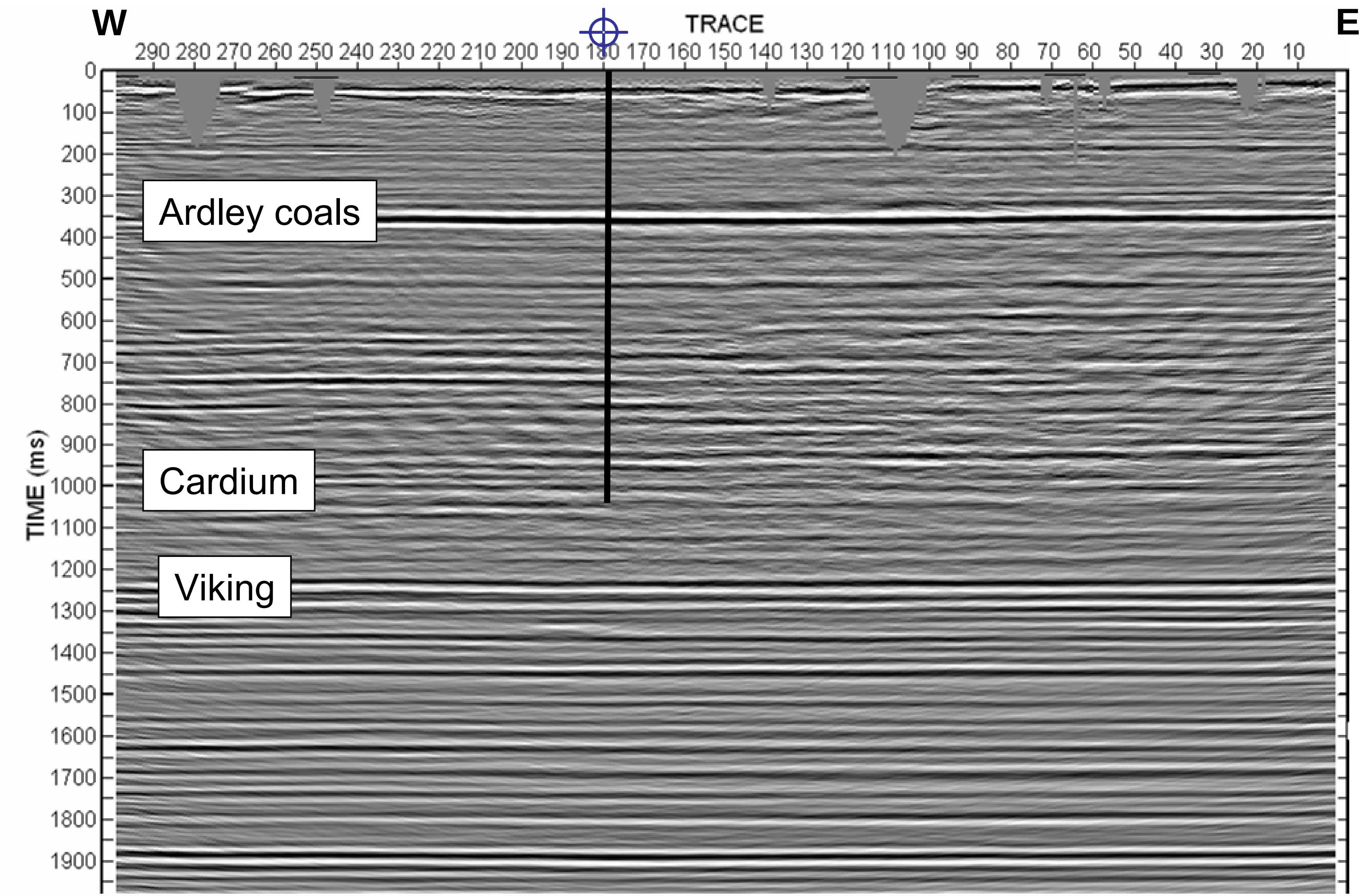
Multicomponent surface seismic and vertical seismic profile (VSP)



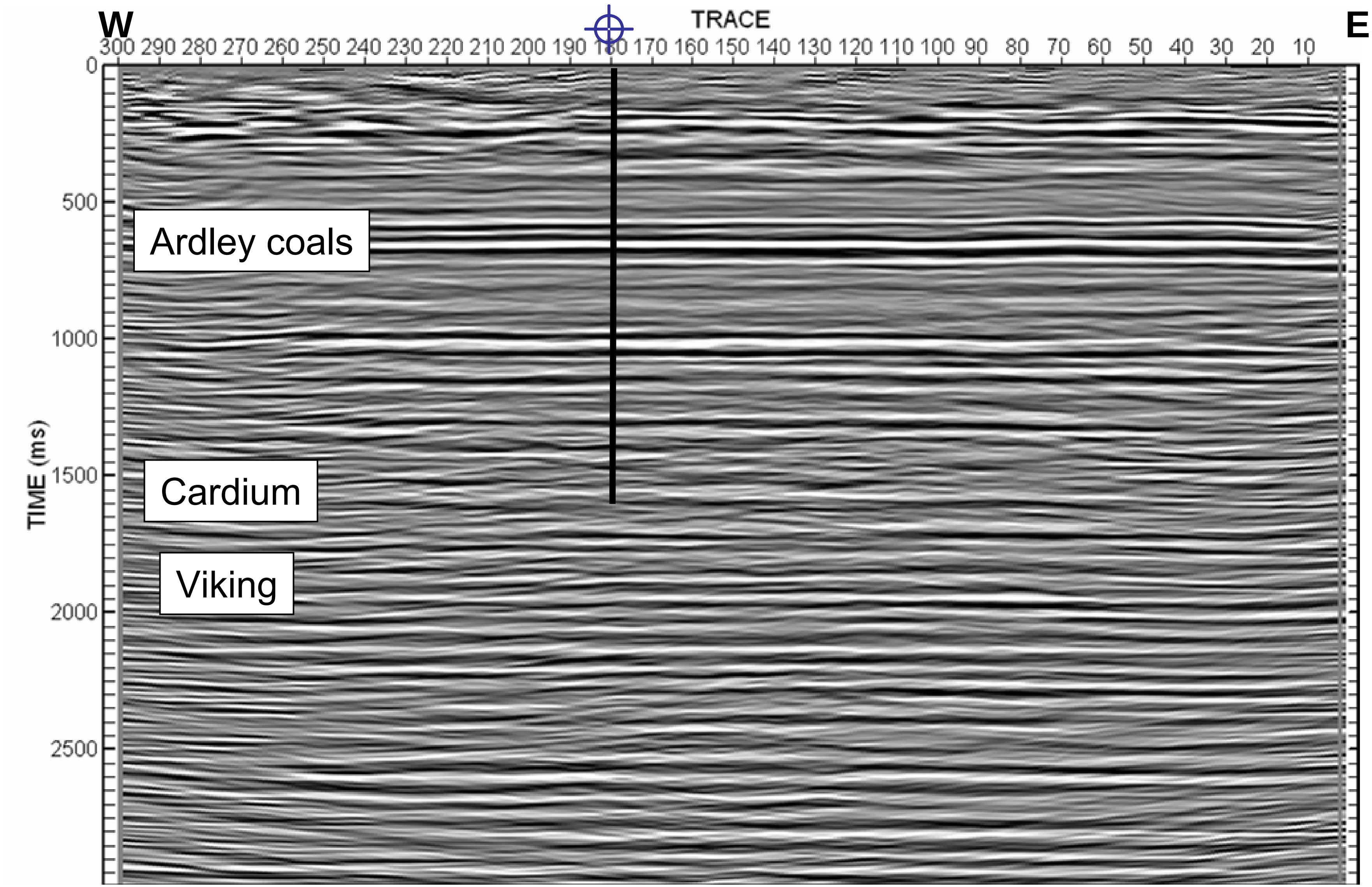
Seismic lines, Penn West CO_2 EOR Pilot



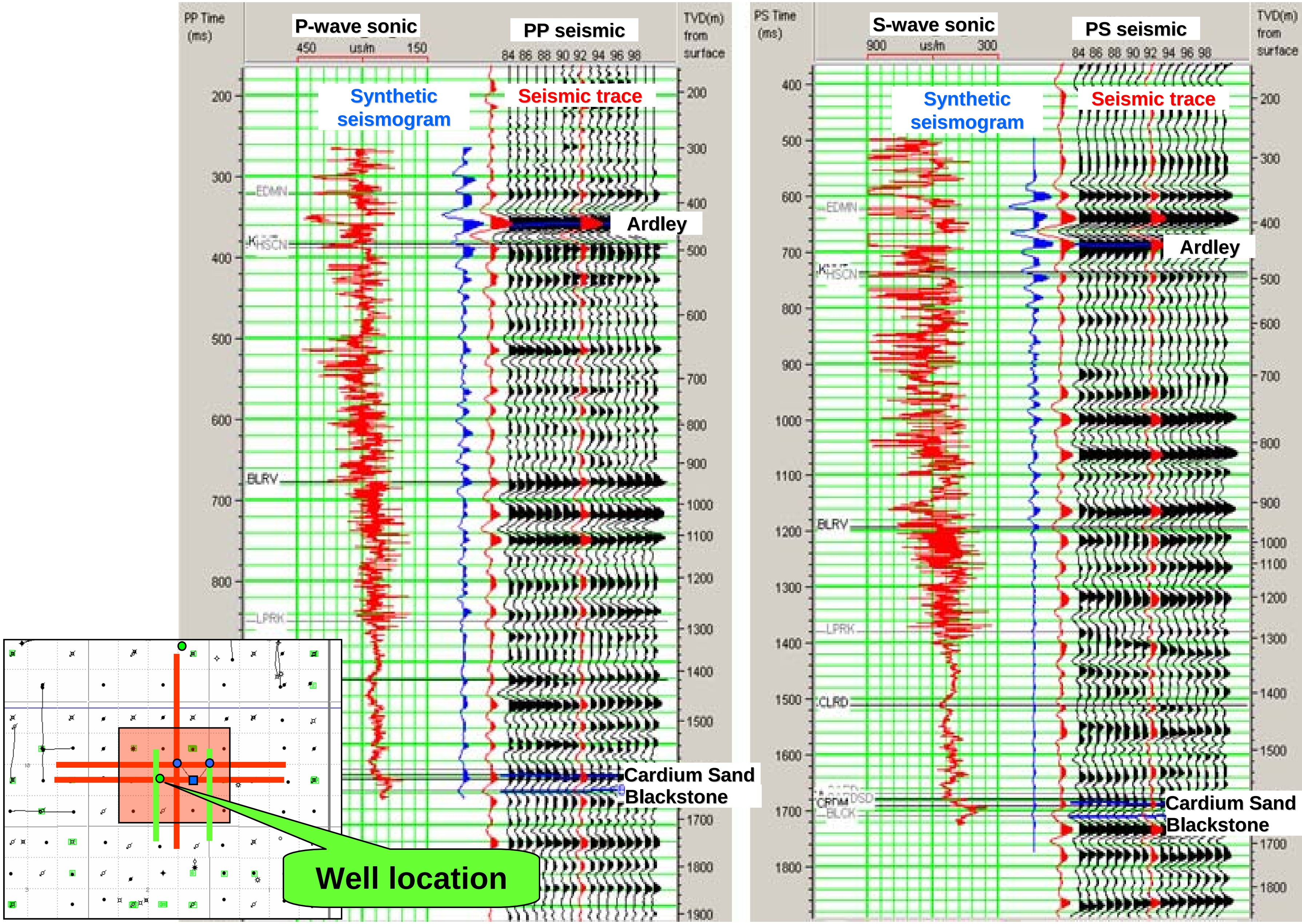
Line 3 migrated P-P section (Phase I)



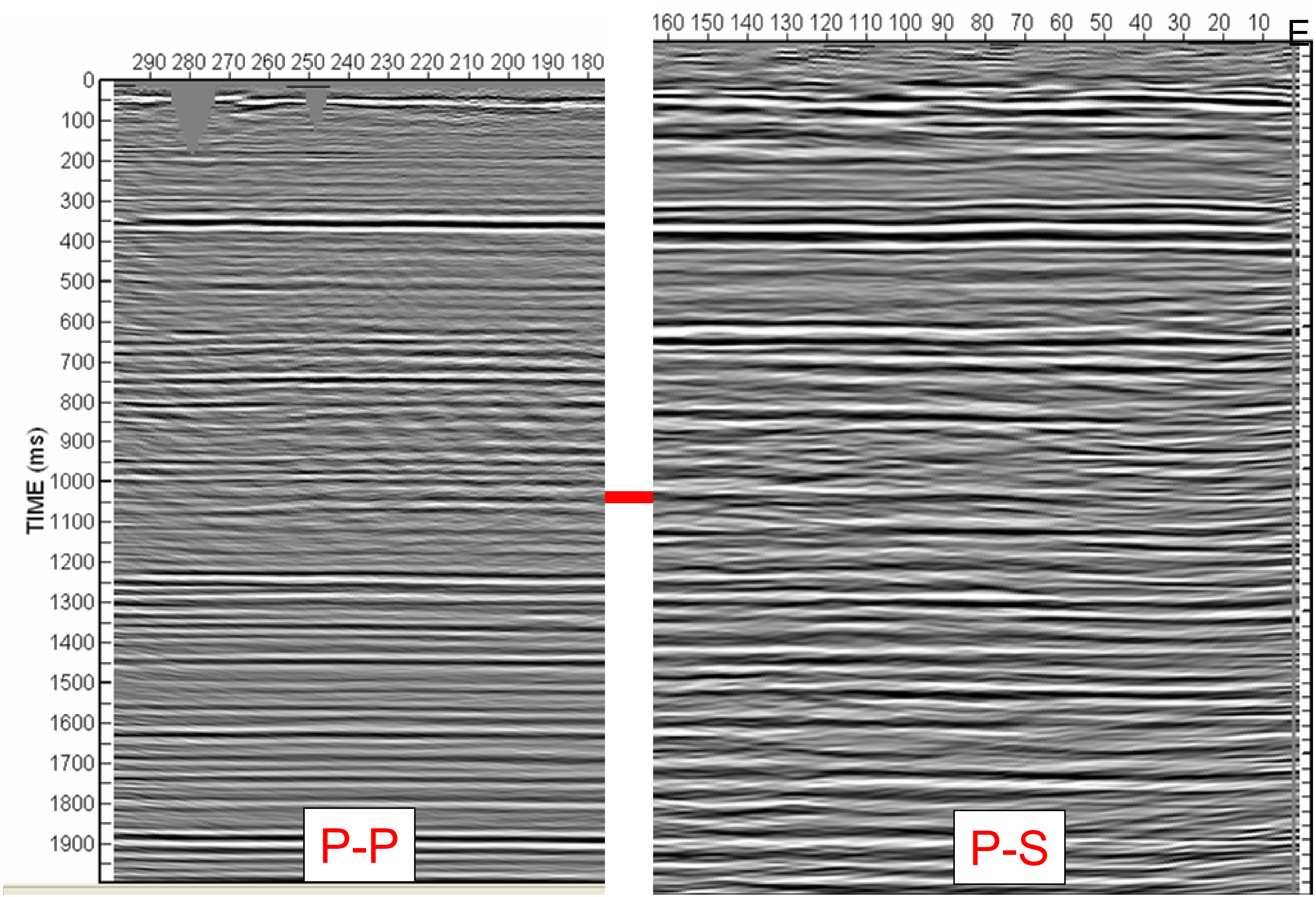
Line 3 migrated P-S section



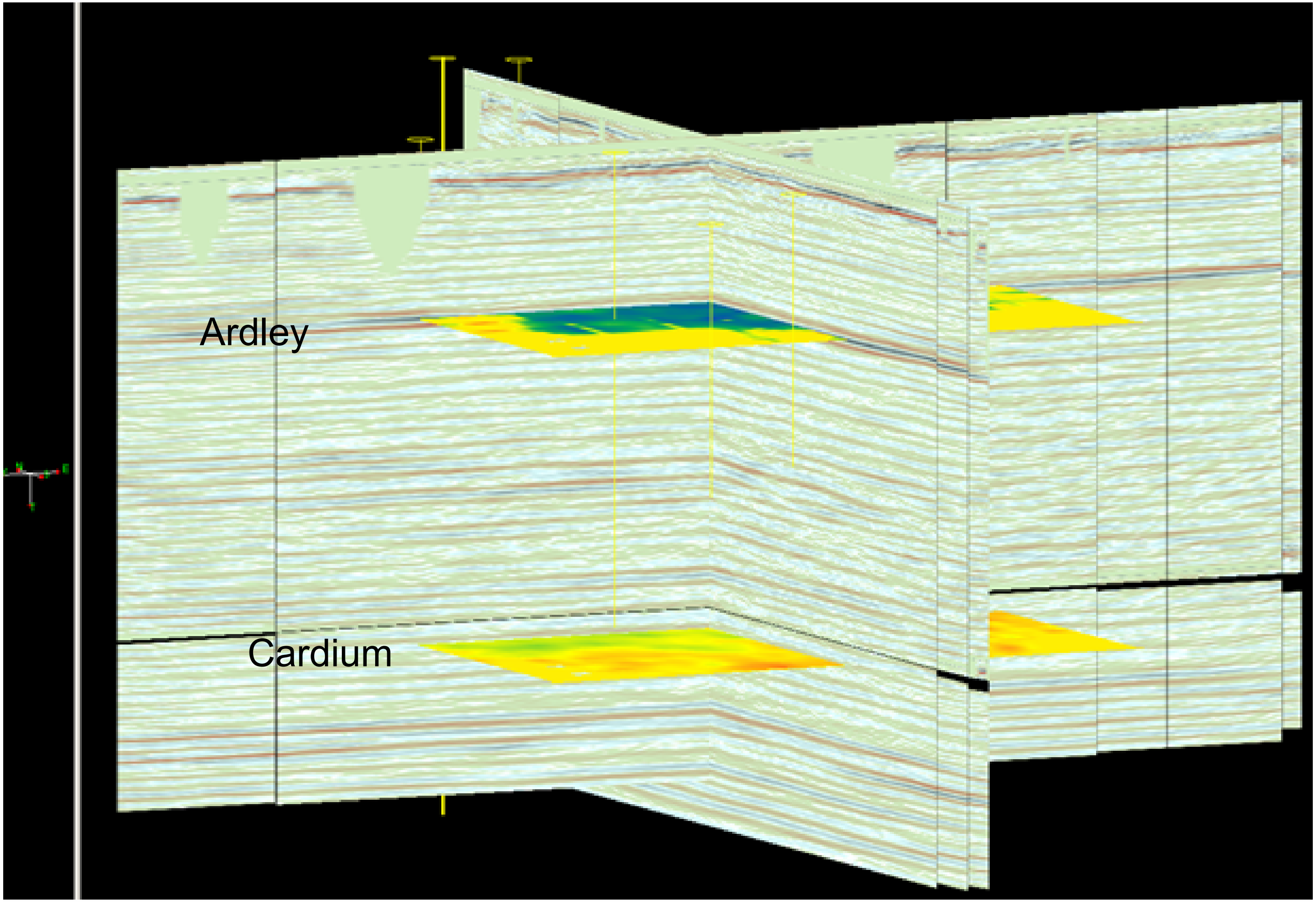
PP (left) and PS (right) correlation



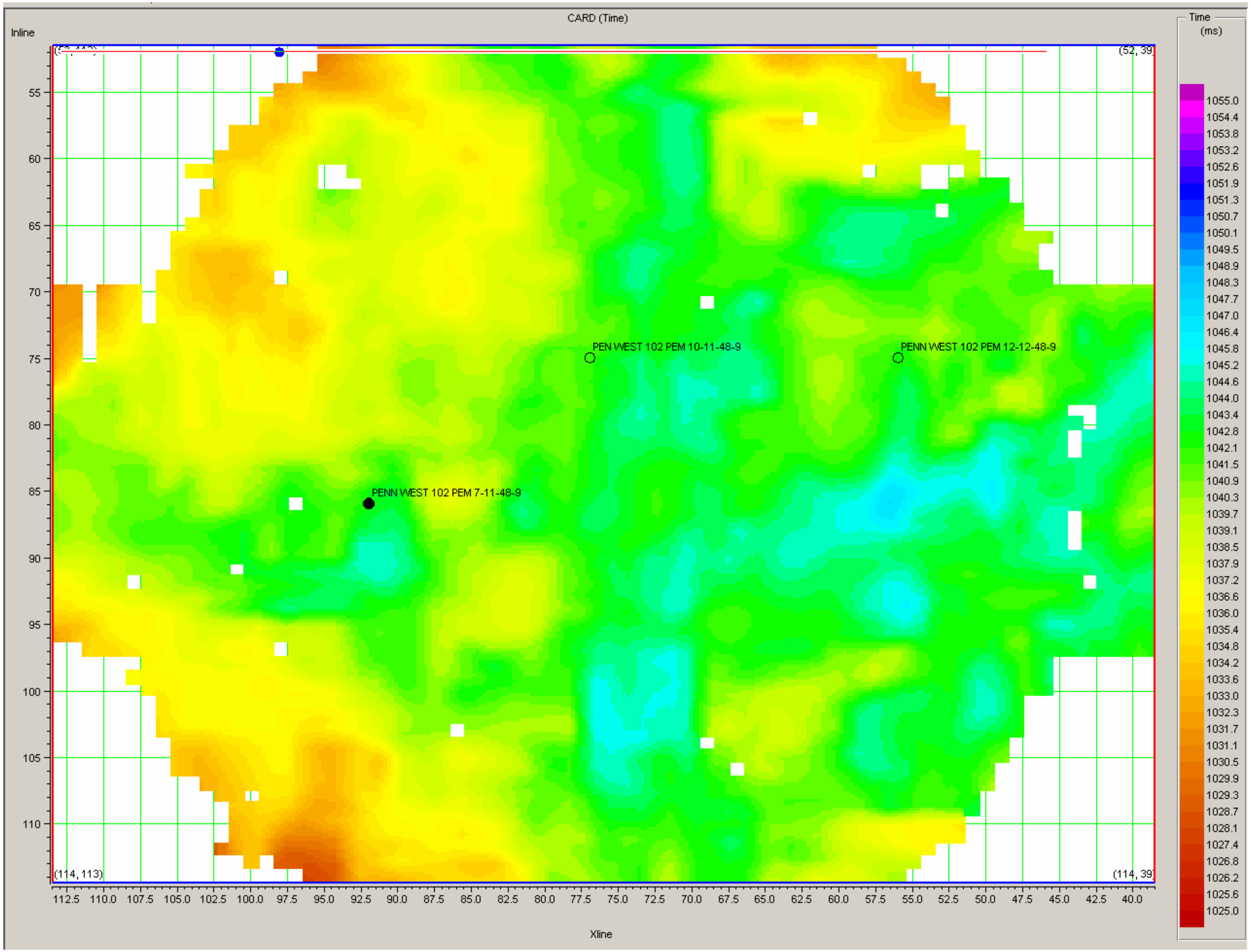
Line 3 P-P & P-S correlation

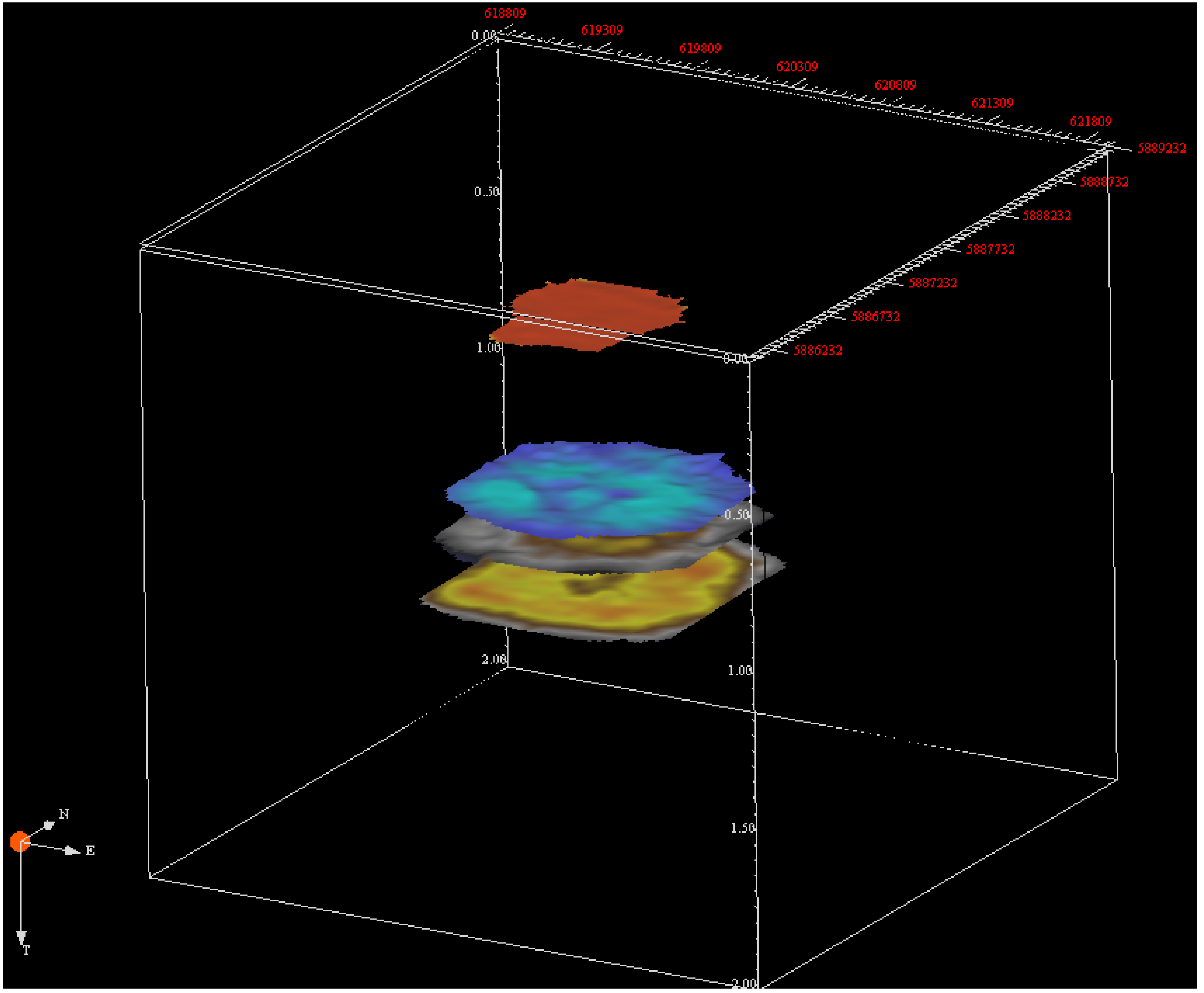


3D volume display [P-P]



P-P time structure - Cardium





618809
619309
619809
620309
620809
621309
621809
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5888732
5888232
5887732
5887232
5886732
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0.00
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1.50
2.00
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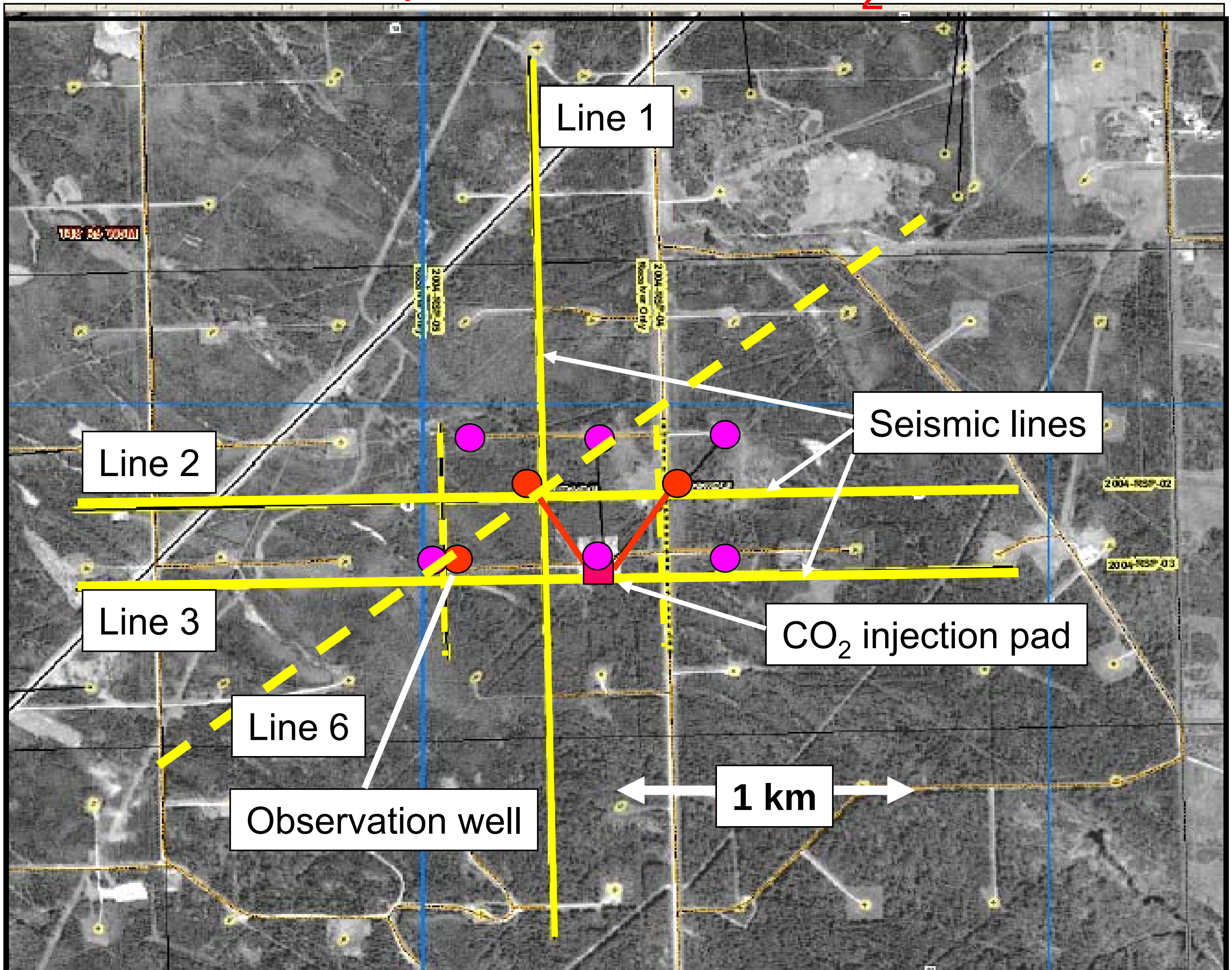
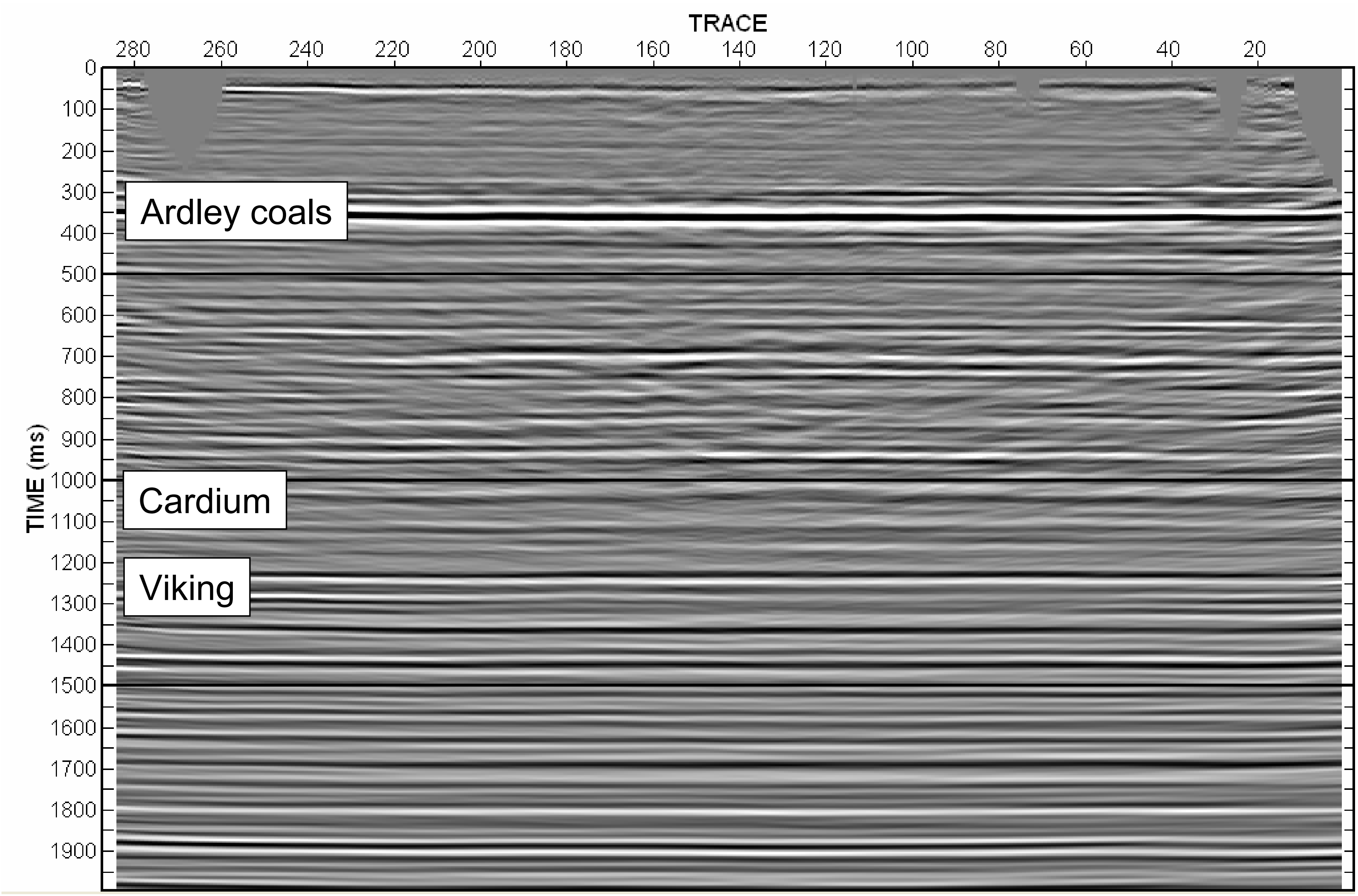
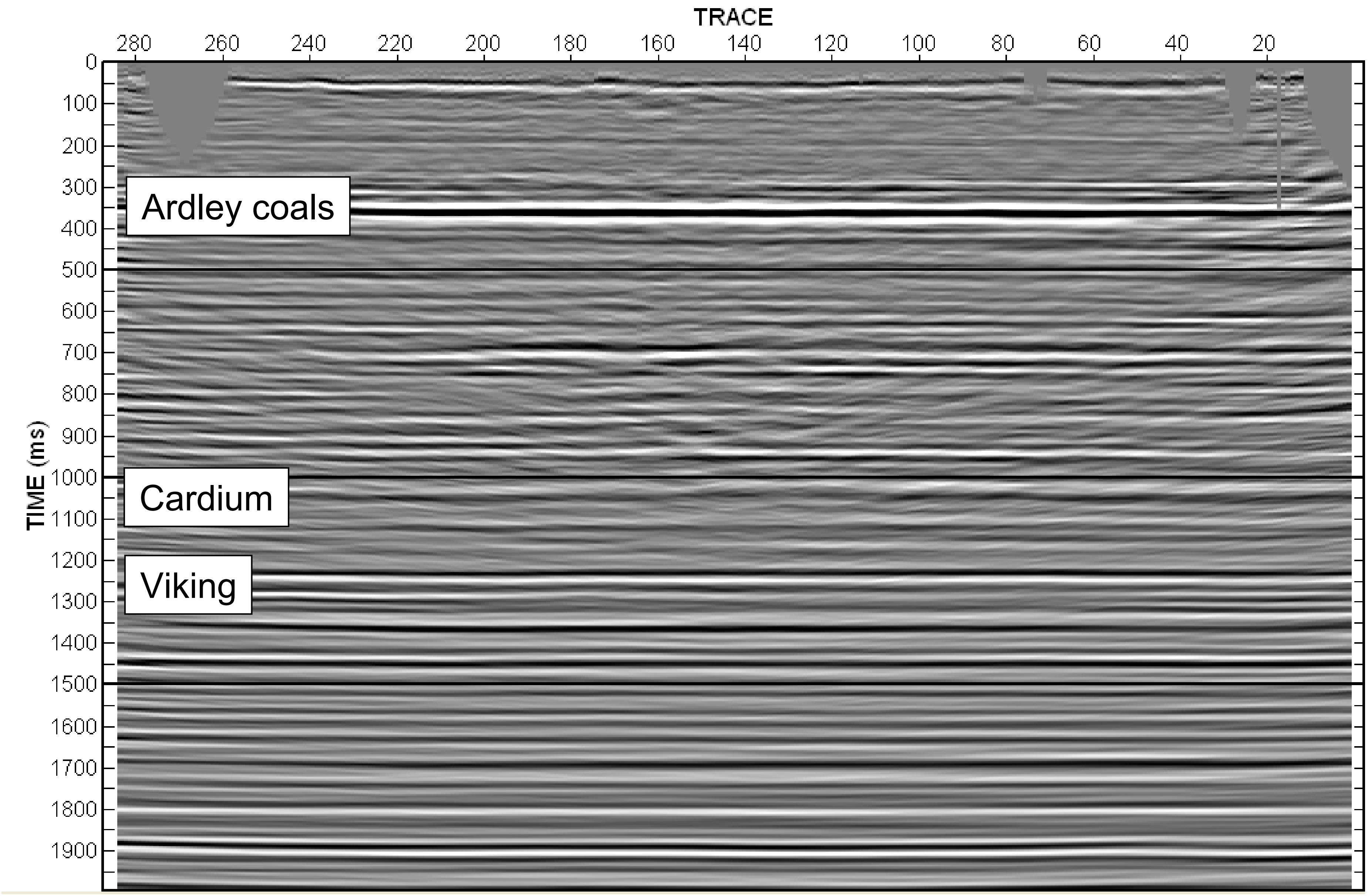
Seismic lines, Penn West CO_2 EOR Pilot



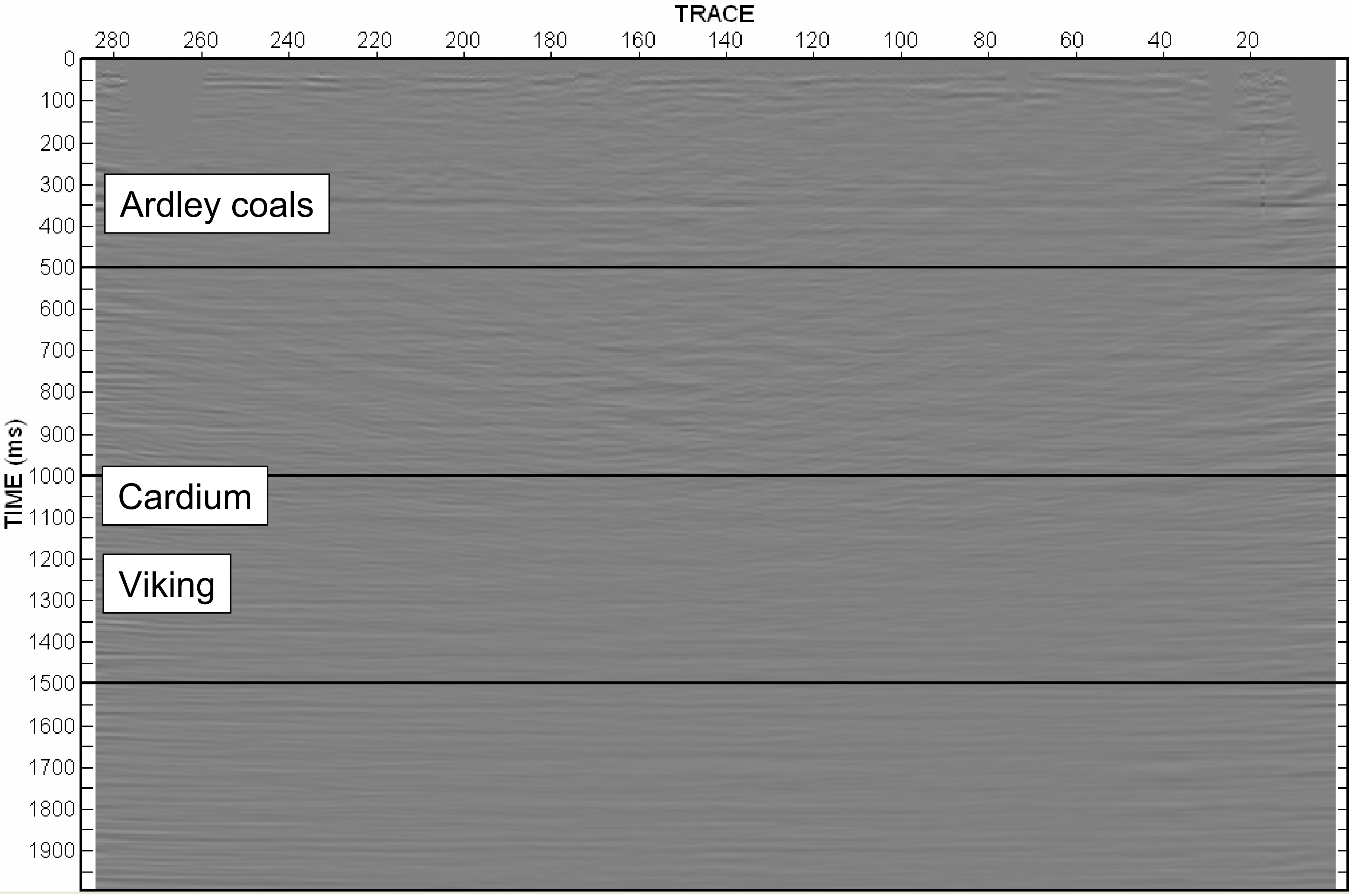
Line 1 Phase I



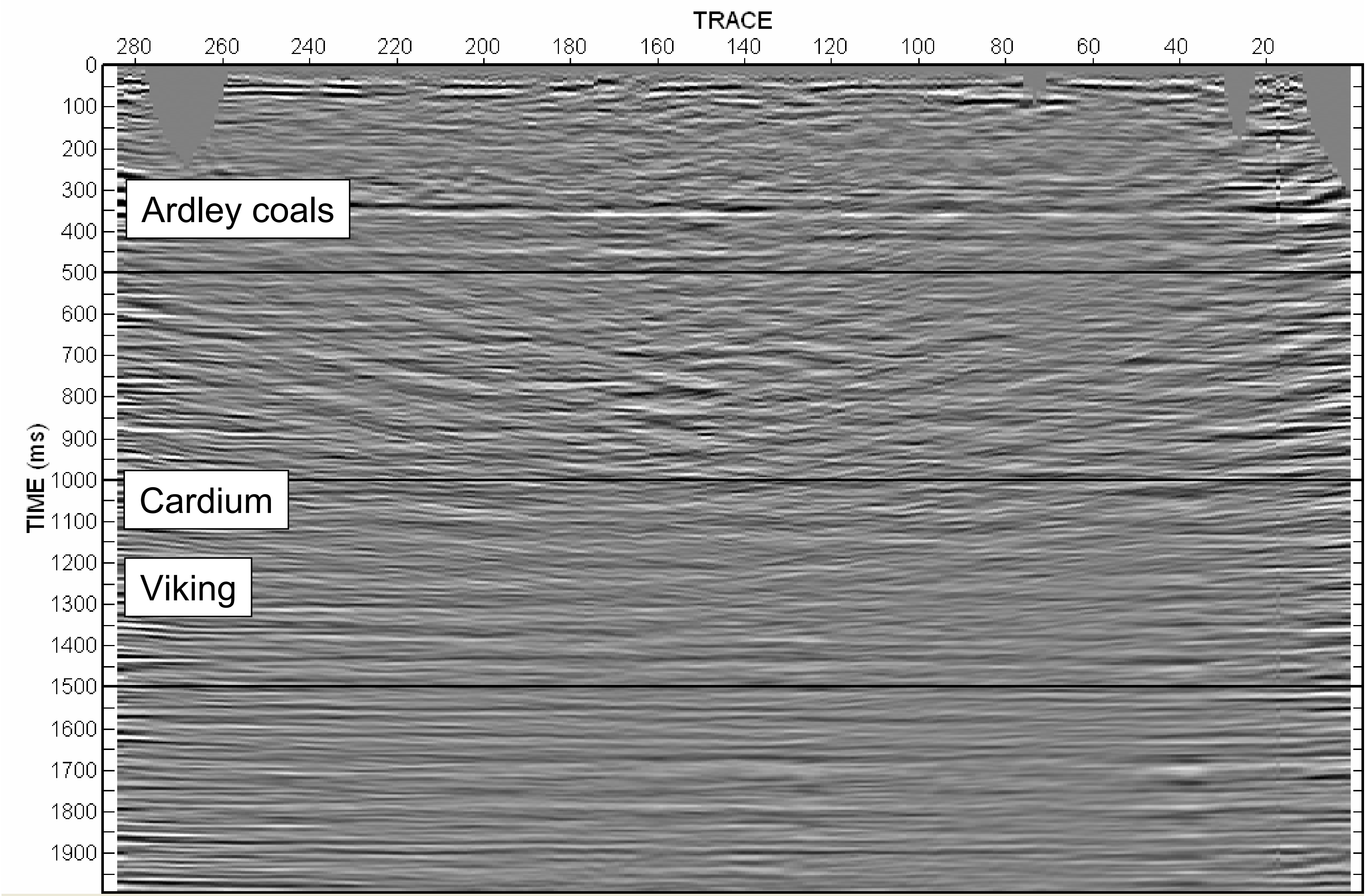
Line 1 Phase III



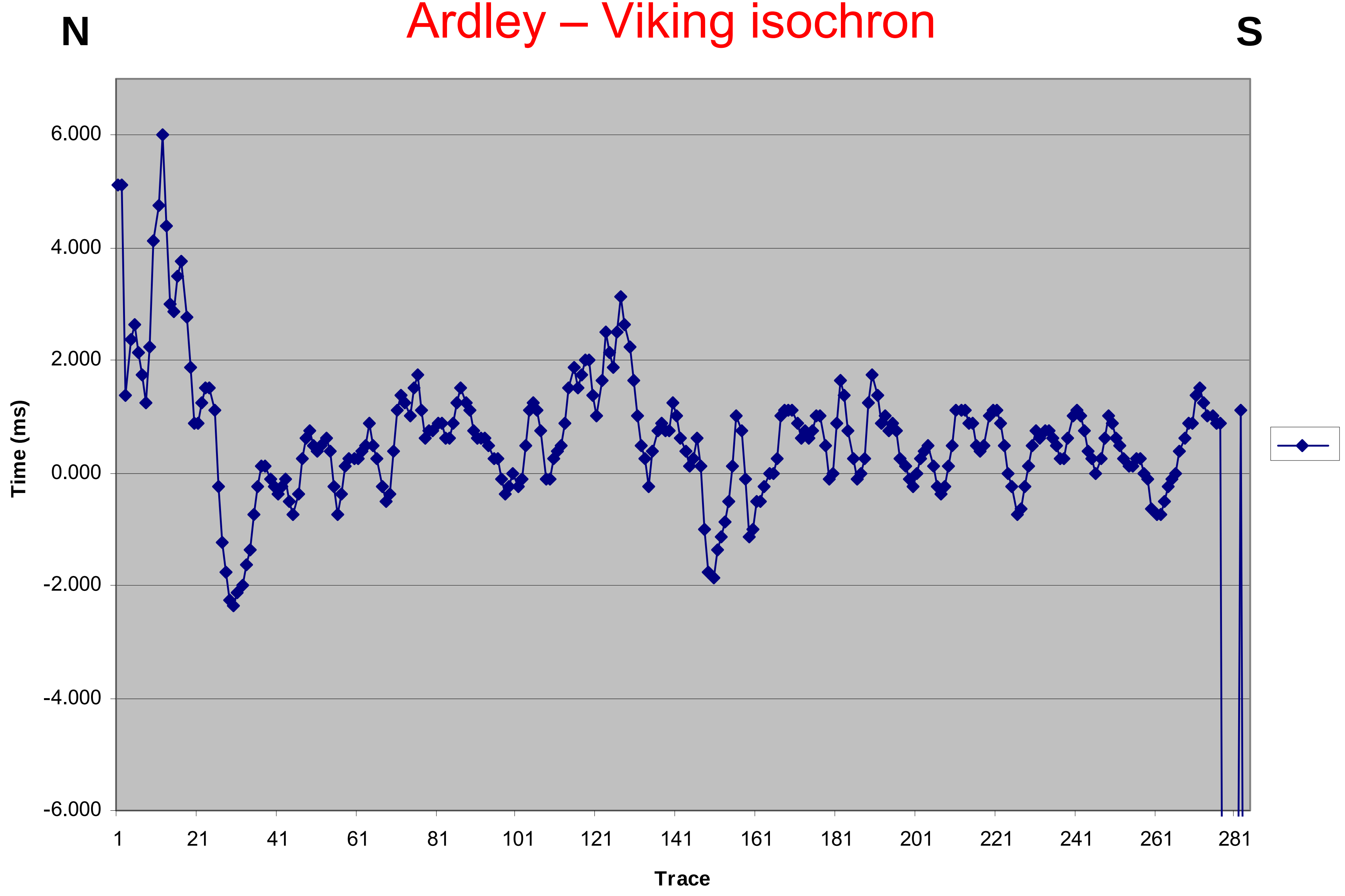
Line 1 Phase III – Phase I



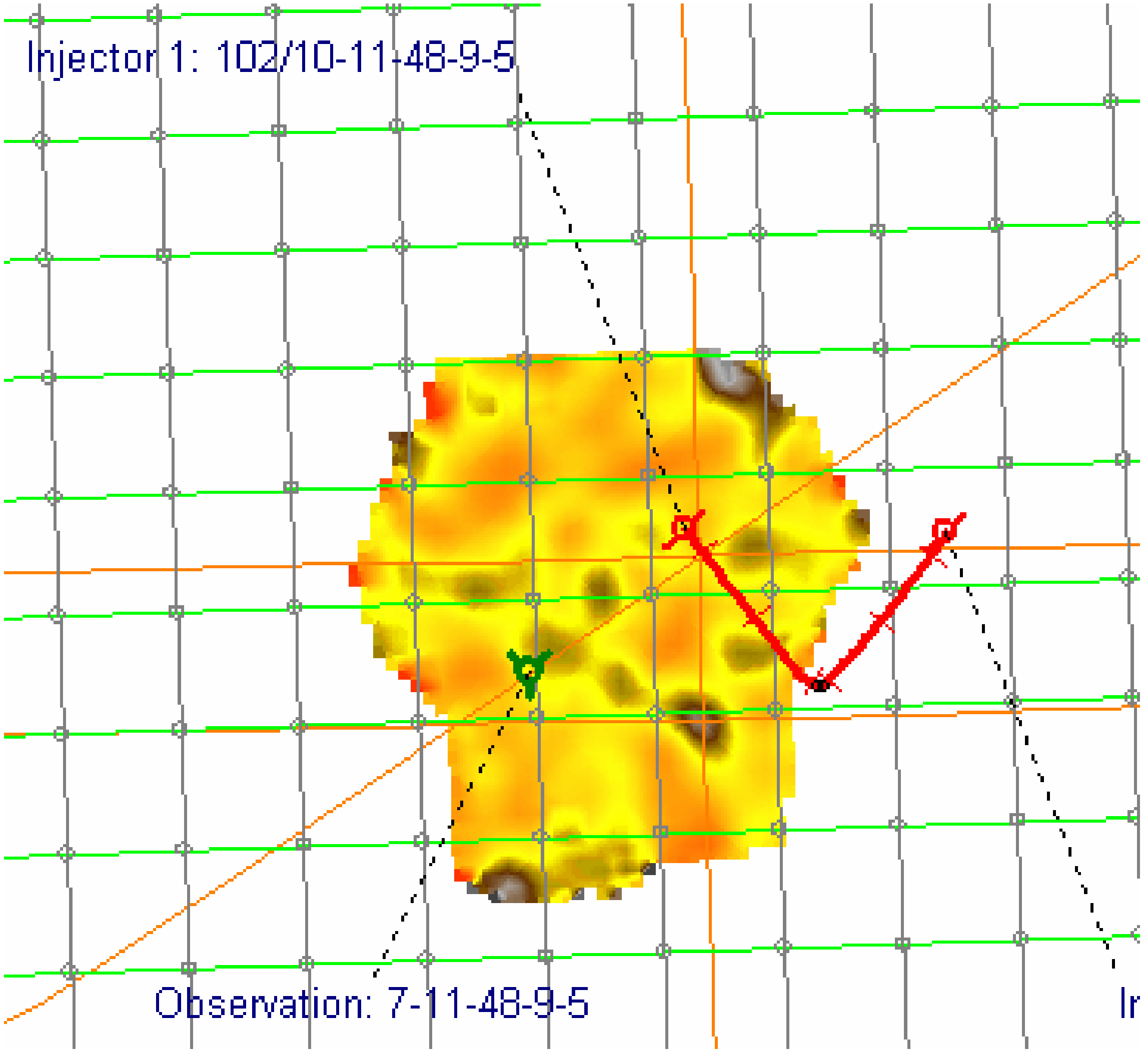
Line 1 Phase III – Phase I



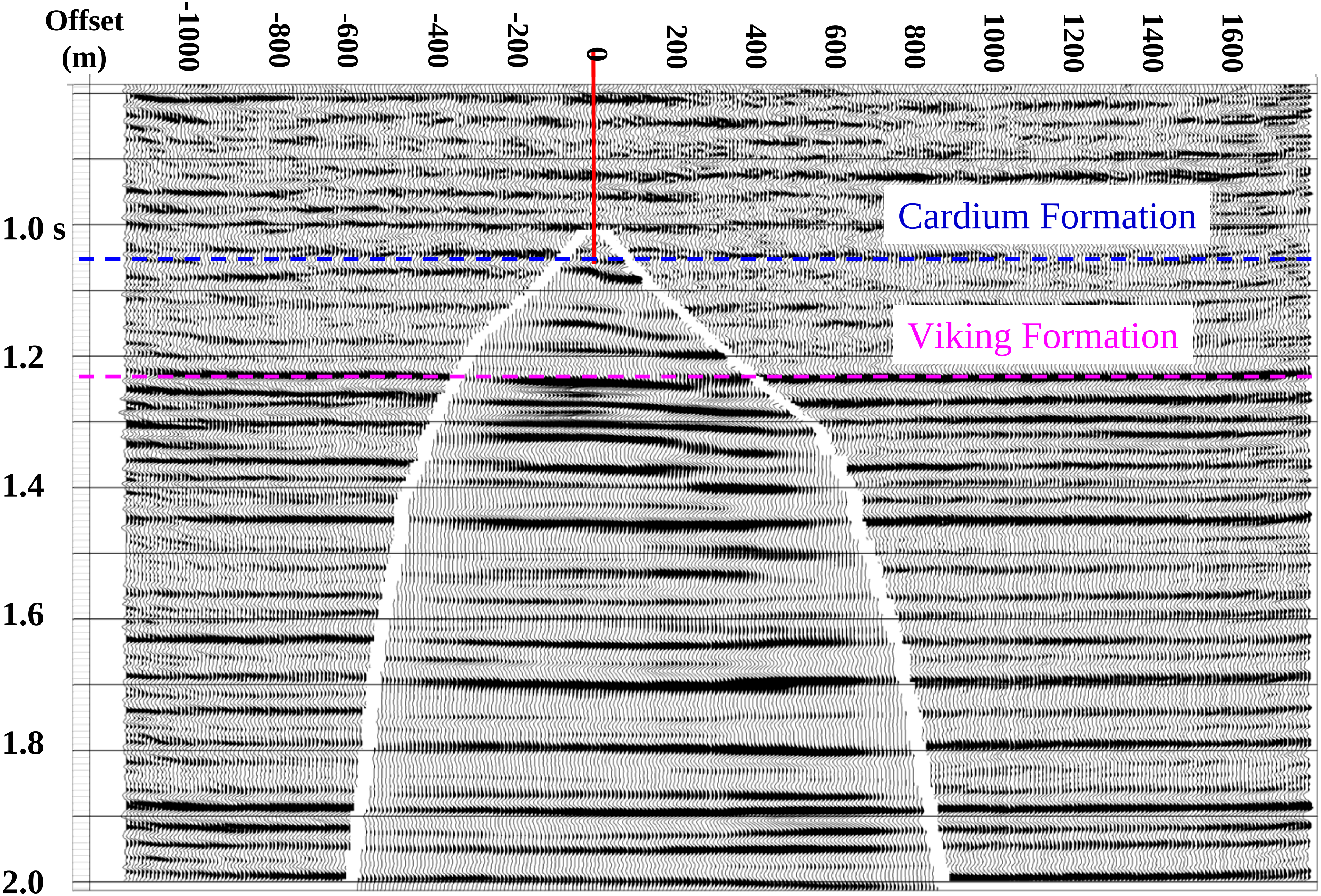
Line 1 Phase III – Phase I
Ardley – Viking isochron



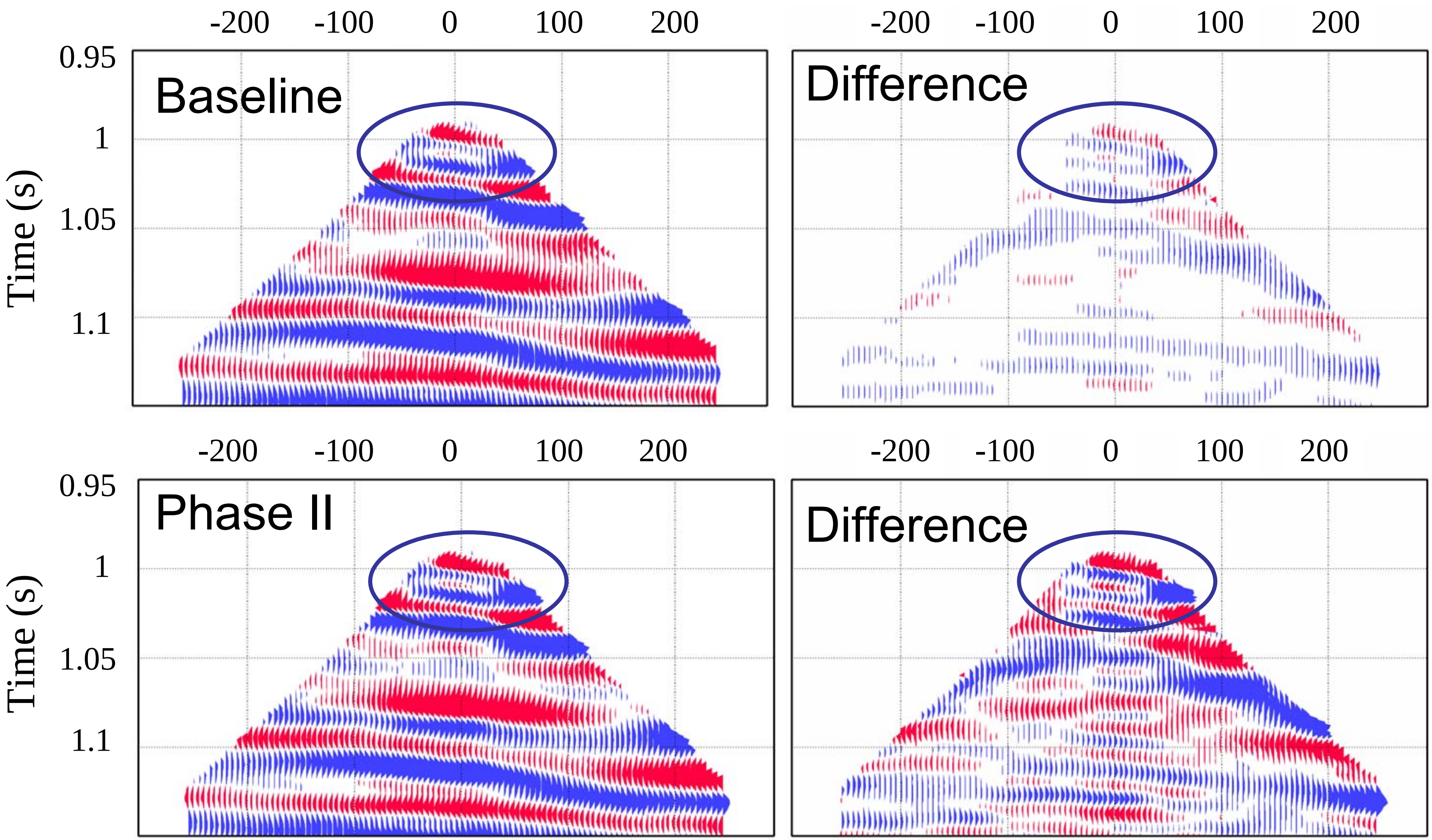
Viking – Ardley Δt (Phase II – Phase I)



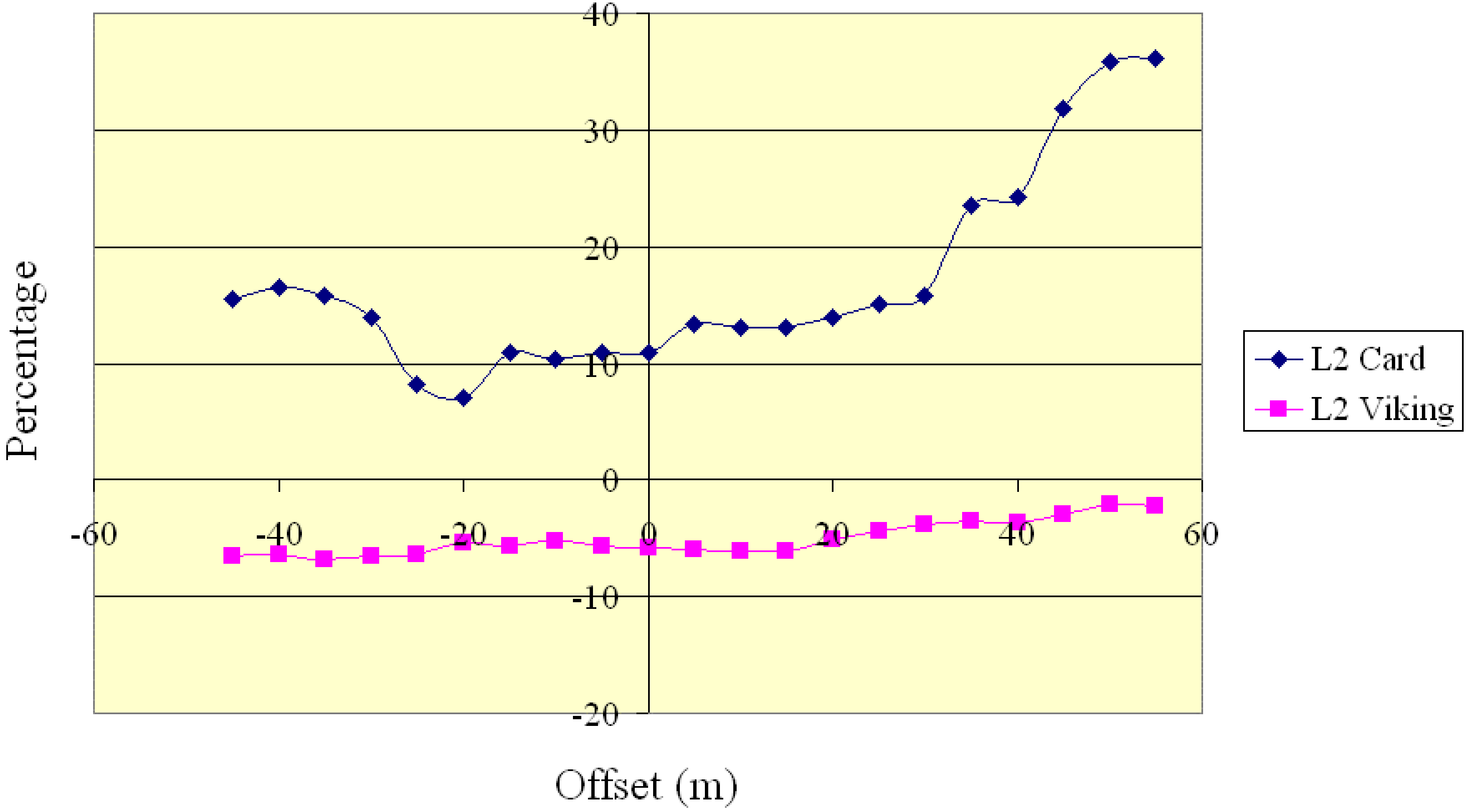
Line 3: PP Surface Seismic & VSP



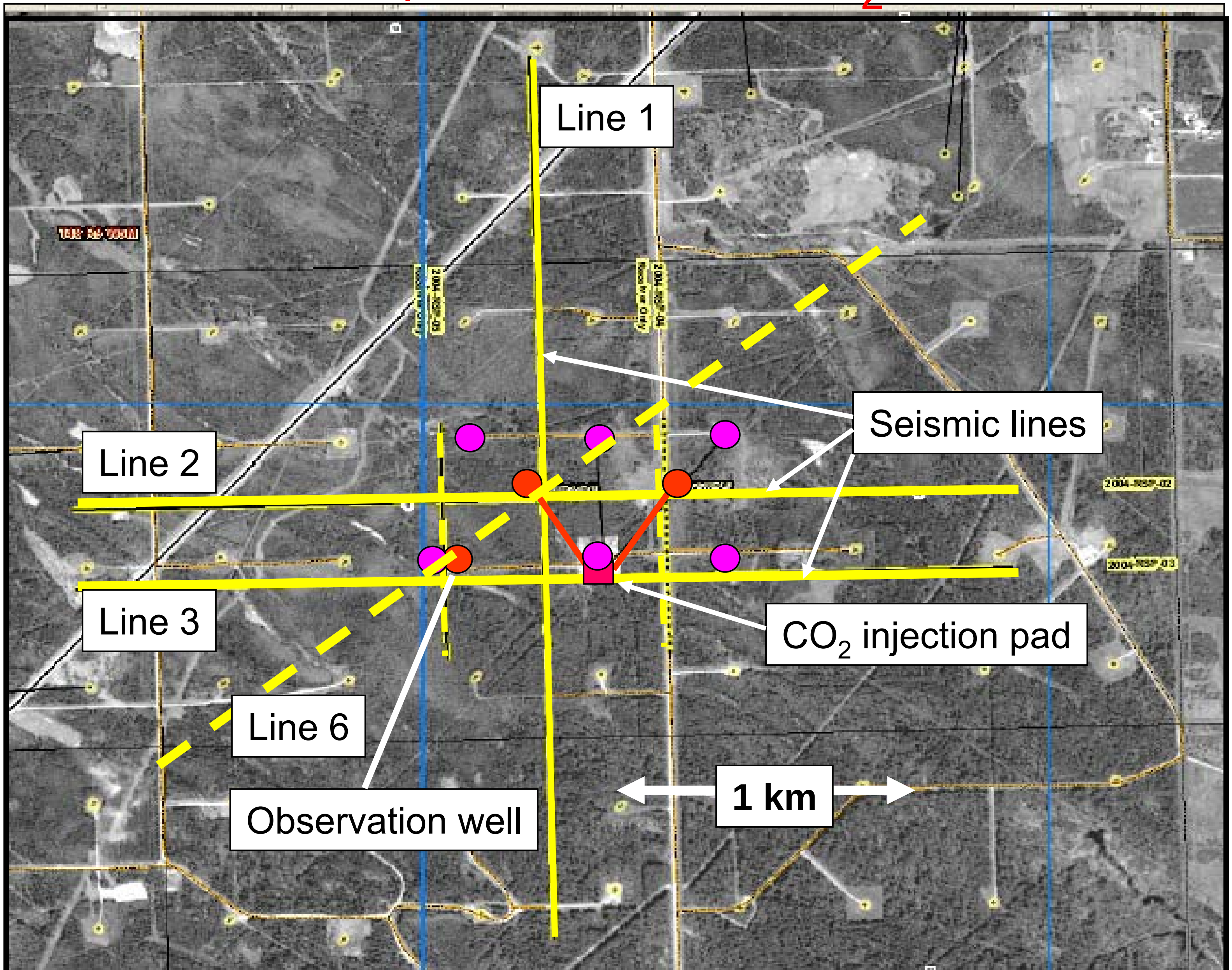
Timelapse VSP surveys – processed data



VSP amplitudes, Viking and Cardium events, Phase II – Phase I (Line 2)

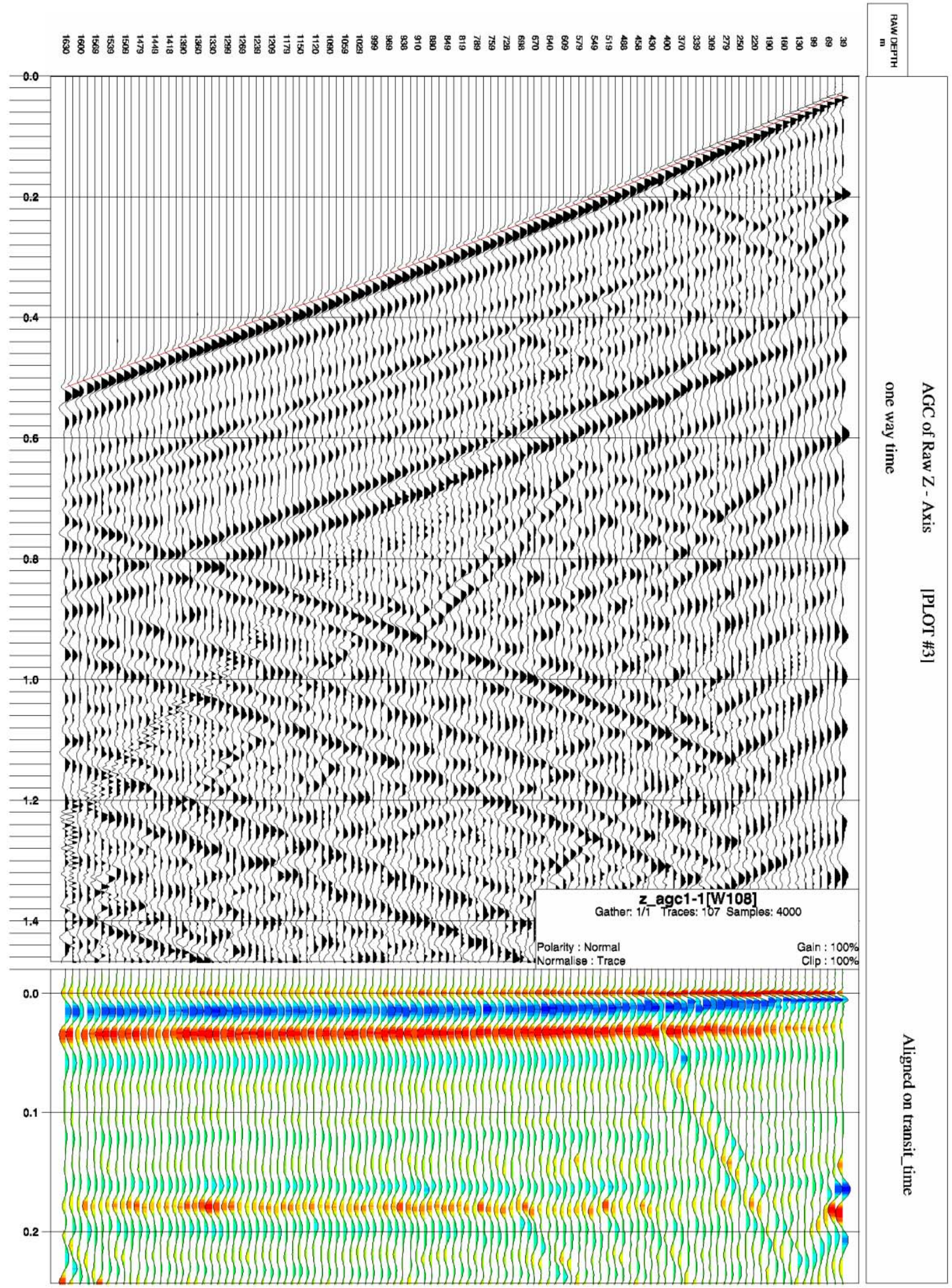


Seismic lines, Penn West CO_2 EOR Pilot

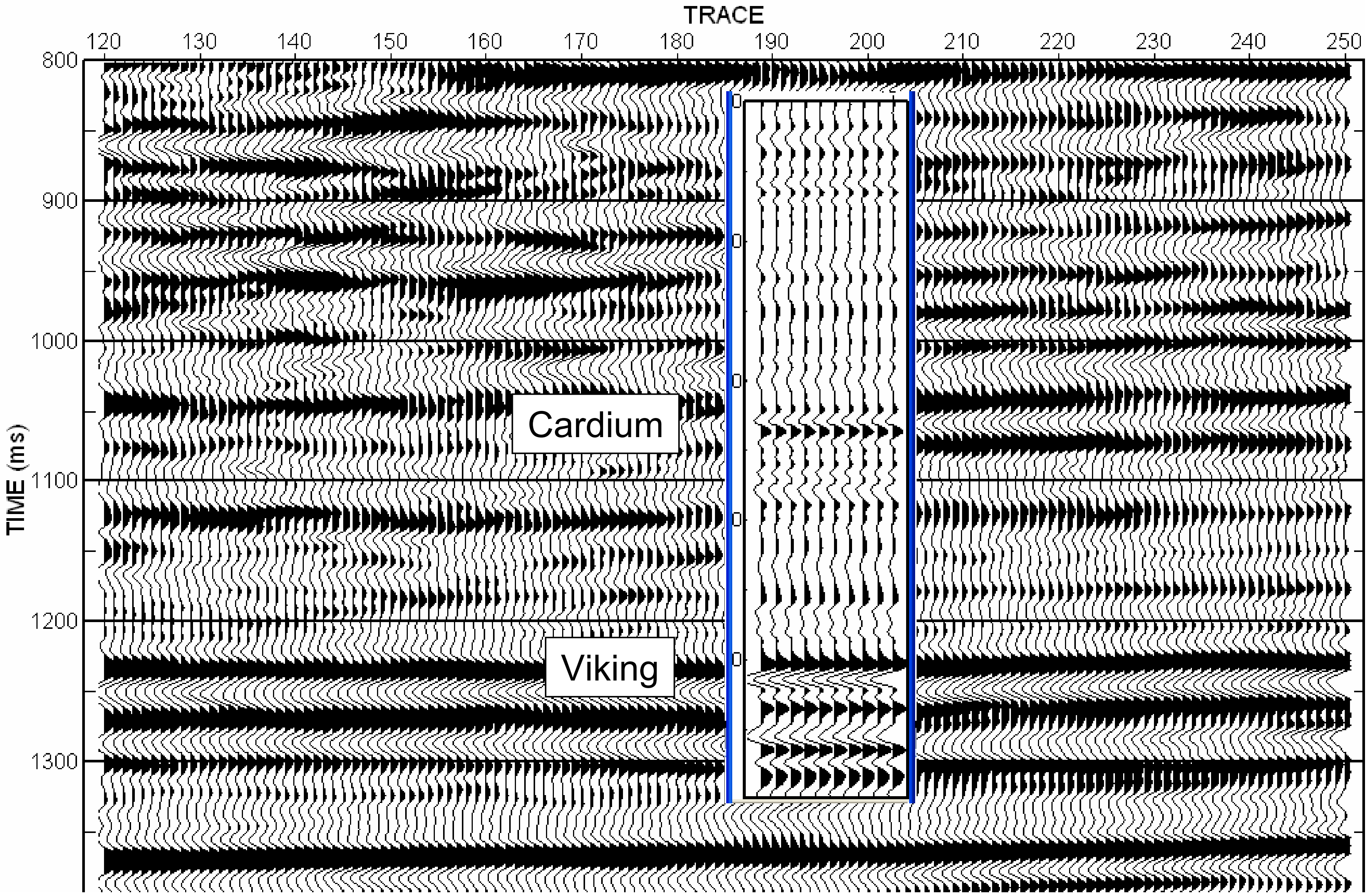



445
1110
0
1389.0

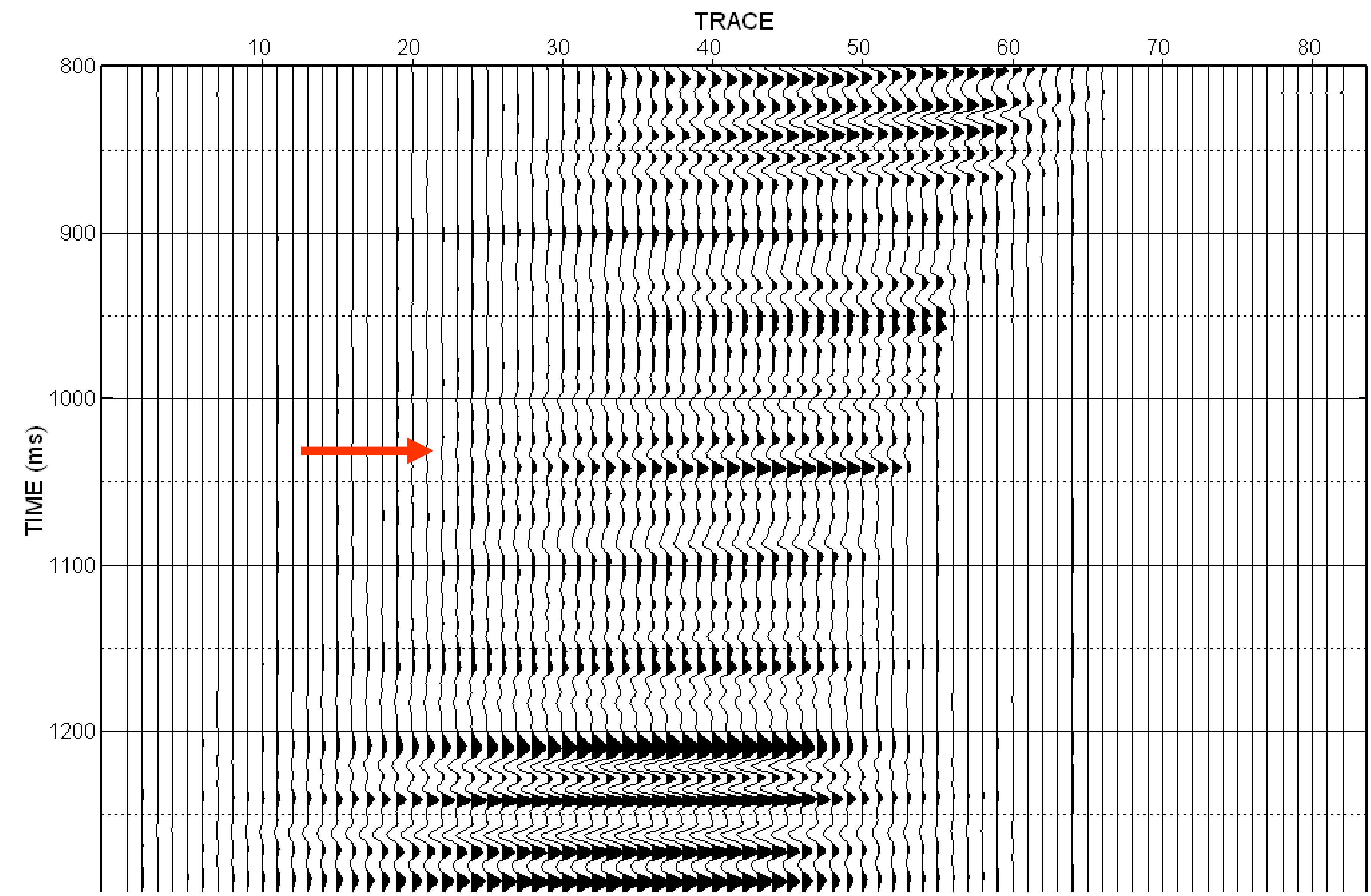
102/10-11 VSP
Raw data



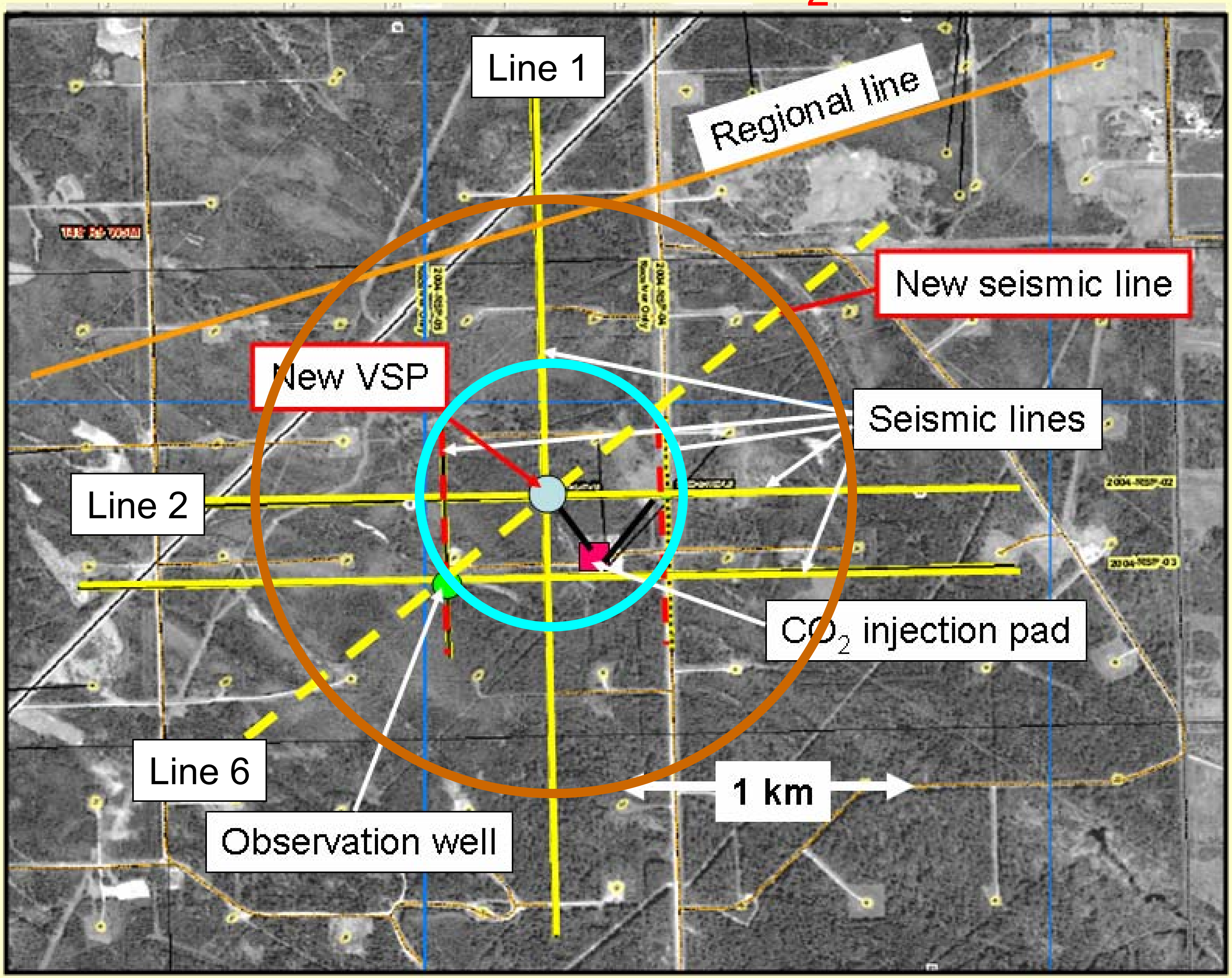
Surface seismic and VSP tie



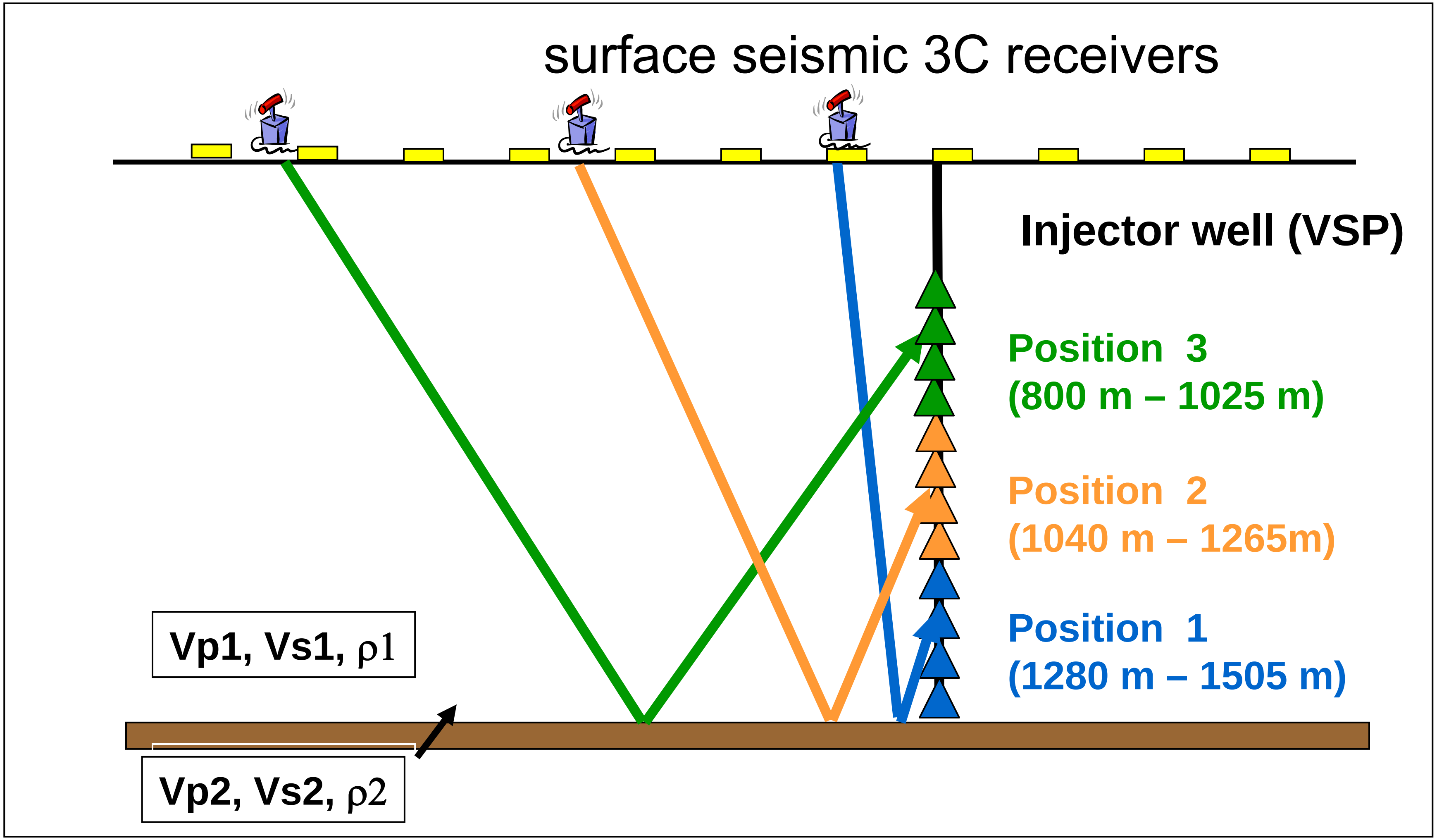
Offset VSP, migrated image



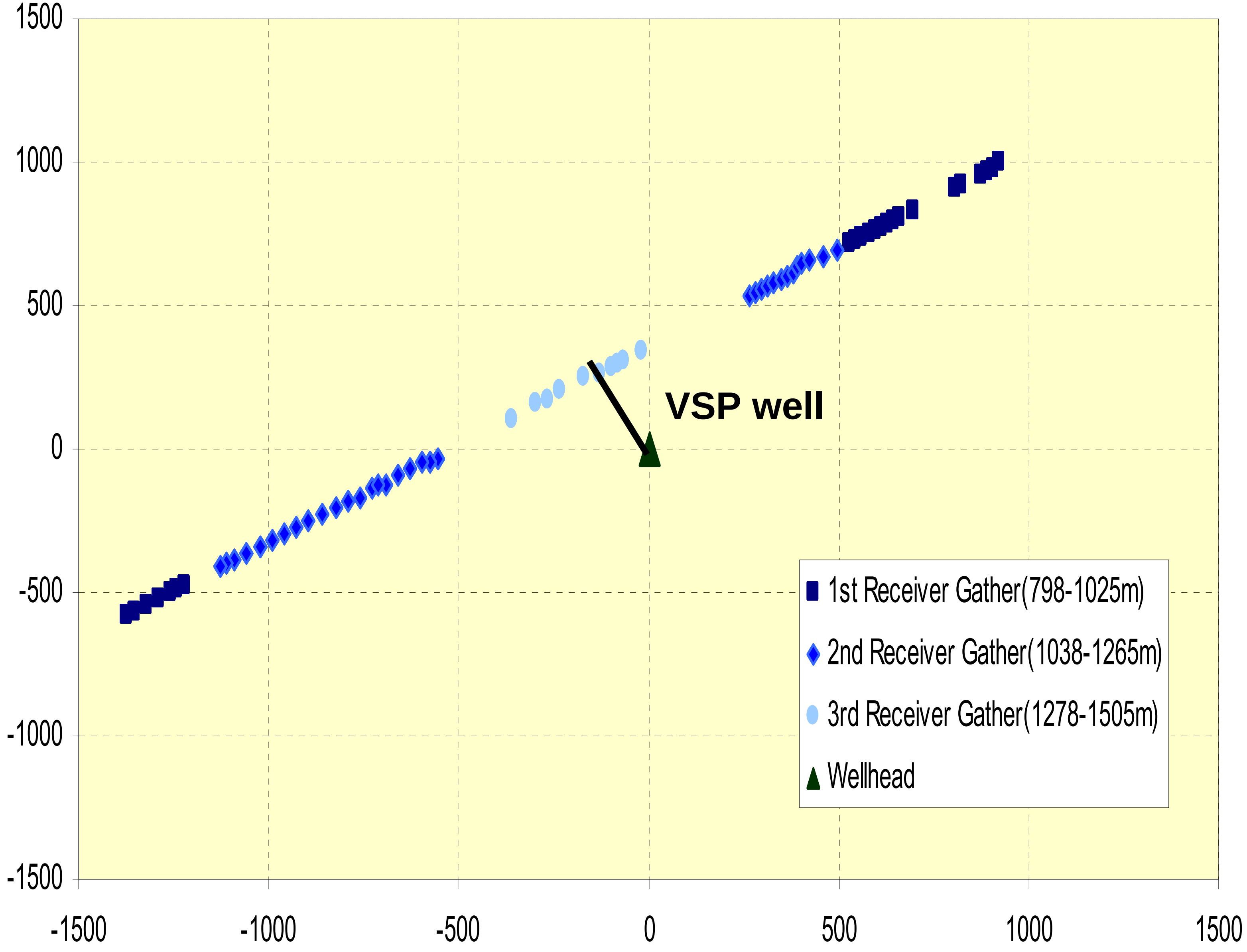
Phase III Penn West CO_2 EOR Pilot



Multicomponent surface seismic and vertical seismic profile (VSP)



Line 6 walkaway VSP



Discussion

- Surface seismic data integrated with local geological model
- No faults were mapped in pilot area
- Time-lapse seismic data indicates no leakage above reservoir, but difficult to track CO_2 within reservoir
- Timelapse VSP data exhibits amplitude change at Cardium event
- Passive monitoring continuing – no significant events recorded, but noise problems exist

Acknowledgements

- Alberta Energy Research Institute [AERI]
- Western Economic Diversification [WED]
- Natural Resources Canada [NRCan]
- CREWES & Dept staff and students
- Penn West Petroleum Ltd
- Veritas DGC
- Mike Jones (Schlumberger Canada)
- Landmark Graphics Corporation

Monitoring Results from Permanent Instrumentation Systems Deployed in Observation Well at Penn West CO2-EOR Pilot, Alberta, Canada

Gonzalo Zambrano
Rick Chalaturnyk
University of Alberta
Edmonton, Alberta, Canada

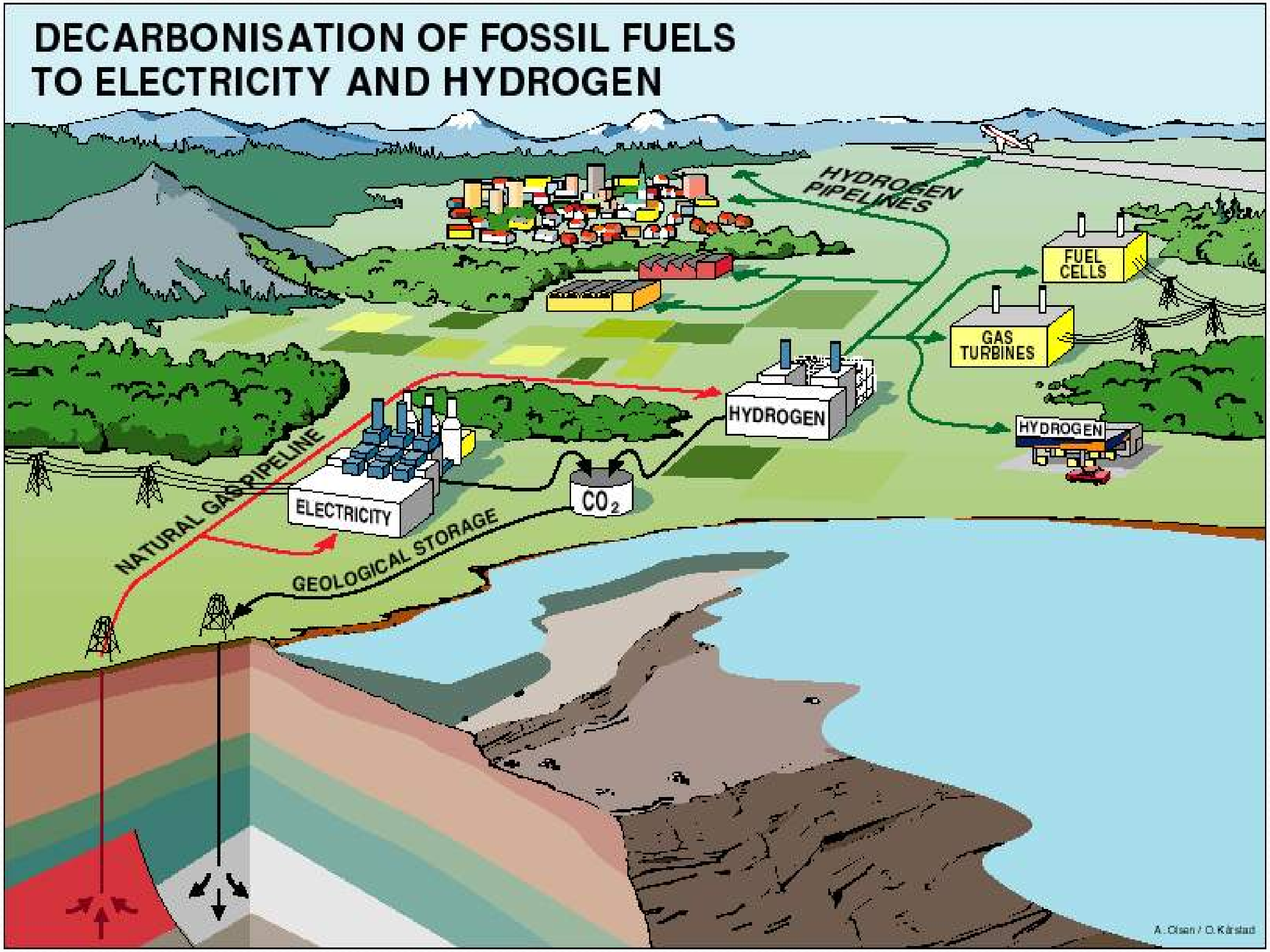
Reviews and Updates: CO_2 Projects

MMV Program Design, Deployment and Case Histories

Outline of Presentation

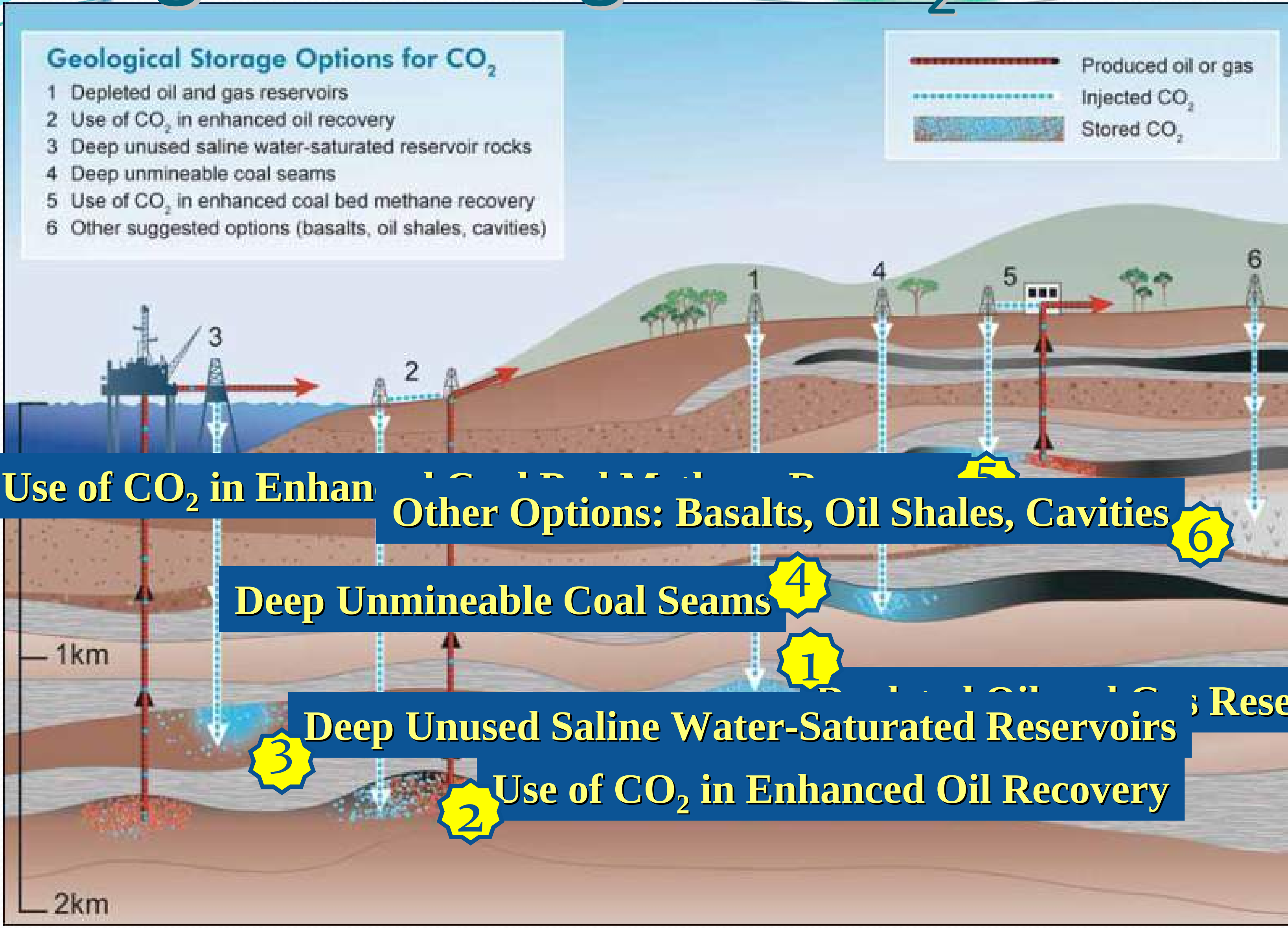
- Carbon Capture and Storage Overview
- Options for Geological Storage of CO_2
- Penn West CO_2-EOR Monitoring Project
- Integrated Instrumentation System in Observation Well
- Summary

Carbon Capture and Storage (CCS)



The production of electricity and hydrogen while capturing and storing the CO_2

Geological Storage of CO_2



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PENN WEST ENERGY TRUST

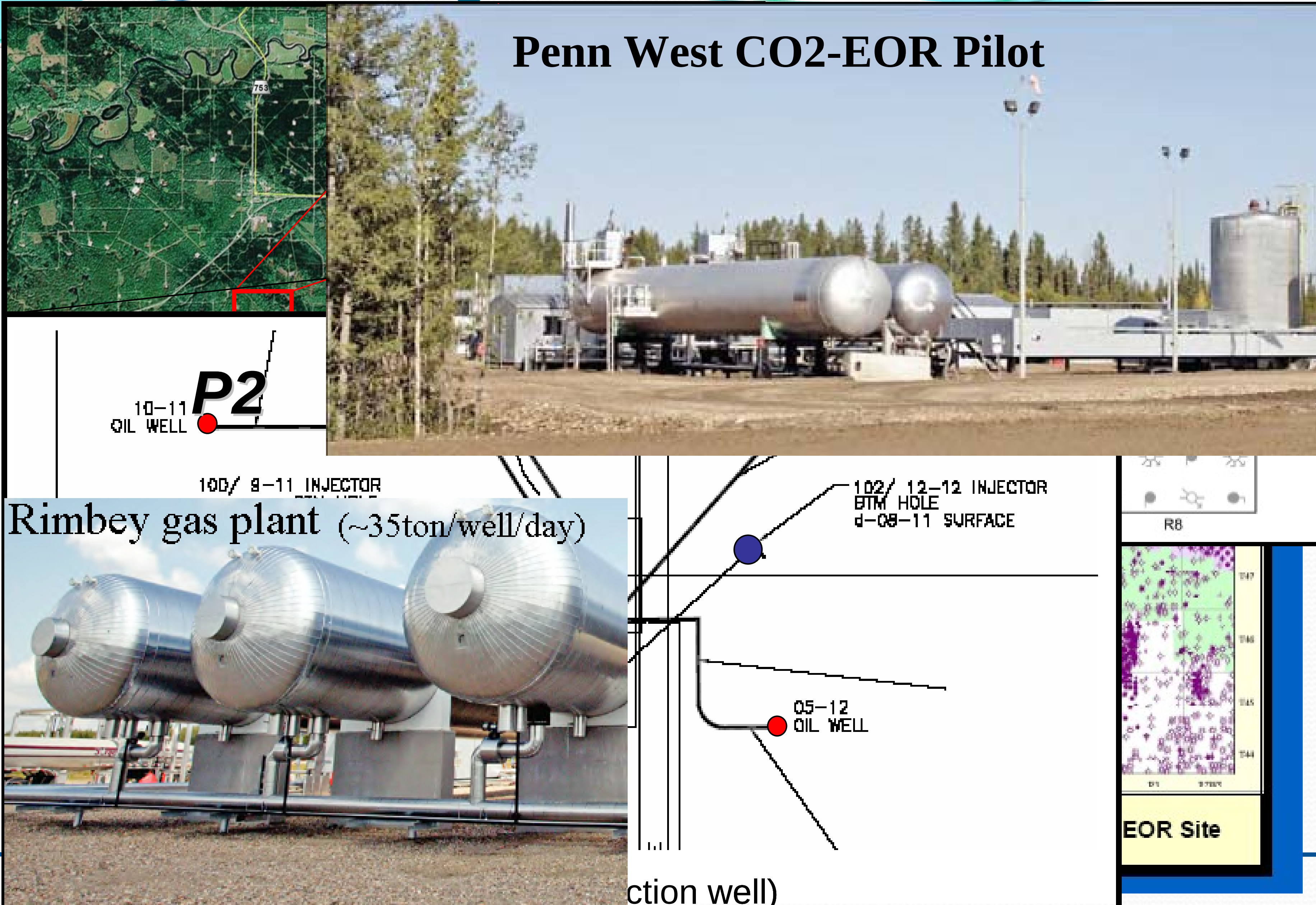
AERI
Alberta Energy Research Institute

University of Alberta

Penn West CO_2-EOR Monitoring Pilot Project

- A multi-year, multi-agency project for the monitoring of CO_2 used for an enhanced oil recovery pilot in central Alberta owned and operated by Penn West Energy Trust.
- The Alberta Energy Research Institute, Alberta Environment, Western Economic Diversification, Environment Canada, Natural Resources Canada and Penn West Energy Trust are partners in this three-year CO_2 monitoring pilot project, the first of its kind in Alberta.
- Five organizations involved in research program
  - Penn West Energy Trust
  - Alberta Research Council
  - Alberta Geological Survey
  - University of Calgary
  - University of Alberta

Penn West CO_2-EOR Pilot Location



Penn West CO2-EOR Monitoring Pilot Project

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

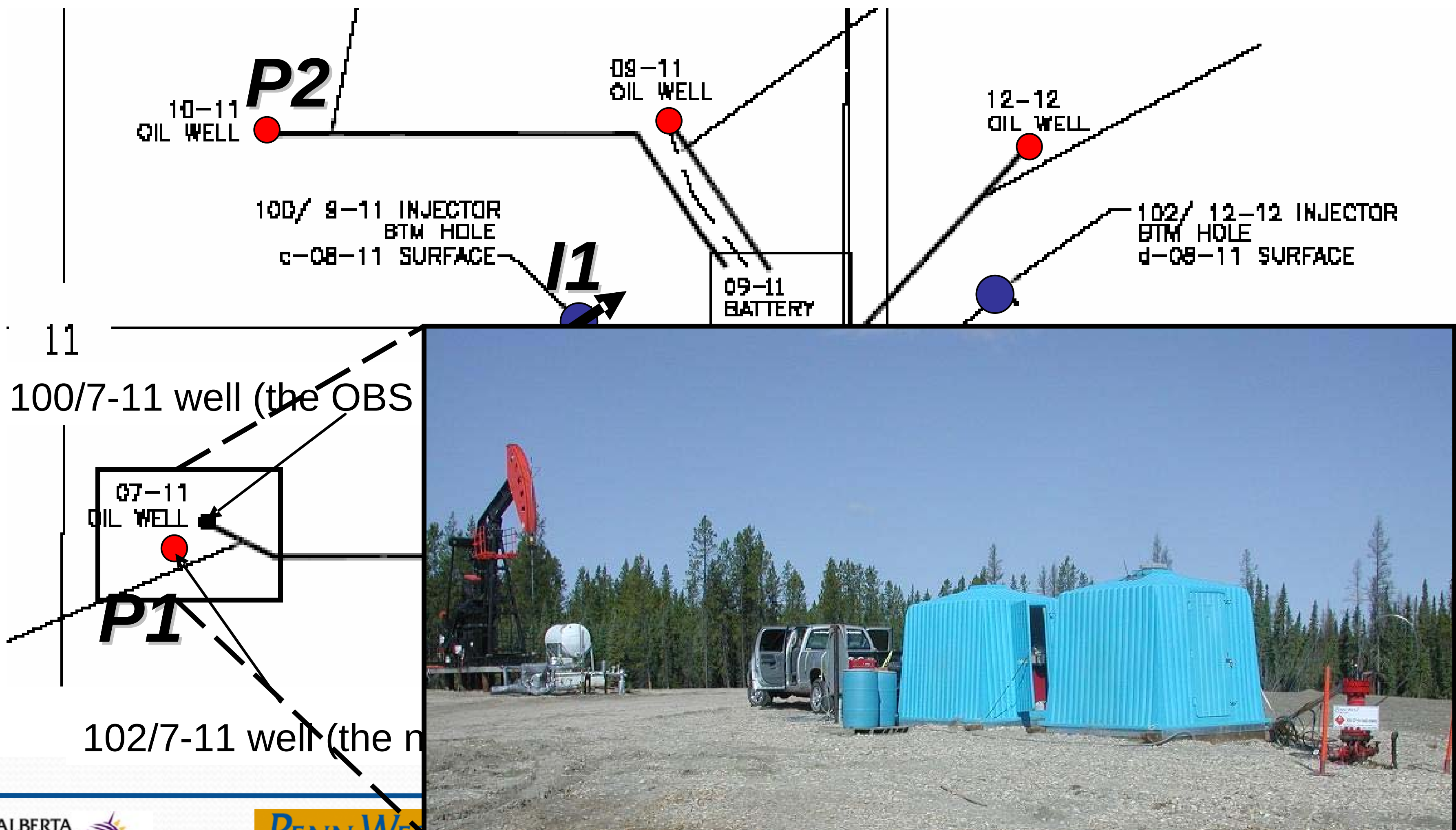
Goals of Research Program

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

Elements of the Integrated Instrumentation System

- **Overview of Instrumentation Well Design**
- **Remote Access to Data**
- **Wellbore Completion**
- **P/T Data Interpretation**
- **Fluid Sample System**

Observation Well, 6 Production Wells and 2 CO2 Injection Wells



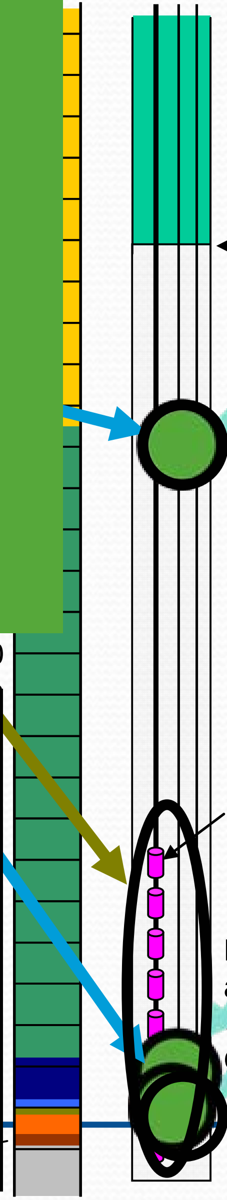
Geology and Design Com

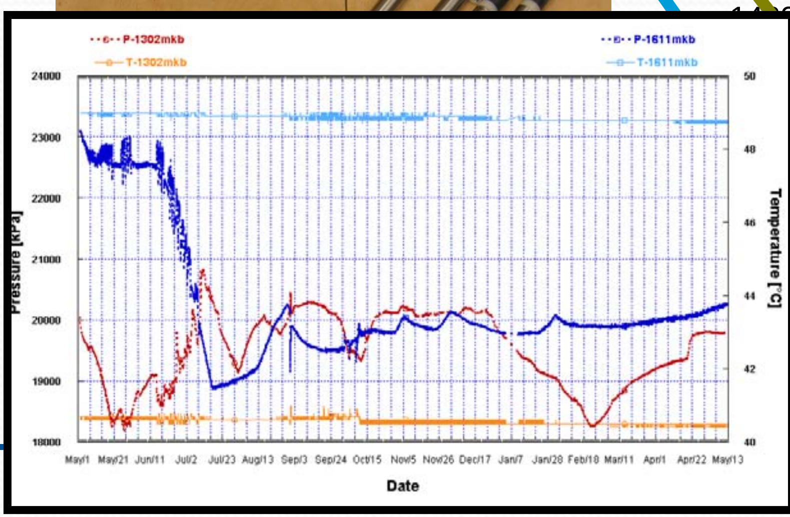
SUBSURFACE PRESSURE:

• Formation pressure

• Annulus pressure

• Groundwater aquifer pressure



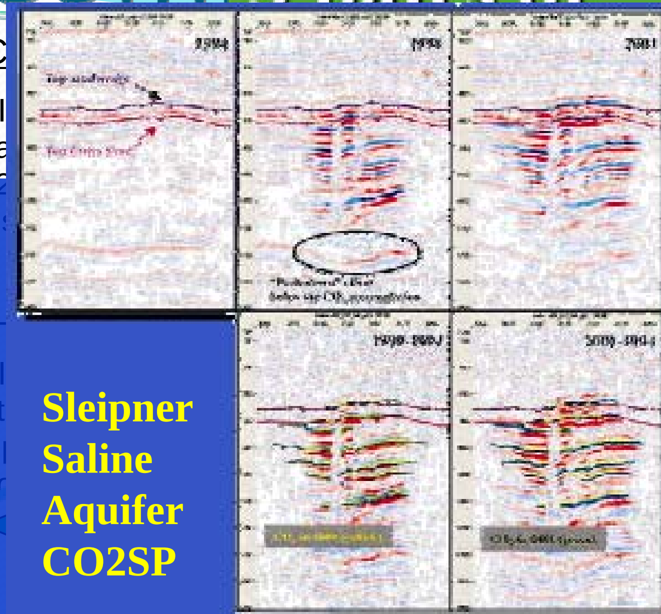


3 pairs of

ment

ON:

Sleipner Saline Aquifer CO2SP



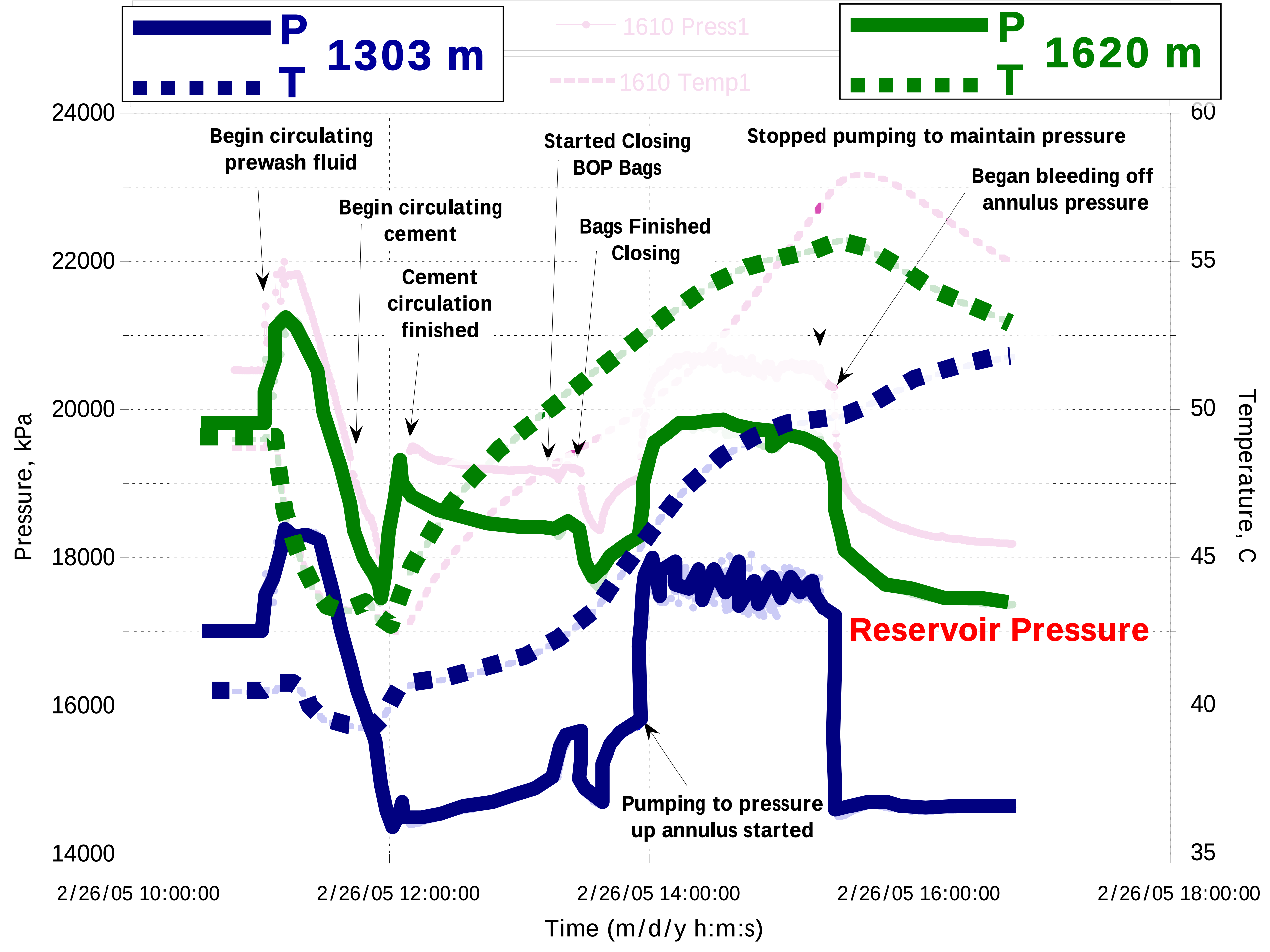
• Salinity

Time-lapse 3D seismic imaging:

•P and S wave velocity

•Reflection horizons

•Seismic amplitude attenuation



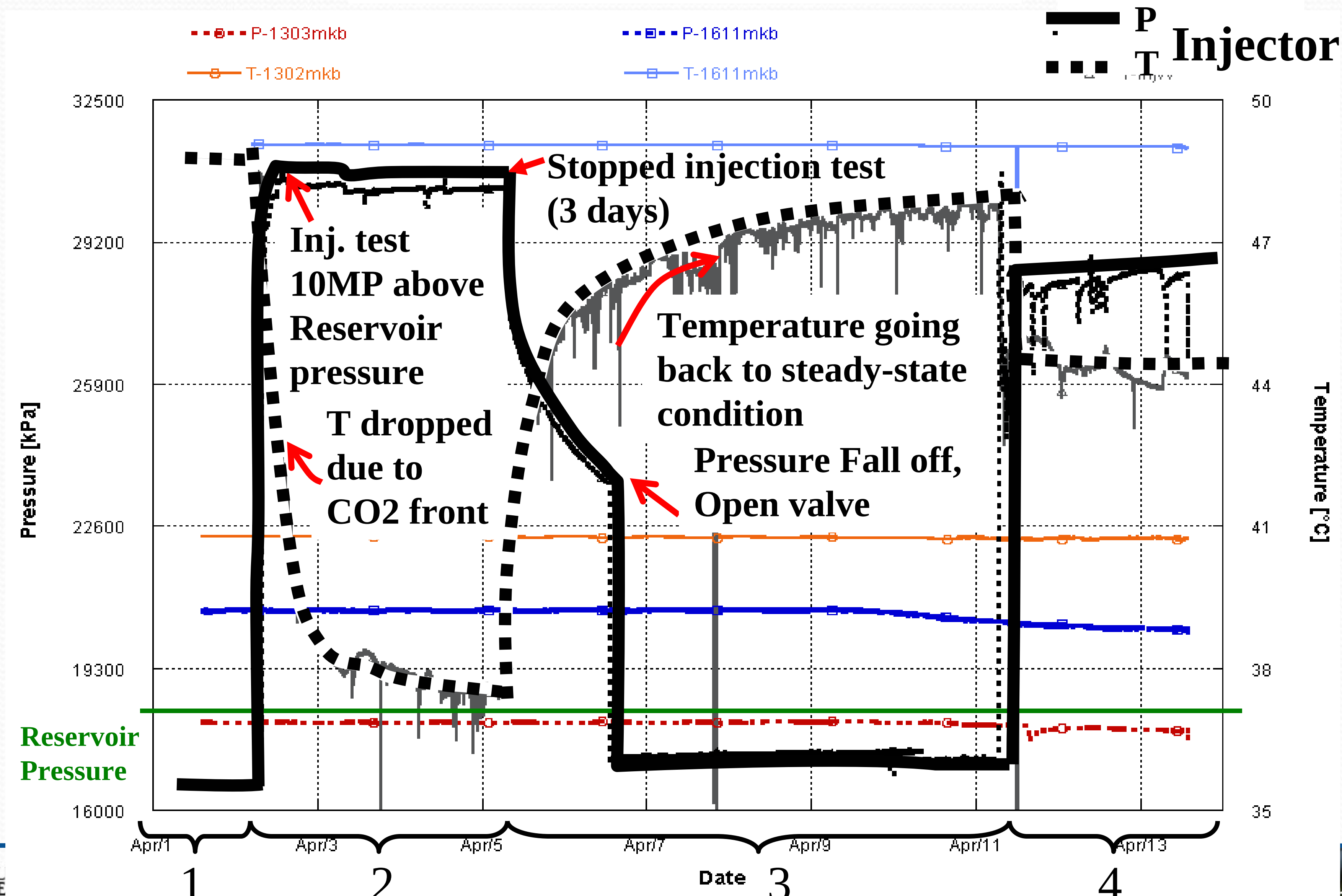
P
T
1303 m
1610 Press1
1610 Temp1
P
T
1620 m
Begin circulating prewash fluid
Begin circulating cement
Cement circulation finished
Started Closing BOP Bags
Bags Finished Closing
Stopped pumping to maintain pressure
Began bleeding off annulus pressure
Reservoir Pressure
Pumping to pressure up annulus started
Pressure, kPa
Temperature, C
24000
22000
20000
18000
16000
14000
60
55
50
45
40
35
2/26/05 10:00:00
2/26/05 12:00:00
2/26/05 14:00:00
2/26/05 16:00:00
2/26/05 18:00:00
Time (m/d/y h:m:s)


HYDRIL
DANGER


TELLUS T22

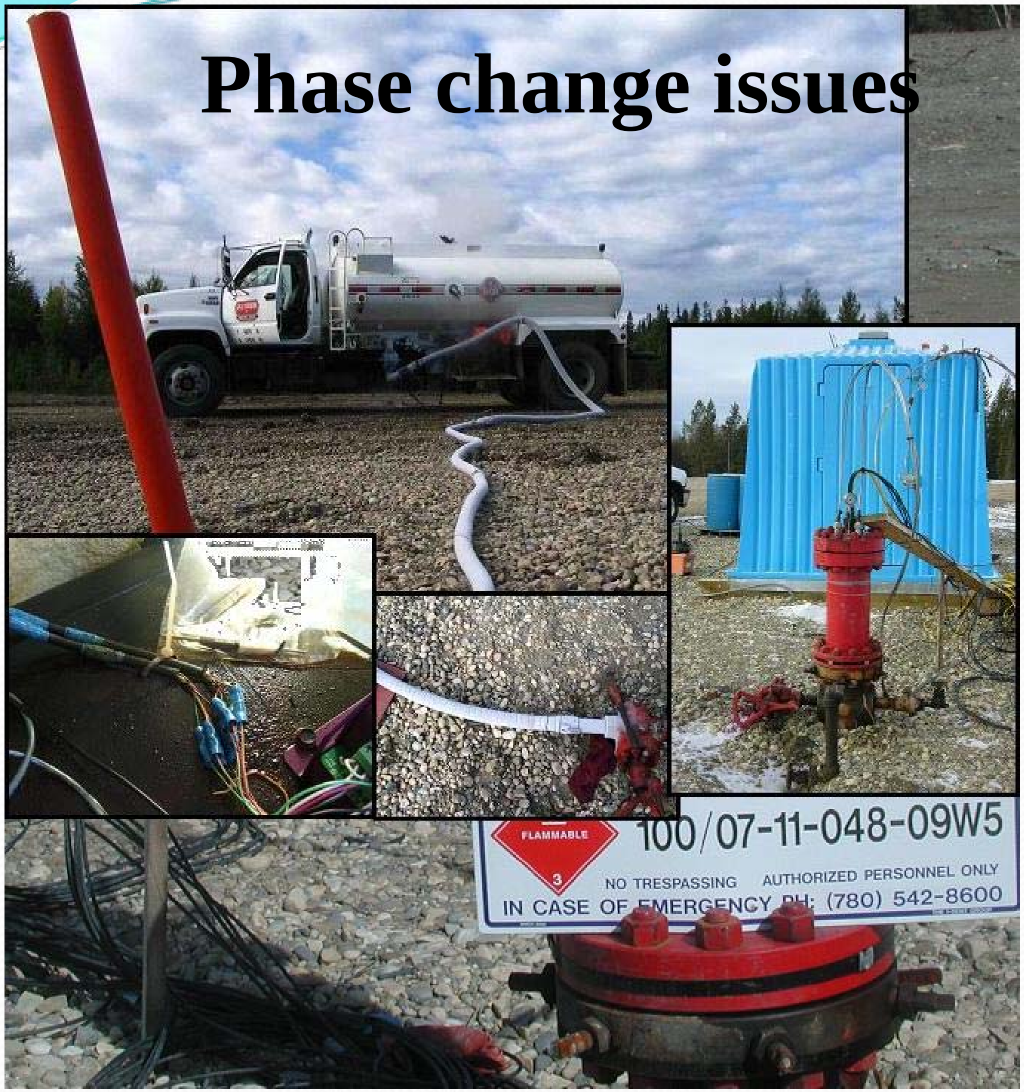
Early P/T Reading

4. System on production



Pressure and Temperature Assessment

Phase change issues



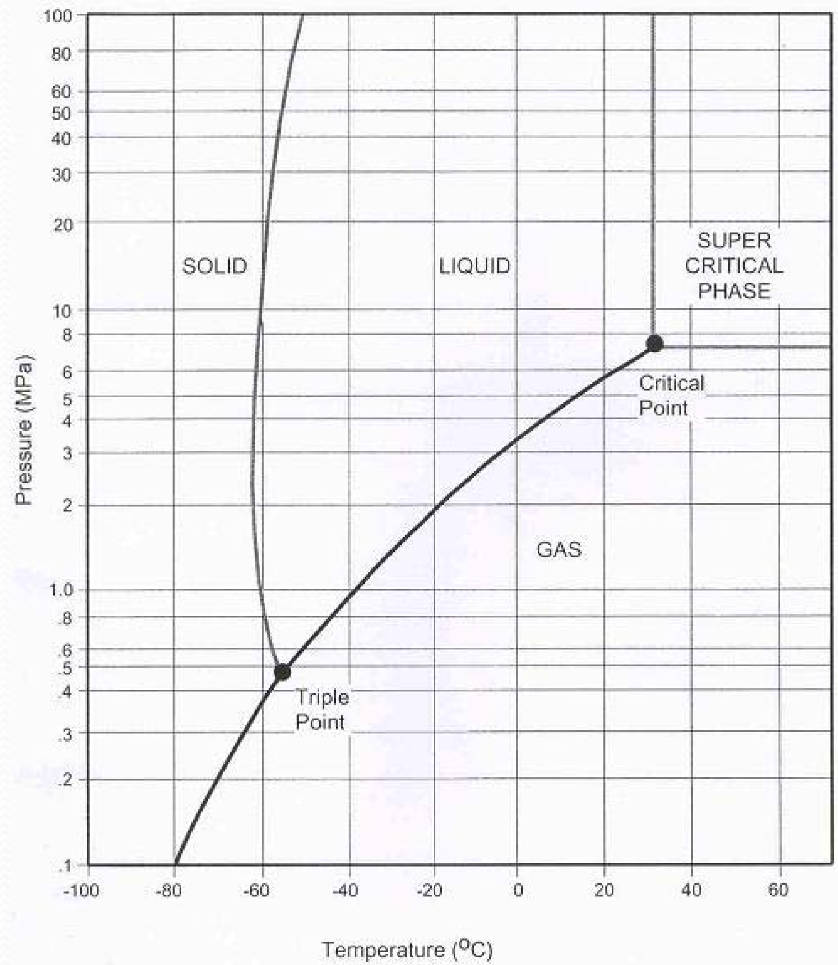


Figure 1: Carbon-dioxide phase diagram.

