2nd Meeting of the Monitoring Network

Report Number: 2006/9

Date: June 2006

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 in co-operation with BP. The organisers acknowledge the financial support provided by EPRI for this meeting and the hospitality provided by the hosts Istituto Nazionale di Geofisica e Vulcanologia (INGV).

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

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Kevin Dodds, CSIRO
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The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "2nd Meeting of the Monitoring Network, 2006/9, June 2006".

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2nd MEETING
of the
MONITORING NETWORK

Date: 4 – 6 October 2005

Offices of INGV
Rome, Italy

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

Executive Summary

The 2nd meeting of the monitoring network met in at Rome in September 2005. The meeting had two main aims which were: first to begin to engage regulatory bodies from around the worldwide on their thoughts on monitoring needs and second, to provide an update on monitoring technique development since the last meeting.

Regulatory bodies from four countries were prepared to discuss their thoughts on monitoring needs. The countries concerned were: Australia, Canada, USA, and UK. The UK's position related principally to the inclusion of CCS in the European ETS. There was an obvious difference in approach between the countries. In the USA and Canada which have mature regulatory regimes for underground injection it was clear that existing regulations would be extended to cover CCS. In the case of the USA this would be the Underground Injection Control Programme and in the Canada the model could be acid gas injection regulations. Both however would likely need reinforcement in the area of sub surface monitoring. For the USA, the US EPA would like to move to a regime involving modelling but recognise that modelling tools are not yet developed enough to be fit for purpose on their own and that monitoring coupled with model development was needed in the near term. For Australia, there are no current regulatory regimes in place for underground injection and regulators there were open minded and wanted to learn what their best approach would be. The concept of a "due diligence" exercise at a storage site based on detailed site selection prior to permitting as proposed by the UK DTI was well received.

As far as tool development was concerned, presentations by Statoil, BP and University of Calgary highlighted a common thread of thinking in terms of future monitoring needs. All three groups recognise that currently seismic monitoring is the most accepted tool for assessing the migration of CO_2 underground. Certainly in the near term it was felt that any regulatory regime would involve seismic monitoring, until other techniques are proven. Repeat 3D seismic monitoring is however expensive and all three groups were considering moving to an initial 3D survey followed by taking 2D lines across the areal extent of the CO_2 bubble as projected by reservoir simulation. Providing the bubble spreads out as predicted no further 3D shoots are needed. However if it does not manifest itself on the 2D lines then a further 3D shoot would then be required. Repeat 2D seismic is much cheaper than repeat 3D seismic. This monitoring approach will be demonstrated at Snohvit, In-Salah and Penn West in the future. BP also provided some of their experience of trying to monitor in real

situations where pilfering can destroy fixed arrays, compression of sand can disrupt seismic monitoring because vehicles get bogged down and trying to dig pits for surface monitoring in a desert can be extremely problematical.

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1. Introduction

The monitoring of CO_2 injected into geological formations is a topic of growing 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.

The meeting was attended by 53 delegates. A full list of delegates is available in Appendix 1.

At the inaugural meeting of the Monitoring Network it was demonstrated that there is a large tool box of monitoring techniques that can be applied for both surface and sub surface monitoring of CO_2. The status of many of these techniques was discussed and reviewed. However, it was clear that no single technique would be sufficient to meet all the different monitoring needs. Therefore, the aim of the second meeting of the network was to focus more on monitoring programmes rather than individual techniques. The meeting aimed to bring together both the regulatory groups involved in setting monitoring programmes and those projects that are implementing such programmes in different environments. The objective for facilitating this interchange was to determine their different perspectives on monitoring needs and requirements.

Workshop aims and objectives

The objective of the workshop was to address the following questions:

1. What are the monitoring requirements that need to be met?

2. What sort of monitoring programmes are needed to meet these requirements?

It was planned to address these questions from two perspectives; firstly by considering the regulatory view point and secondly by considering the operators view point.

The question to be addressed during the meeting was what do the regulators need to know in terms of the regulatory setting? Note: In attempting to answer this question it was considered that the regulations should not control what is done but should guide what is done. With regard to operator perspective the meeting aimed to review existing monitoring projects that are underway and pose the following questions to these projects, firstly, what do we know?, and secondly, what have we learnt to date?

Finally, a series of scenarios were devised to help round off the discussions. These scenarios aimed to address the final questions, what can we do? And what will we do?

The organisers did not expect that by the end of this workshop that they would be in a position to fully answer all the questions posed. The reason for this is that not all regulatory bodies in the various countries that are considering implementing CCS are at the same status level in terms of having firm ideas on monitoring requirements to meet their respective regulatory needs. However, the workshop aimed to set this in motion by bringing those groups that are in the process of developing their plans to present their ideas. In this way it is hoped that one outcome of the meeting will be an initial reference point that other regulatory bodies can consider when developing their own plans for monitoring.

Workshop Programme

The Programme for the two days was as follows:

Day 1 - Tuesday October 4 2005	
Session 1. Introductions	
Opening	IEA GHG
Introduction and Welcome	BP
Shallow Soil Gas and Gas Flux Monitoring of the Weyburn CO2 EOR Injection Site	Università di Roma "La Sapienza" (URS)
CO_2 Geological Storage by ECBM techniques in the Sulcis area (SW Sardinia Region, Italy)	Istituto Nazionale di Geofisica e Vulcanologia (INGV)
Session 2. Monitoring Requirements	
CCS monitoring needs: Australian regulatory viewpoint	Australian Greenhouse Office (AGO)
EU ETS and UK Regulatory Issues	UK Department of Trade and Industry (UK DTI)
EPA Efforts and Regulatory Overview	U.S. Environmental Protection Agency (U.S. EPA)
Session 3. Monitoring Programmes	
Experience from ongoing projects	
Update on the Frio Brine Pilot: One year after injection	Bureau of Economic Geology, University of Texas at Austin
Geophysical Monitoring of CO_2 Storage at an Onshore Saline Aquifer in Nagaoka, Japan	Engineering Advancement Association of Japan (ENAA)
Can we estimate the injected carbon dioxide prior to the repeat seismic survey in 4D scheme? - Nagaoka	Japan Petroleum Exploration Co., Ltd (JAPEX)
Monitoring at In Salah	BP
Experience from developing projects	
Otway Project	Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)
Snohvit	Statoil
Developments since the first meeting of the Monitoring Network	
Application of Soil Gas Concentrations, and Gas Fluxes to the Atmosphere in Order to Detect Low Rates of Leakage from CO_2-Storage (EOR or CBM) Projects	Colorado School of Mines

Day 2 - Wednesday October 5 2005	
Session 4. Monitoring Scenario Development	
Introduction to Scenarios session - Kevin Dodd.	
Scenarios - Acid Gas Scenario - Frio Scenario - Gippsland Scenario - Viking Graben Scenario	
Session 5. Developments since the last meeting	
Gorgon Development – LNG with CO_2 Storage	Chevron Energy Technology Co.
CO2GeoNet Activities in monitoring geological storage	British Geological Survey (BGS)
Integrated multicomponent surface and borehole seismic surveys for monitoring CO_2 storage; Penn West Pilot, Alberta, Canada	University of Calgary University of Alberta
Results and New Directions of the IEA GHG Weyburn CO2 Monitoring and Storage Project	Petroleum Technology Research Centre (PTRC)
Tracer, shallow aquifer, direct CO_2 flux, and geophysical survey results from the Frio brine sequestration site, Texas	National Energy Technology Laboratory (NETL) - U.S. Department of Energy (DOE)
Session 6. Technical Tour to Ciampino and the Phlagrean Field	
The Campi Flegrei CO_2 Analogue	Istituto Nazionale di Geofisica e Vulcanologia (INGV)

2. Welcomes and Introductions

BP opened the meeting followed by background by INGV and University Roma the hosts of the 2nd Monitoring Meeting. The introductory presentations of the hosts can be found in Appendix 2.

3. Monitoring Requirements

Representatives from three regulatory bodies that felt able to come and present at the meeting[1]. Australia gave their regulatory perspective, whilst the UK outlined the regulatory developments in Europe that are being considered as part of including CO_2 Capture and Storage (CCS) in the European Trading Scheme a number and the USA sent a presentation on their regulatory perspective, which was shown at the meeting.

3.1 Australian Perspective – Australian Government Department of the Environment and Heritage – Australian Greenhouse Office (AGO)

This section is adapted from the written presentation kindly provided by Kate Roggeveen. It demonstrates the thought process behind the development of monitoring regulations in Australia which is highly relevant to the content of the meeting.

Australia has a federal system of government, with Commonwealth, State and Territory jurisdictions. Identified as an important point is public perception of CCS, it will not happen unless the public understands it and supports it. The Australian regulating bodies recognise that monitoring is key to that understanding.

Context

Australia is at the point of refining its most broad level performance criteria for a CCS monitoring and verification regime down to something workable. This is difficult when some technical risks and uncertainties of CCS are still unclear; and when the monitoring technologies need development in their own right. The presentation acknowledged that it was possible at this stage to raise more questions than answers.

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[1] Regulatory bodies from a number of countries were approached to attend the meeting but many declined because at that time they did not consider themselves ready to comment. It is hoped that as the by the time the next meeting is held in autumn 2006 that more regulatory bodies might feel in a better position to discuss their needs.

There is not much point mandating levels of monitoring performance when there is no minimum standard identified and understood (except some industry-set de facto standards). So at this stage the regulators are trying to resolve which end of the spectrum should be pursued, whether that is performance requirements or identifying minimum standards for monitoring.

As an observation, monitoring is often noted as being important, but it's usually expressed 'off to the side' and is not actually being resourced much yet – this is understandable on one level given development issues for even getting CCS off the ground. For example though, throughout the IPCC Report monitoring is pointed to for a range of fundamental risk management requirements, yet it is often left out of costings, status-of-development tables and so on.

It is important for monitoring and verification to be an integral part of any CCS activity from the outset. Critical work on monitoring and verification is needed now; to be ready when CCS projects come on line (there are some substantial projects in the 'pipeline' in Australia). This work is essential for accurate, usable verification down the track.

Finally, effective and robust monitoring and verification is needed if we are to have informed policy (and debate) on CCS. It's a crucial part of transparency.

The difficulty is… how to do this work when CCS is so site specific?

Key terms

In the Australian context, CCS refers to CO_2 capture, transport and *geological* storage. Australia is not considering ocean storage at this time, and mineral carbonation or industrial uses are considered minimal.

Monitoring refers to measuring and reporting CO_2 behaviour during CO_2 injection and storage:

- within the reservoir (chemically/physically, movement/migration)
- atmospheric (leakage)

(with a note that capture and transport need to be measured too)

Verification means establishing whether CO_2 is behaving as predicted and/or within accepted boundaries defined in performance standards. This is to ensure the CCS project:

- manages health, safety, environmental and economic requirements and risks;
- is meeting its greenhouse objective;
- is accurately represented in the national inventory; and
- Informs a potential future market in CO_2.

Brief outline of Australian regulatory/policy setting

The complex nature of implementing a new technological system such as CCS, and the reasons for doing so, mean many portfolios have a key interest in this. There is a range of whole-of-government and intergovernmental committees and working groups that manage the various policy matters related to CCS.

The state governments will be the main regulators of CCS.

In the Commonwealth Government, key roles are played by:

- the Industry, Tourism and Resources portfolio; and
- The Environment and Heritage portfolio, both on environmental matters and climate change.

Other parts of government have a key role on specific issues; for example, on issues surrounding long-term liability, the Treasury and legal portfolios would be heavily involved.

Climate change mitigation through CO_2 emission abatement is central to CCS; and key policy issues also include health, safety and the environment (and also risk management and community preferences in relation to these); economically efficient deployment; and dependable delivery of the emission outcome.

The Australian Government is developing partnerships with industry in these matters. This is shown by the way the Low Emissions Technology Demonstration Fund has been set up, and by the strong links with industry initiatives such as COAL21 (which is a partnership between Commonwealth Government Departments, the coal and electricity industries, relevant research institutions and relevant state governments). COAL 21 was set up by the Australian Coal Association to, among other things; facilitate low emission technologies as a major step towards greenhouse gas emission reductions.

Government agencies are also very conscious of the public, and the public's concerns and involvement are important. The agencies are spending taxpayers' money – and every dollar spent on one mitigation option is a dollar not spent on another. Further, while addressing climate change is largely about protecting people's standard of living in the future; there are obviously concerns that people might have about how safe and equitable options like CCS are.

It's notable that the IPCC Special Report had very little on public perception of CCS, because there haven't been many studies on it. Public perceptions are dependent on knowledge and education, and good monitoring and verification provides the basis for reliable information, for everyone.

Policy background

The background to why Australia is looking at CCS is an important factor to remember when policymakers are considering what type of monitoring and verification regime would be appropriate.

Firstly, Australia can meet its short-term mitigation requirements without CCS. And there are no commercial drivers for CCS in Australia at present – no monetising of the benefits of reducing emissions. But the Australian Government is committed to taking action now to prepare the economy and society for the future; recognising that a strategy needs to be introduced to prepare the economy to respond to any future emissions constraints.

The Government has set a clear objective – to maintain a strong and dynamic economy, while ensuring a reduction in the greenhouse signature in the long term. Because production and use of energy is Australia's largest source of greenhouse gas emissions, the government is very interested in proving technologies that can reduce emissions in the energy sector.

Two documents released in 2004 act as a guide: The 2004 Budget announcement included The Climate Change Strategy; and the Energy White Paper, *Securing Australia's Energy Future*, described a range of initiatives, not least of which is investment in low emissions technologies such as CCS. It should be noted that CCS and other low emission technologies are recognised as one mitigation option in a portfolio of options.

Australian Government principles on monitoring and verification

The Australian Government recognises the need for a nationally consistent regulatory regime to govern future commercial CCS activities. In this context, it has endorsed the following principles (among others) in relation to any future regulatory regime governing commercial CCS activities:

- Regulation should provide for appropriate monitoring and verification requirements enabling the generation of clear, comprehensive, timely, accurate and publicly accessible information that can be used to effectively and responsibly manage environmental, health, safety and economic risks; and

- Regulation should provide a framework to establish, to an appropriate level of accuracy the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of leakage.

This is the broad framework and the objective is to manage risks and to provide confidence for the public and investors alike.

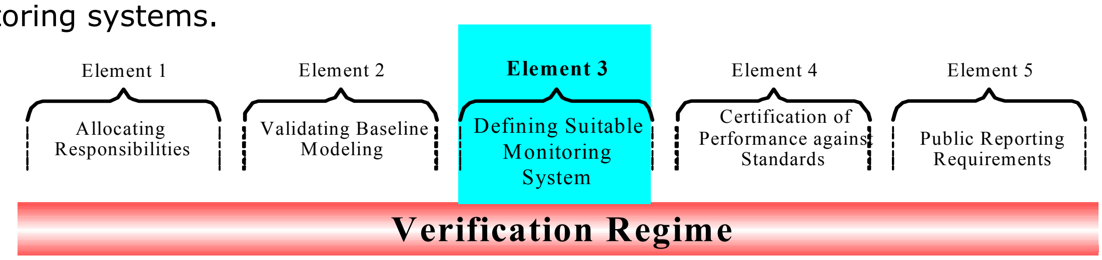
These principles, as well as several others on regulation of CCS, were developed in consultation with state governments, industry, research groups and environment non-government organisations. It should be expected though, that as the principles develop into requirements, divergent priorities will continue to emerge between the various stakeholders, and that these will need to be worked through.

When the Australian Government considers introducing new regulatory regimes, it produces a public document called a Regulatory Impact Statement. The one that was associated with the principles mentioned above recognised that:

"*Although projects will necessarily be assessed on a case-by-case basis, any monitoring and verification system needs to ensure industry provides accurate and relevant information, which is readily available to the community and independently verifiable. This is likely to come in the* *form of operating and reporting standards or objectives that apply to all projects to deliver a high degree of certainty to operators and the community*."

Monitoring system requirements

More recently, work has been conducted identifying the core elements needed to establish a monitoring and verification regime relevant to Australian conditions. Monitoring is one of five elements critical for a verification regime. The simplistic diagram below presents the relationship seen between a verification regime and monitoring systems.



The first element of a verification regime involves a clear allocation of all responsibilities (including for monitoring systems) across all relevant entities and phases of a CCS project. This is to ensure that all regulatory or contractual requirements are met during the transfer of CO_2 ownership across all phases (capture, transport, injection, short and long-term storage).

The second element is a validation of the baseline modelling of conditions in the reservoir and of the expected behaviour of the CO_2 and co-sequestered gases. Before defining a monitoring system for a site, it will be necessary to validate the critical aspects of the site (for example, fault orientation and estimation of fault activation pressures, provide for upper limit injection rates and pressures).

The third element involves defining a suitable monitoring system across a broad range of storage sites to generate a quality of data that will allow for the following:

- determination of whether the sequestered CO_2 and co-sequestered gases, storage site and environments are behaving as predicted (real site data reconciled back to the baseline, to assess performance);
- compliance and or compatibility with national and international standards (such as monitoring technology performance standards; and accounting protocols that enable an estimation of the net abatement of CO_2 emissions for any site);

- sufficient flexibility to include new/improved technologies over time and to be applicable to different sequestration scenarios; and
- best practice and continuous improvement in monitoring technology.

There are two timescales relevant to the deployment of monitoring technologies: near- and long-term – or predictive – technologies. The application of these technologies will differ according to the operational and post-operational phases of CCS activity.

For example, during CO_2 injection, the technologies will need to provide some confidence in the reservoir and injection well integrity (including pressure tests, mechanical integrity tests etc). Many of these technologies are already industry standard and research and demonstration projects should probably focus on less developed or predictive monitoring technologies. Measuring long-term behaviour of CO_2 in the subsurface, predicting future leakage (or migration) and taking quantitative measurements of CO_2, presents researchers with relatively greater uncertainty in regards to demonstrating monitoring systems.

The monitoring and verification research priority should be storage. Research on monitoring and verification techniques for the capture and transport phases are a lower research priority, given that:

- these phases already happen in other applications and circumstances (though adaptations will be needed for CCS); and
- they are easier to control, given their short-term nature and the fact that they are in the realm of human engineering (compared to post-injection being in the realm of the elements).

Nevertheless, they are important, and a verification regime will need to incorporate them.

The fourth element is a certification process of the performance of CO_2 and co-sequestered gases that embraces both transparency and inclusiveness of the community. This will ensure that in reporting the performance of CCS sites, the community has confidence that the CO_2 remains in the subsurface and does not damage the surrounding environment – this also leads to the fifth element of a verification regime, which is public reporting requirements, such as national inventories.

Monitoring and verification research funding

The Australian focus is clearly in the third element of the regime described above. The Australian Government is demonstrating its commitment to supporting research in this area, by providing about $8 million under its Low Emission Technology and Abatement measure. This is to enhance Australia's capacity to monitor the movement of CO_2 geologically sequestered in Australia.

Other questions

The other elements of the verification regime are no less important and do need attention – and the monitoring research will affect these too. Also, there are other factors that will influence the criteria for monitoring and verification that haven't been worked out yet – such as ownership of the CO_2 and who is responsible for any leakage (or other damage) during the various phases of CCS.

This will affect not only what data needs to be collected, but also who collects it and whether it's practical and aligns with other greenhouse reporting the organisation might already conduct. Further, the monitoring can not be cost restrictive on the overall operation.

How much verification will be needed? And how accurate will it need to be? It depends on:

- the certainty of the storage;
- the risks (and level of risk) that might apply to any given site;
- the policy settings in place (e.g. if you had an emissions trading scheme you would require more strident verification than if the system was based on voluntary action); and
- Community preferences.

Other questions include:

- Is each site going to be so different that it requires a completely different monitoring regime? Would this mean a fairly broad-level verification regime would be better, with case-by-case monitoring systems established?
- Is the level of certainty that there won't be leakage to the atmosphere enough to satisfy government's national and international reporting responsibilities (once CCS is part of inventory)?
- Would we have more regulation in early cases, leaving it open as to whether we'd need less in future decades if early projects demonstrated high levels of certainty?

Conclusion

The current situation that policymakers (and probably scientists and all those involved in the Monitoring Network) find themselves in, is one of trying to design a verification regime to manage risks that it is not possible to be 100% sure about.

The reason for involvement in the network is to try to gauge whether it is possible to begin to join these two parts of the equation; as well as share knowledge with other regulators; and appreciate where the science, and the experts, are right now.

The emphasis should be on the urgency of trying to join these two parts within the next five years or so. As the number of projects increase, there is the possibility that those on the monitoring side of regulation may lose the opportunity to implement holistic regulation that is both efficient (less red tape for industry) and effective (guarantees as best as possible the safety and abatement aspects of the activity).

Why? Because the momentum is likely to be with action – actually getting storage projects up and running – and this will not be held up by the need to spend years getting the monitoring and verification regime perfect. (For example, those that come under RD&D might have less onerous requirements than fully commercial ventures.)

As the monitoring and verification regime – or set of standards – will inevitably be an evolving one, the task of the regulators is to establish one that is both flexible and strong, to give themselves, and more importantly the public, the confidence that CCS is an effective climate change mitigation option.

3.2 USA Perspective – U.S. Environmental Protection Agency (U.S. EPA)

An internal U.S. EPA working group has been formed to deal with CCS regulatory development in the USA. The working group consists of approximately 30 members from several offices plus U.S. EPA regions and labs. Their efforts focus on technical and regulatory issues, risk assessment, communication and outreach. They have been heavily involved in the IPCC Inventory Guidelines.

The key technical issues for the working group are:

1. Site Selection Criteria
2. Injection Well Construction & Integrity of Pre-Existing Wells
3. Ability to Demonstrate Reservoir Capacity & Integrity
4. Monitoring Techniques/Approaches
5. Remediation Options
6. Site Closure and Plugging & Abandonment Practices

The existing U.S. Federal Programme identified as most relevant to CCS is the National Environmental Policy Act (NEPA). This programme uses environmental impact statements so that federal agencies consider the environmental impacts of their proposed actions and the reasonable alternatives. The other relevant programme is the Safe Drinking Water Act (SDWA) which includes the Underground Injection Control programme (UIC). This regulates the injection of fluid (liquid, gas or slurry) underground. UIC could provide an existing framework for CCS. The programme contains several classifications of well including Class II wells, covering oil and gas production and EOR, and Class I wells which provide a framework for conditions most similar to saline aquifers. Class I wells cover hazardous and non hazardous waste.

Individual States make their own regulations to control on-shore injection but they must meet or surpass the Federal regulations and can not be lower than those set by the Federal Government.

Class I wells, which would appear to be the most relevant class for saline aquifers, has 2 categories. This classification covers both hazardous and non-hazardous waste and each have separate restrictions and regulations. Hazardous waste is far more restrictive and this type of Class I well has what is called a "no migration petition"[2]. Class I type wells for hazardous waste with a no migration petition have regulations that define what needs to demonstrated for approval. This includes an evaluation of the geology, modelling of plume development in the sub surface, assessment of defined area of review based on modelling, and monitoring of injection wells. These types of petitions are costly and time consuming. Therefore, it is important for CCS that CO_2 must be shown to not be hazardous and it does not move from the injection area with a 10,000 year timescale. Models are used to bound the limits of the waste plume.

Requirements for storage include:

- Defining a cone of influence, where existing wells are identified and assessed as to whether they are a risk for leakage. Old wells may need to be re-drilled and sealed.
- Annual monitoring requirements for Mechanical Integrity Tests (MIT) which include annulus pressure tests, radioactive tracer and fall off tests.
- Five year monitoring – temperature surveys
- Casing inspection logs
- Continuous operational monitoring, including annulus pressure, injection pressure, injection rate, injection volume and waste stream temperature.

The major question for CCS is does it fall under existing UIC regulations? EOR is already covered by Class II wells and Texas permitted a Class V well (experimental technology) for a CO_2 demonstration project (Frio Project).

Some of the major issues for regulating CCS are:

- What timescale is adequate for CO_2 storage? CO_2 injection projects will operate over much longer timescales than current injection projects.
- What is minimum depth can the CO_2 be allowed to migrate to protect the drinking water and to minimise or eliminate leakage back to the surface?

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[2] Requires that no migration from the "injection zone" can be demonstrated through modelling over 10,000 year timescale

- The area of review currently defined is fixed to ¼ mile radius from the injection well but is this sufficient due to buoyancy and the higher mobility of CO_2?
- What type of model should be used? Currently models for subsurface CO_2 migration are at any early stage of development and are not proven like those used for waste injection.
- How much field data is required? There is a need to consolidate existing data from the oil and gas industry. It is often stated that there is lots of experience from industry but consolidating that experience has not been done.
- Can a reasonable time, effort, and cost be associated with modelling CO_2 storage?
- Can the costs associated with acquiring the model input data be reduced?
- What is the purity of CO_2 injected? What will be the other constituents? Does it make sense to purify prior to injection?
- Can assumptions be used to reduce the costs associated with modelling CO_2 storage?

In conclusion:

- At the moment CO_2 is not classed as a legal hazardous waste.
- Any monitoring that will be undertaken would be site specific[3].
- The existing no migration petition from Class I wells is not entirely applicable for CCS but it is a good analogue.
- Knowing the site at the beginning saves both monitoring and remediation costs.
- The level of monitoring necessary for health and safety and local environmental issues may be different to that required for GHG accounting.
- Simple risk assessment tools and practical monitoring programmes will help reduce the burden on project operators and regulatory agencies.

3.3 UK Perspective – UK Department of Trade and Industry (UK DTI)

The UK DTI (Department of Trade and Industry) is responsible for energy policy and DEFRA (Department for Environment Food and Rural Affairs) for regulation. The DTI

[3] A common theme

are working closely with DEFRA. The UK can look at relevant regulation from current experience, it has a mature oil and gas industry but it is not in a position at this moment to provide guidance for CCS through regulation, it is still learning what the implications are. The focus of the discussion at this meeting is on offshore storage in a UK context.

It is the UK's policy to use market mechanisms to reduce Greenhouse Gas (GHG) emissions, with EU Emissions Trading Scheme (ETS[4]) a key one. CCS is in the portfolio of options and was mentioned in the Energy White Paper. The UK Prime Minister used the presidency of G8[5] and the EU[6] to look at the feasibility of CCS recognising its value in reducing GHG emissions. Therefore, it is high on the political agenda and the UK would like to see it included in the EU ETS. However, there is a time limit, a narrow window of opportunity of 10 years.

The EU is using the carbon credits to make CCS projects economic. There is also the opportunity for EOR which also helps to improve the economics of a project. However, the Governments within the EU will allocate the levels individually leaving uncertainty. Robust reporting guidelines for monitoring CCS operations in EU ETS will be required.

The DTI looked at what monitoring would be required and created and an ad hoc group of EU experts to develop monitoring and regulation guidelines. Conclusions of the group were:

- That it was essential to maintain integrity of the capture and storage process
- That there was a more robust framework for monitoring than what currently exists for "transfer arrangements" (e.g. those used in the drinks industry where the scale of the operation is not comparable)

The study looked at monitoring fugitive emissions all along the route of CCS from source to injection. The responsibility for measurement could be from a number of different operators across the chain. The storage part would be accounted for by a different regime to that established for capture and transport of CO_2 because of the

[4] EU ETS – World's first large scale GHG emissions trading system, started January 05, 12 000 installations, 25 countries, 6 sectors
[5] The Group of Eight (G8) is Canada, France, Germany, Italy, Japan, the United Kingdom, the United States of America, and the Russian Federation. The G8 holds an annual economic and political summit meeting of the heads of government with international officials, though there are numerous subsidiary meetings and policy research.
[6] The European Union's (EU) is an intergovernmental and supranational union of 25 democratic countries known as member states. Its activities cover all areas of public policy. The European Commission (EC) is the executive body of the European Union. Its primary roles are to propose and implement legislation, and to act as 'guardian of the treaties' which provides the legal basis for the EU.

timescales involved. The regulation for storage needs to be robust enough to include seepage in both the short and long term and would not be included in the EU ETS.

The next step for the UK and the Carbon Abatement Technologies Strategy is to take a lead in national and international regulatory frameworks. The UK DTI can not give guidance on regulation requirements but they can provide confidence from the experience gained to date. DEFRA are likely to be the regulators for CCS and it is already acknowledged that regulations will have to be able to adapt to site specific conditions.

The presentation referred to a recent report of the DTI prepared by Environmental Resources Management Ltd (ERM) and Det Norske Veritas (DNV). A summary of the report can be found on the DTi[7] website but a short summary is provided bellow. The report reviews the key issues presented by CCS when considering its inclusion in emissions trading, and outlines a proposed approach for developing interim guidelines for monitoring, reporting and verification for CCS under the EU ETS. It covers the whole of the CCS process (capture-transportation-injection). The possible long term seepage of CO_2 from the storage site back to the atmosphere is not included in the proposed monitoring and reporting guidelines.

DTI report R277

Page 1: The EC produced guidelines for monitoring and reporting of greenhouse gas emissions from instillations included under the EU ETS Directive in early 2004. The guidelines do not include any specific guidelines for monitoring and reporting greenhouse gas emission from CCS. However, the EC invited Member States interested in the development of such guidelines to submit their research findings, based on the invitation ERM and DNV have produced this DTI report R277.

Page 20: Under the proposed methodology, emissions from the CO_2 geological storage site would not need to be monitored and reported by the installation as part of its EU ETS Directive reconciliation requirements. It has been assumed that the evolution of storage site licensing and permitting regimes, at least within the EU, will include the necessary monitoring and reporting obligations for site operators. This is anticipated to include quantifying the amount of CO_2 emitted from the site as a consequence of natural seepage, as well as other forms of physical leakage.

[7] DTI Report R 277:
http://www.dti.gov.uk/energy/coal/cfft/cct/pub/pdfs/r277.pdf?pubpdfdload=05%2F583

Page 28: To account for any potential future emissions of the stored CO_2 back to the atmosphere, many observers have suggested that any emission reduction credits given to project or installation operators employing CCS should be subject to some form of discounting. However, current constrains in the understanding of specific CO_2 fluxes from potential storage reservoirs presents a barrier to setting credible rates. Therefore, for the monitoring and reporting framework methodology for CCS under the EU ETS it has been proposed that CO_2 emissions from storage sites be excluded from an installations inventory.

Page 29: However, this certainly does not mean that CO_2 emissions from storage sites should not be accounted for at all. An alternative approach to discounting might be considered, based on a number of assumptions about storage site permitting and licensing:

i) The storage site operator would be required to show appropriate due diligence during storage site selection, such that all the available geological survey data and other evidence regarding the security of gas storage in the reservoir suggest within reasonable expectation, that the reservoir would not leak;

ii) In the event of any short-term leakage, an emergency plan was in place to minimise loses;

iii) Storage site operators would be required to make a commitment to monitor and report quantified emission of CO_2 leaking, by seepage or sudden release from the site, using good practice techniques likely to evolve over time.

iv) These losses would need to be reported to the host government, who would then take them into account in their National Greenhouse Gas Inventories under the UNFCCC

v) Operating licences would be time limited and subject to renewal/approval on the grounds that the storage site was operating satisfactorily (i.e. not leaking at an unacceptable rate). At license renewal time, the regulator would be required to review the performance of the storage site, based on the emissions data submitted under iv)

vi) The requirements to monitor and report leakage by seepage or sudden release would be ongoing after the sealing of the injection wells and closing of the site. Ultimately, this responsibility would fall to the government under who's territory the CO_2 is being stored i.e. the host government would make a long term commitment to take responsibility for the stewardship of a storage site, including emissions monitoring and measurement, and also in the event of insolvency of the site operator, or license withdrawal or expiry.

Page 30: One further issue to consider in relation to leakage from geological storage is CO_2 breakthrough during EOR operations where some fugitive emissions may occur.

Page B6: The frequency of monitoring will depend on the monitoring methodology used, for instance:

i) Down hole pressures and temperatures should be measured quite frequently, perhaps monthly;

ii) 3D (or 4D taking into consideration the temporal dimension) seismic monitoring may be carried out pre- and post- injection and at certain extended intervals;

iii) Microseismic activity monitoring, if required, should be continuous and should continue until there is no further injection unless one is in a possibly seismically active area, in which case it may have to become an extension of the regions' ongoing seismic monitoring programme. Other methods would probably be best synchronised with the seismic campaigns as they can be used to enhance the seismic results.

3.4 Discussion on Monitoring Requirements

A series of comments were raised after the presentations these are summarised below.

It was noted that UIC monitoring is restricted to wells and not other subsurface monitoring. This is a deficiency in applying the UIC regulations for CCS, which would need to be reinforced if these regulations were adapted for CCS, this was agreed. In response it was stated that although the UIC programme may only be considering the wells but there is a lot of information about the injected CO_2 that can be gained at the well head and UIC has 30 years experience of monitoring at the well head

One additional comment relating to the UIC programme was that it covers much smaller injection amounts and substances that were not underground before. In this case it is not comparable to CO_2 storage. Again, in response, it was noted that UIC may be simple and may be inadequate but it is important to address why. This would help develop new regulations suitable for CCS. Following on from this it was stated that although there maybe some modification required to the UIC programme these regulations were a good starting point to move forward from.

One note of caution raised referred to the reliance on modelling alone, rather than monitoring, was that modelling can not currently accurately account for faults. It was generally agreed that models need to be developed further before they can be relied upon solely for CO_2 injection. Monitoring programmes of course can help the development of models by providing data to allow the models to be calibrated against.

Wells were raised by many people as a serious source of concern. In designing a monitoring programme the age of wells should be a consideration. In North America onshore wells from 1930-1950 will not be plugged to the same extent as later wells and hence represent a higher risk potential. The same maybe true offshore.

Another issue raised regarding wells is that there has been discussion regarding going in and reworking old wells to seal them before a project starts. This can be an expensive task especially if there are a lot of old wells present on a site. The question was raised whether it might not be more cost effective to monitor old wells rather than rework them. In response, it was agreed that the risk of leakage from old wells will be different in different locations, onshore/offshore location, and dependant on the age of wells. How to deal with old wells may also be different.

It was raised that frequency analyses of well bore failure has shown that there have been 17 big leaks over 20-35 years. Most, importantly the frequency of leaks drops off with improvement in technology/experience. Therefore, it is necessary to look at modern practices rather than comparing with historical trends.

4. Monitoring Programmes

4.1 Experience from ongoing projects

Frio – Bureau of Economic Geology, University of Texas at Austin

From October 4 to 14, 2004 the Frio Brine Pilot team injected 1,600 tons of CO_2 1500m below surface into a high permeability brine-bearing sandstone of the Frio Formation beneath the Gulf Coast of Texas, USA. Analytical results completed during the 10 months following the end of injection have improved our understanding of techniques and process that are useful in monitoring the post injection storage period.

Key new findings are:

(1) Field measurements using neutron logging for saturation, cross well seismic, and VSP were successful in measuring CO_2 retained in the formation over time

(2) Models and conceptualization significant CO_2 is retained as relative permeability to gas decreases over time (two phase trapping); the measurements confirm the correctness of this process

(3) Follow-on testing is designed to better quantify the two-phase processes under reservoir conditions as well as buoyancy effects. This second round of testing will begin in October, 2005.

The Frio Brine Pilot experiment is funded by the Department of Energy (DOE) National Energy Technology Laboratory (NETL) and led by the Bureau of Economic Geology (BEG) at the Jackson School of Geosciences, The University of Texas at Austin with major collaboration from GEO-SEQ, a national lab consortium led by Lawrence Berkeley National Lab (LBNL).

The main project objectives are:

(1) Demonstrate to the public and other stakeholders that CO_2 can be injected into a brine formation without adverse health, safety, or environmental effects,

(2) Measure subsurface distribution of injected CO_2 using diverse monitoring technologies,

(3) Test the validity of conceptual, hydrologic, and geochemical models, and

(4) Develop experience necessary for development of the next generation of larger-scale CO_2 injection experiments.

The first objective was accomplished through outreach, which included numerous site visits by researchers, local citizens, and environmental groups, major media interviews, an online log of research activities (www.gulfcoastcarbon.org), a technical e-newsletter, and an informal non-technical "neighbour newsletter". These activities continue as results of analysis are obtained. Public and environmental concerns were moderate, practical, and proportional to minimal risks taken by the project and included issues such as traffic and potential of risks to water resources. Press coverage was balanced and positive toward research goals. Safe site operation was managed by Sandia Technologies LLC, Praxair Inc., and Trimeric Corporation.

The second objective, measurement and monitoring of the subsurface CO_2 plume, was accomplished using a diverse suite of technologies in both the injection zone and in the shallow near-surface environment. Each monitoring strategy used a pre-injection and one or more post injection measurements. Wireline logging, pressure and temperature measurement, and geochemical sampling were conducted also during injection. In-zone objectives were to measure changes in CO_2 saturation through time, in cross section, and areally, and to document accompanying changes in pressure, temperature, and brine chemistry during and in the months following injection. The in-zone measurement strategy was designed to test the effectiveness of a selected suite of monitoring tools in measuring these parameters. The near-surface monitoring program measured soil gas fluxes and concentrations, introduced tracers, and fluid chemistry in the vadose zone and shallow aquifer in an attempt to detect any leaks upward out of the injection zone, especially those rapid enough to cause releases in a short time frame such as behind well casing.

Tools used for in-zone monitoring included five repetitions of logging with the Schlumberger pulsed neutron capture reservoir saturation tool (RST), which under conditions of a maximum 35% porosity and 125,000 ppm salinity was successful in obtaining high-resolution saturation measurements across the injection interval. During the injection, CO_2 saturation increased toward a maximum of 60% of pore space filled with CO_2 in both the injection and observation well. Saturation declined in the post injection period; the last log run Feb 23 quantified the CO_2 permanently trapped in-zone by two-phase (residual) trapping. The log analysis team includes researchers from BEG and Schlumberger–Doll Labs.

An innovative geochemical sampling tool, developed and operated by Barry Freifeld and Rob Trautz (LBNL) to support in-zone fluid chemistry sampling, is the U-tube. The U-Tube is composed of a double length of 9.5 mm O.D. $\times$ 1.2 mm wall thickness stainless steel tubing, with a check valve open to the reservoir at 1500 m. Formation fluid that was collected in the U-Tube was driven at reservoir pressure into evacuated sample cylinders at the surface by high pressure ultra-pure nitrogen. Samples were collected hourly to facilitate accurate delineation of CO_2 breakthrough and recover uncontaminated and representative samples of two-phase fluids. Initial CO_2 breakthrough to the observation well 30 m updip of the injection well occurred 51 hours after initiation of injection. Steady increases in the ratio of CO_2 to brine produced recorded increasing saturation and plume thickness as the front of the plume expanded past the observation well. Free gas in the sample and gases coming out of solution were pumped from the top of the gas separator through a quadrapole mass spectrometer analyzer and a landfill gas analyzer to measure changes in gas composition in the field. During the 12 hours after breakthough, CO_2 replaced brine as the fluid in the perforated zone of the well bore and became the only fluid produced. At the same time that CO_2 was detected at the observation well, the pH of produced, partly degassed brine dropped from 6.7 to 5.7, alkalinity increase from 100 to 3,000 mg/L bicarbonate as a result of mineral dissolution, and iron increased from 20 mg/L to 2000 mg/L, changing the fluid from clear to coffee colour (Yousif Kharaka [USGS] and Seay Nance [BEG]). Downhole sampling with a Kuster sampler in April, 2005 allowed us to assess geochemical changes as CO_2 saturated brine react with the mineralogially complex sandstone matrix for 7 months.

The suite of tracers injected with the CO_2 includes perfluorocarbon tracers (PFTs), the noble gases, krypton, neon, and xenon, along with sulfur hexafluoride. Tracer injection and analysis was performed by researchers from Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, and Alberta Research Council. The tracer arrival times and elution curves allow assessment of the percentage of CO_2 that is trapped by dissolution into the brine, based on partitioning of the tracers from CO_2 into the brine, along with facilitating estimation of evolution of CO_2 saturation as injection proceeded.

Pressure and temperature histories during injection provided comparative effective permeability under brine- and evolving CO_2 + brine conditions. Downhole installation of pressure and temperature gauges proved to be critical for interpretation of complex (gas, supercritical CO_2, brine) phases in the well bore. LBNL and Sandia Technologies designed the hydrologic test program.

Geophysical measurements of plume evolution include cross-well seismic, an azimuthally dependent vertical seismic profile, and cased-hole cross-well electromagnetic (EM) surveys. These surveys were made pre- and post injection and analyses to-date show that tools were successful in measuring CO_2. The entire test is a proxy for a leak that might escape from a large injection; additional analysis is underway to determine success of geophysical methods in leak detection under these conditions. The geophysical team includes LBNL, Paulsson Geophysical, Schlumberger-EMI Technology Center, and Australian CO_2CRC/CSIRO.

Near-surface monitoring includes soil-gas CO_2 flux and concentration measurements, aquifer chemistry monitoring, and tracer detection of PFT with sorbants in the soil and aquifer. Pre-injection baseline surveys for CO_2 flux and concentration-depth profiles over a wide area and near existing wells were done in 2004. Minor variability in aquifer pH and gas concentrations have been measured but analyses of tracers needed to determine whether change is related to leakage are still underway. The near-surface research team includes BEG, NETL SEQURE, Colorado School of Mines, and LBNL.

The third objective is to test the validity of conceptual hydrologic and geochemical models. Reservoir characterization by BEG to provide inputs to the simulations used existing and newly collected wireline logs, existing 3-D seismic survey, baseline geochemical sampling by USGS and Schlumberger, and core analyses by Core Labs. A drawdown interference test and a dipole tracer test conducted by LBNL researchers provided interwell permeability estimates (2.3 Darcys) confirmed that the core-based measurements of the porosity-thickness product (6.2 m thickness with 0.35 porosity) were appropriate at site scale for the Frio C sand targeted for CO_2 injection.

Two groups of modellers, LBNL using TOUGH2 and The University of Texas Petroleum Engineering Department using CGM, input geologic and hydrological information along with assumptions concerning CO_2 /brine multiphase behaviour to predict the evolution of the injected CO_2 through time. The observed CO_2 breakthough occurred somewhat faster and in a narrower zone than the predicted arrival. Further refinement of the relative permeability and capillary pressure-saturation properties allow the model to better match the acquired data. Geochemical modelling by Lawrence Livermore National Lab predicted elements of brine composition evolution.

As the Frio experiment analysis and modelling continue, it supports the fourth objective, development of the next generation of larger-scale CO_2 injection experiments. Confidence in the correctness of conceptual and numerical models and the effectiveness of monitoring tools tested will encourage the next pilots to investigate more complex factors such as stratigraphic and structural heterogeneity and upscaling. The Frio Pilot results provide a model for the US Regional Partnerships Program participants as well as international collaborators to us to design test programs in various settings.

The pilot site is representative of a broad area that is an ultimate target for large-volume storage because it is part of a thick, regionally extensive sandstone trend that underlies a concentration of industrial sources and power plants along the Gulf Coast of the United States. The Gulf Coast Carbon Center, in cooperation with the Southeast Regional Carbon Sequestration Partnership, is proposing one of these ambitious pilots in the Frio or related sandstone to conduct a multi-month injection to "prove- up" the concept of stacked storage in an oil reservoir in decline and the underlying brine-bearing sandstones.

A list of the Frio Brine Pilot Project Research team is available in Appendix 3.

Nagaoka monitoring surveys – Engineering Advancement Association of Japan (ENAA)

The preliminary results from CO_2 monitoring surveys performed at Nagaoka were presented at the Inaugural Meeting of the Monitoring Network at Santa Cruz, November 2004 (Ziqiu Xue & Daiji Tanase). At Nagaoka, the CO_2 was injected into a 12m thick permeable sandstone reservoir at a depth of 1,100m below ground surface at the rate of 20-40 tonnes per day. The CO_2 injection ended on January 2005 with the total injected CO_2 amount of 10,400 tonnes within eighteen months. A series of CO_2 monitoring techniques were deployed these consisted of: time-lapse cross-well seismic tomography and geophysical well logging. These techniques provided valuable insight into the CO_2 movement within the porous sandstone reservoir. The follow-up monitoring in Nagaoka will be continued till 2007.

The measurement and observation programme at Nagaoka included:

- Measurement (continuously)
    - Pressure & Temperature (well bottom and well head)
- Cross-well Seismic Tomography
    - Five times : Before the injection – After the injection

- Time-lapse Logging (2 week to one month interval)
    - Induction Log
    - Neutron Log
    - Sonic Log
    - Gamma Ray Log
- Observation (continuously)
    - Micro earthquake

The Nagaoka project has four wells. There is a central injection well and three other observation wells spread between 40 and 120 m away from the injector well. Cross-well seismic tomography was taken across the longest distance between observation wells. The time-lapse logging confirmed CO_2 breakthrough in the observation wells and that the CO_2 bearing zone was getting wider.

Four monitoring surveys were undertaken following an initial baseline survey in February 2003. The cross-well seismic tomography detected a P-wave velocity decrease (CO_2 invaded zone). An area of P-wave velocity decrease appeared near the injection well and the injected CO_2 was found to be migrating along the formation in an up-dip direction. The results confirmed the usefulness of cross-well seismic tomography.

The project identified some limitations of the present analysis. The velocity reduction is smaller than true velocity reduction, and the velocity reduction zone swelled in a vertical direction. To detect a thin layer of 4 – 5 m using this technology is difficult and a ghost image similar to the field result occurs. A new analysis with a constraint that CO_2 invades only into Zone-2 (high permeability, no change in well logging) will be undertaken in the next phase.

Results were obtained using various techniques:

- Time-lapse Logging CO_2 saturation History, Vp History, CO_2 breakthrough
- Cross-well Seismic Tomography, tomogram of CO_2 distribution
- Simulation Study, using CO_2 saturation history
- Laboratory Test

The results provided mutual verification and the project operators felt that they understood the movement of CO_2 and were in a position to predict it.

Conclusions:

- 10,400 tonnes of CO_2 were injected into an onshore saline aquifer within eighteen months in Nagaoka, Japan.
- Using time-lapse logging the project succeeded in detecting the CO_2 breakthrough and estimating CO_2 saturation history.
- Using cross-well seismic tomography allowed the project to recognize the shape CO_2 invasion into the aquifer.
- A simulation study using CO_2 saturation history gives a more exact understanding and prediction of CO_2 movement.
- The follow-up monitoring in Nagaoka will be continued until 2007.

Nagaoka 4D seismic survey – Japan Petroleum Exploration Co., Ltd (Japex)

Time lapse 3D seismic survey is a promising method to efficiently detect the fluid movement and the change of pore pressure in the aquifer. The project was located onshore Japan at the CO_2 injection field (Nagaoka). Recently a repeat 3D seismic survey was conducted. Prior to the repeat survey, the baseline 3D seismic data with wireline data was evaluated. From the 3D data, the spatial permeability distribution was estimated. This is a prediction of carbon dioxide movement prior to the repeat survey if carbon dioxide were controlled solely by permeability. Evaluation of the estimated permeability map could be done by time–lapse 3D seismic data and/or by baseline 3D seismic data using permeability distribution by wireline logging data of four wells. It is hoped that the prediction can be compared with the repeat 3D seismic survey.

This research looked at what seismic can reveal. The logging data provides physical and geological constraints for evaluation of permeability by 3D seismic data. The baseline survey was followed two years later by monitoring after completion of CO2 injection. Both the baseline survey and the monitoring were undertaken at the same time of the year for consistency in prediction and reality.

In Salah – BP

The natural gas produced at In Salah contains CO_2, in some cases as much as 10%. The natural gas is supplied to Europe and to be suitable for the markets the amount of CO_2 must be reduced, so that the maximum non-burnable content does not exceed 0.3%. The CO_2 is removed using a regenerative amine process. In the past, CO_2 would have been vented to the atmosphere.

The In Salah project is a joint venture of Sonatrach, BP and Statoil and compresses the CO_2 from 3 fields and injects into the Krechba field. Injection at the site has already begun with storage at a rate of around 1 million tonnes of CO_2 per year. The injection is really into a saline aquifer as it is 2km away from the water/gas contact.

In the case of this project, storage has not been regulatory driven. So why store at this site? There is a possibility that the project may receive CO_2 credits in the future but this is not guaranteed. The primary current benefit is the promotion of green brands value.

The monitoring programme at the In Salah site is not regulatory driven either, so why monitor? The project operators believe that it provides information which will help better manage the injection storage process. It also provides the assurance that the CO_2 injected is remaining underground.

The benefit of monitoring is that:

- It provides information to better manage the injection storage process by assessing the location of the CO_2 "front" as it percolates through brine-filled portions of reservoir, identifying the fracture zones that dominate flow and characterising the stress state of the reservoir.
- It also provides assurance that CO_2 placed underground remains underground by detecting thief zones and migration pathways that lead out of the target reservoir and by providing meaningful lower/upper bounds for total amount of CO_2 that can be directly established to be "in place" based on monitoring measurements rather injection history.

A feasibility study has been undertaken on seismic amplitude which changes when CO_2 is substituted for brine. Under the assumption that the results would be positive, permanent monitoring systems are being designed. As part of the permanent system, geophones will be deployed in parallel rows of detectors (4D receiver systems). The rows will track above the most likely path for the CO_2 to migrate in the subsurface from the injector well. To accommodate the Saharan conditions of the injection site the receivers will have to be buried to protect them from the elements. It will also reduce noise, improve geophone coupling and enhance the physical security of the equipment. The difficulty is that the ground surface is very stony making it very difficult to get probes into the ground and the trenches themselves can not be more than 1m depth for health and safety reasons or else they need supporting walls which will significantly increase the cost of this type of monitoring.

Since it is not feasible to transmit every byte from a remote location (In Salah is located in southern Algeria), only events which exceed a threshold amplitude will be stored to disk, and that disk will be periodically interrogated remotely. As resources permit, there is a possibility of a dedicated well containing a vertical array of geophones. Such an array, placed far below the attenuative low-Q weathering and subweathering zones could act as an early warning system for the surface array, causing events to be recorded onto disk that might not exceed the threshold criterion for any single geophone, but which could be summed together to produce a high quality signal.

The experience from the In Salah project further highlights that factors of the local climatic conditions have to be addressed when developing a monitoring programme.

Conclusions:

The prize for effective monitoring is at least two-fold. Firstly, by determining where the CO_2 is moving, and where it is not, better decisions can be made as to the rate of injection and location of injector wells, and additionally to inform well intervention decisions. Secondly, and perhaps more importantly, monitoring can serve to assure all interested parties that the CO_2 which has been buried underground remains underground, and has not found a travel path back to the surface.

With these twin goals in mind, remote monitoring is a likely addition of all CO_2 injection programs, and will be key to optimal management of subsurface storage.

4.2 Experience from developing projects

Otway Basin – Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

CO2CRC undertook a CO_2 Source-Sinks study of Australia. 48 basins were considered viable sites for study, 102 sites were analysed, and 65 were proved viable ESSCIs[8].

The site for the CO2CRC pilot programme is Otway Basin. The source of CO_2 is the Buttress-1 field which contains CO_2 and CH_4 (~85% CO_2). The CO_2 and CH_4 is produced and sent to a separation and compression unit. The CO_2 is then transported by pipeline to the injection well. The storage site could have been one of several well bores but the Naylor-1 was chosen, a near-depleted single well gas producer. The CO_2 is injected to a depth of 2100m on the edge of an anticline in a depleted gas field. A monitoring well has been drilled at the crest of the anticline, in the direction that the CO_2 is expected to migrate in. The distance from the injection and the observation well is 500m.

The objectives of the pilot study are:

- To demonstrate that CCS is a viable, safe, secure option for greenhouse gas abatement in Australia by
    - Safely transporting CO_2 from its source to a suitable storage site;
    - Safely injecting CO_2 into a subsurface reservoir;
    - Safely storing CO_2 in the subsurface;
    - Modelling and monitoring stored CO_2 and confirming its storage effectiveness;
    - Build and maintain an effective Risk Register;
    - Safely removing facilities and restoring the site after the project ends.

[8] Environmentally Sustainable Site for CO2 Injection

In addition, the project plans to

- o Conduct the pilot project within approved time and budget (CO2CRC);
- o Capture all research outcomes (CO2CRC);
- o Communicate to all stakeholders that these activities have been completed.

The Otway Basin project has taken the Frio project as a template. The injection rate is the same for both projects but the Otway basin project expects to operate for a longer period of time, injecting 100,000 tonnes of CO_2 in 2 years.

The project is currently waiting for permits and approvals but it is hoped that baseline surveys can begin by the end of 2005, with injection beginning at the end of 2006. The project has created a risk register for the project consisting of activities in developing the site and transportation of gas to the site. It also produced a risk register for storage but the two registers are separate.

The following list of containment risk issues were evaluated as part of the risk register completed for CO_2 storage at the site:

- Permeable zones in seal;
- Faults;
- Wells;
- Leakage via the seal;
- Regional scale over-pressurisation and local scale over-pressurisation;
- CO_2 exceeding the spill point of the storage site;
- Earthquake - induced fractures;
- Incorrect modelling of migration direction;
- Unintentional over-filling of the storage site;
- Well-head, pipeline, or compressor failure.

Key monitoring objectives for the project are:

- Soil and atmospheric measurements to confirm non leakage/seepage of injected CO_2.
- Water well monitoring to ensure no leakage of CO_2 into the overlying aquifers
- Monitor the injected CO_2 plume to:
    - Validate migration paths with respect to model predictions
    - Validate migration times with respect to model predictions
    - Validate likely shape of CO_2 plume with respect to model predictions
    - Validate containment of the injected CO_2

Monitoring at the Otway Basin Pilot Project will involve:

- Atmospheric monitoring
- Soil gas sampling over a defined grid. The grid will be wide enough to cover area over any faults that terminate relatively close to surface.
- Water well monitoring downstream of the hydrodynamic flow.
- Geochemical sampling of monitor with U-tube (LBNL), and injection horizon
- Regular suite of tracers including Deuteriated methane
- Geophysical Monitoring
    - Microseismic potential
    - Well Logs
    - Surface seismic/VSP
- Predictive forward models for above.

Initial monitoring will be undertaken using existing wells. A new well will be drilled for further monitoring. Time-lapse monitoring will use all three wells.

The responsibility of CO_2 containment will change, as the project develops, between the Oil Company, the electric company and in the long term, the Government. The question of who manages this transition is still to be answered.

Snohvit - Statoil

Snohvit is located in the Norwegian offshore, and to get an acceptance for the CO_2 storage from the Norwegian Pollution Control Authority it was necessary to develop a monitoring plan and justify it.

The injection well has been drilled and a monitoring plan developed. Monitoring will include continuous pressure and temperature monitoring at the wellhead and down hole, and seismic surveys. 2D seismic lines are planned to cross the injection well. It is expected that reservoir simulation based on well and seismic monitoring will occur over time and give an indication of plume development.

Initial 3D baseline seismic surveys were undertaken in 2003 prior to production. The plan is to acquire additional 2D seismic, which may be repeated approximately every 3rd year. If a 2D seismic survey identifies abnormal CO_2 movement then further 3D seismic could be done. The worst case scenario has been identified as a gas leak into an overlying gas-bearing formation - and not to the biosphere.

Development is still driven by the Norwegian Tax on CO_2.

Gorgon - Chevron

The Gorgon development is Chevron (50%, Operator), Shell (25%) and ExxonMobil (25%). The greater Gorgon area resources are ~40 Tcf. The screening processing involved accommodating a processing/LNG plant and suitable storage reservoirs. Barrow Island became the optimal choice for the site for both economic and technical reasons. The natural gas in this area contains a certain percentage of CO_2, it will be removed and compressed and then re-injected into a deep saline aquifer (Dupuy Formation). The plan is to inject CO_2 unless it is technically infeasible or cost prohibitive. The proposed injection will reduce GHG[9] emissions by 40%.

Barrow Island is a "Class A Nature Reserve" but has been under oil production for around 40 years. The Gas Processing and LNG facilities were selected to avoid sensitive areas and the injection site avoids sensitive areas whilst optimising performance.

Key CO_2 storage issues include geological characterisation, CO_2 movement and trapping, and monitoring. There will be two injection centres with up to seven lateral wells. A simulation of the injection and trapping shows that the permeability

[9] Greenhouse Gas

distribution of the Dupuy formation prevents rapid vertical and lateral migration. The pressure field peaks at around 30 years. It is expected that most of the CO_2 will be trapped by the major mechanisms[10] within 1000 years. The reservoir simulations model predictions show the aerial extent of the plume increases slowly after 40 years (operational phase). During this phase it avoids major faults but does intersect 27 wells; another 3 wells over 1000 year timescale.

It was concluded that through the lifetime of the project, key issues needed to be resolved in terms of geology and geography. They included being able to follow the spread of the CO_2 plume both onshore & offshore, identifying any interference in the monitoring results that could come from near-surface karst formations, understanding anything about the structure and stratigraphy of the reservoir that could be an influence on the direction of the plume migration, and the impact of the rock properties on CO_2 migration and behaviour.

The project has also identified unknowns in the reservoir that could result in possible deviation from simulation predictions. These included unidentified high permeability layers in the reservoir, whether down dip migration would occur, the failure to include all the wells present within the area that the plume could spread to or the ability to predict what they might do, and finally, the presence of faults & fractures that had not been identified. In all cases these could lead the CO_2 not behaving as expected since these features are not accurately represented in models.

Monitoring activities planned include:

- Injection rate metering and pressure measurements
- HSE – oriented surveillance for leak detection
- Verification via seismic surveys and/or observation wells supplemented by conventional wire line logs to detect CO_2 migration at wells or up well bore and Geochemical analysis of formation waters

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[10] It is considered that in a suitable storage site CO_2 will be stored by physical or geochemical trapping or a combination of both. Physical trapping includes: *stratigraphic trapping*, where the CO_2 is held below a low-permeability seal (cap rock); *structural trapping*, where CO_2 is trapped by physical structures such as those formed by faults and folds of the rock; or *hydrodynamic trapping* in saline formations, where fluids migrate very slowly and the buoyant CO_2 migrates upwards to the top of the formation. Chemical trapping includes: *solubility trapping*, where CO_2 dissolves into the formation water; *ionic trapping*, where the CO_2 forms ionic species as the rock dissolves and the pH rises; and *mineral trapping*, where finally, and over long period, the CO_2 might form a stable carbonate mineral.

Options for monitoring:

- Seismic (Image Quality; Minimize Impact)
- Observation Wells (Sampling/Analysis; Sensors; Tracers)
- Shallow Subsurface (Shallow Imaging & Wells)
- Atmospheric (Soil Gas, Flux, Near Surface LS, Remote)

Potential failure of the storage project could result in leakage from surface injection facilities, migration events from the proposed storage site, reduced injectivity, earthquakes, and environmental impacts.

Considerations identified as significant to this particular storage site are:

- Environmental – Class A nature reserve; adjacent reserves
- Geography – sea/land boundary
- Geology – shallow karst; multiple sinks/seals
- Simulation results – unexpected migration
- Presence of wells – condition; remediation strategy

The five bullets emphasises the specific nature of a site and highlight how a monitoring programme needs to be able to adapt to specific conditions.

5. Monitoring Scenario Development

To assist in the process of developing monitoring programmes coupling both regulatory and industry requirements four scenarios were developed for consideration by the workshop members. The four scenarios were typical geological reservoirs selected to have different features, these are discussed later. The workshop participants were spilt into four interdisciplinary groups to consider the scenarios in a set time.

The four scenarios were:

- Frio - an onshore aquifer in South East USA. The regulatory system is mature in this region for underground waste injection and for CO2-EOR.
- Viking Graben -The case scenario was based upon a generic example of the Viking graben in the North Sea. The conceptual project was an EOR project regulated under existing Oil and gas exploration/production standards.
- Gippsland – a depleted oil field lying both on shore and offshore the Australia coastline. In this case the offshore area is regulated by the Australian Government and onshore is regulated by the State authorities.
- Acid Gas project on shore Canada – this scenario was chosen to see how easily existing regulatory frameworks could be adapted for CO_2 storage.

A detailed description of each scenario was given prior to the breakout sessions. The detailed descriptions have not been reproduced in this report.

Each group was then asked to consider the specific risk issues for each scenario, their potential consequences and how these might be mitigated. A risk register was provided to act as a tool and guide to evaluate the risks involved. Then each group was asked to develop a monitoring programme taking into account both the risk and regulatory environments for each scenario. Wherever possible the programme should observe sensible economic constraints and be generic and not overly detailed given the time available.

The key results from the breakout groups assessing the scenarios are as follows:

5.1 Frio

The key regulatory constraint identified was that any operations cannot impact underground aquifers. The monitoring programme must therefore be designed to demonstrate that such an impact does not occur. Wells were considered as a key risk factor for leakage but for the purposes of the scenario well design was considered to be based upon standard practice per Texas rule book

The key areas to monitor were identified as:

- pH changes in surface waters
- Monitor groundwater up- & down-gradient in major aquifer at 30m depth, not at surface
- Monitor in existing oil wells

It was also identified that there was a need to monitor for credits, however it was noted that the soil surface is very difficult to monitor because of high surface water and high vegetation levels which would prevent the use of most static soil monitoring techniques.

The monitoring scheme devised included:

- Baseline
    - Geologic model and reservoir simulation
    - hydrogeology
    - hydrogeochemistry in dynamic system,
    - 3D seismic for identifying faults and devises geological model
    - Well identification & completions
- Initially in reservoir, utilising existing wells
- Monitoring in shallow aquifer, deep aquifer immediately above regional aquifer
    - Alkalinity
    - Cation changes (Fe)

- Tracers

- Seismic could monitor losses into overlying aquifers, if leaks were big enough

- Cross-hole seismic to monitor movement in reservoir and possible leakage
  - Noise & reproducibility

- Oil wells – measure annular pressure
  - Needs setting up

One question the group attempted to answer was how long do you need to monitor for? In the case of a small project like Frio, if it was until well injection pressure declines to ambient pressure, then it would be a relatively short time. For a larger injection project there would undoubtedly need a longer monitoring time, although this was not quantified.

Another issue raised was that of the buoyancy effect of CO_2 means that you could small column height, but it was considered that you could use 4D seismic to monitor this. The Frio site allows for stacked injection at several heights. Both the buoyancy effect and stacked injection could help improve solubility and mineral trapping through fast migration and mixing

5.2 Viking Graben

The field is offshore and since it will be an EOR project there are no legal restrictions under the international conventions such as Ospar or London. Features of the scenario that need to be considered are that:

- The field already contains CO_2 so any monitoring programme will need to ensure that the injected and the original CO_2 can be distinguished between.

- The field is in sour gas area and is very deep which means it will be a difficult environment for instrumentation.

- There are a lot of early exploration wells drilled in the region that were drilled before people became aware of the presence of H_2S, the wells were not designed for H_2S and could pose a leakage risk.

- Care will need to be exercised that the injected CO_2 does not impinge on neighbouring operations

- The field is in a seismically active region of the North Sea, which could affect any faults that are present.

- There may be natural methane seepage from the field, and there would be a need to distinguish between CO_2 derived biogenically from CH_4 seepage and actual CO_2 seepage. One difficulty will be a lack of baseline CH_4 seepage data.

One other issue raised was that since this was an EOR project some of the injected CO_2 would be recycled and a methodology for accounting for the amount of recycled CO_2 would need to be considered if credits were to be applied for in such a case.

The monitoring programme developed included the following components:

- Accurate seismic monitoring

- Identification of injected CO_2 through isotopic monitoring or organic chemical fingerprinting

- Characterization of shallow interval fluids and geology

- Development of a regional flow model

- Consideration should also be given seabed seepage monitoring

- Well bore monitoring, both operational wells, and early exploration wells.

Post-closure requirements were raised as an issue. Here it was felt that existing regulations on well abandonment might not be sufficient and that these exiting regulations need to be augmented. A particular issue raised was the depth of cement plug and whether current practice was sufficient to ensure the long term integrity of the wells. This highlighted the issue of long term stewardship. In this case wells were considered to be the highest risk for leakage, it was questioned whether regulations should include well plug and annulus monitoring and the use of passive well bore monitoring tool to help ensure the long term integrity of wells post project closure.

5.3 Gippsland

The regulatory situation in this scenario is complex because it involves both on shore and offshore regulations, with on shore governance in the hands of State regulators and off shore governance in the hands of the Federal government. Industry is also involved and needs to be engaged, will industry stakeholders be happy to make the transition from oil producers to CO2 disposal field operators.

Issues that will need to be resolved in this multi stakeholder/multiplayer scenario will include: potential for water contamination in onshore aquifers, who is liable for any leakage should it occur?.

The project could utilise existing infrastructure, (pipelines and wells) but an assessment of engineering needs will be required to assess whether the infrastructure is fit for CO2 use. The reuse of equipment and the subsequent liability for abandonment of such equipment will need to be resolved.

Monitoring needs will depend on whether the choice is made to exist into depleted gas fields, or underneath such traps. If the oil fields are used then existing wells could be used for monitoring in conjunction with seismic. If the decision is made to inject under the traps then only seismic can be used. In either situations ground water monitoring and surface monitoring will be required.

5.4 Acid gas

The acid gas scenario tested whether the existing regulatory framework would be suitable for CCS.

The selection of an acid-gas injection site needs to address various considerations that relate to:

- proximity of the injection site to the sour oil and gas facility that is the source of acid gas;
- confinement of the injected gas;
- effect of acid gas on the rock matrix;

- protection of energy, mineral and groundwater resources;
- equity interests; and
- well bore integrity and public safety.

To optimize disposal and minimize risk, the acid gas needs to be injected:

- in a dense-fluid phase, to increase storage capacity and decrease buoyancy;
- at bottom-hole pressures greater than the formation pressure, for injectivity;
- at temperatures in the system generally greater than 35^{o}C to avoid hydrate formation, which could plug the pipelines and wells; and
- with water content lower than the saturation limit, to avoid corrosion

Every geological storage project will go through a series of phases which constitute the life-cycle of the project. During each phase, monitoring will serve different purposes and each phase will have its own activities that will determine for how long monitoring will be required. For the purposes of this scenario, the following should be addressed:

- Baseline Monitoring
- Operational/Verification Monitoring – This phase of the project (where acid gas is injected into the reservoir) is expected to last between 20 and 30 years.
- Closure Monitoring – This phase of the project begins after the final survey and after injection stops. It goes on until the wells are abandoned if they are no longer required for monitoring.

Overall it was felt that the existing regulatory regime for acid gas injection could provide a framework for CCS injection, with additional sub surface monitoring requirements

5.5 Summary

The scenario exercises were found to be extremely valuable by the workshop participants since they allowed time for detailed discussion on specific problems relating to monitoring needs. The scenarios provided real sites to consider and served as a useful framework to highlight many of the issues that need to be considered in designing a monitoring programme in a real situation.

6. Progress since last meeting

6.1 Application of Soil Gas Concentrations, and Gas Fluxes to the Atmosphere in Order to Detect Low Rates of Leakage from CO2- Sequestration (EOR or CBM) Projects - Colorado School of Mines

(Presentation given by Ron Klusman at the end of Day 1)

At the time of the Inaugural Meeting of the Monitoring Network in Santa Cruz, November 2004, there was no data available on the 10 meter holes at Teapot Dome. The Teapot Dome project is now complete. There will be heavy emphasis on use of stable isotopes, and on carbon-14 in the 10m holes to provide strong evidence that there is micro-seepage, even in an under pressured system. This contrasts with Rangely which is over-pressured.

Three sources of CO_2 are always present; 1) atmospheric, 2) near-surface inorganic, and 3) biological. Other possibilities are methanotrophic oxidation of CH_4 to CO_2 and CO_2 leaking from an underground storage site. The measurement of stable isotopes is critical in assessing the sources of measured surface CO_2.

CH_4 is as important as CO_2 for monitoring programs in CO_2 storage projects, as it is more likely to seep to the near-surface than CO_2 in over pressured conditions. Methanotrophic oxidation of CH_4 will be critical for the attenuation of micro-seepage.

To detect and confirm the presence of micro-seepage it is important to measure in the winter season. Gas Chomatographic (GC) measurements of CH_4 must be better than routine, and there should be liberal application of stable isotopic ratio measurements. It should be possible to use flux magnitudes, soil gas concentration gradients, and isotopic shifts to find “interesting” locations. These measurements have been correct 8 out of 8 times at Rangely and Teapot. It is then possible to complete thorough characterization with “nested” soil gas sampling to at least 5 meters depth, preferably 10 meters, which will be less sensitive to seasonal changes. Additional confirmation of thermogenic sources can be made with stable isotopes and carbon-14.

It is possible to miss the presence of micro-seepage. This can easily be done by measuring in the “wrong” season, or avoiding the search for CH_4 or by poor precision in GC measurement of CH_4 so that determination of direction and magnitude of flux is lost in sampling and analytical noise. It is important to perform replication of the measurements to allow assessment of the sampling and analytical error. Stable isotopes of carbon can be used for confirmation but they can miss represent the information is they are used too minimally. Other difficulties include coal-derived CO_2 being isotopically similar to near-surface biological CO_2 and warm, wet climates will be more difficult for monitoring and verification, even with good methodology.

Other methodologies to detect microseepage include:

- 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 (C. Ballentine-University of Manchester, UK),
- Eddy covariance mainly applied in pristine environments; practical problems in oil-field environments
- fluorohydrocarbon tracers (Wells, NETL)

6.2 CO_2GeoNet Activities in monitoring geological storage – British Geological Survey (BGS)

CO_2GeoNet is a "Network of Excellence" with 13 partners. The network was launched in April 2004, with a budget for 5 years. The EC contribution to the network is €6million and a further €3million from network partners and external funding. From 2009 the network will be funded independently by the EC.

The requirement for monitoring CO_2 is to verify its effectiveness as a greenhouse gas mitigation technique, to be able to address local health and safety issues and local environmental impacts post closure. CO_2GeoNet would like to be a key forum to develop guidelines on how a CO_2 storage site should be monitored. The guidelines would be based on knowledge from the different monitoring techniques and sites.

CO_2GeoNet identified three themes for monitoring research:

- Monitoring migration through caprocks and the overburden.
- Monitoring the potential impacts of near-surface leaks on both marine and terrestrial ecosystems.
- The use of industrial, experimental and natural sites as test facilities for developing monitoring technologies.

The key developments of CO_2GeoNet will be the development of European test facilities, monitoring guidelines and best practise. There should also be improved understanding of gas migration processes in the overburden, methods to assess the potential impacts of a CO_2 leak on ecosystems and improved seismic modelling capabilities.

Several Joint Research Activity (JRA) plans within CO_2GeoNet include monitoring. The JRA's are listed in Table 1.

JRA	**Joint research activities (Months 13-30)**
JRAP-2	Creation of a conceptual model of gas migration in a leaking CO_2 analogue
JRAP-3	Development of advanced seismic modelling capabilities
JRAP-4	Ecosystem responses to CO_2 leakage - model approach
JRAP-5	Geochemical monitoring for onshore gas releases at the surface (Builds on Nascent and Weyburn soil gas work)
JRAP-8	Monitoring of submarine CO_2 fluxes and ecological impact
JRAP-10	Testing remote sensing monitoring technologies for potential CO_2 leaks
JRAP-12	Application of Tracers for Monitoring CO_2 Storage

Table 1: CO_2GeoNet JRA's

In summary, CO_2GeoNet hopes to bring together researchers and institutes from across Europe, to develop and test new monitoring techniques and the long-term aim of developing test facilities. The test facilities will be at all scales from laboratory work to field scale, at both industrial and natural sites, under controlled and understood conditions.

6.3 Integrated multi-component surface and borehole seismic surveys for monitoring CO_2 storage – University of Calgary and University of Alberta

Time lapse seismic surveys are now being used at a number of sites to monitor CO_2 storage in geological formations. In order to properly map the movement of the CO_2 plume in the injection reservoir and to track possible leakage paths, three-dimensional (3D) seismic surveys are required. However, 3D surveys with close line spacing and small shot and receiver intervals are expensive, and surface seismic data may have insufficient bandwidth to adequately resolve thin (<20m) zones. At the Penn West CO_2 injection site in Alberta, Canada, an innovative seismic monitoring strategy has been implemented involving a sparse, multi-component surface seismic program integrated with active and passive monitoring using geophones permanently cemented into an observation well. The surface seismic program provides 3D subsurface coverage of the pilot site while data from the down hole geophones provide high-resolution images around the observation well. For monitoring surveys, the only costs will be for the surface seismic programme since the geophones in the observation well can be recorded simultaneously with the surface shots. The Penn West baseline survey was completed in March 2005 and the first monitor survey is scheduled for early 2006.

The Pembina oil field is the largest onshore oil field in North America. The Penn West project involves five production wells and two new injection wells. The injection wells are to 1620m depth and inject 70t/day CO_2. Access to the site is an issue because of surface vegetation cover. The project is designing a monitoring programme but with a blank cheque book. It is hoped that the project will be able to bring all disciplines together.

The project concluded that measuring fluid substitution or pressure change can be achieved by 2D, 2.5D and low effort 3D surveys which are cheaper in the long run than high effort 3D. The key in surveying should be to look for differences and not be tied down trying to find absolutes. The project will be looking at multicomponent surface seismic which make use of one shot to record two types of waves (both S and P waves). It will also make use of the observation well. The capital cost of an observation well is up front but once created it can be used to provide 'free' timelapse vertical seismic profiling (VSP's), enables passive monitoring, an opportunity for sampling for leakage and to make in-situ PT measurements.

6.4 PTRC's Monitoring Experience from the Weyburn CO_2 Monitoring and Storage Project – Petroleum Technology Research Centre (PTRC)

Phase I of the Petroleum Technology Research Centre's IEA GHG *Weyburn CO_2 Monitoring and Storage Project* was recognised internationally for research excellence in CCS. The initial phase wrapped up in early 2005 and has provided the world with the innovative technologies needed for successful CO_2 storage in depleted oil and gas reservoirs. Since the meeting in Santa Cruz in 2004, the PTRC intensified its focus on monitoring and verification of CO_2 storage. In effect, the PTRC was able to compile the only complete data set in the world from which risk assessment tools can be adequately tested and differences determined. Last year, all datasets for the Weyburn project are being consolidated on a grid computing system combining with the best reservoir simulation software available. Whether it's over a year or 5000 years, the PTRC is working on developing new methods that can be used to predict and track leakages. Now, as the IEA GHG *Weyburn CO_2 Monitoring and Storage Project* continues into its Final Phase, PTRC is the only core group with access to the complete Weyburn CO_2 storage data set. It hopes to evaluate the risk, and provide scientifically tested advice to all storage stakeholders. In addition, the PTRC has made great strides in creating a global data base incorporating the Weyburn data set with all CO_2 projects around the world. In less than a year, the PTRC also laid the foundation to begin other world leading CO_2 storage projects, including storing CO_2 in saline aquifers. Once again, heavy emphasis has been put on the monitoring and verification aspects of each project.

The IEA GHG Weyburn CO_2 Monitoring and Storage Project (Phase 1) involved four years of monitoring and 5000 tons of CO_2 per day injected, 5 million tons of CO_2 has already been injected. CO_2 is found in produced oil but it is compressed and re-injected. Table 2 lists the CO_2 stored and the increase in oil production as a result of this Phase 1 IEA GHG Weyburn CO_2 Monitoring and Storage Project.

CO_2 reduction	**Oil increase**
5000 tons/day of CO_2 stored in ground	Additional 13,000 bbl/day
More than 5 million tons already injected	Project's oil production potential (130 million additional barrels**)**
Project's storage potential (30 million tons of CO_2)	

Table 2: Results of the Weyburn CO_2 Monitoring Storage Project (Phase 1)

Monitoring techniques used during the Weyburn CO_2 Monitoring Project (Phase 1) are listed in Table 3.

Monitoring Techniques utilised at Weyburn	
4D, 3C surface seismic	Geochemical sampling analysis
4D, 9C surface seismic	Tracer injection monitoring
3D, 3C vertical seismic profile (VSP)	Conventional production data analysis
Cross-well seismic	Passive seismic

Table 3: Monitoring Techniques used during the Weyburn Project .

Phase II of the Weyburn CO_2 Monitoring and Storage Project has 6 themes:

Theme 1 – *Geological Integrity (Site Selection)*

Theme 2 – *Well Bore Injection & Integrity*

Theme 3 – *Storage Monitoring Methods*

Theme 4 – *Risk Assessment, Storage and Trapping Mechanisms, Remediation Measures, Environment, Health and Safety*

Theme 5 – *CO_2 Storage Performance Optimization*

Theme 6 – *Data Management/Grid Computing for Worldwide Information Sharing*

The themes aim to build on the experience and success of Phase I.

6.5 Tracer, shallow aquifer, direct CO_2 flux studies at the Frio brine sequestration site, Texas – National Energy Technology Laboratory (NETL) - U.S. Department of Energy (DOE)

These are the results from surface and near surface monitoring for CO_2 leakage at the FRIO deep saline aquifer storage site, 50 miles east of Houston Texas. Monitoring included direct surface CO_2 flux, perfluorocarbon tracers (PFTs) added to the CO_2 and monitored in soil-gas, and monitoring for changes in shallow water aquifer chemistry characteristic of CO_2 infusion.

Direct CO_2 flux was monitored at the surface and in soil-gas where the $^{13}C/^{12}C$ ratio was used to distinguish biological from injected CO_2. Three PFTs were added, one at a time, as 12 and 6 hour slugs during CO_2 injection in the first two weeks in October 2004. The soil-gas monitoring matrix included 22 locations for both direct CO_2 and tracer monitoring, and an additional 18 locations for tracer monitoring. An atmospheric monitoring array was in place at 10 of the soil-gas monitoring locations. The soil-gas monitoring matrix included monitors adjacent to all known wells in the area, and monitors at two fault zones located about a half mile from the injection well, and identified during the geophysical survey. CO_2 can act as a carrier gas bringing Radon to the surface which can be easily detected due to alpha decay; therefore radon can act as an "indicator" of CO_2 movement to the surface.

Six sets of continuously exposed sorbent packets, called CATS, were sequentially exposed to soil-gas over one year (Oct. 2004 to Oct. 2005). Each CAT set exposed also included active atmospheric samplings and 3 minimum exposure blanks. The monitoring matrix was based upon completion of a geophysical survey of the area. This included potential surface faults, adjacent active and inactive wells and other surface features. Two soil-gas depth profiling arrays were placed immediately off the injection well pad, and sampled for PFTs in soil-gas at 0.4 meter intervals to a depth of 2m. Three 100 foot deep, shallow aquifer monitoring water wells were constructed immediately off the injection well pad that accessed two shallow aquifer systems.

Following the start of injection, water wells were sampled for water and headspace-gas about once every other month. On-site water analyses included alkalinity, pH, and conductivity. Samples were then sent to the National Energy Technology Laboratory (NETL) in Pittsburgh for analysis of anions and metals, and for gas analysis. This information was used to evaluate aquifer chemistry changes characteristic of CO_2 infusion.

Conclusions from the tracer, shallow aquifer and direct CO_2 flux studies at the Frio Project were:

1. The location of tracers found in soil-gas remained relatively constant between CAT sets, and between tracers.

2. The overall total concentrations of tracers in soil-gas declined after November 2004.

3. The calculated partial pressures of CO_2 in water well samples were also highest immediately after CO_2 injection.

4. No evidence of CO_2 flux was observed with direct surface monitoring. Isotopic ratios were characteristic of biogenic and atmospheric sources. The post-injection survey was conducted in February when soil-gas tracers and well water CO_2 were low.

6.6 Introduction to the Technical Tour to Ciampino and the Phlagrean Field - INGV

The final presentation of the day was an introduction to the Technical Tour. A partial transcript from the presentation is available in Appendix 4.

7. Conclusions of the Network Meeting

The meeting posed a series of questions to consider which were:

- Where to monitor?
- What to measure?
- When to measure?
- What does it mean? Can the results be explained?

It was accepted that the meeting had not fully resolved all these points however it had taken a big first stride in attempting to answer these questions. It is recognised by the CCS community that there is a need to demonstrate that it is quite possible to tell where the CO_2 injected into the ground has gone and how long it will stay there. This is a simple need but there is not necessarily a simple answer for it. The aim of the network is to continue to make progress towards resolving these questions and to help ultimately that there is no leakage from CO_2 injection projects. A result that will ensure that there are no HSE or verification issues that need to be resolved.

On the issue of carbon credits, those that offer the carbon credits may devalue them to account for a certain amount of leakage i.e. 10% leakage expected. This value is currently unknown.

The other aspect of carbon credits is that the process of CO_2 capture and storage has more than one component; there is a chain of responsibility which begins at the point of capture and involves transportation and finally storage. It is quite possible that the company producing and capturing the CO_2 is not the same company who will inject and store the CO_2. Therefore, will the company providing the CO_2 for storage be guaranteed to receive a set amount of credits and at the point of exchange and becomes no longer responsible for the long term storage of CO_2? What is the responsibility of the storage company to ensure that CO_2 remains underground?

Appendix 1. Delegates

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Appendix 2 Introduction Presentation from Hosts

Introduction by INGV

INGV presented on a new ECBM project which will operate in the Sulcis area in SW Sardinia, Italy.

To be viable the CO_2 needs to be injected into a coal seam that will not be mined in the future. There should also be sufficient permeability, a maximum depth of 2km and a local source of CO_2. INGV have identified one large source of CO_2 from an existing plant which will deliver around 1 million tonnes for the next 3 years. There is also a new power plant which will begin operating in 2006. Finally, there are other small plants and industry sources.

There are no regulations in Italy regarding ECBM. All available rules are for CH_4 and natural gas. From the available list of rules, INGV identified all those that could be viewed as relevant. They also took into account the laws regarding the environmental impacts of well drilling in this area which is a local focus because of tourism.

The preliminary conclusion on CBM-ECBM in the Sulcis coal Province is that ECBM exploitation is relatively encouraging.

The project is in the very early stages and the first injection is not expected before 2012-2015. 1.5million tonnes per year will be the maximum amount for injection.

Introduction by Uníversità di Roma "La Sapienza" (URS)

The presentation reviewed the shallow soil gas and gas flux monitoring of the Weyburn CO_2 EOR injection site undertaken by INGV, URS, BGS and BRGM. The first two years of the study were funded by the European Commission and the third year by PTRC and UK DTI.

As part of the project three types of monitoring were undertaken:

- Soil Gas (URS and BGS)
- Gas Flux (INGV)
- Radon Monitoring (BRGM)

The objectives of the monitoring project were to gather baseline and monitoring data, to define the possible sources of the CO_2 identified and to delineate the possible flow pathways.

The monitoring of the soil gas was undertaken several times during the lifetime of the project and the plot of the statistical distribution for all four years showed a decrease in the percentage of the CO_2 observed. The decrease was linked to cooler, dryer conditions, indicating that the CO_2 had a shallow biological origin.

The CO_2 flux anomalies showed a similar distribution to the soil gas anomalies. As had been seen with the soil gas results, the CO_2 flux values showed a significant decrease with the season. Similarly this indicated that the CO_2 had a shallow biological origin.

The flux measurements of other gases taken during the project confirmed the results of the CO_2 measurements. Radon and CH_4 showed a relatively constant distribution. If radon were transported by deep CO_2 then the amount of radon would be expected to decrease along with CO_2. Ethylene was also measured and decreases like CO_2 also implying a biological origin. Isotopic analysis also indicated biological origin as the values were in the range of local organic matter.

The measurements were taken using a grid system devised for unbiased sampling. However, the project also made specific measurements, taken from the location of abandoned wells, river lineaments and collapse structures (identified as possible vertical pathways at this location). These measurements showed CO_2 concentrations in the same range as the measurements taken within the grid system showing no evidence of CO_2 migrating along these possible vertical pathways.

Appendix 3 Frio Brine Pilot Project Research team:

DOE/NETL project managers
Charles Byrer and Karen Cohen

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Seay Nance
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Jeff Paine
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Paul Knox
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Texas American Resources
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Dan Collins
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Lawrence Berkeley National Lab
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Oak Ridge National Lab
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Alberta Research Council
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CO2 CRC/CSIRO Australia
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Praxair, Inc
Joe Shine
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BP
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T. S. Ramakrishnan
Nadja
Austin Boyd

Schlumberger EMI
Mike Wilt

University of West Virginia
Henry Rauch

Core Labs
Paul Martin

USGS
Yousif Kharaka

Appendix 4 Introduction to the Technical Tour to Ciampino and the Phlagrean Field.

The Technical Tour on day 3 was a visit to Ciampino and the Phlagrean Field. The field trip was organised by INGV in collaboration with University "La Sapienza of Rome" (who provided the information about the Ciampino site and accompanied INGV in the explanation of the sites).

The two municipalities of Ciampino and Marino are located inside the Alban Hills quiescent volcanic structure, 20 Km SE from Rome (Fornaseri et al., 1963). Throughout the volcano as a whole, the Ciampino-Marino sector is particularly affected by a steady-state diffuse natural gases exhalation as well as by historically remembered episodes of strong differential degassing, often in occasion of seismic events.
Natural gas emissions represent extremely attractive surrogates for the study of CO_2 effects both on the environment and human life. Three Italian case histories demonstrate the possible co-existence of CO_2 natural emissions and people since roman time.

The Solfatara crater (Phlegraean fields caldera, Southern Italy) is an ancient roman spa. The Solfatara volcano, is located in the central part of Campi Flegrei caldera (Naples, southern Italy), and is characterized by intense and diffusive fumarolic and hydrothermal activity confirming that magmatic system is still active. There has been a detailed survey of 32 soil gas samples and 40 flux measurements and a large scale survey of 85 radon and thoron soil gas samples. During 1982-84 the earth's surface rose by a total of 1.80 metres. This phenomenon is called bradyseism related to the elastic response of the shallow crust to increasing pressure within a shallow magma chamber. The evidence of this was seen at the second site visit to the "Macellum" (Temple of Serapide, I century a.c.) where the temple which had been semi-submerged is now dry and above sea level.

The work that has been completed in this area includes, soil gas surveys, groundwater surveys. Results from soil gas samples analysed both in the field and in the laboratory are in agreement with gas flux results. Local trends are very similar, although soil-gas concentrations show a more diffusive distribution, as it was reasonable to suppose. Gas flux distribution highlighted a clear correspondence between gaseous emanation and local tectonics, in particular, radon and carbon dioxide have a dominant flux in a NE-SW direction and, in a lesser extent, in a E-W and a NW-SE directions. These directions are in agreement with regional extensional tectonic and with transverse structures considered as transfer faults along which the main regional volcanoes are located.

Presentations

Day 1 - Tuesday October 4 2005	
Session 1. Introductions	
Opening	IEA GHG
Introduction and Welcome	BP
Shallow Soil Gas and Gas Flux Monitoring of the Weyburn CO2 EOR Injection Site	Università di Roma "La Sapienza" (URS)
CO_2 Geological Storage by ECBM techniques in the Sulcis area (SW Sardinia Region, Italy)	Istituto Nazionale di Geofisica e Vulcanologia (INGV)
Session 2. Monitoring Requirements	
CCS monitoring needs: Australian regulatory viewpoint	Australian Greenhouse Office (AGO)
EU ETS and UK Regulatory Issues	UK Department of Trade and Industry (UK DTI)
EPA Efforts and Regulatory Overview	U.S. Environmental Protection Agency (U.S. EPA)
Session 3. Monitoring Programmes	
Experience from ongoing projects	
Update on the Frio Brine Pilot: One year after injection	Bureau of Economic Geology, University of Texas at Austin
Geophysical Monitoring of CO_2 Storage at an Onshore Saline Aquifer in Nagaoka, Japan	Engineering Advancement Association of Japan (ENAA)
Can we estimate the injected carbon dioxide prior to the repeat seismic survey in 4D scheme? - Nagaoka (no presentation available)	Japan Petroleum Exploration Co., Ltd (JAPEX)
Monitoring at In Salah	BP
Experience from developing projects	
Otway Project	Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)
Snohvit (no presentation available)	Statoil
Developments since the first meeting of the Monitoring Network	
Application of Soil Gas Concentrations, and Gas Fluxes to the Atmosphere in Order to Detect Low Rates of Leakage from CO_2-Storage (EOR or CBM) Projects	Colorado School of Mines

Day 2 - Wednesday October 5 2005	
Session 4. Monitoring Scenario Development	
Introduction to Scenarios session - Kevin Dodd.	
Scenarios - Acid Gas Scenario - Frio Scenario - Gippsland Scenario - Viking Graben Scenario	
Session 5. Developments since the last meeting	
Gorgon Development – LNG with CO_2 Storage	Chevron Energy Technology Co.
CO2GeoNet Activities in monitoring geological storage	British Geological Survey (BGS)
Integrated multicomponent surface and borehole seismic surveys for monitoring CO_2 storage; Penn West Pilot, Alberta, Canada	University of Calgary University of Alberta
Results and New Directions of the IEA GHG Weyburn CO2 Monitoring and Storage Project	Petroleum Technology Research Centre (PTRC)
Tracer, shallow aquifer, direct CO_2 flux, and geophysical survey results from the Frio brine sequestration site, Texas	National Energy Technology Laboratory (NETL) - U.S. Department of Energy (DOE)
Session 6. Technical Tour to Ciampino and the Phlagrean Field	
The Campi Flegrei CO_2 Analogue	Istituto Nazionale di Geofisica e Vulcanologia (INGV)

2^{nd} International Monitoring Network Workshop

Hosted by INGV
Rome, Italy
4^{th} – 6^{th} October 2005

Rome Workshop Introduction

The Economics of CO_2 Sequestration

?

$-Credits + $-EOR ≥

$-Capture + $-Transportation + $-Operations

(Operations = Monitoring and Verification, Wells, Remediation, Liability)

?

$- 40 + $- 20 ≥

$- 50 + $-Transportation + $-Operations

Monitoring: From Appraise to Select

- Regulatory Setting
  - What do we need to know
- Project Review
  - What we know
- Scenario Session (3-4, Canada, USA, Australia)
  - Context
  - Regulatory Environment
  - Risk Assessment
  - **Monitoring Program (Cost is an issue)**
  - Report

What can/will we actually do?