Leakage enhanced by CO_2 buoyancy.

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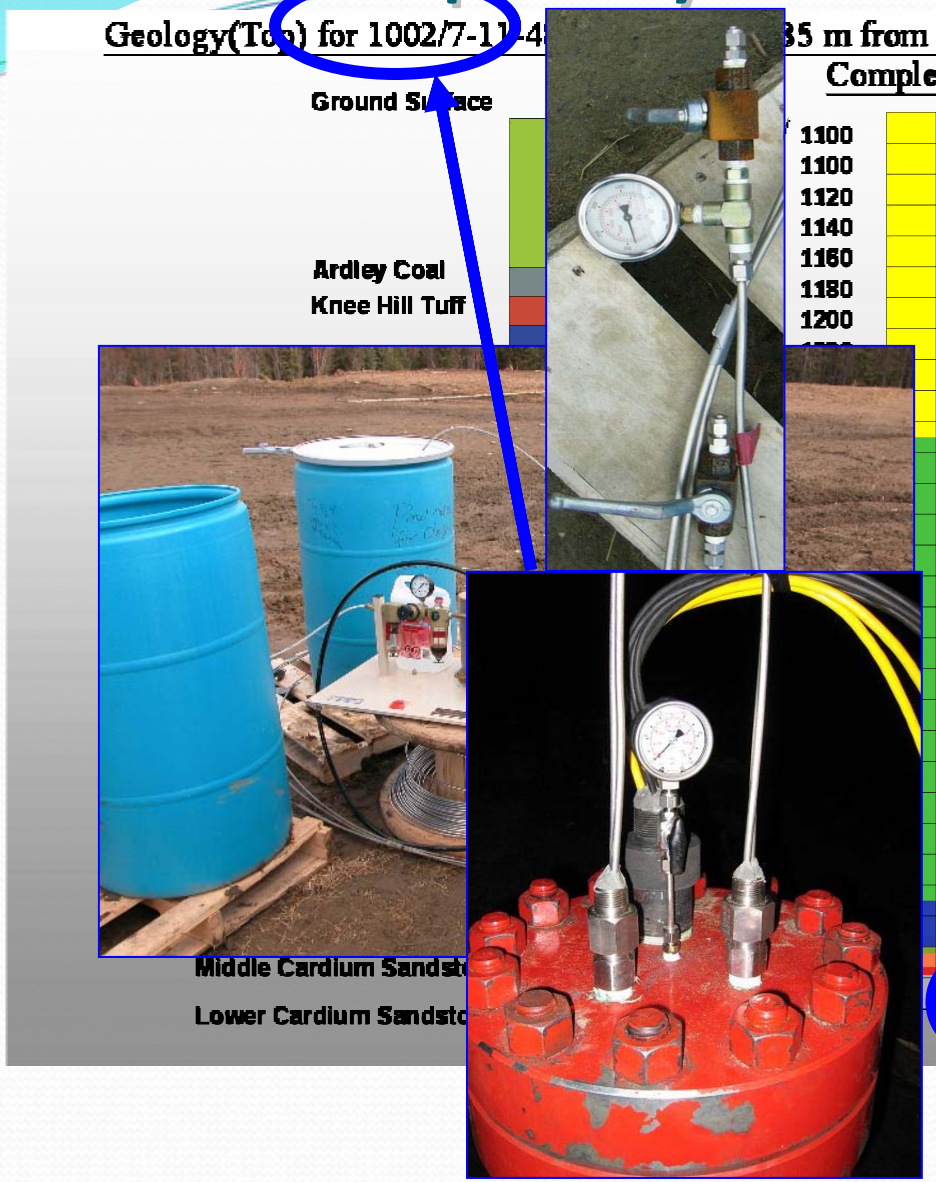
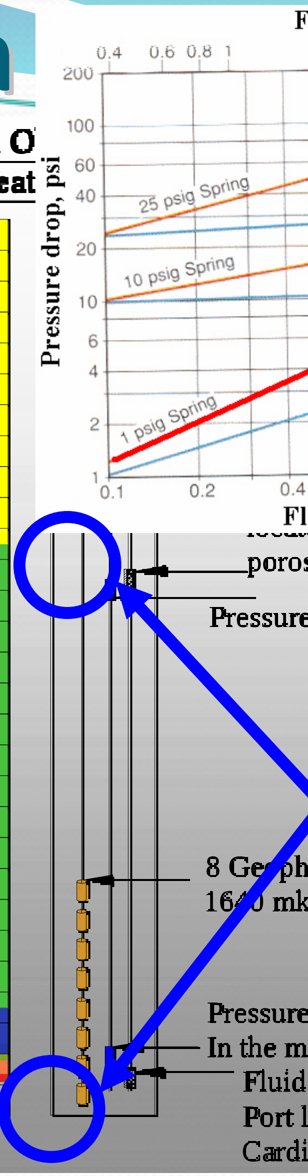
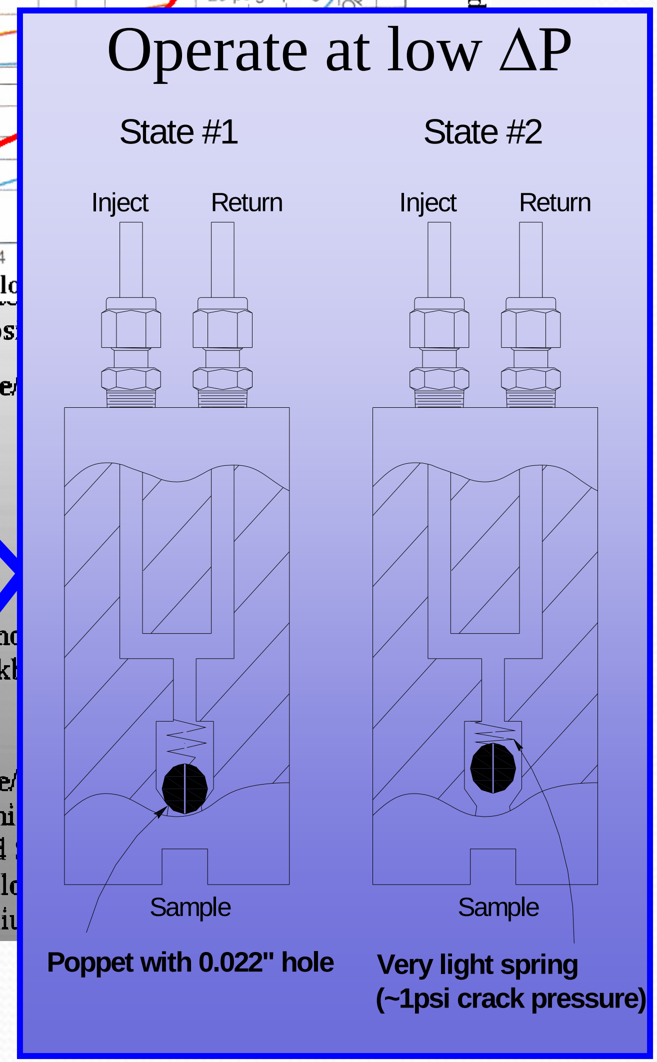
PENN WEST ENERGY TRUST
AERI Alberta Energy Research Institute
University of Alberta

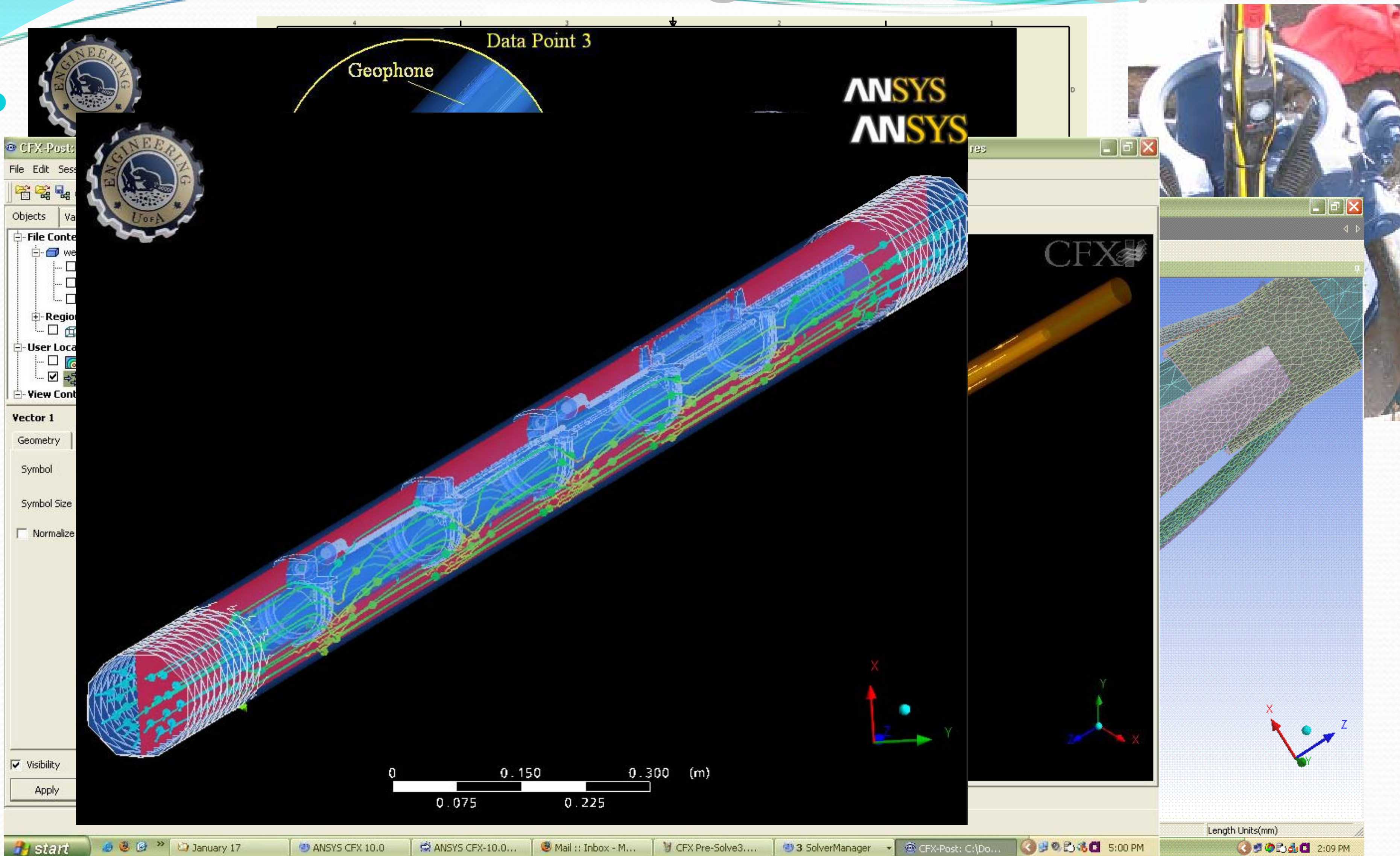
Fluid Sample System







Downhole Monitoring Technology



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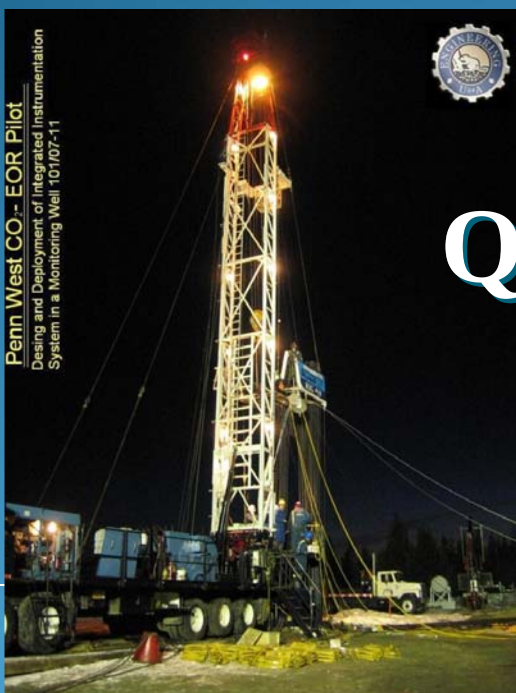
PENN WEST ENERGY TRUST

AERI Alberta Energy Research Institute

University of Alberta

Monitoring Results from Permanent Instrumentation Systems Deployed in Observation Well at Penn West CO2-EOR Pilot, Alberta, Canada



Questions

Gonzalo Zambrano
Rick Chalaturnyk
University of Alberta
Edmonton, Alberta, Canada

Shallow Subsurface and Air Monitoring Program at Penn West CO_2-EOR Monitoring Project

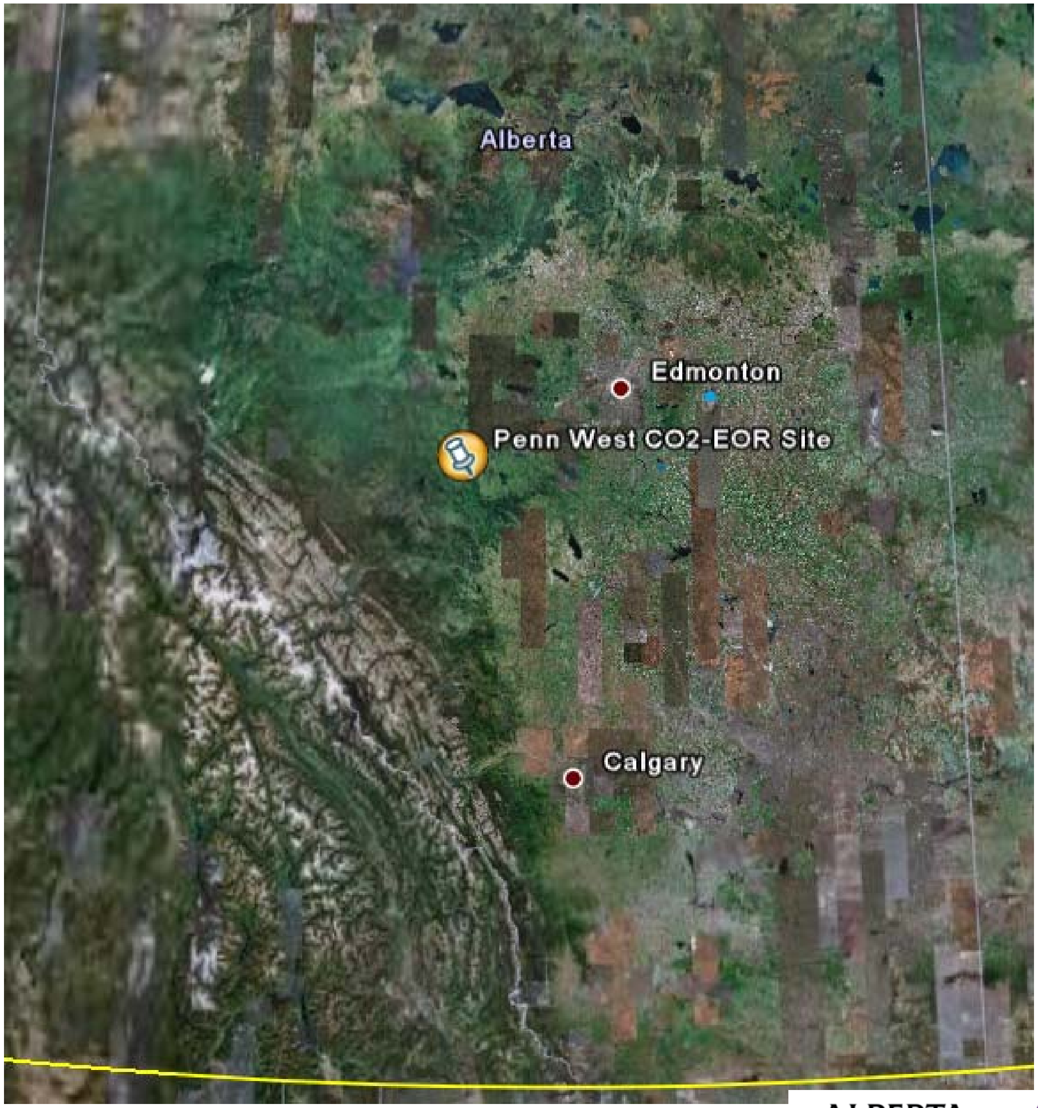
David van Everdingen,
Stephanie Trottier,
Stephen Talman,
W.D. Gunter
Alberta Research Council

November 9, 2007

Outline

- Introduction to Site
- Atmospheric Monitoring
- Shallow Subsurface Monitoring
- Groundwater monitoring
- Relationship to Reservoir
- Conclusions

Penn West CO_2-EOR Monitoring Project Site



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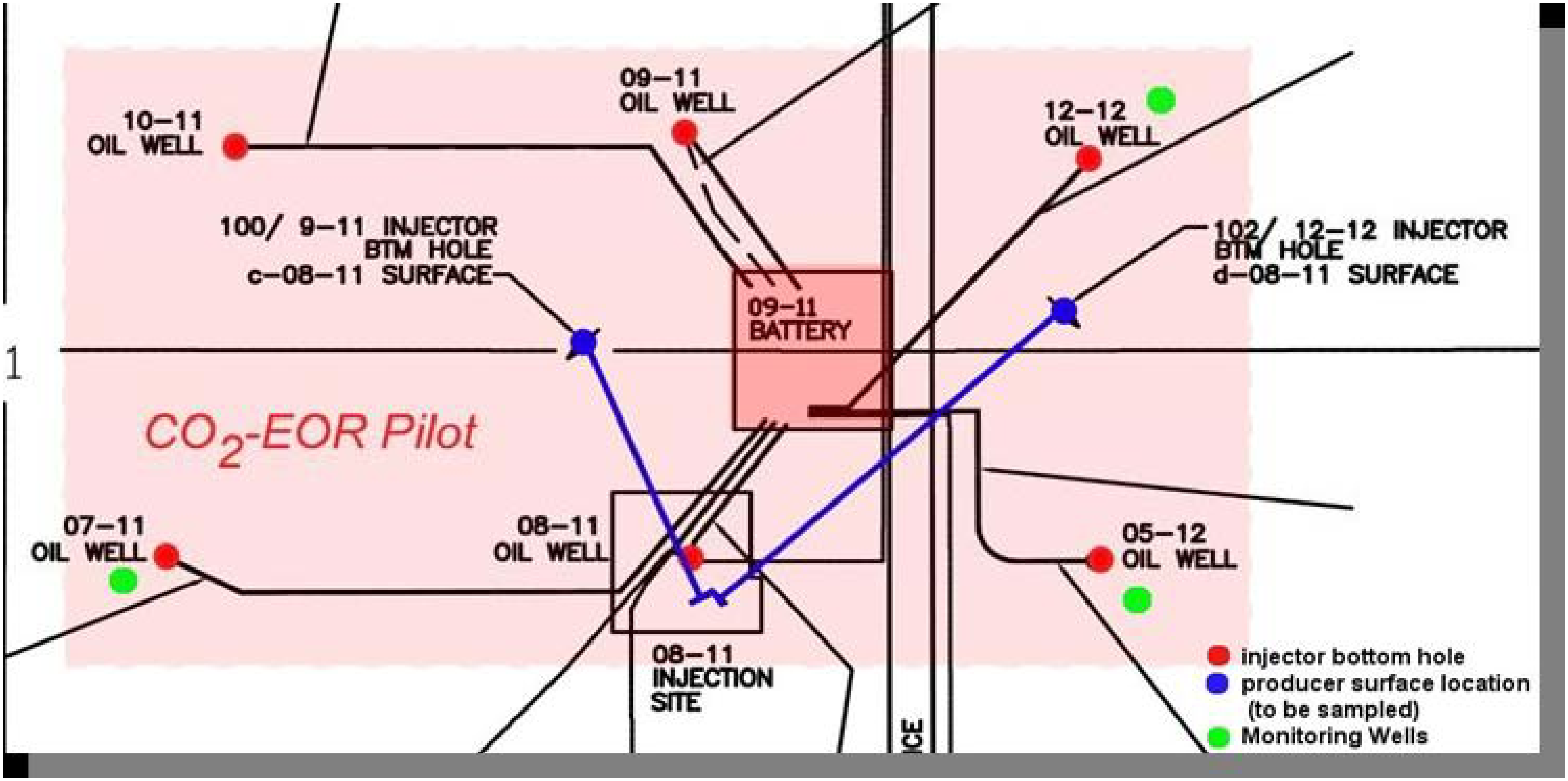
Penn West CO_2-EOR Site



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Atmospheric Monitoring

Atmospheric Monitoring - Introduction

- Investigate open path tunable diode laser technology to detect fugitive emissions of:
  - CO_2
  - CH_4
- Why tunable diode laser system?
  - averages out inhomogeneities of soil gas
  - mobility
  - cost
  - efficient monitoring of large sites
- Using technology from Boreal Laser Inc.

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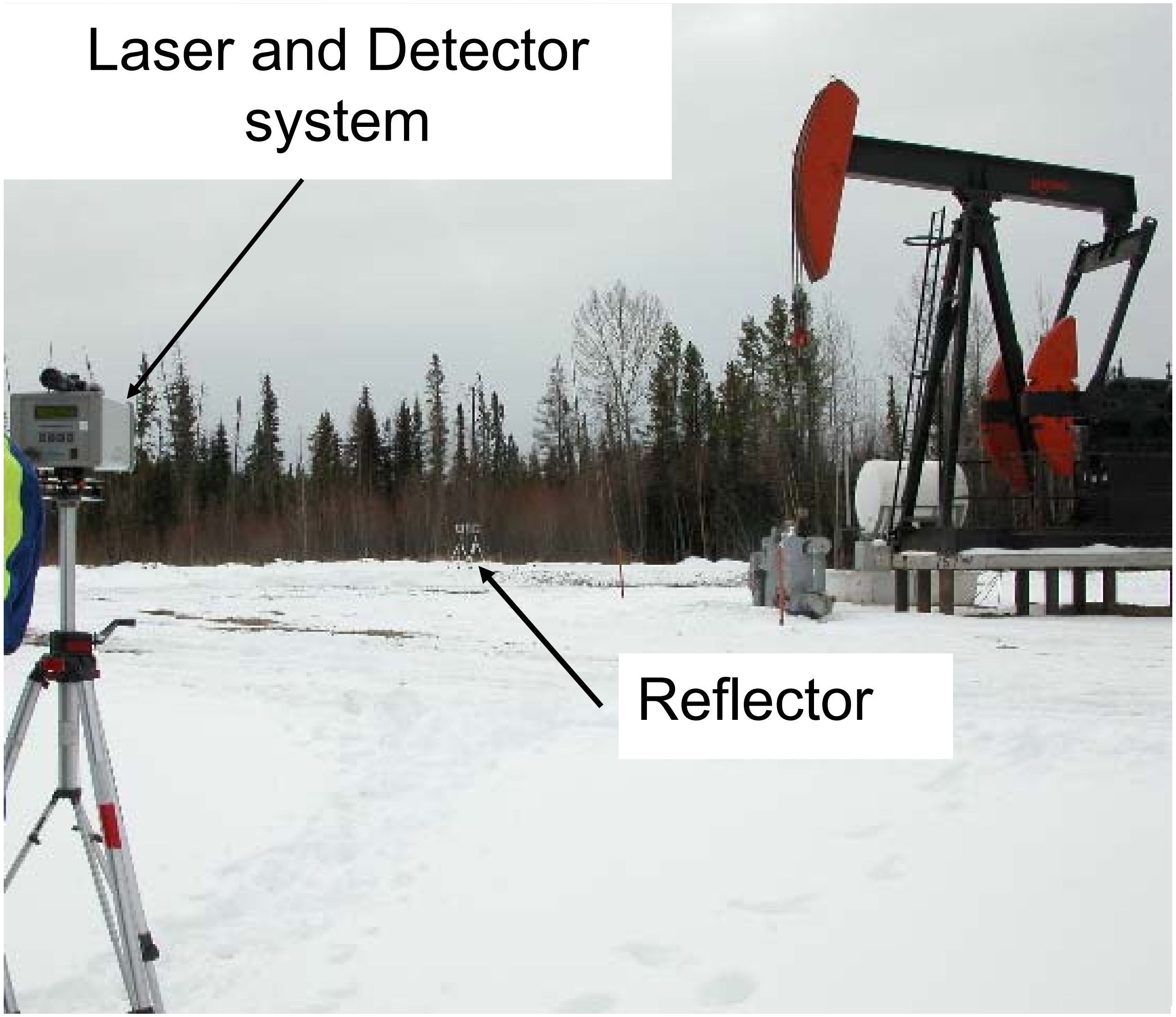
Experimental Setup



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Experimental Setup – cont'd

- Important to correlate measurements with weather assessment
- Weather station and sonic anemometer used

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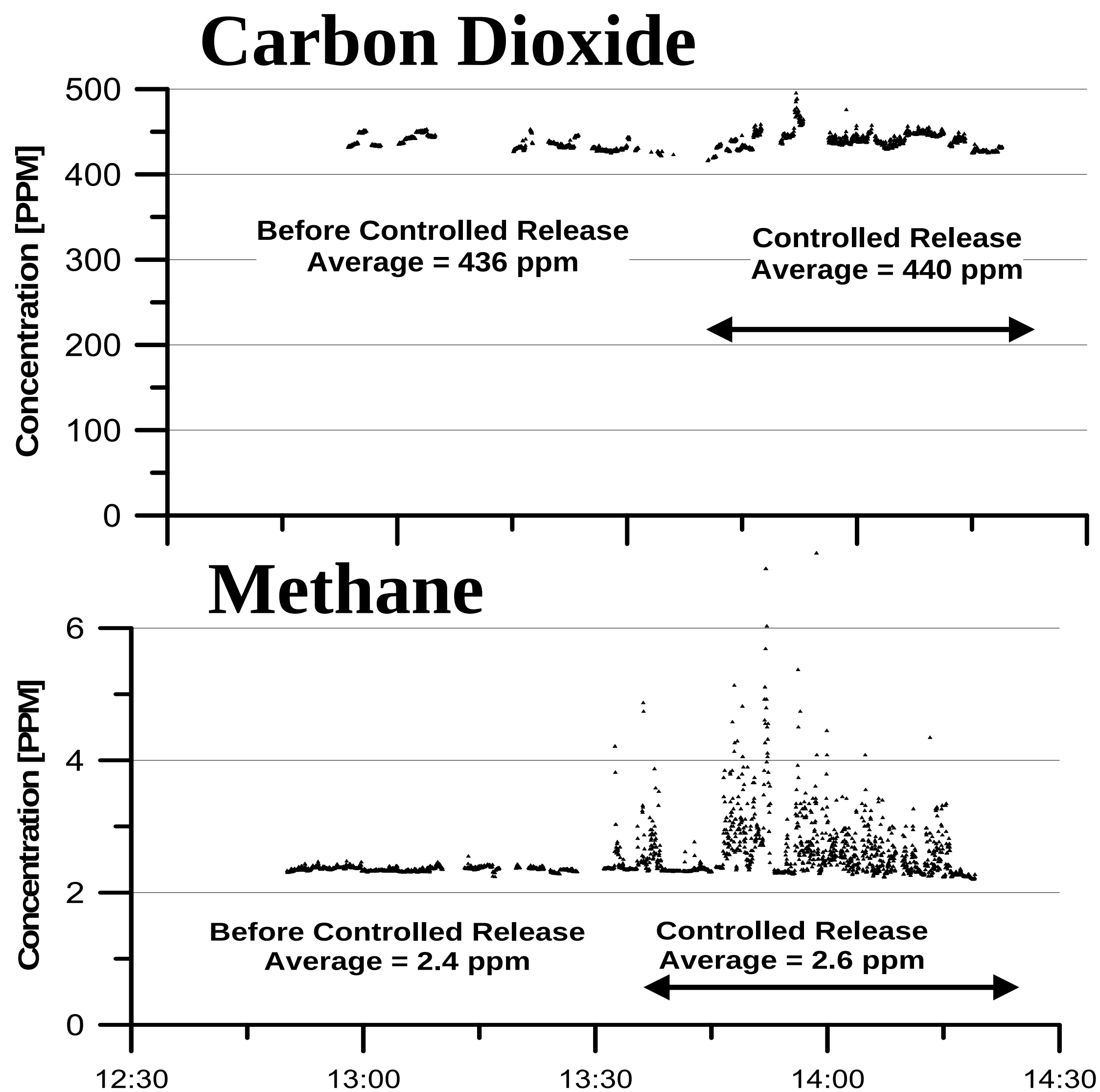
Experimental Setup – cont'd

- Methane
  - Expected background concentration ≈ 1.8 ppm
  - Sensitivity of system 1 ppm-m
- Carbon Dioxide
  - Expected background concentration ≈ 380 ppm
  - Sensitivity of system 1000 ppm-m
- Path length 1- 1000m
- Controlled Release were done to evaluate measurement sensitivity and accuracy

Controlled Releases

- Controlled release 30L/min of ~ 90% CO_2 and 10% CH_4
- Path length = 40m
- Source distance = 20m
- Wind speed =1.2m
- Methane detection very sensitive
- CO_2 system has lower sensitivity due to background concentration



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Site monitoring

- Instruments used to provide upwind and downwind emission measurement of well sites
- Baseline survey done at wells without CO_2 breakthrough
- 2 yearly follow up surveys done to date and one more planned
- No indication of increased fugitive emissions found at any of the well sites monitored

System Performance

- Measurement is path averaged
- Measurement is very dependent on a number of parameters:
  - Path length
  - Atmospheric stability
  - Wind speed
  - Wind direction
- Therefore, not a quantitative measurement
- Evaluate different ways to translate into a quantitative value

  e.g. Windtrax by ThunderBeach Scientific

  Radial Plume Mapping by Arcadis

Shallow Subsurface Monitoring

Shallow Groundwater Monitoring Well Installation

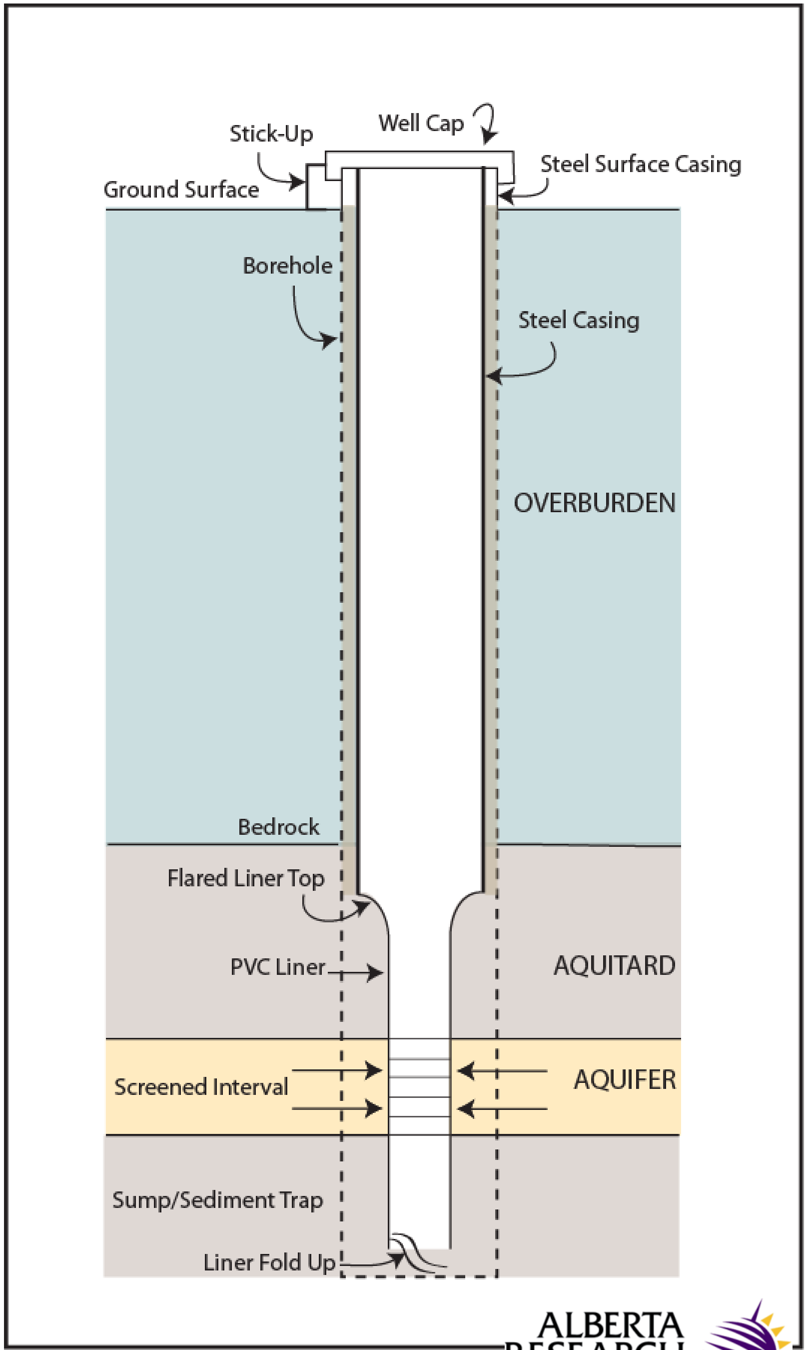
- 3 deep monitoring wells (28-47 m)
- 1 shallow observation well (6 m)

Well Installation

Well Schematic

General Lithology

- Overburden: Clayey or Clayey/Sand
- Aquitard: Shaley/Silty Bedrock
- Aquifer: Sandy/Silty Bedrock



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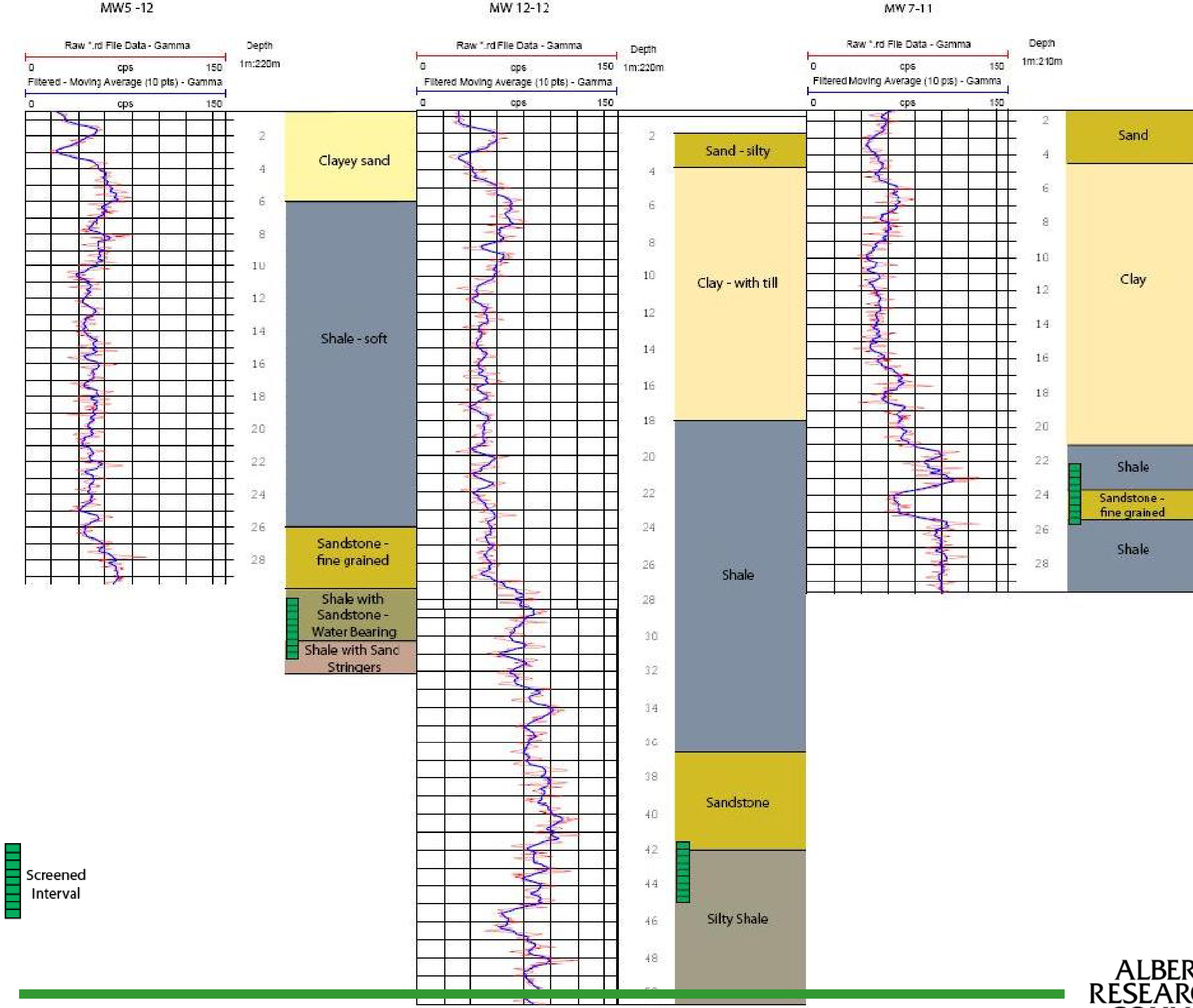
Lithologic and Gamma Logging



Groundwater Monitoring
Water Levels

Instrumentation

- Integrated pressure transducer and data loggers
- Installed in each monitoring well
- Atmospheric pressure monitored at one location

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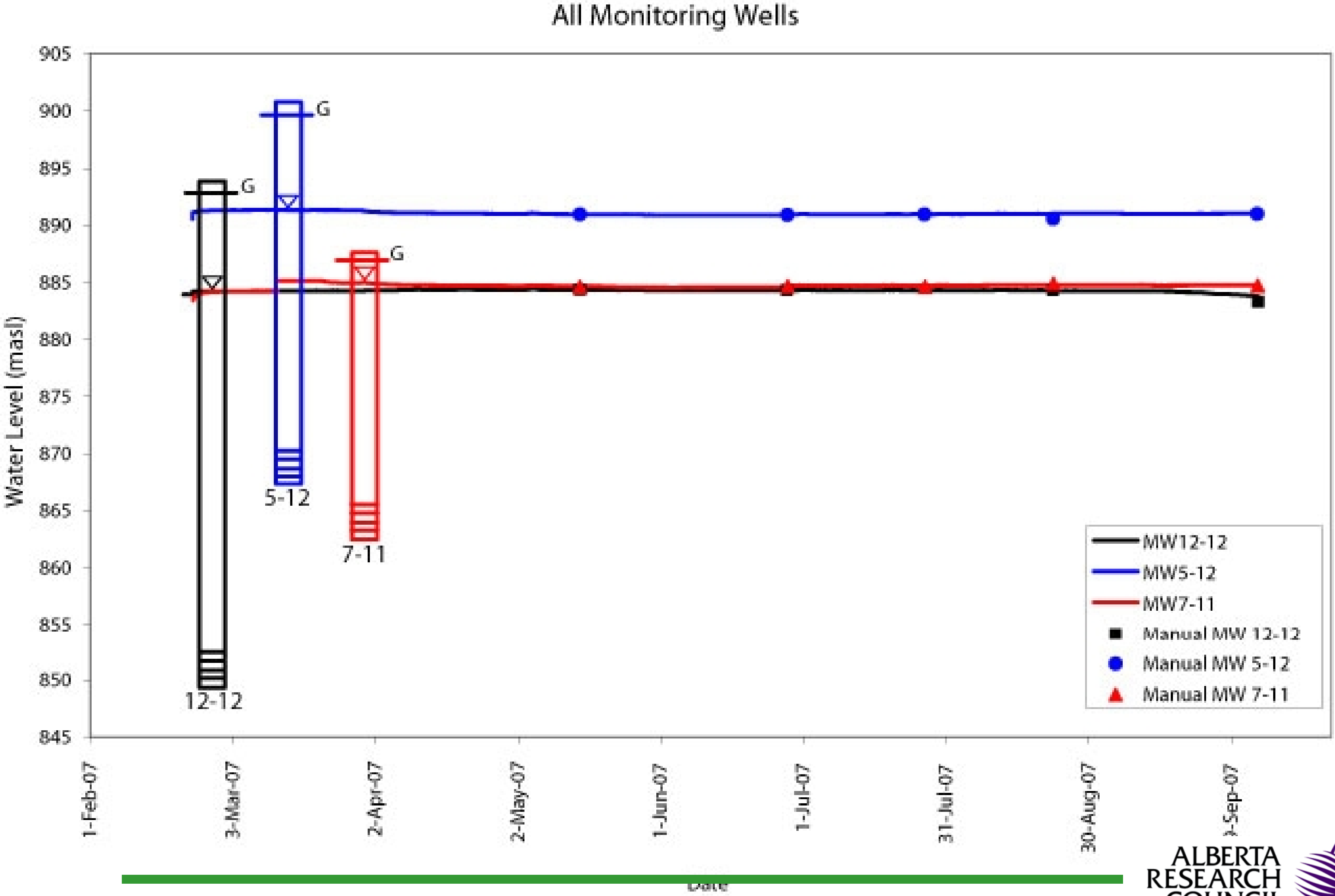
Water Levels over Time



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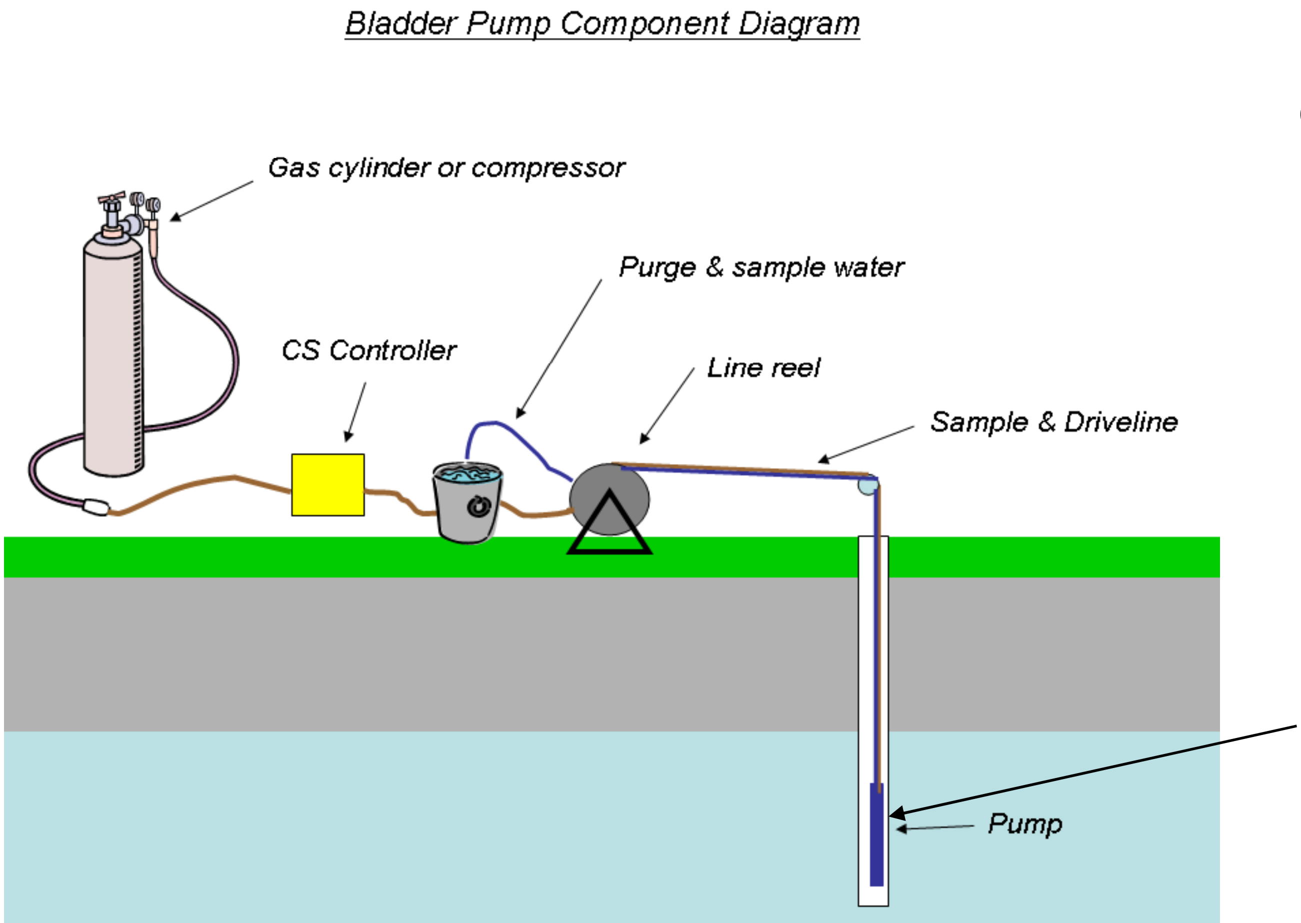
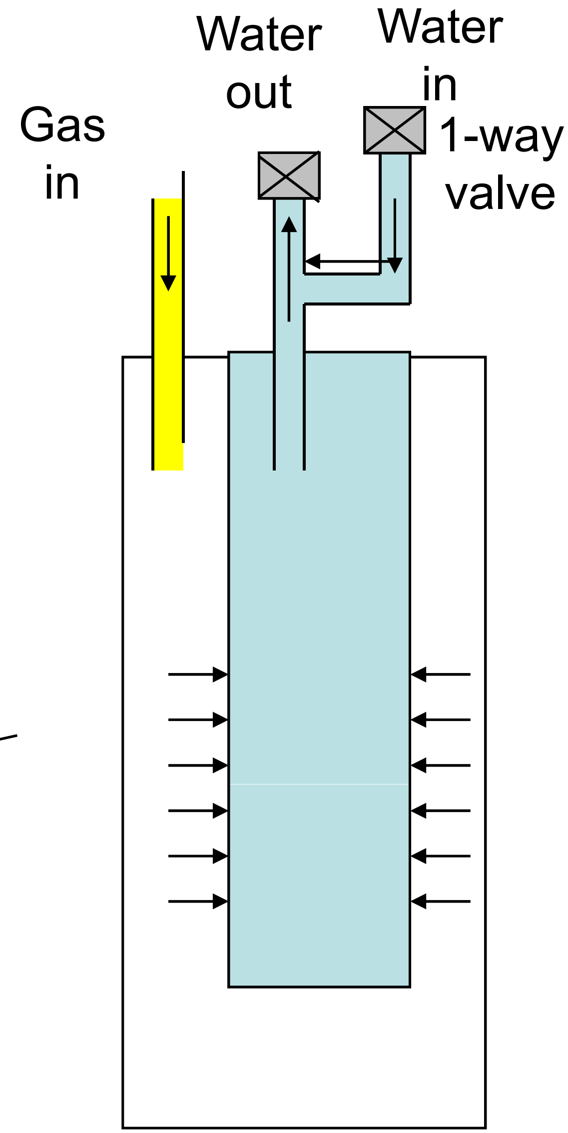
Groundwater Monitoring

Field Parameters
Major Ion Chemistry
Trace metals (in progress)





Bladder Pump Assembly

Flow through cell with two electrodes

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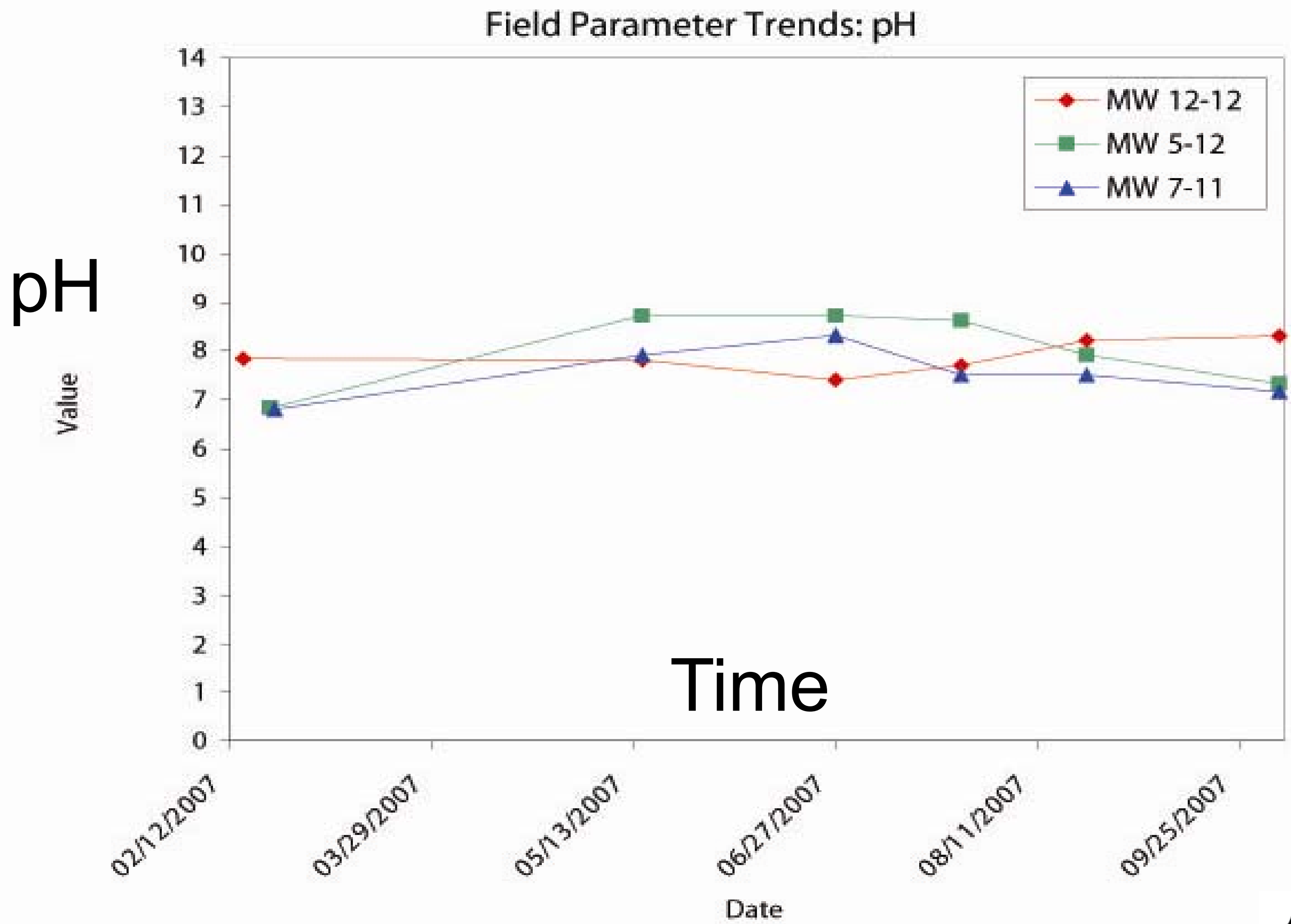
Groundwater Monitoring Field Parameters (pH)



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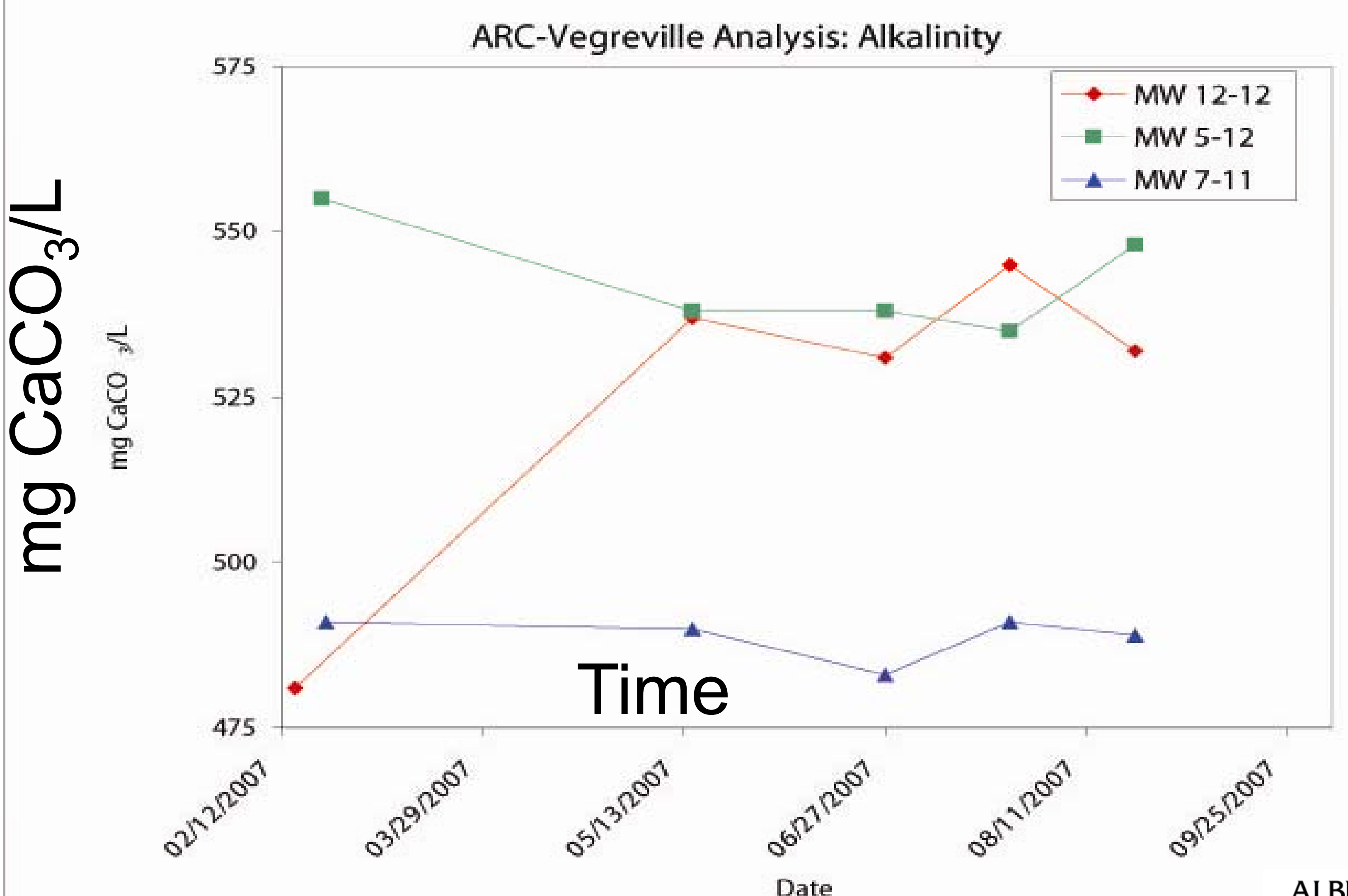
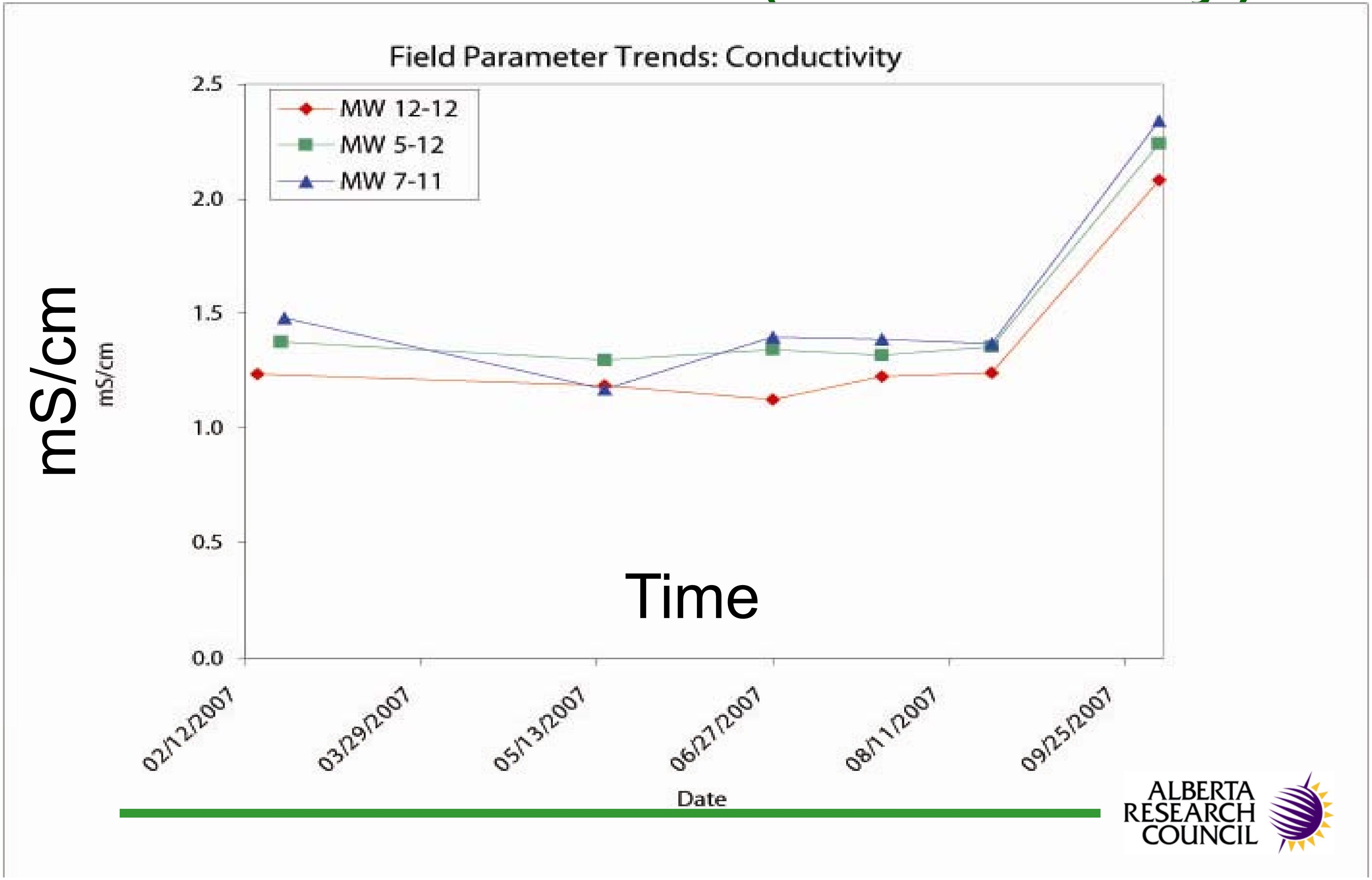
Groundwater Monitoring Field Parameters (Alkalinity)



Groundwater Monitoring
Field Parameters (conductivity)



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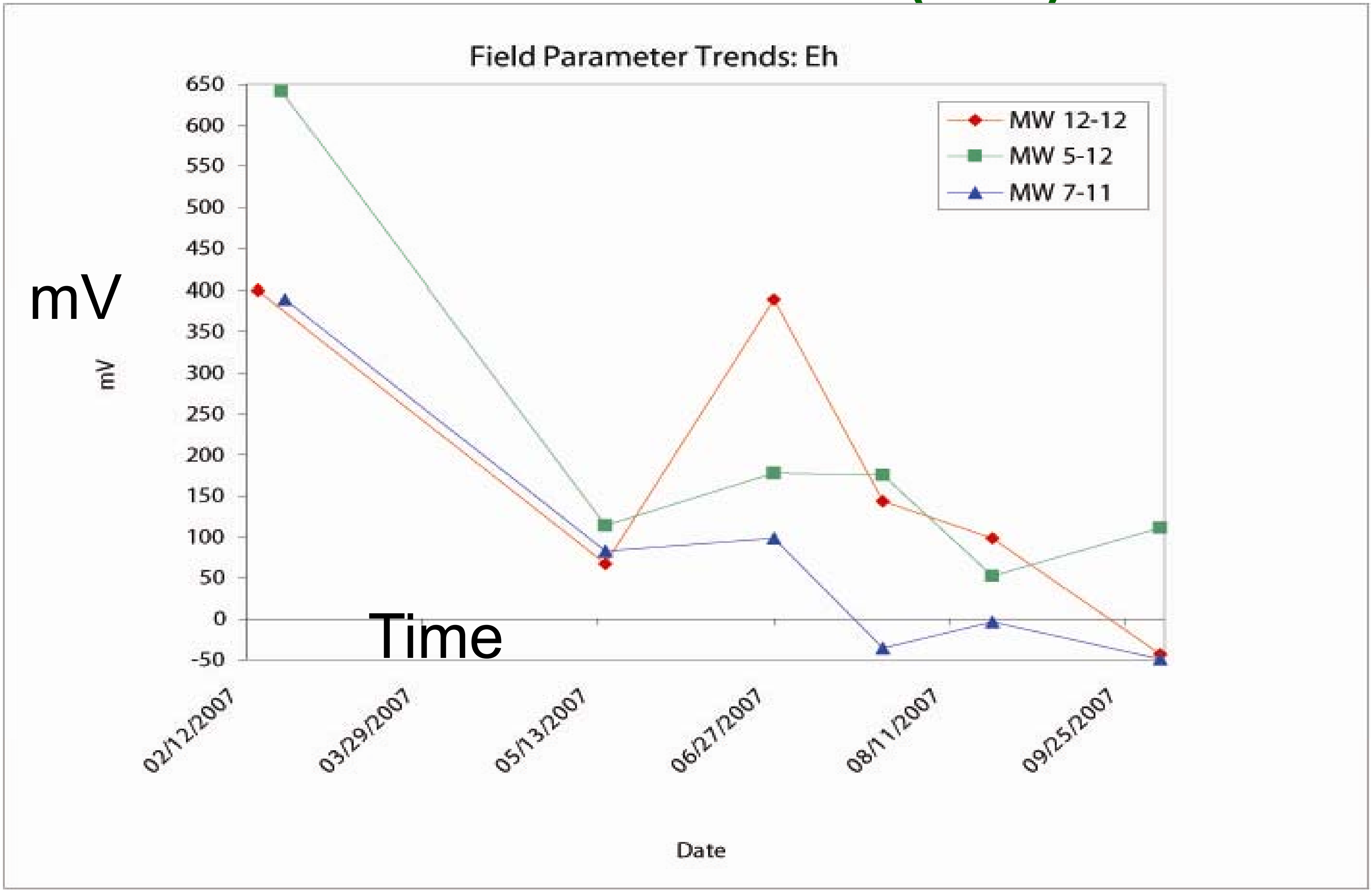
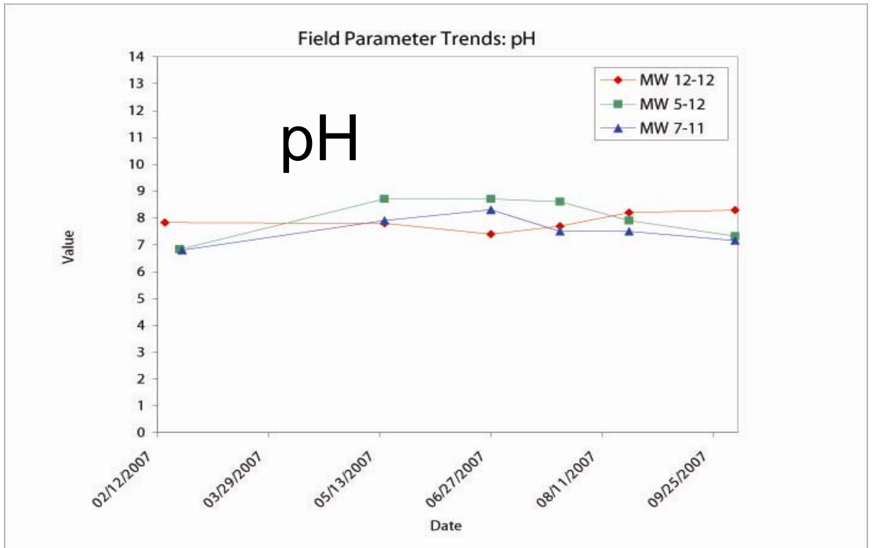
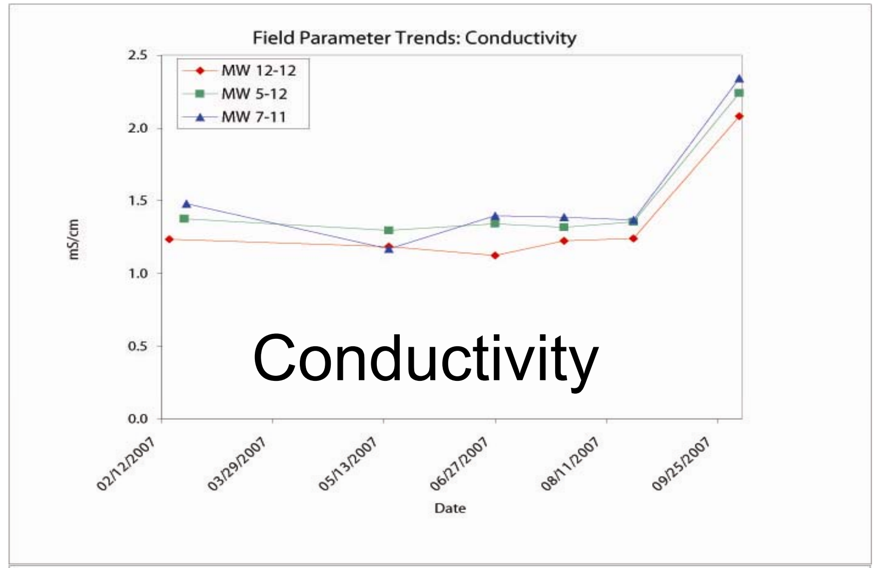
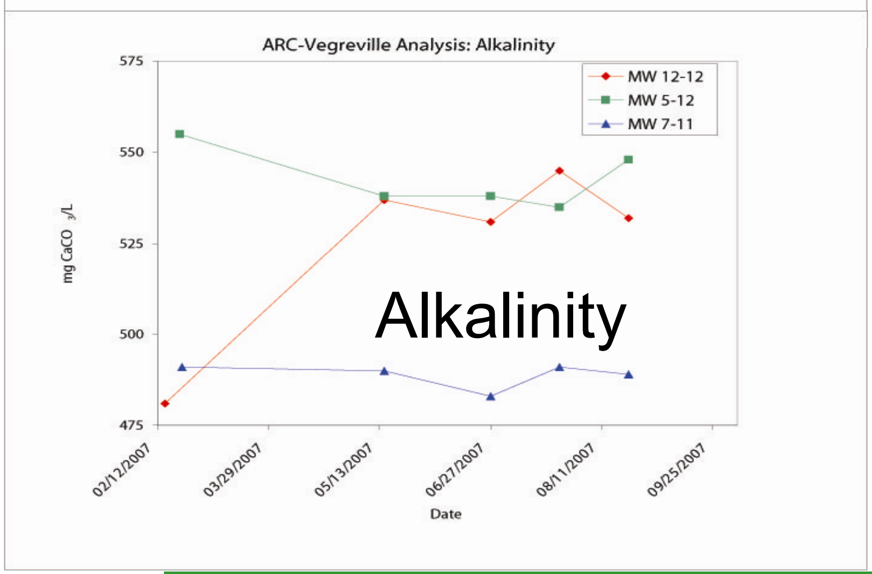
Groundwater Monitoring Field Parameters (Eh)

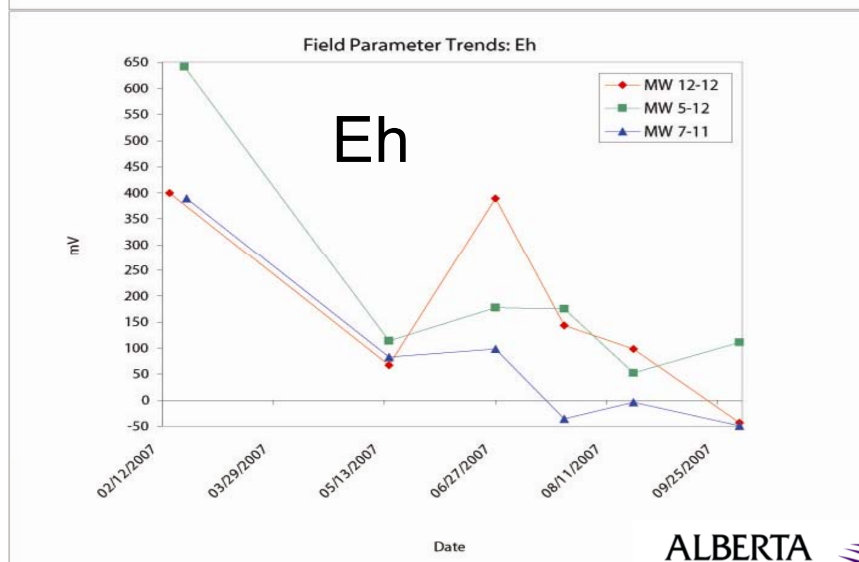


Groundwater Monitoring
Field Parameters









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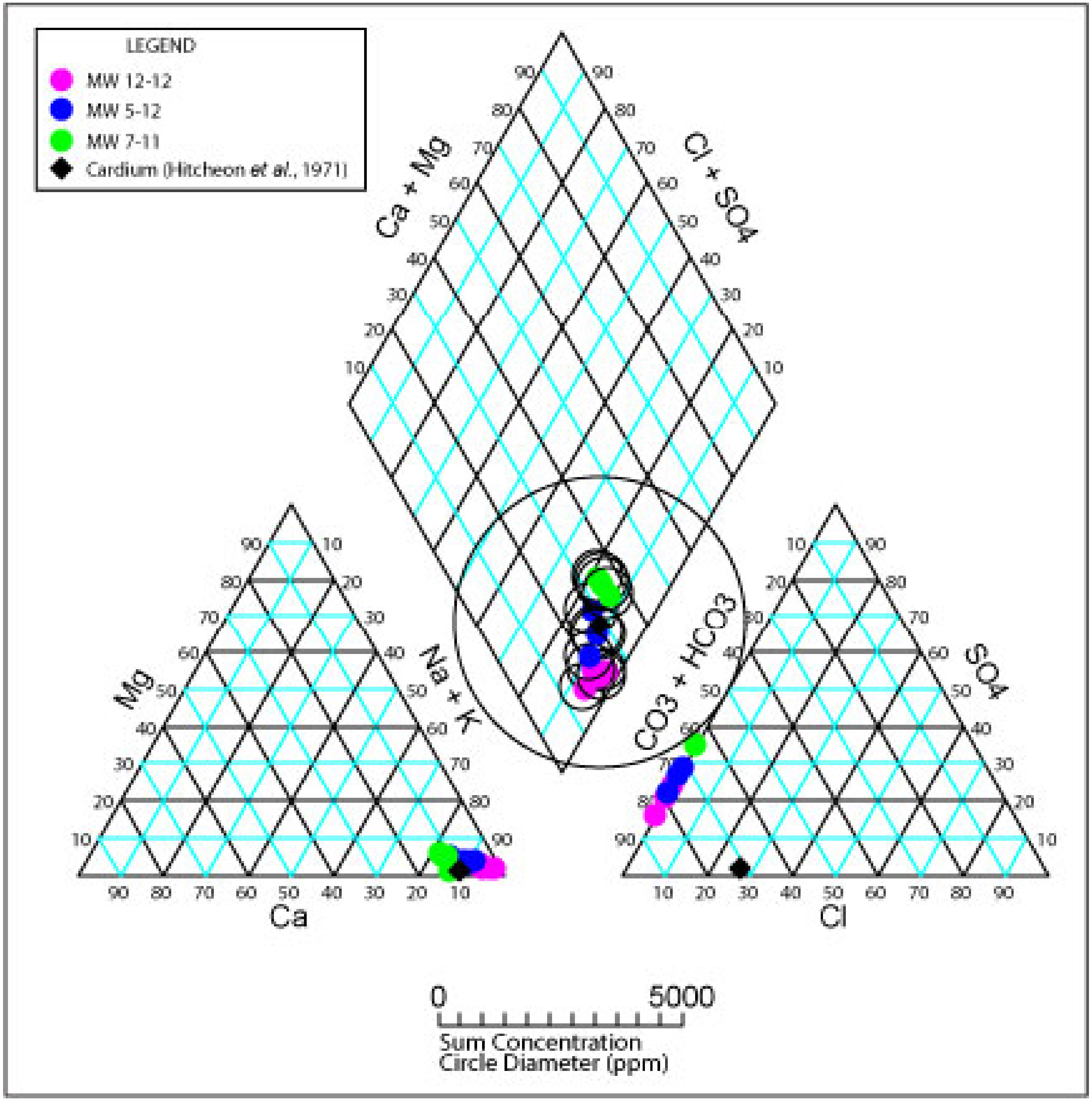

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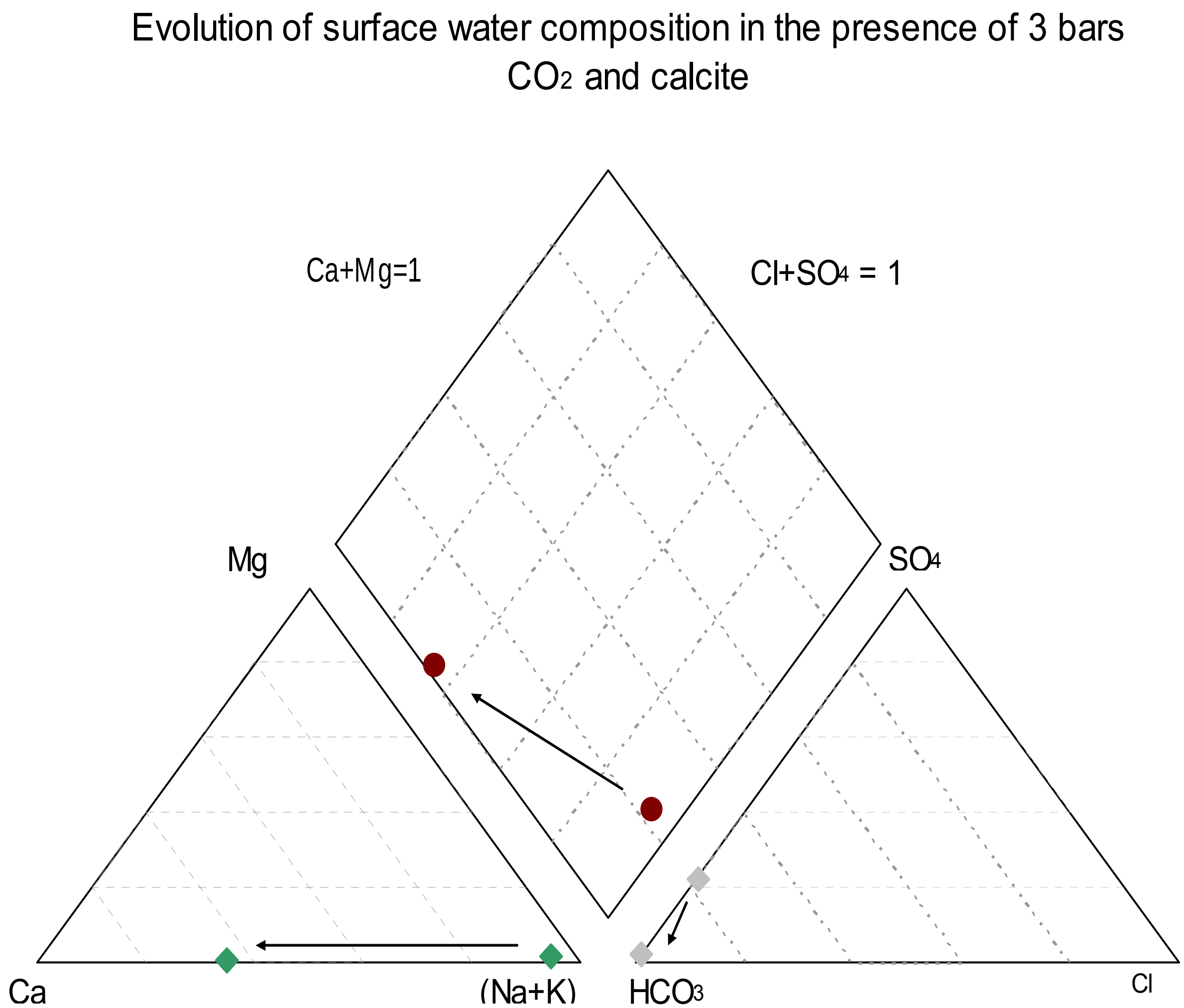
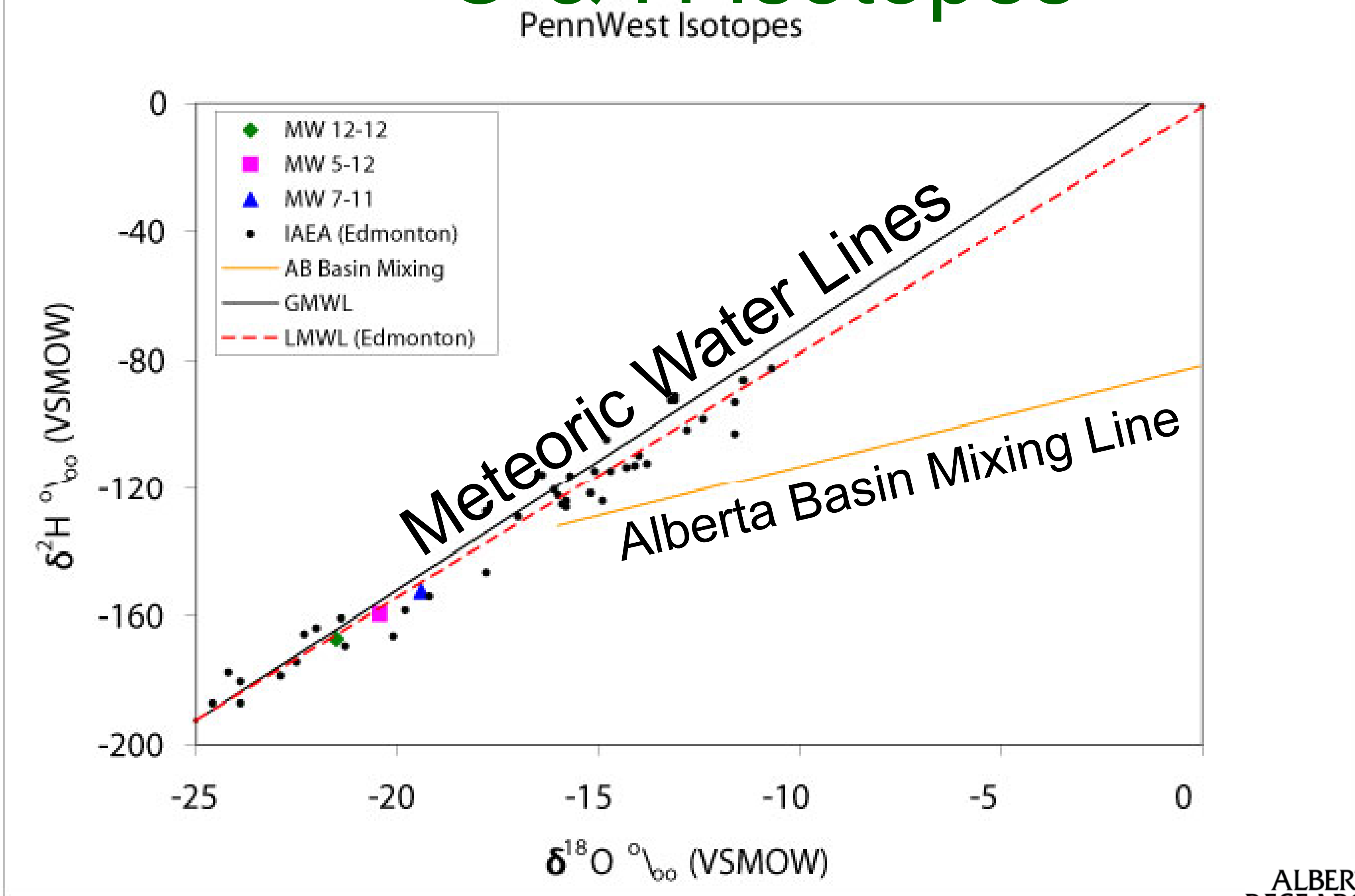
Relationship to Cardium Reservoir Fluids 1600 meters below

Evolution of Groundwater if 3bars CO_2 pressure imposed with excess calcite



Groundwater Monitoring
O & H Isotopes



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Ion exchange and dissolution of calcite controls water chemistry initially

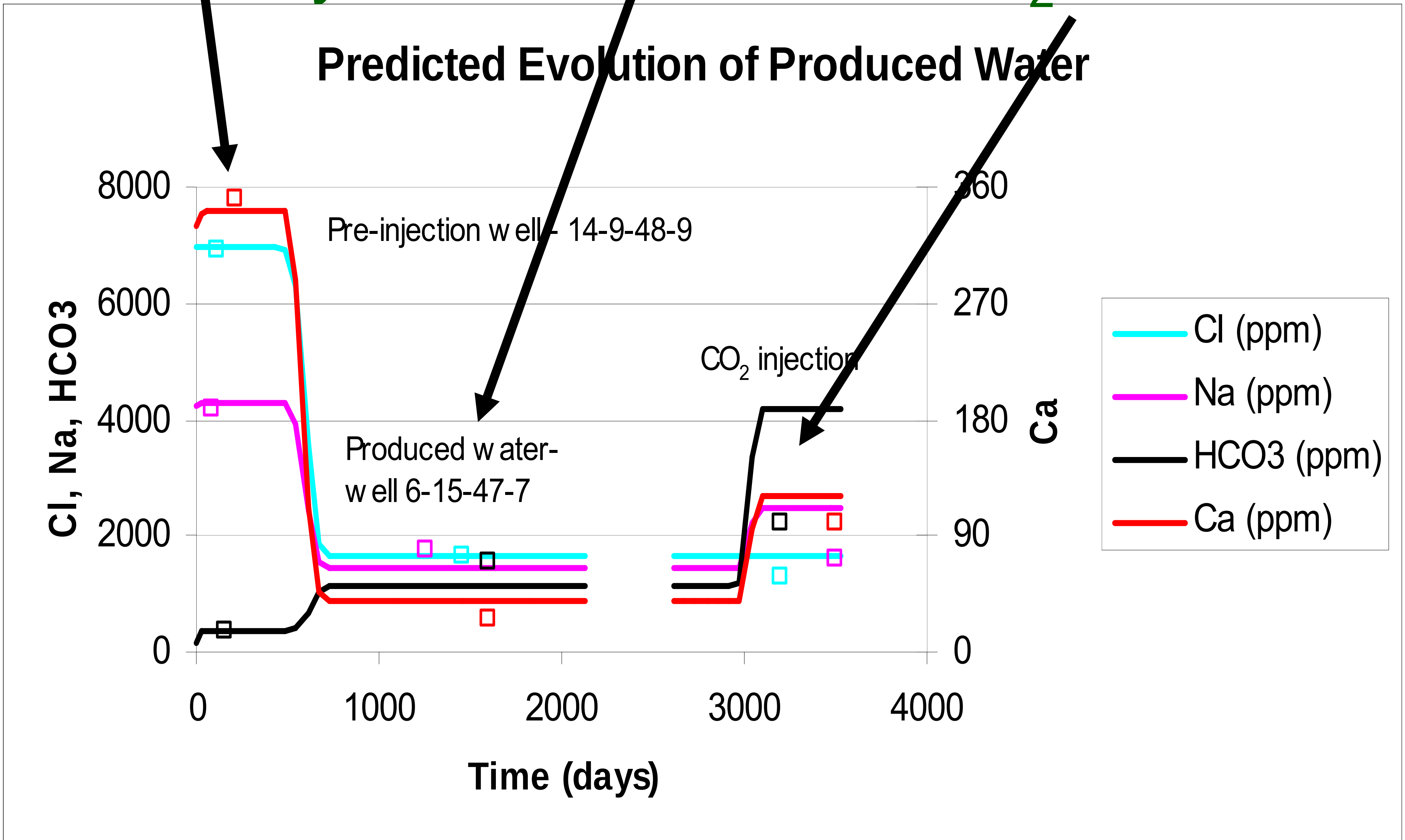
Secondary Recovery by Water Flooding (= dilution):

$2Na\text{-}Clay + CaCO_3 + CO_2$(native to reservoir)
$\rightarrow 2Na^+ + 2HCO_3^- + CaClay$

Tertiary Recovery by CO_2 EOR (= acidification)

$2Na\text{-}Clay + CaCO_3 + CO_2$(injection)
$\rightarrow 2Na+ + 2HCO_3^- + CaClay$

Evolution of Cardium Waters: Primary ->Water Flood -> CO_2 Flood



COUNCIL

Groundwater Monitoring Conclusions

- Water levels constant = no shallow leaks from surface casing of wells
- Chemistry constant = no shallow CO_2 leaks
- Ground atmospheric chemistry constant = no seepage into atmosphere

Groundwater Monitoring Further Work

- Shallow geophysics to investigate shallow geology and structure
- Soil Gas monitoring in the unsaturated zone (2-15m) to investigate source of CO_2 and methane complimentary to surface (0-1m) soil gas monitoring
- Modeling of saturated-unsaturated zone interactions of CO_2 and CH_4.

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Groundwater Monitoring Further Work

- Remote access to piezometric data
- Test deep monitoring tools before deploying them in observation wells in the reservoir

Atmospheric Monitoring Conclusions

- Found tunable diode laser measurements a very promising tool for CO_2-EOR site monitoring
- System sensitivity to methane is higher than for CO_2 due to background concentrations
- System straightforward to use
- Could be combined with dispersion modeling to translate into quantitative results

Atmospheric Monitoring Future plans

- Currently planning on further evaluating tunable diode laser technology in combination with modeling to translate into quantitative measurement
- Also looking at combining with soil gas monitoring for complete site evaluation

ALBERTA RESEARCH COUNCIL

CSEMP

CO_2 **S**torage and **E**nhanced **M**ethane **P**roduction

4th IEA Monitoring Network Meeting

Edmonton, Alberta, November 9, 2007

John Faltinson

Alberta Research Council

CSEMP
Participating Companies

- Suncor Energy Inc.
  - Project Manager
- EnerPlus Resources Fund
  - CBM Well Owner/Operator
- Alberta Research Council
  - Research Program Design and Execution

CSEMP
Project Funding

- Suncor Energy Inc.
- EnerPlus Resources Fund
- Encana
- Quicksilver Resources Canada Inc.
- TransCanada Pipelines
- Penn West Petroleum
- Air Liquide Canada Ltd.
- AERI
- Natural Resources Canada (NRCan)
- Sustainable Development Technology Canada (SDTC)
- Alberta Science and Research Authority (ASRA)
- Environment Canada
- CII Consortium (ARC, NRCan, AERI, US DOE, Conoco Phillips, BP, +)

CSEMP
Project Execution Personal

- Cal Coulter / Susan Campbell (Suncor)
  - Project Manager
- Christen Kolbeck / Marc Melnic (EnerPlus)
  - Alder Flats Production Engineer
- Bill Gunter (Alberta Research Council)
  - Research Program Leader
- Matt Mavor (Tesseract Corp.)
  - Reservoir Engineer
- Andrew Beaton / Christina Pina (Alberta Geological Survey)
  - Geological Advisor
- John Faltinson (Alberta Research Council)
  - Pilot Execution and Operational Monitoring
- Dave Podgurny (Air Liquide)
  - CO2 Injection Skid Operation

CSEMP
Project Execution Personal

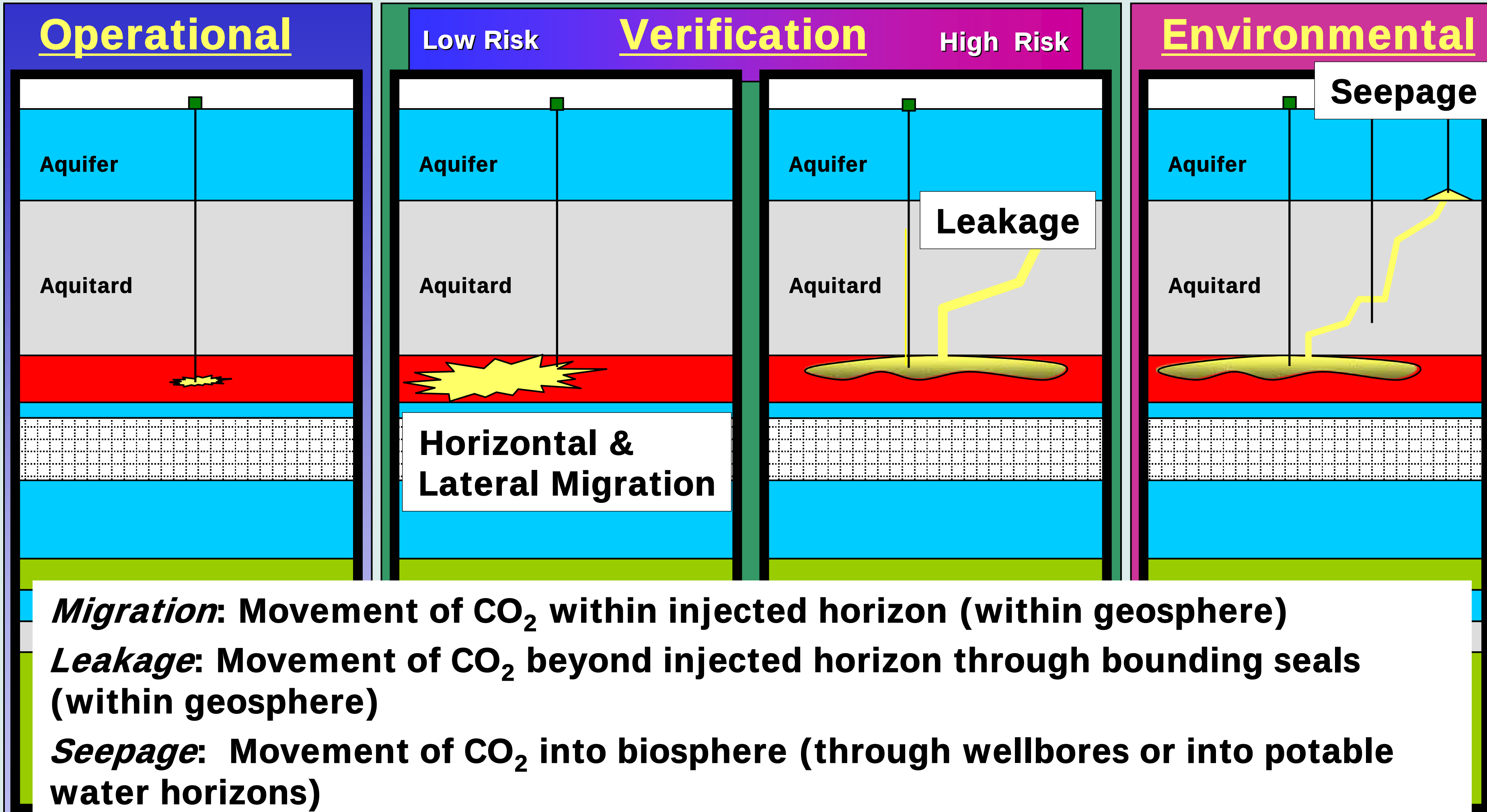
- Alex Blythe / Andrea Mellor (Alberta Research Council)
  - Environmental Monitoring - Shallow Water
- Stephanie Trottier (Alberta Research Council)
  - Environmental Monitoring - Atmospheric Gas
- Hong Li / Xiaohui Deng (Alberta Research Council)
  - Reservoir Simulation
- Gonzalo Zambrano (University of Alberta)
  - Verification Monitoring – Tilt Meters
- Don Lawton (University of Calgary)
  - Verification Monitoring – Seismic
- Bernice Kadatz / Larry Holloway / Mark Olson (Alberta Research Council)
  - Operational Monitoring – Mobile Gas Chromatograph
- Bruce Minors (Lead Operator) and Alder Flats Staff (EnerPlus)
  - Field Execution

CSEMP
Experimental Goals

- Determine baseline production of CBM from the Ardley coals at the pilot location (102/7-28-46-7 W5M).
- Store CO_2 within the coal strata utilizing an injection well and measure storage effects in the coal.
- Determine the effect of CO_2 injection and storage on CBM production from adjacent wells.
- Assess the economics of the collection of the CO_2 and injection into coals as a long-term storage method for the reduction of GHG emissions.

CSEMP

Three Types of Monitoring



Migration: Movement of CO_2 within injected horizon (within geosphere)

Leakage: Movement of CO_2 beyond injected horizon through bounding seals (within geosphere)

Seepage: Movement of CO_2 into biosphere (through wellbores or into potable water horizons)

CSEMP

Research Program – Pilot and Operational Monitoring

P1: Detailed Design and Cost Planning
P2: Injection Well Drilling and Evaluation
P3: Core Analyses
P4: Completion of Injection Well and Micro-pilot Testing

- Water injection / Fall-off test
- Production / Build-up test #1
- Short CO_2 Injection test
- Production / Build-up test #2

P5: Surface Facilities and Monitoring
P6: Nitrogen Injection as a Tracer
P6a: Drilling and Completion of the P3 Producer
P7: Extended CO_2 Injection
P8: Final Production & Shut-in Testing of Injection Well
P9: Pilot Engineering Evaluation and Reservoir Simulation
P10: Final reporting

CSEMP

Research Program – Verification Monitoring

V1: Detailed Design and Cost Planning

V2: Baseline Geological Study

V3: P3 Monitor Well

V4: 4D Seismic

V5: Passive Seismic

V6: Cross Well Tomography

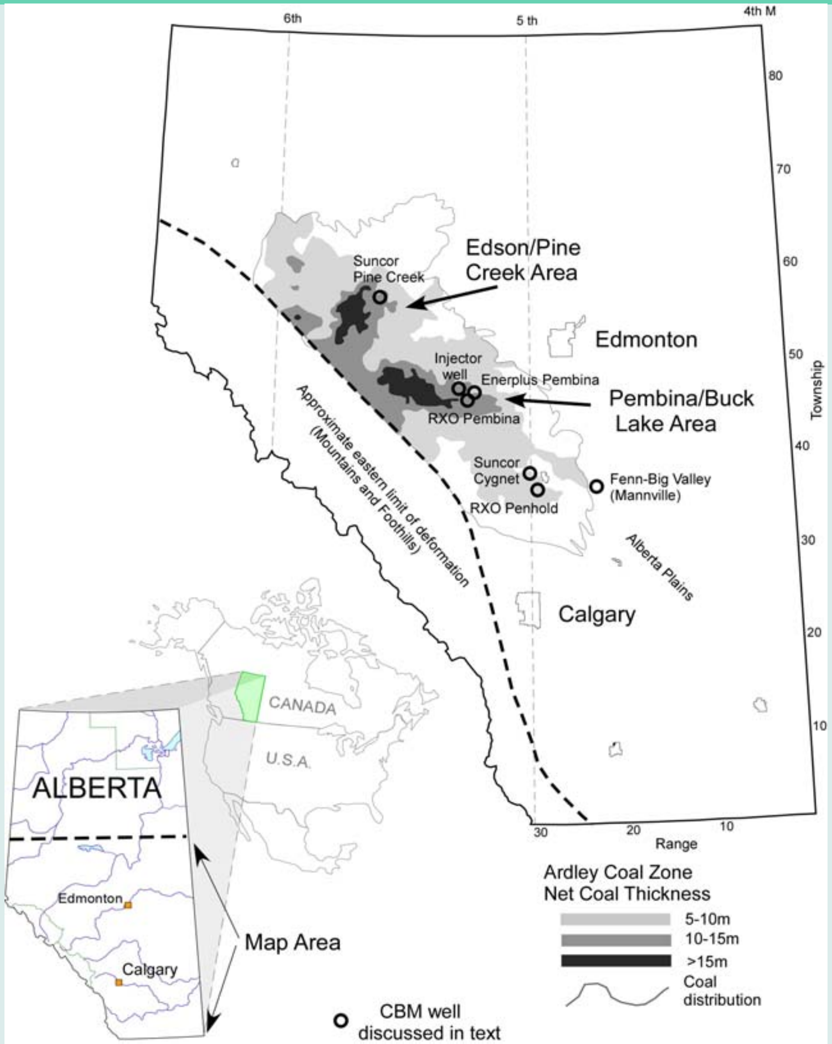
V7: Tilt Meter Surveys – Gonzalo Zambrano Poster Session

V8: Final reporting

Environmental Monitoring Program covered by Bill Gunter previously during Penn West talk.

CSEMP
Confidential Location

CSEMP
Field Location



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Injection Well Lease – 102/7-28-46-7 W5M

CSEMP

Offset Production Well Lease – 100/7-28-46-7 W5M

CSEMP

Offset Production Well Lease – 100/7-28-46-7 W5M

CSEMP

Well-bore Configuration – Down-hole Gauges

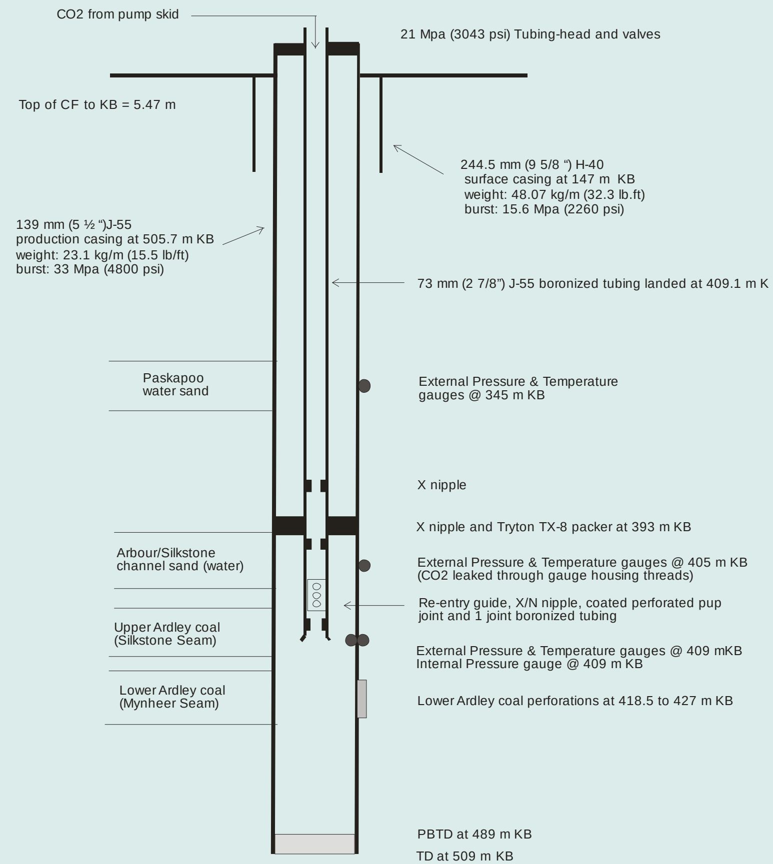
Three external casing press/temp gauge pairs:

- Monitor P/T in overlying channel sands
  - Paskapoo
  - Arbour/Silkstone
- Monitor P/T in Ardley coal

One internal casing pressure gauge:

- Monitor pressure inside casing at Ardley coal depth

Wellbore Configuration - 102/7-28 Injector
(Short CO_2 Injection Test)



CSEMP

Operational History – Micro-Pilot

Nov.04 – Drilled & completed 3 shallow water monitoring wells (50/100/150 m).

Dec.04 – Drilled, cored and logged CO_2 injection well.

Jan.05/06 – One year delay – Alberta Environment water diversion permit.

Jan.06 – Drilled tilt meter wells (16 wells – 6 meters deep).

Mar.06 – Installed CO_2 injection skid and storage bullet.

May 06 – Water injection and fall-off test (pre-frac coal properties)

(Results Confidential)

June 06 – Fracture stimulated CO_2 injection well (12 t of 20/40 sand in ungelled H_2O).

July 06 – Injection well production and build-up test (pre-CO_2 coal flow properties).

(Results Confidential)

Sept. 06 – Short-term CO_2 injection test (180 tonnes CO_2).

Oct. 06 – Conducted workover on injection well.

Jan. 07 – Conduct 2nd injection well production test (post CO_2 coal properties).

(Results Confidential)

CSEMP

CO_2 Injection Skid – Short Injection Test

CSEMP
Short CO2 Injection Test

- CO_2 (L) was pressurized through pump & vaporized through burner.
- On the way down the tubing, CO_2 liquefied and entered the coal as liquid.
- Re-vaporized a short distance out from perforations (< 6”).
- Initial injection pressure: wellhead = 4480 kPa, bottom-hole = 5500 kPa
  - Hydrostatic head of column indicates liquid/gas CO_2 in tubing.
  - ~ 2/3 vapour CO_2 over 1/3 liquid CO_2 column in tubing.
- Down-hole gauge pressure increase - Arbour/Silkstone sand at 405 m.
  - Suggests CO_2 injecting into water sand 4 m above!
- Leak pathway initially believed to be cement channel from Ardley coal to Arbour/Silkstone channel sand (outside casing through cement channel).
  - Very low conductivity leak (virtually undetectable with 1 cp water).
  - Detectable leak with CO_2 (viscosity: liquid – 0.1 cp, vapour – 0.02 cp).
- Bad candidate for cement squeeze – due to poor conductivity of leak.
  - Remedial cement squeeze estimate: $200,000 with 20% chance of success.
  - Unlikely to be undertaken by CSEMP consortium.

CSEMP
Short Injection Test – Down-hole Pressure Data

Initial rate = 40 t/d, Temp = 12 C.

Down-hole Temp. increase due to vapor > liquid phase change of CO_2.

After pump stopped, liquid CO_2 vaporizing in tubing and continued injecting.

<u>Fall-off curve conclusions:</u>

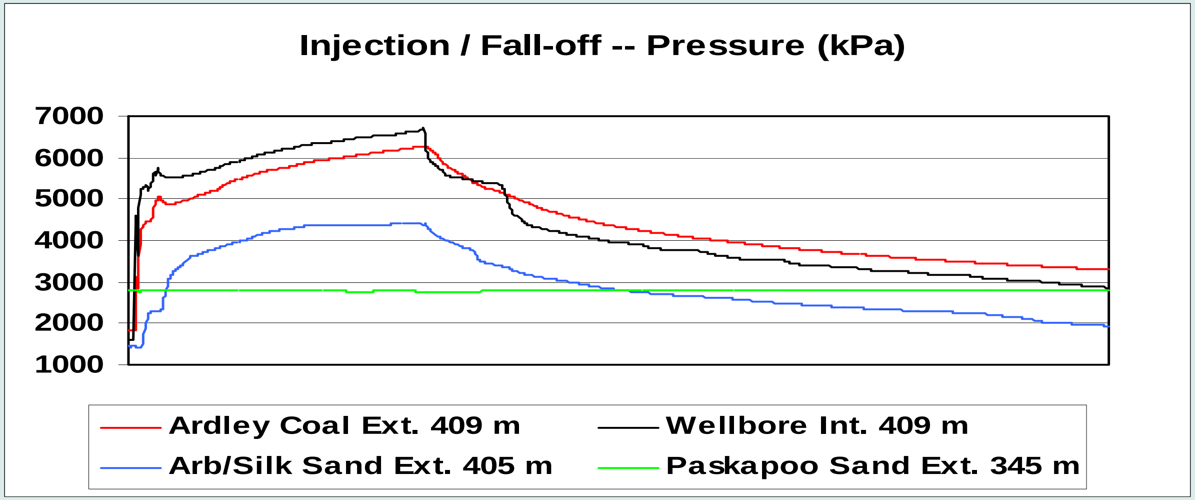
If Leak is cement channel:

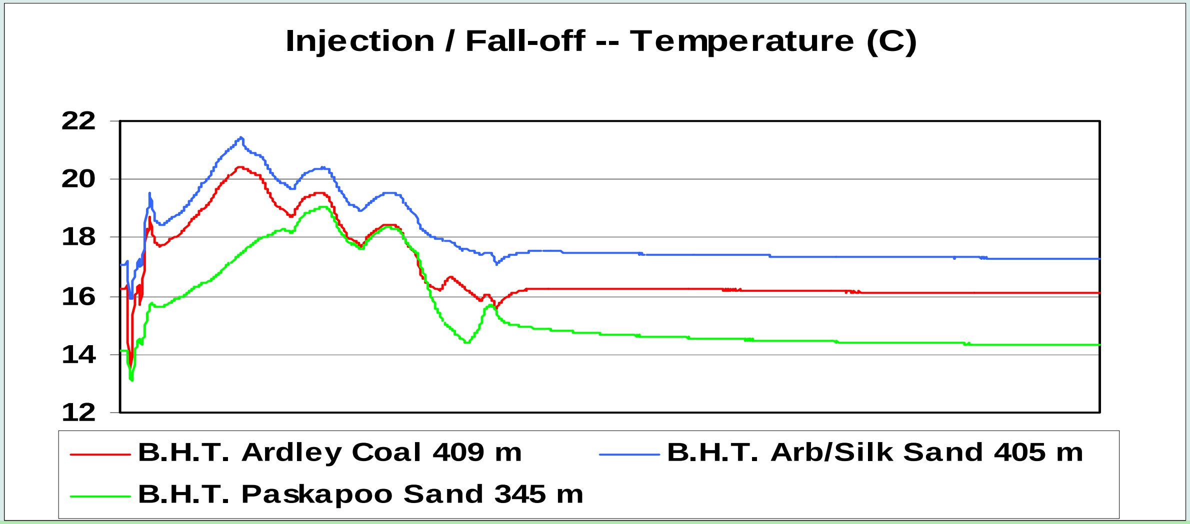
Pathway: Well->Coal->Sand

Fall-off curves should be similar

Coal fall-off shape different than wellbore & sand fall-off.

Pathway: Well->Sand (direct)





CSEMP

Casing Pressure Test – Oct. 2006

- Review of pressure data from Jan. 05 to Jan. 06 (1 year delay) supports theory of casing leak and not cement channel. Good News!
- Casing leak suspected - threads of Arbour/Silkstone PT gauge joint.
- Cause, poor make-up of gauge joint while running casing. Either cross threaded or not enough torque applied. Gauge joints are torqued manually.
- Reconfigured injection well-bore with bridge plug above Ardley perforations and below suspect PT gauge joint. Packer set above gauge joint isolating it.
- Pressure applied to gauge joint with CO_2 down tubing. Leak confirmed. Problem resolved by running a Halliburton retrievable casing patch to seal leak.

CSEMP
Initiation of Multi-well Pilot

- Following resolution of casing leak, a second production test was completed in January, 2007. (test results confidential)   MICRO-PILOT COMPLETE
- Decision by CSEMP consortium (Feb. 2007) to proceed to multi-well phase of project.
- Multi-well pilot plan:
  - Inject N2 tracer slug into injection well.
  - Long term CO_2 injection (~1 year) with offset well production rate, pressure and gas composition sampling.
  - Final production and build-up test on injection well.
- Offset well put on production June 2007 and N_2 tracer slug injected into injection well. Purpose of N_2 was to signal arrival of CO_2 flood front.

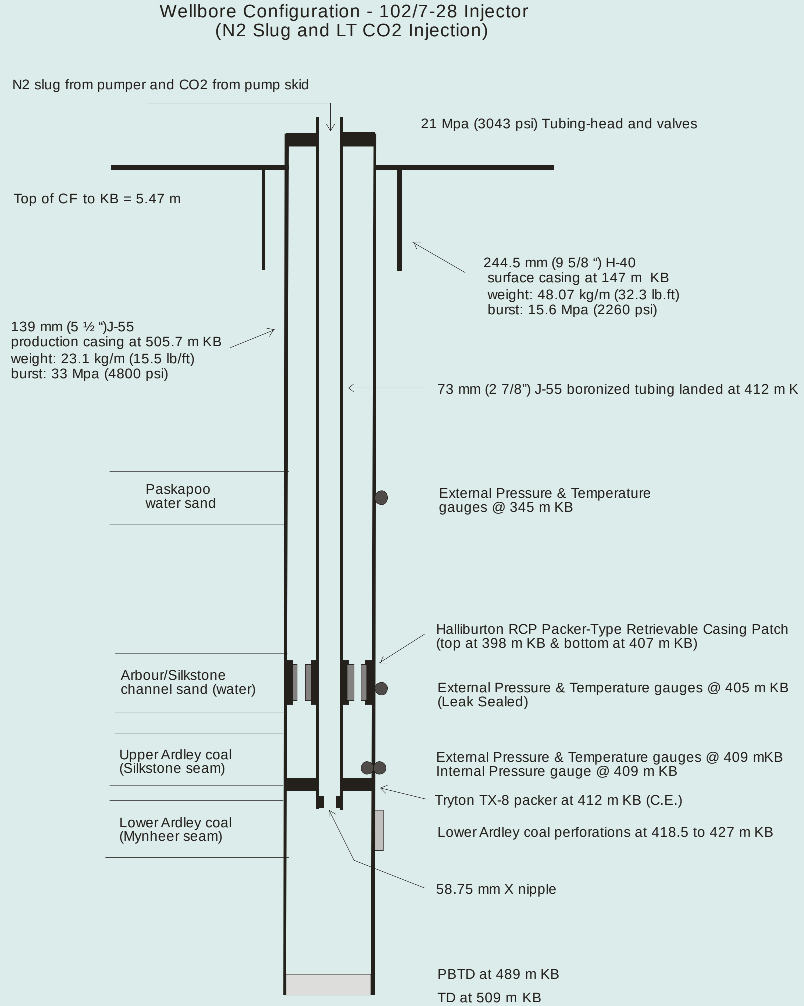
CSEMP

Well-bore Configuration - Long Term CO_2 Injection Test

Halliburton retrievable casing patch landed across leaking gauge joint.

Injection packer set below internal casing press. gauge in error.

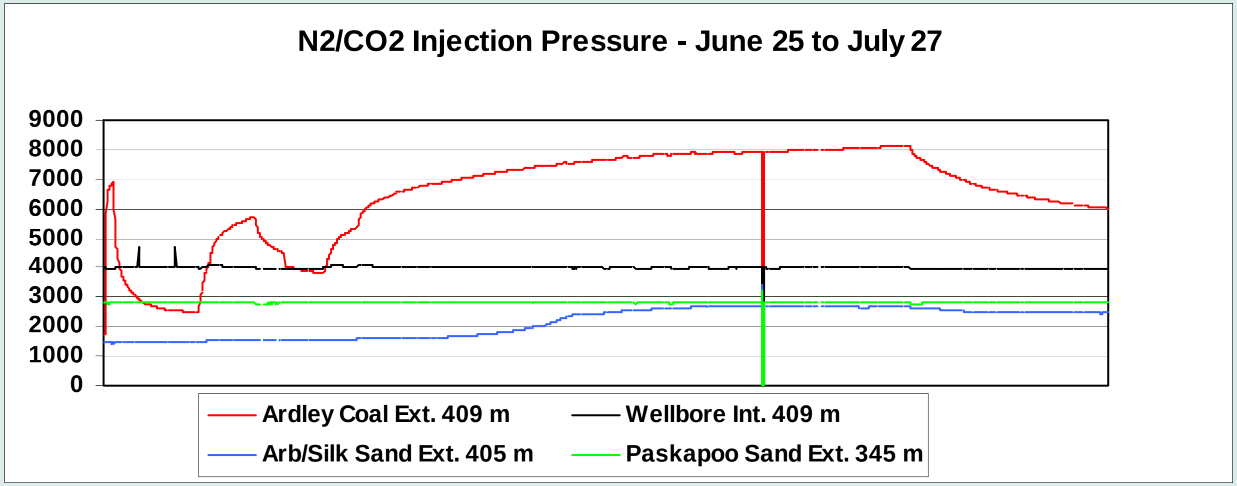
- Gauge unresponsive
- Unable to monitor inside casing pressure during injection / fall-off.



CSEMP

Long Term CO_2 Injection Test – Down-hole Pressure

- CO_2 injection initiated June, 2007 at initial rate of 38 tonnes/day. After a few days, CO_2 rate increased to 45 tonnes/day.
- Twelve days after beginning CO_2 injection, external pressure gauge in Arbour/Silkstone channel sand started to climb.
- CO_2 pressuring-up water sand again! - Injection test suspended. Only 1000 tonnes of CO2 injected.



CSEMP

Long Term CO_2 Injection Test – Leak #2

- Casing pressure at surface zero, indicating that well-bore integrity sound and previous gauge thread leak (#1) remains sealed.
- Evidence suggests pathway of communication (2nd leak) definitely outside of well casing and not through the casing wall (1st leak).
- Possibility pathway - through micro-annulus between well casing and de-bonded cement.
- Currently evaluating options for sealing leak.

CSEMP

Operational Monitoring Benefits of Down-hole Gauges

- Leak detection quickly before significant injected fluid lost to the wrong zone.
- Better pressure monitoring and understanding of non-intuitive CO_2 pressure and phase behaviour during injection and fall-off testing.
- Precise pressure monitoring during production testing. Eliminate the need for running, setting and retrieving wire-line gauges or estimating via fluid levels.
- Real time 24/7 remote monitoring of down-hole pressure / temperature via Zedi Solutions website. No delay as with wire-line gauge data.

CSEMP

Verification Monitoring Program (Actual)

V1: Detailed Design and Cost Planning (completed)

V2: Baseline Geological Study (completed)

V3: P3 Monitor Well (not drilled)

V4: 4D Seismic (insufficient CO2 injected for follow-up survey)

V5: Passive Seismic (pending resumption of injection)

V6: Cross Well Tomography (deferred)

V7: Tilt Meter Surveys (pending resumption of injection)

V8: Final reporting (pending)

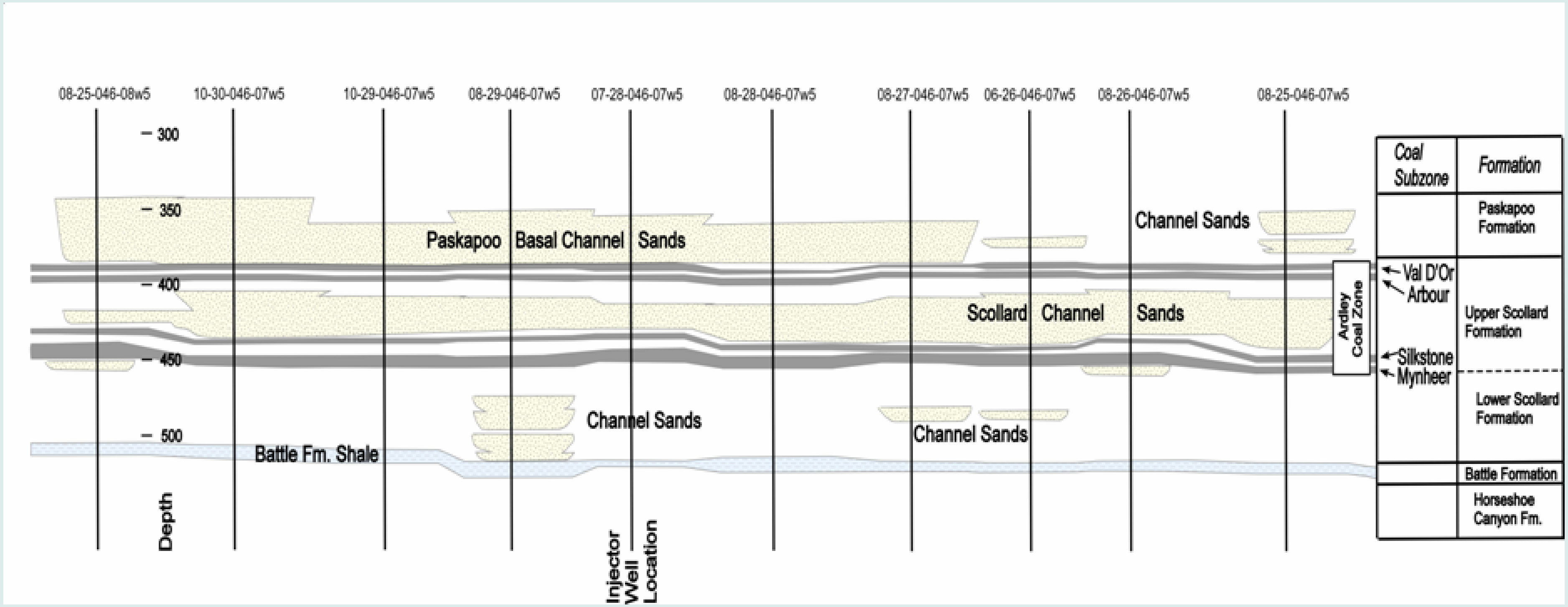
CSEMP

Verification Monitoring – Baseline Geological Study

- Performed by Alberta Geological Survey
- Purpose: Assess suitability of the EnerPlus Pembina site for geological storage of CO_2.
  - Look for issues that indicate communication potential via stratigraphic contact between target coal and adjacent channel sands.
- Best coal zones are the lowest 2 of the 4 zones (Silkstone & Mynheer). Upper Val D'Or zone in contact with overlying Paskapoo channel sand.
- Silkstone coal and Arbour/Silkstone sand are in stratigraphic contact elsewhere in the area, but not at any of the pilot well locations.

CSEMP

Baseline Geological Study – Ardley Coal Zone

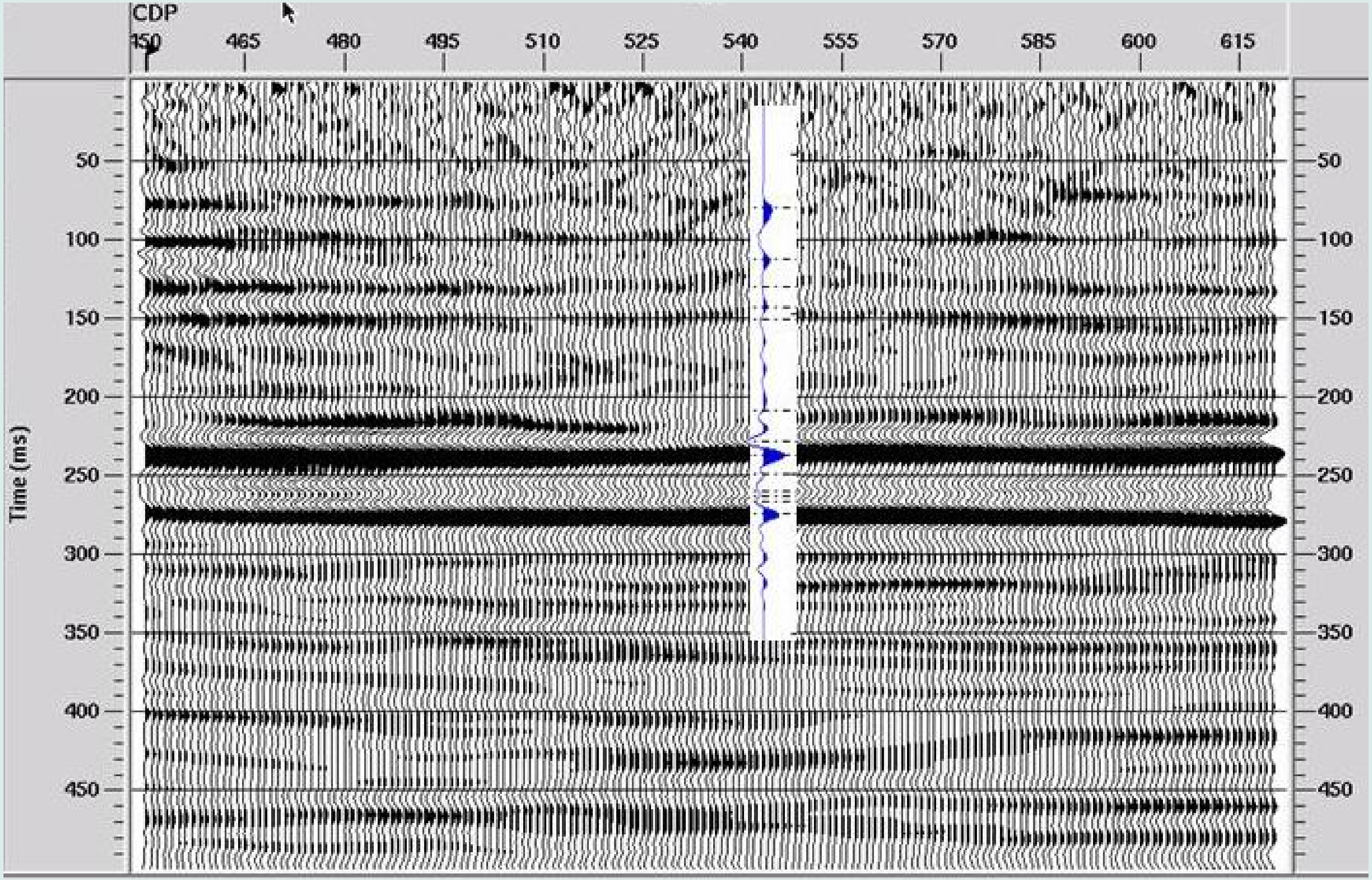


CSEMP
Verification Monitoring – 4D Seismic

- Conducted by University of Calgary (Don Lawton).
- Purpose: To map the CO_2 plume in the coal.
- Baseline survey shot in June 2007.
- Survey area 560 m X 560 m.
- Additional geophones landed in shallow water monitoring wells.
- Follow-up survey dependent on injection of sufficient CO_2.

CSEMP

Post Stack Time Migrated



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ALBERTA RESEARCH COUNCIL

CSEMP
Verification Monitoring – 4D Seismic

Processed data from baseline survey (June 07)

Prior to LT CO2 Injection.

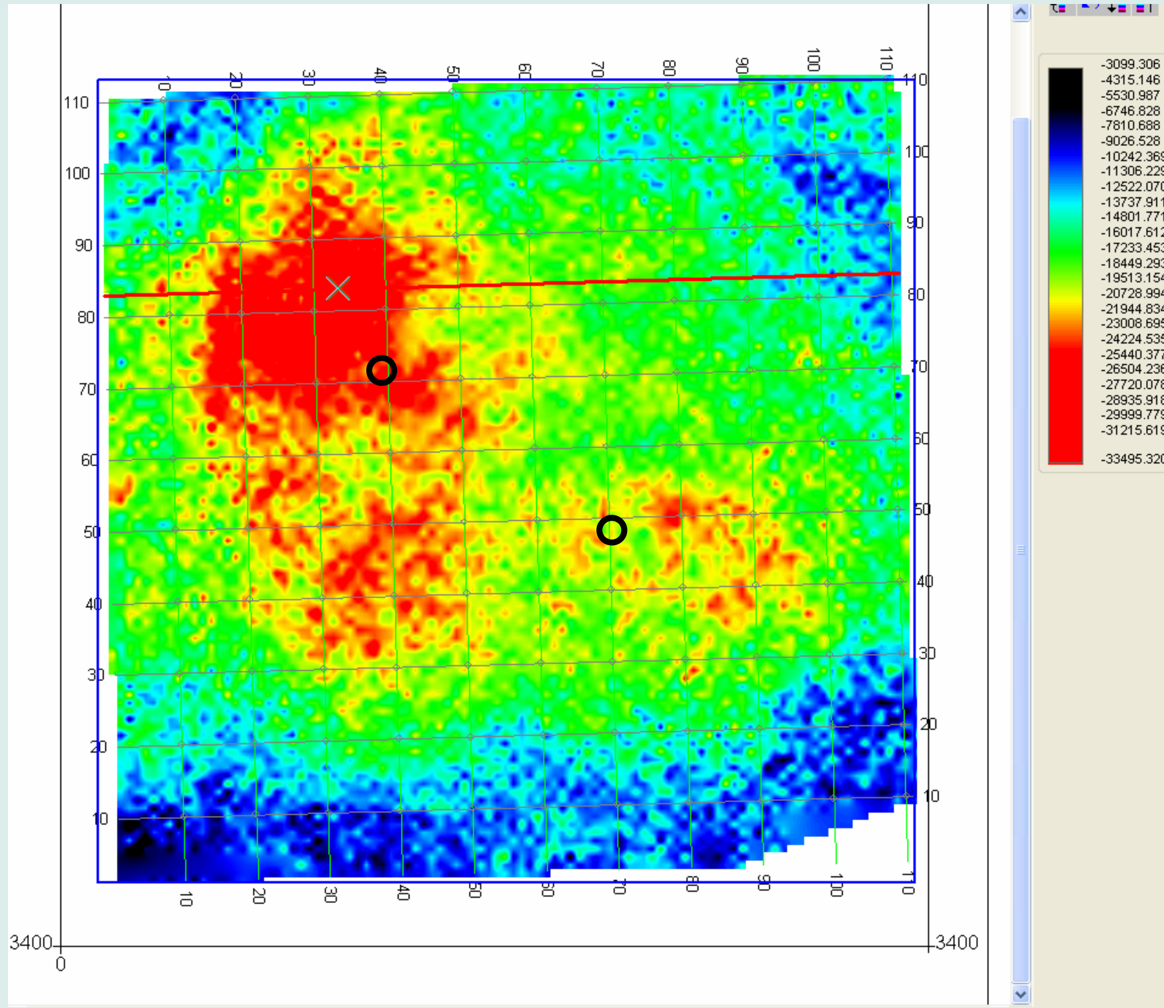
Injection Well – upper left

Offset Producer – lower right

Horizontal slice through seismic volume at base of Ardley coal Mynheer seam.

Red color: Higher absolute amplitude of the seismic reflection.

Blue color: Low signal/noise due to edge of survey.



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ALBERTA RESEARCH COUNCIL

CSEMP

Verification Monitoring – Tilt Meter survey

- Executed by the University of Alberta (Gonzalo Zambrano).

- Purpose:
  1. Map fracture length, height and orientation at injection well during stimulation treatment.
  2. Measure ground deformation caused by injection pressure and CO_2 swelling of Ardley coal.

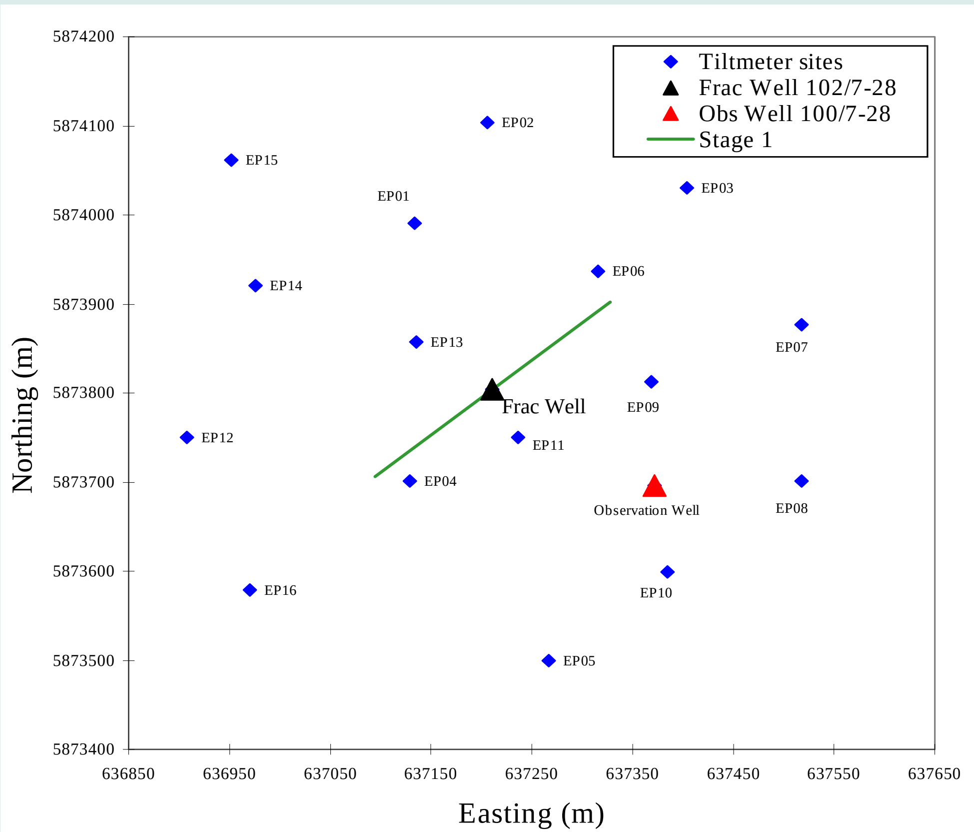
- Surface tilt meters:
  - Sixteen tilt meter wells were drilled (6 m depth), cased with PVC pipe and cemented.
  - Tilt meter tools were run into each well and connected to surface recording equipment.

- Down-hole tilt meters during frac:
  - Twelve tilt meter tools (tandem) were run into offset production well and landed across Ardley coal perforations.
  - Tilt meter assembly was magnetically attached to the inside of casing.

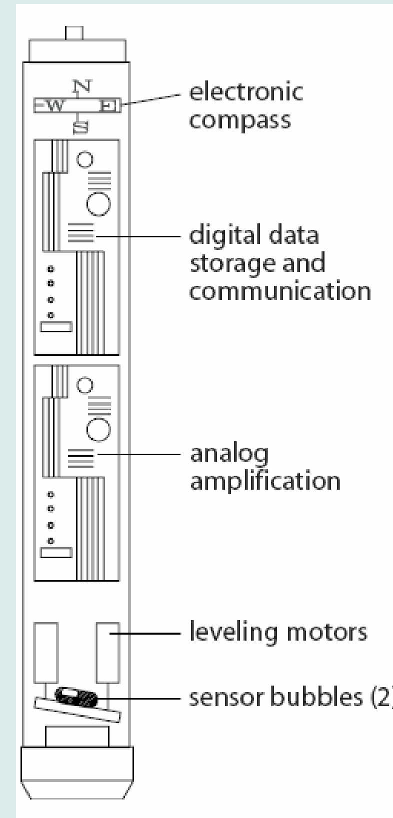
CSEMP

Verification Monitoring – Tilt Meter survey

Surface Tilt Meter Array



Tilt Meter Tool



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ALBERTA RESEARCH COUNCIL

CSEMP

Current Issue:

CO2 leaking from Ardley coal to channel sand has put a hold on remaining Verification & Environmental Monitoring

- **Status of CSEMP Project: Evaluating options**

Thank you for your attention.

Questions?

The Role of Risk Assessment in Designing MMV Programs

November 9, 2007 **IEA GHG Monitoring Network, Fourth Meeting, Edmonton, Alberta**

Presenter: Ken Hnottavange-Telleen, Schlumberger Carbon Services, North America

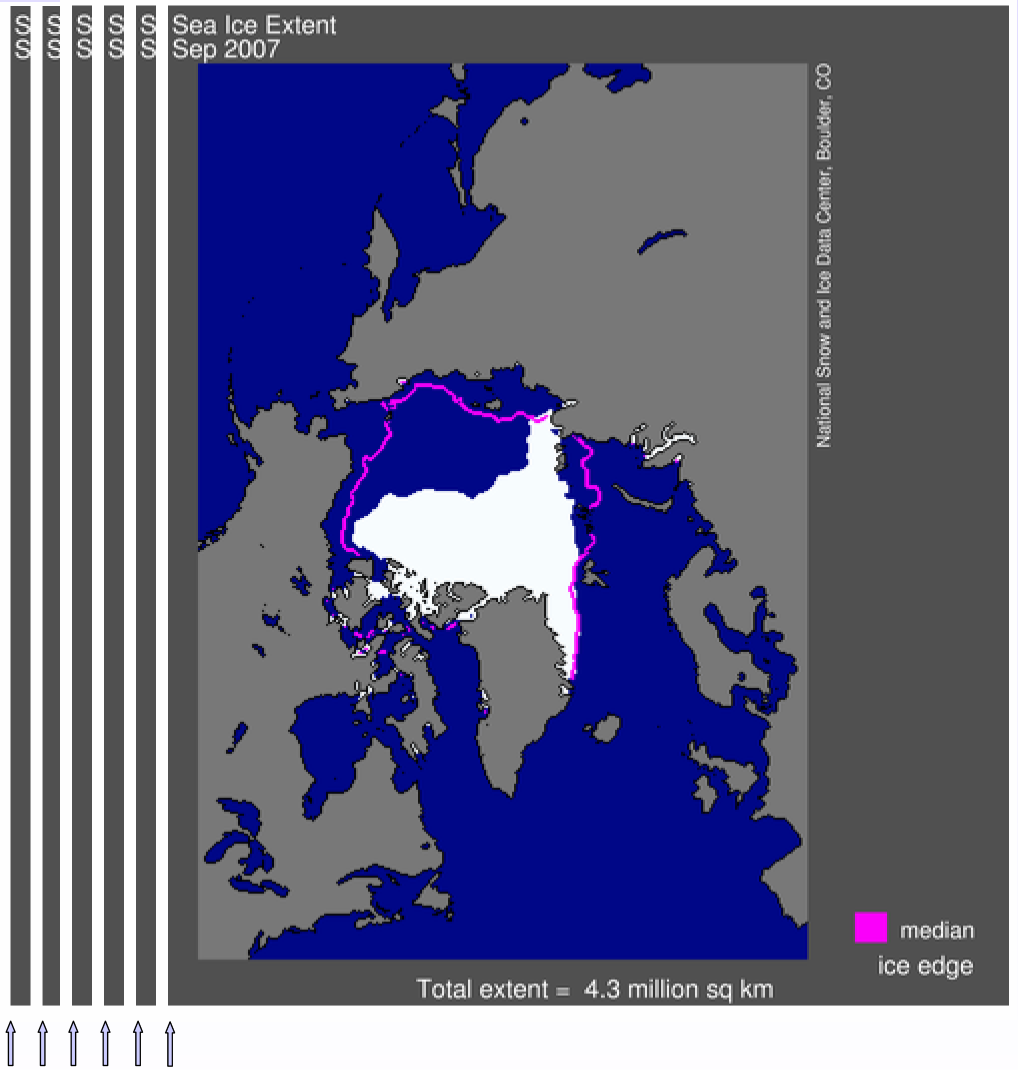
Schlumberger

Outline

1. Identifying Risks: Ranking Systems
2. *Performance & Risk Management drives MMV*
3. Measurements for Injectivity, Capacity, and Containment
4. Modeling – The Central MMV Tool

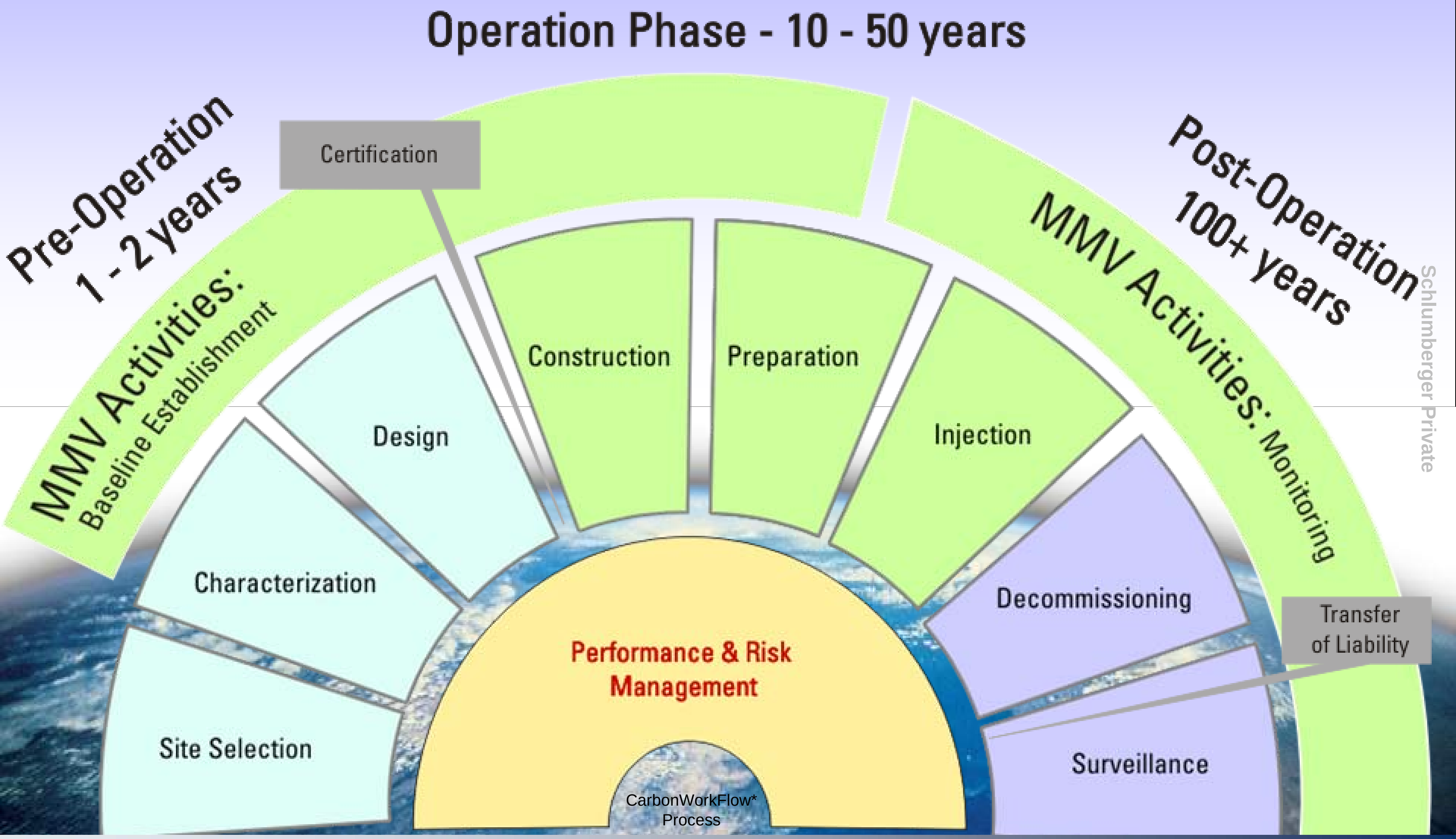
September Sea Ice Extent, 1982-2007

5-year intervals



National Snow and Ice Data Center
Boulder, CO

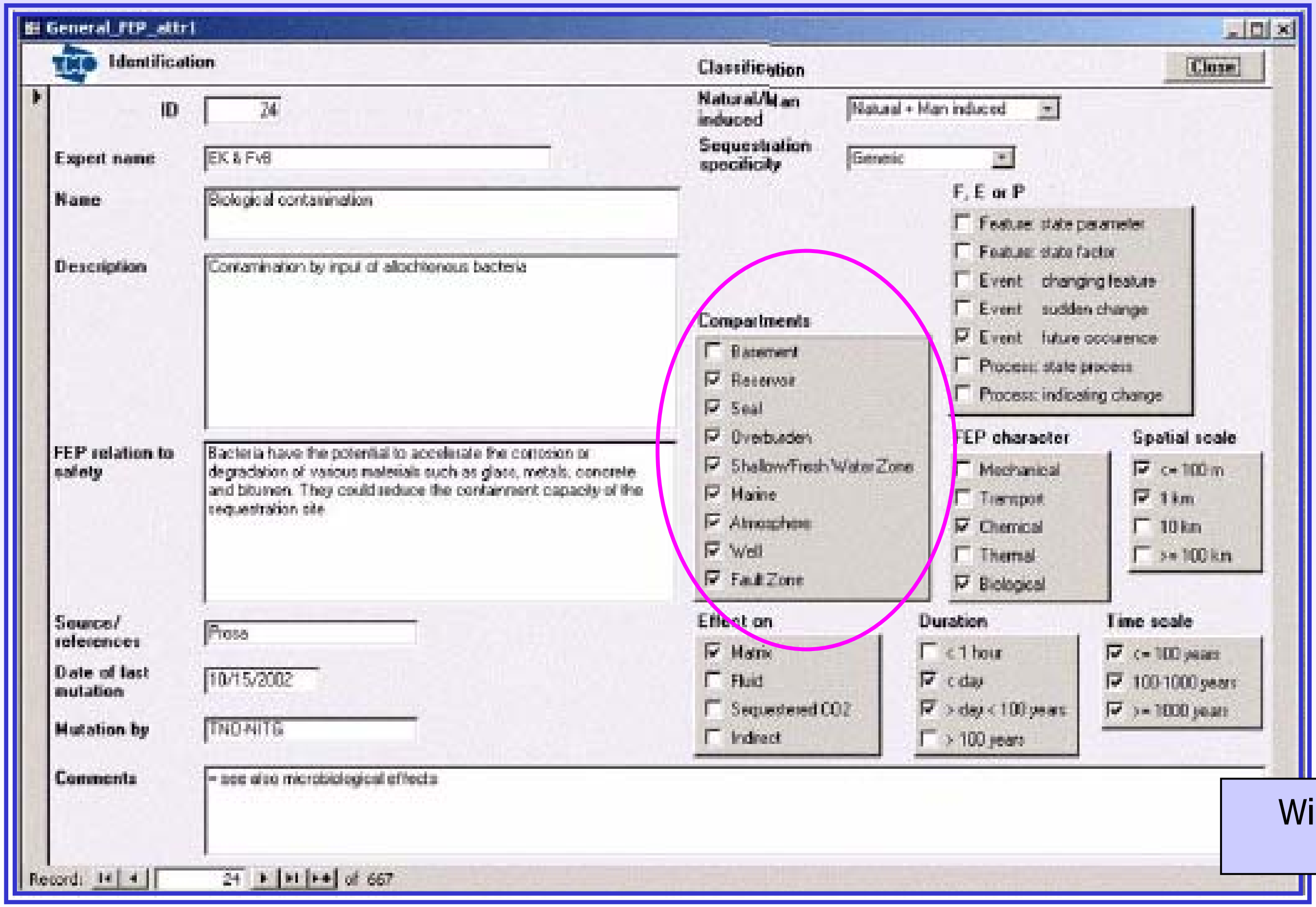
CO_2 Storage Project Lifecycle



Outline

- Identifying Risks: Ranking Systems
- Performance & Risk Management drives MMV
- Measurements for Injectivity, Capacity, and Containment
- Modeling – The Central MMV Tool

F. E. P. Data Entry



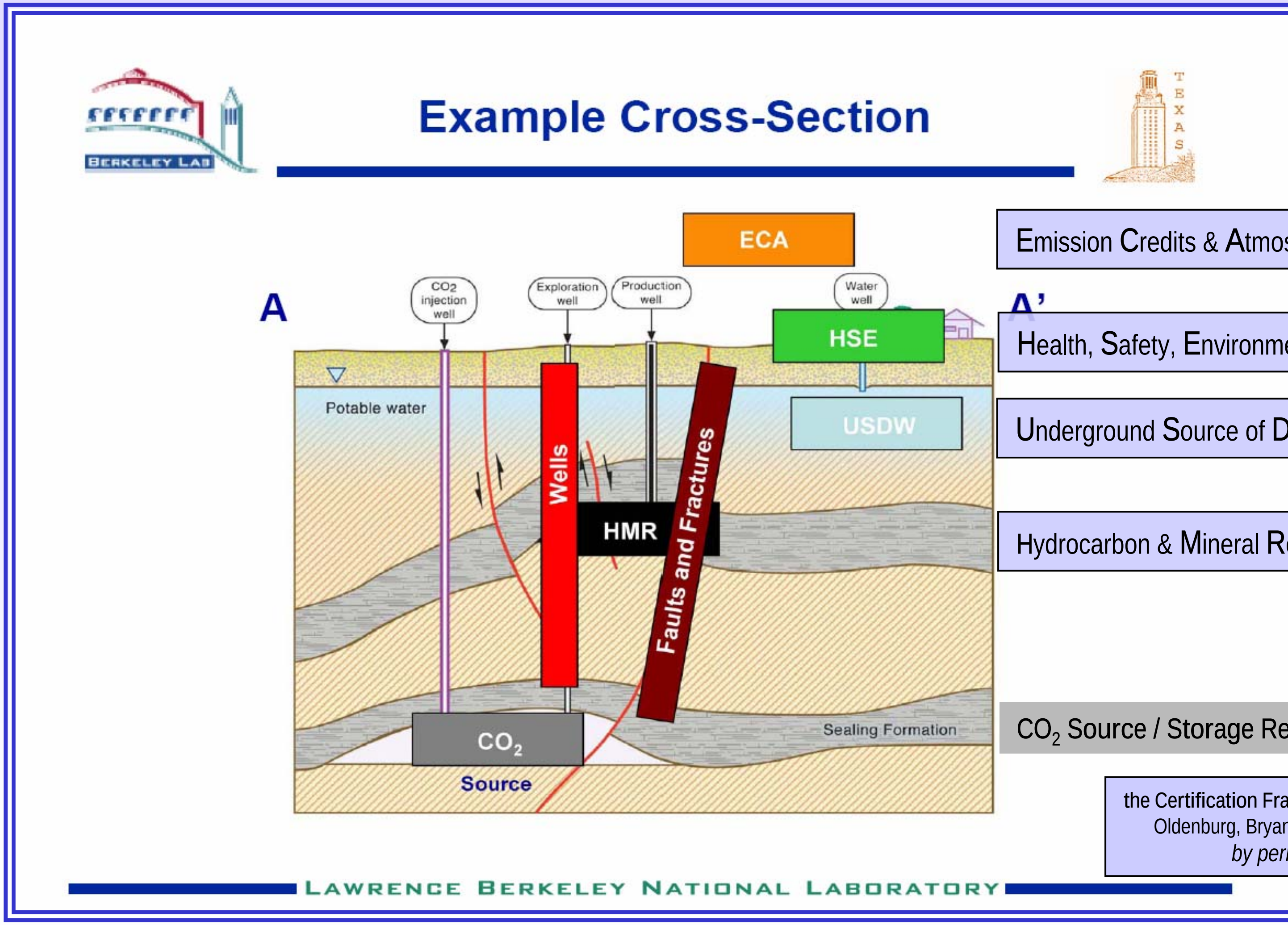
Features

Events

Processes

Wildenborg 2007
by permission

Compartments & Conduits



Emission Credits & Atmosphere

Health, Safety, Environment

Underground Source of Drinking Water

Hydrocarbon & Mineral Resources

CO_2 Source / Storage Reservoir

the Certification Framework (CF) project
Oldenburg, Bryant, and Nicot, 2007
by permission

Polling the Experts

ID	2.9 Drilling a “dry hole”
Description	Drilling reveals that injectivity is not acceptable where well is planned; project is not viable
Timescale	Should be indicated during site characterization or well drilling
Potentially Involved Parties	Site characterization team, well construction team, operator
Preventive Action	Careful site selection
Mitigation Response	Drill to new horizon, if still no viable options, plug first well, drill another or move to a new location and drill new well
Residual Risk	If dry hole not well plugged, could become leakage pathway in the future
Warning Signals	Core samples, seismic survey and other site characterization tests of porosity and permeability, extent of reservoir
Interdependence / Risk Coupling	None
Priority Ranking	2
Mitigation Cost	2
Comments	At least at this early stage of the CCS industry, everyone will be “careful”. There is always residual risk because it is not possible to “fully” characterize the earth.

Event description

Expert responses

World Resources Institute 2007
by permission

Prioritized sources of hazard

An alternative prioritization could be proposed for other cases (e.g., Texas GOM)

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
		Induced seismicity
Pink = highest priority Orange = high priority Yellow = moderate priority		Subsidence/tilt

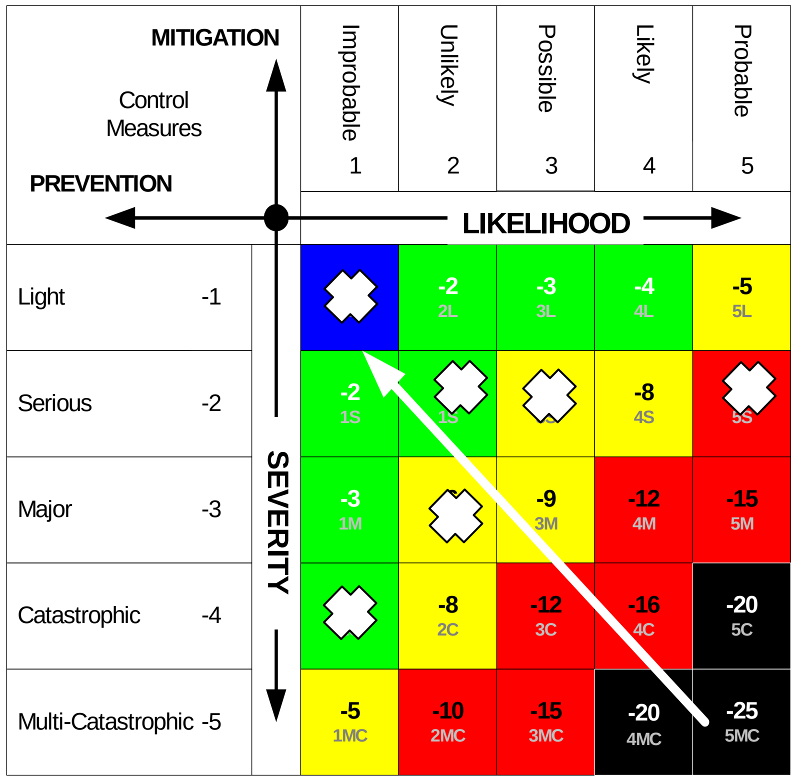
Prioritization uses expert knowledge and can be advised by science and experience

SJF 05-2006

Friedmann 2007
by permission

Qualitative Risk Prevention & Mitigation Matrix

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



White arrow indicates decreasing risk

Outline

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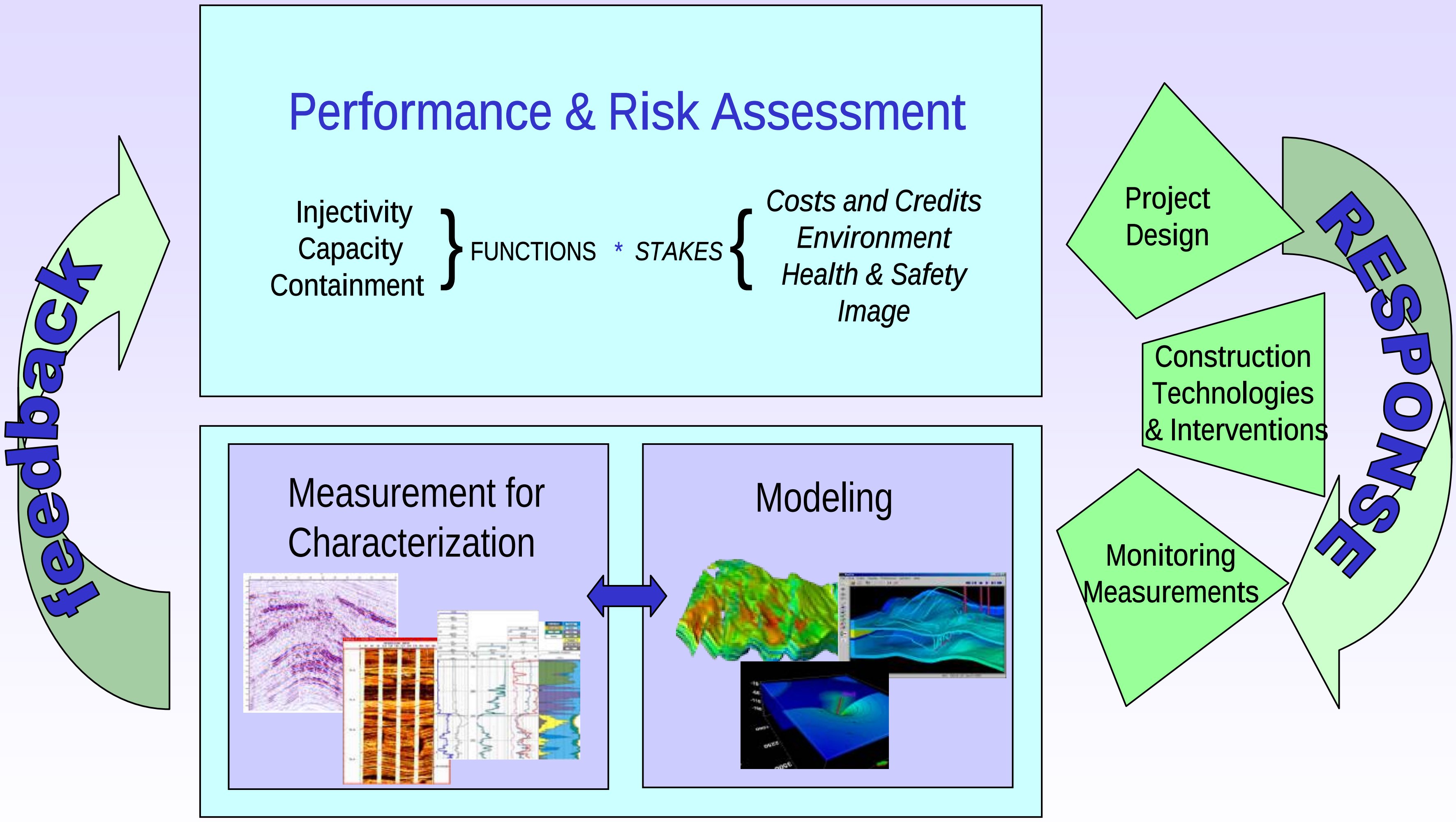
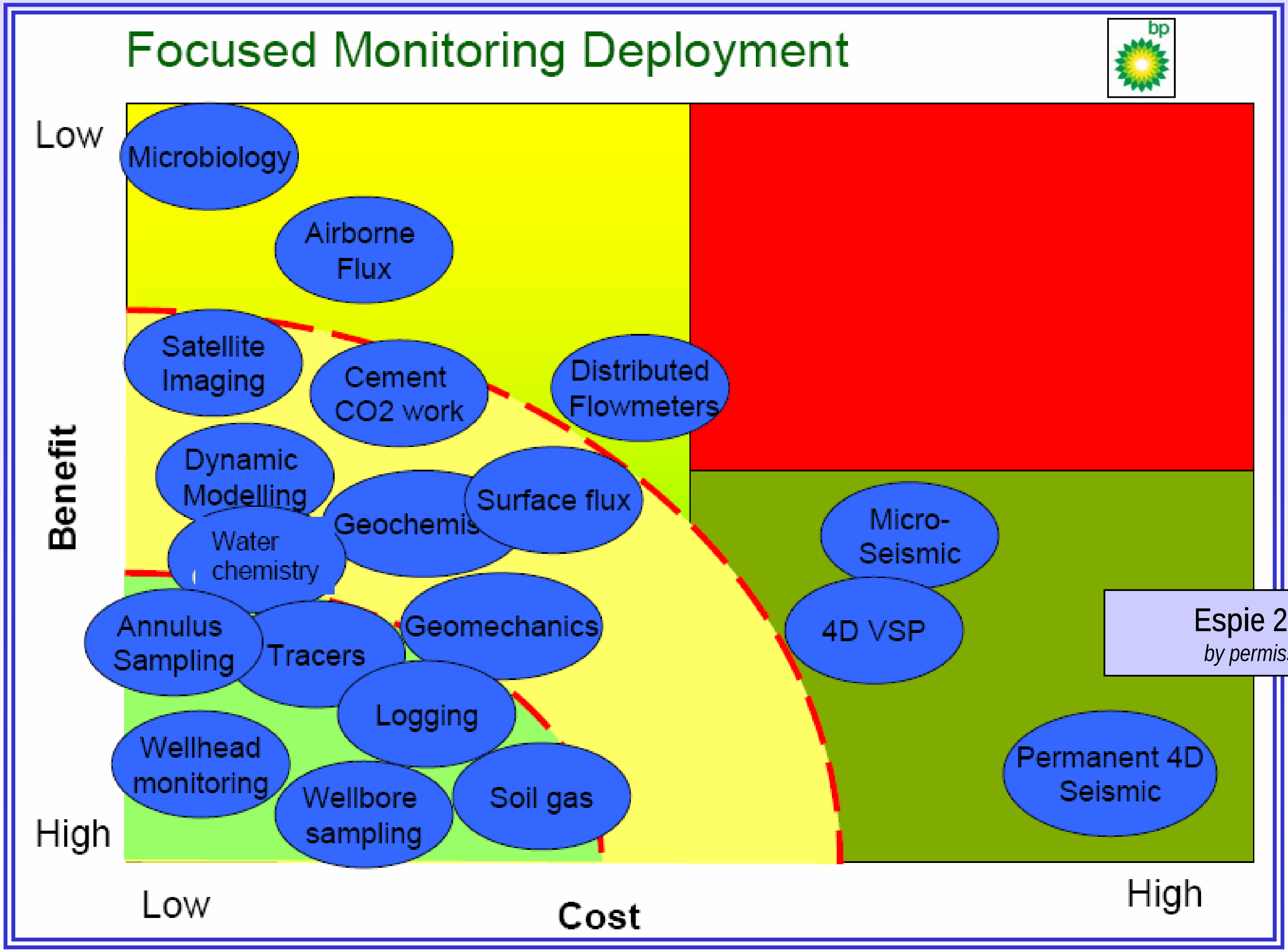
Performance & Risk Management System



Focused Monitoring Deployment



Espie 2007
by permission

Monitoring Targets and Monitoring Methods

Monitoring Targets

Monitoring Methods	Injection-well condition, pressures, flow rates	Solubility and mineral trapping	CO2 plume location	Early warning of caprock failure	Leakage up faults and fractures	Groundwater quality	CO2 conc. in the vadose zone and soil	CO2 conc. and fluxes at ground level
Flow metering, Orifice or other differential	X							
Infrared CO2 detectors	X							X
Borehole logs (casing, cement, fluids)	X		X					
Pressure msmt: Well, reservoir, annulus, aquifer	X		X	X	X			
Gravity measurements			X	X				
EM (electrical, electromagnetic) surveys			X		X			
Seismic: 3-D time-lapse surveys			X	X	X			
Seismic: Microseismicity monitoring			X	X	X			
Seismic: VSP, walkaway, cross-well			X	X	X			
Tiltmeters			X	X	X			
Satellite and/or airborne data			X	X	X		X	
Samples: Fluid; optional tracers		X	X		X	X	X	
Vegetation changes observed on ground					X	X	X	X
Samples: Soil gas					X		X	X
Samples: Air, via eddy-flux towers or grab								X

Injectivity

Capacity

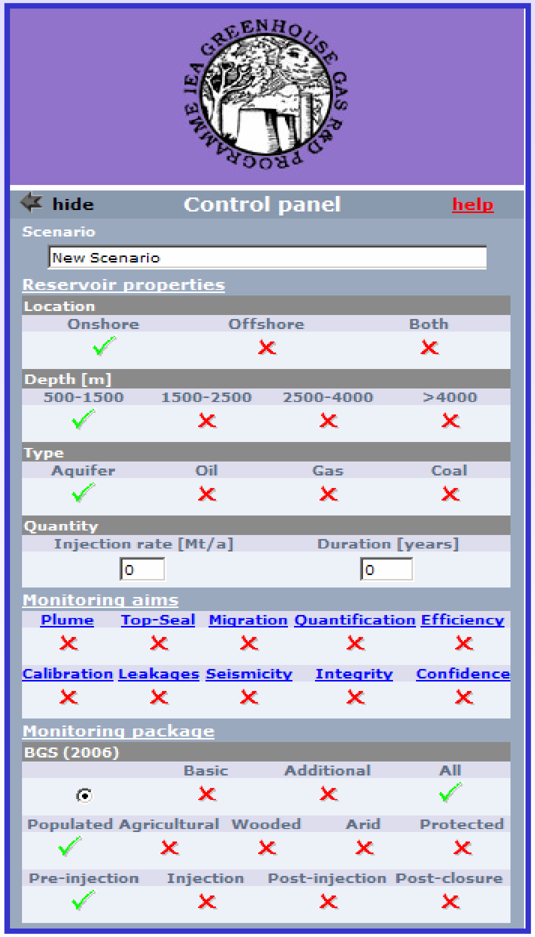
Containment

X = Method applicable to target

Modified after Vu Hoang, Vivalda, and Verliac, 2007

Monitoring Selection Tool

Monitoring Selection Tool



2D surface seismic	3D surface seismic
Airborne EM	Airborne spectral imaging
Boomer/Sparker profiling	Bubble stream chemistry
Cross-hole EM	Cross-hole ERT
Cross-hole seismic	Downhole fluid chemistry
Downhole pressure/temperature	Ecosystems studies
Eddy covariance	Electric Spontaneous Potential
Fluid geochemistry	Geophysical logs
Ground penetrating radar	High resolution acoustic imaging
IR diode lasers	Land EM
Land ERT	Long-term downhole pH
Microseismic monitoring	Multibeam echo sounding
Multicomponent surface seismic	Non dispersive IR gas analysers
Permanent borehole EM	Satellite interferometry
Seabottom EM	Seawater chemistry
Sidescan sonar	Soil gas concentrations
Surface gas flux	Surface gravimetry
Tiltmeters	Tracers
Vertical seismic profiling (VSP)	Well gravimetry

Aim Score	Definition	Explanation	Colour-scale
0	Not applicable	The technique cannot be used for the selected aim.	Green
1	Possibly applicable	The technique may be appropriate for the selected aim but is probably of marginal utility. It is unlikely to be a preferred option but may be useful in combination with other methods. Site-specific conditions or specialised scientific requirements however may call for deployment of the technique.	Green
2	Probably applicable	The technique is likely to be suitable for the storage application, though there are probably other more effective techniques that should also be considered. The technique could be included in a monitoring protocol to provide additional information for a monitoring aim, supplementing other, higher-ranked techniques. Site-specific conditions or specialised scientific requirements however may call for deployment of the technique.	Amber
3	Definitely applicable	The technique would normally be included to meet a particular monitoring aim and its exclusion may reduce the potential for the aim to be achieved. However, site-specific conditions may degrade the efficacy of the technique, or even preclude its deployment.	Amber
4	Strongly recommended	The technique would normally be regarded as a key element in meeting a particular monitoring aim and its exclusion would reduce the potential for the aim to be achieved. However, site-specific conditions may degrade the efficacy of the technique, or even preclude its deployment.	Red

http://www.co2captureandstorage.info/co2tool_v2.1beta/co2tool_panel.php

Outline

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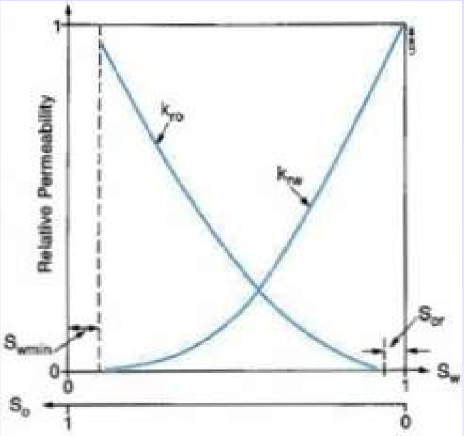
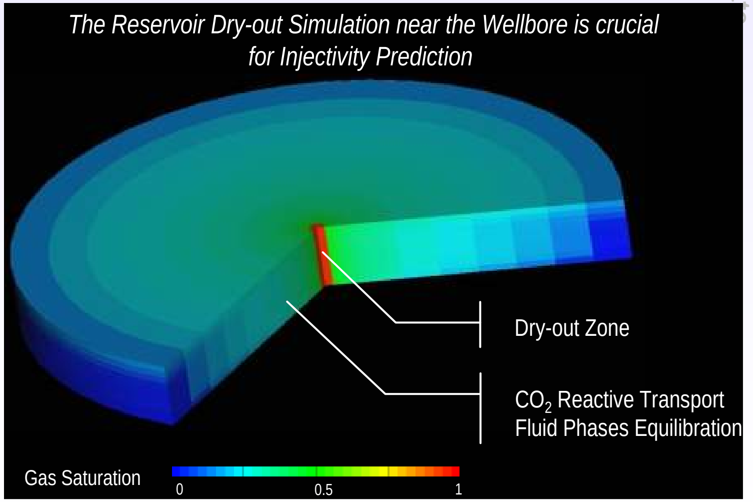
Injectivity

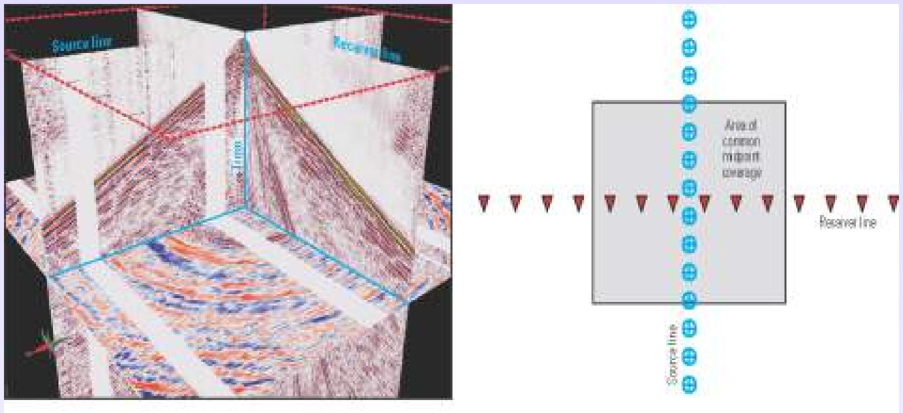
- Permeability
  - Core
  - Logs
  - Formation testers
  - Well tests
- Injection induced near-wellbore effects
  - Dry-out
  - Salt precipitation – Carbonate dissolution
- Mitigation
  - Injection well design and number
  - Hydraulic fracturing

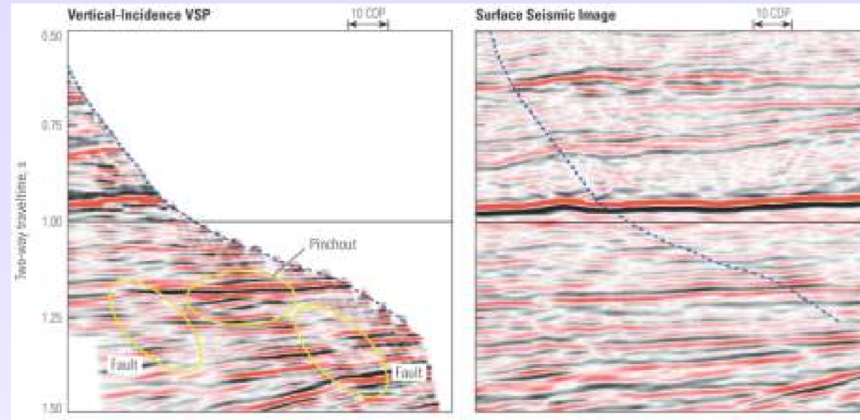




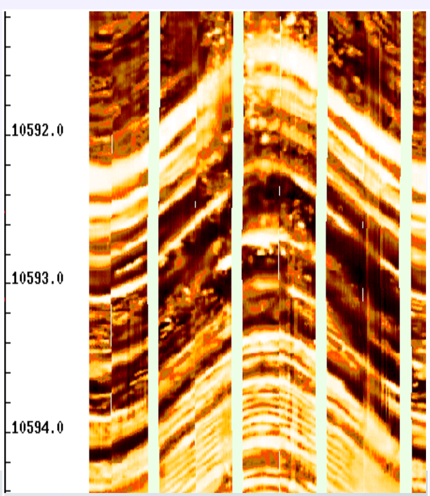
Capacity: Characterization and Monitoring

- High-Resolution Seismic, VSP's, and Sonic

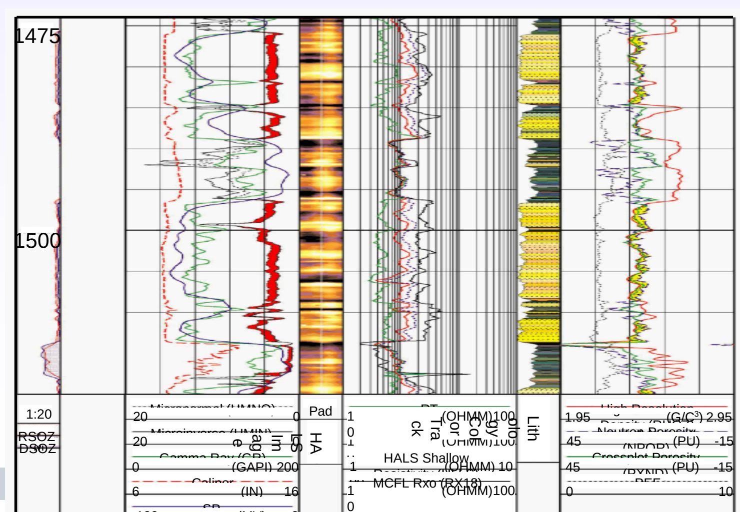




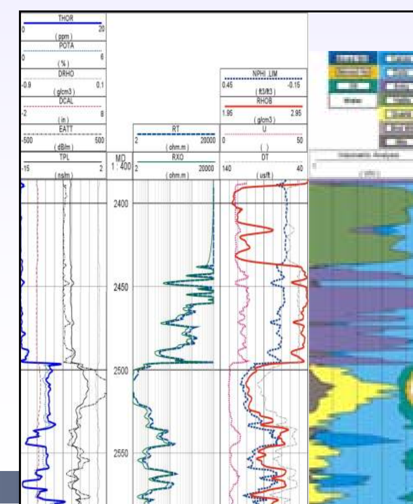
- Borehole imagers



- Formation Evaluation

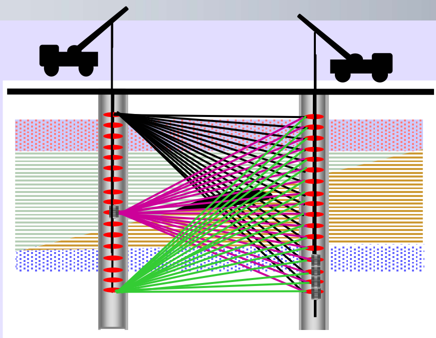


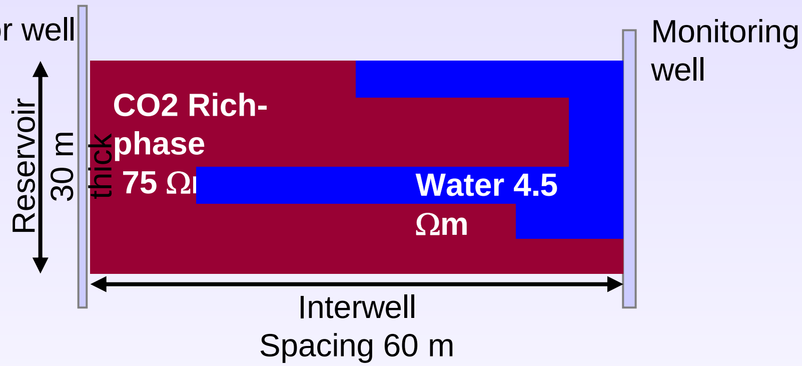
- Mineralogy



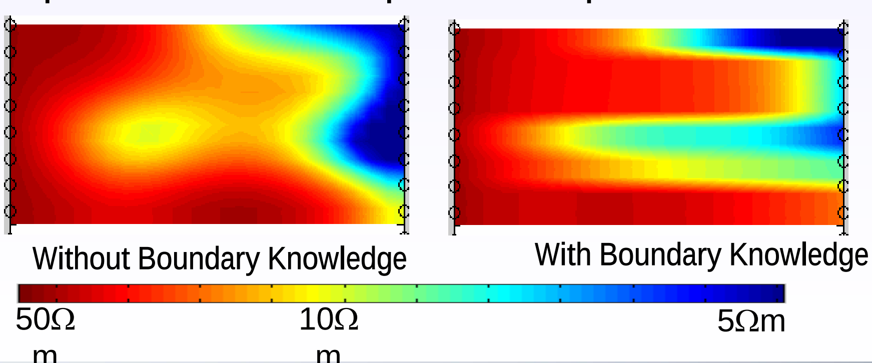
Capacity: Measurements for CO_2 Saturation

X-Well EM Surveys
CO_2 Saturation

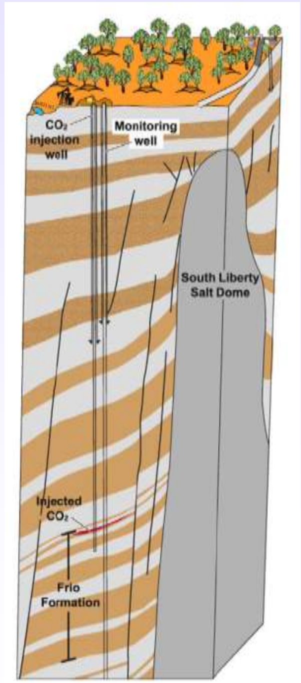


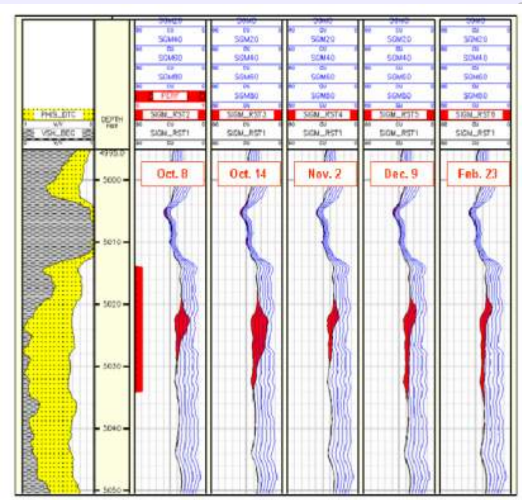


A priori information improves interpretation



Neutron Capture Logging (Σ)
CO_2 Saturation near wellbore
CO_2 breakthrough at a monitoring well
Frio brine experiment in Texas:

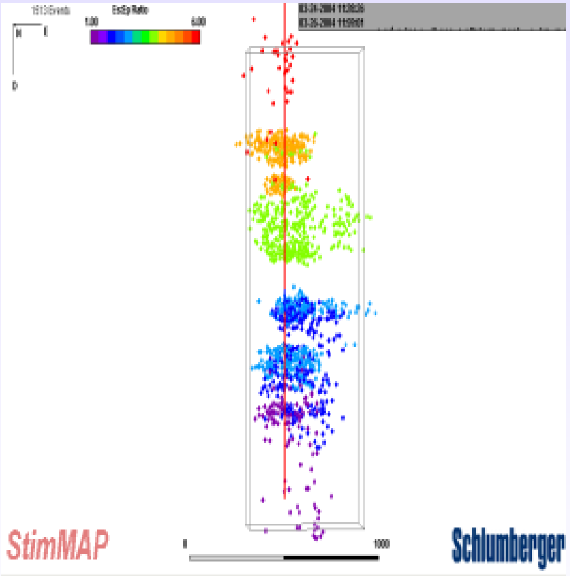




Capacity & Containment: Microseismics

Microseismicity events are micro-cracks occurring in the formation due to pressure increase

Listening to these cracks is a powerful monitoring technique

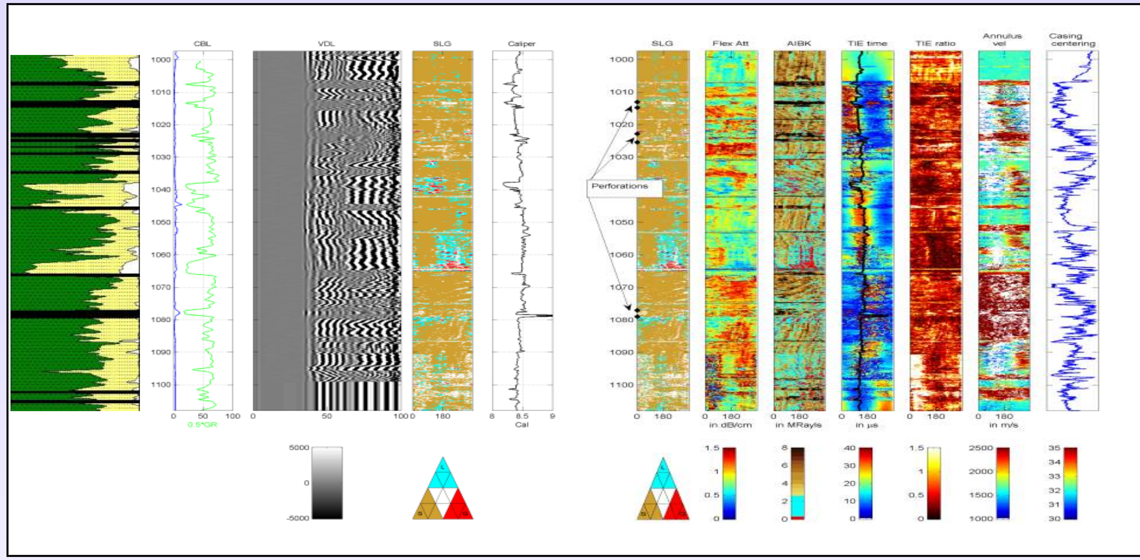


- Detection, 3D Location, and Classification of Microseismicity Events
- Control of Pumping Rate to Avoid Fracturing the Cap Rock
- Detection of Fault Reactivation

Containment: Measurements for Well Integrity

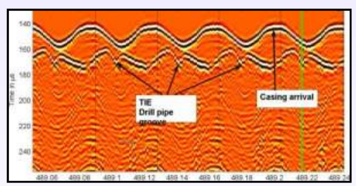
Joint analysis of data from these tools:

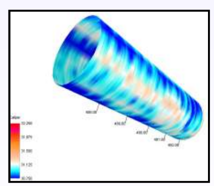
- Multi-finger caliper
- Electromagnetic
- Ultrasonic
- Sonic

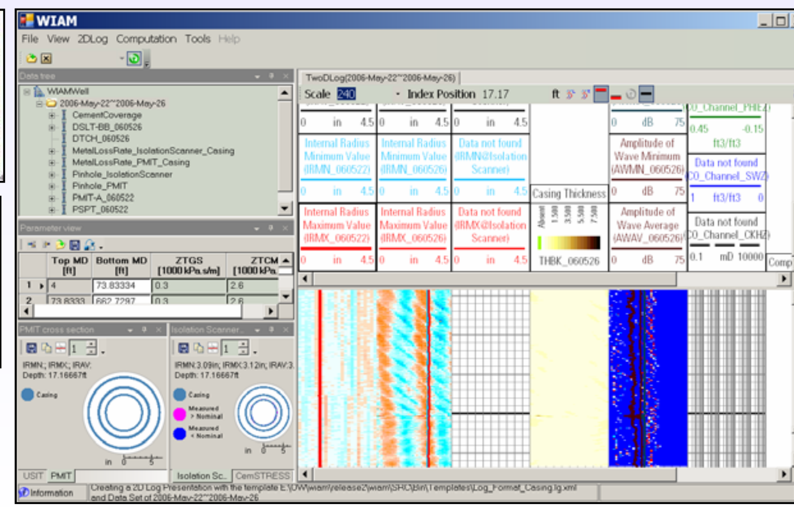


To characterize:

- Casing corrosion
  - Internal / external
  - Corrosion type
- Cement quality
  - Bonding at interfaces
  - Cement properties
- Near-wellbore formation damage







Outline

- Identifying Risks: Ranking Systems
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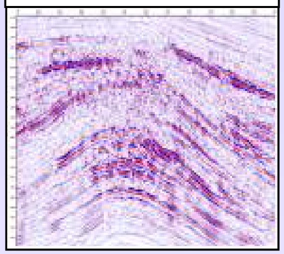
- Measurements for Injectivity, Capacity, and Containment
- Modeling – The Central MMV Tool

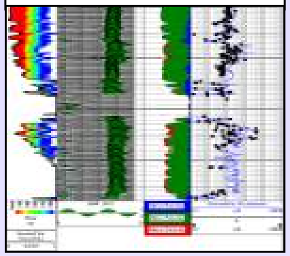
    1. Site conceptual model
    2. Static geologic-geophysical model
    3. Dynamic geophysical model
    4. Measurements
    5. Do Over

Building a Static Model – Structure & Properties

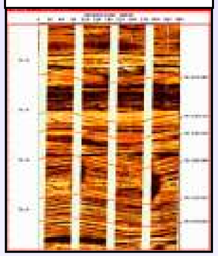
Geophysics



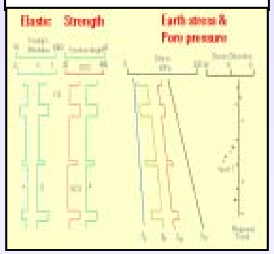
Flow / Transport



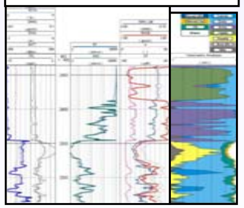
Geology

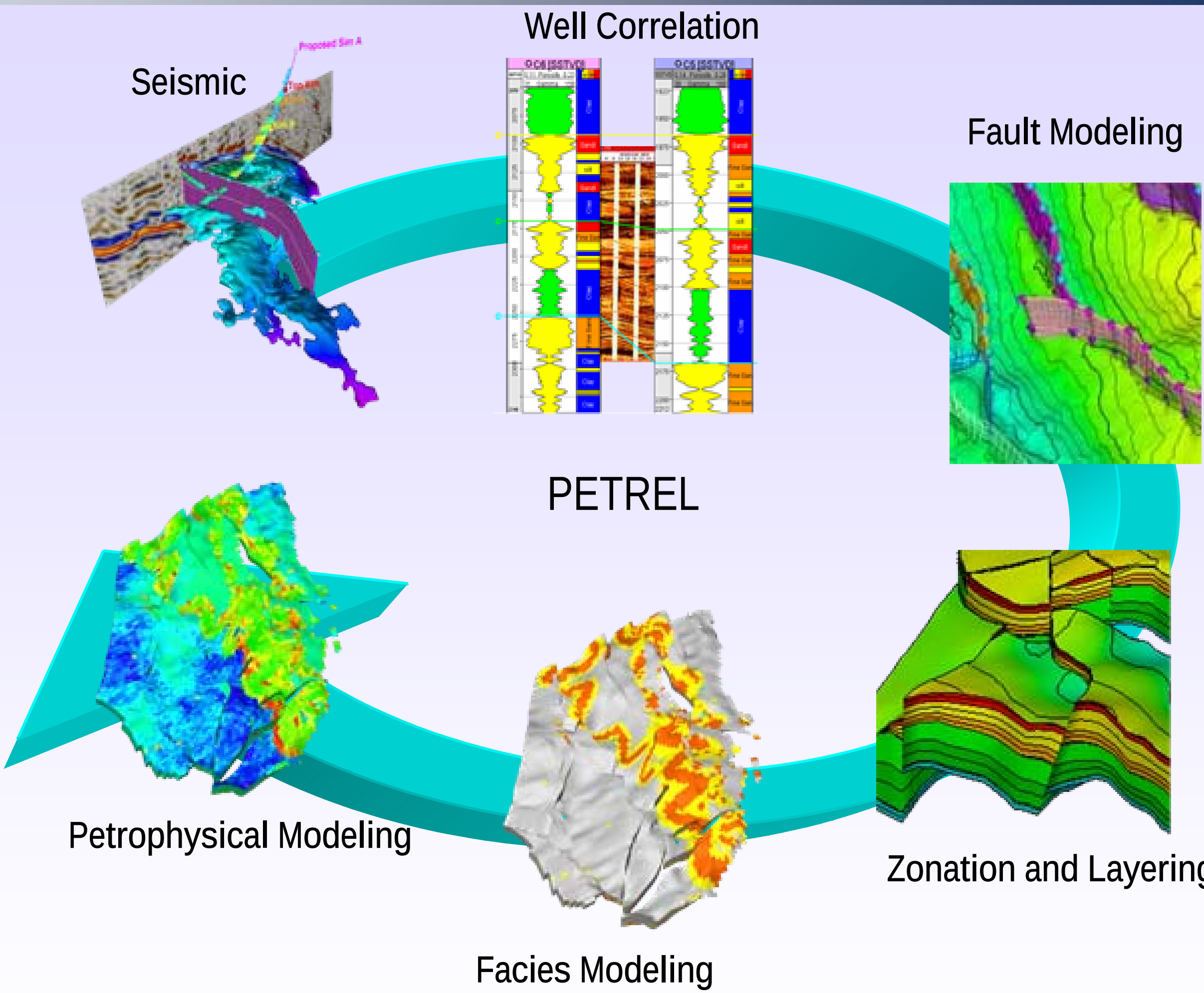


Geomechanics



Petrophysics
Mineralogy

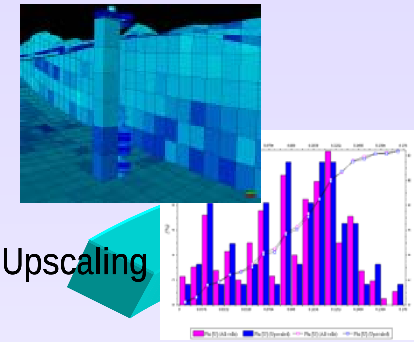




Model should include overburden

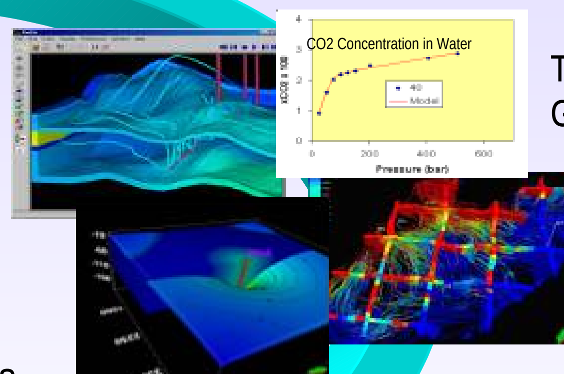
CO_2 Injection Dynamic Modeling

Current status: Improved fluid-fluid / fluid-rock interactions
- Accurate description of mutual solubilities
- Dry-out / Salting out effect
- Salt precipitation
- Coal swelling and shrinkage



Upscaling

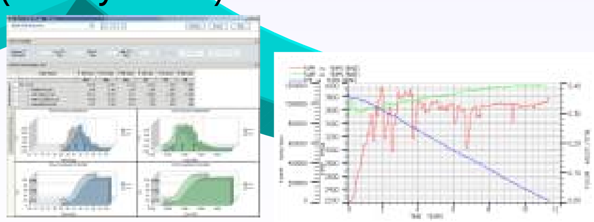
ECLIPSE – E300



Thermodynamics
Geochemistry

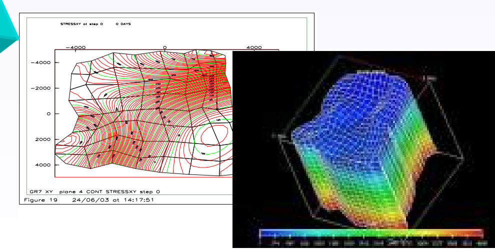
Thermal Modeling

Calibration on monitoring measurements
(History match)

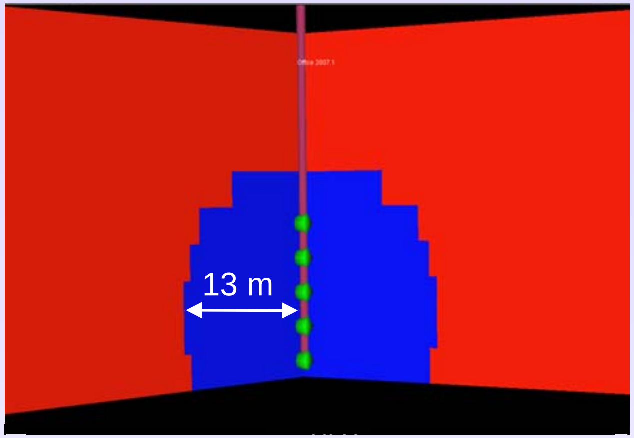


3D Full Compositional Flow Simulator

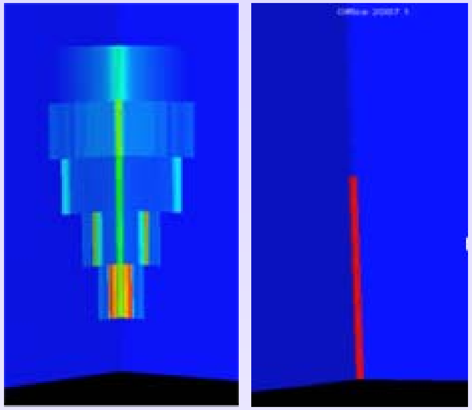
Geomechanics Simulator



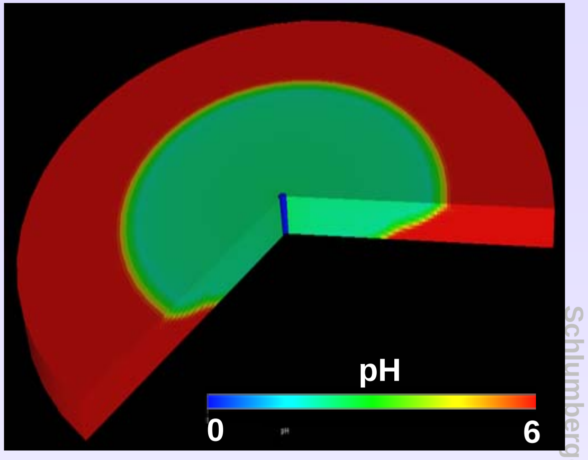
Injectivity – Modeling Near-Wellbore Effects



Dry-Out radius



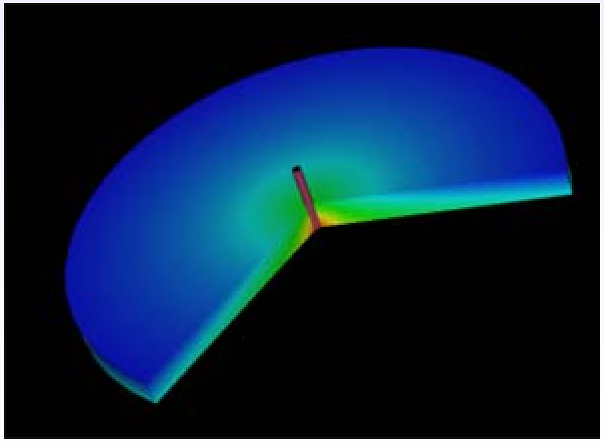
Salt precipitation profile



pH output

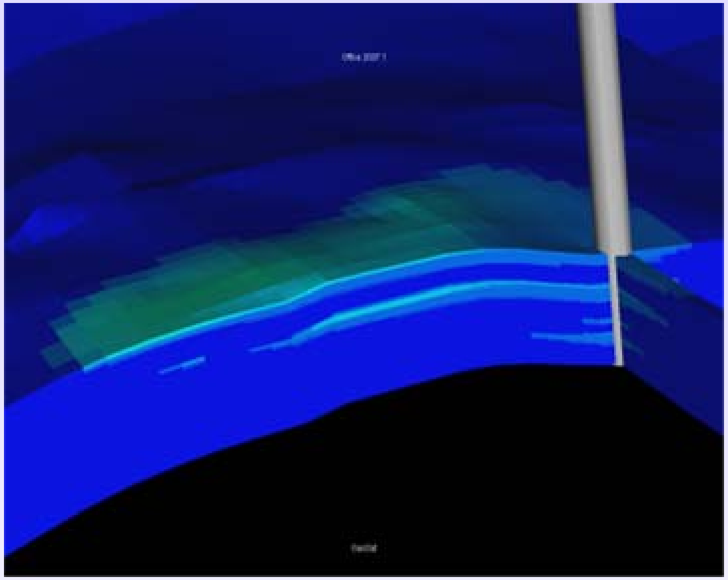
Refined wellbore radial model for injectivity studies

- Is Injection possible?
- Injection rate estimation respecting BHP
- Critical outputs for Injectivity:
  - Injection rate
  - BHP
  - Salt precipitation profile
  - Dry-out radius

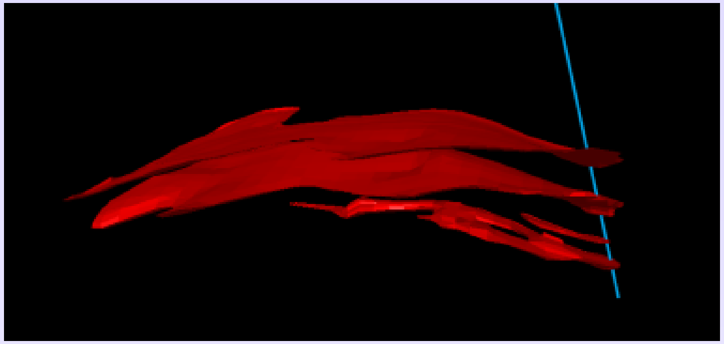


Pressure profile

Capacity – Volumetrics & Trapping



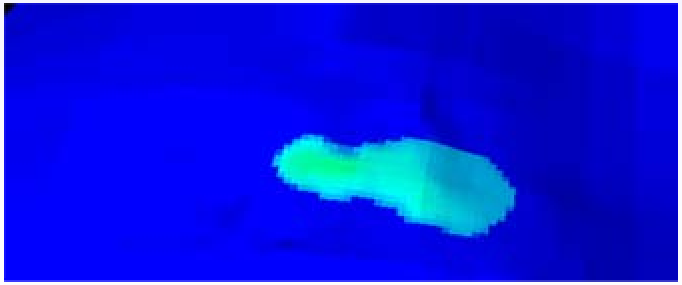
Free CO_2 saturation



Dissolved CO_2 Isosurface

- Capacity estimation
  - Dissolved CO_2,
  - Trapped CO_2 (immobile)
  - Free CO_2 (mobile)

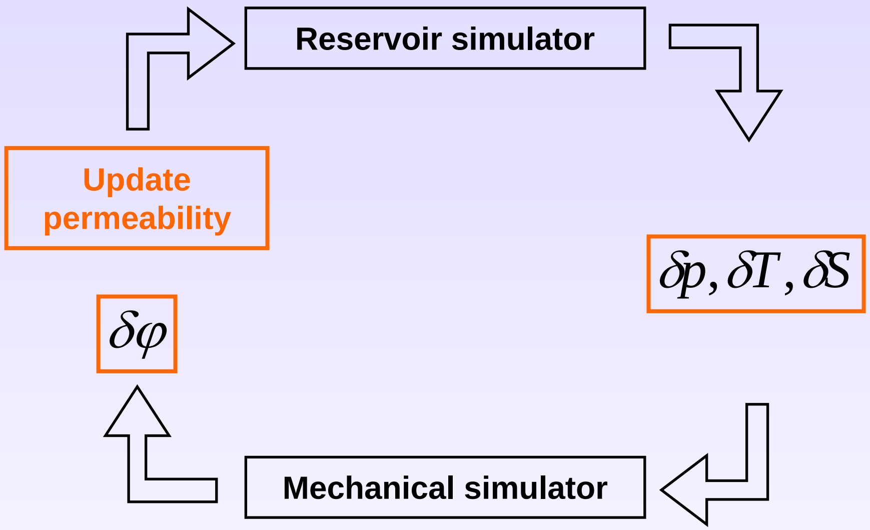
- Plume Monitoring
- Hydrodynamic Trapping
- Flow Gradient impact



CO2 trapped in an Anticline Top

Containment – Reservoir Geomechanics

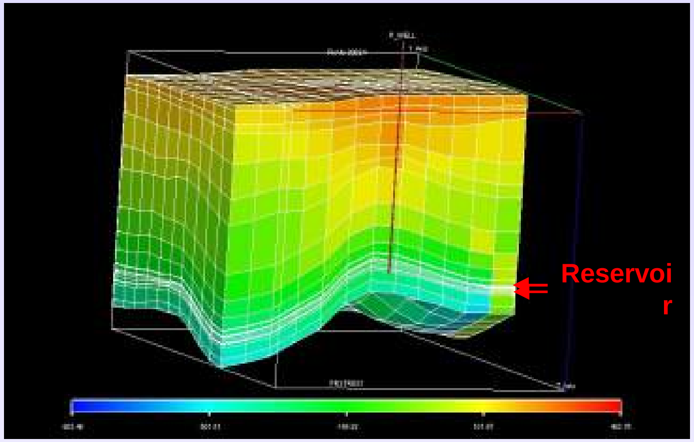
- Coupled simulation



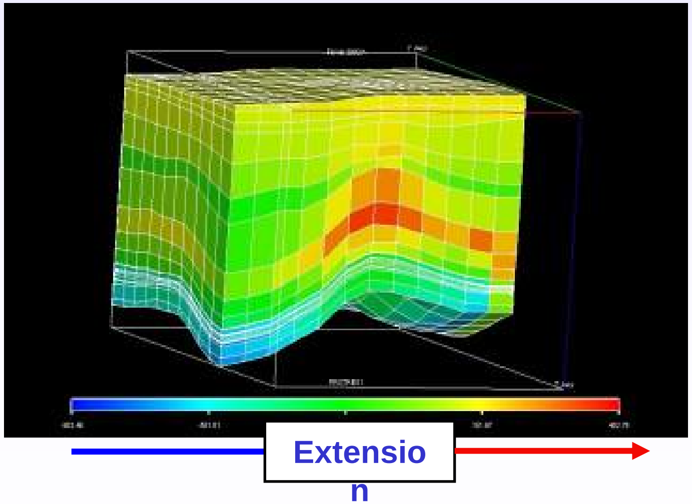
Eclipse-GM (E300)

VISAGE - VIP

Initial minimum stress σ_3



After injection



RECAP

- Risk identification and prioritization methods:

  several ways to slice the universe of risk

- CO_2 Project Functions: Injectivity, Capacity, Containment
- Monitoring techniques exist for each function
- Modeling is key to the "V" of MMV

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Seismic Based MMV Programs: Frio II, Otway Basin, Permian EOR, WESTCARB/SECARB

Tom Daley

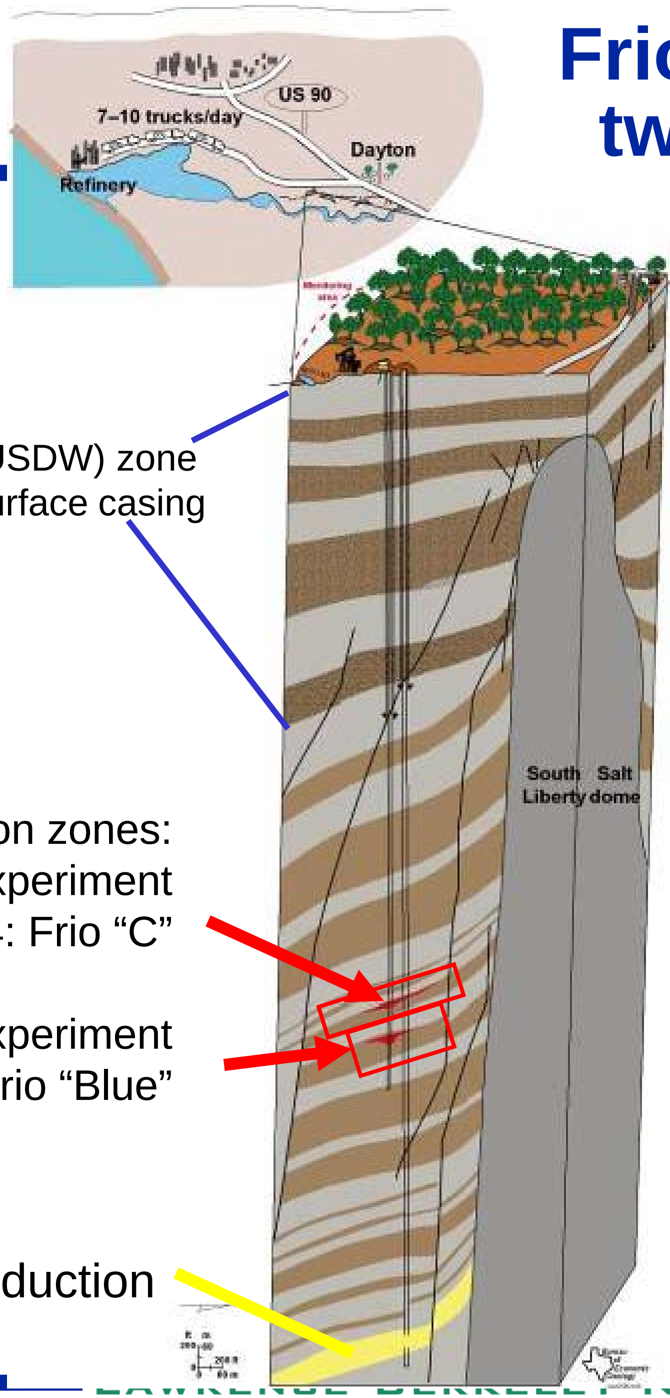
Lawrence Berkeley National Laboratory

Slide 2: Outline

- Discuss Design, Deployment Issues and Results

  - Frio I Seismic Results -> Frio II Planning
  - Frio II Results
  - Otway Design and Deployment
  - Permian Basin EOR Project: ‘Microhole’ VSP
  - WESTCARB and SEACARB Planning

Frio Brine Pilot Site two test intervals



Fresh water (USDW) zone protected by surface casing

Injection zones:
First experiment
2004: Frio "C"

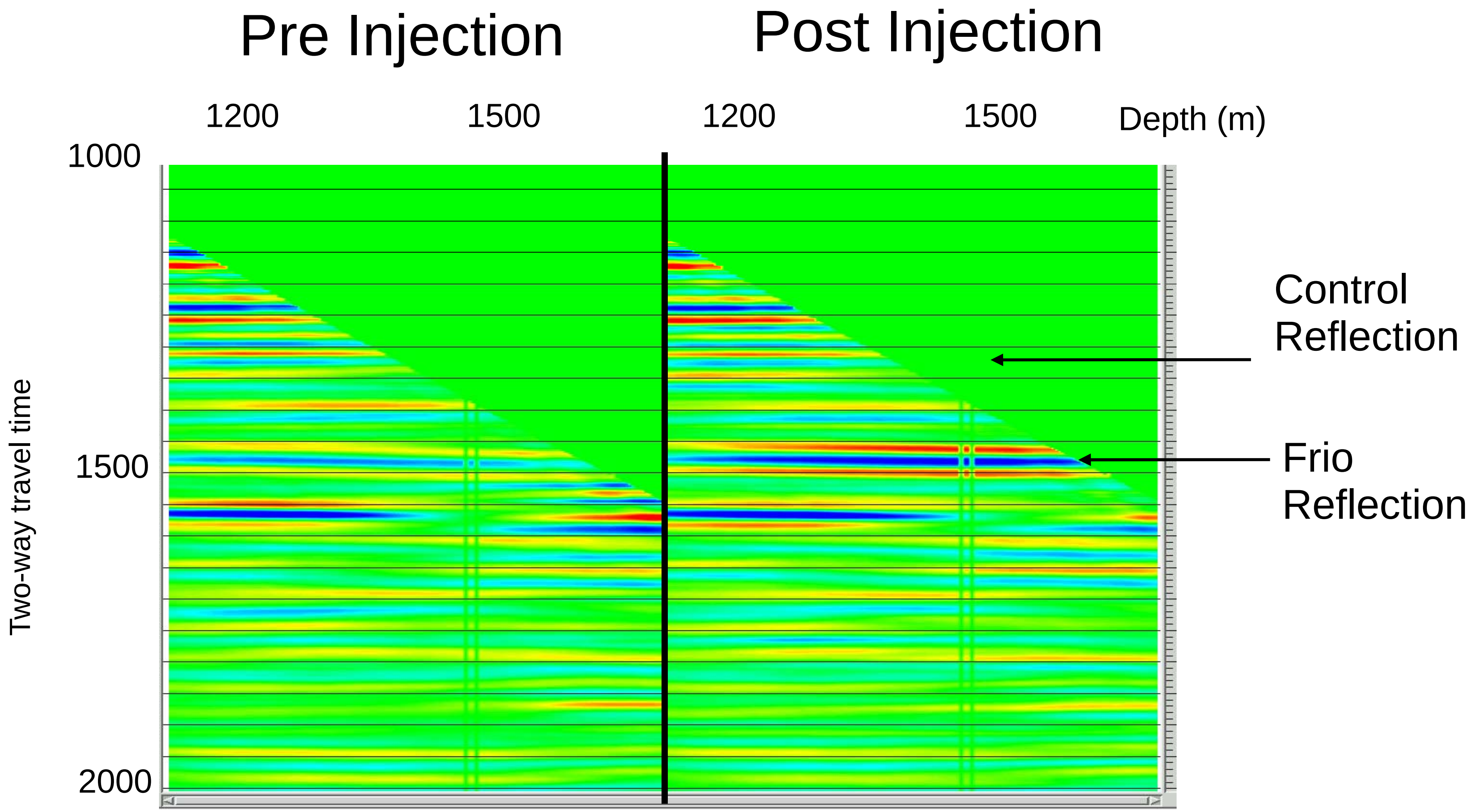
Second experiment
2006 Frio "Blue"

Oil production

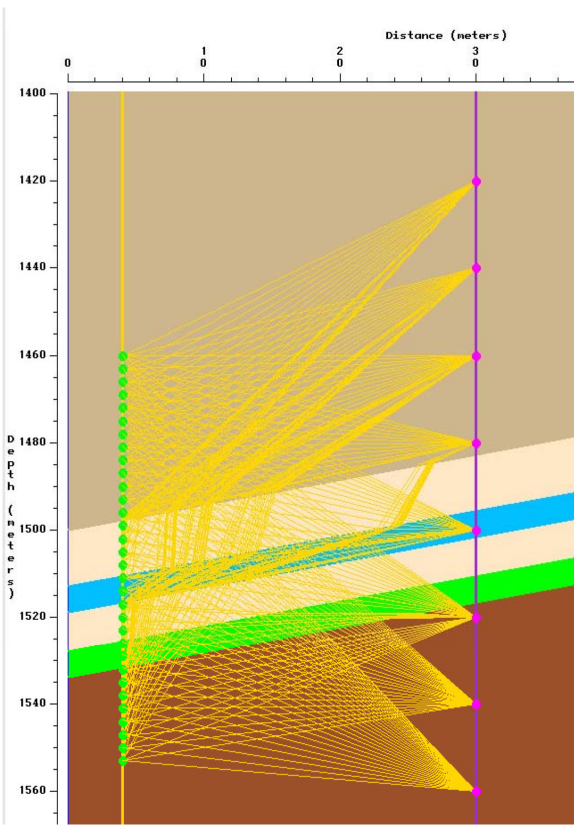
- **Injection intervals: fluvial sandstones, porosity 35%, permeability 4.4 to 2.5 darcys**
- **Steeply dipping 11 to 16 degrees**
- **Seals – numerous thick shales, small fault block**
- **Depth 1,500 and 1657 m**
- **Brine-rock system, no hydrocarbons**
- **150 and 165 bar, 53 -60 degrees C, supercritical CO_2**

From S. Hovorka

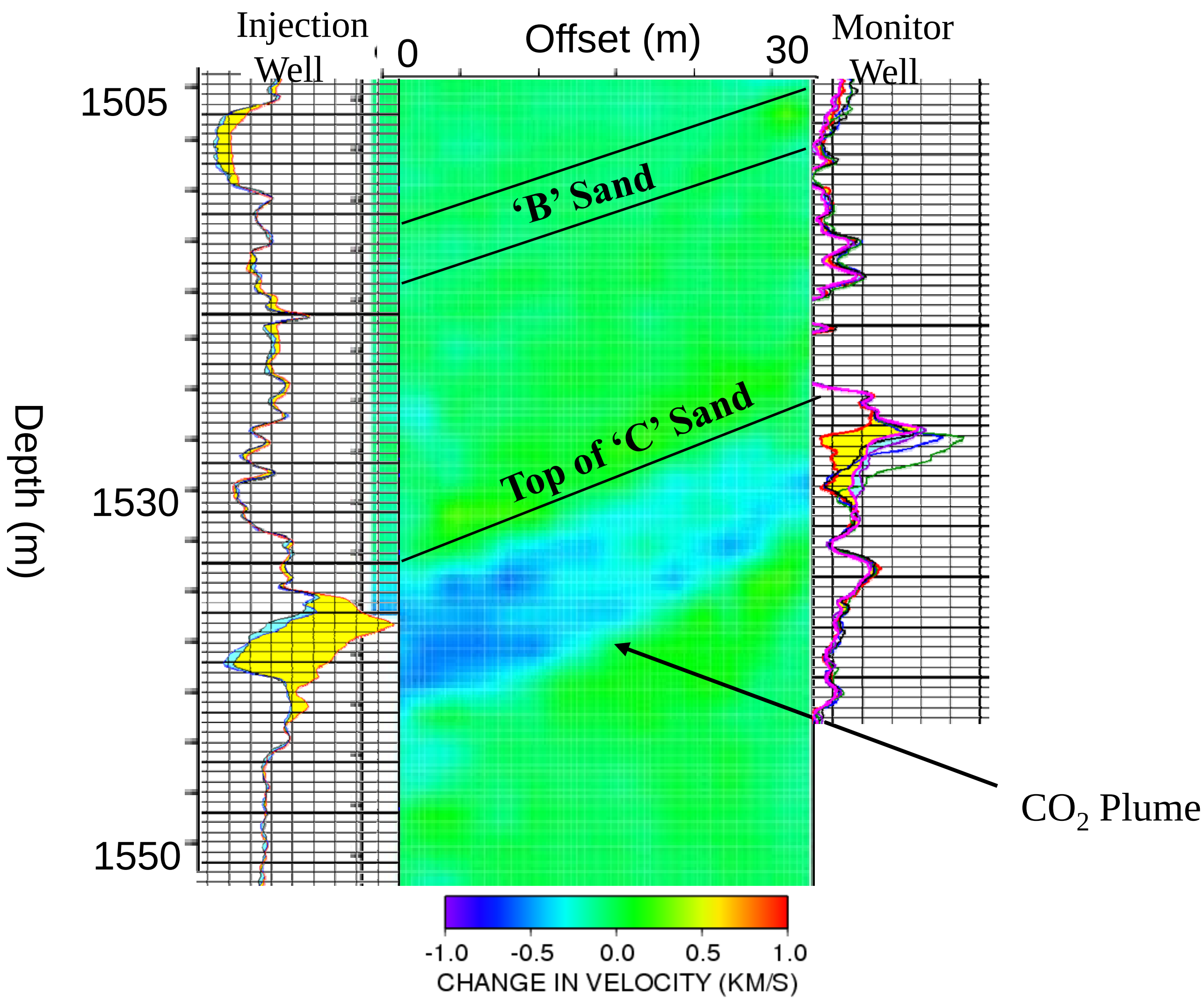
Frio I VSP Site 1



Frio-I: Seismic P-wave Tomography and Pulsed Neutron Logs

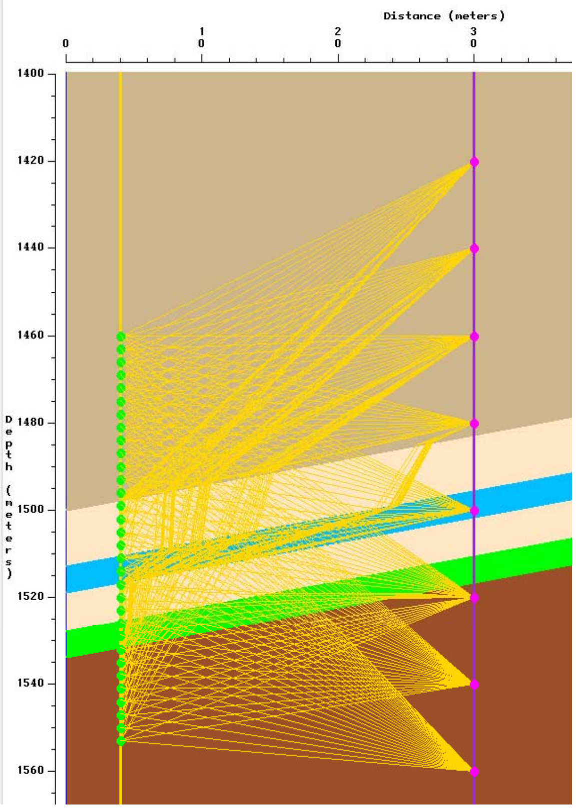


Raypaths

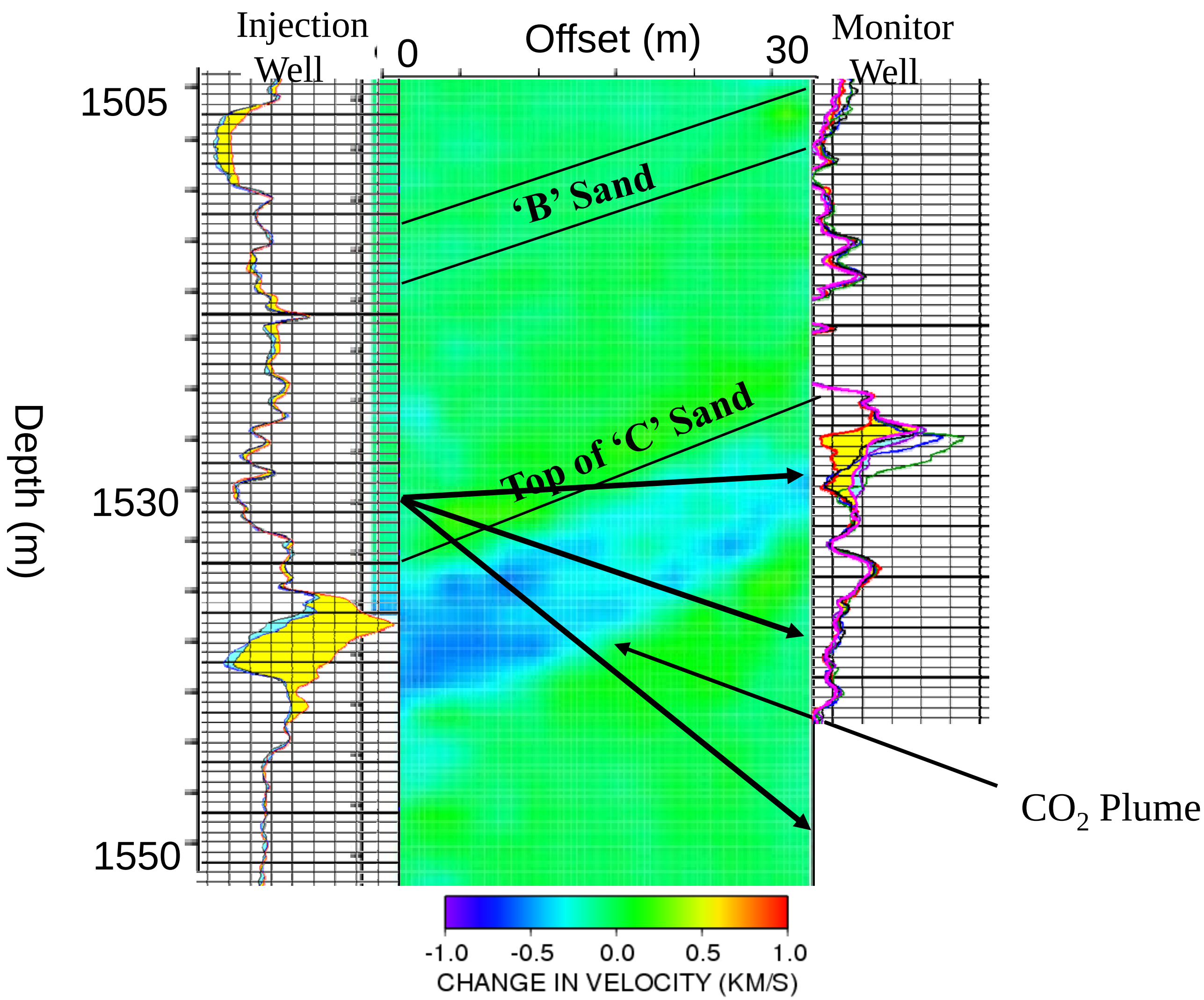


Daley, et al, Env. Geol., 2007.

Frio-I: Seismic P-wave Tomography and Pulsed Neutron Logs



Raypaths

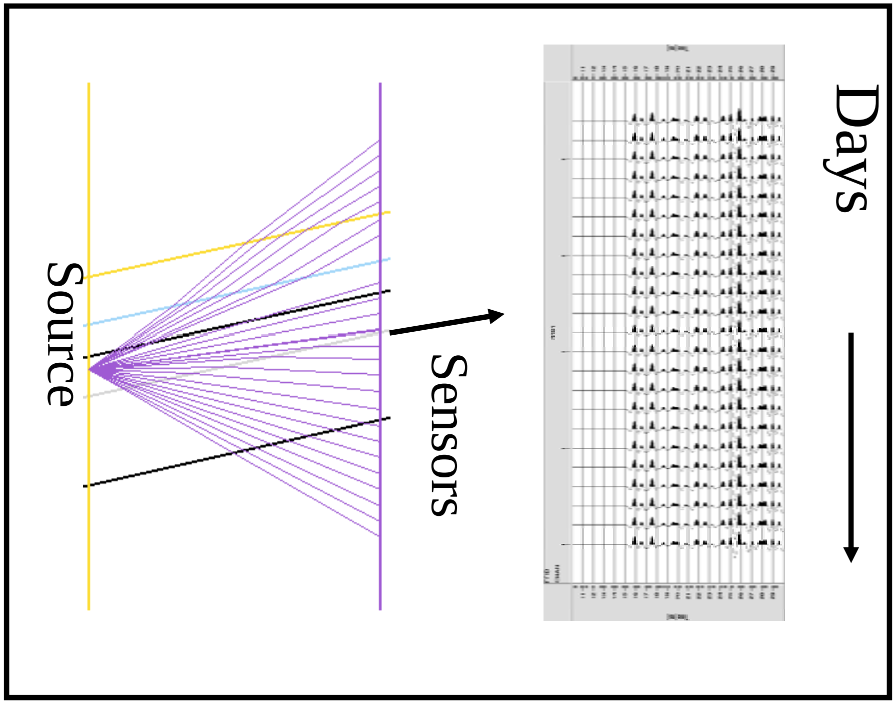


Daley, et al, Env. Geology, 2007.

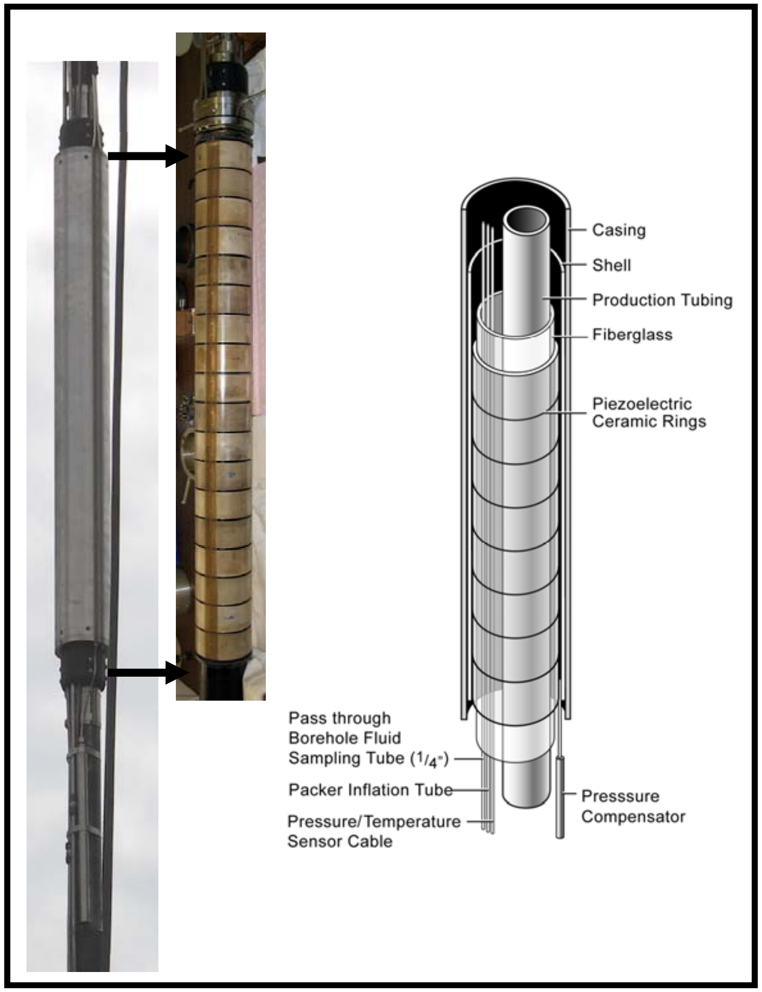
CASSM Background

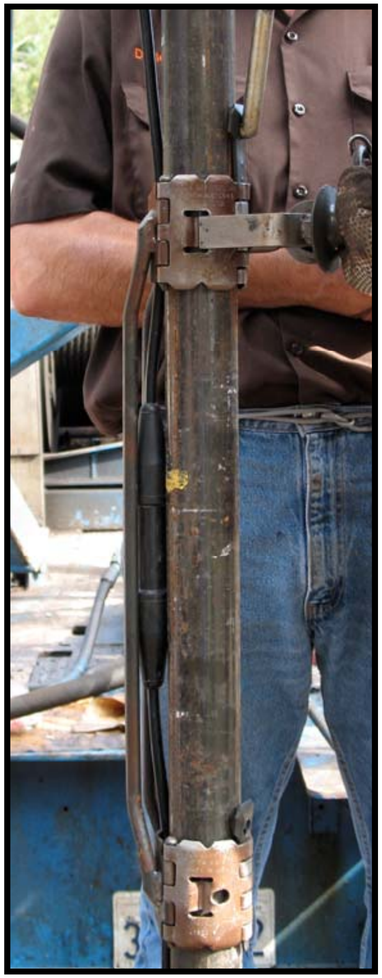
- **Continuous Active Source Seismic Monitoring (CASSM)**
- **Goal: Precision In-situ monitoring seismic travel time**

- **Motivation:**
  - — **Earthquake 'Prediction'**
    - **Measure tectonic stress change**
    - **Silver, et al, 2007, BSSA**
  - — **Monitoring of CO2 sequestration**
    - **Monitoring flow in real time**
      - — **Important in Pilot Studies**
    - **Constraining flow models**
    - **Monitoring for 'leakage'**



"Piezotube" Tubing Deployed Source and Hydrophone Sensor





Daley, et al, Geophysics, 2007.

Injection Well Equipment

Packer

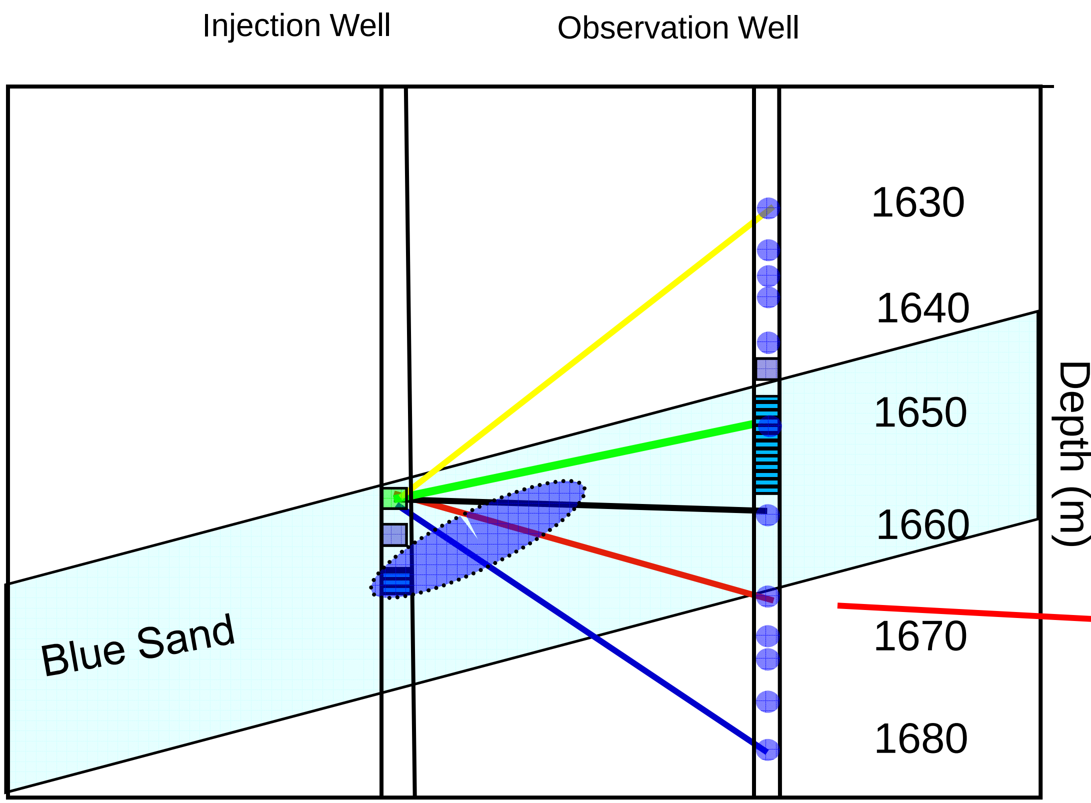
Piezotube Source

CO2 Injection tubing: 2 3/8”

Piezotube Seismic Source

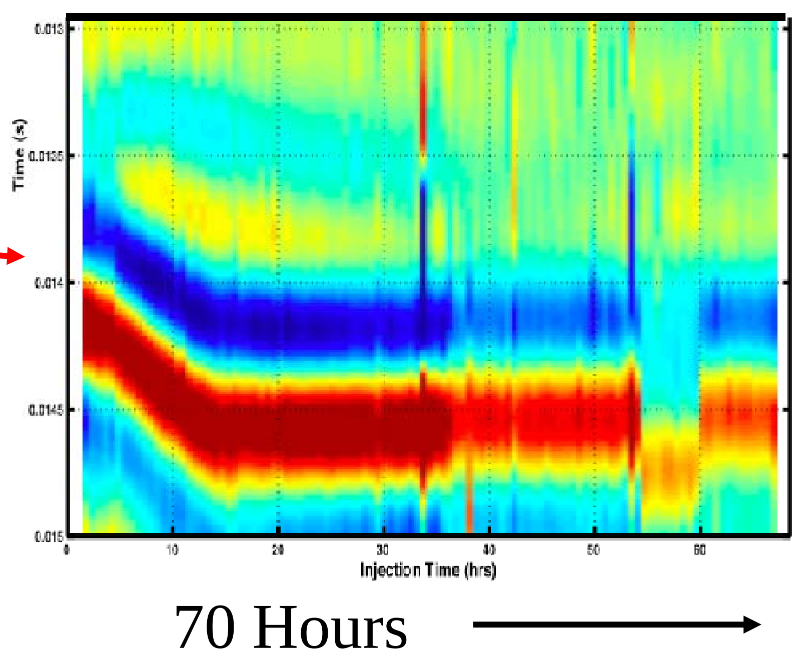
Rolls of tubing for U-tube

10 Frio-II CASSM: 5 Example Raypaths

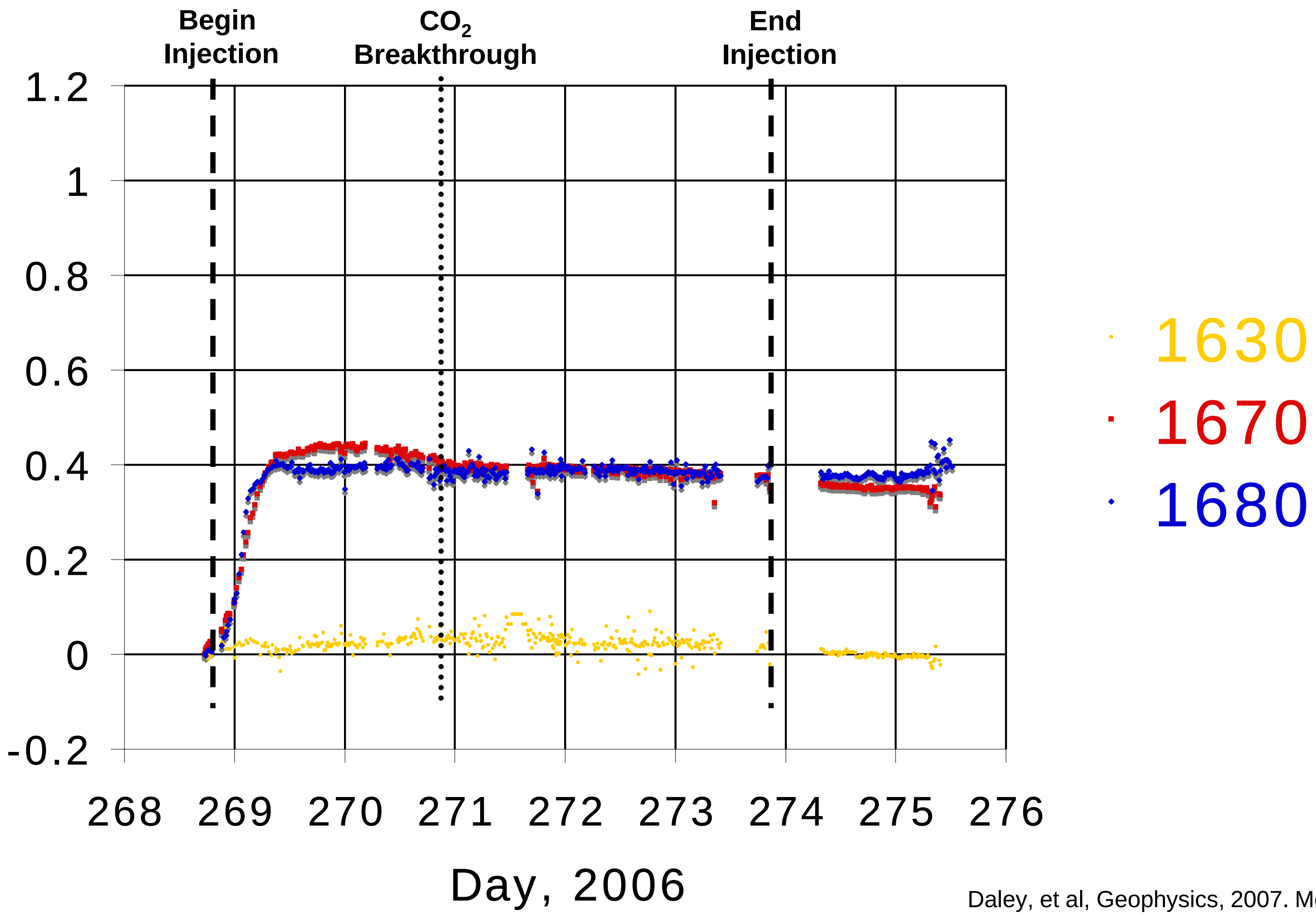


Daley, et al, Geophysics, 2007.