Shallow Soil Gas and Gas Flux Monitoring of the Weyburn CO2 EOR Injection Site

CO2 Monitoring Network Meeting

Rome, Italy; October 4-6, 2005

Contributing Researchers and Institutions

Fedora Quattrocchi
Istituto Nazionale di Geofisica e Vulcanologia (INGV)

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Università di Roma “La Sapienza” (URS)

Mick Strutt, Dave Jones
British Geological Survey (BGS)

Jean-Claude Baubron
Bureau de Recherches Geologiques et Minieres (BRGM)

Acknowledgements

2001 – 2003 funding

European Community (Weyburn Project)

2004 funding

Petroleum Technology Research Centre (PTRC)

United Kingdom Department of Trade and Industry (UK DTI)

Contributions

Soil Gas

Università di Roma "La Sapienza" (URS)

CO_2, O_2, N_2, light hydrocarbon gases, light sulfur gases

British Geological Survey (BGS)

CO_2, O_2, radon, gamma spectrometry

Gas Flux

Istituto Nazionale di Geofisica e Vulcanologia (INGV)

CO_2 flux

Radon monitoring

Bureau de Recherches Geologiques et Minieres (BRGM)

Barasol radon monitoring probes, meteorological monitoring

Objectives

Baseline and monitoring data

Define possible sources of CO_2

Delineate possible flow pathways

Work Done

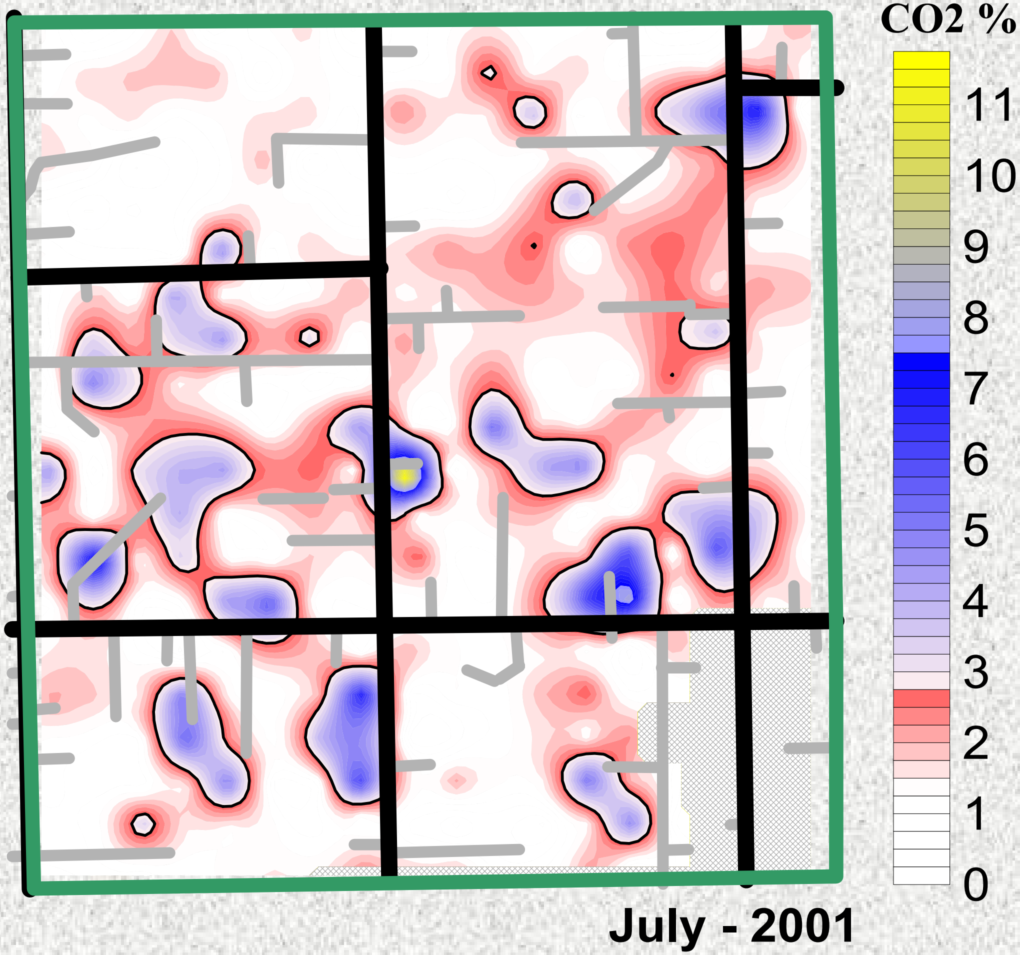
	2001	2002	2003	2004
Regional Grid	soilgas, gasflux	soilgas, gasflux gamma spec.	Soilgas, gasflux gamma spec.	Soilgas, gasflux
Local Grids	gasflux			
Horizontal Profiles	soilgas, gasflux	soilgas, gasflux gamma spec.	soilgas, gasflux gamma spec.	soilgas, gasflux gamma spec.
Vertical Profiles		soilgas	soilgas	soilgas
13C CO2 Isotopes	sampled		analysed	
Salt collapse structure			soilgas	
Abandoned wells			soilgas	soilgas
Background site (Minards)			soilgas, gasflux gamma spec.	soilgas, gasflux gamma spec.
River lineament profiles			soilgas	soilgas
Barasol radon monitoring	yes	yes	yes	yes

Regional Grid

- **360 points**
- **200 m spacing**
- **65% covering original Phase A1 injection area, other 35% outside**
- **Sampled three years during different seasons**

Soil Gas CO2 concentrations

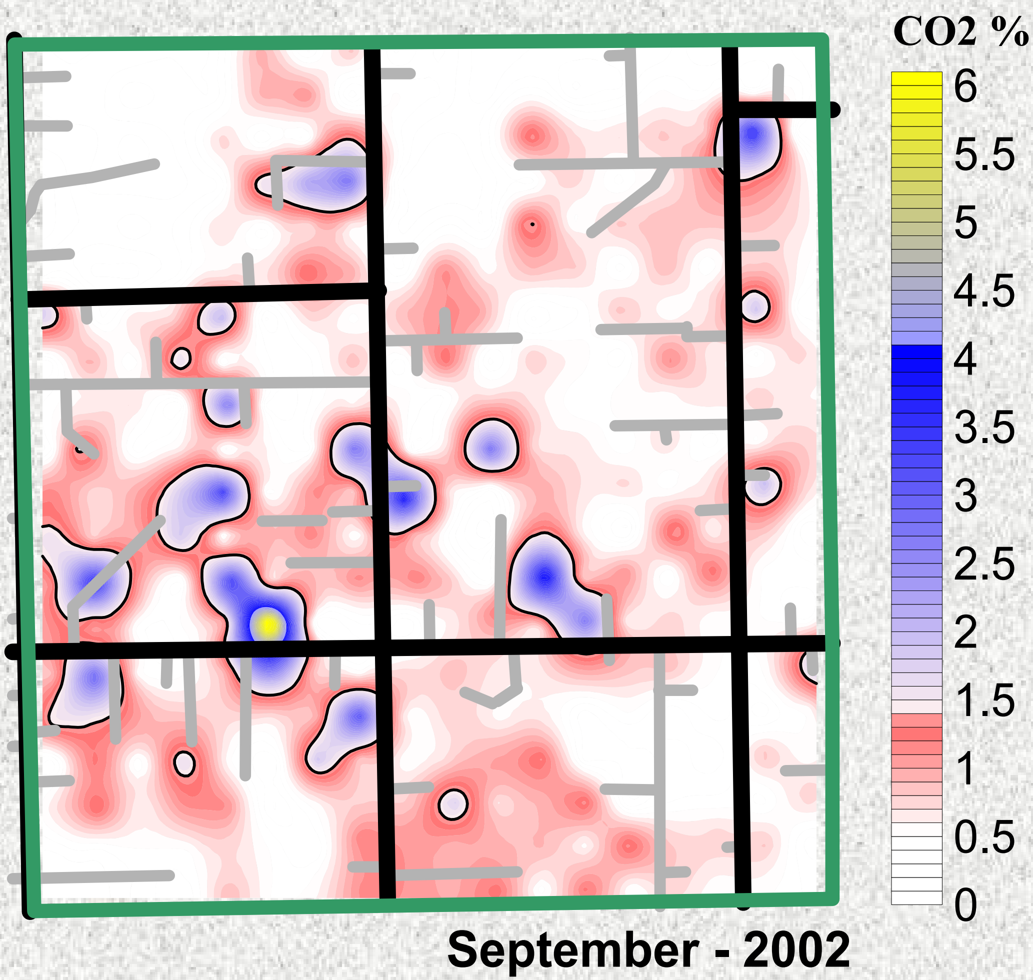
Summer of 2001



- Elevated CO2 concentrations are associated with low-lying areas and surface water
- Maximum value of 12 %

Soil Gas CO2 concentrations

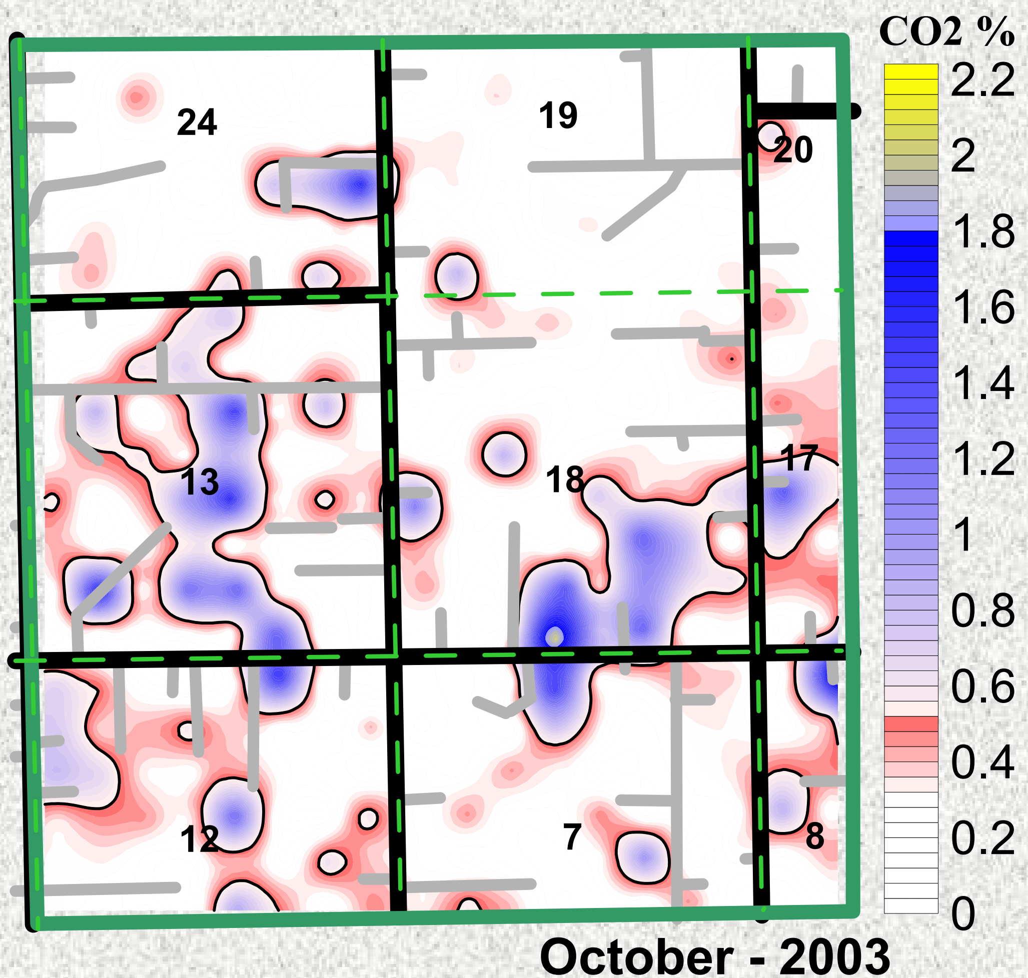
Early Fall of 2002



- In 2002 the anomalies are generally in the same areas but values are lower
- Maximum value of 6.2%

Soil Gas CO2 concentrations

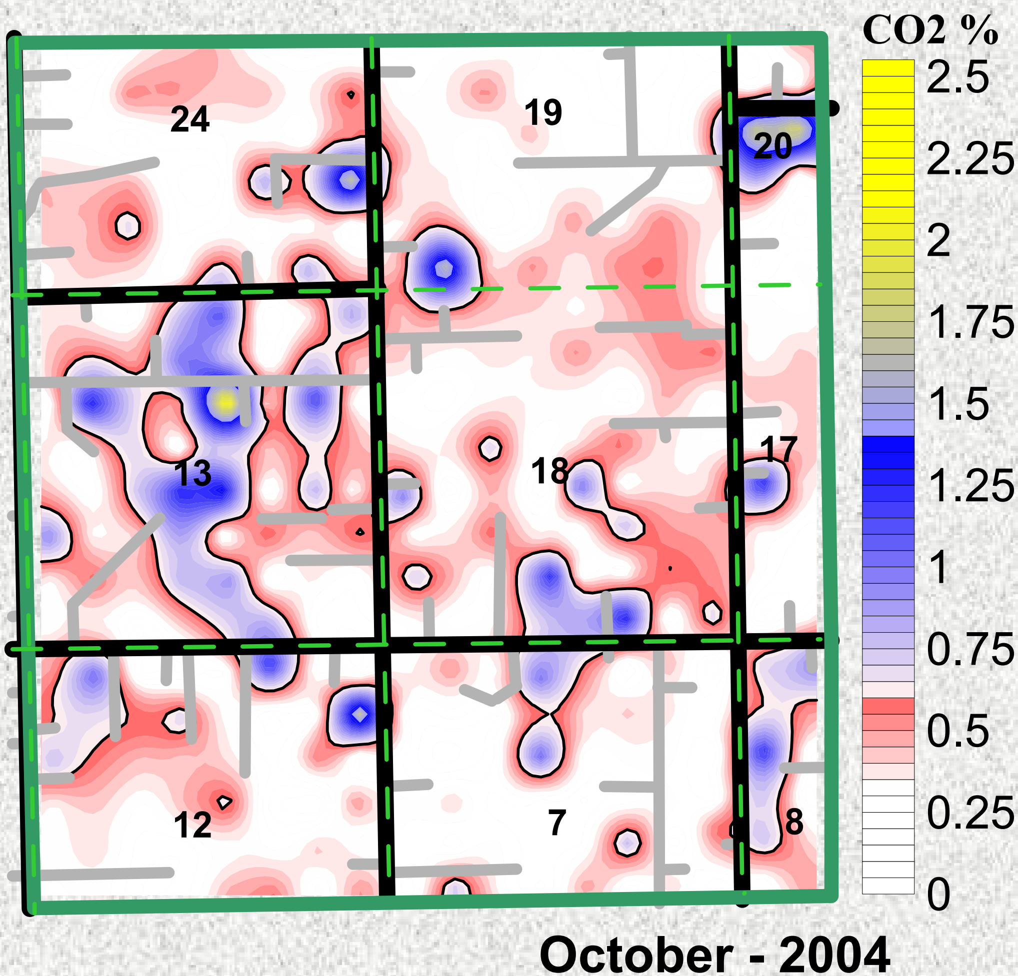
Late Fall of 2003



- Again the anomalies are in the same areas in 2003, but values are much lower
- Maximum value of 2.3%

Soil Gas CO2 concentrations

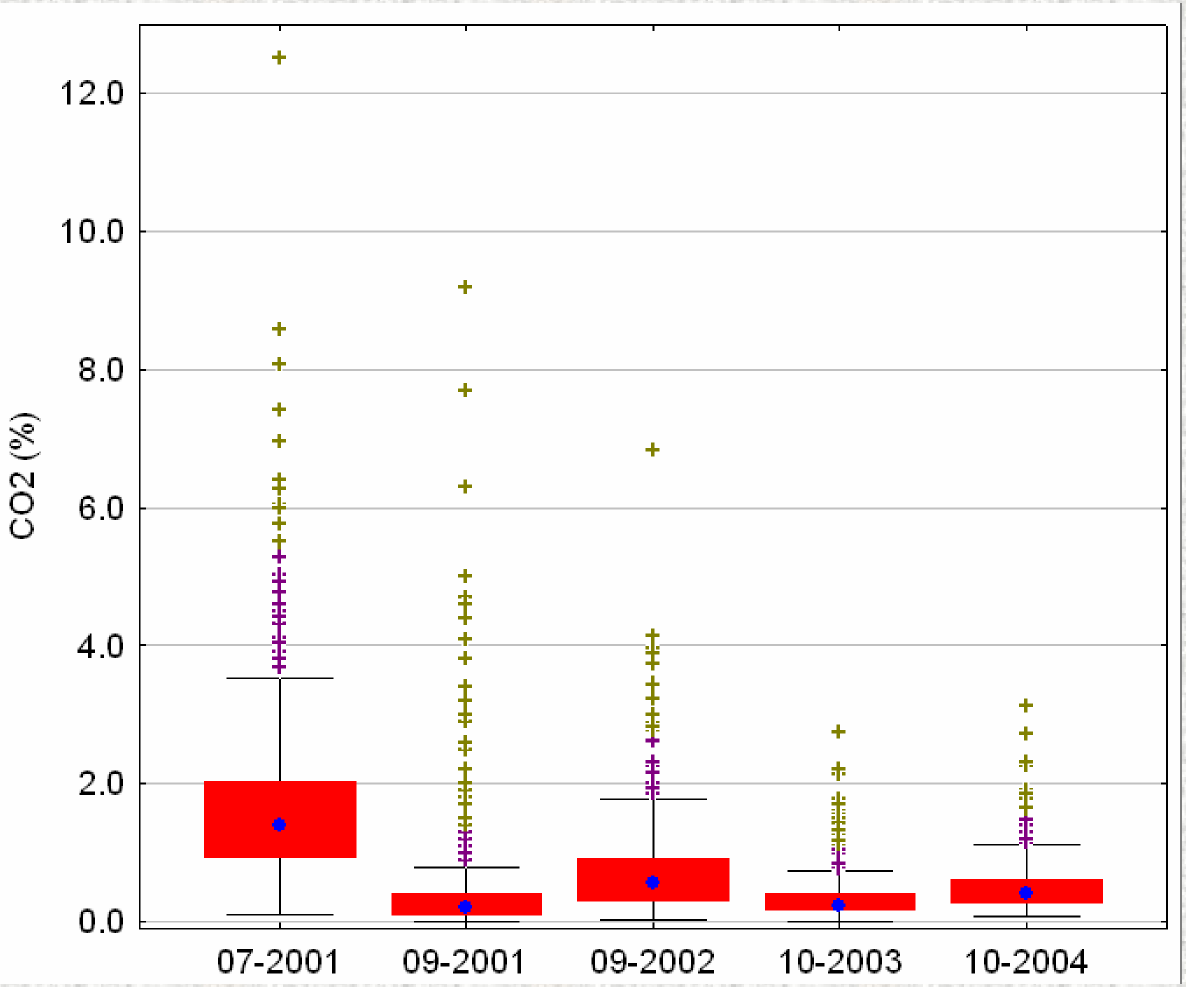
Late Fall of 2004



- 2004 distribution and concentration ranges are very similar to 2003
- Maximum value of 2.5%

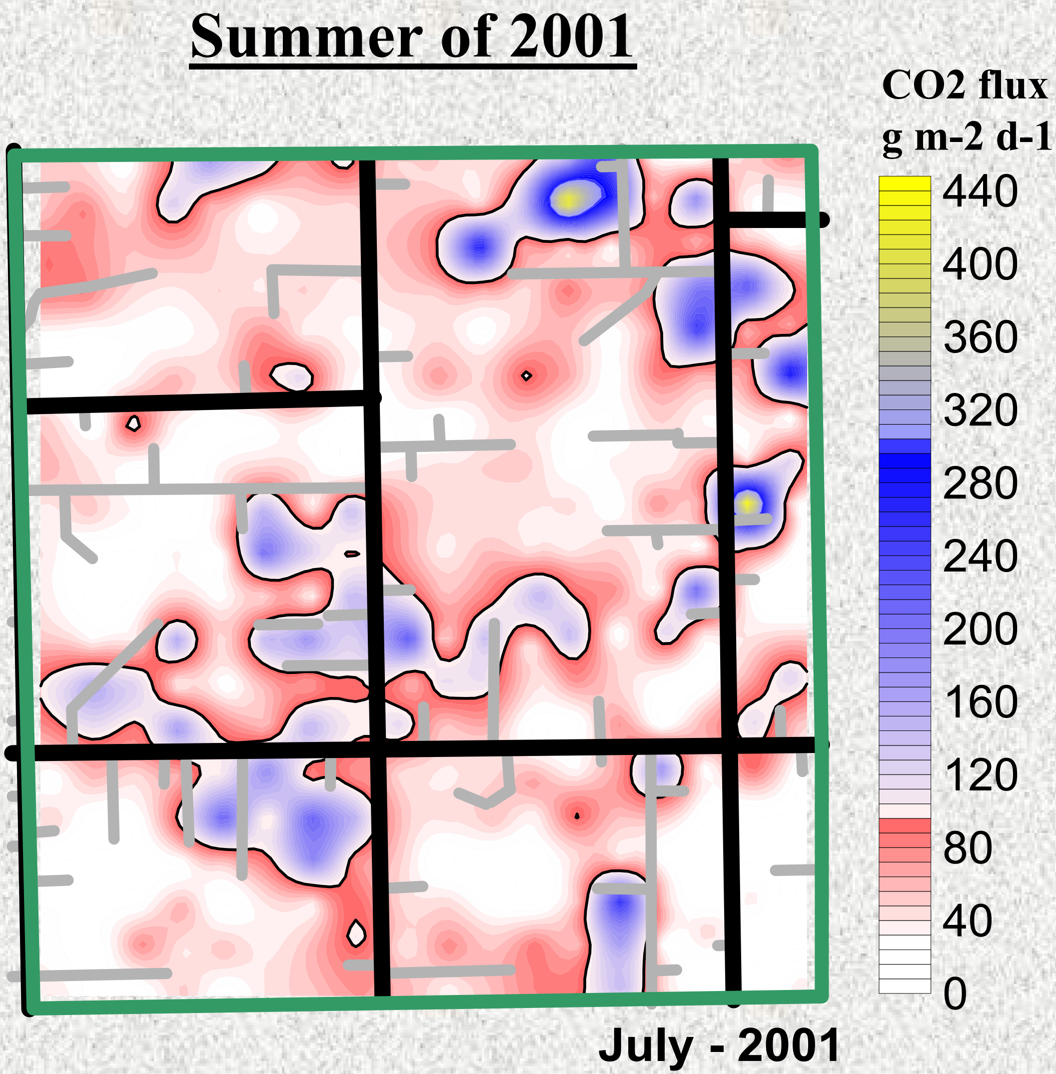
Soil Gas CO2 concentrations

Interannual comparison



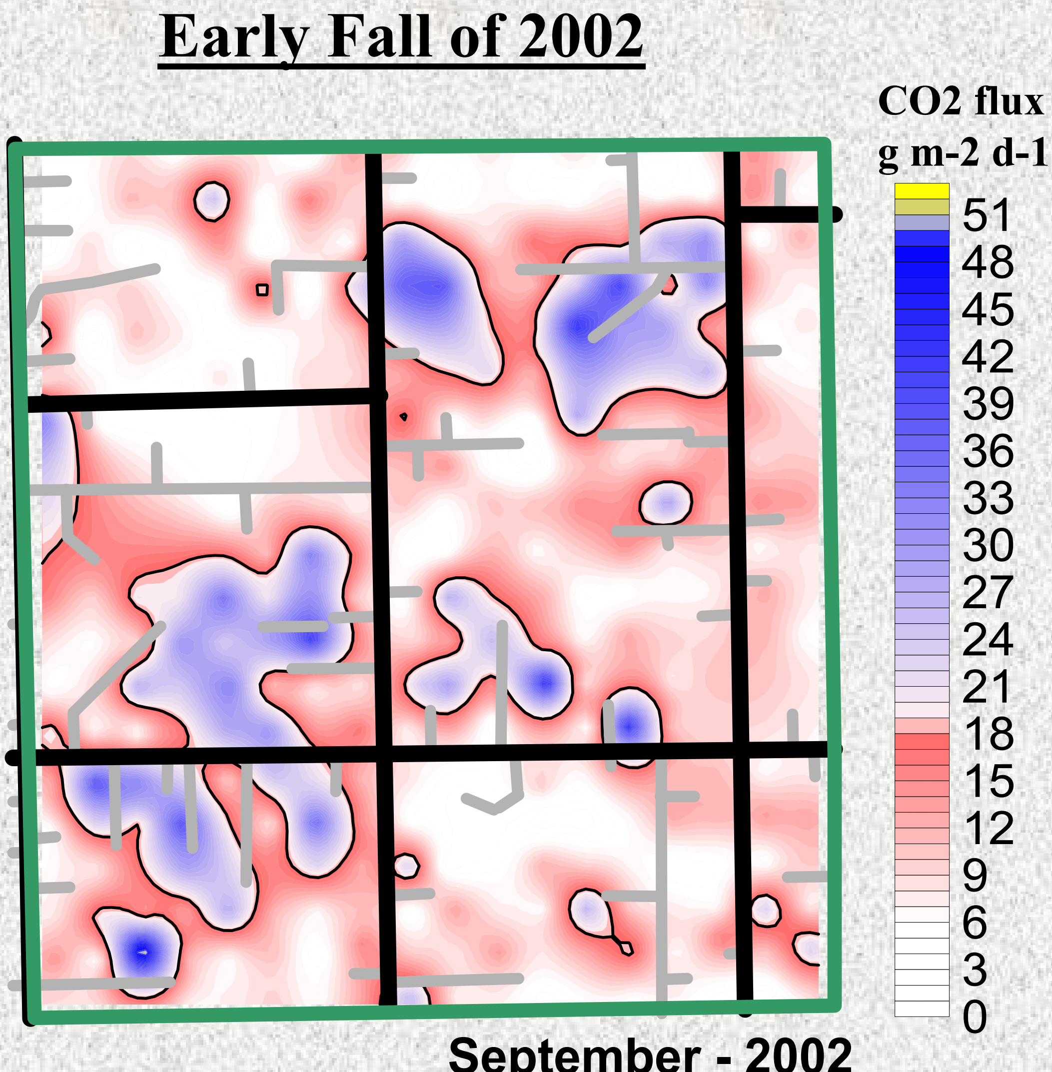
- Box plot shows statistical distribution for the datasets of all four years
- A marked decrease in mean, quartile and outlier values is observed
- Decrease linked to cooler, dryer conditions, indicating CO2 has a shallow biological origin

CO2 Flux Values



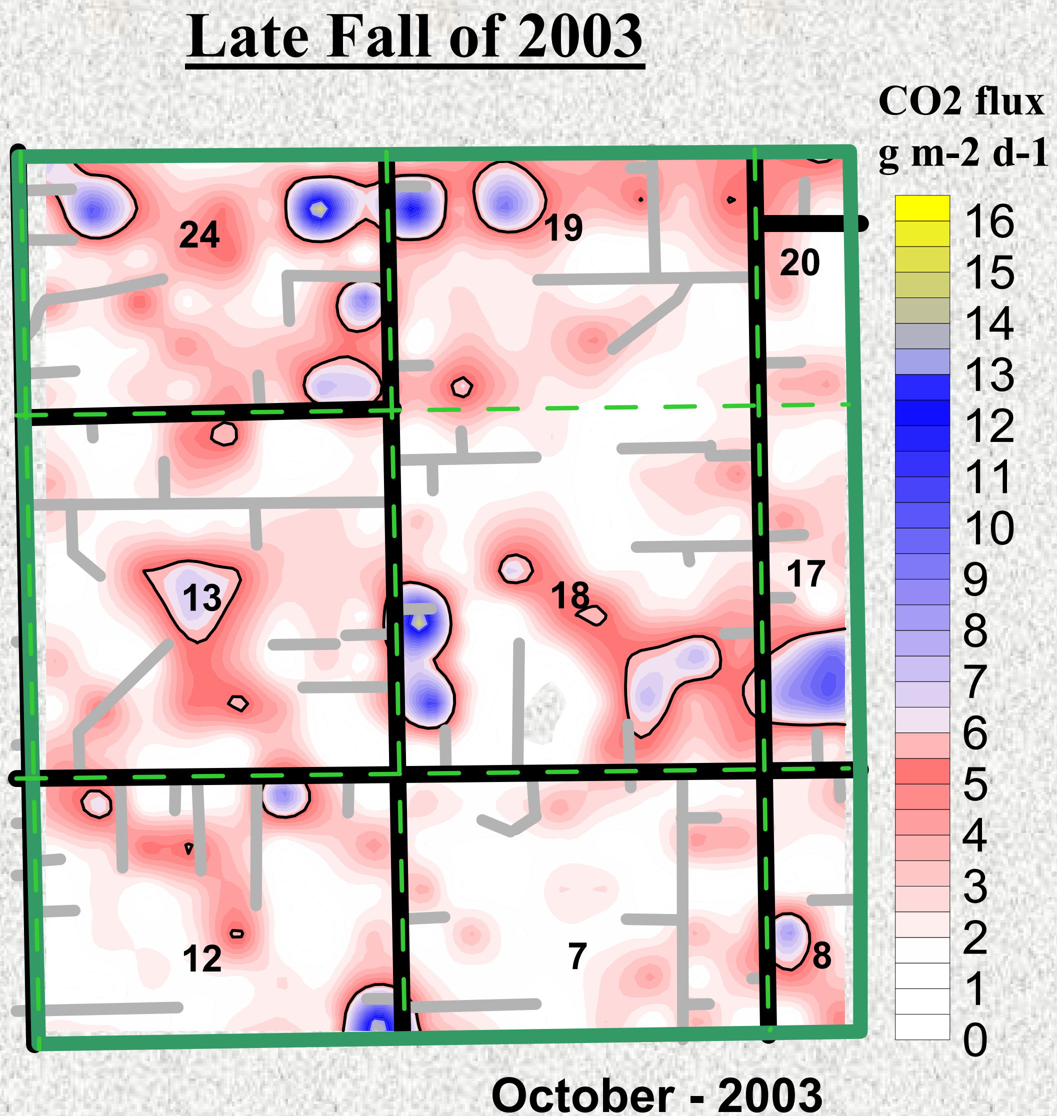
- Similar distribution of flux anomalies as compared to soil gas anomalies
- Maximum value of 450 g/m2/d

CO2 Flux Values



- Subsequent sampling again shows similar distribution but lower values
- Maximum value of 55 g/m2/d

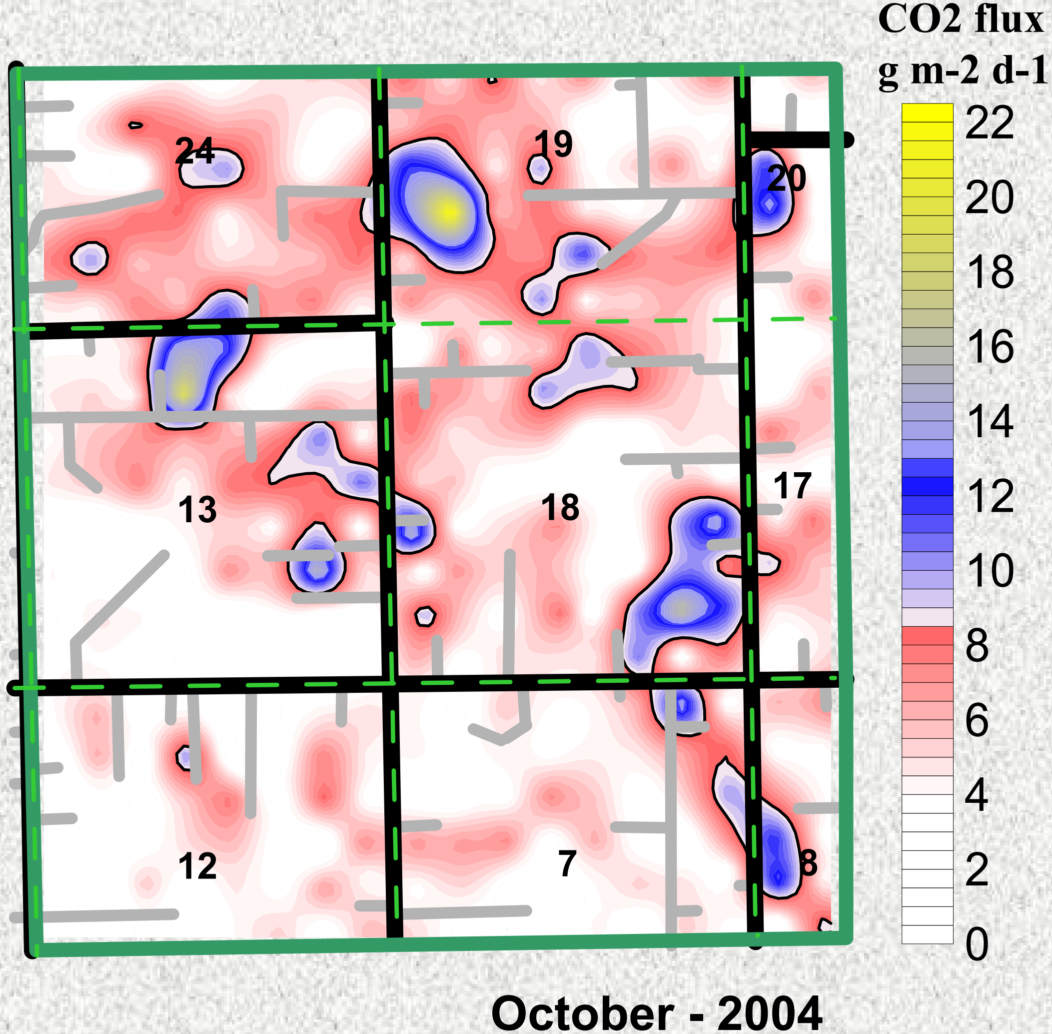
CO2 Flux Values



- 2003 data shows very low values which are in the range of the sensitivity of the method
- Maximum value of 16 g/m2/d

CO2 Flux Values

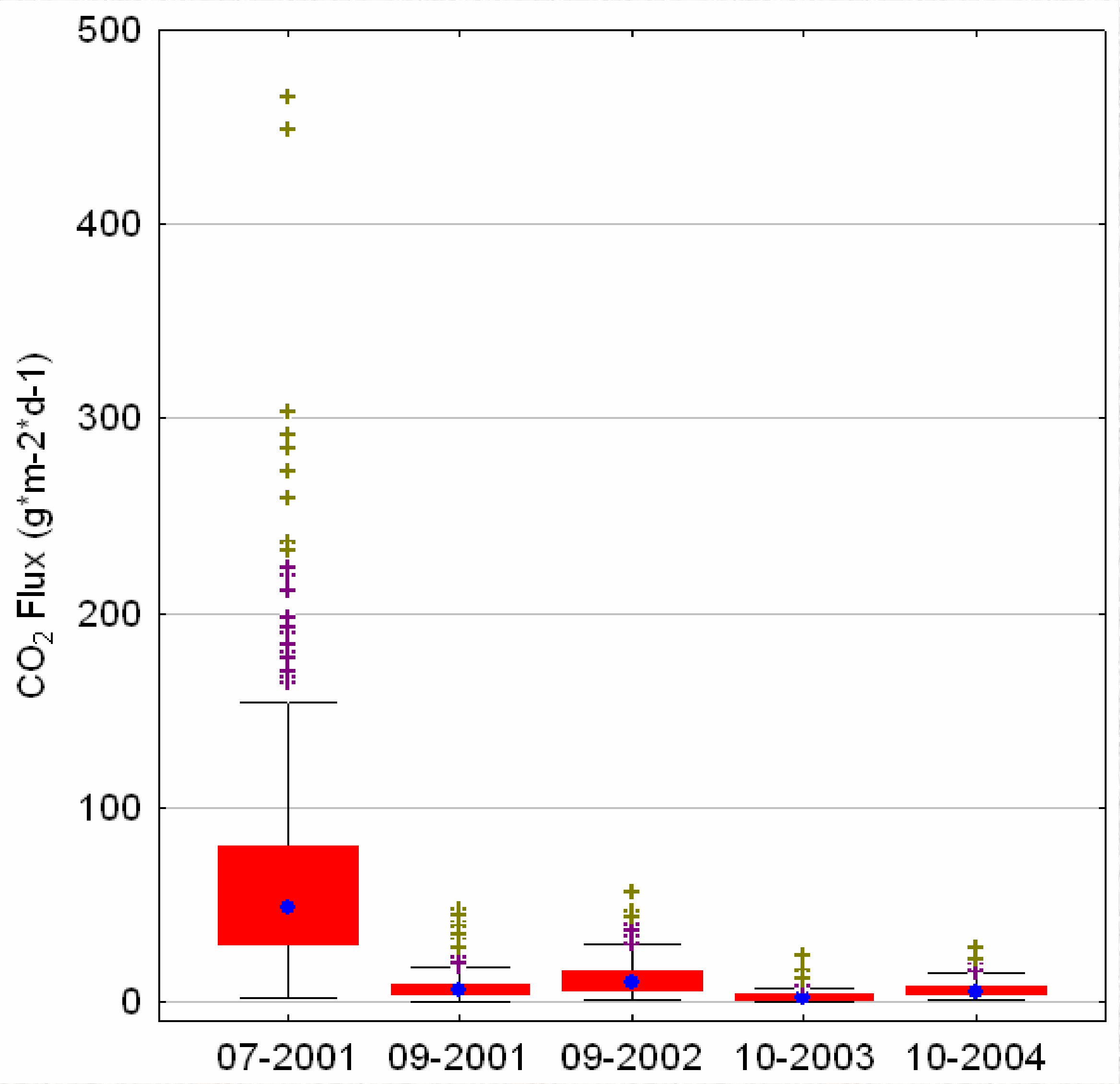
Late Fall of 2004



- Final sampling also shows very low values witha maximum value of 22 g/m2/d

CO2 Flux Values

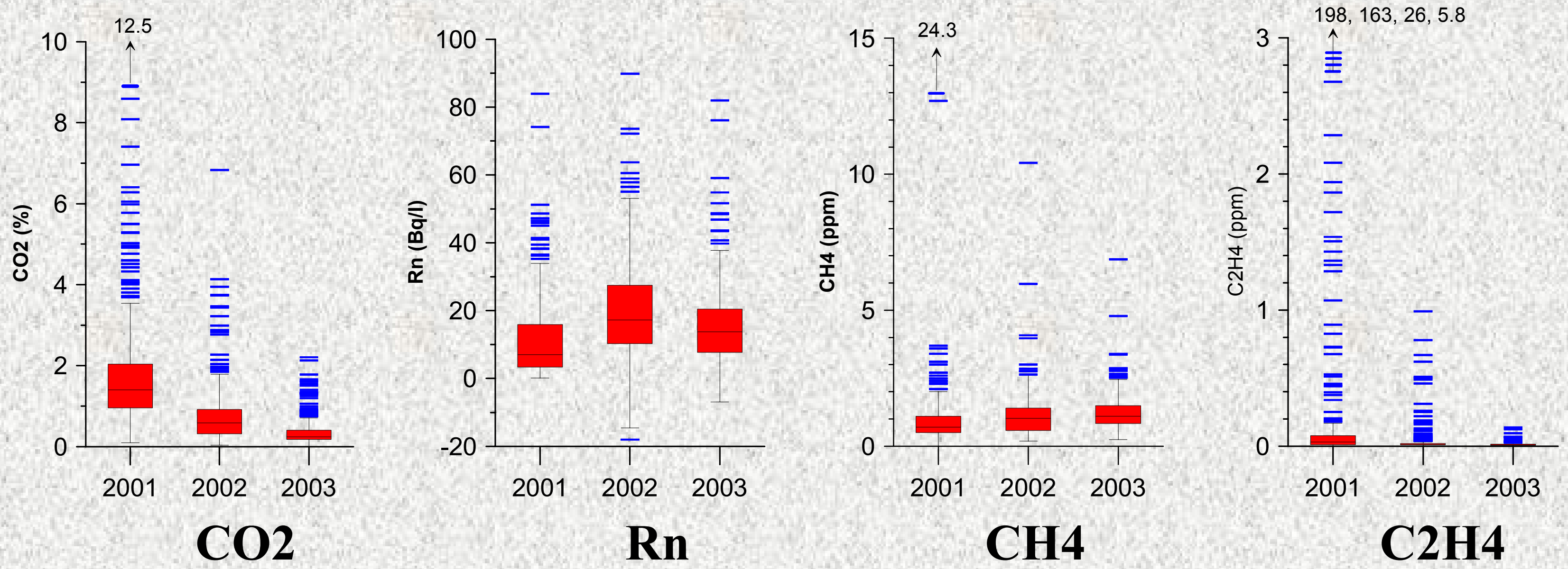
Interannual comparison



- Similar to soil gas CO2, the CO2 flux values decrease markedly with season
- These data also indicate that the CO2 has a shallow biological origin

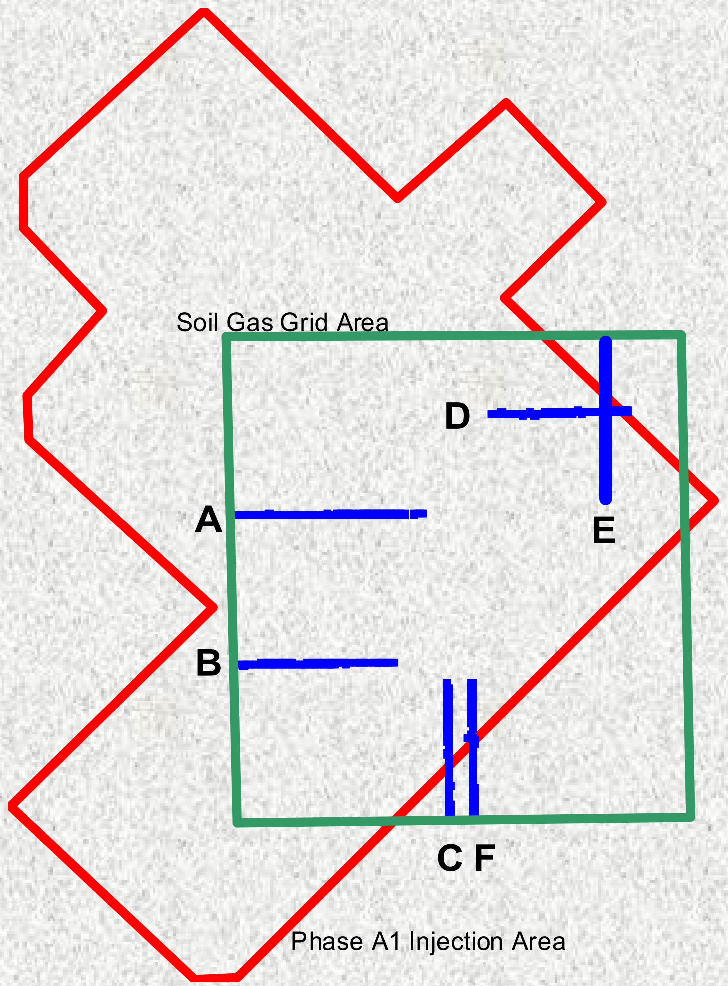
Other gases

Interannual comparison



- In contrast to CO2 and CO2 flux, both radon and CH4 show a relatively constant distribution. If radon were transported by deep CO2 one would expect radon to also decrease
- Ethylene, instead, decreases like CO2, implying the origin of the two gases may be linked by some biological process

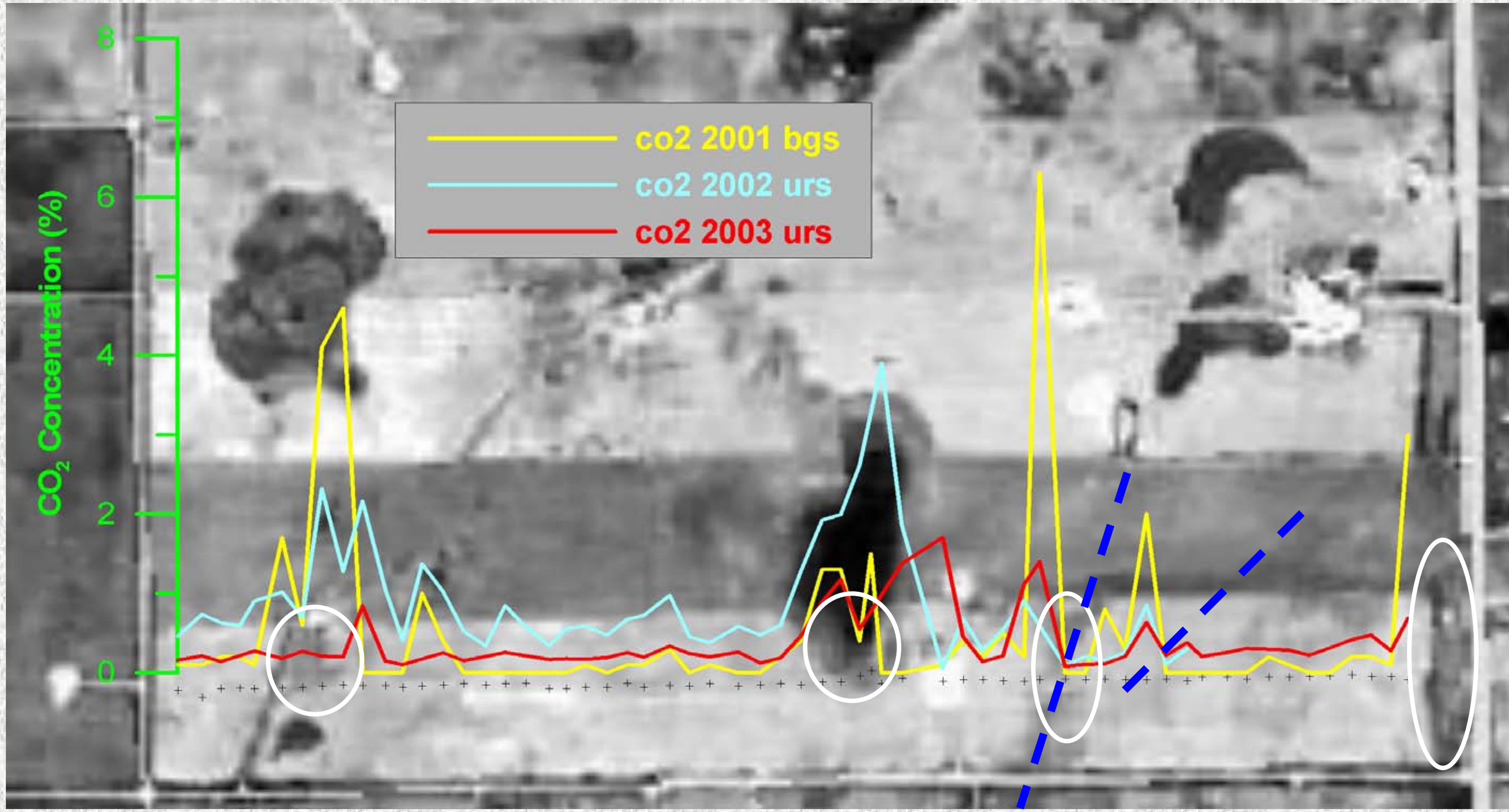
Horizontal profiles



- 6 profiles conducted over CO2 and Rn anomalies defined during the 2001 sampling of the regional grid
- Generally 1000 to 1250 metres long with a sample spacing of 25m
- Profiles A and B were sampled all three years, C and D in 2001 and 2003, E and F in 2002 only
- Will discuss only profile B

Horizontal profile B

CO2 relative to airphoto

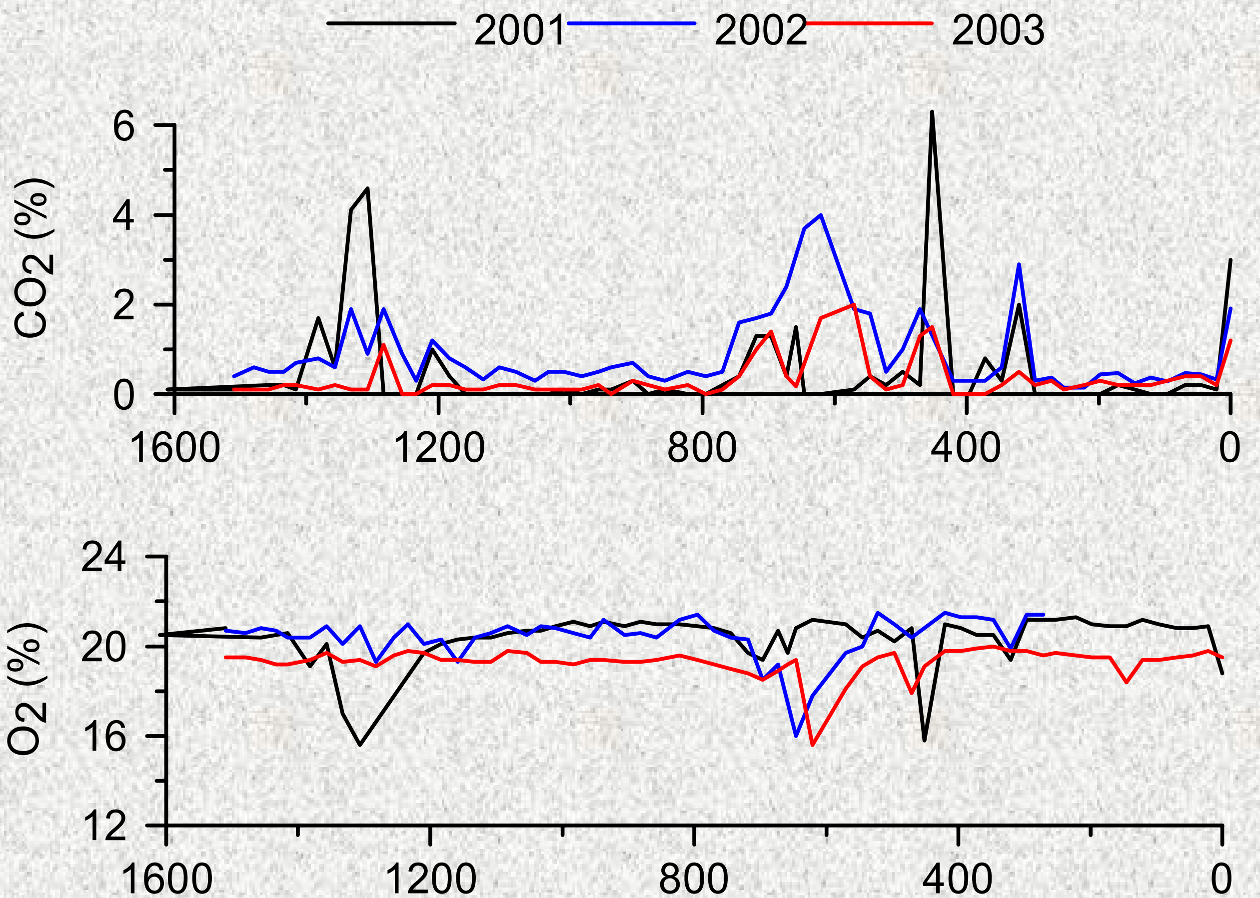


Two peaks correspond with JDMollard lineaments. May just indicate that depressed, damp ground has an alignment (glacial structure?)

Most peaks correspond with depressed, more humid areas

Horizontal profile B

CO2 vs O2



- **Oxygen minimums with carbon dioxide maximums, implying biological reactions**

$\delta^{13}C$ Isotopes

	δ13C value
C3 plants (eg. wheat)	-35 to -21 ‰
C4 plants (eg. corn)	-21 to -9 ‰
Injected CO2	-35‰
Atmospheric CO2	-11‰
Weyburn 19SE-5	-17.3‰
Weyburn 13SE-13	-21‰
Weyburn 13SW-6	-24.6‰

- Values are within range of soil gas CO2 produced by microbial or root metabolism of organic matter from local plants
- Values are substantially higher than that of the injected CO2
- Range of values may be due to different plant types or variable dilution with atmospheric air

Data supporting a shallow origin for CO2

- CO2 concentrations are progressively lower the later the season, in other words cooler, dryer soil conditions and thus less biological activity

- anomalies often associated with surface water

- CO_2 increase results in a 1:1 stoichiometric decrease in O_2 but no change (ie. dilution) in N_2

- isotope values are in the range of the local organic matter.

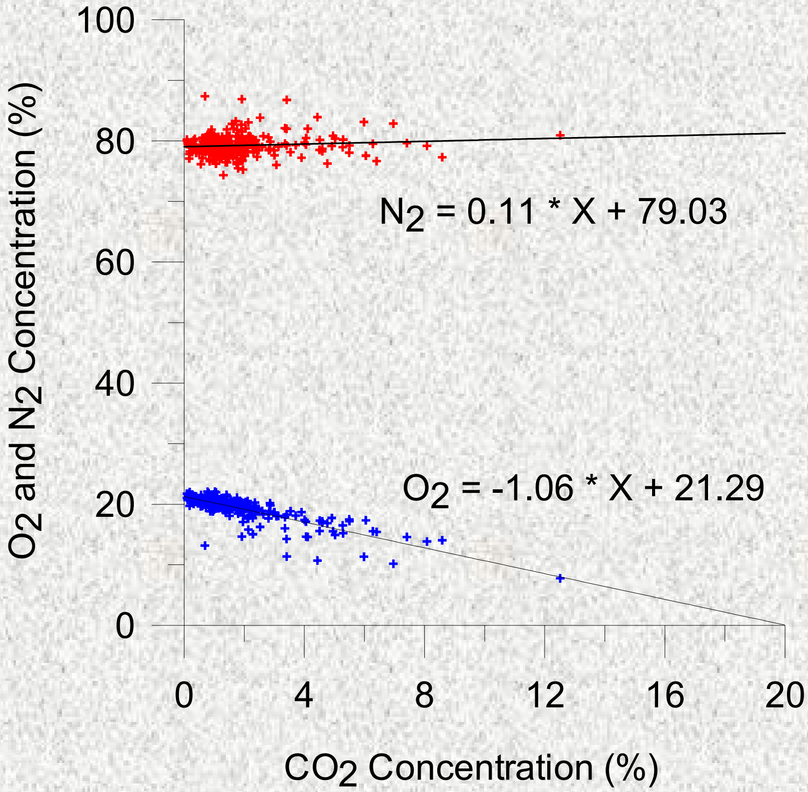
- near abandoned wells, river lineaments and collapse structures (ie possible vertical pathways), CO2 concentrations are in the same statistical range as the main grid

- the background area also shows similar concentrations compared to the main grid

O_2 and N_2 versus CO_2

Weyburn

2001 data

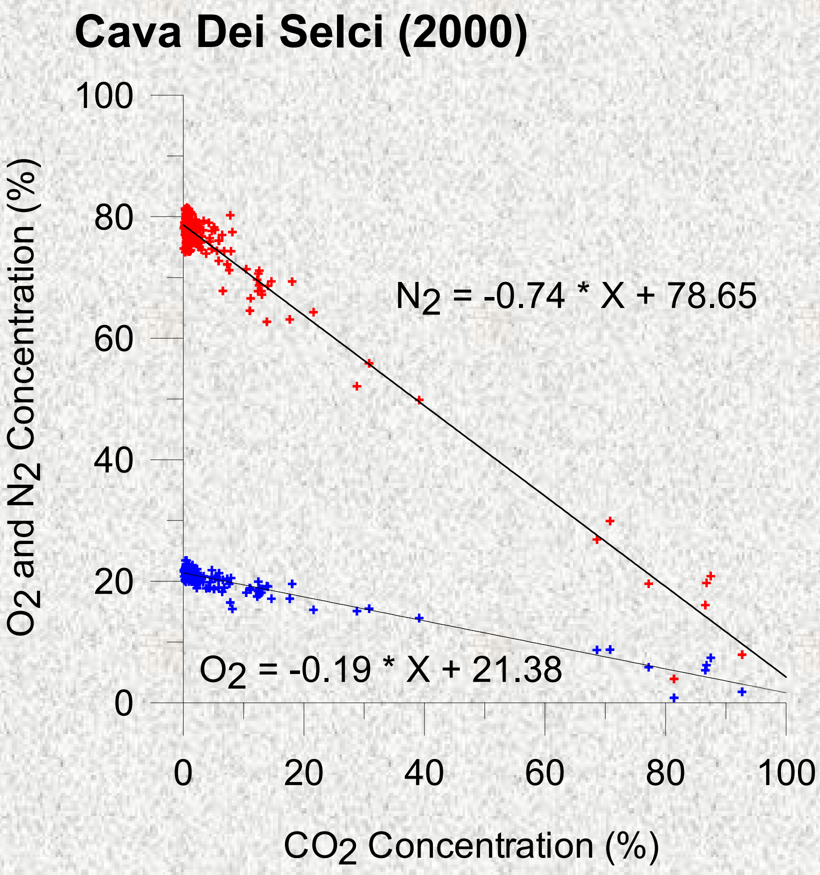


- Plot showing all data points collected from the regional grid in 2001
- N_2 values essentially constant
- O_2 values decrease at a rate of 1:1 towards maximum 20% CO_2
- implies microbial origin of CO_2 via aerobic chemoheterotrophs

organic matter + O2 ------> energy + CO2 + H2O

O_2 and N_2 versus CO_2

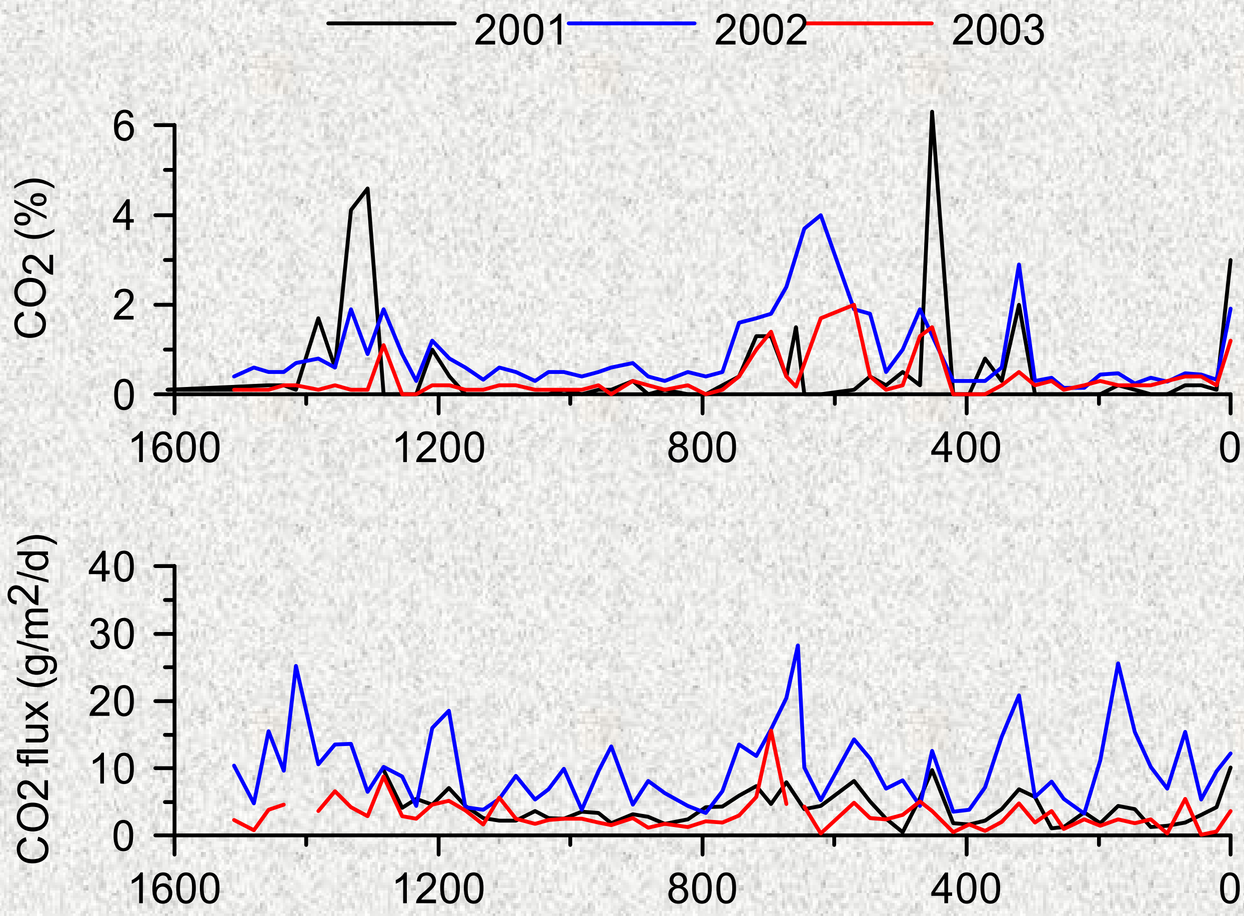
Cava Dei Selci



- In contrast, Cava Dei Selci (Italy) is above a dormant volcano with active CO2 gas vents
- Both N_2 and O_2 values decrease as CO2 increases towards 100 %
- Slope and CO2 concentrations implies dilution with deep origin CO2

Horizontal profile B

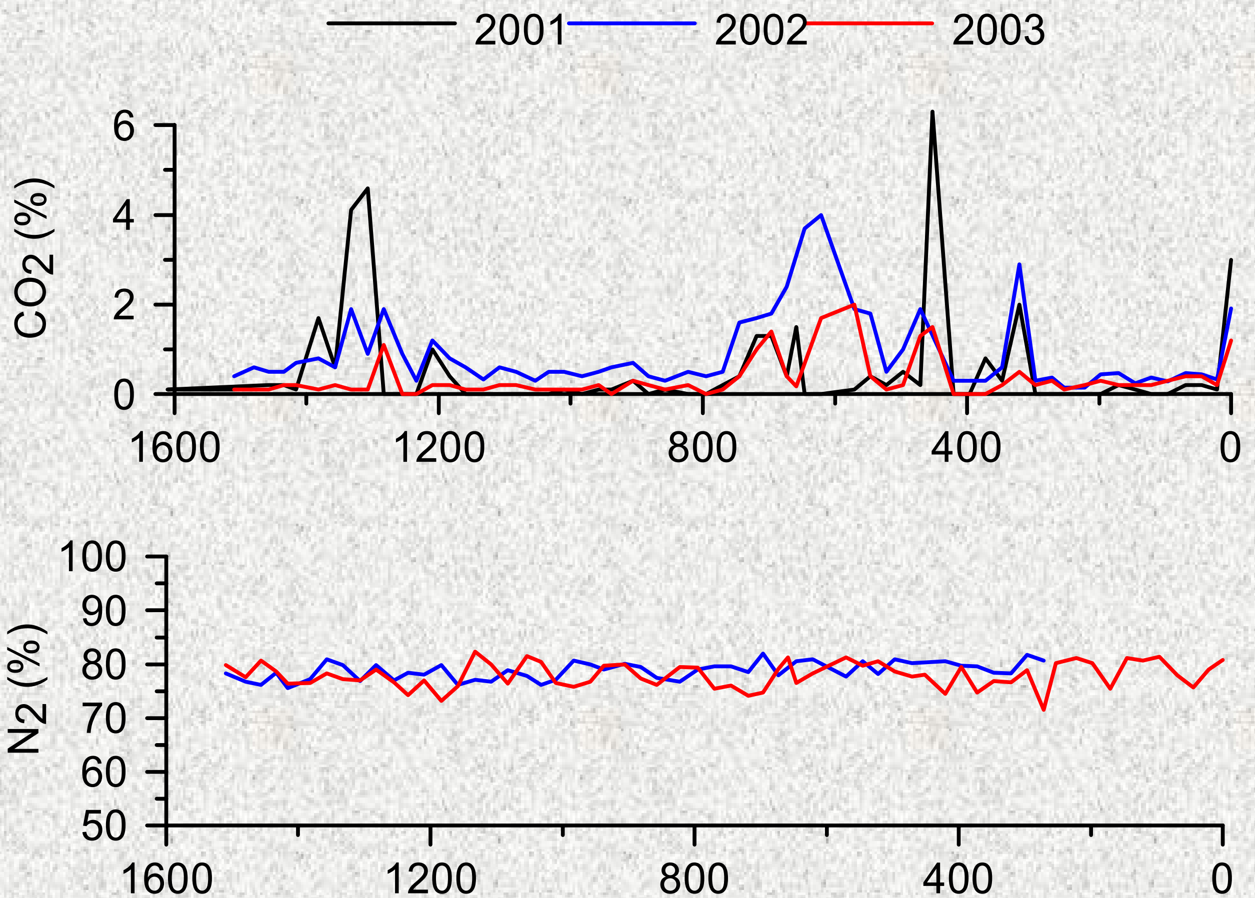
CO2 vs CO2 flux



- **Reasonable correlation with main peaks for both concentration and flux values**

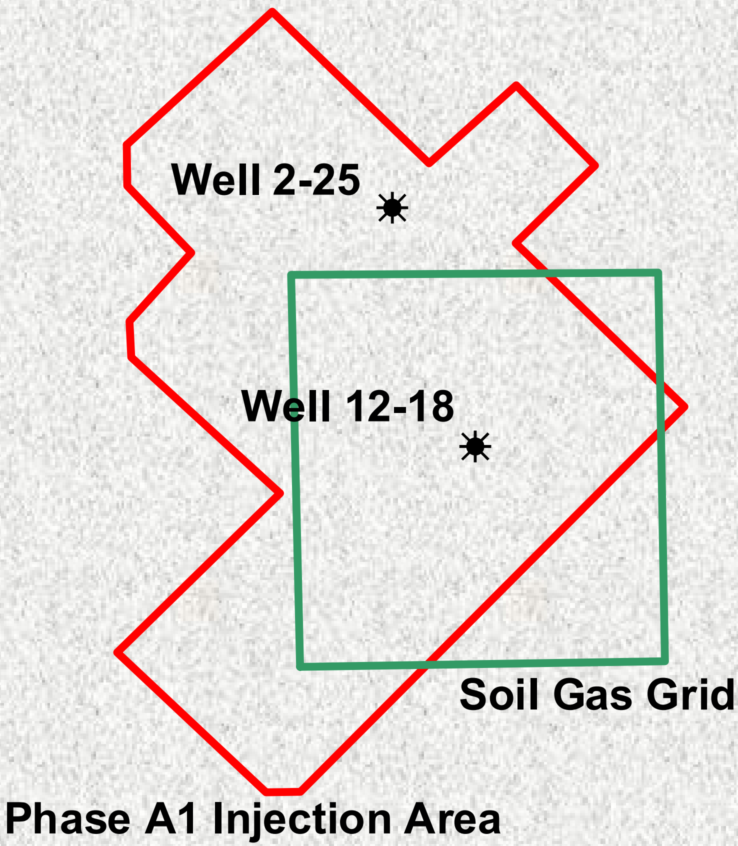
Horizontal profile B

CO2 vs N2



- **This is supported by the lack of any correlation between CO2 and N2**

Decommissioned wells



- Surveys performed above two non-operating well sites within the CO_2 flood area
- Each survey consisted of a 16 point sampling grid above sites chosen by Encana
- Undertaken to better understand role of bore-holes in CO_2 transport, particularly in terms of risk assessment

Decommissioned Wells

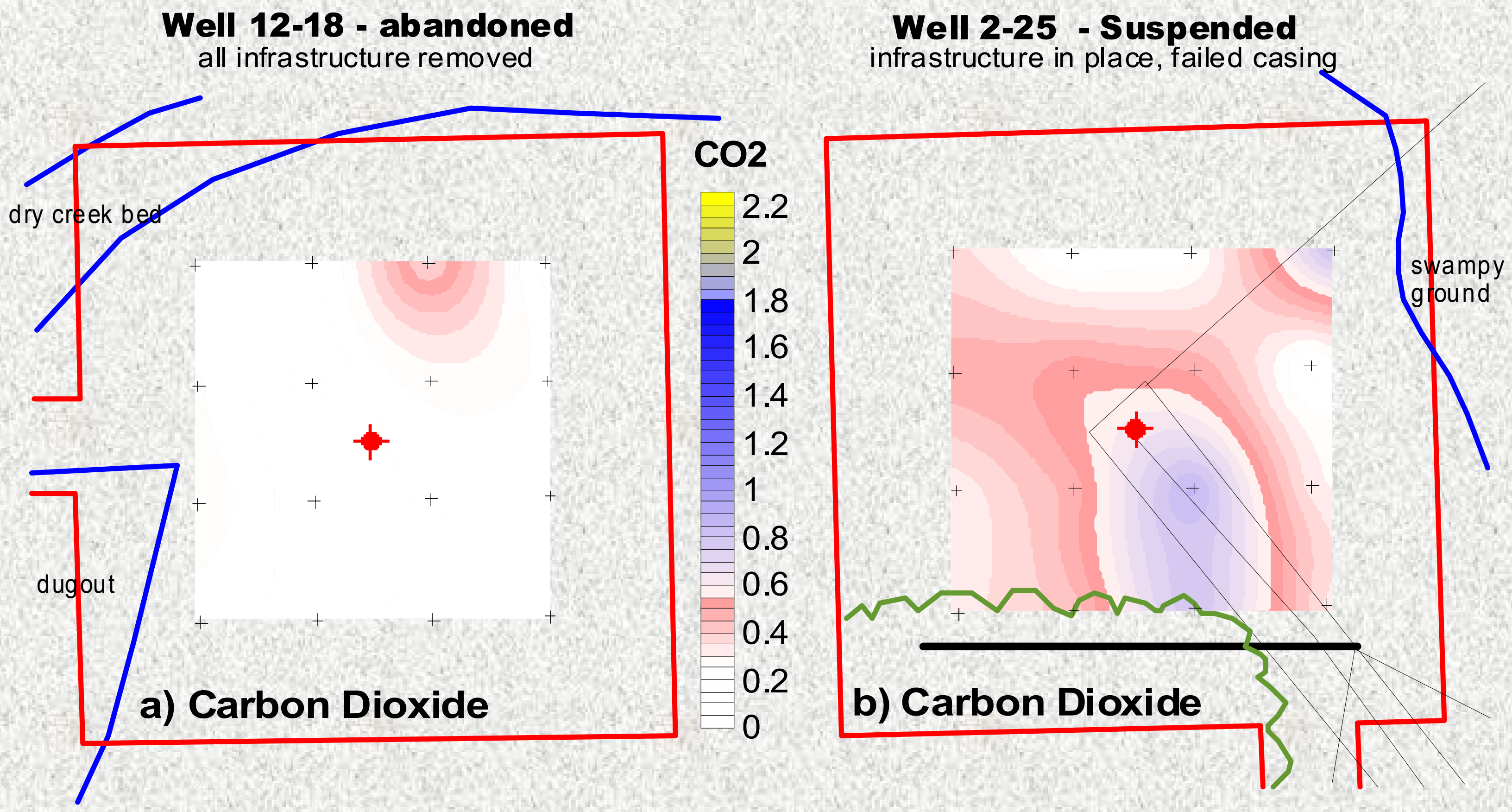
Well 12-18

- Completely abandoned, infrastructure removed and soil returned
- Field is used for animal pasture and is not cultivated
- Within soil gas grid –this general area always had low CO_2 values

Well 2-25

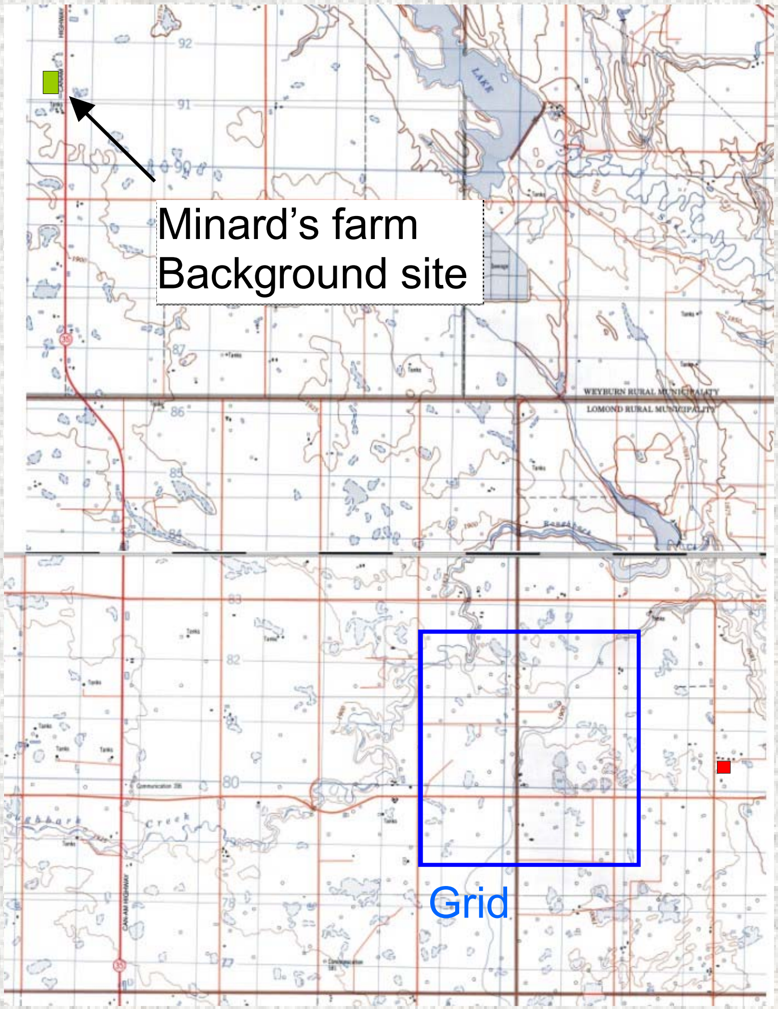
- Operations suspended, casing failed at unknown depth
- All infrastructure, including pumpjack, on site
- Field surrounding pad is cultivated with wheat
- Located just north of soil gas grid, thus no previous data

Decommissioned Wells



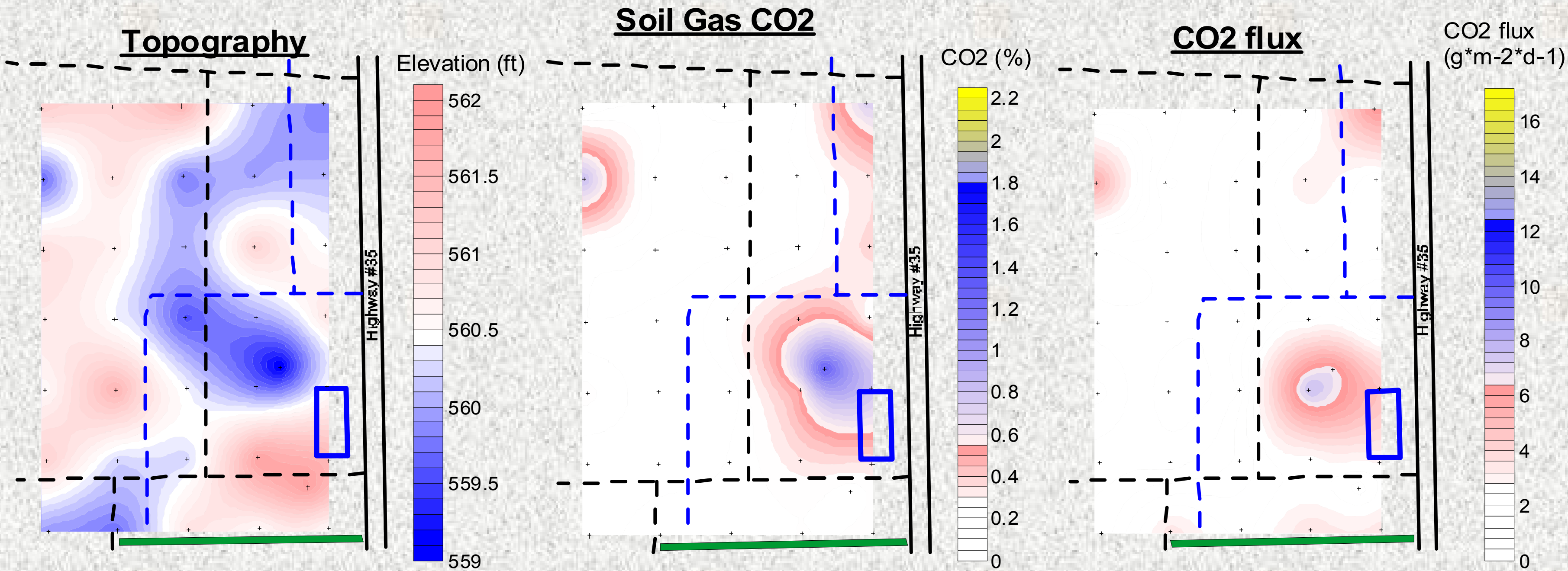
- Lower values at the completely abandoned well
- But the values for both areas are low and lie within the range observed for the entire grid, indicating the values are probably due to shallow biological processes

Background Site



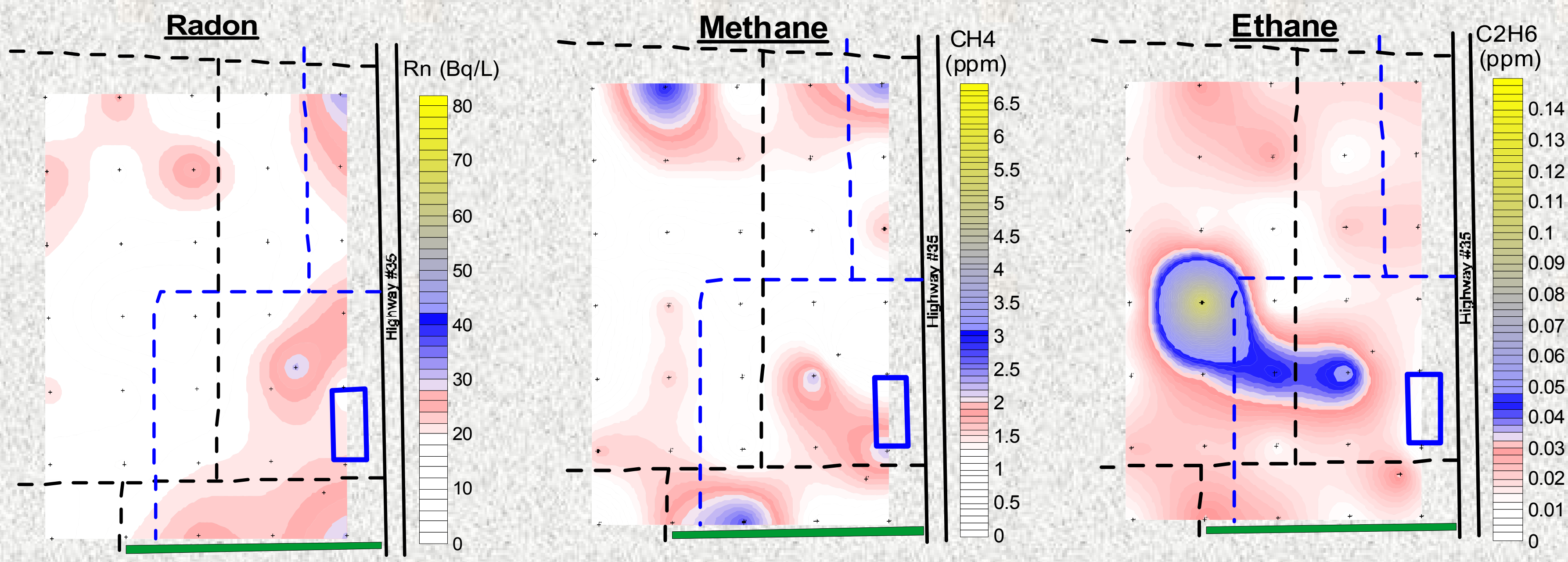
- Site chosen because it has a similar surficial geology, topography and crop-type as the regional grid, however it is not above the Weyburn oil field or the CO2 injection area
- A total of 36 samples (10% that of the regional grid) was collected over an area equal to 2.5% of the regional grid

Background Site



- Values of both CO2 and CO2 flux are low, with anomalies occurring in correspondence with depressions.

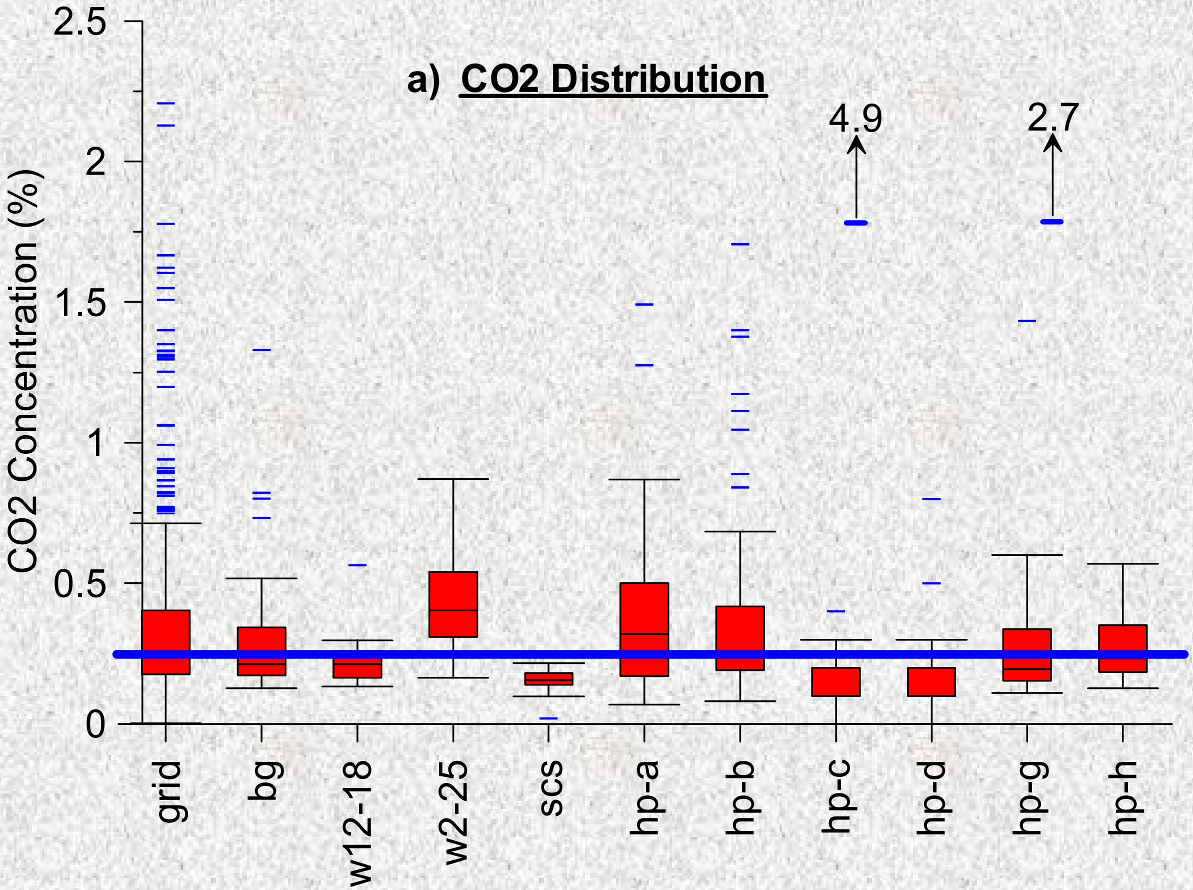
Background Site



- The other measured gases also show concentration ranges that are generally within those of the regional grid

Statistical comparison

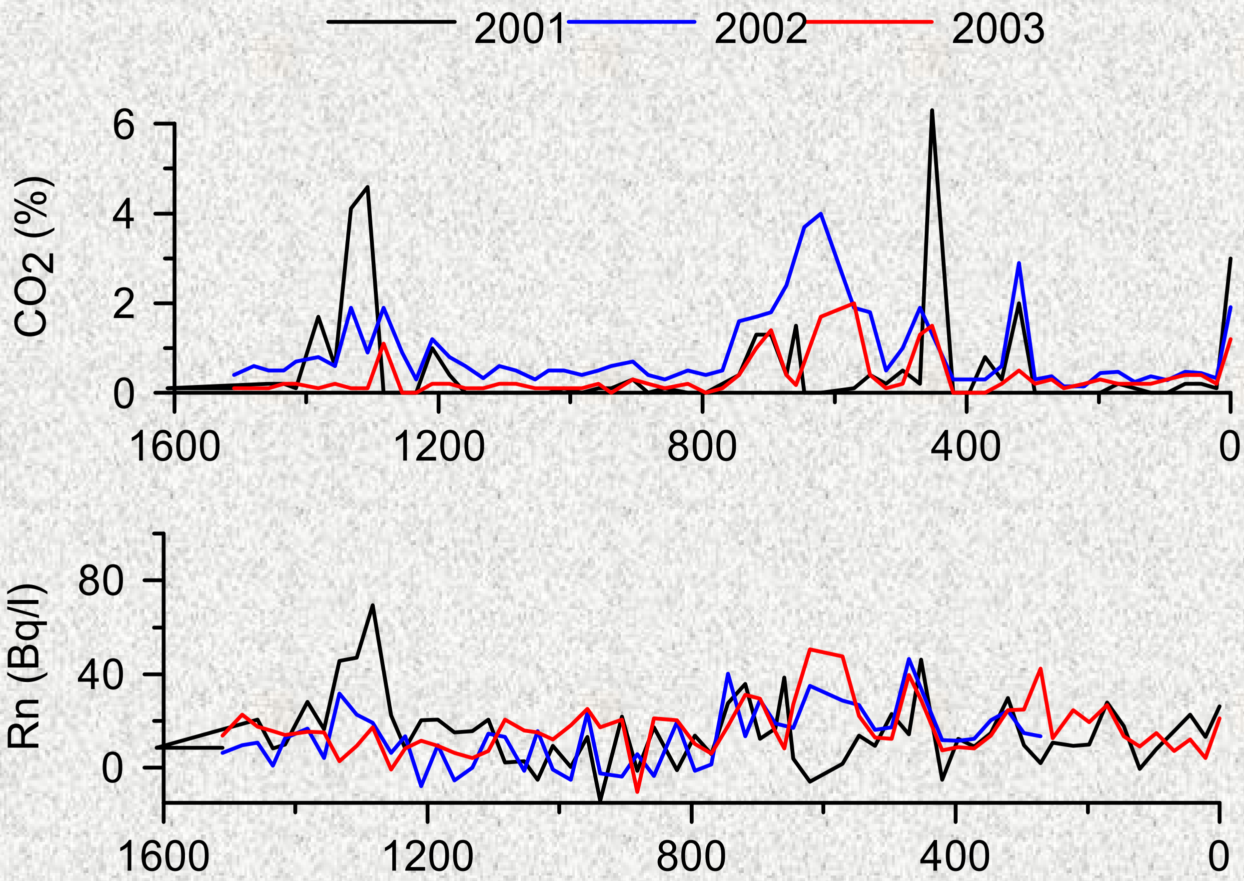
Data from all sites sampled in 2003



- Statistical distribution for all sites is relatively similar. Although the regional grid has more outliers than the background area (BG) this can be explained by the smaller number of samples and smaller area of the latter.

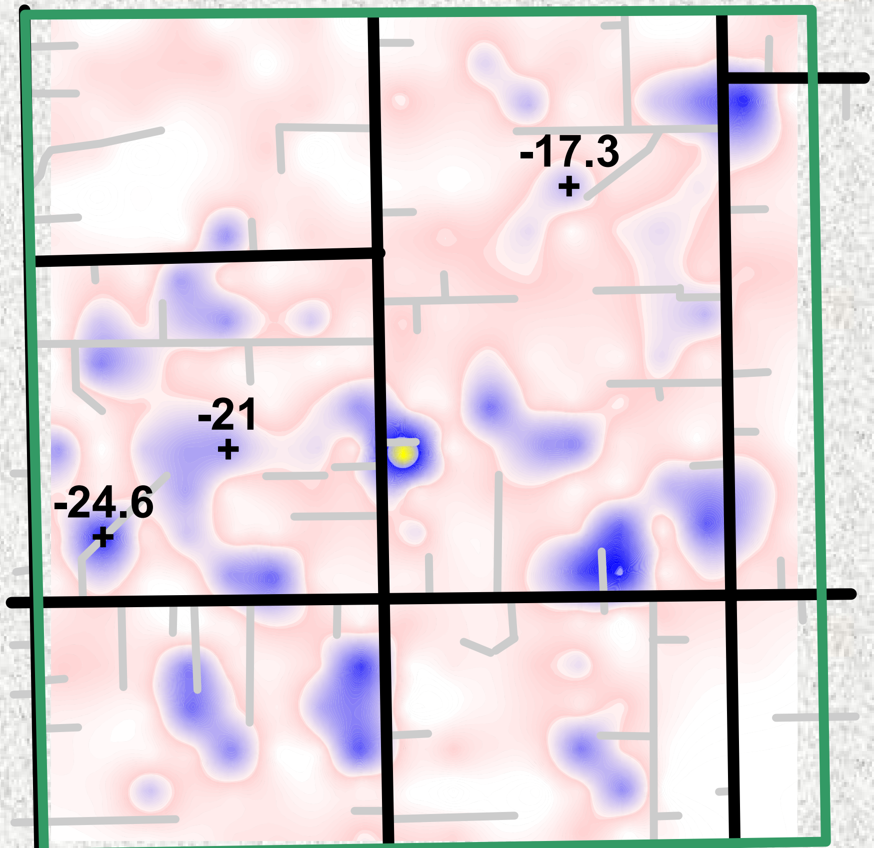
Horizontal profile B

CO2 vs Rn



- **Radon shows some correlation with CO2, particularly at 1300 and 600 m**

$\delta^{13}C$ Isotopes of soil gas CO2



- Samples originally collected in summer of 2001
- Analysed by the University of Calgary
- Plotted here on the soil gas CO2 data from 2001
- Values range from –17.3‰ to –24.6‰

CO_2 Geological Storage by ECBM techniques in the Sulcis area (SW Sardinia Region, Italy)

Amorino C. (2), Bencini R. (4), Cara R. (2), Cinti D. (1), Deriu G. (3), Fandino V. (4), Galli G. (1), Giannelli A. (4), Mazzotti M. (5), Ottinger S. (5), Pizzino L. (1), Pini R. (5) Quattrocchi F. (1), Voltattorni N. (1)

INGV, Section Rome 1, (2) Sotacarbo S.p.A., (3) Carbosulcis S.p.A., (4) IES S.r.l., (5) ETH Swiss Federal Inst. Technology

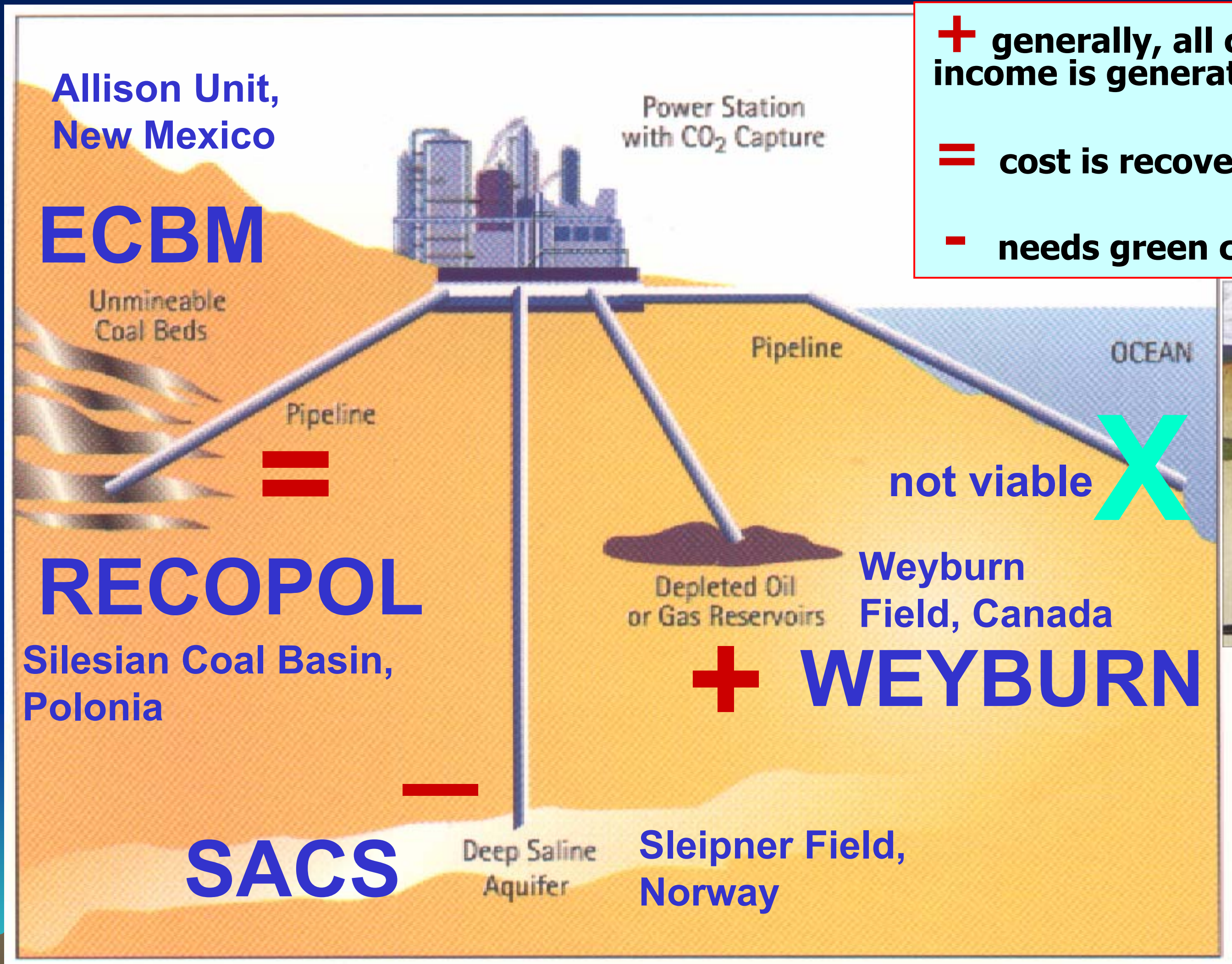
quattrocchi@ingv.it

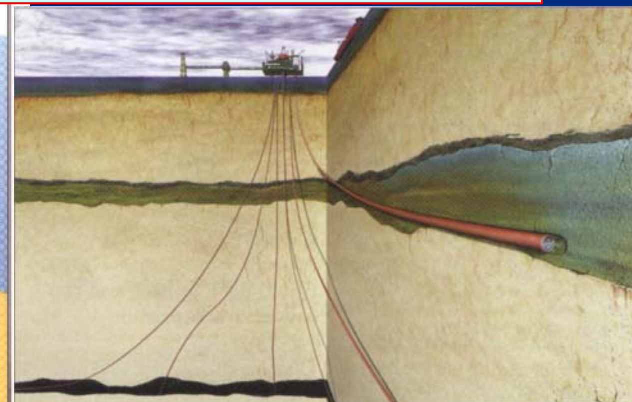
CO_2 Geological Storage Options

+ generally, all costs are covered and income is generated from the extra oil.

= cost is recovered from produced CH_4.

- needs green certificates to be viable.



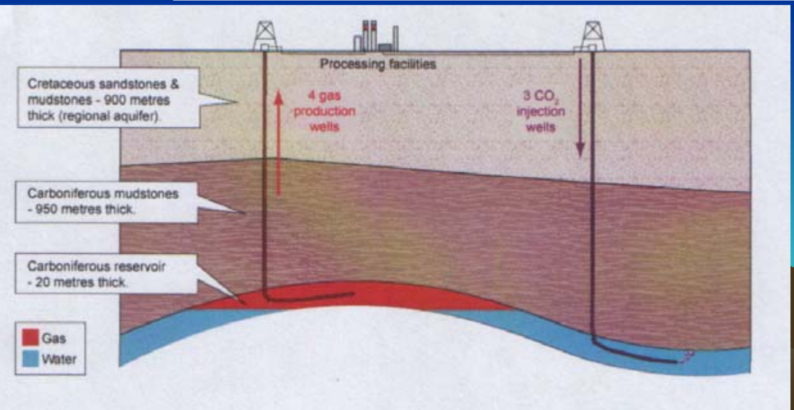


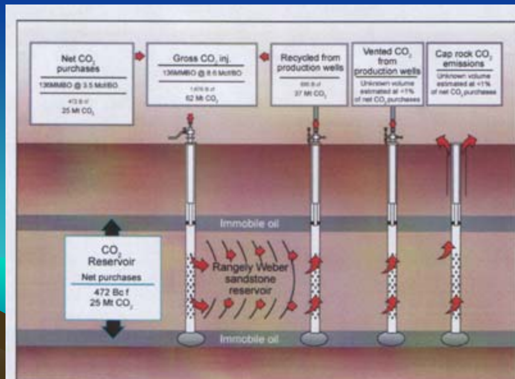
- ECBM = recovery of CH_4 absorbed in deep coals by injecting at P=80 bar industry CO_2, adsorbed preferentially on coal with ratio as 1/2-1/6 (low rank coals).

CO_2 Geological Storage Options

	Storage mechanism	Benefits	Limitations
EOR	physical & mineral trapping	0.33-0.42 t oil/t CO2	▪ oil gravity at least 25º API ▪ primary and secondary recovery methods have been applied ▪ limited gas cap ▪ oil reservoir at least 600 meters deep ▪ local CO2 availability
EGR	physical & mineral trapping	0.03-0.05 t CH_4/t CO_2	▪ depleted gas field ▪ local CO2 availability
ECBM	physical & chemical binding	0.08-0.20 t CH_4/t CO_2	▪ coal that cannot be mined ▪ sufficient permeability ▪ maximum depth 2 km ▪ local CO2 availability
Depleted oil fields	physical & mineral trapping	none	
Aquifer storage	physical & mineral trapping	none	

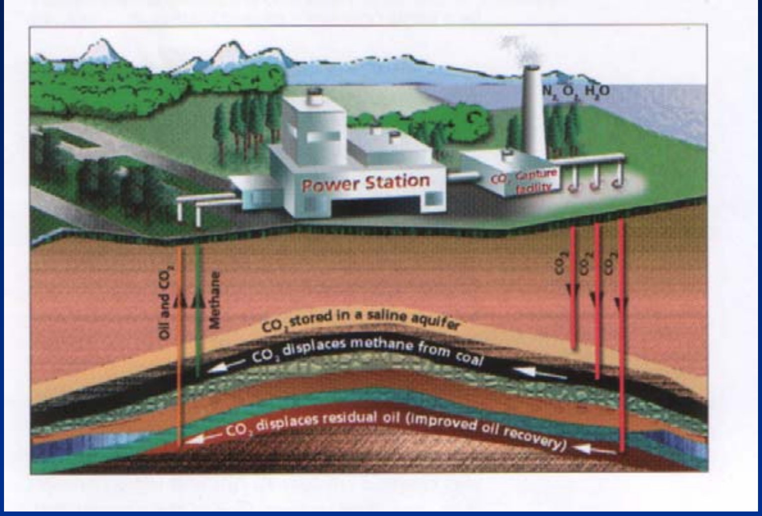
Source: **D. Gielen**, 2003: Uncertainties in relation to CO_2 capture and sequestration. **IEA/EET Working Paper, nr. EET/2003/01**.



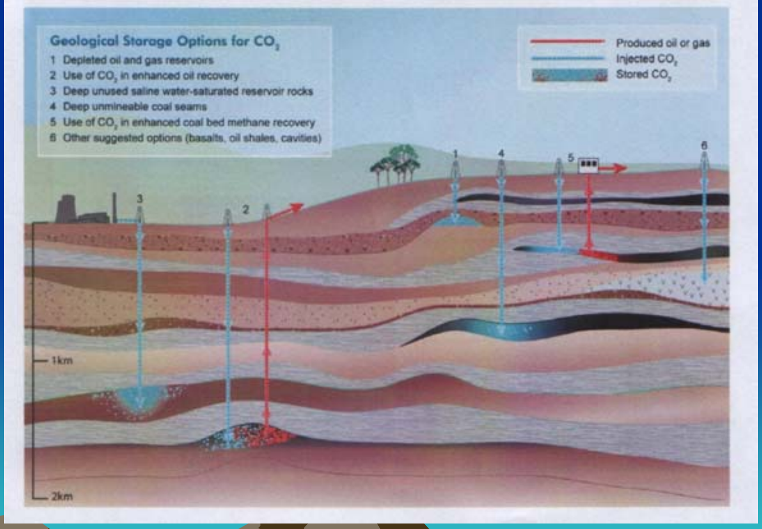


CO_2 geol. storage - Sardinia

- **Saline Aquifers**
  - Campidano Graben (Angelone et al., 2004)
  - Paleozoic Crystalline Basement (PCB), Tertiary clastic formations (2000 m) with self sealing properties.
  - CO_2 storage potential: 1 Gton



- **CO_2-ECBM Sulcis**
  - Tertiary Coal beds
  - (from 800 to 1500 m)
  - CO_2 storage potential : 100-200 MMT tonn CO_2

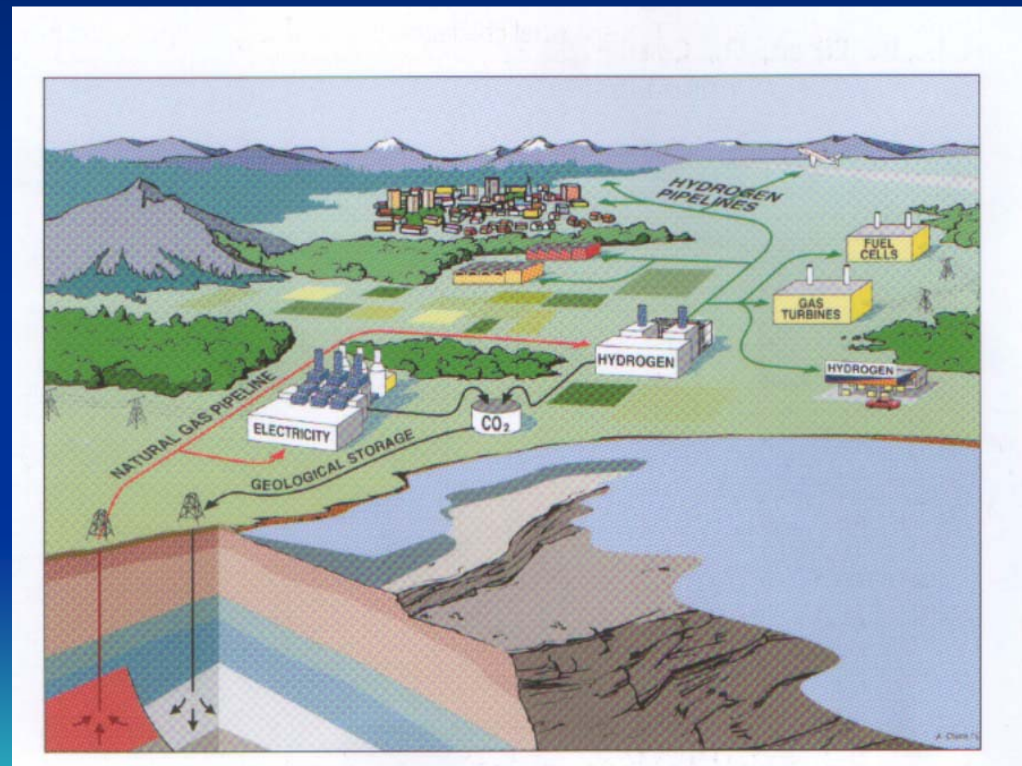


- 1 m^3 CO_2 = 0.121 tonns at supercritical conditions (P = 80 bar)

- 1 m^3 CO_2 = 1.75×10^{-3} tonns (P = 1 bar)

CO_2 Sources in Sardinia

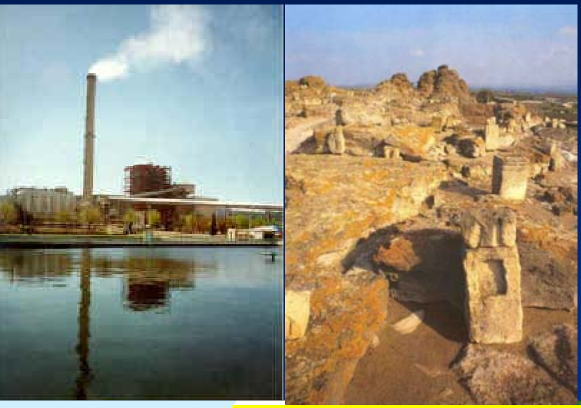
- **ENEL "*Grazia Deledda*"** located inside the Sulcis area. For the next 3 years (2005-2007) *Carbosulcis S.p.A.* will deliver to ENEL around 1.100.000 tonns
- **SULCIS ENEL** power plant (SU3 in the tables of Pettinau & Meloni, 2005), 240 MW section, yet operative, new 340 MW section AFBC SULCIS which will be operative starting from 2006.
- **ENEL, ENDESA, SARLUX,** minor plants
- **Alumina industry**
- **Sites**: Portovesme, Portoscuso, Sarroch, Fiumesanto and Assemini, while other secondary CO_2 sources are renewable energy plants located in S. Gavino Monreale, Arborea, Capoterra, Serdiana, Macomer.

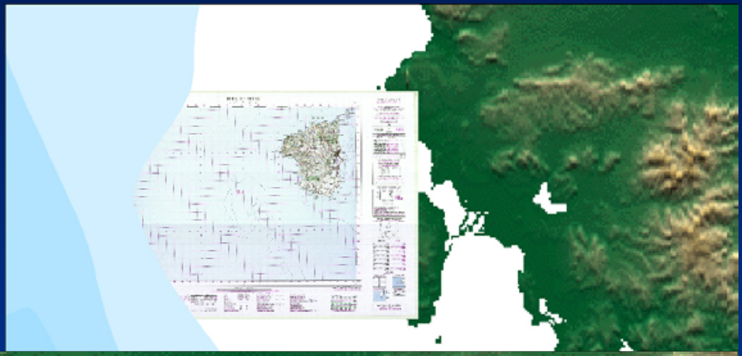


CO2 Sources in Sardinia

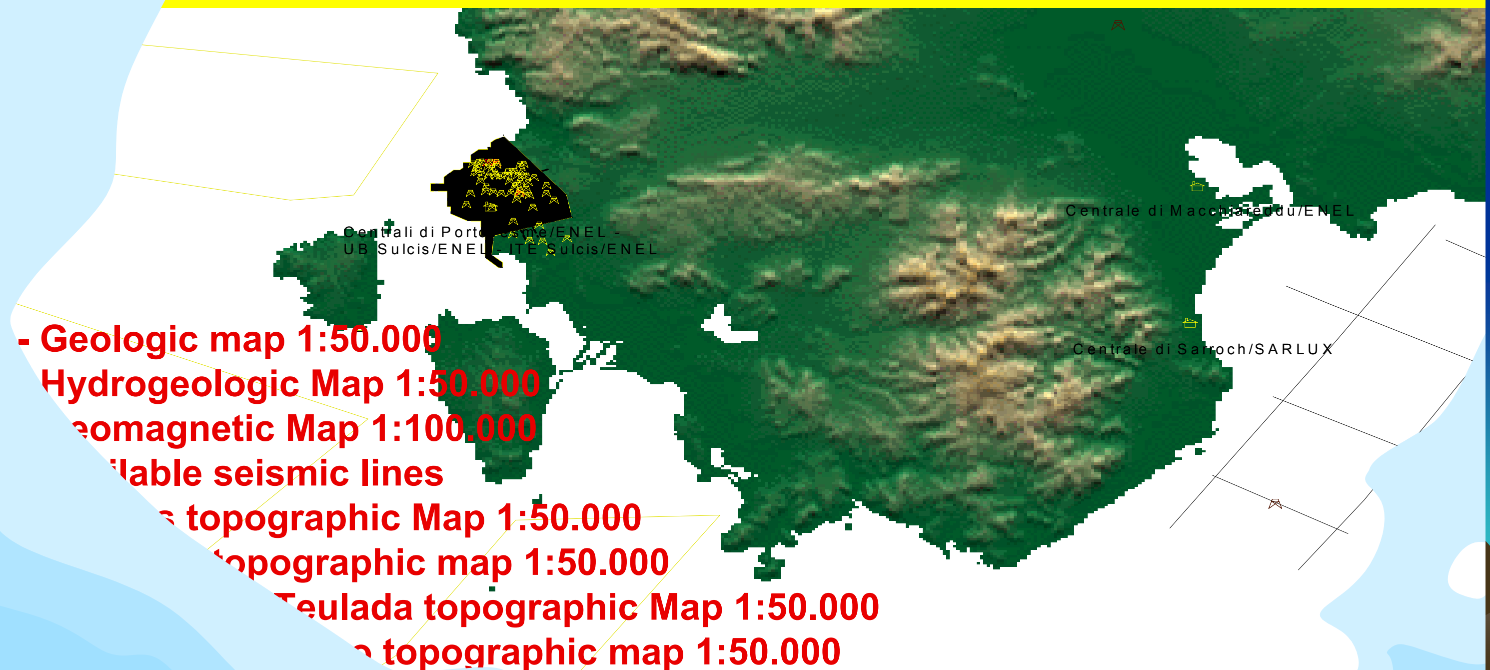
	SARDINIA		ITALY	
	tonn of CO_2	% on tot	tonn of CO_2	% on tot
Transports	2427097	12.32	112420883	23.74
Transports by ship	303410	1.54	7737799	1.63
Transports by air	237346	1.2	2518292	0.53
Transports (others)	370063	1.88	12999233	2.75
Cement production	959011	4.87	30644178	6.47
Thermoelectrical factories	10558648	53.58	173400000	36.62
Refineries	3864589	19.61	25600000	5.41
Siderurgic	0	0	30363371	6.41
Tertiary	707812	3.59	71155347	15.03
Other production activities	278827	1.41	6700000	1.41
TOTAL	19706802	100	473538602	100

GIS on MapInfo ECBM Sulcis (INGV-IES S.r.l.)





. WORK: i) refining iso-piezometric contouring; ii) R_o
nite reflec. contouring to discriminate CBM prone areas.