Field Data 1670 m

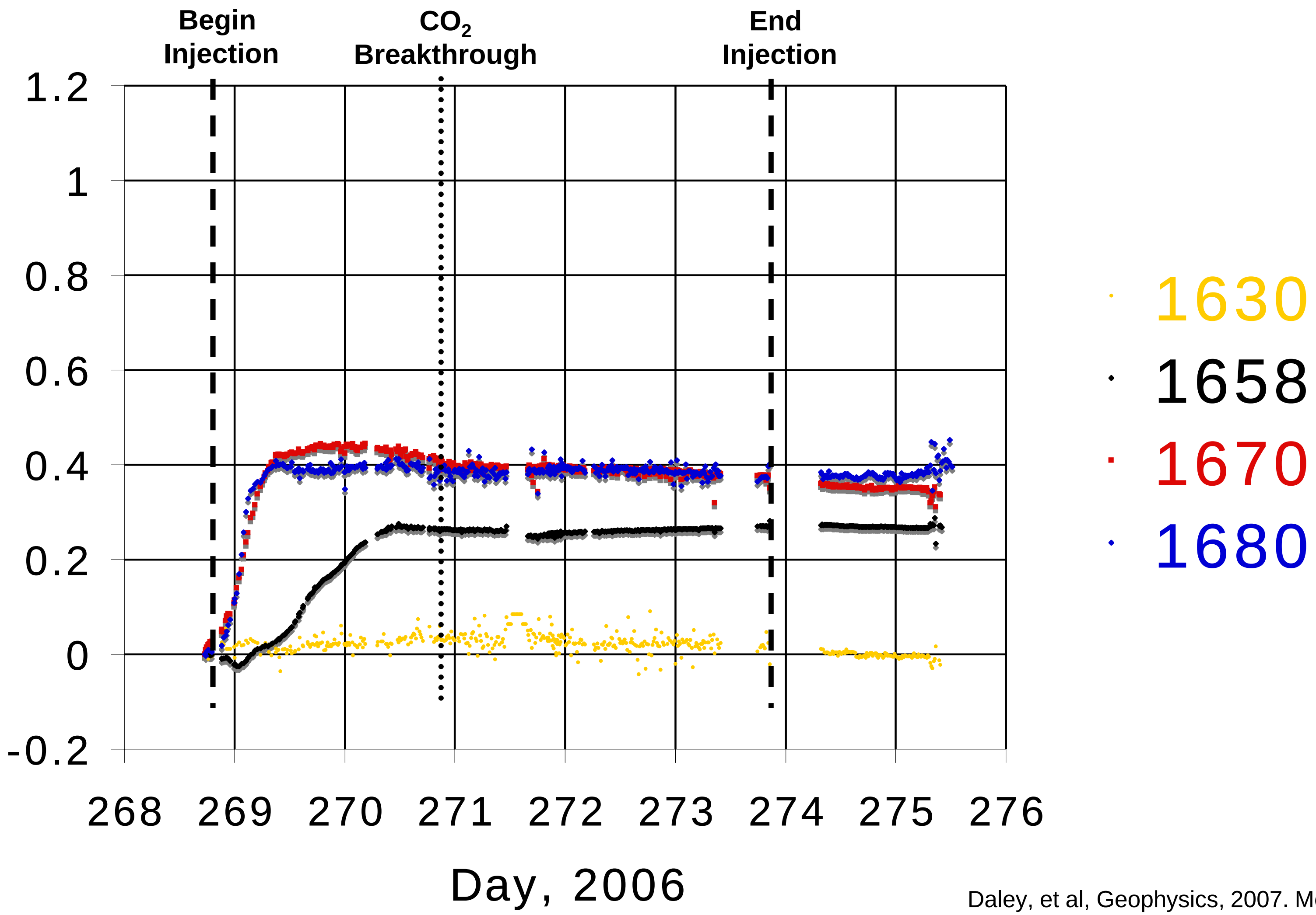


CASSM



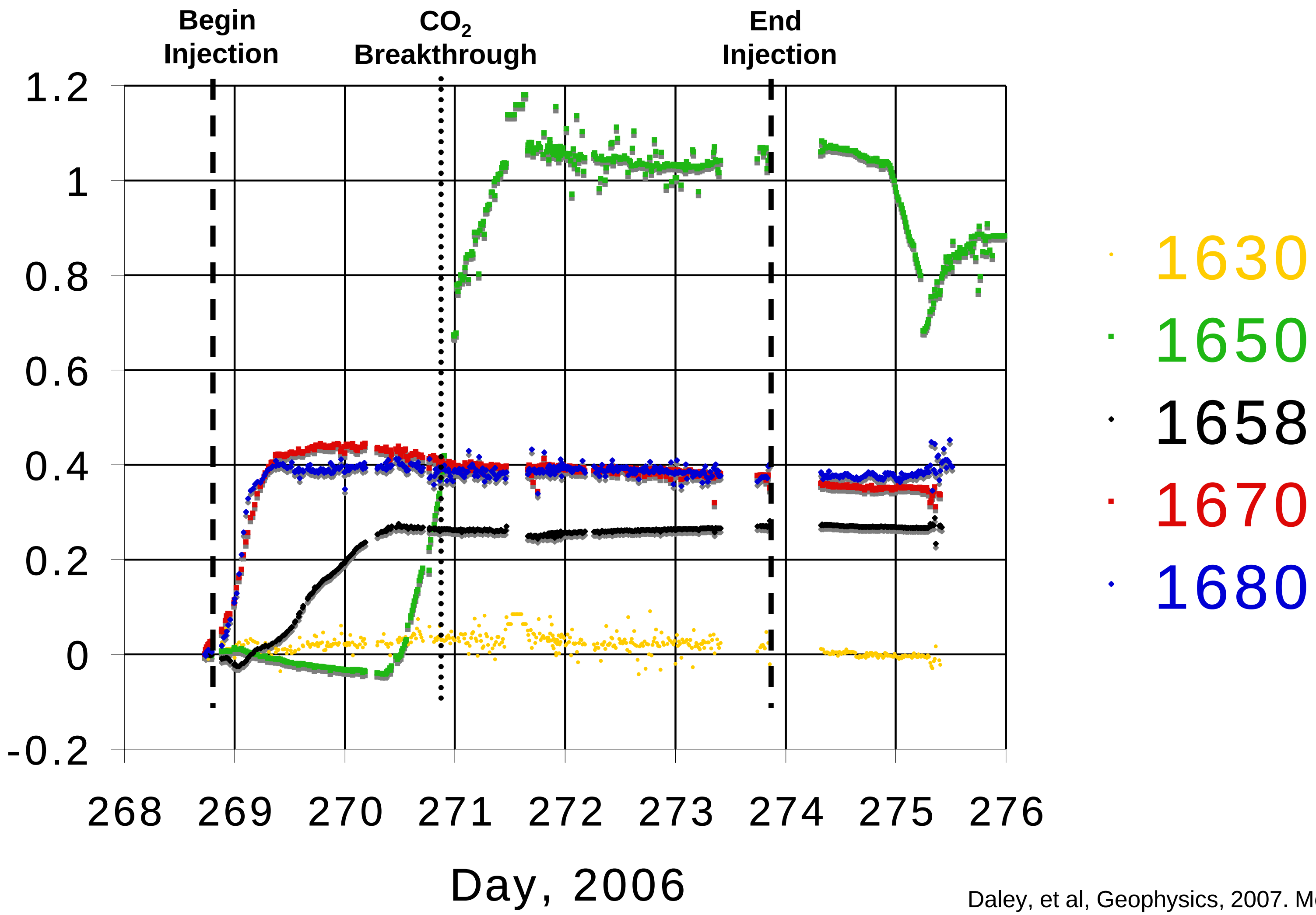
Daley, et al, Geophysics, 2007. Modified

CASSM



Daley, et al, Geophysics, 2007. Modified

CASSM



Daley, et al, Geophysics, 2007. Modified

Frio II Results

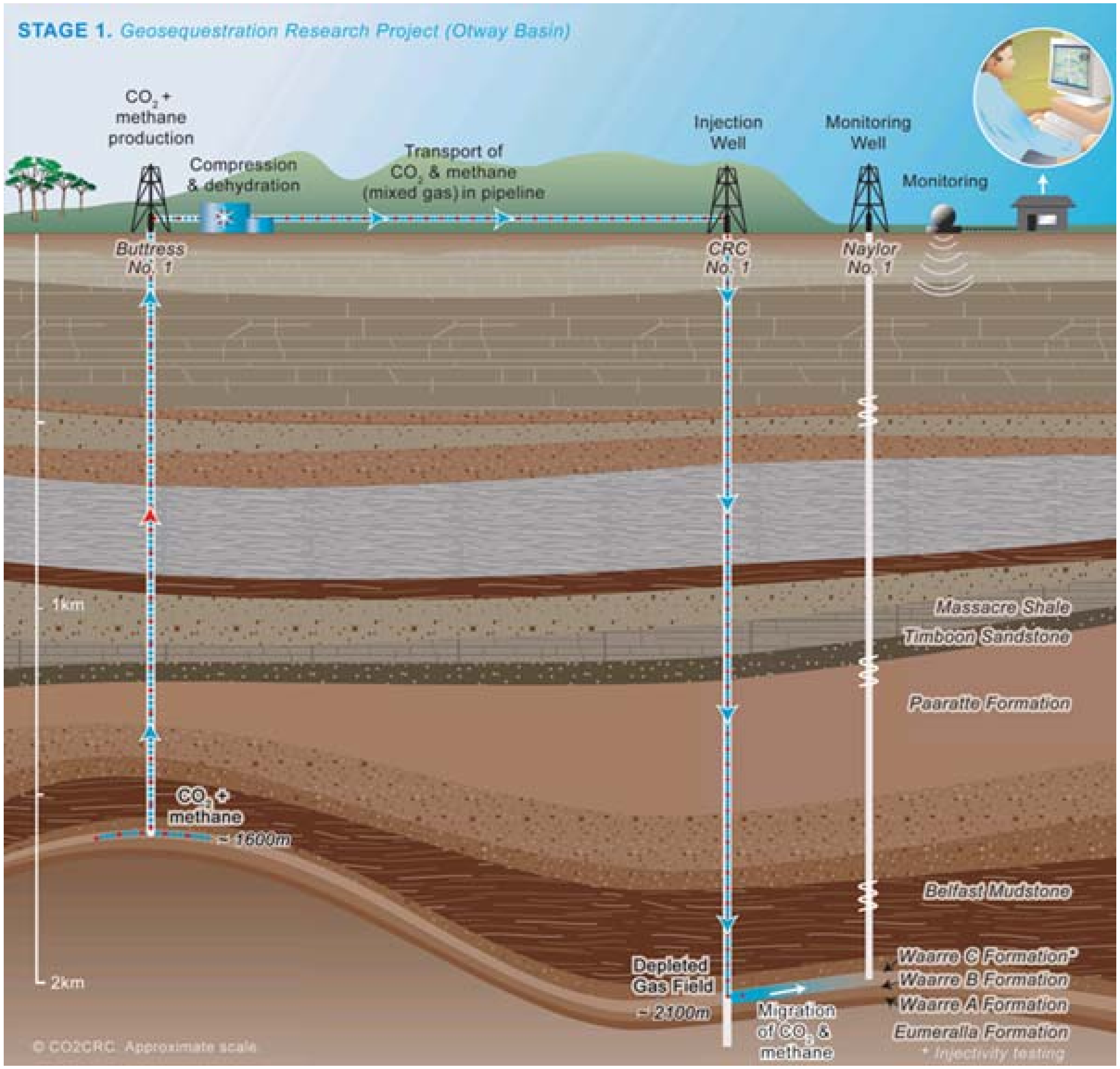
- Continuous monitoring (CASSM) very effective for tracking CO2 between wells
- Required new instrumentation (piezotube source)
- Plan to try CASSM at other sites
- Some lessons learned w.r.t. instrumentation

Lessons Learned from Frio-II

☐Avoid Downhole Electrical Connections - use splice, if possible.

Hydrophone molding needs to be polyurethane.

Otway Basin—Depleted Gas Field



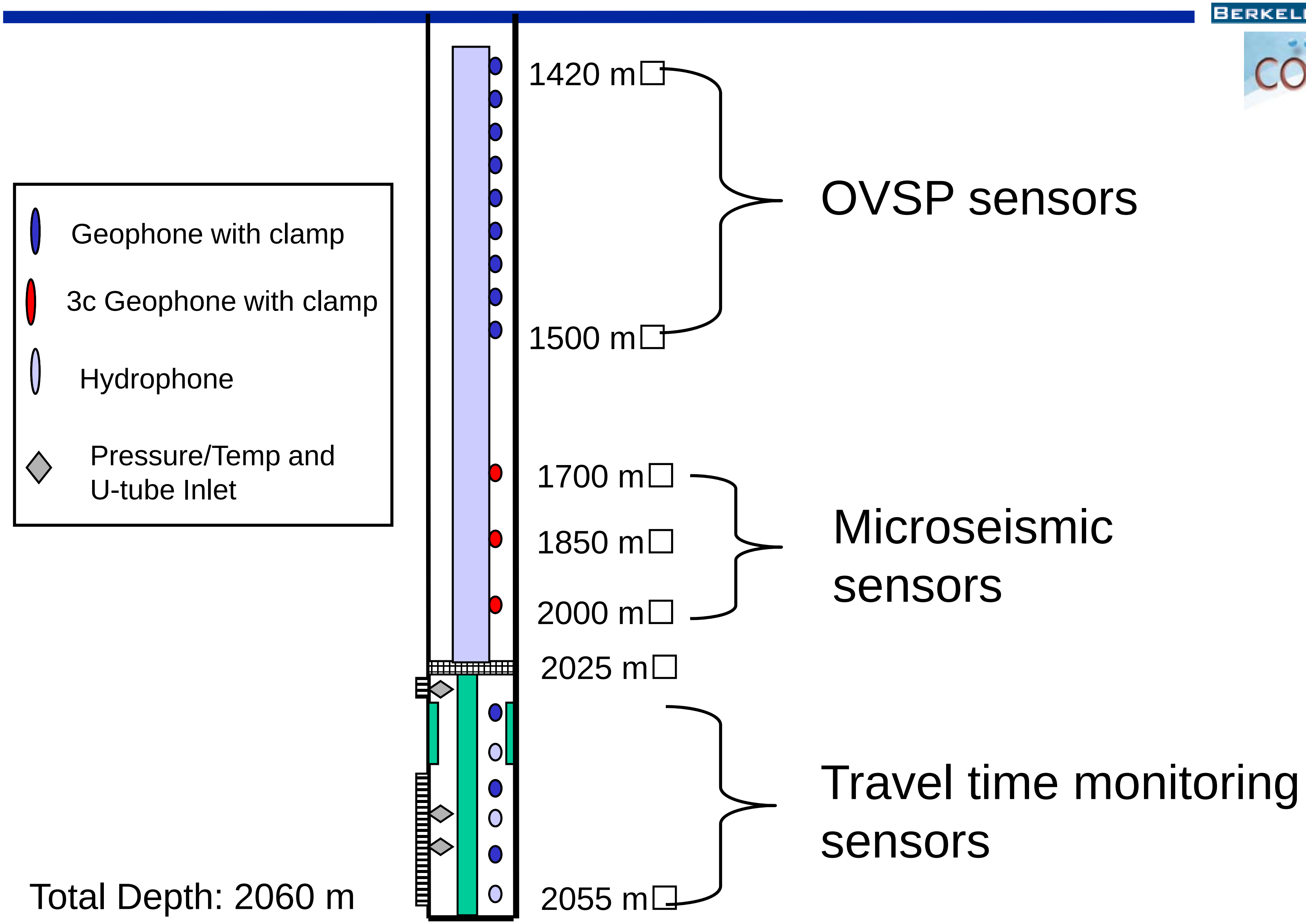
Basic Plan:

- ~ 2 km Depth
- Use Preexisting Gas well for monitoring
- New Injection Well
- Expected seismic change is small - want permanent instrumentation

Technical Challenges

- 2 3/8” casing patch restriction
- Want to install 9, 2 km long tubes, control line, sensor cable
- bottom-hole conditions are:
    - •Mixed CH_4, Brine,
    - •85°C, 17.7 MPa
- Collect P/T, seismic data, geochemical samples, for two years
- Installation is a one way trip—coming out of the hole is cost prohibitive.

Schematic of Otway Project Borehole Monitoring



Novel equipment and procedures

- Sucker rod deployment of instrumentation
  - Joint Protectors, Geophone Bow-Spring Anchors
- Bottom Hole Assembly (BHA)
  - ~34 m long
  - Pneumatic packer
  - 3 U-tubes for sampling
  - 6 seismic sensors
  - 2 P/T gauges
  - ~35 m long, 5 cm tube in ~1.5 m sections

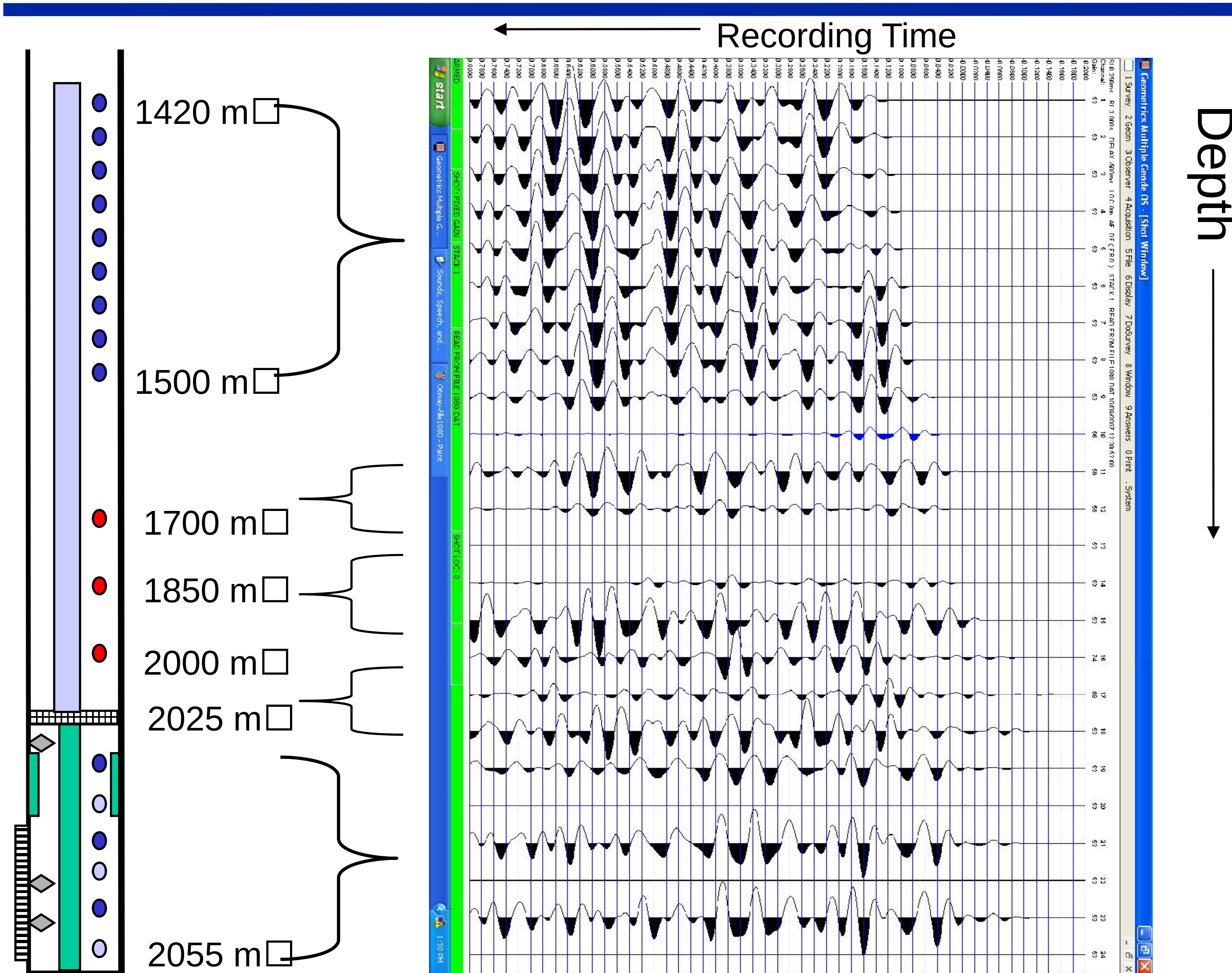
- Many unique processes and issues:
  - Run in hole procedures
  - Well control: kill fluid + shear rams
  - tubes/cables attached to sucker rods
  - Gas lift to purge kill fluid

Shear Ram Test

Multi-Crane Lift of BHA

- **Vertical BHA lift: 3 cranes (incl. 48 m crane) and 1 man-lift**
- **~4 24-hour days to install**
- **~ 260 sucker rods with 5 bands and coupling protector, ~ 10 minutes per rod**
- **12 Geophones attached to sucker rod**
- **9 stainless steel tubes**

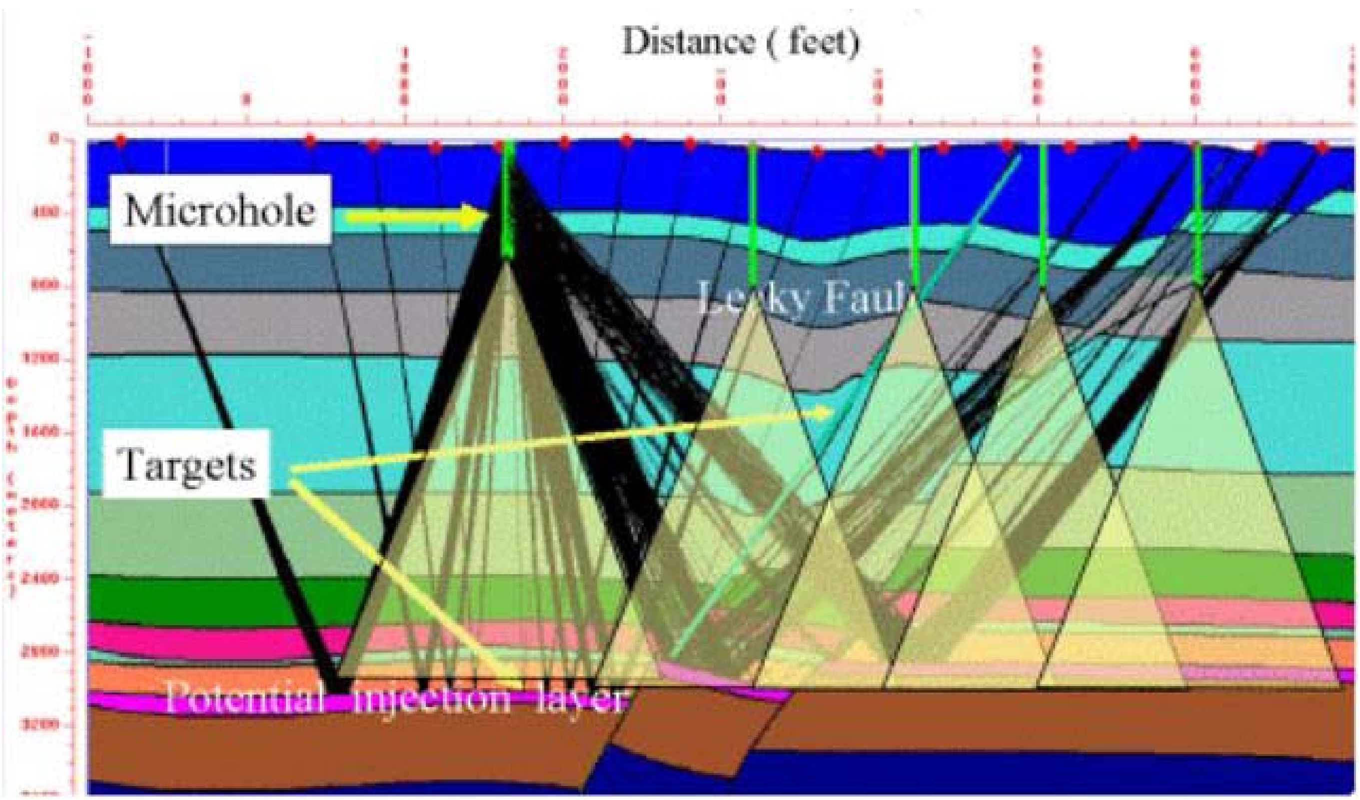
Example of Initial Otway Seismic Data: Probable Source:‘Burp’ During Fluid/Gas Production



Permian Basin EOR: 'Microhole' VSP

Objective:

Demonstrate cost effectiveness of shallow, low cost, VSP instrumented boreholes for continuous monitoring with active and passive seismic

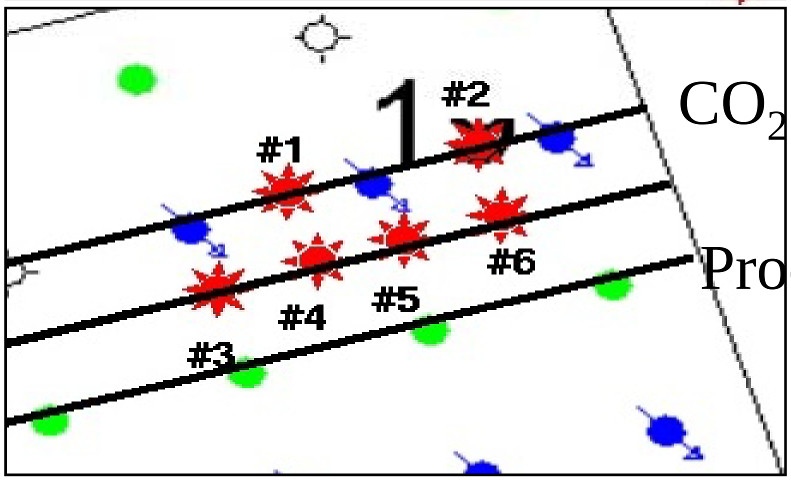


300 m wells

~ 1km reservoir

Whiting Petroleum
West Texas Wickett Field EOR

Wickett Field Micro-Well Locations

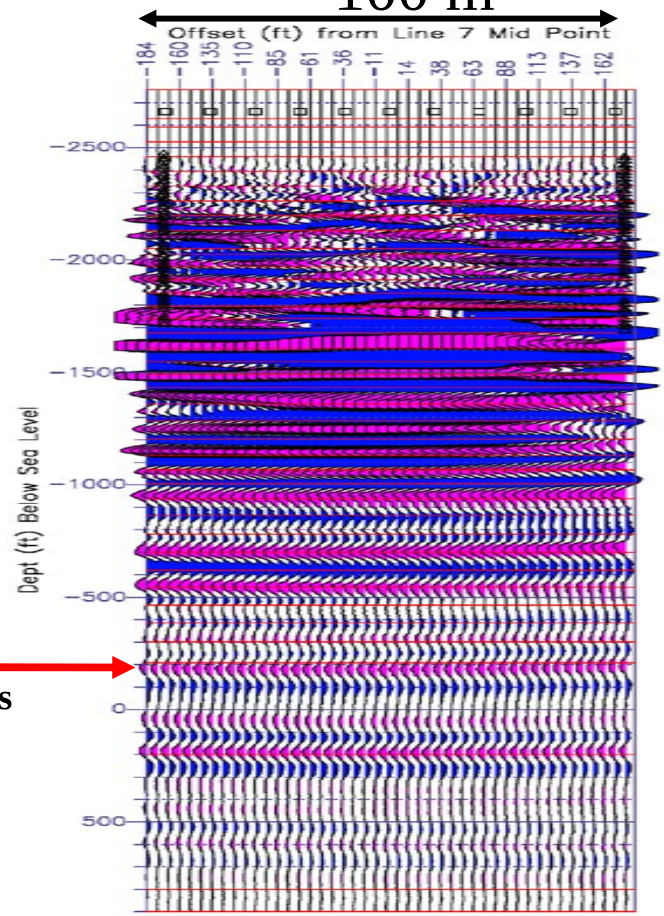


CO_2 Injectors

Producers

Migrated Multiwell Image

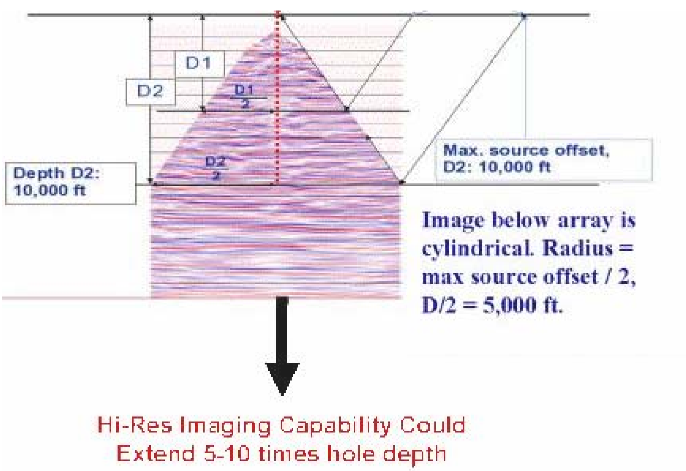
100 m



Top of Yates

Hi-Q Geophysical

Single Well Image



DOE Partnership Pilots

- WESTCARB
  - Sacramento Valley, California
  - 2 part test: depleted gas zone and saline zone
  - Injection and Monitor well: ~ 30 m separation
- Plan VSP and CASSM along with U-tube sampling

- SECARB
  - Phase III: Cranfield Mississippi, planned EOR site, gas/oil/water in anticlinal structural trap
  - Injection adjacent and downdip of EOR, ~ 1 Mtons/year, multiple injection wells
  - Plan 2 dedicated monitoring wells, spacing to be determined
  - Depth and Temp. (3 km, 100C) makes instrumentation more difficult
- Plan CASSM
  - 3D seismic to be acquired by operator, Denbury Resources

Acknowledgements

GEOSEQ Project (Frio and Otway):

Funded by U.S. Dept. of Energy, Office of Fossil Energy, NETL

LBNL: S. Benson (now at Stanford) E. Majer, L. Myer, R. Solbau, J. Ajo-Franklin, J. Peterson, B. Freifeld, D. Wang, C. Oldenburg

TBEG: S. Hovorka

CO2CRC (Otway): S. Sharma, K. Dodds (now B.P.), A. Kepic, D. Sherlock

Microhole Project:

Funded by U.S. Dept. of Energy, Office of Fossil Energy, Gas and Oil Program

LBNL: E. Majer, R. Solbau

U.T. Austin: C. Hoffpauir

Hi-Q Geophysical: J. Queen

Design of Surface Seismic Programs for CO2 Storage Monitoring

Mark S. Egan

WesternGeco North America Geophysics Manager

Houston

Schlumberger

WesternGeco

Objectives

Baseline seismic program

- Structure & stratigraphy of the storage tank & overburden
- Volume of the storage tank
- Is the storage tank is sealed?
- Barriers within the tank

Repeat seismic programs

- Where is the CO2 going? Is it escaping?

Objectives of the survey design

- Survey design required to meet the above objectives
- Permitting restrictions

Agenda

Deliverables

Image of the subsurface

Rock properties (porosity, etc.)

Geophysical issues

Illumination

Resolution

Repeatability

Signal-to-Noise ratio

Survey design parameters

2D vs. 3D

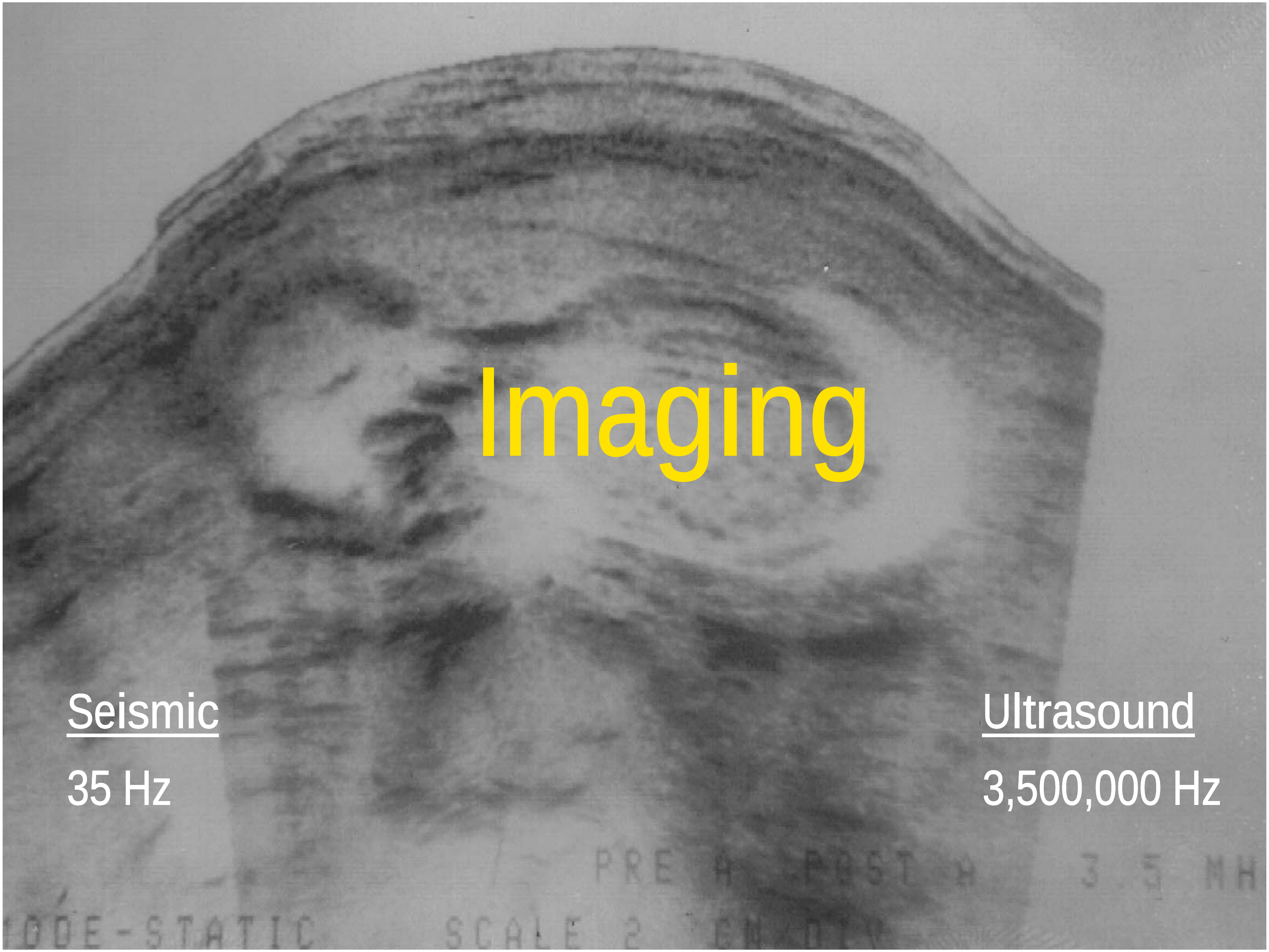
Shooting direction

Narrow azimuth vs. wide azimuth

Aperture

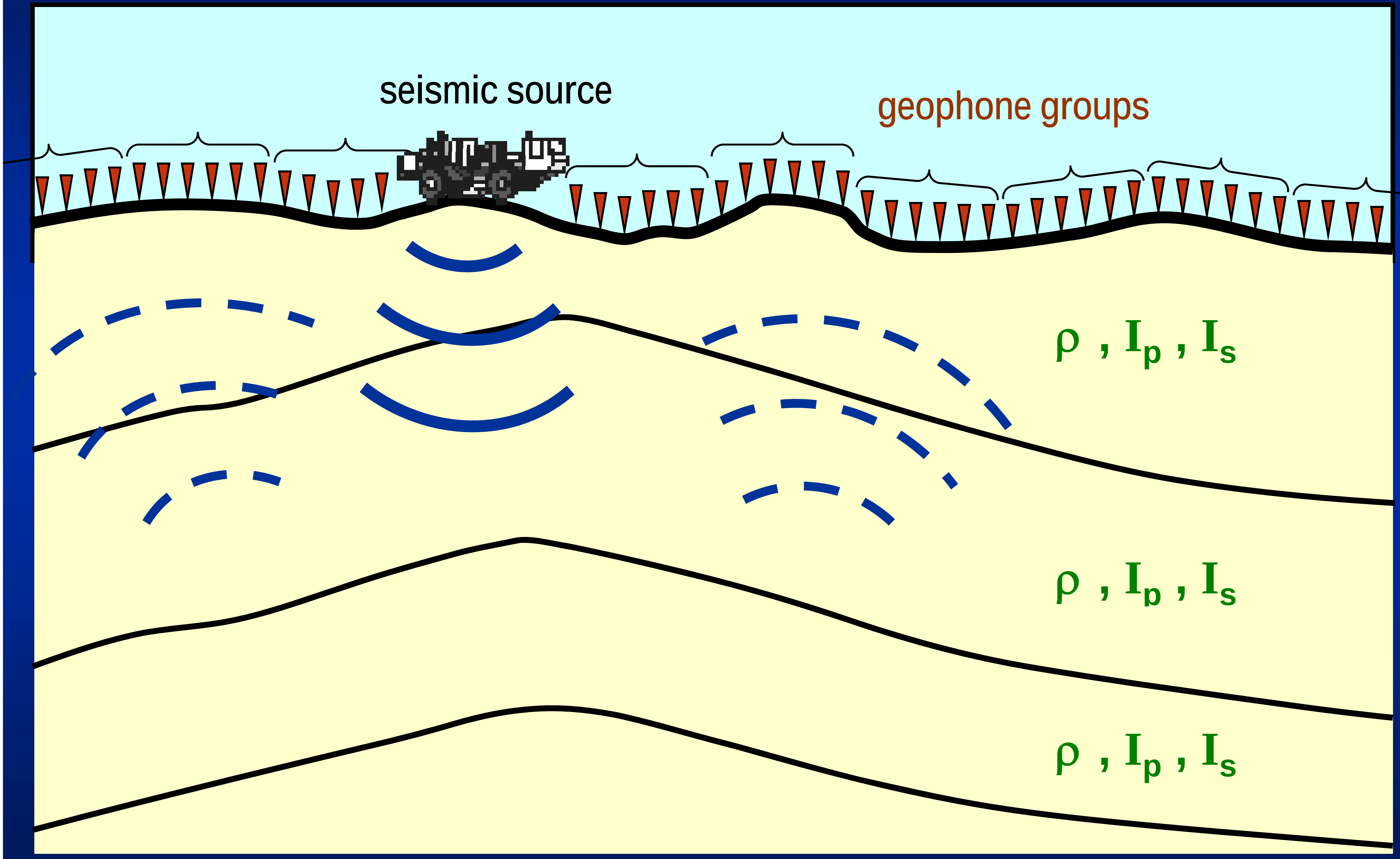
Source-receiver distances

Sampling

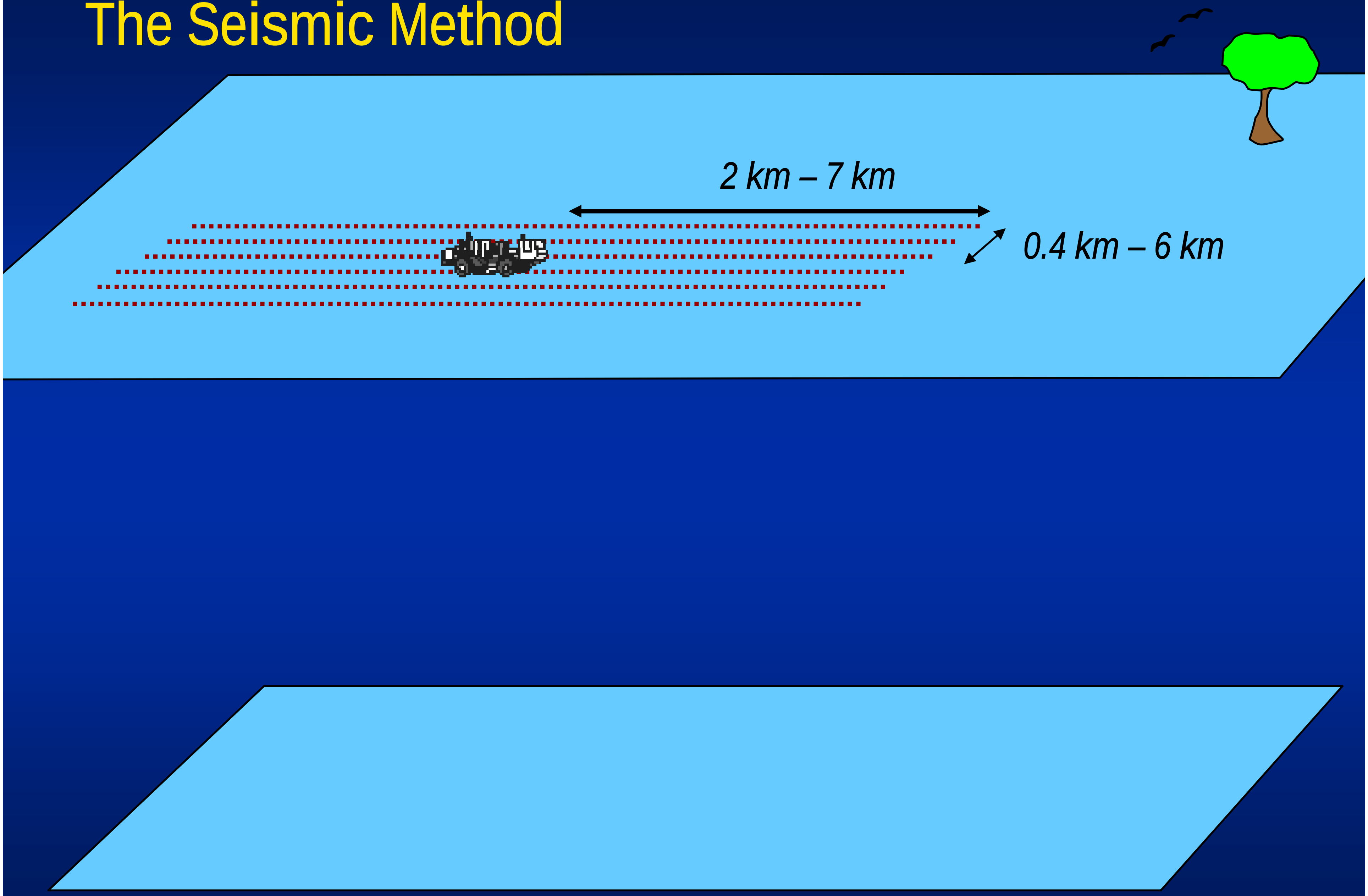

Imaging
Seismic
35 Hz
Ultrasound
3,500,000 Hz
PRE A POST A 3.5 MH
MODE-STATIC SCALE 2

The Seismic Method

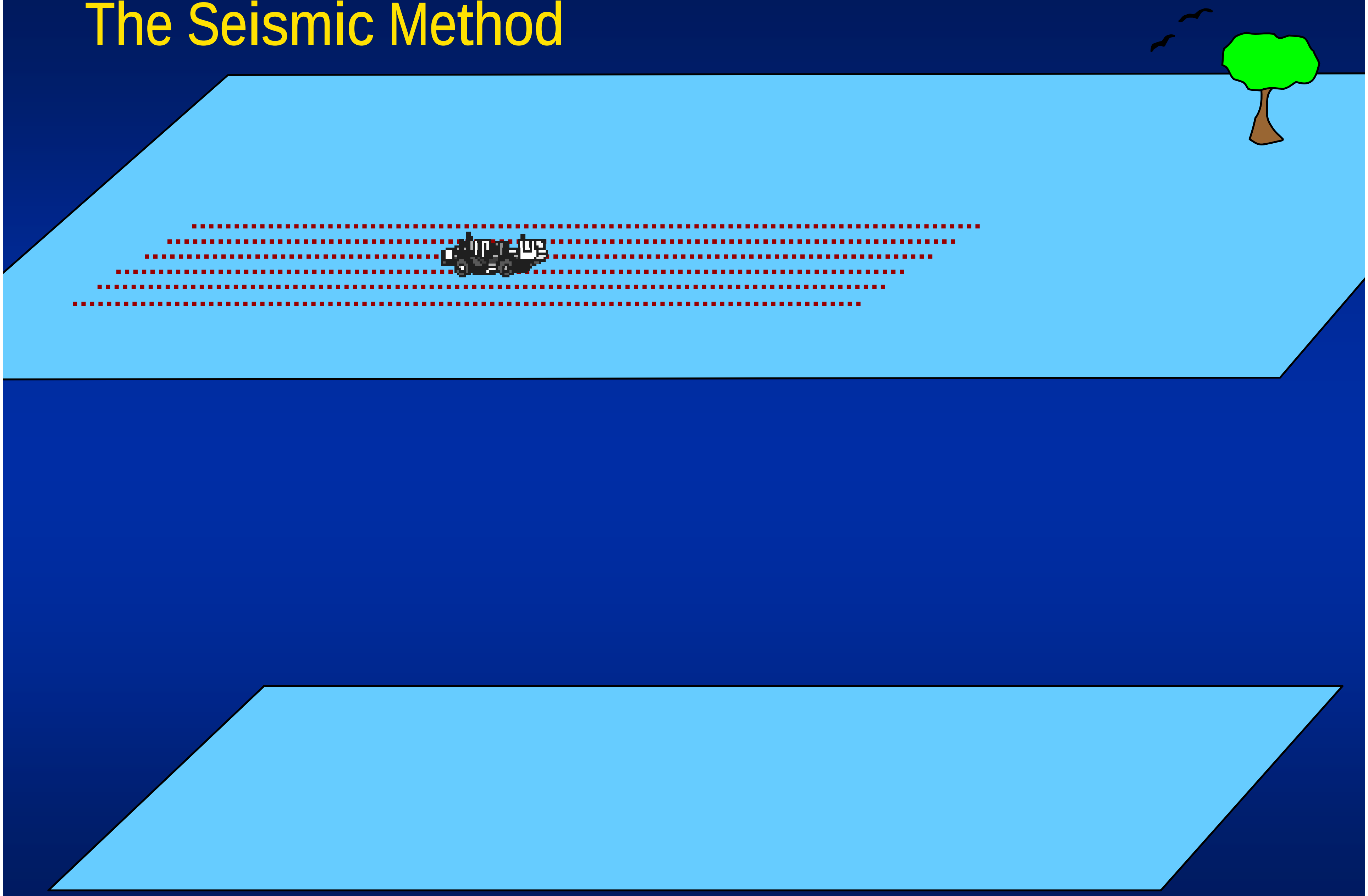
- ❑ Arrival times
- ❑ Amplitudes



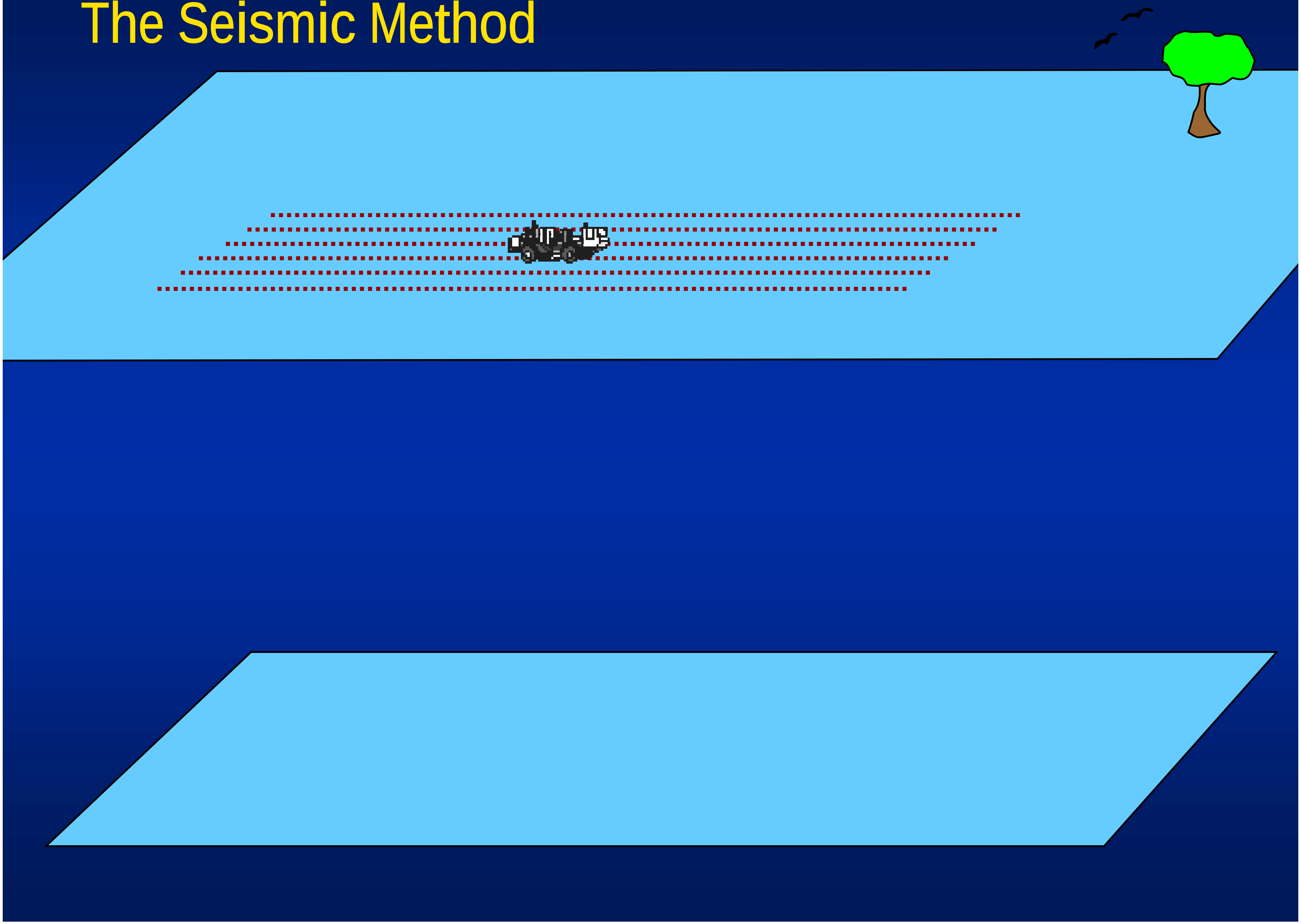
The Seismic Method



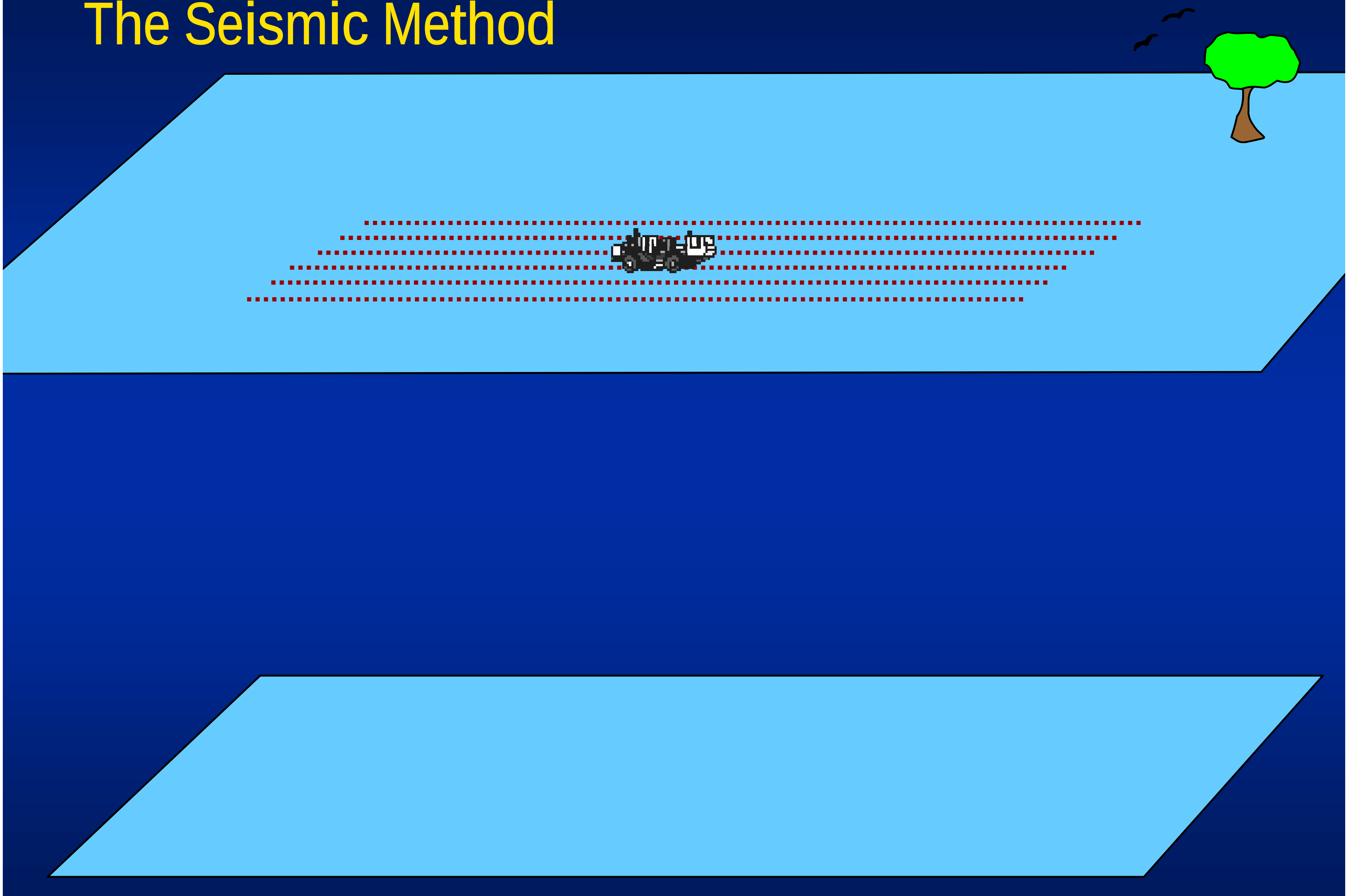
The Seismic Method



The Seismic Method



The Seismic Method



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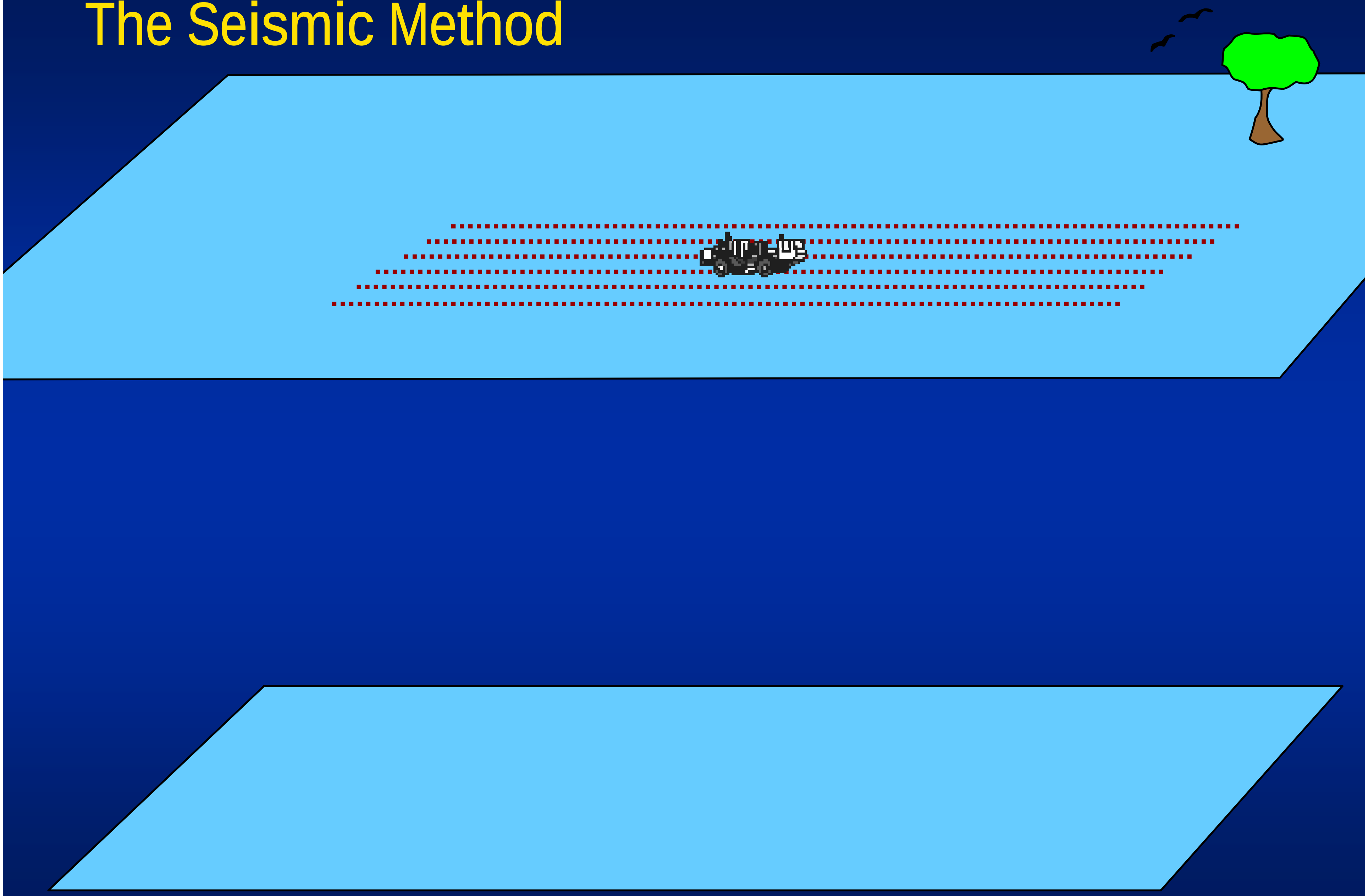

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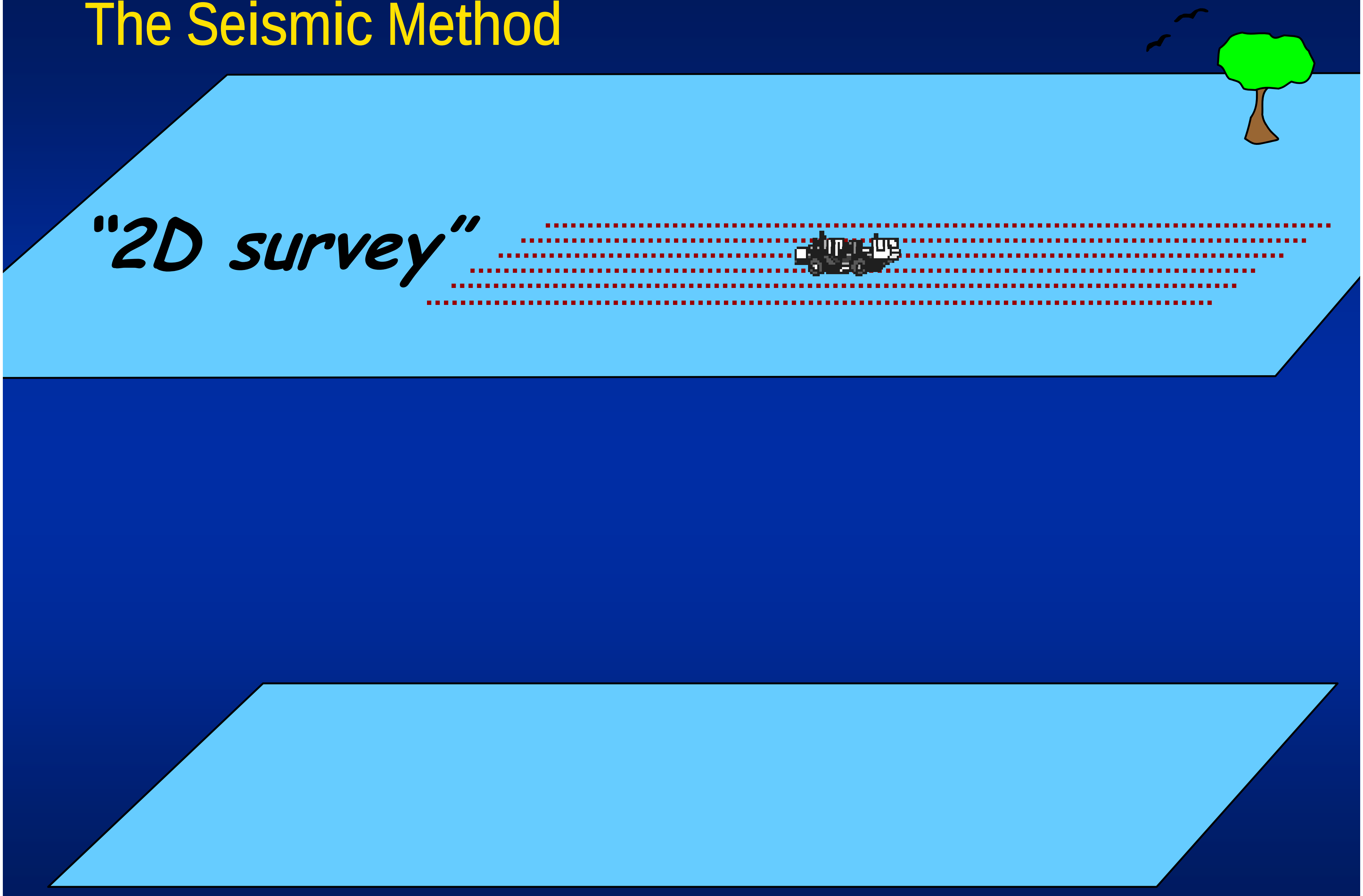

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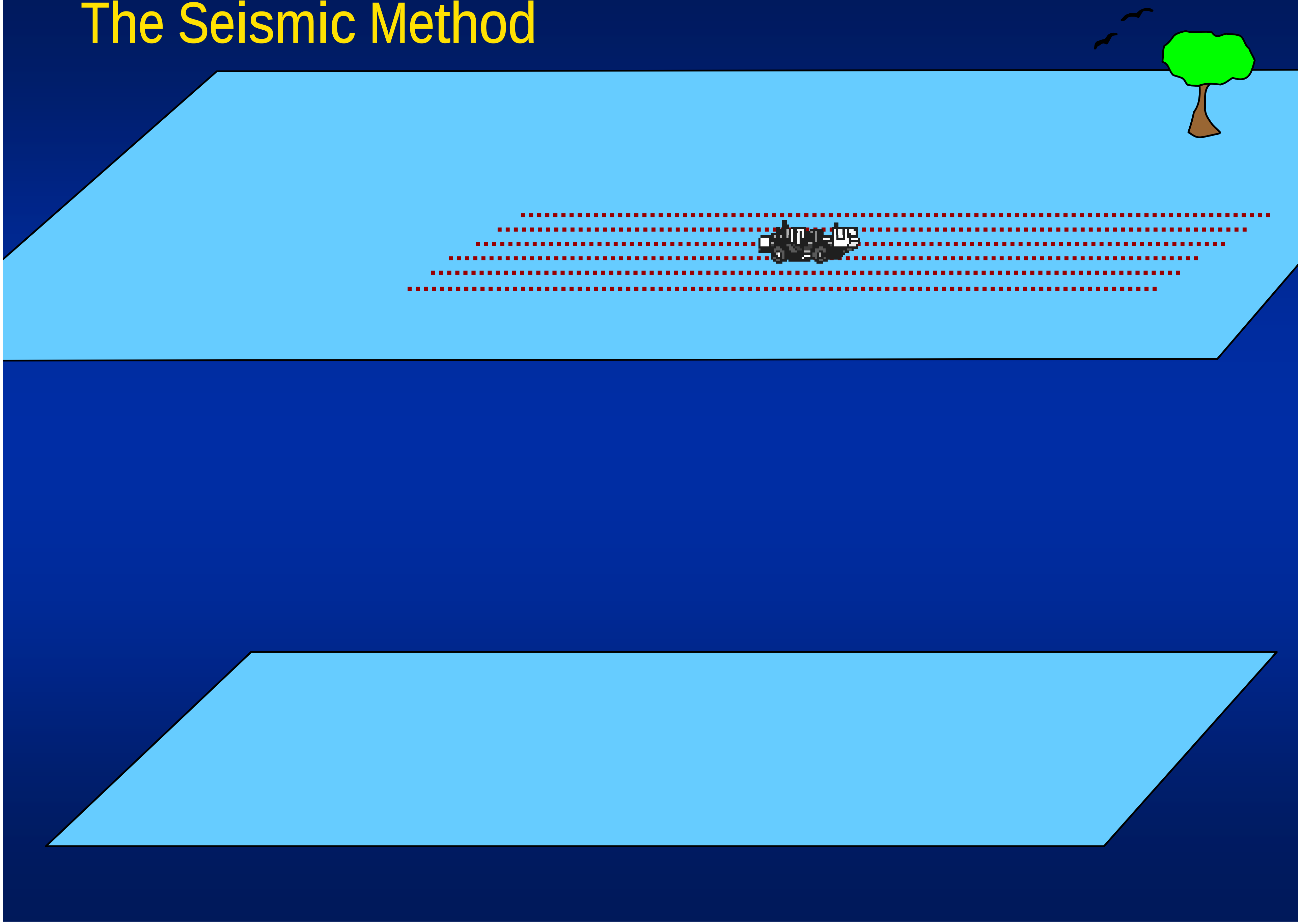

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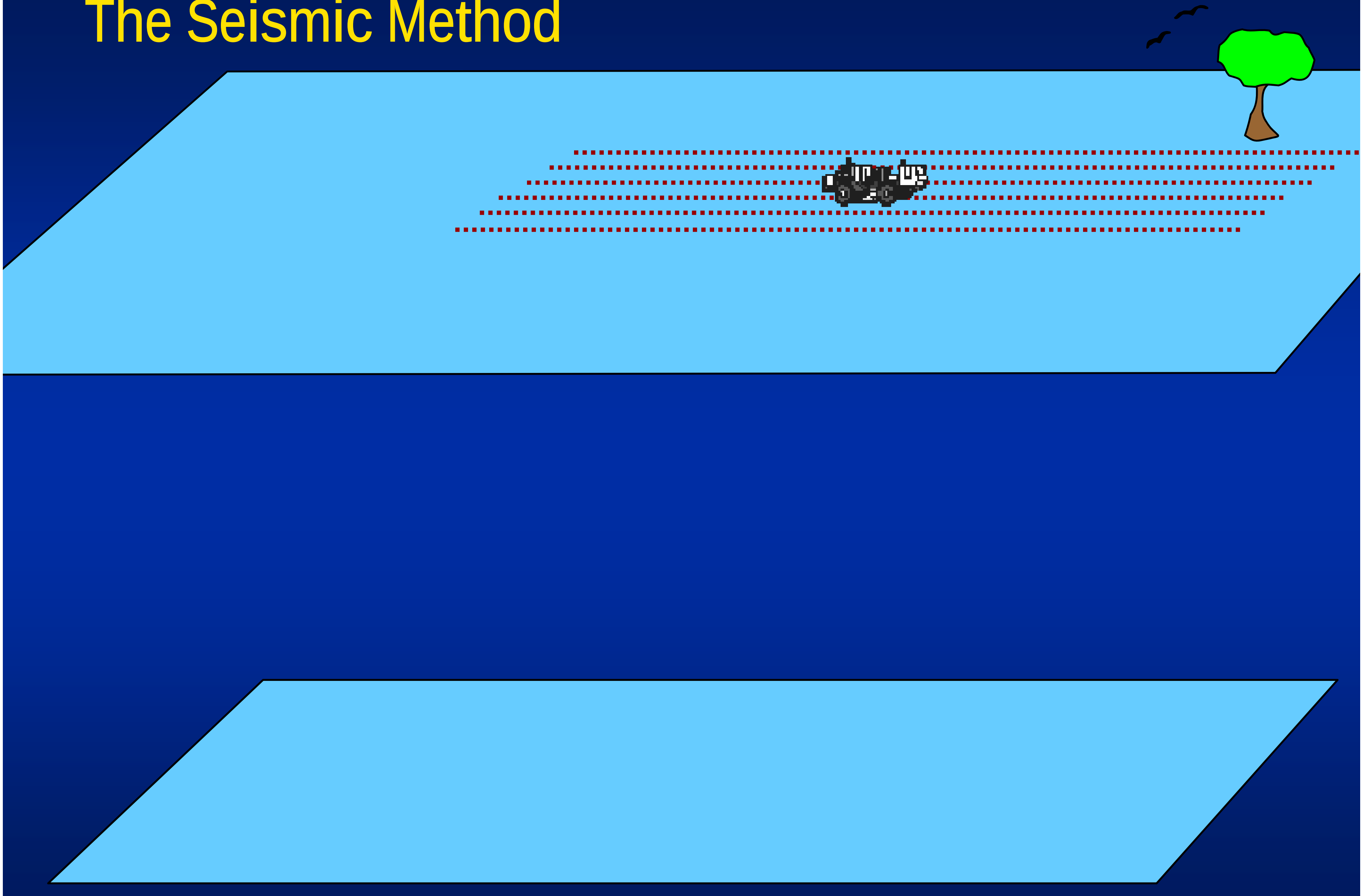

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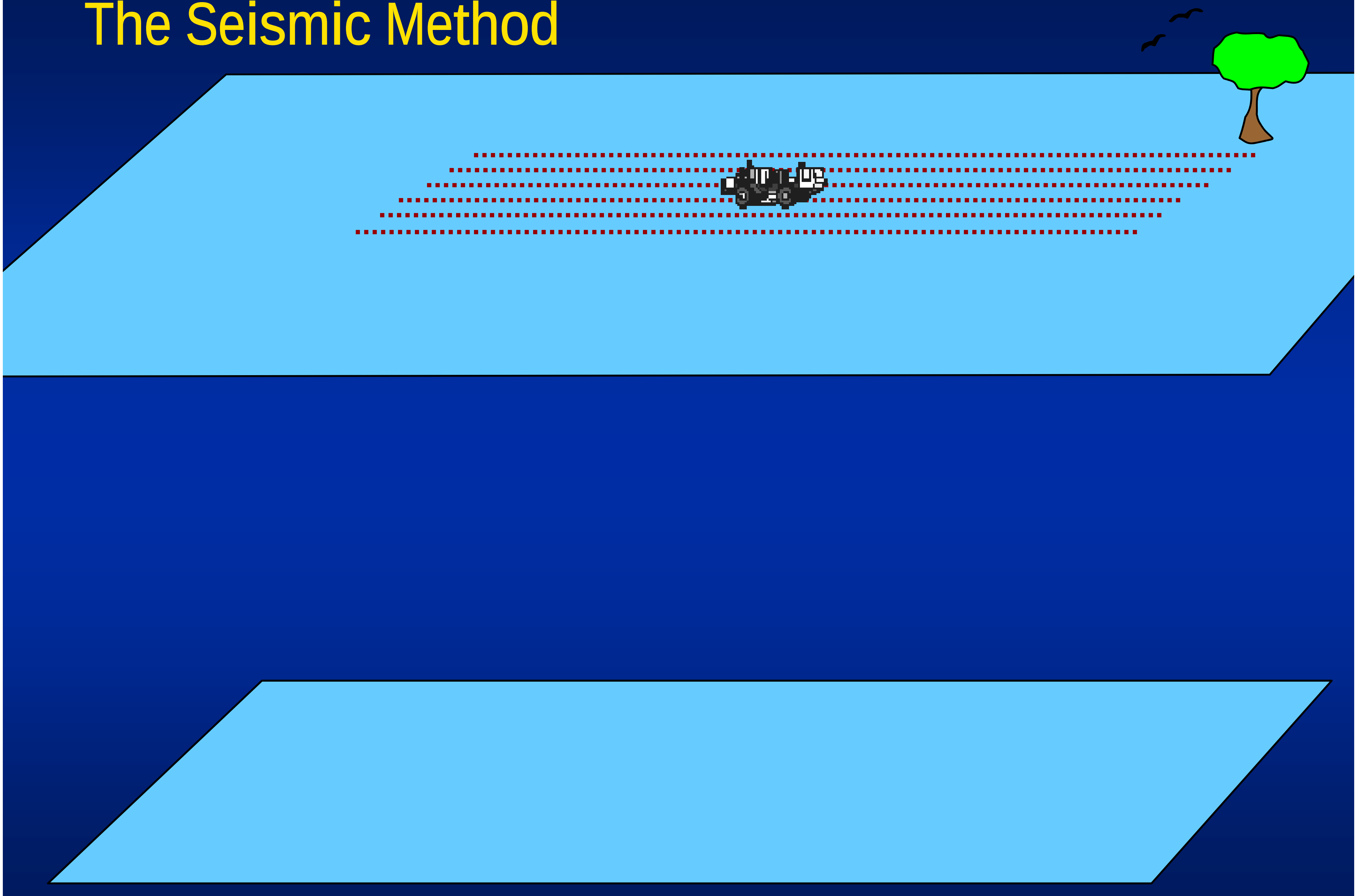
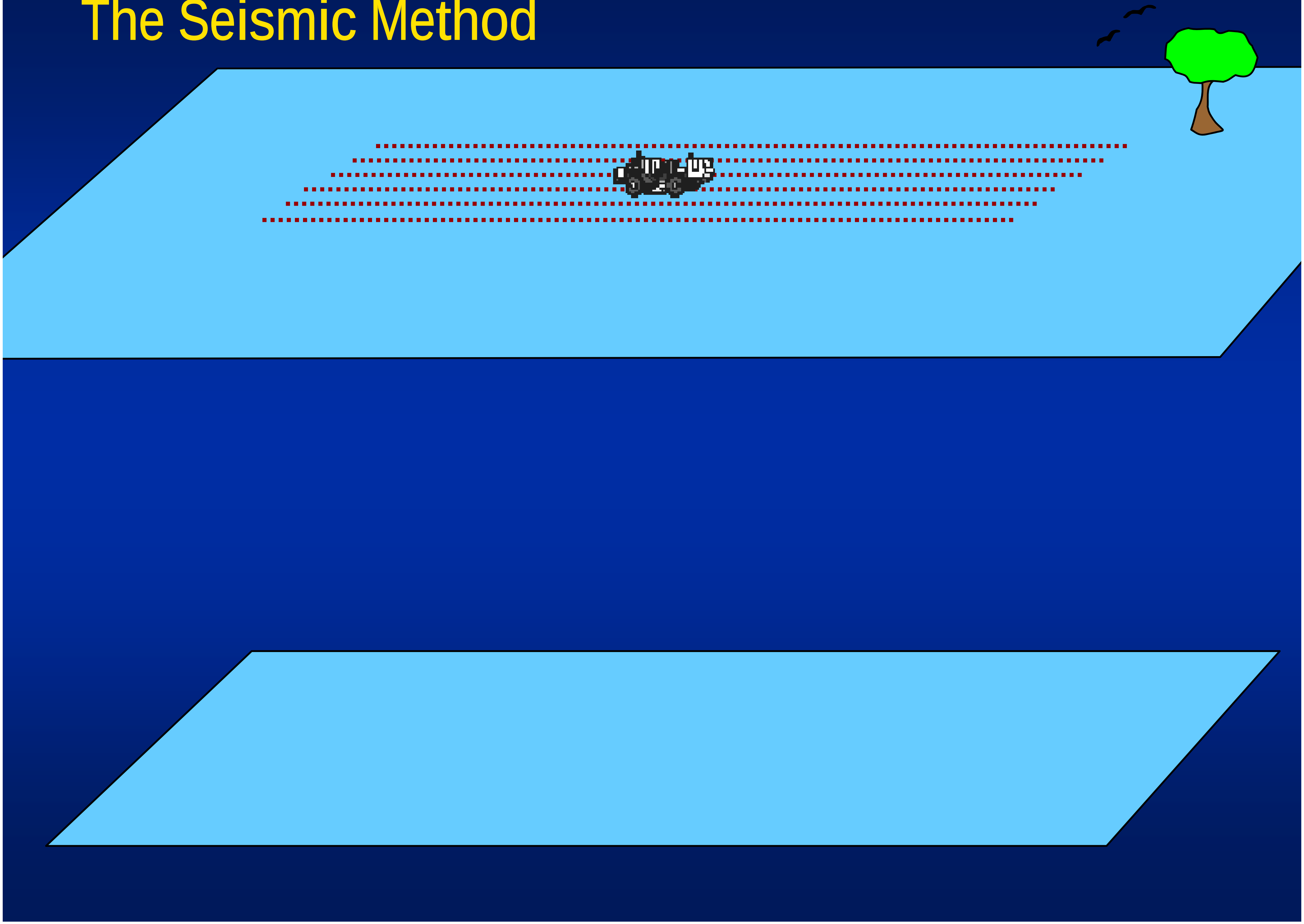
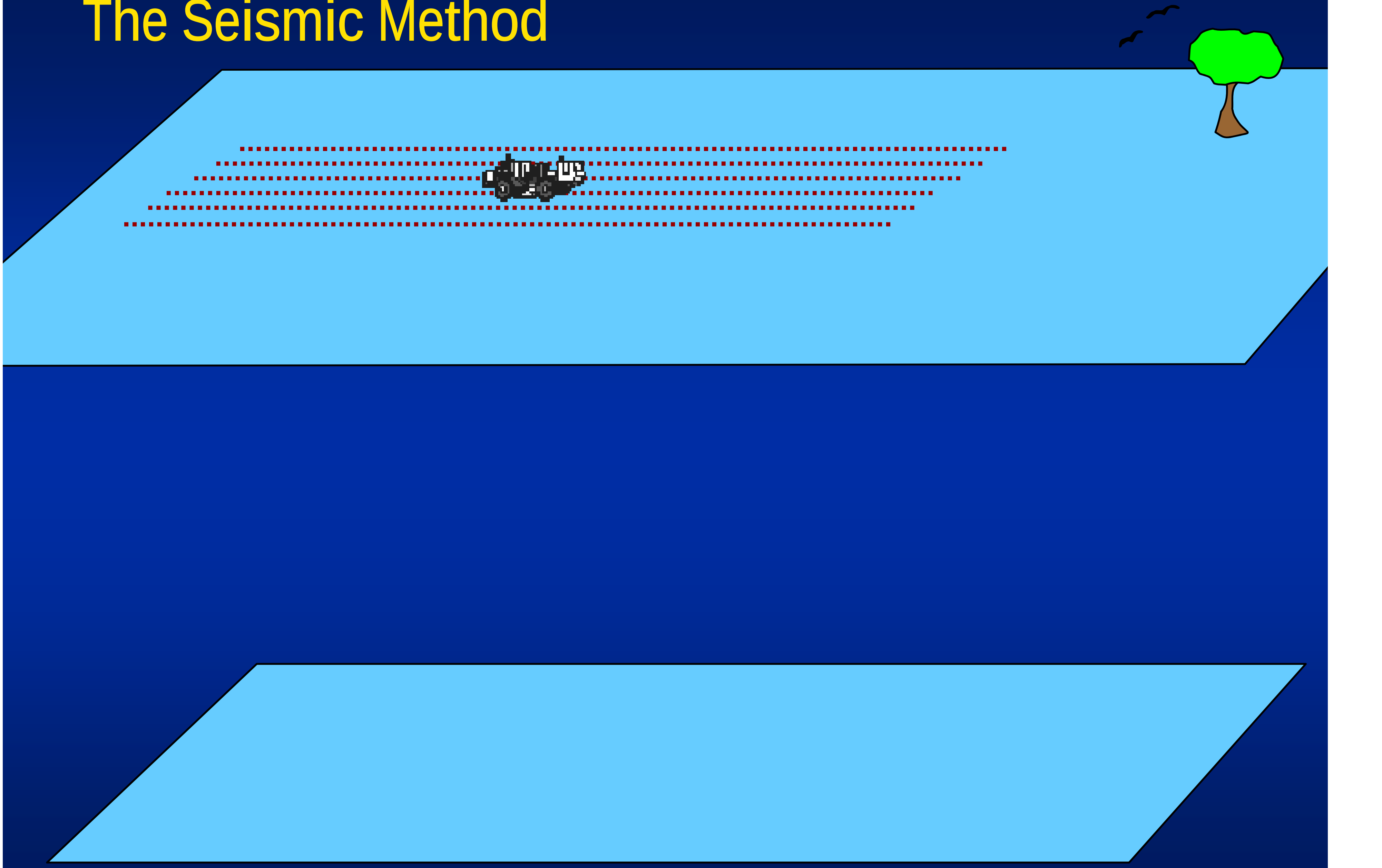


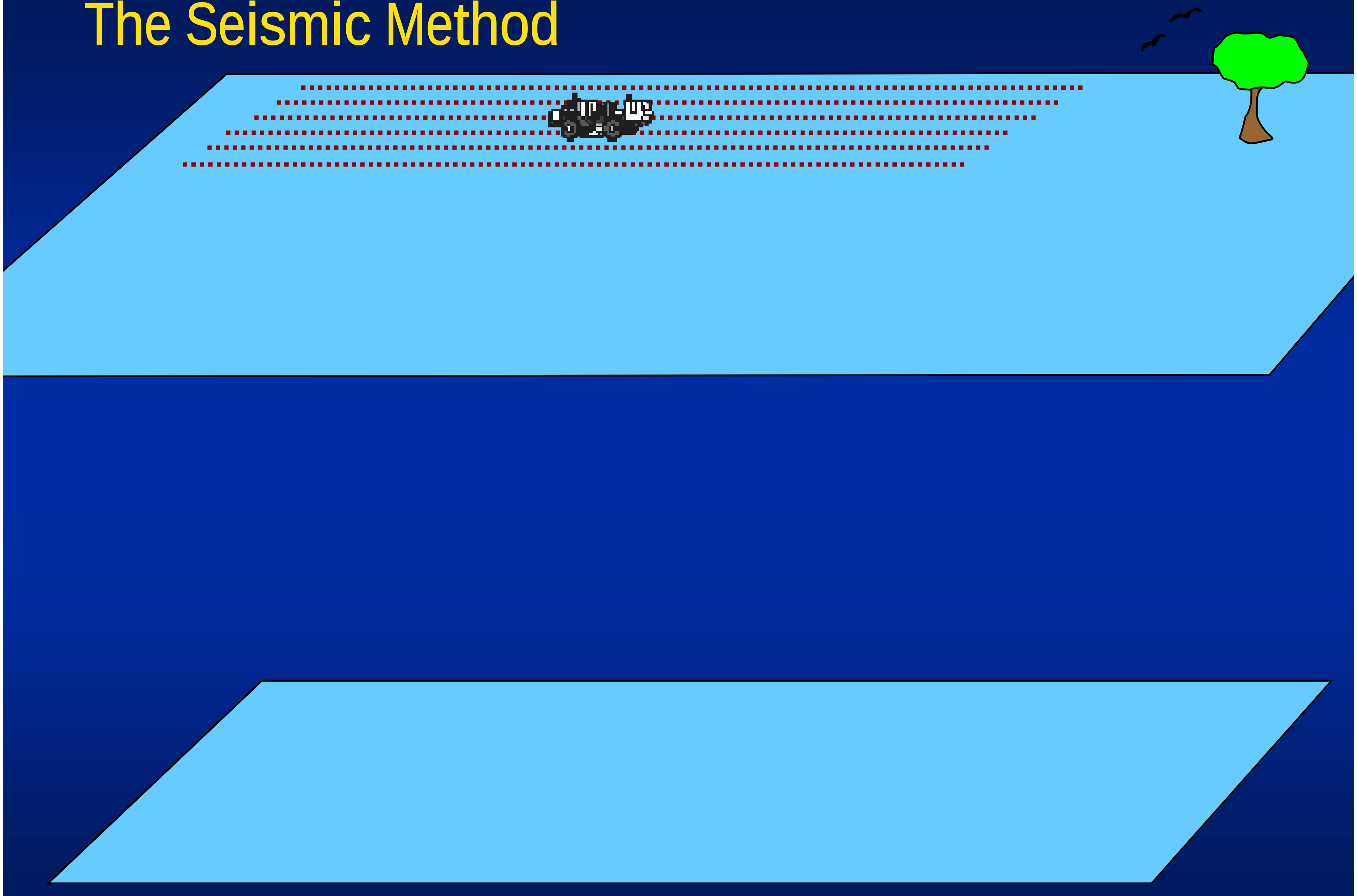
The Seismic Method



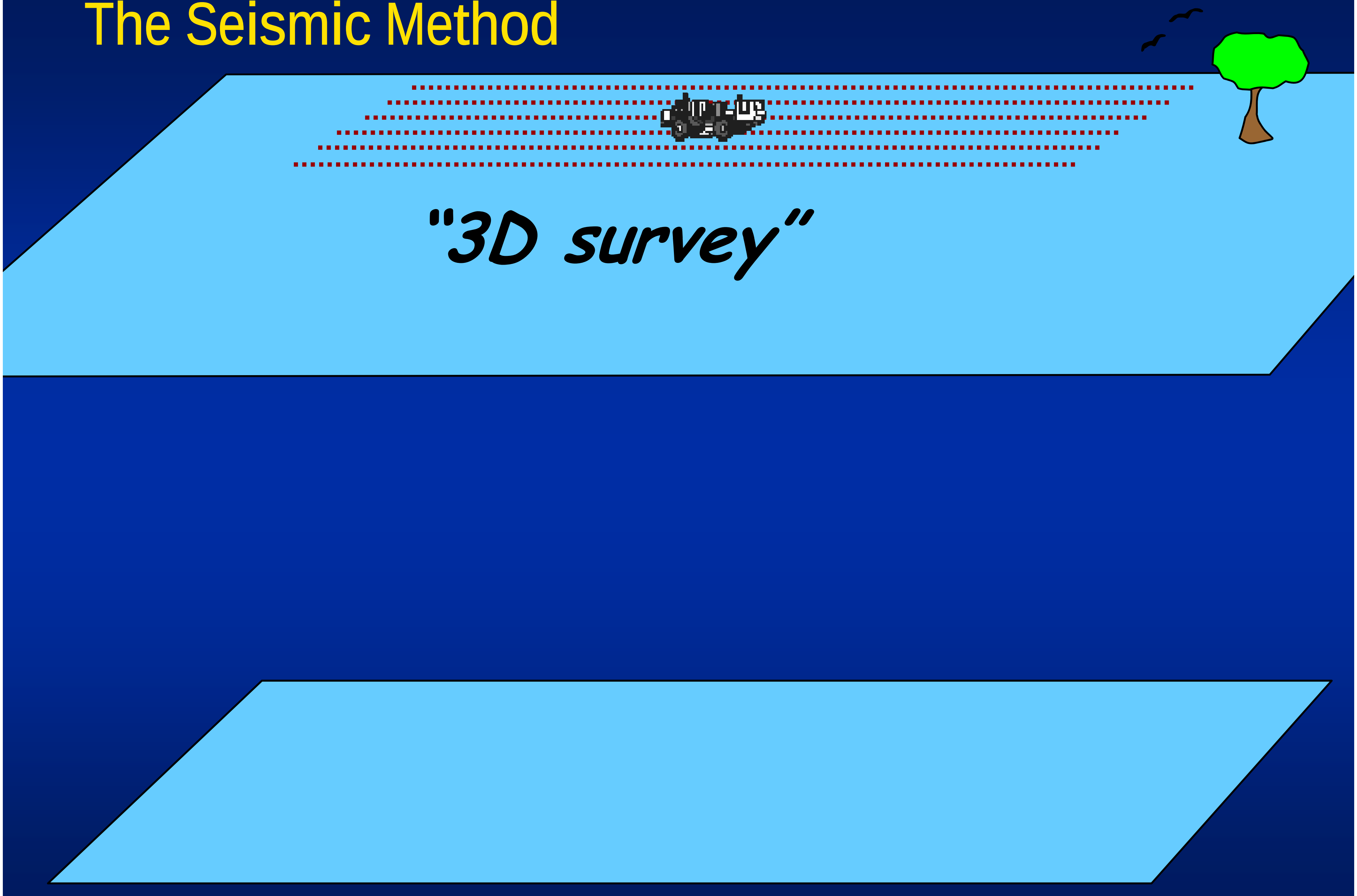
The Seismic Method



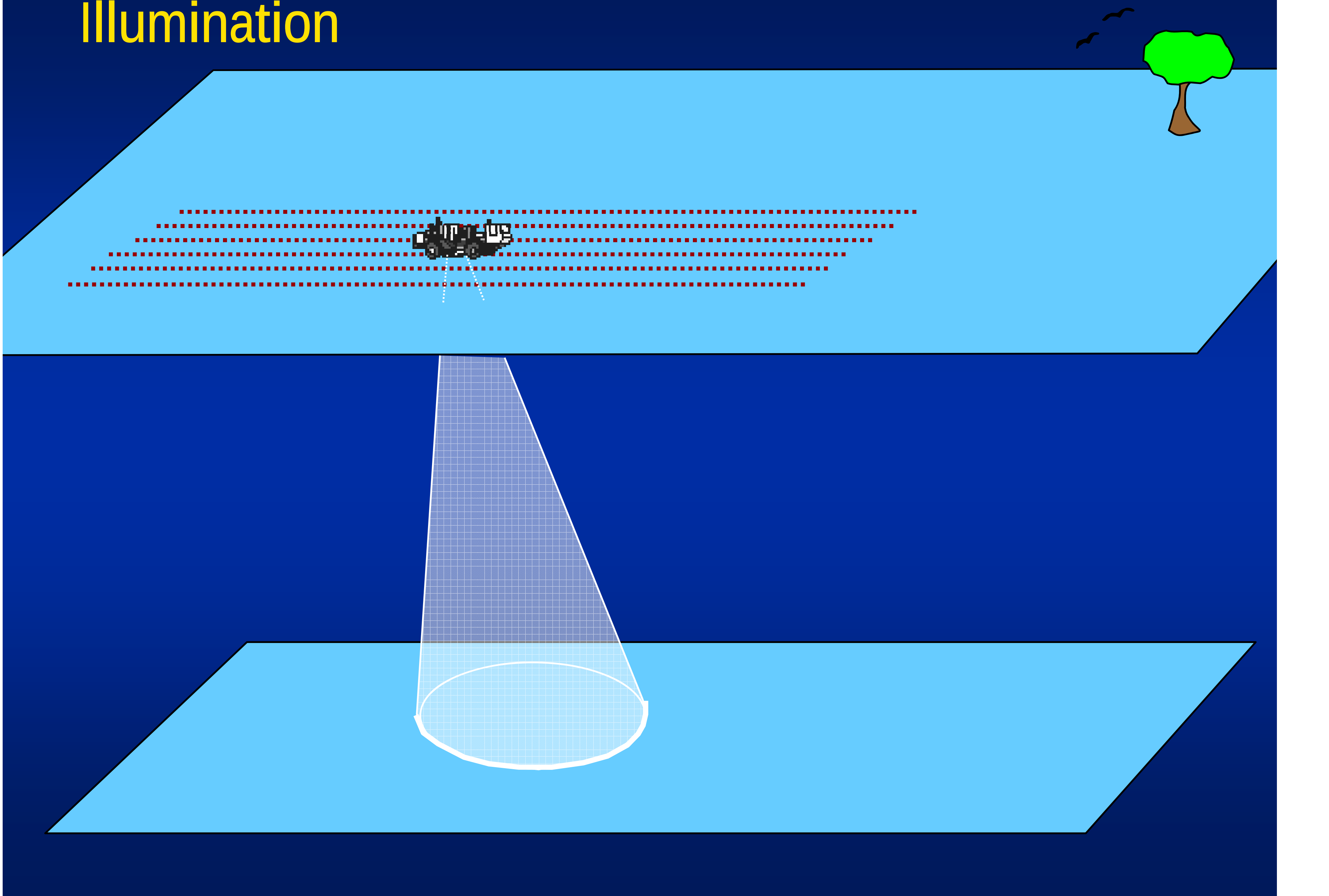
The Seismic Method



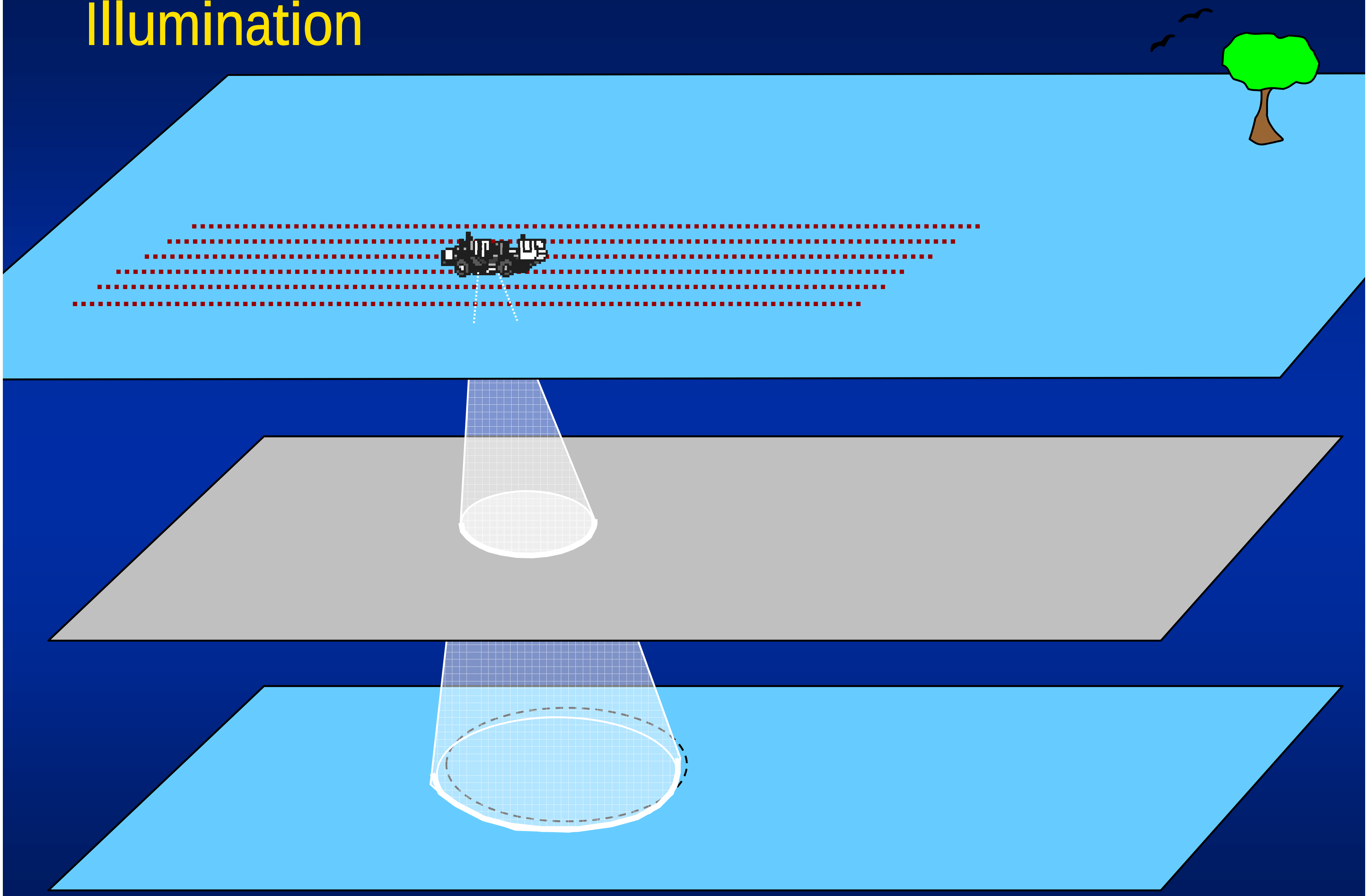
The Seismic Method



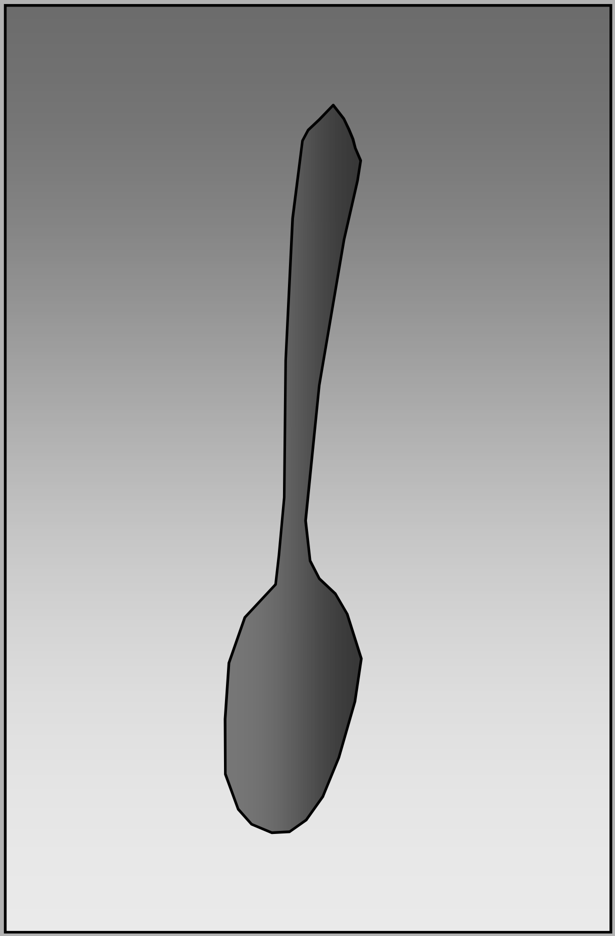
Illumination



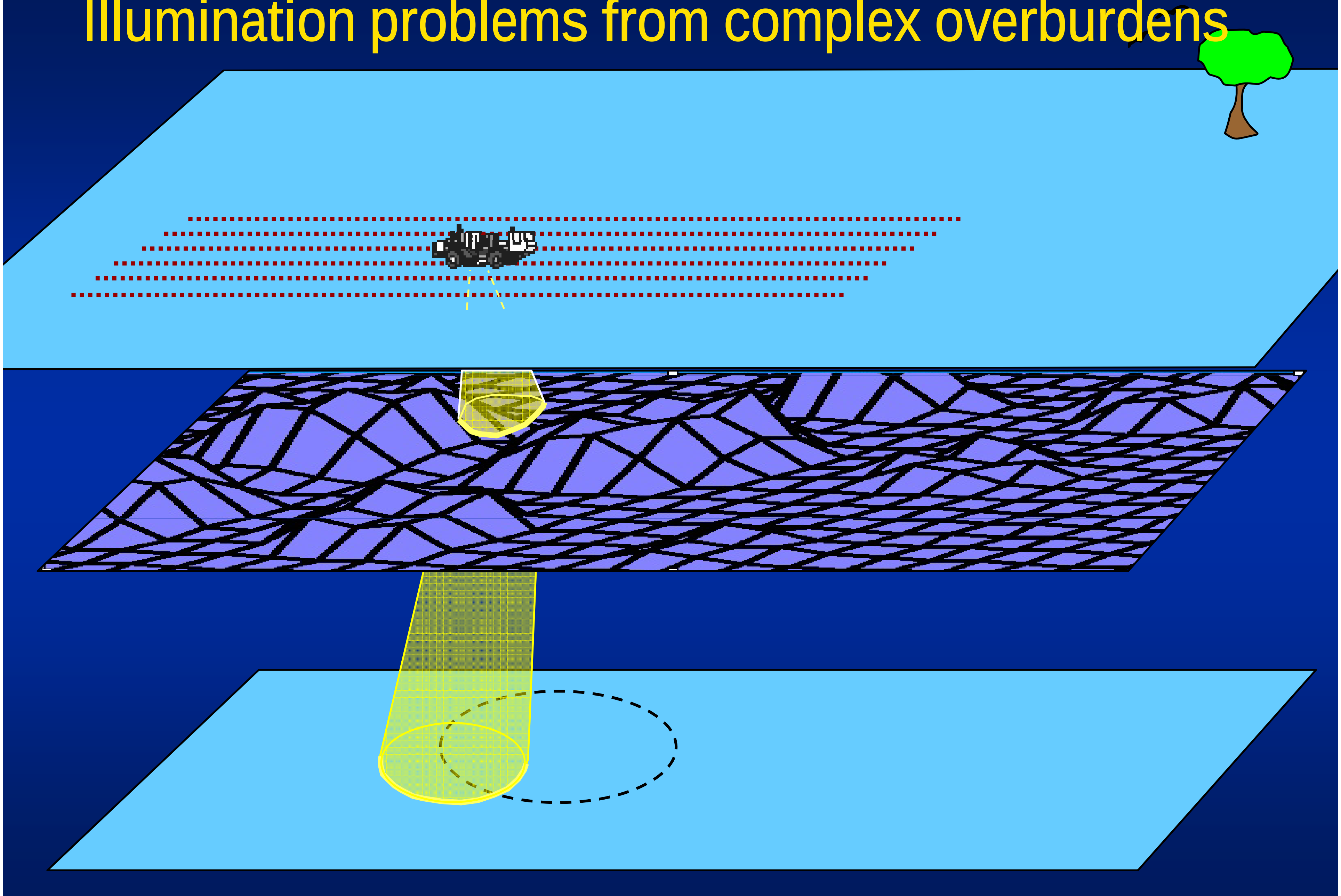
Illumination



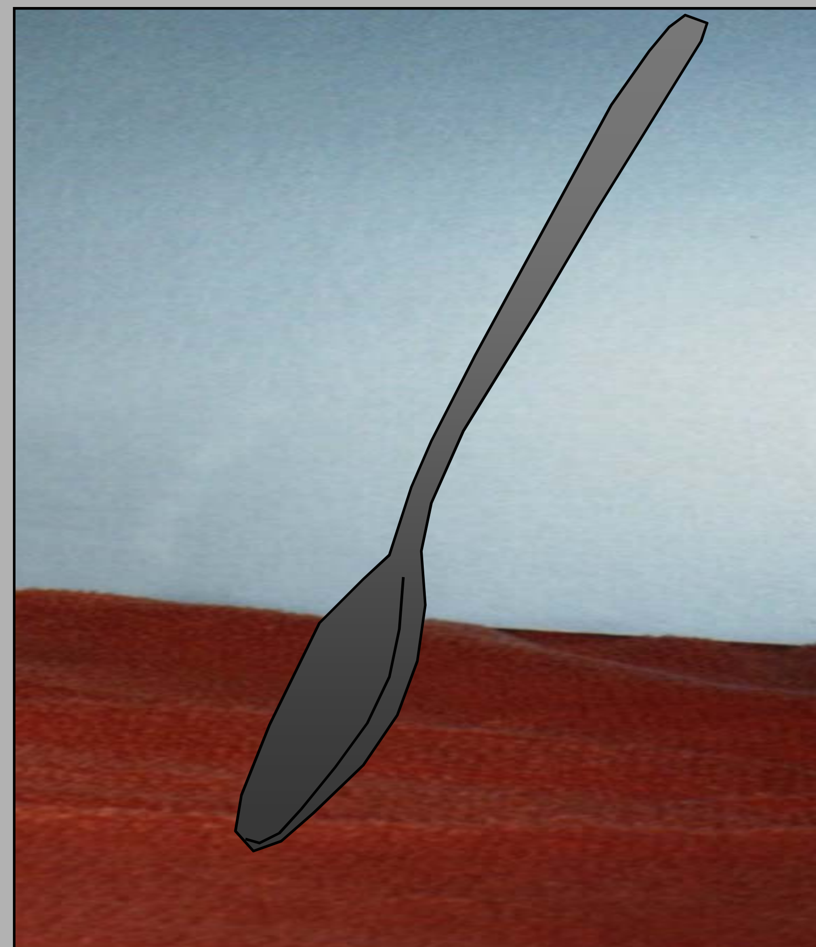
Imaging analogy



Illumination problems from complex overburdens



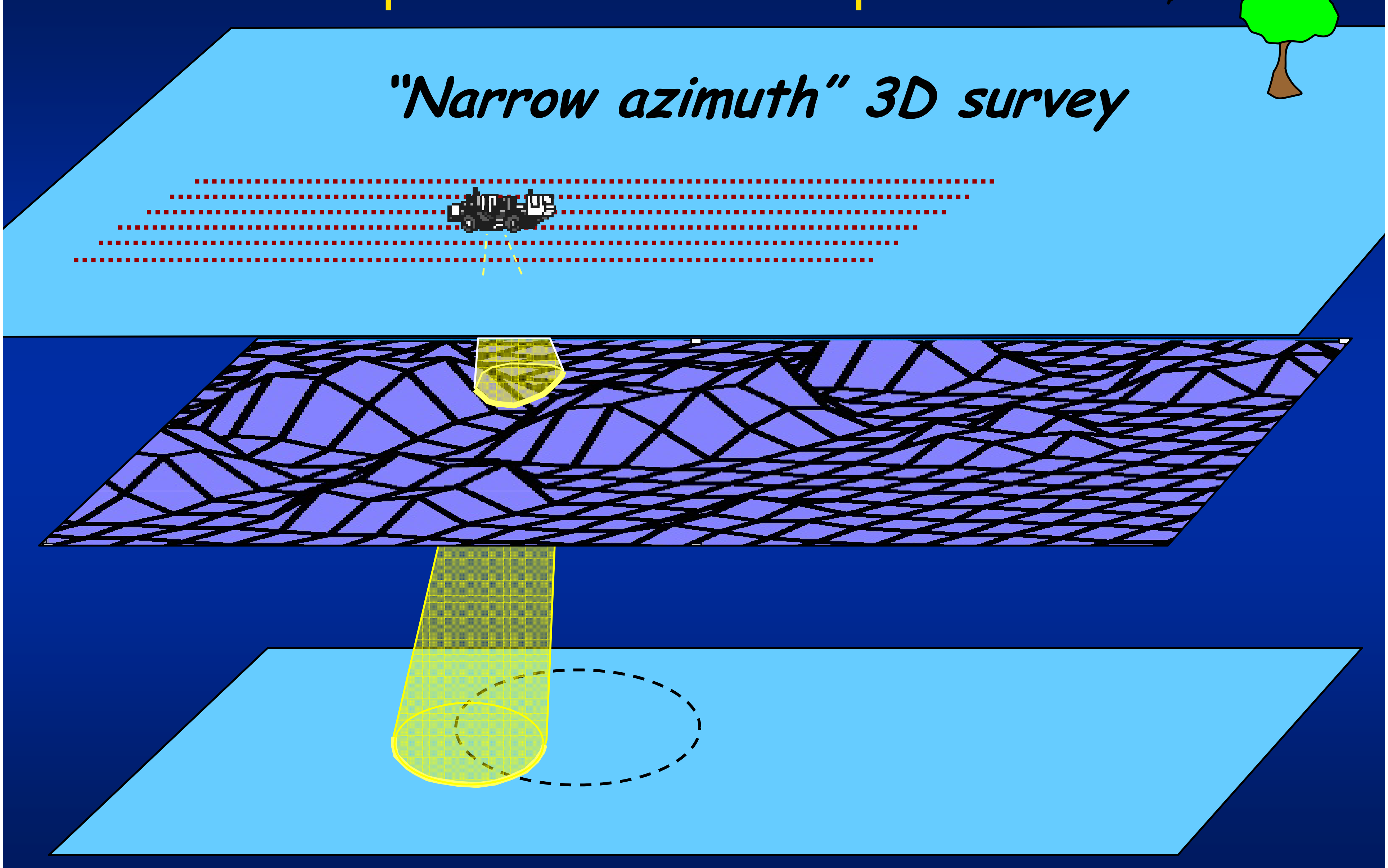
Imaging analogy



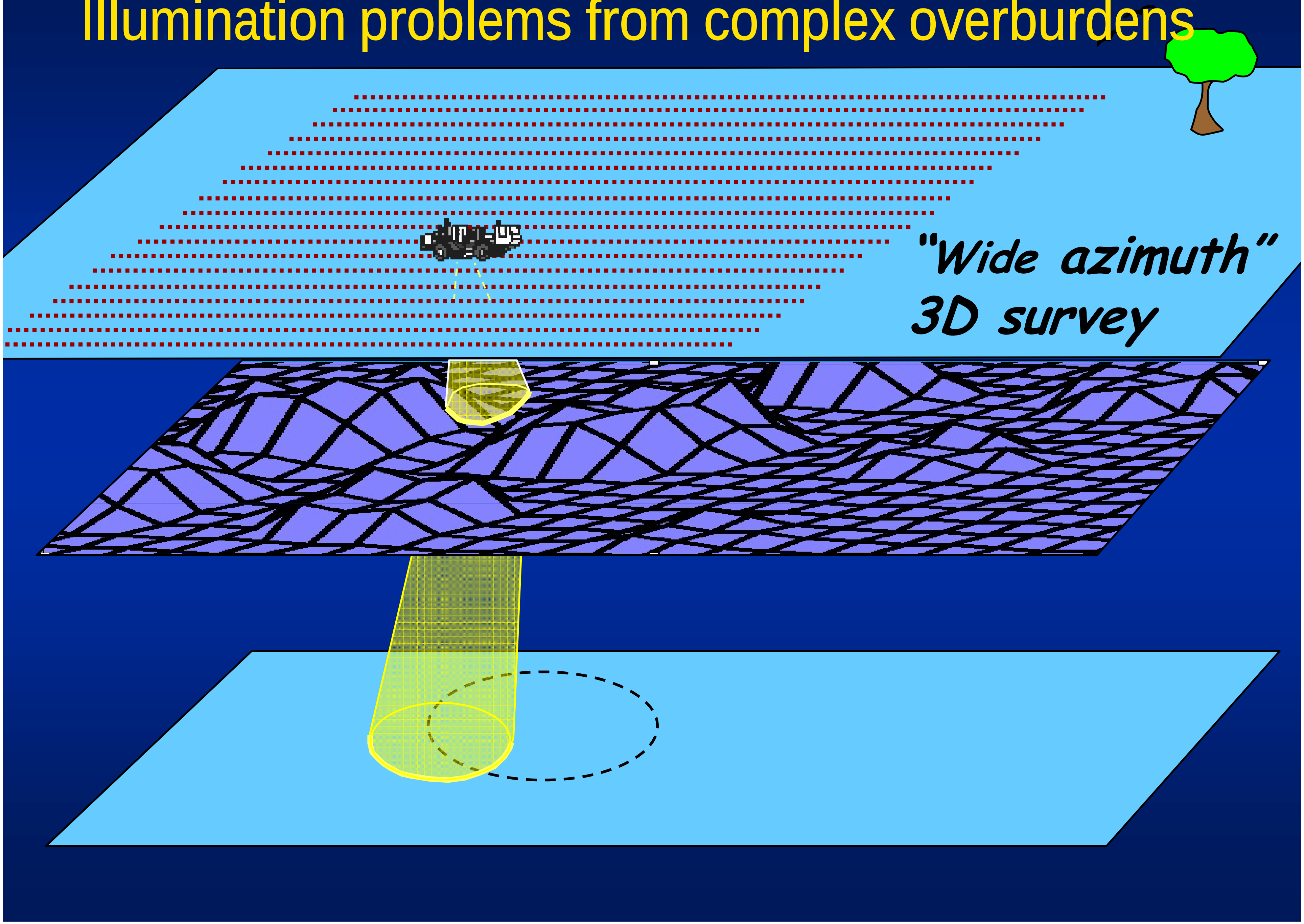
Imaging analogy

- **Shooting direction**
- **All azimuths needed?**

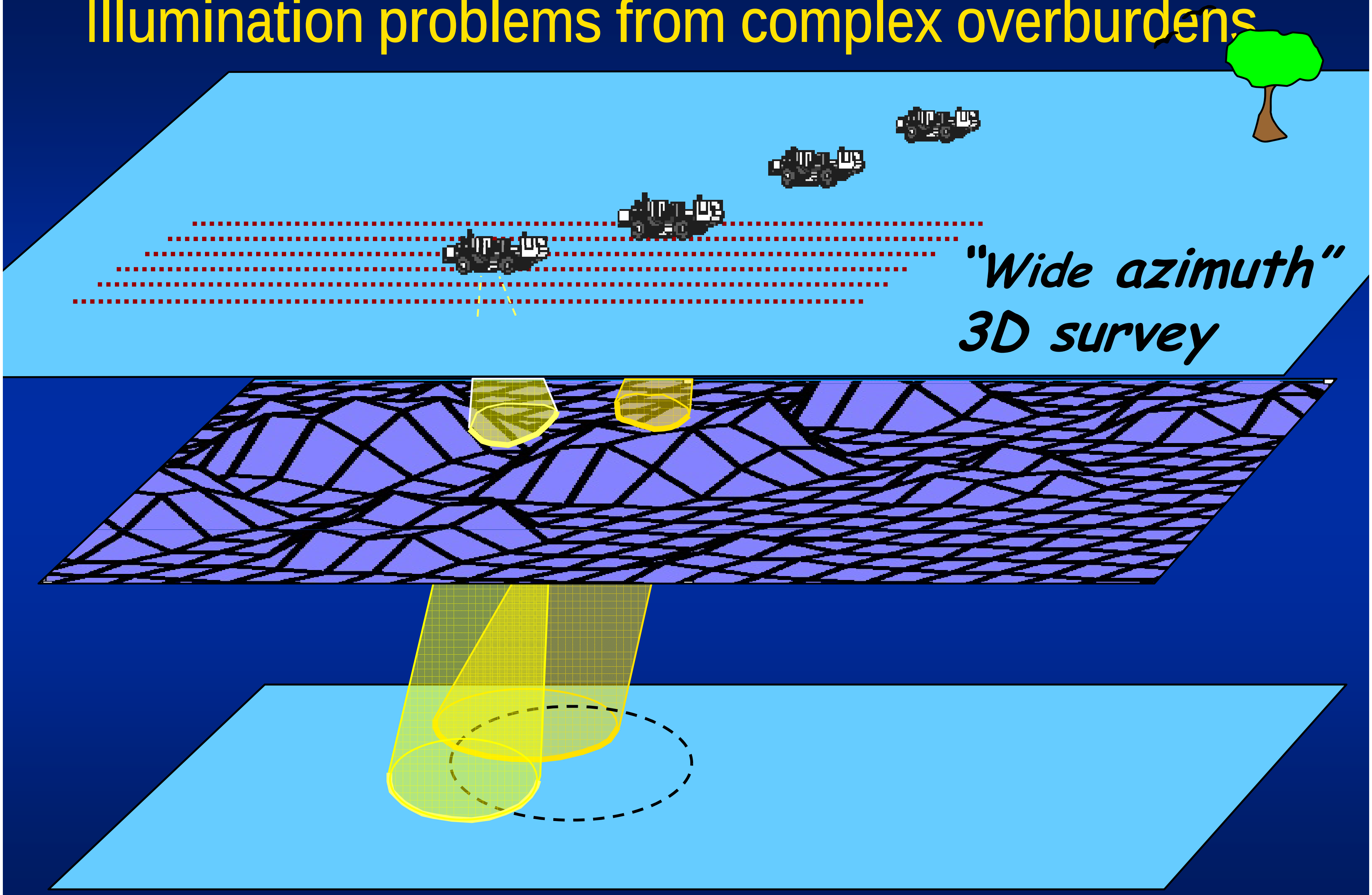
Illumination problems from complex overburdens



Illumination problems from complex overburdens



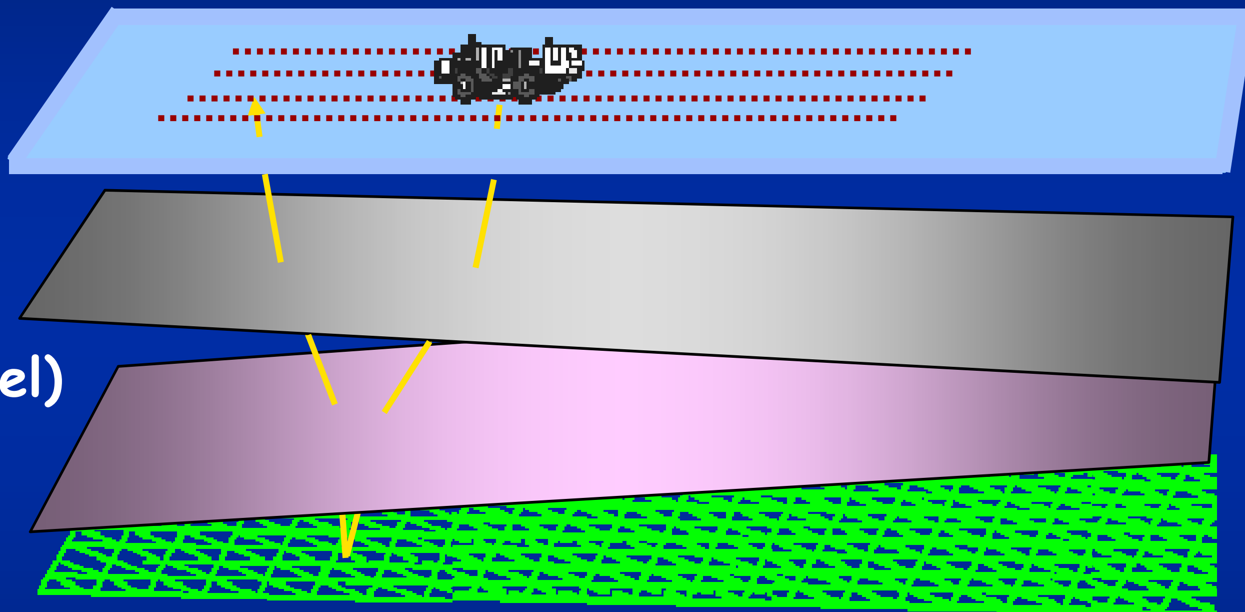
Illumination problems from complex overburdens



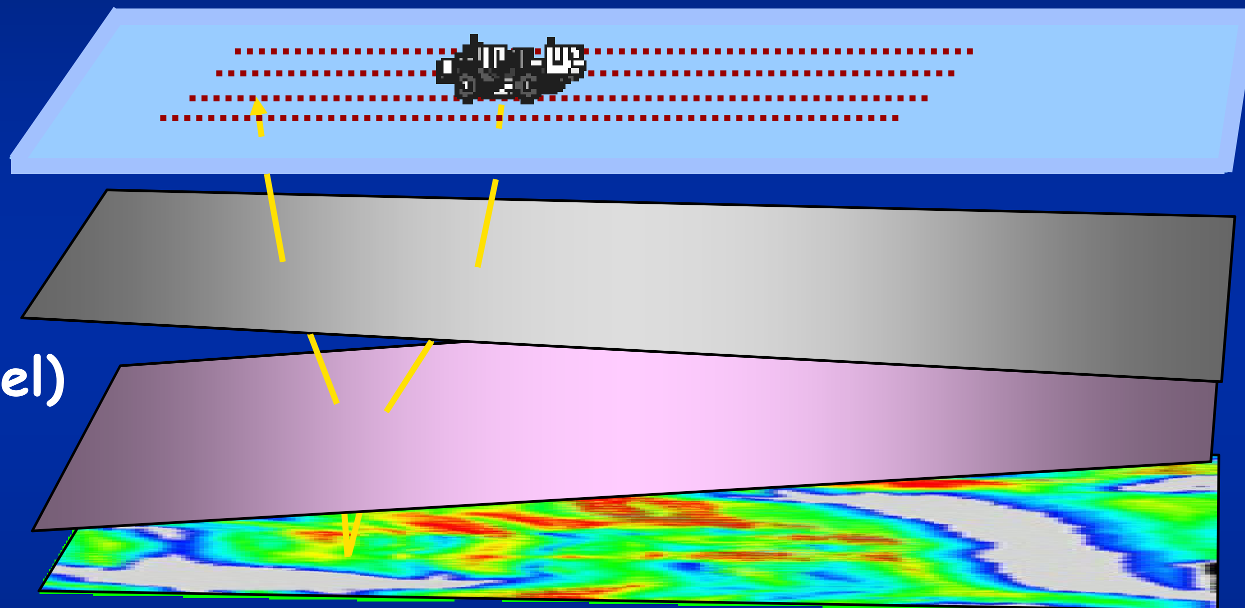
Survey Design

Ray tracing

(Requires an earth model)



Survey Design



Ray tracing

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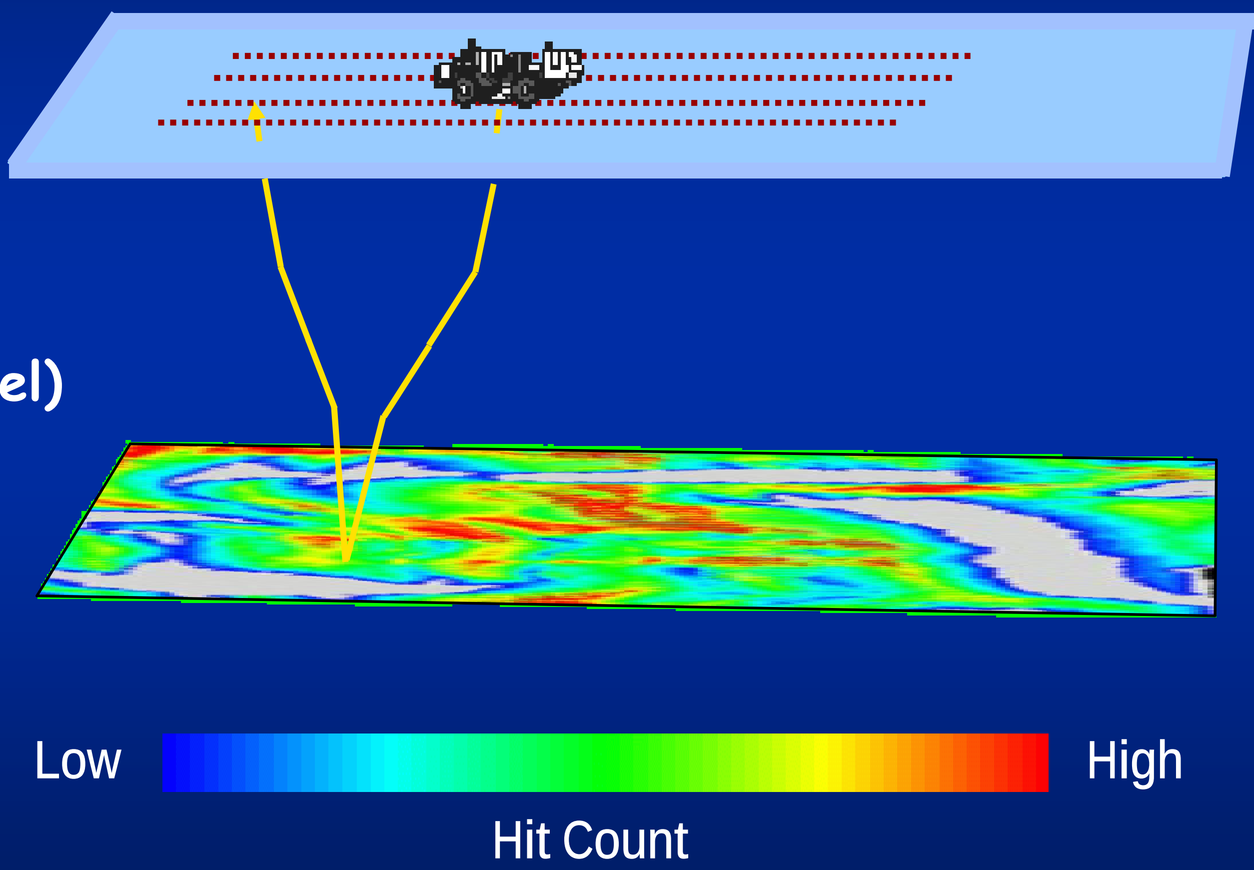
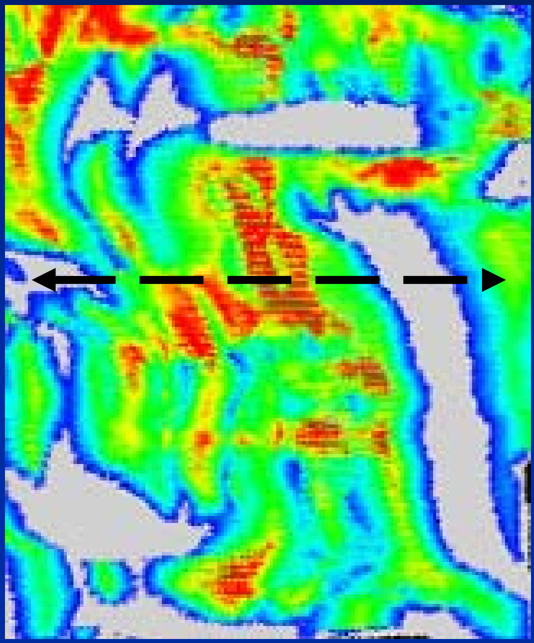
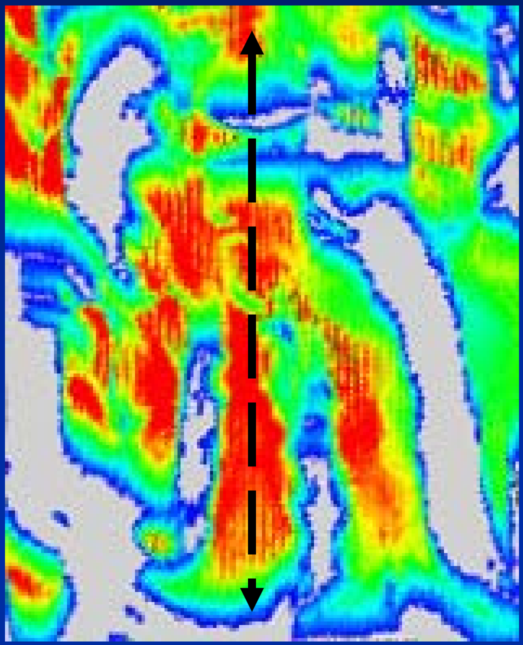


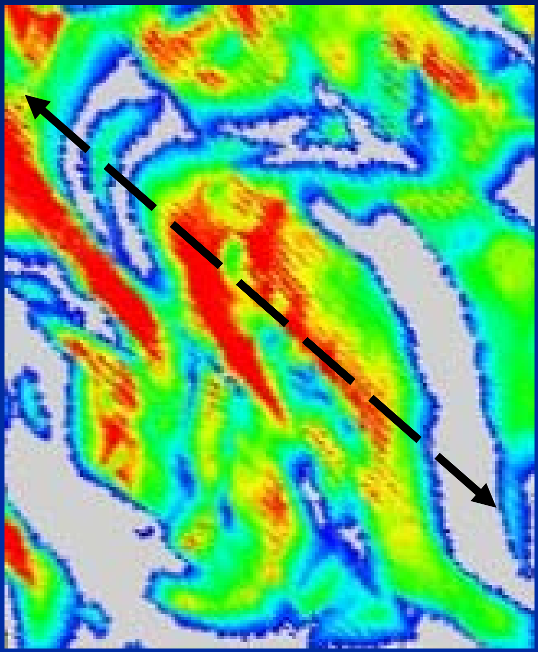
Illumination maps from a survey design study



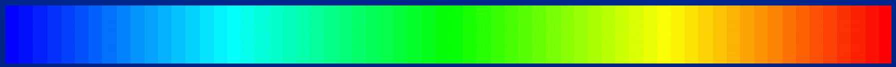
Dip Shooting



Strike Shooting



45° Shooting

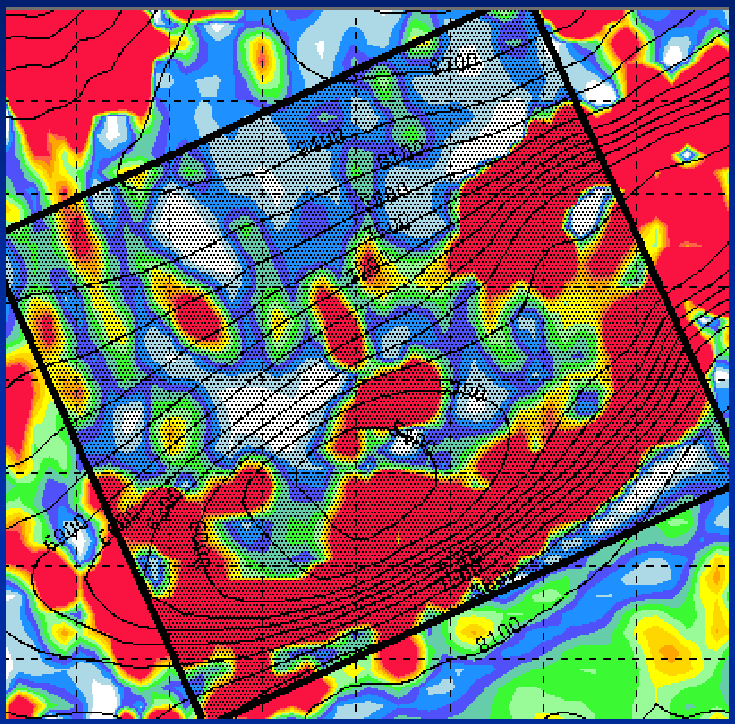
Low  High

Hit Count

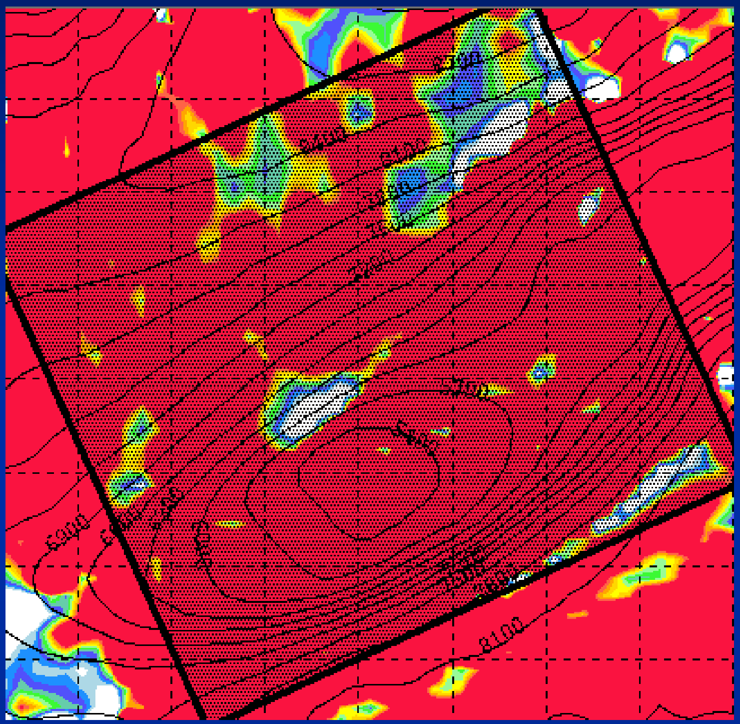
(A top-salt boundary)

In some surveys, a single shooting direction is not sufficient.

Illumination maps from another study



1-azimuth



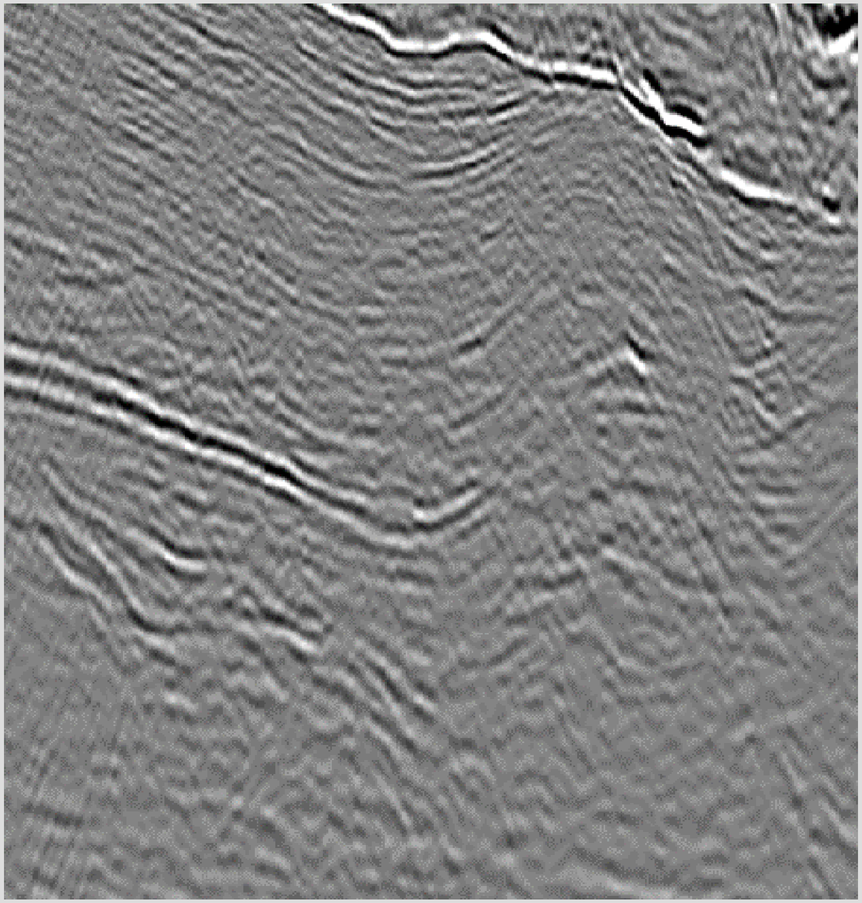
All azimuths

Hit Count

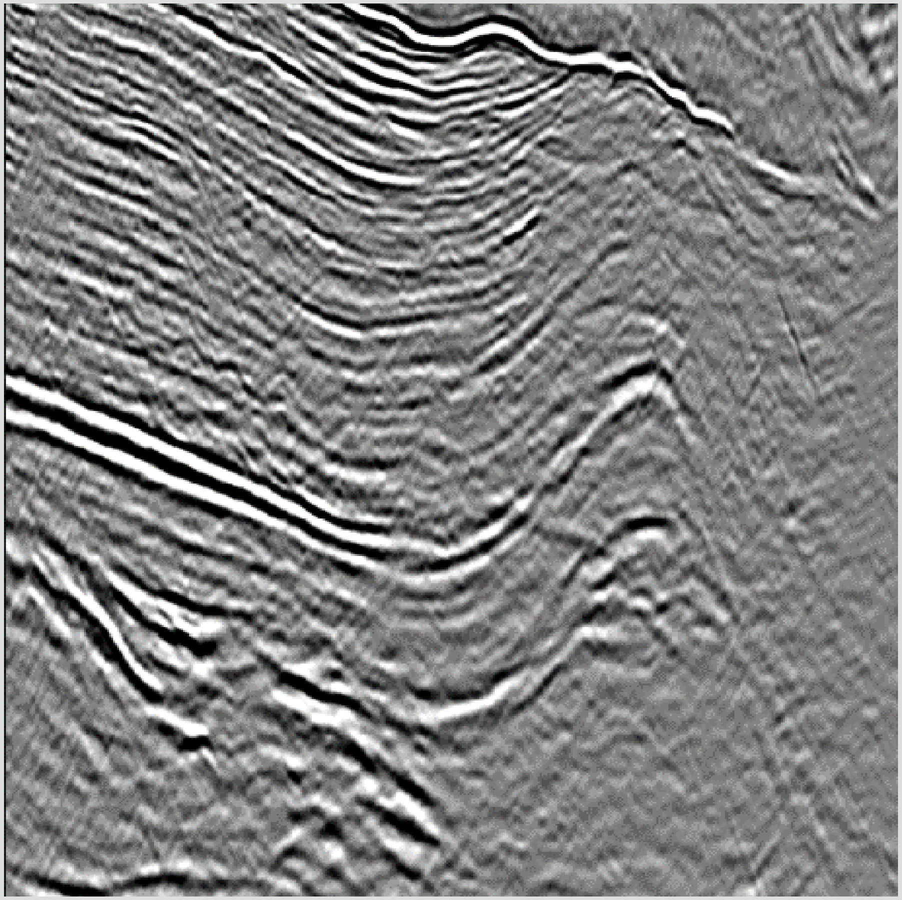
(A base-salt boundary) Low High

Illumination

Data courtesy of BHP Billiton, Hess Corporation and Repsol YPF



Narrow-azimuth 3D



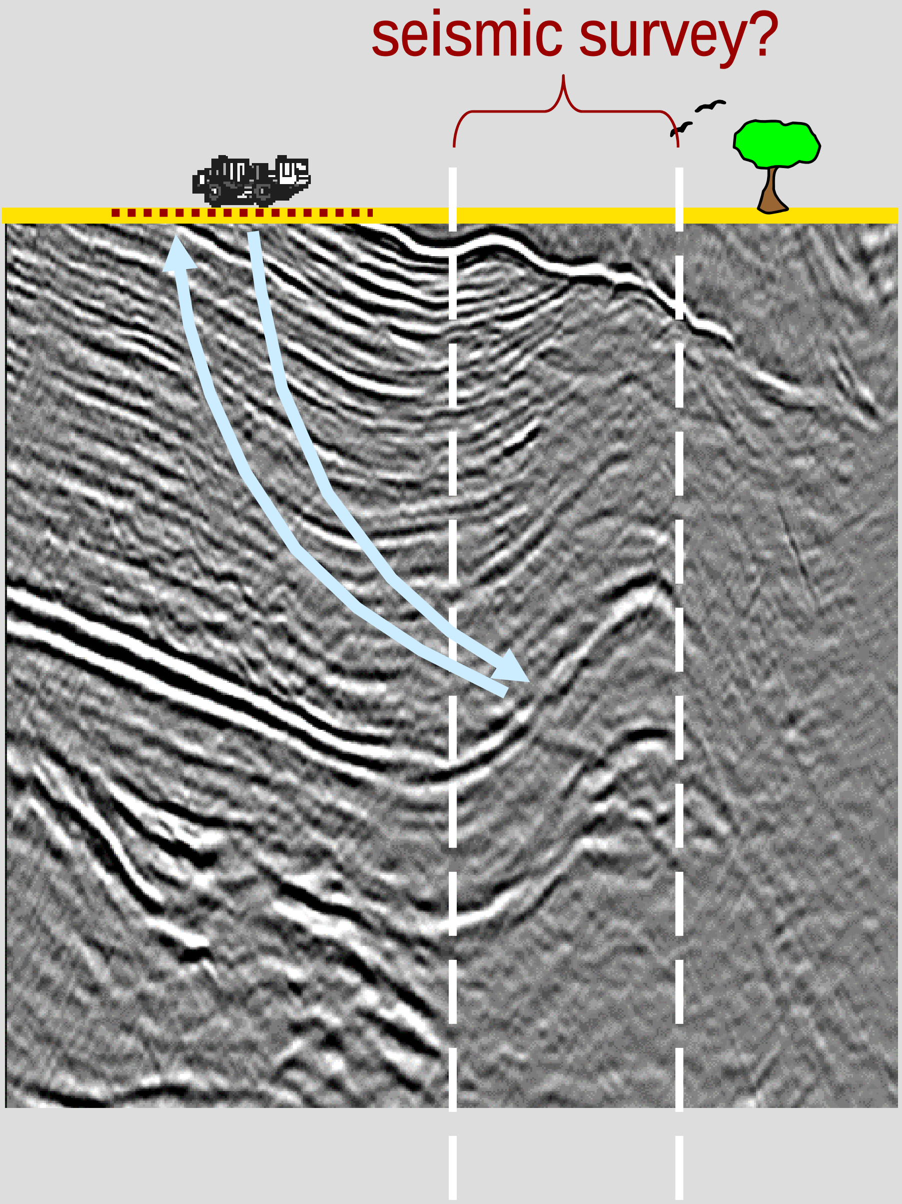
Wide-azimuth 3D

Illumination

So we see that illumination requirements impact the width of the geophone spread and/or the number of source points ...

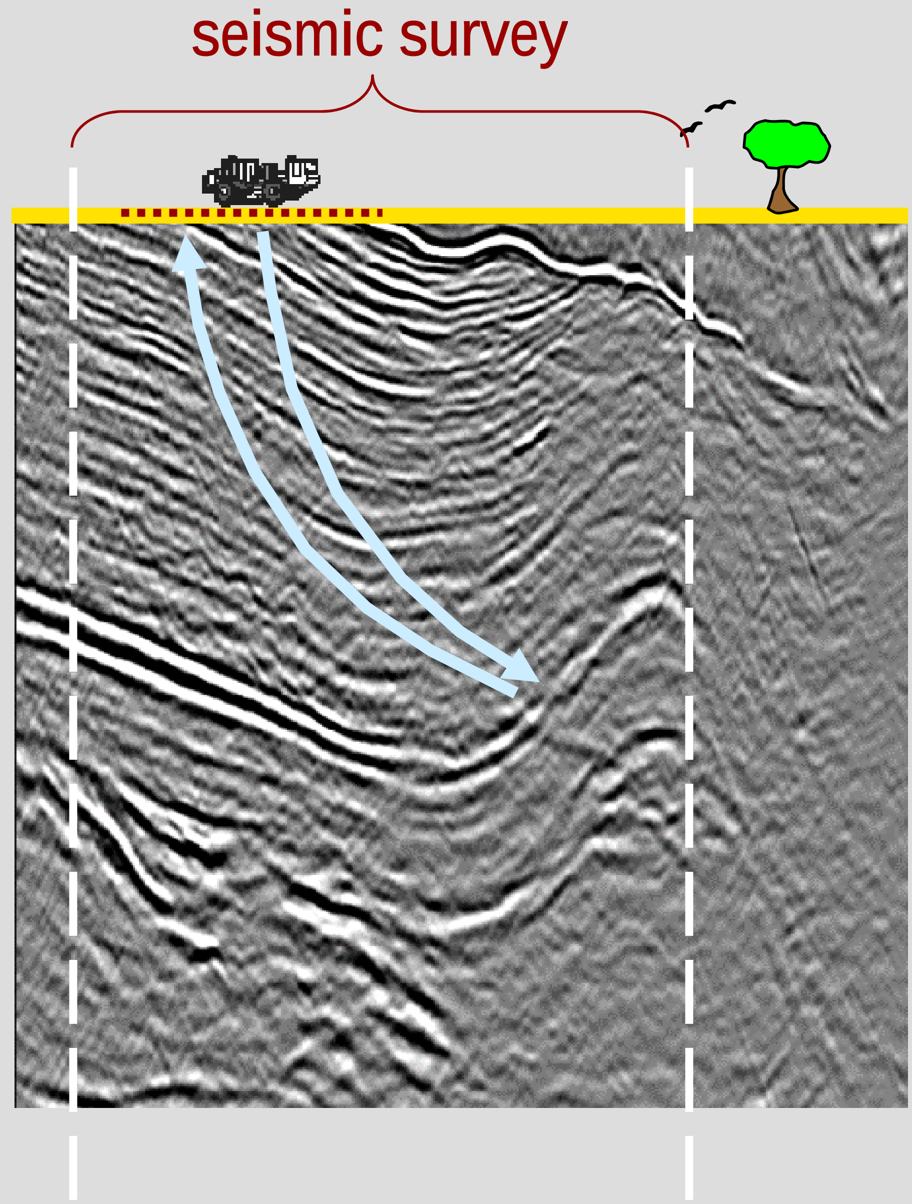
... what about the size of the survey?

Aperture

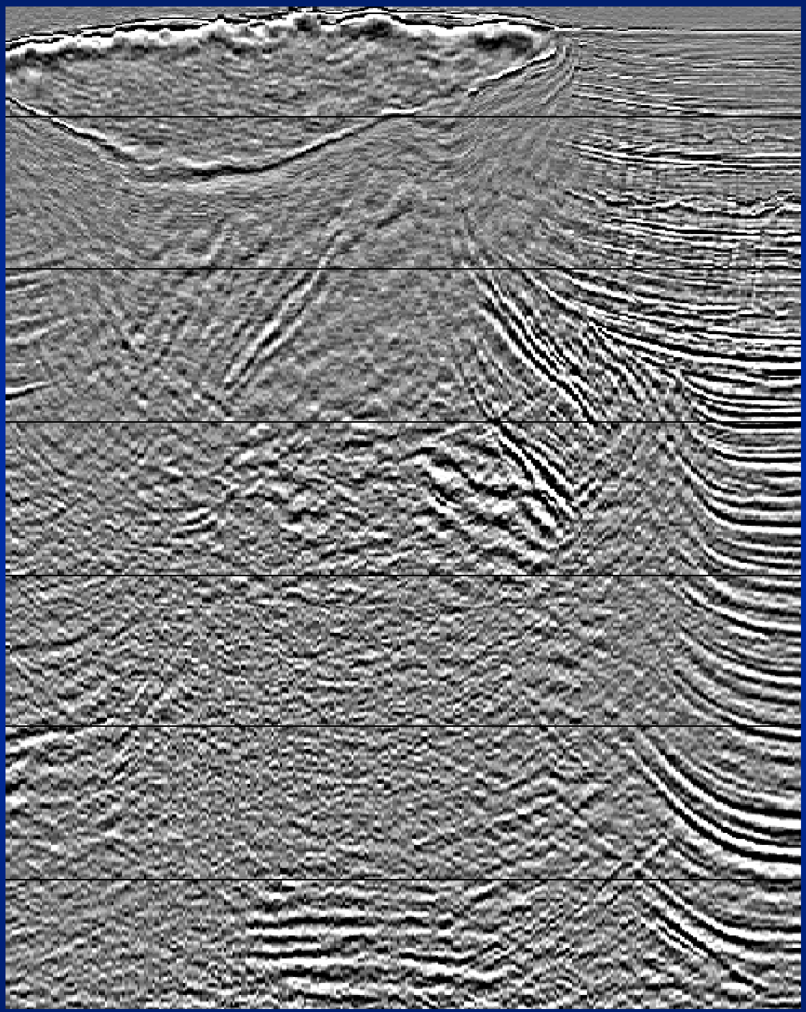


Illumination

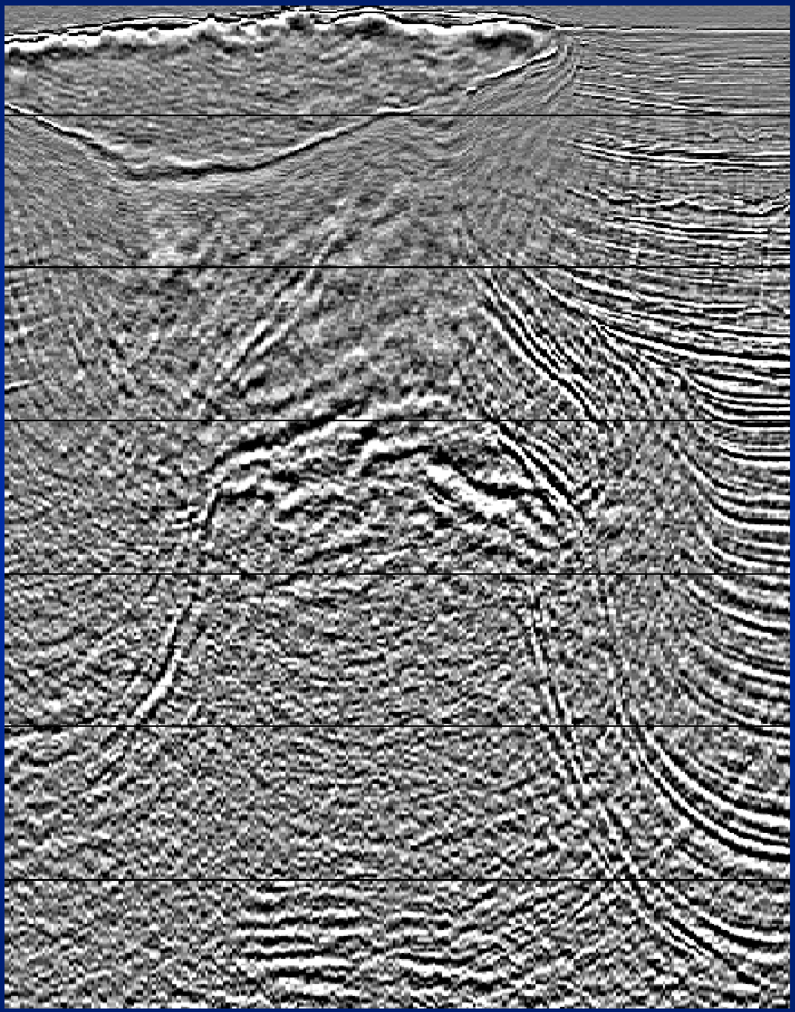
Aperture



Aperture



15,000-ft aperture

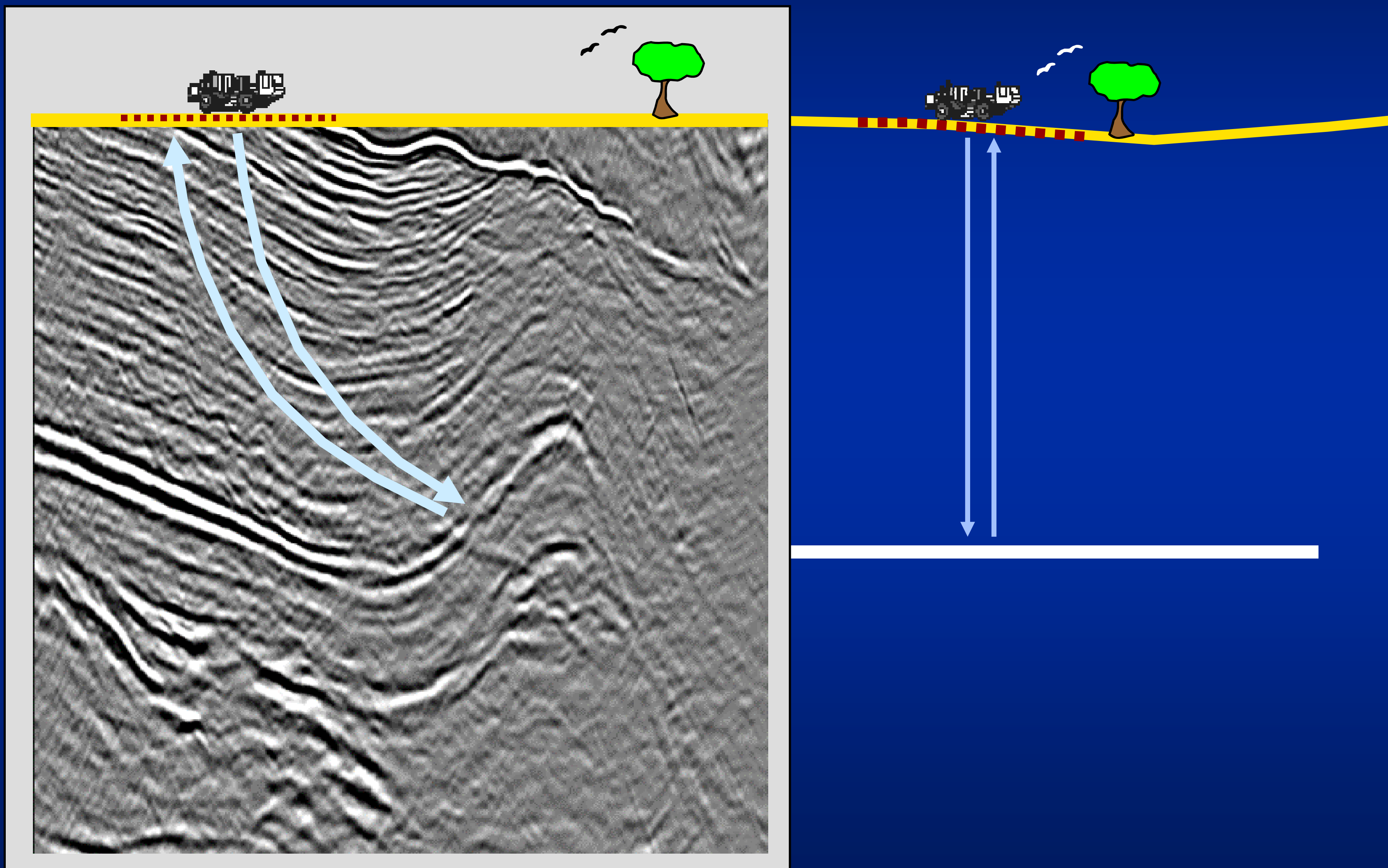


34,000-ft aperture

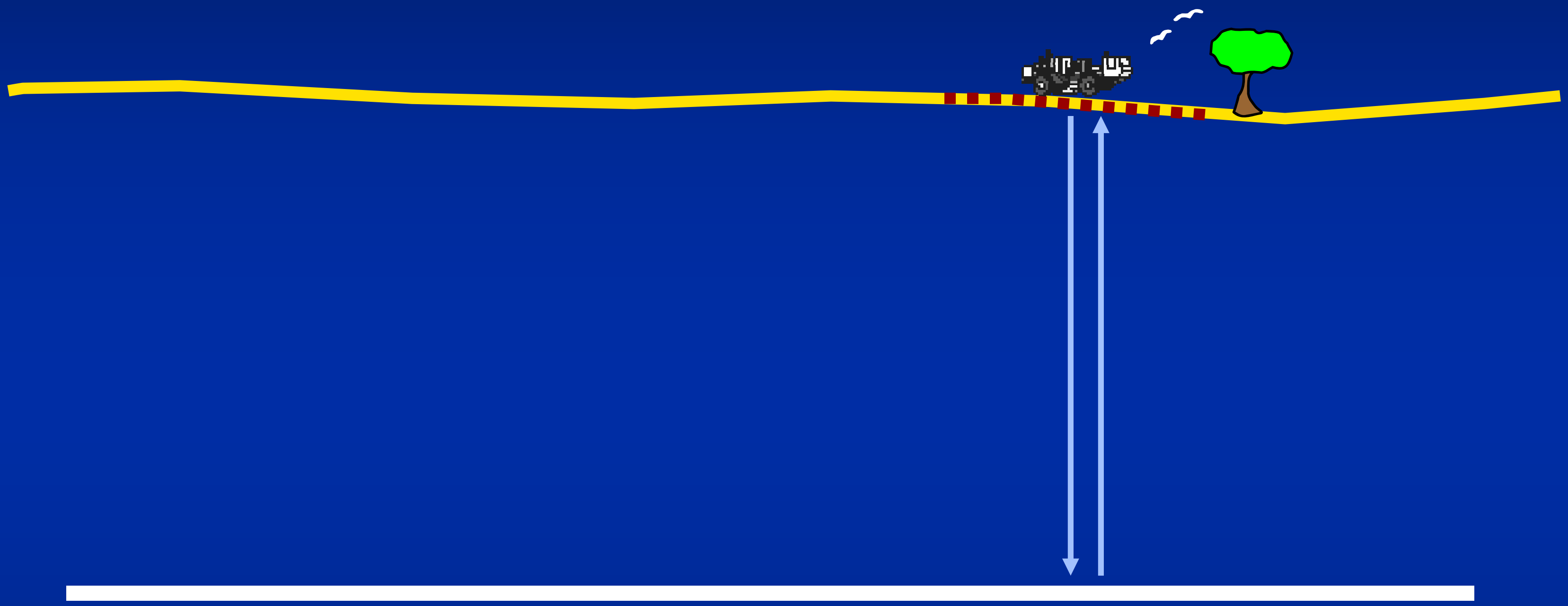
So we see that aperture decisions impact the size of the seismic survey …

… what about the influence of aperture on resolution?

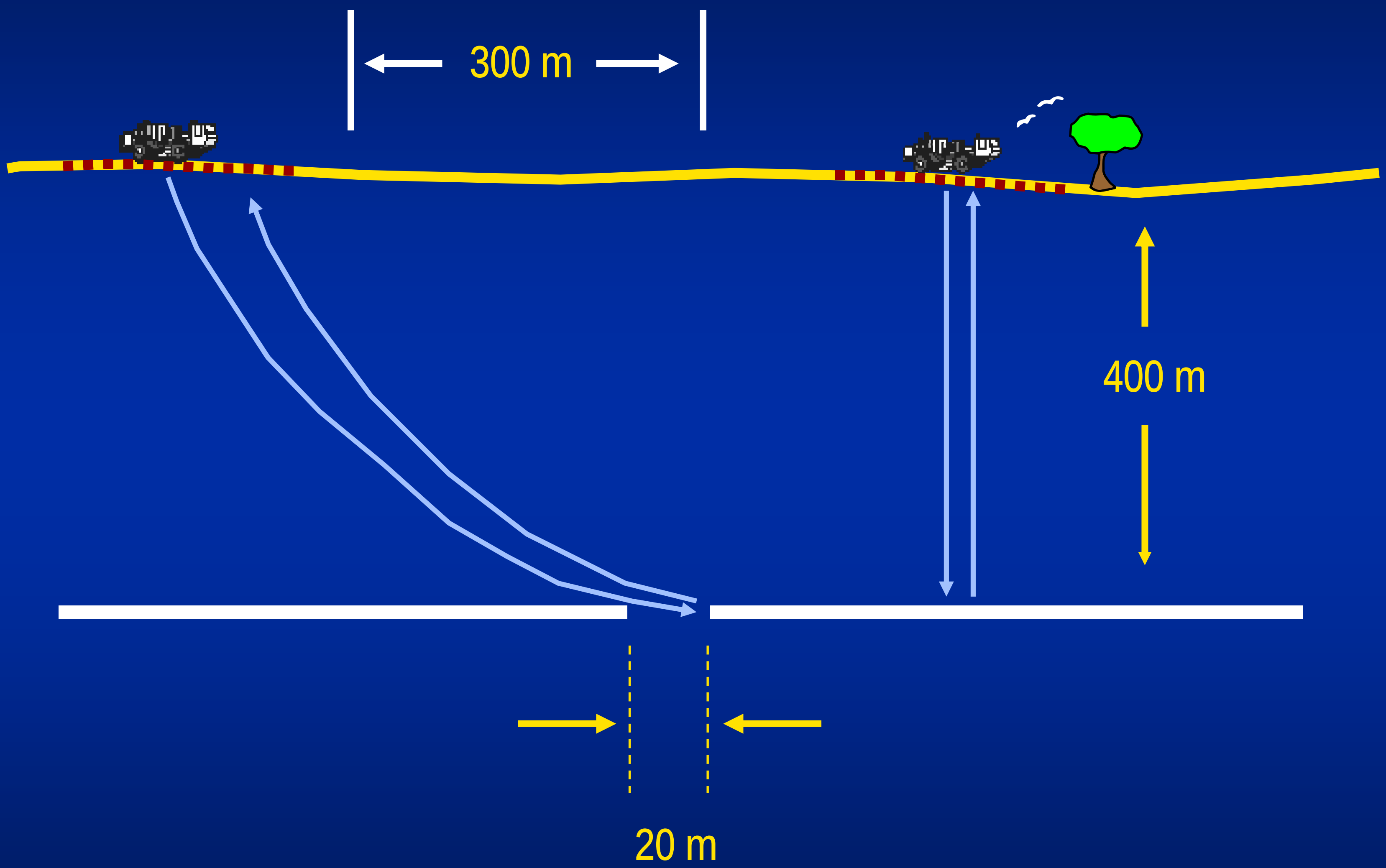
Lateral resolution



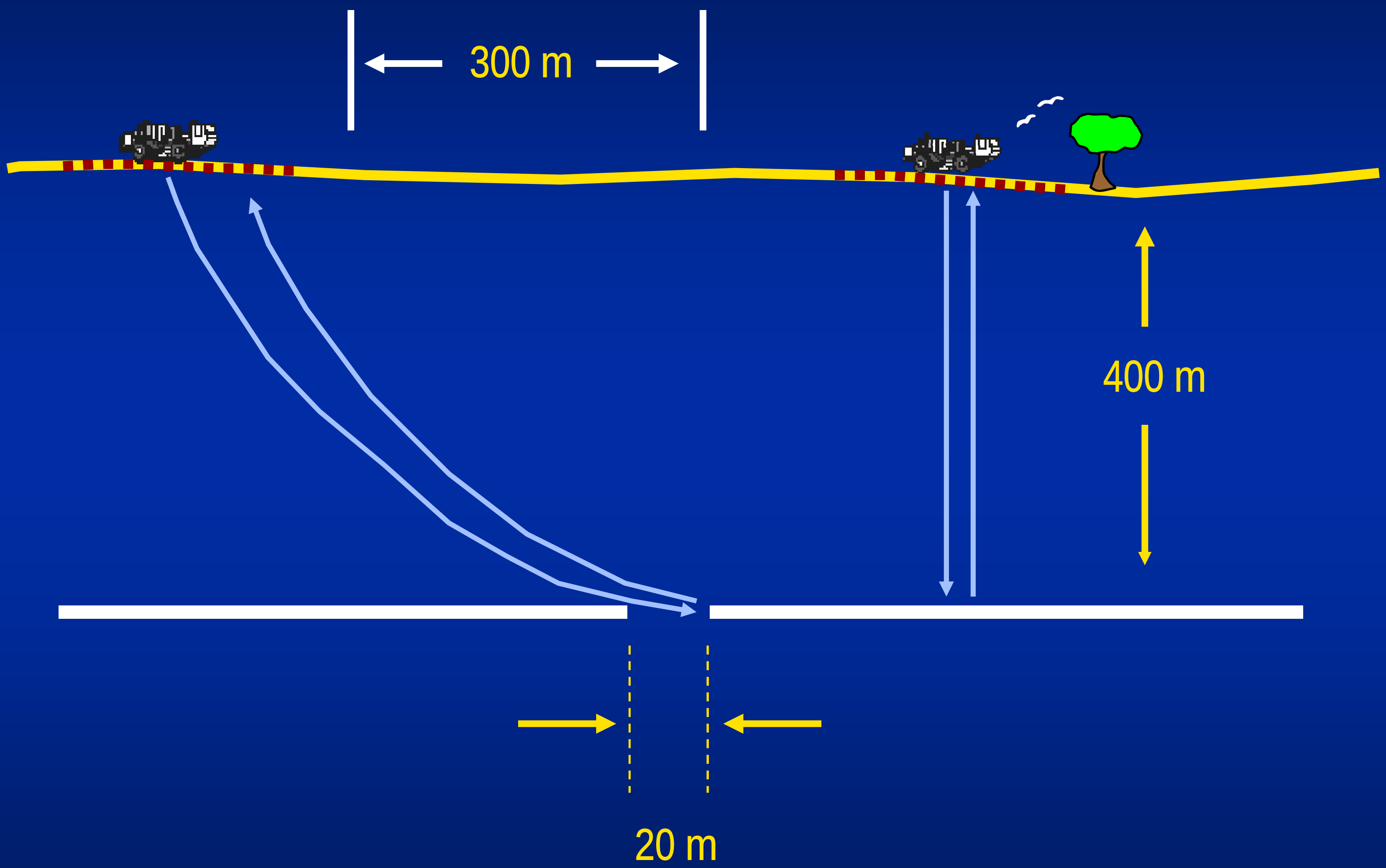
Lateral resolution



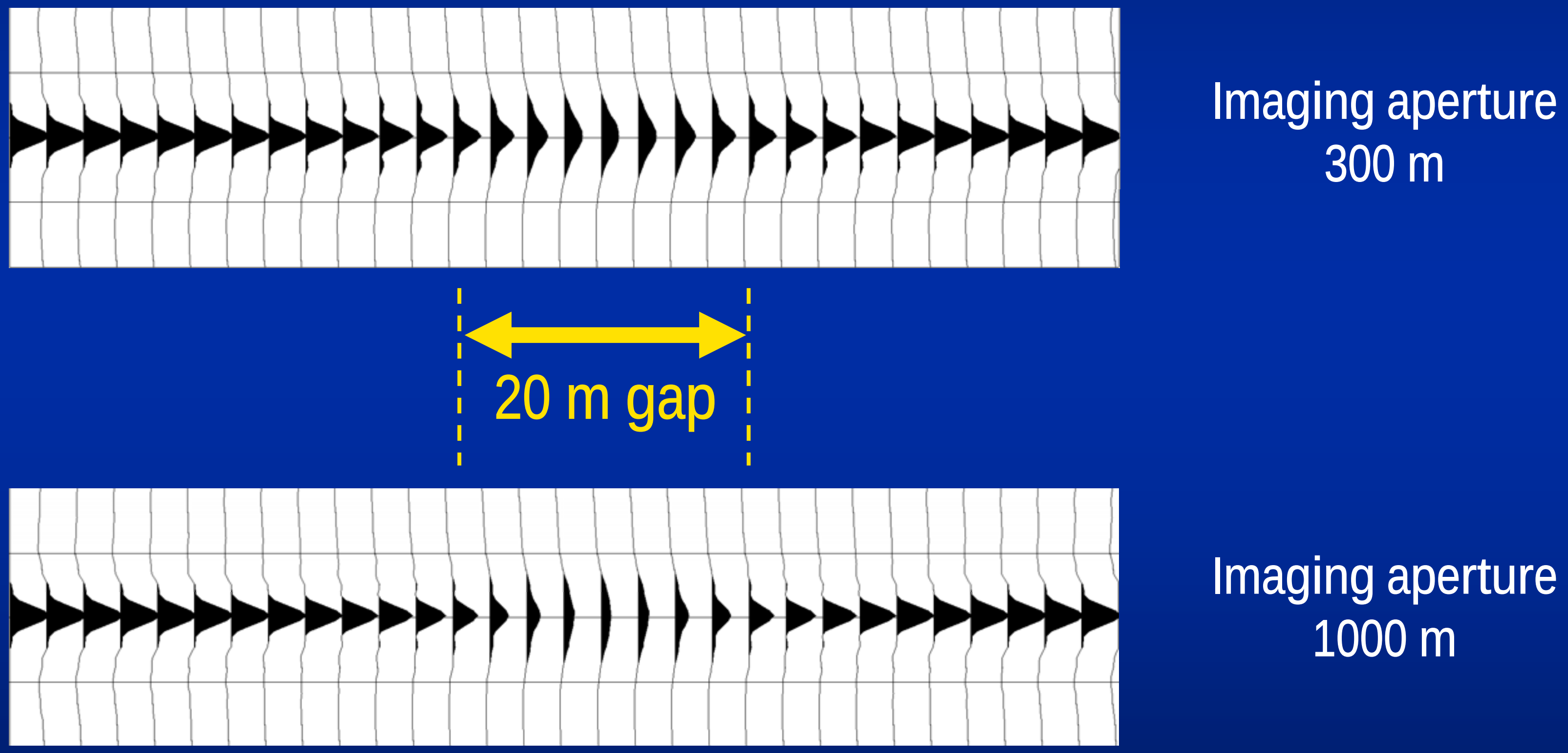
Lateral resolution



Lateral resolution

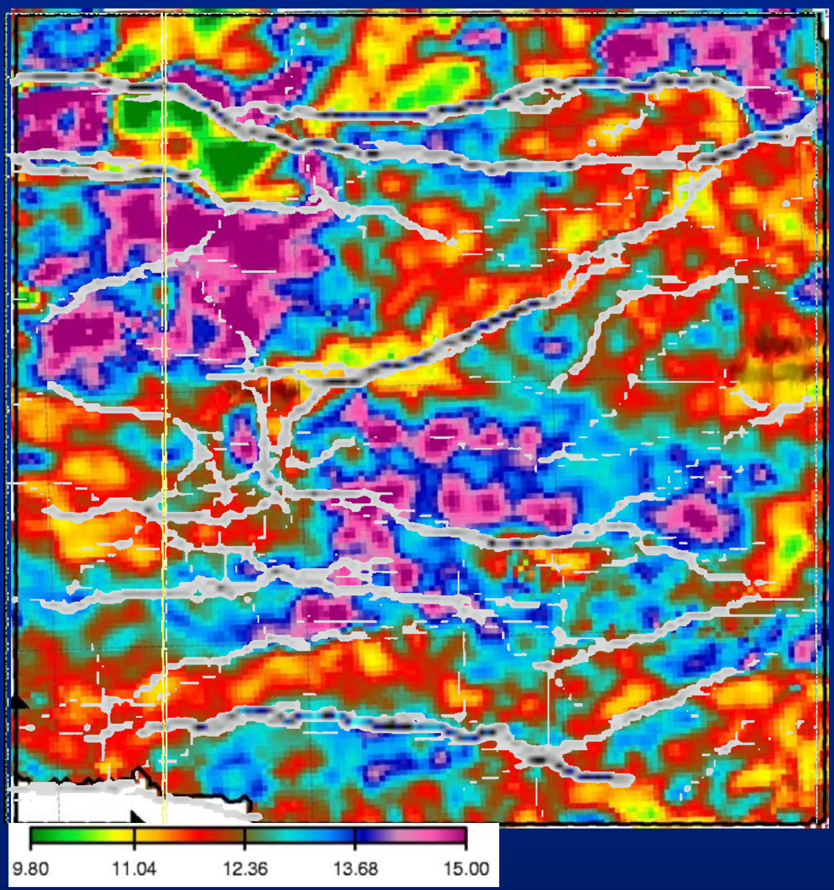


Lateral Resolution in Imaged Section

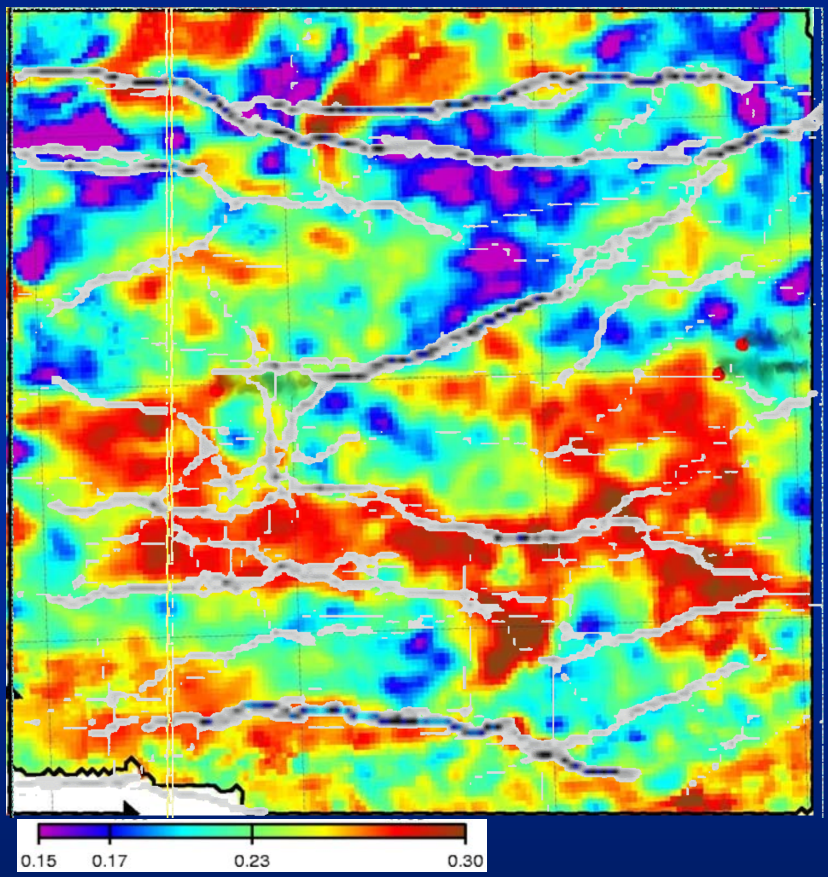


Faults and Fracture Networks

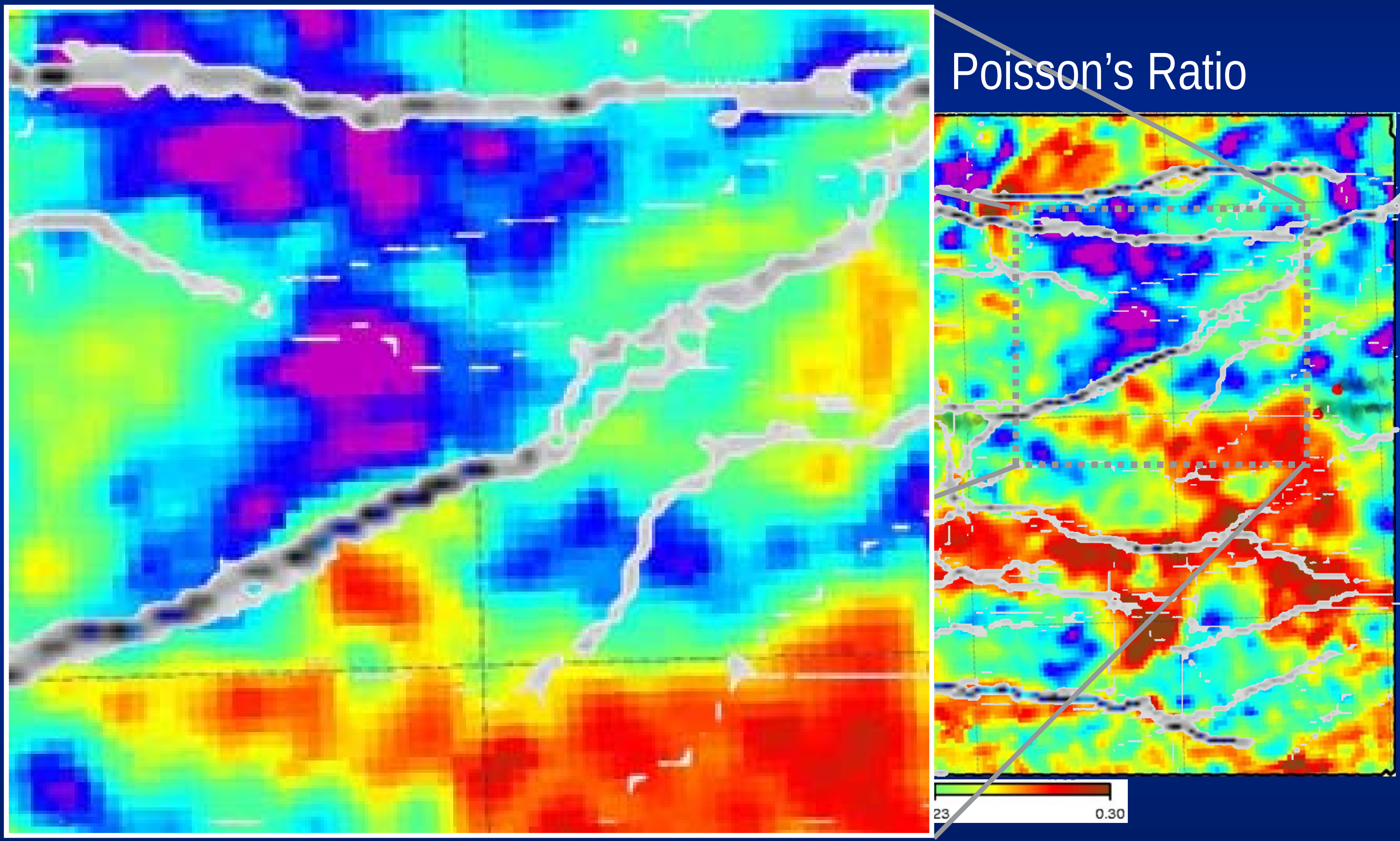
Acoustic Impedance



Poisson's Ratio



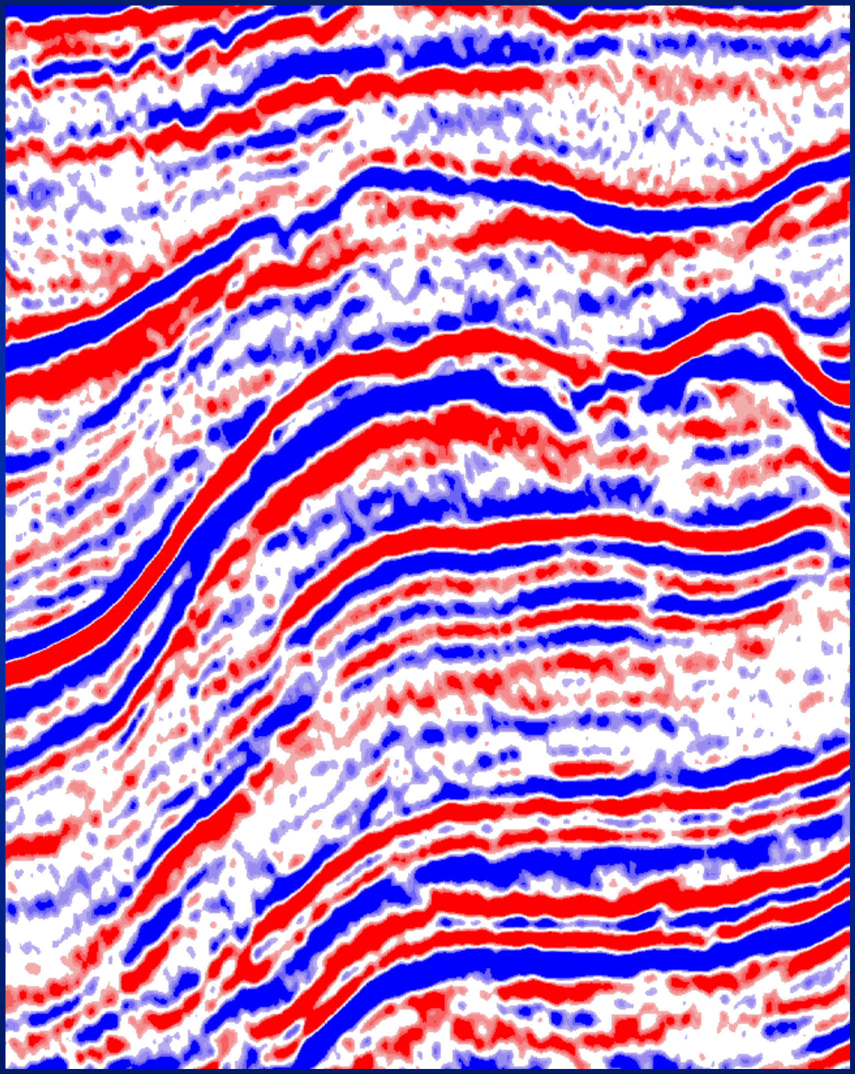
Faults and Fracture Networks



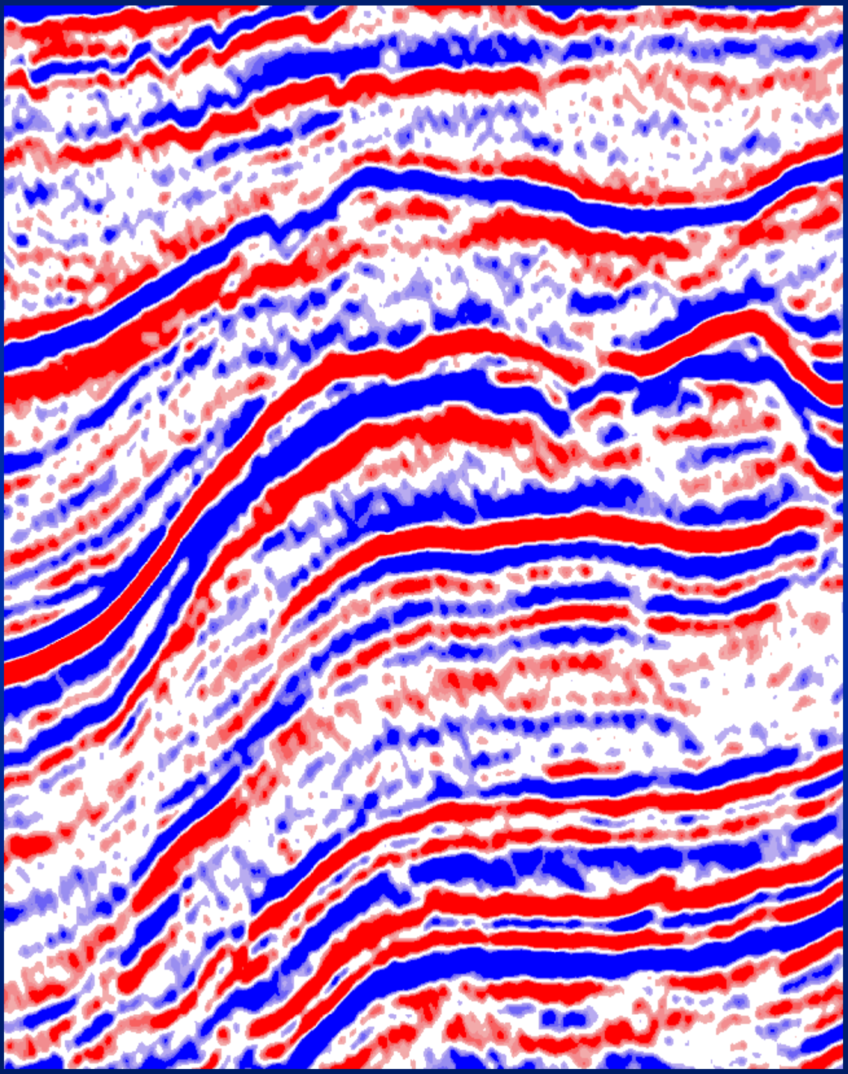
An example of monitoring from the North Sea

- Started production in 1997
- Gas and water injection
- Seismic surveys in 1992, 2001, 2003, …
- The 1992 survey used conventional technology
- Subsequent surveys used better repeatable technology

Comparison of the 2001 & 2003 seismic programs

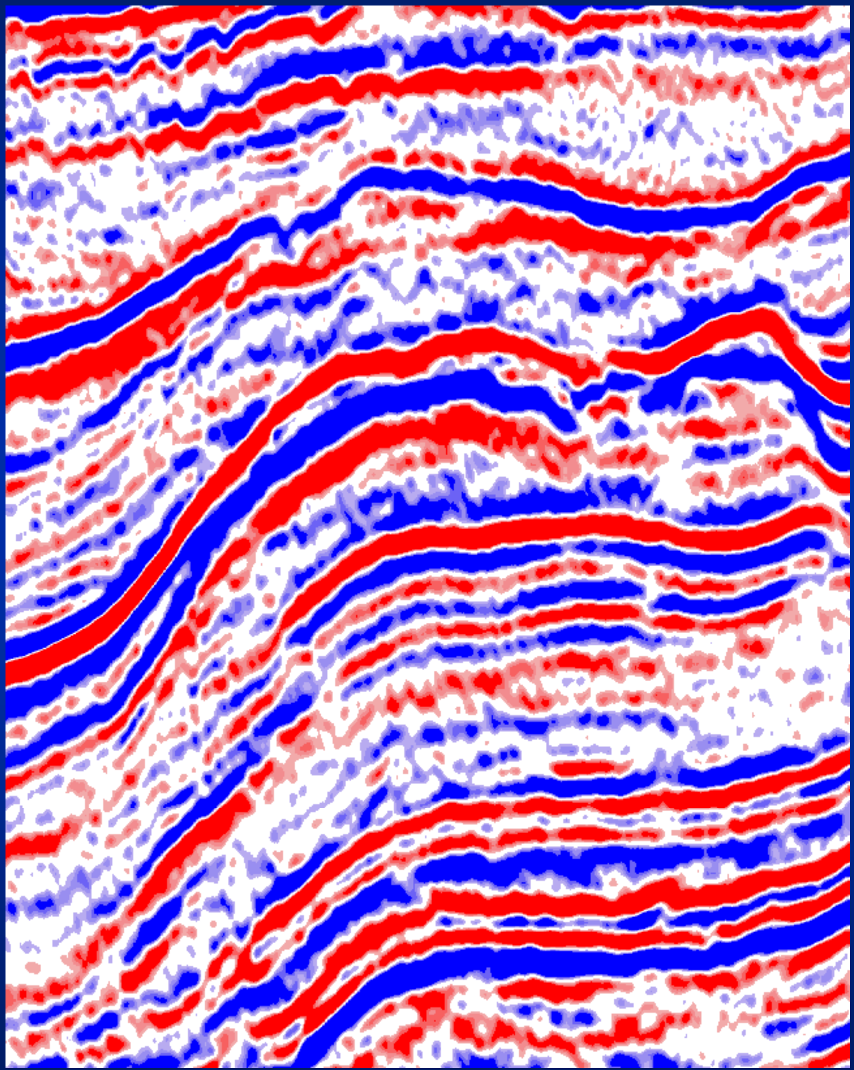


2003

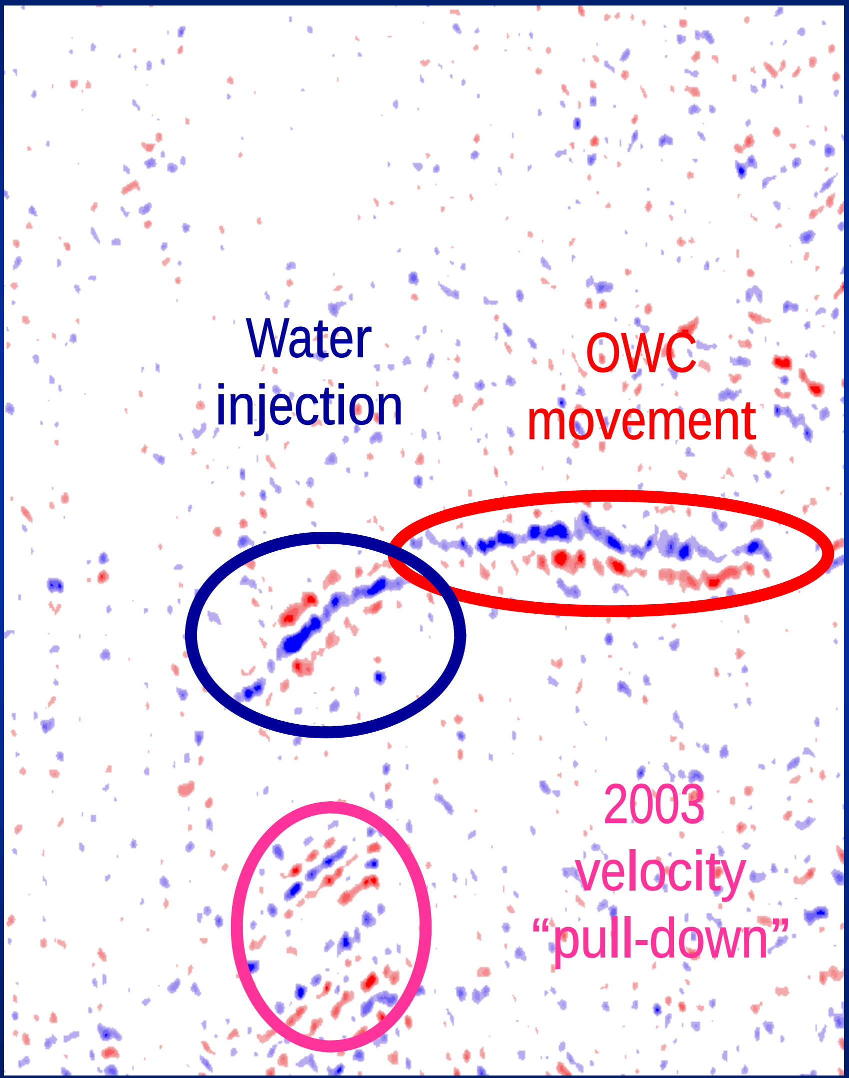


2001

Comparison of the 2001 & 2003 seismic programs

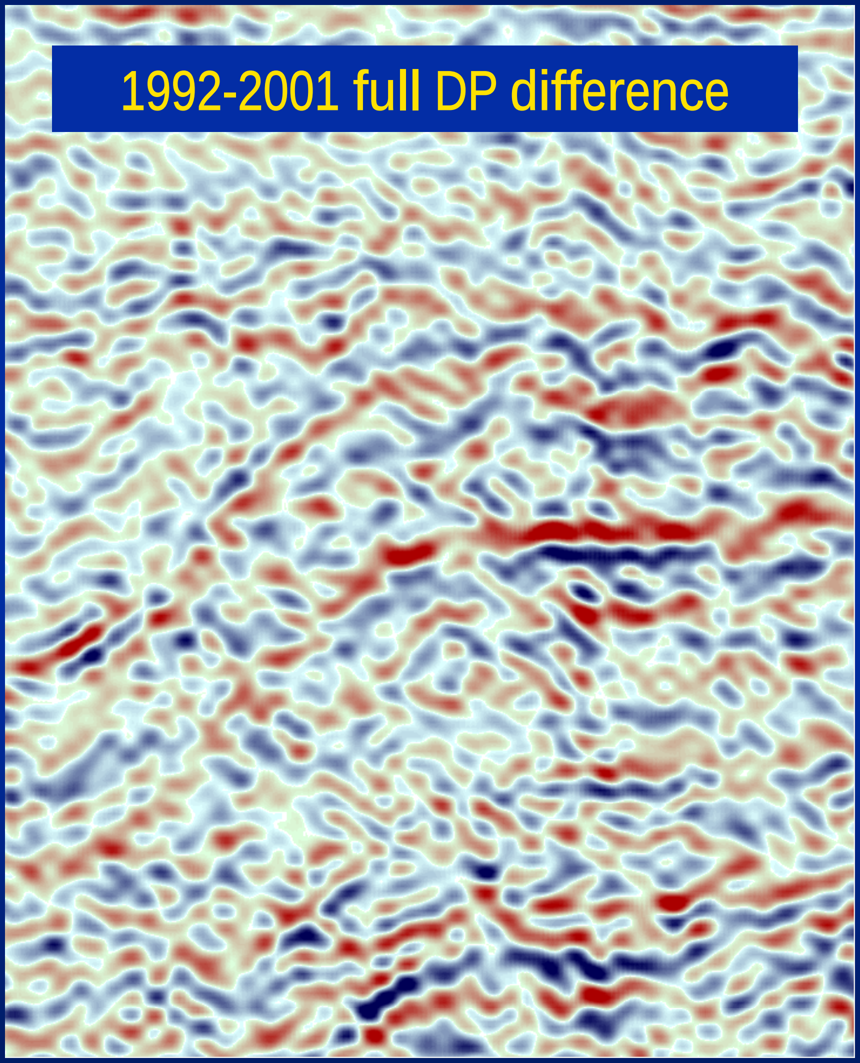


2003

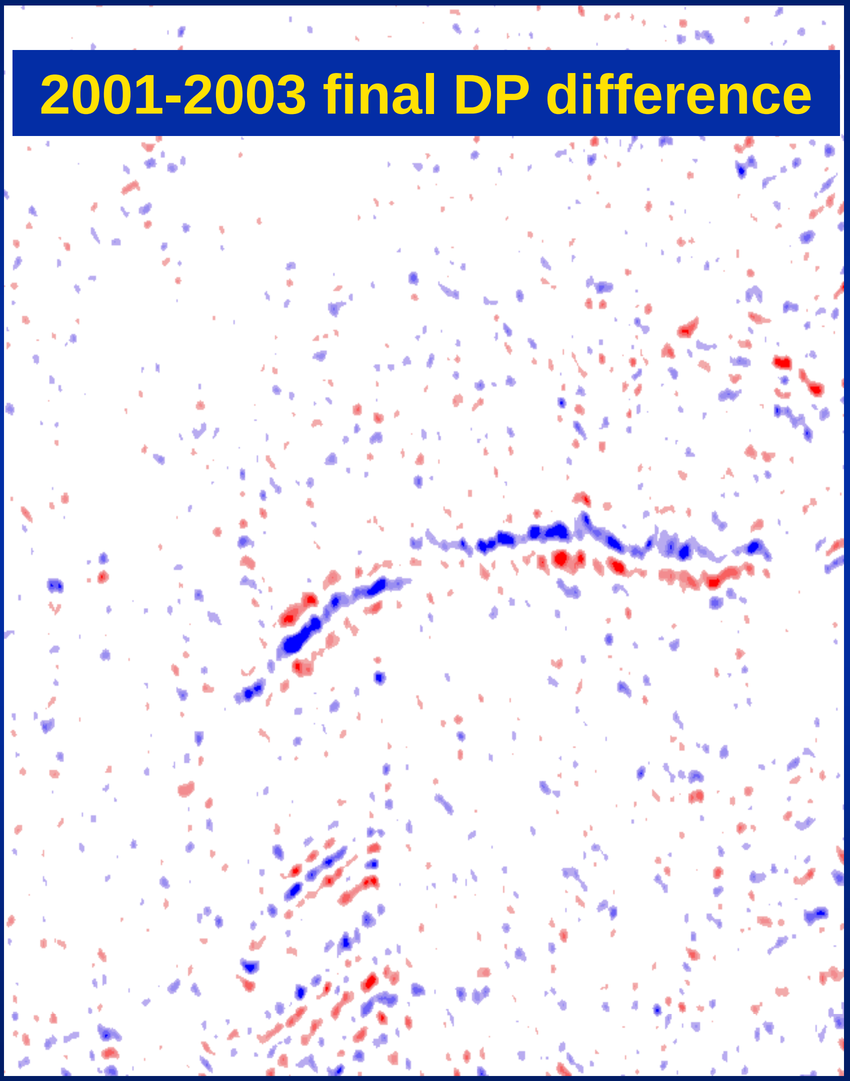


Difference

Comparison of monitoring differences



4 years production

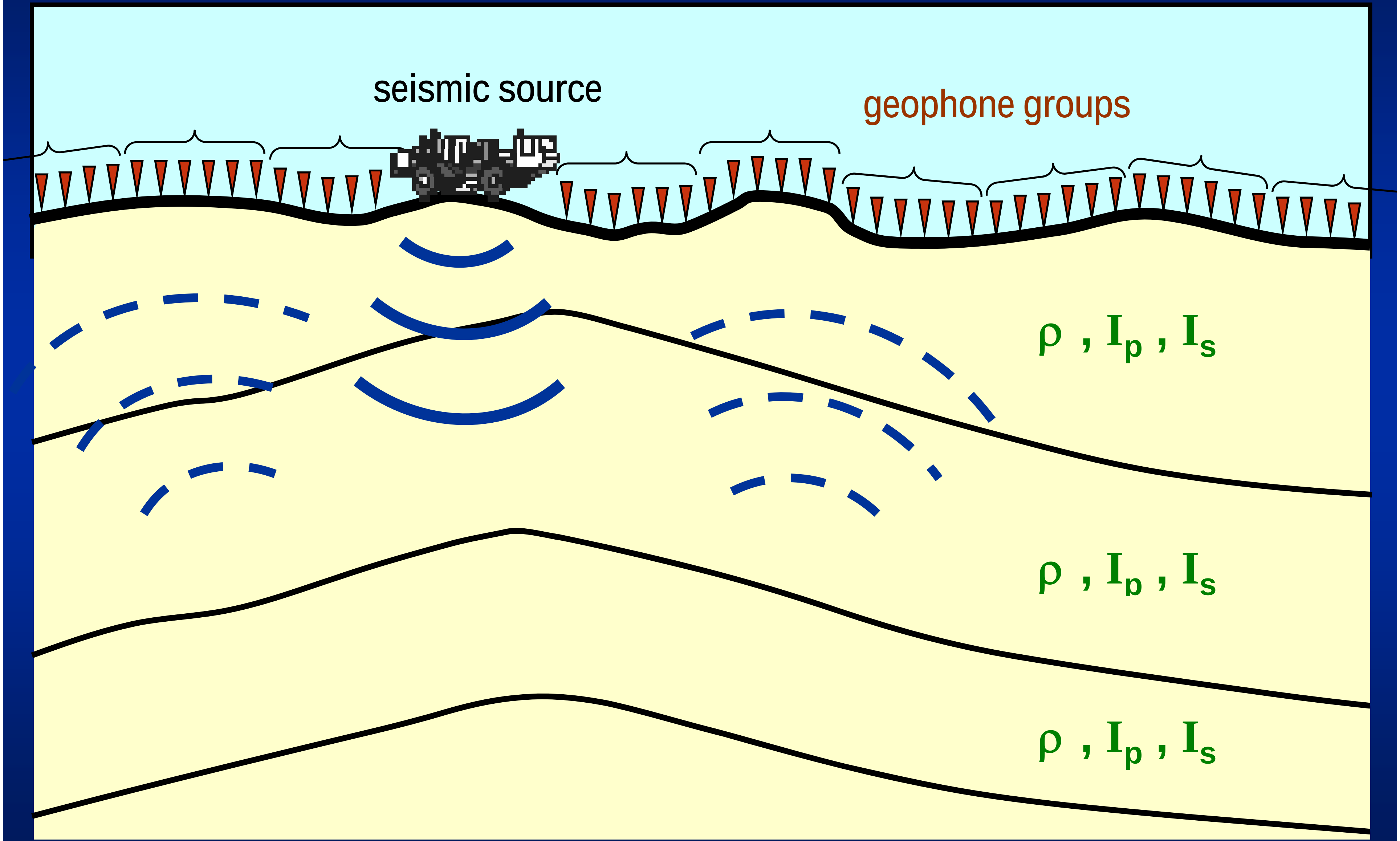


2 years production

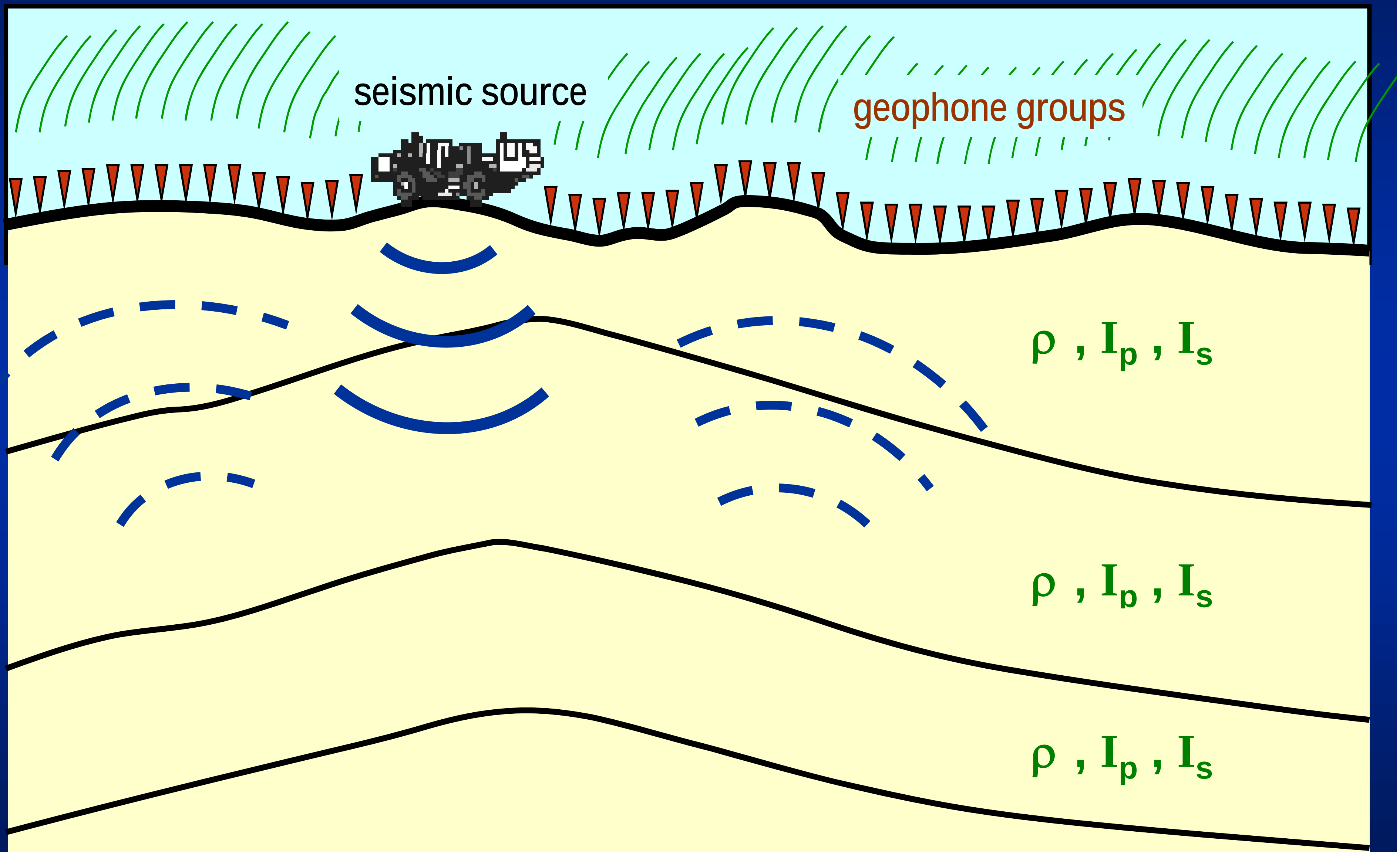
An additional way to improve resolution

- denser sampling

The Seismic Method



The Seismic Method ... with denser sampling

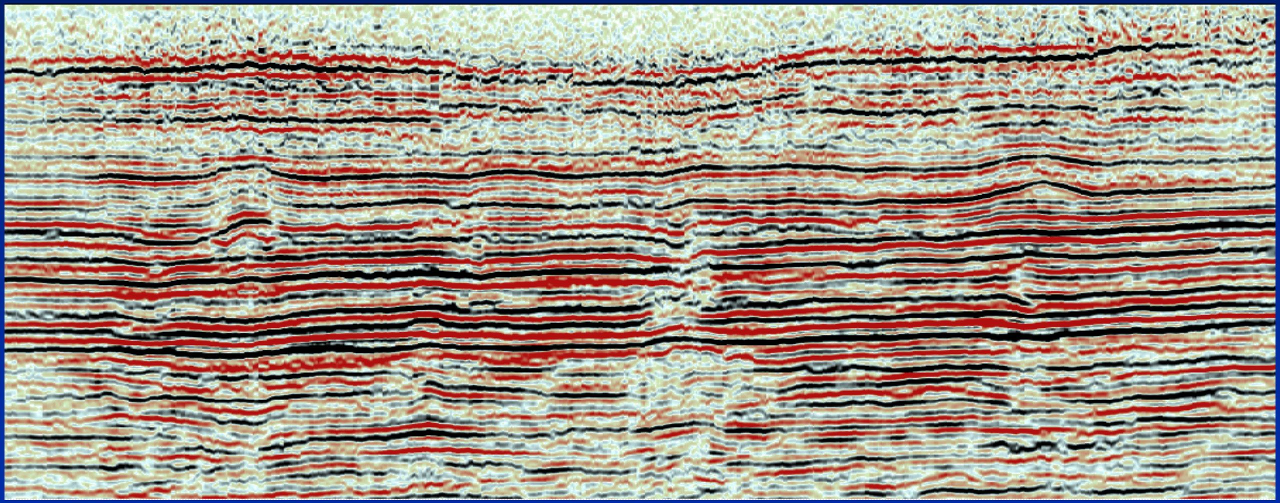


Example from Texas

0

Feet

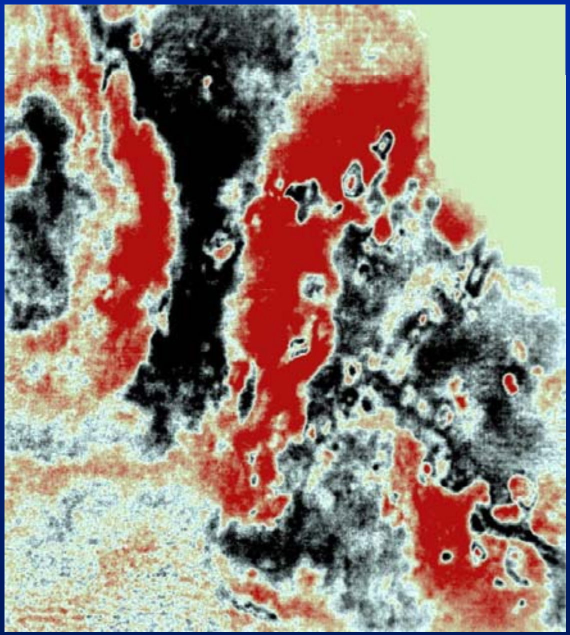
~3000



Q-Land

single-sensor data

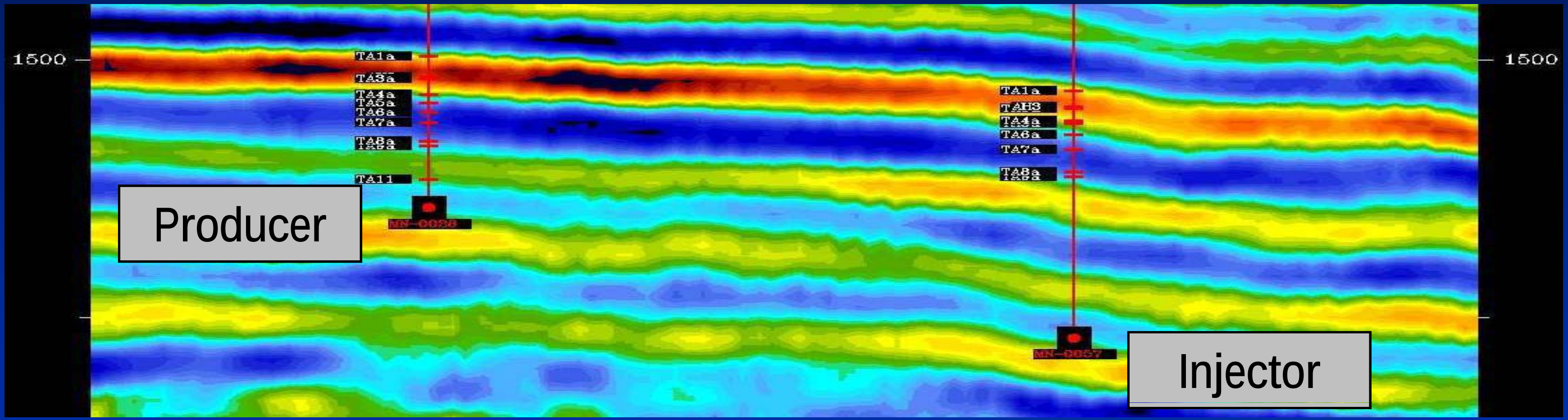
(Decimated)



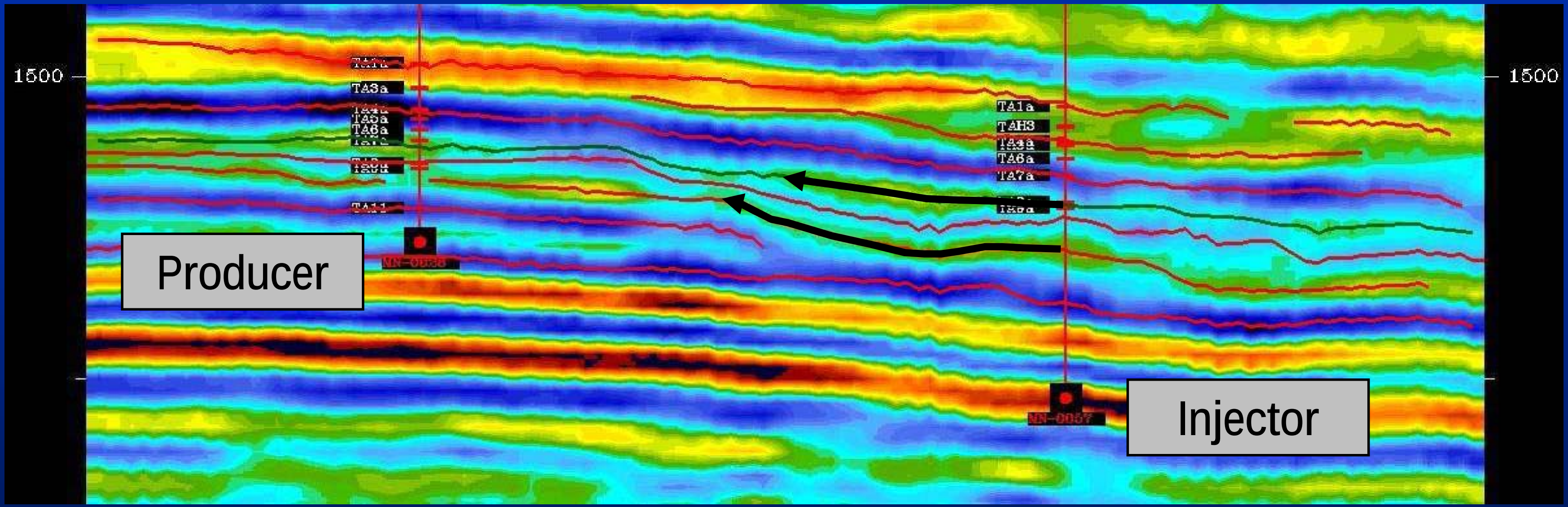
Horizontal slice

~1300 ft depth

Example from Kuwait



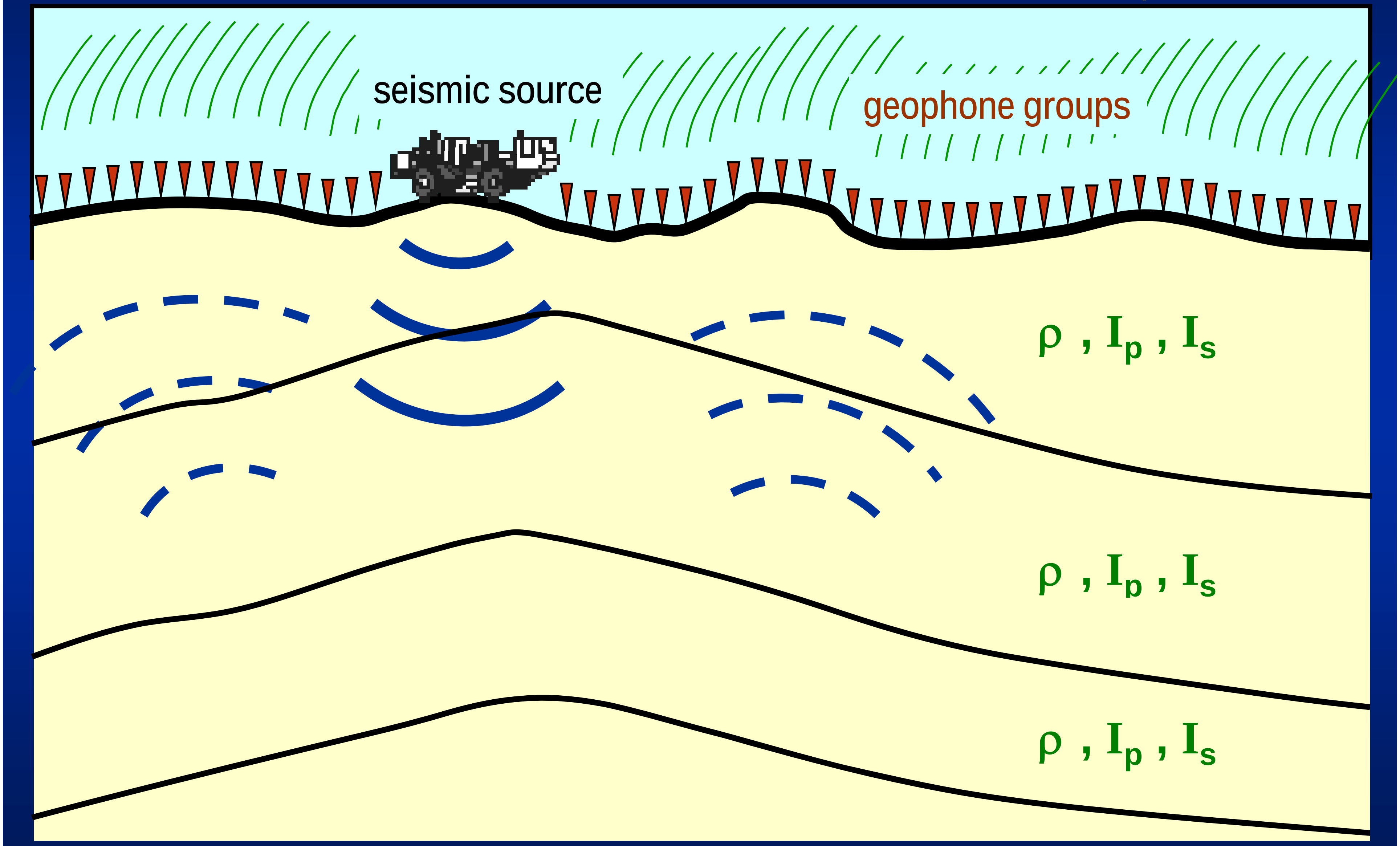
Conventional data – interpretation shows the fluids should flow freely



Q-Land single-sensor data – interpretation shows baffles impeding flow

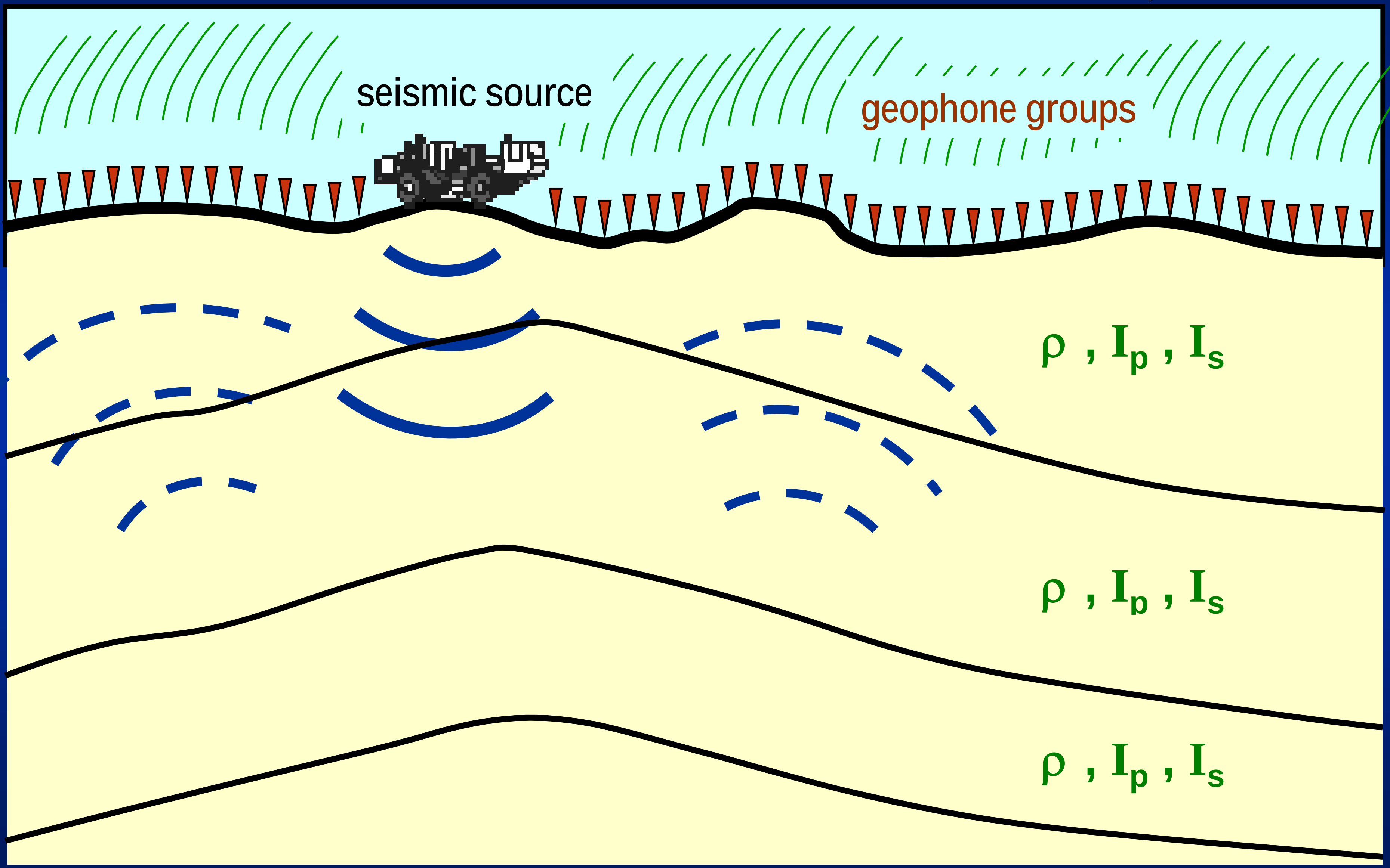
The Seismic Method

- Arrival times
- Amplitudes



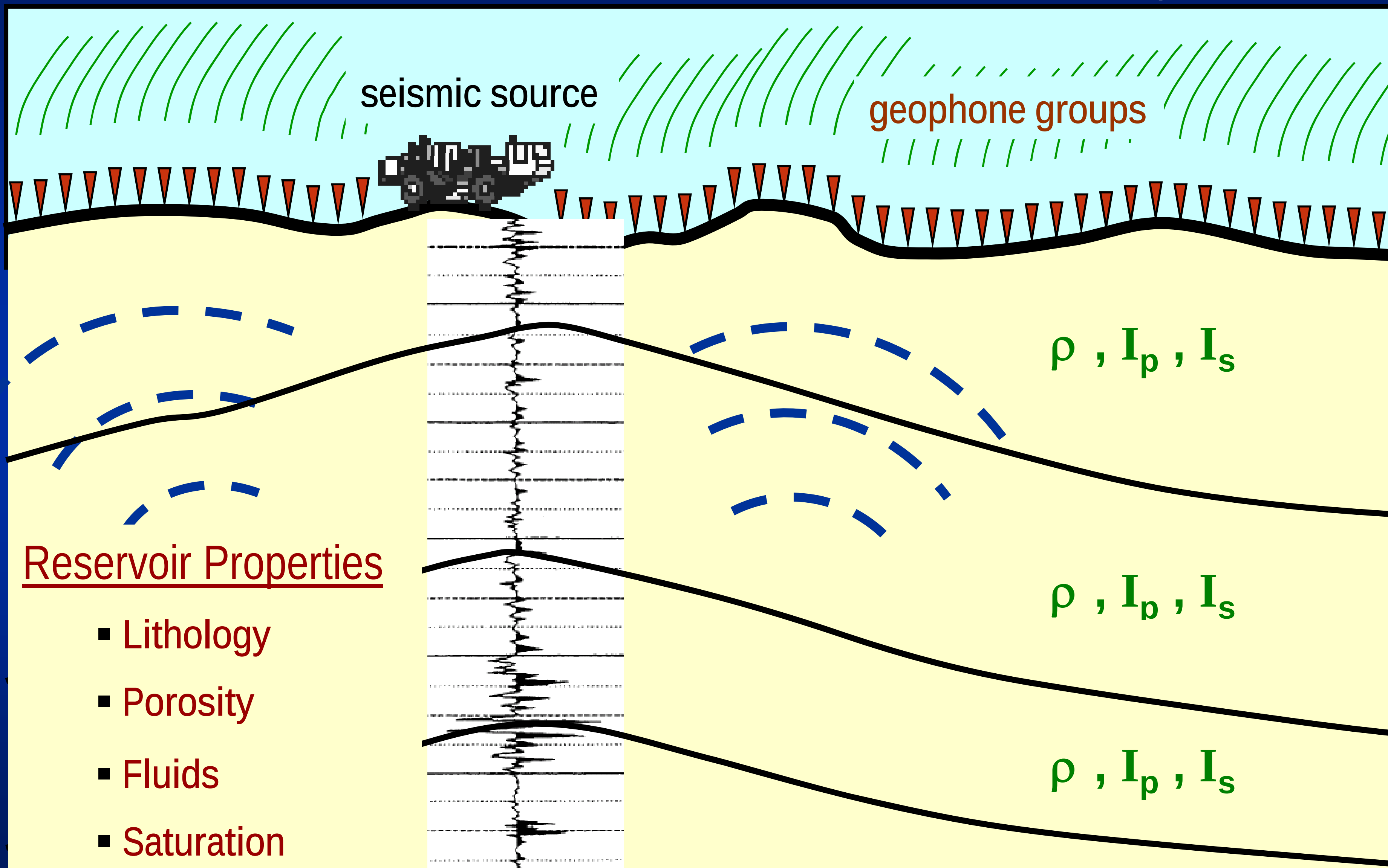
The Seismic Method

- ❑ Arrival times
- ❑ Amplitudes

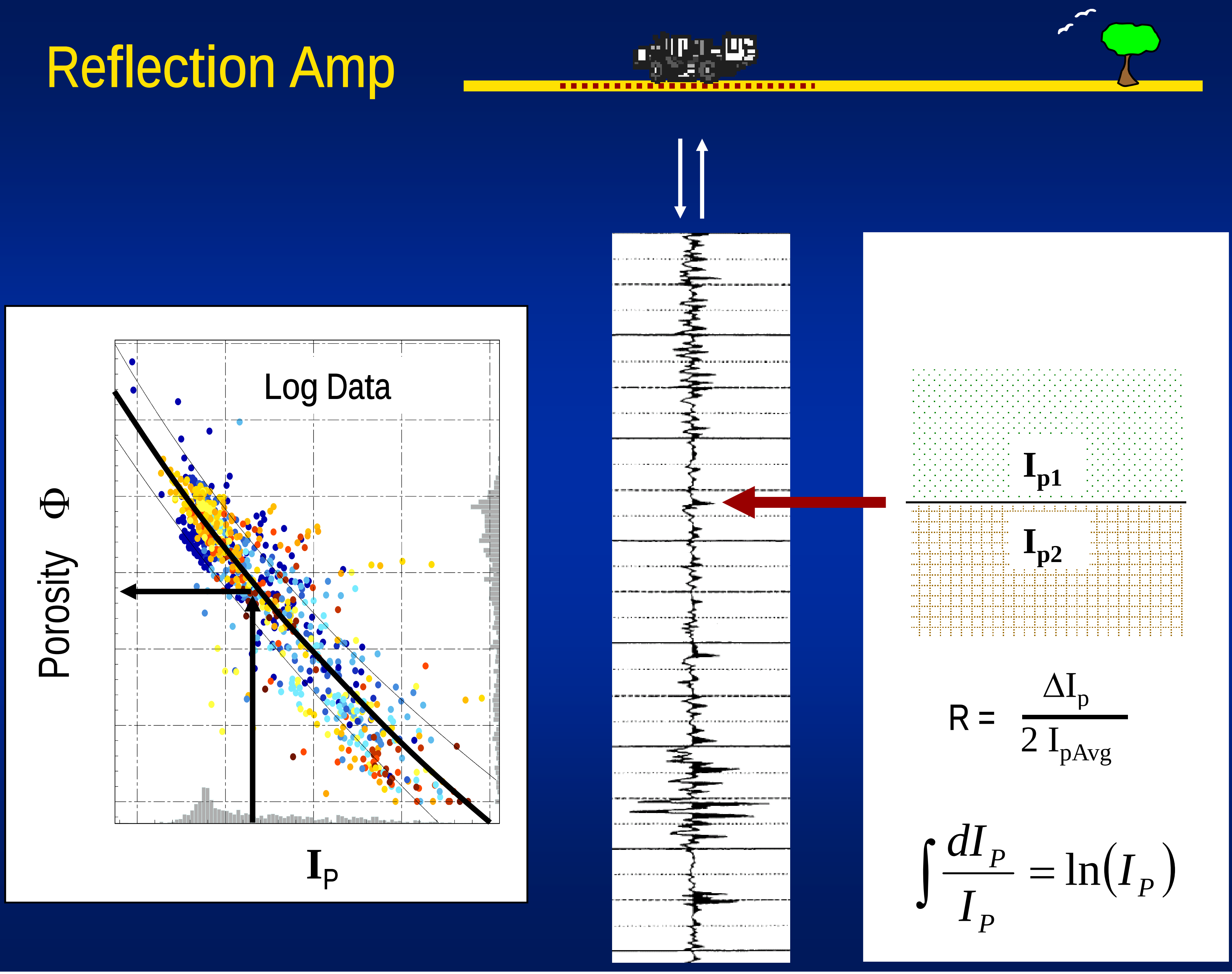


The Seismic Method

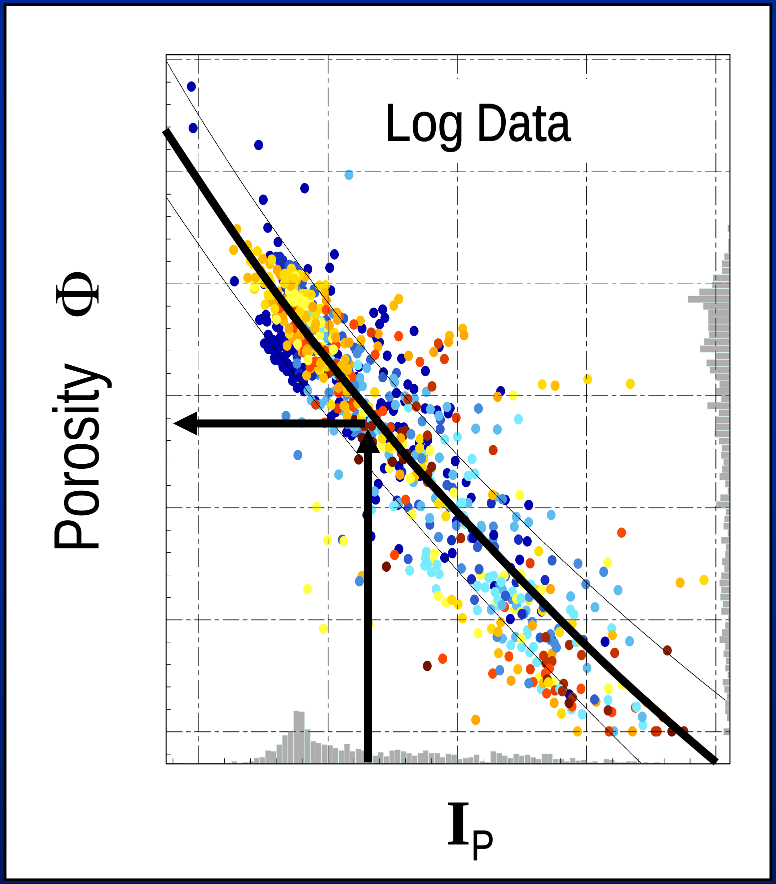
- Arrival times
- Amplitudes

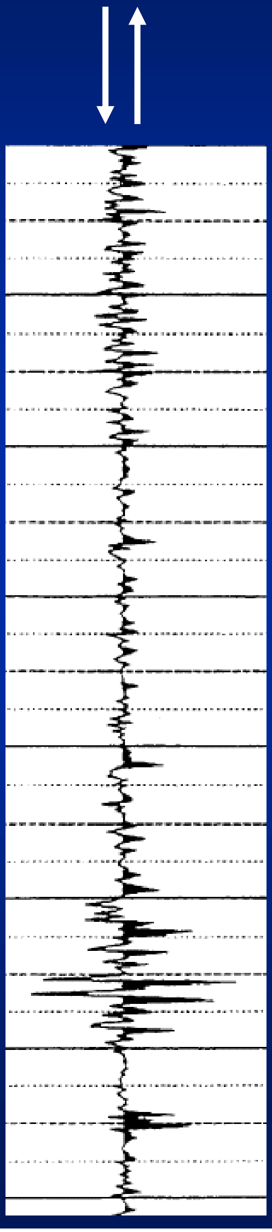


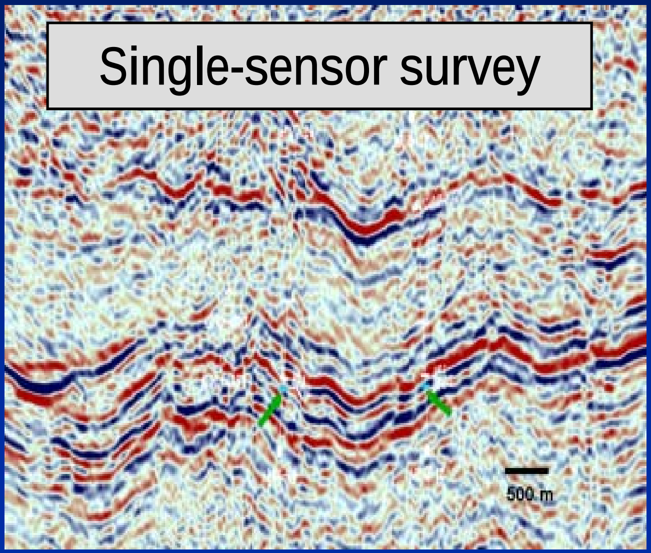
Reflection Amp

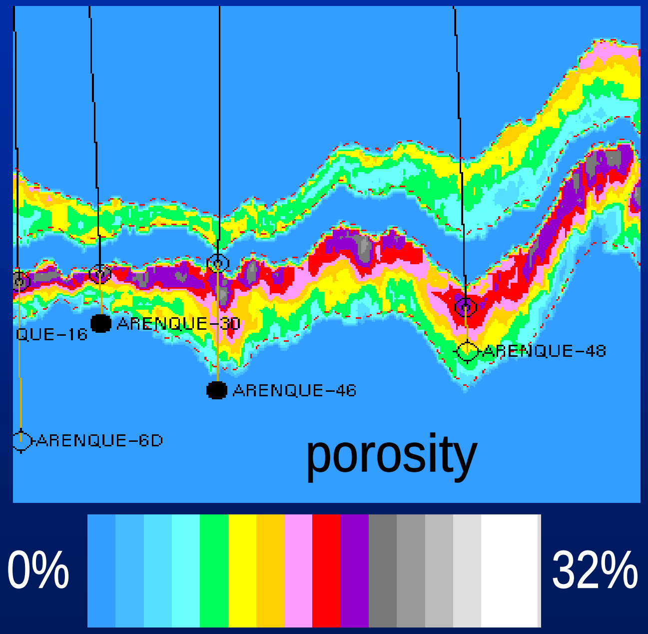


Reflection Amp









Summary

Survey design parameters

2D vs. 3D

Shooting direction

Narrow azimuth vs. wide azimuth

Aperture

Source-receiver distances

Sampling

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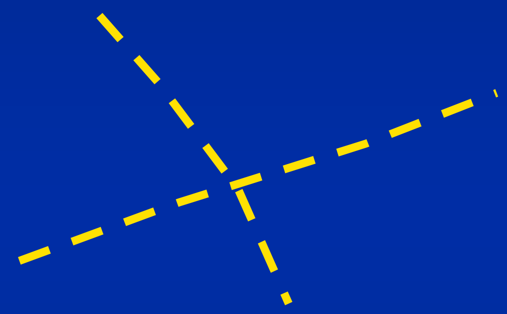

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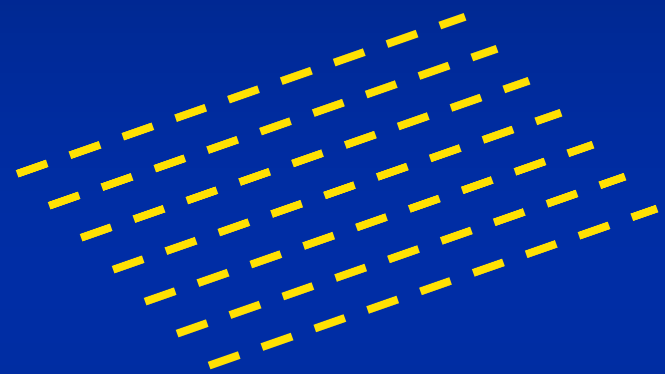

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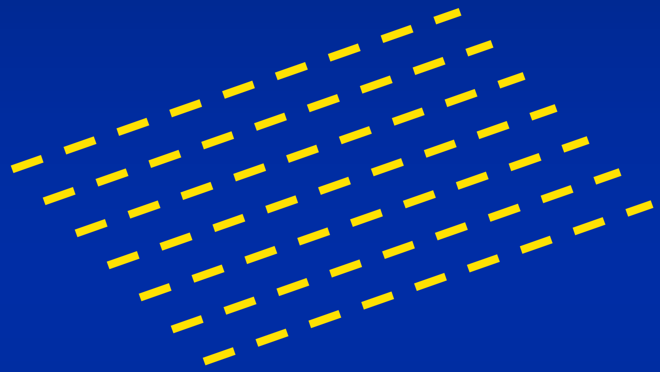

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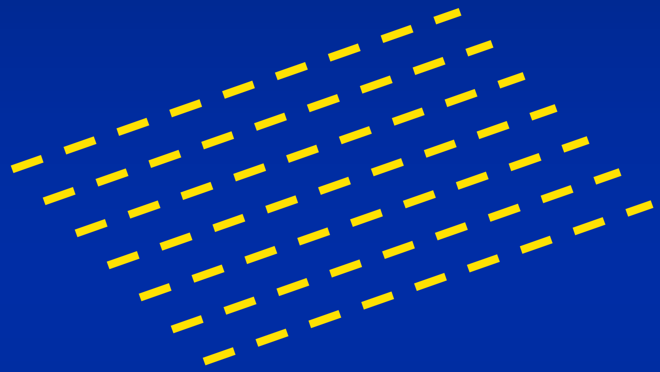

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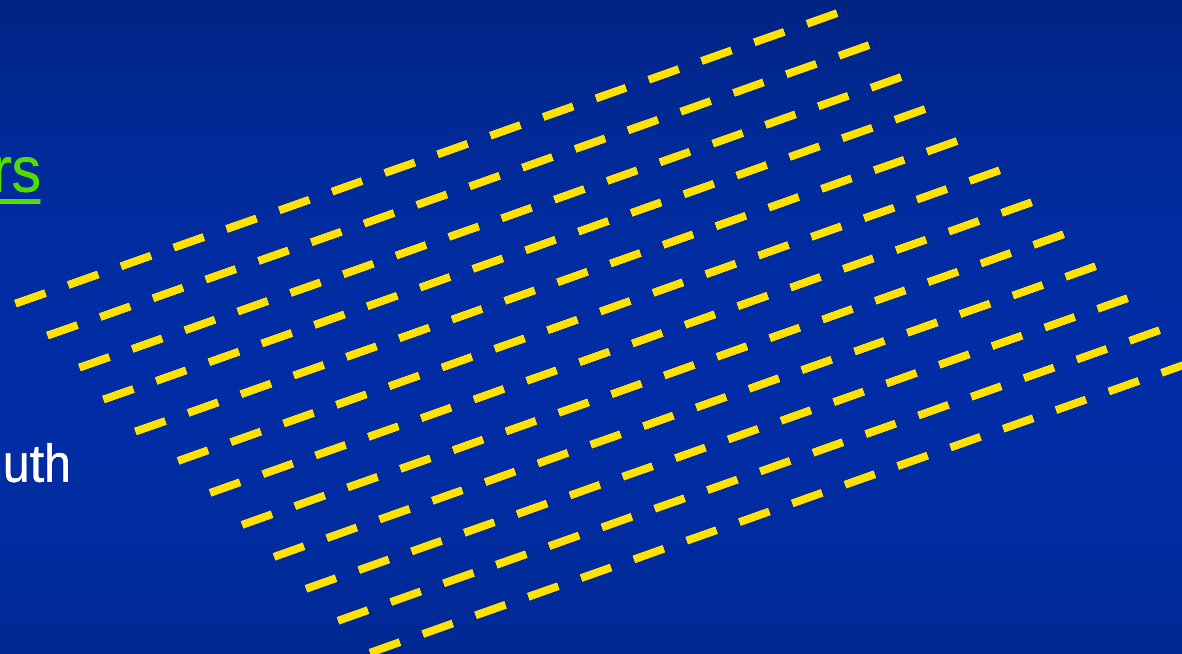

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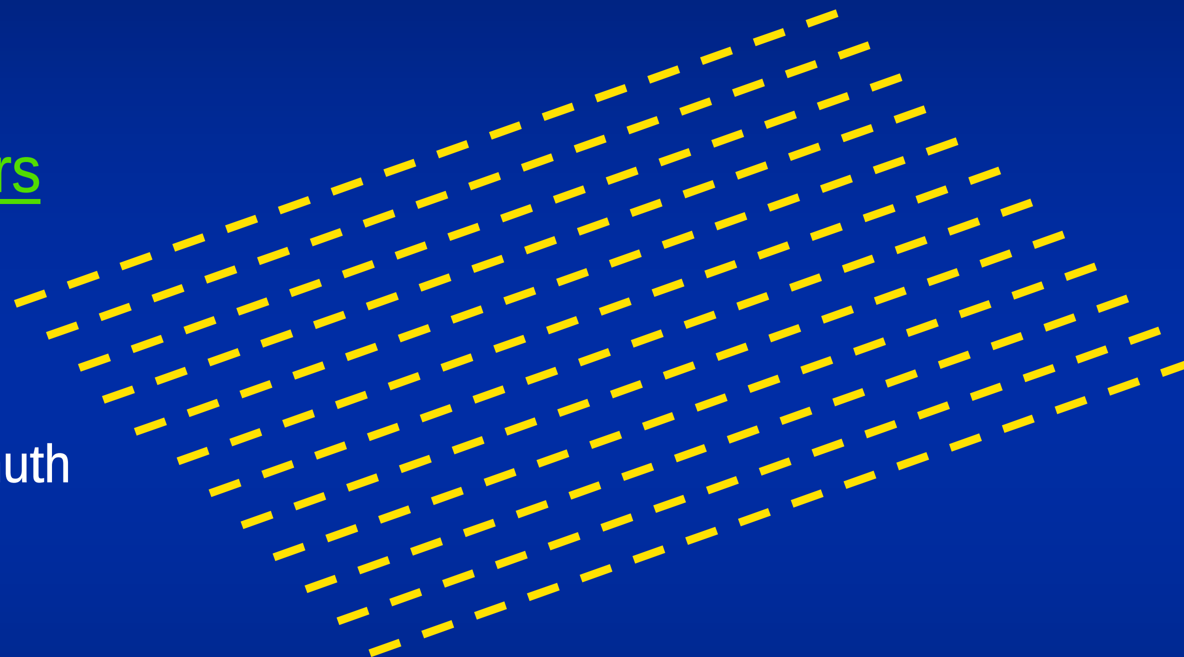

Summary

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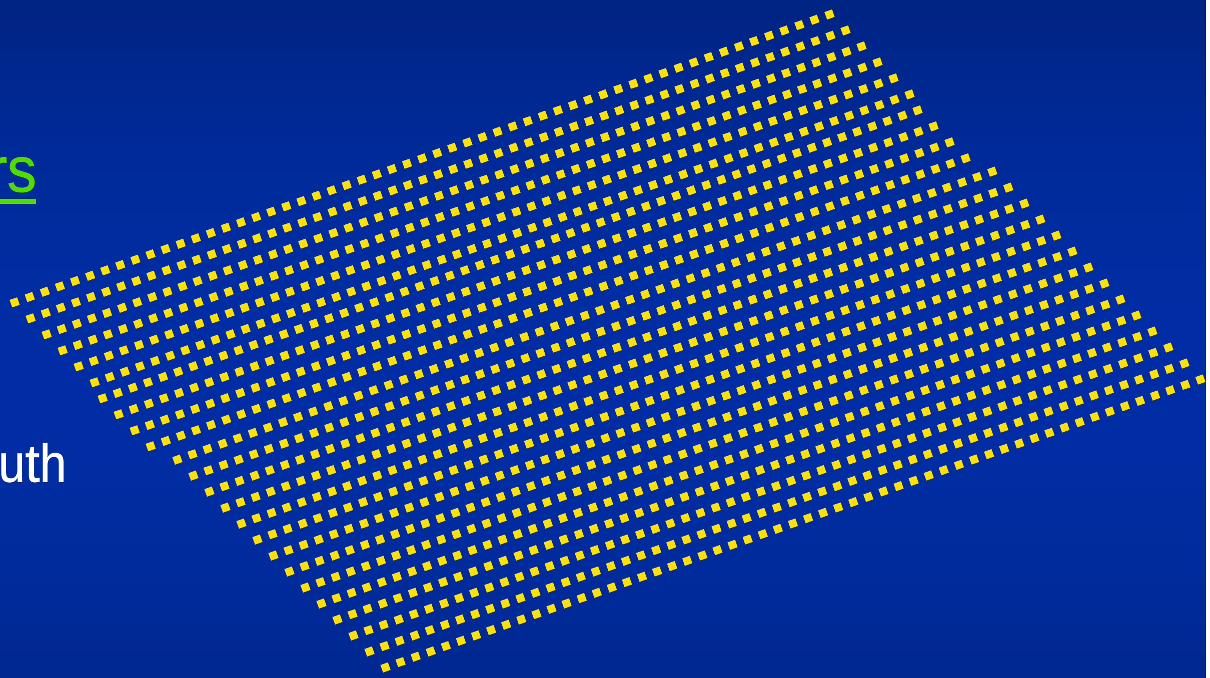


Summary

Noise !!!