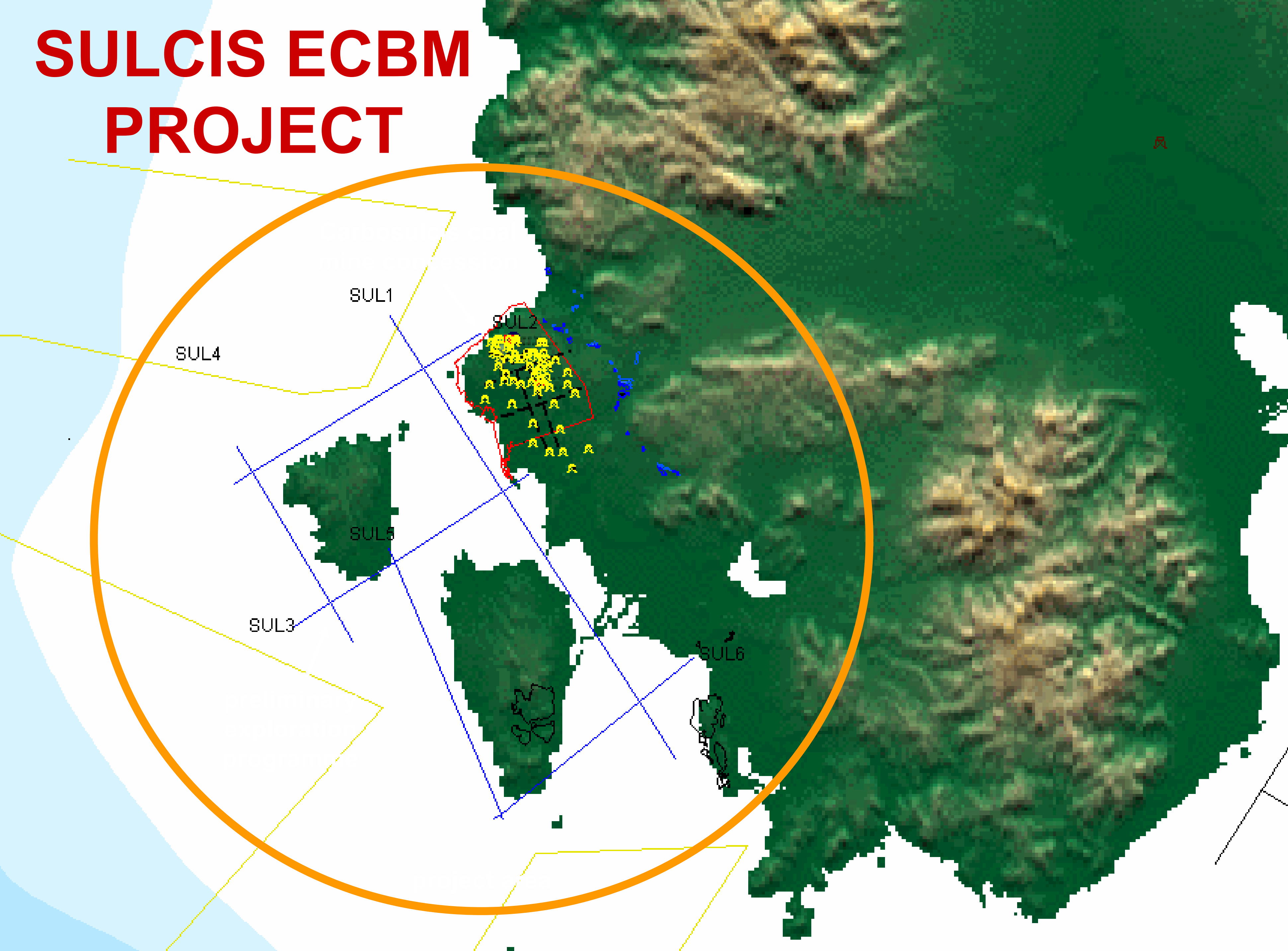


- Geologic map 1:50.000
Hydrogeologic Map 1:50.000
eomagnetic Map 1:100.000
ilable seismic lines
s topographic Map 1:50.000
topographic map 1:50.000
Teulada topographic Map 1:50.000
o topographic map 1:50.000

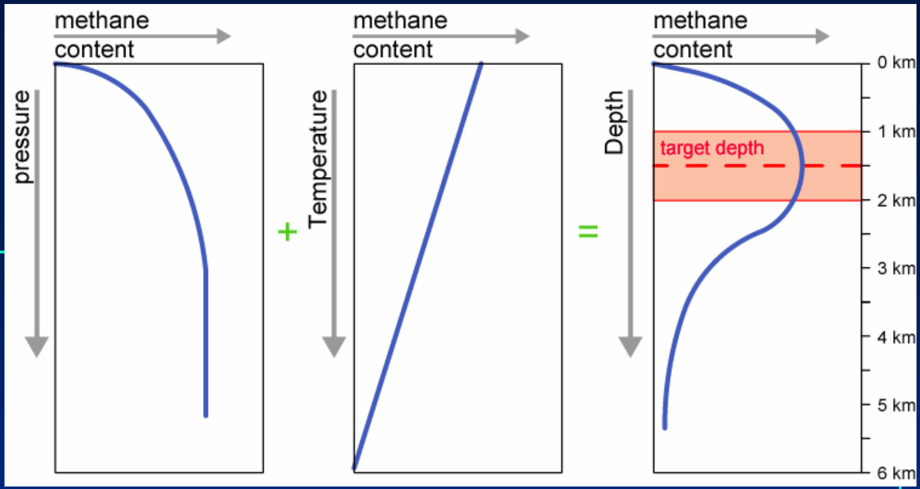
GIS Layers:

- research area
- CO_2 sources
- offshore seismic lines
- inshore seismic lines
- coal mines boreholes
- exploration boreholes
- Montesinni mines
- CBM prone sectors inshore/offshore up to San Pietro Island
- environmentally protected areas
- faults and geologic bodies
- hydrogeological bodies
- possible pipelines
- critical environmental, historic & turistic objects.

SULCIS ECBM PROJECT



Sulcis CBM-ECBM: where and how ?



- CBM under 500 m,
- ECBM under 800 m.

- The thicknesses of coal beds plus coal black-clays are around 150 m. the coal cumulative thickness is around 20 % < 40 %. The cut is 1,40 m high normally and the thickness between two coal beds is > 3,00 m. Around 250 Ml tonn of coal was evaluated in the mining area: IT WILL NOT TO BE EXPLOITED FOR ECBM PURPOSES BUT DEGASSED in early project stage (2-4 years) BY CBM techniques.
- Around 1 Bl tonns of coal could be evaluated in the rest of the sectors toward sea for the remaining areas, including the CBM and ECBM prone areas.
- The geology/stratigraphy is very well fitting with the ECBM purposes: a good cap-rock (500-600 m) thickness i.e., is foreseen able to avoid CO_2 flux break-through at surface, after the injection. Moreover good pH buffer capacity (as WRI power) of the "Miliolidi" limestones host rock able to assure "solubility trapping", in a first stage, and "mineral trapping" on long periods (Gunter et al., 1993; 1997 a-b, 2000).

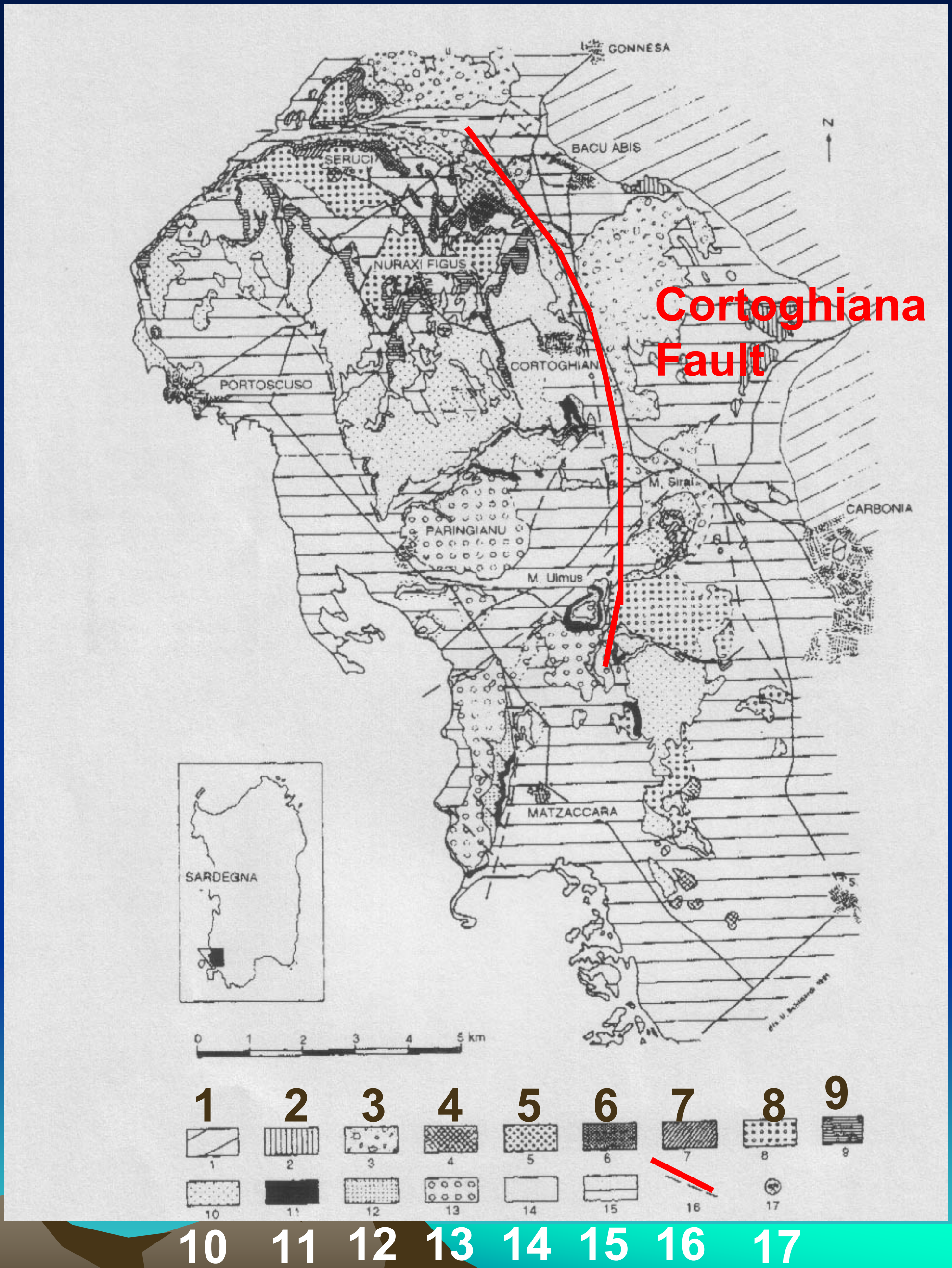
Dependence of CBM potential from geologic history

Dependence of CBM potential from stratigraphy/cap rock

- 1) Cambro-Silurianian Paleozoic Basement (fillads, carboniosus fillads, quartzites, meta-limestone, metaconglomerates);
- 2) Eocene, Paleogene coal bearing (Cuisiano-Luteziano) PRODUCTIVE over a basal congl., "Miliolidico Limestone Formation", marly limestone, lagoon limestone)

  STRATIGRAPHY FACTOR: COAL THICKNESS HAS LITTLE SIGNIFICANCE FOR CBM PRODUCTION.
- 3) Cixerri silico-clastic clay-sand impervious formation

  4) Andesites, Basaltic and. and Oligo-Miocene basalts;
- 5) Unità di Corona Maria (ignimbrites);
- 6) Unità Lenzu (ignimbriti) (ignimbrites, dacites);
- 7) Unità Acqua sa Canna (ignimbrites);
- 8) Unità di Seruci (ignimbrites);
- 9) Unità Conca Is Angius (ignimbrites);
- 10) Unità di Nuraxi (ignimbrites);
- 11) Commenditi (ignimbrites);
- 12) Unità di Monte Ulmus (ignimbrites);
- 13) Unità Paringianu (ignimbrites);
- 14) Unità Serra Paringianu (ignimbrites);

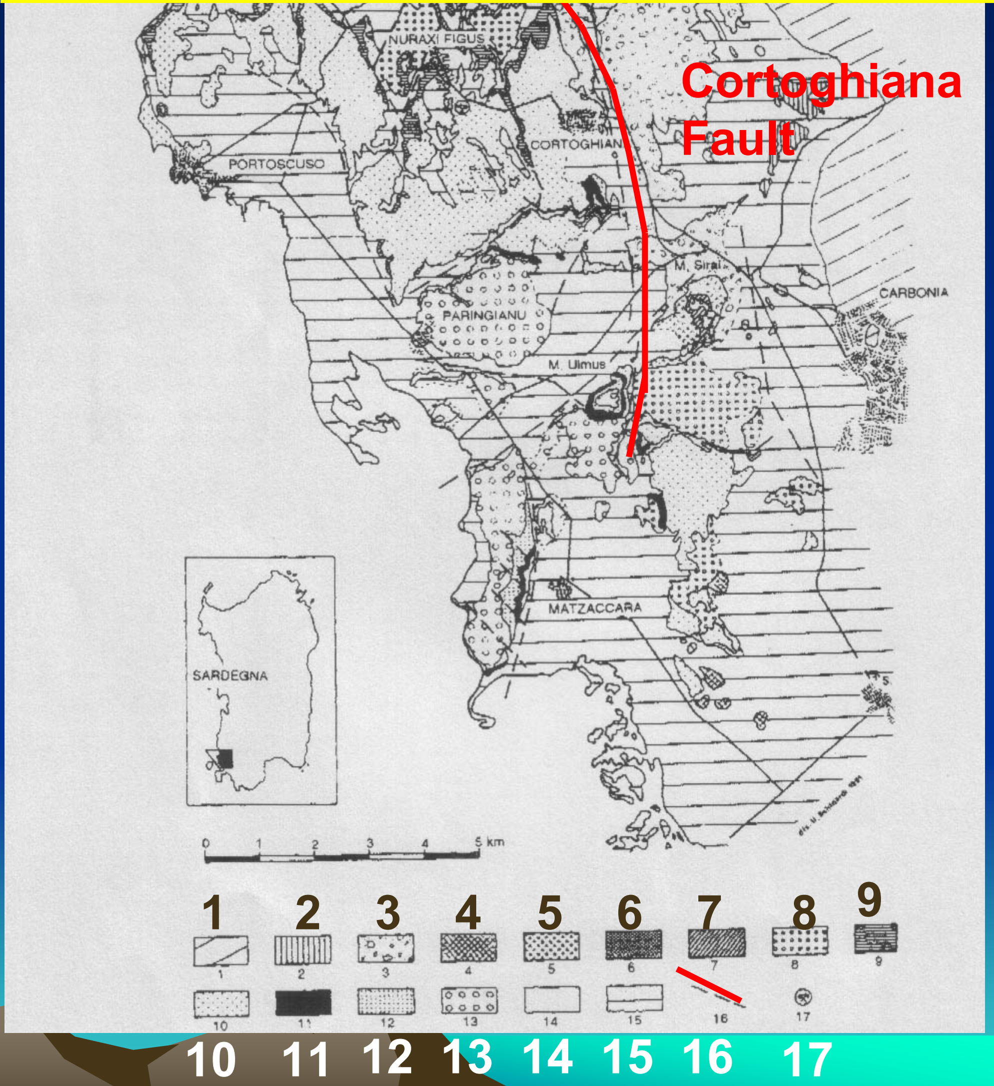


Dependence of CBM potential from tectonics/faults

- **FAULTS**: although they may be seen as potentially facilitating vertical fluid migration and inter-formational flow, they crosscut the coals and create discontinuities in regional intra-formational flow across the basin;
- **Serbariu-Sirai Fault** (Easward, 50 m slip, W Dipping)
- **Sinni Fault** NNE-SSW (N30) ;
- **Cortoghiana Fault** NNW-SSE, N170 vulc. - 3-18 M years;
- **Maiorchina Fault** (NW-SE, slip 7-20 m);
- **Ponente Fault** (N-S, lim. W Seruci 40-100 m)
- **Acqua Sa Canna Fault** post vulcanities, Middle Miocene N80, N dipping, slip 50 m, M. Genere;
- **Paringianu Fault** E-W, N dipping, 20-50 m slip.
- **M. Ulmus Fault** N80E, 100 m slip, limited Perm.

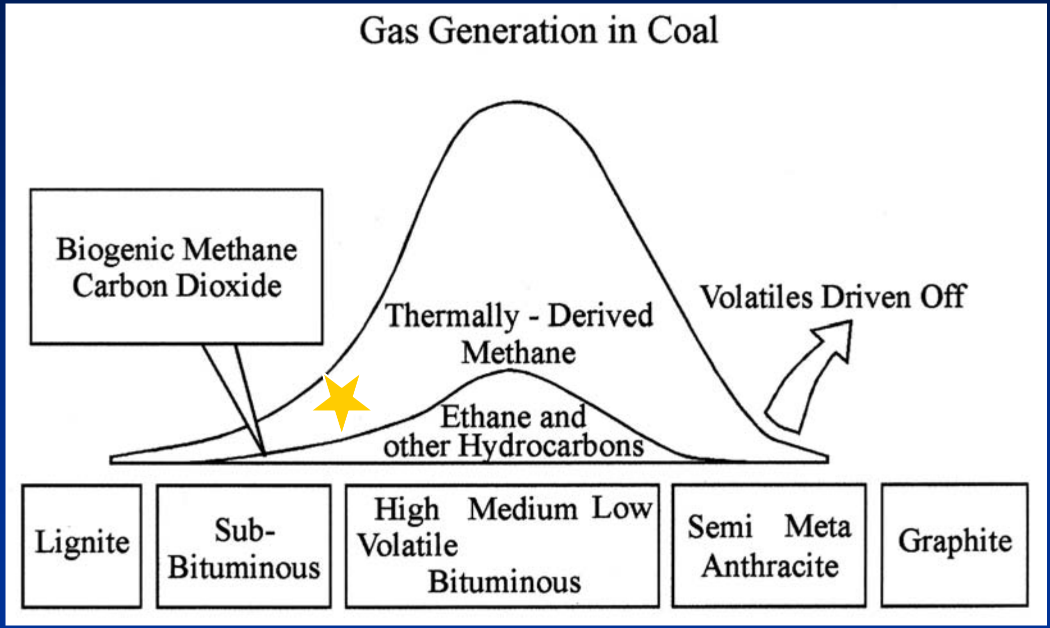
- HALF GRABEN: may enhance transmissivity
- HORSTS and FULL GRABEN: poorest CH_4 producers (Black Warrior Basin, Alabama)

Controversial opinions about the role of faults: 1) expected to lead enhanced production 2) not productive as the blocks between faults.



Dependence of CBM potential from rank

- GIP determined by rank and proximate analyses;
- Increasing rank means increasing CBM, for Ro > 0.7 = CBM production:
- lignite
- sub-bituminous,
- high-volatile bituminous,
- medium-volatile bituminous,
- bituminous,
- low-voltatile bituminous,
- semi-anthracite,
- anthracite;
- With increasing coal rank, the cleat spacing become smaller, potentially enhancing permeability.

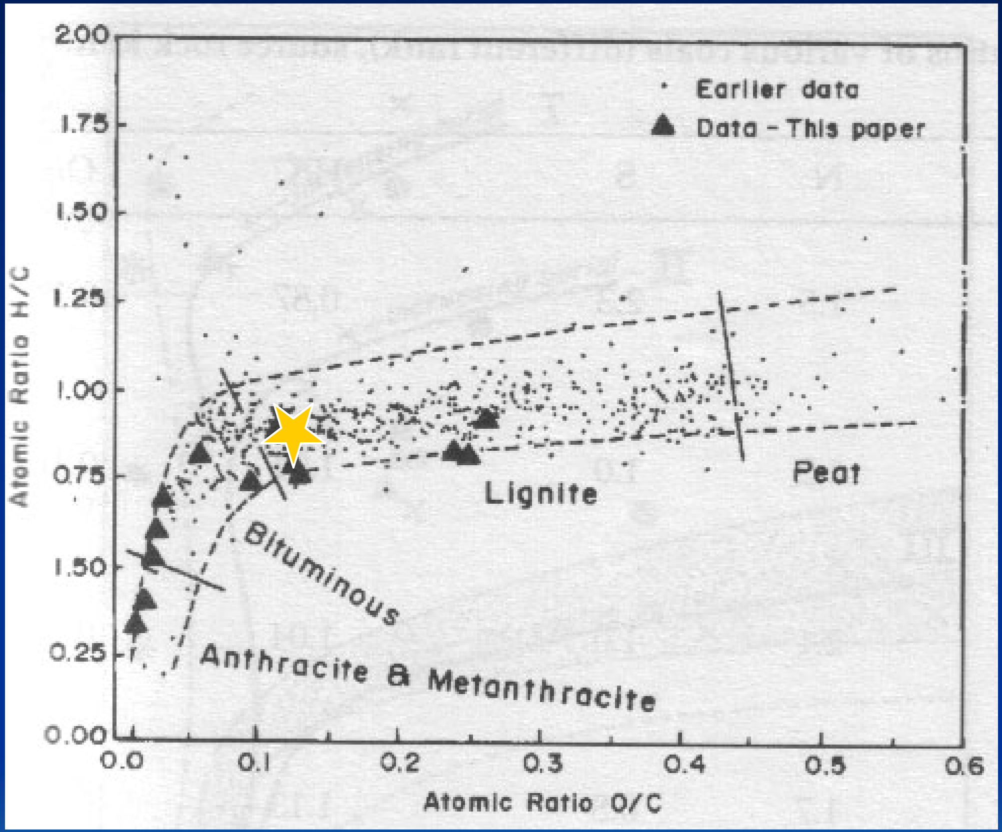


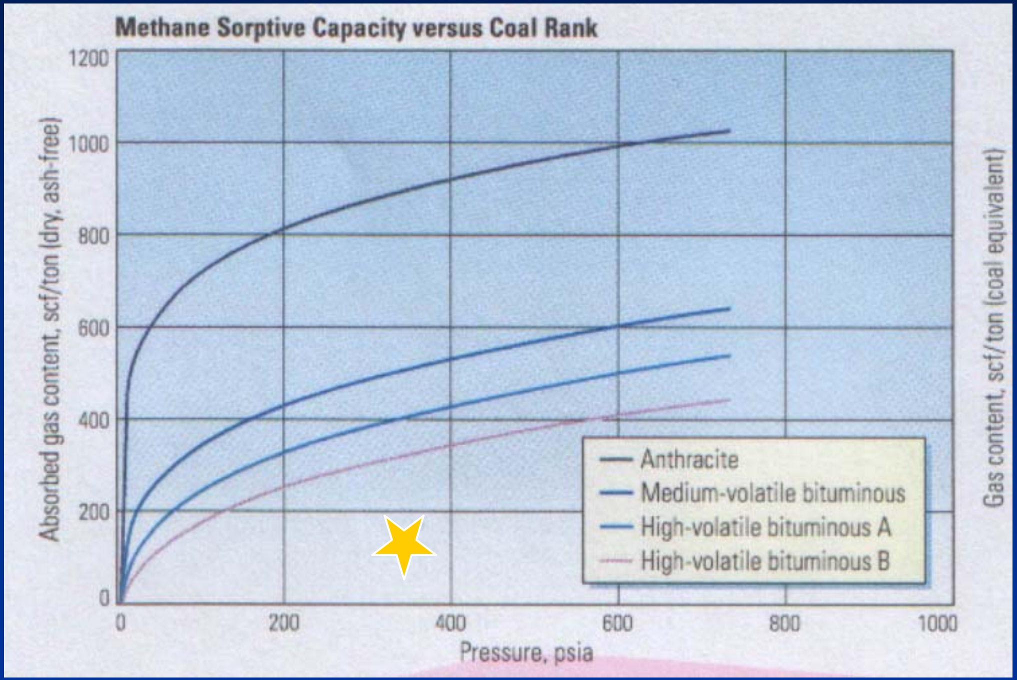
* methane usually present in three states:

adsorbed	in the coal micropores (~95%)
dissolved in water	in the cleats
free	in the cleats, very rare

Sulcis coal: high volatile C Sub-bituminous, Ro = 0.5-0-70

Dependence of CBM potential from rank



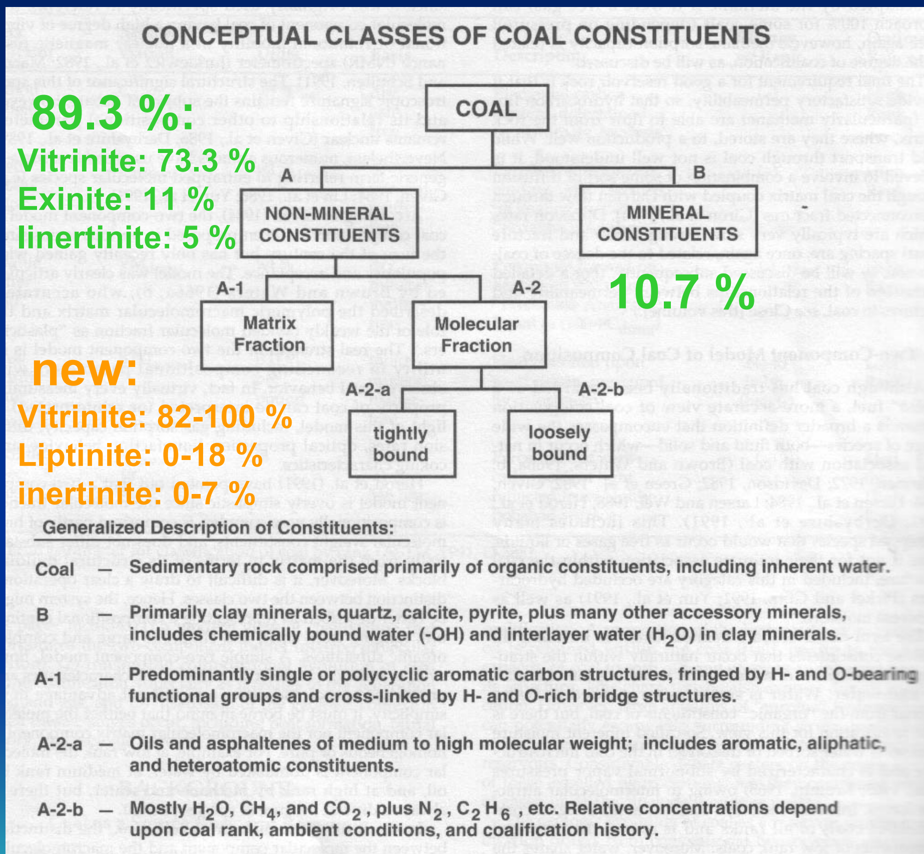


- Sulcis Vitrinite Reflectance = 0.5-070

Sulcis coal High volatile C Sub-bituminous

INITIAL CBM PRODUCTION SENSITIVE TO DESORPTION TIME. IT IS FUNTION OF RANK: higher rank coals generally desorb gas faster than lower rank coals

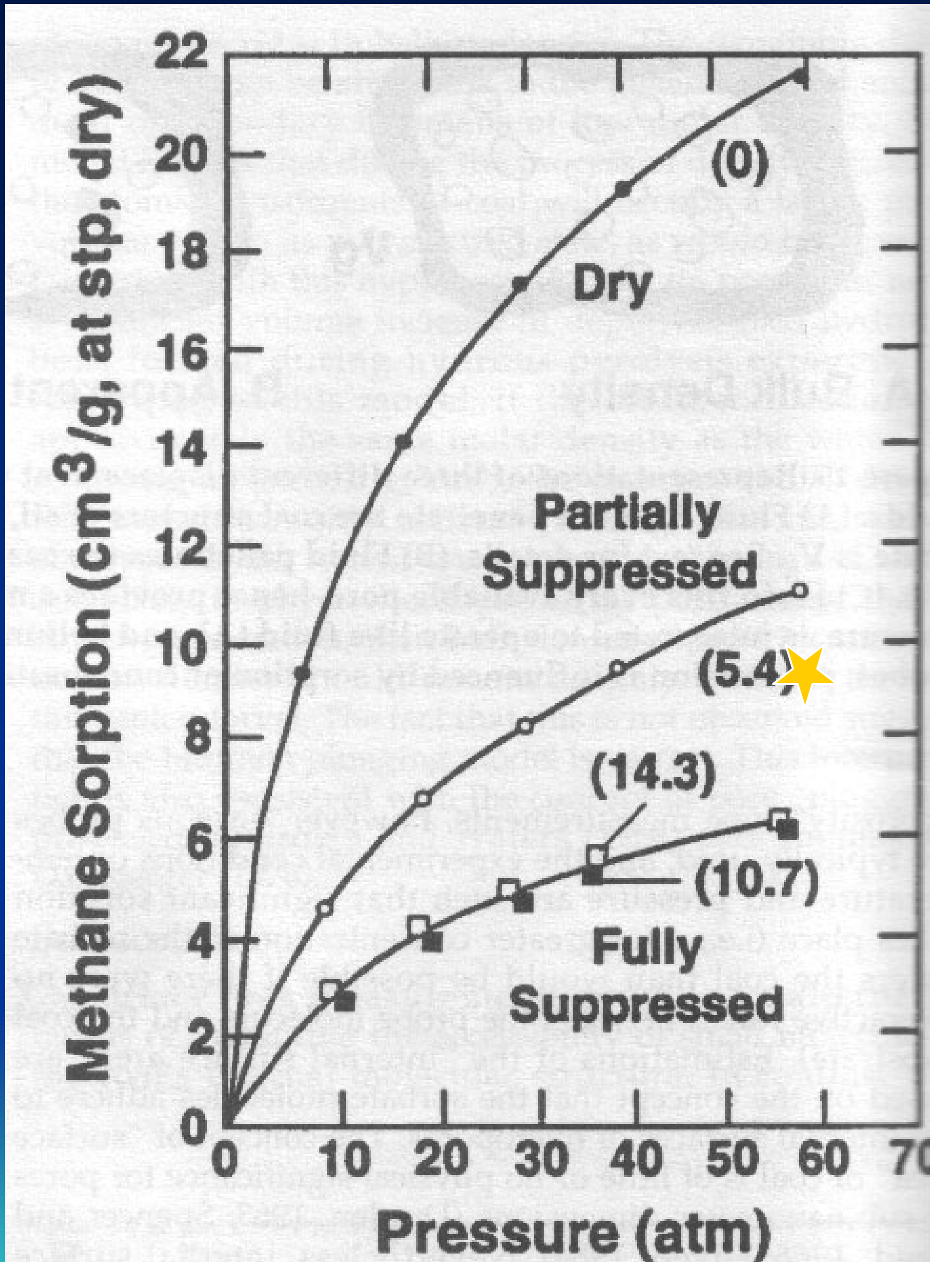
Dependence of CBM potential from composition



Proximate Analyses

Each maceral type stores or adsorb different volumes of methane;

- vitrinite (woosy plant material), liptinite (more resistant parts of plants);
- Inertinite (altered plant material) categories;
- the inertite maceral content and the elemental H/C ratio were the most significant parameters with direct correlation with gas content (Levine, 1991).
- SULCIS: vitrinite prevailing is sound for CBM and ECBM (White et al., 2005)



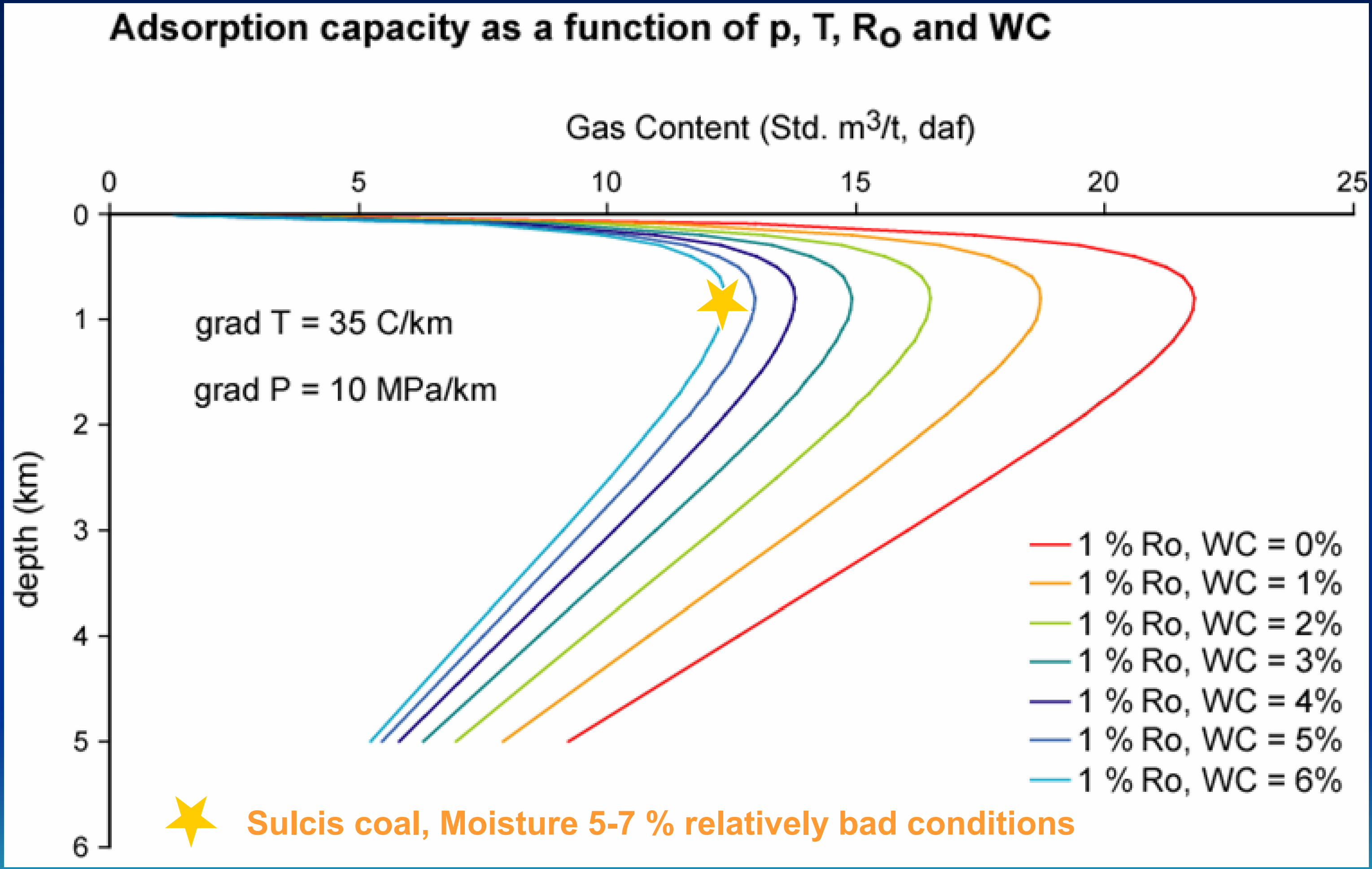
Dependance of CBM potential from coal moisture

The Sorption capacity of coal versus methane as a function of the total gas pressure for a high-volatile bituminous B (hvBb) coal coming from the Illinois Basin (after Joubert et al., 1974) by changing the moisture content (%): the dry coal has significantly more adsorption capacity with respect to wet coal (SULCIS = 6.91 %, 5-7 % as a whole.)

Moisture "…is made of two types of water: free water and sorbed water, both are lost in the process of *geochemical gelification* (lost of organic macerals structures, during which the *vitrinization* occurs namely the transformation from huminite macerals into vitrinite macerals)…" (AAPG SiG, Vol. 38).

Sulcis coal

CBM potential dependence from moisture



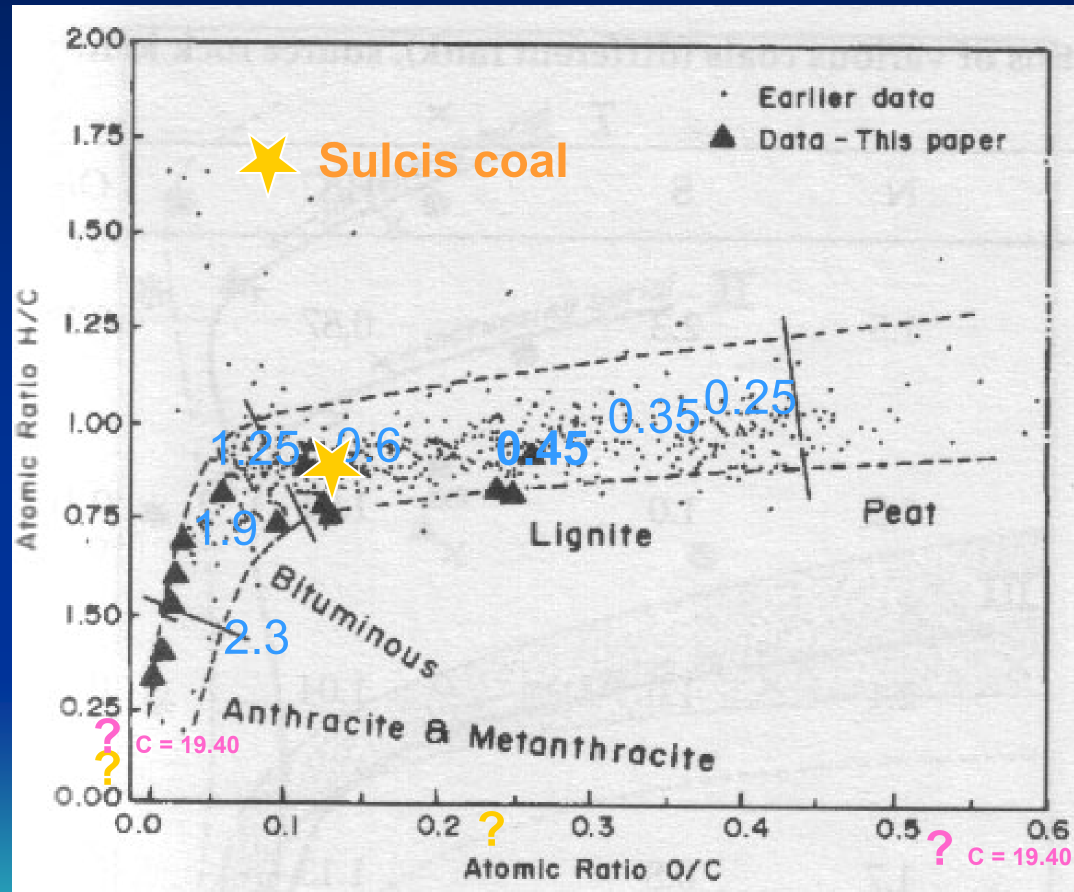
Sapropelitic coal; 50°C ; Campine Basin Moisture between 0.5 and 6 % ; $WC_{crit.}$: 2 – 4%

CO_2 isotherms at 45°C of RECOPOL coal for P 0-100 bar: 0.6-1.4 mmoles/g coal (dry), 0.2-0.8 mmoles/g coal (wet).

Proximate Analyses (ASTM methods)
Sulcis: new experimental data
(other analyses are in progress – INGV)

	Media %	ASTM Method	NOTES
U Tot. %	6.91	3302-02	U_i= 5.25 U_e= 1,75
M.V. %	44.09	5142-02	R_o=0.48 (old datum)
Ash = A %	31.26	5142-02	
C fix %	19.40	5142-02	
C tot %	45.96	5373-02	
H %	4,04	5373-02	
N %	1,21	5373-02	
O diff %	11,93	3176-02	
S tot %	5.60	4239-02	
PCS kcal/kg	4415	PCI kcal/kg	4177

- Sulcis Vitrinite Reflectance = 0.48-0-70
- CO_2 content ($CaCO_3$ in coal-rock) = 9.62 %
- **Krevelen diagram** for "humic" coals *vitrinite macerals* rich as Sulcis (the "sapropelic", coals, rich in *alginite* o *sporinite*, have the higher H/C and lower O/C). The blu numbers are the vitrinite reflectance (Ro).



H/C = 0.089-0.20 ?

O/C = 0.26 – 0.61 ?

Sulcis Adsorption new experimental data

METHODS for determining the gas content are:

- Direct methods (desorption)

- Indirect methods (adsorption/desorption)

- **ADSORPTION INVESTIGATIONS: gravimetric, volumetric and chromatographic PVT methods to measure the sorptive capacity of crushed coal as Gibbs sorption (measured, apparent, differential or excess sorption) while the absolute sorption = Gibbs sorption + correction by He of void volume (important for high pressures).**
- **Density of sorbed phase: 0.422 g/cm^3 for CH_4 , 1.277 g/cm^3 for CO_2**

- **Langmuir isotherms: relation at T=K between total gas pressure and sorbed gas (changing moisture, rank, macerals, ash content, etc…);**
- **V = VM (bP/(1+bP), VM = maximum sorption capacity = value of gas content as the pressure gets very large; b = Langmuir constant = b = f (Q, R, T) Q = heat of sorption [J/Kmol];**

Sulcis Adsorption new experimental data

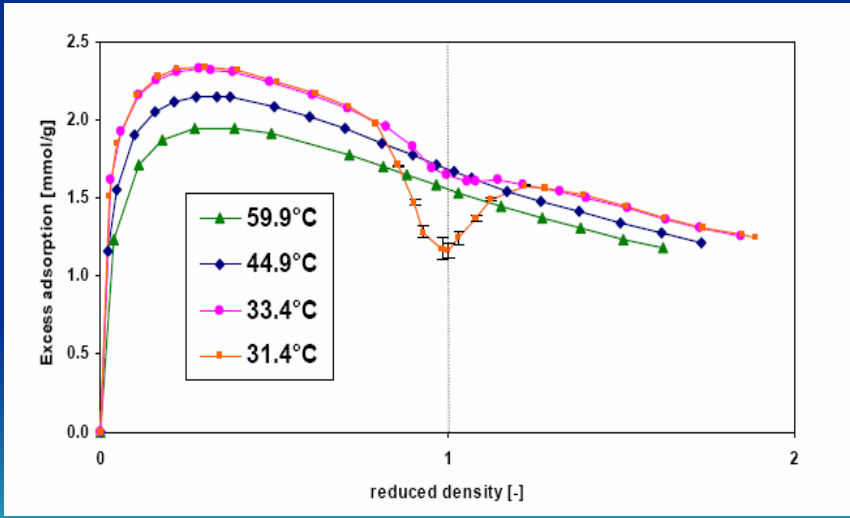
EXPERIMENTAL CONDITIONS: different isotherms, adsorption of CO_2 and CH_4 on coal

Rubotherm Magnetic Suspension Balance **(Rubotherm, Germany);**

- T_{max} = 250 °C, P_{max} = 450 bars, mass resolution 0.01 mg;
- Measurements of temperature, pressure, fluid density and excess adsorption (Gibbs Adsorption);
- Coal grained at 0.25-0.35 mm, dried at 105°C for 24 hours;
- Gravimetric measurement under vacuum and Void Volume measurement at 200 bar, 100°C, by using helium, assuming it does not adsorb.
- Adsorption equilibria are evaluated by the true measurable quantity:

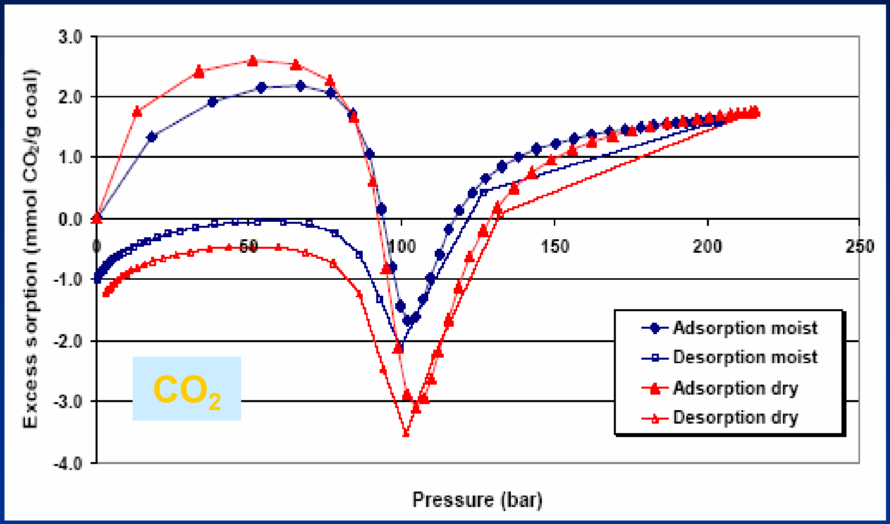
$$m_{ex} = m_{ads} - \rho_b V_{ads}$$

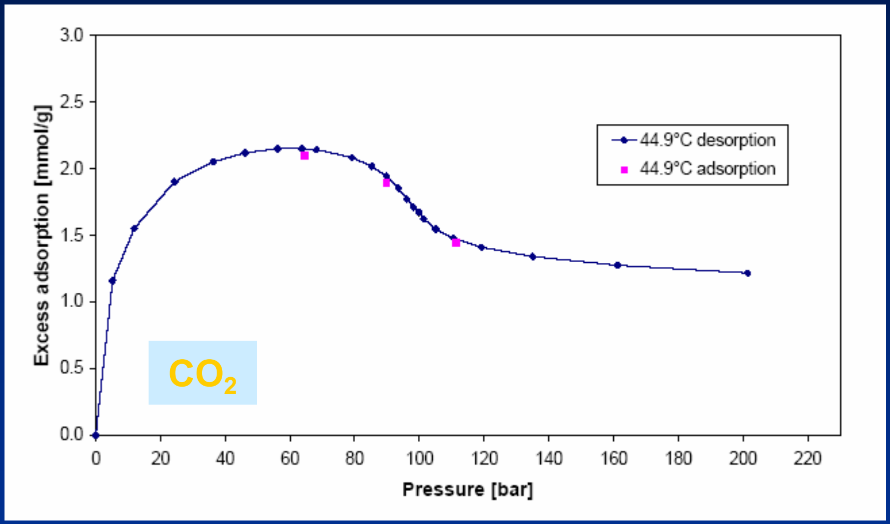
- m_{ex} = excess adsorbed mass amount [mmol/g coal]
  ρ_b/ρ_c = reduced density,
  where ρ_b = fluid density, ρ_c = critical density
- m_{ads} = absolute adsorbed mass amount [mmol/g coal]
- V_{ads} = volume of absolute adsorbed amount [cc]
  ρ_{ads} = density of the adsorbed phase [g/cc]
  (at T_{eb}, P = 1bar: ρ_{CO2}=1.277 g/cc, ρ_{CH4}=0.422 g/cc)
- **Critical depletion** at 33.4 and 31.4 °C
  (T_c of CO_2 =31.0°C)

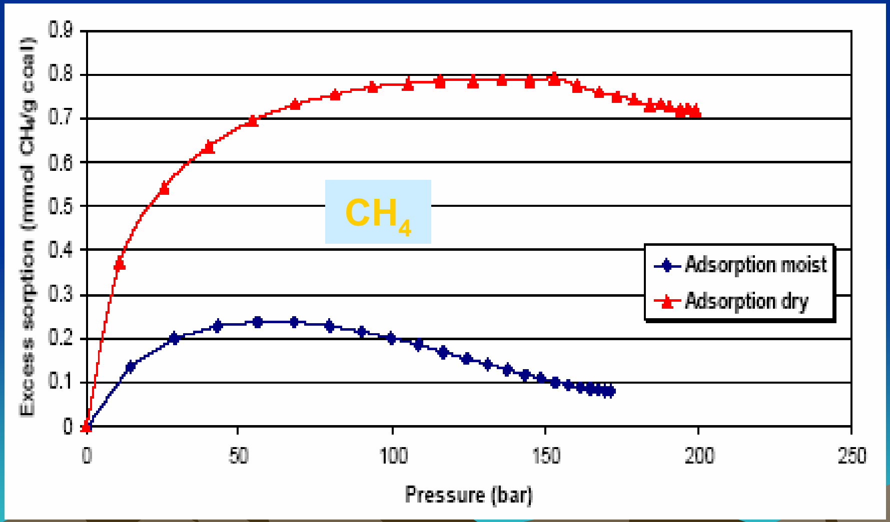


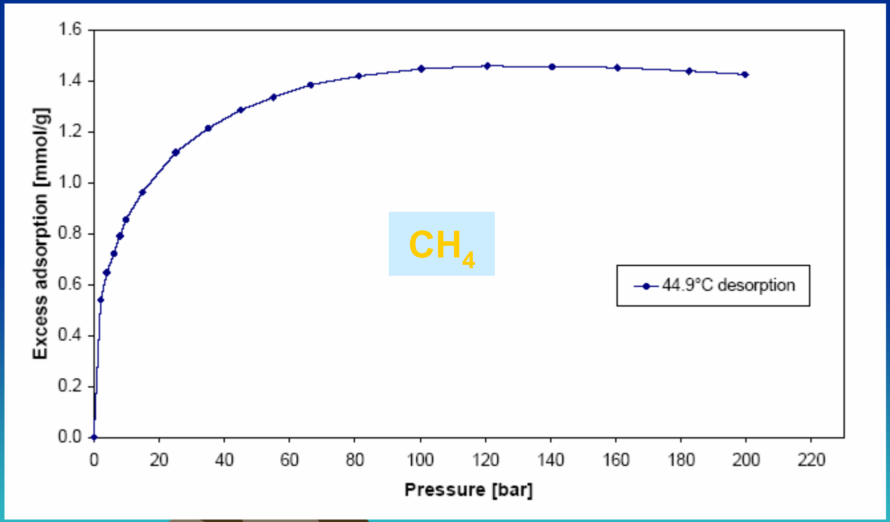
Excess adsorption isotherms for CO_2 on dry coal (Sulcis)

Sulcis Adsorption new experimental data









Brzeszcze (RECOPOL,Poland)

dry and moist coal, T=45°C *Krooss et al. (2002)*

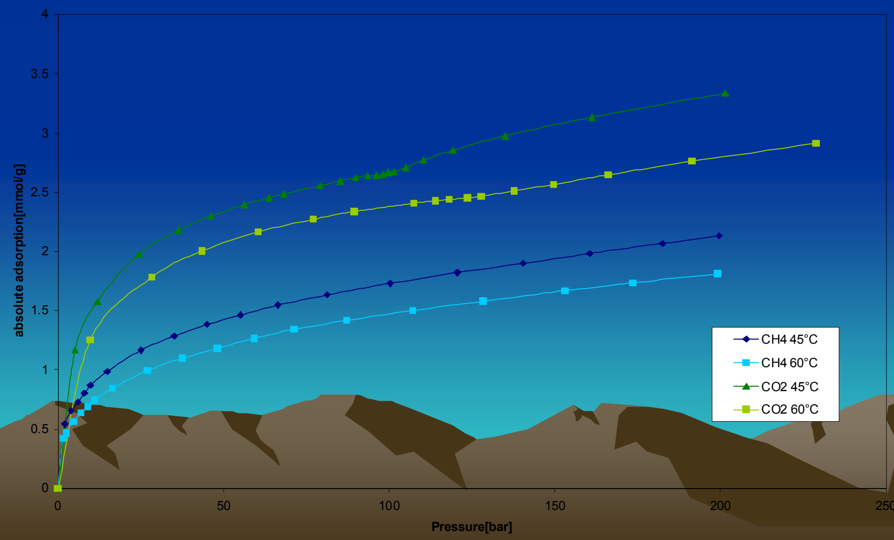
Sulcis (Sardinia, Italy)

dry coal, T=45°C

Sulcis Adsorption new experimental data

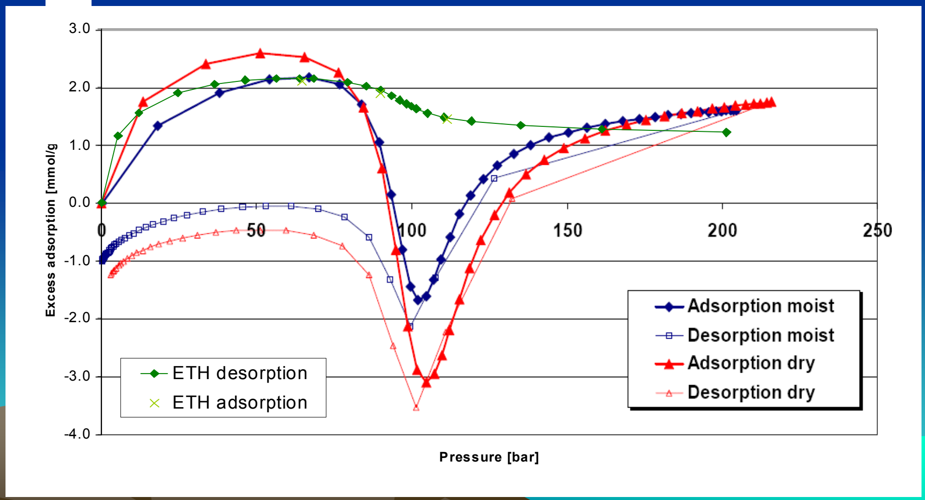
Adsorption experimental results on Sulcis coal powdered at 0.25-0.35 mm, regarding: (a-f) the absorption equilibria by using CO2. (g-m) the absorption equilibria by using CH4. (n-r) the comparison between CO2 and CH4 in the Sulcis coal. (s-t) comparison between the Sulcis coal with respect the RECOPOL Project (Upper Silesian Basin, Poland) coal. Different isotherms at T = 44.9-59.9 oC have been drawn. Mass or Volume units are used: [ccSTP(gas)/g(coal)] is the commercially used. 1 m3 CO2 = 0.121 tonns at supercritical conditions (P = 80 bar) while- 1 m3 CO2 = 1.75 x 10-3 tonns (P = 1 bar).More favourable conditions seems for the Sulcis coal with respect to the Upper Silesian Basin one, as regards the Sulcis coal capacity to adsorb CH4 (and therefore to expect a better GIP situation in situ at depth).

Absolute Isotherms (versus pressure): comparison CO_2-CH_4



Comparison with the literature – CO_2

CO_2 excess adsorption: ETH (dry, SULCIS) – Krooss et al. 2003 (dry+ moist,RECOPOL) T=45°C

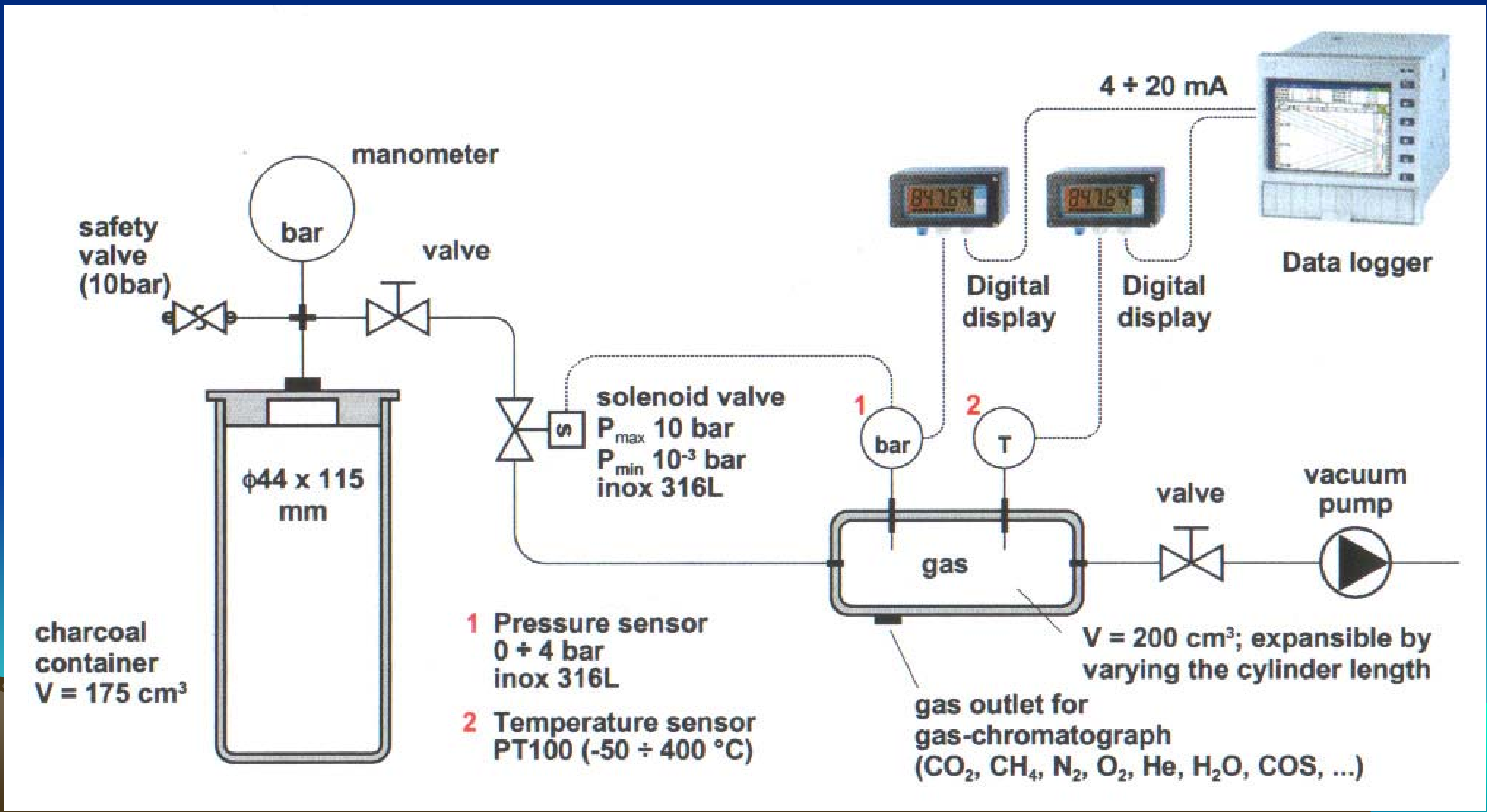


Desorption experiment ongoing (INGV)

• **DESORPTION INVESTIGATIONS** (USBM direct method): the real Gas in Place (GIP) evaluation. The desorbed gas follows a diffusion equation.

• **GIP COMPOSITION** by gas chromatography: GIP is not only CH_4 but also CO_2 (1-3%) and N_2 (0.5-3%) the presence of any N_2 or CO_2 reduce the CH_4 gas content relative to the value of pure CH_4. The total gas content is reduced when nitrogen is present and increased when carbon dioxide is present.

• **GIP VOLUME**: expected maximum around 20 cc/g of coal.

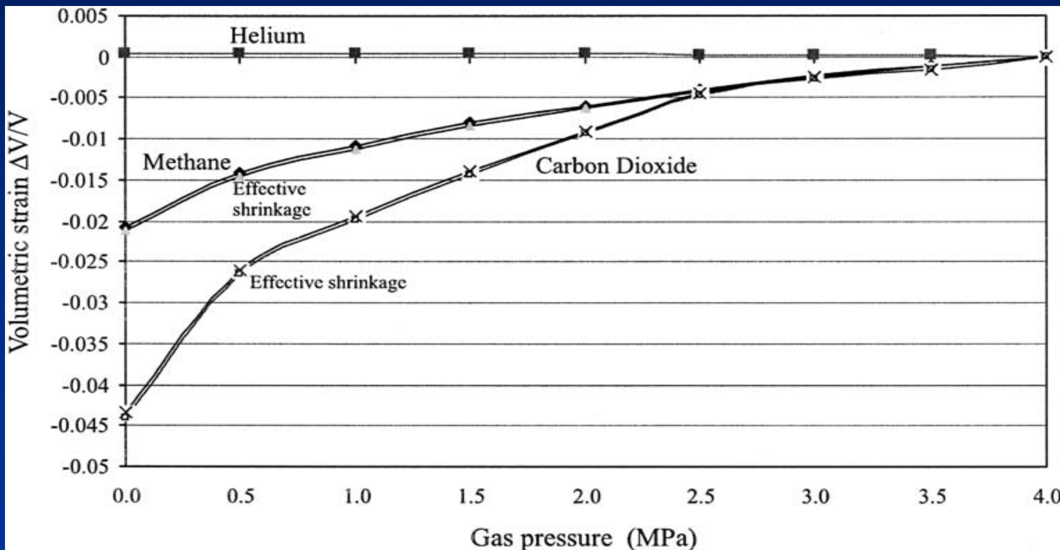


CO_2-ECBM in Sulcis as a whole

- reservoir screening criteria (IEA)
  - Reservoir homogeneity ☺ ?
  - Minimal presence of faults and folds 😐 ?
  - Range of depths (800 – 1500 m) ☺ ?
  - Coal bed condensed geometry ☺ ?
  - Sound permeability ☺ ?
  - Coal composition (macerals, rank, ash) ☺ ?
  - "Miliolitico" groundwater composition ☺ ?
  - **GIP (Gas in Place) and its saturation** 😐 ?
  - **Moisture content** ☹ ?

GIP formula (Laenen & Hildenbrand, 2005) = f (T, P, Ro, U_{tot}%, buried history)

Future work: study of coal swelling behavior



South Island coal (New Zealand)

George & Barakat (2001)

Change in volume of the adsorbent (coal) due to the sorption of the adsorbing gas.

- Swelling by adsorption
- Shrinkage by desorption

Volumetric change affects:

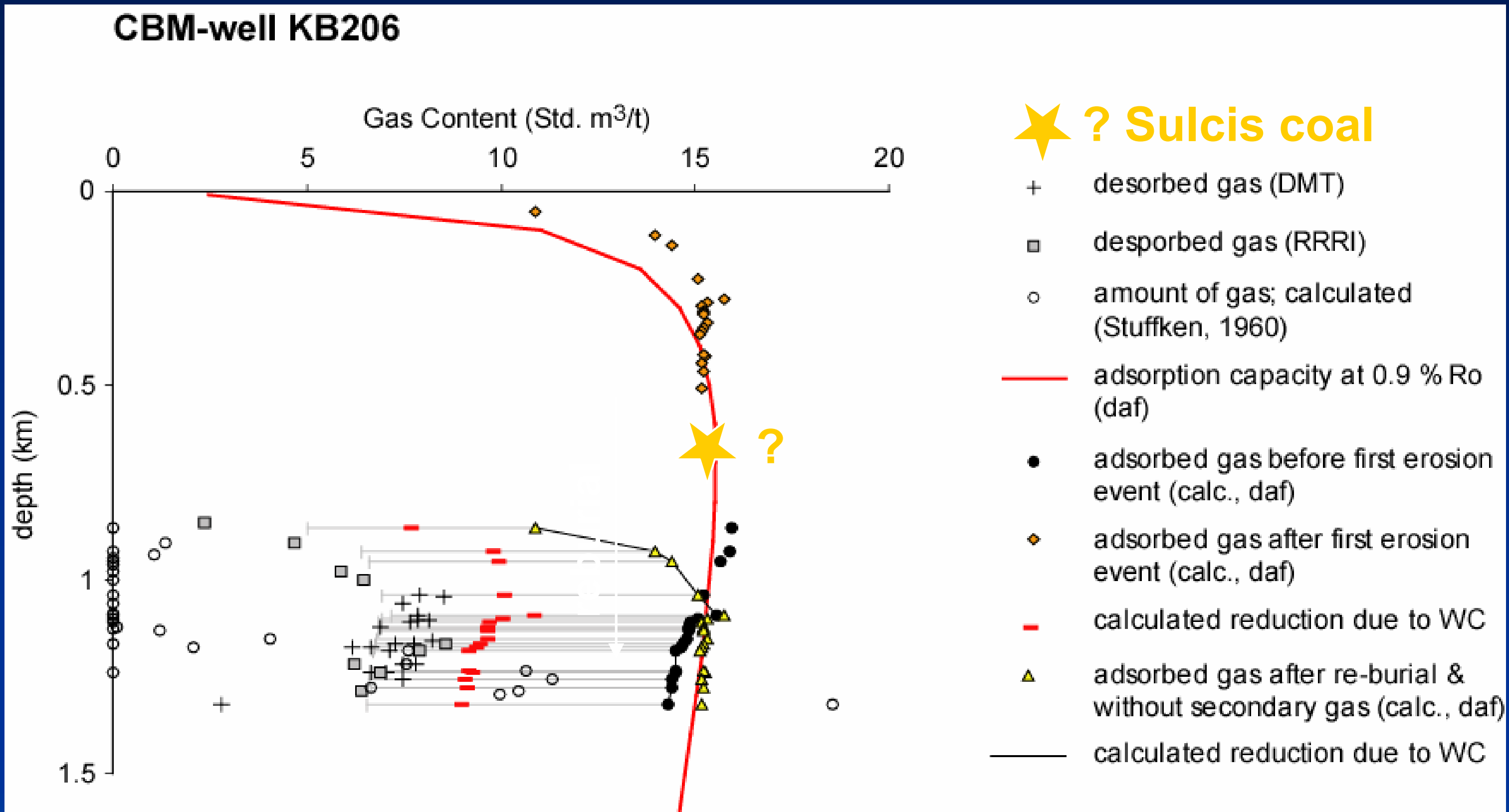
✱ permeability to gases

✱ mechanical properties

➔ *direct measurements of the volume swelling are required*

Future work GIP for CBM at wells

(i.e., KB206, Campine Basin)



water content 55 %

- **High GIP (Gas in Place): around 20 m^3/tonn or cm^3/g (620 Scf/tonn);**
- **Very promising GIP: 6.3 – 29.2 m^3/tonn (202-935 Scf/tonn);**
- **Promising GIP: 1.5-12.48 m^3/tonn (50-400 Scf/tonn);**
- **i.e., San Juan Basin GIP: 0.28 x 10^{12} m^3/year, 1.4 total (Fruitland Formation);**

…A good gas well is usually a good water well, but a good water well is not necessarily a good gas well… **(Groshong et al., 2005, case of Black Warrior Basin, Alabama, USA).**

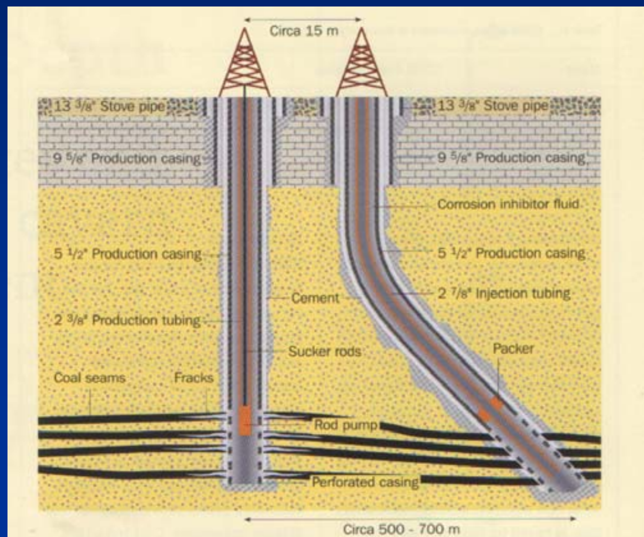
	Onshore	Offshore	Total
Estimated PG by CBM (MMCM)	6687	4566	11253
Estimated PG by ECBM (MMCM)	12037	8219	20256
CO_2 Storage Capacity under ECBM (MMT)	42	29	71
CO_2 Storage Capacity beyond ECBM (MMT)	110,1	83,5	193,6

CBM and ECBM reserves (Producible Gas = PG) and CO_2 storage capacity in Sulcis. MMCM = Millions of Cubic Meters, MMT = Millions tonns. See the formulas below for the calculations.

Preliminary conclusions on CBM-ECBM in Sulcis coal Province

STEPS: Dewatering→CBM→ECBM→Saline Aquifer CO_2 storage

+



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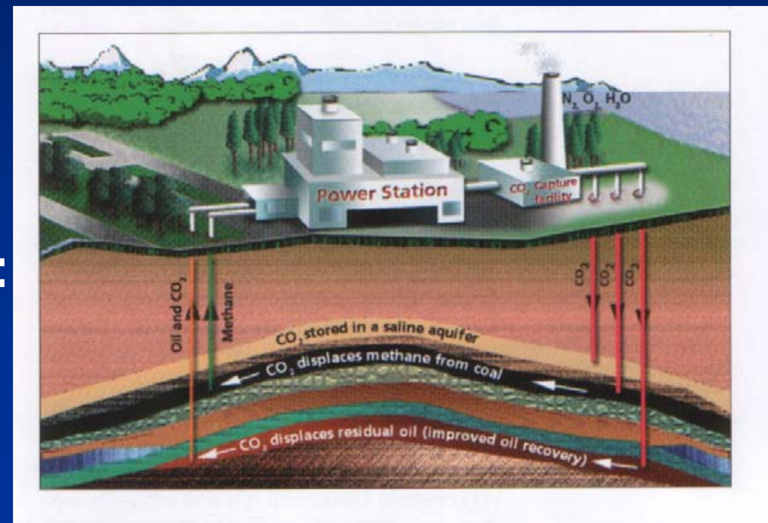
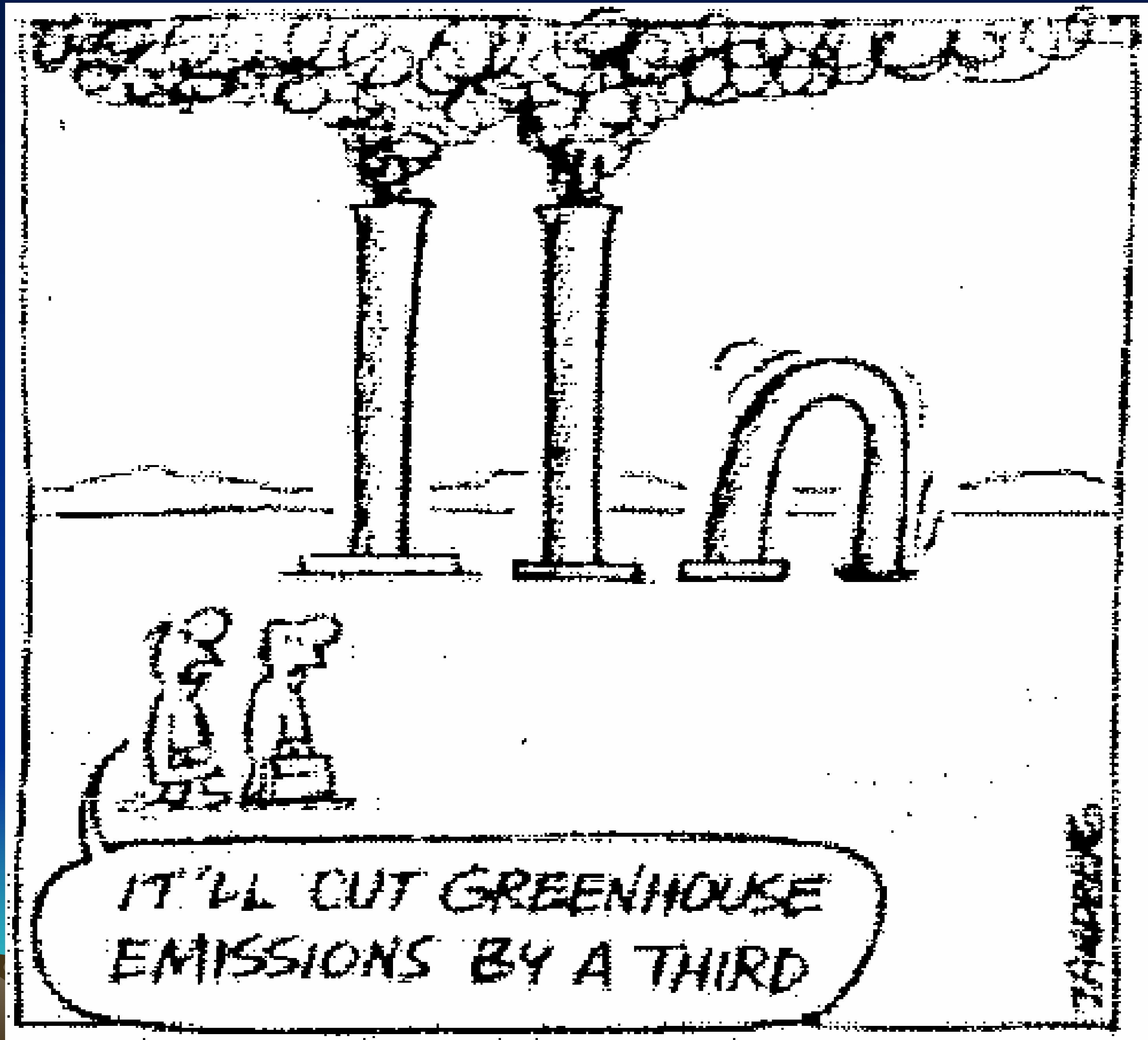


The forecasting for ECBM exploitation is relatively encouraging

Injected gas: pure CO_2 (tank)→ENEL SU3 true flue gas (CO_2, N_2, etc...)→post-combustion captured CO_2→Oxyfuel pre-combustion & CO_2


IT'LL CUT GREENHOUSE EMISSIONS BY A THIRD

APPENDIX

Differences between CBM reservoir and Natural Gas conventional reservoir

- CBM = an unconventional gas reservoir
- Natural Gas Reservoir: conventional sandstone and limestone reservoirs store compressed gas in porosity systems; CH_4 is encountered either in free-gas phase and dissolved in fluids.
- A gas reservoir could have a production rate of 10^6 m^3/day of CH_4 while an ECBM production field could arrive at 5000 m^3/day of CH_4.
- In CBM reservoir, CH_4 is stored in coal by adsorption, a process by which the individual gas molecules are bound by weak electrical forces to the solid organic molecules.
- In CBM reservoirs, the ability to store methane largely reduces the need for conventional reservoir trapping mechanism.
- In CBM reservoirs the storing ability gives coals unique early-time production behavior that is related to desorption and not to pressure depletion.
- As with all conventional gas reservoir, the permeability controls production and largely dictates the amount of gas reserves in coal seams;

Coal classification adopted for CBM (I)

Coals can be systematically described and classified according to three compositional criteria:

- grade: relative proportion of organic matter vs. inorganic constituents;

- type: represents different classes or categories of organic constituents;

- rank: represents the level of physico-chemical alteration of coal composition and structure occurring during coalification not divided by sharp thresholds; it consist of DIAGENESIS 1) peatification, 2) dehydration, CATAGENESIS 3) bituminisation, 4) debituminization; METAGENESIS 5) graphitization. These process may allow distinguish: peat, lignite-sub-bituminous coal, high volatile bituminous coal, medium-low volatile bituminous and anthracite (ASTM, 1991, D-388, Tissot & Welte, 1984).

The rank assume concrete meaning only when measured in terms of a "rank parameter", which might be any one of a variety of physical and chemical properties that change with coalification such as:

- fixed carbon yield;

- vitrinite reflectance;

- heating value;

Coal classification adopted for CBM (II)

Although vitrinite reflectance is now the most widely used parameter that is applicable to all coals, there is no single coal rank parameter that is applicable to all coals or is free of complications relating to type and grade. Hood (1975) proposed the rank scale termed *Level of Organic metamorphism (LOM)* arisen by the evidence that no property universally applicable as a rank parameter. ASTM, 1991, D-388 has various deficiencies e.g. the lack of applicability to inertite-rich coals and its reliance solely on rank for classification (new proposed ICCS = International Coal Classification System, Alpern, 1989).

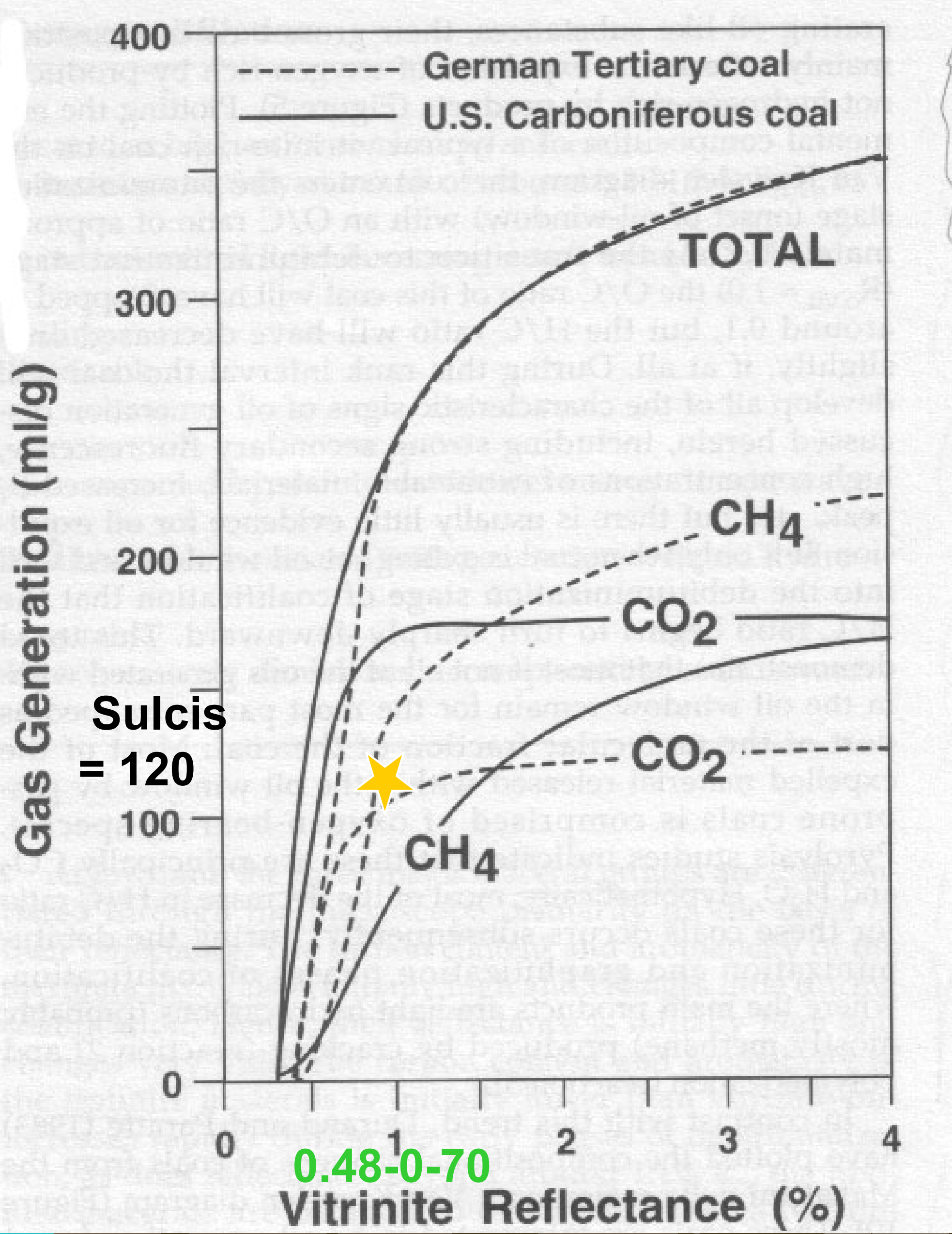
H/C & O/C ratios/sorption capability (Van Krevelen diagram): H/C and O/C are lowering during coalification through the expulsion of low molecular weight hydrocarbons such as methane. During this "*de-bituminization*" process, which continues through medium-low volatile-bituminous ranks, all previous evidence for *bituminisation* begins to reverse (fluorescence properties disappear, molecular concentrations and mean molecular weight of molecular constituents of the coal decrease and, eventually, the molecular structure "reopens" with associated increase in sorbate accessibility).

Most coal properties pass through maximum or minimum values during the transition from *bituminisation* to *de-bituminization.*

Coal classification adopted for CBM (III)

- The CBM problem/techniques include a) a modern view of coalification that incorporates the two-components model (matrix/molecular fraction); b) tracing the compositional evolution of coal during coalification, especially as it relates to the generation of oil and gas; c) discussion of the geologic context in which these changes occur, including peat formation, burial history and tectonic history.
- The two component model: has been proposed in various forms since the turn of the century but has only recently gained wide popularity and acceptance as a consequence of its strength in the utility in reconciling compositional parameters with observed coal behavior. Virtually every measurable property of coal can be interpreted (or reinterpreted) in light of this model, including gas sorption capacity, diffusion rate, optical properties, liquefaction behavior and coking characteristics.
- CH_4: gas of small size, non-polar character, low polarizability, free to enter and exit from the coal structure, even in water-saturated coal; weak but significant attractive forces between methane and other coal constituents giving rise to very high concentrations of methane in some coals at moderate reservoir pressures ("equivalent methane porosity" can approach to 100%).

GIP from rank data

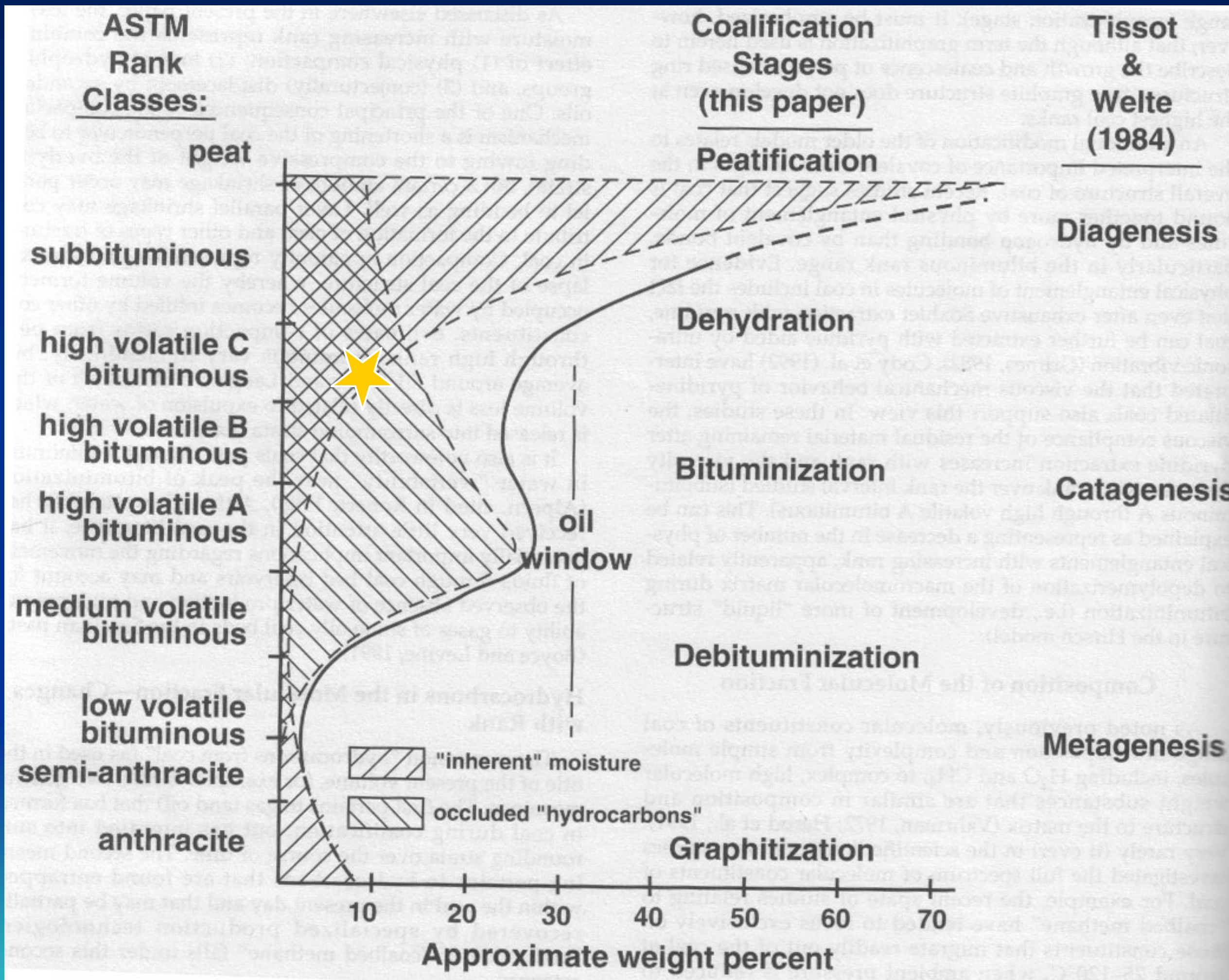


An estimate of the Gas in Place (GIP) as a funtion of rank (vitrinite reflectance coefficient, Ro %, is 0.48-0.70 for the Sulcis coal), on the basis of "Pirolysis Analysis" used to determine the remaining gas potential and the "pyrolysate" composition during the rank increasing (after Higgs, 1986).

During the coalification up to the anthracite rank, a coal of "Carboniferous sub-hydrous" will generate a maximum of 150 mL/g CH_4 while a "Tertiary per-hydrous" coal (as Sulcis) will generate maximum 200 ml/g CH_4 (at 1 bar). The total gas generation amount, including CO_2, is the same for the two coals.

Sulcis coal

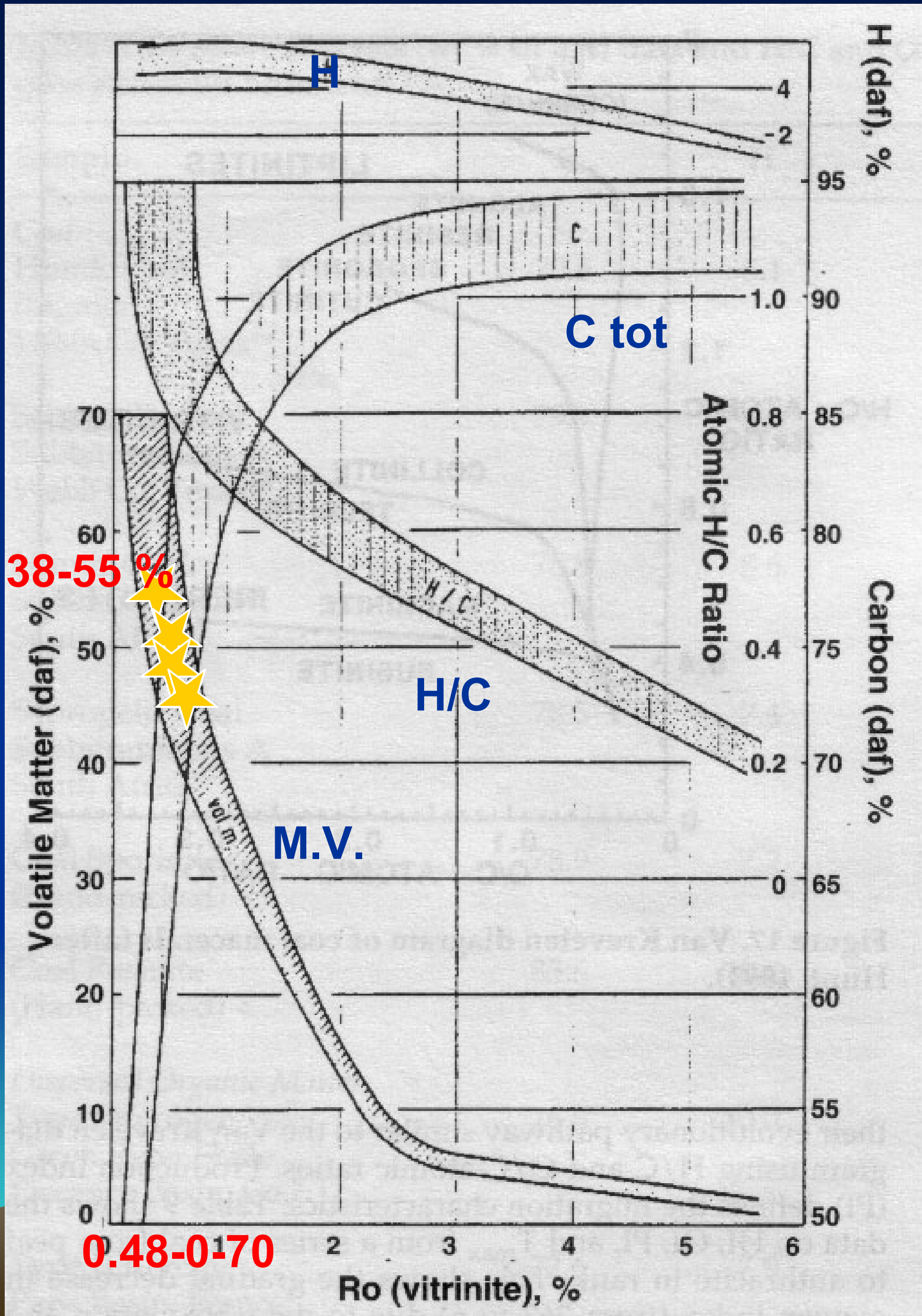
Dependance of CBM potential: moisture - rank – hydrocarbons



Evolution of the Molecolar Fraction composition of a typical coal vitrinite rich as Sulcis (75-85% vitrinite, 11 % exinite, 3-7% inertite, 4-18 % liptinite 11% Mineral Matter) during the coalification. Water dominate a low rank and an high rank, while the intermediate rank is dominated by hydrocarbons comprising oil and asphalts (Levine, 1992). At highst rank the free hydrocarbons are not more present but water appears newly.

★ Sulcis coal

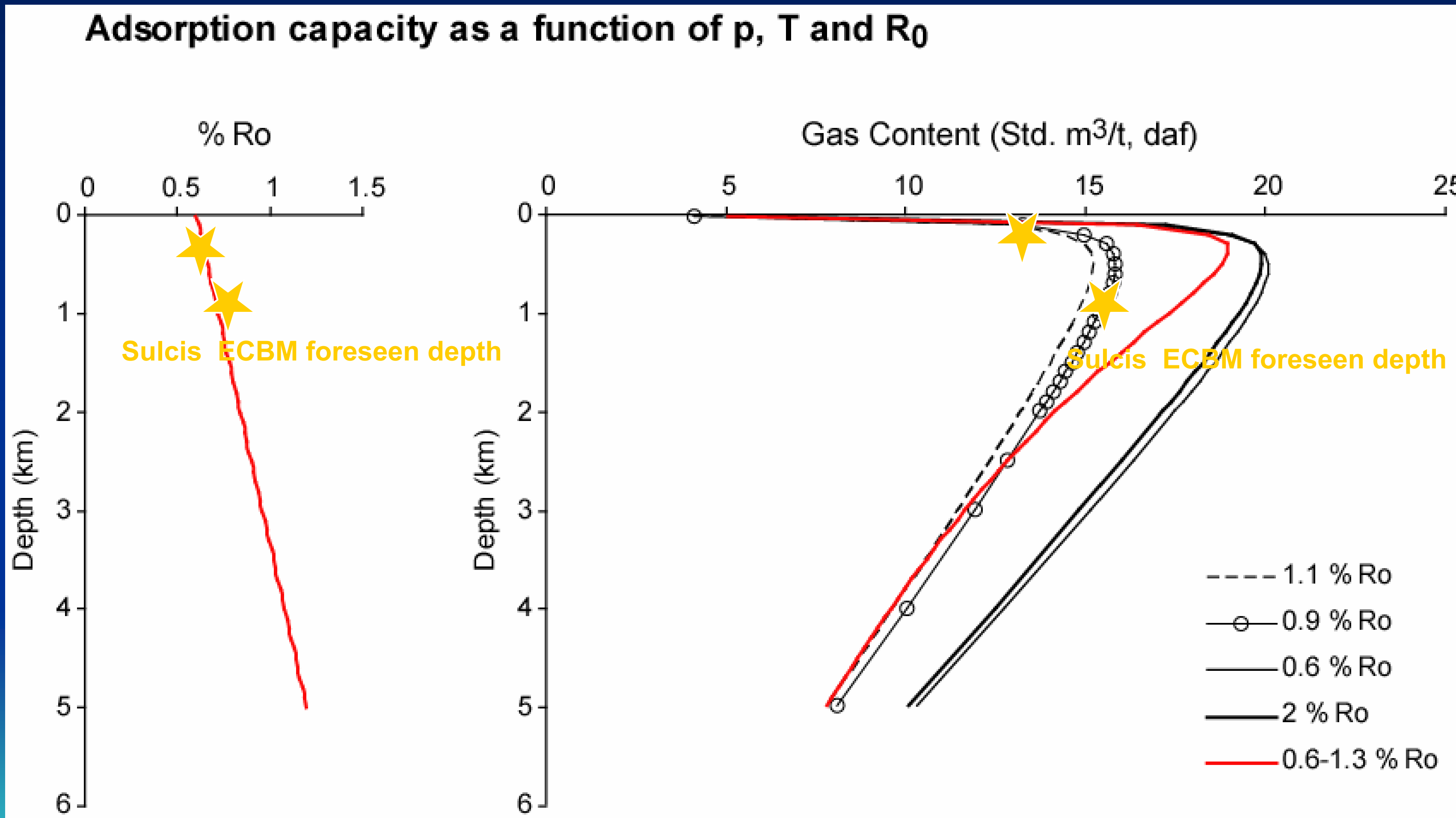
CBM potential dependence from H/C ratio & Volatile Matter



The graph shows the relationship between % of vitrinite reflectance, Ro and the other rank parameters (% V.M., C_{tot}, H/C, Hyrogen on dry basis, mineral-matter free).

For the CBM and ECBM potential estimate, apart the rank, the composition is important: among the "macerals" the inertite undergoes to de-volatilization and aromatization well before of the maturative history of coal with respect to the vitrinite macerals (Sulcis, 75-85 %).

GIP dependance from depth abd rank

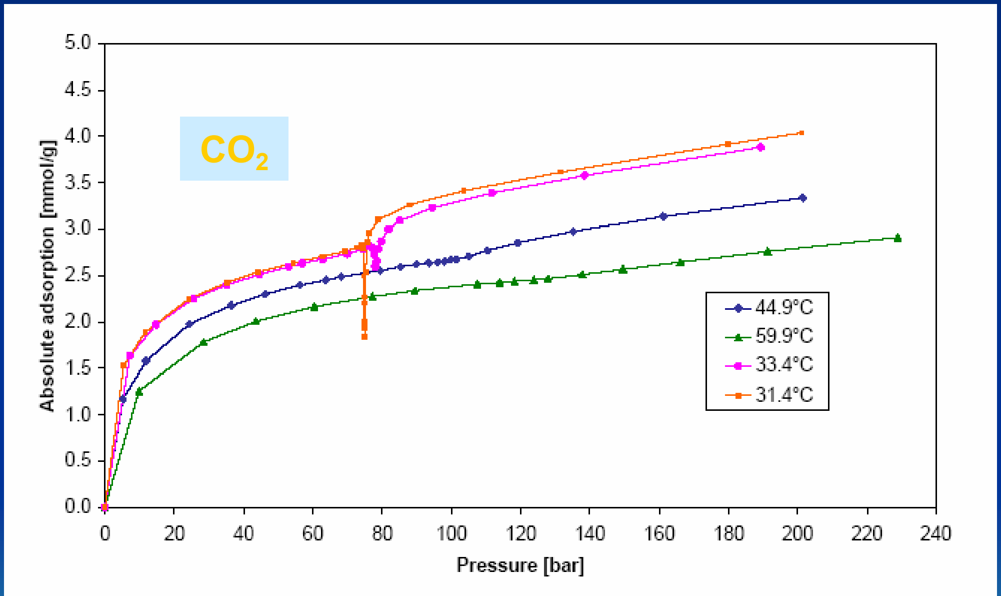


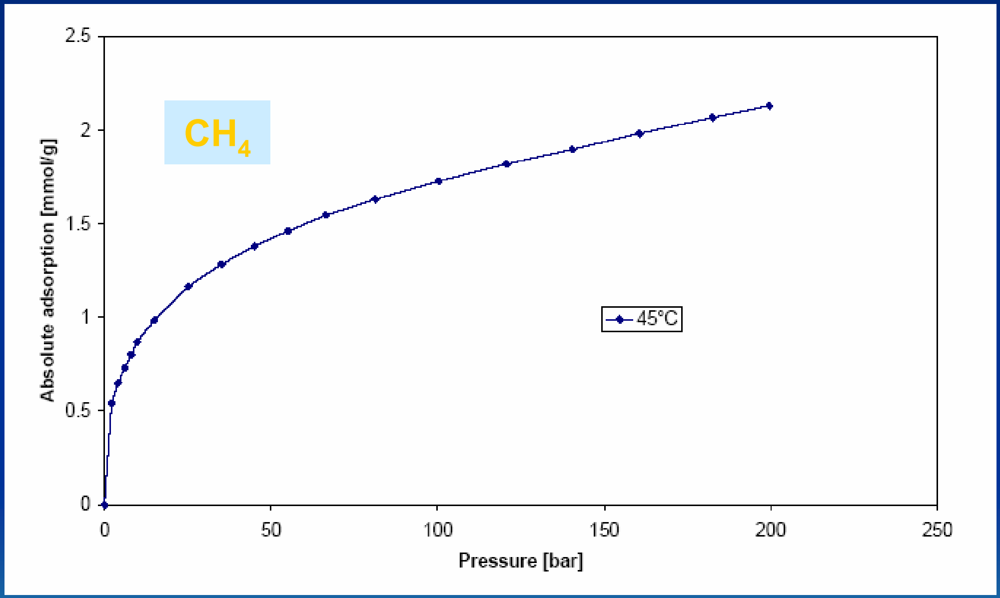
Adsorption data of Arets et al. 1962

Sulcis Adsorption new experimental data

CO_2 and CH_4 absolute adsorption isotherms on dry coal

Constant density method: $\rho^i_{ads}=\rho^i_{liq}$ at boiling temperature.





ρ_{ads}= 1.277 g/cm^3

ρ_{ads}= 0.422 g/cm^3

GIS on MapInfo ECBM Sulcis (INGV-IES S.r.l.)

GIS on MapInfo ECBM Sulcis (INGV-IES S.r.l.)

GIS on MapInfo ECBM Sulcis (INGV-IES S.r.l.)

Session 2

Monitoring Requirements

Australian Government

Department of the Environment and Heritage
Australian Greenhouse Office

CCS monitoring needs: Australian regulatory viewpoint

Kate Roggeveen

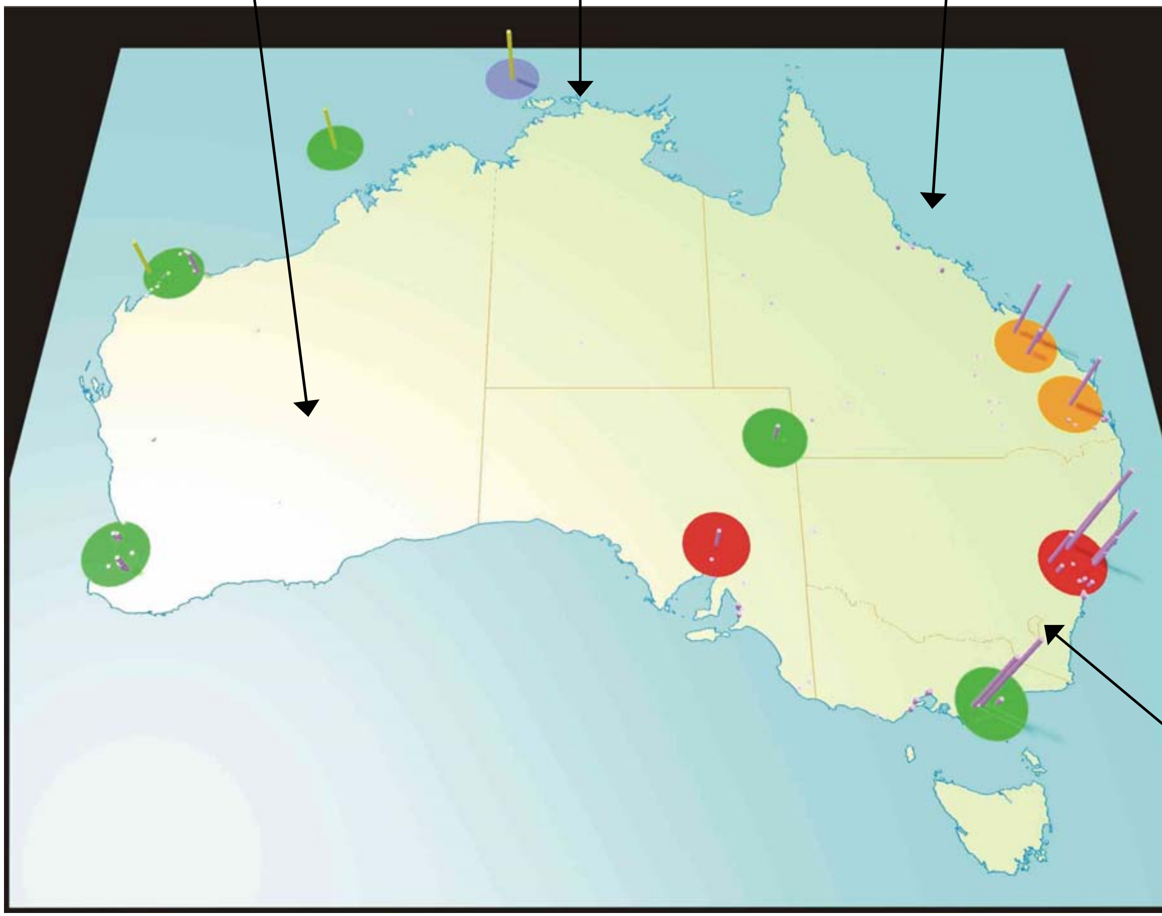
Federal System

Commonwealth, States &Territories

Onshore (mainly State/Territory; some Commonwealth)

State/Territory waters <3nm (coastal zone)

Commonwealth waters (generally) 3nm-end EEZ/Continental shelf



Distance from viable geological storage sites

- 0 to 100 km
- 100 - 300 km
- 300 - 500 km
- > 500 km
- Stationary sources
- Unproduced high CO_2 fields

Some relevant laws:

Petroleum Submerged Land Acts;

Environment Protection and Biodiversity Conservation Act (Comm.) incl. matters of national environmental. significance)

Canberra

Sourced from: Bradshaw and others, 2002

Context

- Refining broad criteria for a monitoring and verification regime
- Complex area – many questions
- Integral to any CCS project
- Critical for transparency

Key Terms

CCS	CO_2 capture, transport and *geological* storage
Monitoring	measuring and reporting CO_2 behaviour
Verification	establishing whether CO_2 is behaving as predicted/within accepted boundaries

CCS Regulatory Setting

Whole of Government and intergovernmental

Issues include:

- CO_2 emission abatement
- health, safety and environment
- economically efficient deployment

Partnerships with industry

Public accountability and confidence

CCS Policy Setting

- Action now to prepare economy and society for the future
- Strong and dynamic economy while reducing greenhouse signature in the long term
- Climate Change Strategy - May 2004 Budget
- Energy White Paper - June 2004

M&V: Australian Government Principles

'…clear, comprehensive, timely, accurate and publicly accessible information … to … manage environmental, health, safety and economic risks.'

'… framework … quantity, composition and location of gas captured, transported, injected and stored … net abatement of emissions … identification and accounting of leakage.'