<u>Survey design parameters</u>

2D vs. 3D

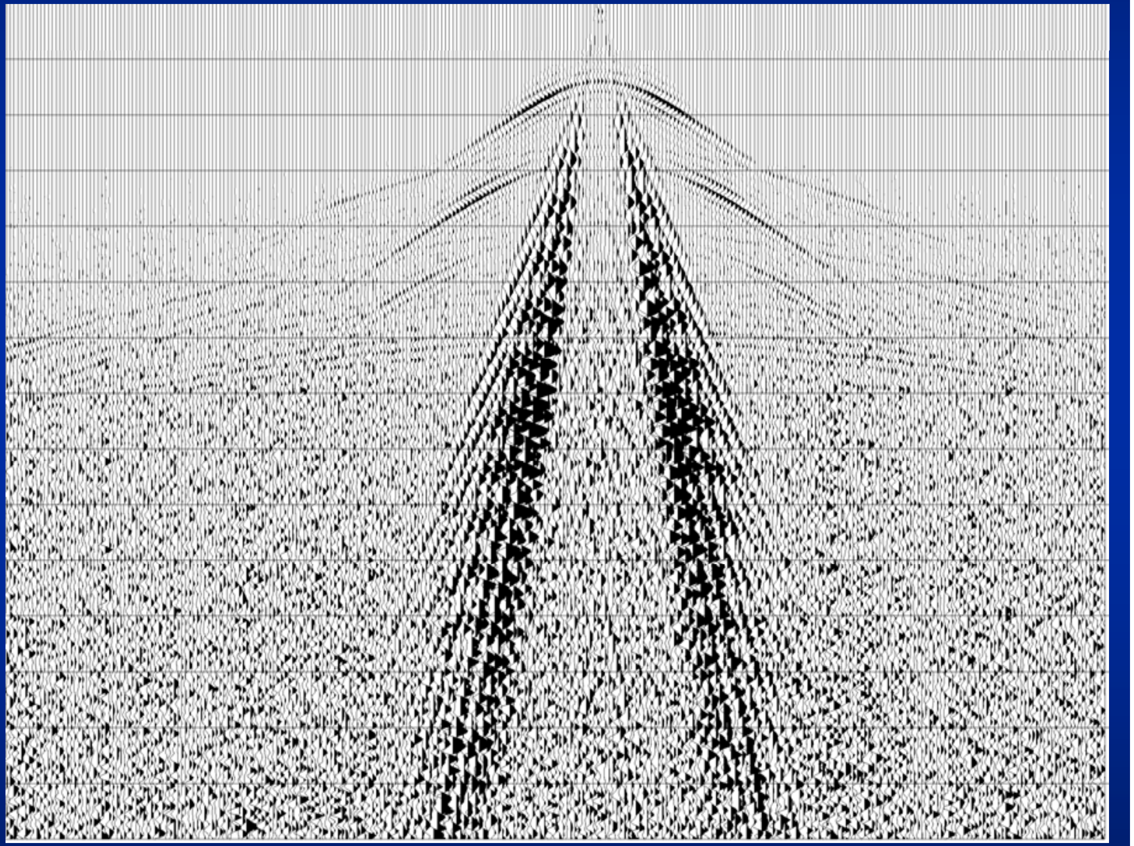
Shooting direction

Narrow azimuth vs. wide azimuth

Aperture

Source-receiver distances

Sampling



Modeled shot record

A New Mode of Seismic Surveillance

by

Leon Thomsen

Principal Geophysicist

4th IEA Monitoring Network Meeting

Edmonton, November 9, 2007

Outline

- Conventional monitoring
- Unconventional 4D Seismics
- Anisotropic Seismics
- Conclusions

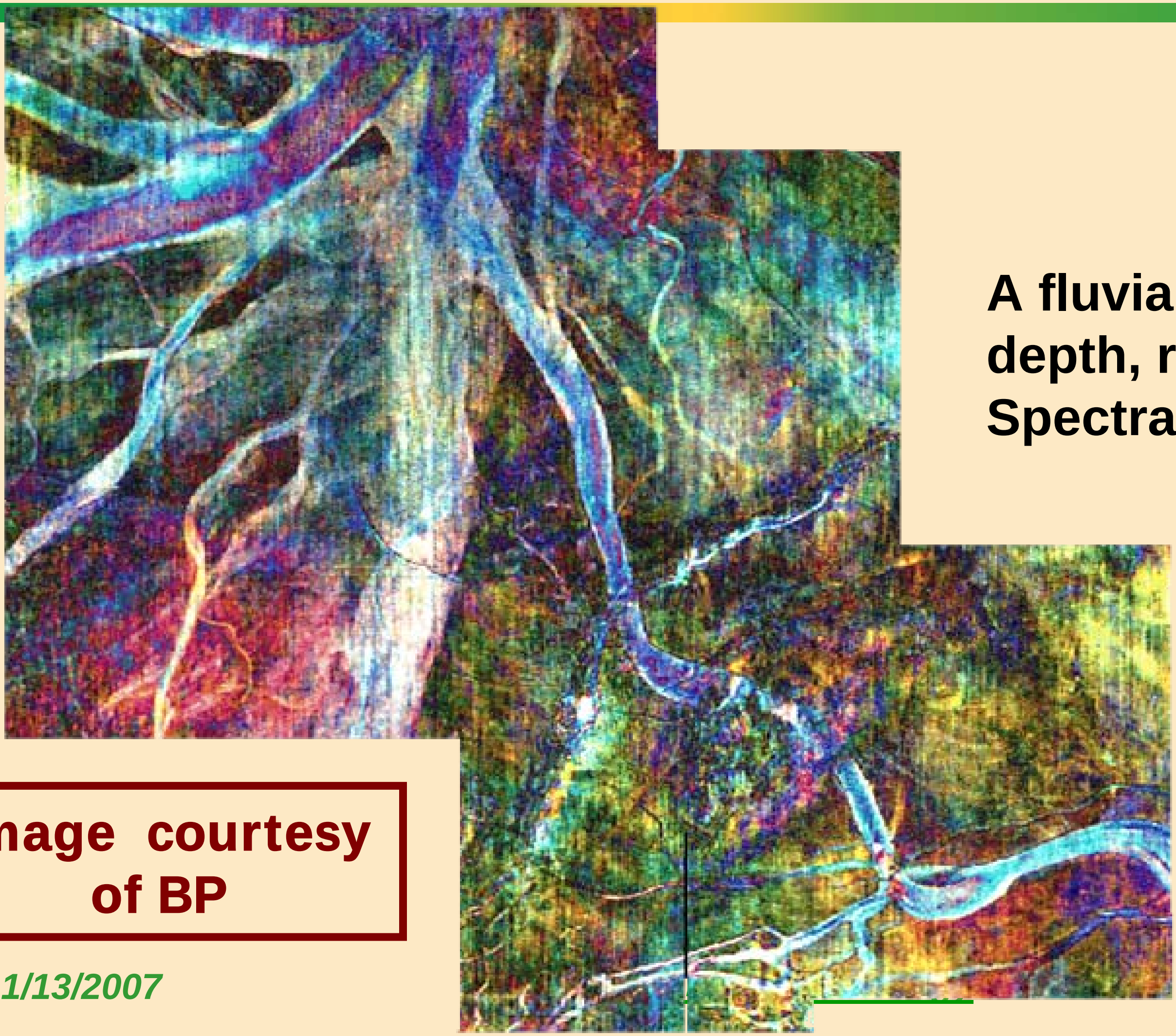
The subsurface permeability is highly heterogeneous

- Measurements at a few wellbores can be seriously misleading, as they <u>inadequately sample</u> this heterogeneity.
- <u>Hydraulic modeling</u> is almost always based on over-simplified distributions of permeability, not confirmed by subsequent full-volume measurements.
- The *only* technology which measures the full volume with high resolution is <u>seismic</u>.

Cost issues

- The need for *economical* surveillance => sparse acquisition effort.
- This calls for innovative survey design
  - Note: design for detection of CO_2 leakage is probably different that design for reservoir performance.
- A particular challenge is the requirement to "prove a negative".

This sort of subsurface heterogeneity is commonplace



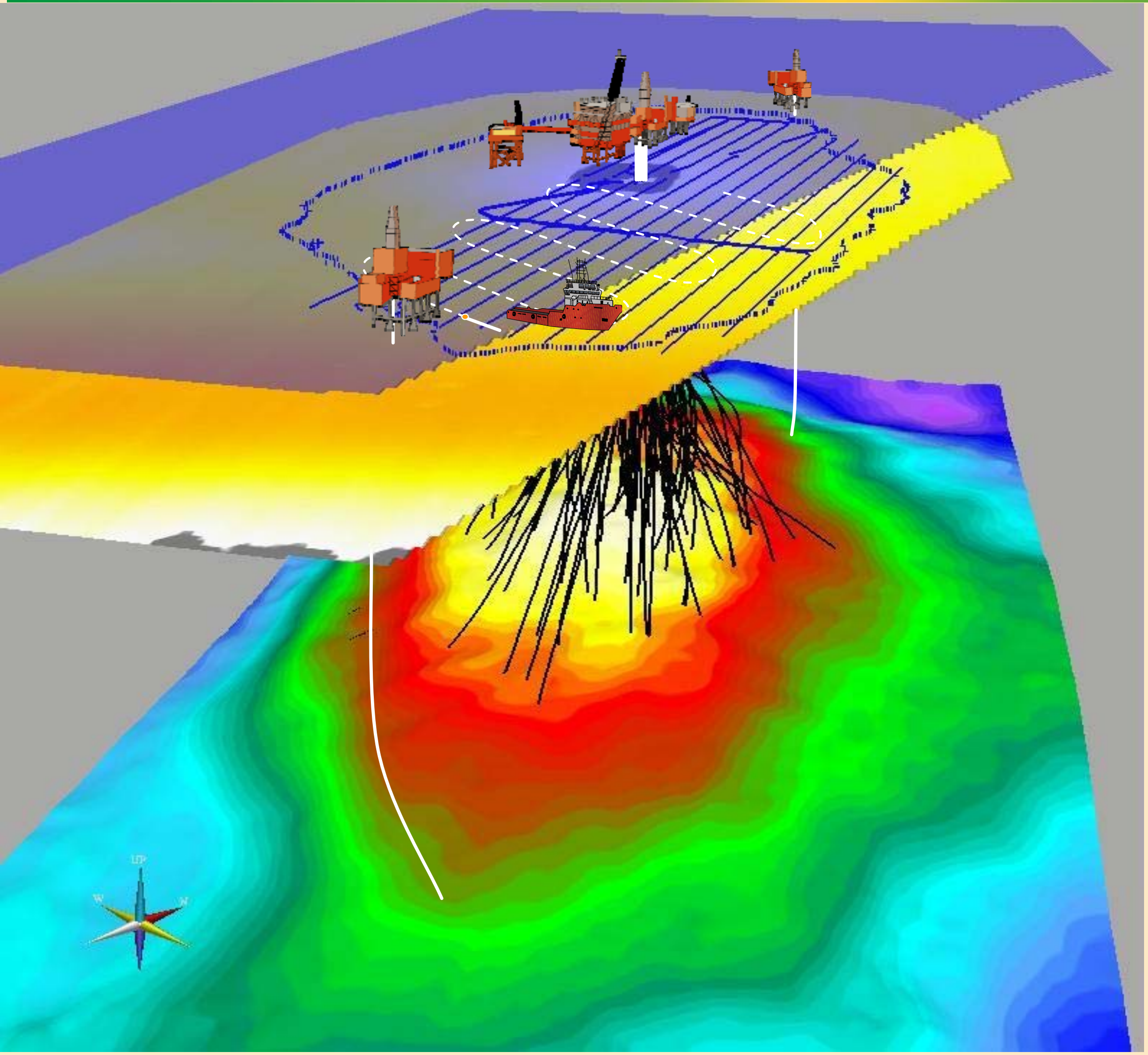
A fluvial system at 10,000’ depth, revealed by Spectral Decomposition

Image courtesy of BP

Conventional 4D seismics…

- assumes purely isotropic rock properties
- relies on the differences in P-wave velocity and impedance caused by
  - fluid substitution
  - pore pressure
- Not suitable in hard rocks

The best 4D monitoring happens when receivers are permanently installed



The Life-of-Field Seismics installation at BP’s Valhall field in the Norwegian North Sea:

- 2500 4C receivers, buried in the mud
- 9 4D reshoots in 3 years
- <u>Minimal</u> repeatability issues

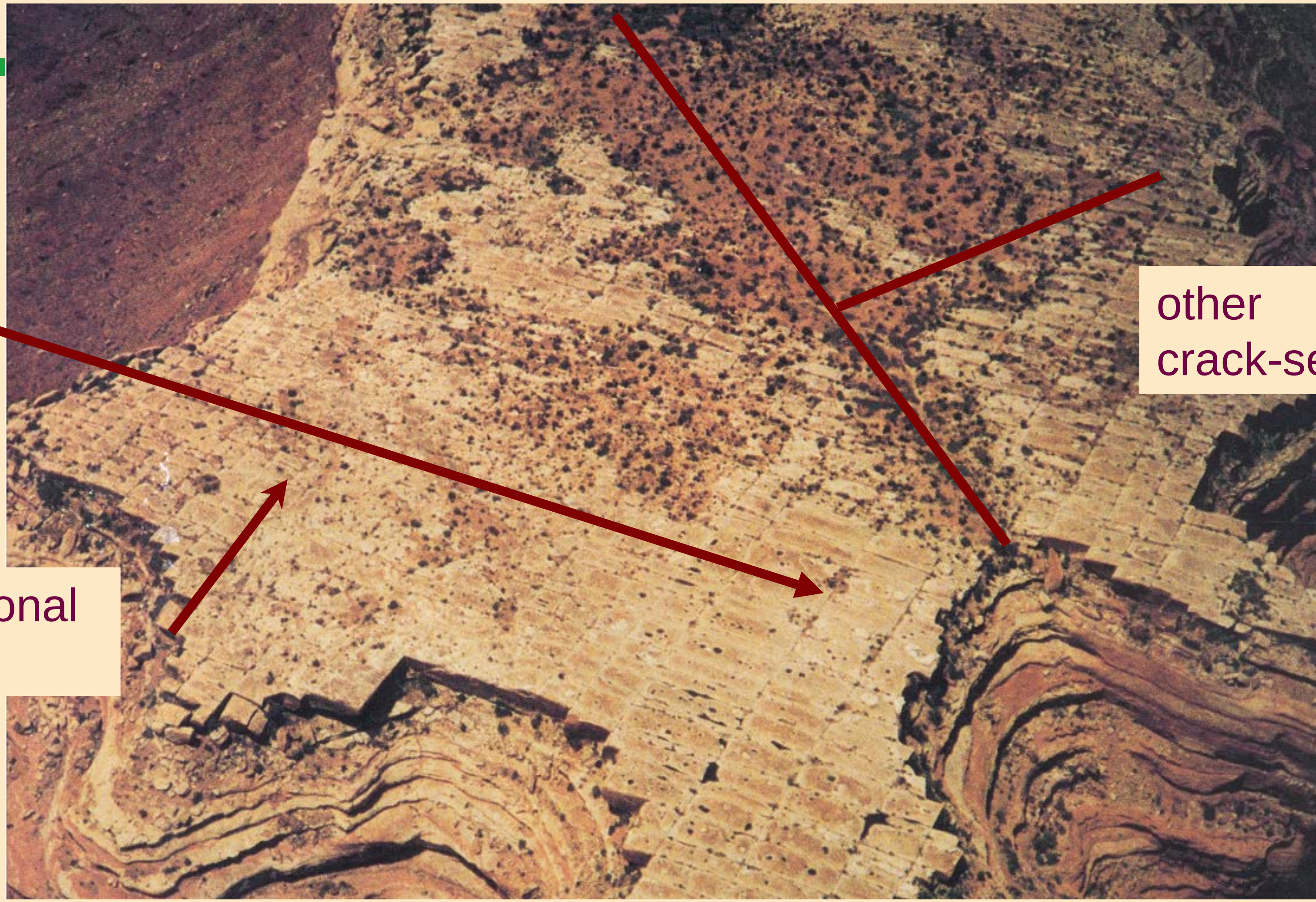
This is <u>more</u> than just *imaging* with seismic data…

it is seismic *characterization* of the

- **physical properties of the rocks, and**
- **the in-situ environmental conditions**

To succeed, one needs to employ an accurate model of the rock physics…

Hence, conventional 4D seismics is ill-suited for rocks like these:



Outline

- Conventional 4D Seismics
- Unconventional 4D Seismics
- Anisotropic Seismics
- Conclusions

There is an <u>entirely different</u> way to do 4D seismics

- **<u>independent</u> of fluids**
- **<u>independent</u> of pressure**
- **looking at the 4D changes in the <u>azimuthal anisotropy</u> of the reservoir.**

To do this, we need an accurate understanding of the rock physics, <u>including</u> their fractures.

Outline

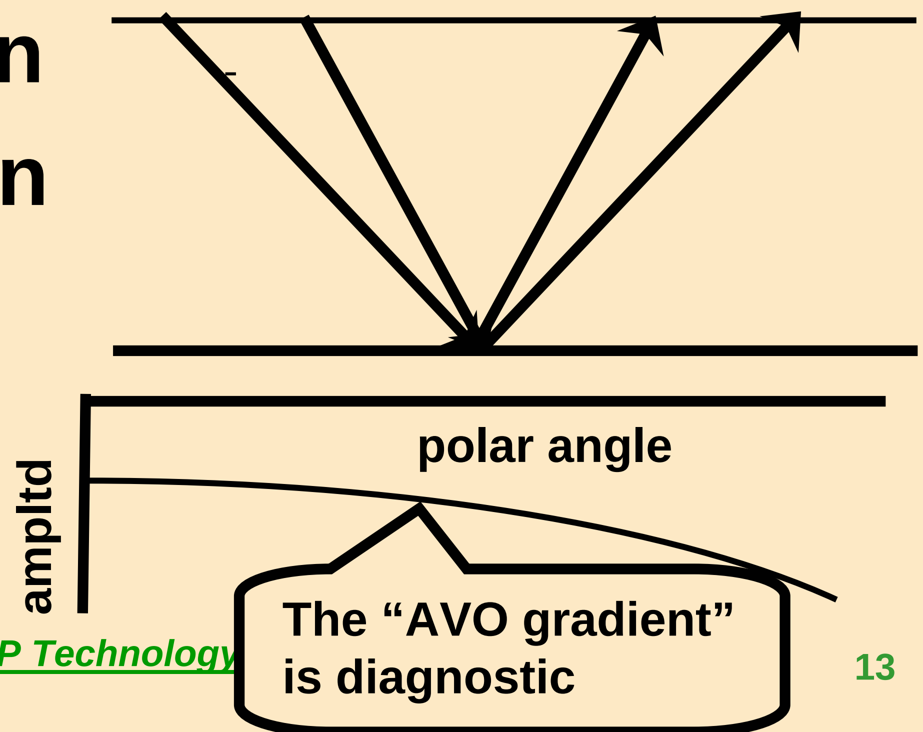
- Conventional 4D Seismics
- Unconventional 4D Seismics
- Anisotropic Seismics
  - P-AVOAz
  - Shear-wave splitting
- Conclusions

P-wave Amplitude Variation with Offset

It is well known that the offset-variation of P-wave reflection amplitude (P-AVO) carries information about

- lithologic variation
- fluid-type variation

at the interface.

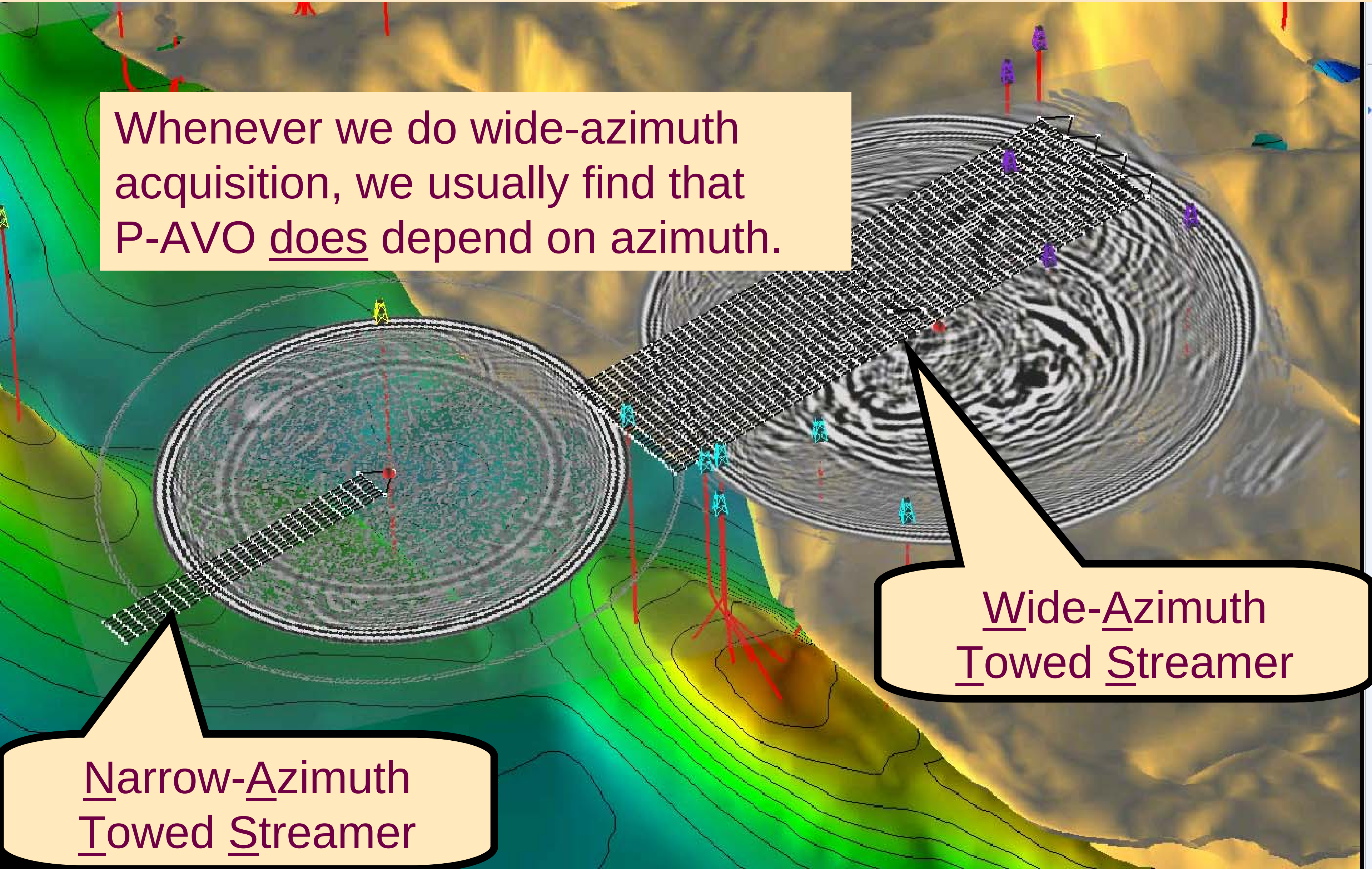


Almost without exception…

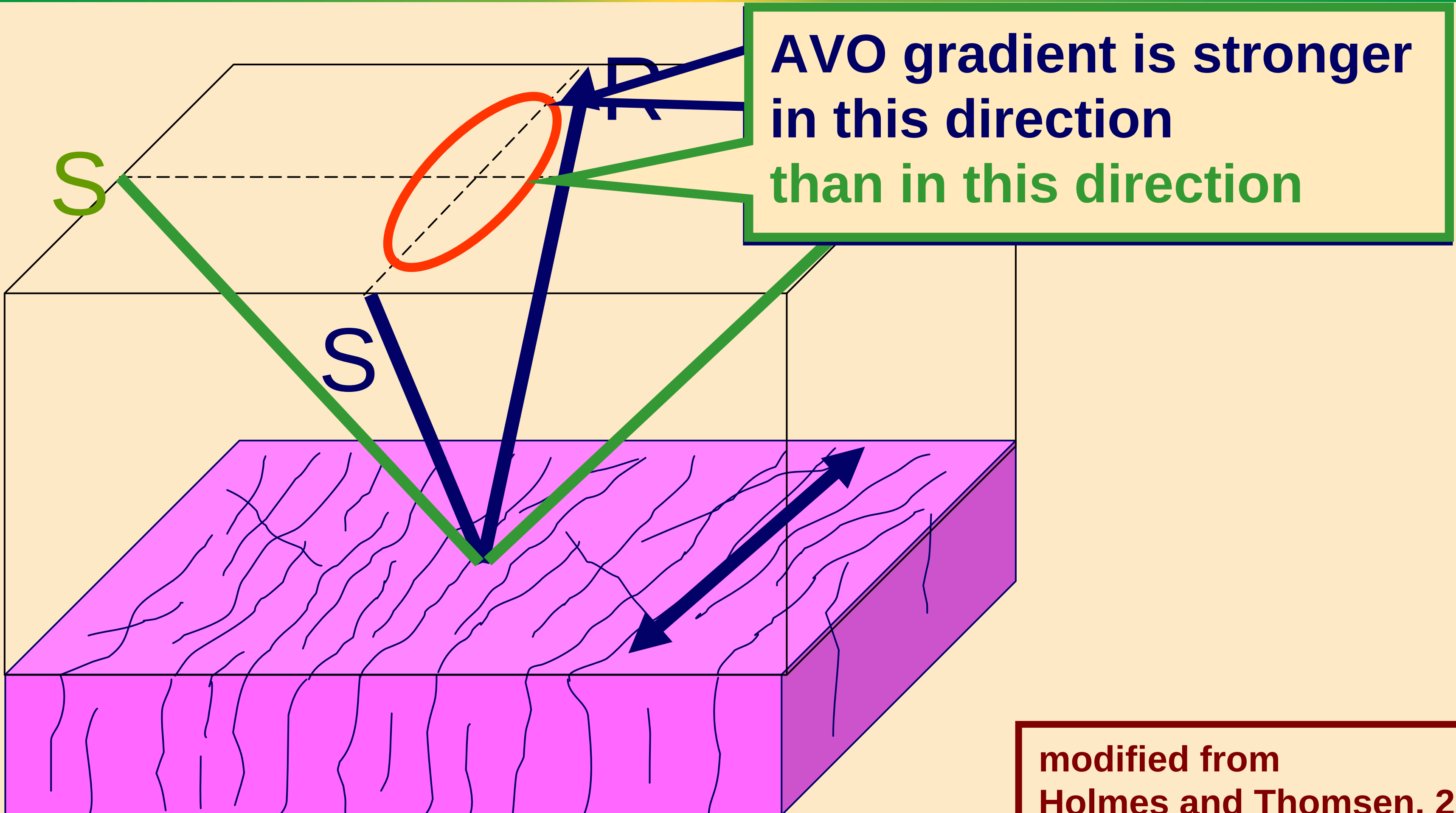
the practitioners of P-wave AVO assume that the results are independent of the azimuth of data acquisition.

This presumption happens because most 3D (marine) acquisition has a narrow range of source-receiver azimuths.

But, acquisition is being done in new ways…

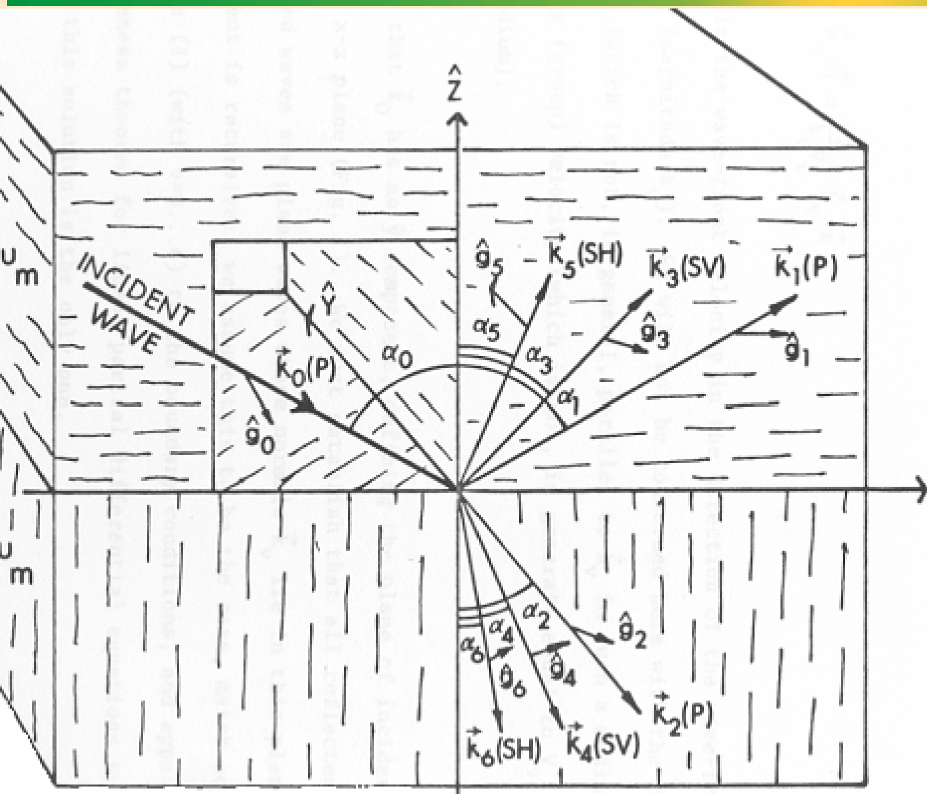


Reflectivity dependency on azimuth, in the presence of fractures



modified from
Holmes and Thomsen, 2002

P-AVOAz was first recognized in 1981



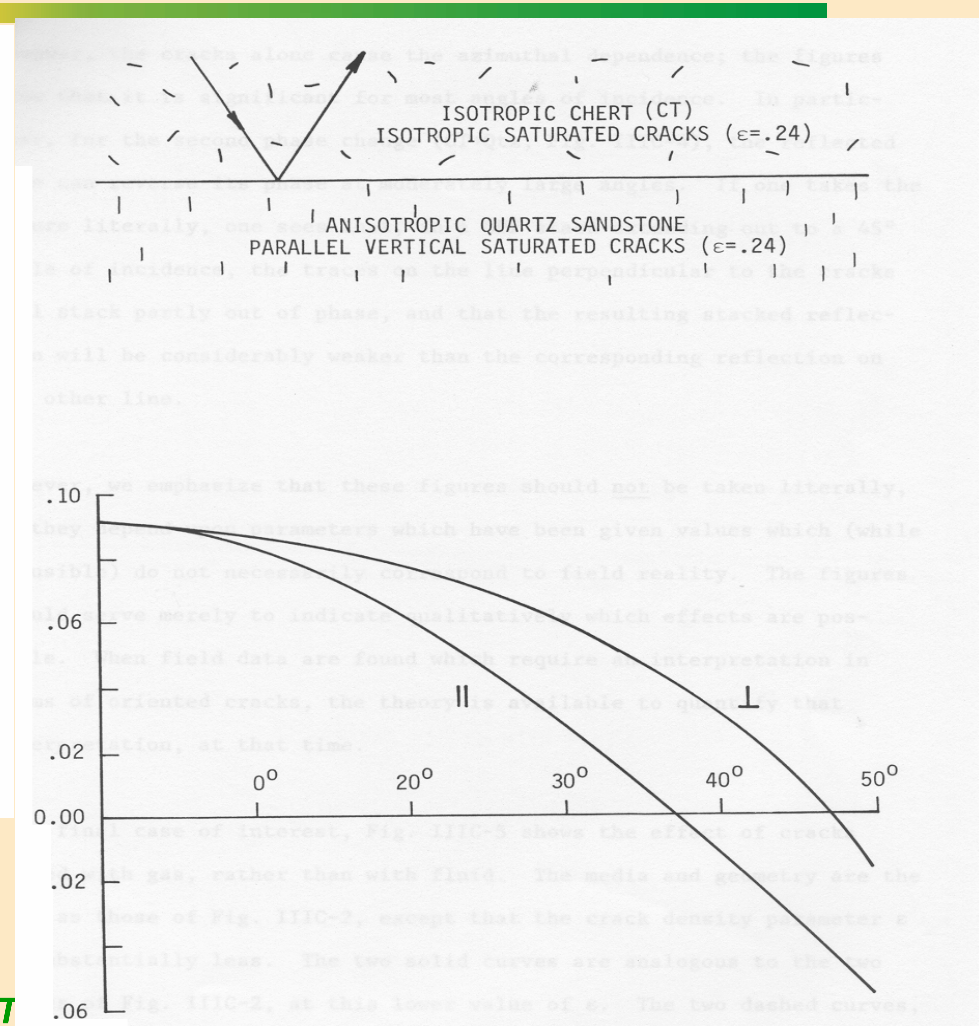
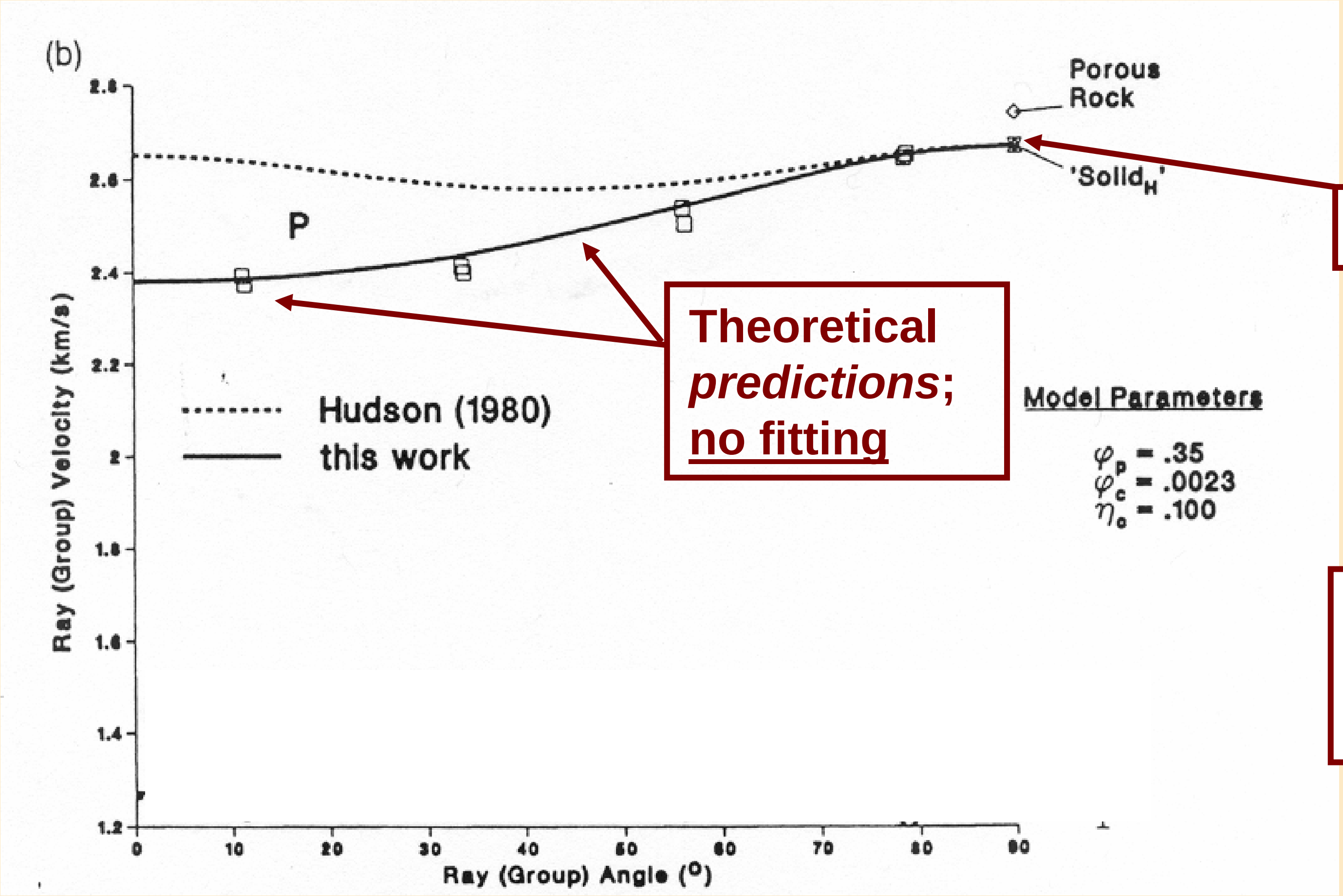


FIG. III C-4 P-P REFLECTION COEFFICIENT VS ANGLE OF INCIDENCE.

Thomsen, Amoco Research Report, 1981

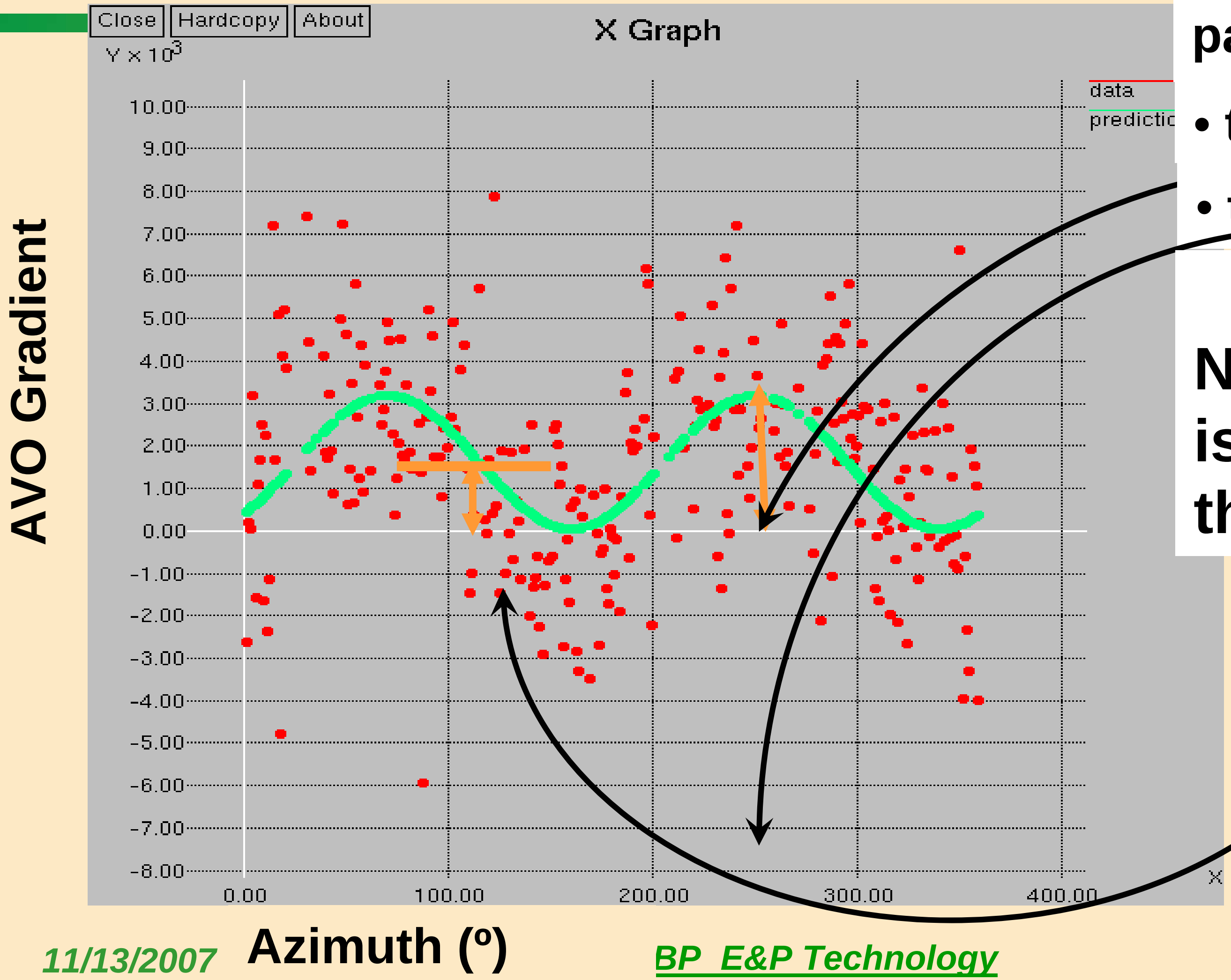
Confirmation of theory for saturated, porous rocks with known cracks



Data from Rathore *et al*, 1994

Thomsen, 1994

We fit an ellipse to noisy amplitude data, and test the goodness-of-fit

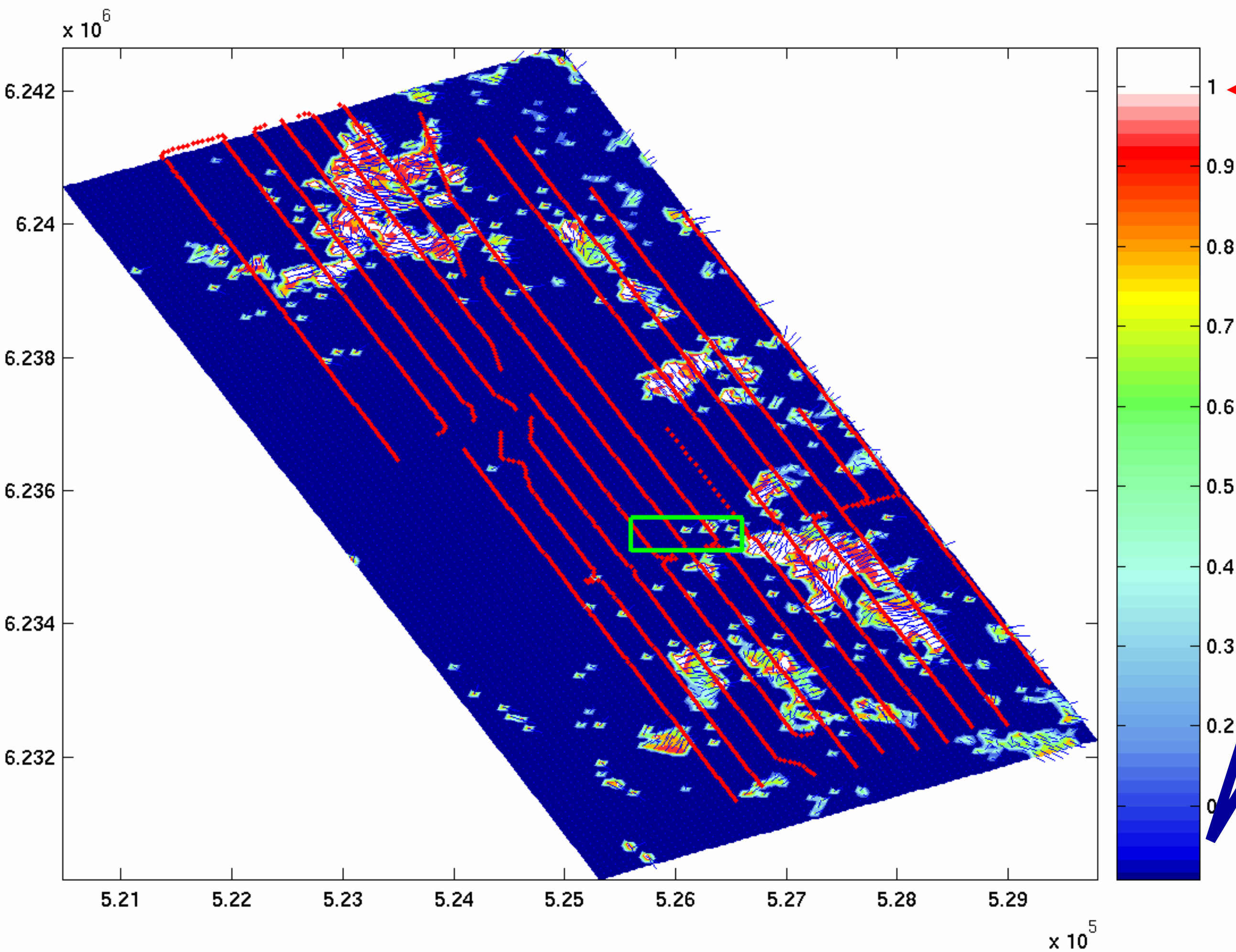


The elliptical parameters are:

- **the ellipticity and**
- **the orientation**

Note the variation is comparable to the average!

PZ AVOAz at Valhall Top Chalk: Life-of-Field-Seismic 1



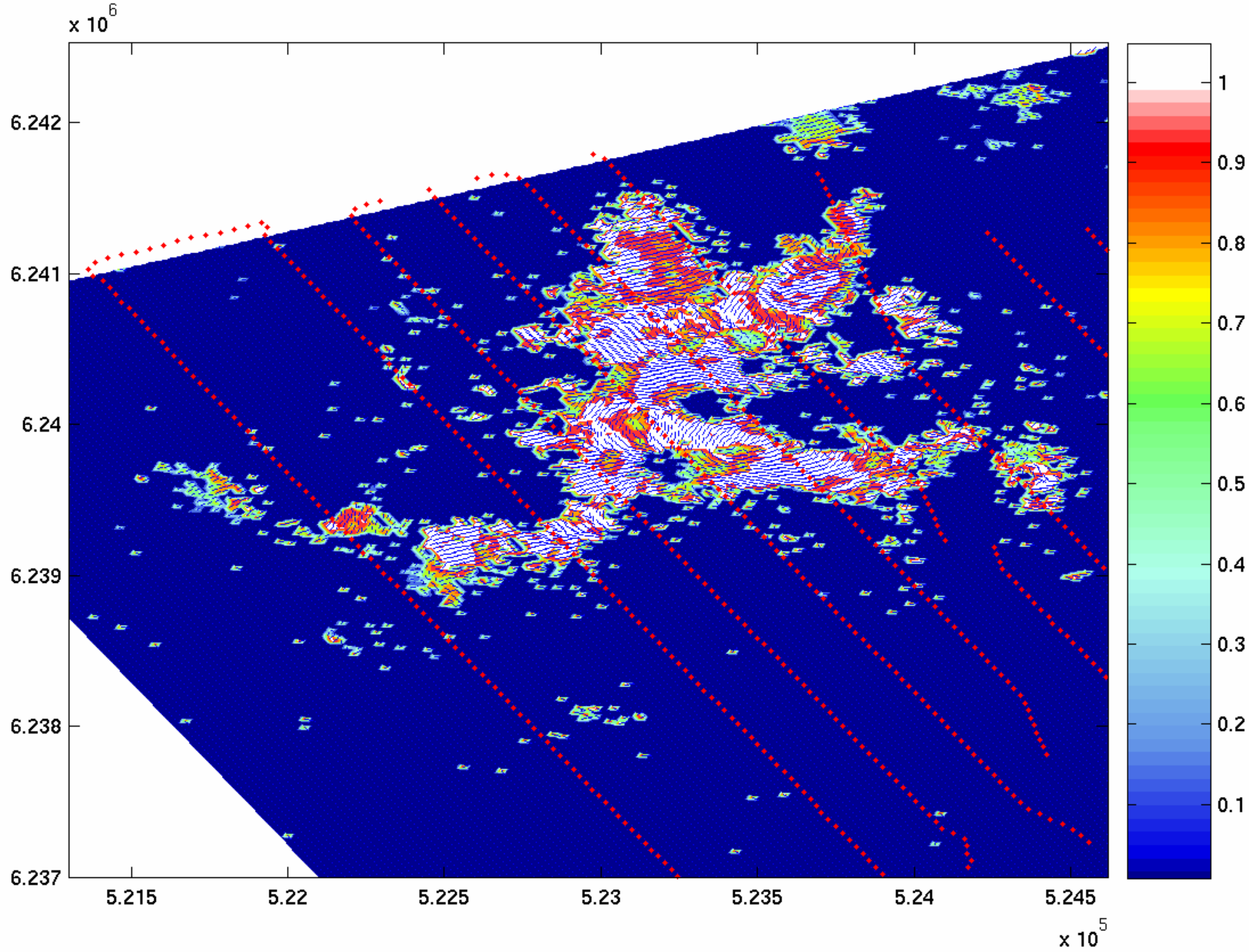
Maximum values show <u>100%</u> difference

Values are <u>only</u> shown where confidence in fit is >95%

from Xia, Thomsen, and Barkved, 2006

Close-up, NW corner

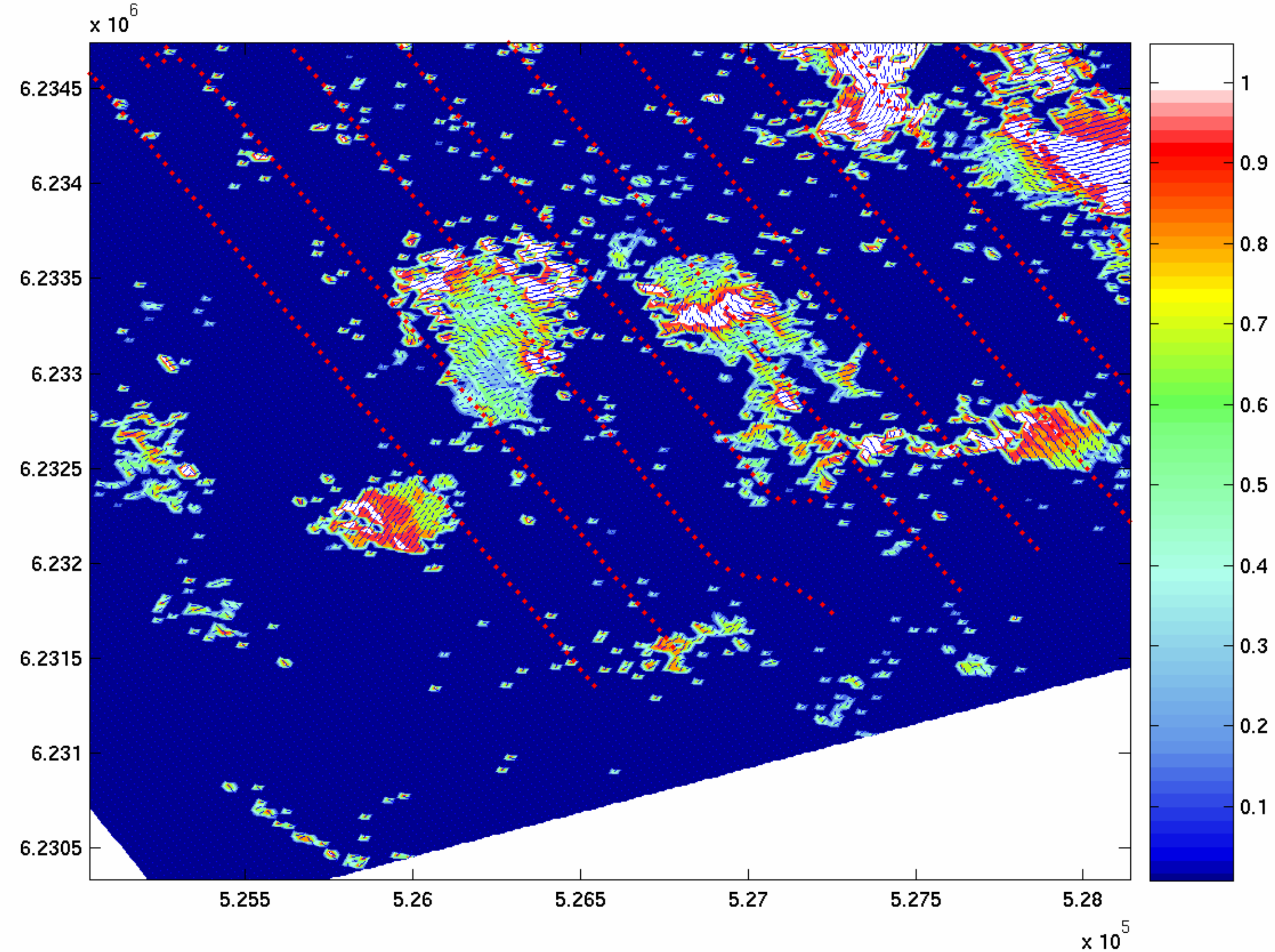
LoFS 1



from Xia, Thomsen, and Barkved, 2006

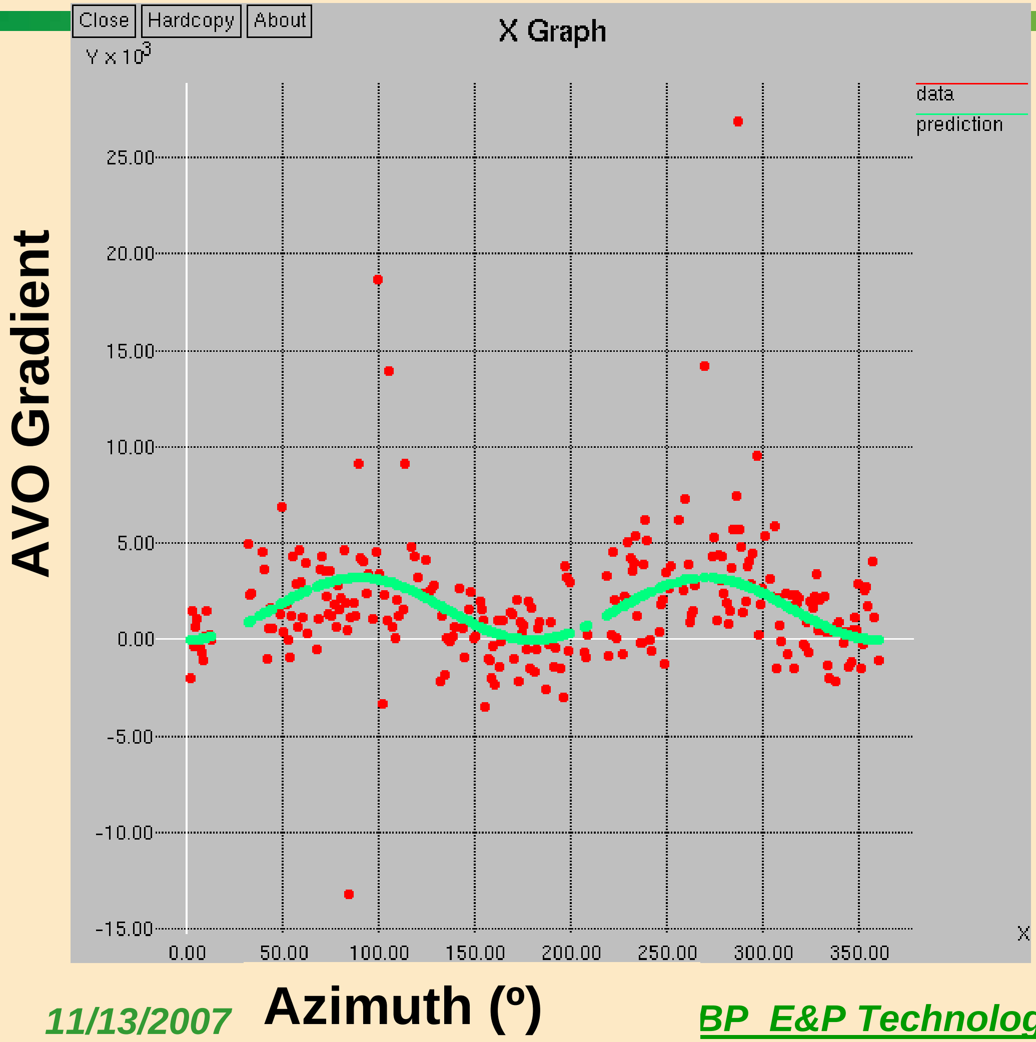
Close-up, SW corner

LoFS 1

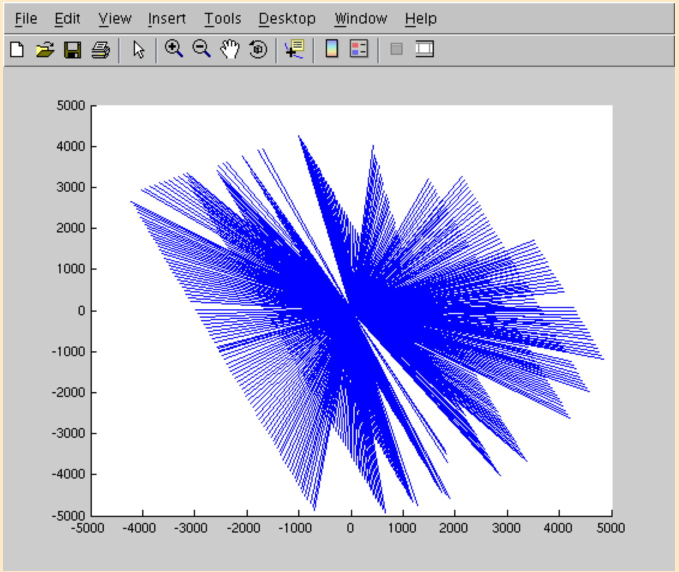


from Xia, Thomsen, and Barkved, 2006

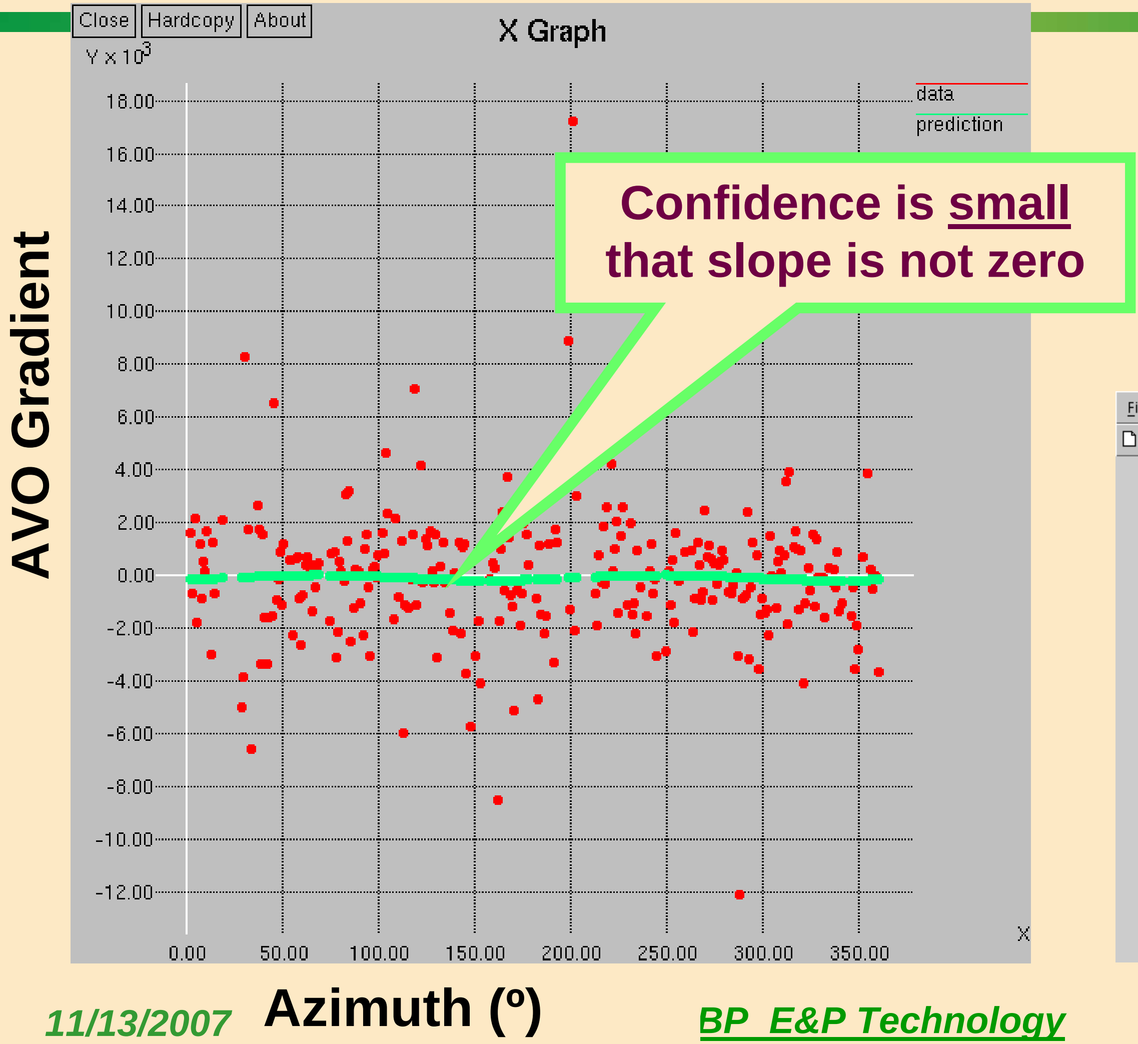
AVO gradient prediction near water injectors



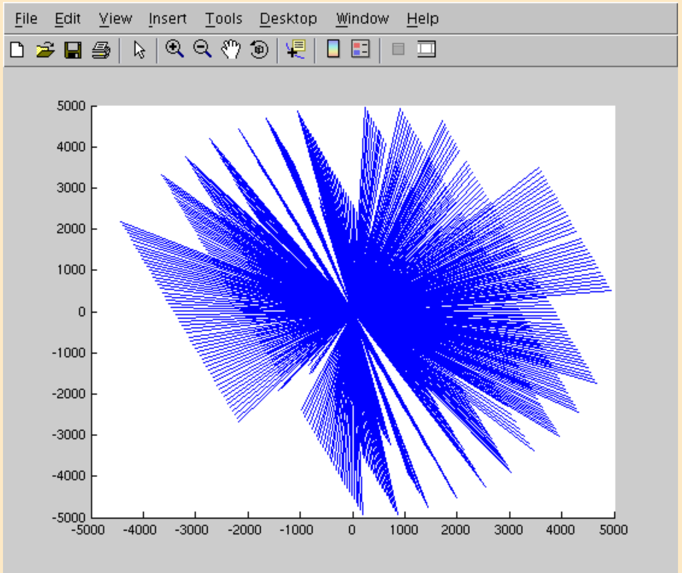
Spider plot showing source-receiver pairs for the CMP location



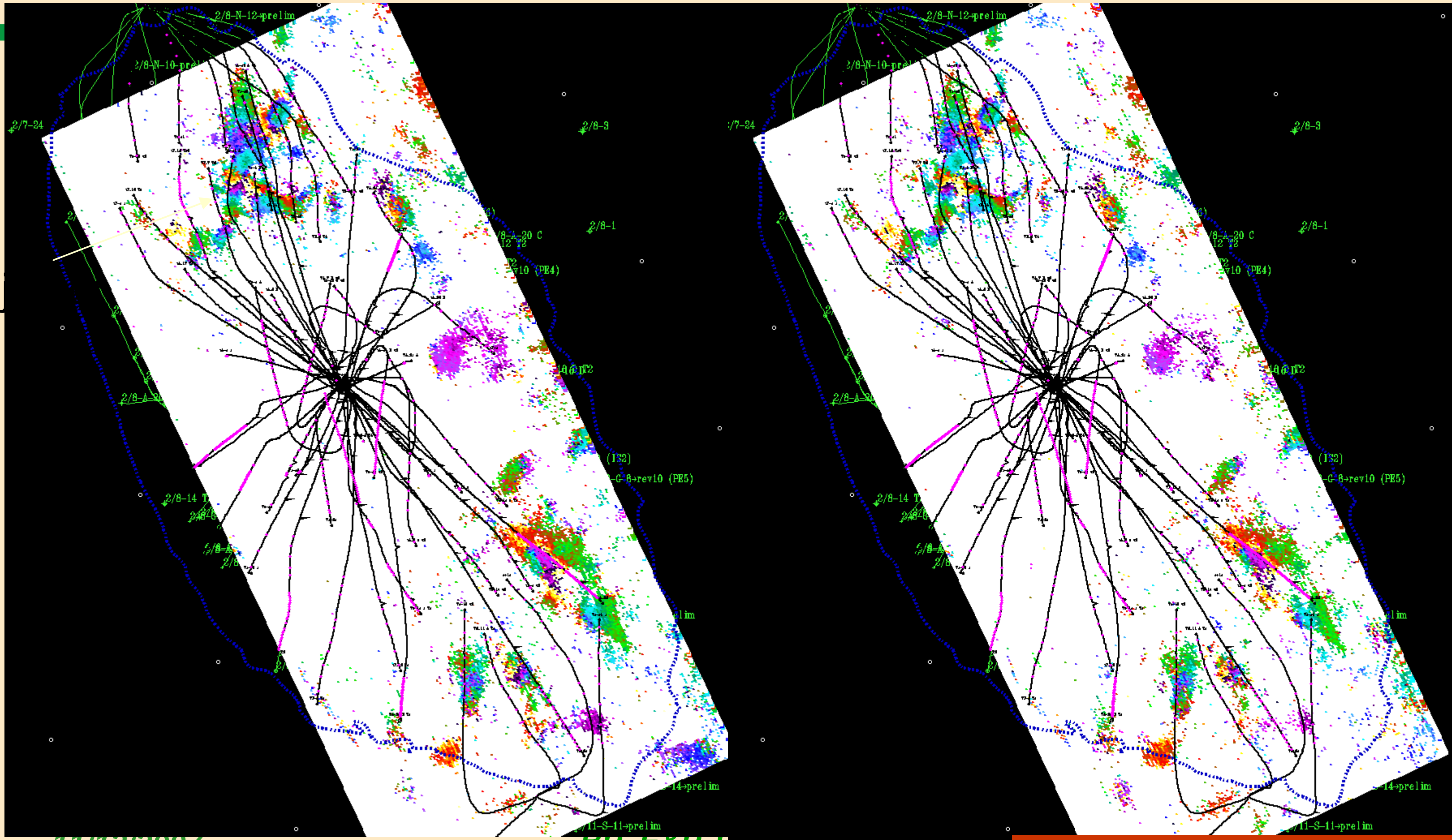
AVO gradient prediction under gas cloud



Spider plot showing source-receiver pairs for the CMP location



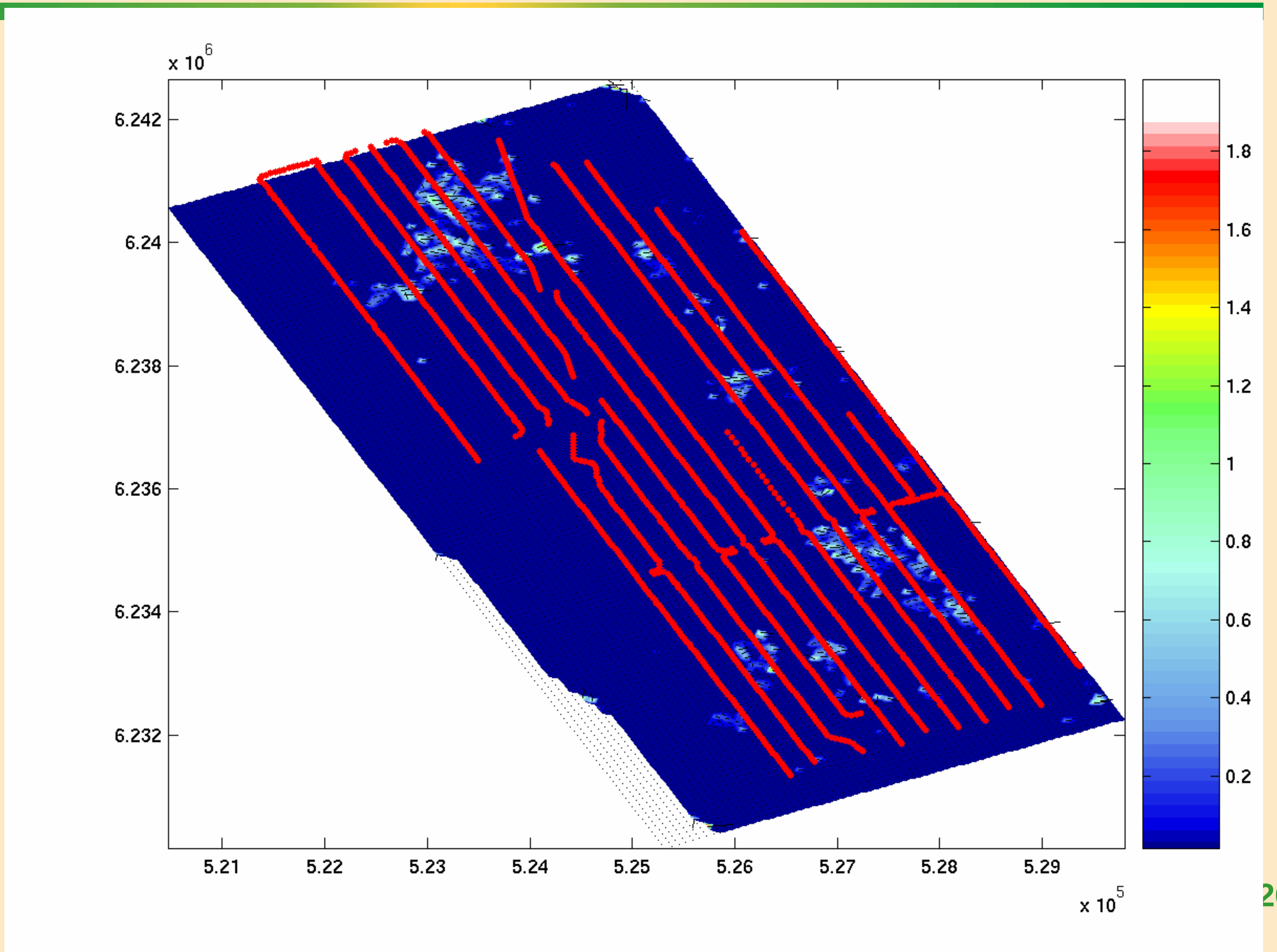
LOFS 1 & 2 with well trajectories



Inj

Courtesy of Olav Barkved

4D PZ AVOAz at Valhall Top Chalk: LoFS2-1



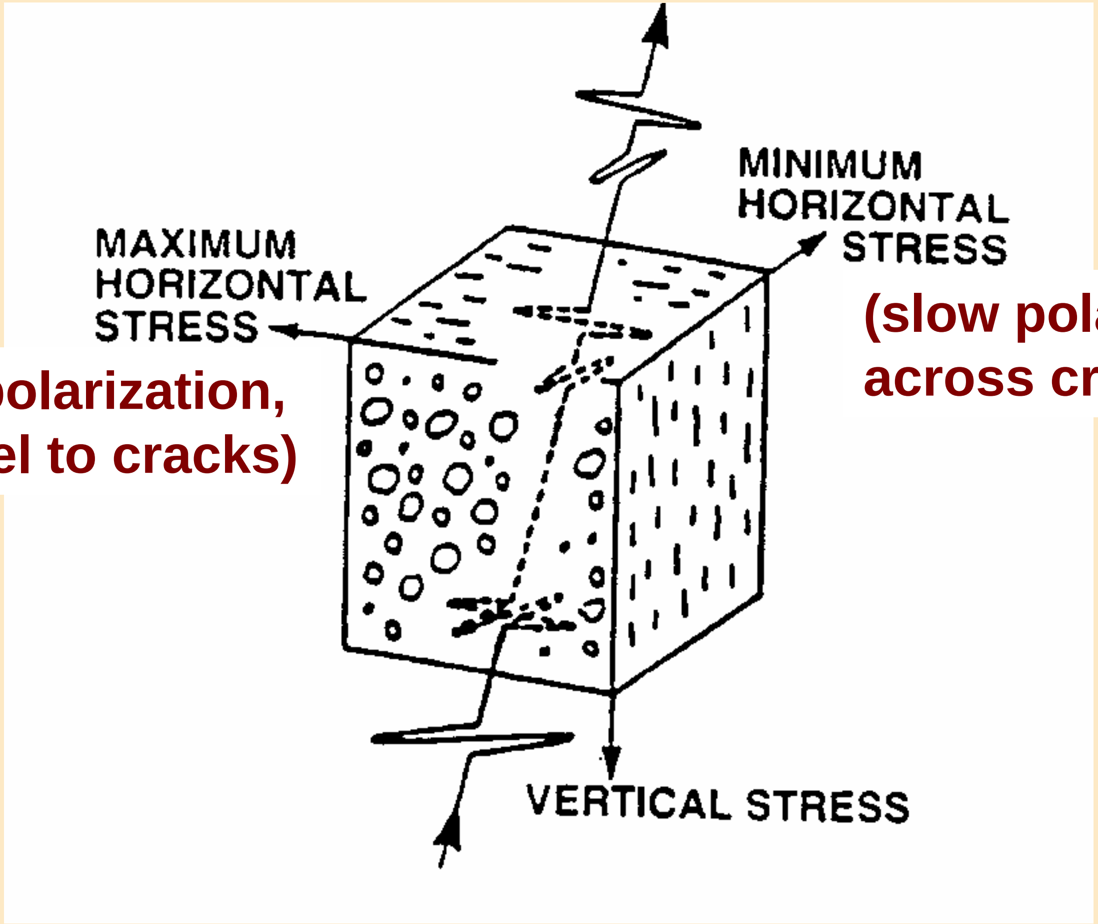
What does it mean to operations?

- It means that the permeability is augmented by fractures, with a known orientation.
- It means that future wells will be placed with this anisotropic permeability in mind, thus optimally producing the reservoir.

Outline

- Conventional 4D Seismics
- Unconventional 4D Seismics
- Anisotropic Seismics
  - P-AVOAz
  - Shear-wave splitting
- Conclusions

The stress-cracks-anisotropy-shear wave splitting connection:



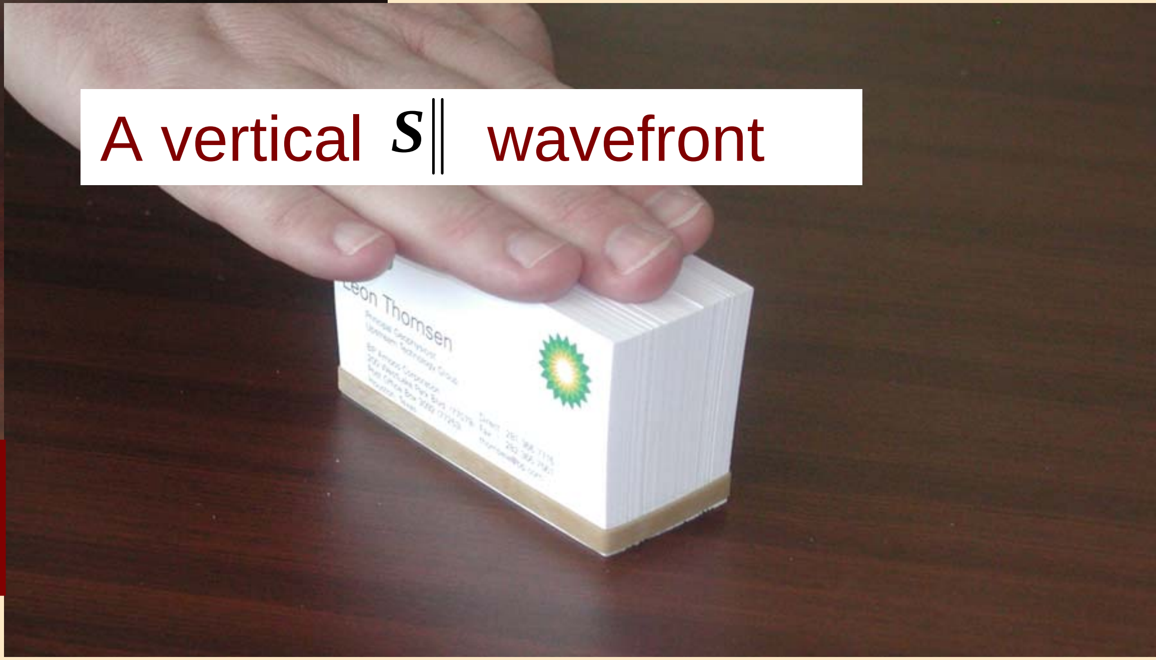
(fast polarization, parallel to cracks)

(slow polarization, across cracks)

Crampin, <<1997

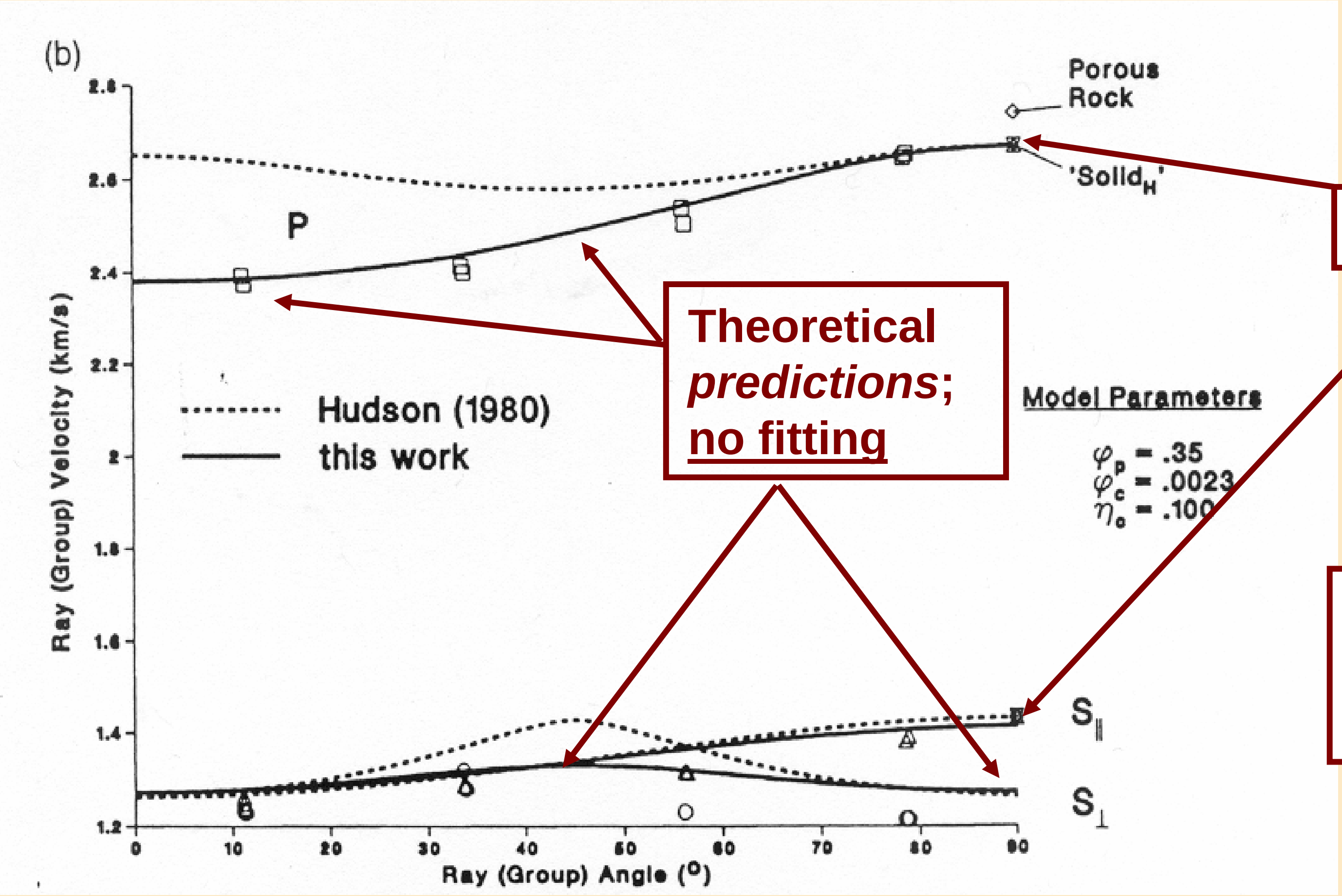
Card tricks: azimuthal anisotropy

The palm shows the wavefront; the fingers show the polarization.



following Thomsen (1986b)

Confirmation of theory for saturated, porous rocks with known cracks



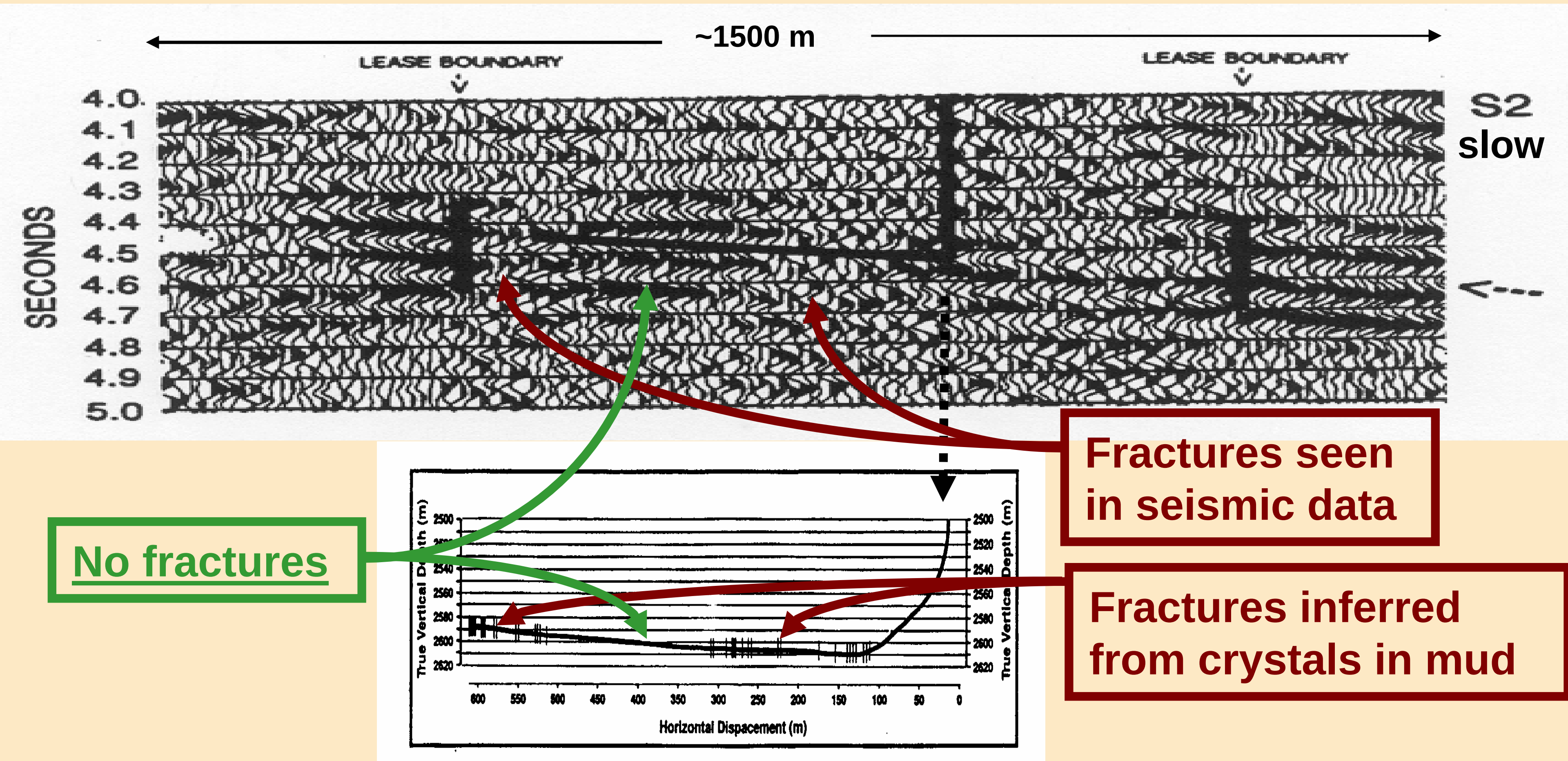
Theoretical *predictions*; no fitting

fit

Data from Rathore *et al*, 1994

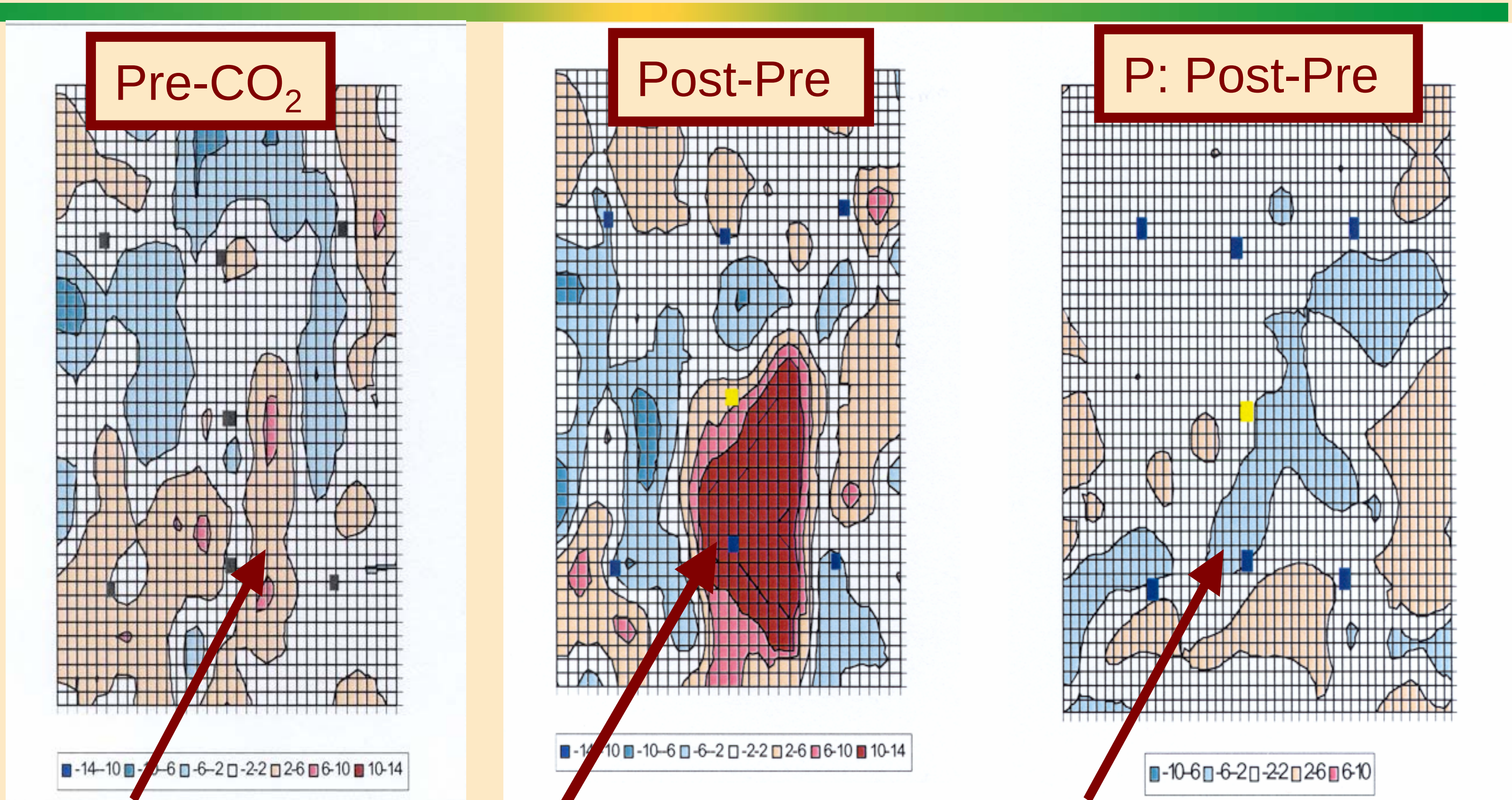
Thomsen, 1994

The zones of slow-mode amplitude anomaly correspond to fractures, as seen in cores from a horizontal well:



Mueller, 1991

Time-lapse changes in shear-wave splitting in a dolomite



γ ~ 4% prior to ΔP_p

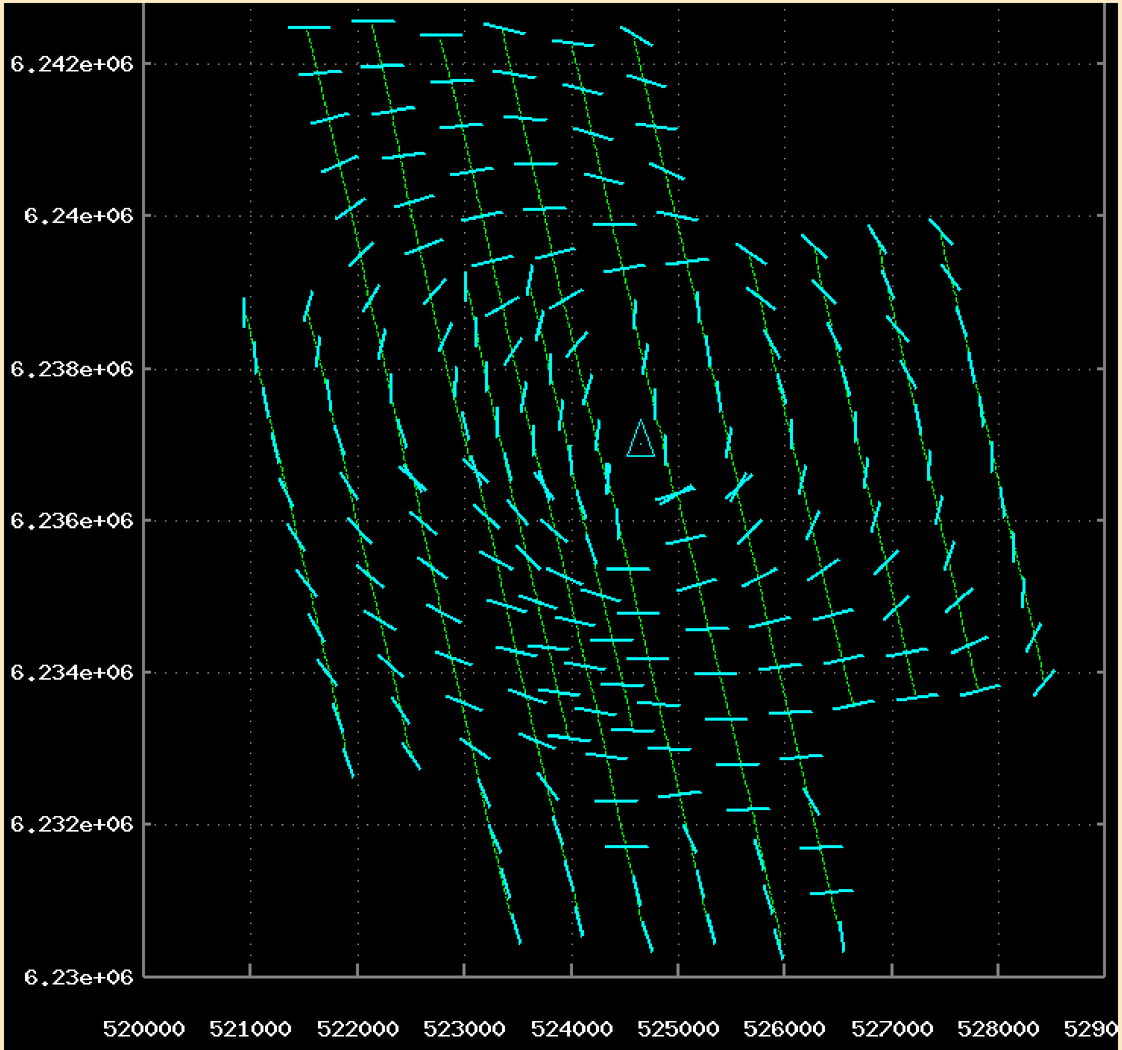
$\Delta\gamma$ ~ -14% due to ΔP_p

ΔV_{p0} ~ 4% due to ΔP_p , ΔS_g

Angerer, et al., 2001

Alignment of split C-waves at Valhall reveals the subsidence bowl

This pattern, of the fast polarization direction in the shallow subsurface, is centered on the area of subsidence due to depletion of oil from the reservoir.



Analysis by
B. Olofsson
J. Kommedal
O. Barkved

WesternGeco

bp

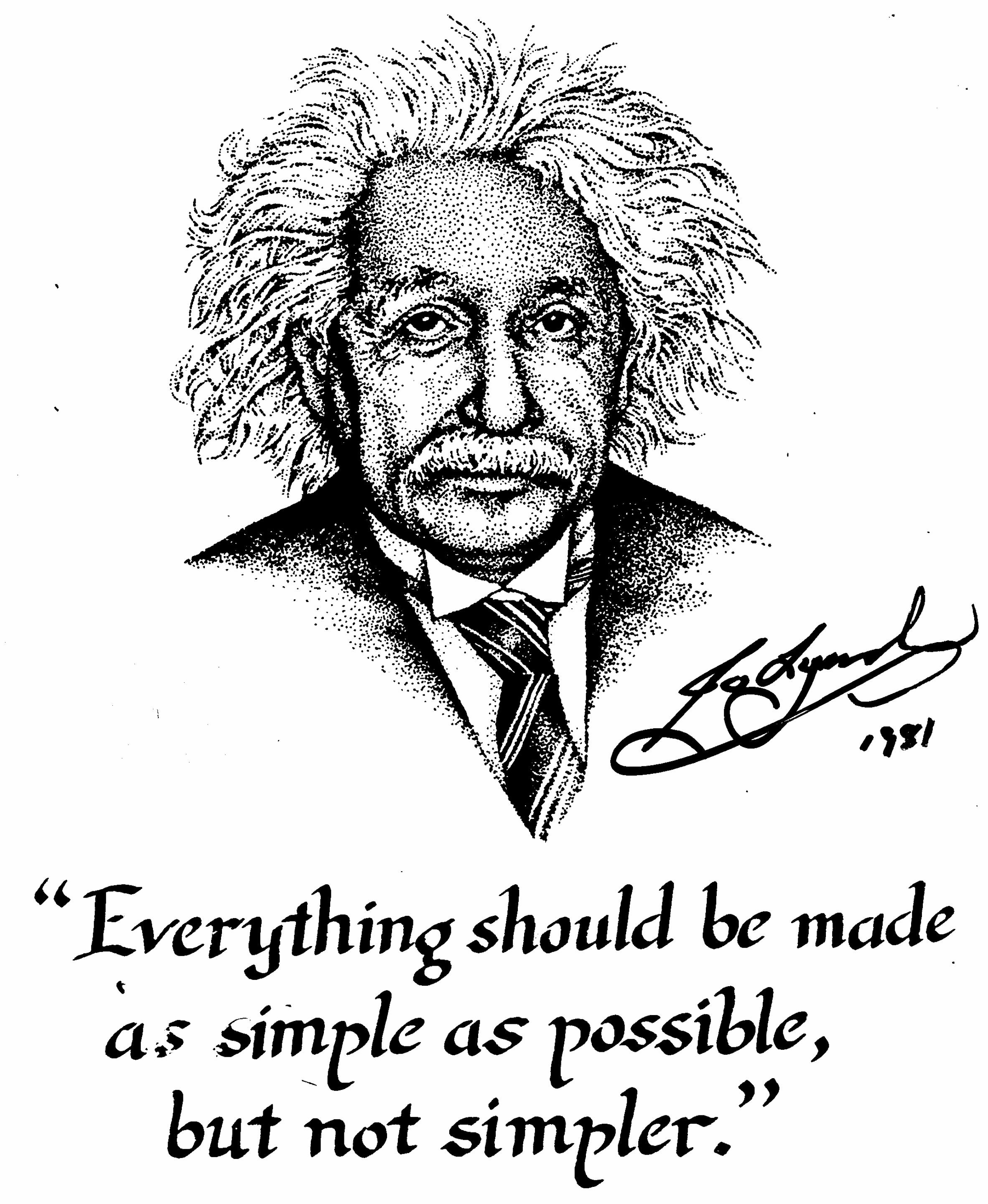
Conclusions$_1$

- **CO2 sequestration monitoring requires *full-field* measurements, *not* just borehole measurements: hence <u>seismics</u>**
- **Seismics provides *only indirect* measurements of CO_2, but <u>there is no substitute</u> for the high-resolution 3D coverage it supplies.**
- **Time-lapse seismics is best done with <u>permanent</u> sources and receivers, in order to avoid acquisition-variant artifacts, and to reduce costs.**

Conclusions$_2$

- Conventional 4D seismics assumes a (heterogenous) isotropic subsurface.
- This may not be accurate, as it ignores the possibility of subsurface fracturing.
- An alternative mode of 4D seismics uses the signatures of azimuthal anisotropy:
  - P-wave AVOAz
  - S-wave splitting

to detect such fractures directly


"Everything should be made
as simple as possible,
but not simpler."

Acknowledgements to

- BPAE, BP E&P Technology, and the
- Canadian Society of Exploration Geophysicists

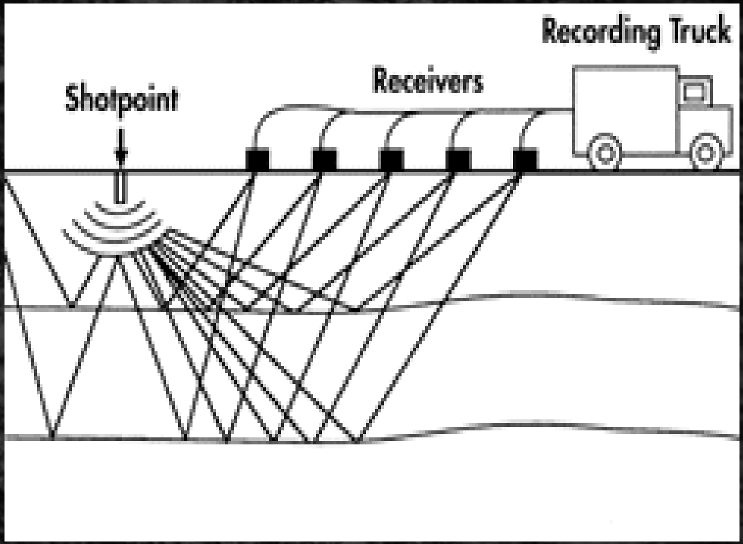
Detailed CO2 Injection and Sequestration Monitoring Through Crosswell Imaging

Mark McCallum
Z-Seis Corporation

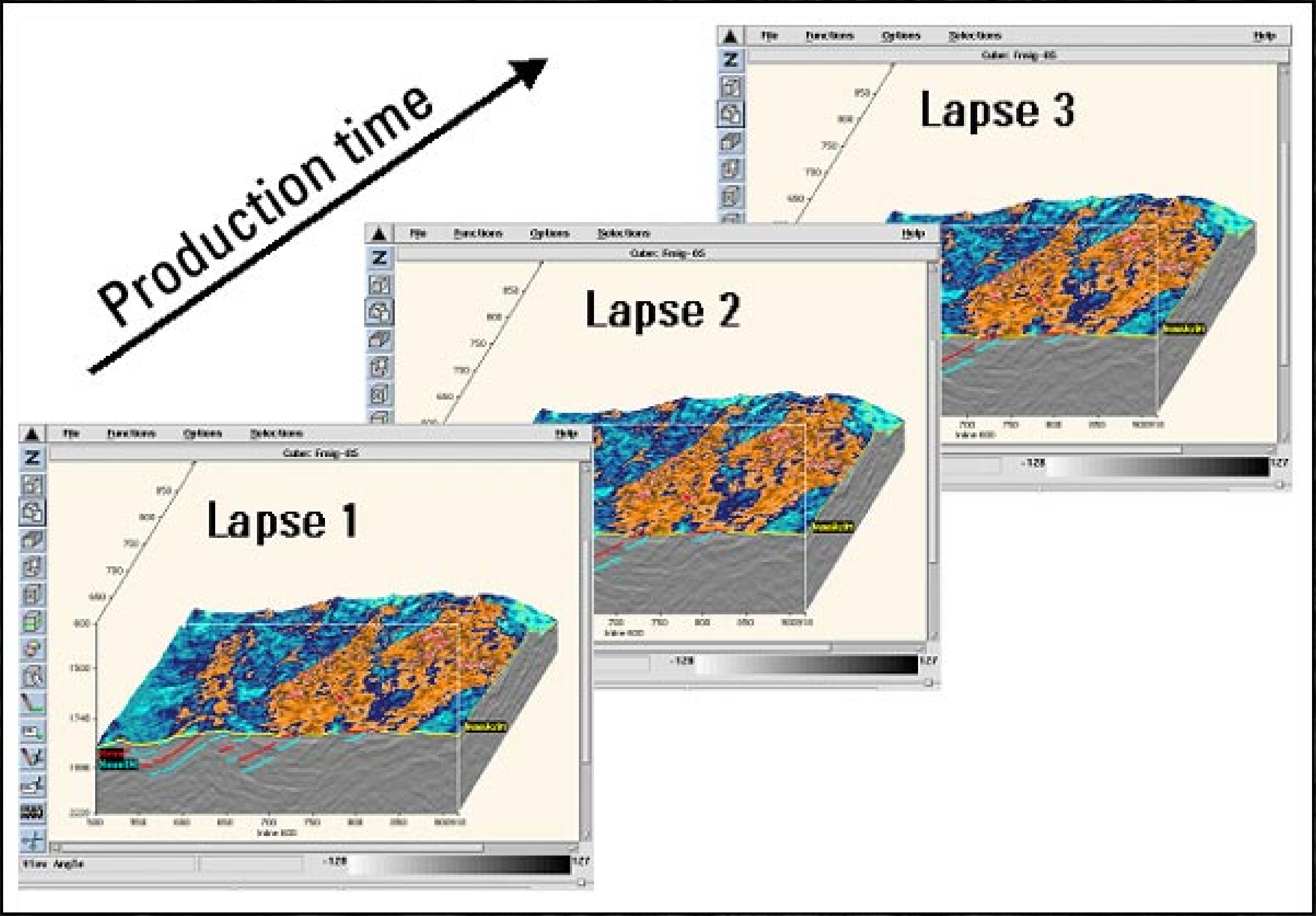
Who We Are

- **TomoSeis: 1992 – 1999**
  - **Innovators in Practical, Low-Cost Crosswell**
- **TomoSeis Division of Core Lab: 2000 – 2003**
- **Z – Seis: 2003 --**
  - **Continuing the Crosswell Seismic Tradition**
  - **Improving and Innovating Technology**
  - **Broadening into Reservoir Seismic Services**
  - **Z-Seis Canada Ltd formed in 2004**

Surface Seismic Technique

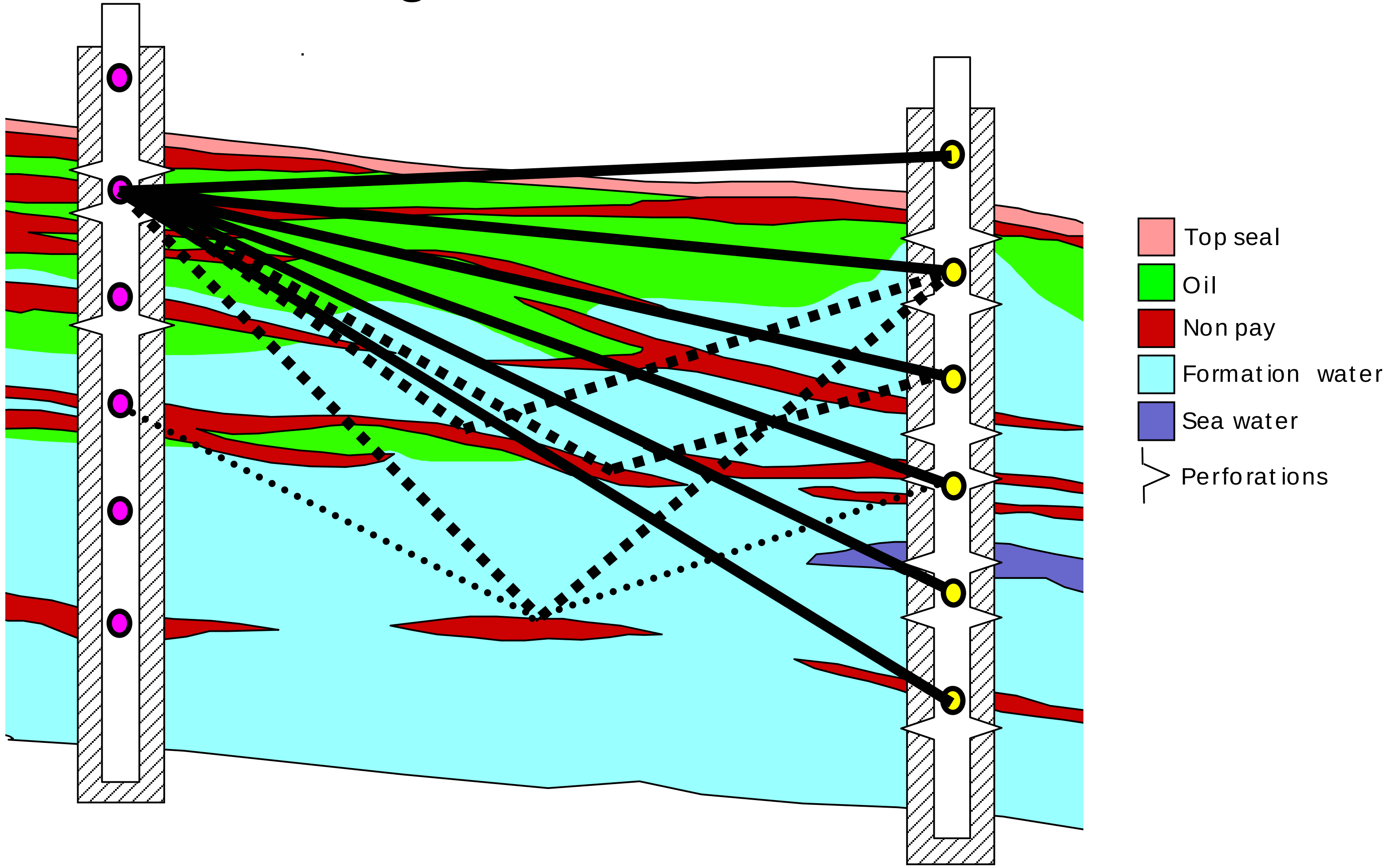


4D Surface Seismic



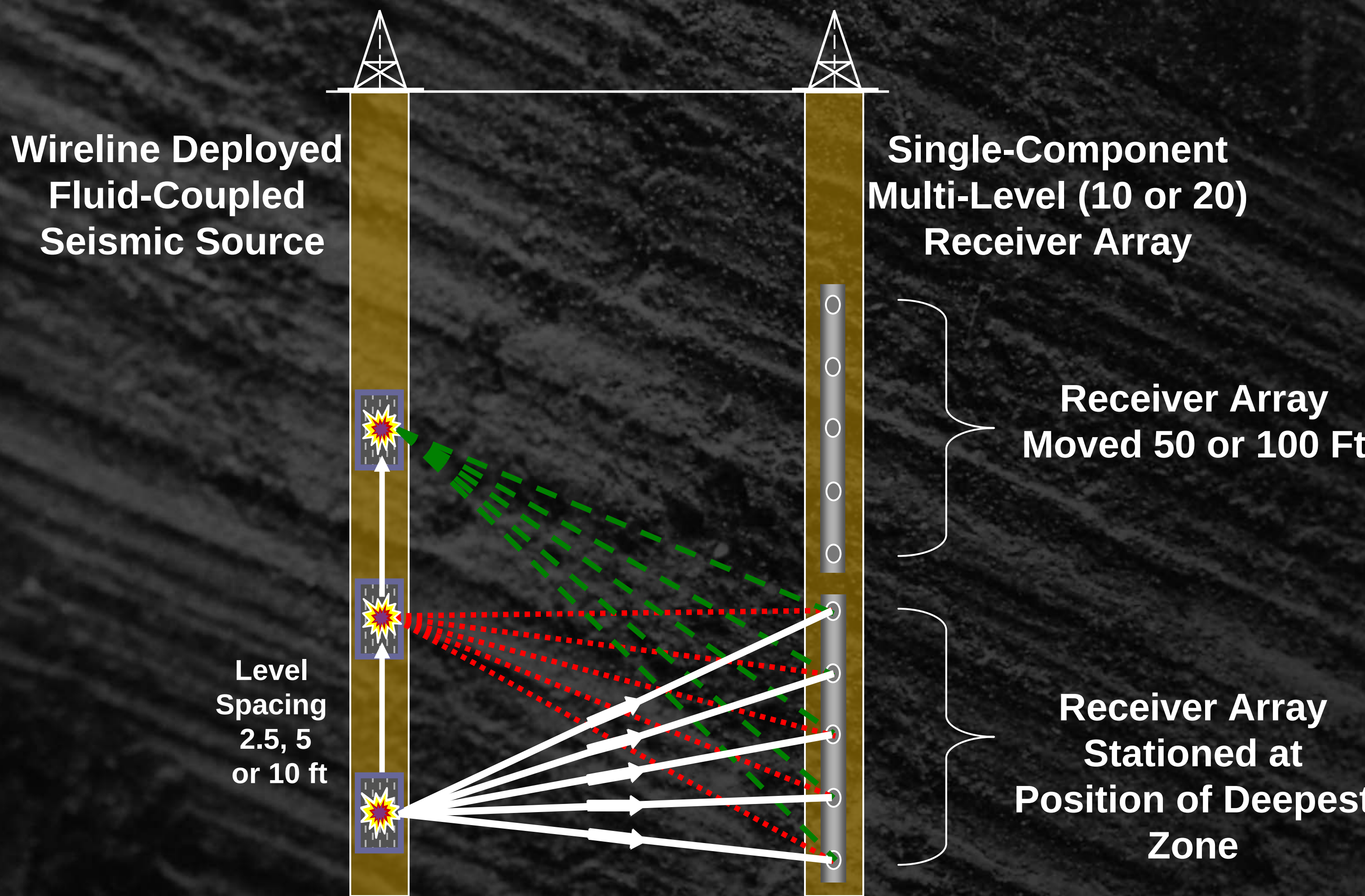
Crosswell Seismic Imaging

Crosswell: Moving Seismic Into the Reservoir

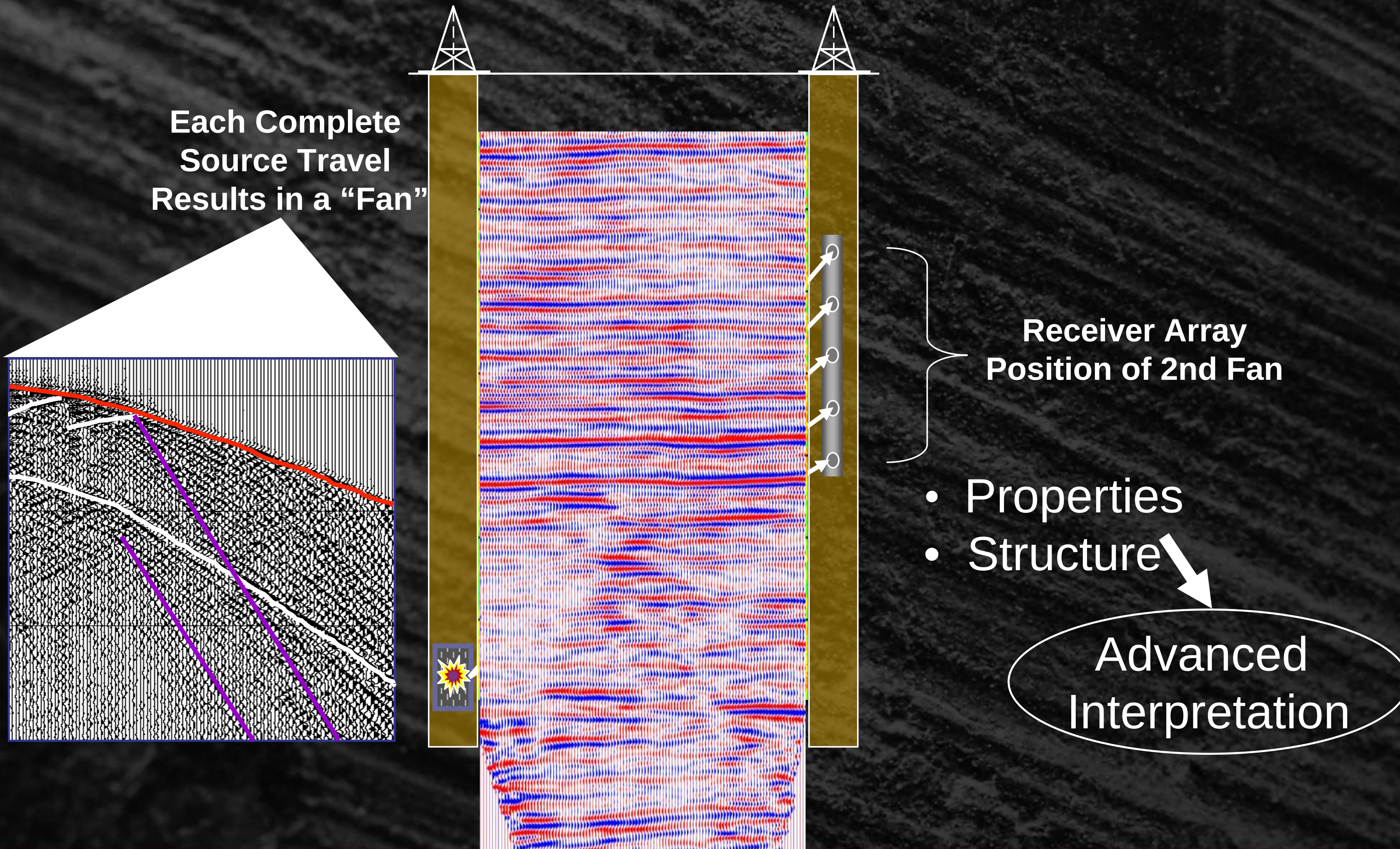


After Ed Stoessel / BP

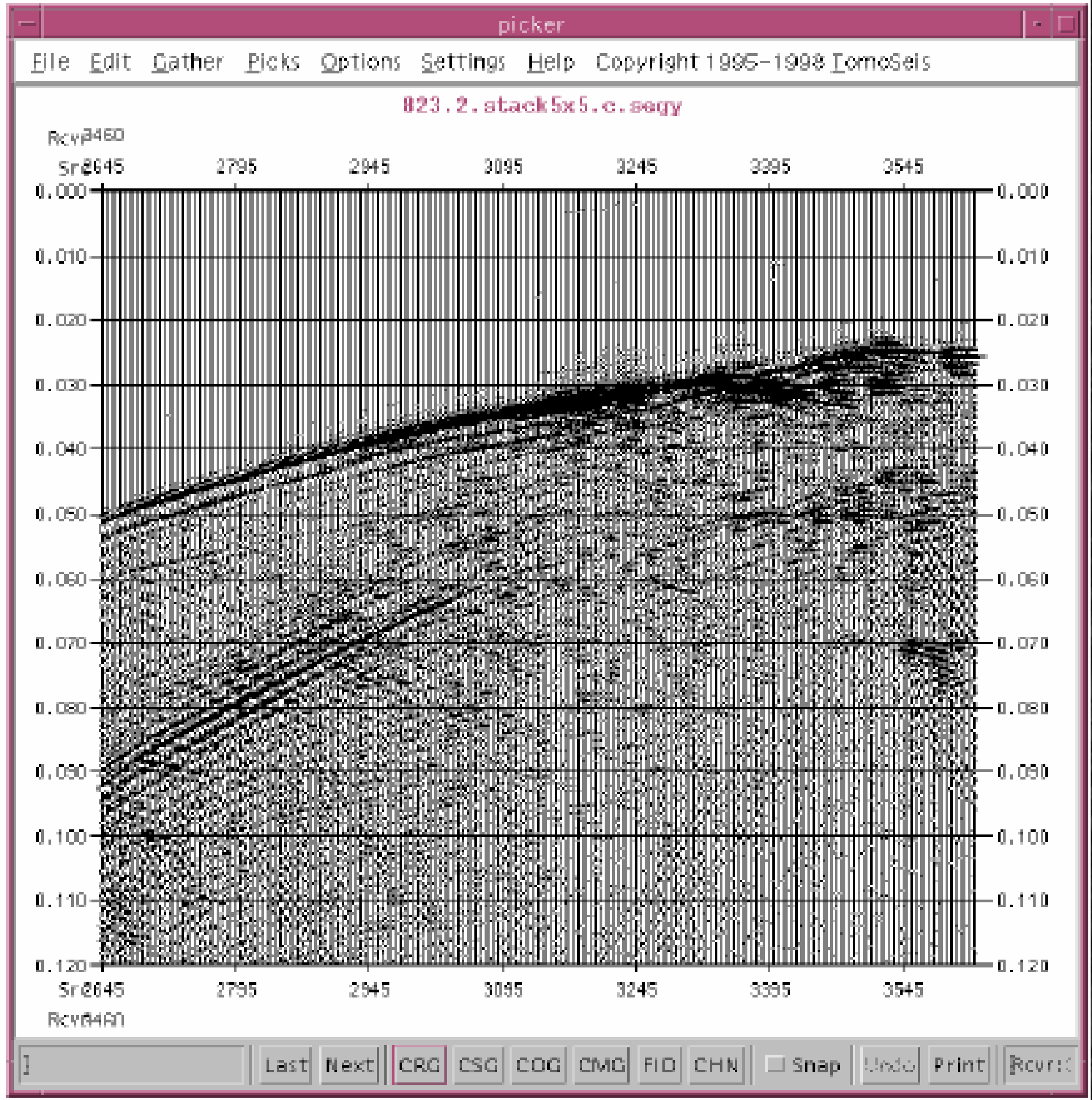
Crosswell Seismic Operations - High-Speed Data Acquisition



High-Speed Data Acquisition - Processing & Interpretation



Raw Data Set From CO2 Sequestration Project Charlton, MI



Crosswell Operations

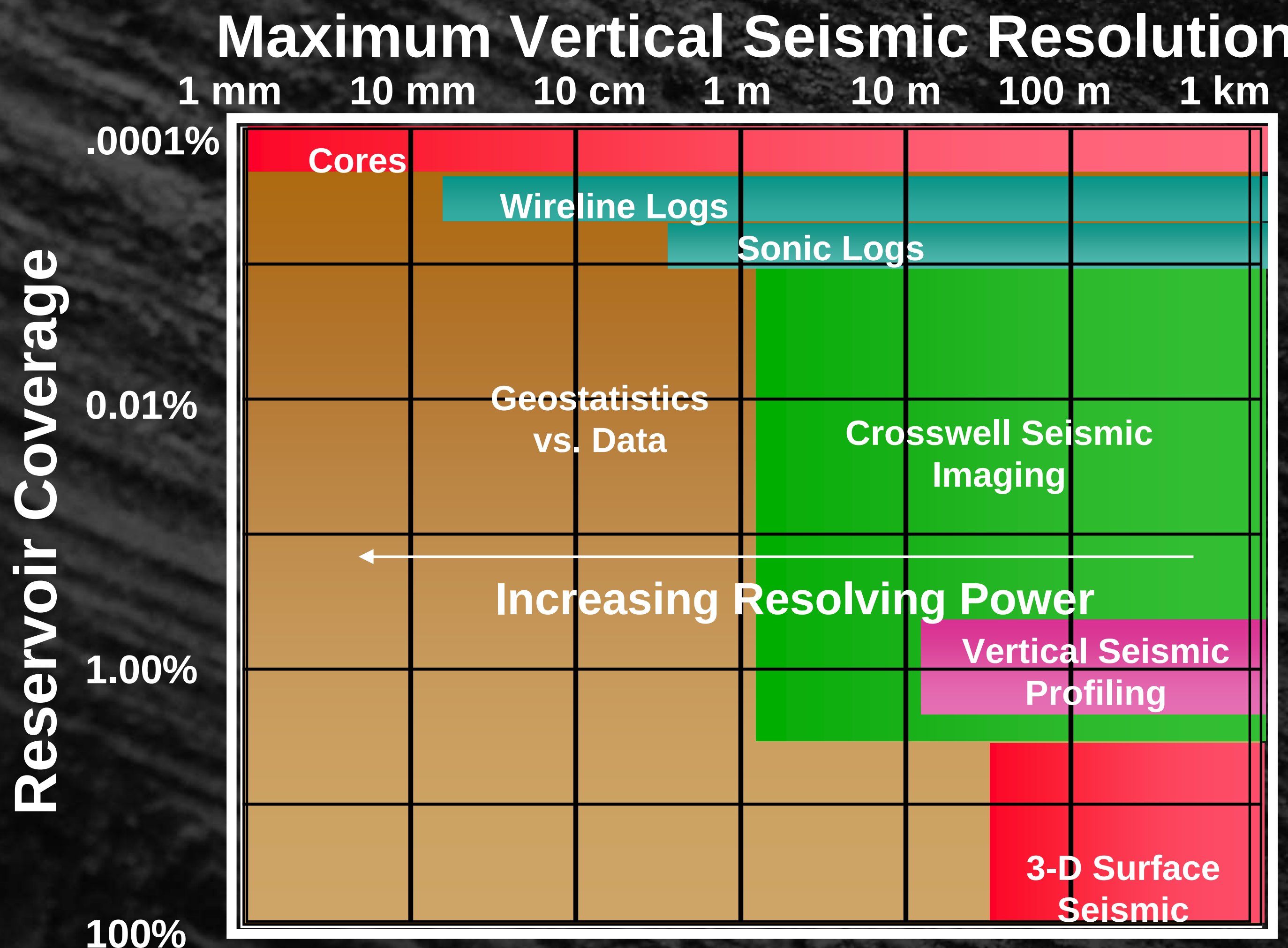
Powerful Piezoelectric Source

Efficient Multi-level Receivers

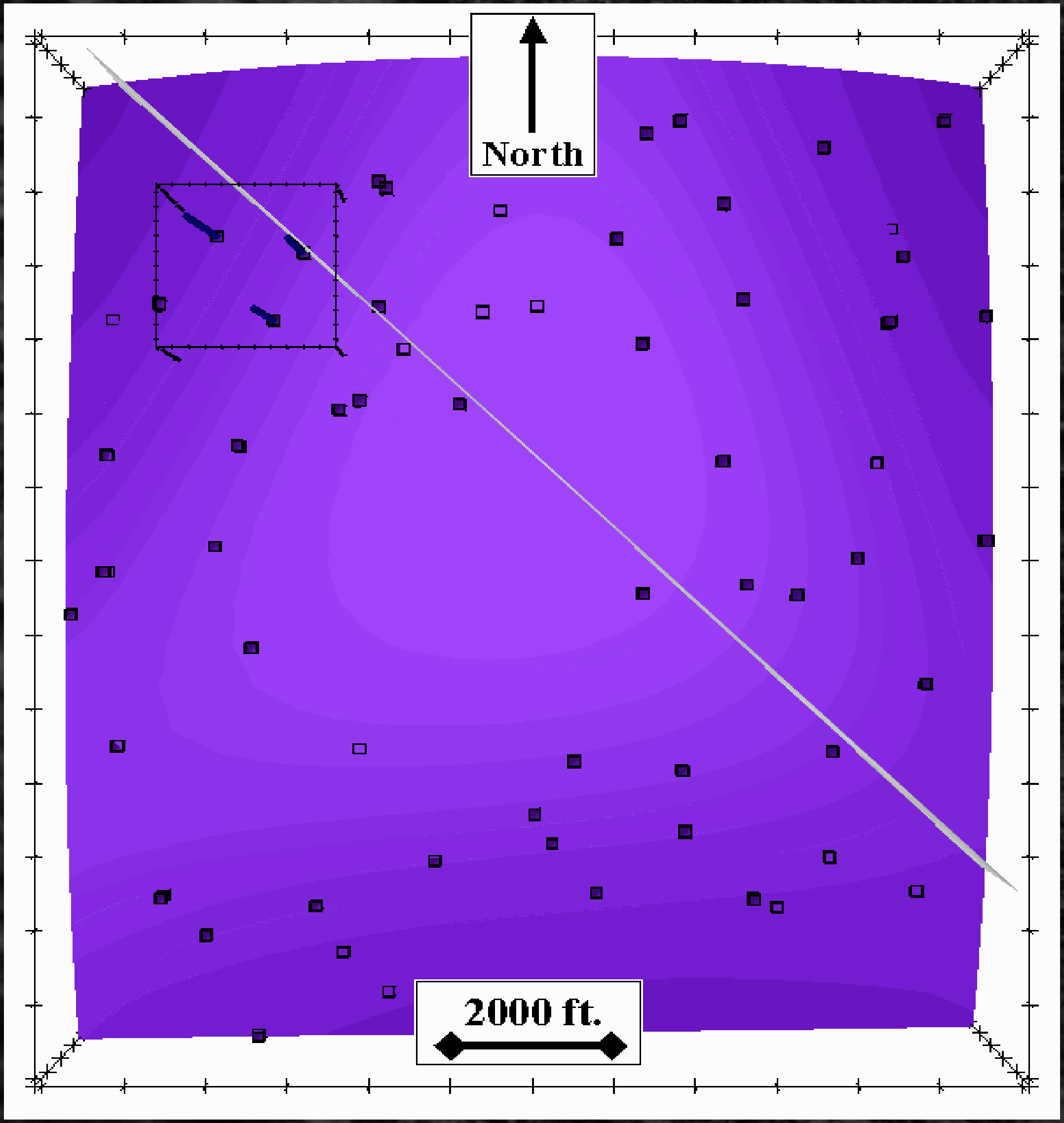
Typical Operating Envelope:

Well depth	20,000+ ft
Well spacing	½ mile
Temperature	350°F
Receivers OD	1-11/16”
Source OD	3-1/2”

Why Crosswell Seismic ?