Verification Regime

Element 1
Allocating Responsibilities

Element 2
Validating Baseline Modeling

Element 3
Defining Suitable Monitoring System

Element 4
Certification of Performance against Standards

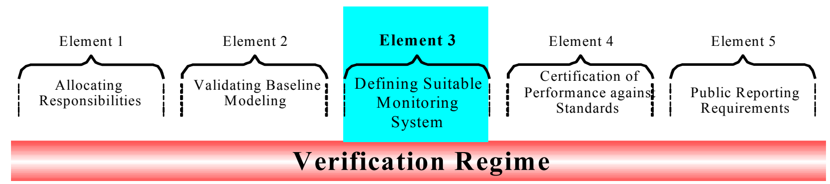
Element 5
Public Reporting Requirements

Verification Regime

Defining Suitable Monitoring System

Data that will allow for:

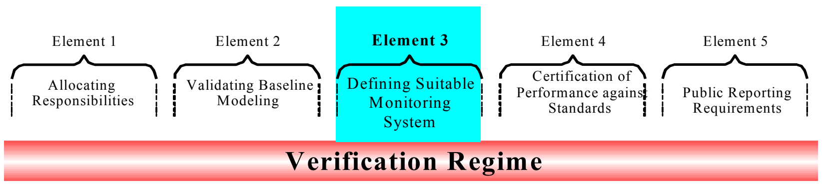
- determination of whether behaving as predicted
- compliance/compatibility with standards
- flexibility
- best practice and continuous improvement



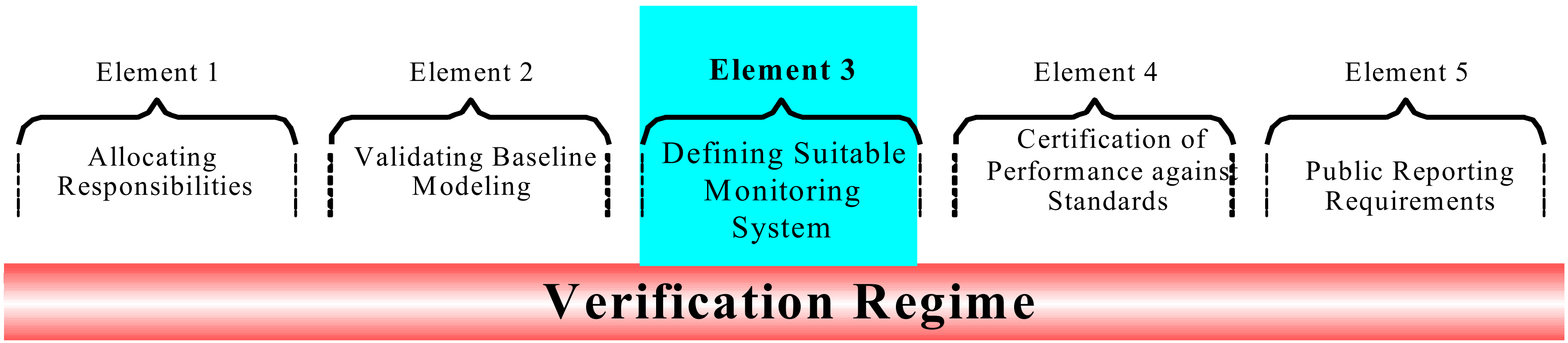
Defining Suitable Monitoring System

Near- and long-term technologies

M&V research priority on storage phase



Verification Regime



Other Questions

- Who owns the CO_2?
- How much verification is needed?
- How accurate should verification be?
- Will site specific monitoring regimes be necessary?
- Is the level of certainty enough for inventory requirements?
- Would the level of regulation differ over time?

Conclusion

- Trying to design a system to manage risks we're not 100% sure about
- Urgency to bring these two parts together
  - For efficient and effective regulation
- Flexible and strong m&v regime needed for confidence in CCS

EU ETS* and UK Regulatory Issues

Tim Dixon DTI

*Paul Zakkour ERM

Overview

- **Considering CCS in the EU ETS**
- **Recommendations**
- **Storage regulatory issues**
- **UK regulation of storage – gap analysis**

CCS in the EU ETS: Why?

- **UK policy to encourage use of market-based mechanisms to reduce GHG emissions**
- **UK recognises value of CCS for GHG reduction**
- **EU ETS – World's first large scale GHG emissions trading system, started Jan 05, 12000 installations, 25 countries, 6 sectors**

CCS in the EU ETS: Why?

- **Current costs for CCS high: >20 Euros/tonne CO_2 abated (Current EUA price ~ 15 Euros/t CO_2)**
- **Integrating *carbon value* will greatly improve overall CCS economics**
- **Narrow window of opportunity in North Sea for EOR: next 10 years or so..**
- ***What's needed? Evolution of credible fiscal and regulatory framework, including*:**
  - development of robust installation level Monitoring & Reporting (M&R) guidelines for CCS operations in EU ETS

Background to development of M&R guidelines

- **Decision C(2004)130 [*M&R Guidelines]* invites:**
  - *"MS interested in the development [of M&R guidelines for CCS] to submit research findings to the Commission"*
  - *"MS may submit interim guidelines….subject to approval"*
- **UK DTI response: form *ad hoc* group of EU experts to develop M&R guidelines:**
  - ERM, DNV, SGS, TNO
  - BGS, GEUS, BRGM
  - BP, Statoil, Shell
  - Norwegian Govn, UK DTI, UK Defra, EC DG Env and DG Res
  - IEA GHG
  - Alstom
- Commissioned ERM and DNV for study

Background to development of M&R guidelines

- Need to maintain integrity of overall EU ETS cap, otherwise; simply export CO_2 from installation then vent from a pipeline or storage site
- Need more robust framework than current CO_2 ‘transfer’ arrangements in Decision C(2004)130
- **Note: focus is on “installations” as defined in EU ETS**

Considerations for CCS in the EU ETS

- **Fugitive emissions: can occur across whole CCS chain (capture, transport, injection)**
- **Indirect emissions: additional power requirements for capture, transportation, injection (energy penalty, booster stations etc.)**
- **Seepage from storage reservoirs: Short and long term seepage issues to consider**
- **Responsibility for measurement: Potentially number of different operators across chain**
- **Verification requirements: what data? from who?**
- **Timeframes: Annual versus geological**

Conclusion

- **Reconcile fugitive emissions back to installation up to point of injection**
- **Storage – different regulatory regime**

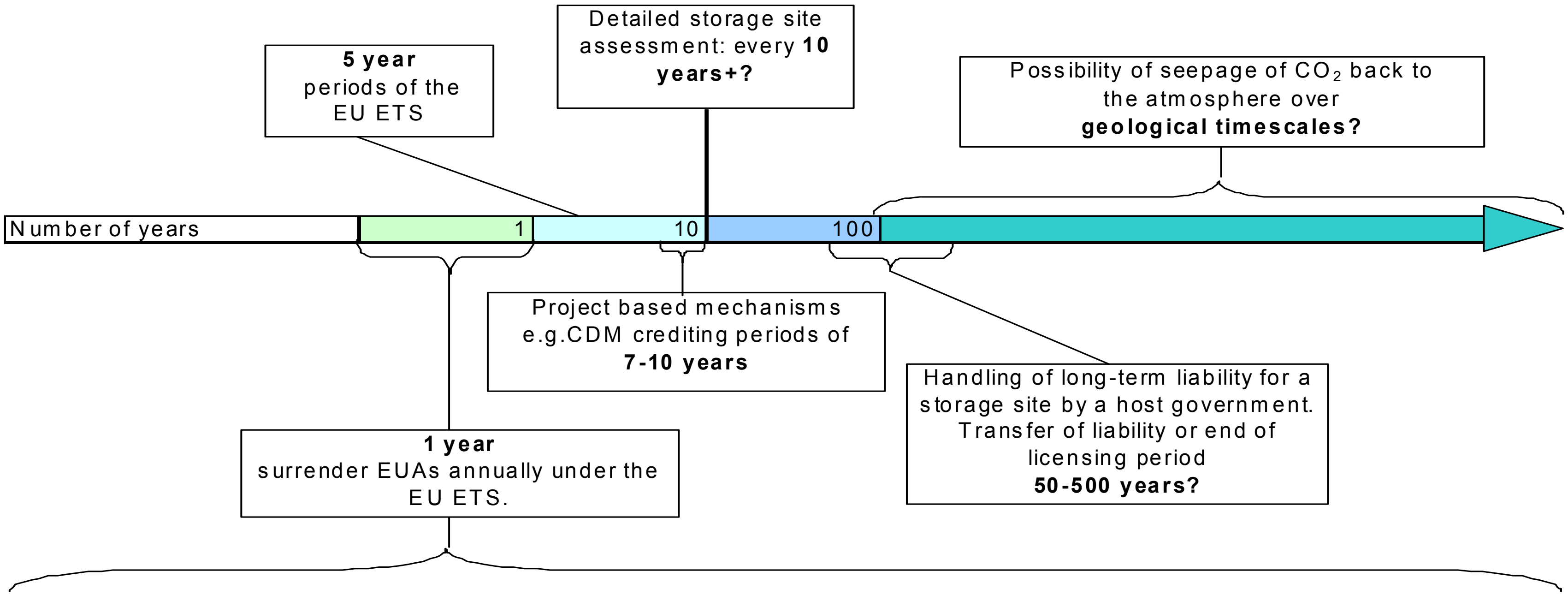
Fugitive emissions

- **<u>Calculate</u> CO_2 emissions using approved M&R plan for installation, based on primary fuel input to operations**
- **<u>Measure</u> (metering to custody transfer standard):**
  - exports of CO_2 to pipeline
  - imports of CO_2 to injection facility
- **<u>Reconcile</u>: estimate fugitive losses across the chain using a *mass balance* calculation**
- **Medium-term goal: to develop *emissions factors* for CO2 pipelines – will improve accuracy**

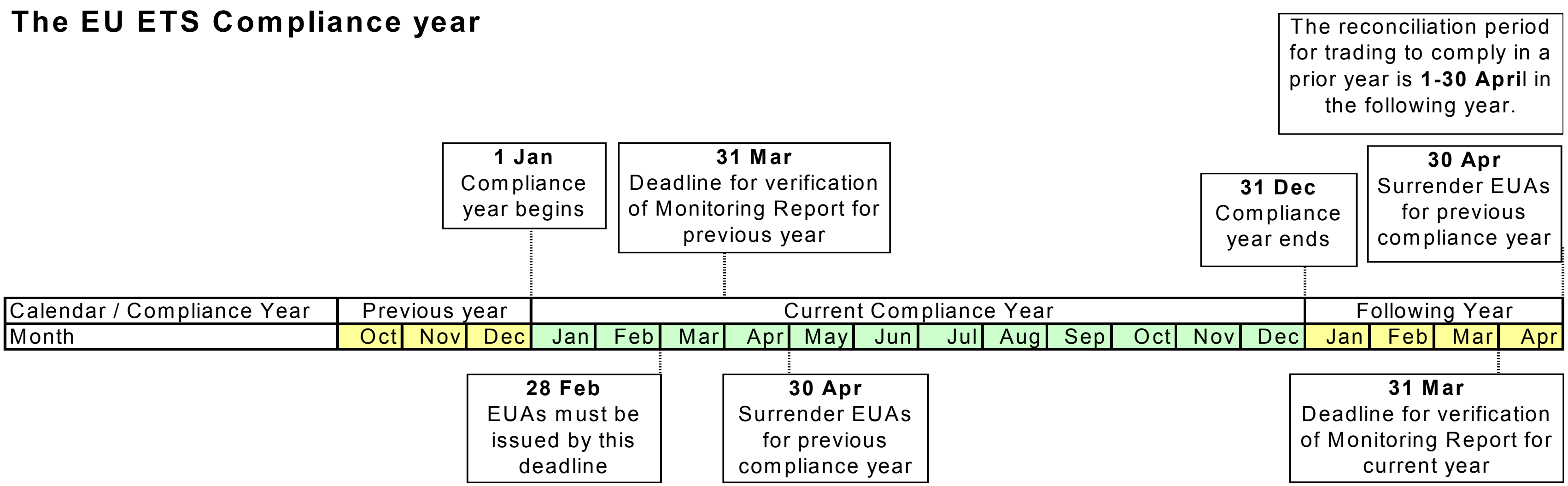
Indirect emissions

- **Energy penalty for capture: accounted for by calculating CO_2 produced at installation using primary fuel inputs**
  - Can use existing guidelines (Decision C(2004)130) for all “installations” covered by scheme
- **Booster stations:**
  - >20MW thermal input = installation in its own right
  - <20MW thermal input = outside scope of EU ETS
- **Need to avoid *double accounting* in electrically powered booster stations, thus not included**

Milestones in a CCS project



The EU ETS Compliance year



Seepage from storage sites (1)

- **Range of literature looking at *ex ante* methods to account for possible future seepage:**
  - Discounting of emissions (like DCF)
  - Default factors
  - Temporary crediting (like for LULUCF)
- **Creates a number of problems:**
  - Assume storage site *will* leak
  - That the timeframe and flux rate can be determined *ex ante*
  - Discount factor could be so small to = <1 EUA / yr etc.

Seepage from storage sites (2)

- **Thus, need to exclude any storage site seepage from an exporting installations' inventory**
- **But need to maintain integrity of emissions cap in the EU ETS cap and trade regime**
- **Therefore, propose an alternative approach to *ex ante* methods**
- **Alternative approach dependent on the development of *coherent and robust storage site permitting/licensing regime***

Seepage from storage sites (3)

- **Licensing requirements for storage sites:**
  - Operator due diligence – operator shows all available evidence suggests a good storage site
  - Emergency plan to control any short-term seepage
  - Commitment to monitor, quantify and report any seepage
  - Include seepage emissions in National Inventory
  - Time limiting license (TLL) and subject to review based on storage performance
  - Operator required to purchase EUAs = to any seepage; could make this over 5 or 10 year period and align to EU ETS periods and TLL

Seepage from storage sites (4)

- **Operator could manage this risk by:**
  - Ensuring contract with installation requires installation operator to set-aside some EUAs until license renewal
  - Buy EUAs out of the MS NER surplus left over at the end of the EU ETS Period
  - Buy EUAs during first year of next EU ETS Period
  - A combination of the above
- **Benefits:**
  - Removes uncertainty over *ex ante* methods
  - Aligns with EU ETS Periods
  - Maintains integrity of EU ETS overall cap

Responsibilities and Verification

- **Need to introduce specific requirements to publicly report data at various points across CCS chain**
- **Verifiers: will need to collate disparate data in order to complete verification**
- **Storage site licensing: verifier will require Installation operators to provide evidence that CO_2 exported to a licensed storage site**

Conclusions, challenges & next steps

- **Conclusions:**
  - Separate regulatory regimes for ETS and storage
  - Reconcile fugitive emissions back to installation up to injection
- **Implementation and next steps:**
  - DG Env considering proposals: like approach, looking for ways to consider the licensing issues
  - Need to consider breakthough CO_2 in EOR
  - Issues to be resolved regarding CCS in project-based mechanisms

UK Regulation of Carbon Dioxide Storage in Geological Structures

Offshore - who covers

- **DTI Licensing and Consents Unit**
  - Regulates all oil and gas activities onshore and offshore - Petroleum Act 1998
  - Offshore Pollution Prevention and Control
- **DEFRA MC&EU (with DTI LCU & FRS/SE)**
  - Licence for deposits in sea and seabed – FEPA 1985 Pt II Deposits in the sea
- **Crown Estate** – marine estate - owns territorial waters and rights to exploit natural resources (not fossil) on UKCS (inc seabed)
- **Health and Safety Executive**

Existing regulation relevant to long-term liability

Petroleum Act 1998, includes:-

- Abandonment of offshore installations (Ch17 Part IV)
  - **requires approved plans to decommission old installations offshore (inc under seabed)**
  - (also onshore version, with Local Authorities control)
- Guidance Notes on Decommissioning of Offshore Installations and Pipelines and subsea equipment
  - **liability remains with owner in perpetuity**
- Decommissioned oil and gas reservoirs revert to state (DTI LCU)

Existing regulation relevant to long term liability

FEPA

- Covers construction
- Covers injection except direct land-sub-seabed
- Does not cover long term storage

Conclusions on gap analysis for regulation of offshore storage

Long term liability split:

- Subsea equipment, boreholes etc to owners for perpetuity
- for EOR - oil and gas reservoirs to state (DTI)
- for storage in saline aquifers - to state ? (Crown Estate / DTI ?) – need regulatory regime

caveat: indicative only - not legally agreed or tested

Next Steps:- Carbon Abatement Technologies Strategy

- "Lead in preparing the national and international regulatory frameworks.."
- "Establishment of a working group of regulatory agencies…to examine how to develop any additional systems"
- "Develop a route map.."
  - Regulation – Detail of needs, actions, and who

EPA Efforts and Regulatory Overview

Monitoring Network Meeting
Rome, Italy
October 4-6, 2005

Anhar Karimjee
EPA's Office of Air and Radiation

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Presentation Outline

- **Background on EPA Efforts**
- **Summary of the minimum *Federal* requirements within the UIC program (State programs may differ)**
- **Overview of reservoir modeling in EPA's "no migration" petition demonstrations**
- **CO_2 Sequestration Considerations**

EPA Geologic Sequestration Workgroup

- **Collaborative effort led by Office of Air and Office of Water**
- **Internal EPA Workgroup includes ~30 members from several Offices plus EPA Regions and Labs**
- **Efforts focus on technical & regulatory issues, risk assessment, communication & outreach**

Key Technical Issues for Workgroup

1. **Site Selection Criteria**
2. **Injection Well Construction & Integrity of Pre-Existing Wells**
3. **Ability to Demonstrate Reservoir Capacity & Integrity**
4. **Monitoring Techniques/Approaches**
5. **Remediation Options**
6. **Site Closure and Plugging & Abandonment Practices**

EPA Technical Workshops

- **Geologic Modeling and Reservoir Simulation**
  - April 6-7, 2005 in Houston, TX
  - Assess modeling capabilities for site characterization, risk assessment, and simulating long-term storage
- **IPCC Inventory Guidelines & US GHG Inventory Methods**
  - March 9, 2005 in Washington, DC (IPCC Guidelines)
  - September 27, 2005 in Portland, OR (EOR/US Inventory)
  - Encourage active participation and expert input in development of IPCC Guidelines and improving US Inventory
- **Risk Assessment & Management**
  - September 28-29, 2005 in Portland, OR
  - Share information and solicit expert input from a wide range of stakeholders including researchers, industry, NGOs, and regulators.

US Federal Programs

- **National Environmental Policy Act (NEPA)**
  - **Requires federal agencies to consider the environmental impacts of their proposed actions and reasonable alternatives to those actions**
  - **A detailed Environmental Impact Statement (EIS) is prepared to meet this requirement**
  - **EPA reviews, comments on, and maintains a national filing system for EISs: www.epa.gov/compliance/basics/nepa.html**

- **Current Efforts**
  - **The EIS will be made available for public comment and DOE will host public meetings: www.netl.doe.gov/coal/Carbon%20Sequestration/eis/**
  - **EPA encourages stakeholders to participate in this process**

Ocean Programs

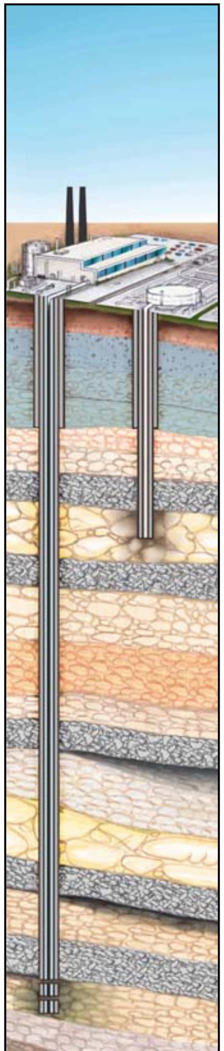
- **London Convention (LC)**
  - **Covers deliberate disposal of wastes at sea**
    - **Prohibits disposal of certain hazardous materials**
    - **Requires a permit for disposal other wastes or matter**
  - **Oil and Gas (including Sleipner and EOR) operations are** exempt
  - **LC Implemented through Marine Protection, Research, and Sanctuaries Act (overseen by EPA)**
- **Current Efforts**
  - **LC is evaluating technical and legal aspects of sub-sea bed disposal of CO_2**
  - **Scientific Group concluded that CCS is an important technology and risks can be low if projects are properly sited and managed**
  - **Legal issues will be discussed at the Consultative Meeting Oct. '05**
  - **A technical working group will meet in April '06 to review the IPCC Special Report and discuss risk assessment**

US Drinking Water Program

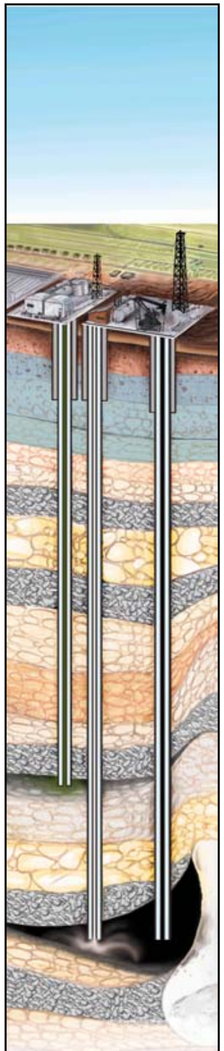
- **Safe Drinking Water Act (SDWA)**
  - **Underground Injection Control (UIC) Program regulates injection of fluids – liquid, gas or slurry**
  - **Program covers injection of wastes and commodities (e.g. liquid hydrocarbons, drinking water)**
  - **Only exemption is for <u>gaseous</u> *hydrocarbon* storage and hydraulic fracturing using certain fluids**
  - **Provides an existing framework for CCS**
- **Current Efforts**
  - **EPA is evaluating technical issues and applicability of SDWA and UIC regulations**
  - **An experimental well category has been used for temporary R&D projects (non-EOR) such as Frio Brine - these Class V wells can be permitted on a case-by-case basis**
  - **EOR wells are covered by Class II**

UIC Program Well Classes

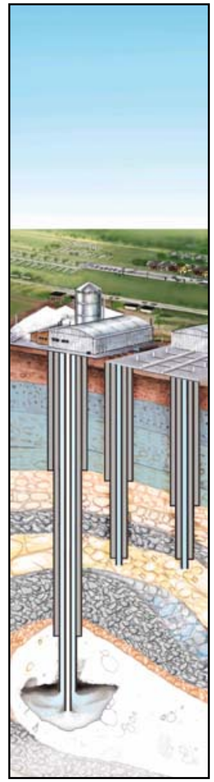
Class I



Class II



Class III



Class V

Class IV: Prohibited

Well Class and Description

- All UIC wells have specific minimum *Federal* regulatory requirements outlined in 40 CFR Part 146
- Class II (40 CFR Part 146, Subpart C)
  - Wells used to manage fluids from oil and gas production and may be commingled with non-haz waste waters from gas plants
  - Enhanced recovery of oil or gas (EOR)
  - Storage of liquid hydrocarbons

Well Class and Description

- Class III (40 CFR Part 146, Subpart D)
  - Wells associated with mineral recovery
- Class IV (40 CFR Part 146, Subpart E)
  - Wells injecting hazardous waste in USDWs
  - Prohibited
- Class V (40 CFR Part 146, Subpart F)
  - Wells not included in Class I, II, III, or IV
    - Includes injection wells used in experimental technologies

Well Class and Description

- Class I (40 CFR Part 146, Subparts B & G)
  - Wells used to manage hazardous waste
  - Industrial and municipal disposal wells
  - Wells used to dispose of radioactive waste
- Class I <u>non-hazardous</u> wells have different requirements than Class I <u>hazardous</u> wells
  - For example, hazardous waste deep wells have the following requirements:
    - Siting, expanded area of review (AOR), corrective action, construction, logging/sampling/testing prior to new well operation, operating, testing and monitoring, reporting, closure, post-closure, and financial responsibility requirements

Dually Regulated Class I Wells

- Class 1 restricted hazardous waste disposal wells
  - Dually regulated by SDWA and RCRA
- 40 CFR Part 146 Subpart G
  - SDWA
  - Hazardous wastestream
  - UIC Permit
- 40 CFR Part 148
  - RCRA
  - *Restricted* hazardous wastestream
  - No Migration Petition

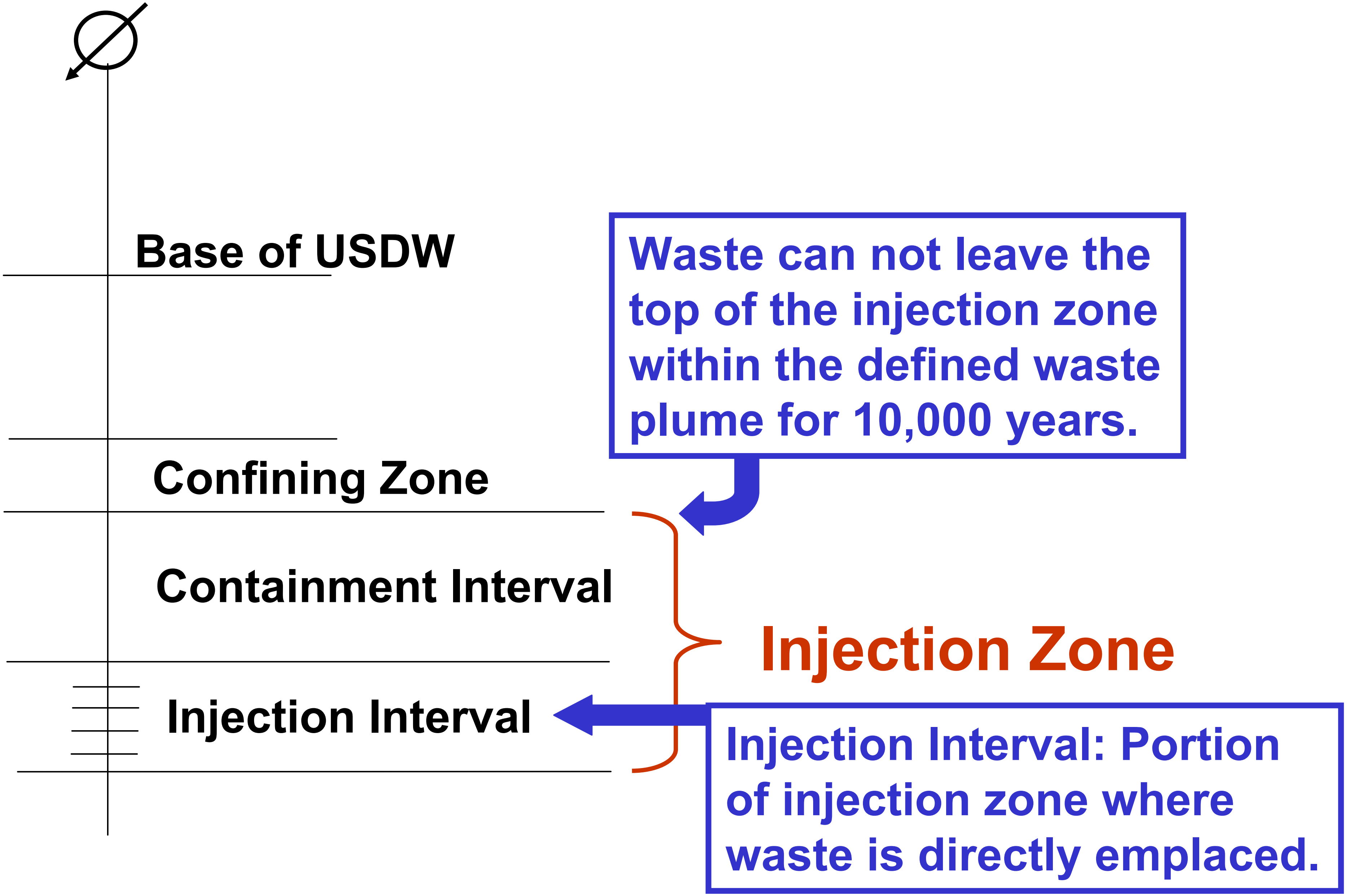
No Migration Petitions

- **Regulations define the type of demonstration needed for approval**
  - **Geology**
  - **Modeling**
  - **Area of Review**
  - **Monitoring**
- **Petitions are a costly and time consuming process**

No Migration Petitions

- Disposal of restricted hazardous waste
  - Requires an exemption to the land disposal restrictions from EPA
- 40 CFR Part 148
  - Waste can not leave the defined Injection Zone
  - Requires determination of maximum vertical movement through:
    - Containment interval
    - Geologic structures
    - Improperly plugged wells
  - Timeframe defined as 10,000 years or until waste is no longer hazardous

No Migration Petition Definitions



No Migration Petition Geology

- Each demonstration is site specific
- Geologic study areas
  - Regional
  - Local
- Structure and Isopach Maps
  - Injection Interval
  - Injection Zone
- Cross-sections
- Containment and Confining Zones

No Migration Petition Modeling

- **Models are used to bound the limits of the waste plume:**
  - **Maximum pressure buildup from disposal operations**
  - **Maximum horizontal and vertical extent of waste plume at the end of the 10,000 year containment period**

No Migration Petition Modeling

- **Types of Models Used**
  - **Numerical (Finite Difference)**
  - **Analytical**
- **Model complexity driven by the geology and no migration demonstration request**

Pressure Buildup (PBU) Demonstration

- **Predicts the maximum pressure from disposal operations**
  - **Use of a conservative transmissibility (kh/💻) maximizes the PBU in the reservoir**
  - **Historical and annual falloff test data verifies the validity of the PBU demonstration**
  - **Maximum PBU considered in abandoned well evaluations**

10,000 Year Horizontal Waste Plume

- **Delineated by the concentration reduction factor (CRF)**
  - **Concentration at which the waste is safe to human health and the environment**
- **Bounds the location of the waste plume**
  - **Easier than predicting exact plume location**
  - **Uses a conservative mobility (k/💻) and net thickness (h)**

10,000 Year Vertical Demonstration

- **Advective movement through intact strata**
  - **Typically calculated analytically**
- **Molecular diffusion**
  - **Intact strata**
  - **Artificial penetration**
  - **Typically calculated analytically**
- **Maximum vertical movement of fluid (advective + diffusion) must be contained within the defined Injection Zone**

Typical Modeling Assumptions

- Horizontal and vertical waste plume demonstrations do not consider degradation of the waste
  - ChemFate demonstration always an option
- Single phase model
  - Similar characteristics between the injectate and formation fluid
  - Correlations used for PVT data
- Single layer model used to determine horizontal plume movement
  - No vertical permeation allowed to maximize horizontal movement

AOR (Parts 146 & 148)

- Define a cone of influence (146 & 148)
  - Confirm each well within the defined pressure is plugged or constructed to prevent the movement of waste from the injection zone
- Review map of the waste plume (148)
  - Confirm no geologic features exist that allow any vertical movement of waste
  - Identify all wells located within the bounded plume
    - Confirm each well prevents migration of waste

Annual Monitoring (Part 146)

- **Mechanical integrity tests (MIT)**
  - **Annulus pressure test**
    - **Ensures the integrity of the packer along with the tubing and casing located above the packer**
  - **Radioactive tracer**
    - **Evaluates the bottomhole cement**
    - **Ensures waste is emplaced into injection interval**
  - **Falloff tests**
    - **Measures the pressure buildup in the reservoir**
    - **Evaluates the completion condition of the well**

Additional Monitoring (Part 146)

- 5 year monitoring
  - Temperature surveys
- Casing inspection logs
  - Following workover or at Director discretion
- Continuous operational monitoring
  - Annulus pressure
  - Injection pressure
  - Injection rate
  - Injection volume
  - Wastestream temperature

CO_2 Sequestration Issues

- **Does it fall under UIC regulations?**
  - EOR regulated as UIC Class II injection well
  - Texas permitted a Class V well (experimental technology) for a CO_2 demonstration project
- **How will the CO_2 plume be delineated?**
- **Are there concerns after CO_2 is introduced to the formation?**
  - Formation of carbonic acid

CO_2 Sequestration Issues

- **What constitutes "adequate" for CO_2 sequestration?**
  - **Timeframe**
  - **Shallowest depth CO_2 is allowed to migrate**
    - **Ensure protection of USDW**
    - **Minimize or eliminate leakage to the atmosphere**
  - **Area of review**
    - **Is a fixed ¼ mile radius sufficient due to buoyancy and higher mobility of CO_2?**

What Level of Detail is Needed?

- Type of model?
  – Multilayer
  – Multiphase
- How much field data is needed?
  – Cores and logs of confining and injection intervals
  – Relative permeability curves
  – PVT and geochemistry data

CO_2 Sequestration Issues

- Can a reasonable time, effort, and cost be associated with modeling CO_2 sequestration?
  - Are the time and costs associated with modeling CO_2 higher or lower than modeling a restricted hazardous waste?
- Can the costs associated with acquiring the model input data be reduced?
- Purity of CO_2 injected
  - What other constituents?
  - Does it make sense to purify prior to injection?

CO_2 Sequestration Issues

- **Can assumptions be used to reduce costs associated with modeling CO_2 sequestration?**
  - **Will approximation of input data reduce the credibility of the model prediction?**
  - **Is bounding the movement of the CO_2 plume sufficient?**
    - **Are reservoir storage costs an issue?**
    - **Will CO_2 recovery ever occur?**

CO_2 Sequestration Issues

- **Need to consolidate existing CO_2 data from the oil and gas industry**
  - **Operational concerns**
    - **Corrosion**
  - **CO_2 breakouts**
  - **Abandoned wells**
  - **Modeling**
  - **Other problems associated with the handling and injection of CO_2**

Don't reinvent the wheel!

Petition Modeling vs. CO_2 Sequestration

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

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

Conclusions

- Monitoring should be based on site specific technical considerations.
- "No migration" approach may not be entirely applicable, but does provide a useful analogue.
- Focusing efforts on site characterization/selection and modeling may help target and reduce monitoring burden.
- Level of monitoring necessary to protect human health and the environment may be different than monitoring needed for GHG accounting.
- Simple risk assessment tools and practical monitoring programs will help reduce the burden on project operators and regulatory agencies.

Contact Information

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Session 3

Monitoring Programmes

Session 3

Monitoring Programmes
-Experience from Ongoing Projects

Update on the Frio Brine Pilot: One year after injection

Susan D. Hovorka
Bureau of Economic Geology
Jackson School Of Geosciences
The University of Texas at Austin

Karen Cohen
DOE NETL Project Manager

Frio Brine Pilot Research Team

- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, 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
- Schlumberger: T. S. Ramakrishna, Nadja Mueller, Austin Boyd, Mike Wilt
- Oak Ridge National Lab: Dave Cole, Tommy Phelps, David Riestberg
- 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
- SEQUIRE – 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 Thorsen
- Praxair: Joe Shine, Dan Dalton
- Australian CO2CRC (CSIRO): Kevin Dodds, Don Sherlock
- Core Labs: Paul Martin and others

Frio Experiment: Monitoring CO_2 Storage in Brine-Bearing Formations

Project Goal: Early success in a high-permeability, high-volume sandstone representative of a broad area that is an ultimate target for large-volume sequestration.

- **Demonstrate that CO_2 can be injected into a brine formation without adverse health, safety, or environmental effects**
- **Determine the subsurface distribution of injected CO_2 using diverse monitoring technologies***
- **Demonstrate validity of conceptual and numerical models**
- **Develop experience necessary for success of large-scale CO_2 injection experiments**

* Well beyond regulatory requirements

Frio Experiment: Status of Results

1600 metric tons CO_2 was introduced into well-characterized relatively homogenous high permeability sandstone system characteristic of the Gulf Coast region of the US and monitored before, during, and after injection

- **Vigorous public/industry outreach - favorable response**

- **Saturation and transport properties measured horizontally, vertically, and through time using multiple tools**

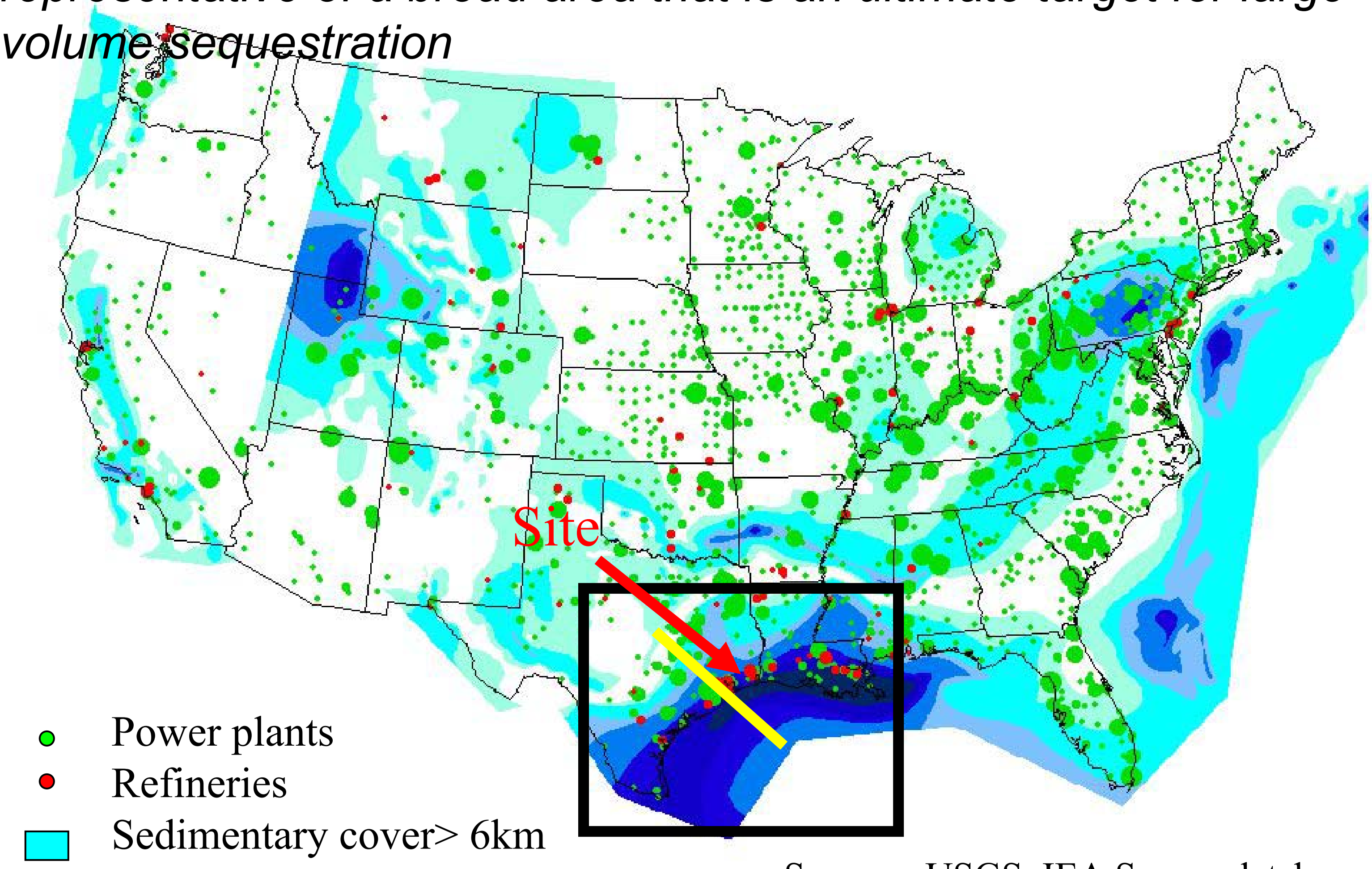
- **Improved model conceptual and numerical inputs**

- **Make results available to field projects planned by Regional Sequestration Partnerships and to Carbon Sequestration Leadership Forum projects**

- **Frio 2 Kick off October 1, 2005**

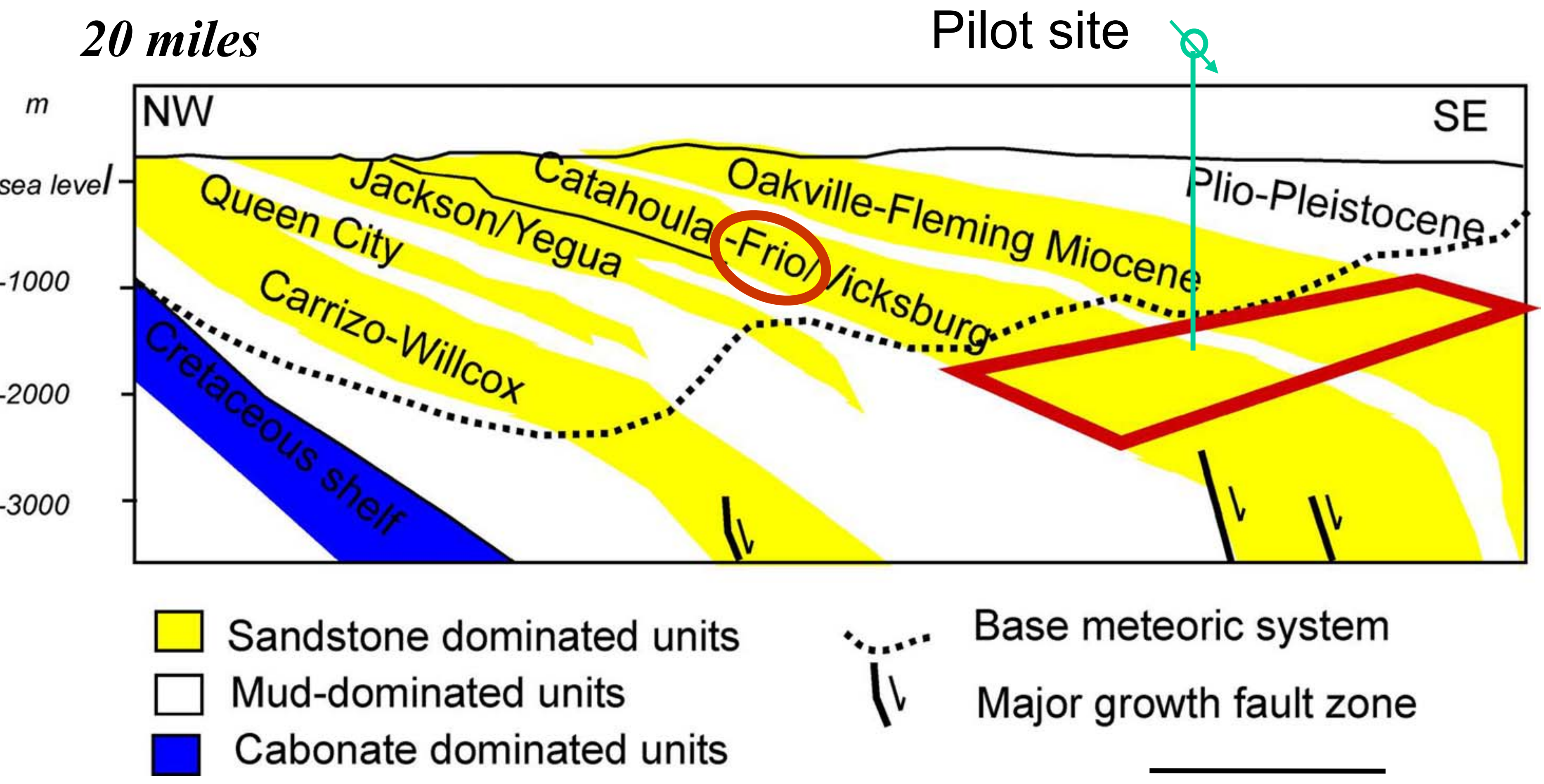
Site Search

Locating a high-permeability, high-volume sandstone representative of a broad area that is an ultimate target for large-volume sequestration



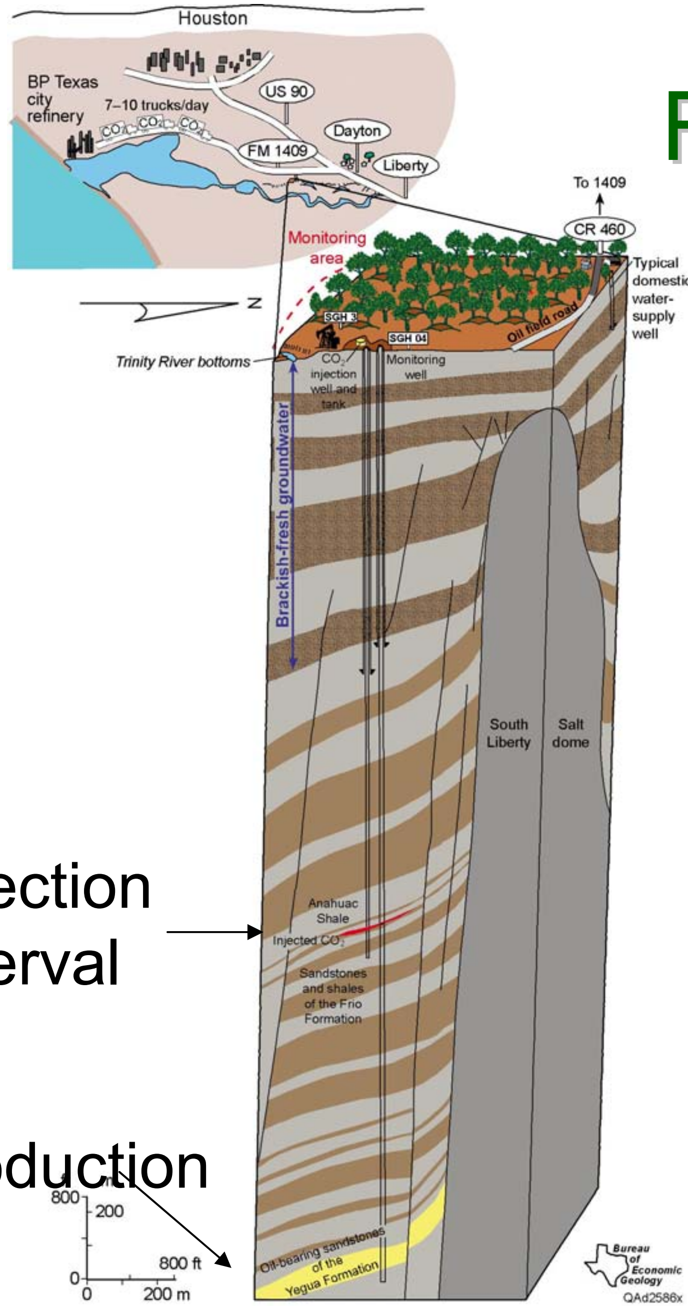
Sources: USGS, IEA Source database

Regional Geologic Setting – Cross Section



Modified from Galloway and others, 1982

Frio Brine Pilot Site



Injection interval

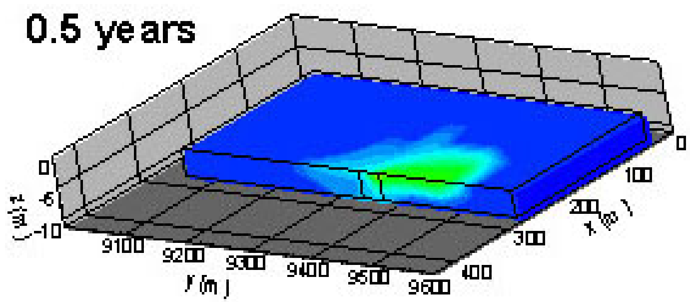
Oil production

- Injection interval: 24-m-thick, mineralogically complex Oligocene reworked fluvial sandstone, porosity 24%, Permeability 2.5 Darcys
- Steeply dipping 18 degrees
- 7m perforated zone
- Seals – numerous thick shales, small fault block
- Depth 1,500 m
- Brine-rock system, no hydrocarbons
- 150 bar, 53 degrees C, supercritical CO_2

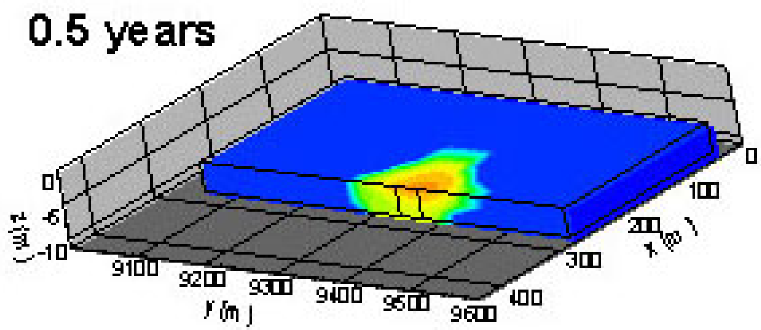
*The purpose of monitoring was to match observed to modeled performance

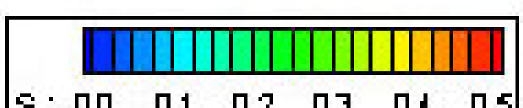
How Modeling and Monitoring* Demonstrate Permanence

Residual gas saturation of 5%



Residual gas saturation of 30%





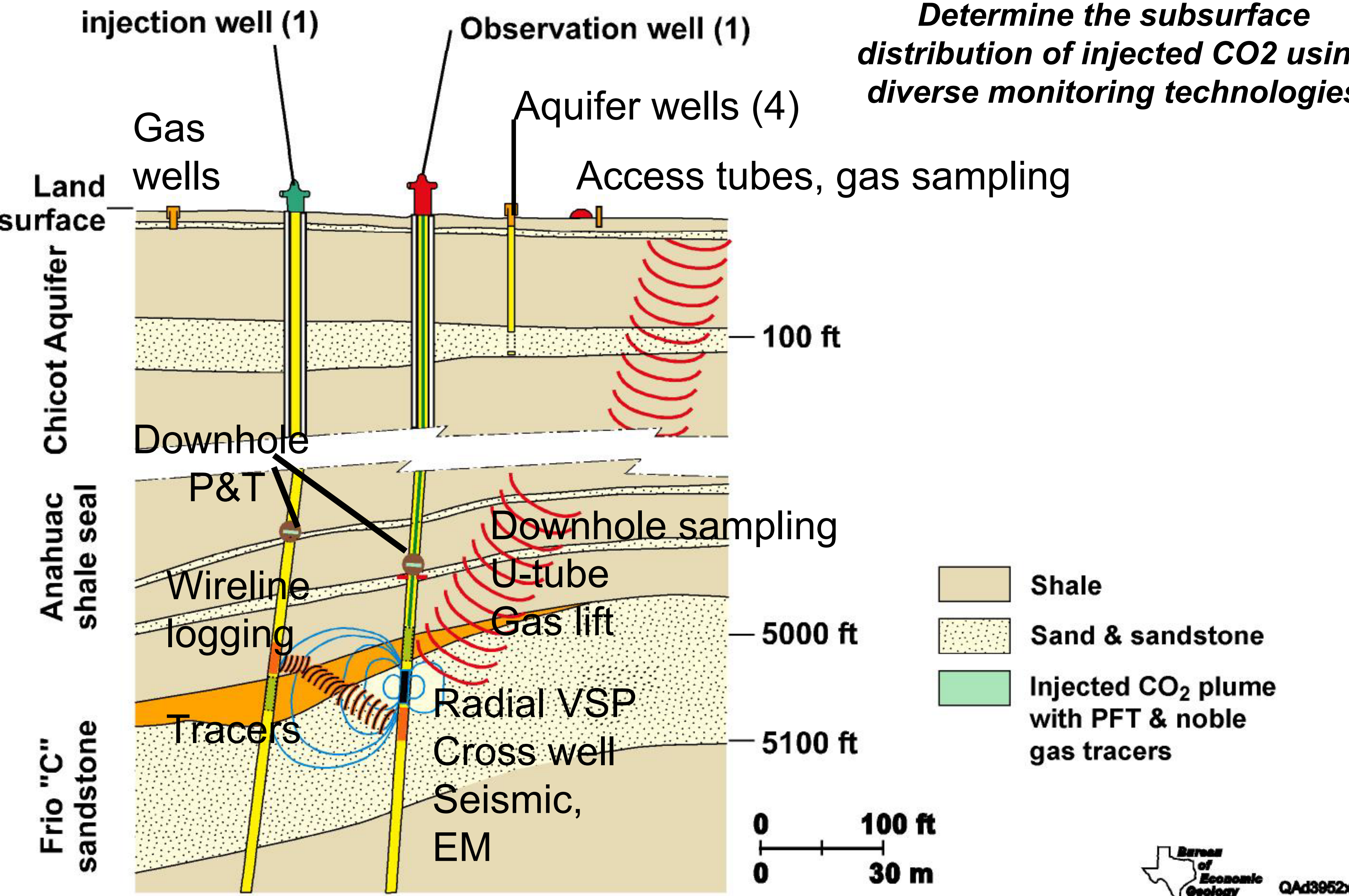
- Modeling has identified variables which appear to control CO_2 injection and post injection migration.
- Measurements made over a short time frame and small distance confirm the correct value for these variables
- Better conceptualized and calibrated models will now be used to develop larger scale longer time frame injections

TOUGH2 simulations

C. Doughty LBNL

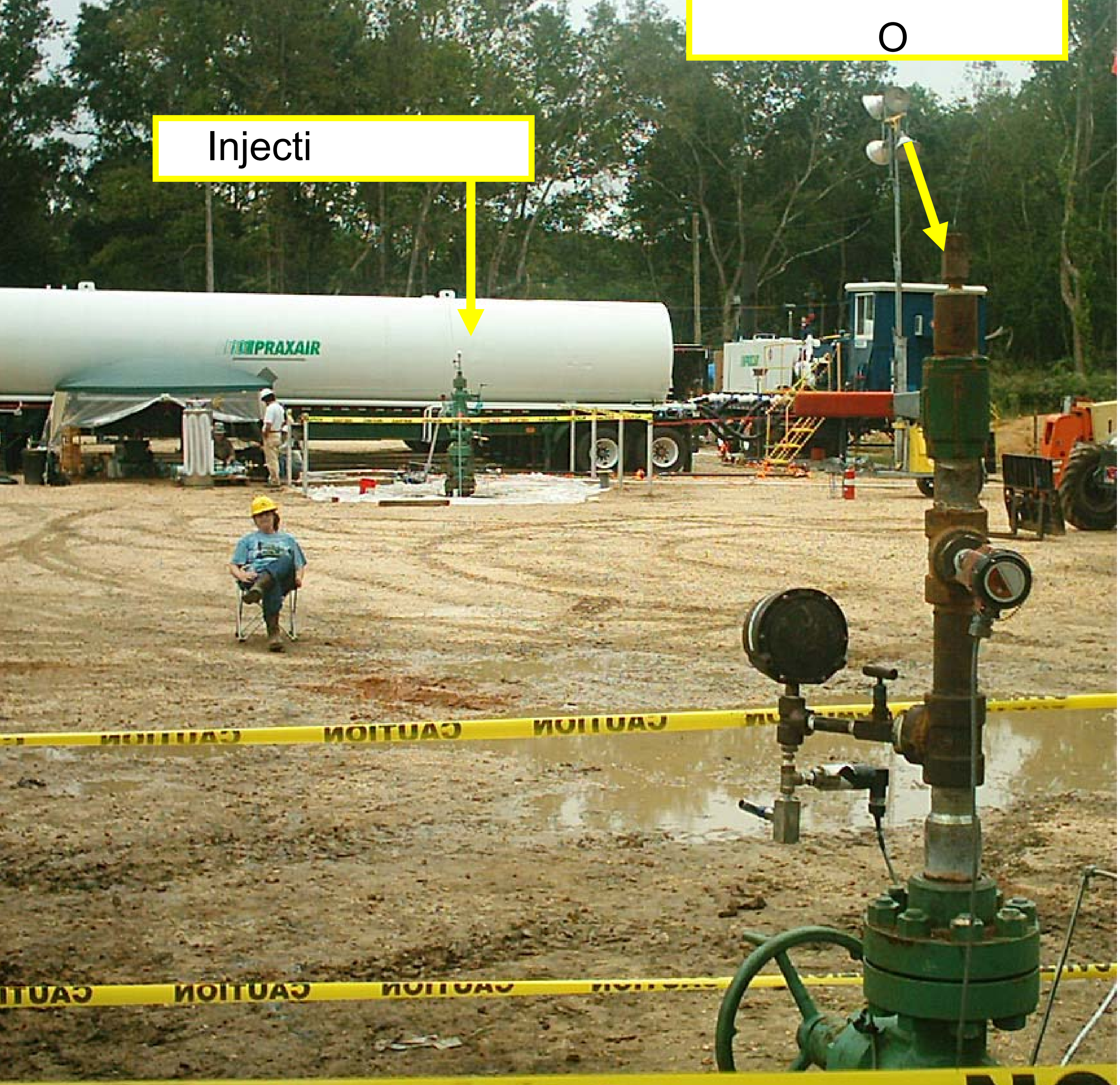
Monitoring at Frio Pilot

Determine the subsurface distribution of injected CO2 using diverse monitoring technologies



Research Monitoring vs. Regulatory Monitoring

- Regulatory
  - Detailed characterization
  - Volume injected monthly
  - Injection pressure at well head
  - Annular pressure
- Research
  - Observation well
  - Down hole logs
  - Down hole pressure and temperature
  - Seismic
  - Surface monitoring



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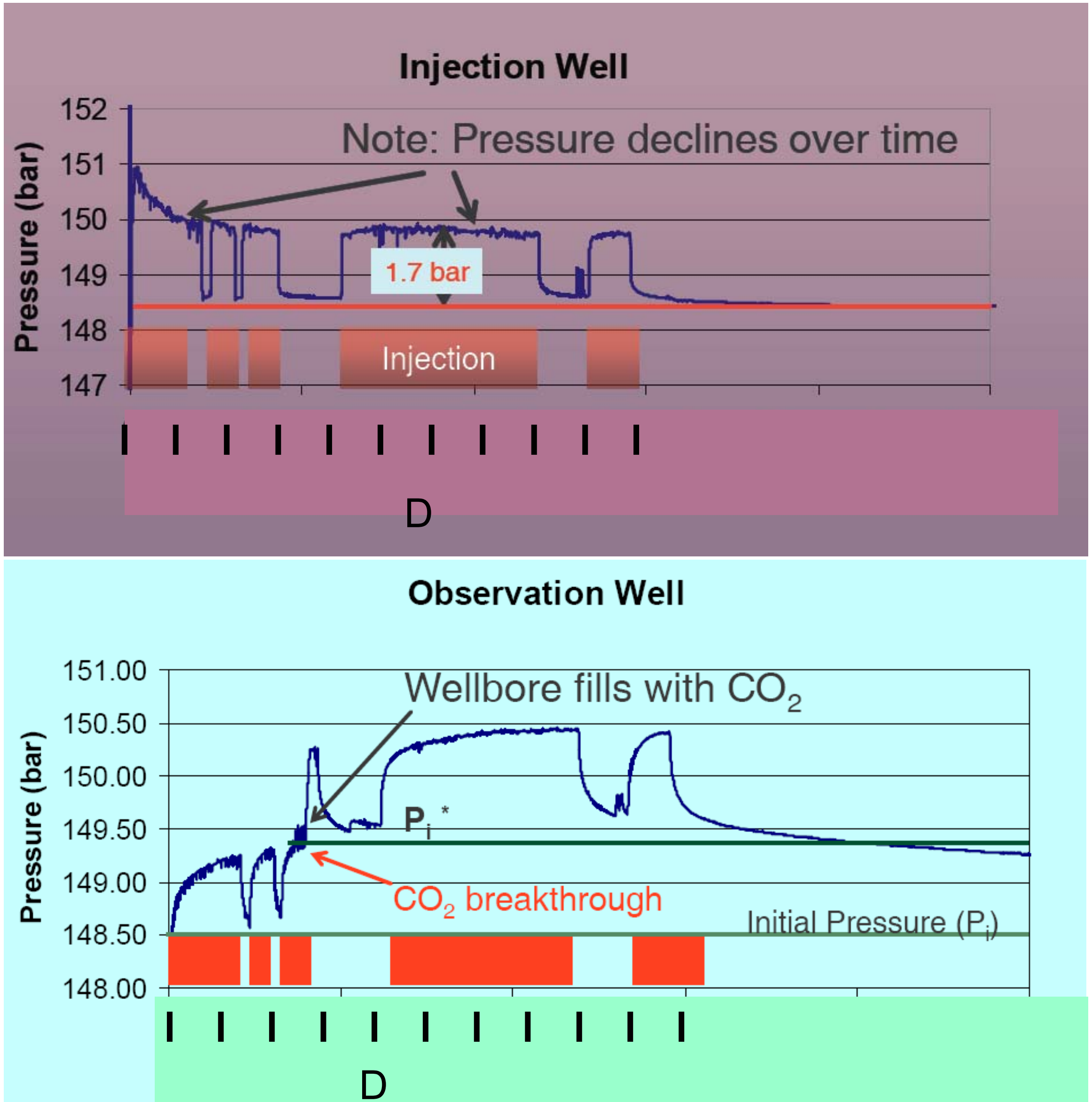
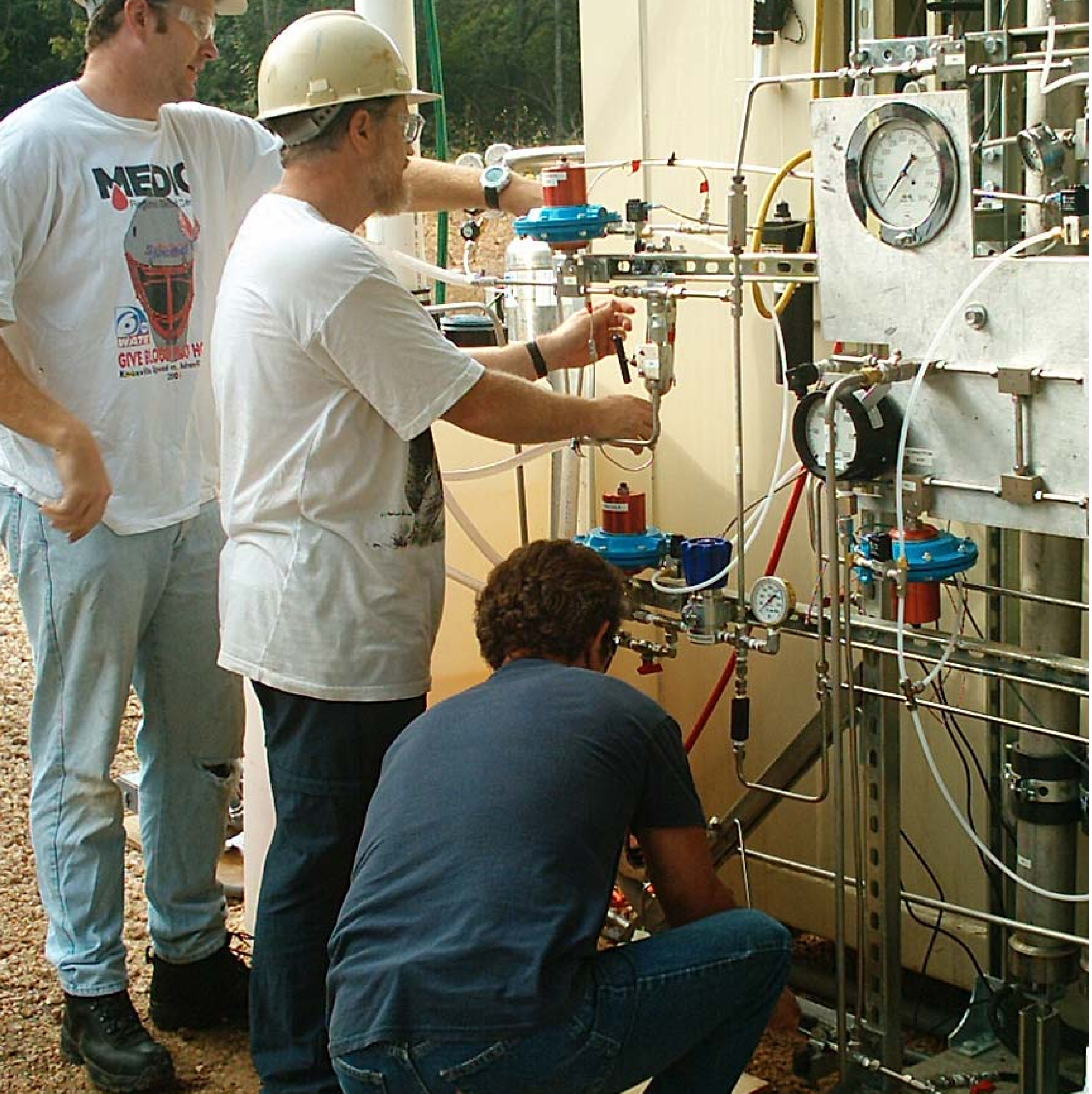

Injection Well
Pressure (bar)
152
151
150
149
148
147
Note: Pressure declines over time
1.7 bar
Injection
D
Observation Well
Pressure (bar)
151.00
150.50
150.00
149.50
149.00
148.50
148.00
Wellbore fills with CO_2
P_i *
CO_2 breakthrough
Initial Pressure (P_i)
D

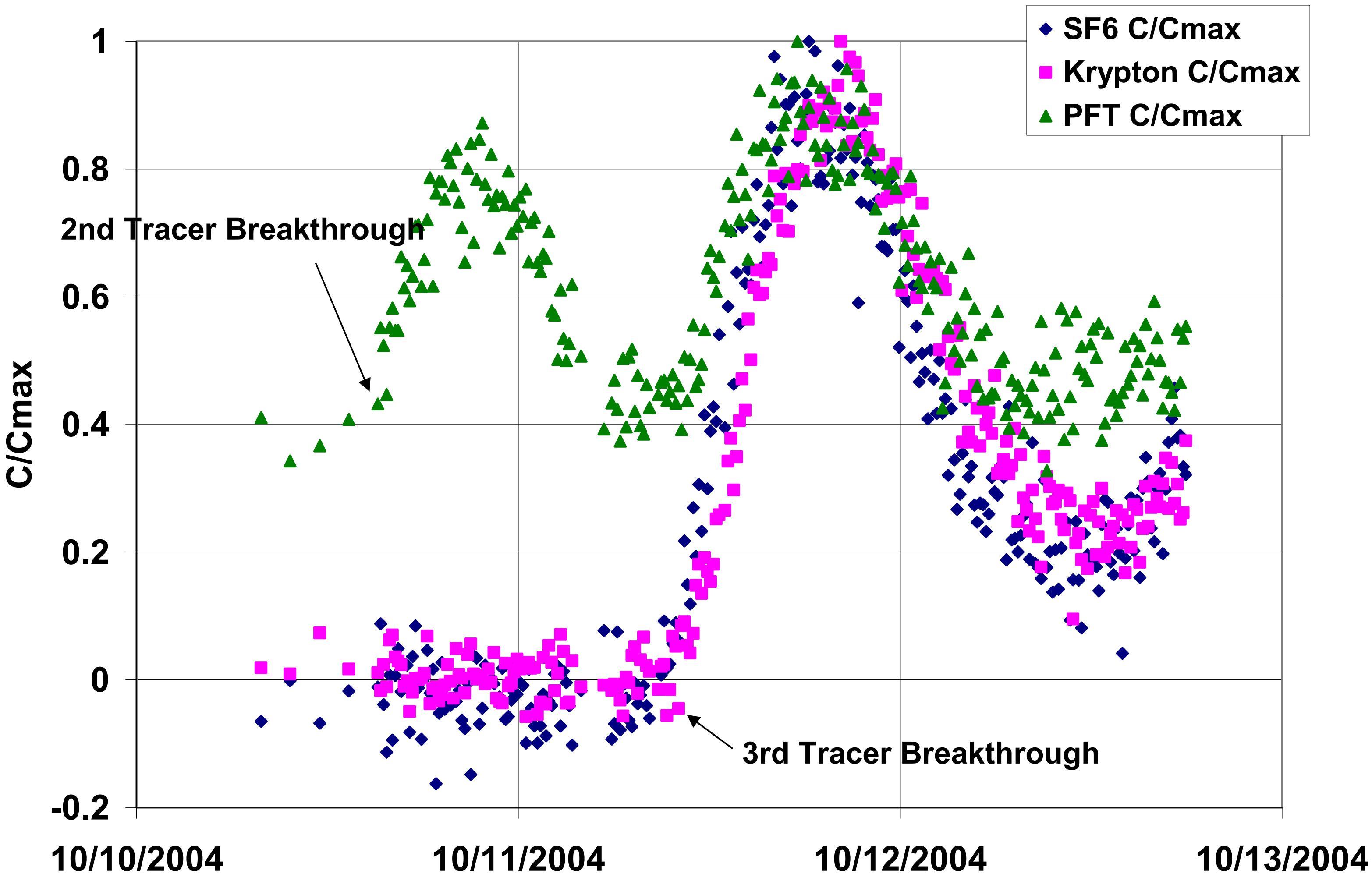
P
A
e
o



New tool to do the job:
LBNL U-tube

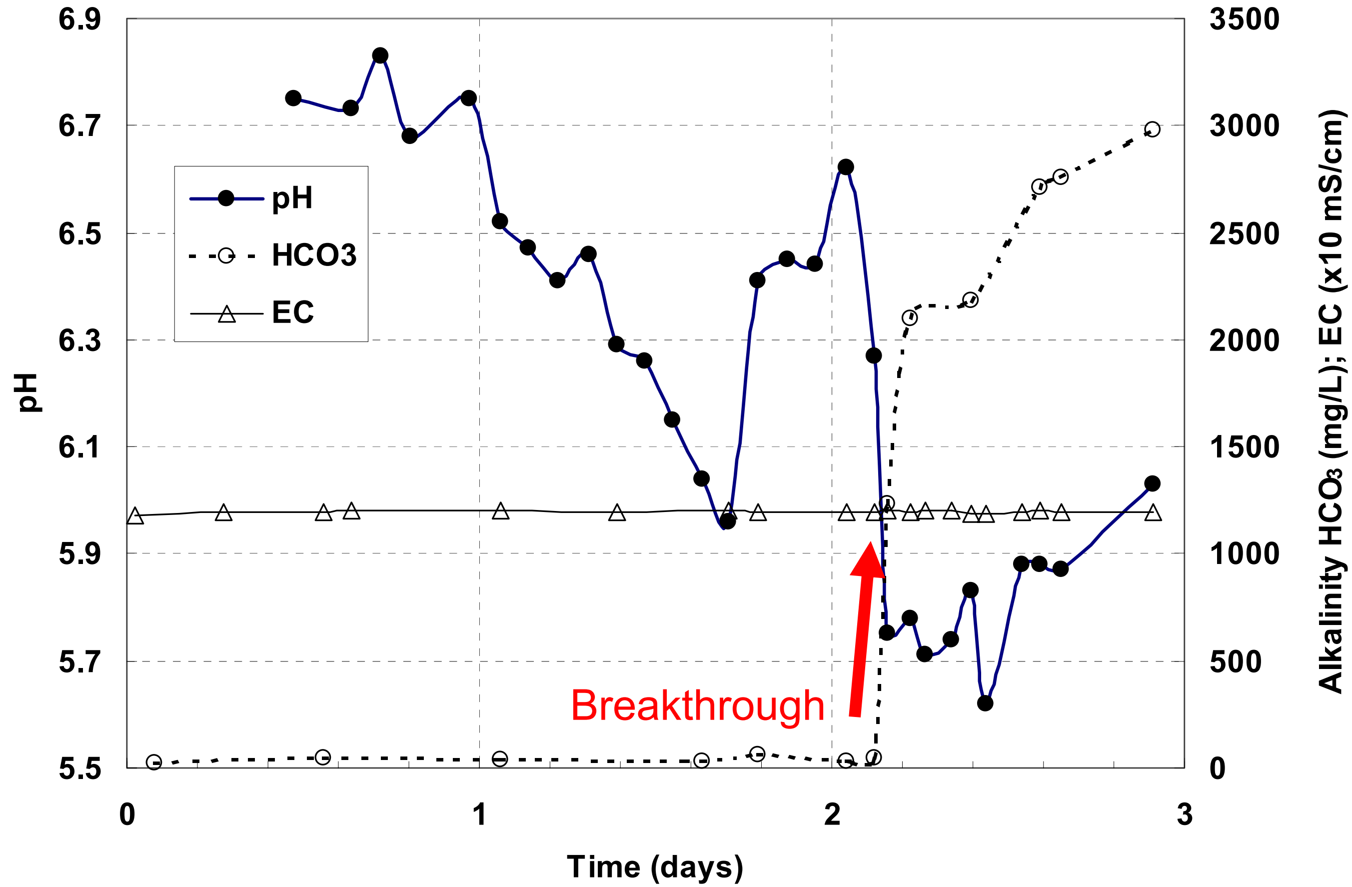
instrument to collect high frequency,
high quality two-phase samples

Tracer Breakthough



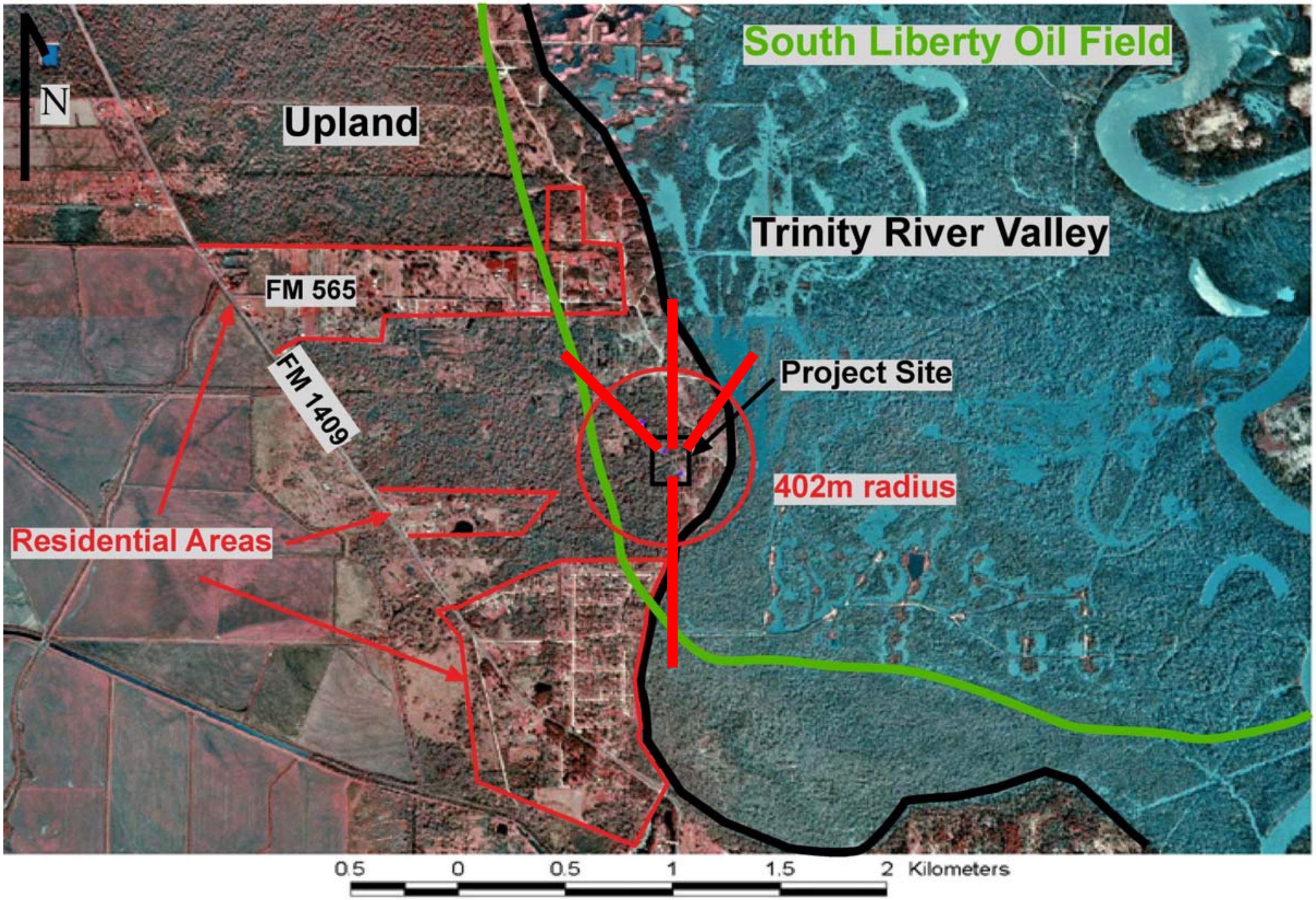
Barry Friefeld, LBNL; Tommy Phelps ORNL

Fluid Chemistry: alkalinity and pH of brine from Observation Well During CO_2 Injection



Y. Kharaka, USGS; H. S. Nance, BEG

Azimuthal Array of Vertical Seismic Profiles

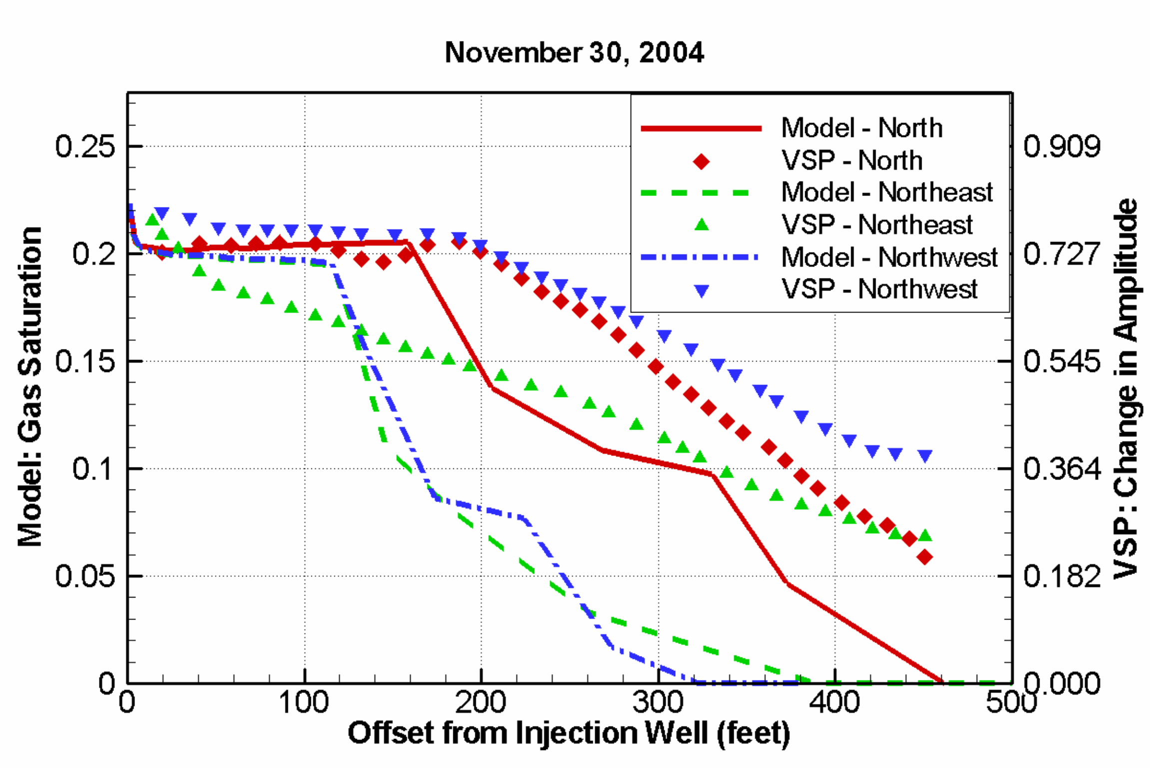


VSP Imaged CO_2

Demonstrates the usefulness of the seismic techniques for leak detection

Site 1 (North, Up Dip)
Reflection Section Tom Daley

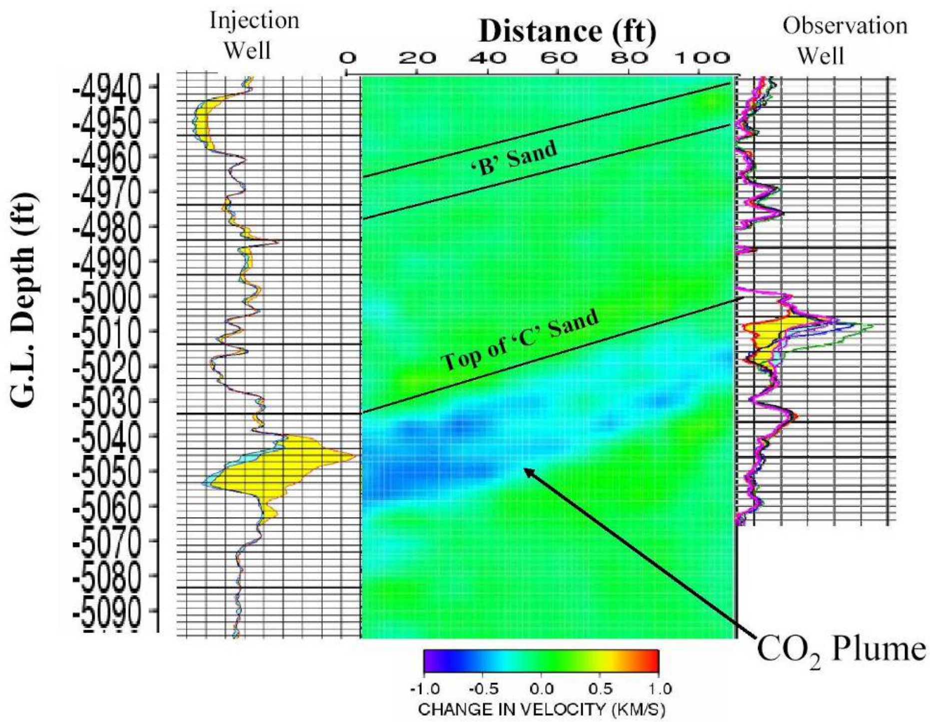
Plume Size Measured with VSP vs. modeled plume size

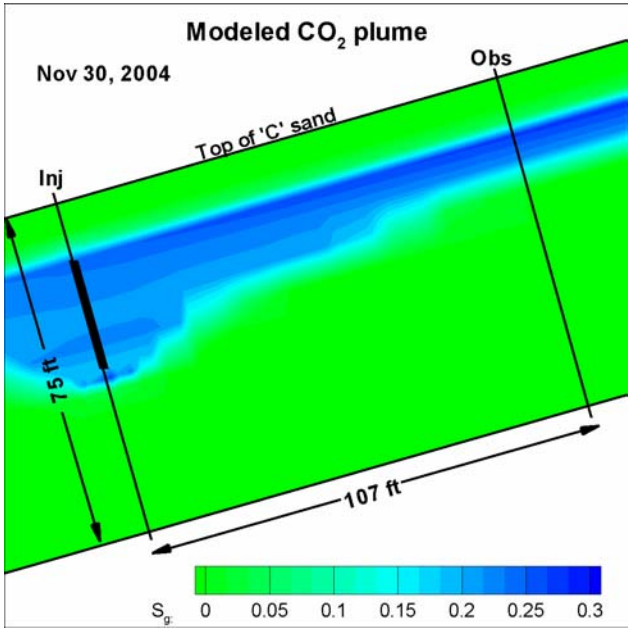


Tom Daley and Christine Doughty LBNL

CO2 Saturation Observed with Cross-well seismic tomography vs. Modeled

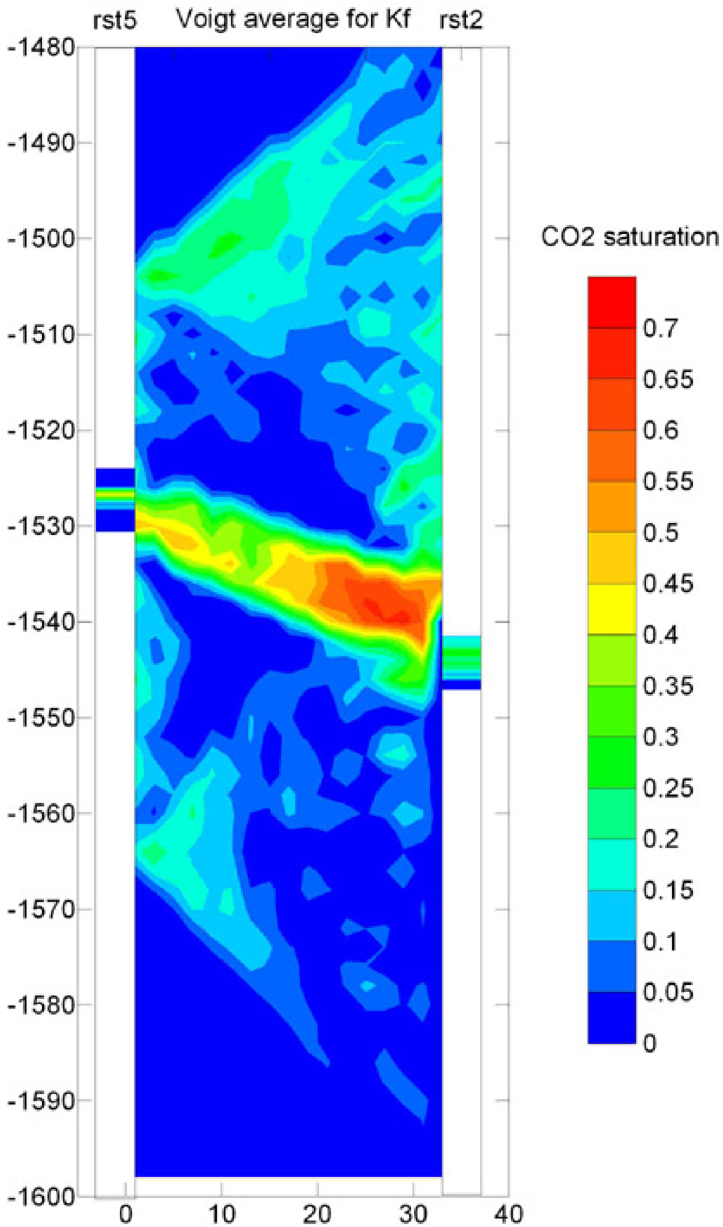
(B)

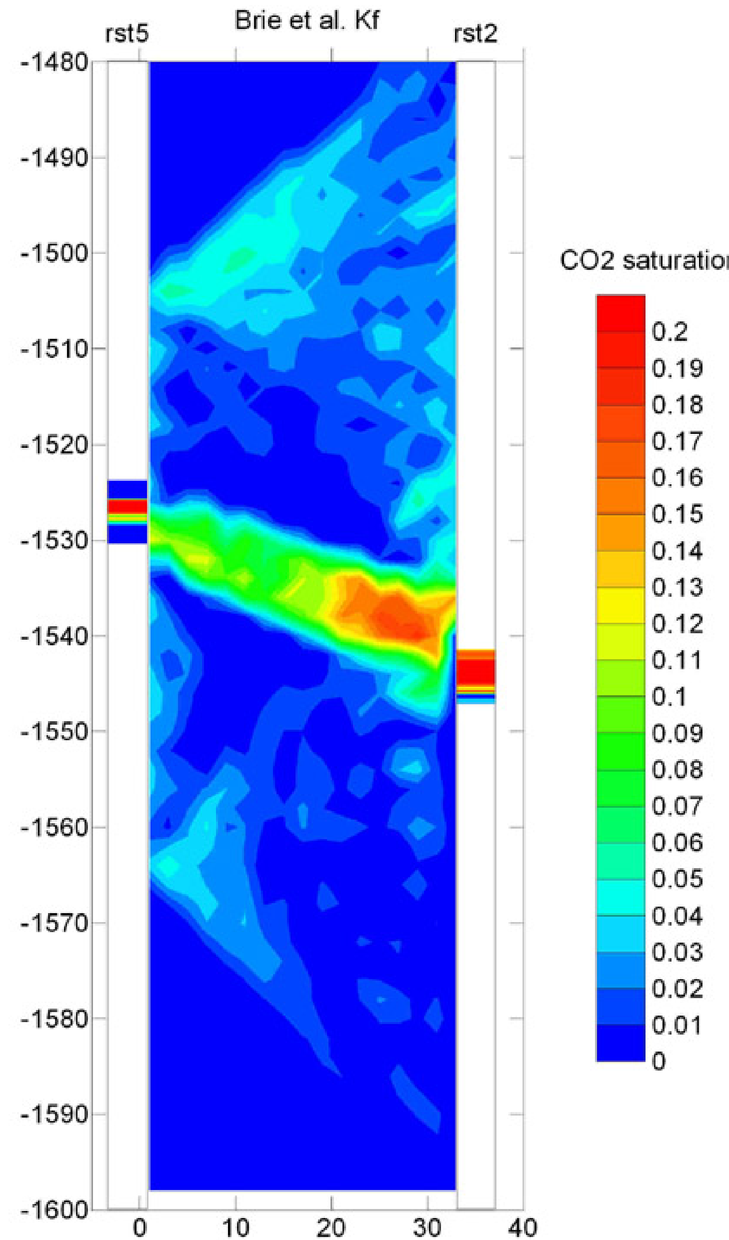




Tom Daley and Christine Doughty LBNL

Saturation from Cross Well Seismic Tomography

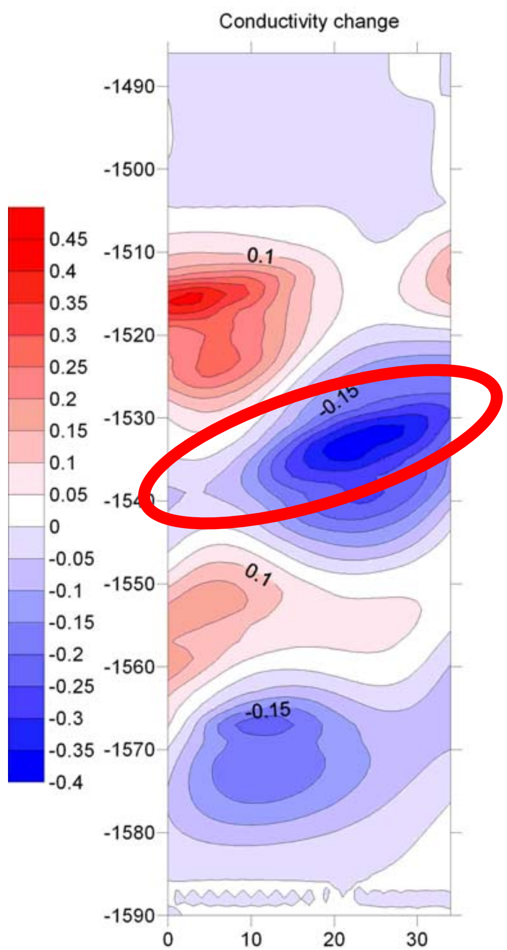




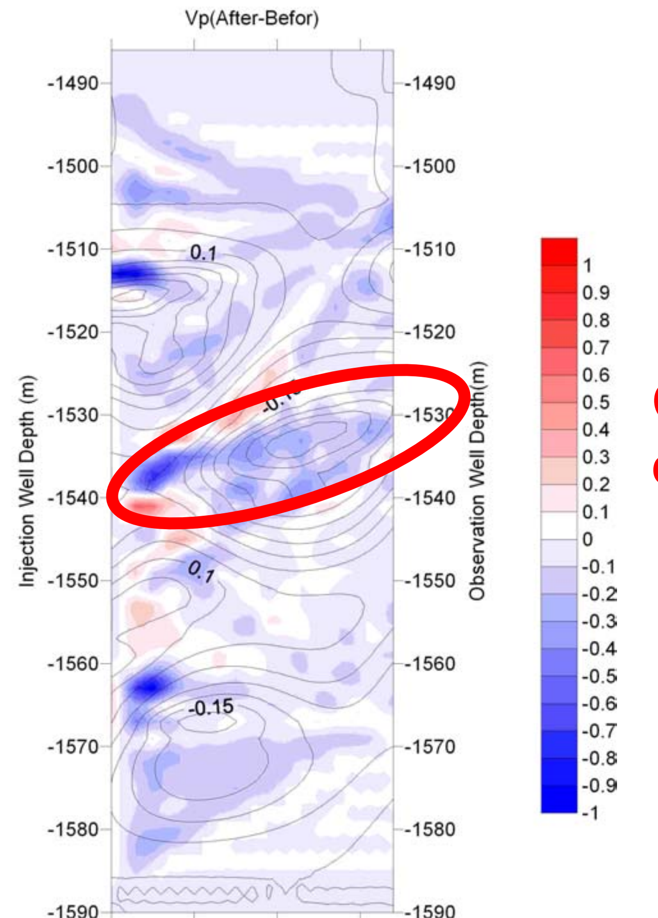
Mike Hoversten

Measurement of CO_2 distribution with cross-well techniques

EM Inverted Resistivity Difference



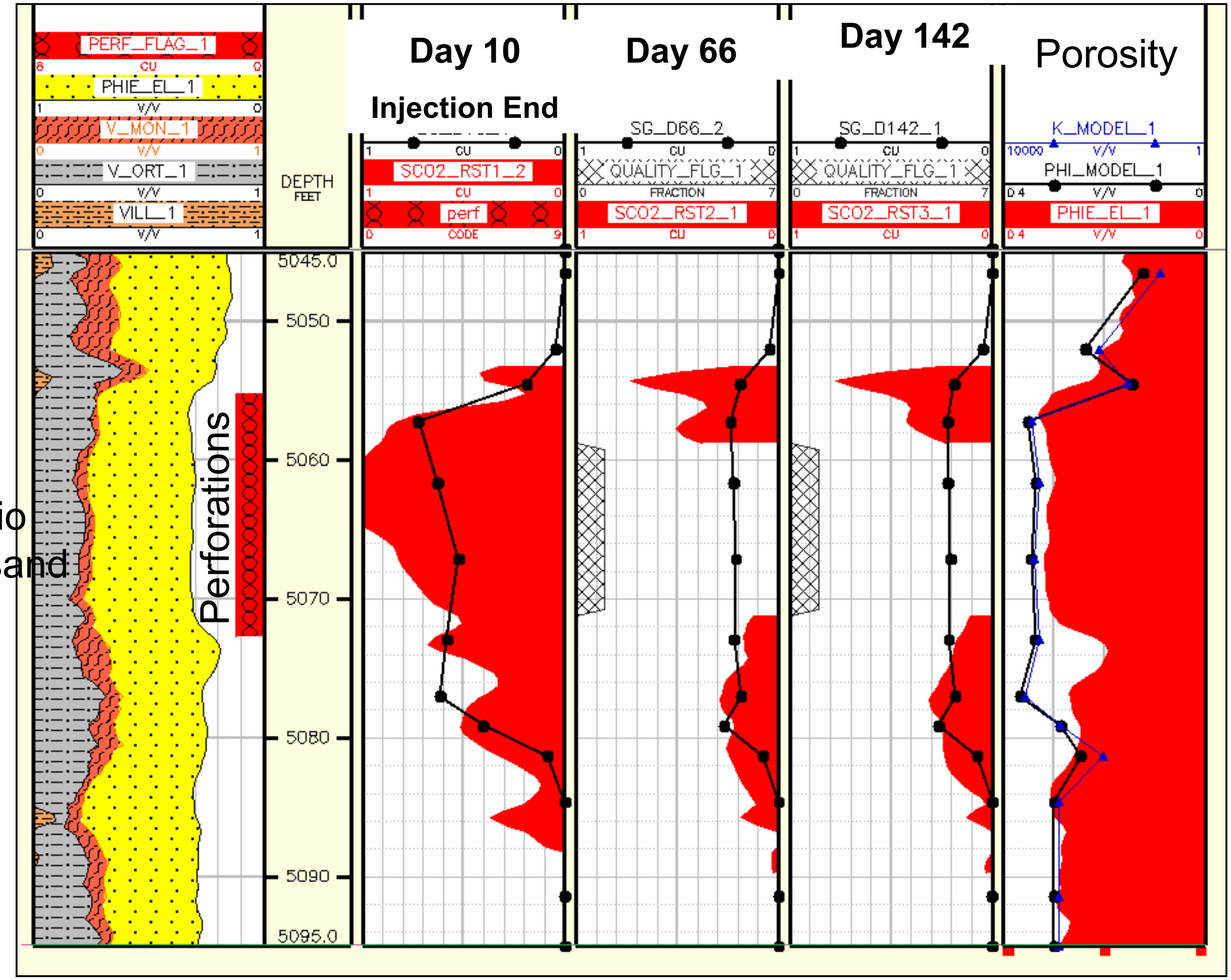
Time Lapse Cross well Seismic With Tim-lapse EM contours



CO_2 detection

Mike Hoversten LBNL and Kevin Dodds CO2CRC

Wireline logging to measure changes in CO_2 saturation – match to model

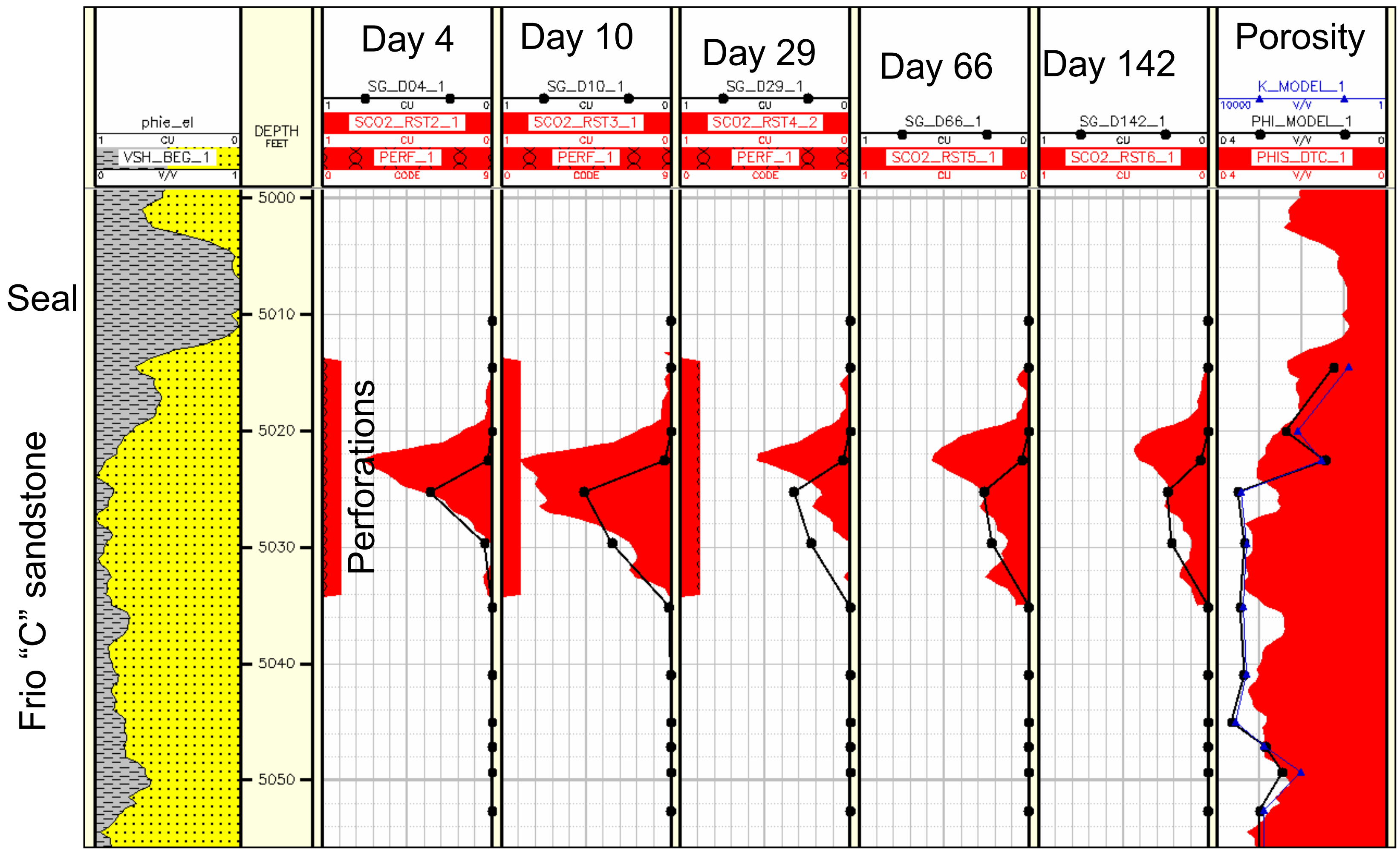


Frio "C" sand

Quantitative,
High resolution
Low cost

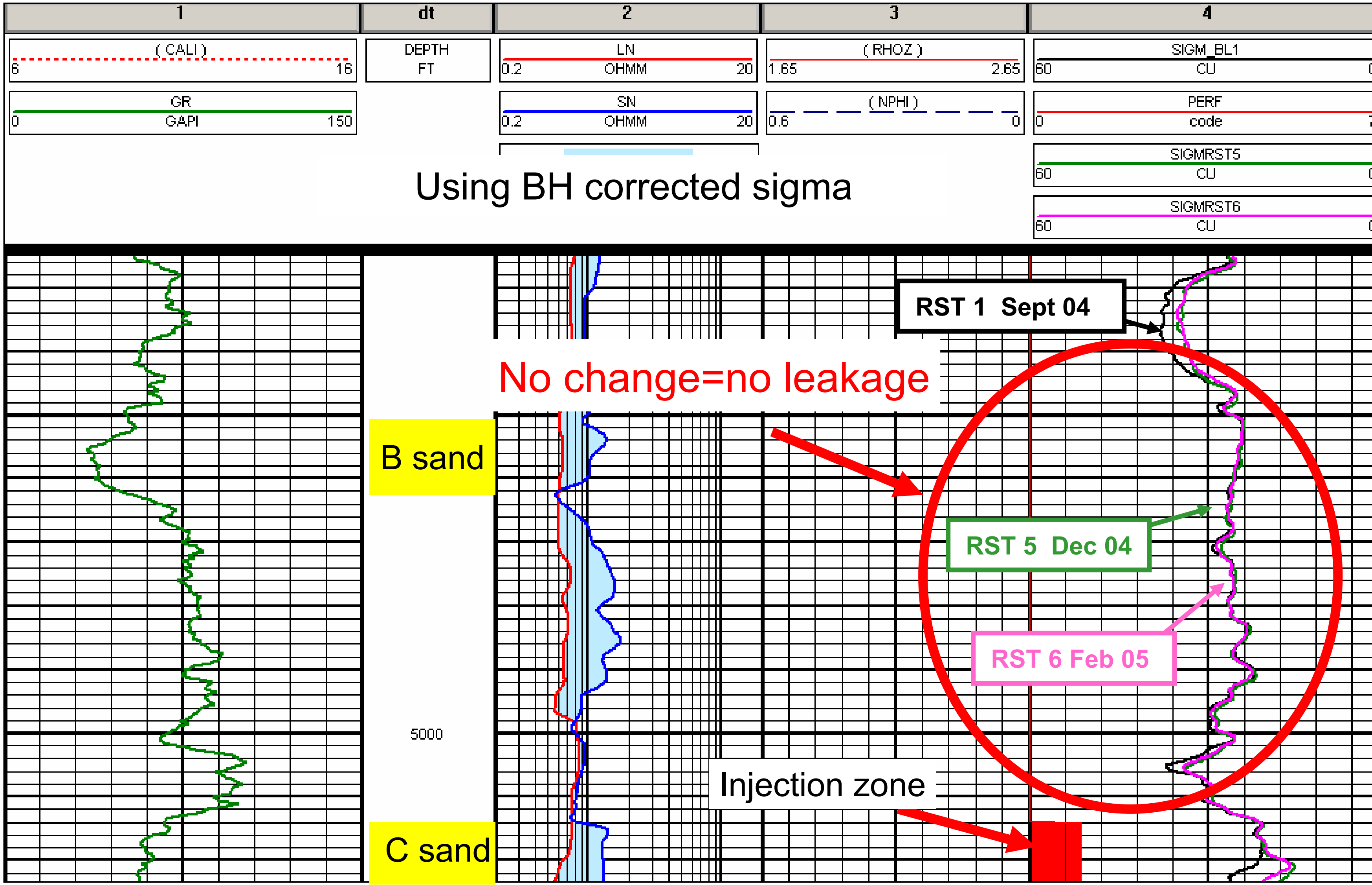
Shinichi Sakurai BEG and Schlumberger

Wireline logging observation well to measure changes in CO_2 saturation – match to model



Shinichi Sakurai BEG and Schlumberger

Evidence of upward leakage? From saturation logs: No



Surface Monitoring continues: results pending

Soil gas sampling

Water well sampling

Gas well sampling

Conclusions

- CO_2 introduced into well-characterized relatively homogenous high permeability sandstone system
- Vigorous public/industry outreach favorable response
- Saturation and transport properties measured horizontally, vertically, and through time using multiple tools
- Improved model conceptual and numerical inputs
- Make results available to Field projects planned by regional sequestration partnerships and to Carbon Sequestration Leadership Forum projects

Invitation to participate in Frio 2

Geophysical Monitoring of CO_2 Sequestration at an Onshore Saline Aquifer in Nagaoka, Japan

Daiji Tanase[1)], Ziqiu Xue[2)] , Hiroyuki Azuma[3)] ,Jiro Watanabe[4)]

1: Engineering Advancement Association of Japan (ENAA)
2: Research Institute of Innovative Technology for the Earth (RITE)
3: Oyo Corporation
4: Geophysical Surveying Co., Ltd.

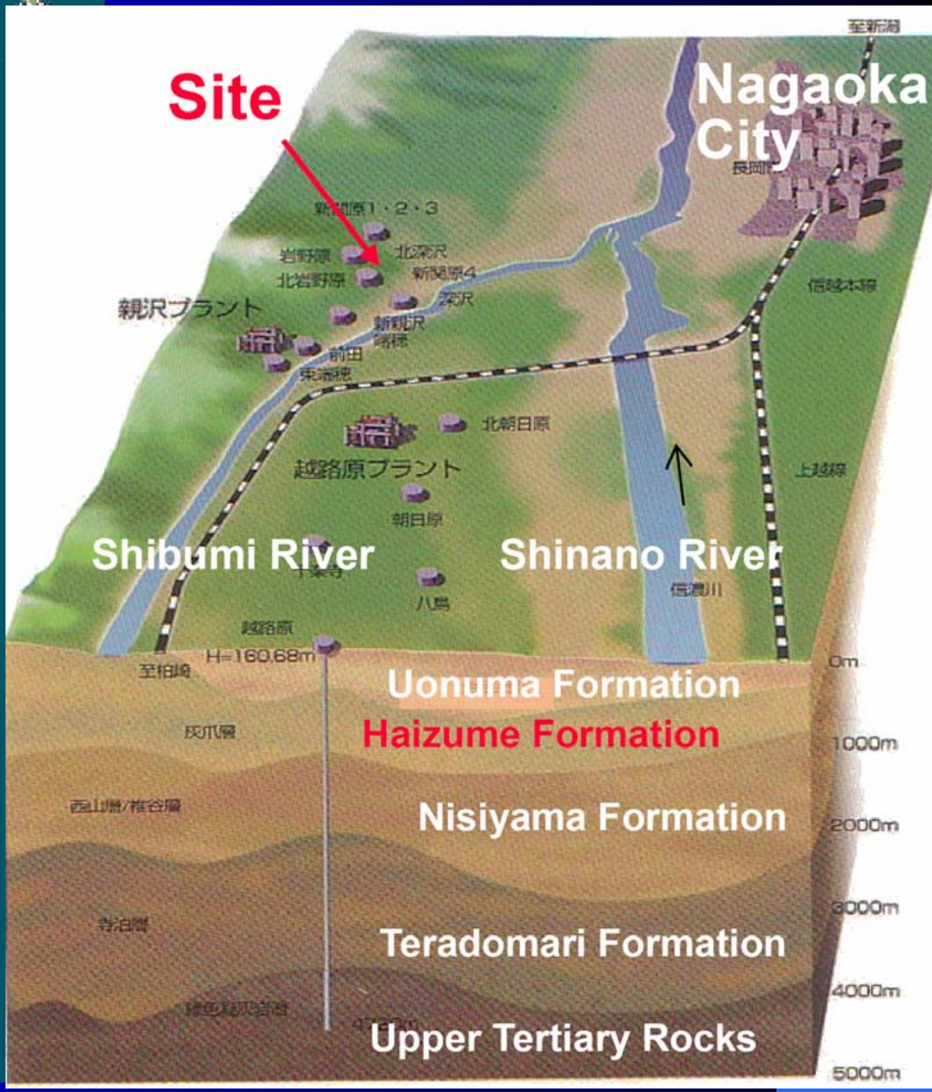
Oct. 5th, 2004

Main Features of CO_2 Injection

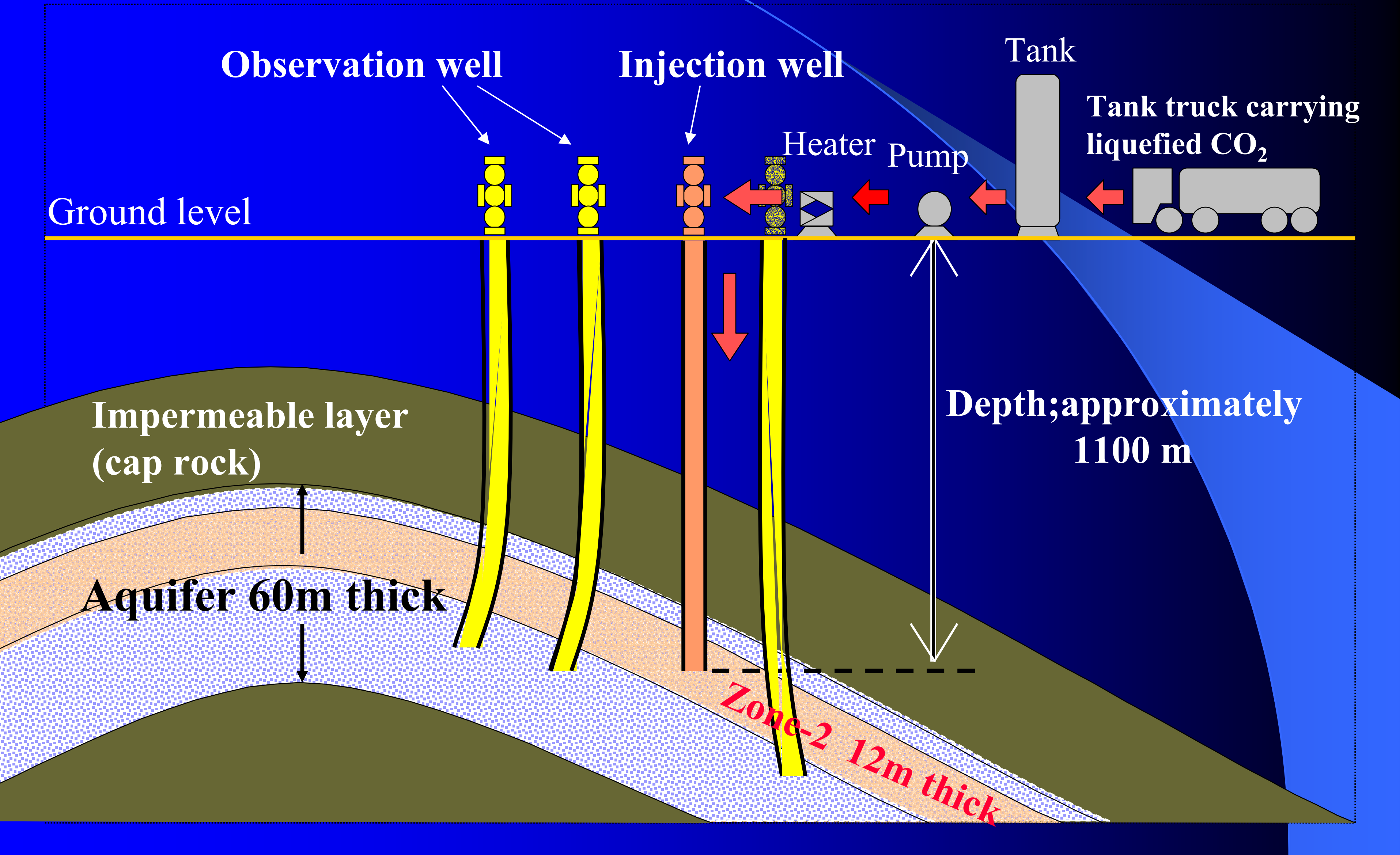
- Reservoir: Aquifer of 1,100m deep
- Injection started on 7 July 2003, ended 11 January 2005
- Injection Rate: 20~40t /day
- Injection Pressure
  - Well Head 6.6 - 7.4 MPa
  - Well Bottom 11.9 - 12.6 MPa
- Temperature of CO_2
  - Well Head 32.0 - 35.5 ℃
  - Well Bottom 45.0 - 48.6 ℃
- CO_2 Phase: kept to be Supercritical Phase (at Well Bottom)
- Duration of Injection: About 18 months
- Total Amount of CO_2 : 10,402 t-CO_2

Location

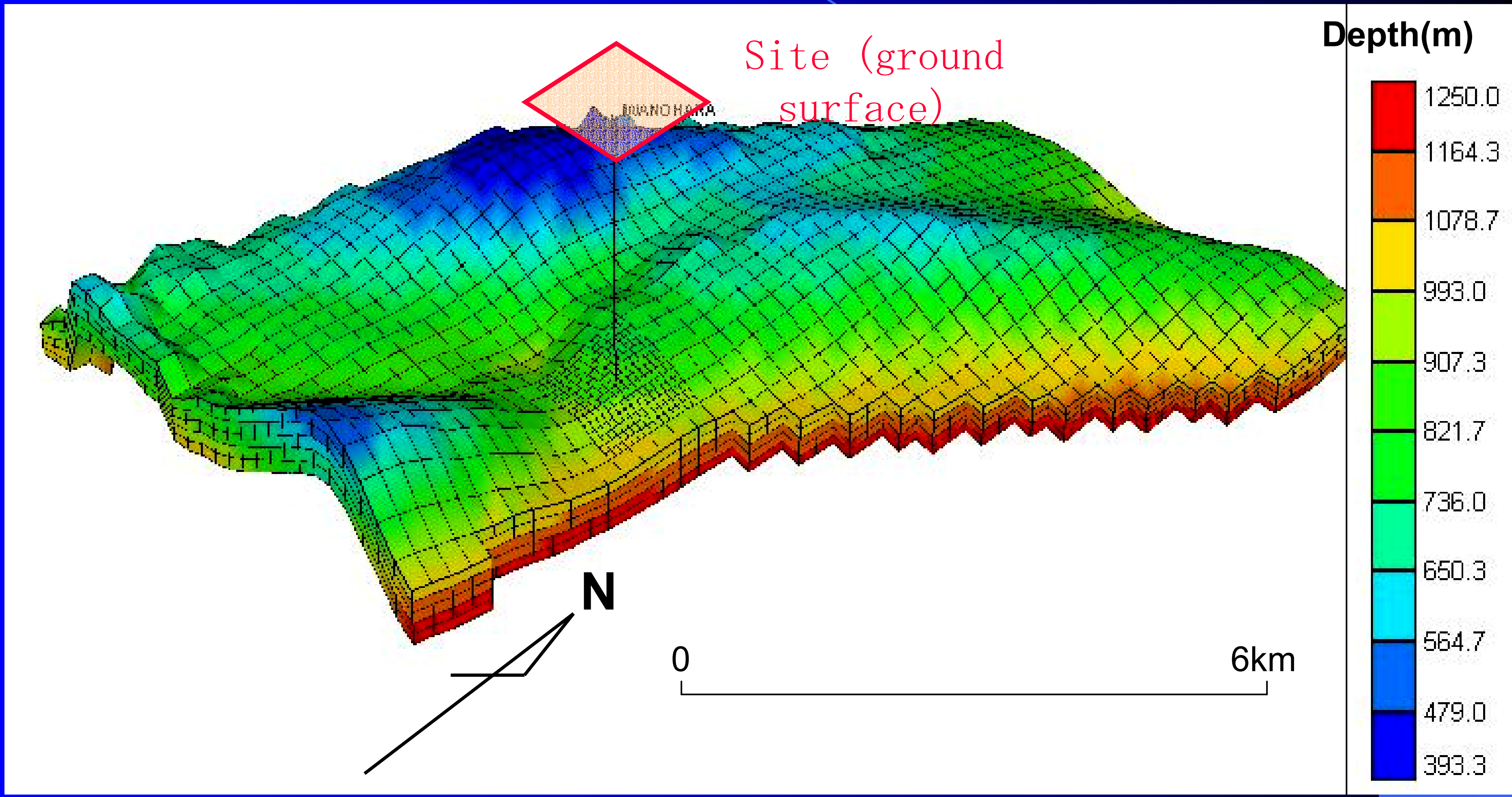
Location and Outline of Geology



Sketch of CO_2 Injection



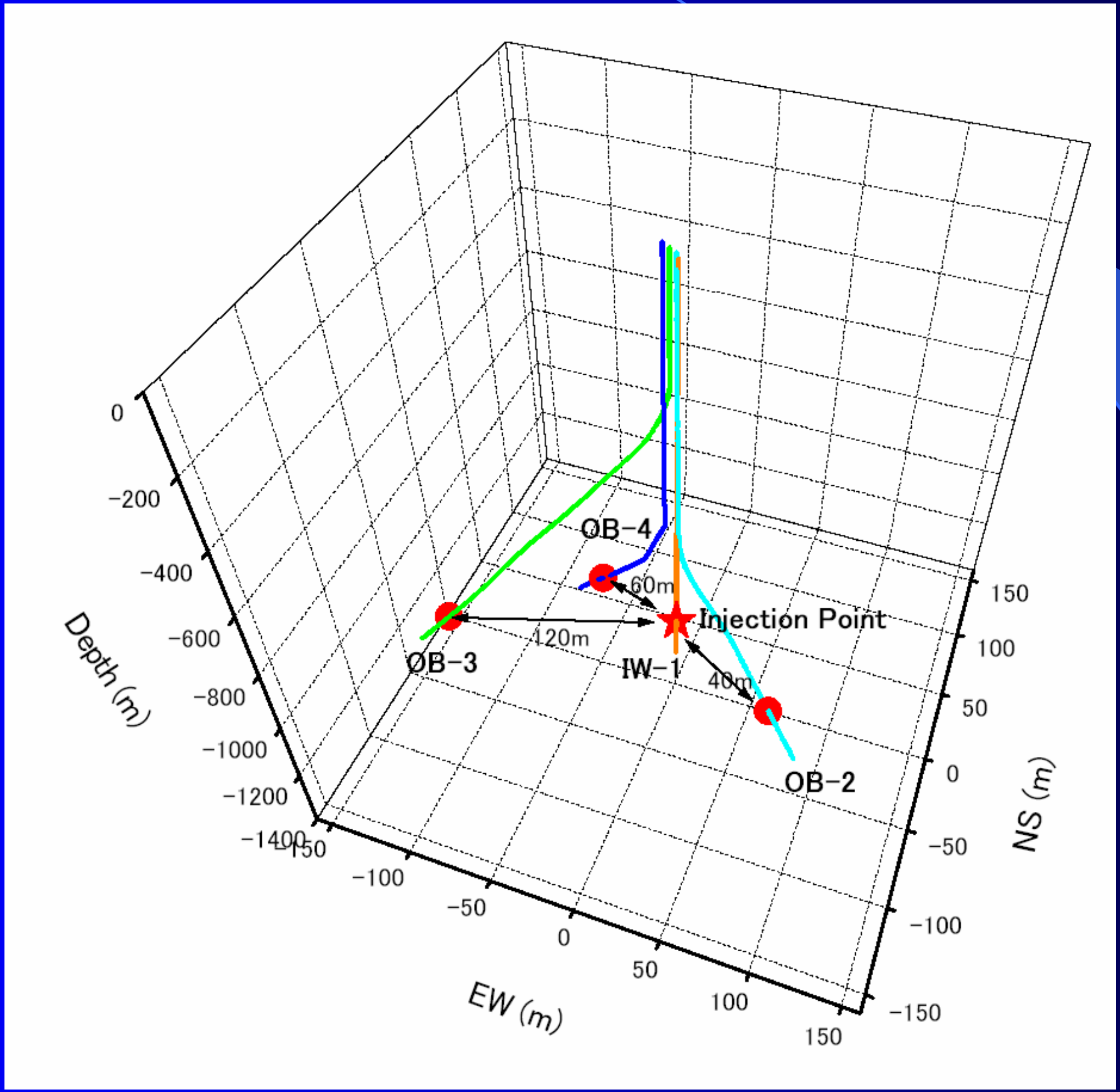
Shape of Aquifer



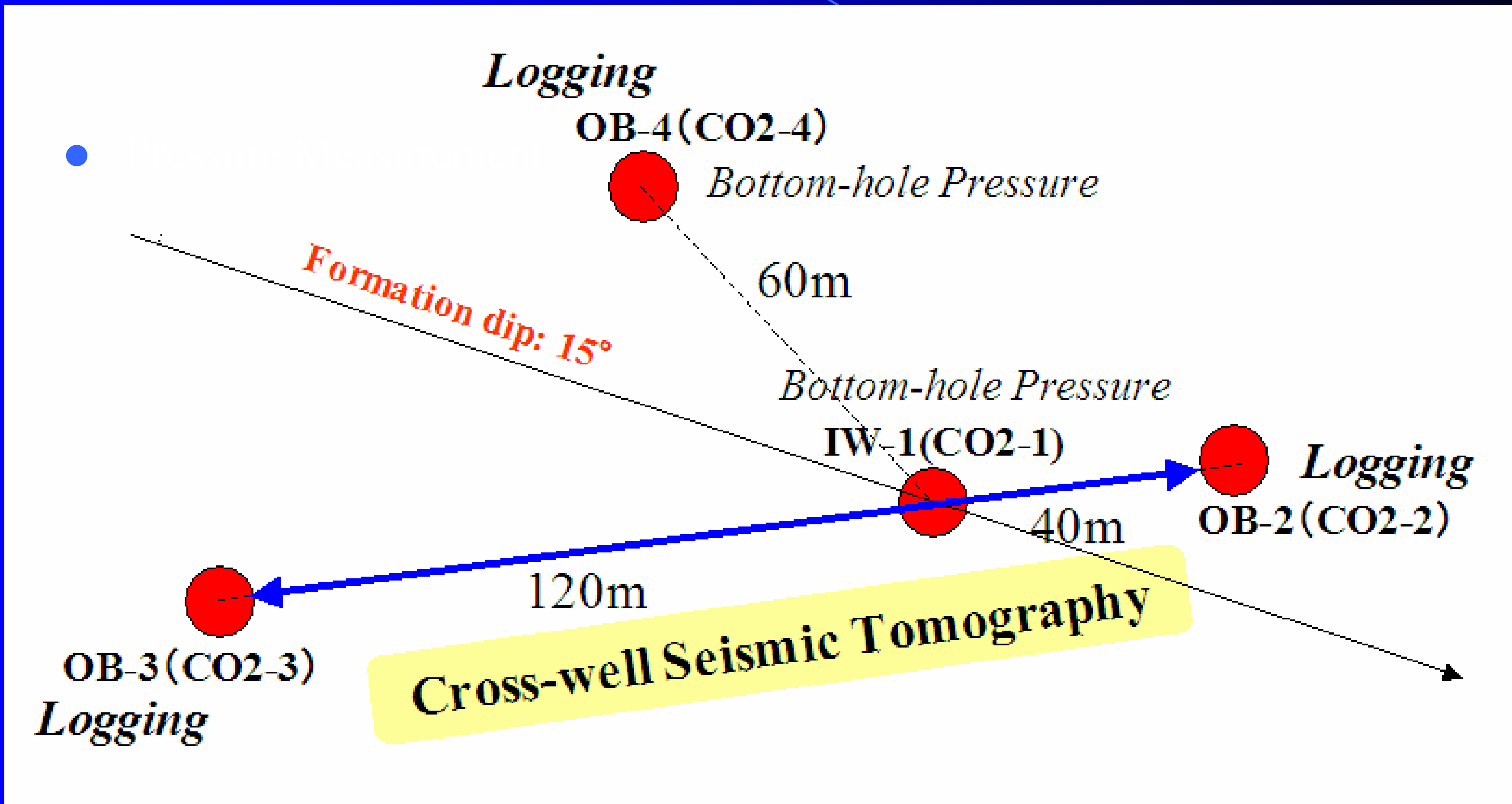
Measurement and Observation

- Measurement (continuously)
  - Pressure & Temperature (well bottom and well head)
- Cross-well Seismic Tomography
  - Five times : Before the injection – After the injection
- Time-lapse Logging (2 week to one month interval)
  - Induction Log
  - Neutron Log
  - Sonic Log
  - Gamma Ray Log
- Observation (continuously)
  - Micro earthquake

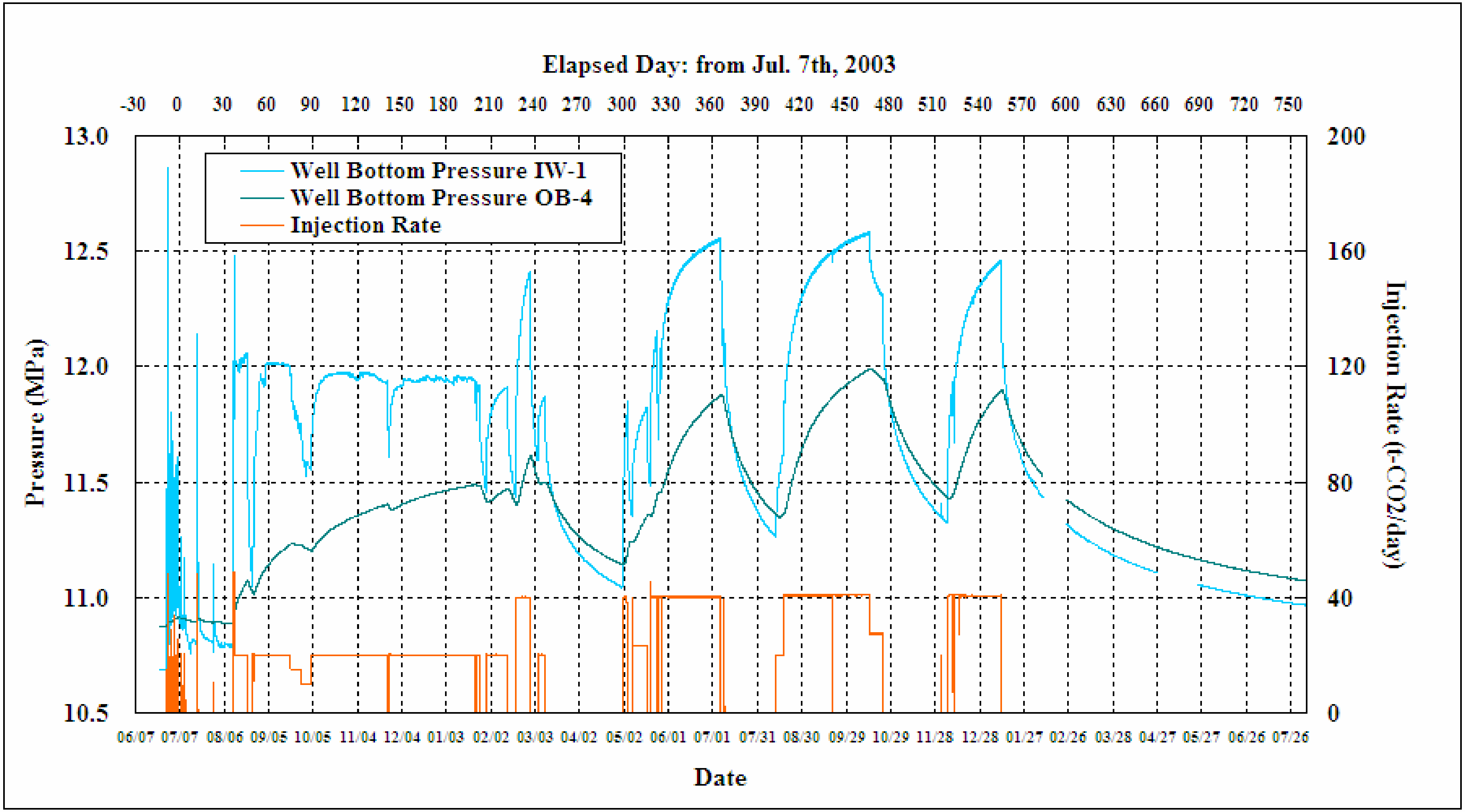
3-D Configuration of the Injection Well and the Observation Wells



Arrangement of Measurements Observations



Pressure Measurement



Well Logging and Breakthrough

- Induction Log
- Neutron Log
- Sonic Log
- Gamma Ray Log

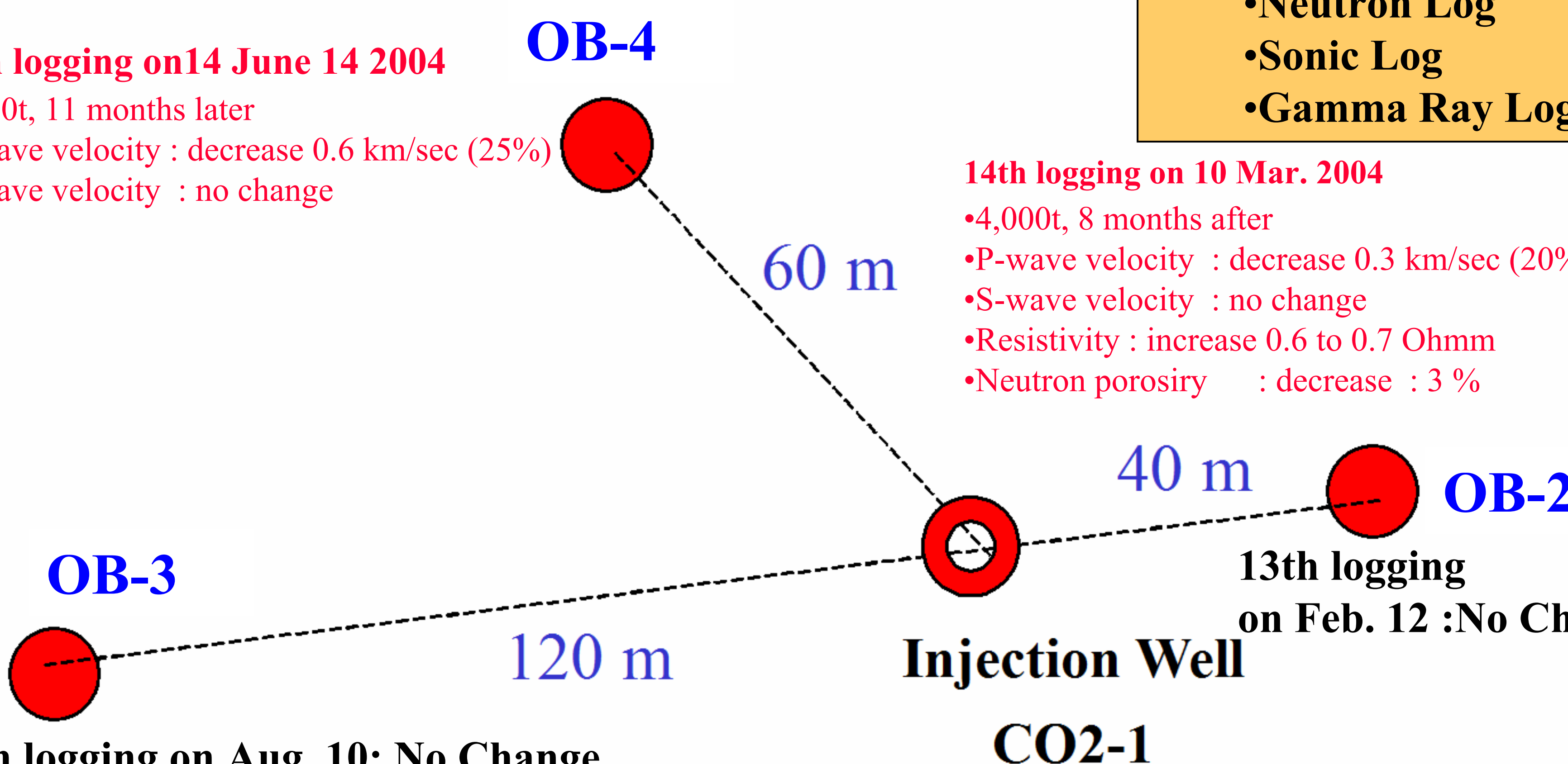
16th logging on May 12:No Change

17th logging on14 June 14 2004

- 5,300t, 11 months later
- P-wave velocity : decrease 0.6 km/sec (25%)
- S-wave velocity : no change

14th logging on 10 Mar. 2004

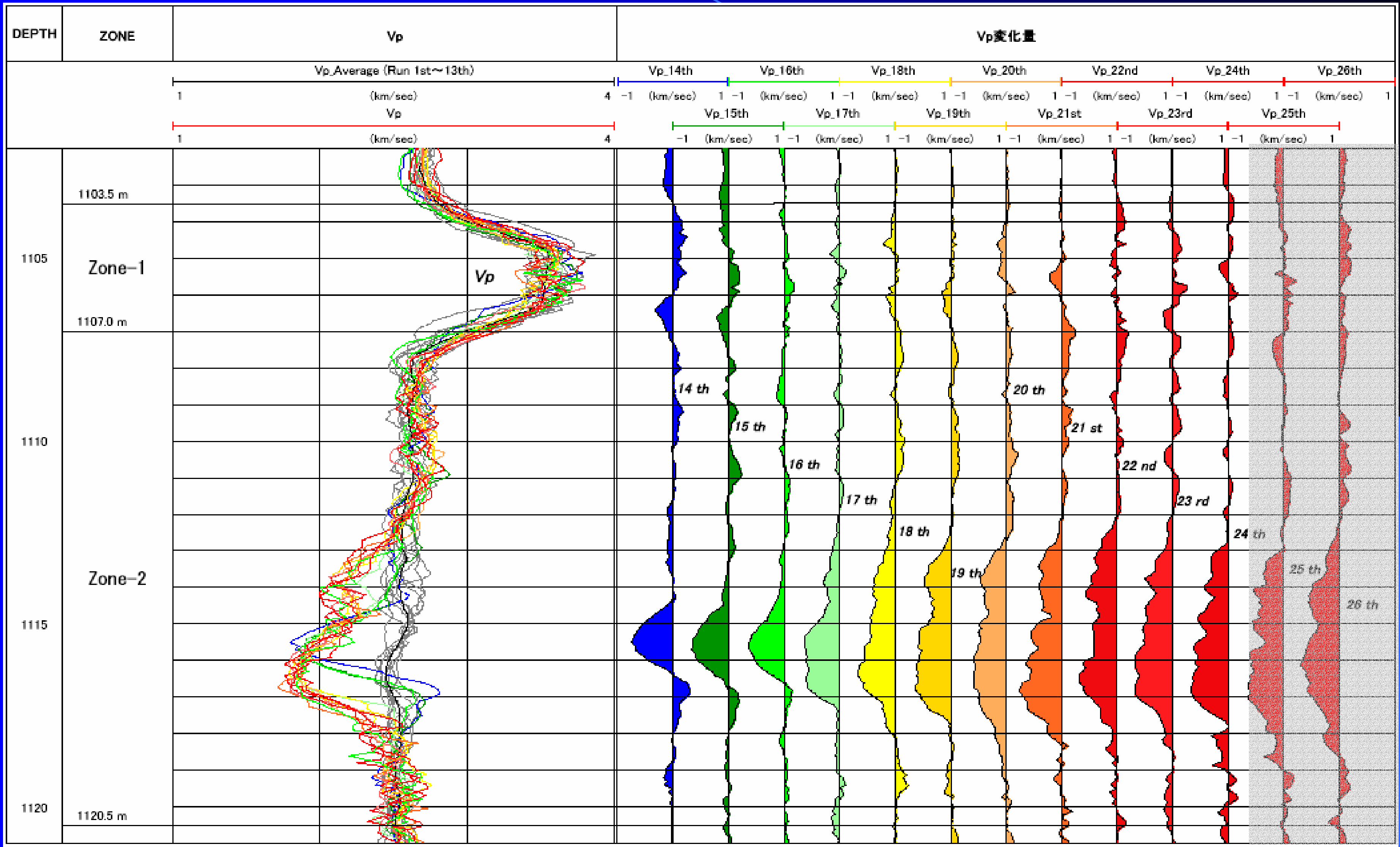
- 4,000t, 8 months after
- P-wave velocity : decrease 0.3 km/sec (20%)
- S-wave velocity : no change
- Resistivity : increase 0.6 to 0.7 Ohmm
- Neutron porosiry : decrease : 3 %



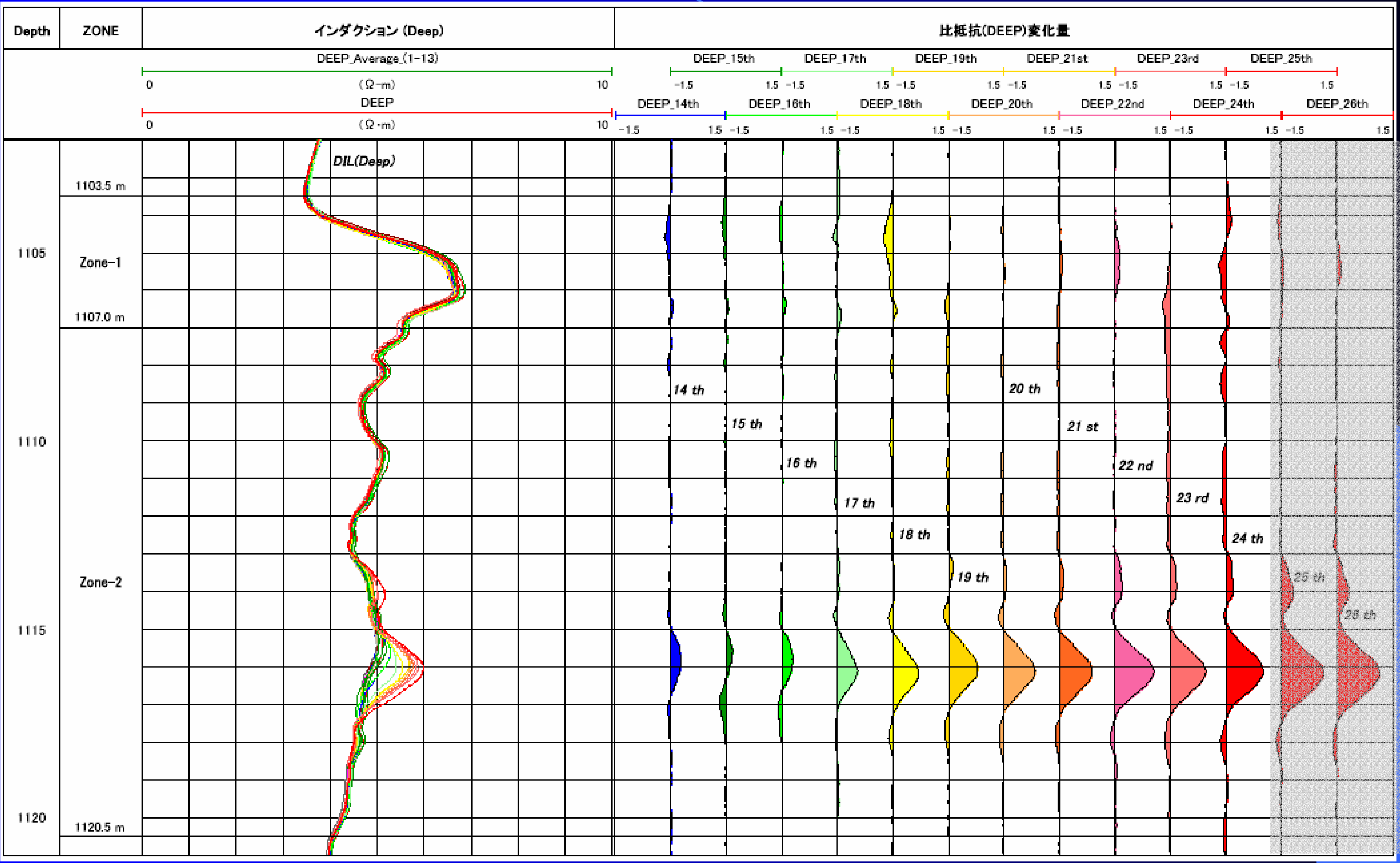
13th logging on Feb. 12 :No Chang

19th logging on Aug. 10: No Change

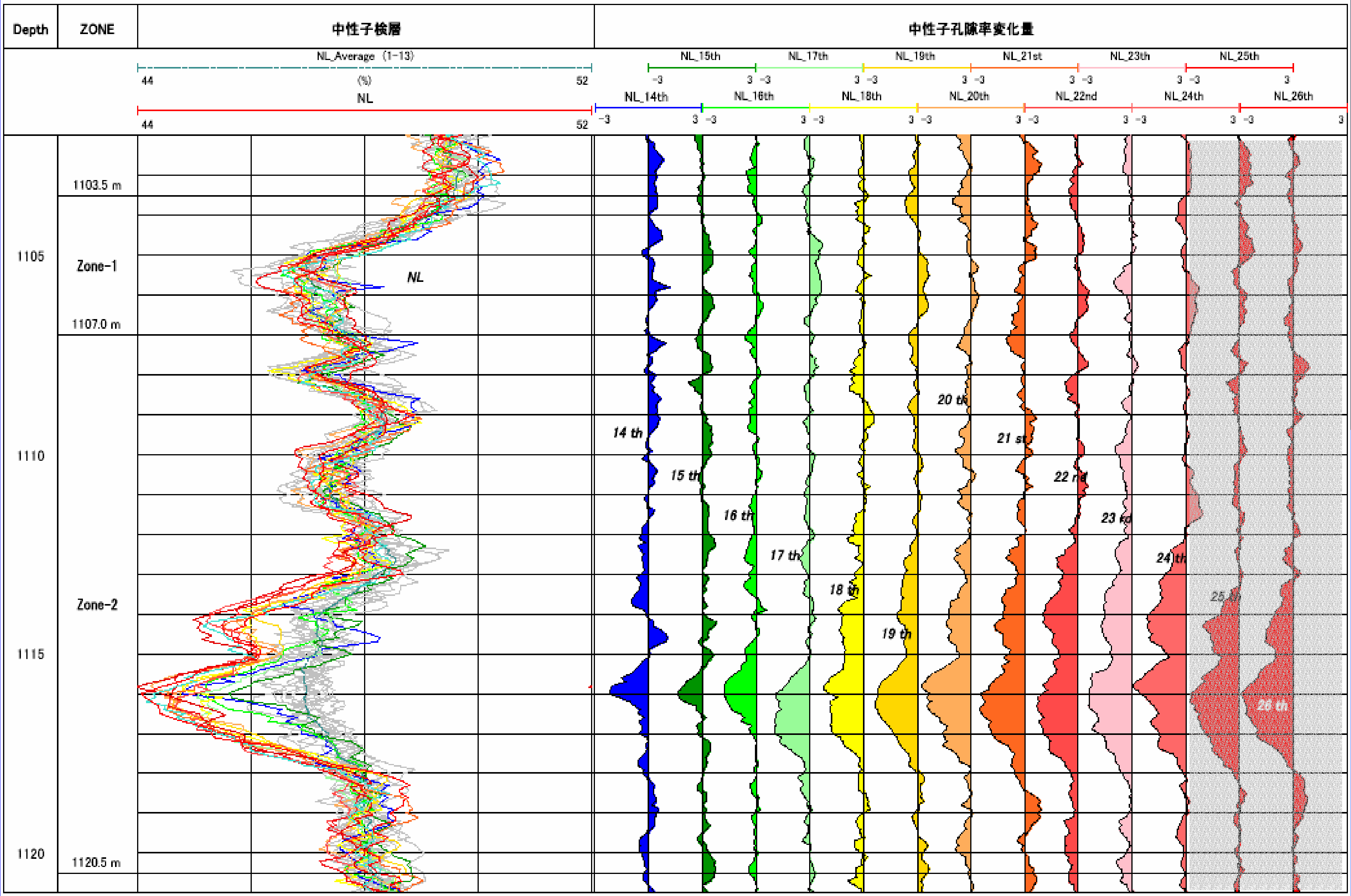
Well Logging Result :OB-2 (Sonic Vp)



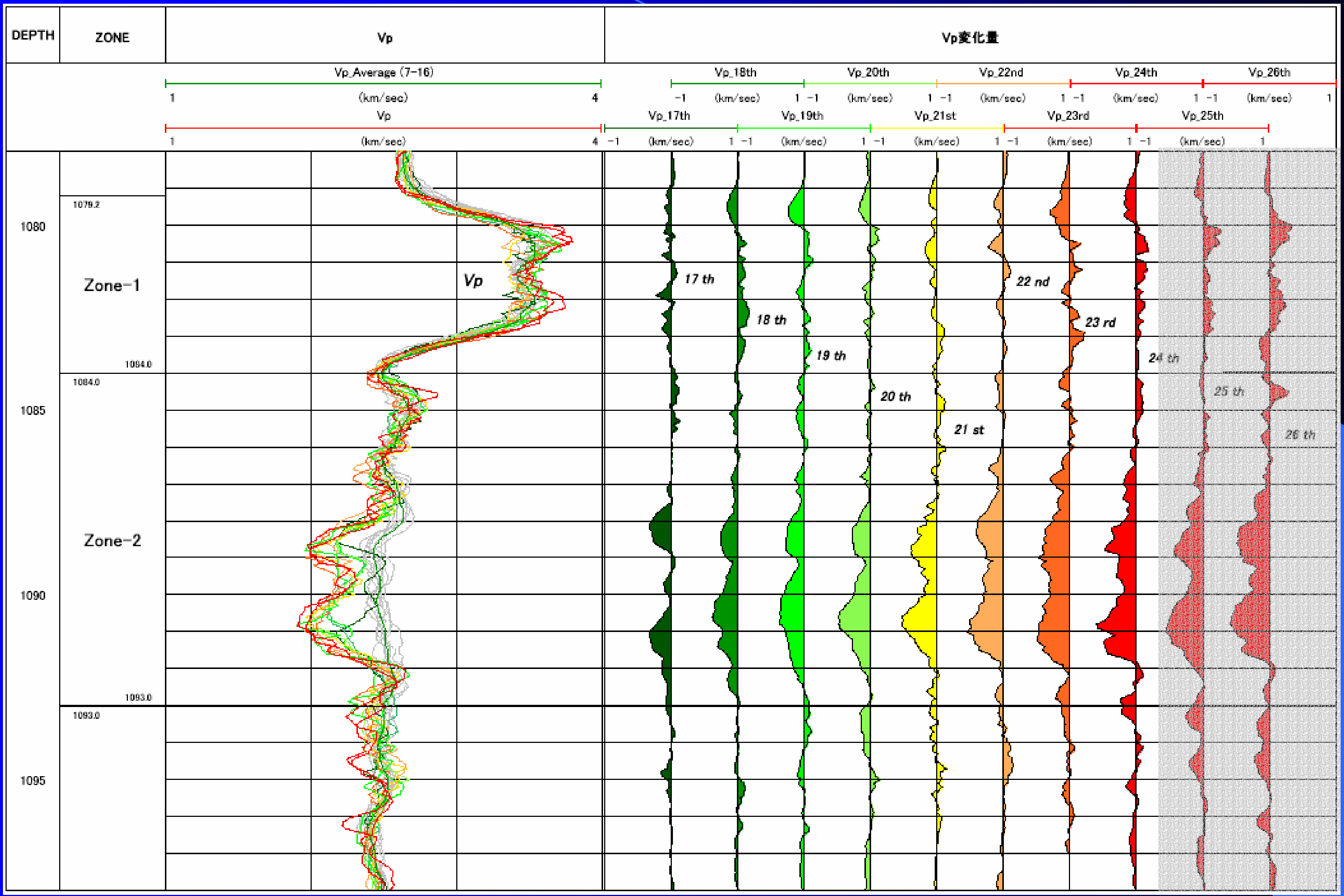
Well Logging Result :OB-2 (Induction)



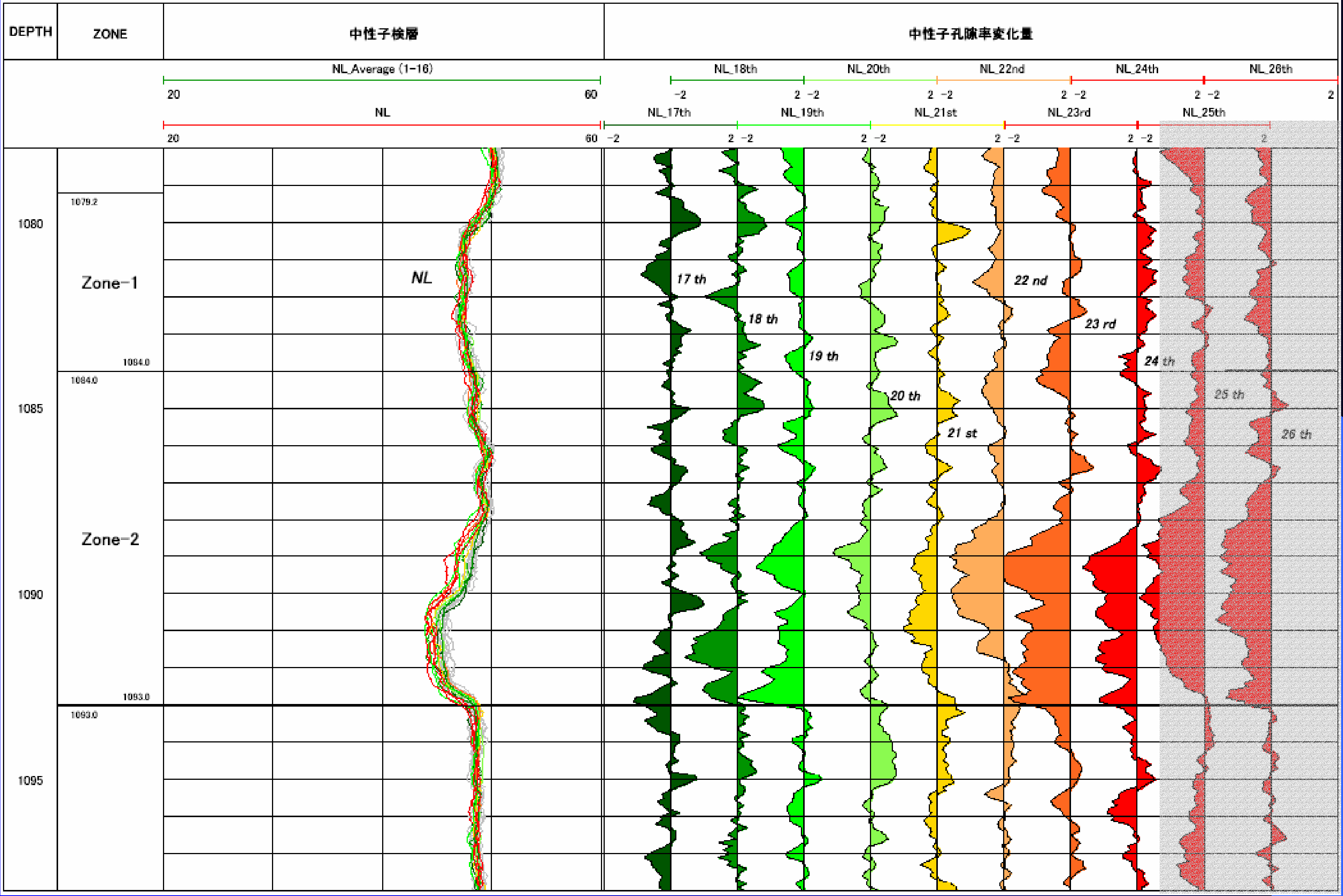
Well Logging Result : OB-2 (Neutron)



Well Logging Result : OB-4 (Sonic Vp)



Well Logging Result : OB-4 (Neutron)

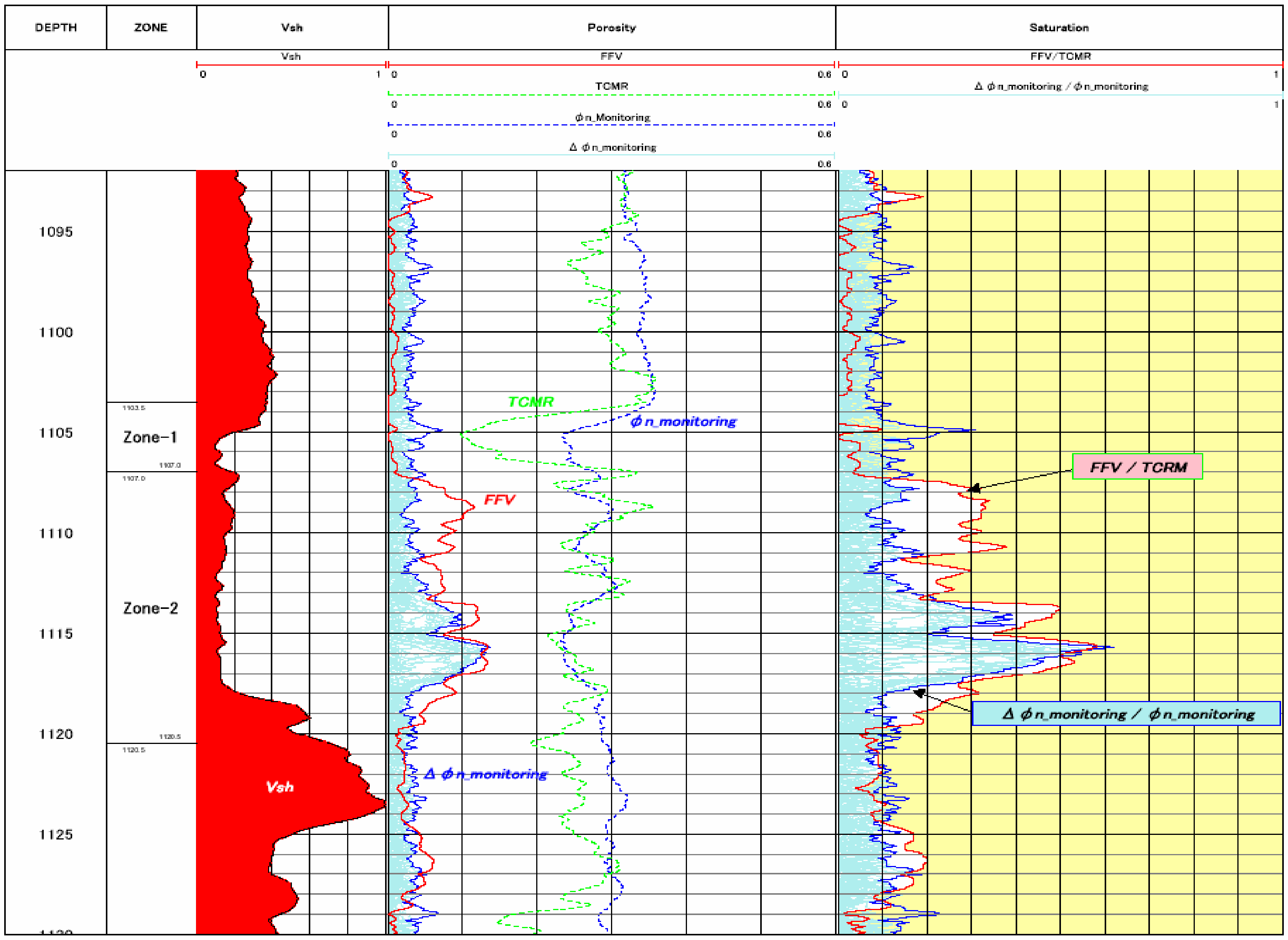


Time-lapse Logging

- Confirmed the CO_2 breakthrough in the observation wells.

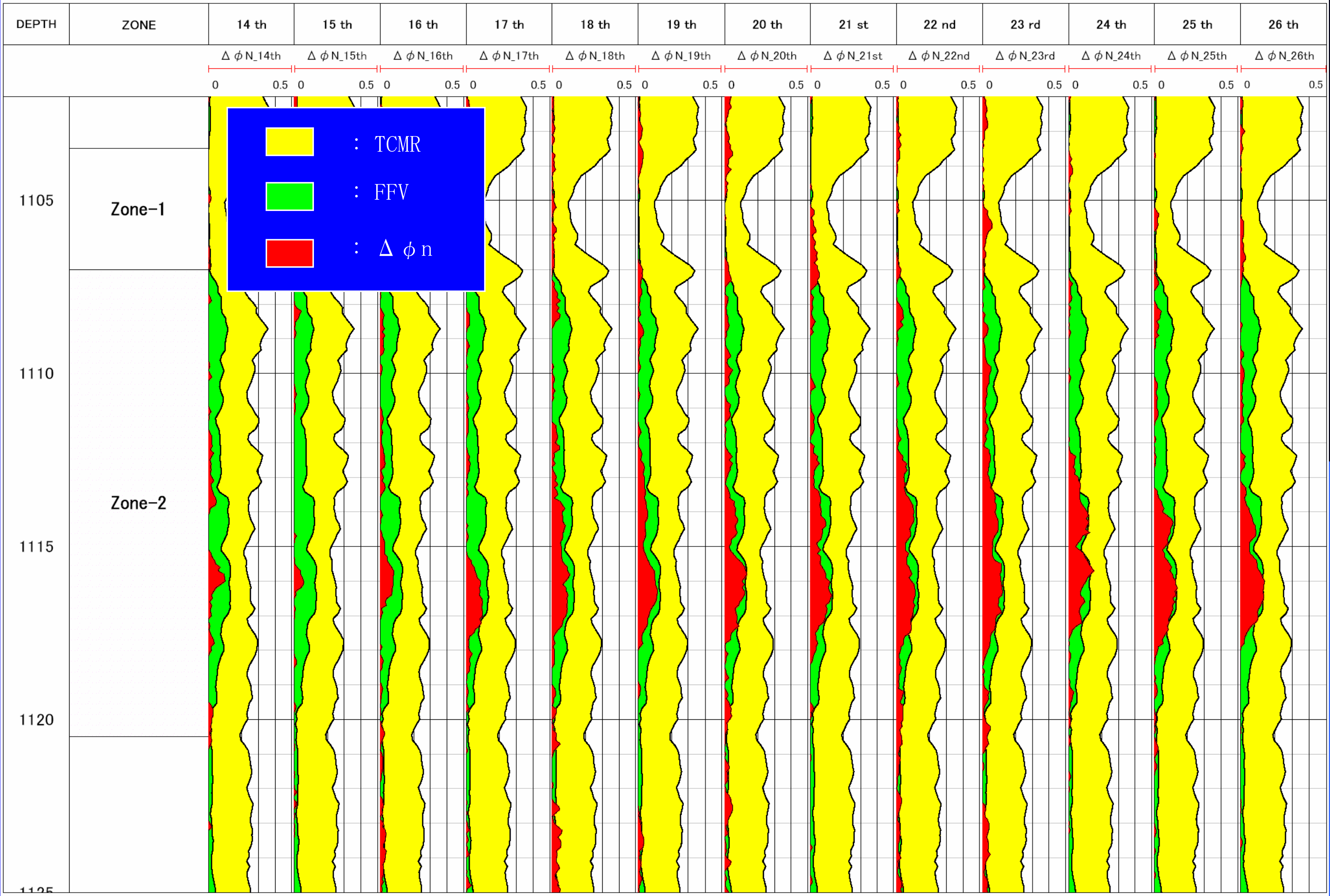
- CO_2-bearing zone in the observation wells getting wider during CO_2 injection (Sonic, Induction, Neutron).

Change of Neutron Porosity (Δ Φn) and FFV*at OB-2

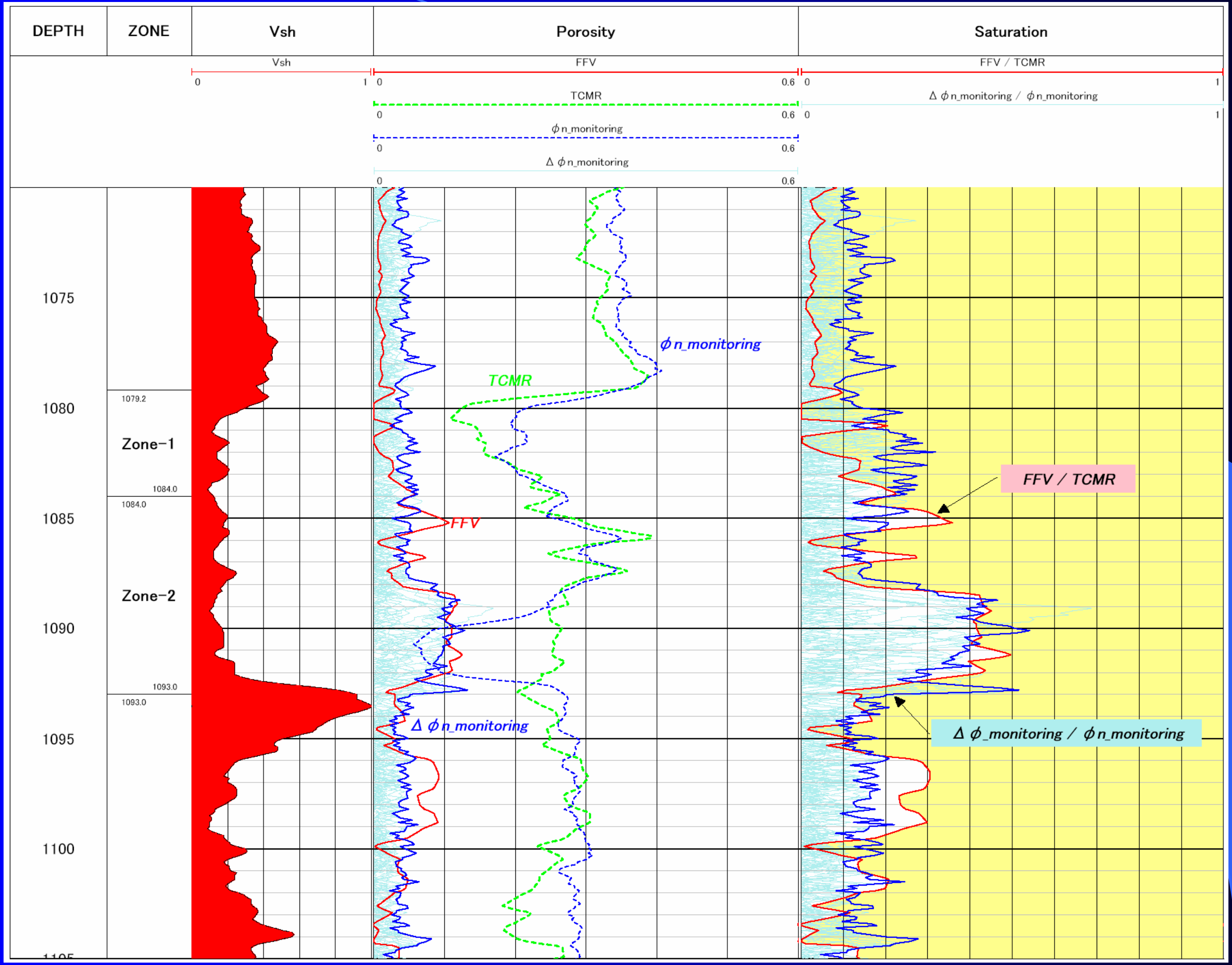


*Free Fluid Volume

History of Δ Φn (OB-2)

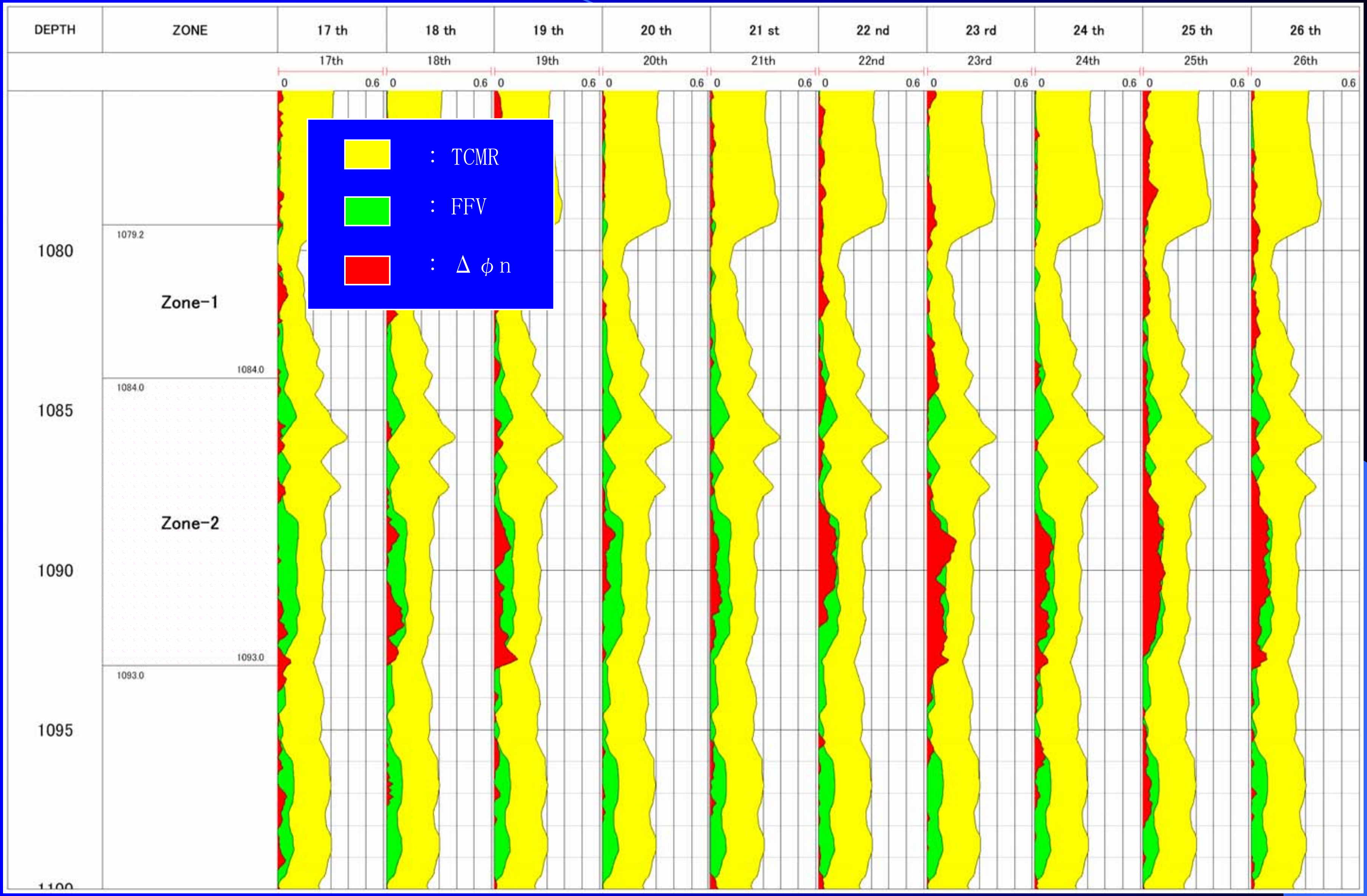


The Relationship Between Φn and FFV* (OB-4)



*Free Fluid Volume

History of Δ Φn (OB-4)



Time-lapse Logging

- Confirmed the CO_2 Breakthrough.
- CO_2-bearing Zone Getting Wider during CO_2 injection (Sonic, Induction, Neutron).

- History of CO_2 Saturation at Observation Wells.

Simulation Study
(by Bottom-hole Pressure and CO_2 Breakthrough)

↓

Innovated Simulation Study
(by CO_2 Saturation History , Bottom-hole Pressure, CO2 Breakthrough)

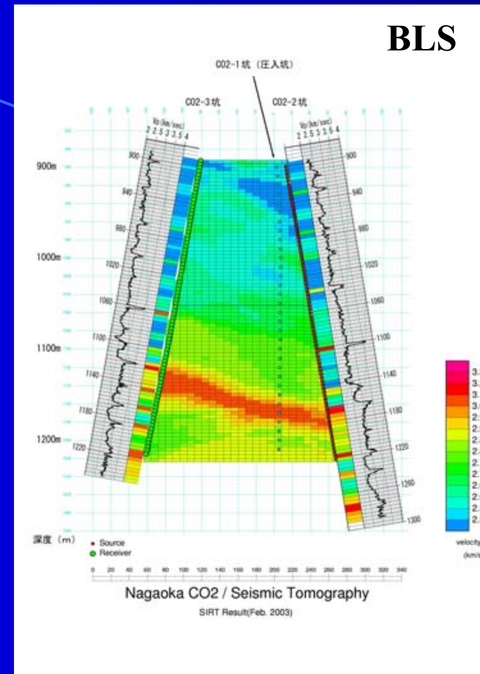
Crosswell Seismic Tomography

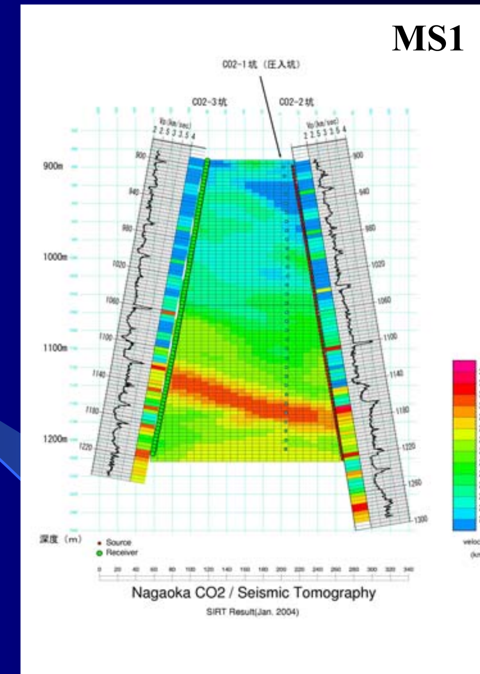
baseline survey	BLS	before injection	Feb 2003	
			Jul 2003	injection started
monitoring surveys	MS1	3,200 t CO2	Jan 2004	
	MS2	6,200 t CO2	Jul 2004	
	MS3	8,900 t CO2	Nov 2004	
	MS4	10,400 t CO2	Jan 2005	injection ended

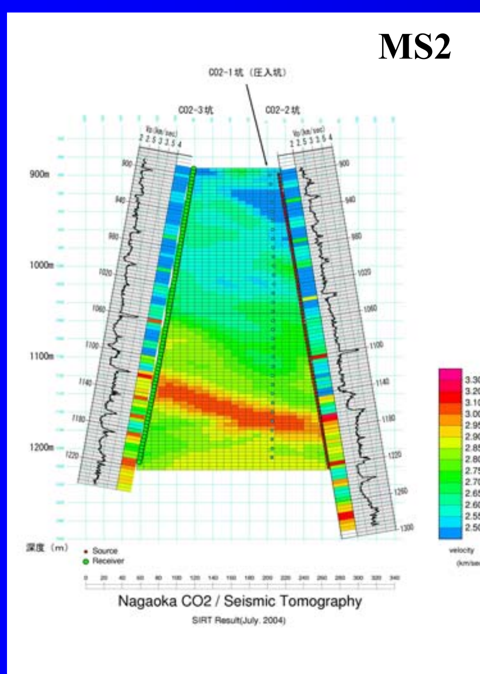
・ OB-2~OB-3

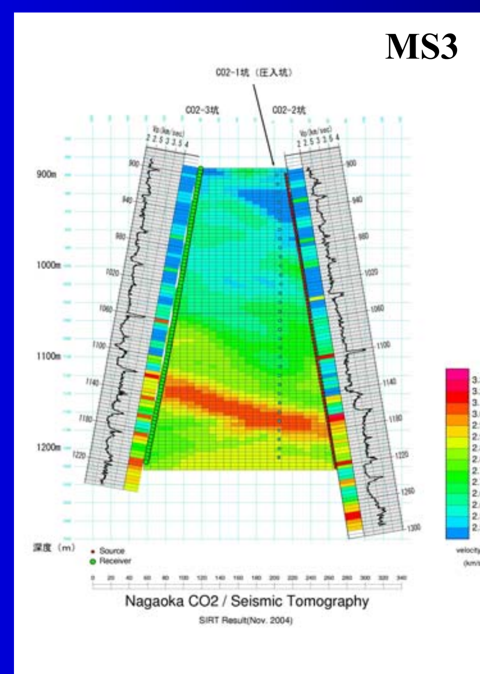
Velocity Tomogram

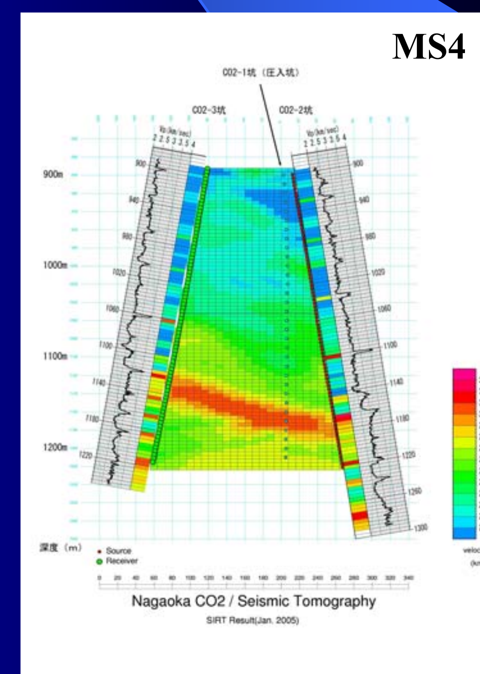
（BLS～MS4）



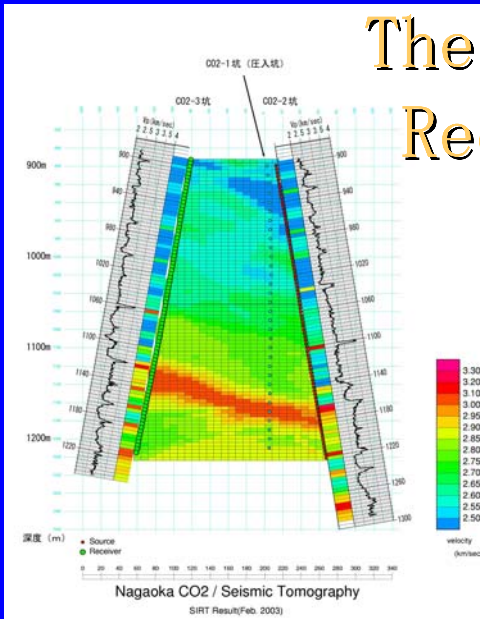




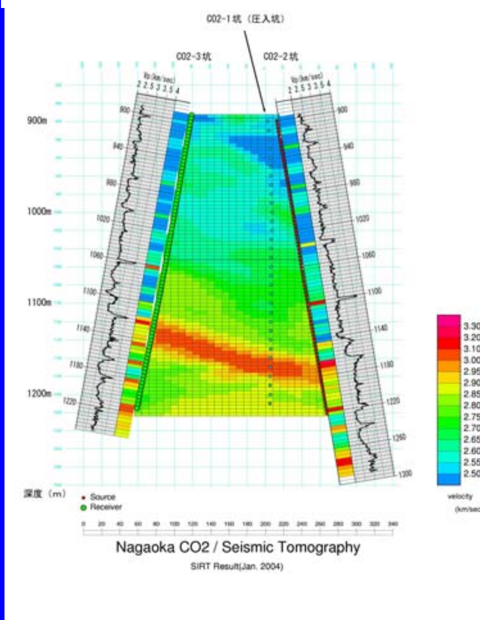




The Rate of Velocity Reduction MS1/BLS



BLS

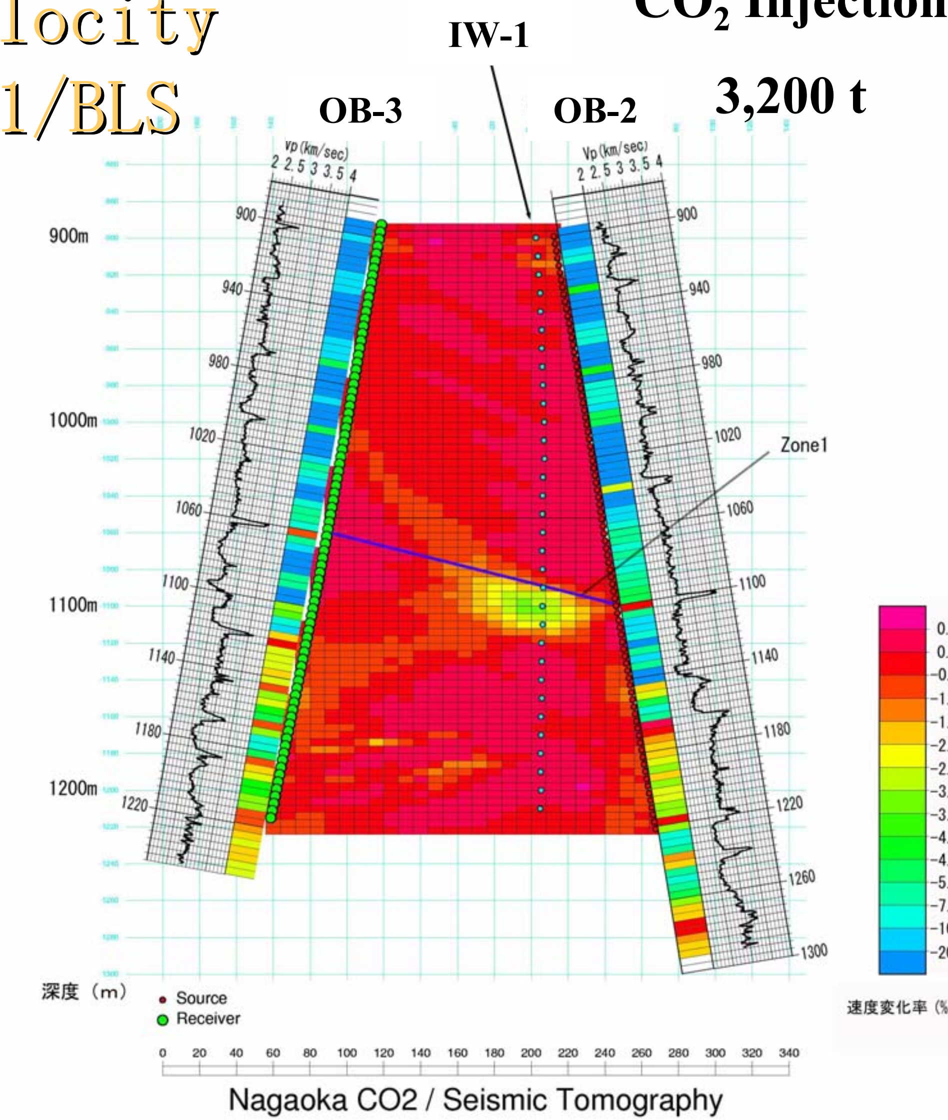


MS1

3,200 t –CO2

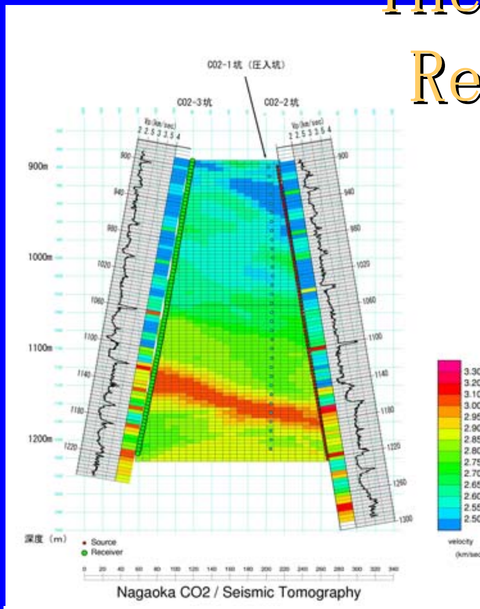
CO_2 Injection

3,200 t

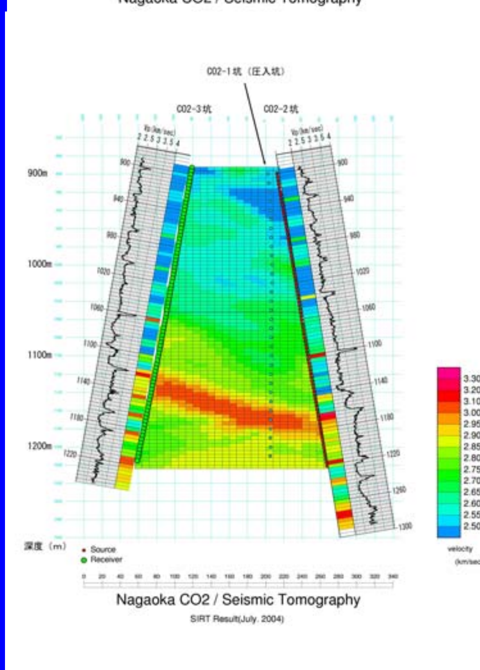


The rate of reduction :Max -3.0%

The Rate of Velocity Reduction MS2/BLS



BLS

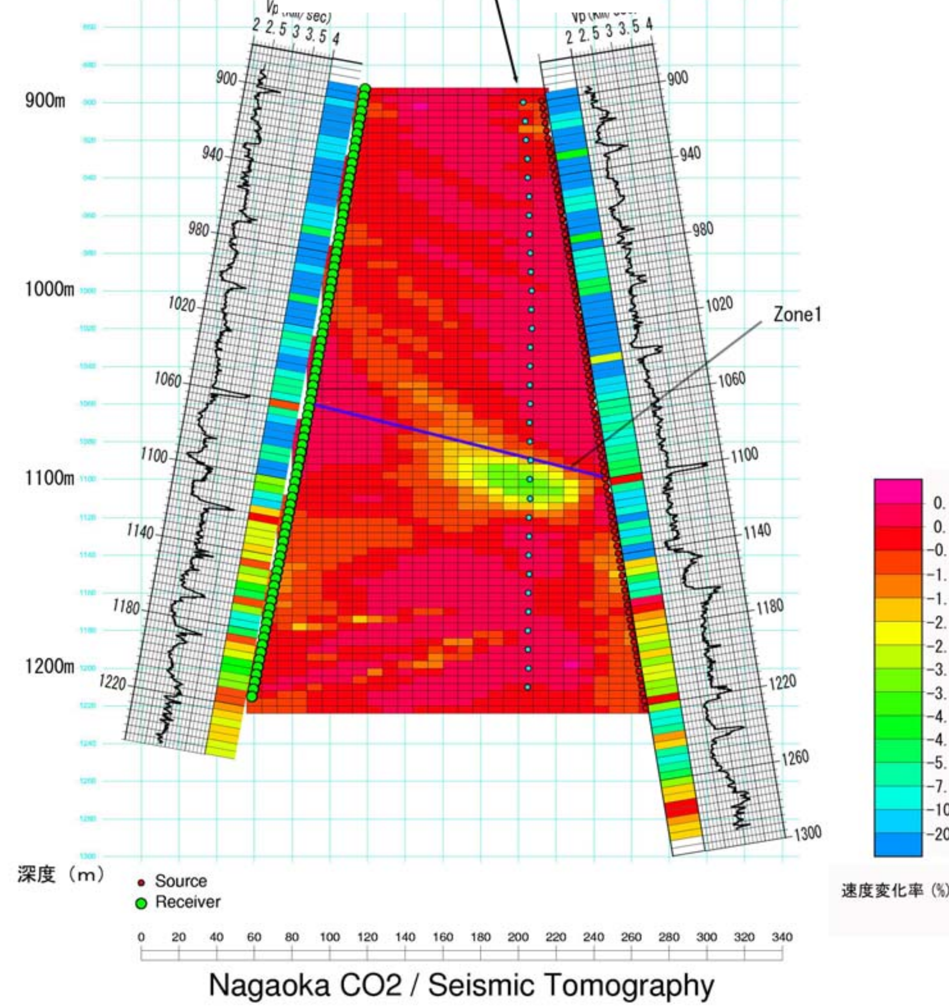


MS2

6,200 t –CO2

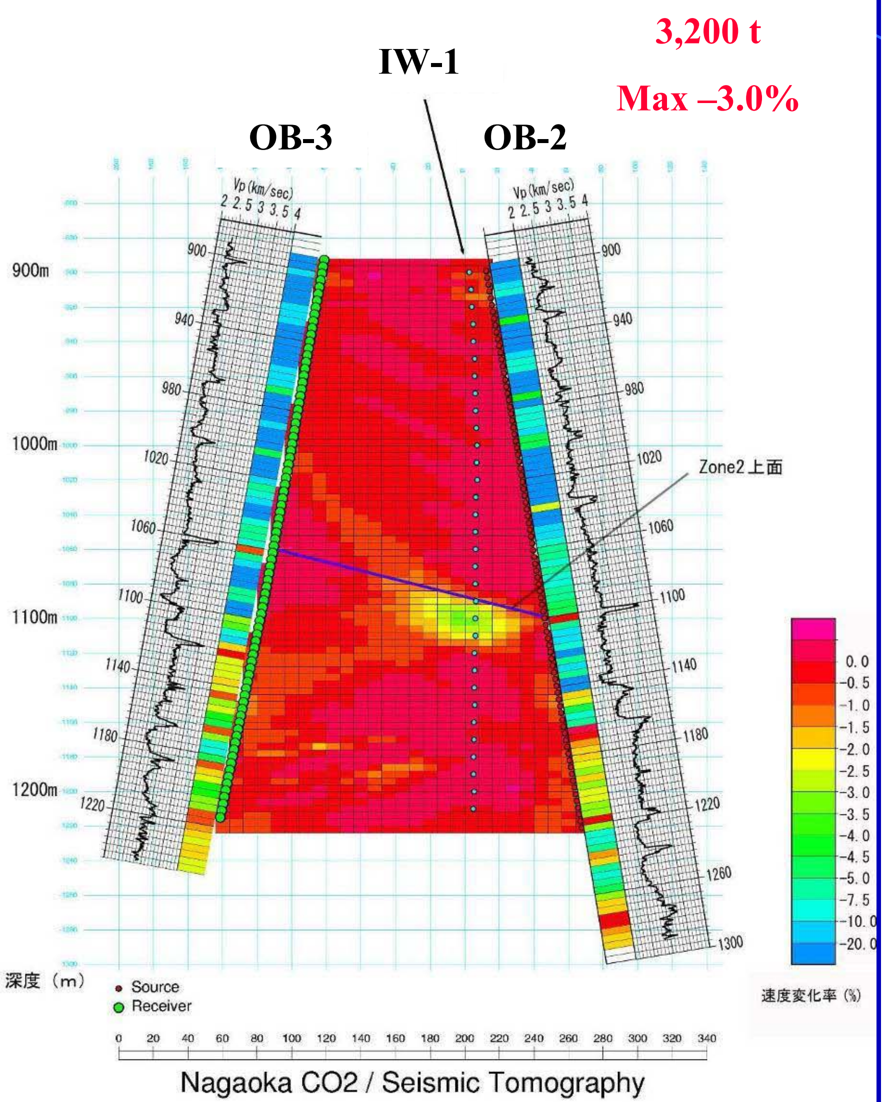
CO_2 Injection

6,200 t

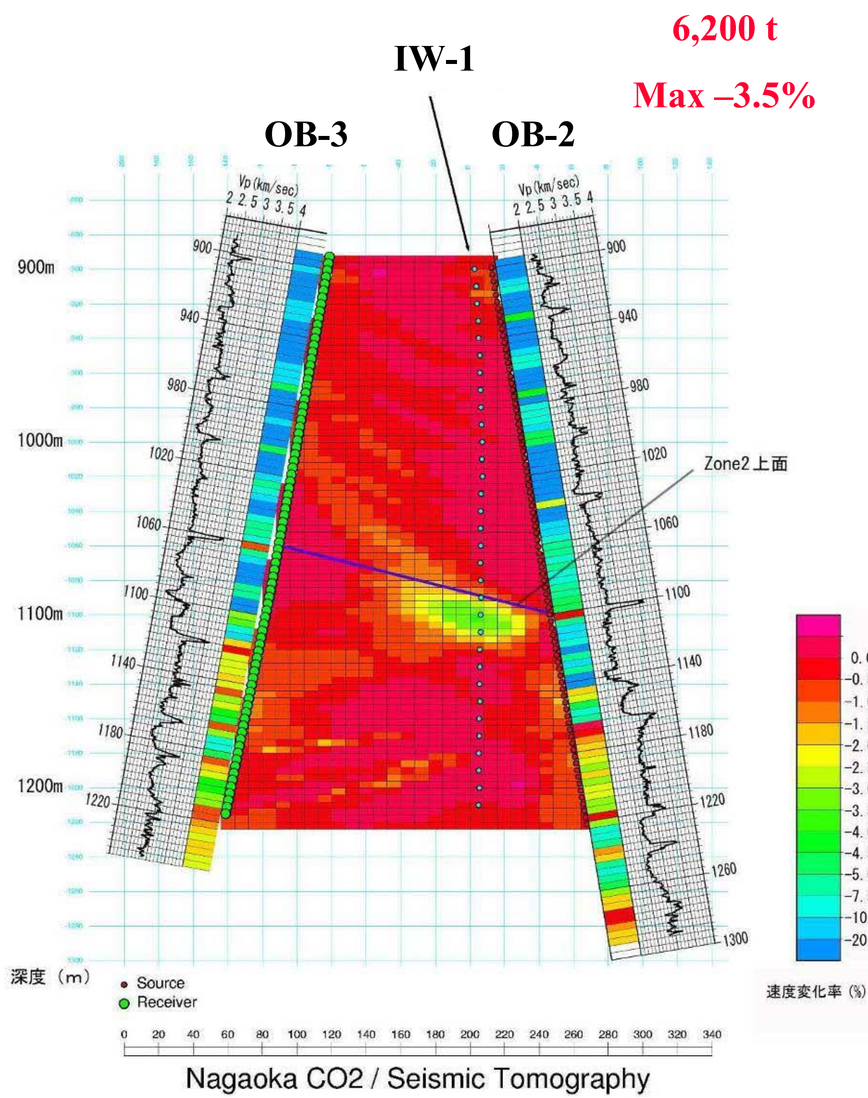


The rate of reduction :Max -3.5%

Rate of Velocity Reduction

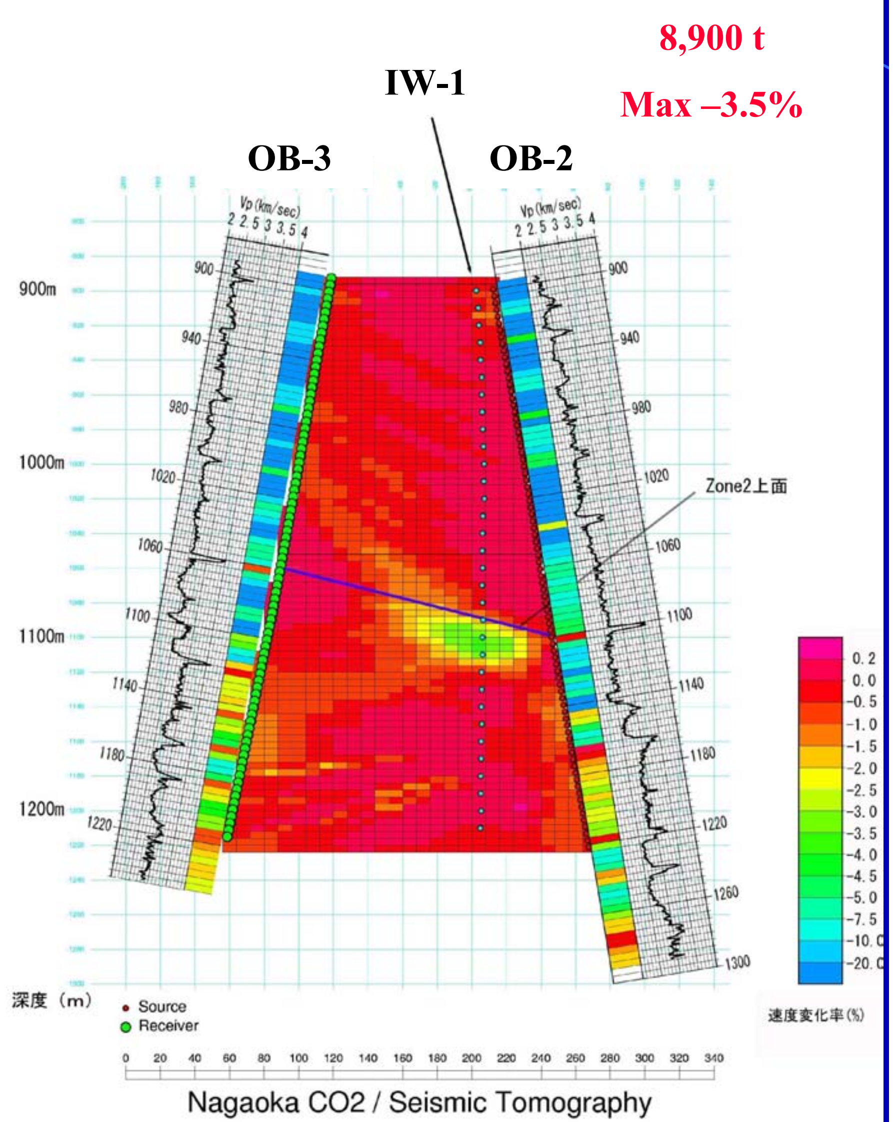


MS1

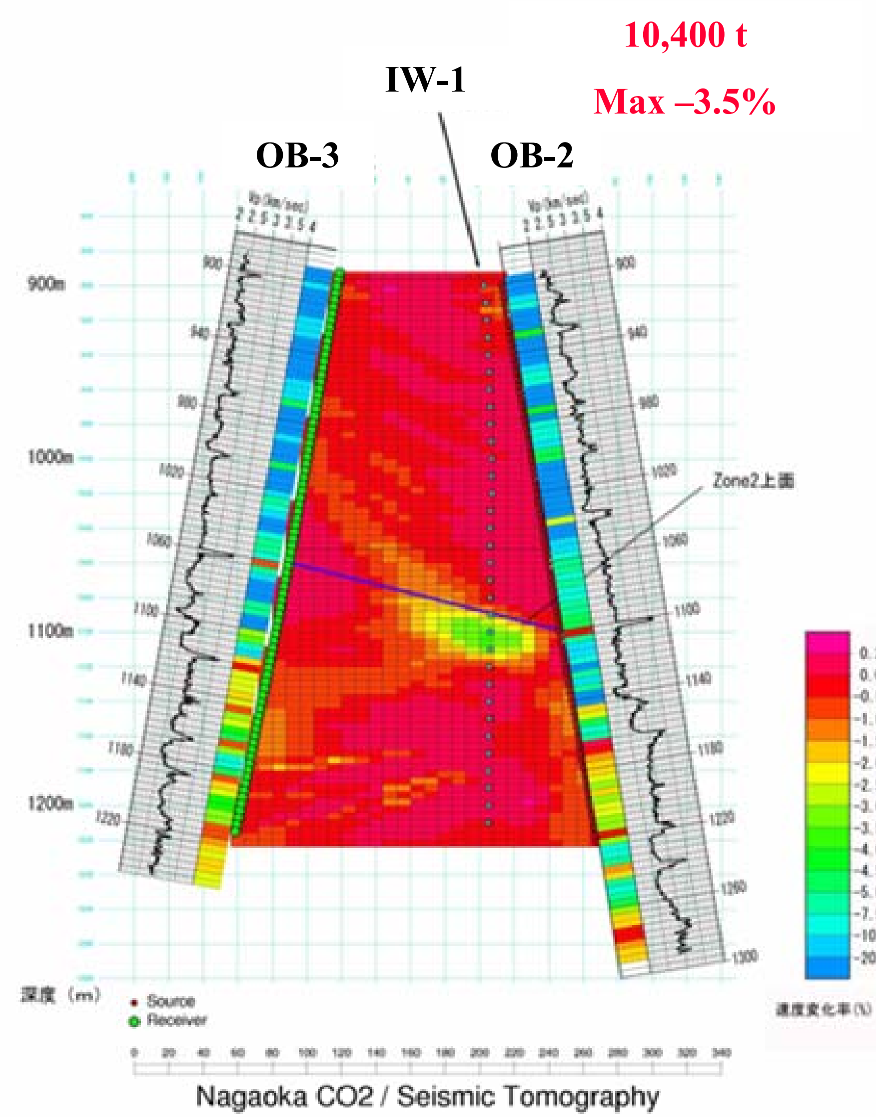


MS2

Rate of Velocity Reduction



MS3



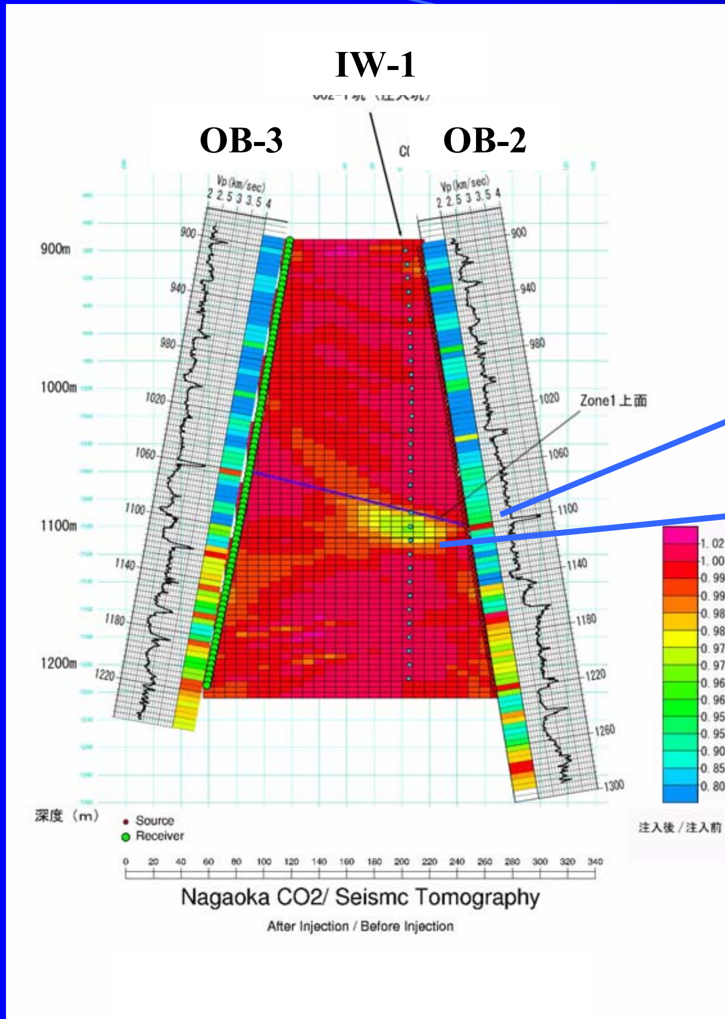
MS4

Crosswell Seismic Tomography

- Detected P-wave velocity decrease (CO_2 invaded zone).

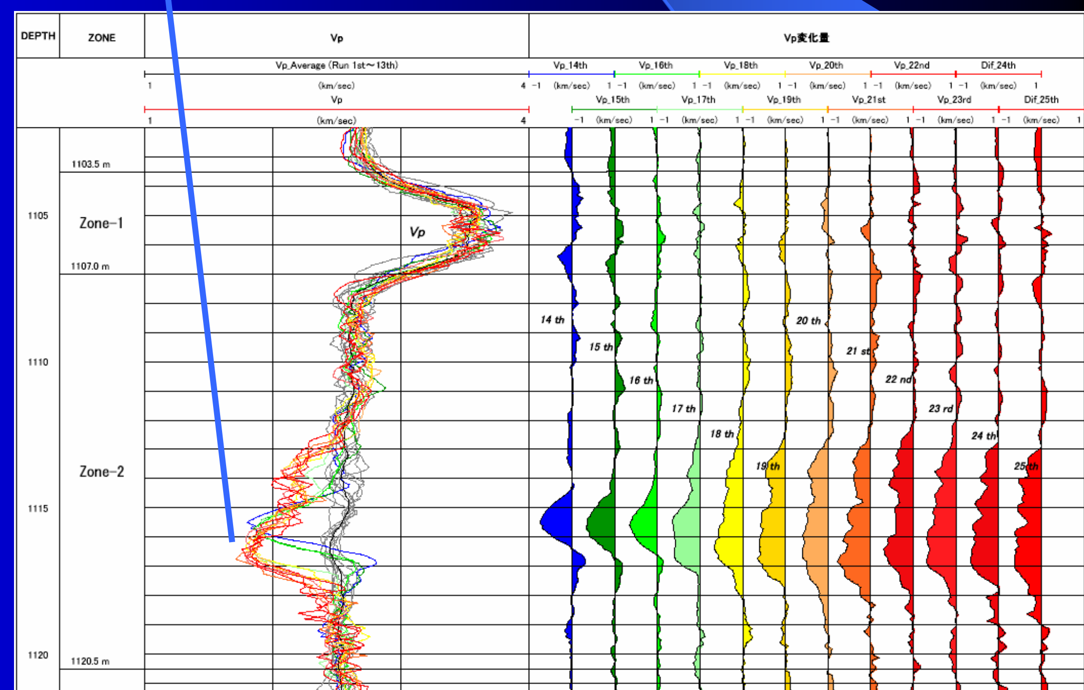
- An area of P-wave velocity decrease appeared near the injection well and the injected CO_2 is migrating along the formation direction during CO_2 injection.

- Confirmed the usefulness of crosswell seismic tomography.

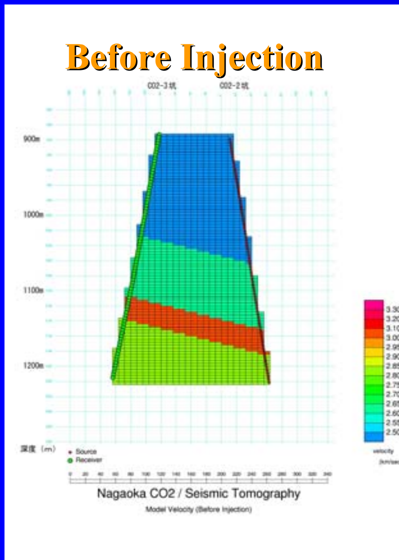


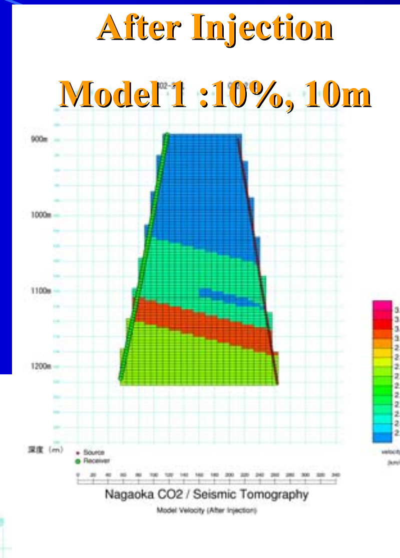
No breakthrough ?