High Resolution Reservoir Imaging



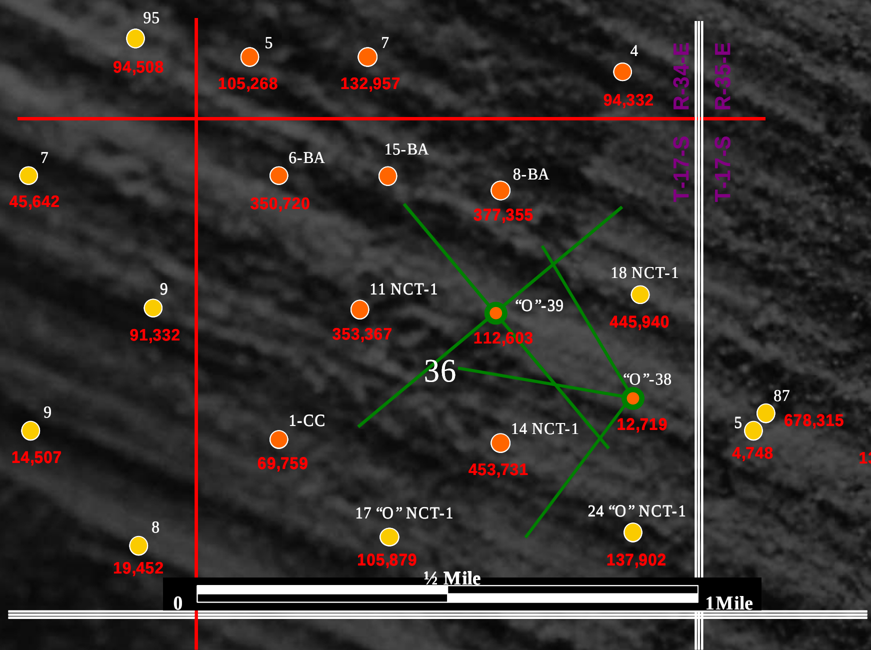
CO_2 EOR and Sequestration

- Site Selection
  - Reservoir Characterization
  - Cap Rock/Seal Integrity
  - Thief Zone Identification
- Injection Period
  - Sweep Efficiency
  - Model Fit
  - Problem Identification

CO_2 EOR and Sequestration

- Post Injection
  - Long Term Monitoring
  - Movement of CO_2 Plume
  - Measure Stress Changes in Reservoir

Wolfcamp Reservoir Characterization



Wolfcamp Reentry Candidate

Wolfcamp Producer

Wolfcamp Abandoned Producer

Horizontal Path Possibilities

10/98

(Revised 04/01)

R. Martin

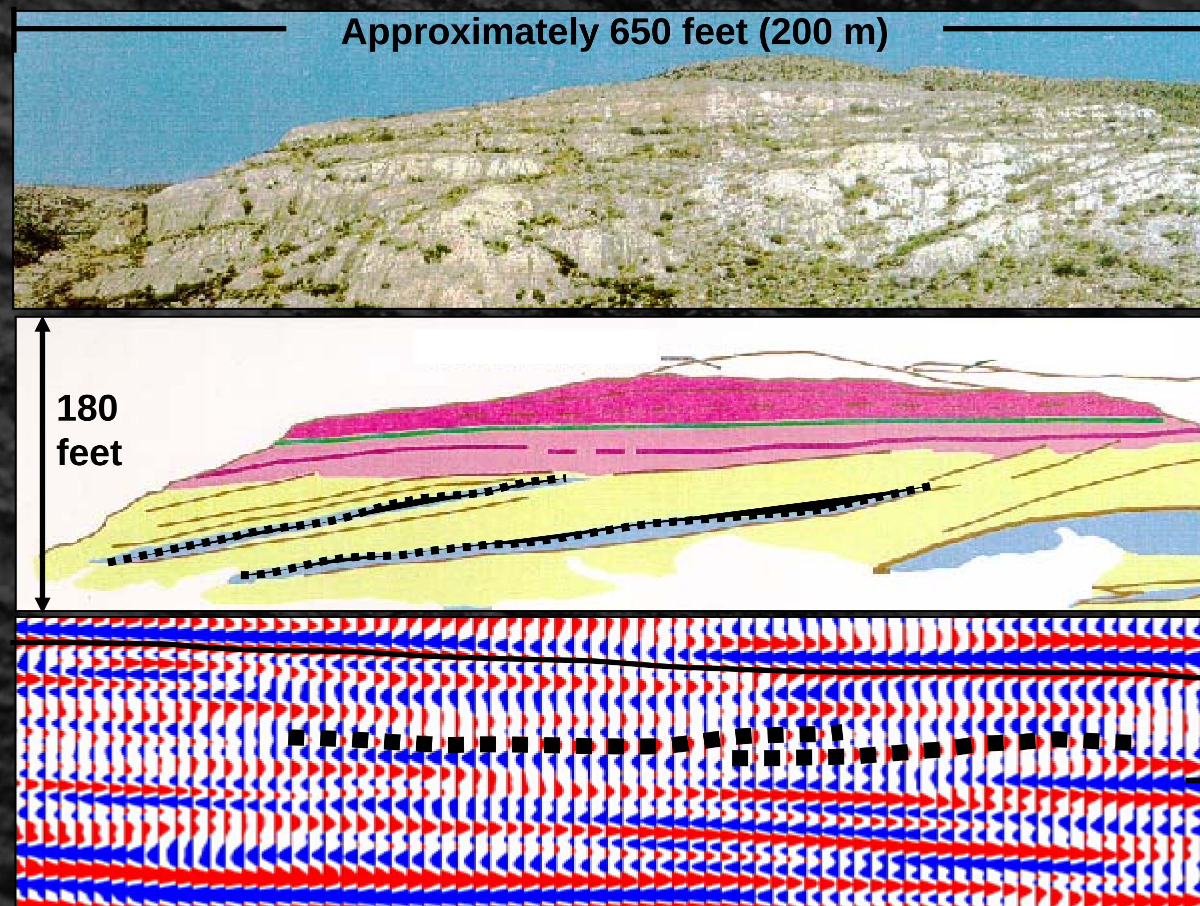
Detailed Architecture

Crosswell Seismic: An "Outcrop" Between Wells

Crosswell reveals unexpected complexity in a West Texas Wolfcamp reef.

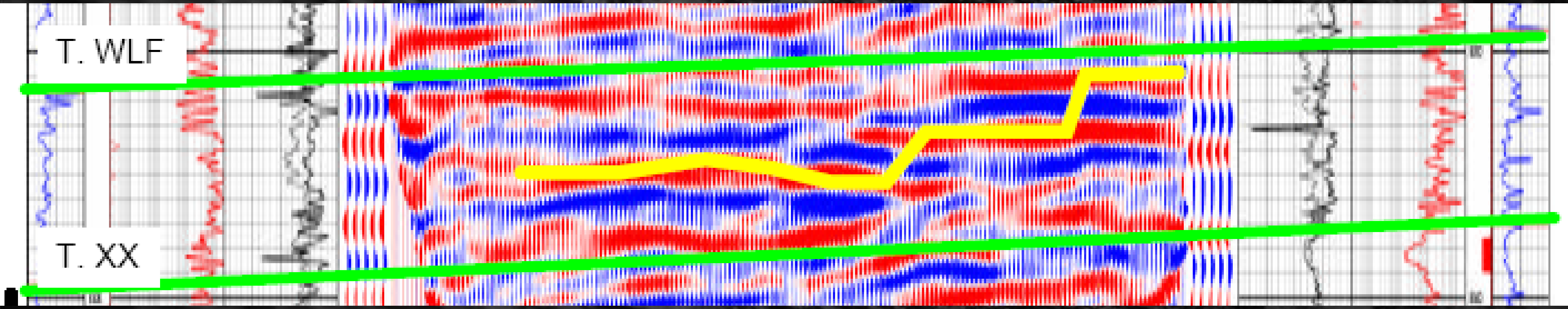
Clinoforms and structure observed in outcrops and crosswell seismic compartmentalize the reef.

Horizontal drilling strategy is made possible by enhanced understanding of reservoir architecture through crosswell seismic.

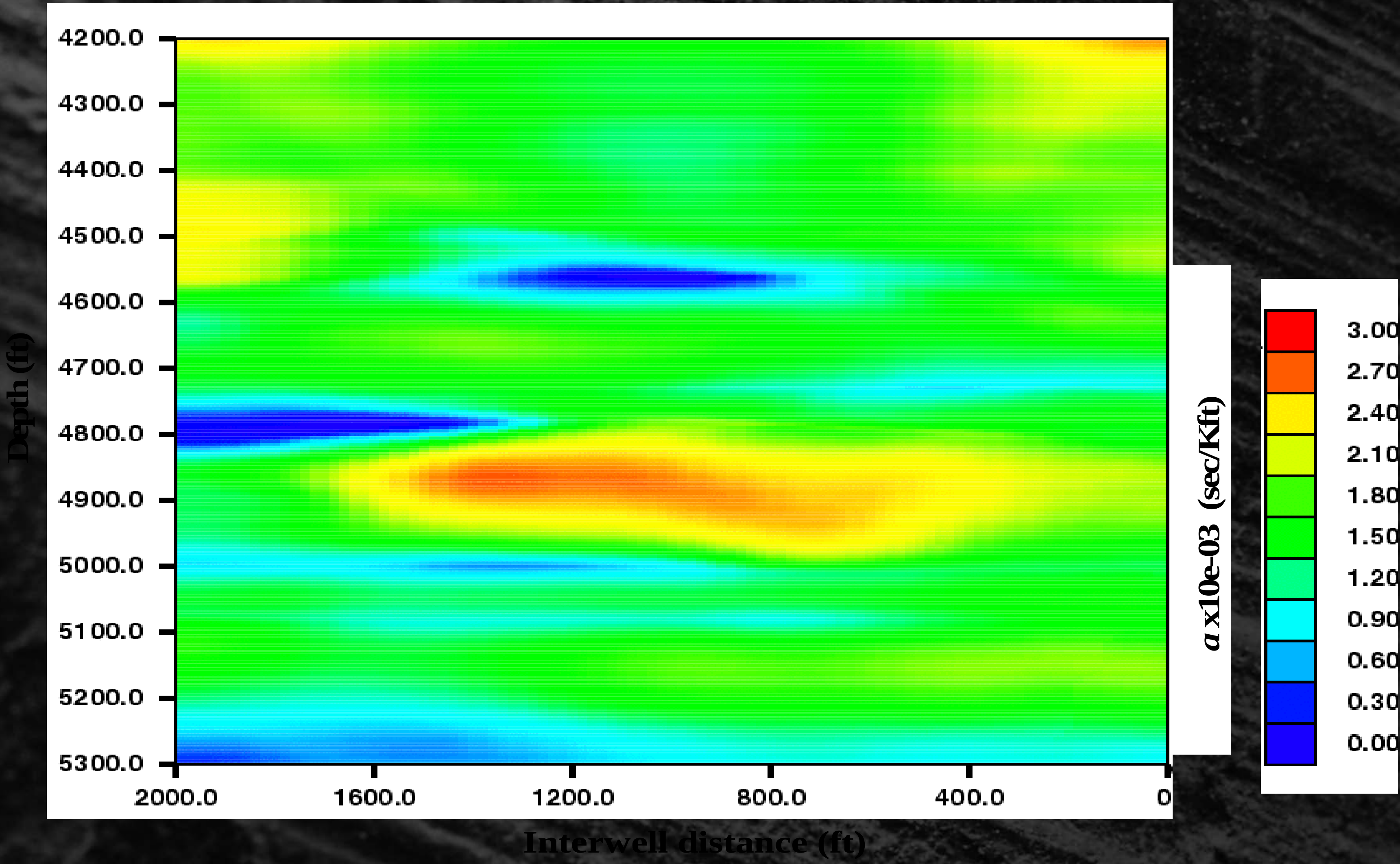


Detailed Architecture

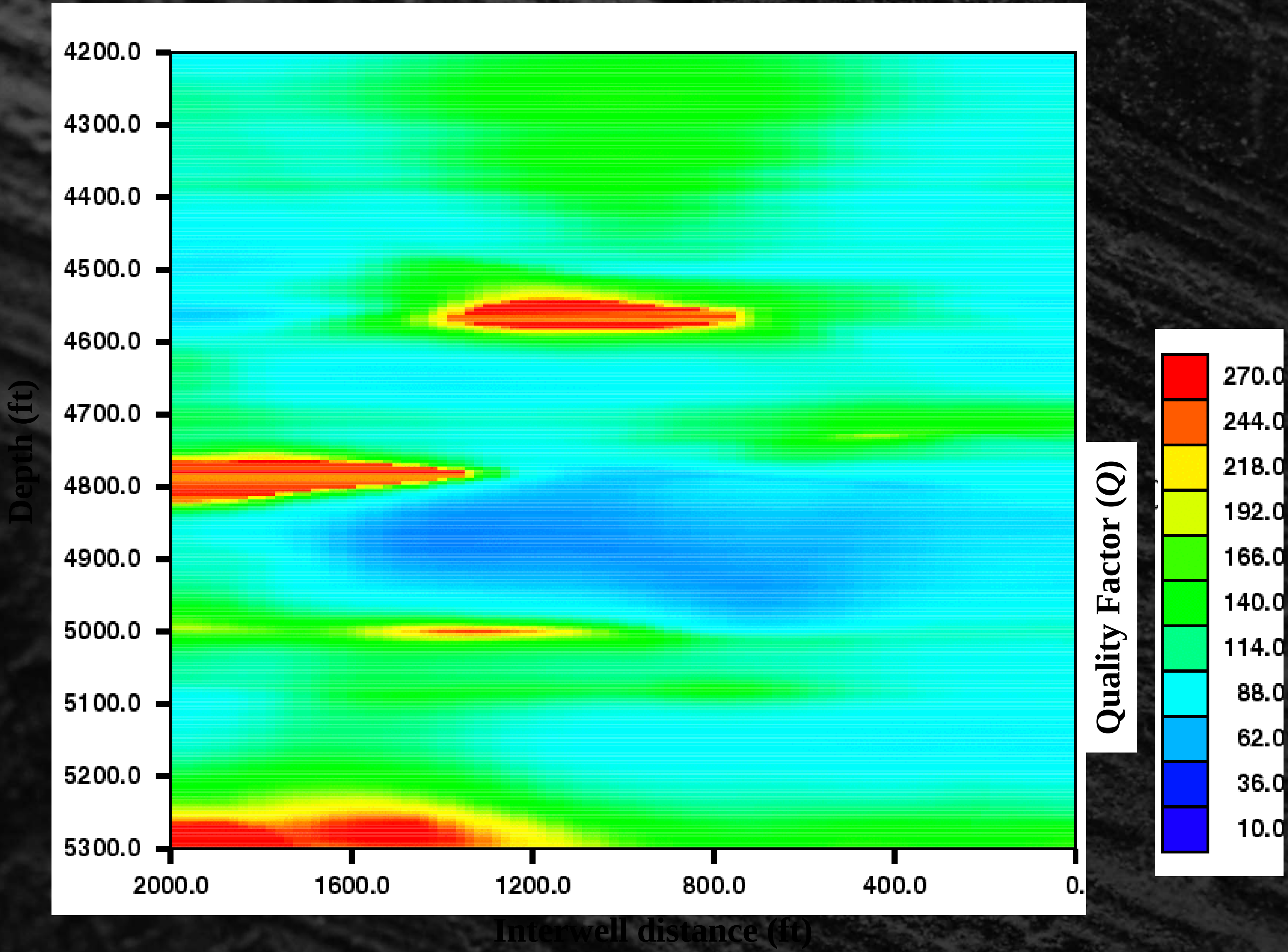
Horizontal drilling strategy is made possible by Crosswell reservoir imaging ***increased production 300%.***



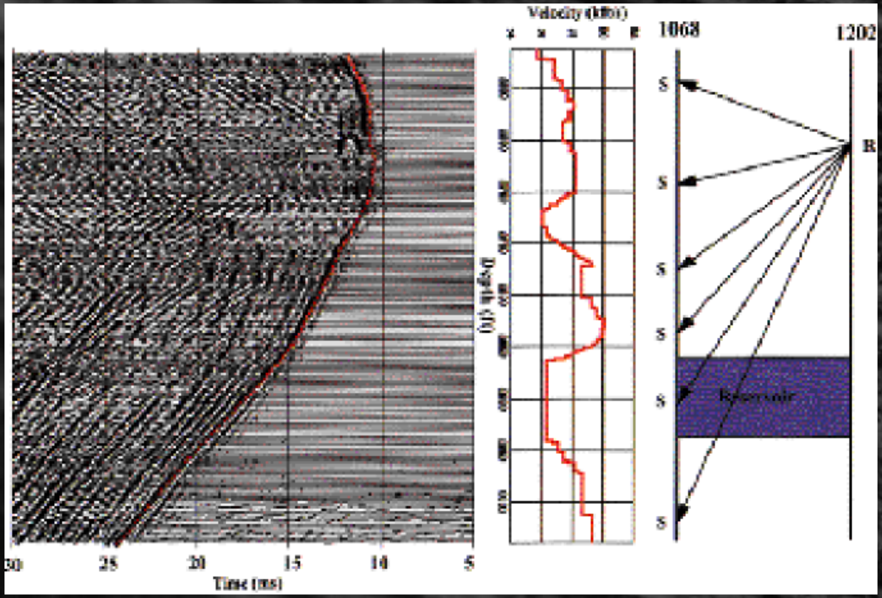
FACT - Attenuation Coefficient Tomogram

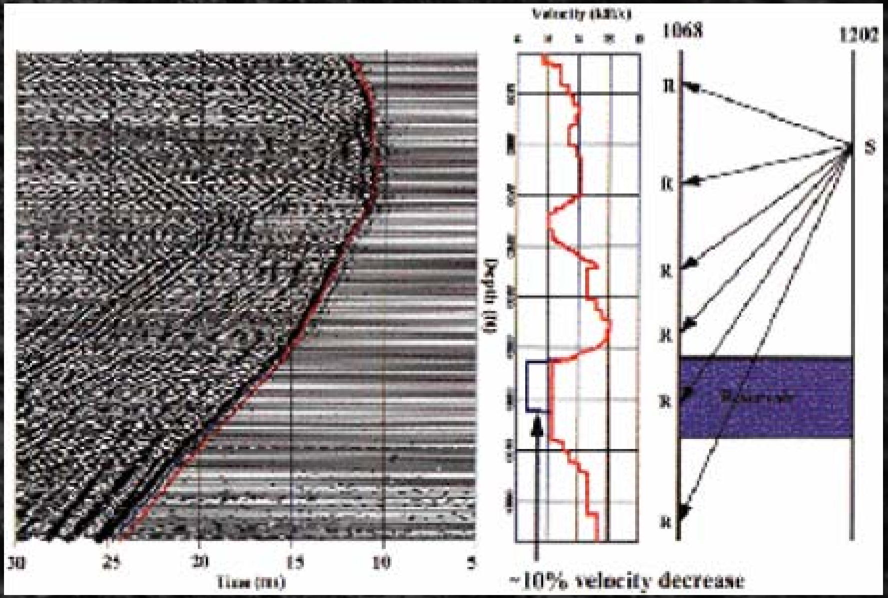


FACT - Q-Values Distribution



CO2 Flood Monitoring – Chevron, McElroy Field TX



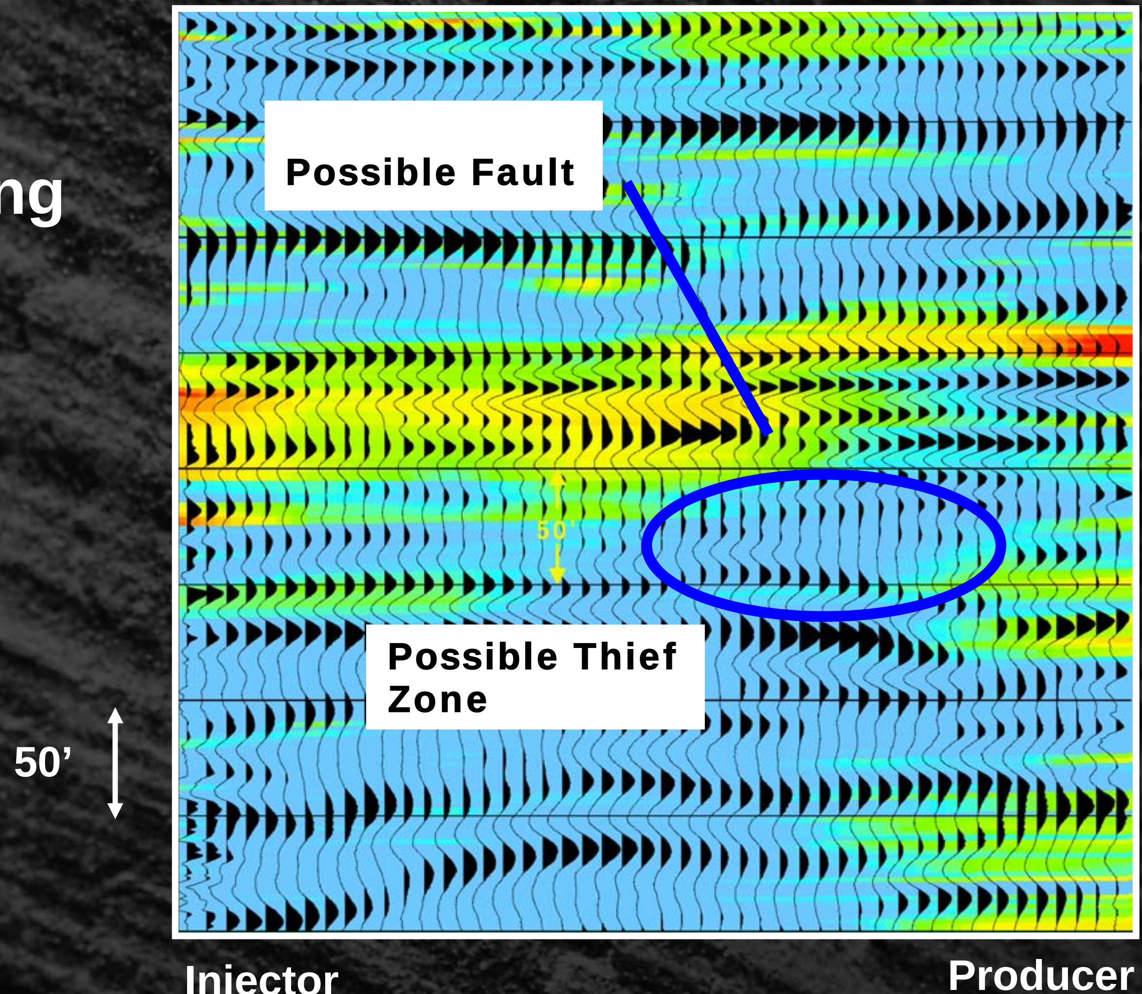


Raw Data Provides Evidence of 10% Decrease in Velocity or 10% Increase in Travel Time After Injection of CO_2

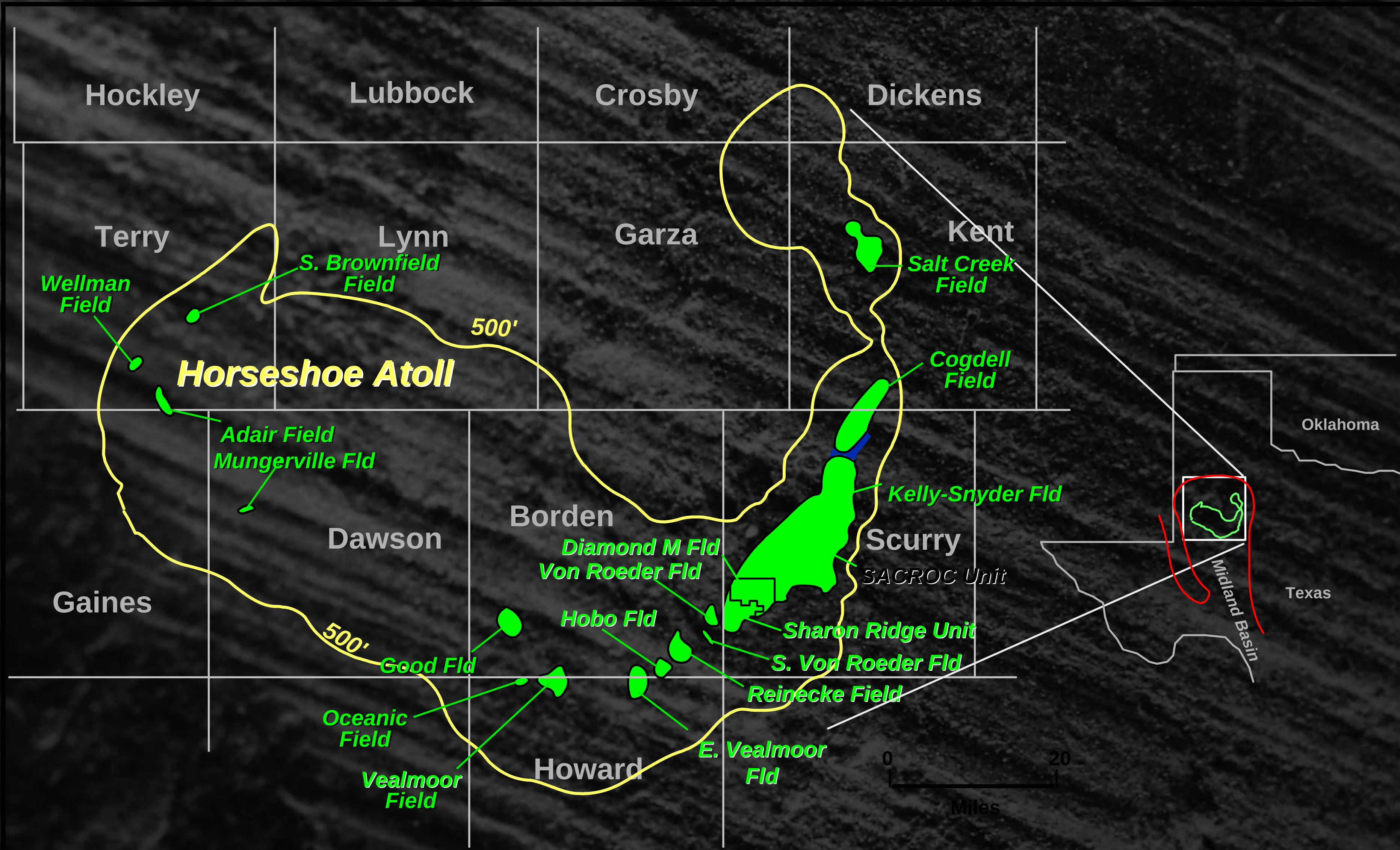
CO2 Flood Monitoring – Chevron, McElroy Field TX

Imaging and Monitoring of Reservoirs

- CO_2 Flood Monitoring
- Understanding Reservoir Heterogeneity

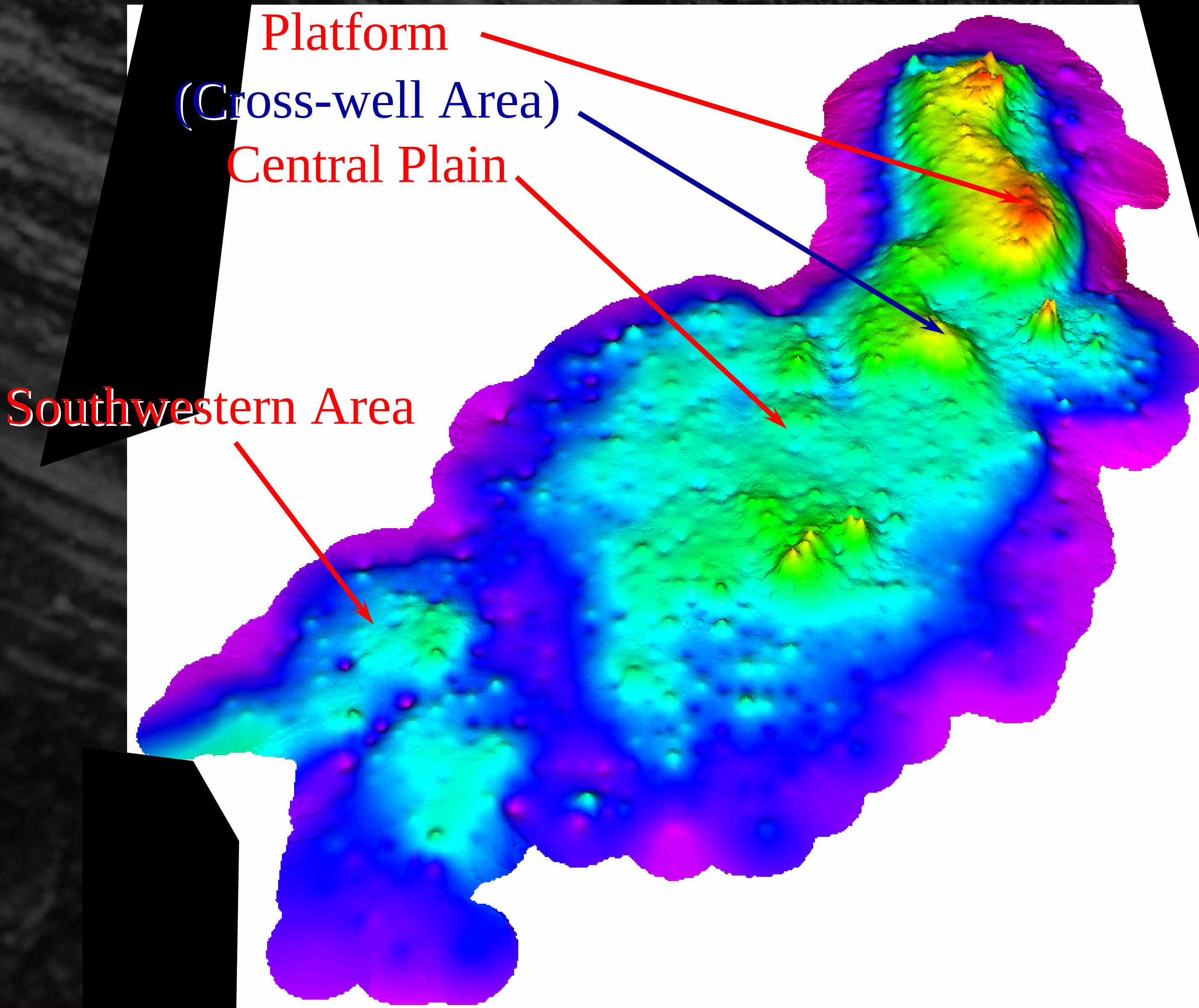


SACROC Location Map

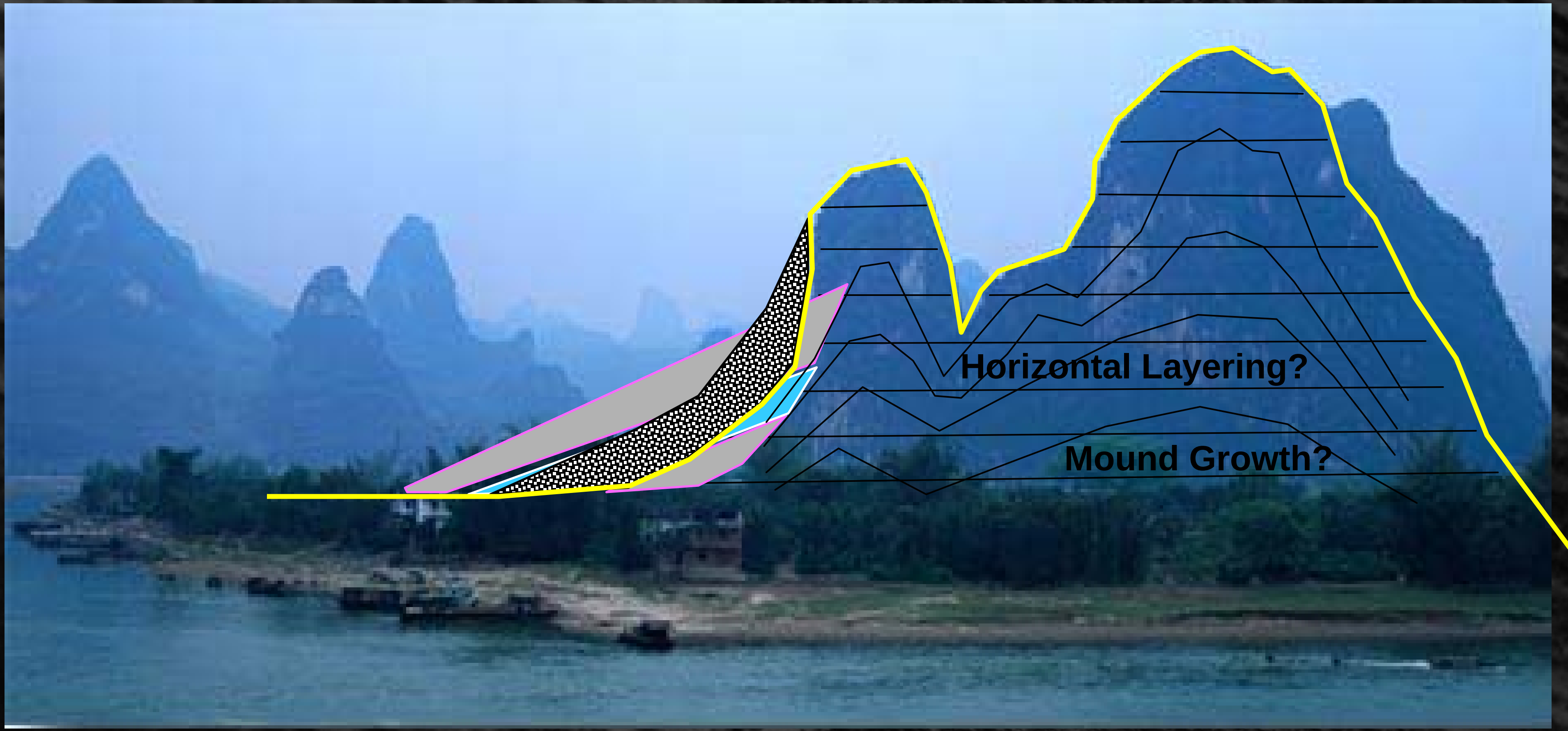


Modified from Vest (1970)

SACROC 3-D Structure



Structural Variation: Pinnacle Example

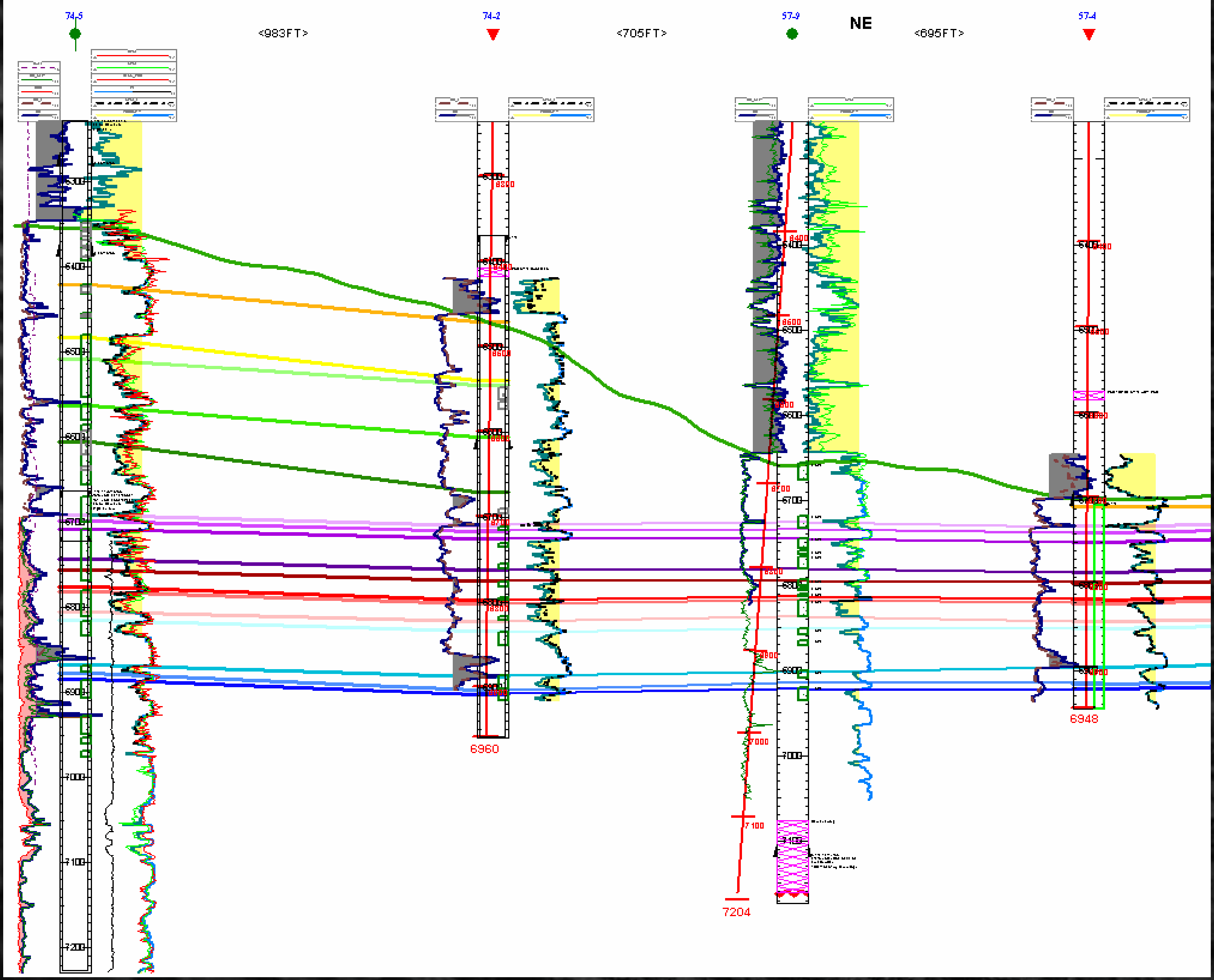


Tower Karst – China. Photo courtesy of J.B. Ward, Oxy Permian.

Cross-well Line: Log Picks

Dip Line

SW



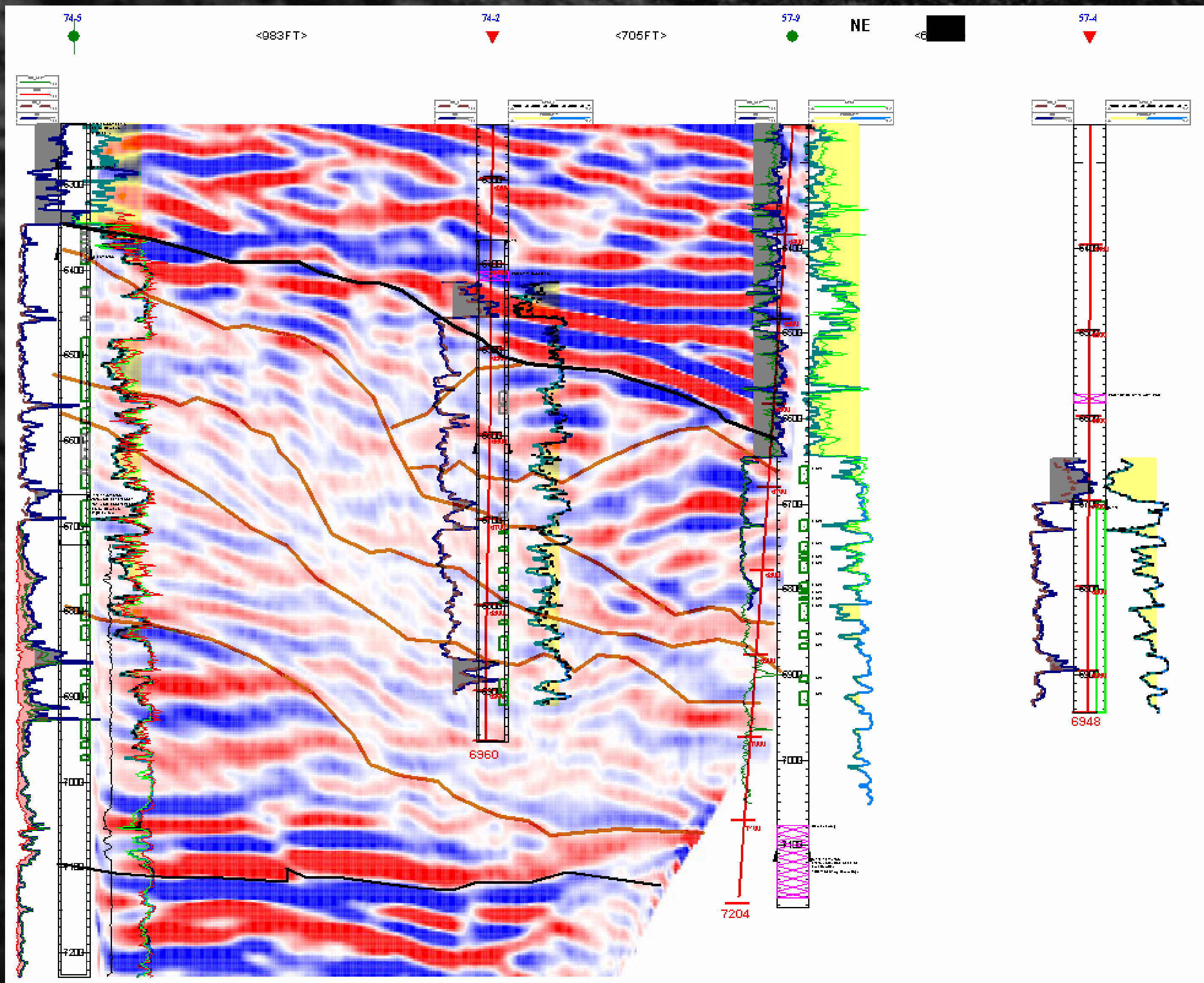
NE

Cross-well Line: One Possible Interpretation

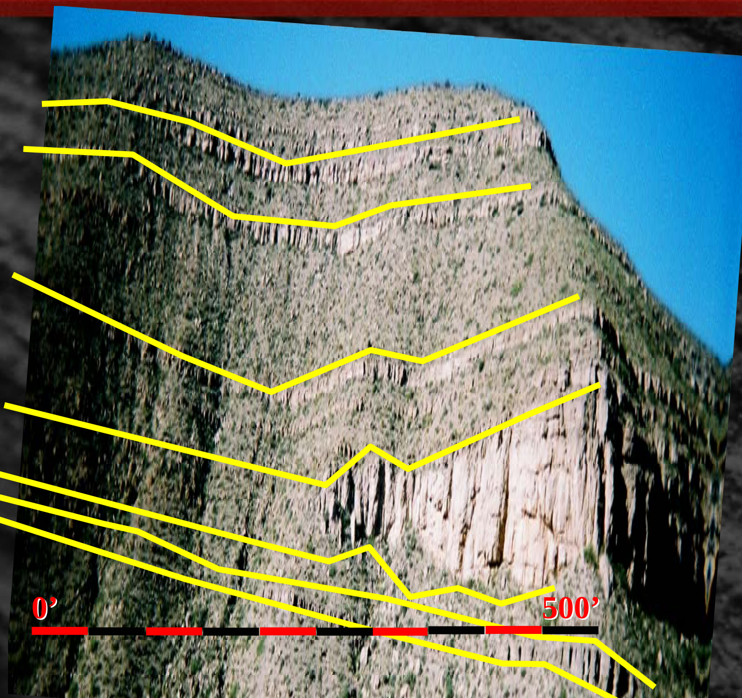
Dip Line

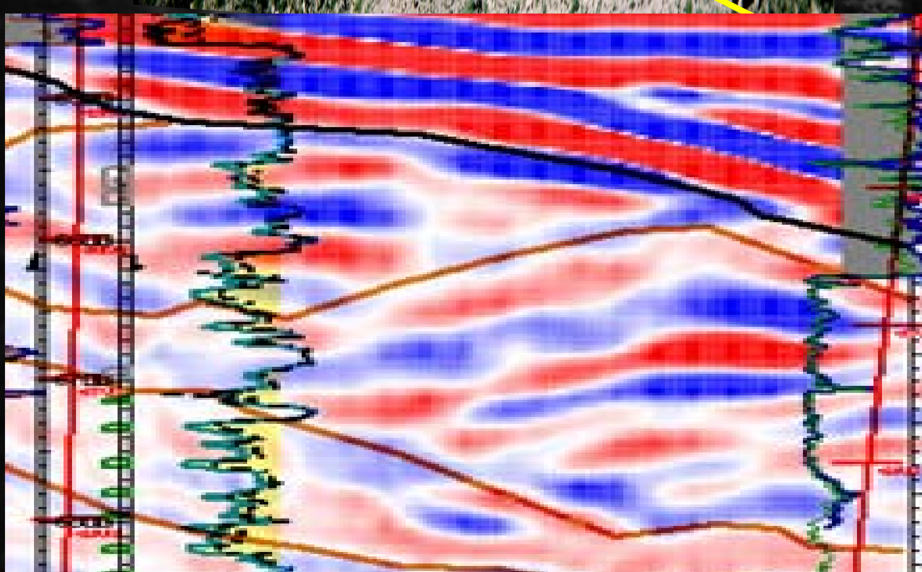
SW

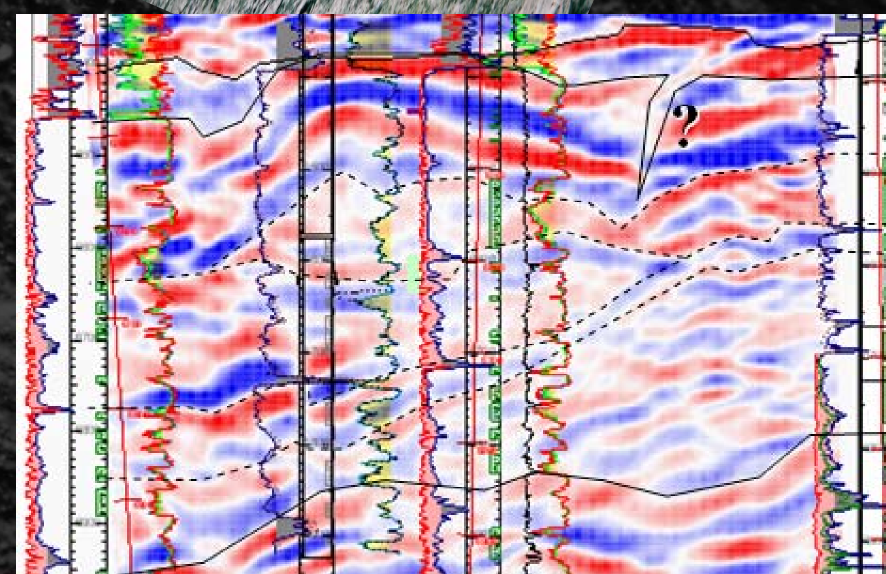
NE



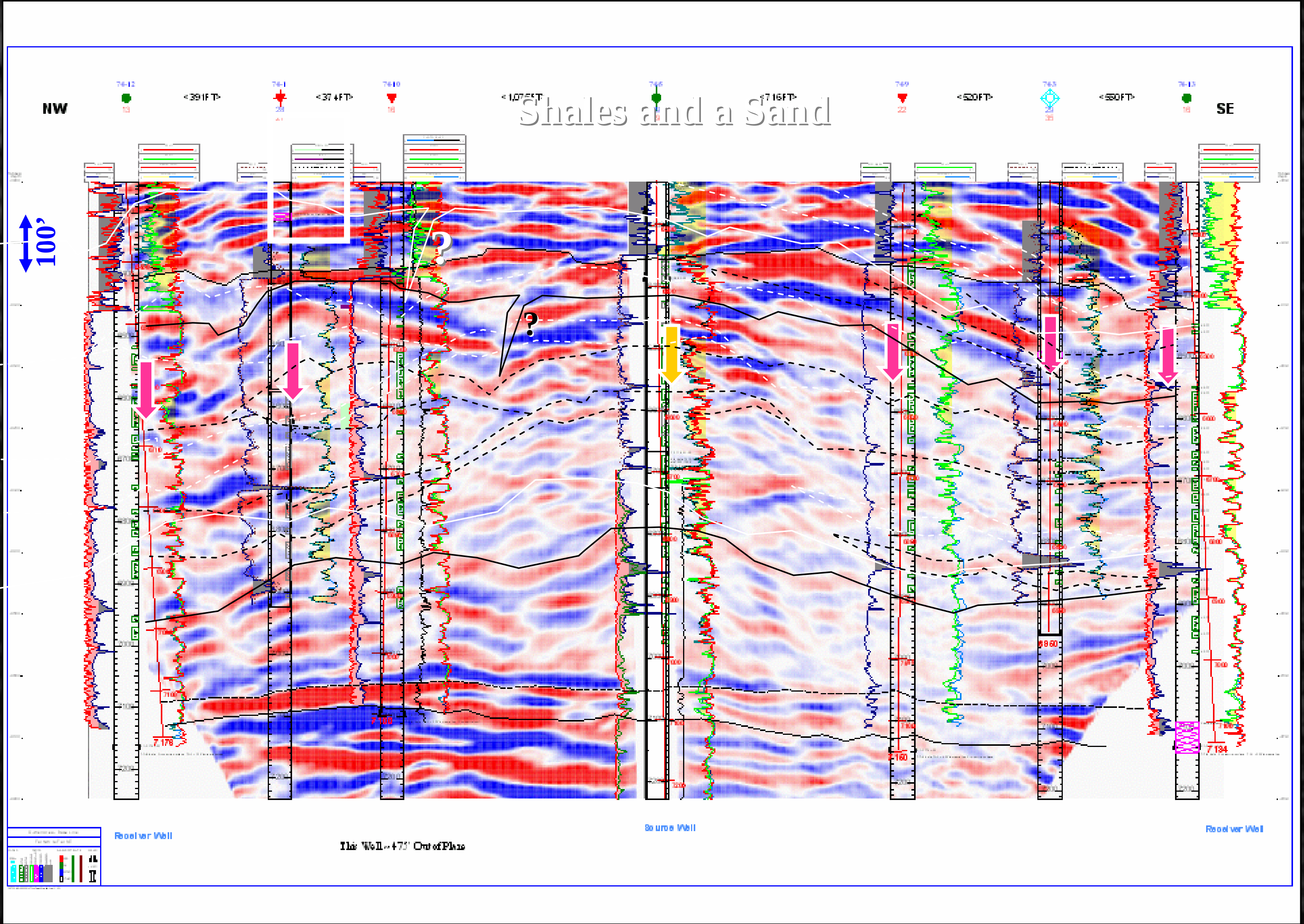
Outcrop Vs. Crosswell



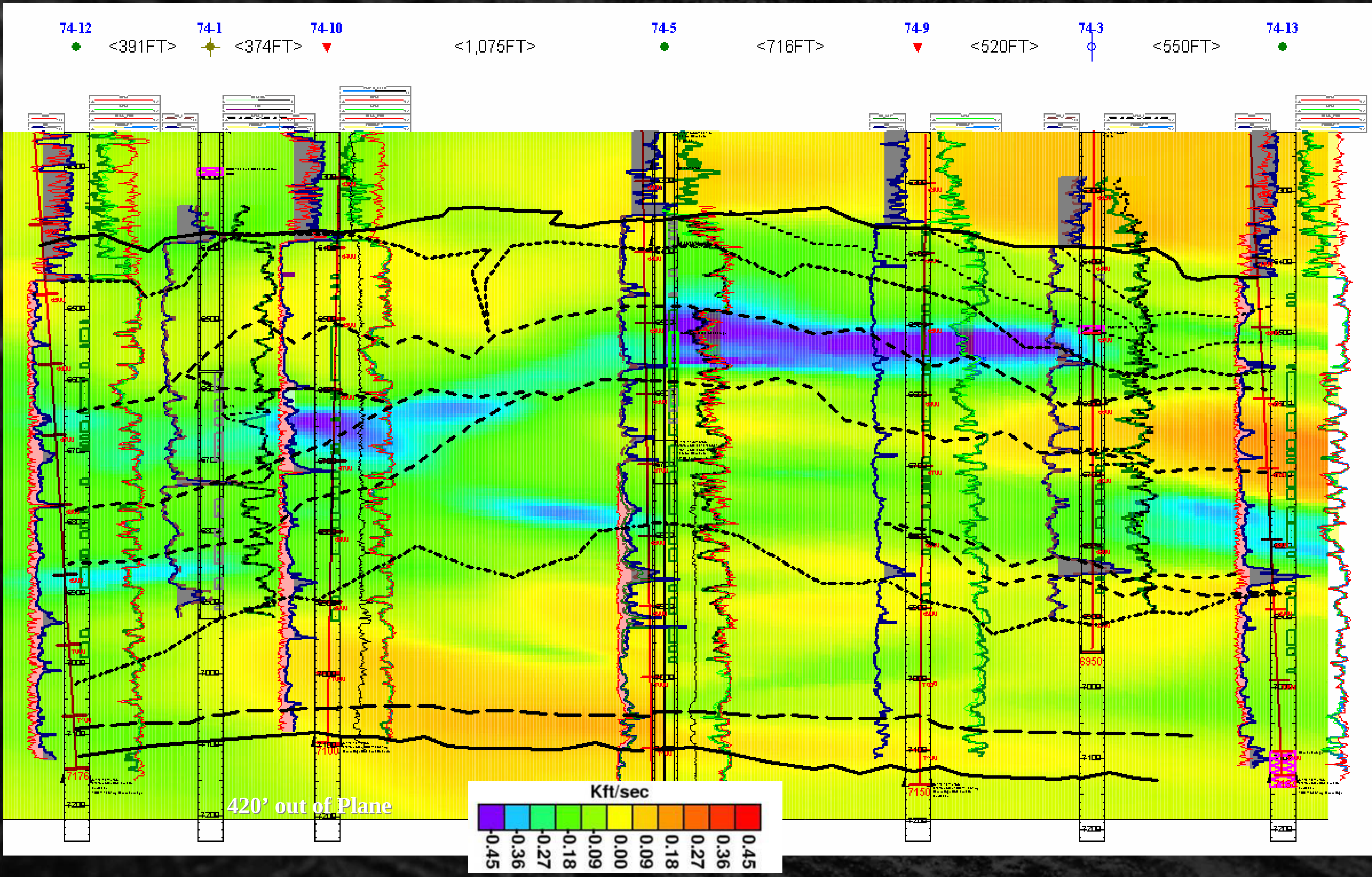




SACROC Cross-well Project

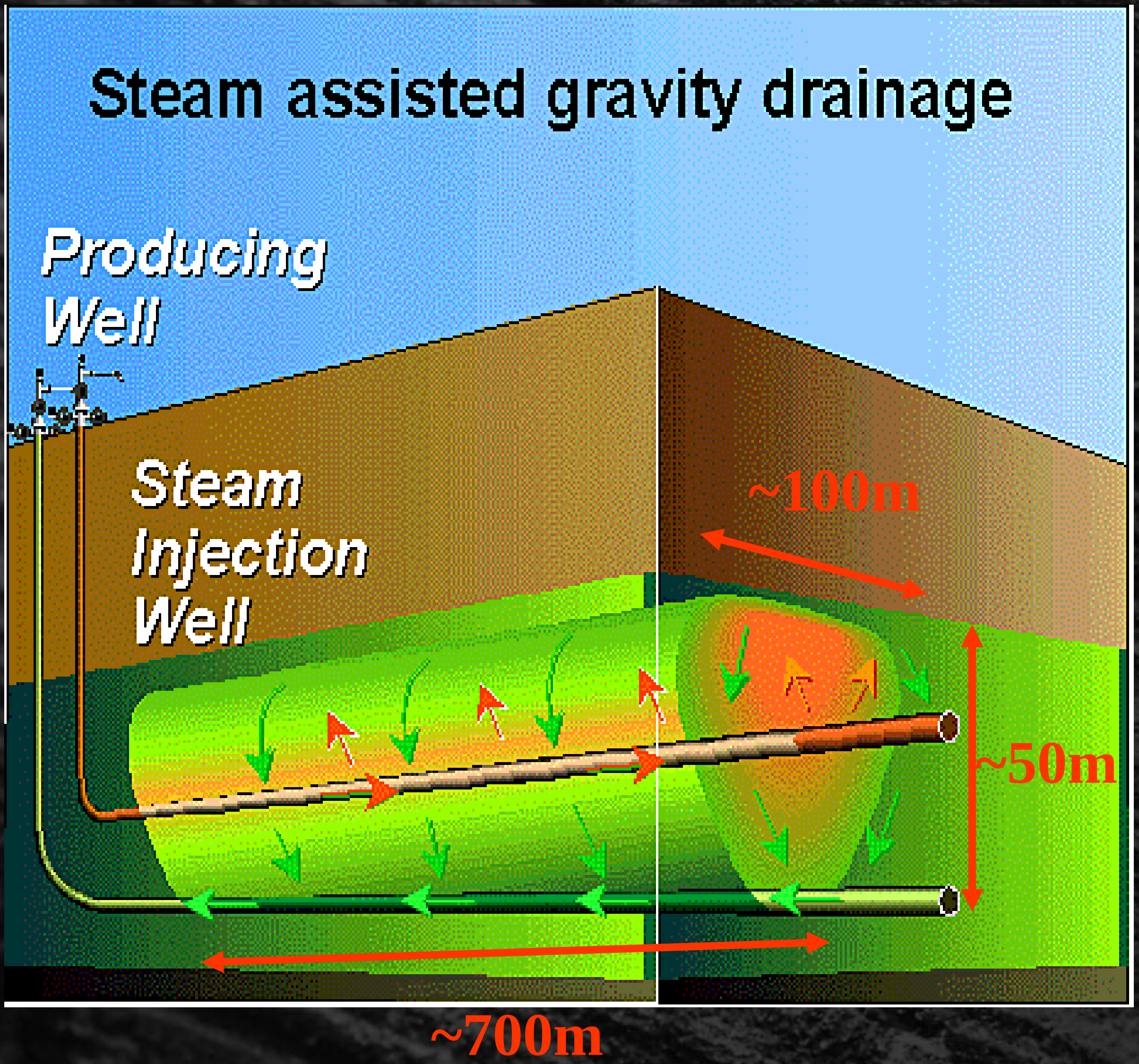


Time-Lapse (4D) Example

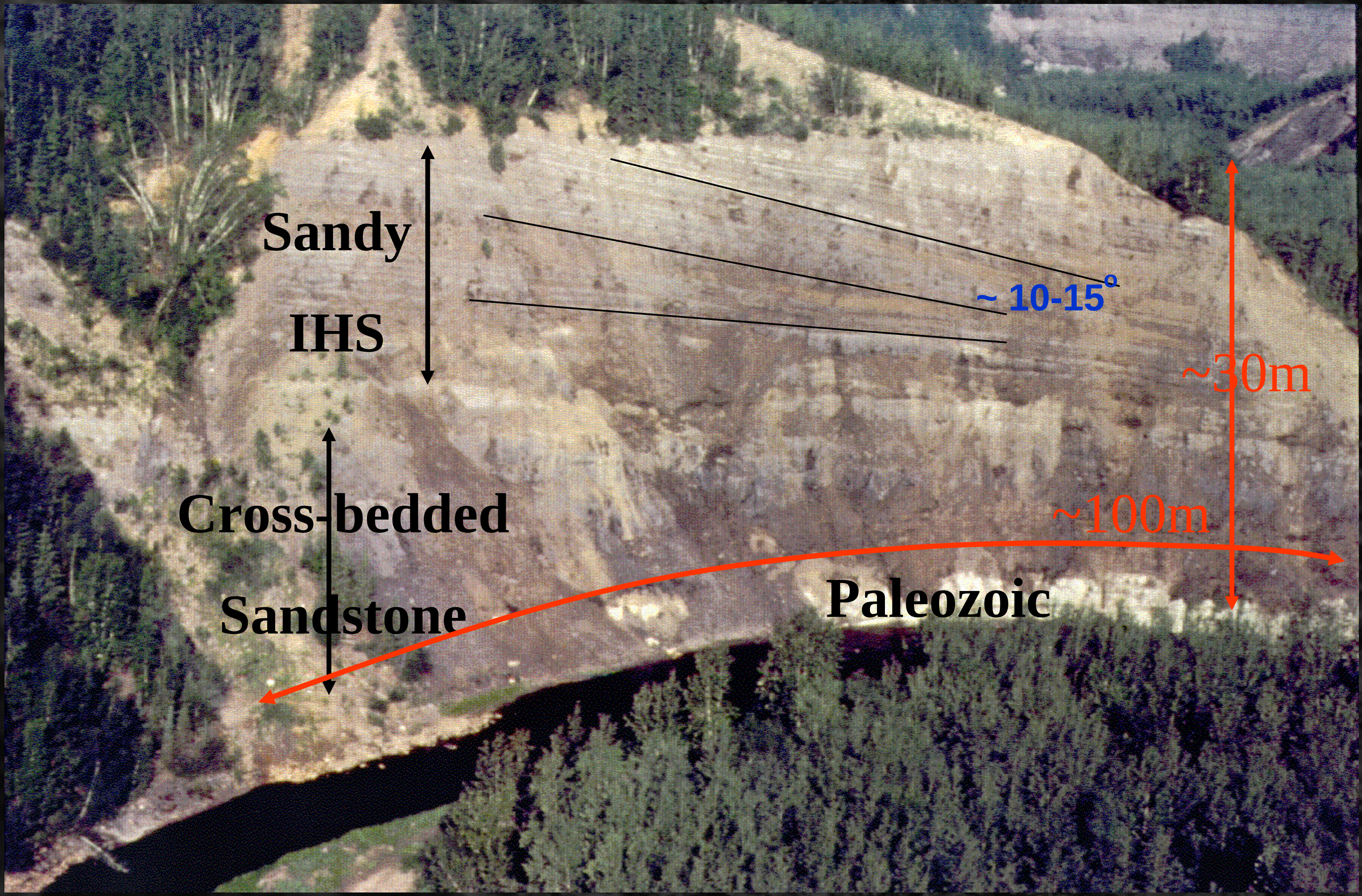


Steam Monitoring Applications

- Steam Assisted Gravity Drain (SAGD)
- Cyclic Steam Operations

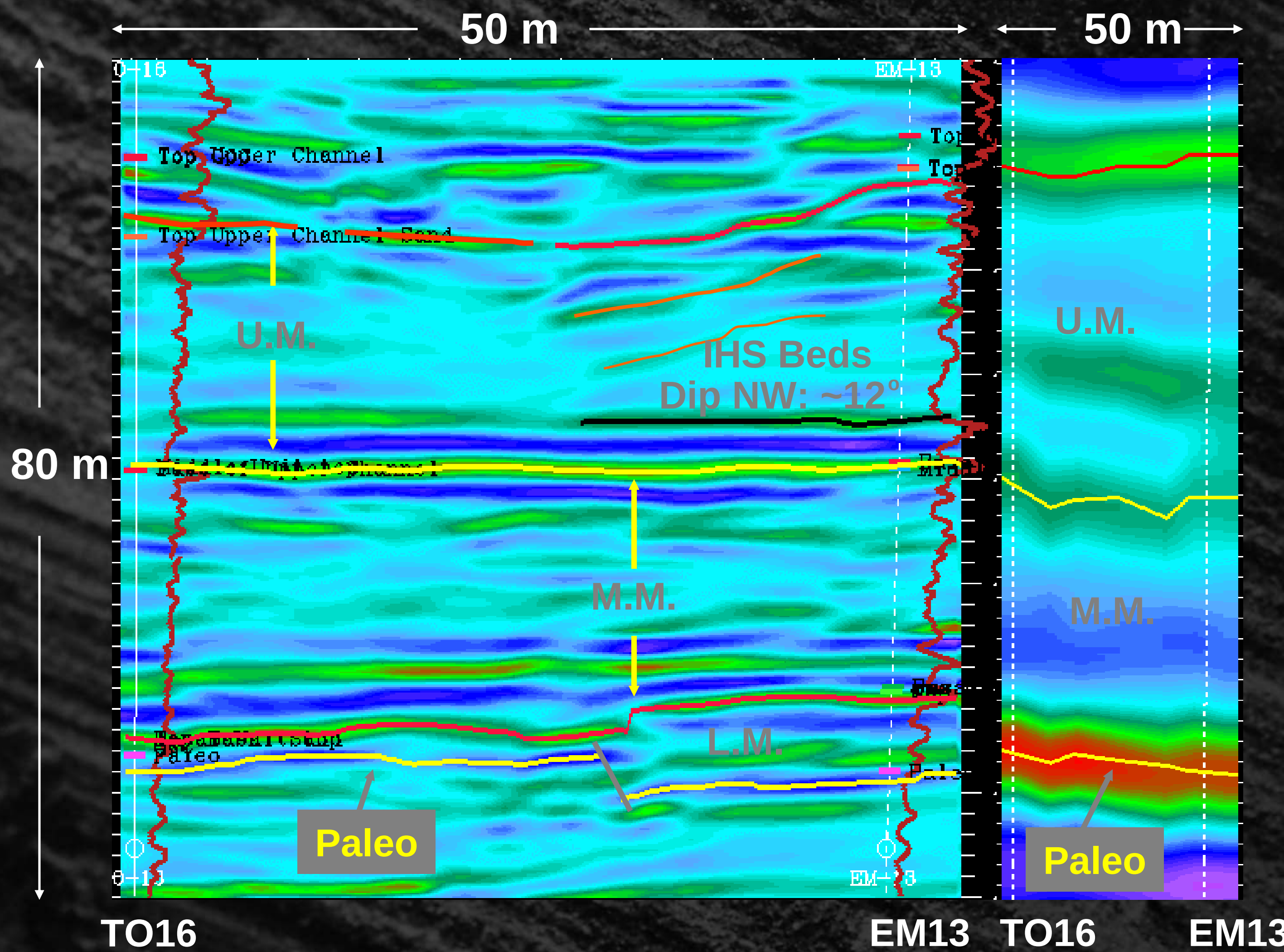

Steam assisted gravity drainage
Producing Well
Steam Injection Well
~100m
~50m
~700m

Reality: Outcrop of McMurray

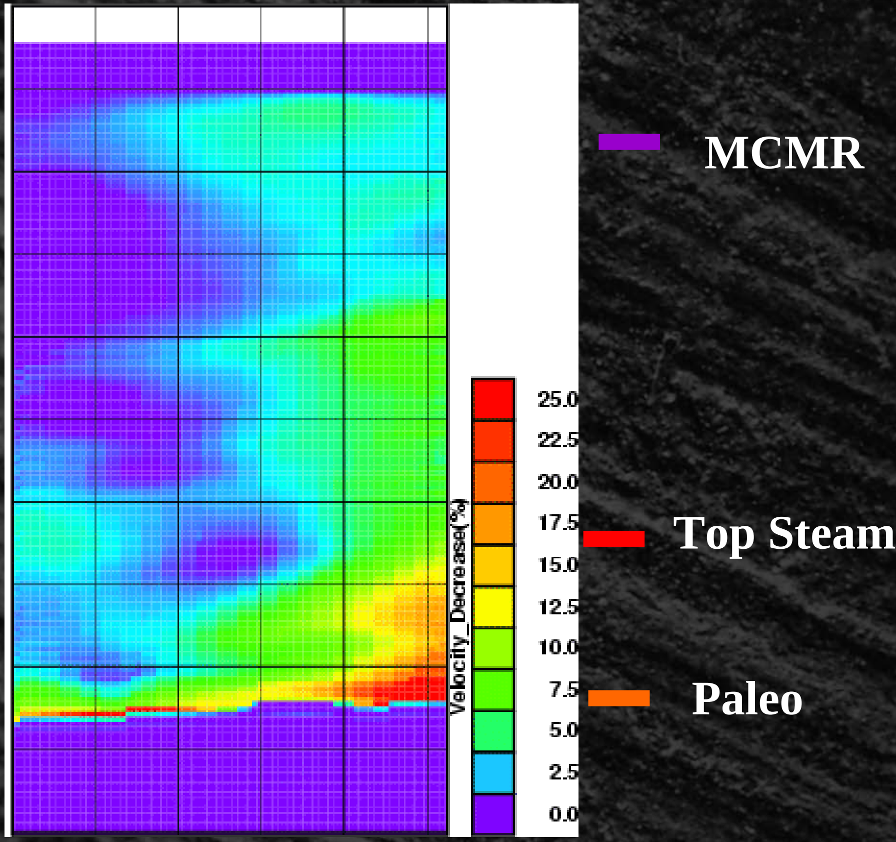


Shale Continuity / Channels

Zhang, et al, CSEG 2002

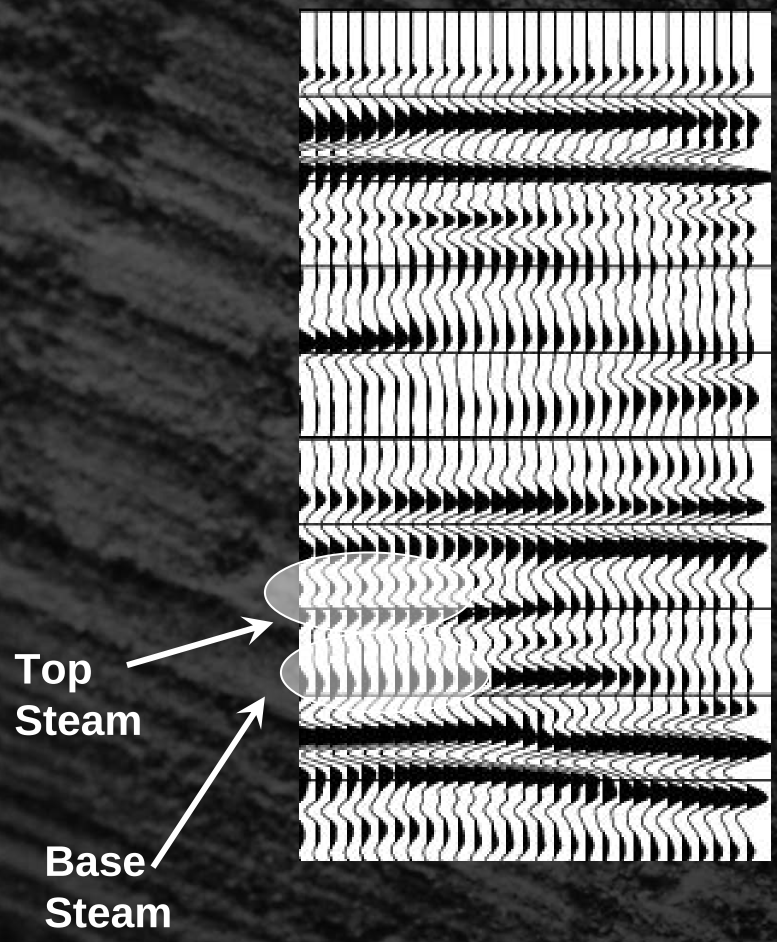


SAGD Monitoring

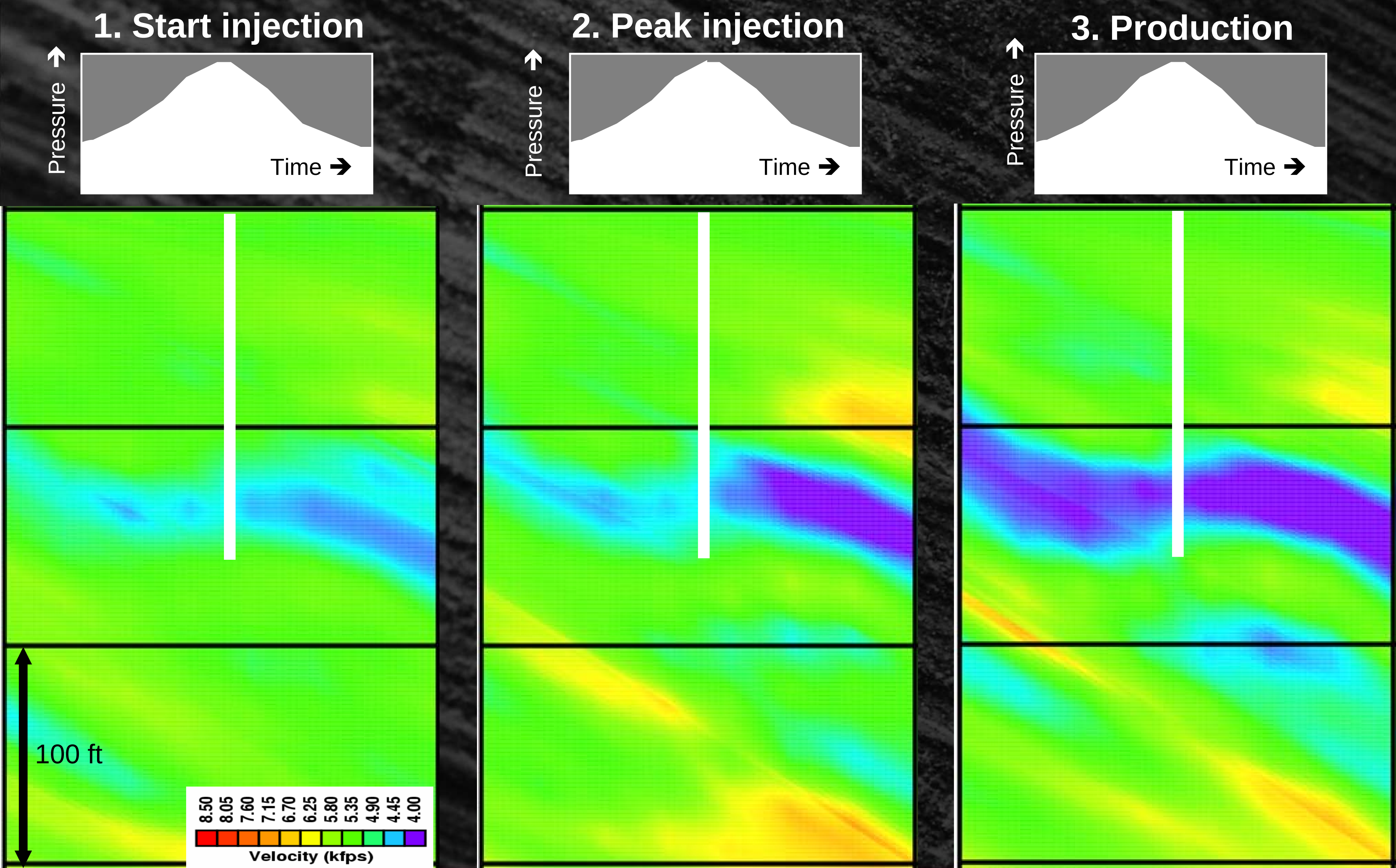


OB wells drilled only to the Paleo
Reflection tomography provides coverage

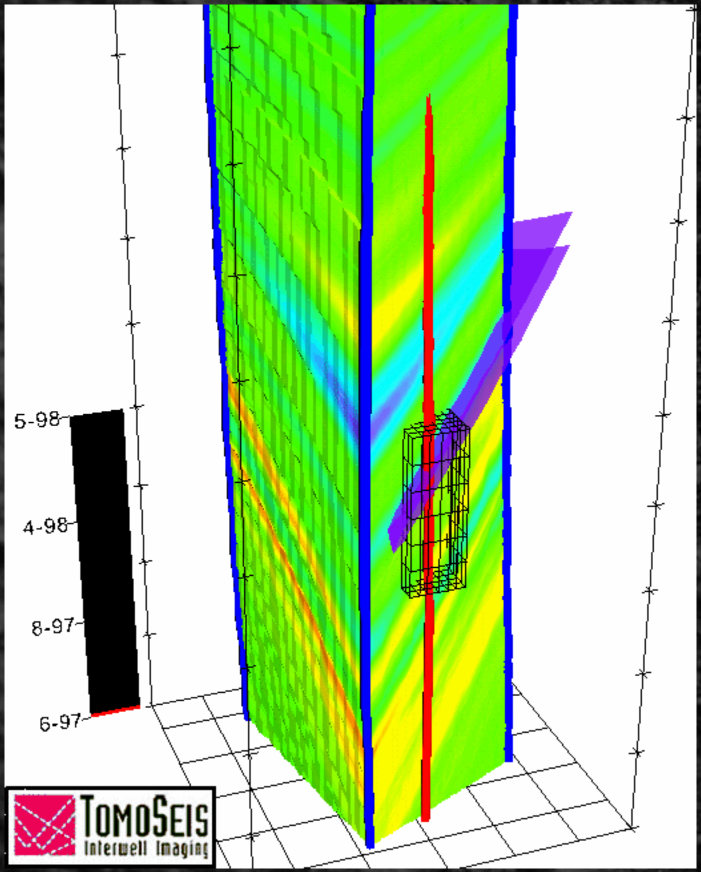
Steam Reflectivity



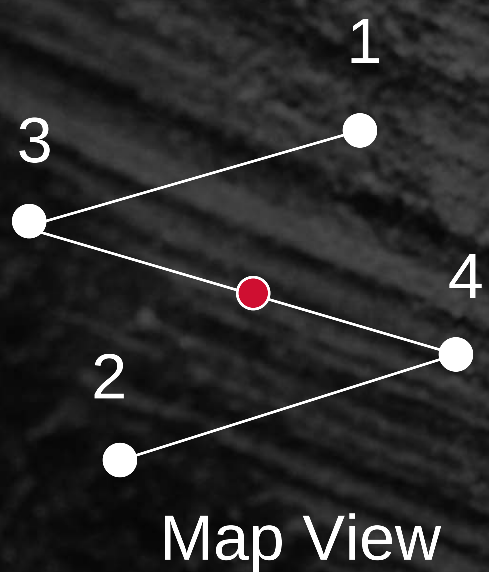
Time-Lapse Monitoring of Steam Injection

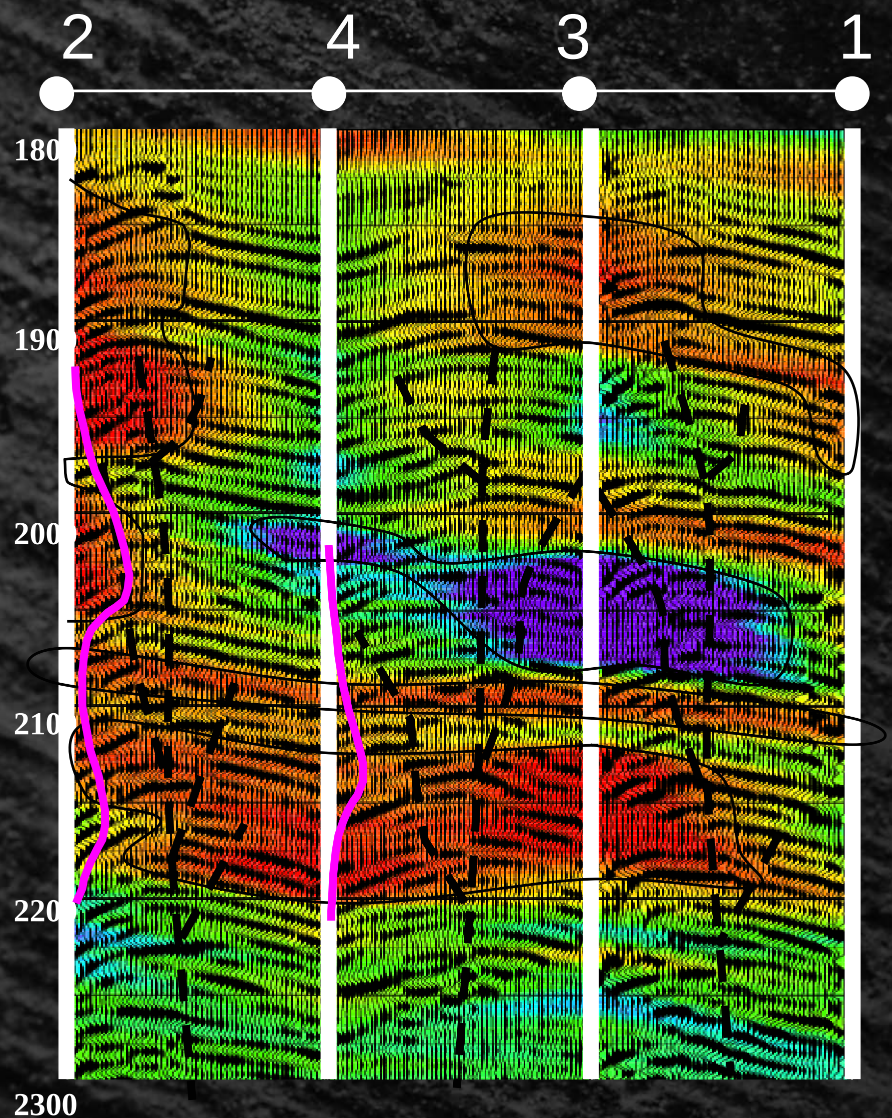


Time-Lapse Monitoring of Steam Injection



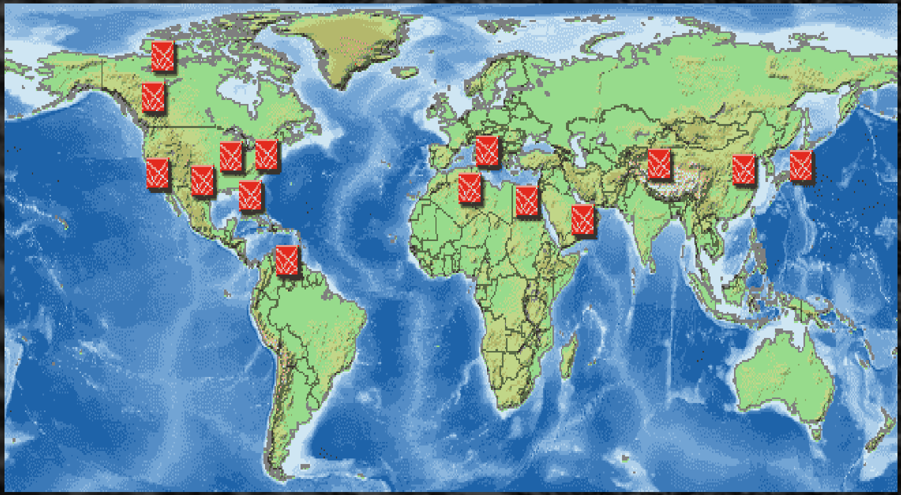
Monitoring Steam in a Faulted Reservoir





Summary

- Outcrop scale detail of reservoir architecture
- Ability to see very small changes in reservoir from optimization processes



400+ Surveys

- Crosswell is Proven and Reliable Technology

Passive Seismic Monitoring: Listening for the Snap, Crackle, Pop

Marcia Couëslan

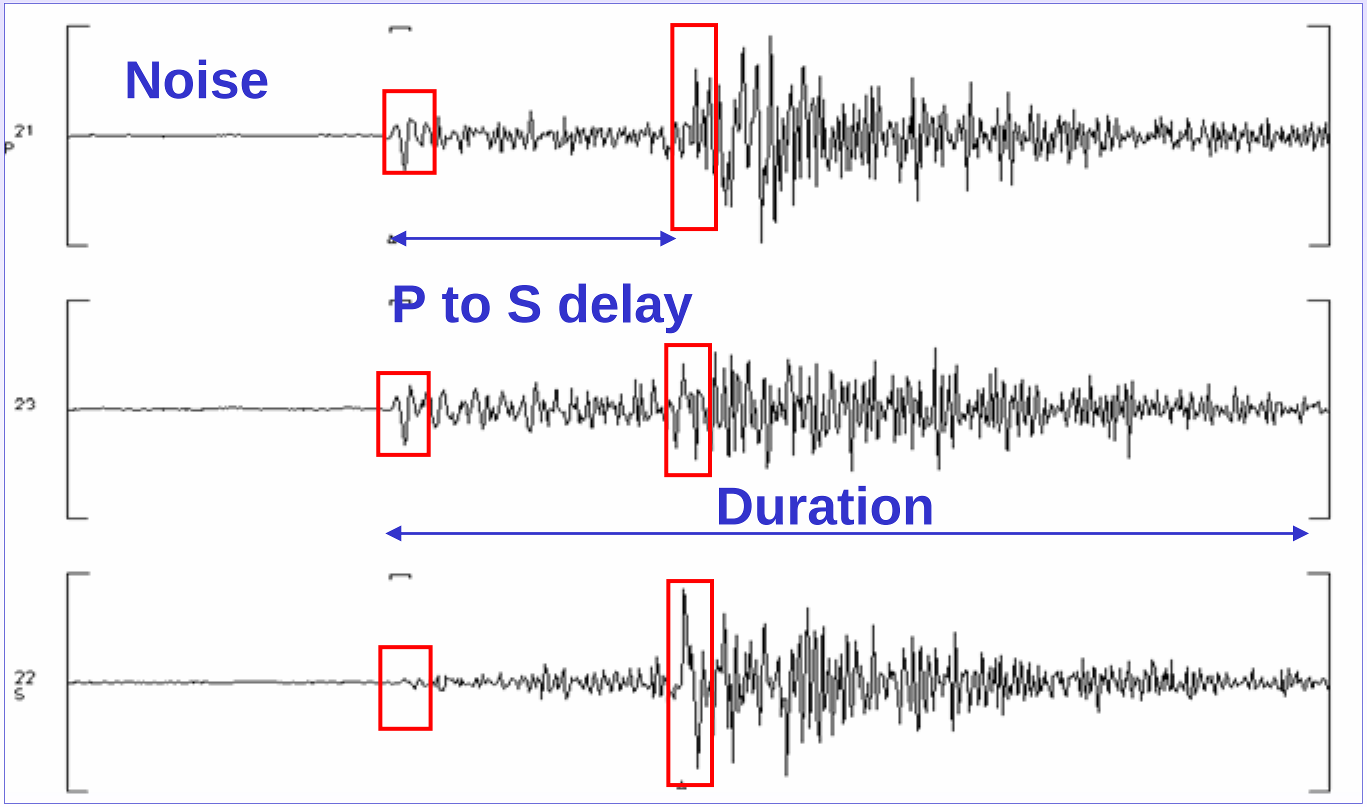
Schlumberger Carbon Services

Outline

- What is microseismic activity?
- Where else is it used?
- What causes microseismic activity & what does it tell us?
- Hardware Options
- Potential Workflow
- Integration with geomechanical modelling
- Feasibility Studies
- Conclusions

What Is Microseismic Activity?

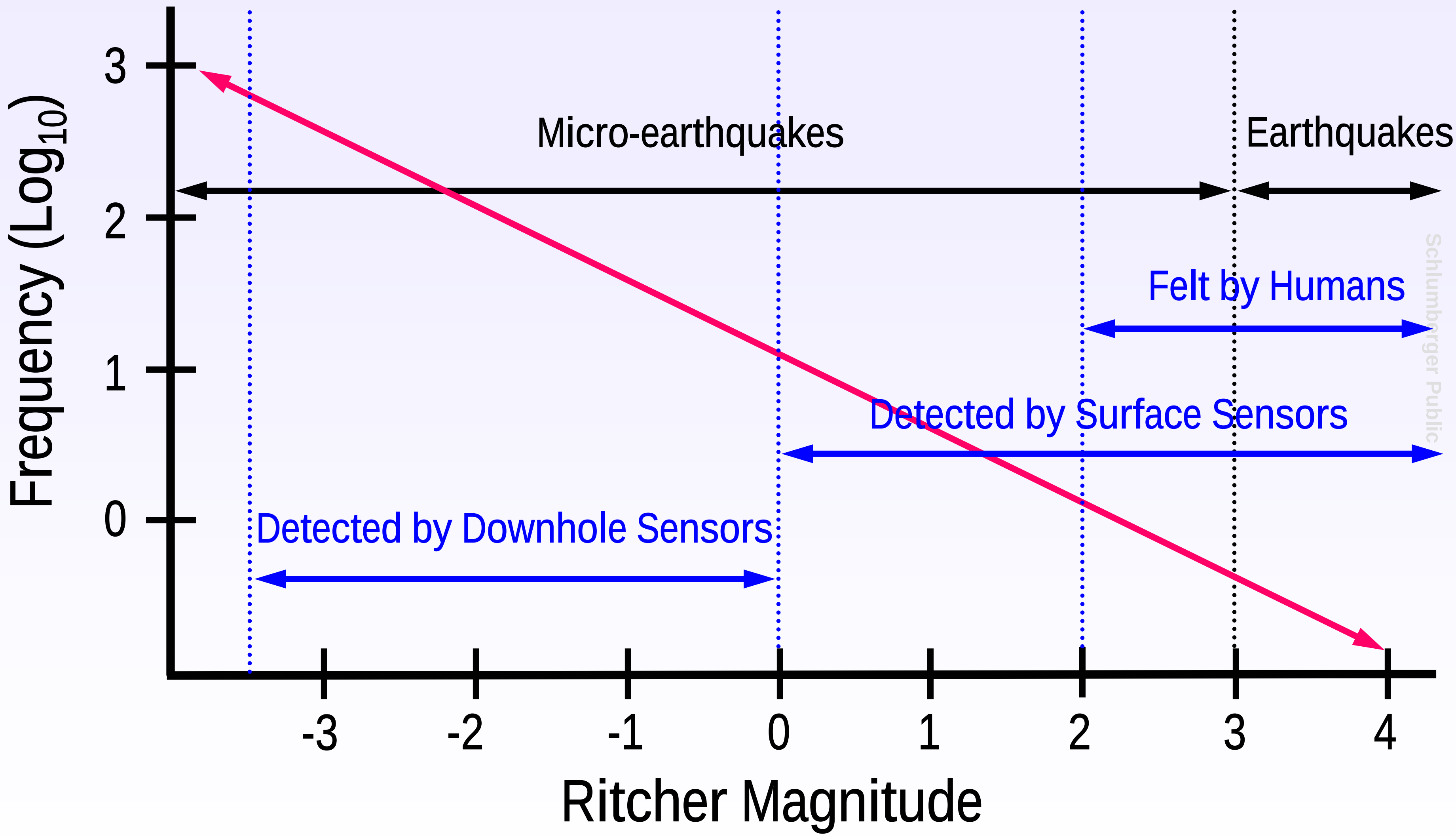
- Microseismic monitoring is based on global seismology
  - P- and S-wave arrivals are used to locate an event in x, y, z space



Schlumberger Public

Schlumberger

What Is Microseismic Activity?



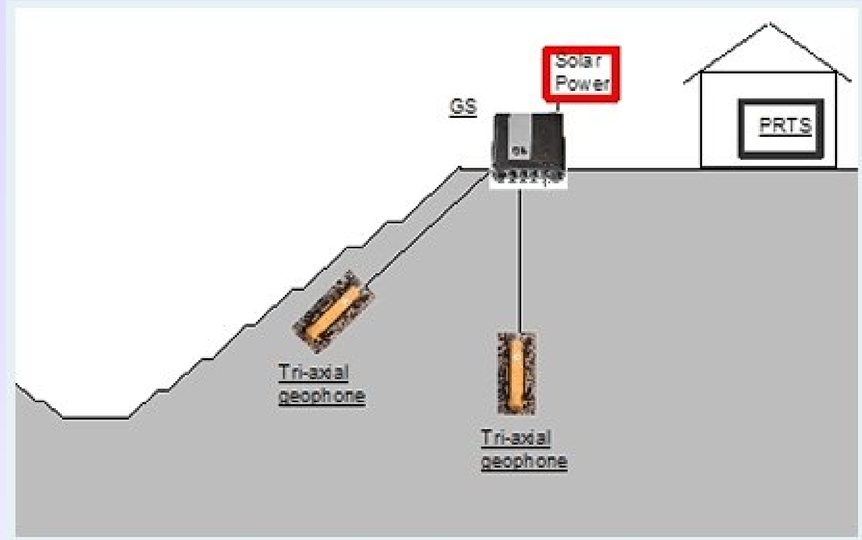
Where Else Is It Used?

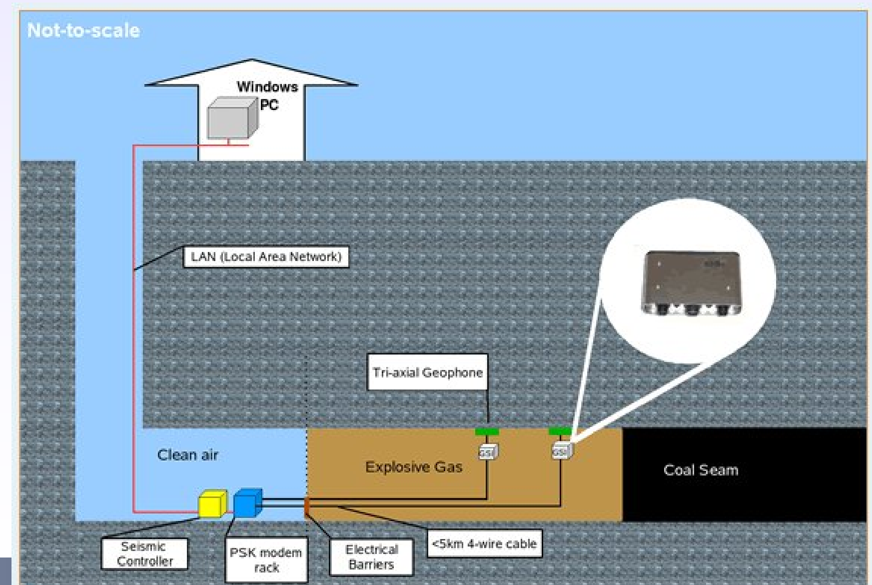
- Mining Industry
- Geothermal Industry
- Underground waste disposal
  - Could be fluids or cuttings
- Geotechnical projects
  - Slope stability, dams, tunnel stability
- Hydrofracture monitoring

Courtesy of Natural Resources Canada

Mining

- Monitor 4D stress release
- Caving
- Underground gas emissions
- Rock burst prediction
- Slope stability

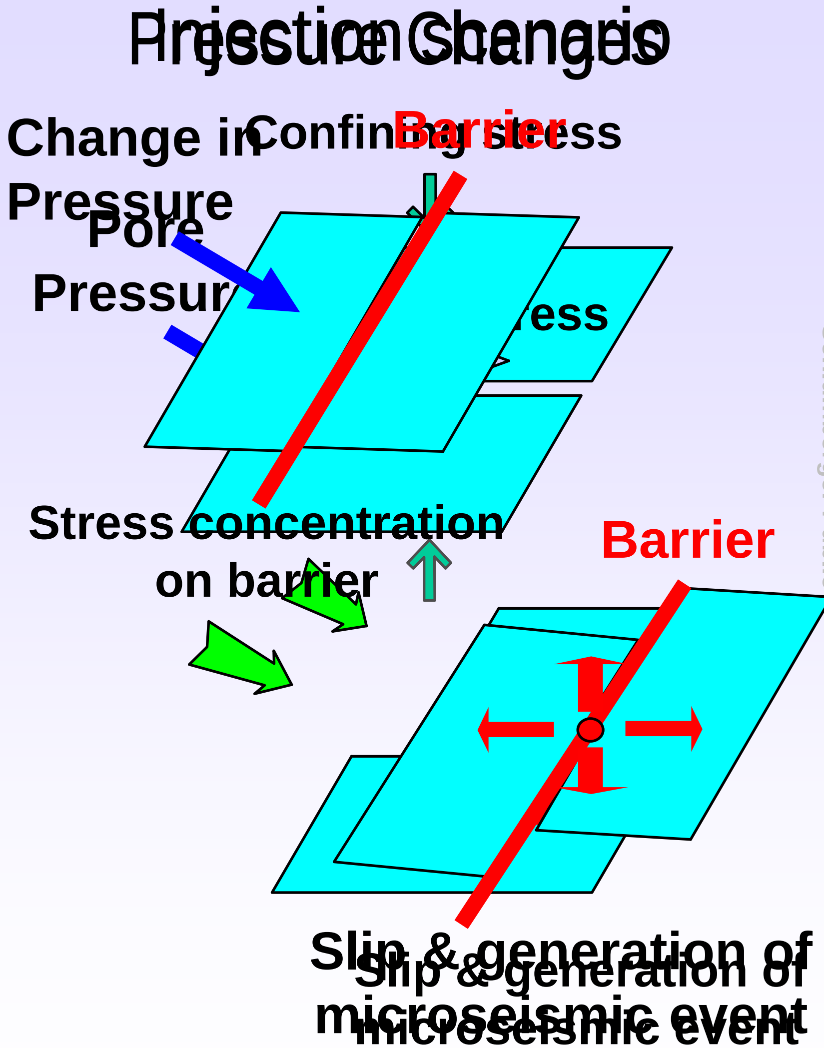




Courtesy of ISS International

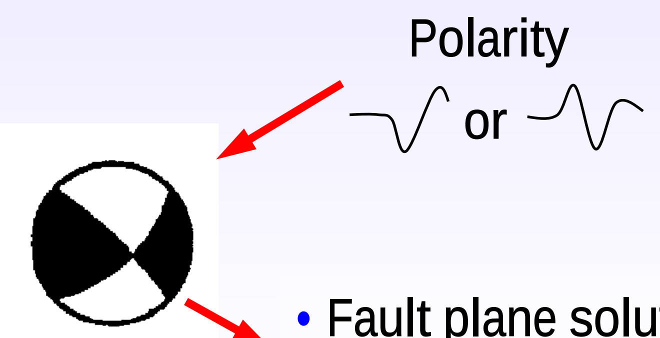
What Causes Microseismic Activity?

- Associated with brittle deformation
- Caused by stress changes related to production or injection
- Events may occur on failure surfaces such as faults and fractures
- May be related to stress transfer to the surrounding rock bodies

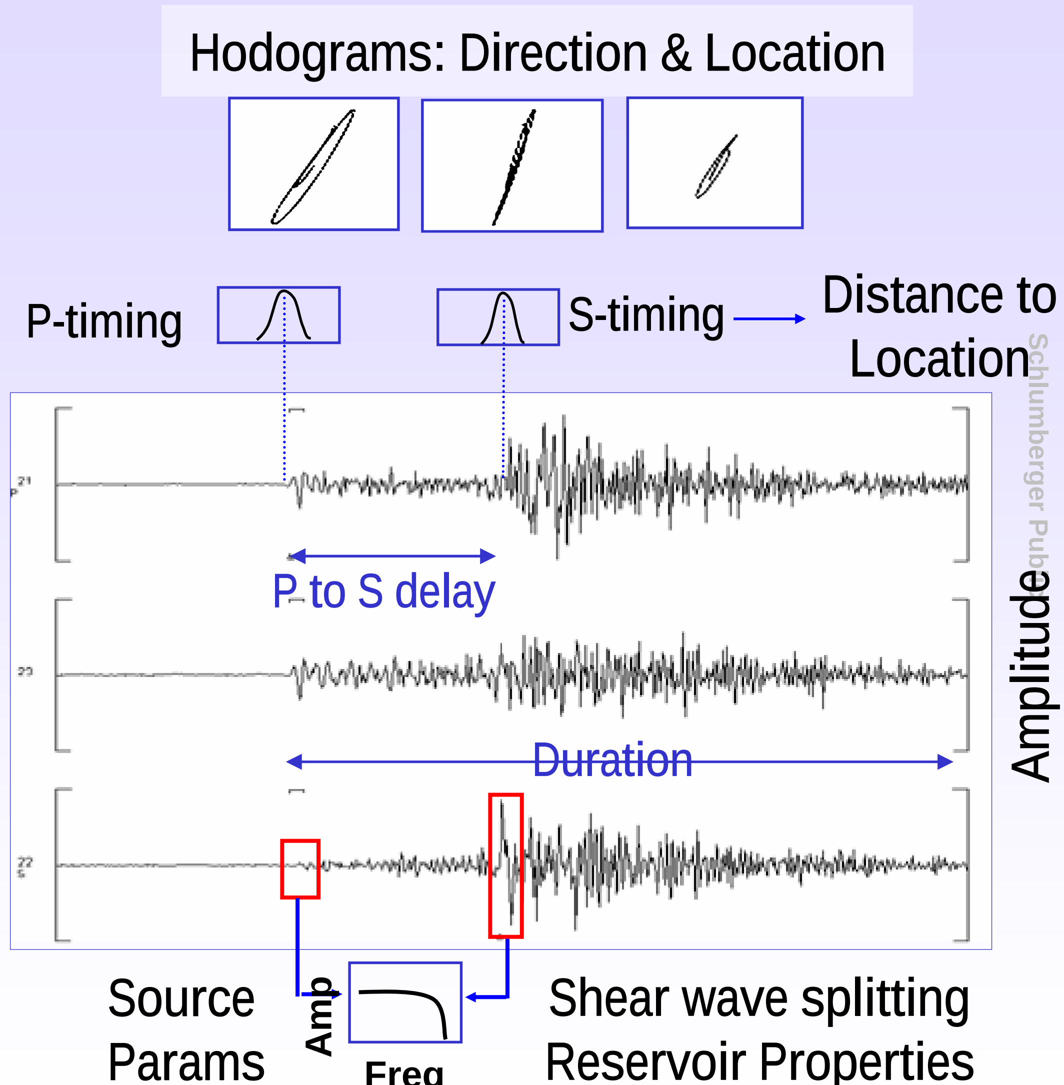


Potential Reservoir Information

- Event location
- Orientation of failure surface
- Mode of failure
- Shear wave source



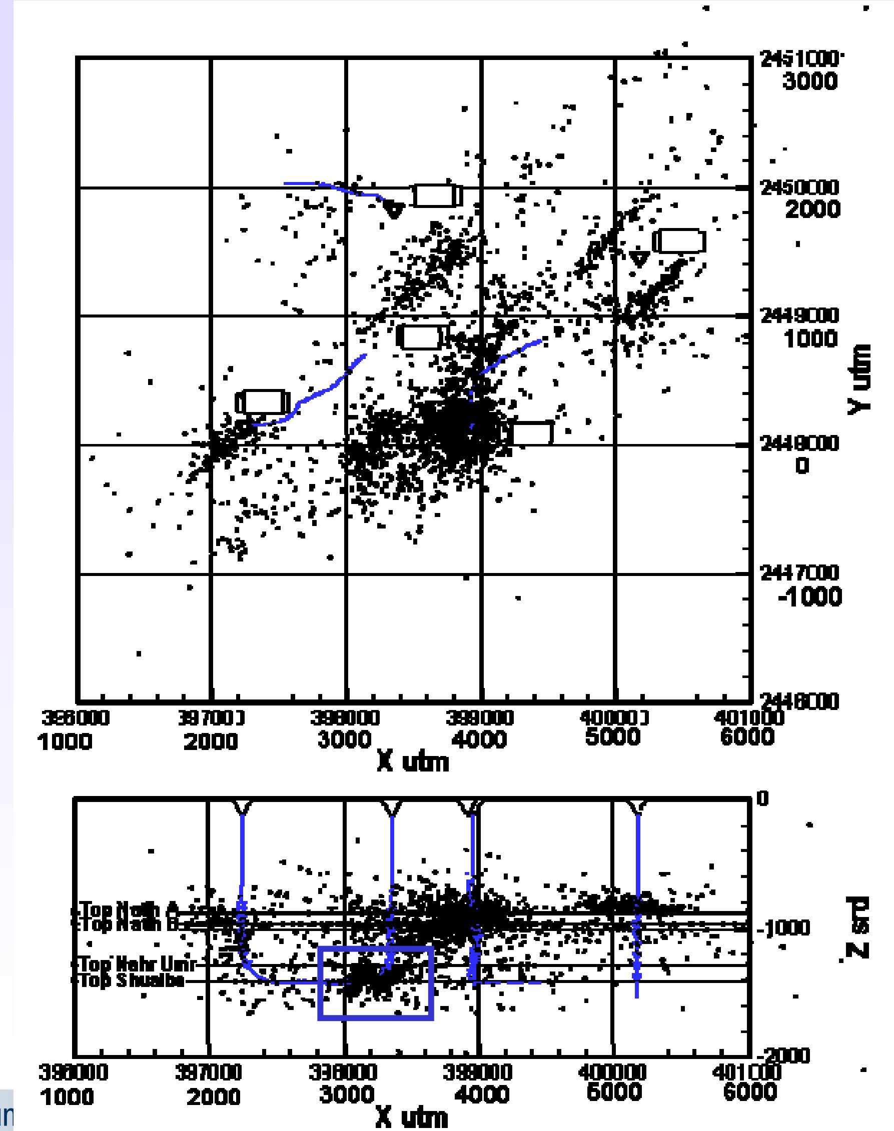
- Fault plane solutions
- Fracture orientation

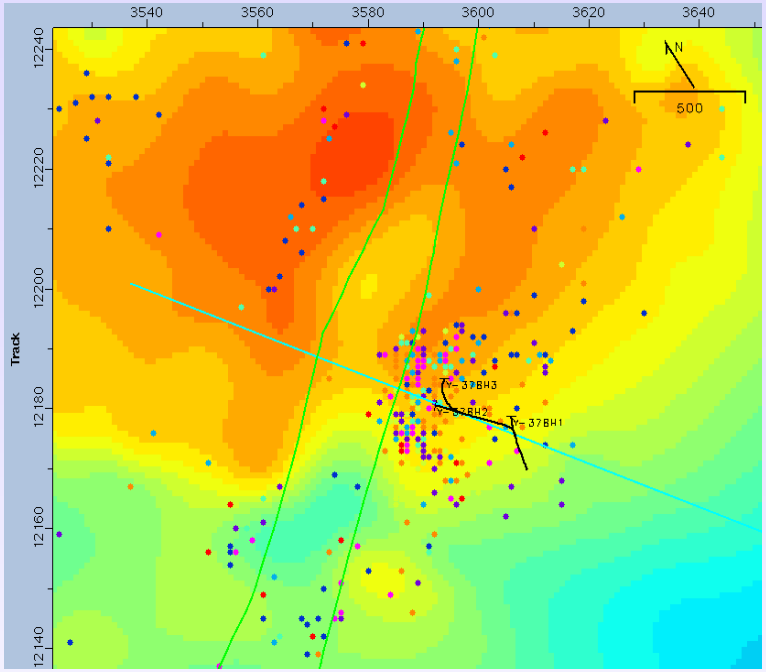


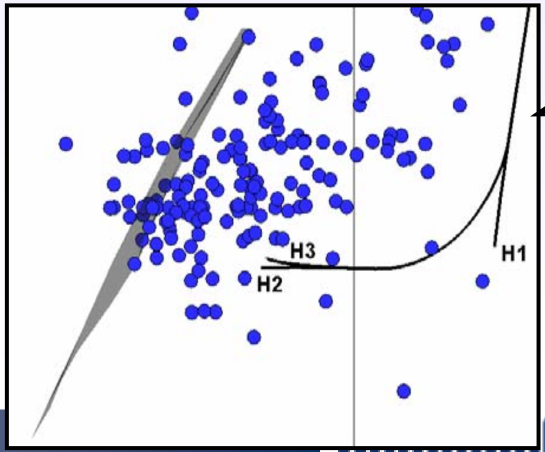
What Can We Monitor With It?

- Cap rock integrity
- Fault/ fracture re-activation or propagation
- Can reveal fractures and compartments on a sub-seismic scale
- Fault transmissibility
- May image the pressure fronts associated with fluid movement
- Monitor deformations that may result in well integrity problems

What Can We Monitor With It?