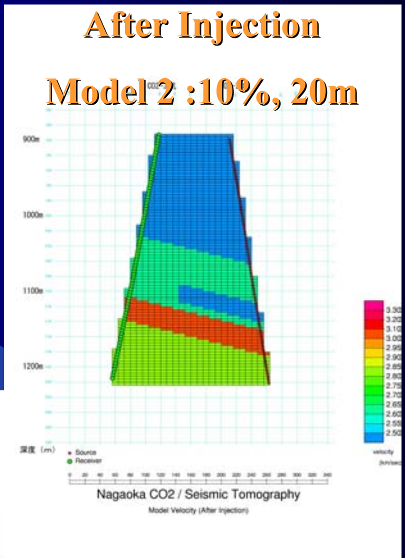
Velocity reduction ?

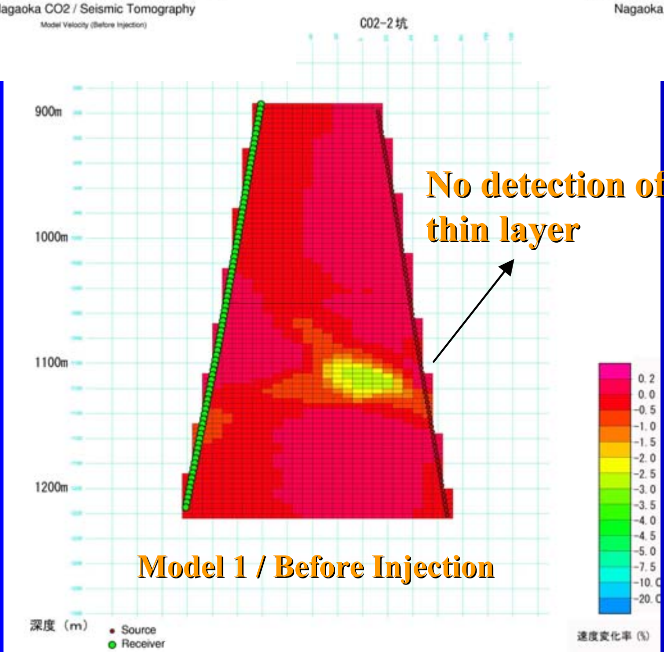


Numerical Simulation Shows Limitation of the Present Results



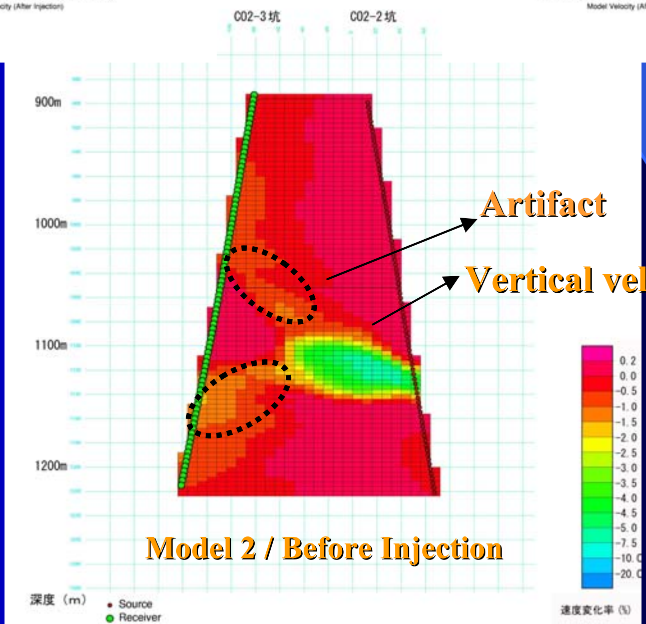






Velocity reduction

Max. －2.9%



Velocity reduction

Max. －5.9%

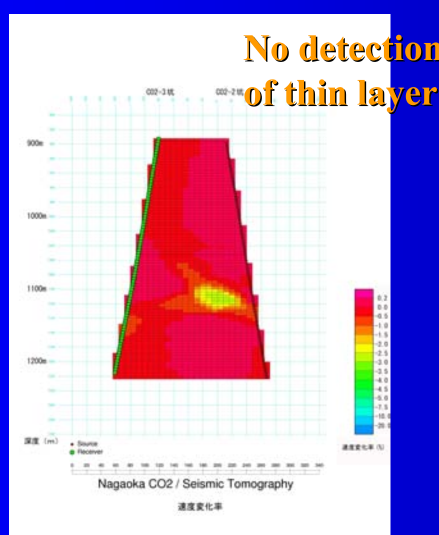
Limitation of the Present Analyses

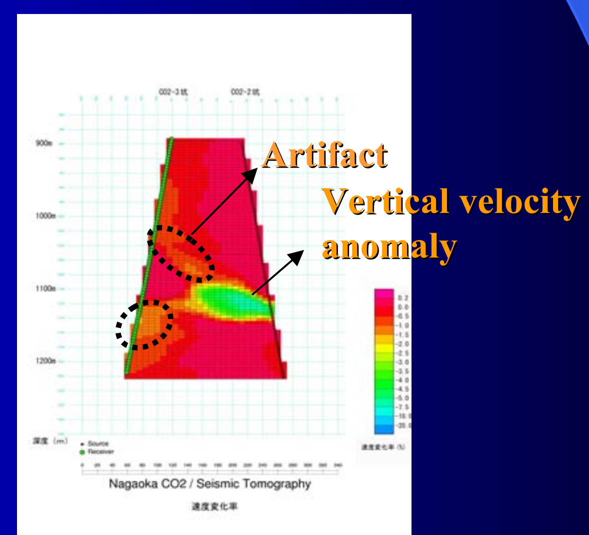
• Velocity reduction is smaller than true velocity reduction. Velocity reduction zone swelled in vertical direction.

•To detect thin layer of 4 – 5 m is difficult.

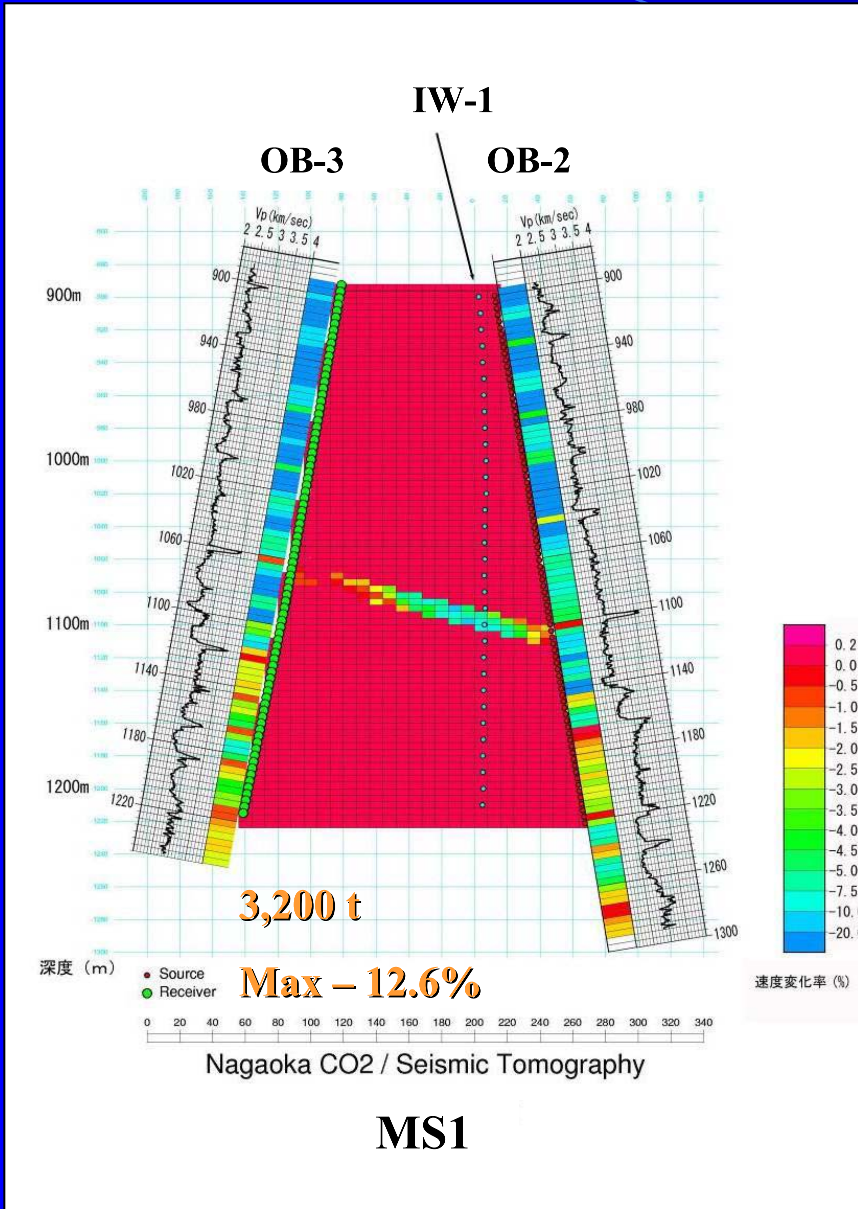
• Ghost similar to the field result occurs.

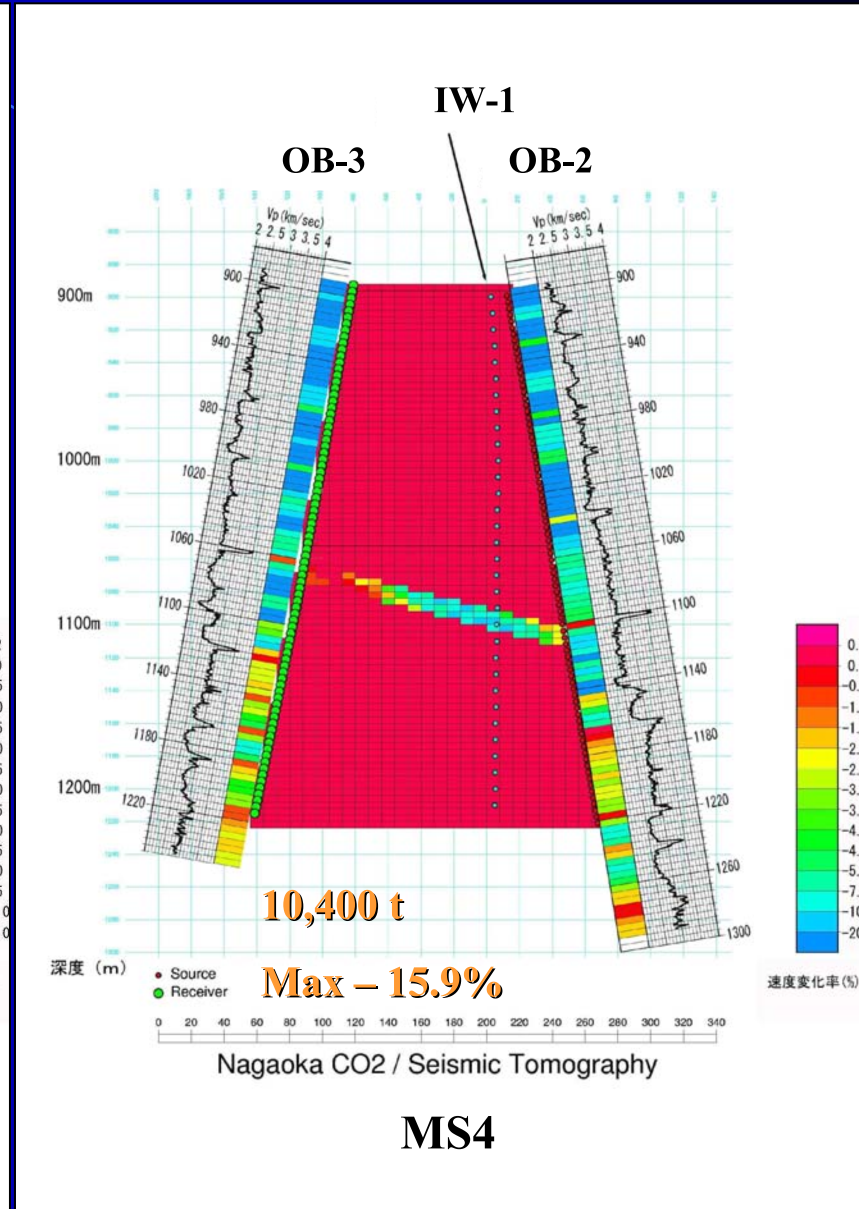
New Analysis with a constrain that CO_2 invades only into Zone-2 (high permeability, no change in well logging)





The New Tomogram under the Constraint

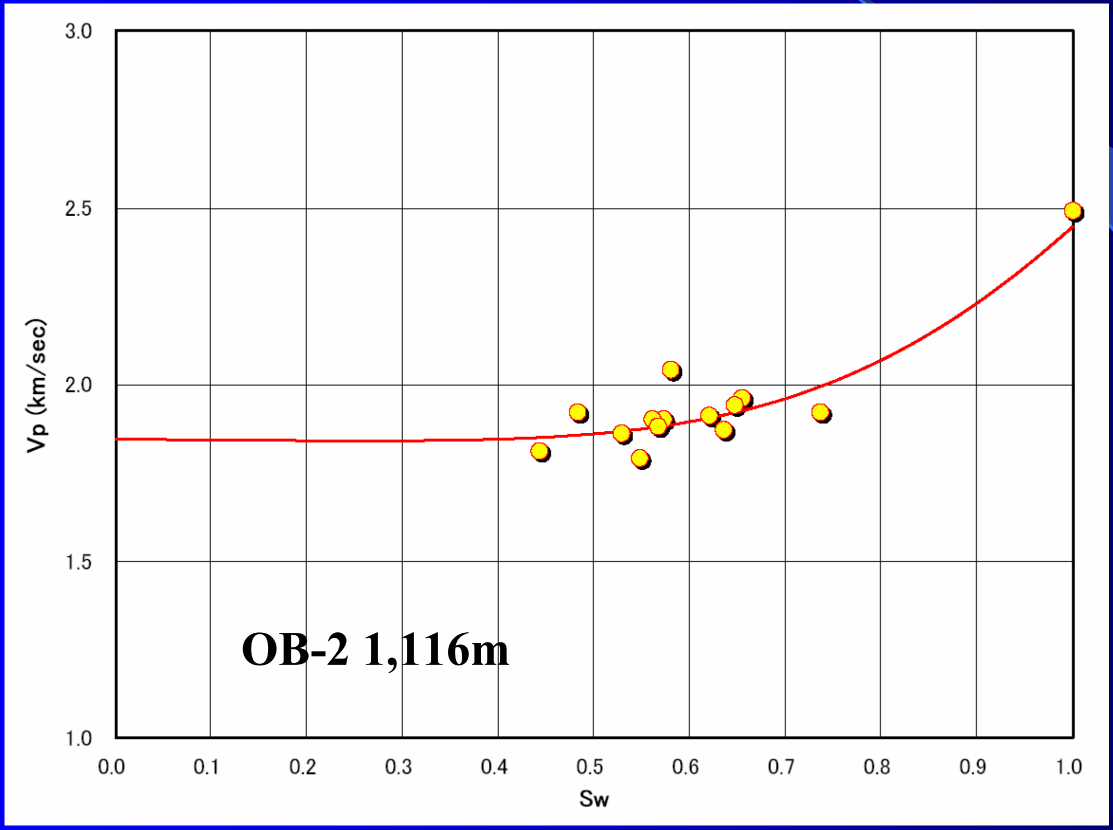




These are shape of CO_2 by Vp.

Time-lapse Logging

- Porosity Neutron Log → CO_2 Saturation, Water Saturation
- Vp form Sonic Log Vp at the same depth → CO_2 Saturation, Water Saturation



Vp from Sonic log vs. Water Saturation from Neutron Log

Mutual Verification among - -

Time-lapse Logging

- CO_2 Saturation History
- Vp History
- CO_2 Breakthough

Crosswell Seismic Tomography

- Tomogram of CO_2 Distribution

Simulation Study

- Using CO_2 Saturation History

Laboratory Test

We came to the door of precise understanding and prediction of CO_2 movement.

Summary

- 10,400 tonnes of CO_2 was injected into an onshore saline aquifer within eighteen months in Nagaoka, Japan.

- By time-lapse logging, we succeeded to detect the CO_2 breakthrough and to estimate CO_2 saturation history.

- By crosswell seismic tomography, we could recognize the shape of CO_2 invasion into the aquifer.

- Simulation Study using CO_2 saturation history will give us more exact understanding and prediction of CO_2 movement.

- The follow-up monitoring in Nagaoka will be continued till 2007.

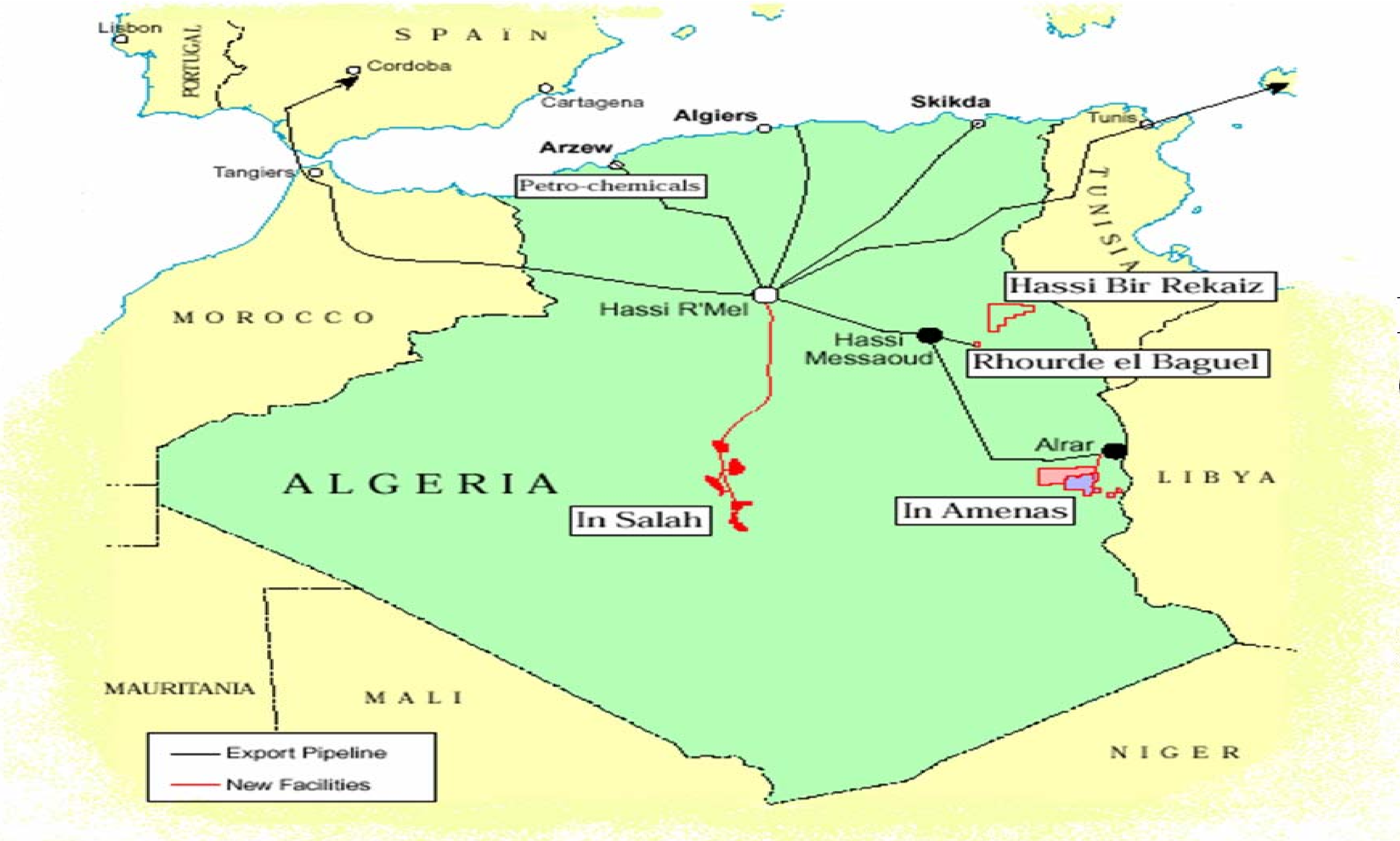
ACKNOWLEDGMENTS

This project is funded by Ministry of Economy, Trade and Industry (METI) of Japan.

Monitoring at InSalah

Dan Ebrom, Charles Christopher, Tony Espie
BP
Upstream Technology Group

CO2 Capture and Storage
2nd Monitoring Network Meeting
Rome, Italy
4-6 October, 2005



In Salah Natural Gas Project – This natural gas has CO_2 component of about 5.5%.

Contractually, this must be reduced to 0.3% before export.

What to do with the separated CO_2?

Saharan Desert

Teg Falaise

InSalah CO2 storage review – June 2005 *Scientific American*

CO2 predominantly from natural sources:

produced along with associated natural gas

Some produced gas as high as 10% CO2: pipeline delivery contracts

specify maximum 0.3% “non-burnables”.

CO2 removed with regenerative amine process.

What to do with CO2? In the past, would have been vented to atmosphere.

InSalah Gas, a joint venture of Sonatrach, BP, and Statoil chooses instead to compress and reinject the CO_2 from 3 fields (Krechba, Reg, Teguentour) in 1 field (Krechba).

CO_2 injection has already begun.

Storage rate are circa 1 million tonnes CO_2 per annum.

Storage is not regulatory driven.

Why store?

Possibility of CO_2 credits at later date, but not guaranteed.

Primary current benefit is promotion of green brand values.

Monitoring is not regulatory driven.

Why monitor?

1. **Provides information to better manage the injection storage process**

2. **Provides assurance that CO2 placed underground remains underground.**

1. Provides information to better manage the injection storage process

a. Location of CO_2 “front” as it percolates through brine-filled portions of reservoir

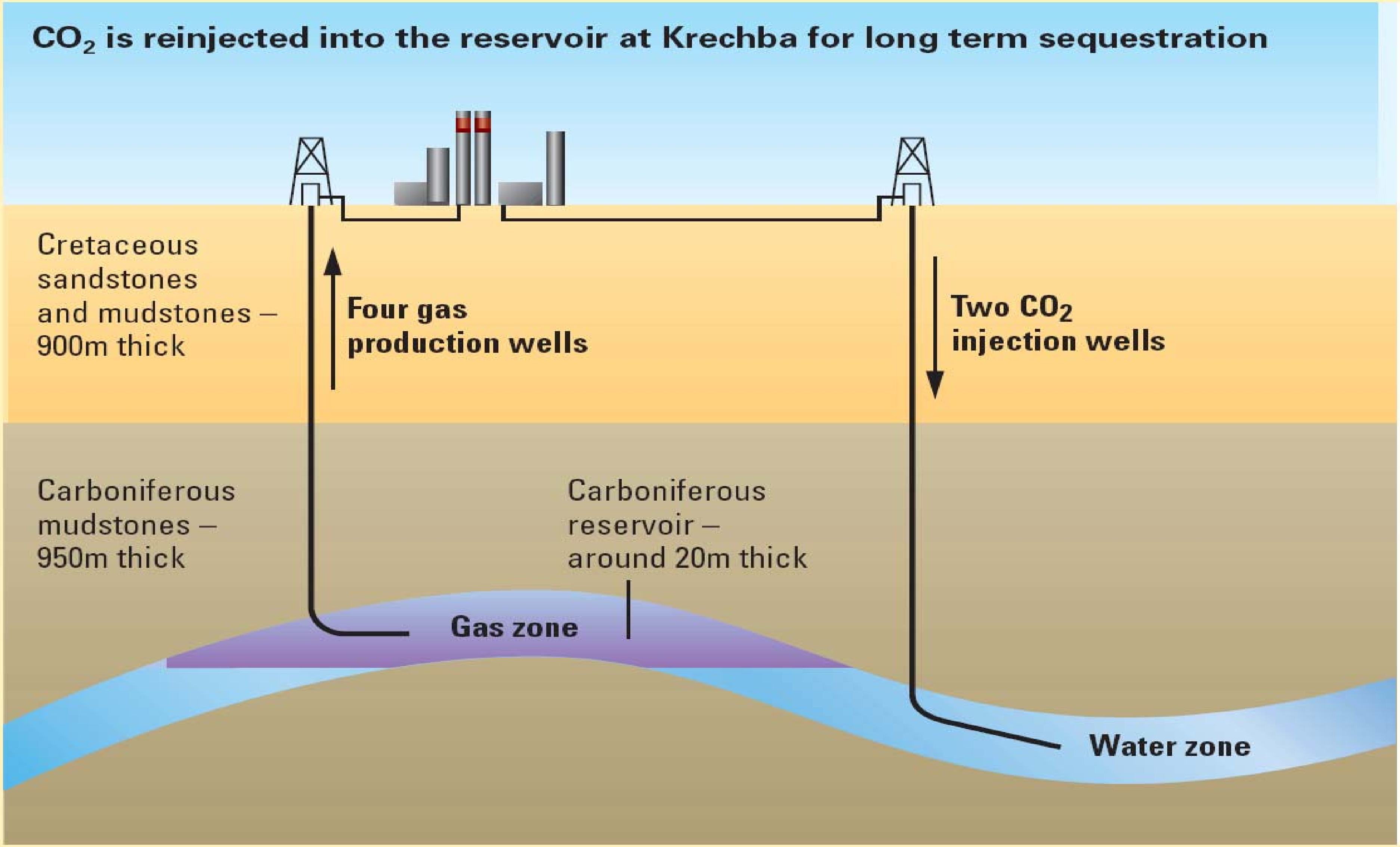
b. Identification of fracture zones that dominate flow

c. Characterization of stress state

2. Provides assurance that CO_2 placed underground remains underground.

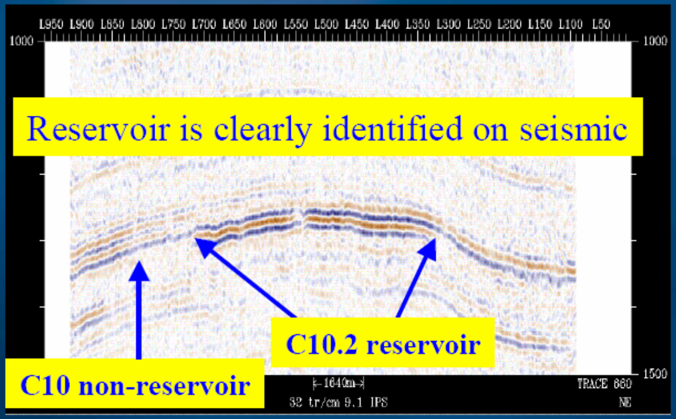
   a. Detect thief zones and migration pathways that lead out of the target reservoir

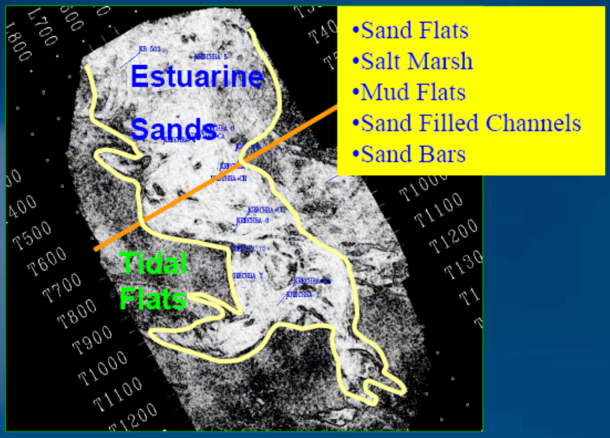
   b. Provide meaningful lower/upper bounds for total amount of CO_2 that can be directly established to be “in place” based on monitoring measurements rather injection history.

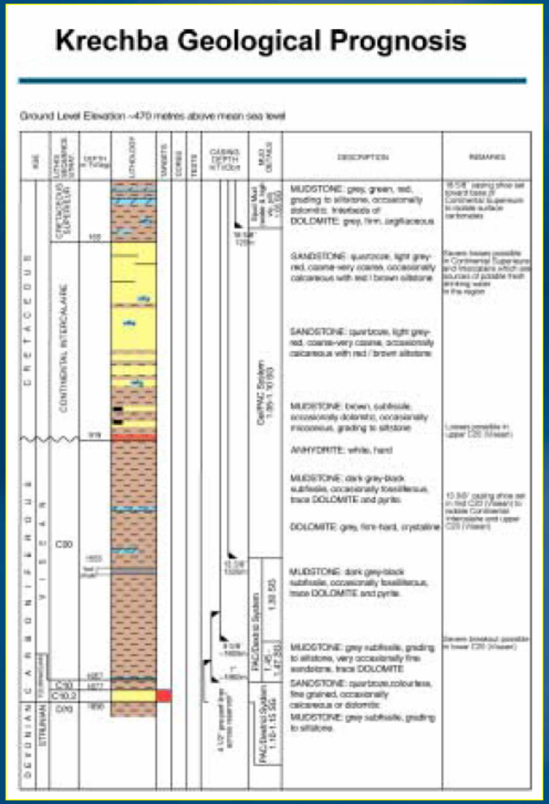


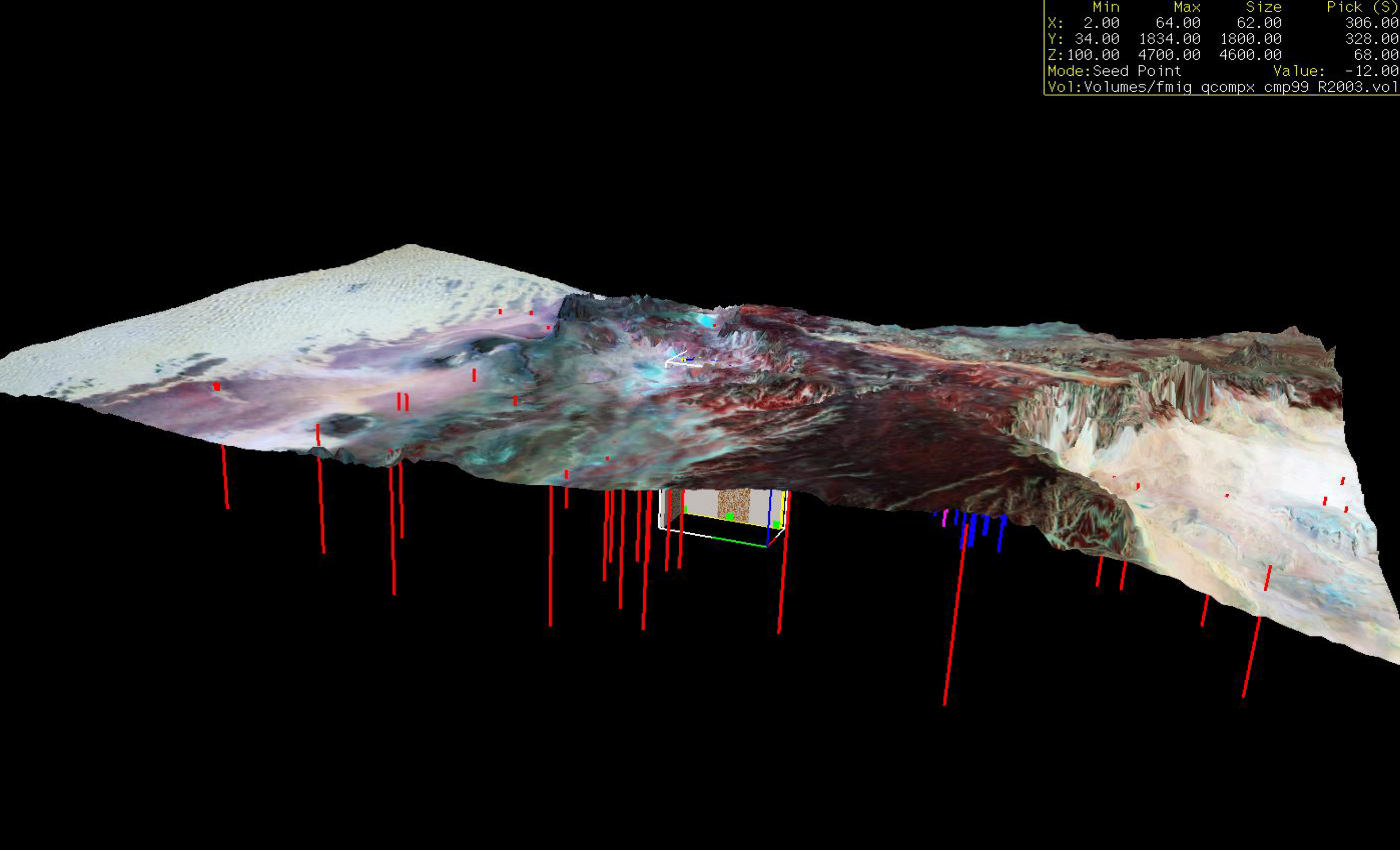
In Salah CO2 re-injection schematic

Krechba Geology

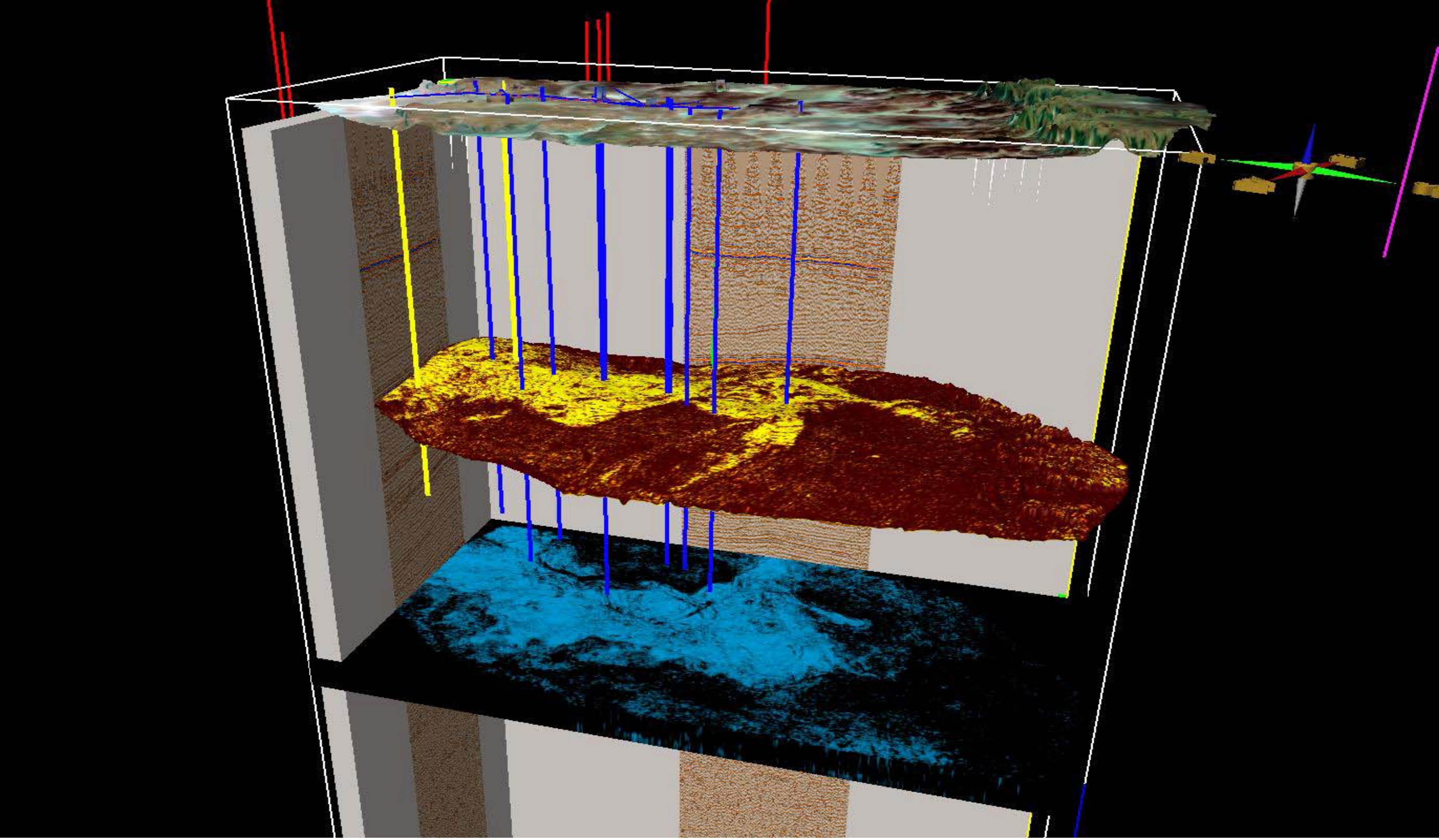






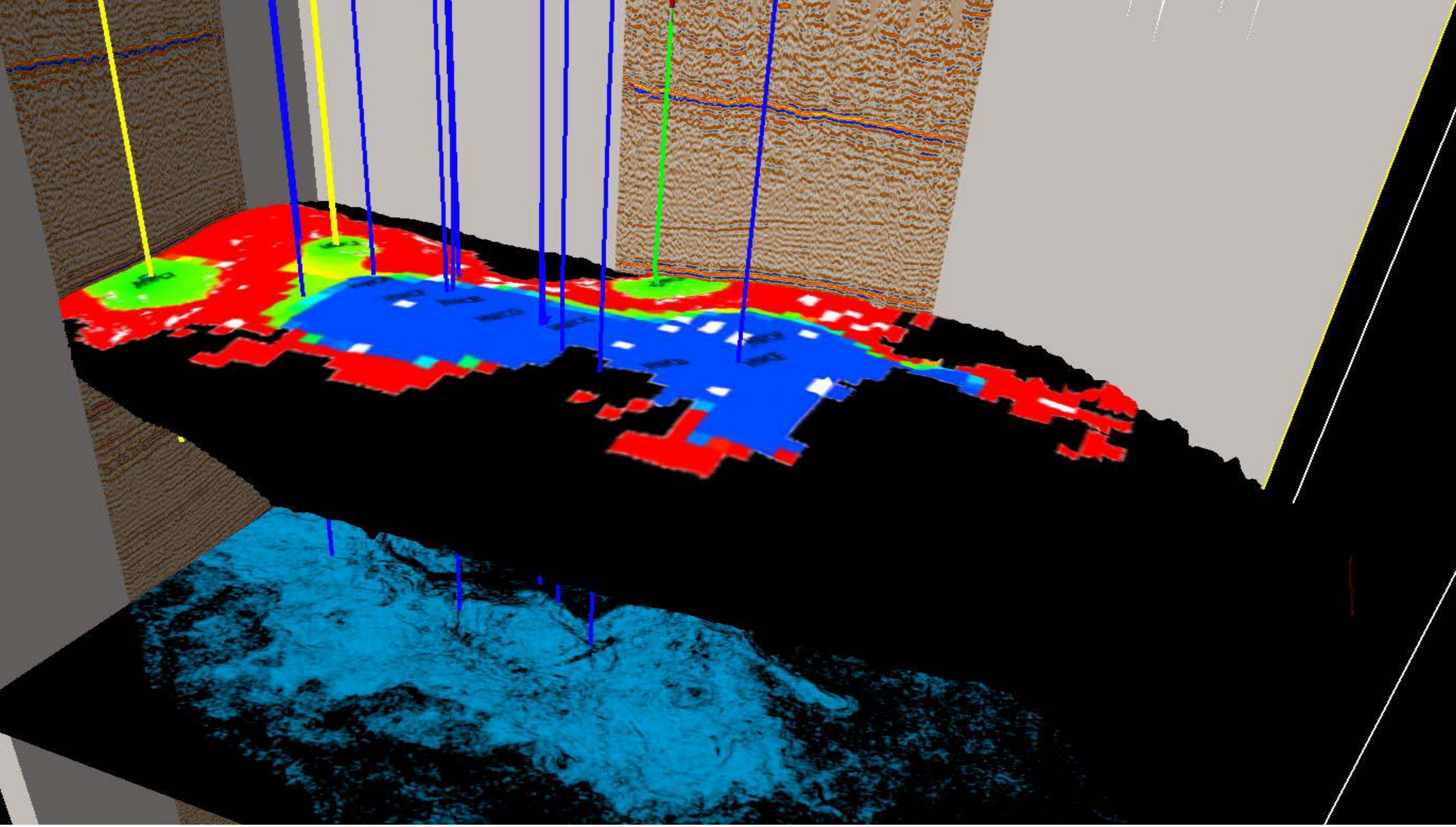


In Salah Topography with with wells



In Salah subsurface view

- 2 horizons with wells and seismic data



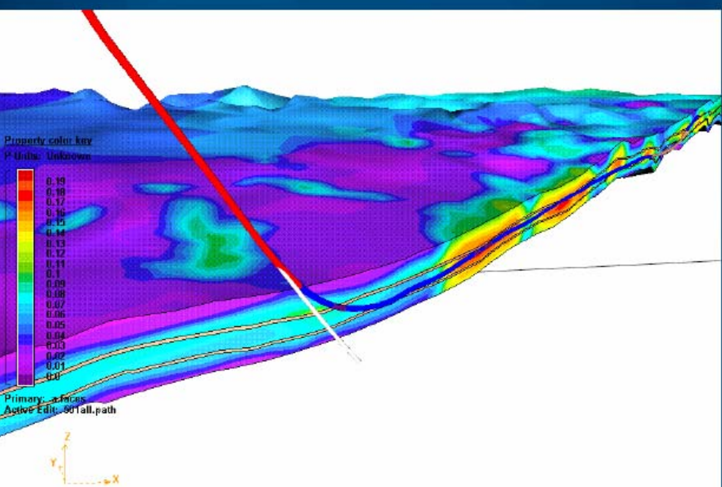
In Salah reservoir simulation

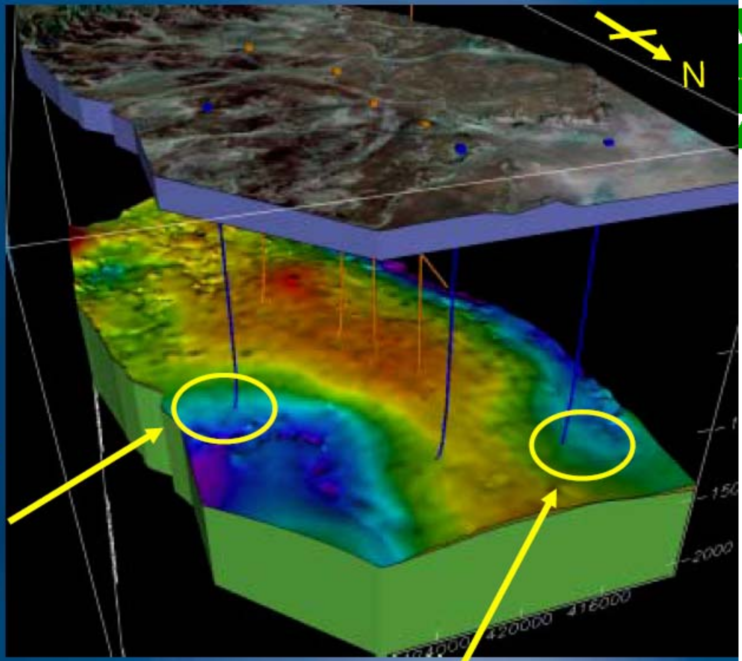
with injection and production wells

Drilling of the First CO_2 Injection Well

1250 metres of horizontal section in Krechba 501 completed in January 2003

15 mmscf/d injectivity potential





Kb-503 will follow Kb-12 in the well schedule

Monitoring current state of play

Feasibility study being done on seismic amplitude changes when CO_2 is substituted for brine.

Pluses: Shallow reservoir, high-Q overburden
Minuses: Harder, older Paleozoic (Carboniferous) reservoir

In parallel, permanent monitoring systems are being designed with
The assumption that the results of the feasibility study will be positive.

A pre-injection 3D seismic baseline survey is available.

Monitoring current state of play

Feasibility study being done on seismic amplitude changes when CO2 is substituted for brine.

Pluses: Shallow reservoir, high-Q overburden
Minuses: Harder, older Paleozoic (Carboniferous) reservoir

In parallel, permanent monitoring systems are being designed with The assumption that the results of the feasibility study will be positive.

A pre-injection 3D seismic baseline survey is available.

Permanent System

Geophones to be deployed in parallel rows of detectors.

The parallel rows will track above the most likely path for the CO_2 to migrate in the subsurface from an injector well. (Assumes movement up anticline parallel to inferred fracture system.)
Circa 400 m between rows, 50 m between sensors.

This 4D receiver system will almost certainly be trenched to a depth of a meter in order to protect the system elements from
•the extremes of temperature common in the Sahara,
•reduce wind noise,
•improve geophone coupling, and
•enhance physical security of the equipment.

•Cannot trench deeper than 1 m without shoring up trench walls: costs then escalate.

Options for sensors:

1. Single vertical geophones.

2. Multicomponent geophones – detect and utilize converted (shear) modes

3. Arrays of vertical component geophones.

- Shear wave polarizations give direct information on fracture orientation,
- but this can also be inferred from P-wave velocity fields.

Seismic sources will be standard (vertical) Vibroseis

- Will re-occupy the source positions in successive 3D surveys, so as to produce (with immovable receivers) a high-repeatability 4D program.

- Challenges that need to be met to achieve highest repeatability include the identification of zones of feshfesh, fine sand that may compact more on initial surveys than later surveys, leading to time-variable seismic signatures.

- On the plus side, the reservoir depth is relatively shallow (just a couple of kilometers), and the overburden should have relatively high P-wave Q (often associated with more compacted sediments).

- When the permanent array is not being used for repeat seismic surveys, the receivers will nonetheless still be active.

- Microseismic events, the result of brittle rock failures in the subsurface, can map out zones of fault activation or other geomechanical responses to increased pore pressure (due to CO_2 injection).

- Since it is not feasible to transmit every byte from a remote location (southern Algeria), only events which exceed a threshold amplitude will be stored to disk, and that disk will be periodically interrogated remotely.

- Possible realtime diffraction hyperbola summation to recognize weaker microseismic events?

•As resources permit, there is a possibility of a dedicated well containing a vertical array of geophones.

•Such an array, placed far below the attenuative low-Q weathering and subweathering zones could act as an early warning system for the surface array, causing events to be recorded onto disk that might not exceed the threshold criterion for any single geophone, but which could be summed together to produce a high quality signal.

What about non-seismic geophysics?

Initial assessment for gravity and electromagnetic surveys at InSalah has been carried out by Mike Hoversten of LBL.

He found promise for both methods at InSalah:

1. Gravity can resolve 10% saturation changes (6 microgal signal with 3-4 microgals as a usual noise basement).
Lateral resolution circa 500 meters.

2. E/M also produces a signal above noise basement with a lateral resolution of circa 500 meters.

Conclusions

The prize for effective monitoring is at least two-fold.

First, by determining where the CO2 is moving, and where it is not, better decisions can be made as to the rate of injection and location of injector wells, and additionally to inform well intervention decisions.

Second, and perhaps more importantly, monitoring can serve to assure all interested parties that the CO2 which has been buried underground remains underground, and has not found a travelpath back to the surface.

With these twin goals in mind, remote monitoring is a likely adjunct of all CO2 injection programs, and will be a key to optimal management of subsurface storage.

Session 3

Monitoring Programmes
-Experience from Developing Projects

CO2CRC : Otway Project

Kevin Dodds

M&V Research Leader

Australian

Cooperative Research Centre

For Greenhouse Gas Technologies

CO2CRC participants:

CRC AUSTRALIA

Australian Government
Geoscience Australia
Australian Greenhouse Office
Department of Industry, Tourism and Resources

Victoria
The Place To Be

xstrata coal

bp

NZ RESOURCE CONSORTIUM

STANWELL CORPORATION LIMITED

CSIRO

MONASH University

RIO TINTO

PRIMARY INDUSTRIES AND RESOURCES SA

THE UNIVERSITY OF MELBOURNE

curtin University of Technology Western Australia

ACARP Australian Coal Association Research Program

WOODSIDE AUSTRALIAN ENERGY

ChevronTexaco

UNSW

THE UNIVERSITY OF ADELAIDE AUSTRALIA

bhpbilliton

Schlumberger

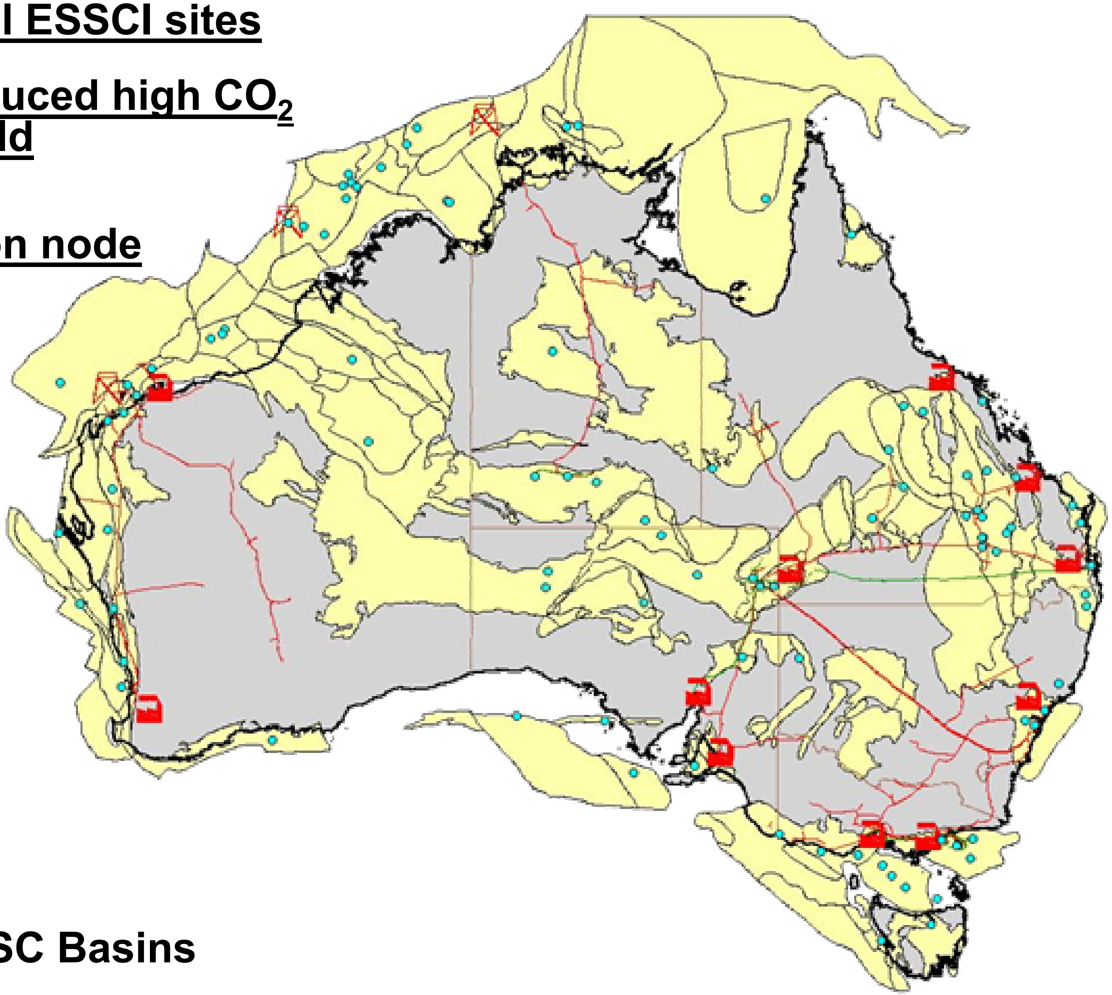
CO_2 Source-Sink Studies

(after Bradshaw et al)

Potential ESSCI sites

Unproduced high CO_2 gas field

Emission node



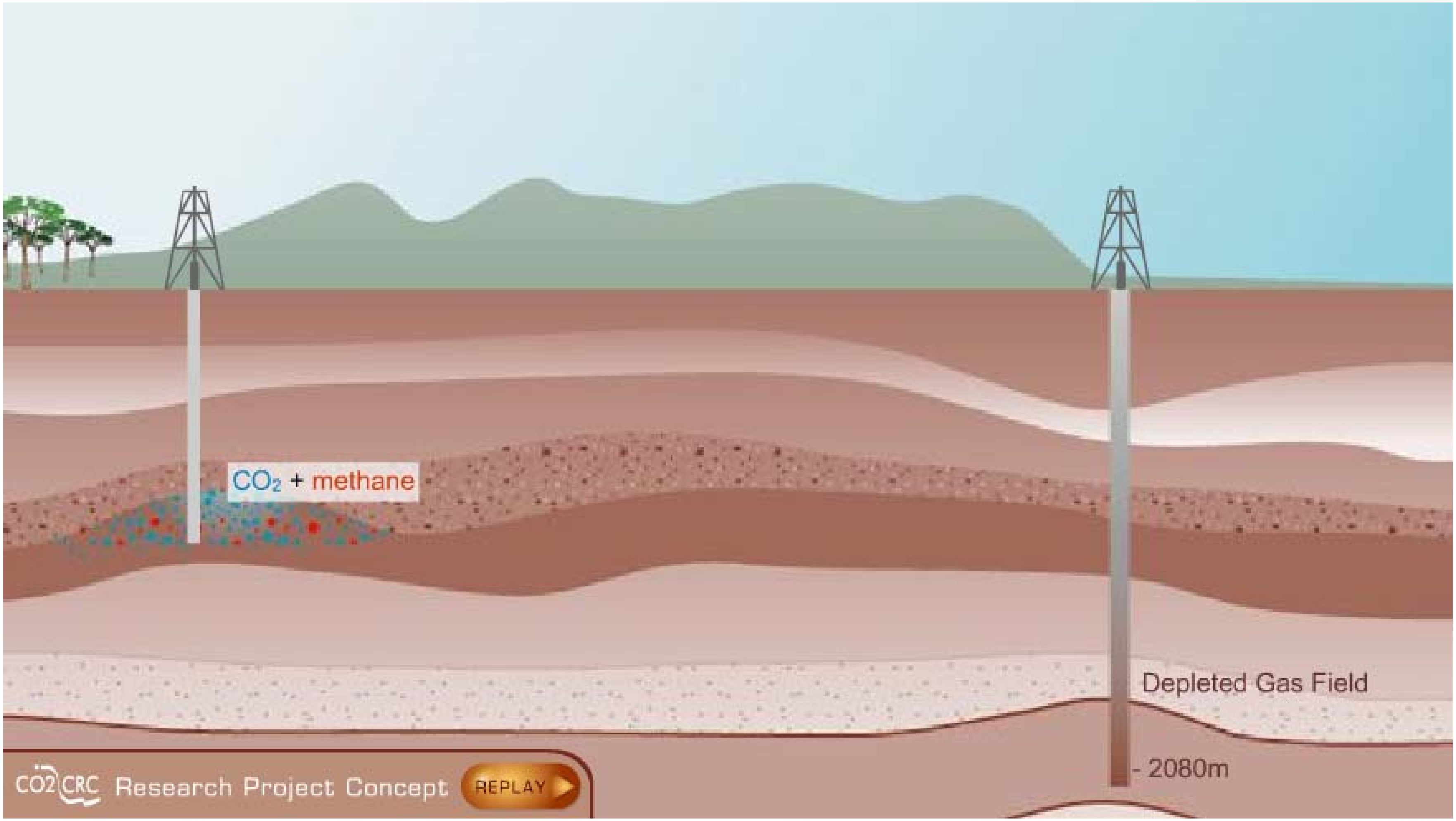
GEODISC Basins

- **48 basins were considered viable sites for study (out of > 300)**
- **102 sites analysed**
- **65 proved viable ESSCIs**
- **22 sites not viable; 15 regional basin overviews**

Outline

- CO2CRC Pilot Program Objectives
- Description
- Monitoring Workscopes
- Timeline

Conceptual Representation of Pilot Project



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Assets : Source and Sink

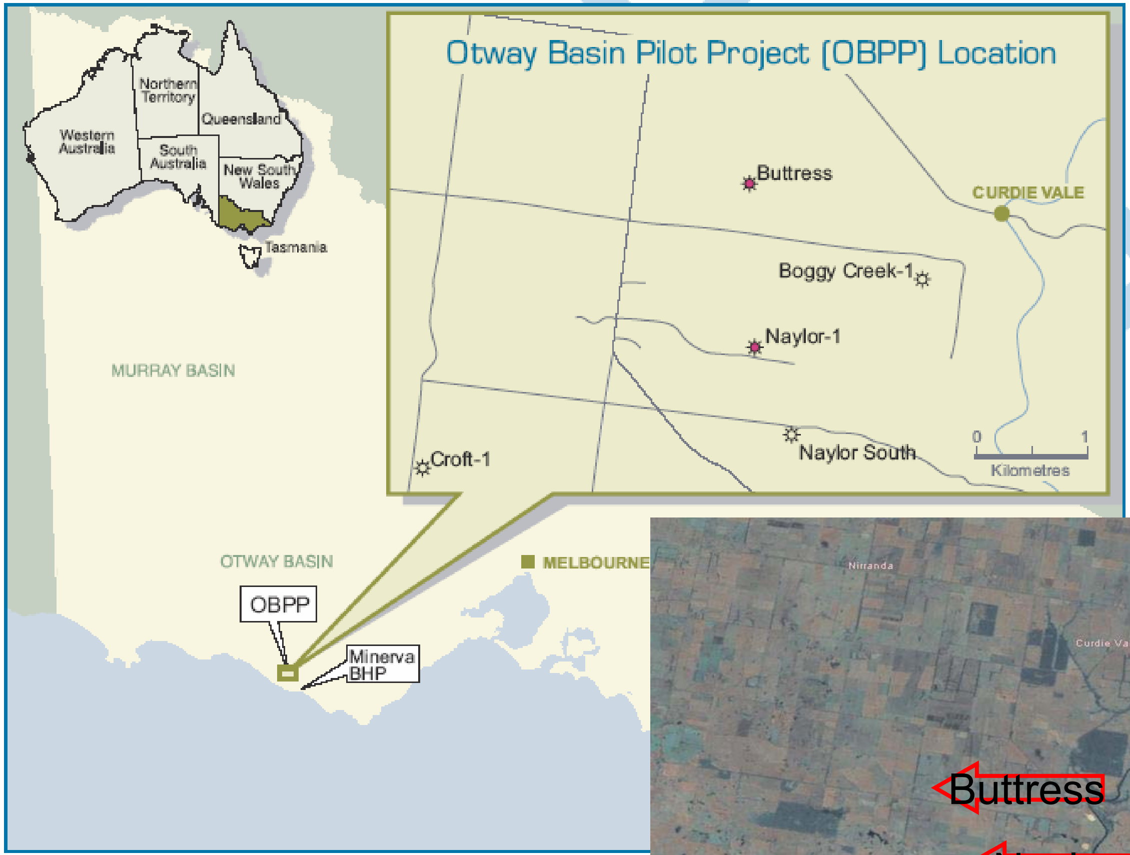
- **Assets considered by CO2CRC in the onshore Victorian Otway Basin**

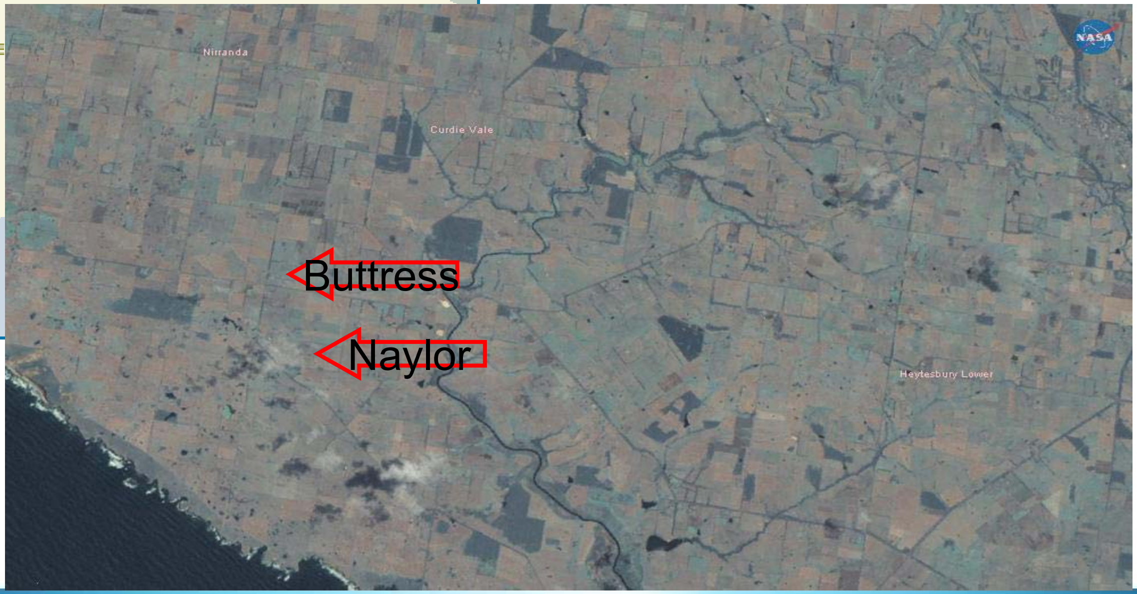
- **<u>Source of CO_2</u> from suspended, but never produced, Buttress-1.**
  - **85% (possibly greater) CO_2 and 15% methane from the Cretaceous Waarre Formation around 1960m**
- **<u>Sink for CO_2</u> could have been at several well-bores**
  - **Naylor-1, a then "near-depleted" single well, gas producer about 3-4 km from Buttress-1**

Pilot Project Objectives

- To demonstrate that CO_2 capture and storage is a viable, safe, secure option for greenhouse gas abatement in Australia by
  - Safely transporting CO_2 from source to sink
  - Safely injecting CO_2 into subsurface reservoirs
  - Safely storing CO_2 in the subsurface
  - Model and monitor stored CO2 and confirm effectiveness
  - Build and Maintain effective Risk Register
  - Safely removing facilities and restoring sites
- And
  - Communicating to all stakeholders that this has been done
  - Conducting the pilot project within approved time and budget (CO2CRC)
  - Capturing all research outcomes (CO2CRC)

Locality Map





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Frio-Otway Comparison

Pilot Project		**Frio**	**Otway**
Reservoir		**Saline aquifer**	**Depleted gas field**
		Poorly consolidated SS Homogeneous	Consolidated SS Possibly fractured
		26m thick	26m thick
Depth		1500m	2000m
Trapping		**Residual (phase)**	**Structural (fault/anticline)**
Distance between wells		**30m**	**500m**
Quantity/time		**1600 tonnes/ 10 days**	**100,000 tonnes/ 2 years**
Injection rate		160 Tonnes/day	160 Tonnes/day
Breakthrough at obs. well		2 days	6 months
Monitoring	Key technologies	RST logs U-tube Crosswell EM/seismic	Logs? U-tube? VSP/ 2D-3C seismic?
	Challenge	Detection of small volume	Detection in presence of methane
CO_2 purity		**Pure (food grade)**	**~97% (~3% CH_4)**
Project life		**12 months**	**4 years**
Main leakage risk		Old wells	Fault

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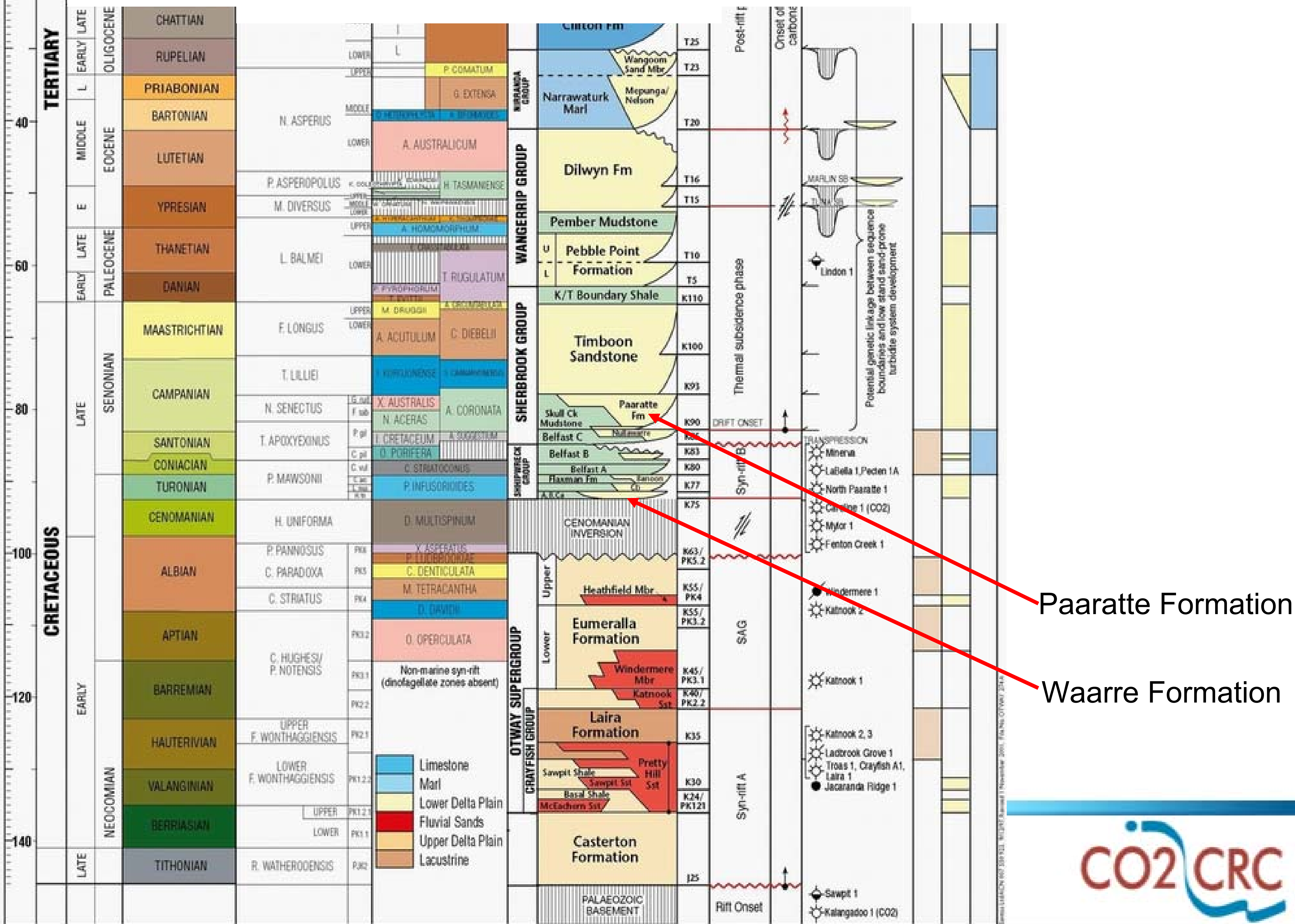
Otway Basin Stratigraphic Column



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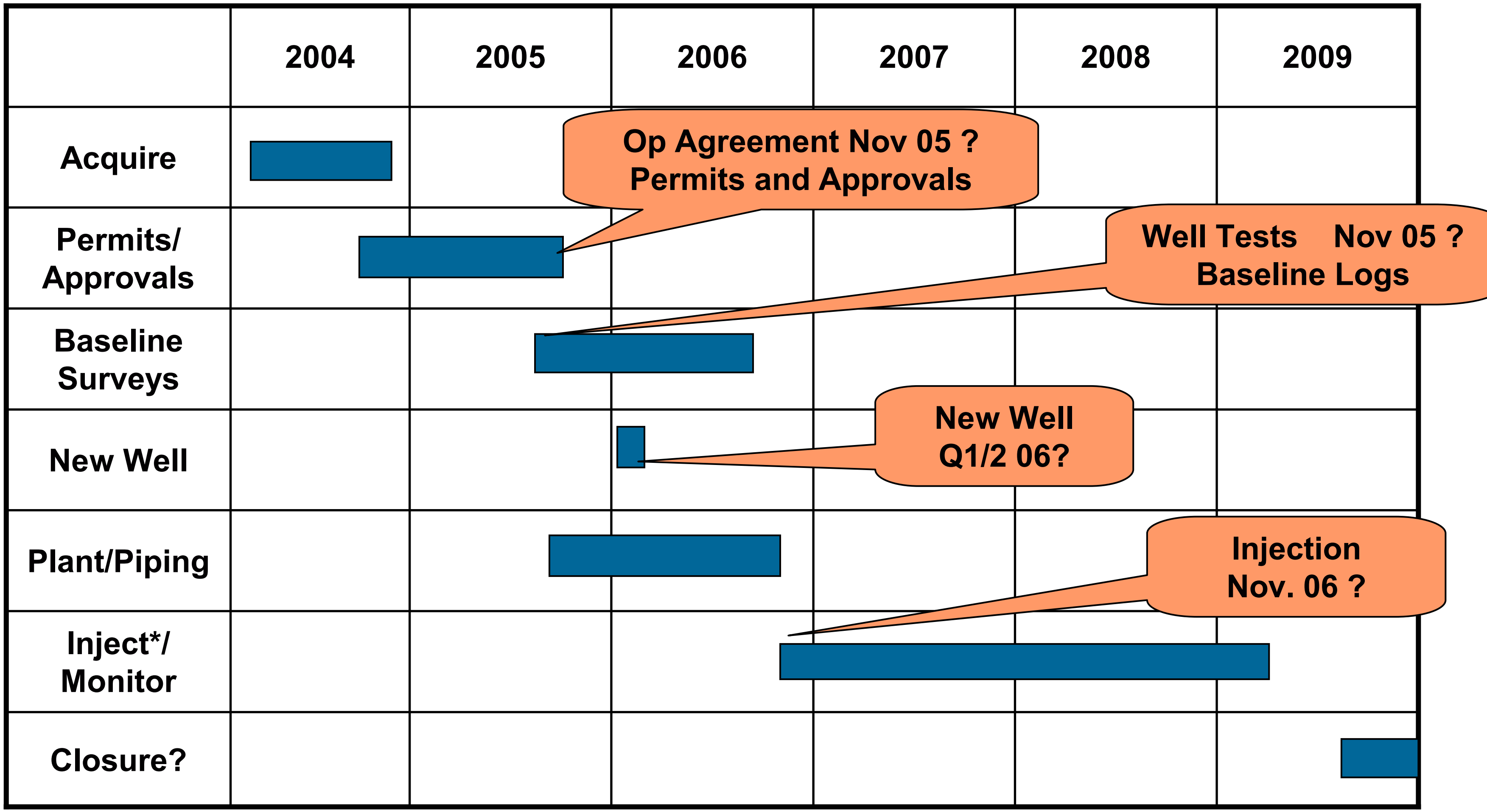
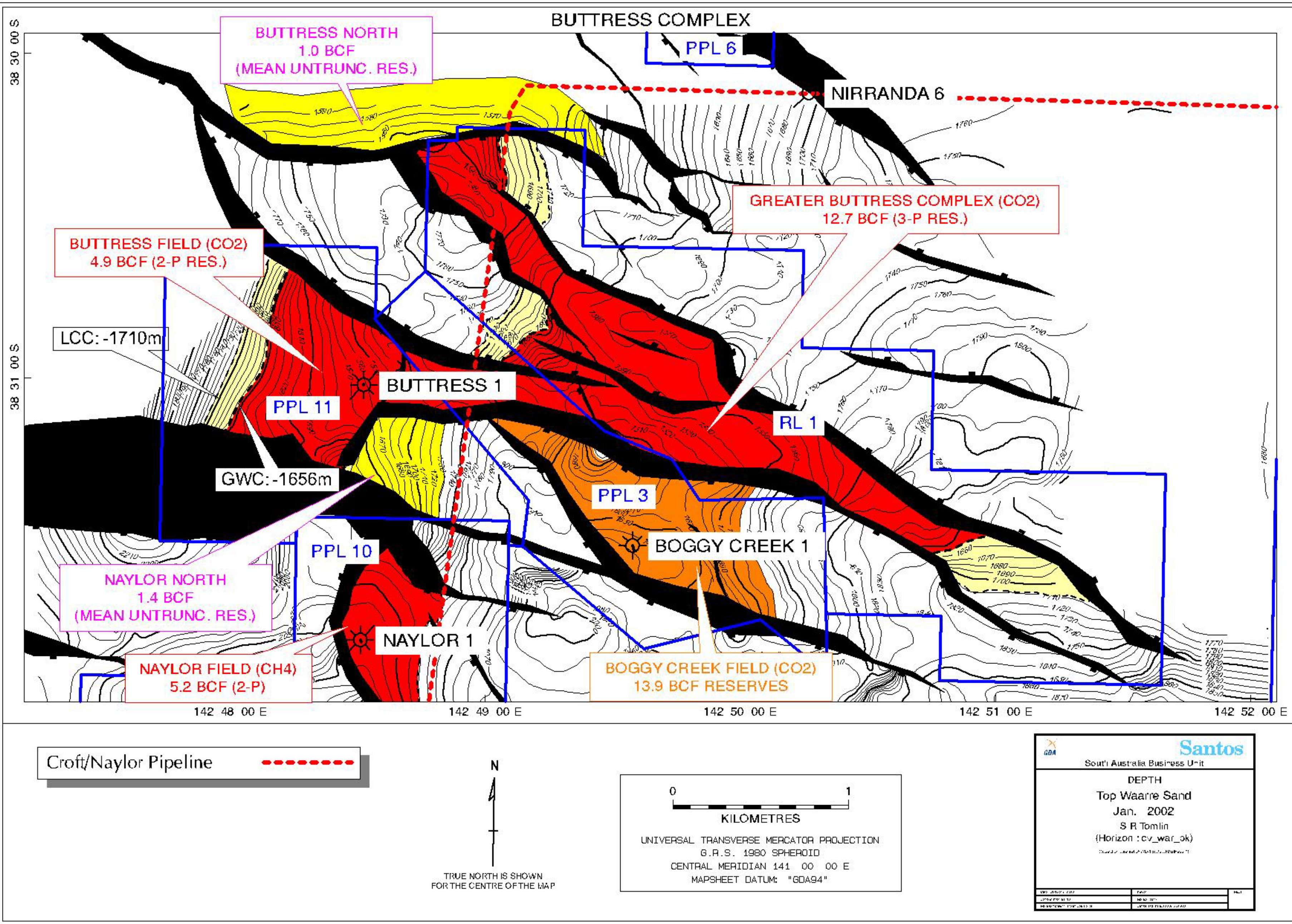
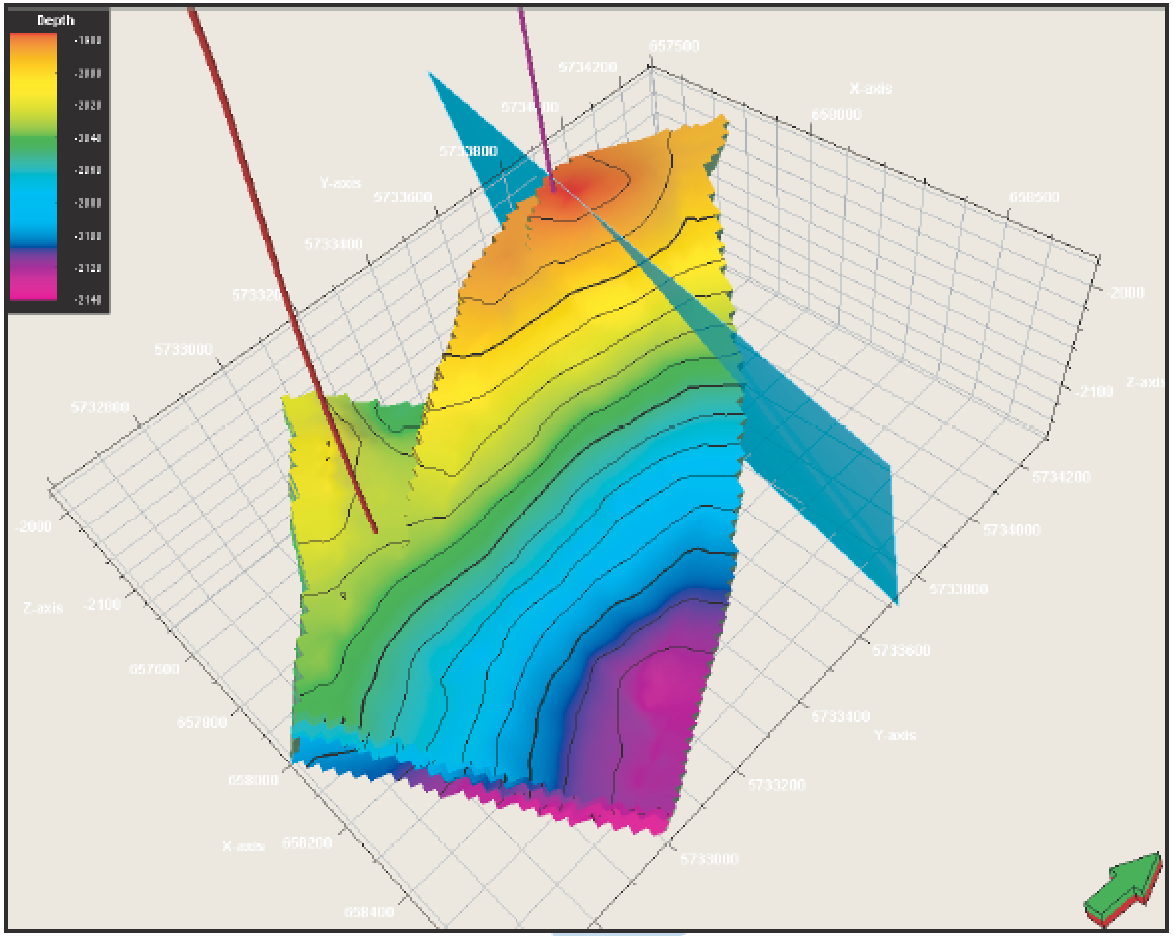
Conceptual Pilot Project Timeline



Structure Map - OBPP Fault Distribution



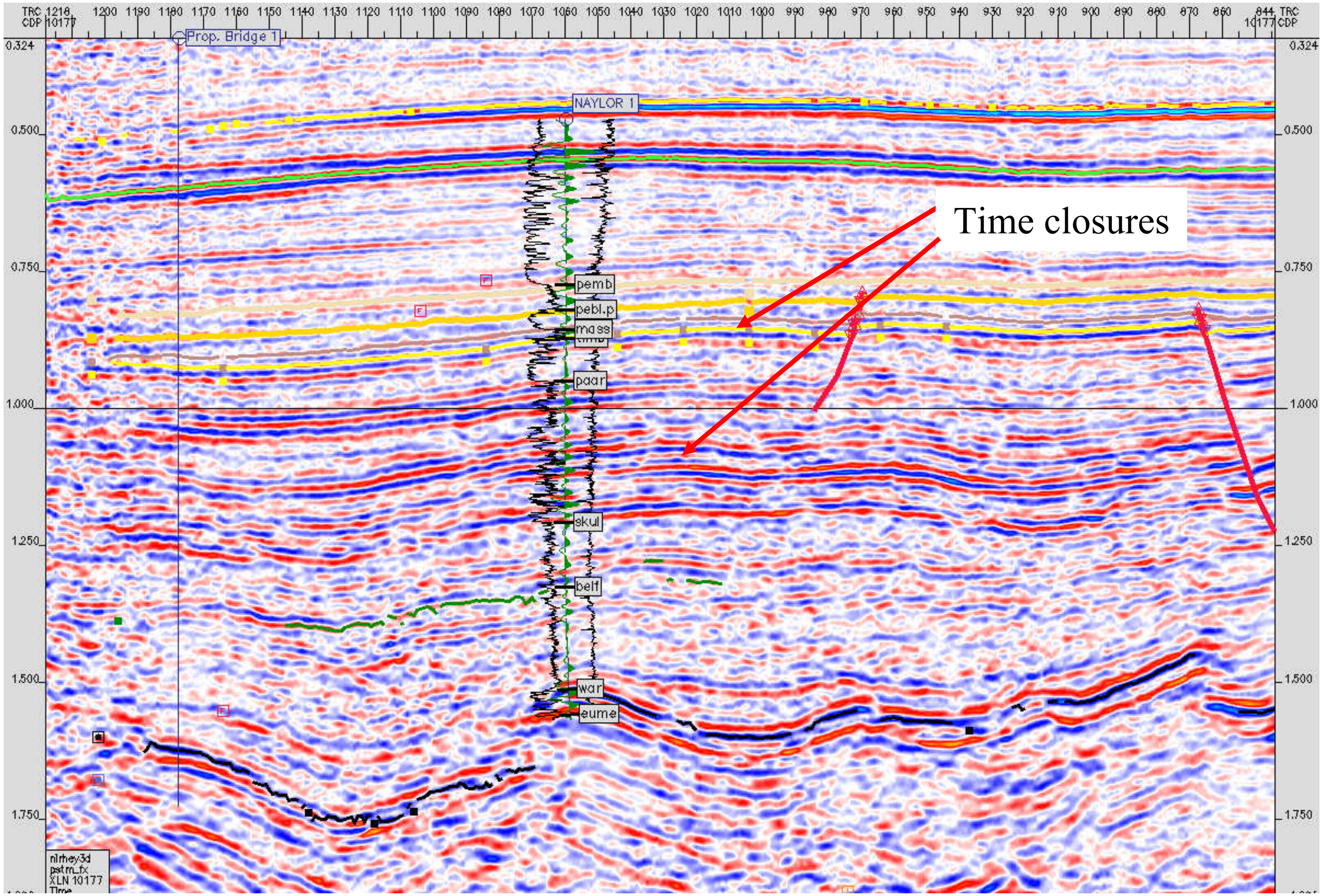
Structural Map



Top of the Waarre C in the Naylor field, as determined from the geophysical measurements.

CO2CRC

Geoscience
Naylor-1 Seismic Line



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Risk Assessment Profile

The context of risk assessment is set by the expected scope of work and the current (August 2005) OBPP configuration for this exercise is as follows;

- Secure appropriate regulatory approvals and landowner consents.
- Produce approximately 3 MMSCFD (Million standard cu ft/day) of gas with an estimated composition of 87%-92% CO_2 and 8% methane for 1 to 2 years from the presently suspended Buttress-1 well. Over two years the volume of gas injected will be approximately 100,000 tonnes.
- Process this gas mixture at surface facilities close to the Buttress-1 wellhead, separating the CO_2 from most of the methane, dehydrating prior to injecting into the pipeline.
- Transporting the gas to the injection location via a buried 3" diameter pipeline.
- Inject the CO_2 as a supercritical fluid into the Waarre C formation via a new injection/monitoring well (yet to be drilled at a location yet to be finalised but expected to be approximately 300-500 m to the SE of the Naylor-1 suspended gas well)
- Undertake both pre-injection baseline and subsequent monitoring phases during and after injection
  - To verify the amount of CO_2 injected
  - To confirm predicted behaviour of the CO_2 plume as it migrates through the essentially depleted (methane) gas reservoir

Risk Register

Risk	Specific Issues	Consequences	Mitigation	Rating
Production risk	- Inadequate reserves in source - Inadequate production rate from source	Unable to meet the project objectives	- Through geologic mapping of resource structure - Production test to validate flow rate and pressures	L
Data Acquisition risk	- Loss of downhole equipment - Unable to acquire data	- Cost - Not able to reduce resource uncertainty	- Insurance for services - Back up services to cover for failure	L
Plant and Processing risk	- Resource Gas composition un-known - Malfunction	- Cost and high uncertainty of the plant being able to meet output specifications. - Environmental and pos-sible human impact due to leaks/noise	-Well test to reduce uncertainty - Plant to be designed using industry best practices and failsafe mechanisms. Hazop's to be performed before operation.	L
Gas Transportation risk	- Leaks from pipelines	- Environmental and human impact	- Designed using industry best practices. - 3" buried pipeline poses minimal risk in transporting non-toxic gas.	L L

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Risk Register

Risk	Specific Issues	Consequences	Mitigation	Rating
Drilling Risk	- Drilling difficulties and losses. - Well Blow Out	- Cost and delays - Environmental and possible human impact	- Many wells in the area. - Designed using industry best practices. Low risk as drilling into depleted reservoir.	L
Injection risk	- Unable to inject - Well integrity problems	- Unanticipated work leading to cost over-runs - Environmental and possible human impact due to leaks	- Detailed reservoir studies to define reservoir. - Well integrity assurance before starting to inject.	L
Personnel risk	- Hazards of site work and travel to and from site.	- Safety incident and potential for worker compensation.	- Insurance - Minimise site work. - Site journey management program and induction training	L
Decommissioning risk	- Residual leakage post decommissioning	- Cost to rectify	- Follow industry proven dual barrier process	L

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Storage Risk Register

Risk	Specific Issues	Consequences	Mitigation	Rating
Leakage to surface through reservoir risk	- Breach of containment zones in the reservoir.	- Environmental and possible human impact due to leaks	Detailed geo-science based site characterisation has confirmed multiple containment zones. Minimal risk of migration to surface	L
Leakage to surface through well risk during monitoring phase	- Breach of well integrity.	- Environmental and possible human impact due to leaks	Leakage through well unlikely due to well control. Leakage from behind casing unlikely and would result in dispersal in secondary containment zone.	L
Leakage to surface through well risk post decommissioning	- Breach of well and permanent barriers integrity.	- Environmental and possible human impact due to leaks	Follow well established industry standard decommissioning procedures. Very unlikely event due to existence of multiple barriers.	L
Leakage into potable water aquifers	- Breach of primary and secondary containment zones in the reservoir.	- Environmental impact	Characterisation has confirmed contained dispersion in secondary aquifer even if primary seal is breached.	L

Containment Risk Assessment

The following list of containment risk issues was evaluated

- permeable zones in seal;
- faults;
- wells;
- leakage via seal;
- regional scale over-pressurisation; local scale over-pressurisation;
- CO2 exceeding spill point of the storage site;
- earthquake - induced fractures;
- incorrect modelling of migration direction;
- unintentional over-fi lling of the storage site;
- well-head, pipeline, or compressor failure.

Key Monitoring Objectives

- Conduct all tasks safely and to the satisfaction of all stakeholders.
- Soil and atmospheric measurements to confirm non leakage/seepage of injected Co2.
- Water well monitoring to ensure no leakage of Co2 into the overlying aquifers
- Monitor the injected CO2 plume to :
  - Validate migration paths viz model
  - Validate migration times viz. model
  - Validate likely shape viz. model
  - Validate containment
    - Pressure measurements
    - Movement of Water/Co2 interface.

CO2 CRC

Monitoring Domains

- Atmospheric
  - LoFLo sensors
  - Flux Mast
- Soil gas sampling over defined grid. Be wide enough to cover area over faults terminating relatively close to surface.
- Water well monitoring downstream of the hydrodynamic flow.
- Geochemical sampling of monitor with U-tube (LBNL), and injection horizon
- Regular suite of tracers including Deuteriated methane
- Geophysical Monitoring
  - Microseismic potential
  - Well Logs
  - Surface seismic/VSP
- Predictive forward models for above.

Monitoring : Surface Geophysics

- Existing 3 D seismic is pre-production and of good quality. Some velocity anomalies to be validated in Naylor through VSP.
- Goals
  - Monitor movement of Co2 plume
- Approach
  - Re-process existing PSDM
  - AVO analysis and fracture orientation
  - Elastic inversion and saturation.
  - Re-shoot 3 azimuths of long offset 2D/3C
  - Evaluate using VSP-W as an imaging option
  - Collaborative linkage with LBNL exploring mutual interests in high precision continuous seismic monitoring
- Timing
  - #1 : Dec 05 – Jan 06
  - #2 : At breakthrough (6 months after injection)
  - #3 : end 2008 : several months after stopping injection

Monitoring: Rock physics sensitivity modelling CO_2 in a depleted gas field

Unknown:

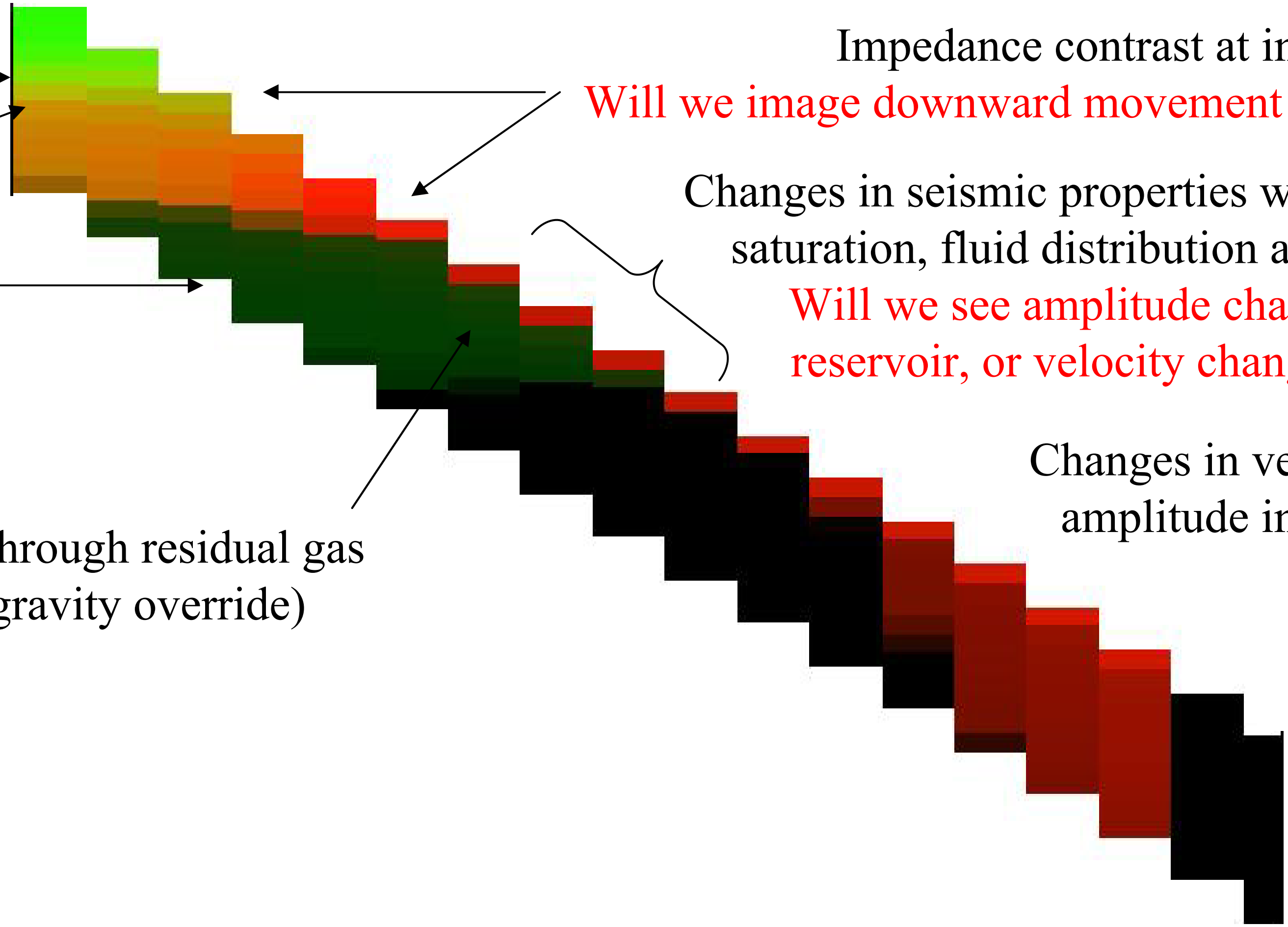
Present GWC

Transition zoneCH4/CO2

Residual CH4 saturation

Original GWC

Flow behaviour through residual gas (sweep, mixing, gravity override)



Modelling:

Impedance contrast at interface(s)

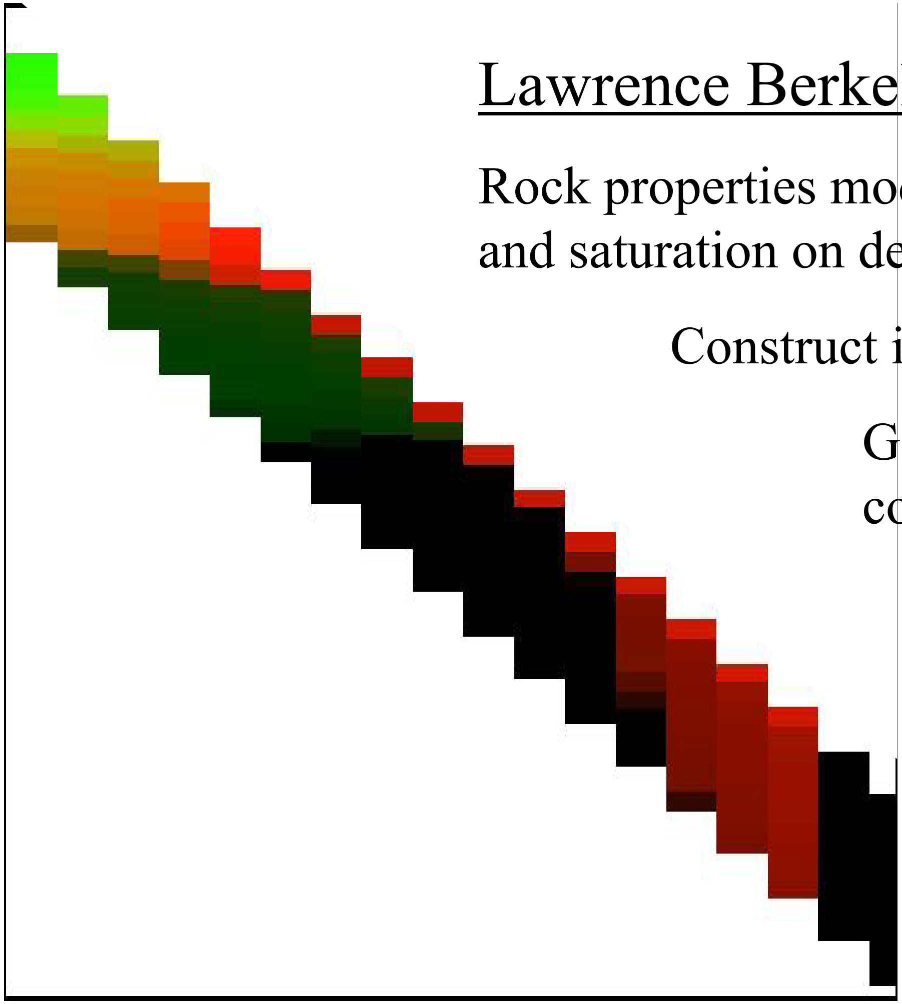
Will we image downward movement of GWC?

Changes in seismic properties wrt residual saturation, fluid distribution and mixing

Will we see amplitude change @ top reservoir, or velocity change within?

Changes in velocity and amplitude in water leg

Monitoring: Geophysics forward modelling



Lawrence Berkeley National Laboratories (GEM)

Rock properties modelling – effect of pressure, temperature and saturation on density, resistivity and seismic

Construct initial conditions model from logs

Generate new models for a range of new conditions

Model 2D seismic and 3D gravity and resistivity

Monitoring : Microseismic

SW bounding fault potentially critically stressed

•Sensors to be below shallow carbonates (>500m)

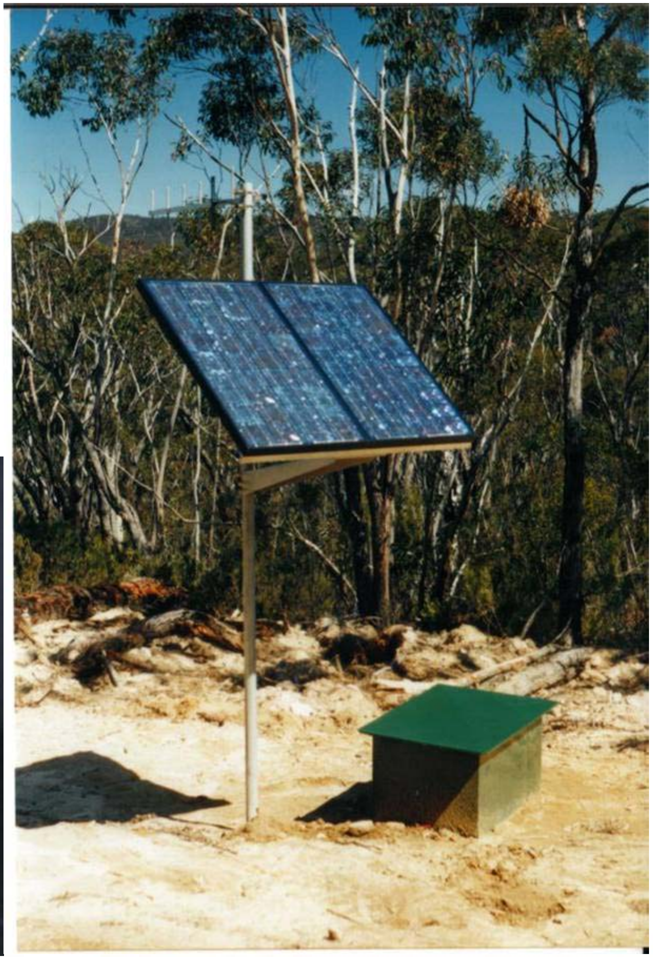
•Need to be within 100m to detect m -2 event, up to 5km for m=0 with standard geophones

•12 levels of 3-C at up to 100m spacing

OR - dense array of hydrophones to combine VSP with wider spaced 3-C phones for μ-seismic

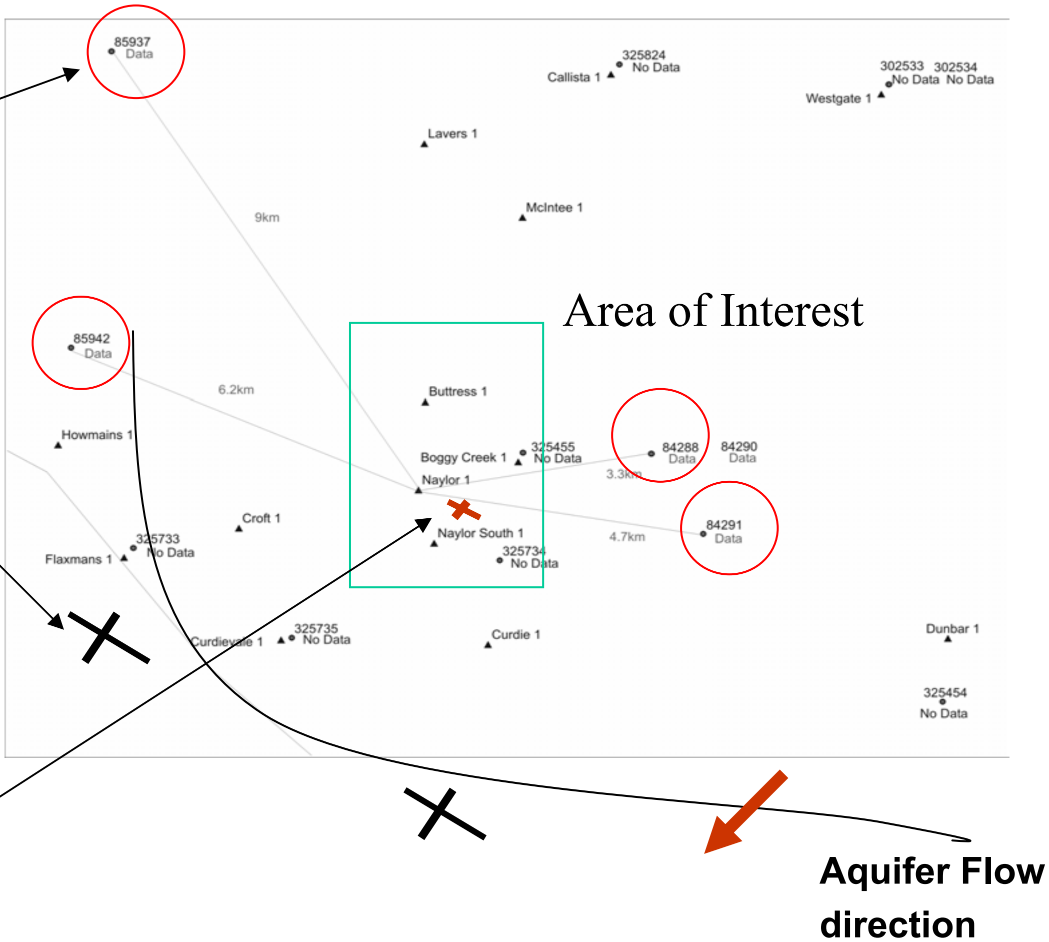
•Continuous or triggered recording

•Radio telemetry between seismometer and central computer



Monitoring : Water Wells

- Marked wells are the deep ones being monitored by Victorian Government.
  - Dilwyn formation
  - 900M
- Consideration for new water wells in the aquifer flow direction
  - Multiple wells targeting different shallow aquifers
  - One well selectively completed for simultaneous monitoring of different aquifers.
- Potential for micro seismic to be installed in one new water well. Location of this well will likely be close to Naylor and in the same containment block.



Atmospheric LoFlo CO_2 analyser system

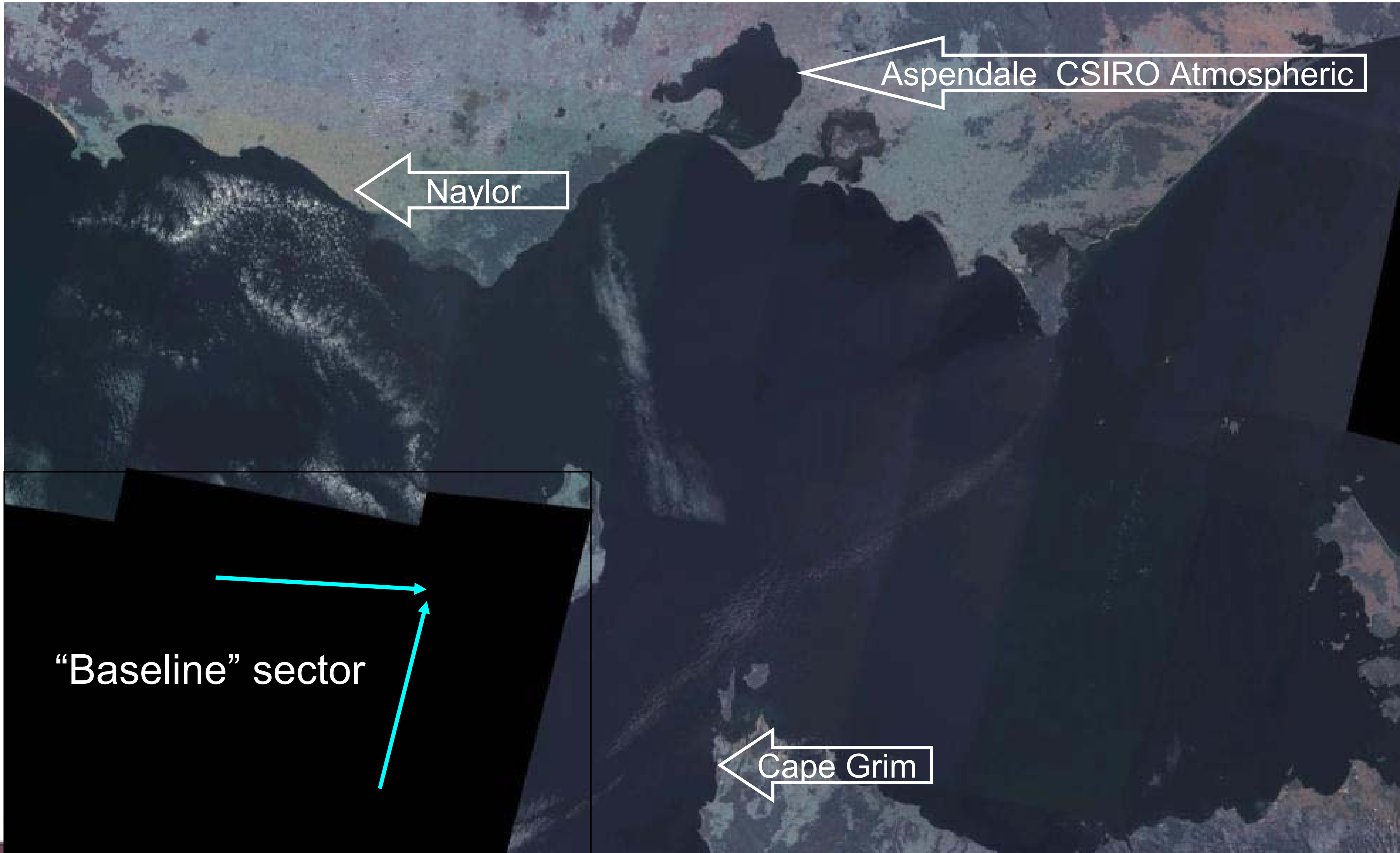
Demonstrates:

- 10 times better precision,
- 1/10th operating cost

compared to a conventional CO_2 analyser system

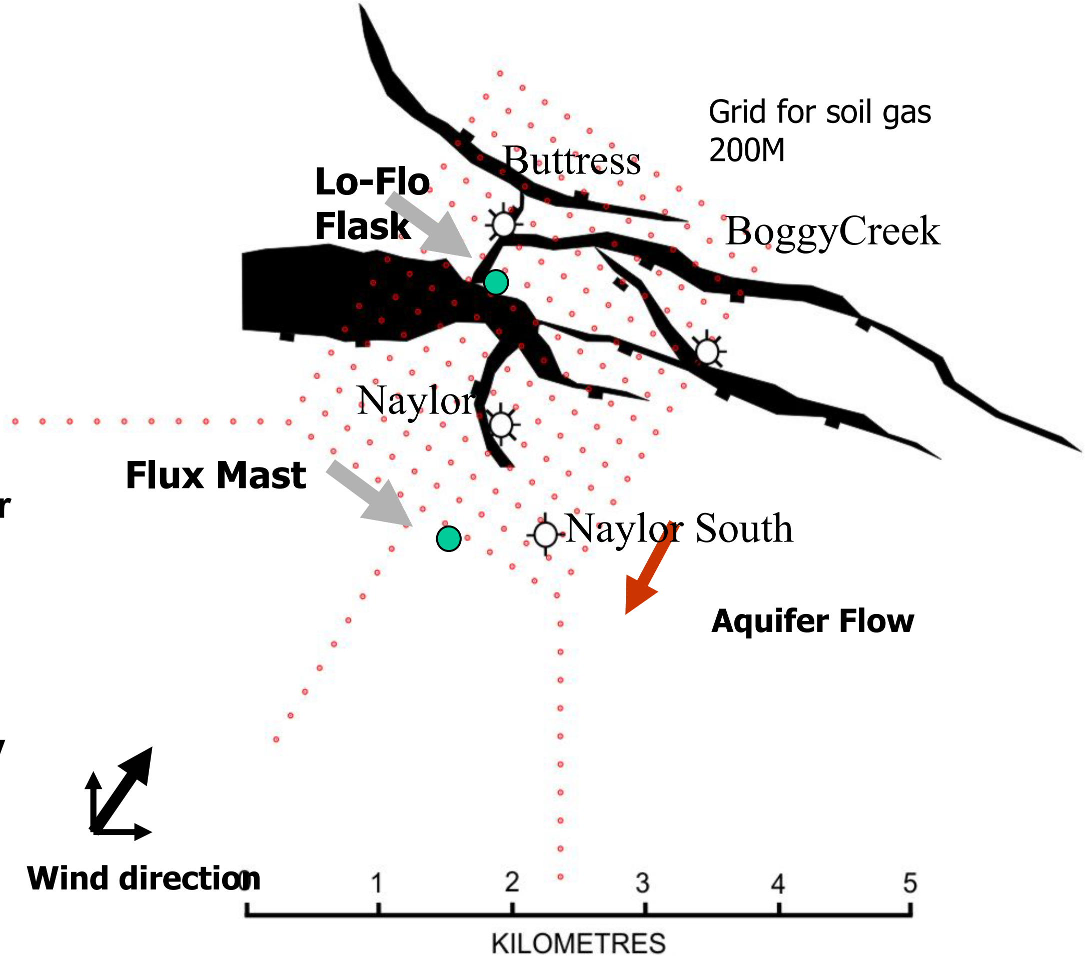
Scientific recognition:

Victoria Prize 2001
Federation Fellowship offer 2003

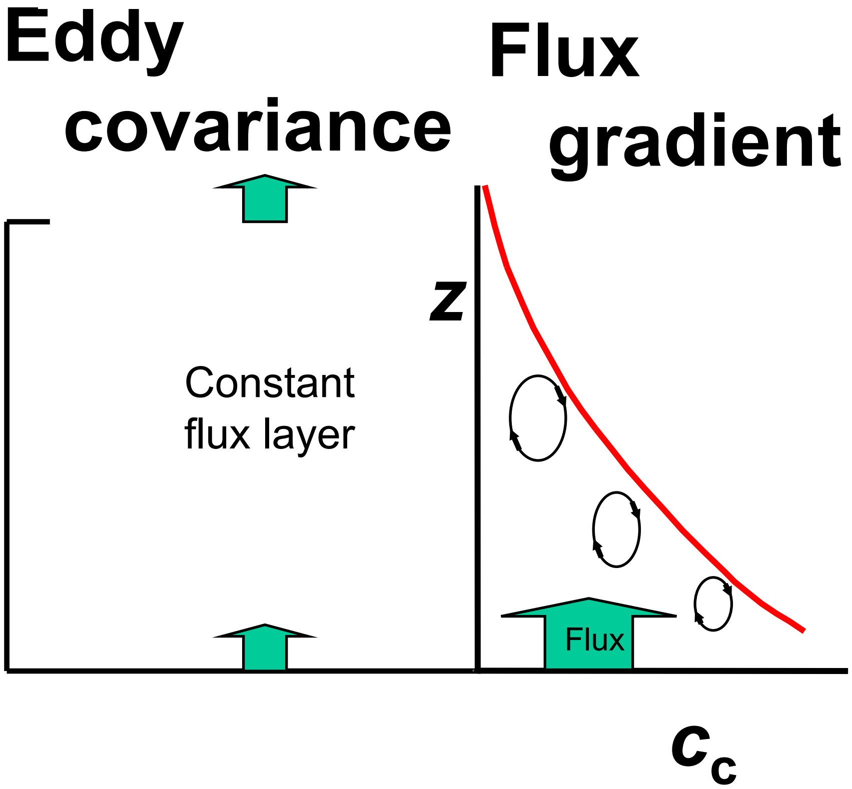

Aspendale CSIRO Atmospheric
Naylor
"Baseline" sector
Cape Grim

Monitoring: Atmospheric/Soil Gas

- **Atmospheric LoFlo Sensor**
  - **Continuous precise Co2 concentration measurements.**
- **Atmospheric Flux Mast**
  - **Quantify ecological Co2 upwind of site and establish bio-spheric baseline.**
- **Soil gas sampling over defined grid (200M spacing), wide enough to cover area over faults terminating relatively close to surface.**
  - **Using push gas apparatus (picture).**
  - **Some tubes may be permanently installed**
  - **Portable GC used for sampling**



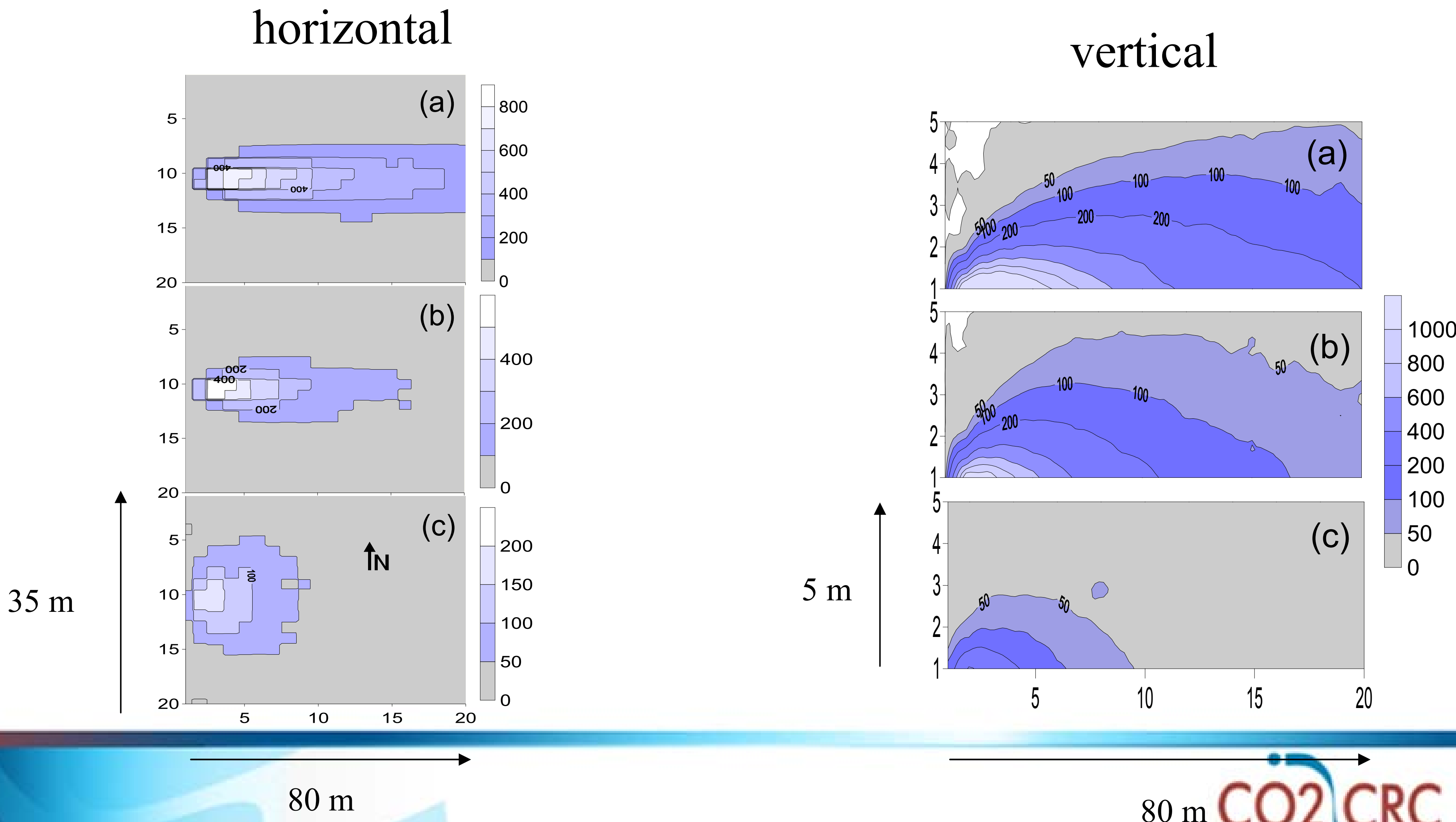
Aerodynamic methods



Dispersion into local atmosphere

1000 t/yr storage leak CO_2

(a) moderate stability (b) neutral and (c) moderate instability



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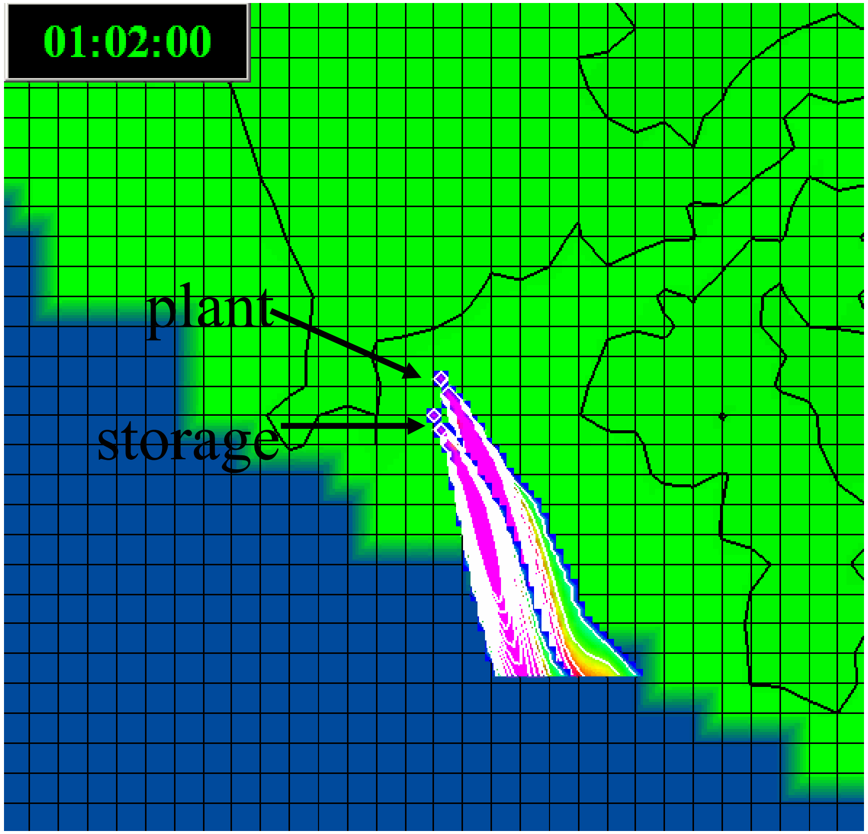
Dispersion into regional atmosphere
-process plant fugitive emissions
-sequestration storage leaks

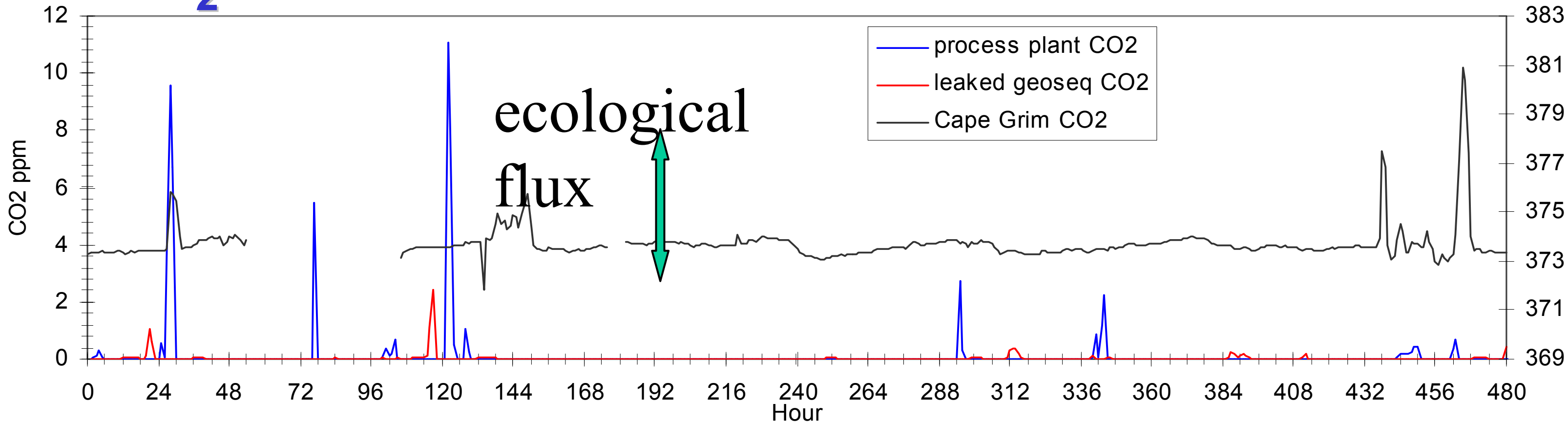
- Plant (Buttress): 9000 t CO2/yr
- Leak (Naylor): 1% of 2 yr store = 1000 t CO2/yr
- Dispersion TAPM (CSIRO AR)
- Jan and Aug 2004
- Tracer eg. SF6 at 1:10^6
- Ecological flux range (not yet modelled)



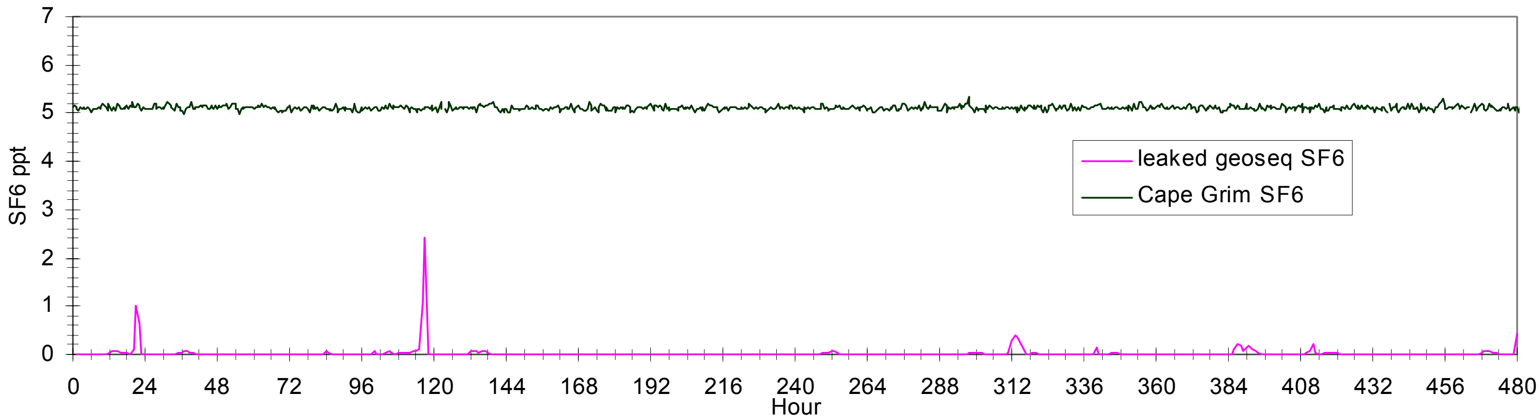
Concentration perturbations cf. Cape Grim background

From TAPM simulation: 700 m NE of pilot project Jan 2004

CO_2



SF_6 tracer (1:10^6 dilution)



Initial Monitoring – Existing Wells

Monitoring : New Well

Time Lapse Monitoring

Technology Options

- Data acquisition programs and frequency of time-lapse measurements
  - Implications and tradeoffs vs completion design
  - Prioritization of relative importance of each measurement to ease decision making

Objective	Criticality	Surface Seismic	X-Well	Water Wells	Atmos	Soil Gas	U tube	RST	SFRT	Integrity Logs
Breakthrough detection										
Plume shape										
Plume travel path										
Plume travel speed										
Containment										
CO2 area of accumulation										
Public Acceptance										

Operational Phases and Requirements

. OBPP Phases of Operation and Licensing Requirements

	Phase 1 A Pre-Injection	Phase 1 B Production & Injection	Phase 2 Post injection	Phase 3 Post Closure	Phase 4 Longer Term
Surface Activities	Plant, Gathering Line, Baseline Monitoring	Atmospheric, Seismic, Geochem Monitoring	Atmospheric, Seismic, Geochem Monitoring Closure	Surface Monitoring (Atmospheric, Hydrology)	Surface Monitoring (Atmospheric, Hydrology)
Legislation	Petroleum	Petroleum -Prod EPA - Injection	Petroleum EPA	EPA	EPA
Risk Management	Insurance	Insurance	Insurance	TBA	TBA
Sub-Surface Activities	Well Operations, New Well Drilling and Completions	Injection, Well Operations, M&V	Logging and sampling, Well operations Closure of wells	None	None
Legislation	Petroleum EPA	Petroleum -Prod EPA - Injection	Petroleum (Standard Ops, Closure)	EPA	EPA
Risk Management	Operational Insurance Reservoir: Controlled	Operational Insurance Reservoir: Controlled	Oper: Insurance Reservoir: Controlled	TBA	TBA

KPI for Phases of Operation

Phase	KPI
Phase 1A	1. Establish injection and migration models and uncertainties
Phase 1B	2. Environmental impacts within SEPP bounds 3. Injection/Migration within model prediction bounds
Phase 2	4. Verified stable plume within model prediction. (3 individual KPIs) • Measurements (logs) show no evidence of injected CO_2 beyond secondary containment in Naylor-1 and Naylor-2 • Air samples collected from existing deep-water wells show no evidence of the injected CO_2. There are four such wells that are monitored by Southern Rural Water. • Air samples collected over a few days in the proximity of the Naylor-1 and Naylor-2 wells shows no evidence of the injected CO_2 5. Appropriate decommissioning certificate(s) from the authorities • Wells decommissioned as per regulation • Sites restored as per regulation
Phase 3	6. No evidence of injected CO_2 over 2 years would lead to end of phase. • Air samples collected from existing deep-water wells show no evidence of the injected CO_2. There are four such wells that are monitored by Southern Rural Water. • Air samples collected over a few days in the proximity of the Naylor-1 and Naylor-2 wells shows no evidence of the injected CO_2
Phase 4	7. No evidence of injected CO_2 over 2 years would lead to end of phase. • Air samples collected from existing deep-water wells show no evidence of the injected CO_2. There are four such wells that are monitored by Southern Rural Water.

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Initial Monitoring – Existing Wells

- Source well : Buttress 1 (Rigless Operation)
  - Cement Logs, RST and VSP
  - Perforate and Well Test Buttress
- Monitoring well : Naylor 1 (Rigless Operation)
  - Cement Logs, RST
  - Slimhole Full Wave Sonic ?
  - VSP using slim shuttle tool. Will not be able to run a VSI due to "live well" and lack of large riser for well control.
  - SFRT (slim hole cased hole resistivity?)
- Issues
  - Testing High Co2 well and disposal of test fluids
  - Well integrity of Buttress – corrosion outside casing.
  - Remedial cement work in small casing.
  - Uncertainty reg. GWC in Naylor 1.
  - Engineering of U tube sampling system for Naylor 1.

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Monitoring : New Well

- Tasks Ongoing
  - Full geo-model for Naylor being built
  - Location likely to be 300-400M SE of Naylor 1 downdip.
- Program : 8 1-/2” OH section
  - Core through seal and reservoir with detailed core analysis
  - Well design and modeling to ensure no pooling of CO_2 near well bore.
  - On completion install permanent P&T gauges
  - Logs :
    - PEX with short axis logging for density
    - ECS, FMI, DSI (x-dipole)
    - Single well imaging ?
    - MDT
      - Mini fracs - dual packer for leak off tests?
      - Water samples from Warre, Paratte, Timboon,Dilwyn
      - Across zone interference testing
    - VSP – Walkaway. (link with surface seismic)
    - After casing
      - RST baseline
      - USI, CBL/VDL

Time Lapse Monitoring - Wells

- Source well : Buttress 1 (Rigless Operation) post completion of production.
  - Cement Logs, RST
- Monitoring well : Naylor 1 (Rigless Operation)
  - RST Runs
    - Before anticipated breakthrough not possible because of U tube?
    - Post breakthrough and at regular intervals
  - Slimhole Full Wave Sonic at same frequency as RST?
  - VSP post breakthrough, towards end of injection period and post injection.
  - SFRT (slim hole cased hole resistivity?)
- Injection/Monitoring Well Naylor –2
  - RST and VSP-W at the end of the injection period
  - Cement Integrity logs
- Issues
  - Post breakthrough Naylor –1 will have to be killed and perforated intervals squeezed. Impacts on RST response?
  - Well integrity of Buttress – corrosion outside casing.
  - Remedial cement work in small casing.

Session 5

Developments Since Last Meeting

Application of Soil Gas Concentrations, and Gas Fluxes to the Atmosphere in Order to Detect Low Rates of Leakage from CO_2-Sequestration (EOR or CBM) Projects

Ronald W. Klusman
Colorado School of Mines
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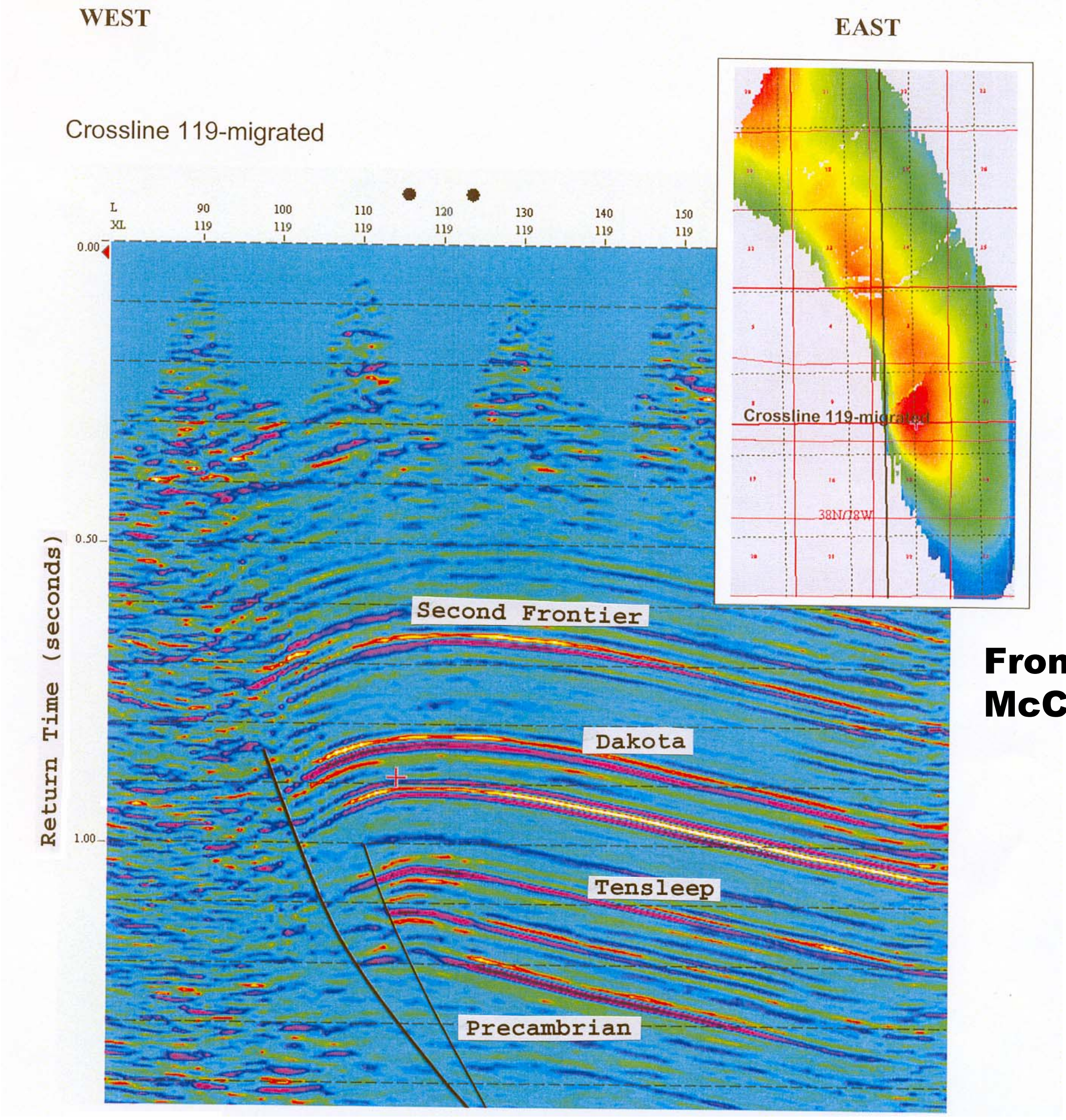
Teapot Dome
Rangely
Wyoming
Colorado
Continental
Divide

RANGELY FIELD CHARACTERISTICS

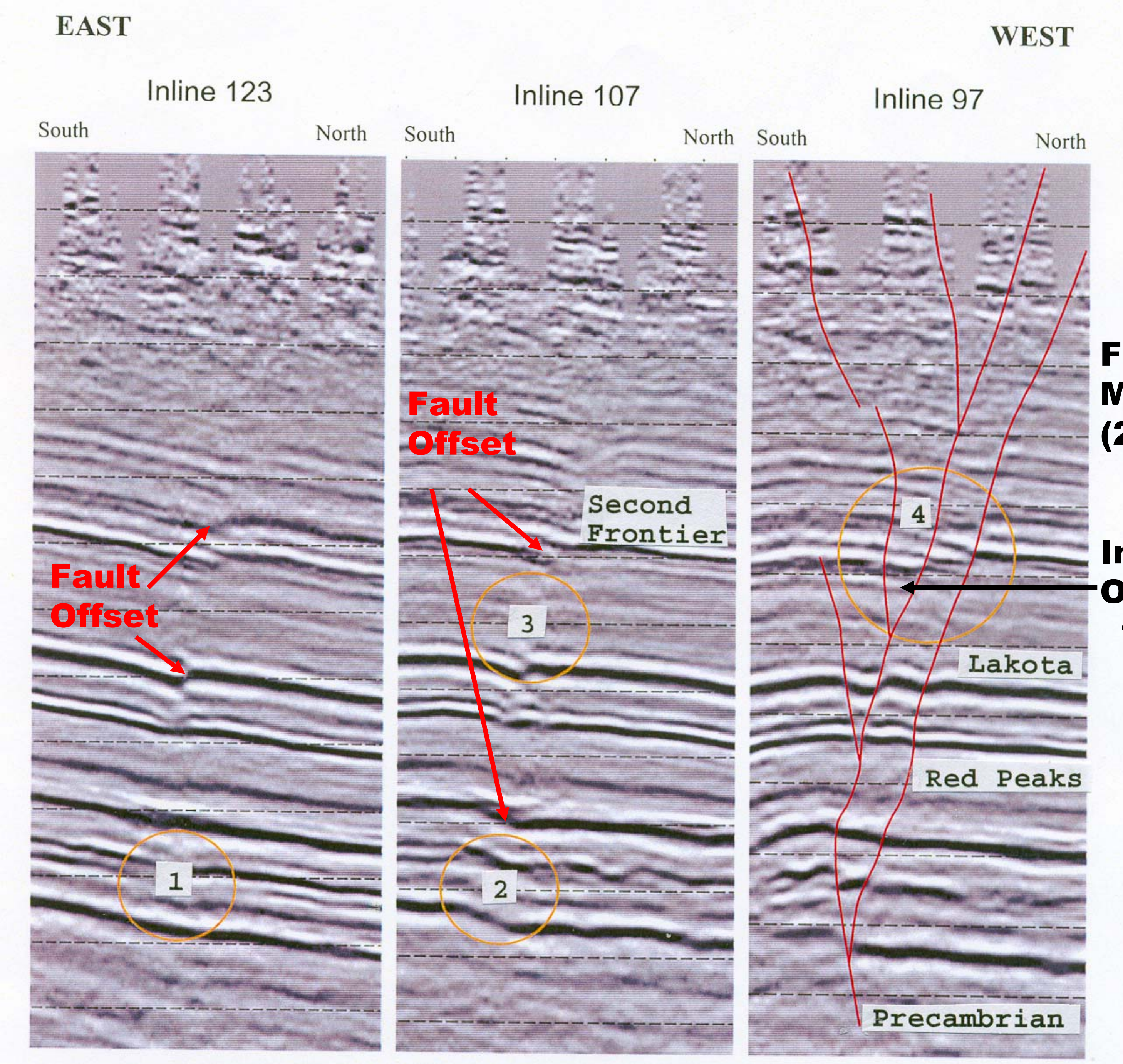
- **The depth of the Weber reservoir is≈ 2000 m (6500 ft),**
- **Initiation of CO_2 flood in 1986 using Water-Alternating-Gas (WAG) process to produce 16,000 bbl/day (2002),**
- **Injection of 160 million ft^3/day (4.5 million m^3/day) of gas,**
- **Surface injection pressure is 2000 psi (14 Mpa), static down-hole is 5000 psi (35 Mpa), with hydrostatic at 3600 psi (21 Mpa),**
- **Approximately 23 million tonnes of CO_2 is in storage (2002).**

TEAPOT DOME FIELD CHARACTERISTICS

- Approximately 18 mi^2 (42 km^2),
- Completely depleted, with production approximately 400 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 sequestration experimentation.



From McCutcheon (2003)



From McCutcheon (2003)

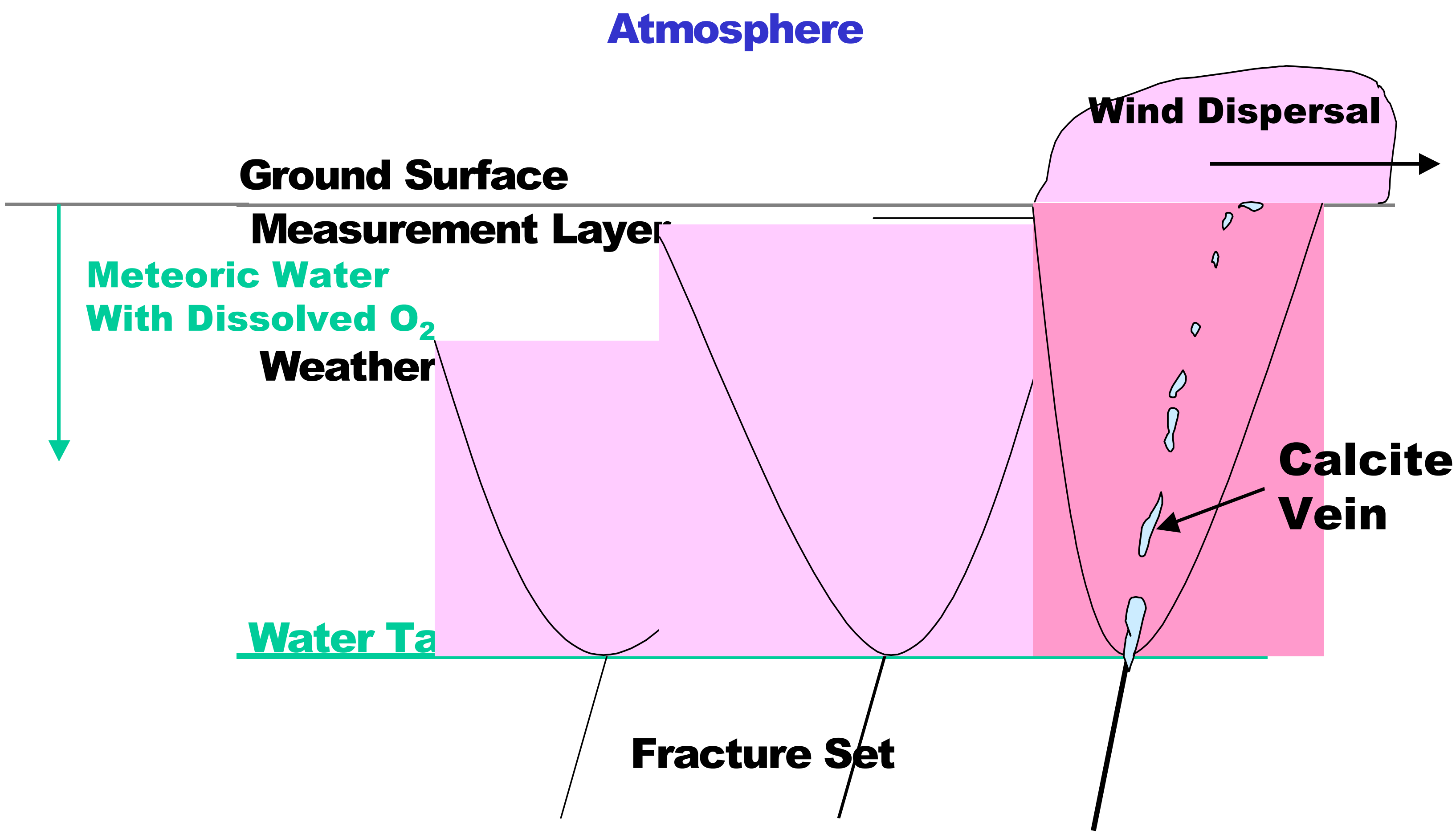
Inverse flower Or "horse-tail" faults

IMPORTANCE OF CO_2 AND CH_4

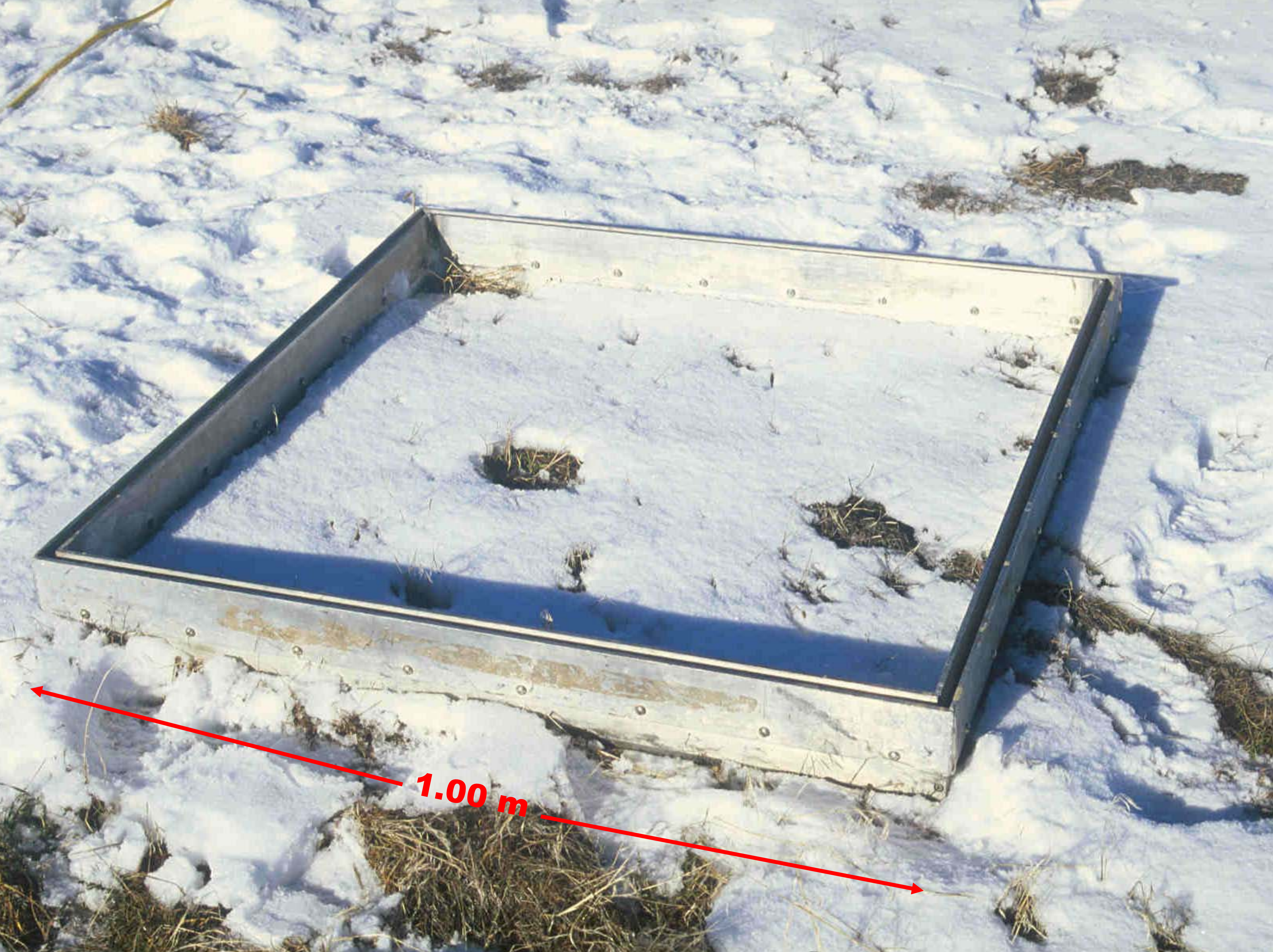
- CO_2 soluble in, and reactive with water,
- CH_4 is not soluble, nor reactive, being relatively stable in the subsurface environment,
- CH_4 likely ubiquitous in early sequestration options,
- CH_4 is a more mobile molecule when overpressured,
- CH_4 has a greater GWP if it reaches the atmosphere,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

SUMMER VS WINTER MEASUREMENTS

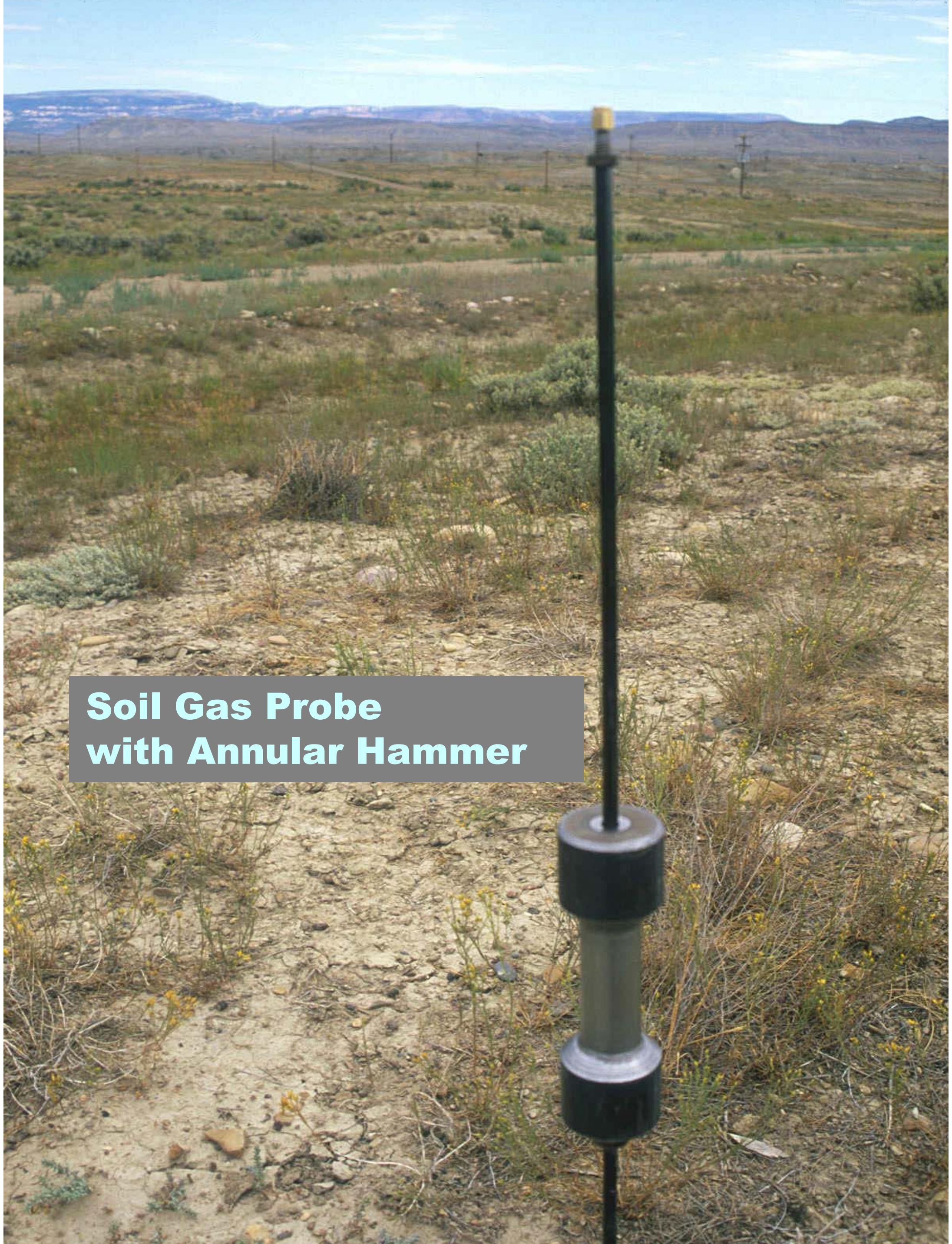
- Searching for a subtle signal in the presence of substantial surface noise,
- Microbial oxidation of soil organic matter to CO_2, and root respiration producing CO_2 is lower in winter,
- Methanotrophic oxidation rate of CH_4 in unsaturated zone is lower in winter,
- Therefore, the best chance of detecting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



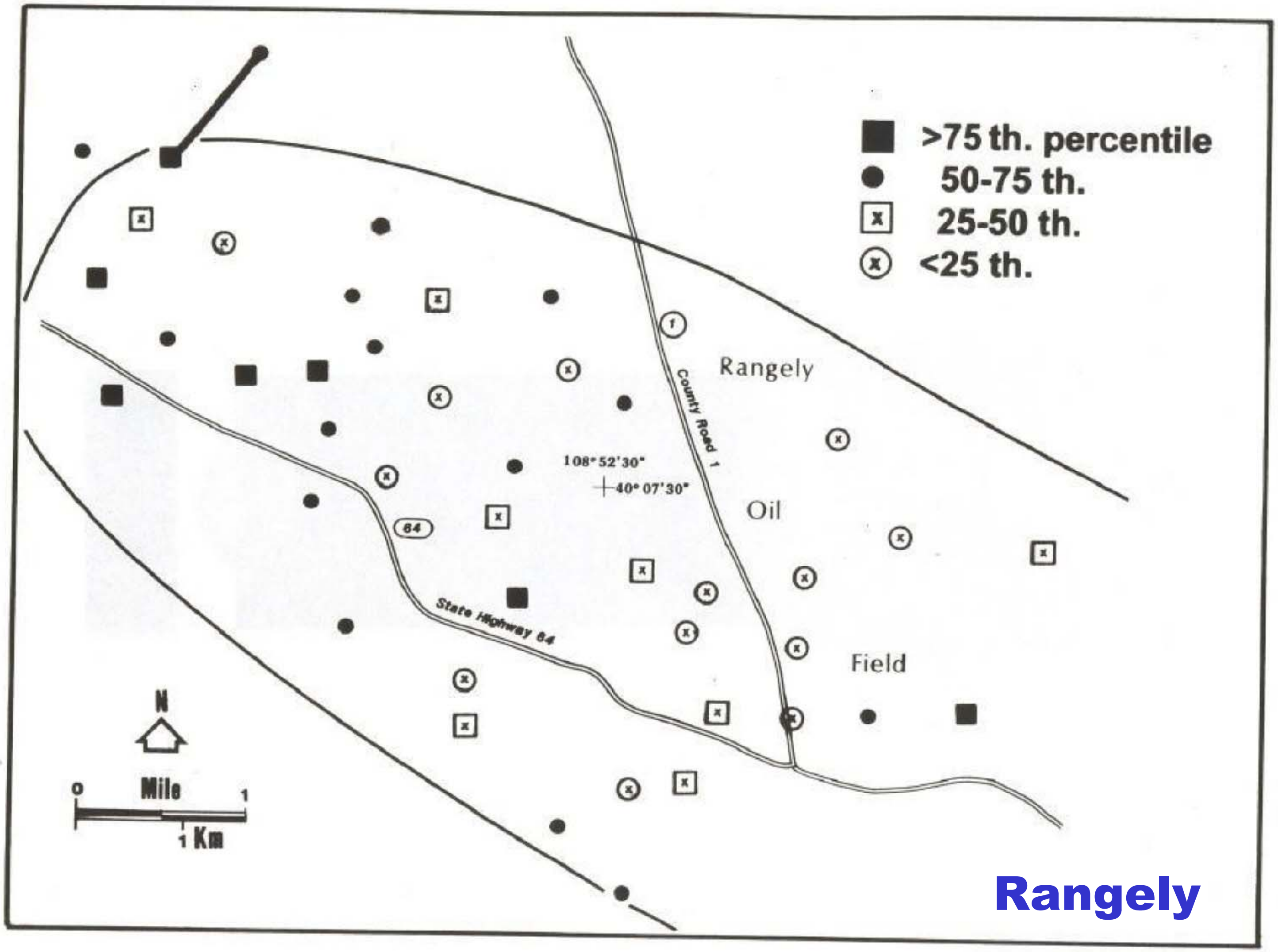
Atmosphere
Wind Dispersal
Ground Surface
Measurement Layer
Meteoric Water
With Dissolved O_2
Weather
Calcite
Vein
Water Ta
Fracture Set


1.00 m

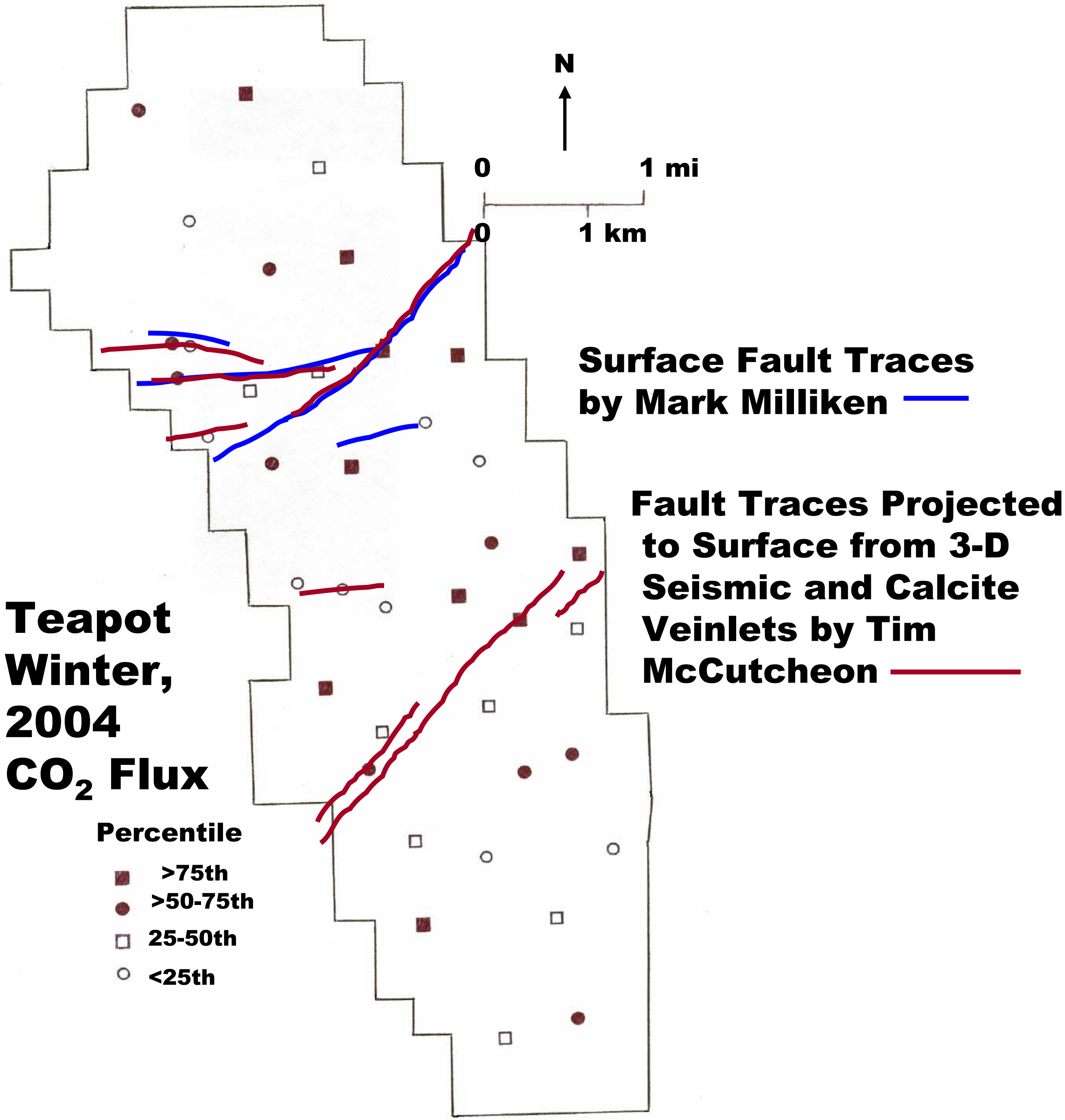

LI-7000 CO2/H2O Analyser


Soil Gas Probe
with Annular Hammer

RANGELY CO_2 FLUX - WINTER, 2001/2002



Teapot Winter, 2004 CO_2 Flux



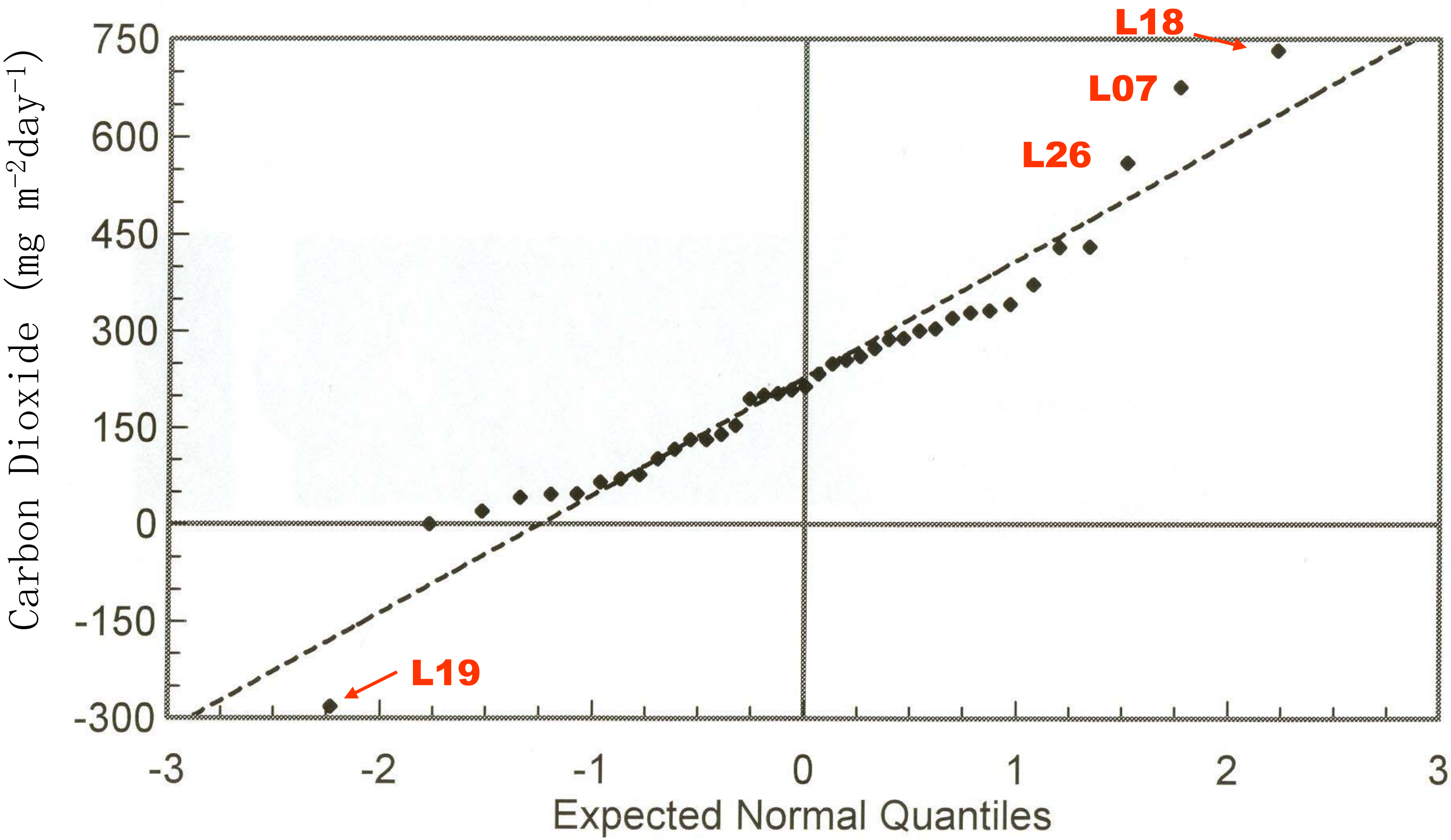
COMPARISON OF WINTER GAS FLUXES (mg $m^{-2}day^{-1}$)

CO_2	Mean	Median	Std. Dev.
Rangely W01/02	302.	67.9	1134.
Teapot W04	228.	187.	214.
CH_4			
Rangely W01/02	25.1	0.875	135.
Teapot W04	0.137	0.102	0.326

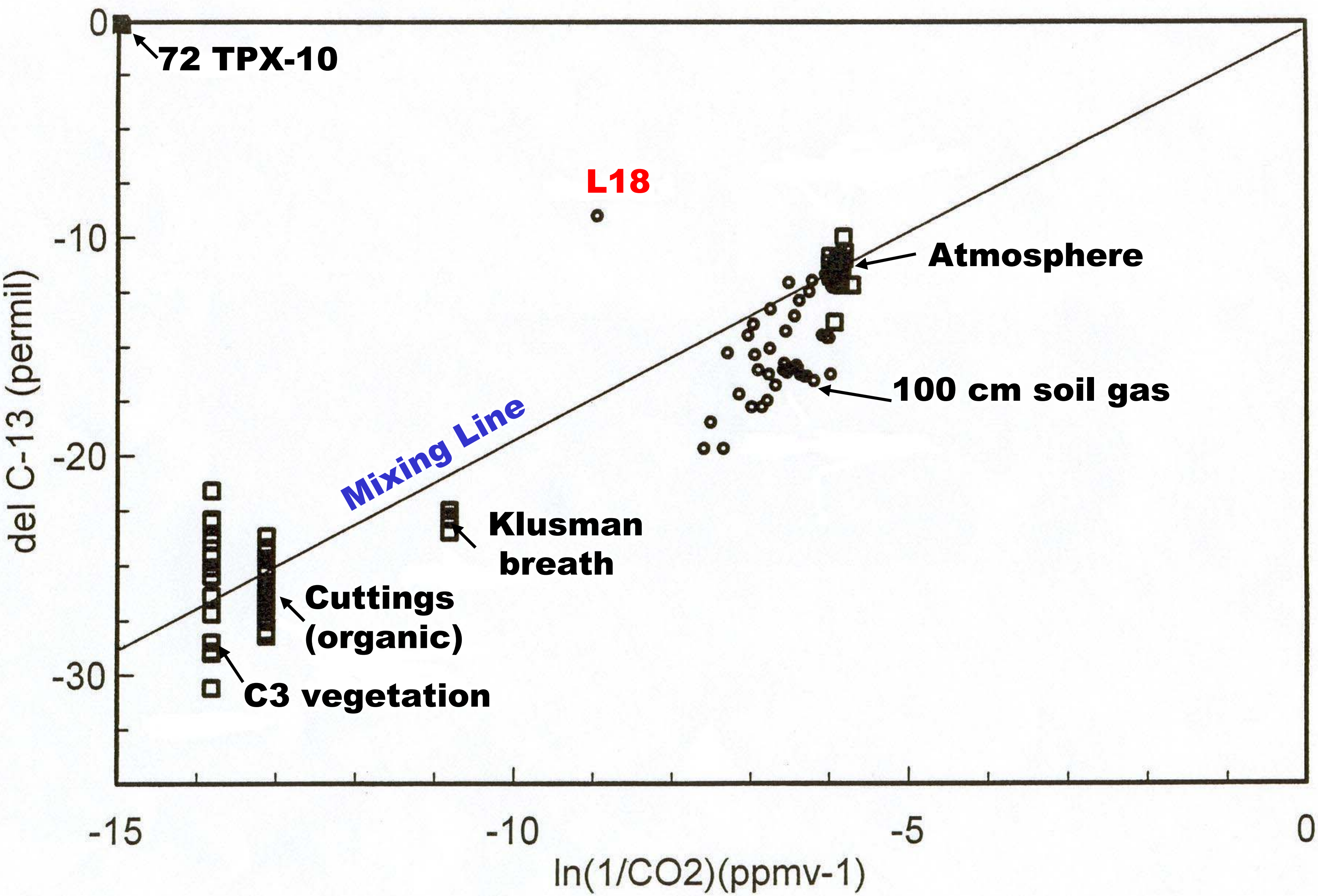
SELECTION OF "INTERESTING" LOCATIONS FOR 10-m HOLES

- **Magnitude <u>and</u> direction of <u>both</u> CO_2 and CH_4 fluxes,**
- **Magnitude <u>and</u> gradient of <u>both</u> CO_2 and CH_4 in soil gas profiles,**
- **Isotopic shift in 60-, and 100 cm soil gas CO_2 , relative to the atmosphere.**

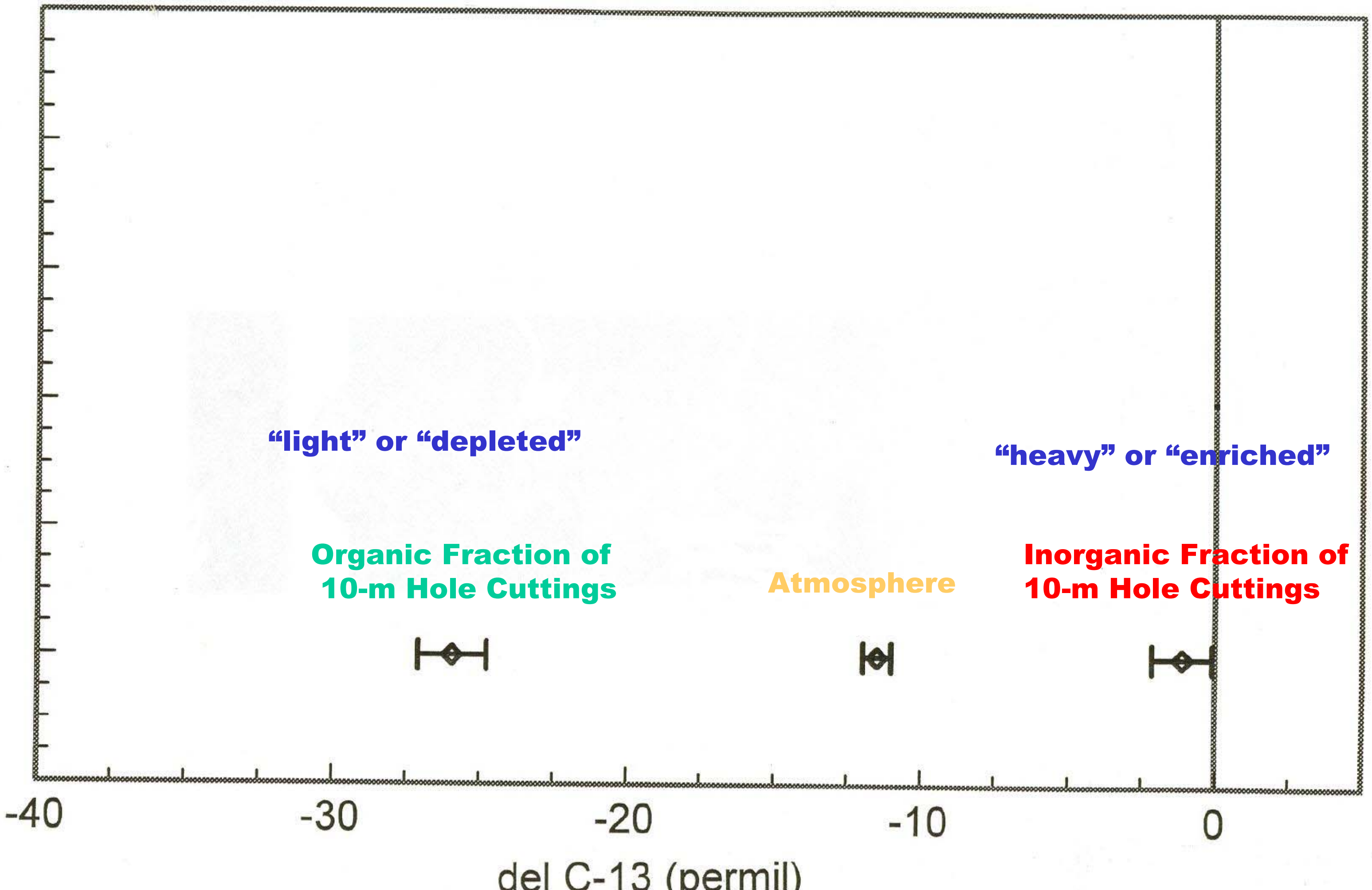
Teapot, Winter, 2004
Carbon Dioxide Flux



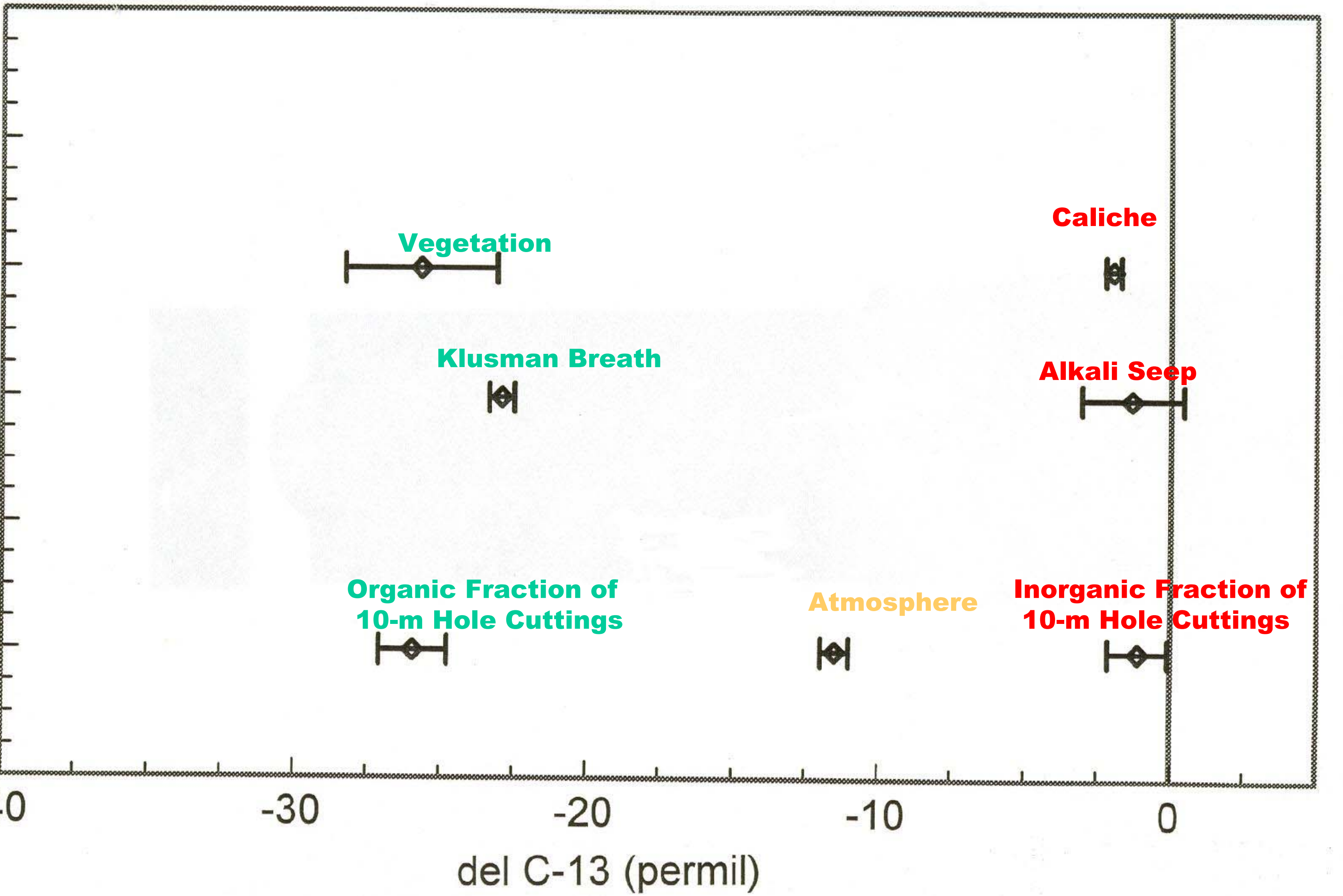
TEAPOT, WINTER, 2004



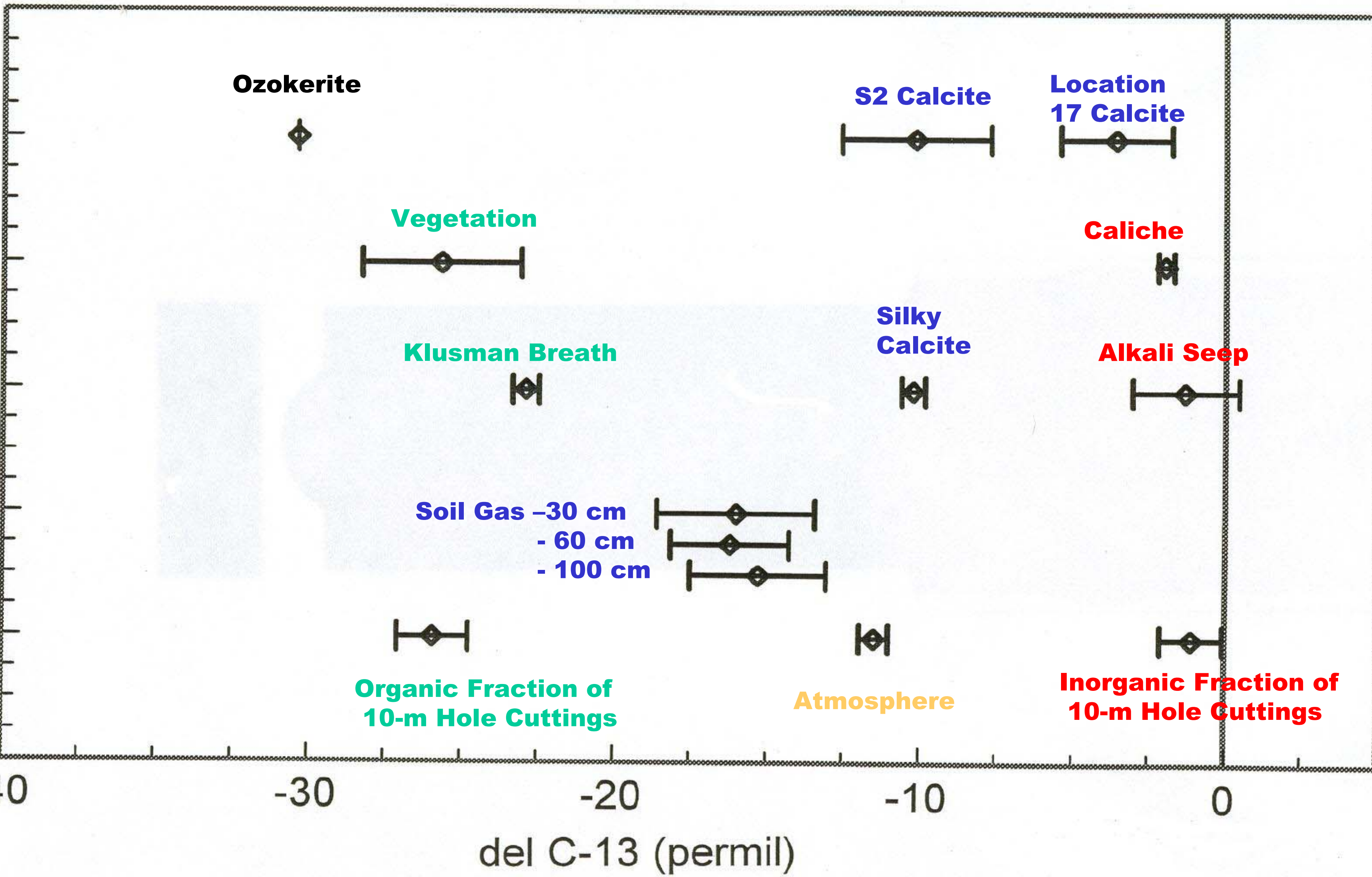
TEAPOT, WINTER, 2004

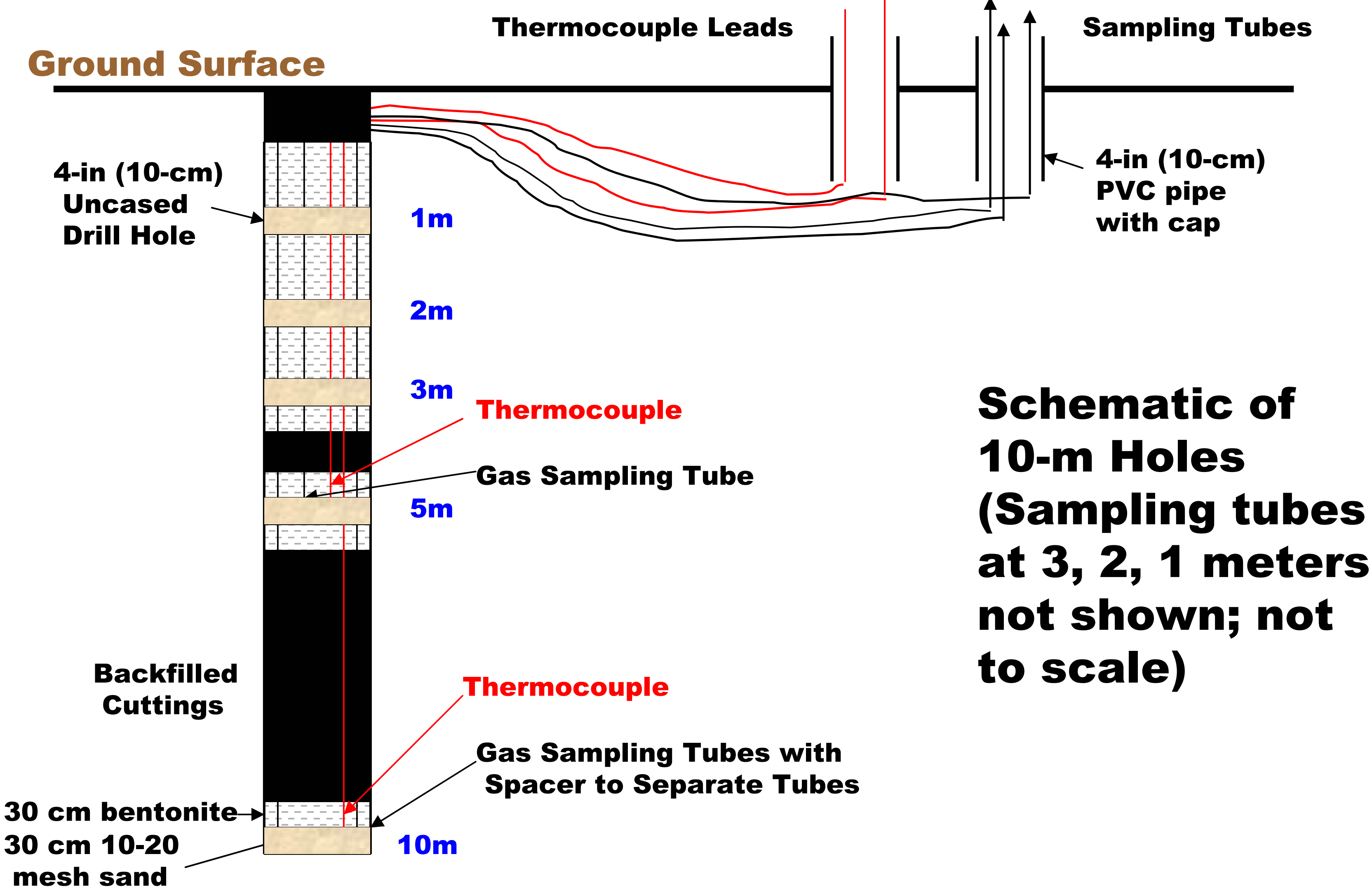


TEAPOT, WINTER, 2004



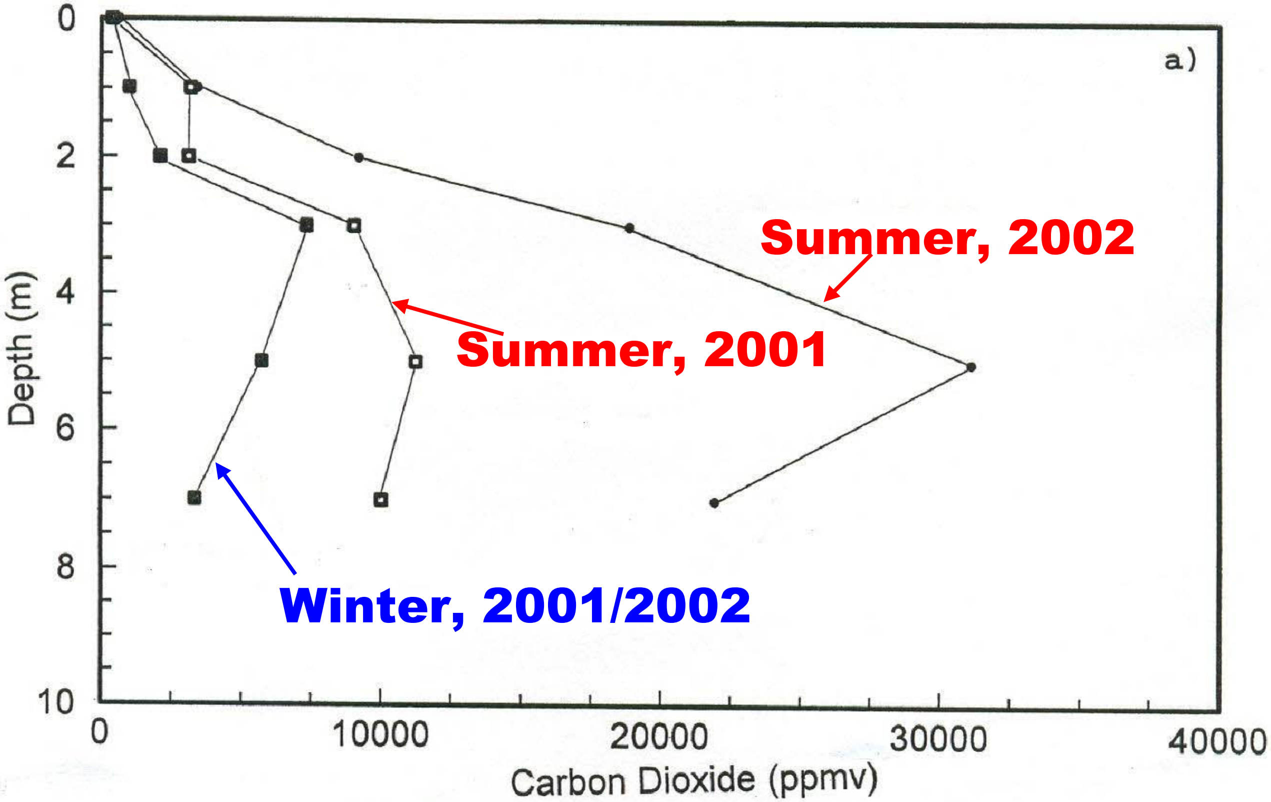
TEAPOT, WINTER, 2004



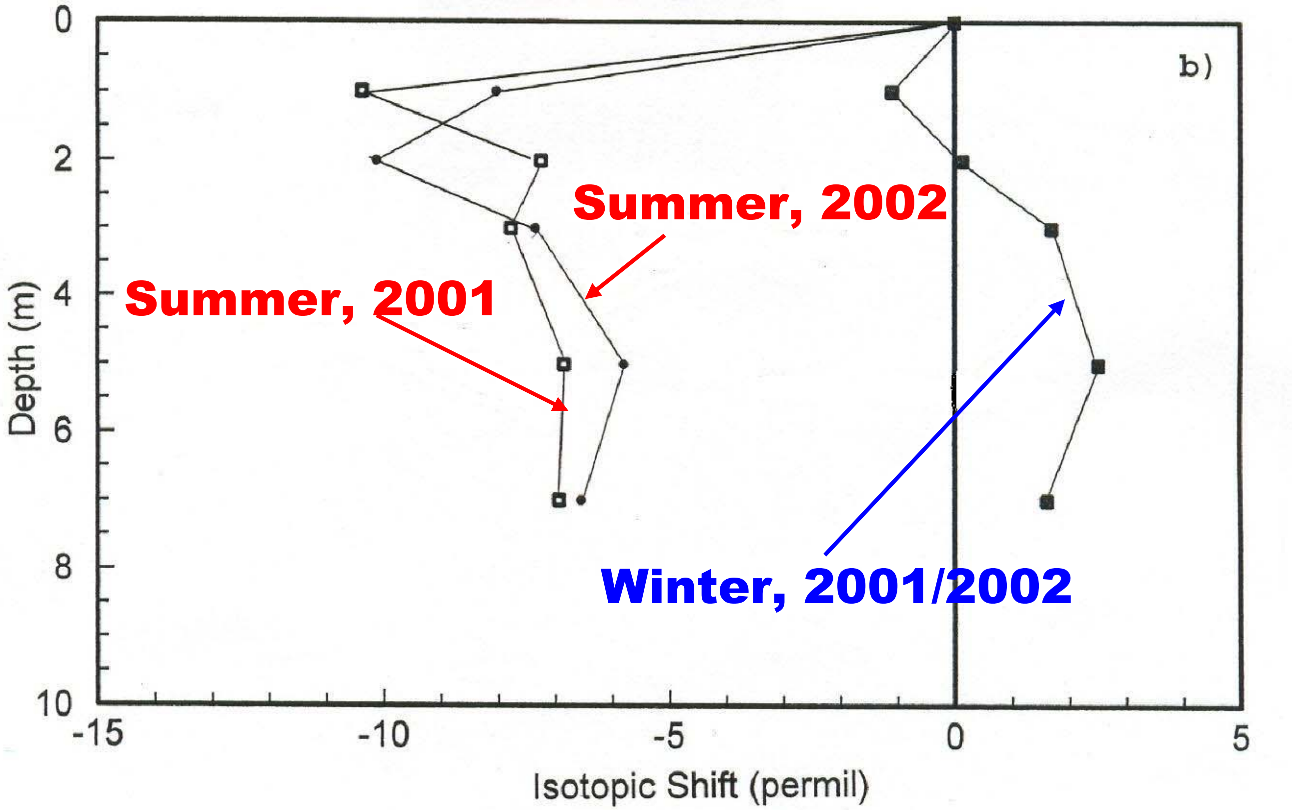

Thermocouple Leads
Sampling Tubes
Ground Surface
4-in (10-cm) Uncased Drill Hole
1m
2m
3m
5m
10m
4-in (10-cm) PVC pipe with cap
Thermocouple
Gas Sampling Tube
Backfilled Cuttings
Thermocouple
Gas Sampling Tubes with Spacer to Separate Tubes
30 cm bentonite
30 cm 10-20 mesh sand
Schematic of 10-m Holes (Sampling tubes at 3, 2, 1 meters not shown; not to scale)


O2
Tube
O2
Temp

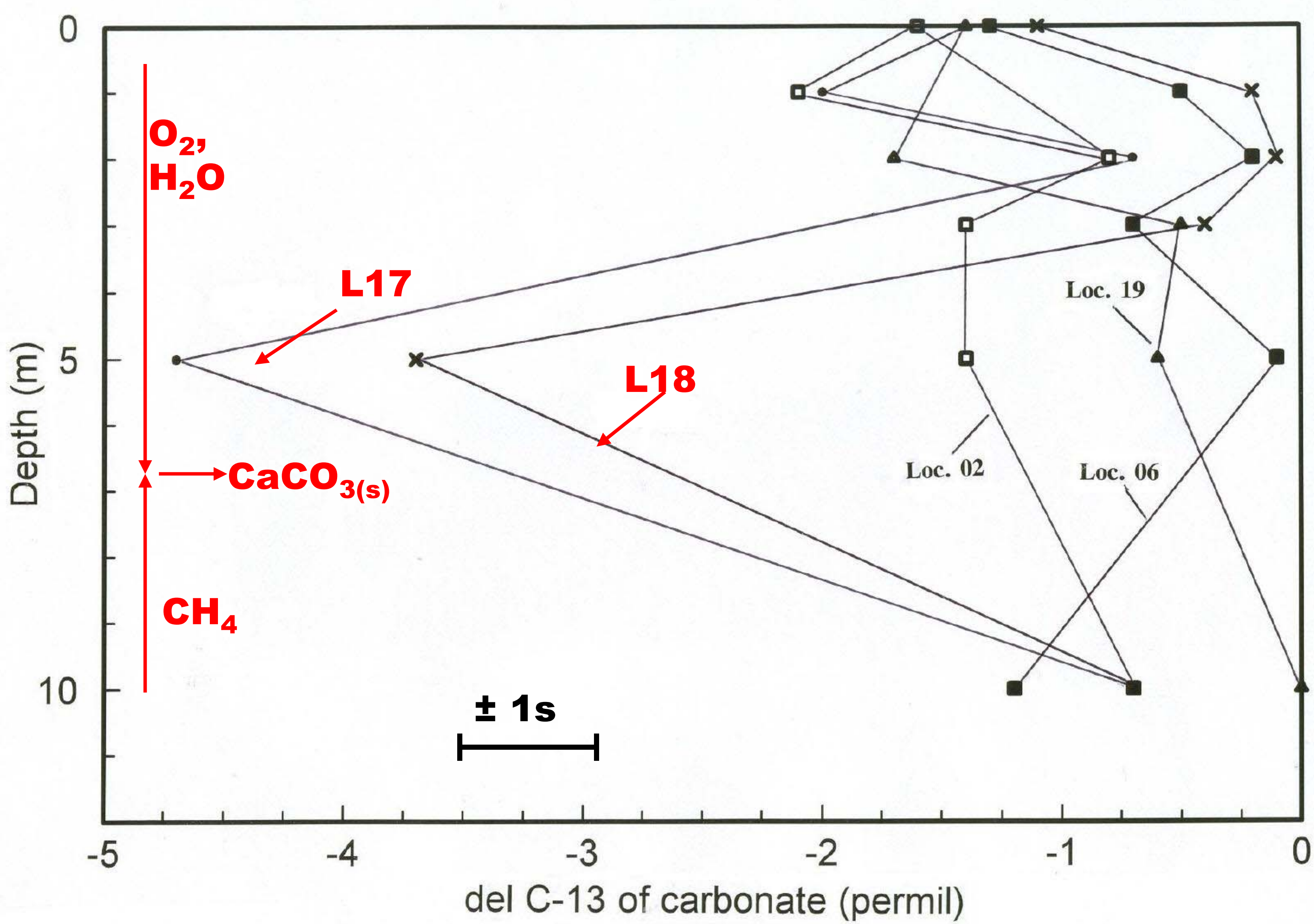
RANGELY – CO_2 IN 10m HOLE L01



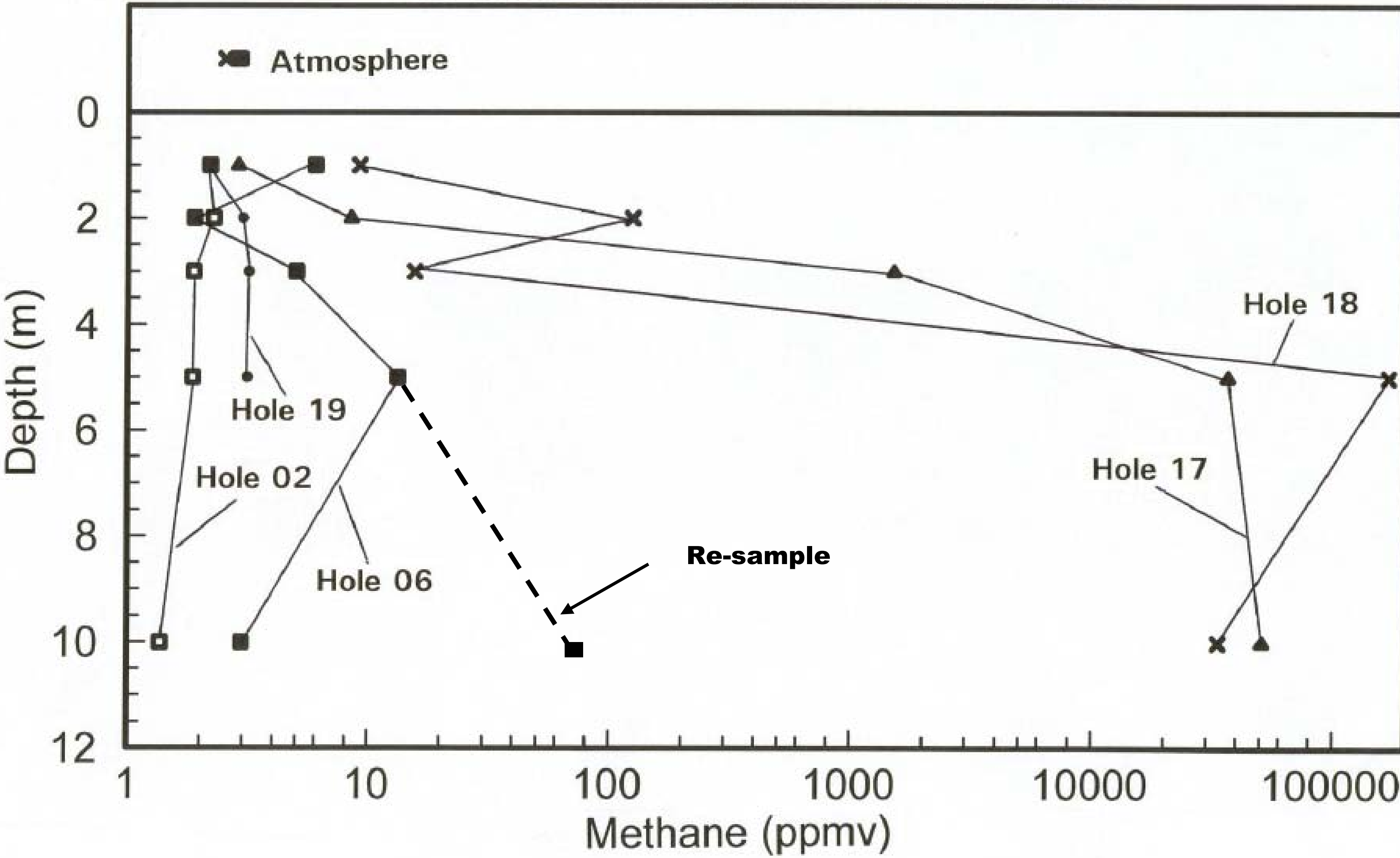
ISOTOPIC SHIFT OF $\delta^{13}C$ OF CO_2 IN 10m HOLE L01 FROM THE AVERAGE SEASONAL ATMOSPHERIC $\delta^{13}C$ OF CO_2



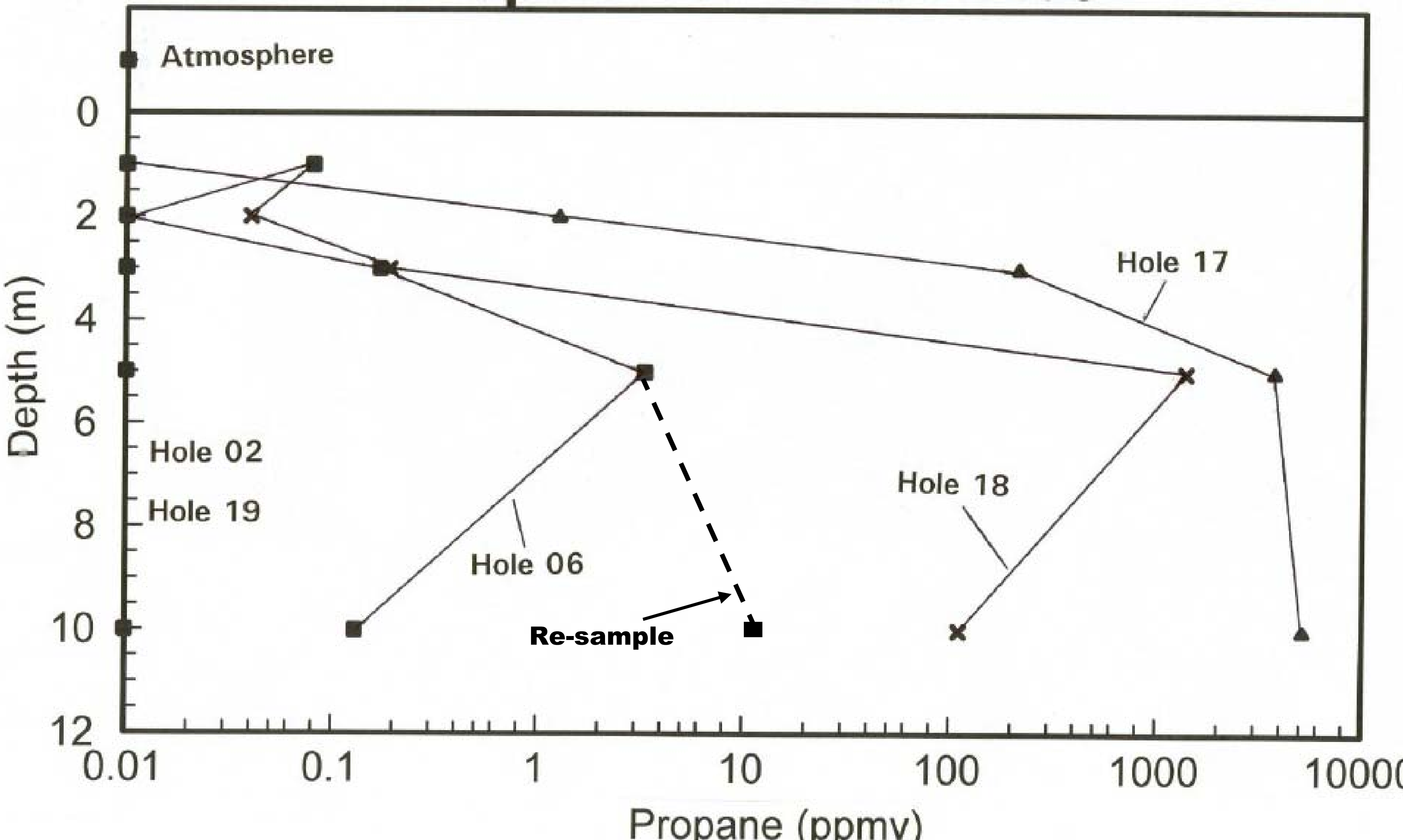
TEAPOT - δ13C OF INORGANIC CARBON (‰)



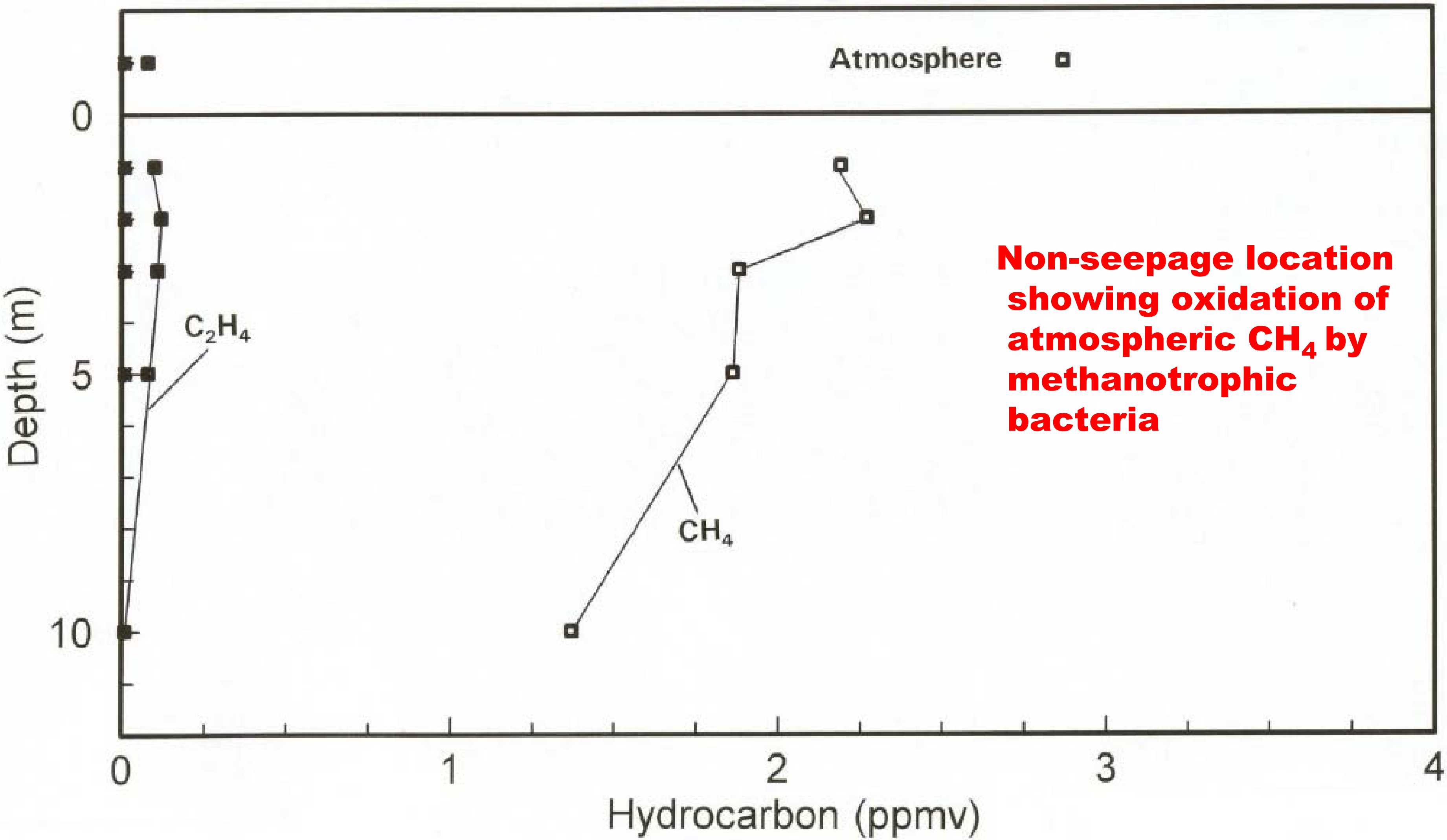
Teapot - Winter, 2005
Methane in 10-m Holes