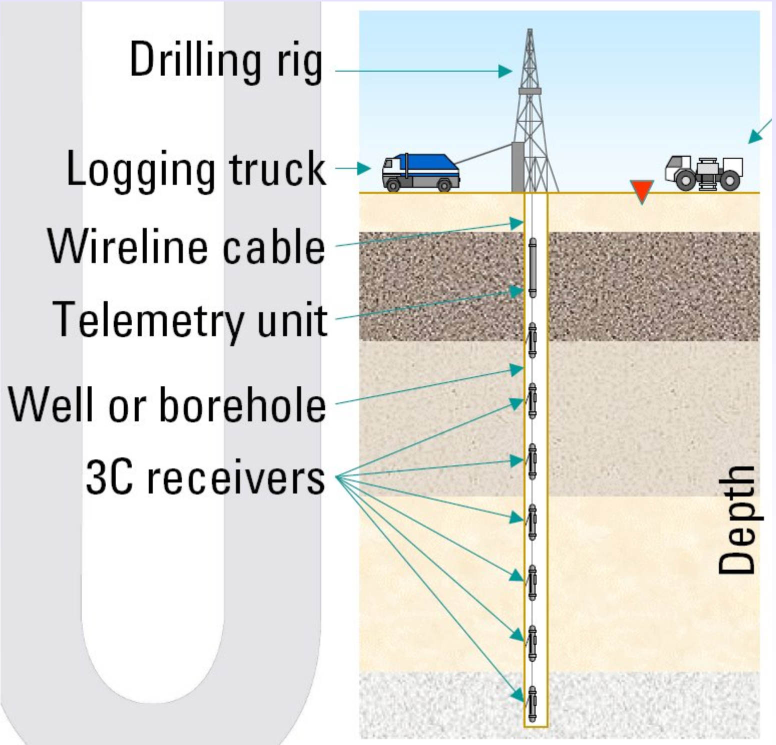




Injector

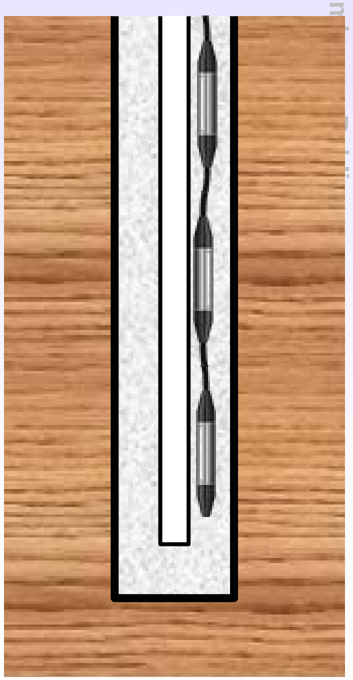
Hardware Options

- Seismometers at the surface
- Geophones in monitor wells: temporary to permanent

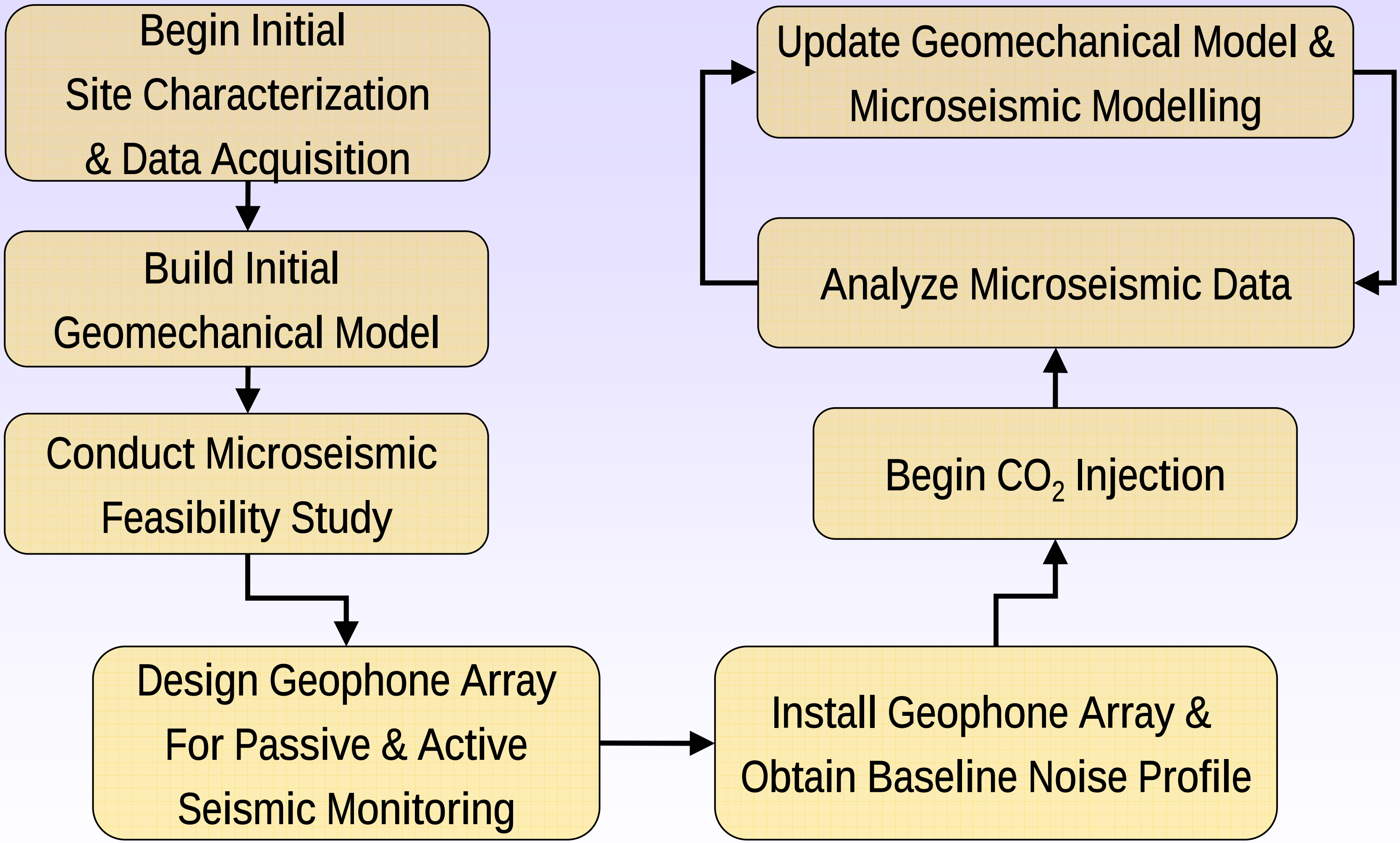


PS³ Semi-permanent

Cemented



Potential Workflow



Integration With Geomechanics

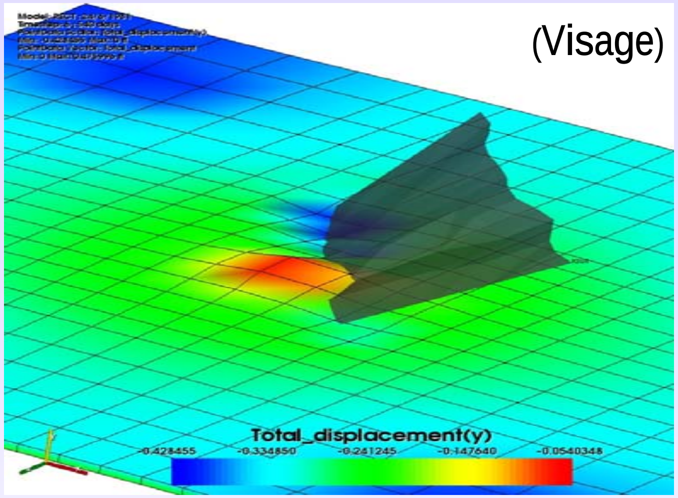
Geomechanical modelling can:

- Predict stress changes with time
- Estimate future fault activity
- Risk analysis for wellbore stability

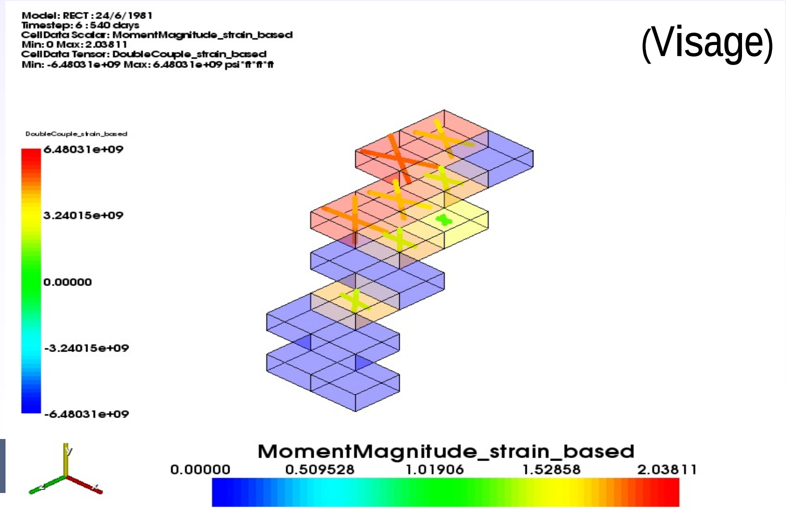
Microseismic data can:

- Verify & update geomechanical models
- Map how stress tensors change with time
- Indicate fault re-activation or generation

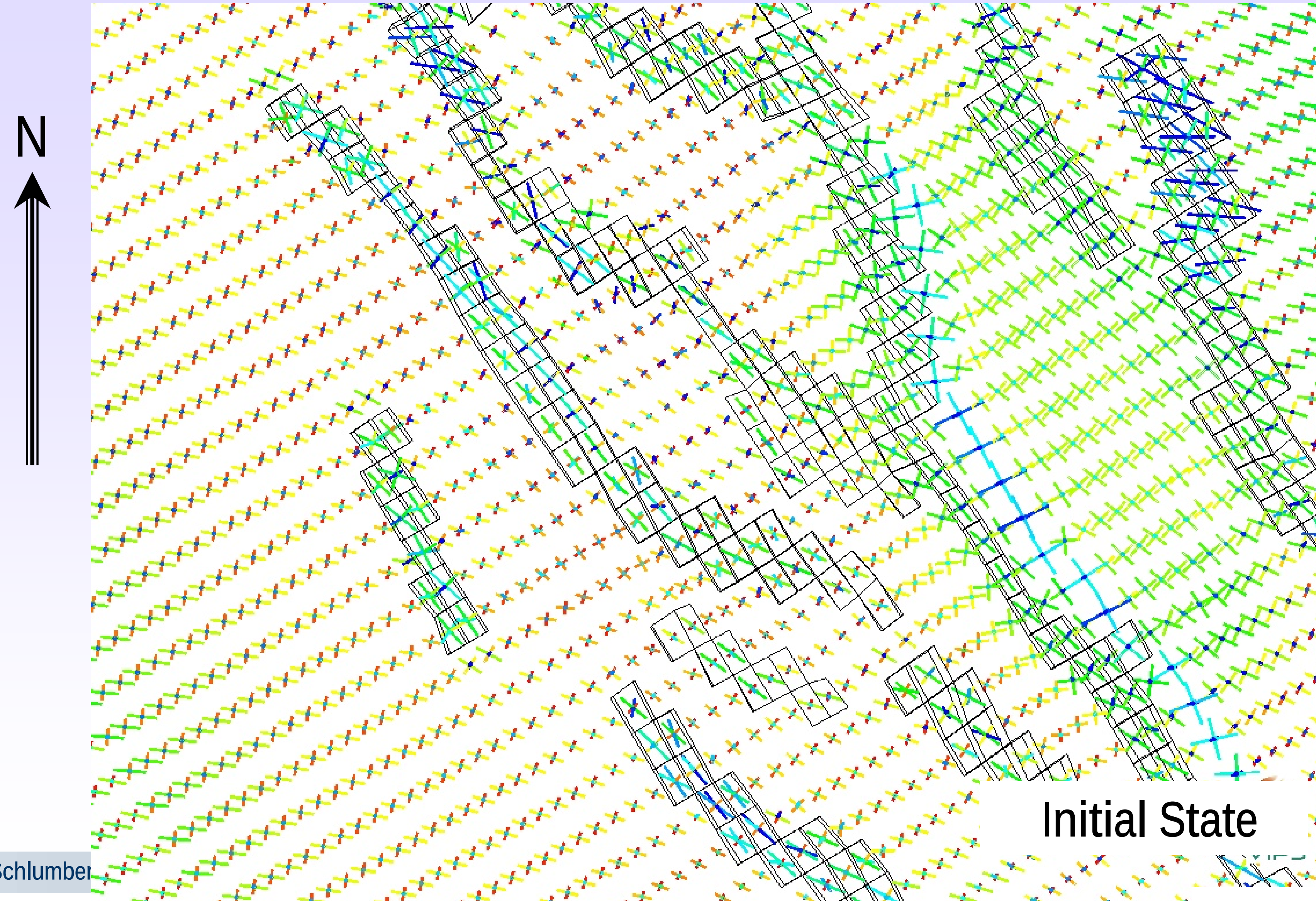
Vertical displacement



Moment magnitude

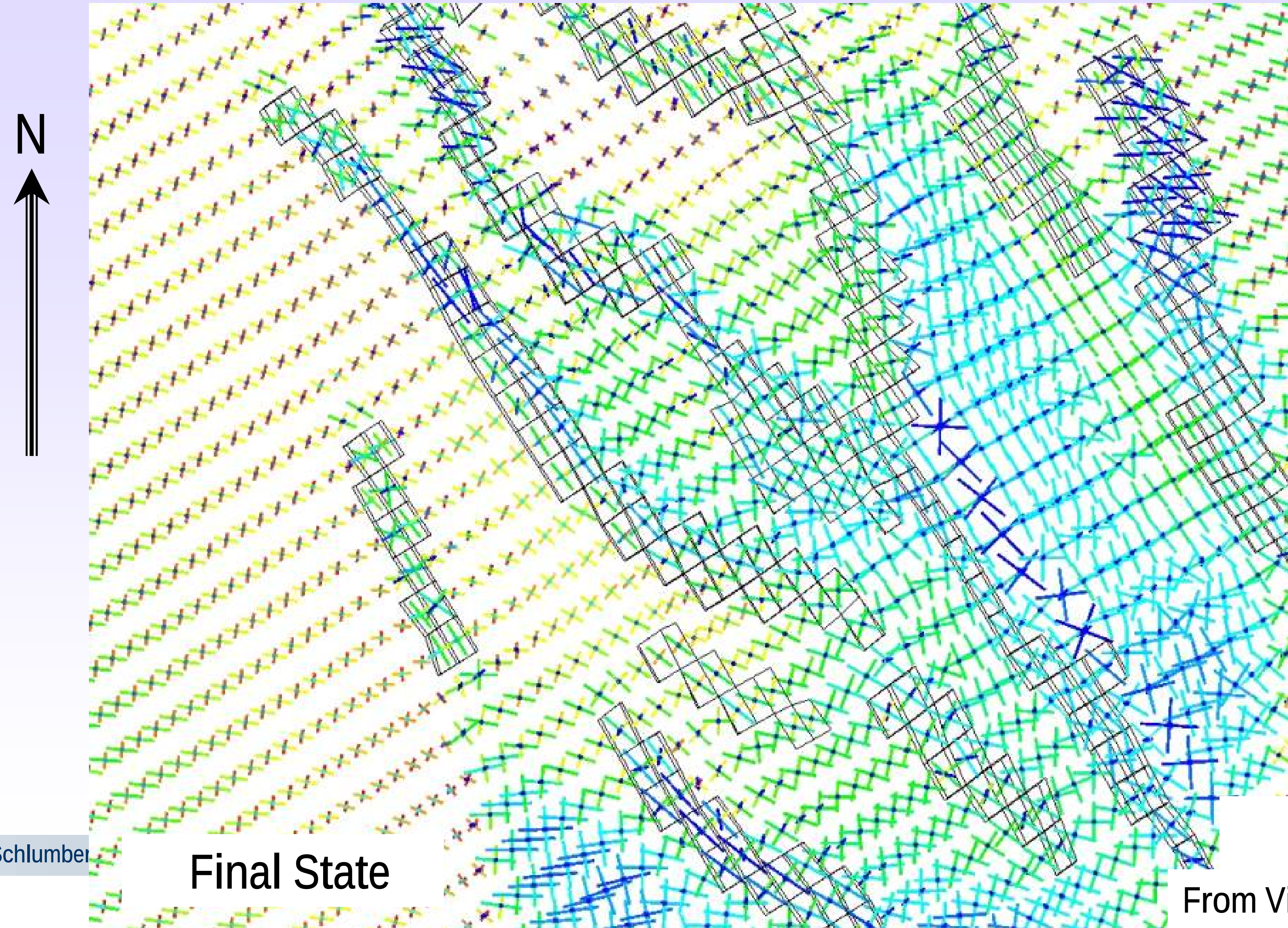


Initial Stress Orientation



From Visage

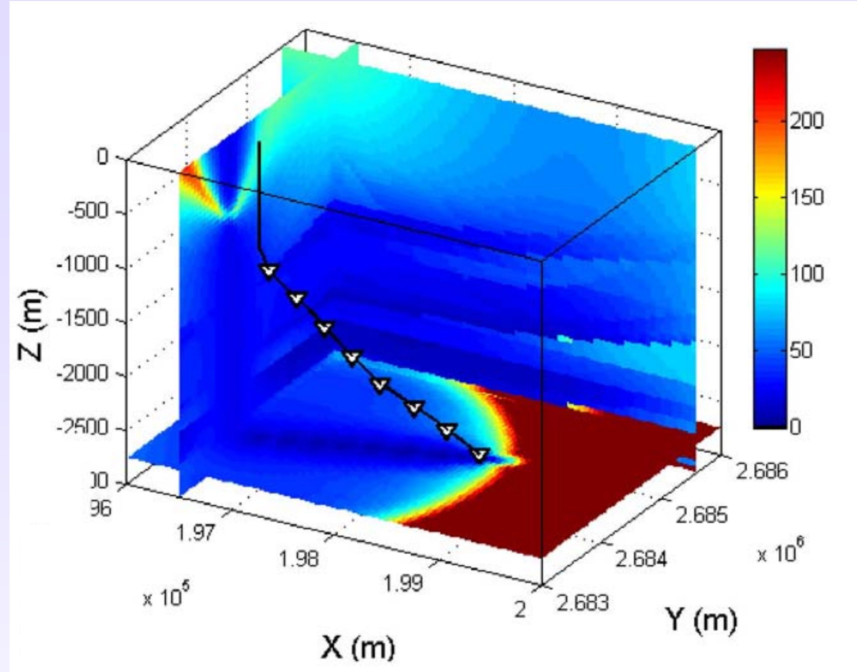
Change in Stress Orientation

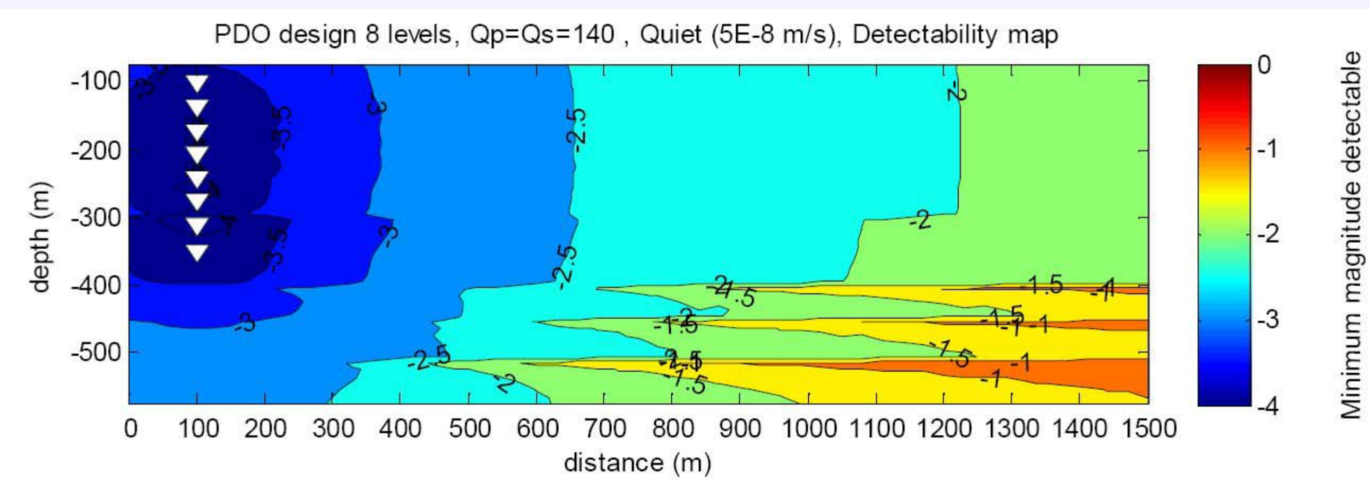


From Visage

Feasibility Studies

- Geomechanical model
- Requires velocity model, well trajectory, operational info, etc
- Modelling can determine
  - Potential size of events detected with distance
  - Uncertainty in positioning



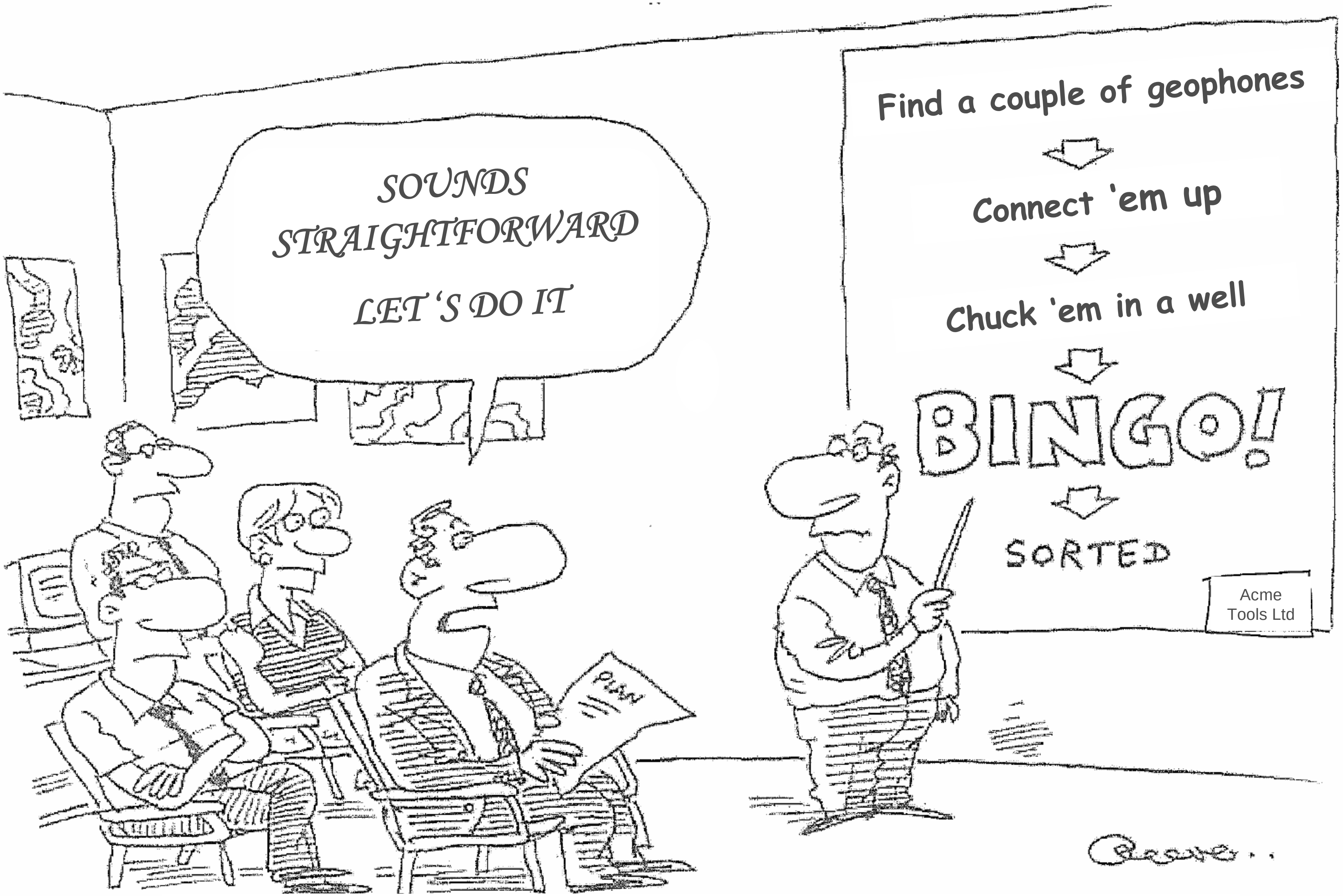


Conclusions

- Microseismic monitoring is an established technology in a number of other industries
- Microseismic installations can effectively be deployed to monitor a range of activity at CO_2 storage sites
  - Cap rock integrity
  - Illumination of sub-seismic features
  - Re-activation or propagation of faults/fractures
- Microseismic monitoring should be used in conjunction with geomechanical modelling
- Feasibility studies should be completed to ensure that the microseismic monitoring system meets objectives

Acknowledgements

- Rob Jones and Stephen Wilson, Schlumberger
- Mike Kendall, University of Bristol
- Thomas Bérard, Schlumberger Carbon Services
- Robert Newman & Nick Koutsabeloulis, SLB Geomechanics Centre of Excellence (formerly VIPS)



New Permanent Technology development meeting (Acme Tools Ltd)

Employing Novel MMV Technology Integration Techniques To Increase Accuracy of Injection Monitoring

Eric Davis

11/9/2007

Pinnacle

A CARBO Company

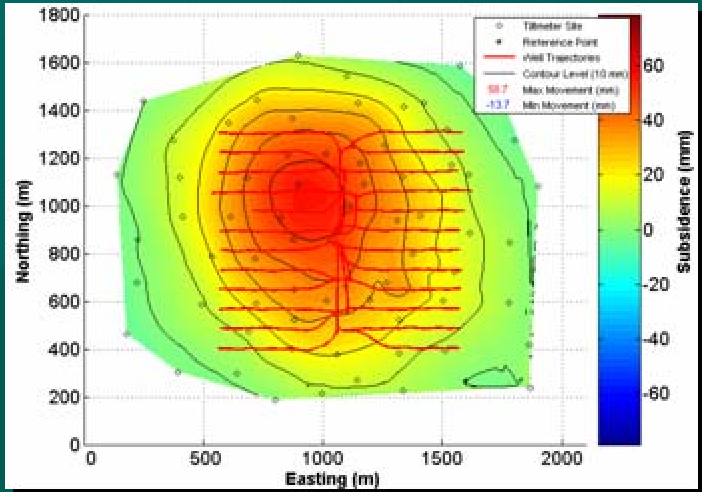
Goal of monitoring:

- The goal of any monitoring program is to constrain as much as possible the set of potential events downhole.
- More constraints are always better, but the result is only useful if an uncertainty is associated with each constraint.

Tilt Monitoring Integrated with GPS

Pinnacle

- Tilt provides by far the highest precision deformation measurements and is the most common deformation monitoring tool.
- The uncertainty of a tilt based solution increases with time.
- Tilt measures the deformation gradient. Integrating back to deformation involves assumptions about areas without tools.



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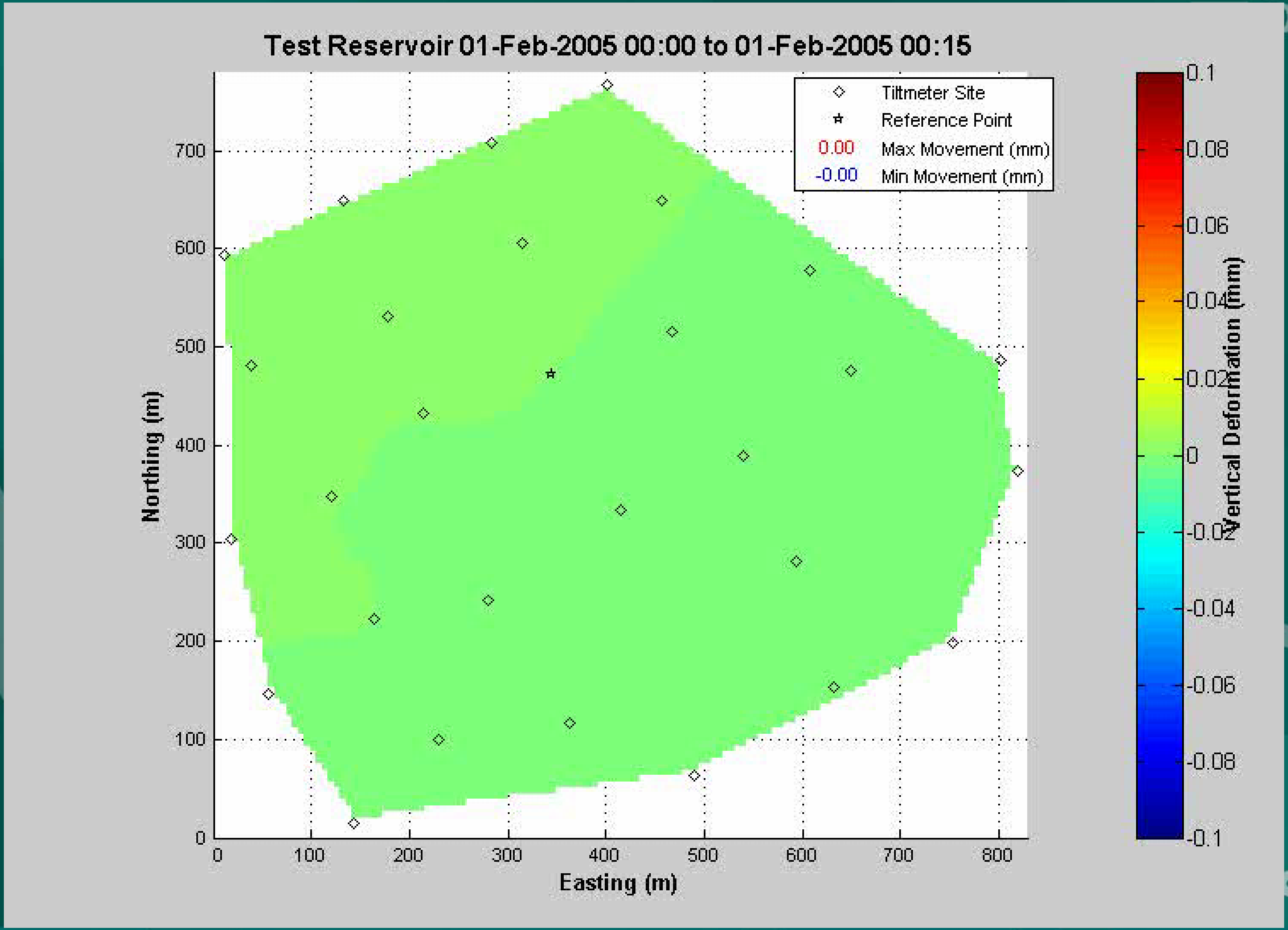
Solid Earthtides



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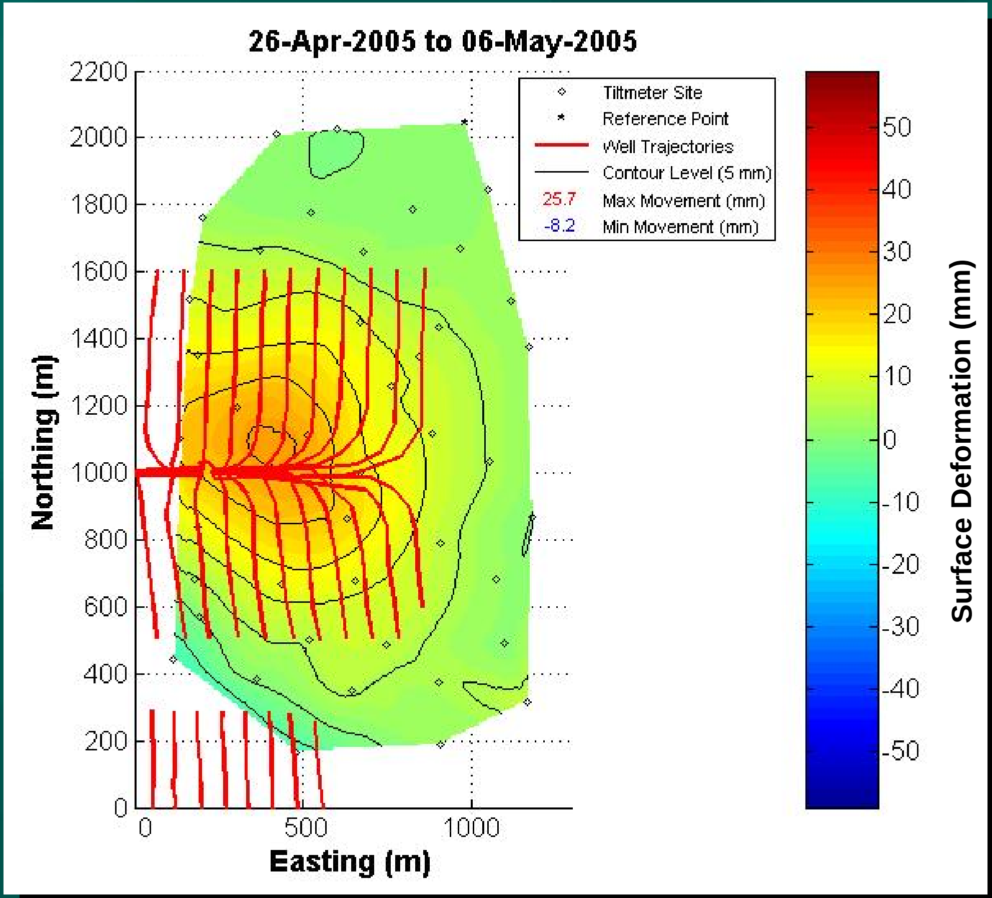
Tilt-Based Deformation Monitoring

Pinnacle



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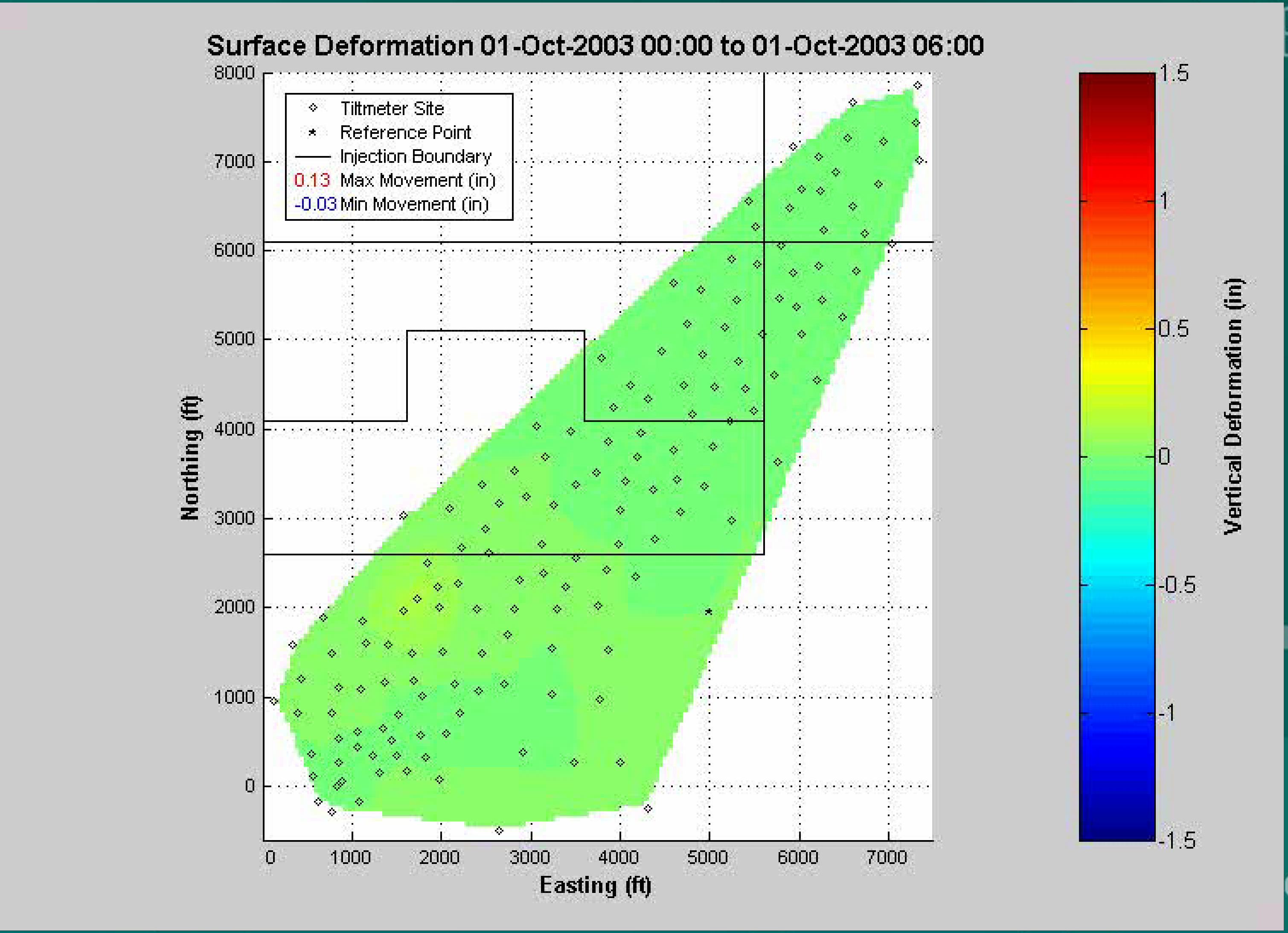
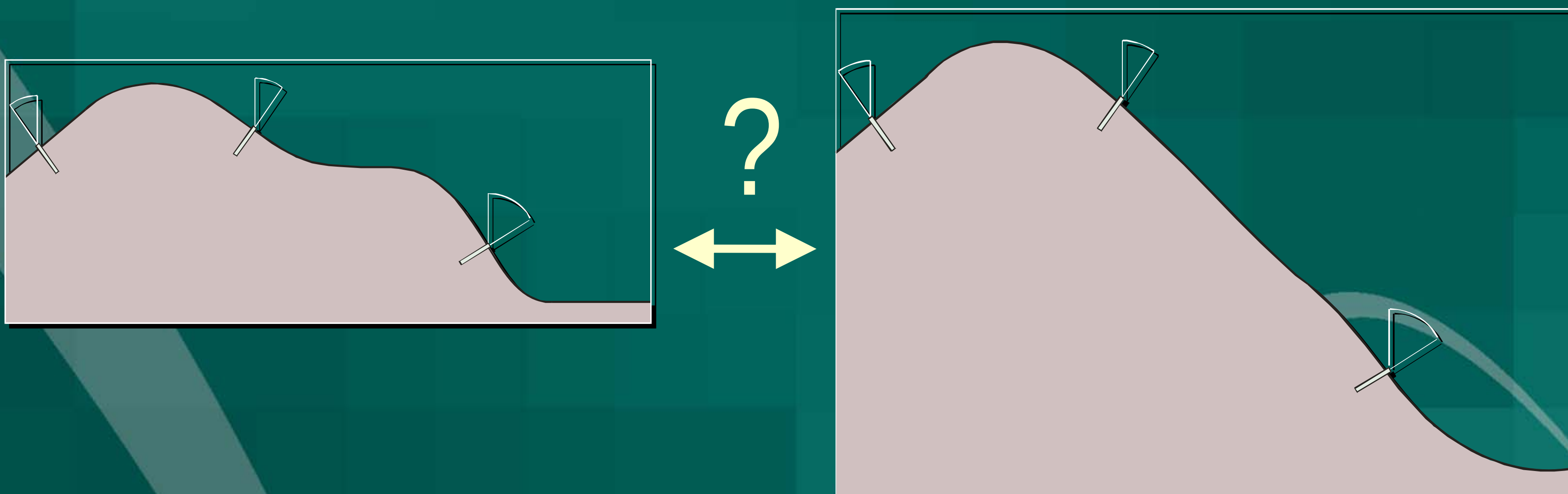
Cyclic Steam with Depth Analysis

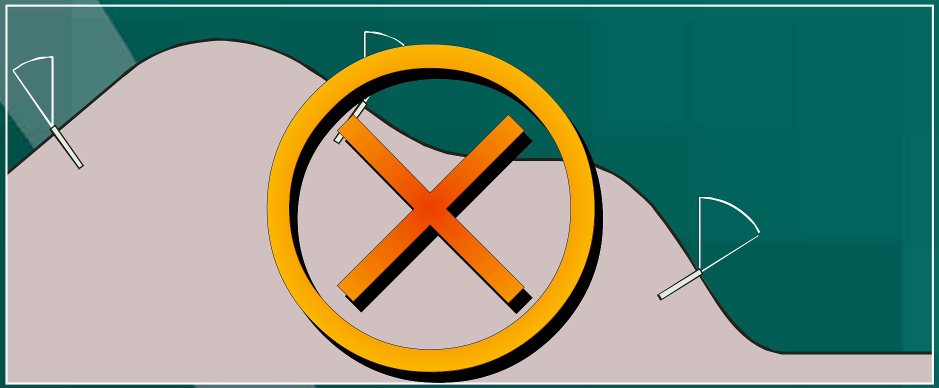


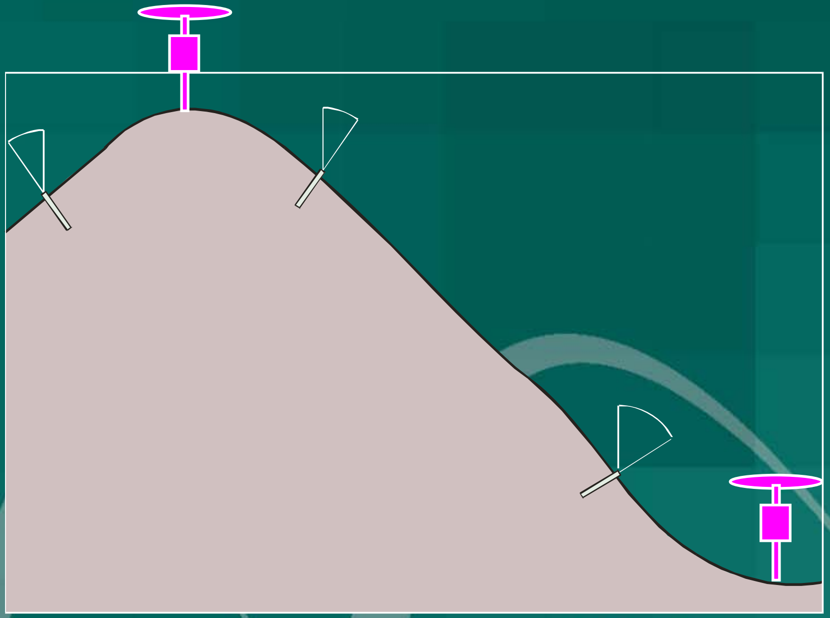
Extreme example: Both of these deformed surfaces are based upon the same response from the tiltmeters, but each experiences a very different elevation change.



Three methods to help choose the right solution:

- Pave the surface with tiltmeters
- Apply geomechanical constraints using injection information
- Place a few GPS sites in the array to get absolute references

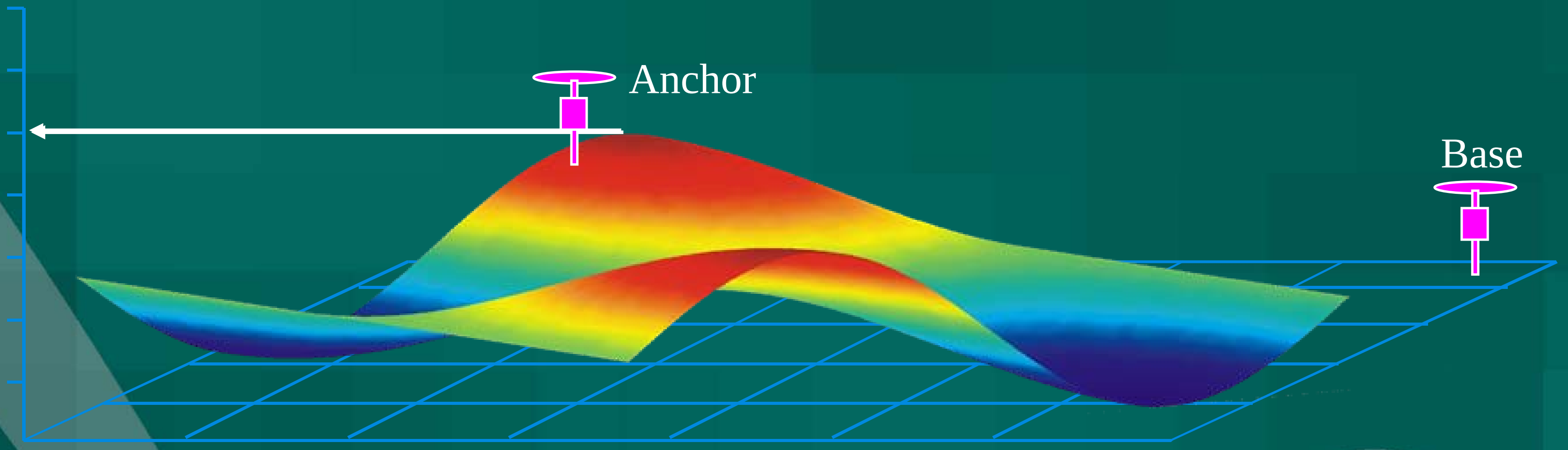




Integration of high-resolution GPS

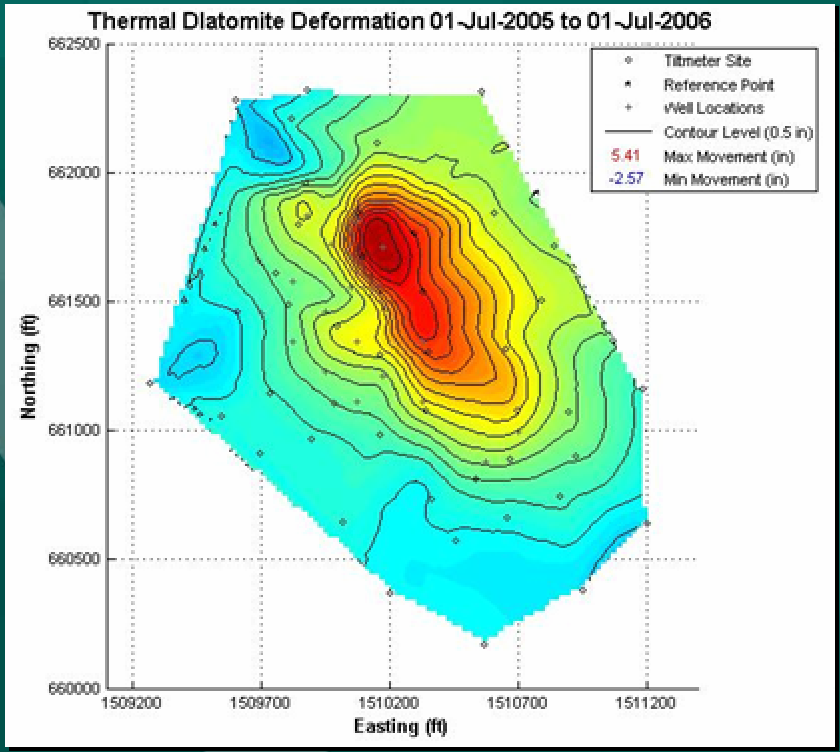
- Excellent long term stability
- Proven accuracy to 1mm
- Addresses some of the uncertainty inherent in Tilt, results using fewer instruments.

GPS integration: Why?

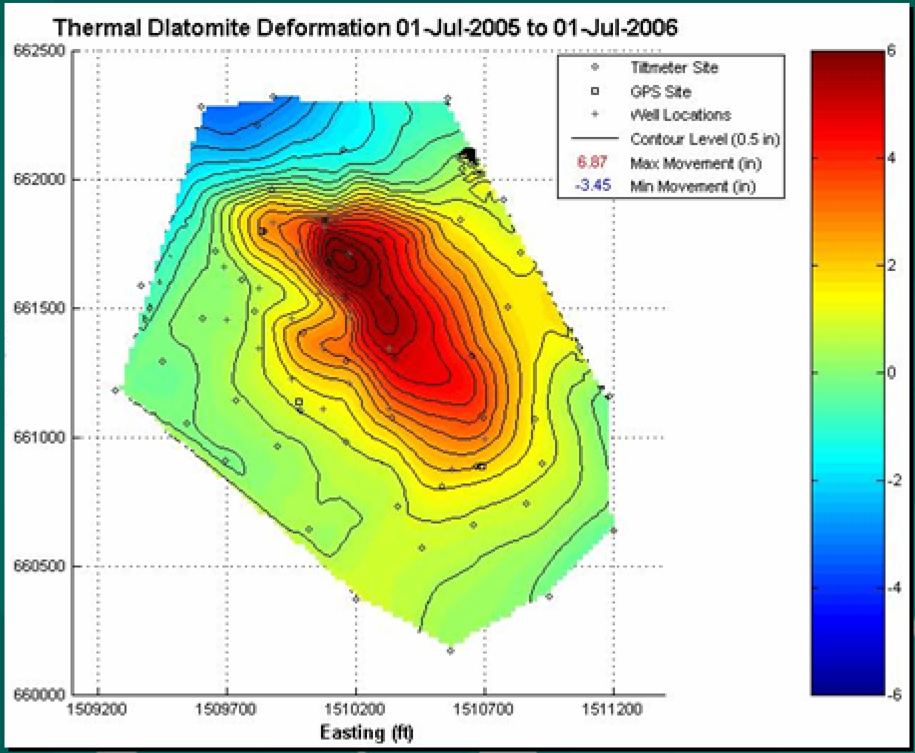


How Data Integration Improves Results

Use a few GPS points within tiltmeter arrays to provide tiltmeter precision with GPS stability



Tiltmeters Only



Tiltmeters and GPS

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InSAR Integrated with GPS

Pinnacle

- InSAR provides tremendous spatial coverage at high pixel resolution with reasonable precision.
- InSAR requires no ground instrumentation, or simple reflectors
- InSAR measures line of sight, only one component of 3D motion.
- InSAR is more susceptible to atmospheric and topographic error than GPS.

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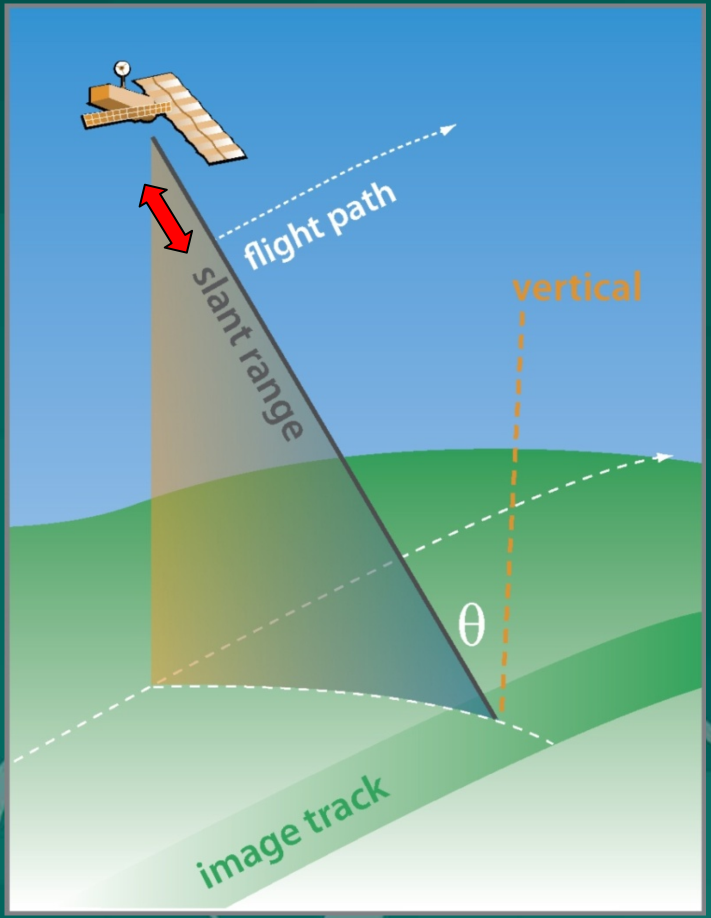
InSAR is a Slant Range Monitoring Tool

Pinnacle

- 3-D displacements are projected onto the radar line-of-sight. This angle varies between 20 and 47 degrees from vertical.
- Multiple SAR observations from multiple angles are required to extract additional motion parameters from an InSAR only product.
- Horizontal motions are often a significant component of reservoir induced ground deformation patterns



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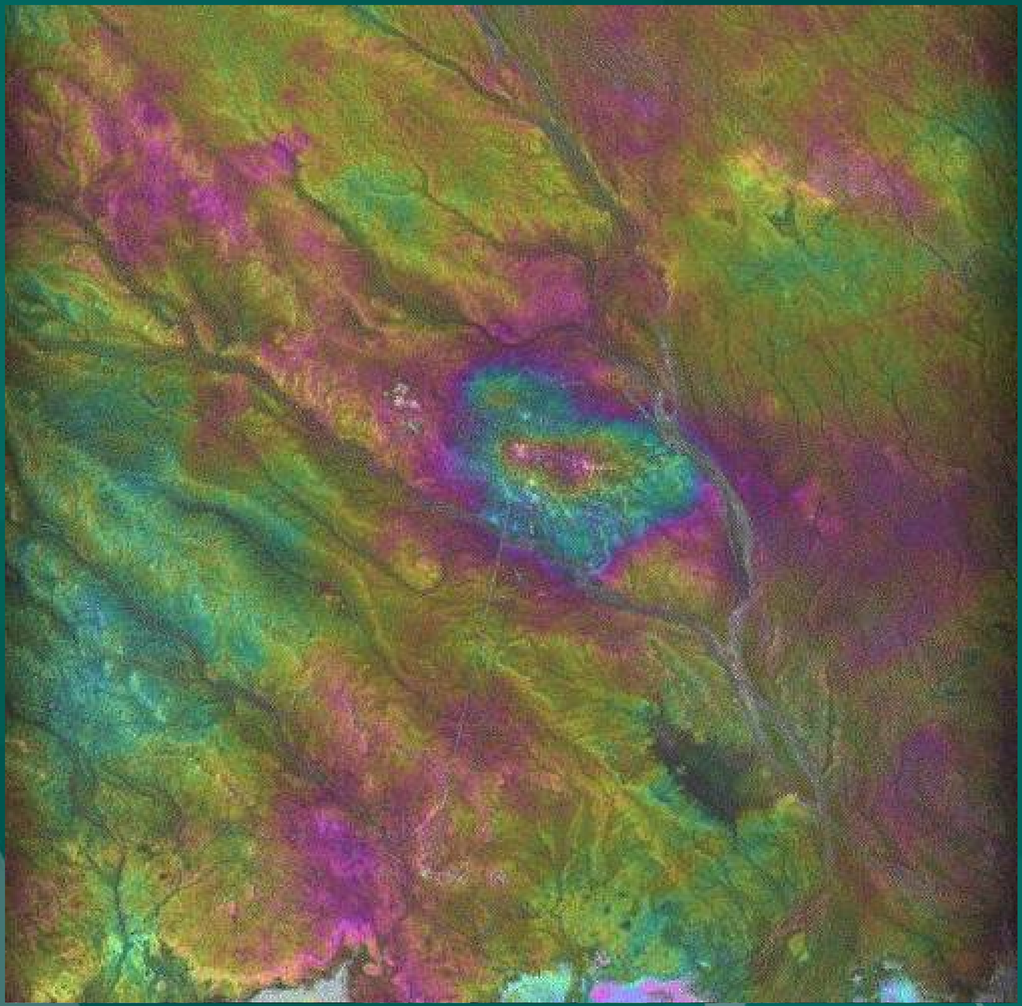
Subsidence Monitoring – Oman Oil Fields



50 kilometers

50 kilometers

SAR Amplitude Image

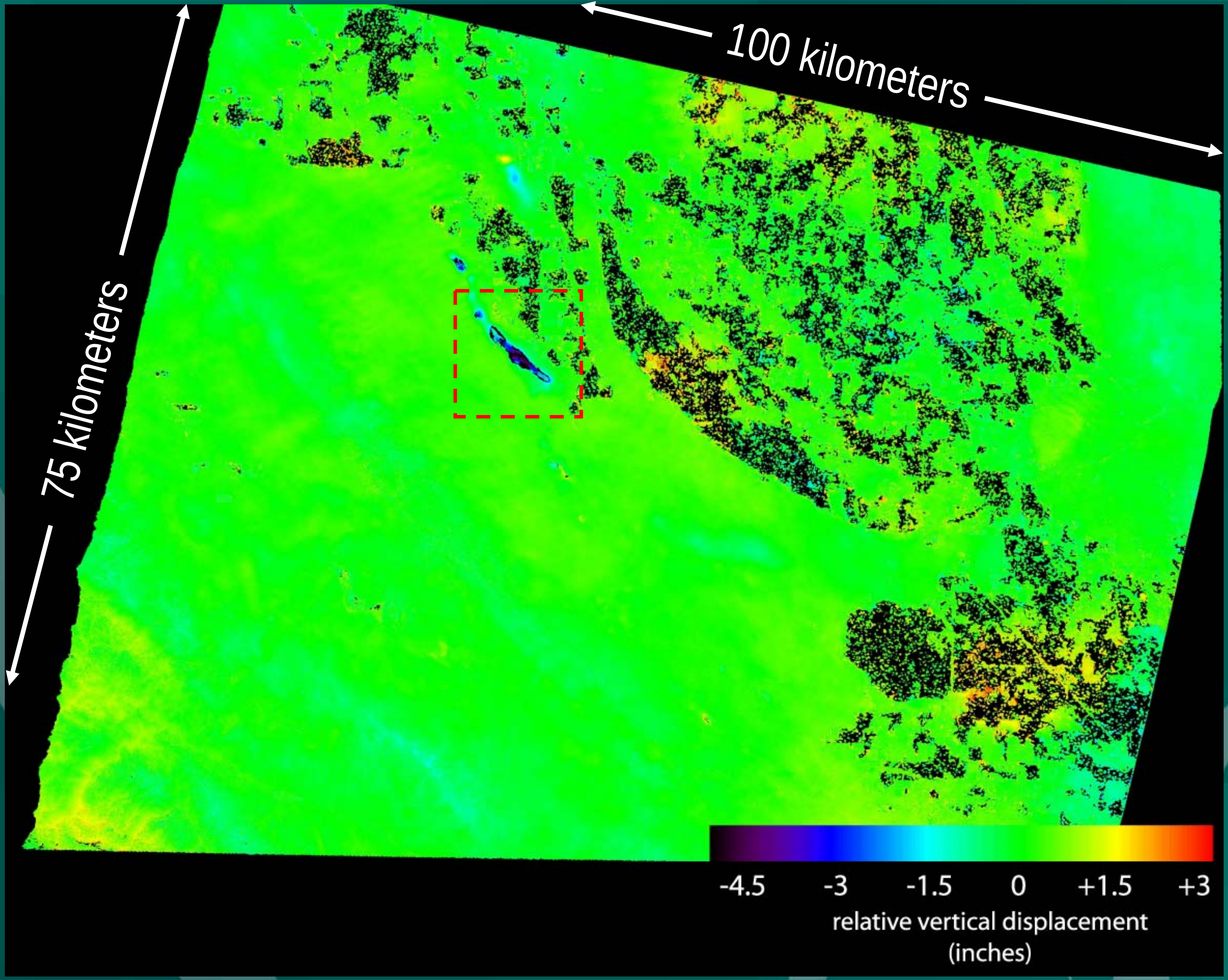
Phase SAR 2

-

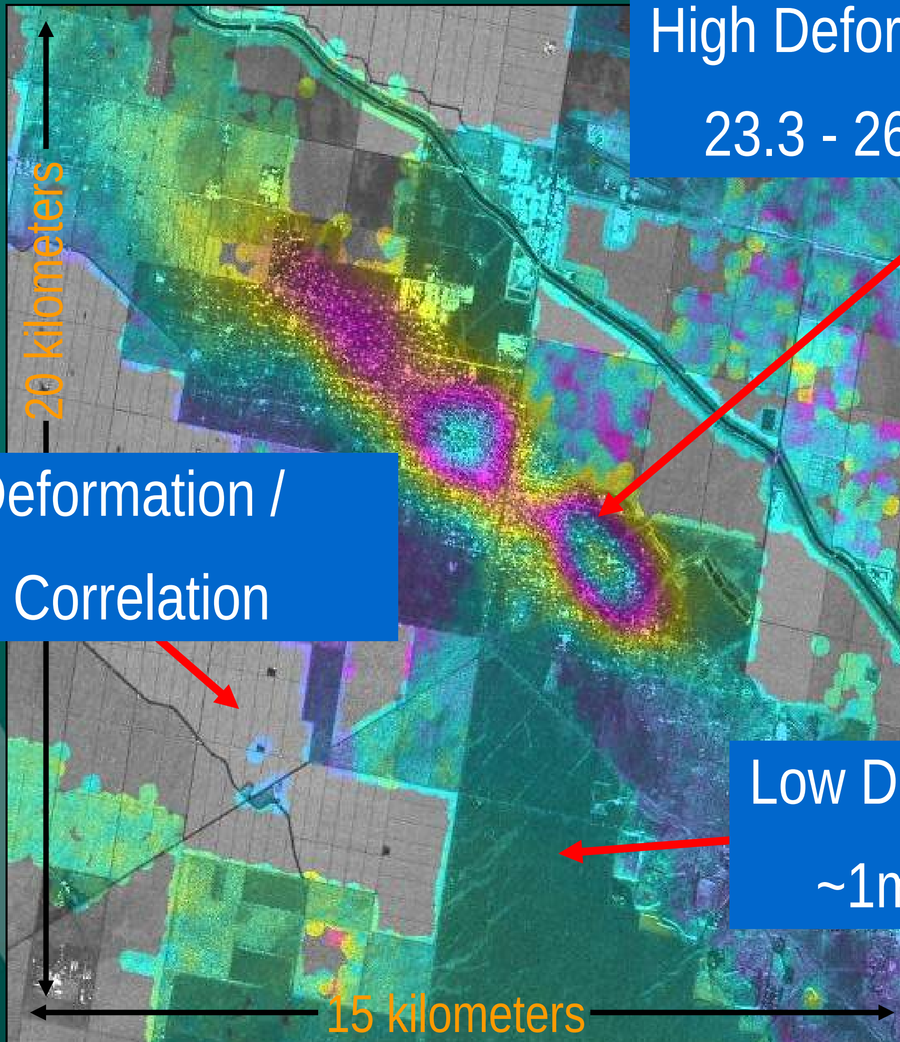
Phase SAR 1

Interferogram

Subsidence Monitoring – Southern California



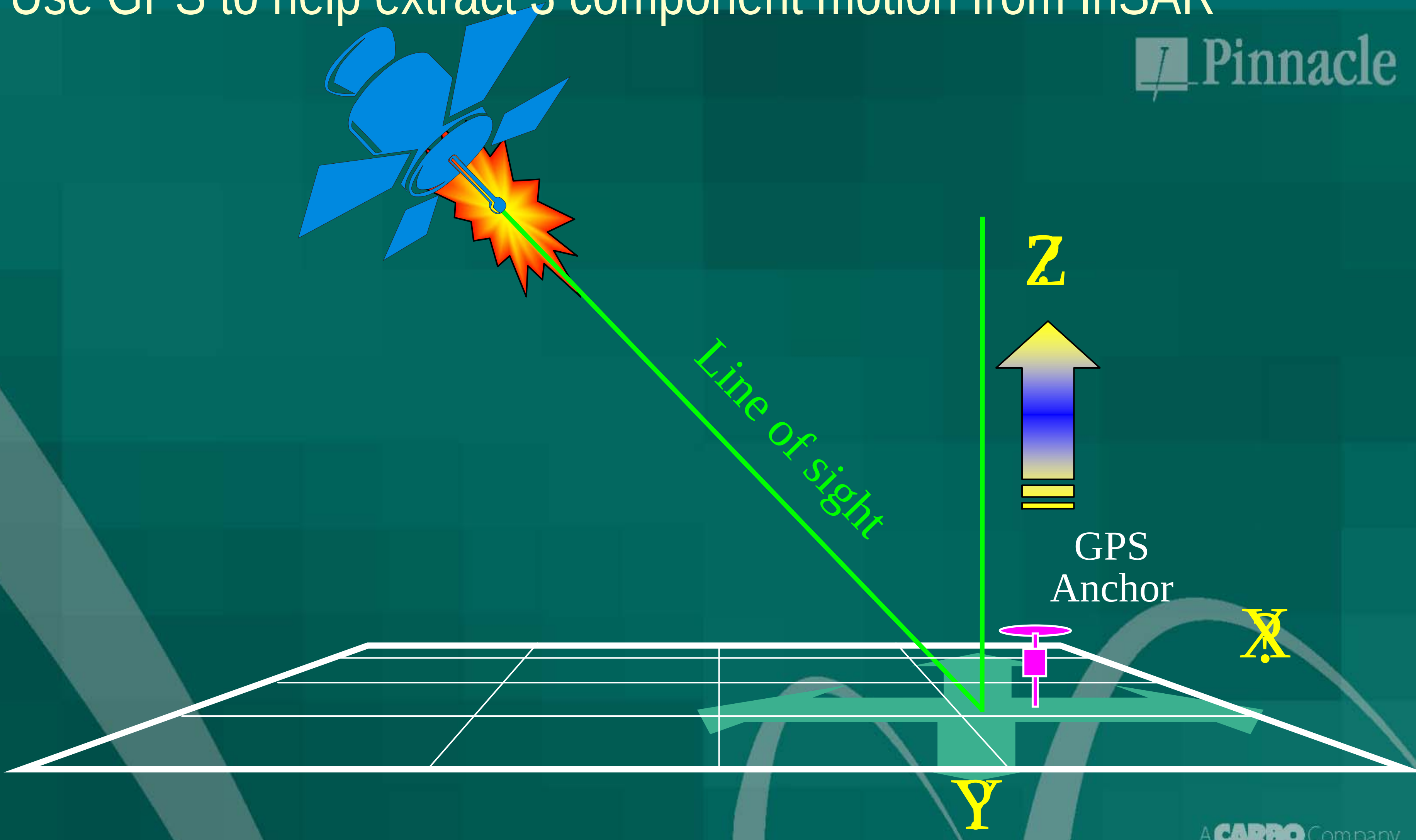
Subsidence Monitoring – Southern California



Belridge Oil Field

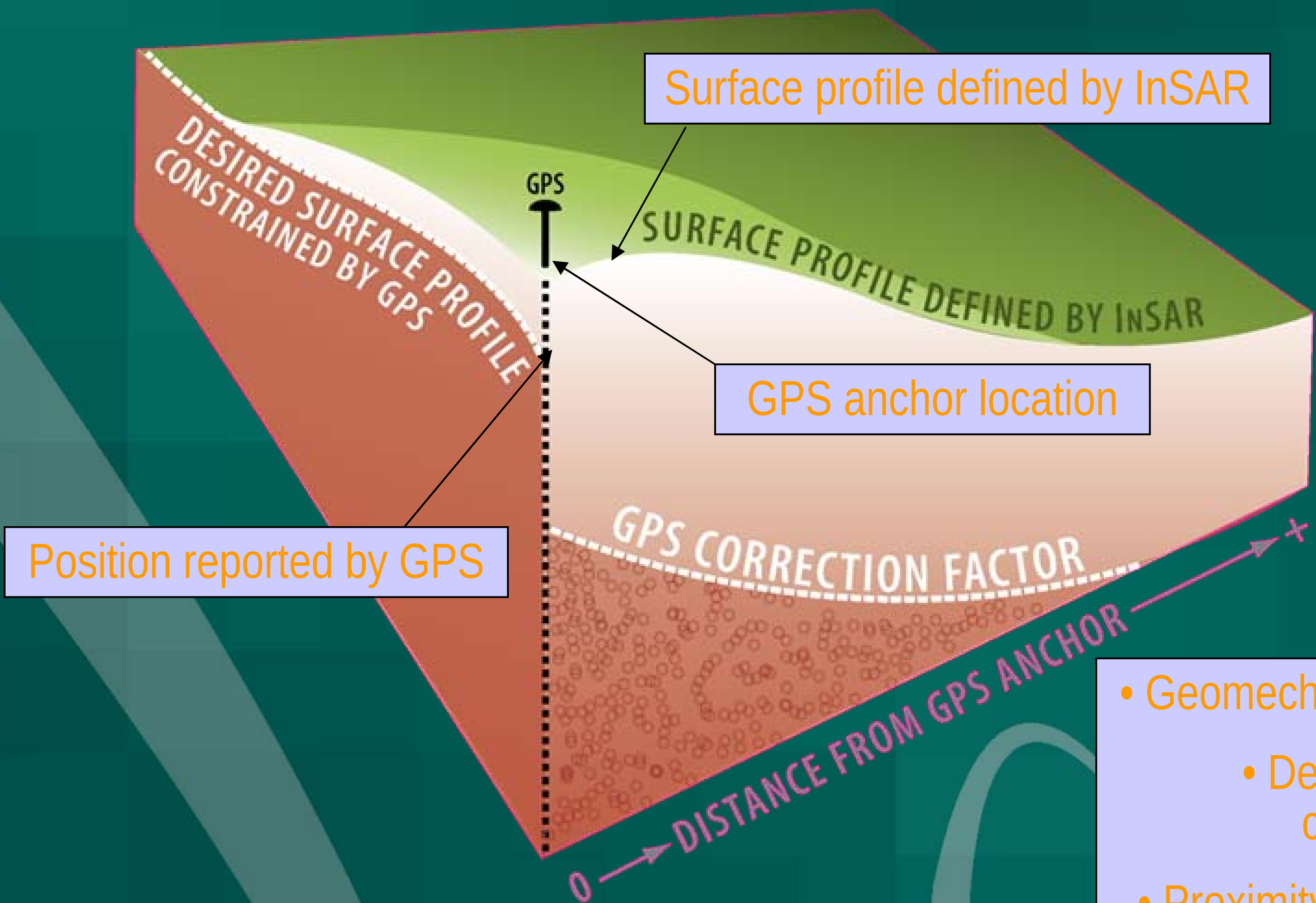
California

Use GPS to help extract 3 component motion from InSAR



Correcting InSAR with GPS Observations

Pinnacle

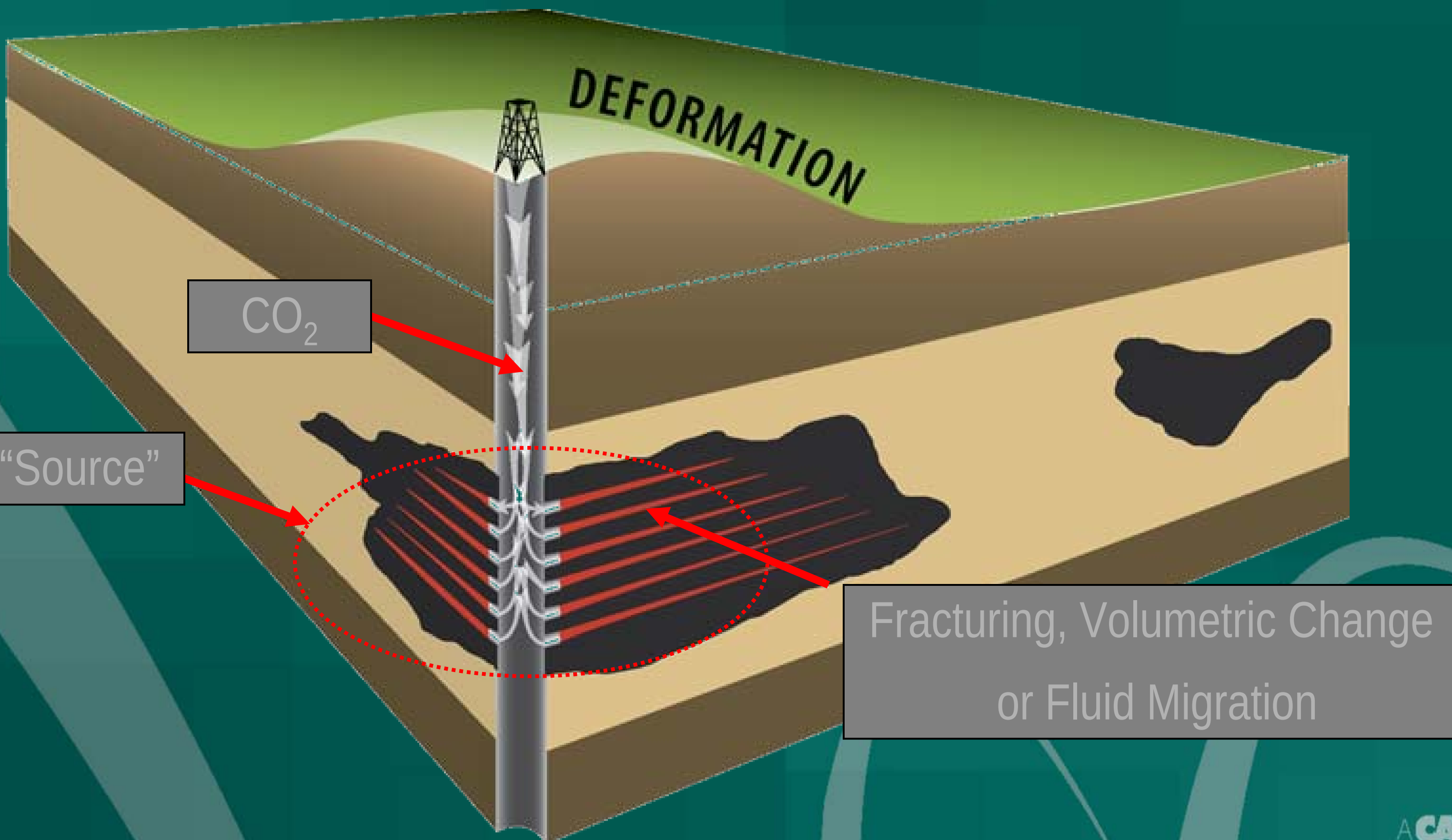


Attenuation of the GPS correction factor is a function of distance from the GPS

and …

- Geomechanical model at location
- Deformation source characteristics
- Proximity of other GPS stations

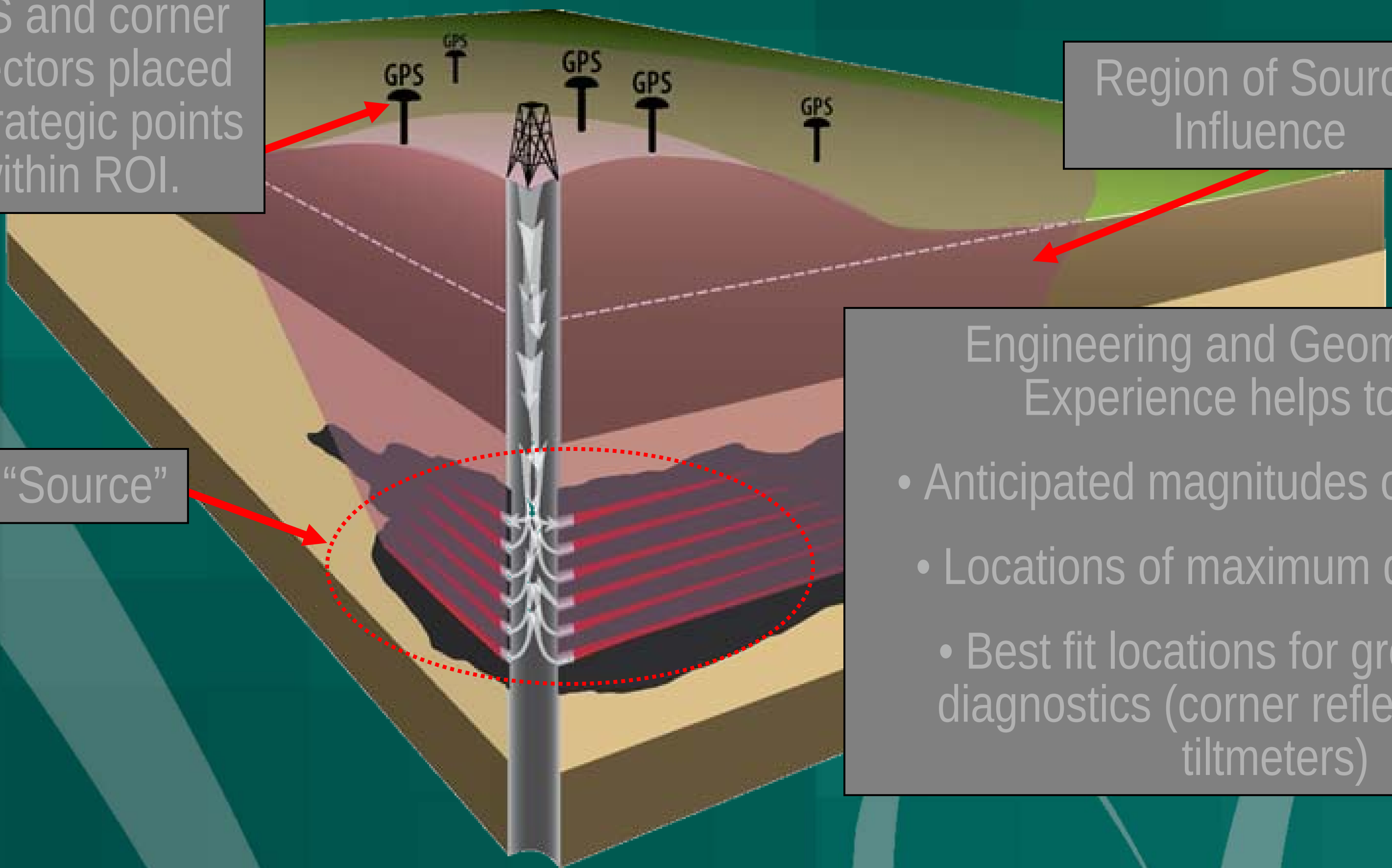
Ground Deformation Prior to Deployment of Monitoring Diagnostics



Utilizing Geomechanics and Engineering Experience in Array Design

GPS and corner reflectors placed at strategic points within ROI.

Region of Source Influence



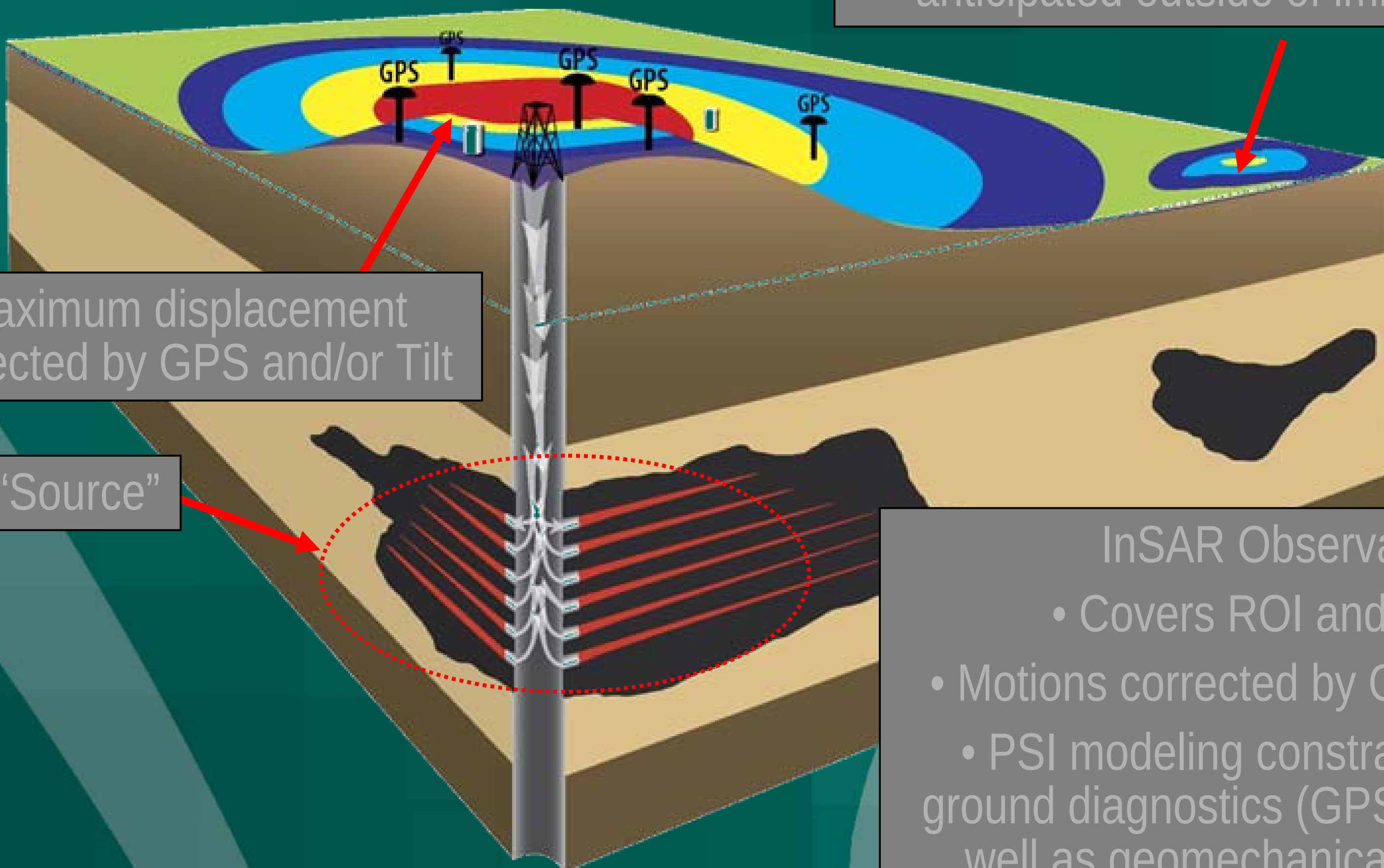
"Source"

Engineering and Geomechanical Experience helps to define

- Anticipated magnitudes of deformation
- Locations of maximum displacement
- Best fit locations for ground based diagnostics (corner reflectors, GPS, tiltmeters)

Integration of Ground Diagnostics and Geomechanics into Final InSAR Product

The exceptional spatial range of InSAR allows the identification of motions not anticipated outside of immediate ROI



Maximum displacement corrected by GPS and/or Tilt

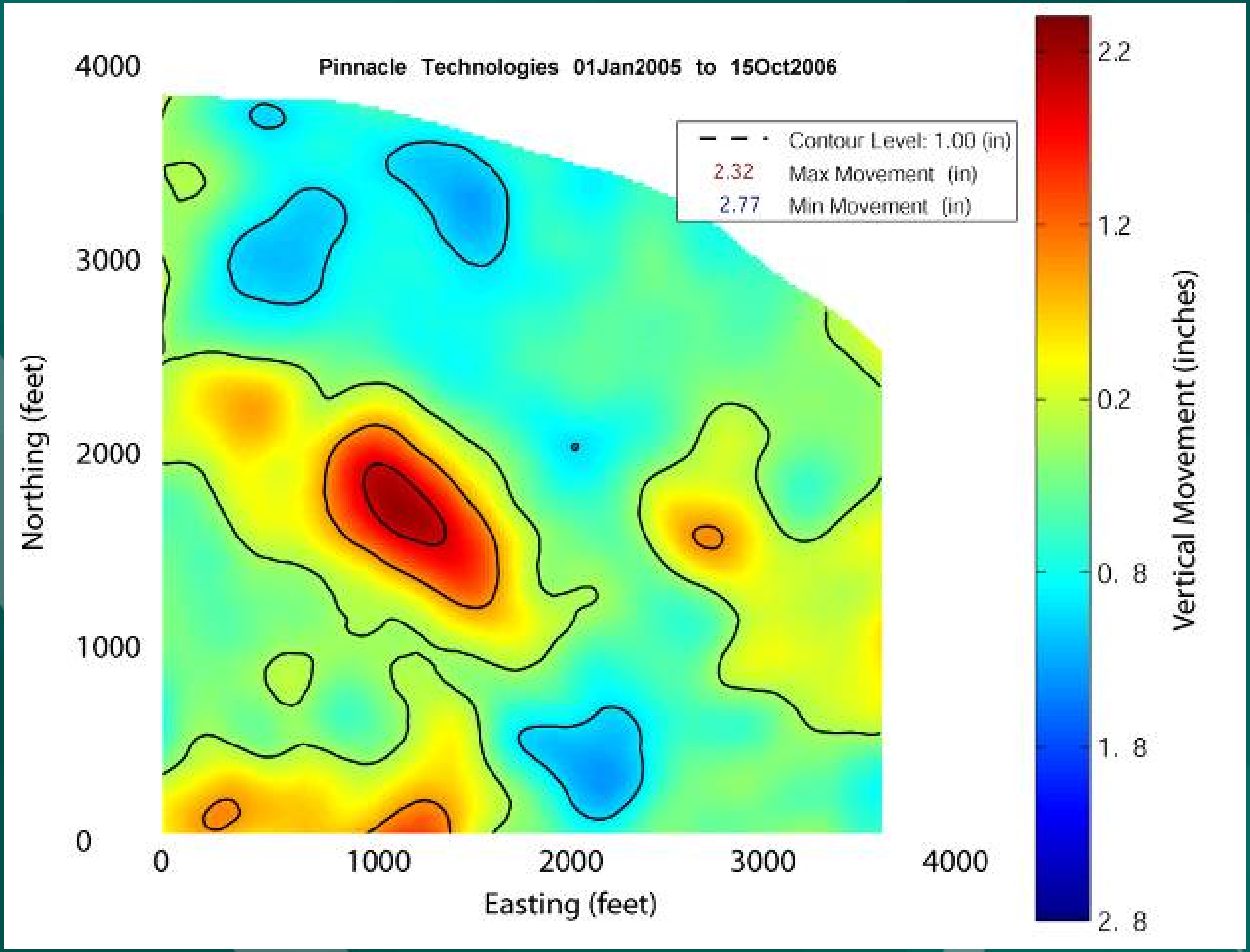
“Source”

InSAR Observations

- Covers ROI and beyond
- Motions corrected by GPS and/or Tilt
- PSI modeling constrained by both ground diagnostics (GPS, tiltmeters) as well as geomechanical parameters

Integration Example: Correcting InSAR with GPS Observations

Pinnacle



Uncorrected InSAR

Motion Observations

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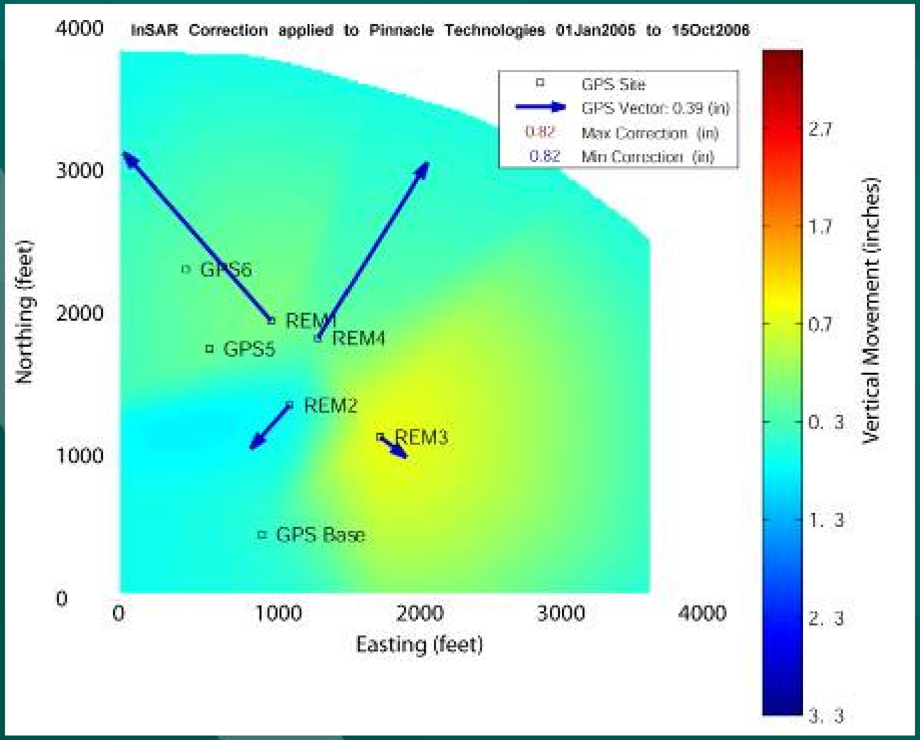
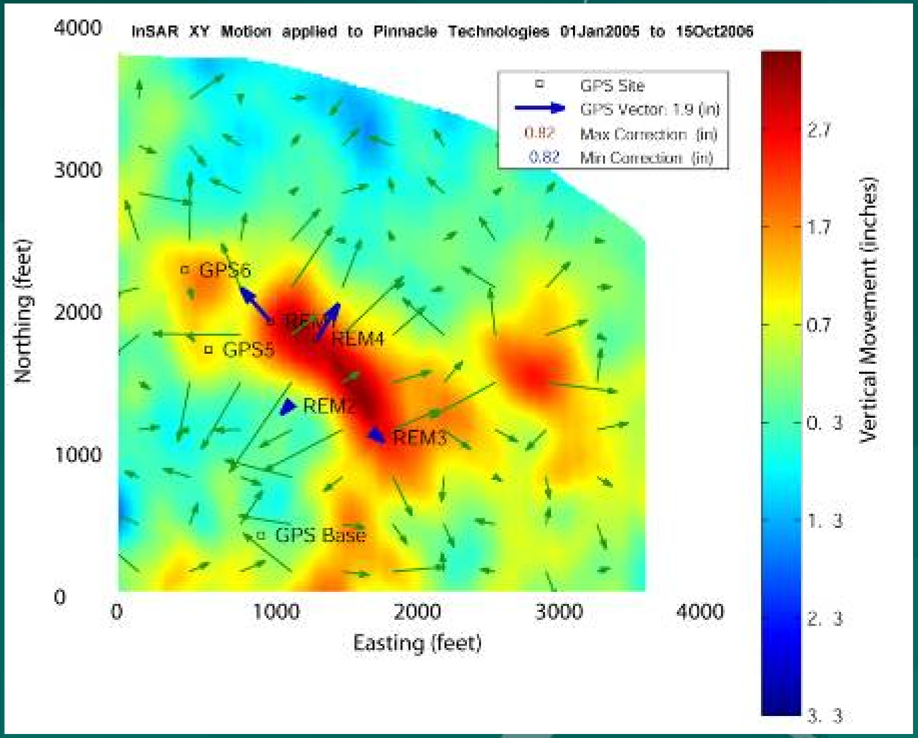
Integration Example: Correcting InSAR with GPS Observations

Pinnacle

Slant-range corrections applied to raw InSAR motions





X/Y corrections applied to unwrap slant-range InSAR motions

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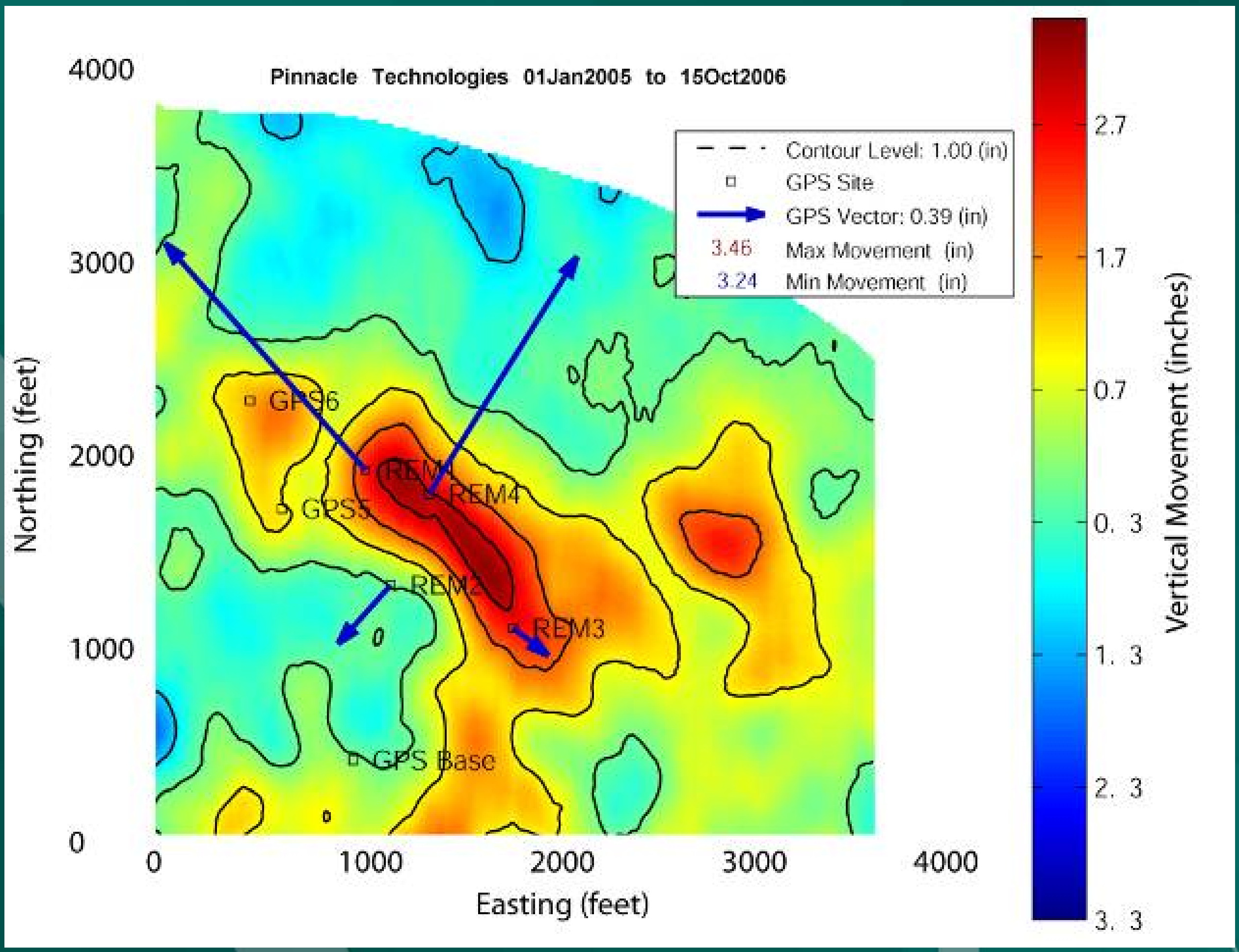
Integration Example: Correcting InSAR with GPS Observations

Pinnacle



- GPS corrects InSAR using known 3-D displacements at continuously operating monitoring stations
- Correction extends to other portions of the interferogram.
- Allows for multiple beam modes of InSAR data to be incorporated into the processing. This can further improve displacement field resolution.

Corrected InSAR Motion Observations

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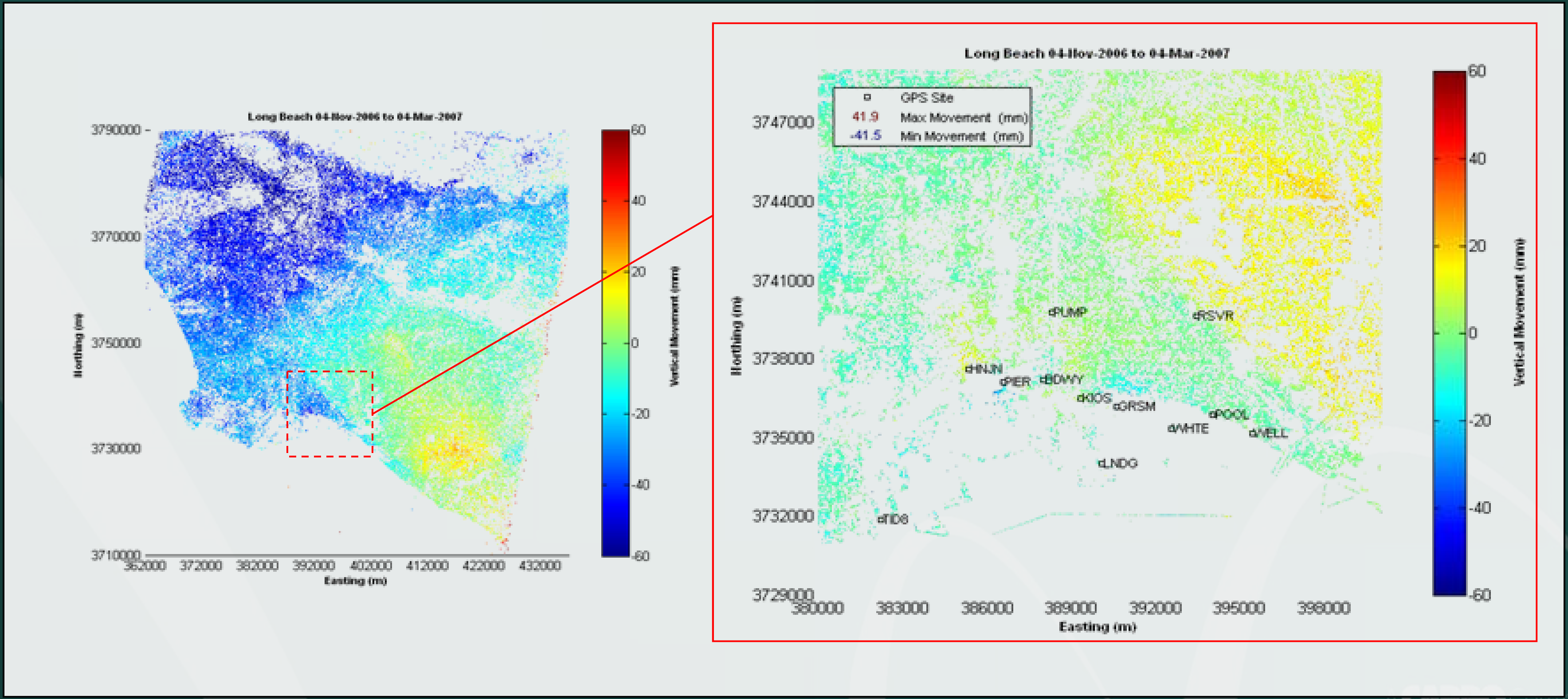
InSAR/GPS Integration Applications

Pinnacle

Subsidence / Heave Monitoring – Long Beach, California



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Microseismic Integrated with Tilt

Pinnacle

- Microseismic monitoring can provide detailed fracture growth and fluid movement information, but is subject to both false positives and false negatives.
- Tilt does not suffer from either false positives or false negatives, but often provides less information. For example, downhole tilt is sensitive to the fluid closest to the instruments, and may miss information further away.
- Downhole tilt alone often does not provide critical information, like azimuth of a hydraulic fracture.

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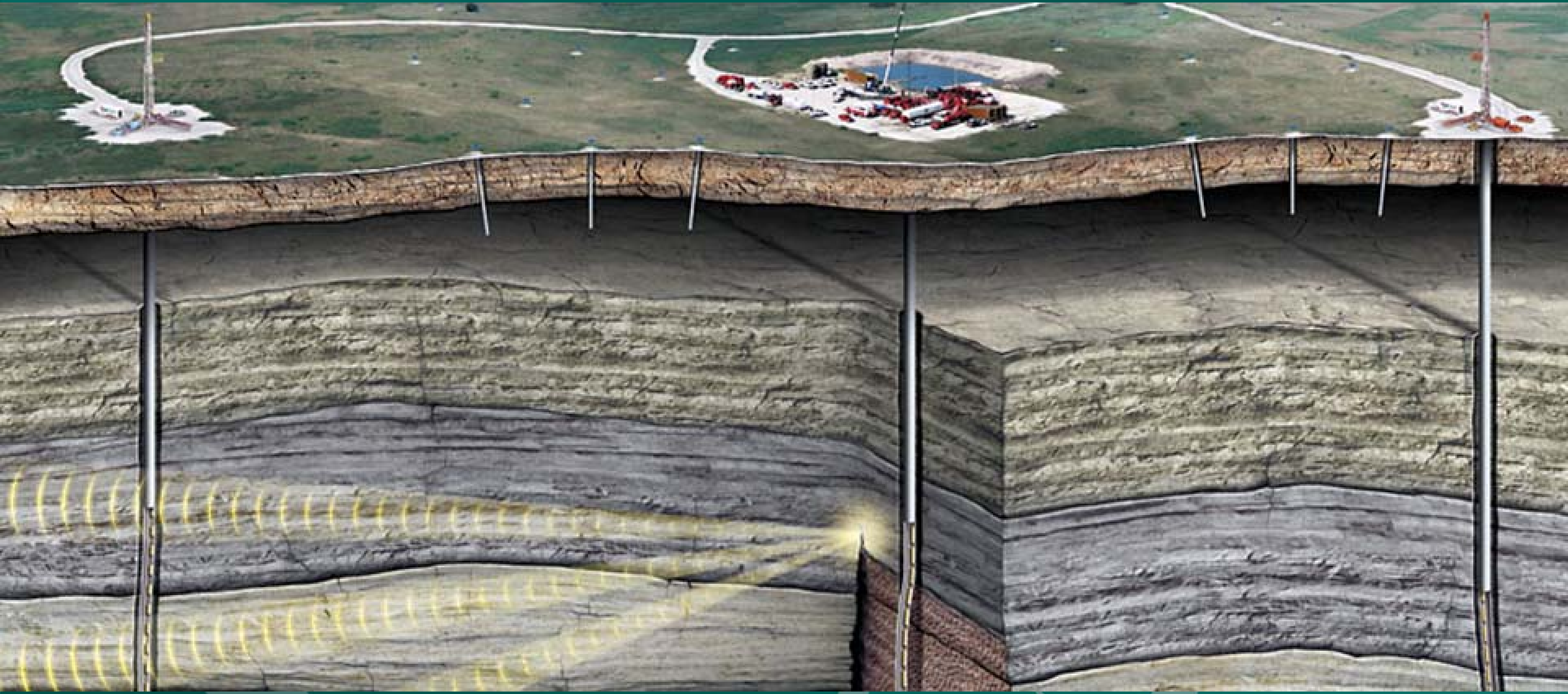
Tiltmeter and Microseismic Mapping

Pinnacle



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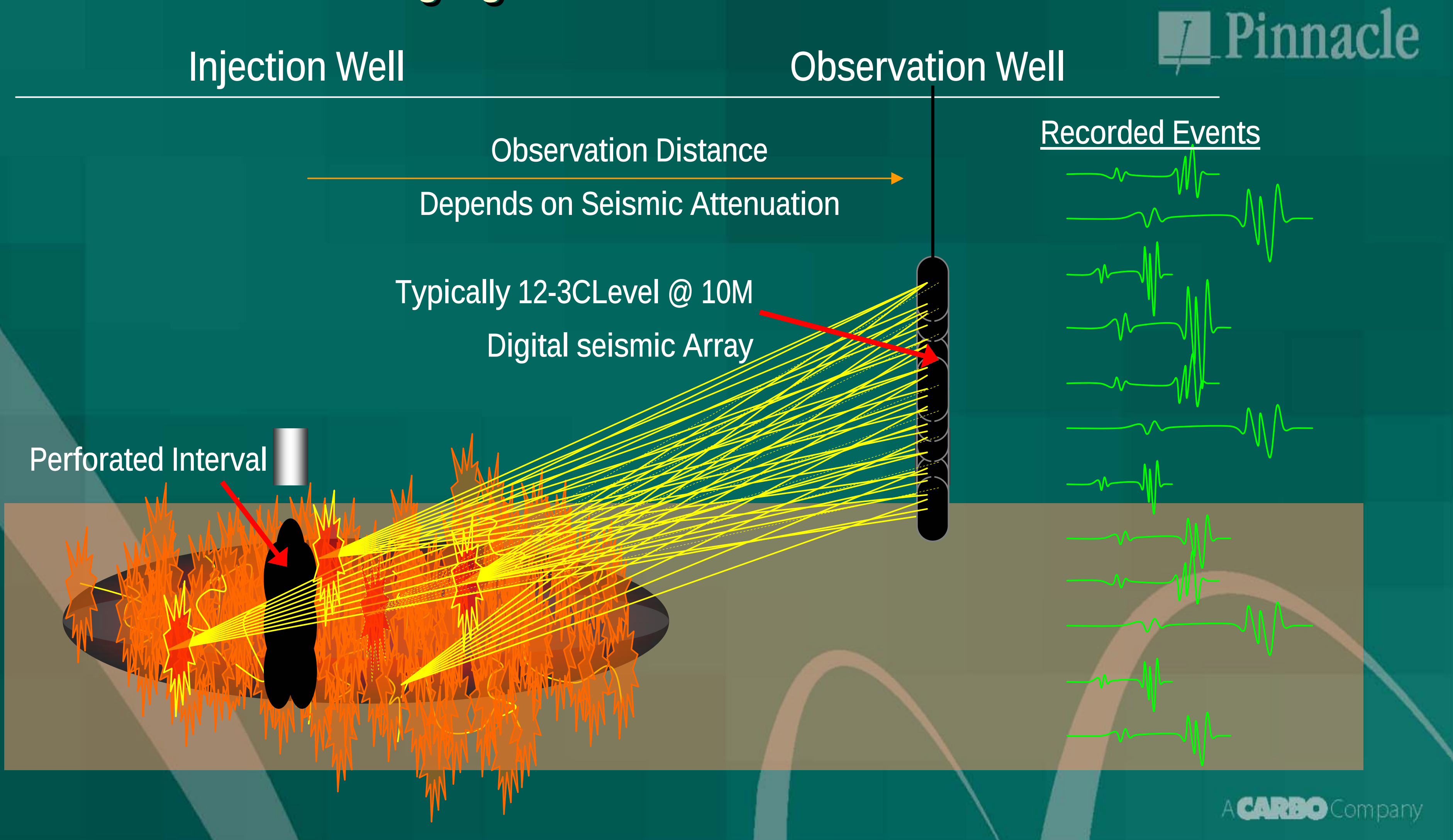
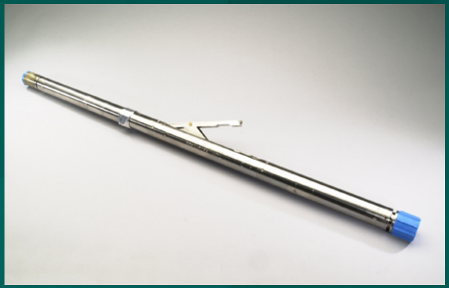
Microseismic Imaging



Microseismic/Tilt "Hybrid" Equipment

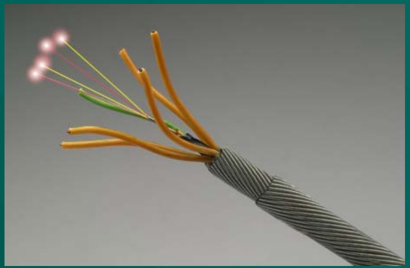
Wireline Deployment



Digital 3 Component Microseismic Tool

High Resolution Downhole Tiltmeter Tool

Digital Surface Recorder



Electrical-Fiber Optic Wireline

Rigid or Flexible Interconnects

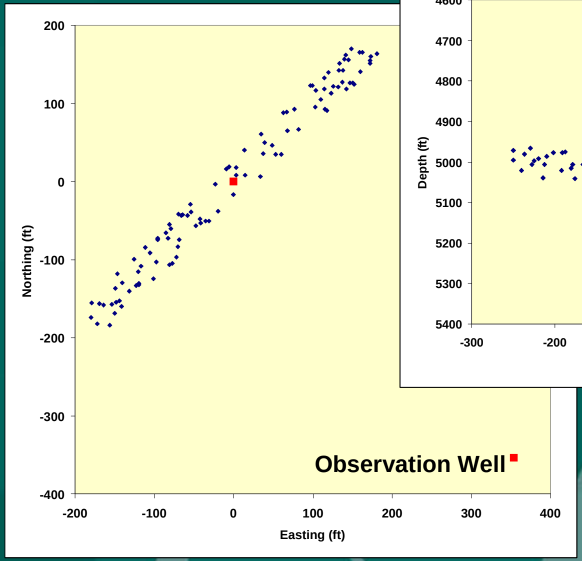
Multi-Level

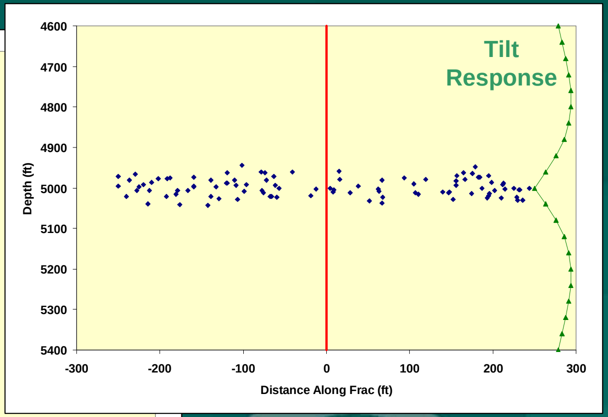
Downhole

Toolstring

Tilt and Microseismic Integration

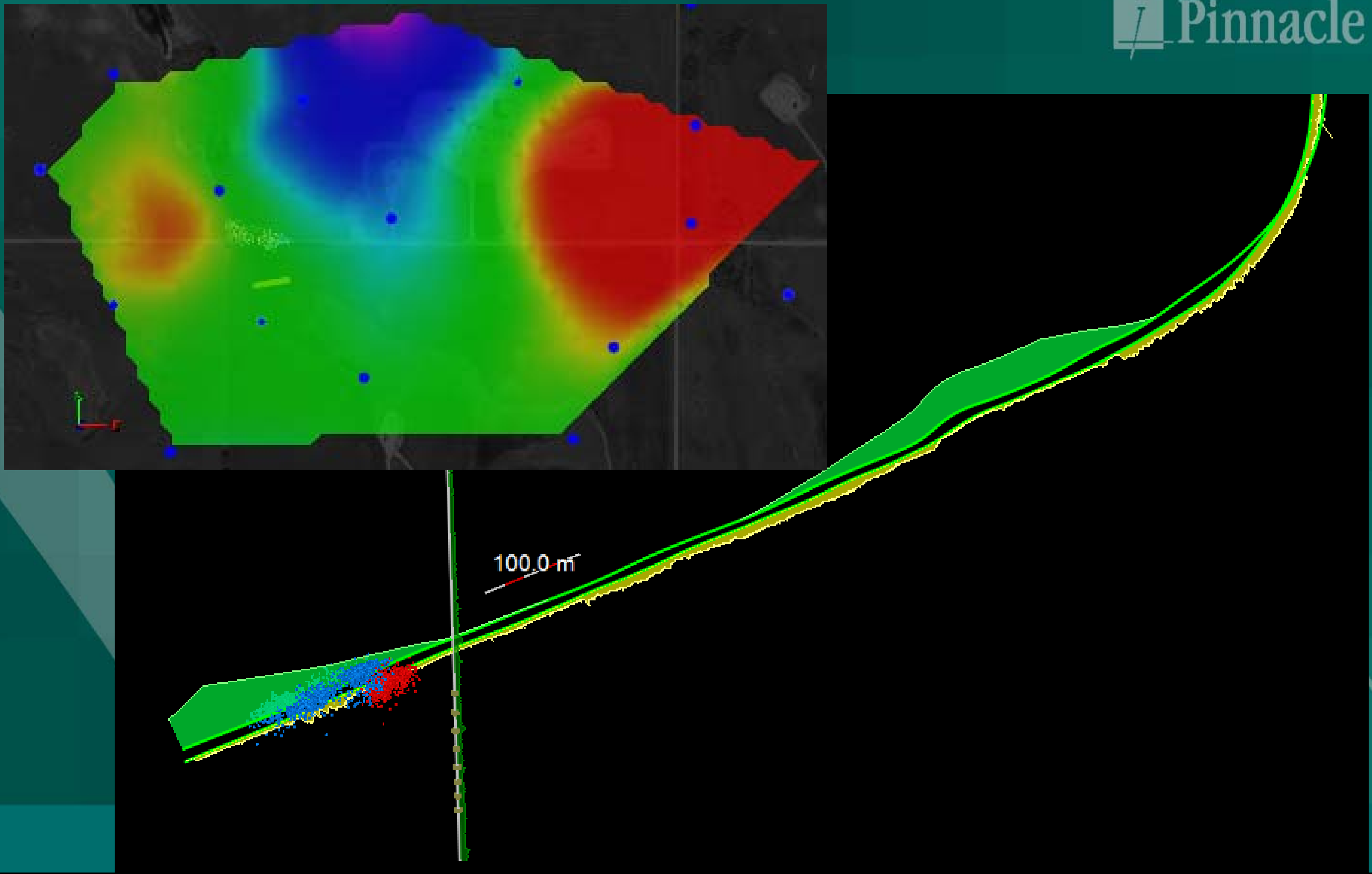
- Perform an inversion on a dislocation, considering the microseismic data as modeling an 'average' azimuth, dip, length and height with an uncertainty based on the distribution of events about the average.
- The added constraints from the microseismic data speed the inversion process, giving a more robust solution than tilt alone.





Reservoir Steam Injection Image

Pinnacle



Micro-deformation coupled with Geomechanics

Pinnacle

Improved surface deformation measurements, together with microseismic data, can be used to greatly constrain the possible strain changes in the layers affected by injection.

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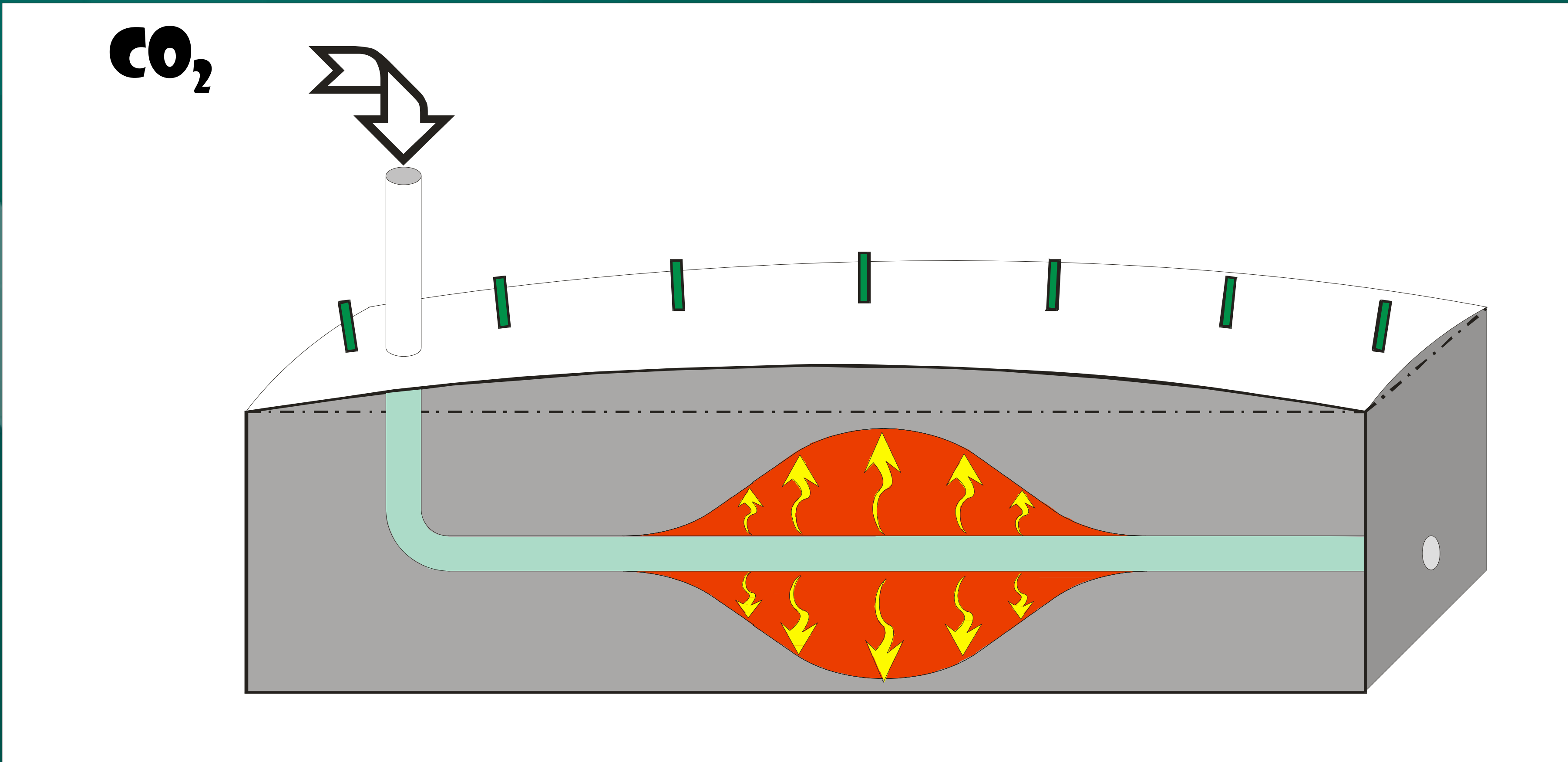
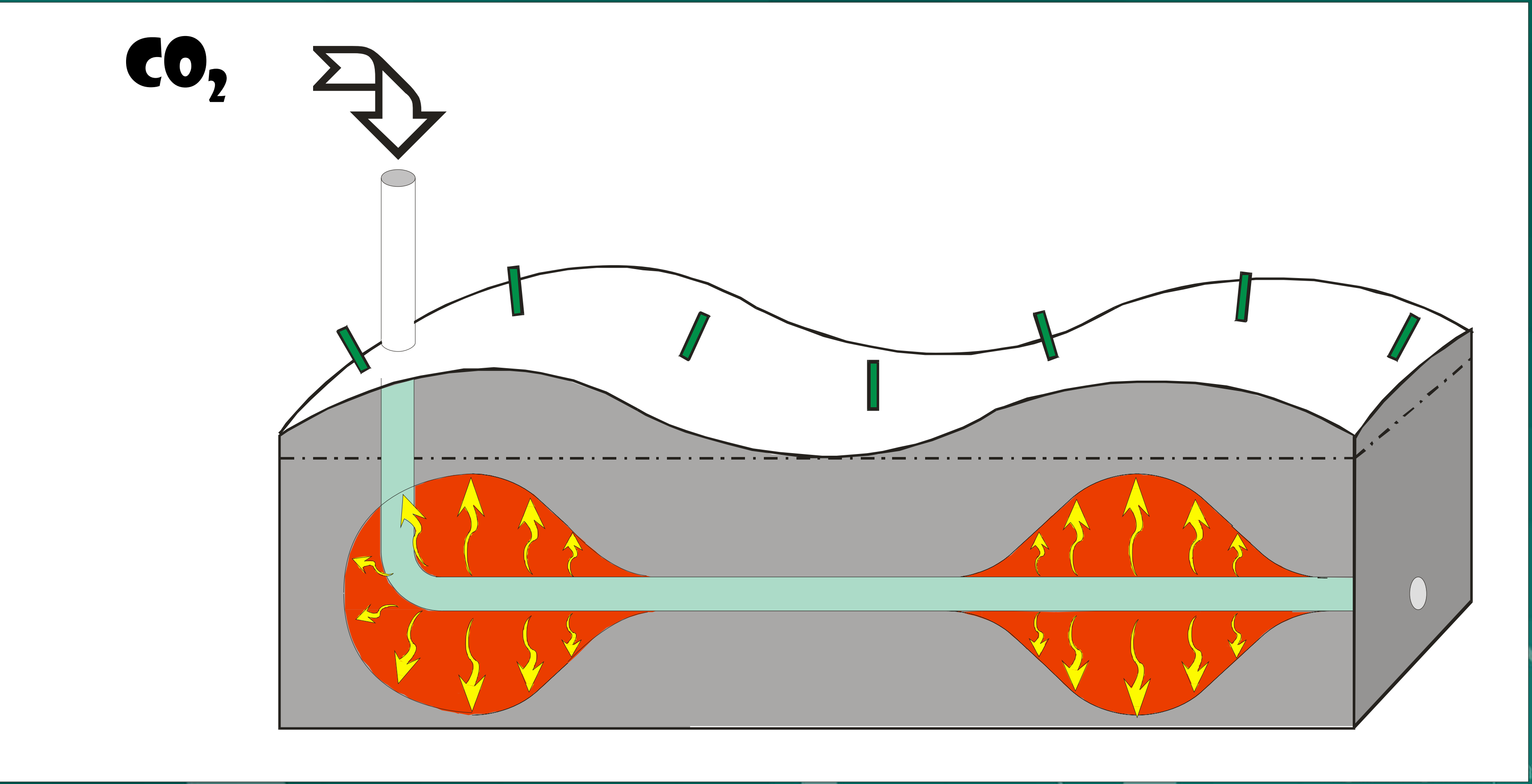
Deformation patterns mirror their subsurface causes

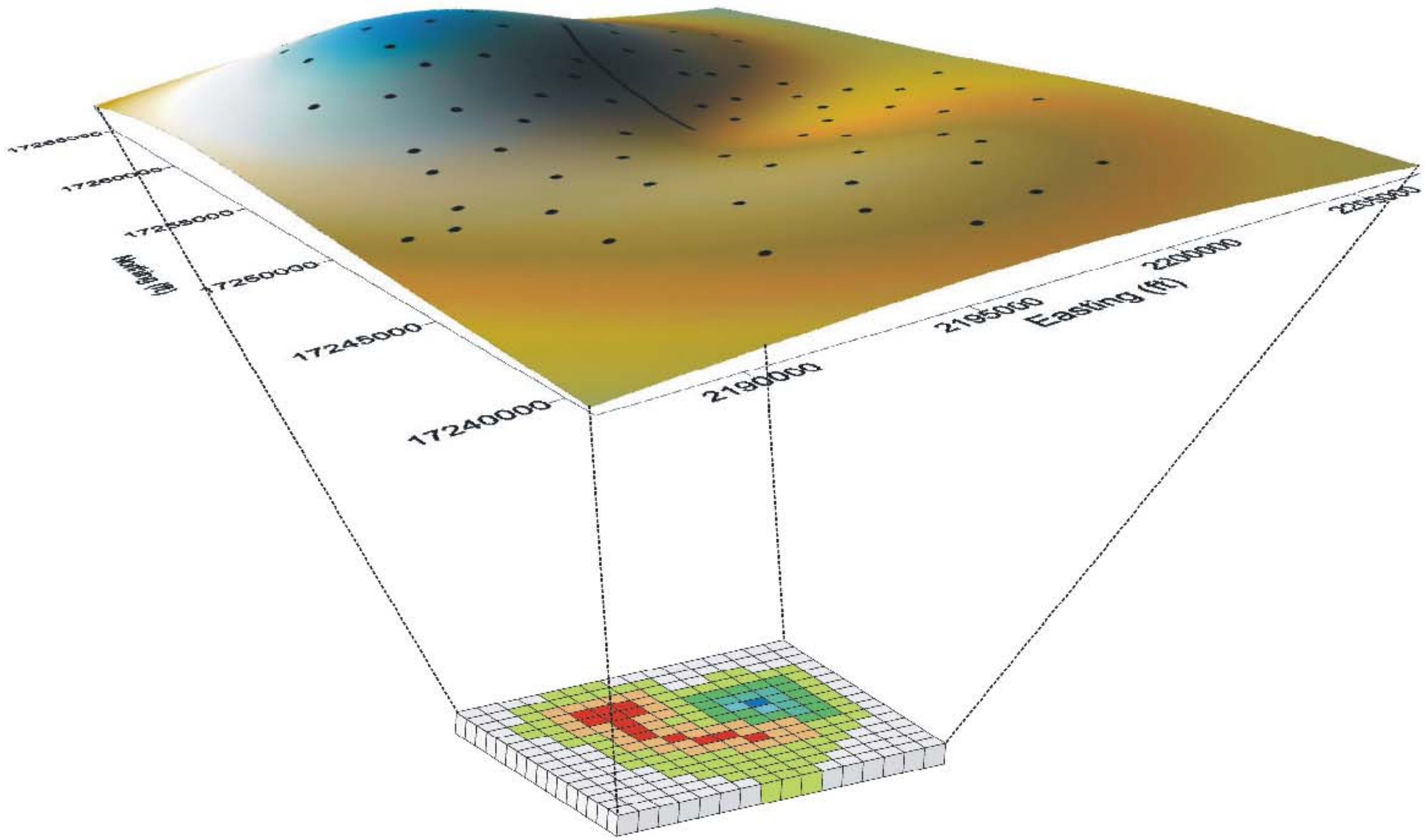
Pinnacle



Deformation patterns mirror their subsurface causes

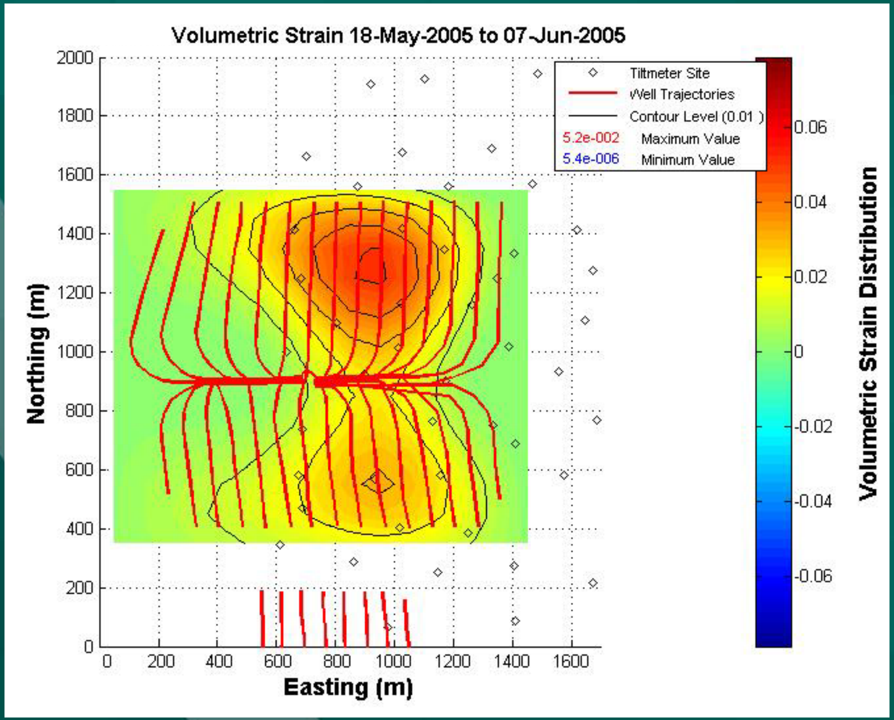


Inversion method reveals subsurface processes



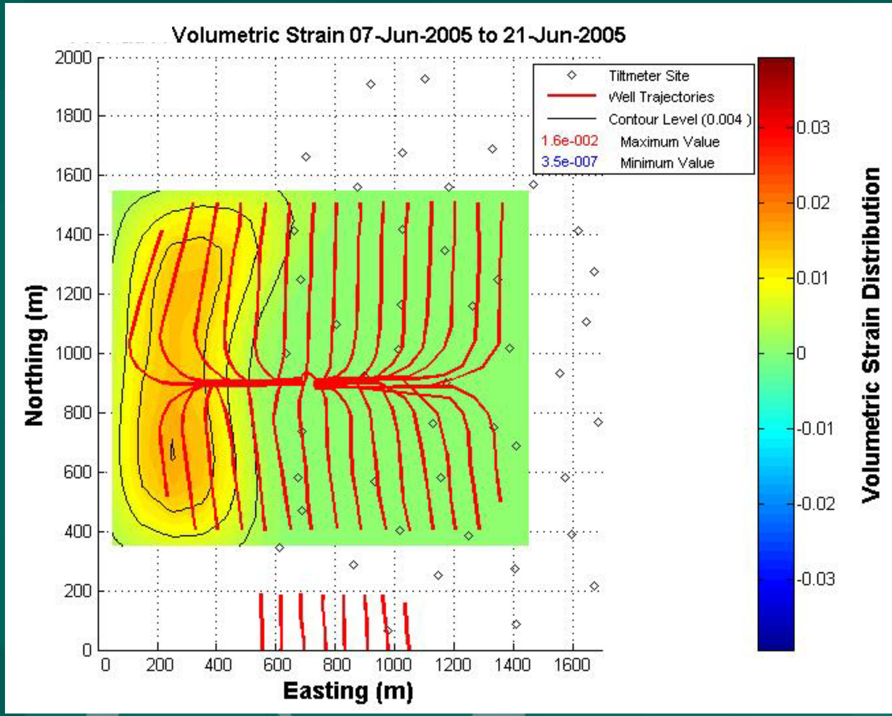
Reservoir Volumetric Strain

18 May - 7 June



Period-IV

7 June - 21 June



Period-V

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Future Possibilities

- GPS is more affected by ionospheric disturbances, InSAR by tropospheric. Moving the integrating upstream in the analysis should allow better estimation and mitigation of those errors.
- Integrate Fiber Optic sensors that provide temperature and/or strain data into fluid flow models
- Analyze microseismic waveforms and tilt deformation simultaneously using a time-dependent model

Conclusions

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- Recognizing the strengths and weaknesses of various sensors allows combinations that perform better than the sum of the parts.
- The ultimate goal remains to use sensor-provided constraints to direct a geomechanical model, continuously reducing the range of possible solutions from that model.
- Sensor systems need to be designed for each application, taking into account the specific goals of the monitoring and the unique aspects of each location.

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4th International Monitoring Network Workshop

IEA Greenhouse Gas R&D Programme

Edmonton, Canada

7th – 9th November 2007

Wrap Up

- Day 1: Monitoring and Regulation
  - Regulation is being developed in the US, Canada, Europe and Australia
  - Although not completely transferable lessons can be learned from other regions processes
  - There are parallels that can be drawn with acid gas injection but the scale is very different to CO2 storage
  - There are still some big regulatory issues to be solved – when and how to hand over

Wrap up

- Days 2 & 3: Review and Updates: CCS projects
  - Encouraging to see the number of projects existing and planned
  - Encouraging to see the wealth of monitoring techniques are being developed, tested and applied
  - As the data is collected and interpreted we will slowly start to build monitoring standards and best practices

Questions?

- How do you accurately quantify the CO_2 in the reservoir?
- How do you accurately locate the CO_2 in the reservoir?
  - Assurance Monitoring vs. Risk Monitoring
- What to do if a system parameter goes outside predicted values?
  - Second phase monitoring
- Seismic:
  - When is it not applicable?
  - What additional information can it give us?
  - If it is not enough, what more do you need to complement it?

Questions?

- How much monitoring is required…
  - for the operator?
  - for regulators?
  - for creditors?
  - for the public?
- Can the current monitoring techniques provide what the want?
- How long do you monitor for? When and how does handover occur?

Next Steps

- Presentations will be on the website next week
- Report will follow...
- We would encourage you all to submit papers to the journal
- Next meeting will be the Joint meeting in the Chicago, USA in June 2008
- Next monitoring network meeting will be in Kyoto, Japan in early 2009