Teapot - Winter, 2005
Propane in 10-m Holes

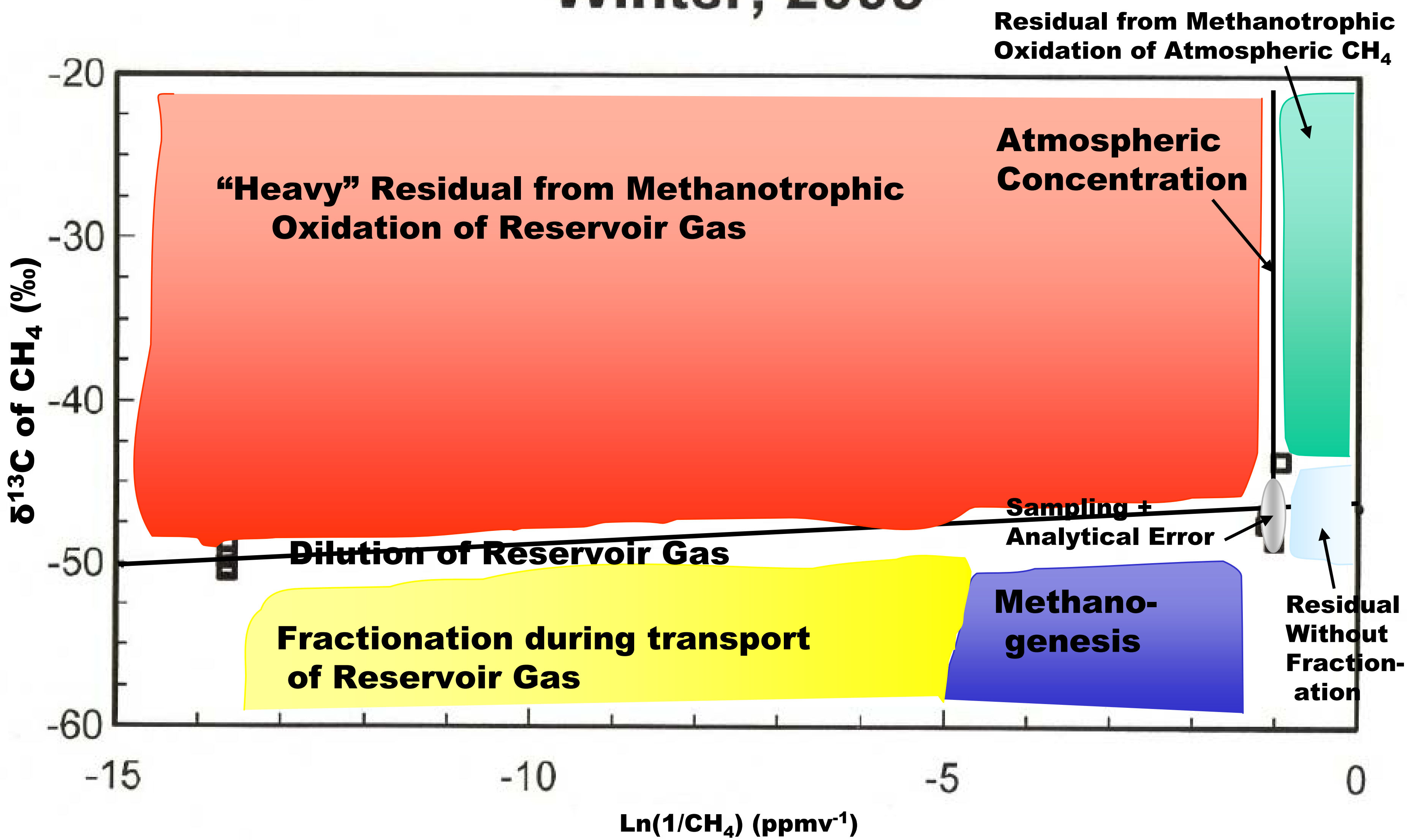


Teapot - Winter, 2005
10-m Hole 02

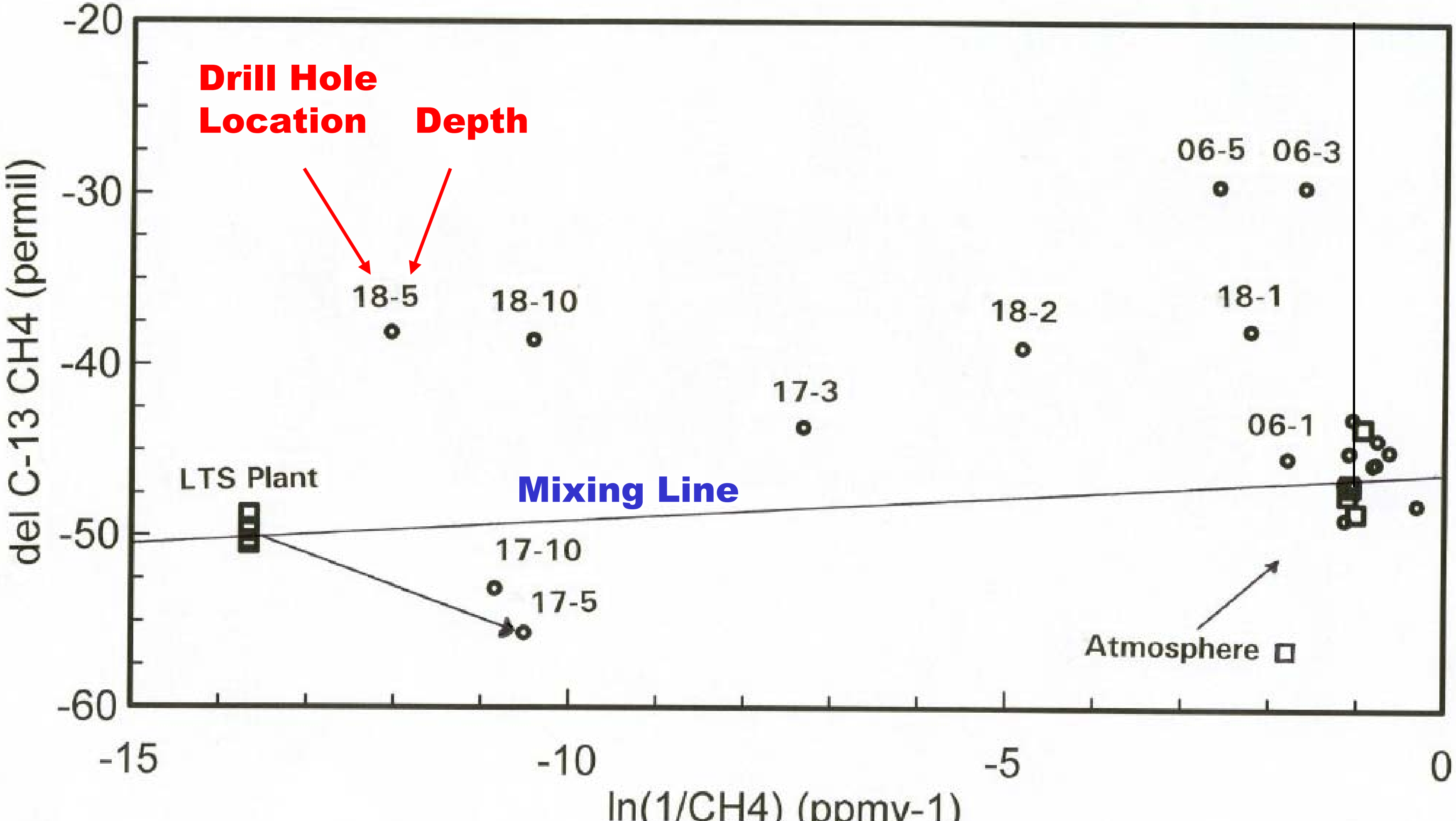


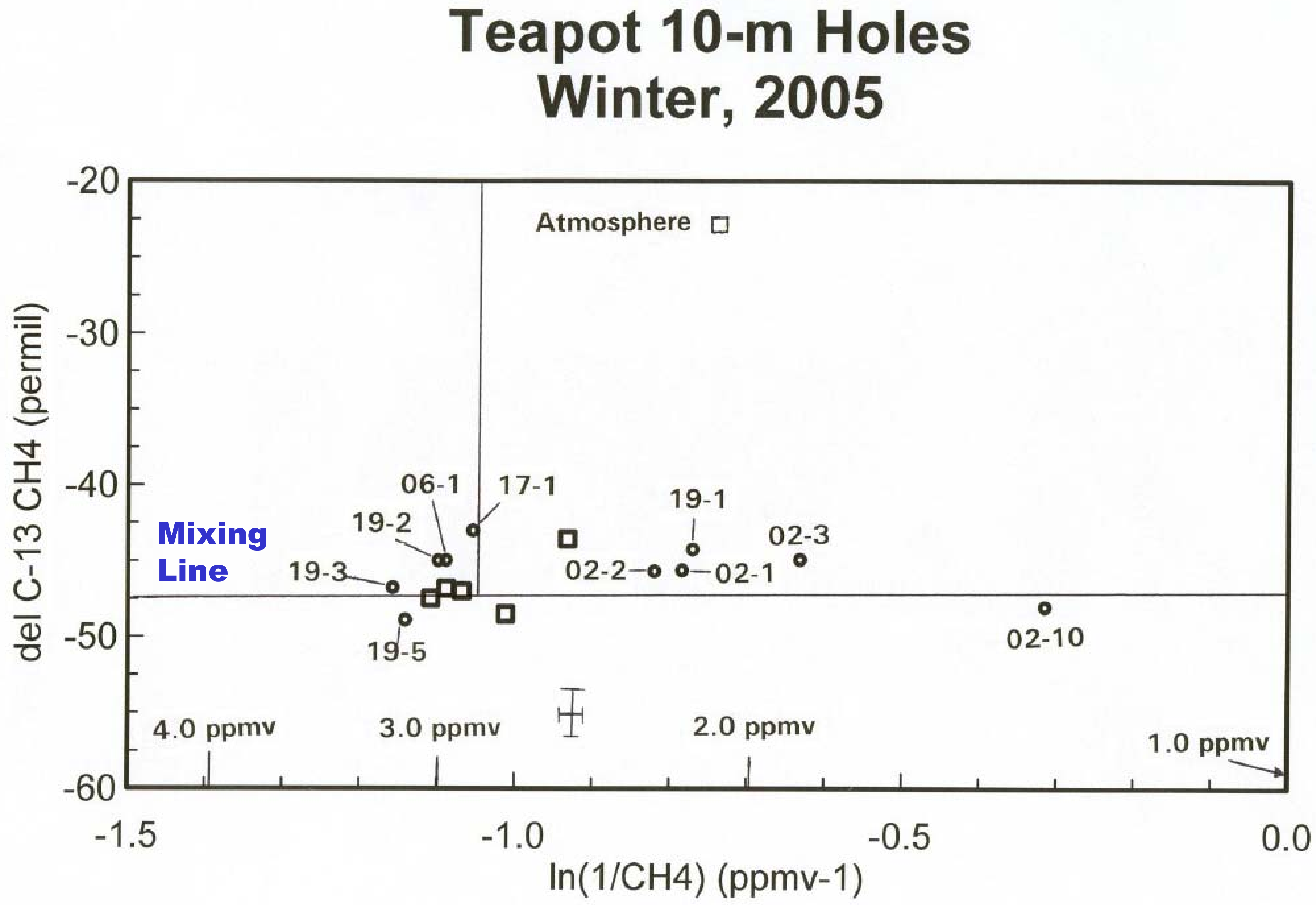
Non-seepage location showing oxidation of atmospheric CH_4 by methanotrophic bacteria

Teapot 10-m Holes
Winter, 2005

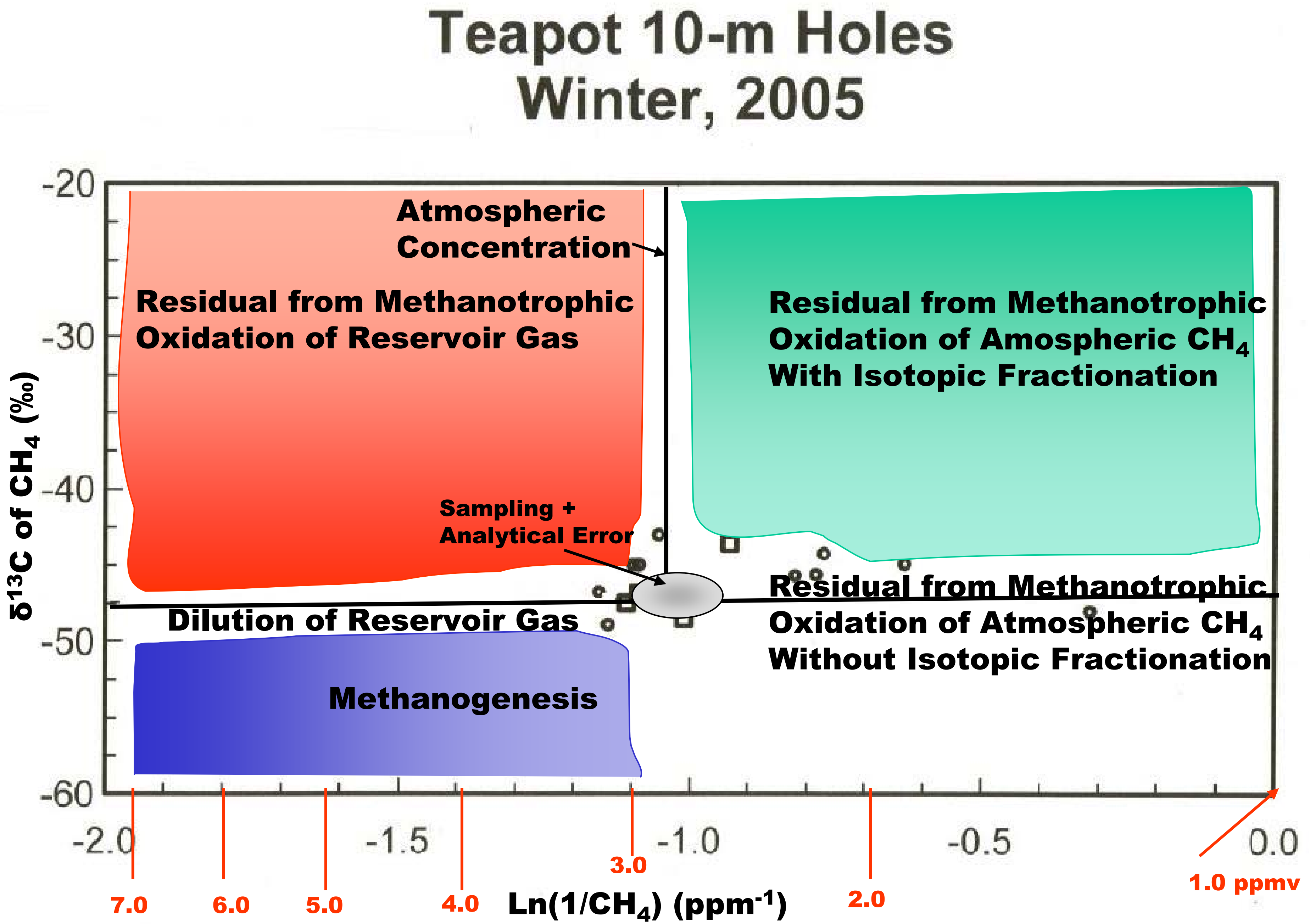


Teapot 10-m Holes
Winter, 2005



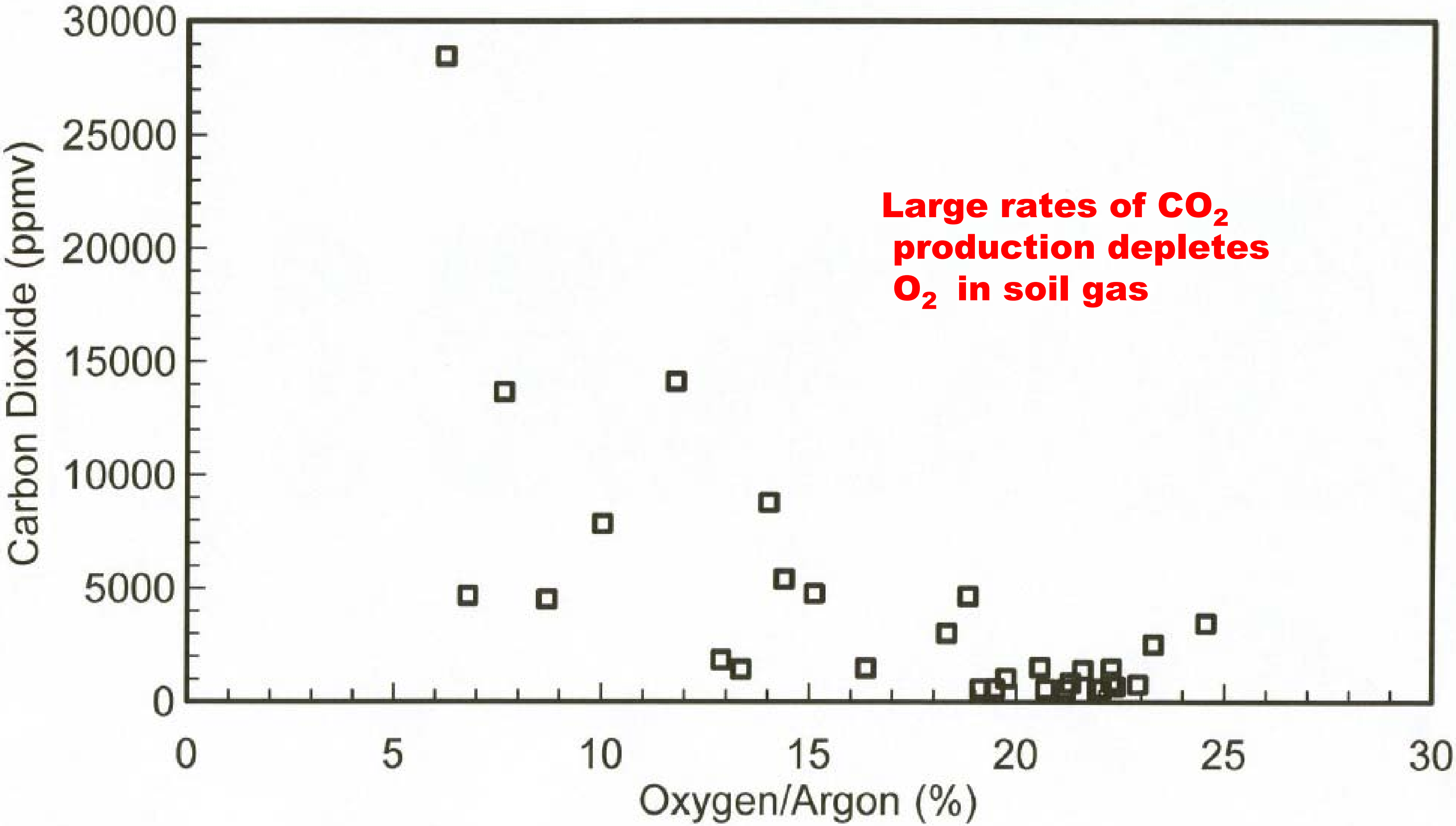


Teapot 10-m Holes
Winter, 2005
Atmosphere
Mixing
Line
06-1
17-1
19-2
19-3
19-1
02-3
02-2
02-1
19-5
02-10
4.0 ppmv
3.0 ppmv
2.0 ppmv
1.0 ppmv
-20
-30
-40
-50
-60
del C-13 CH4 (permil)
-1.5
-1.0
-0.5
0.0
ln(1/CH4) (ppmv-1)

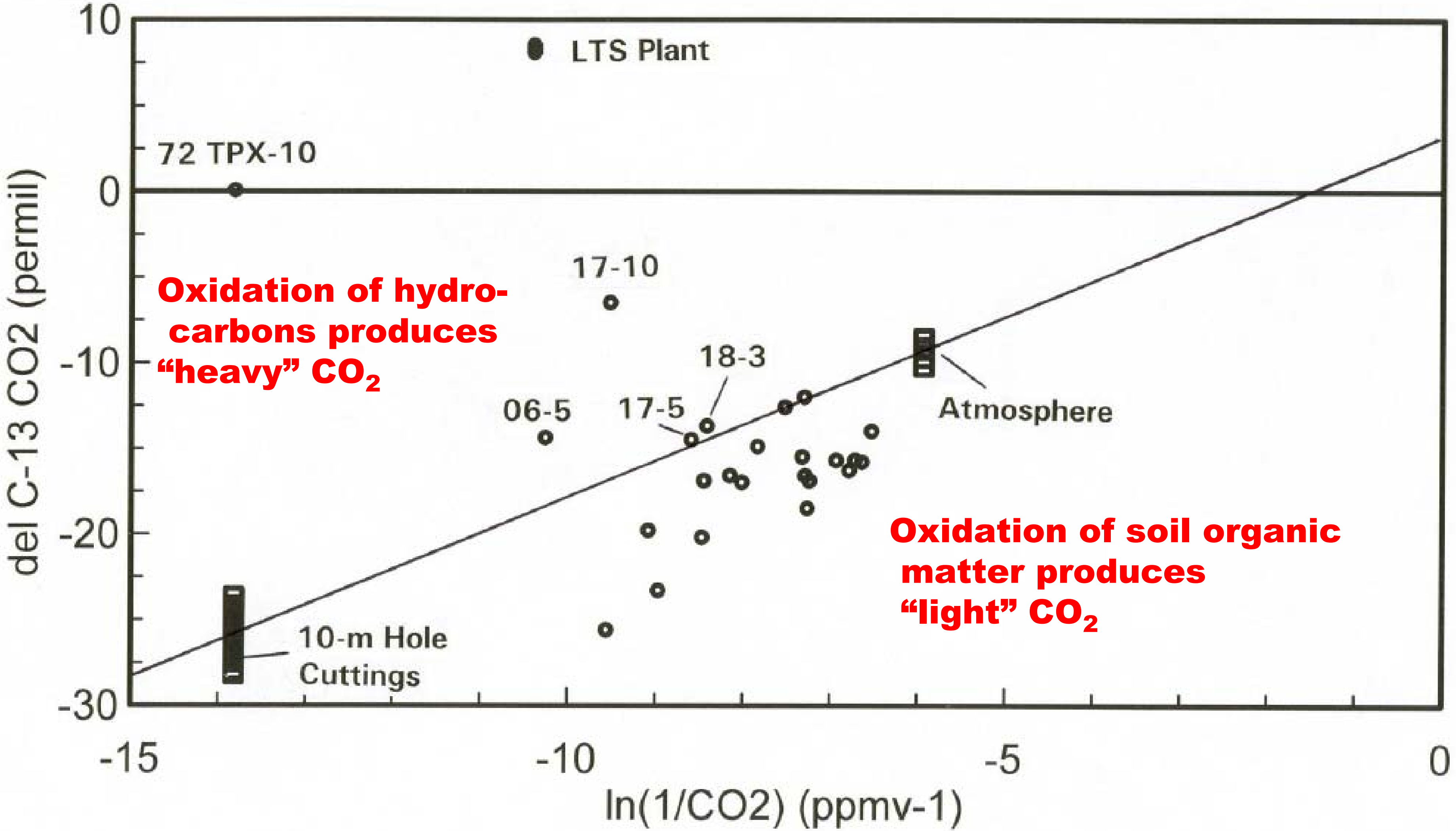


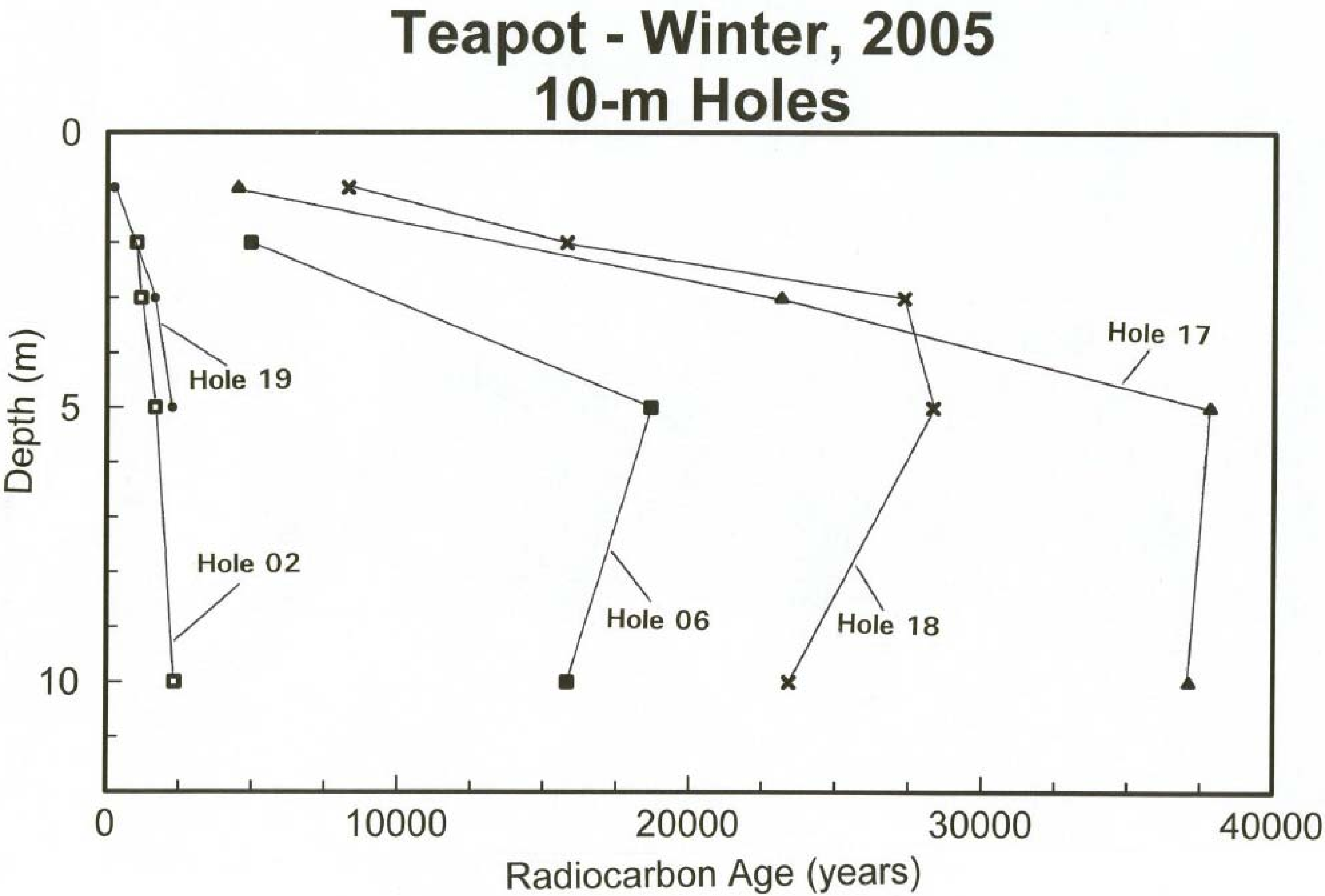
Teapot 10-m Holes
Winter, 2005
Atmospheric Concentration
Residual from Methanotrophic Oxidation of Reservoir Gas
Residual from Methanotrophic Oxidation of Amospheric CH4 With Isotopic Fractionation
Sampling + Analytical Error
Residual from Methanotrophic Oxidation of Atmospheric CH4 Without Isotopic Fractionation
Dilution of Reservoir Gas
Methanogenesis
-20
-30
-40
-50
-60
-2.0
-1.5
-1.0
-0.5
0.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0 ppmv
δ13C of CH4 (‰)
Ln(1/CH4) (ppm-1)

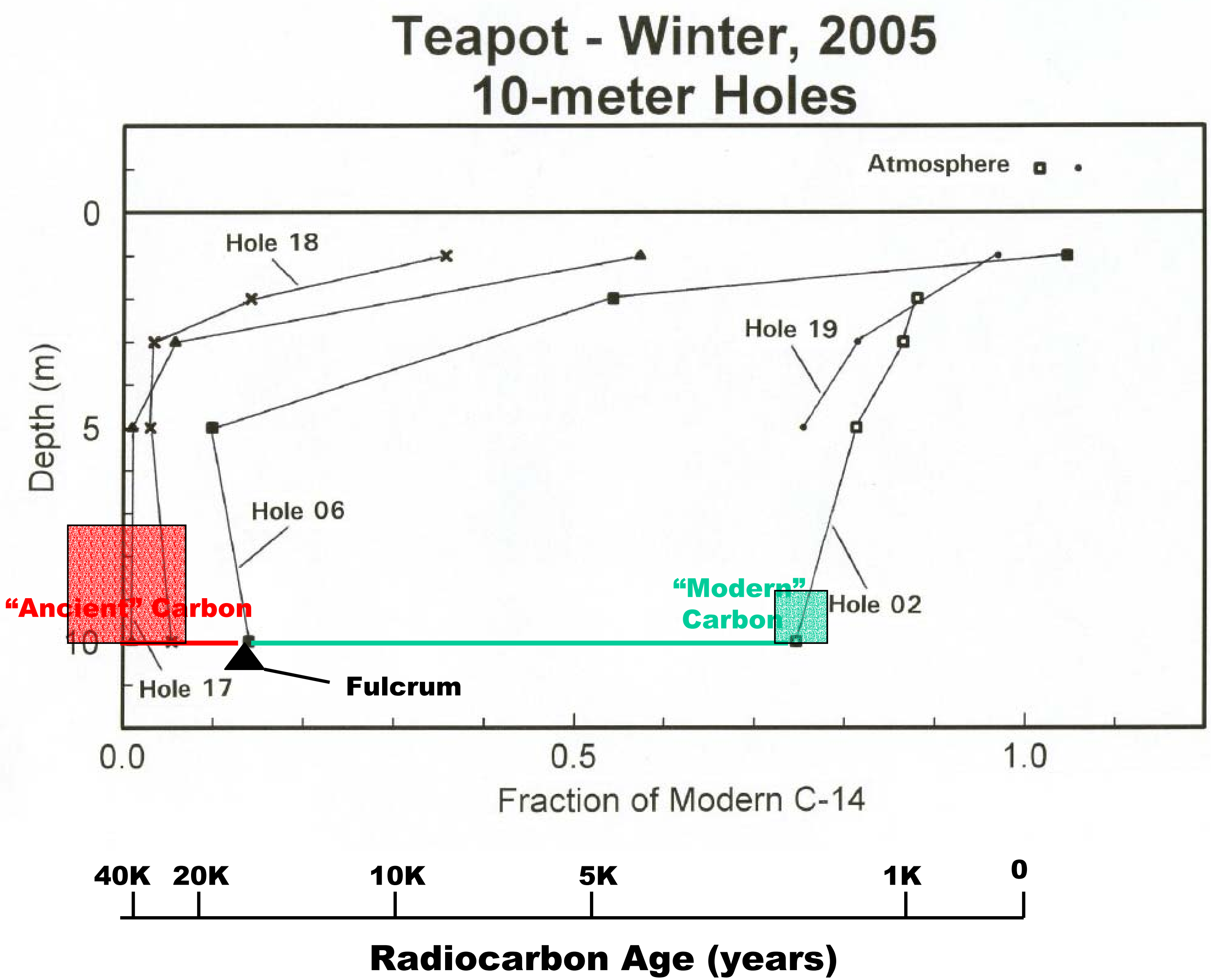
Teapot - Winter, 2005
10-meter Holes

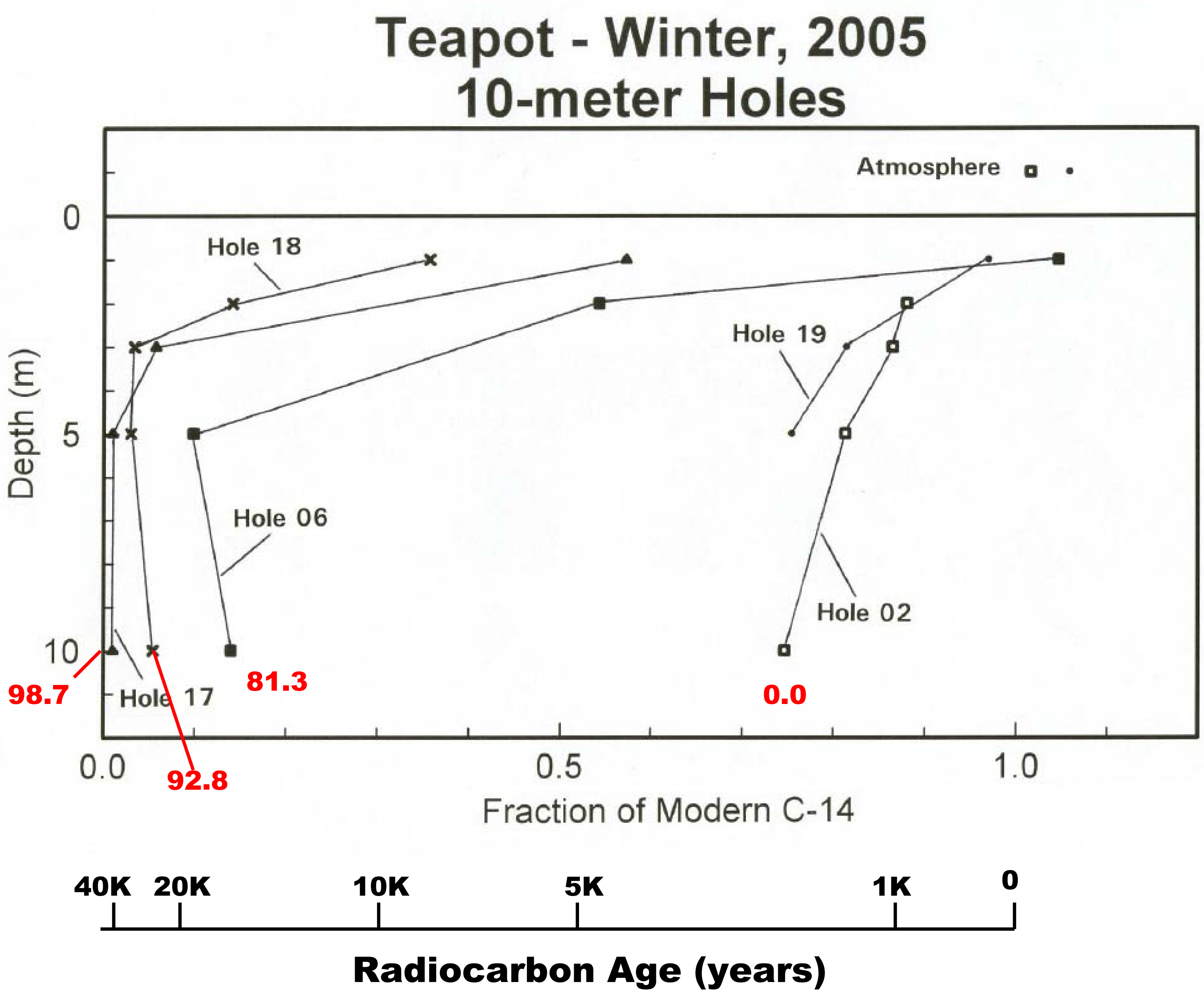


Teapot 10-m holes
Winter, 2005

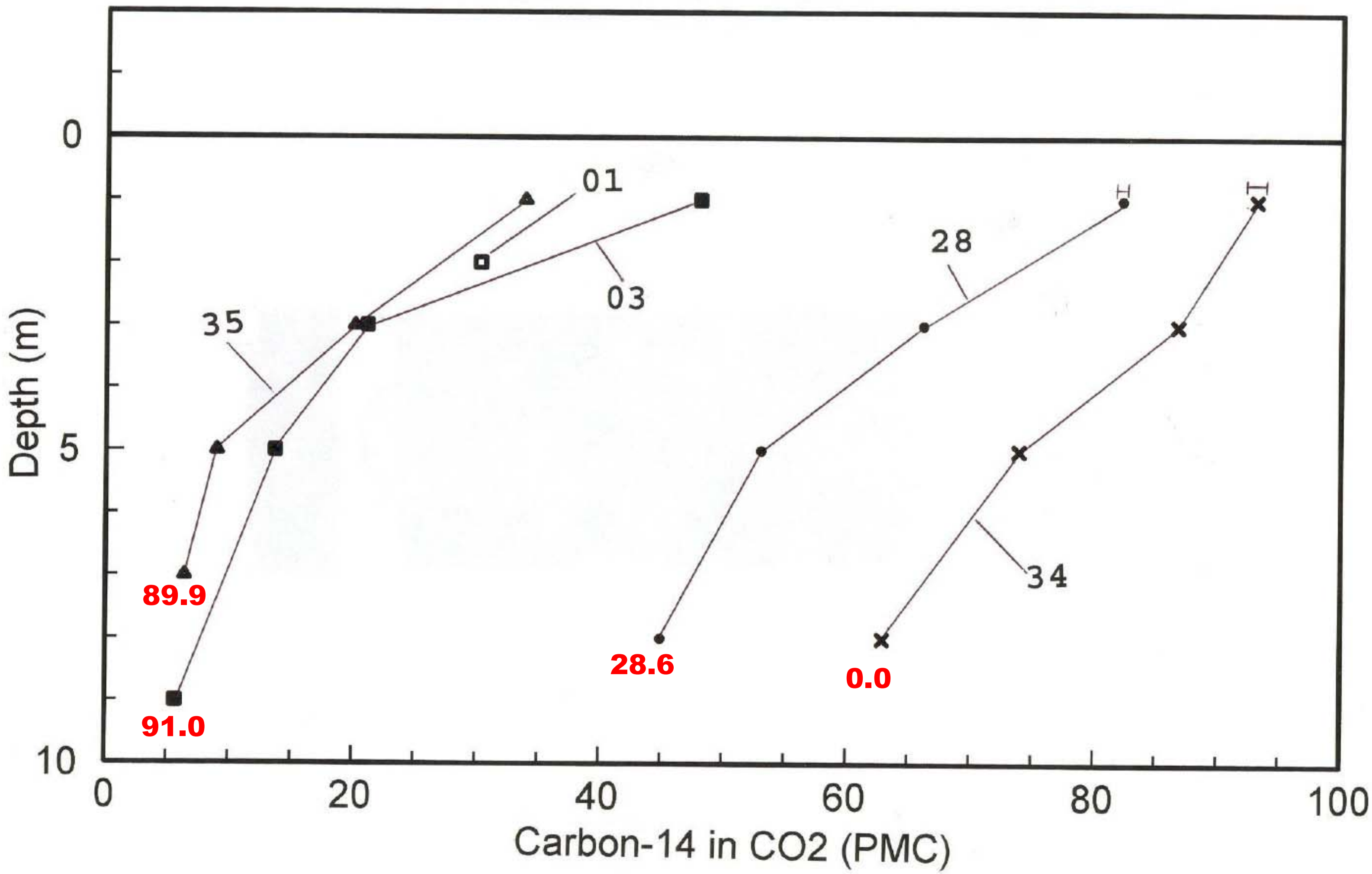



Teapot - Winter, 2005
10-m Holes
Depth (m)
0
5
10
Radiocarbon Age (years)
0
10000
20000
30000
40000
Hole 19
Hole 02
Hole 06
Hole 18
Hole 17

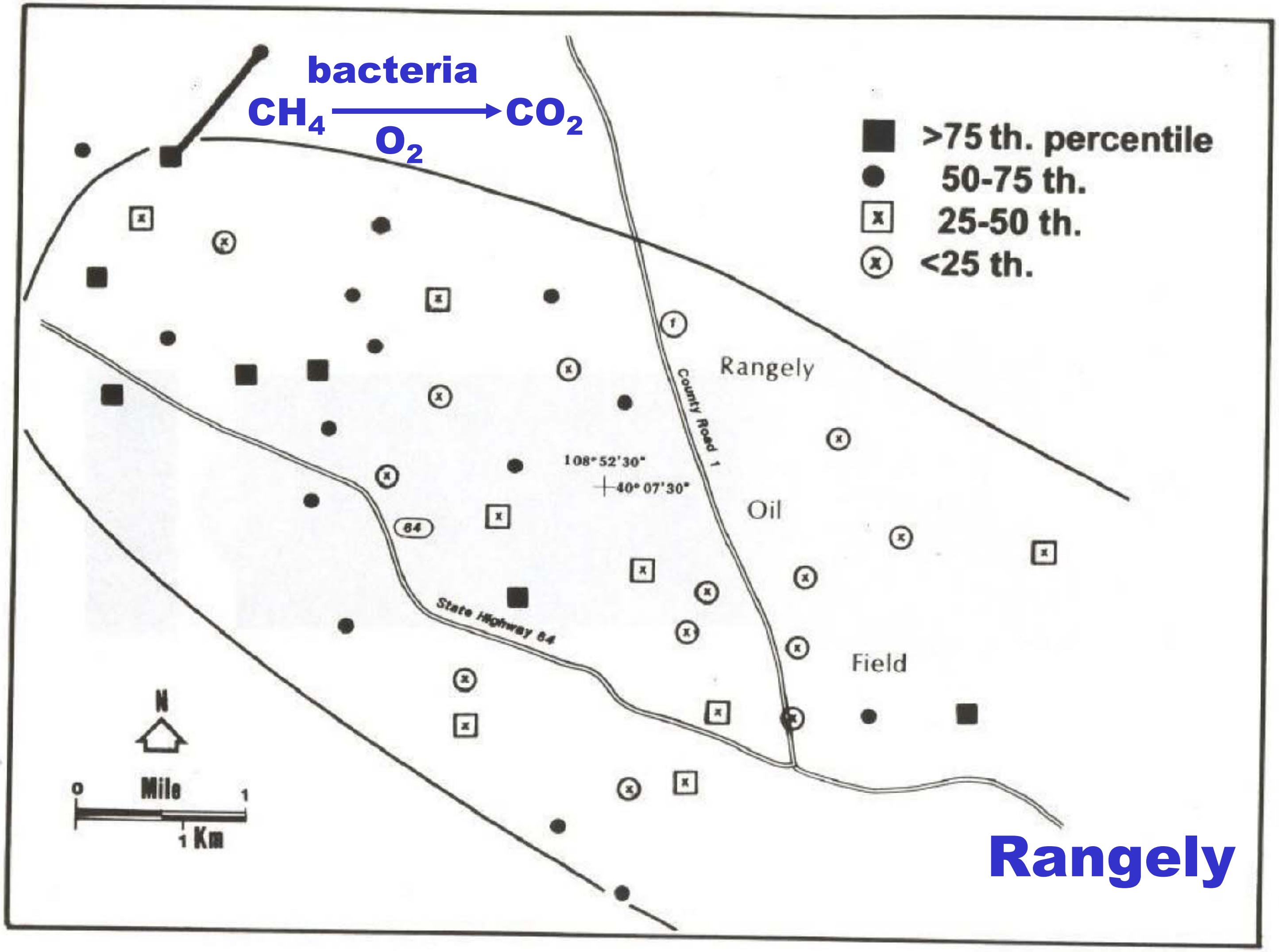

Teapot - Winter, 2005
10-meter Holes
Atmosphere
Hole 18
Hole 19
Hole 06
Hole 02
Hole 17
"Ancient" Carbon
"Modern" Carbon
Fulcrum
Depth (m)
0
5
10
0.0
0.5
1.0
Fraction of Modern C-14
40K
20K
10K
5K
1K
0
Radiocarbon Age (years)


Teapot - Winter, 2005
10-meter Holes
Atmosphere
Hole 18
Hole 19
Hole 06
Hole 02
Hole 17
Depth (m)
0
5
10
0.0
0.5
1.0
Fraction of Modern C-14
98.7
92.8
81.3
0.0
40K
20K
10K
5K
1K
0
Radiocarbon Age (years)

Rangely – Winter, 2001/02
10-m Holes



RANGELY CO_2 FLUX - WINTER, 2001/2002



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 sources of CO_2.**

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" season,**
- **GC measurements of CH_4 must be better than routine,**
- **Liberal application of stable isotopic ratio measurements,**
- **Use flux magnitudes, soil gas concentration gradients, isotopic shifts to find "interesting" locations,**
- **Correct 8 out of 8 at Rangely and Teapot,**
- **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 of carbon,
- Other Problems Increasing Difficulty
- 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.

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 (C. Ballentine-University of Manchester, UK),**
- **Eddy covariance mainly applied in pristine environments; practical problems in oil-field environments(?)**

ESTIMATION OF CO_2 MICROSEEPAGE INTO THE ATMOSPHERE AT RANGELY

- **Using total winter-time CO_2 flux gives an estimate of 8600 metric tonnes year^{-1}**
- **Using the $\delta^{13}C$ offset for CO_2 from atmospheric value gives <3800 metric tonnes year^{-1},**
- **Using the C-14 data on 4 anomalous locations gives ≈ 90% of the CO_2 as ancient,**
- **The average winter CO_2 flux over the field is 0.302 g m^{-2}day^{-1}, 4/41 locations on the field are “anomalous,” yielding 170 metric tonnes year^{-1},**
- **The anomalous CO_2 is primarily derived from methanotrophic oxidation of CH_4, so <170 tonnes is final estimate,**
- **$2.55x10^3/23x10^6$ = 0.00011 (≈ 0.01%/year).**

ESTIMATION OF CH_4 MICROSEEPAGE INTO THE ATMOSPHERE AT RANGELY

- **The gross CH_4 microseepage into the atmosphere over 78 km^2 is 700±1200 tonnes $year^{-1}$ using the winter rate,'**
- **The net CH_4 microseepage into the atmosphere is 400 metric tonnes $year^{-1}$±?, subtracting the control area.**
    - **Non-parametric Wilcoxon test indicates the mean rate is positive at α =0.015.**

ESTIMATION OF GAS MICROSEEPAGE AT BASELINE CONDITION OVER TEAPOT DOME (BASED ONLY ON WINTER MEASUREMENTS)

CO_2 = 3400 ± 2300 metric tonnes $year^{-1}$ over 42 km^2 of field, (entirely biological sources),

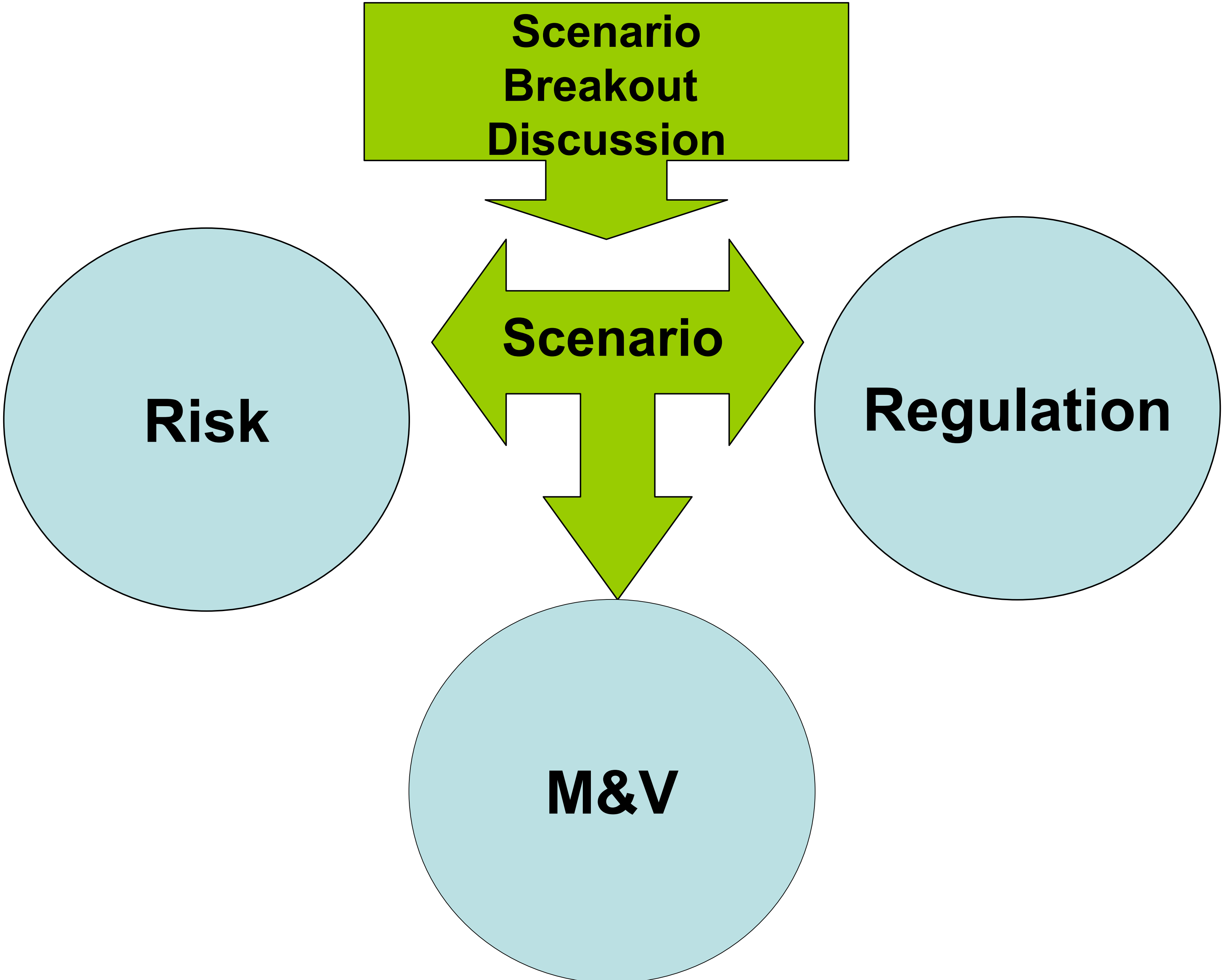
CH_4 = 2.1 ± 1.6 metric tonnes $year^{-1}$ over 42 km^2 of field (entirely geological source?).

ACKNOWLEDGEMENTS

- The Department of Energy-Basic Energy Sciences supported the Rangely research through a grant (DE-FG03-00ER15090) to the Colorado School of Mines; Nick Woodward was the Program Manager,
- The Department of Energy-Rocky Mountain Oilfield Testing Center (RMOTC) supported the Teapot Dome research; Vicki Stamp and Mark Milliken are the Program Managers,
- Numerous individuals at the Colorado School of Mines, Chevron USA Production (Chevron-Texaco), and Naval Petroleum Reserve No. 3.

Session 4

Monitoring Scenario Development



Scenario Breakout Discussion
Scenario
Risk
Regulation
M&V

COAG suggested for purposes of M&V providesto a regulatory framework:

- *Provide for the generation of clear, comprehensive, timely and accurate information effectively*
- *Responsibly manage environmental, health, safety and economic risks*
- *Ensure that set performance standards are being met*
- *Determine to an appropriate level of accuracy*
  - *–the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of fugitive emissions.*

Consequently the goals of monitoring framework is to provide

- *A comprehensive set of information from direct measurements and remote sensing of the process of storage*
- *Appropriately document the complete storage process within the following tasks:*
  - *–Safely transport CO2 from source to sink;*
  - *–Safely inject CO2 into subsurface reservoirs;*
  - *–Safely store CO2 in the subsurface; and*
  - *–Safely abandon facilities and restore sites.*

Verification at each stage is critically important to achieve public and stakeholder satisfaction that the CO2 has been removed permanently from the surface environment.

Process of Scenario Evaluation

- **Scenario Context**
  - **Guidance from Leader only**
- **Risk Register**
  - **Risk - Specific Issues-Consequences-Mitigation**
  - ***Consider consequences for all stakeholders***
  - ***Consider subsurface to surface***
  - ***Consider phases,***
- **Regulatory**
  - ***Don't get tangled with legal aspects***
  - ***Define possible, sensible framework that will verify performance at each stage***
  - ***Address risks***
  - ***Give thought to liabilities, short term, long term, abandonment*.**
  - ***Define possible KPIs…one sentence***
- **M&V Program**
  - ***Should address risk and regulatory environment***
  - ***Should have eye on economic but complete***
  - ***Should be generic and high level, unless illustrative***

Scenarios

- **Acid-gas Canada**

-

- **Gippsland Australia**

-

- **Frio Texas**

- **Mullet**

Scenario 1. Gippsland, Aus

Coal onshore, offshore storage, active hydrodynamics?

• Kevin Dodds	CO2CRC/CSIRO Australia
• Ernie Perkins	CO2CRC Australia
• Bill Koppe	Anglo Coal Australia
• Alan Rezigh	ConocoPhillips
• Massimo Angelone	ENEA
• Sergio Persoglia	OGS
• Fedora Quattrocchi	INGV
• Gianfranco Galli	INGV
• Gianluca Patrignani \	Snamprogetti div. Aquater/RISAMB
• Brent Lakeman	Alberta Research Council Inc.
• Hubert FABRIOL	BRGM
• Don White	Geological Survey of Canada
• Daiji Tanase	Engineering Advancement Association of Japan
• Scott Imbus	Chevron Energy Technology Co.
• Tim Dixon	UK DTI

Scenario 2. Mullet, Europe

Deep 4km, offshore, European consequences

• Nick RILEY	British Geological Survey
• Tony Espie	BP
• Malcolm Wilson	Energy INET
• Fabio Moia	CESI S.p.A.
• Francois KALAYDJIAN	IFP
• Roberto Bencini	INGV
• Barbara Cantucci	INGV
• Johannes Petrus van Dijk	ENI Div. Exploration & Production
• Neeraj Gupta	Battelle
• K. MICHEL	BRGM
• Hiroyuki Azuma	Oyo corporation
• Arthur Wells	U.S. Department of Energy
• Pascal Winthaegen	TNO
• Anhar Karimjee	US EPA

Scenario 3. Acid Gas, Canada

Regulatory environment is mature…is it adequate ?

• Rick Chalaturnyk	University of Alberta
• Don Lawton	University of Calgary
• Dan Ebrom	BP
• Ernesto Bonomi	CRS4
• Yann Le Gallo	IFP
• Antonella Cianchi	INGV
• Janpieter van Dijk	Eni E&P Division
• Umberto Fracassi	INGV
• Hideki Saito	Oyo Corporation
• Bernard BOURGEOIS	BRGM
• Ola Eiken	Statoil
• Anne-Marie Thompson	Natural Resources Canada
• Laurent Jammes	Schlumberger

Scenario 4. Frio US

Mature regulatory environment Answers looking for the questions ?

• Susan Hovorka	Bureau of Economic Geology
• Charles Christopher	BP Americas
• Richard Rhudy	EPRI
• Kate Roggeveen	Australian Greenhouse Office
• Giuseppe Girardi	ENEA
• Salvador Rodriguez	IFP
• Sonia Topazio	INGV
• Lombardi Salvatore	University "La Sapienza of Rome"
• Maria Teresa Mariucci	INGV
• Jonathan Pearce	British Geological Survey
• Akio Sakai	Japex
• Paitoon Tontiwachwuthikul	University of Regina, Canada
• Christian Bernstone	Vattenfall Utveckling AB
• Angela Manancourt	IEA GHG
• John Gale	IEA GHG

Risk Elements
Containment

- ***Permeable Zones in Seal***
- ***Leakage Through Faults***
- ***Leakage Through Wells***
- ***Regional Over-Pressurisation***
- ***Local Over-Pressurisation***
- ***Exceeding Spill Point***
- ***Earthquake***
- ***Migration Direction***
- ***Compressor Failure***
- ***Platform Failure***
- ***Pipeline Failure***
- ***Well-Head Failure***

Risk Elements
Effectiveness

- *Lack of Capacity*
- *Reduced Injectivity*
- *Inadequate Source*
- *Groundwater Displacement*
- *Regulatory Change*
- *Stakeholders Reject or Oppose Project*
- *Poor Public Perception of Other Projects*
- *Sub-Surface Biological Concerns*
- *Lack of Regulations*
- *Licensing/Ownership/Liability/Insurance*

Regulatory Environment

Players

- Private – NGO – Indigenous
- Government – State – National – International
- Need to balance deal across the spectrum
- Identify issues and reconcile

Constraints

- Environment, petroleum, offshore, onshore
- Law of Ocean

Definitions

- How CO2 defined, how injected
- Saline formations…van use ocean salinity a benchmark

Risk Register for Regulatory Environment

- Risk
- Specific Issues
- Consequences
- Mitigation

Considerations for Regulatory Environment

- Production Risk
  - Data Acquisition
  - Plant and processing
  - Gas Transportation
  - Drilling Risk
  - Injection Risk
  - Personal Risk
  - Decommissioning

Considerations for Regulatory Environment

- Storage
  - Leakage to surface through reservoir path
  - Leakage to surface through wells during monitoring
  - Leakage to surface post decommissioning
  - Leakage into potable water supply

Considerations for Regulatory Environment

Project Phases

- Phase 1 : Pre Injection and Injection related activities

KPIs

- Phase 2 : Post Injection but pre-closure related activities

KPIs

- Phase 3 : Post Closure Monitoring. How the ownership will pass from Operator to another entity (expected to be a Govt. entity)

KPIs

- Phase 4 : Long term monitoring.

Responsibilities ?

M&V Addressing Regulatory & Risk Questions

Monitoring and Verification

- M&V framework including frequency of monitoring
- Trigger points to identify anomalies per phase
- Baseline establishment
- KPI’s to define transition points to a different monitoring regime (move from 1 phase to another)
- Contingency planning for monitoring responses outside uncertainty bands
- Roles and Responsibilities

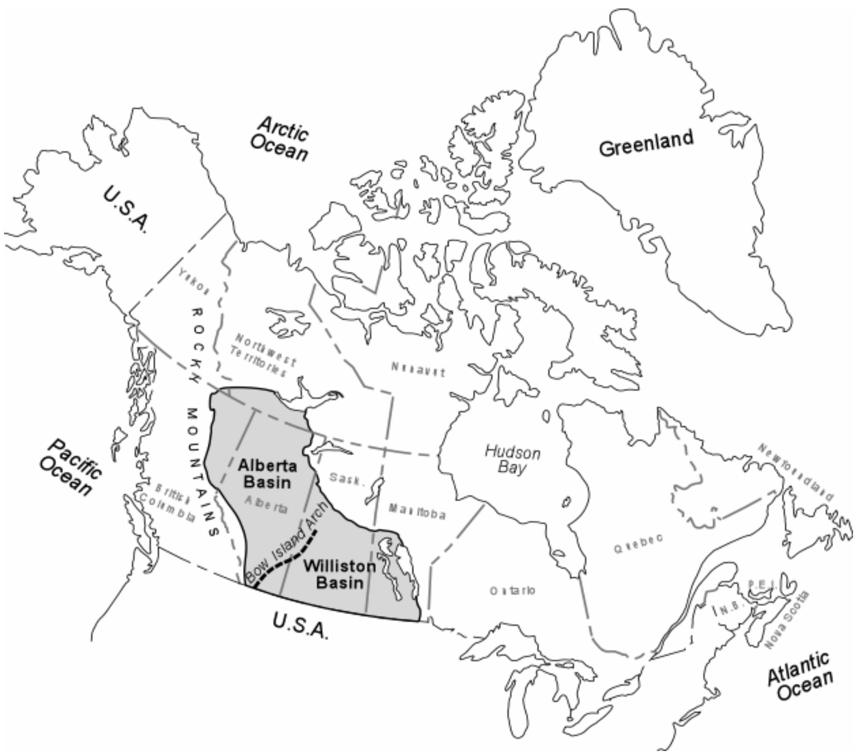
Acid Gas Scenario

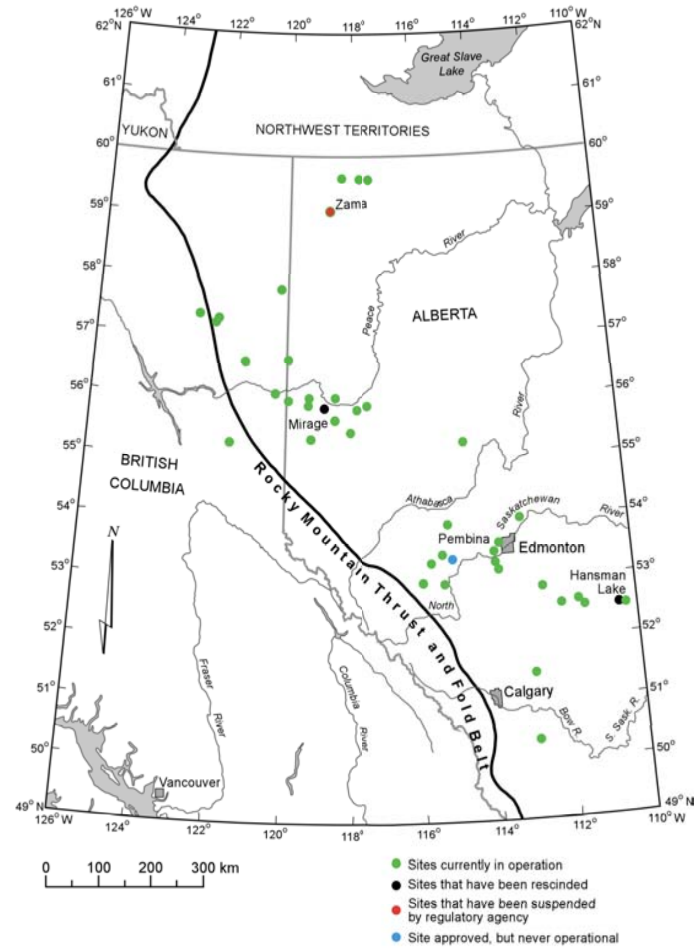
Rick Chalaturnyk
University of Alberta

Acknowledgements

The summarized information contained in this scenario description were extracted from a report "Development of a Generic Monitoring Plan" prepared by R.J. Chalaturnyk, J. Jimenez, S. Bachu and B. Gunter for the Alberta Research Council's project entitled "Characteristics of Existing Acid Gas Injection Operations in Western Canada Phase IIIA-1: Volume V". Approval to utilize this information as a "Monitoring Scenario" in the 2nd Monitoring Network Meeting is gratefully acknowledged.

Location


Arctic Ocean
Greenland
U.S.A.
Pacific Ocean
ROCKY MOUNTAINS
Alberta Basin
Williston Basin
Bow Island Arch
Hudson Bay
U.S.A.
Atlantic Ocean


NORTHWEST TERRITORIES
YUKON
Great Slave Lake
Zama
ALBERTA
Mirage
BRITISH COLUMBIA
Rocky Mountain Thrust and Fold Belt
Pembina
Edmonton
Hansman Lake
Calgary
Vancouver
0 100 200 300 km
Sites currently in operation
Sites that have been rescinded
Sites that have been suspended by regulatory agency
Site approved, but never operational

Regulatory Requirements

The selection of an acid-gas injection site needs to address various considerations that relate to:

- proximity of the injection site to the sour oil and gas facility that is the source of acid gas;
- confinement of the injected gas;
- effect of acid gas on the rock matrix;
- protection of energy, mineral and groundwater resources;
- equity interests; and
- wellbore integrity and public safety.

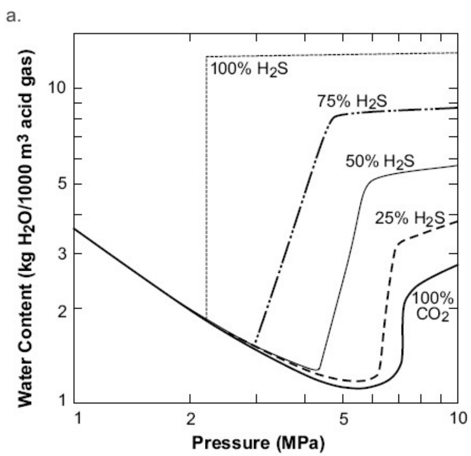
To optimize disposal and minimize risk, the acid gas needs to be injected:

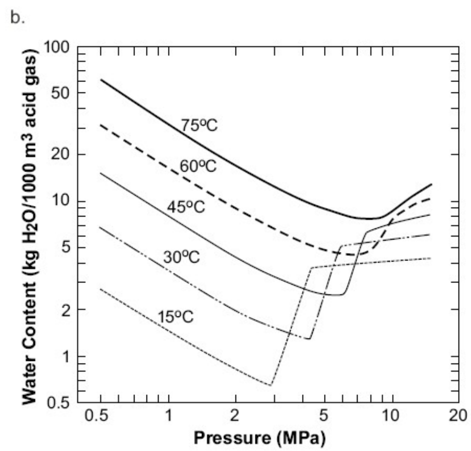
- in a dense-fluid phase, to increase storage capacity and decrease buoyancy;
- at bottom-hole pressures greater than the formation pressure, for injectivity;
- at temperatures in the system generally greater than 35^{o}C to avoid hydrate formation, which could plug the pipelines and wells; and
- with water content lower than the saturation limit, to avoid corrosion.

Some pertinent processes/issues:

- Highly non-ideal compression behavior of acid gases. Acid gas has ~ 1.5-2.5 times greater storage potential than original gas pore volume. The risk is that huge volumes of potential lethal gas are contained in a relatively small volume of reservoir;
- Non-ideal solubility in liquid phases. Acid gas solubility is much more pronounced in liquid hydrocarbons than water. Acid gases may strongly de-asphalt many oils (potential plugging issues);

Some Properties of Acid Gas





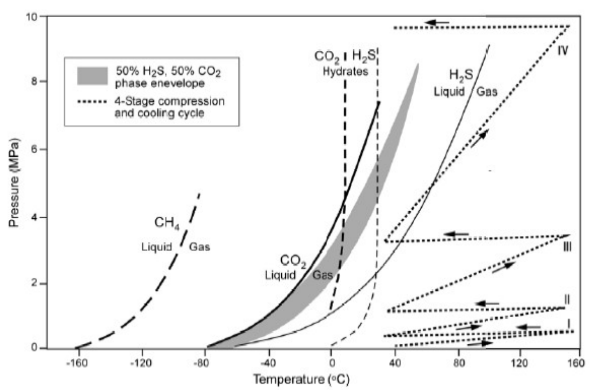
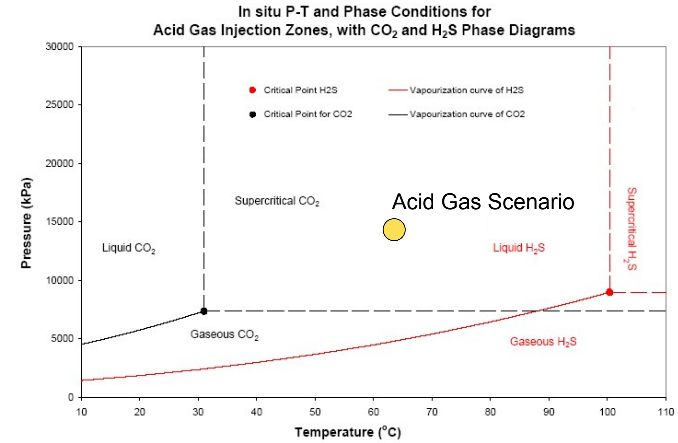


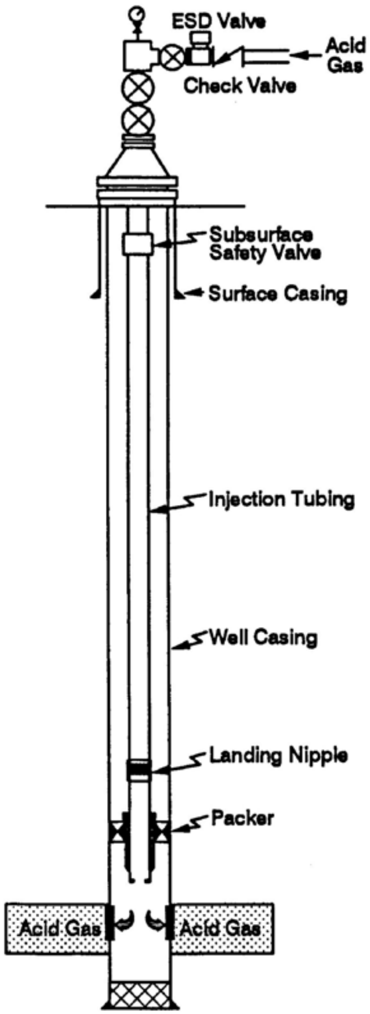
Figure 8. Phase diagrams for methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and a 50%-50% acid-gas mixture; hydrate conditions for CO_2 and H_2S; and a 4-stage acid-gas compression cycle (after Wichert & Royan, 1996, 1997).



Generic Project Conditions

The following information is assumed to have been collected, synthesized and reported in the application for regulatory approval for the acid gas injection project and is utilized in the design of a monitoring program:

- complete diagrams of disposal well location and completion as well as location and status of other completions in the proposed injection reservoir;
- locations of surface rights and land title holders within 3 km radius;
- status of all wells within 3 km of the injection well;
- structure and net pay maps;
- geological cross sections;
- oil, water and gas contact information;
- reservoir rock properties and sealing competency of caprock;
- natural fracturing presence and pool boundaries;
- analysis of native reservoir fluids and acid gas stream (phase behavior);
- possible fluid-fluid or fluid-rock interactions;
- migration calculations to investigate radius of influence and interface movements;
- injectivity calculations with specification of acid gas injection rate;
- discussion of maximum bottomhole pressure and fracture pressure;
- expected total volume of acid gas to be injected;
- effect of acid gas injection on recovery of in-place hydrocarbons;
- plans for monitoring reservoir pressure and fluid migration;
- diagram of surface injection facilities; and
- diagram showing measurement facilities for monitoring volume of gas injected.



Production Casing			Production Tubing			Type of Fluid in the Annulus	Packer Depth (m KB)
Depth (m KB)	Size (mm)	Density (kg/m)	Size (mm)	Density (kg/m)	Grade		
1495	177.8	39	60.3	6.99	J-55	Diesel	1484

1.1 Subsurface Characteristics of the Injection Zone

The following sections summarize the main factors describing the subsurface characteristics of the acid gas injection project:

- Injection reservoir depth = 1500 m;
- Reservoir thickness = 140 m;
- Net pay thickness = 30 m (actual net pay is defined by layers with porosity and permeability adequate for injection);
- Porosity = 12% ;
- Reservoir Type: Siliclastic
- Formation pressure = 14.0 MPa;
- Formation temperature = 65 °C;
- Formation salinity = 150,000 mg/L ;
- Formation permeability = 50 mD ;
- Maximum wellhead injection pressure = 12.0 MPa ;
- Maximum approved bottomhole pressures = 18.0 MPa
- Daily injection rates = 200,000 m^3/day
  All the injection rates and volumes presented in this report are at standard conditions (15°C and 101.3 kPa)
- No. of surrounding wells = 54 which includes 12 abandoned wells.
- Maximum allowed injection volume = 1000 x 10^6 m^3 ;
- Emergency planning zone (radius from well) = 3.0 km
- Injected gas composition: 50% H_2S and 50% CO_2

Monitoring Phases and Timeframe

Every geological storage project will go through a series of phases which constitute the life-cycle of the project. During each phase monitoring will serve different purposes, and each phase will have its own activities, which will determine for how long monitoring will be required. For the purposes of this scenario, the following should be addressed:

- **Baseline Monitoring**
- **Operational/Verification Monitoring**

  This phase of the project (where acid gas is injected into the reservoir) is expected to last between 20 and 30 years.

- **Closure Monitoring**

  This phase of the project begins after the final survey after injection stops and goes until the wells are abandoned if they are no longer required for monitoring..

- **Post-Closure Monitoring**

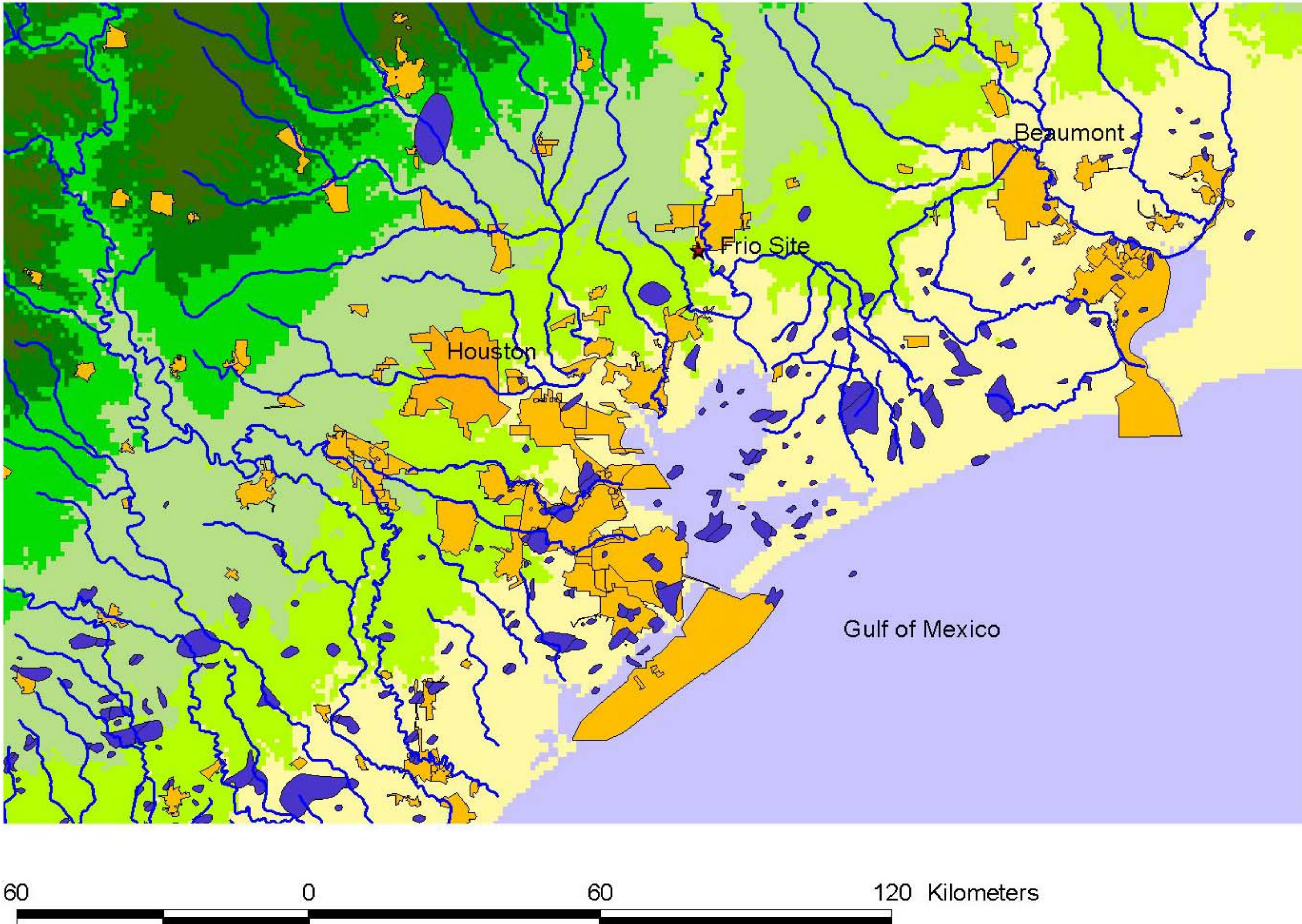
At the end of the closure phase, as required by EUB, the operator must submit a complete set of records about the project. Monitoring will no longer required except in the event of monitoring ongoing leakage, legal disputes or other matters that may require new information about the status of the storage project

For the purposes of the Monitoring Network Workshop, **four** possible scenarios for configuration of an acid gas injection project are considered:

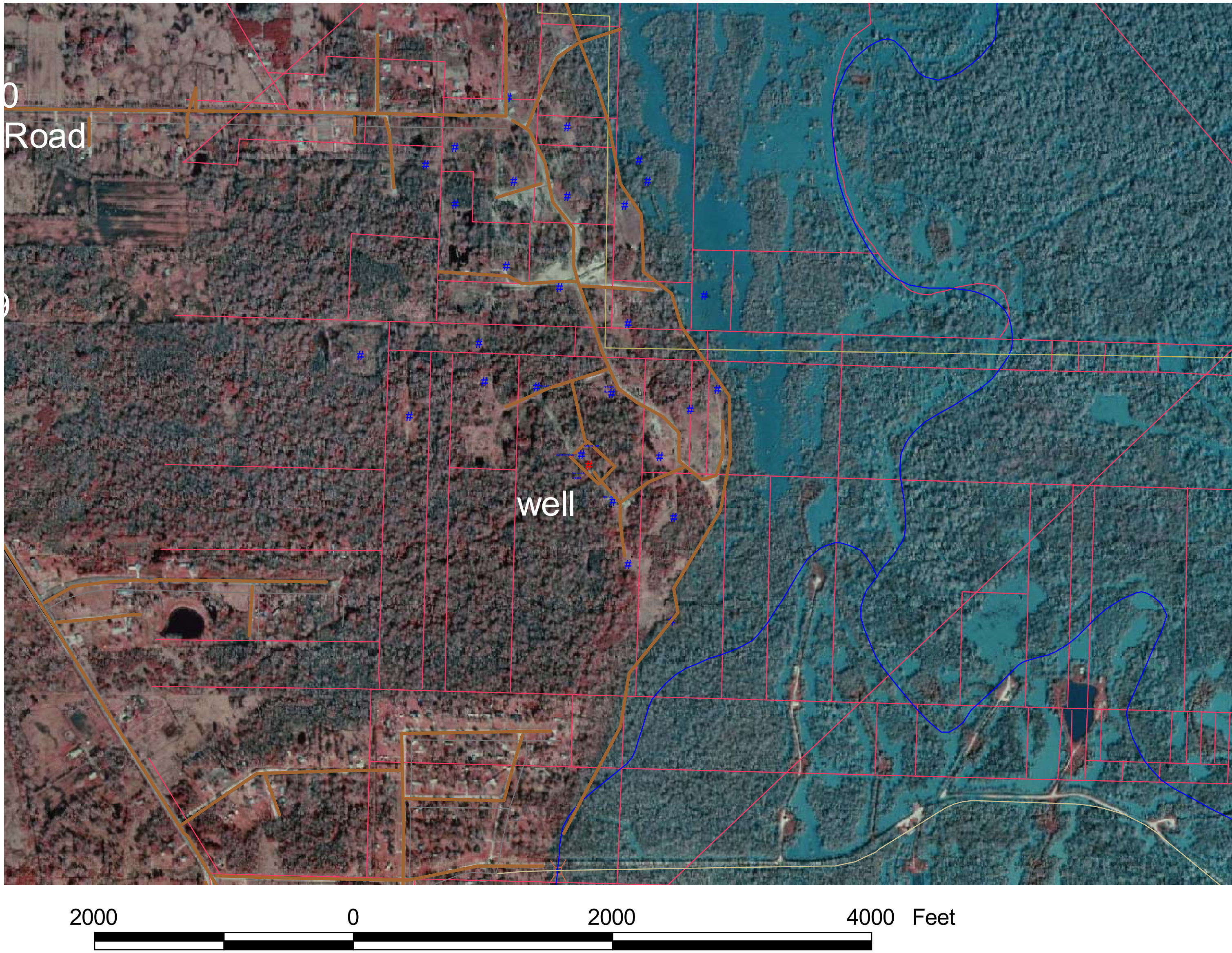
- New acid gas injection well - no offset wells;
- New acid gas injection well – two (minimum) offset wells;
- New acid gas injection well and a producer;
- Acid gas injection into existing well – with or without offset wells.

It is anticipated that these four conditions will cover most of the well configurations for an acid gas project, regardless of the type of reservoir selected for acid gas injection

ALTHOUGH for the purposes of this Workshop, it is assumed to be a saline fluid reservoir.

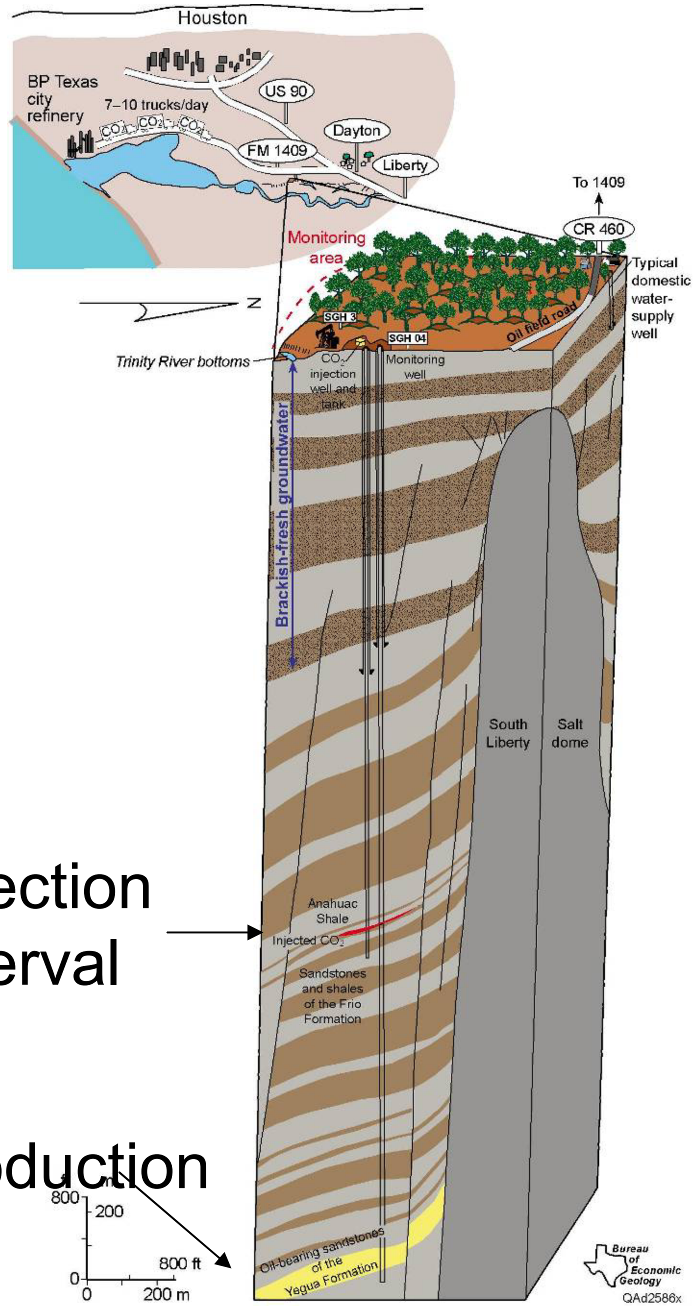

Beaumont
Frio Site
Houston
Gulf of Mexico
60
0
60
120 Kilometers

Historic Oil Field



Road
well
2000
0
2000
4000
Feet

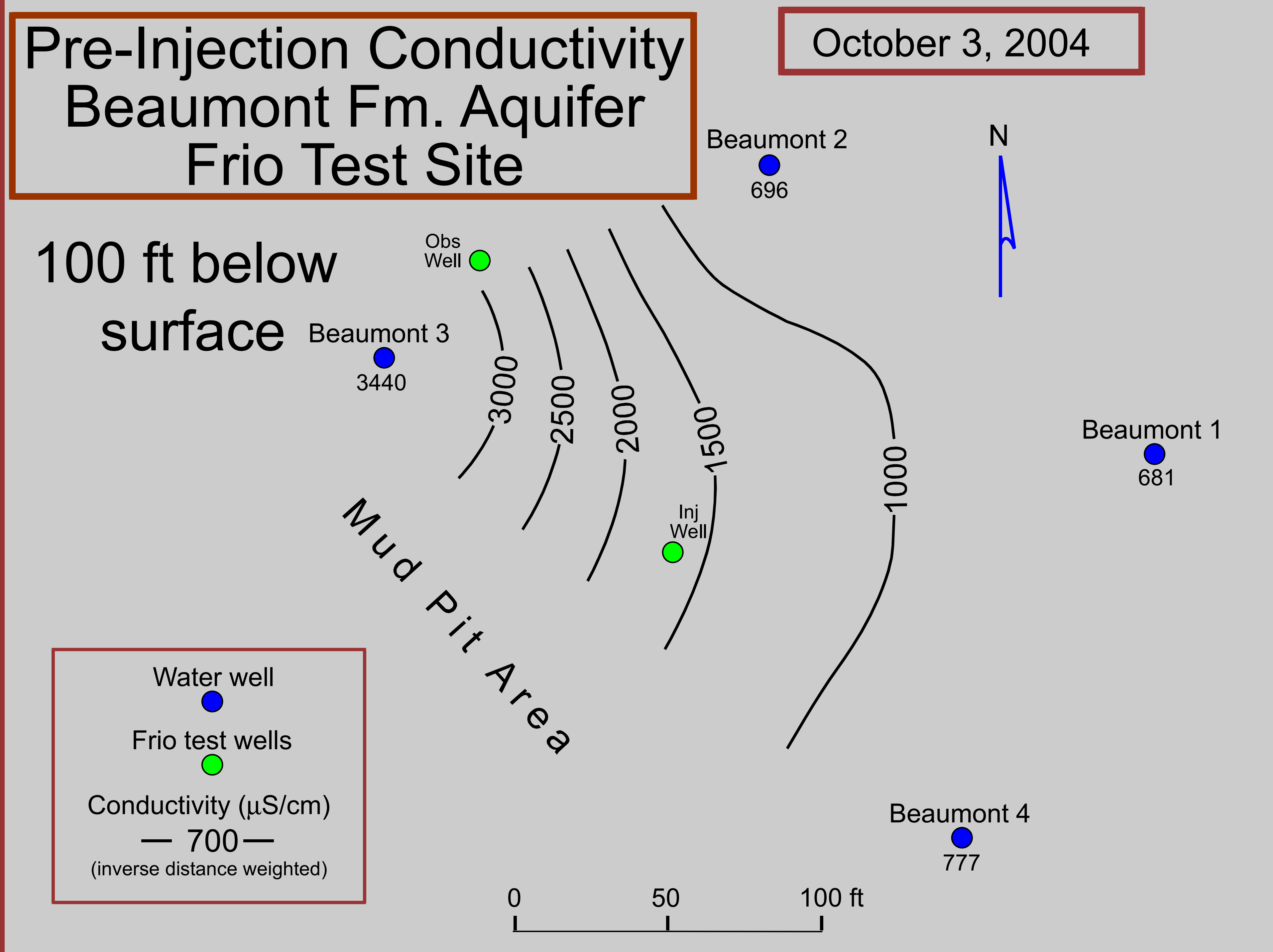
Frio Brine Pilot



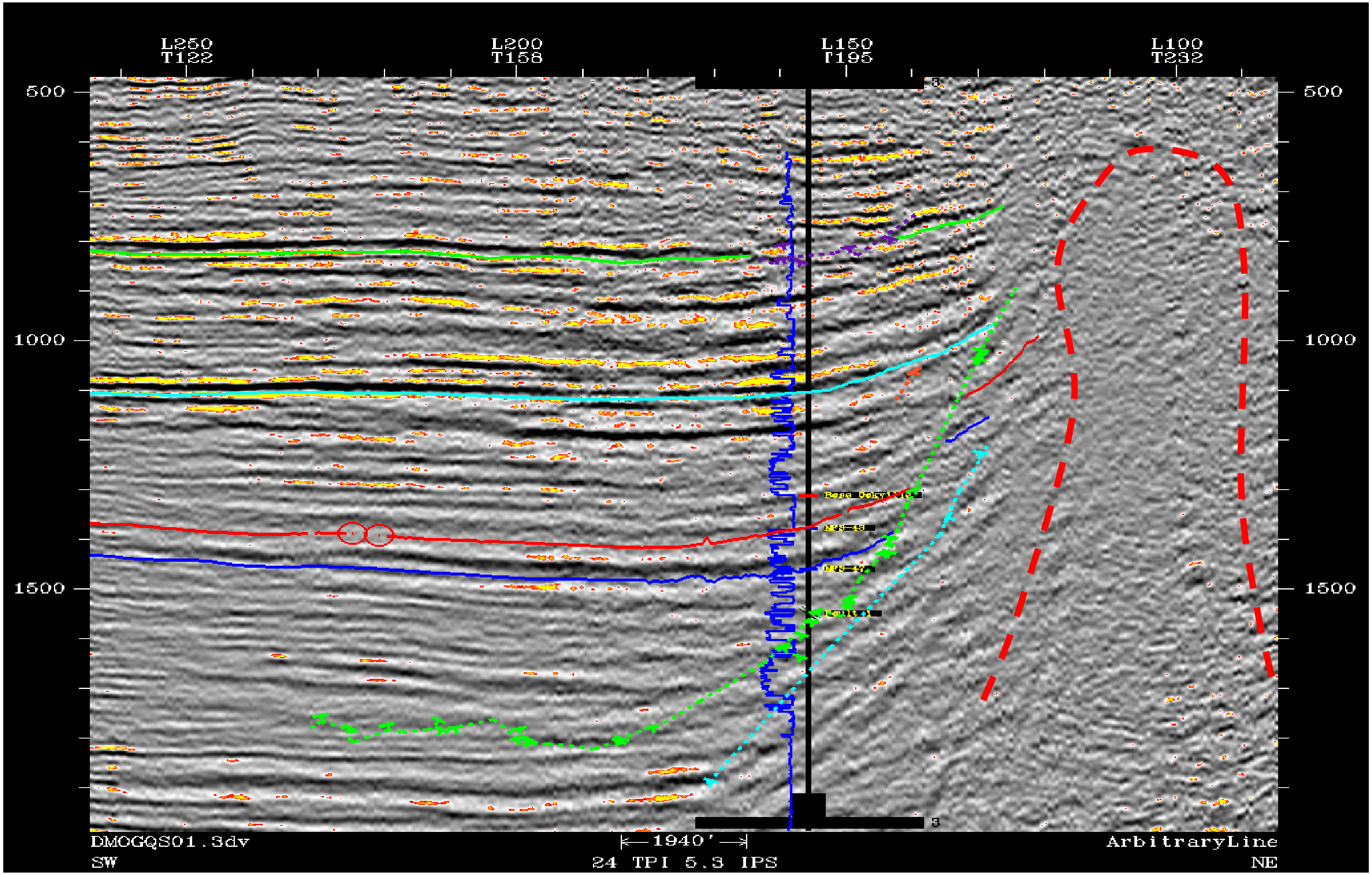
Injection interval

Oil production

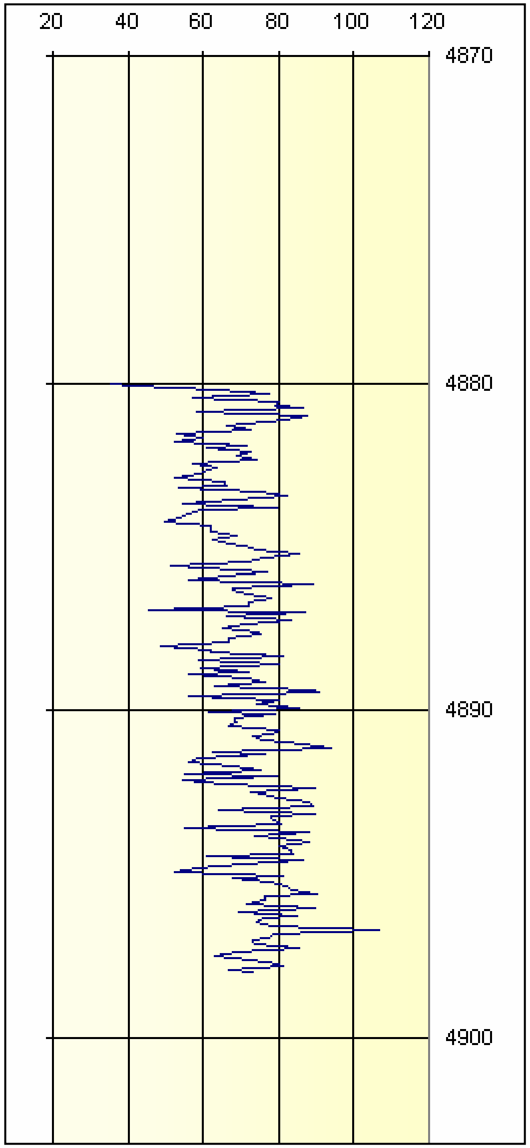
- Injection interval: 24-m-thick, mineralogically complex Oligocene reworked fluvial sandstone, porosity 24%, Permeability 50 -300 md
- Seals – numerous thick shales, small fault block
- Depth 1,500 m
- Brine-rock system, no hydrocarbons
- 150 bar


Pre-Injection Conductivity
Beaumont Fm. Aquifer
Frio Test Site
October 3, 2004
100 ft below surface
Beaumont 2
696
N
Obs Well
Beaumont 3
3440
3000
2500
2000
1500
1000
Beaumont 1
681
Inj Well
Mud Pit Area
Water well
Frio test wells
Conductivity (µS/cm)
700
(inverse distance weighted)
Beaumont 4
777
0
50
100 ft

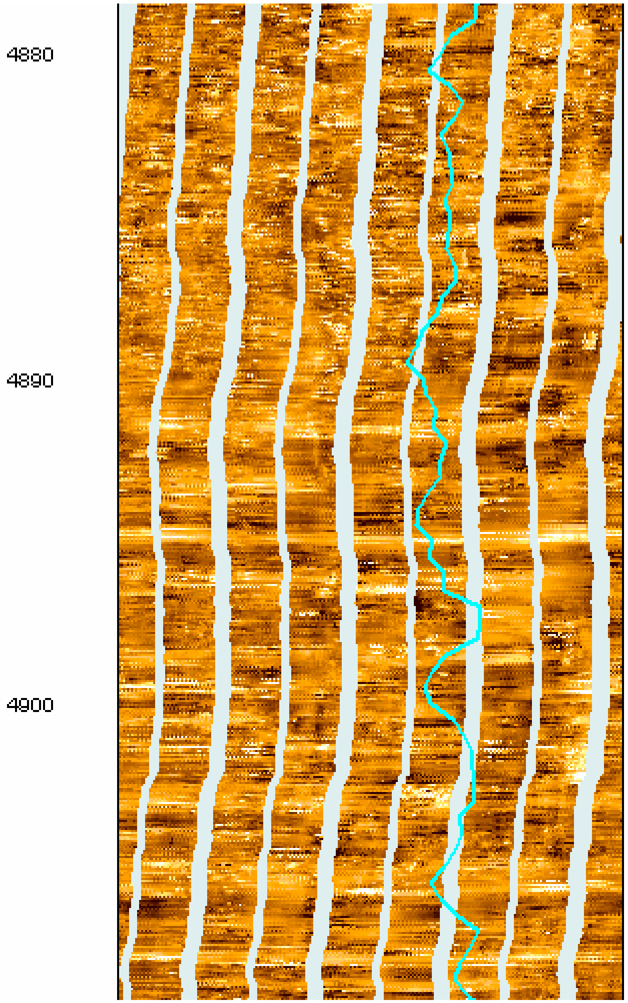
Representive line from spec 3-D

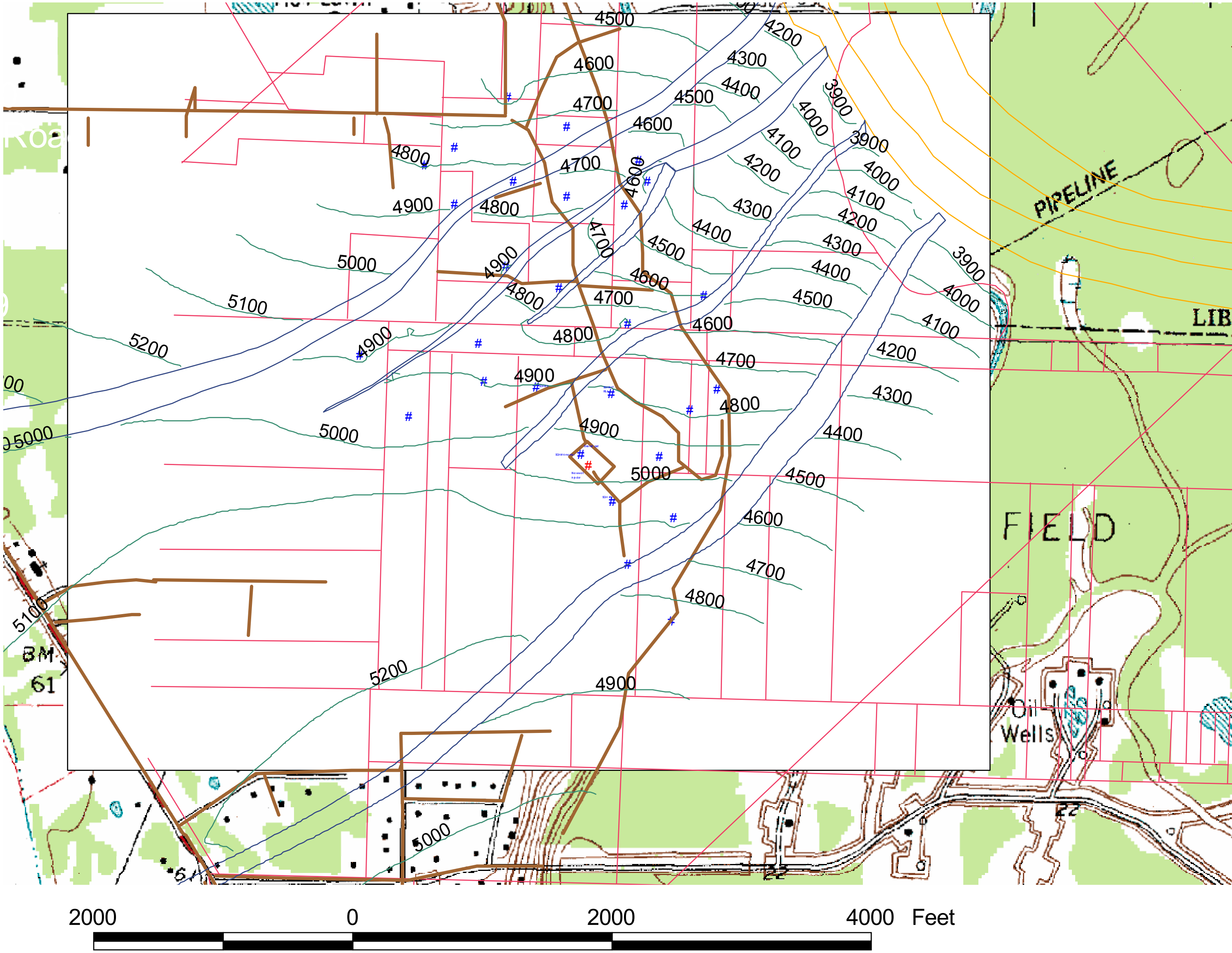


Core 1, Anahuac Shale Core

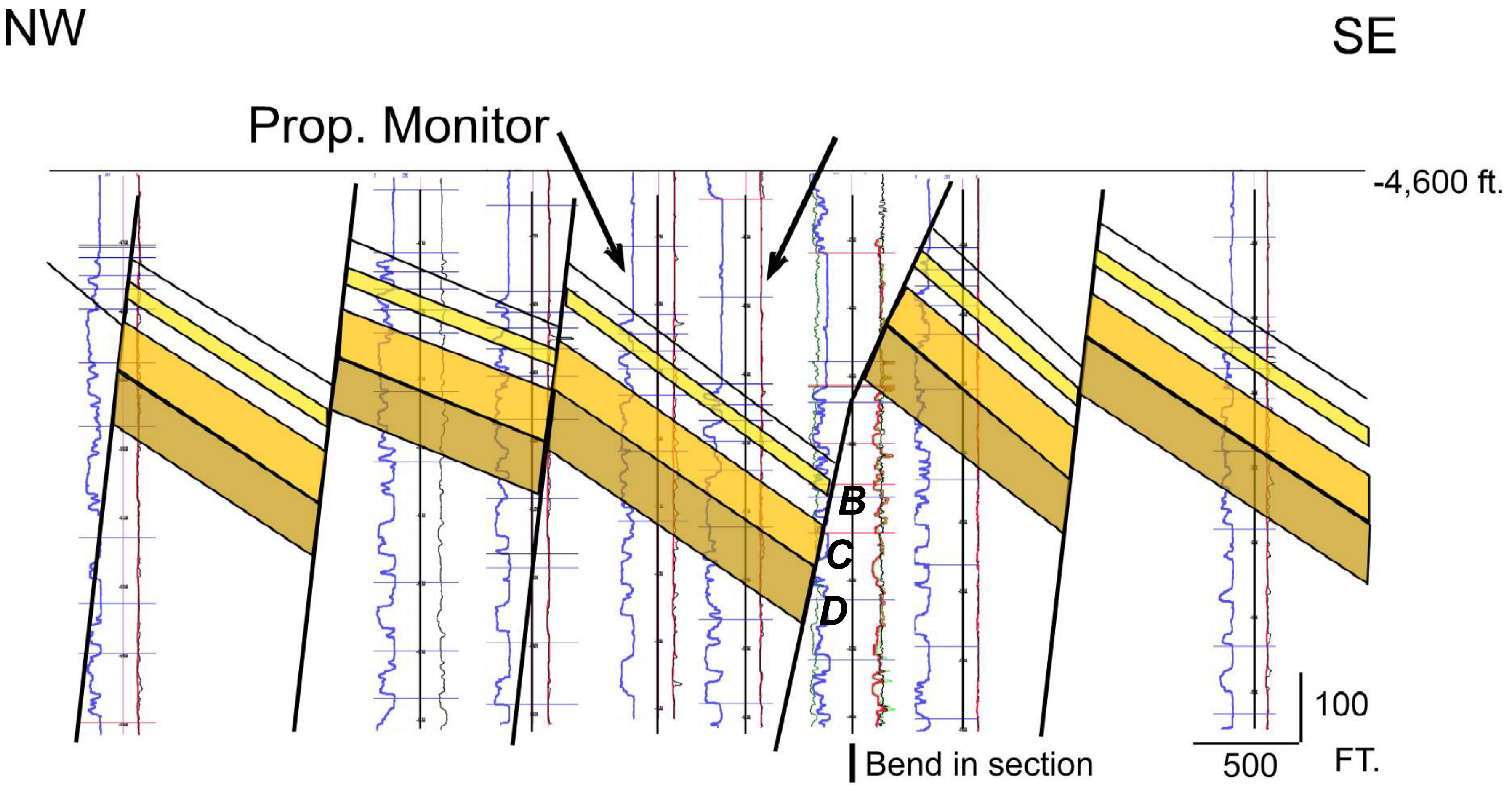


Log GR & FMI Image

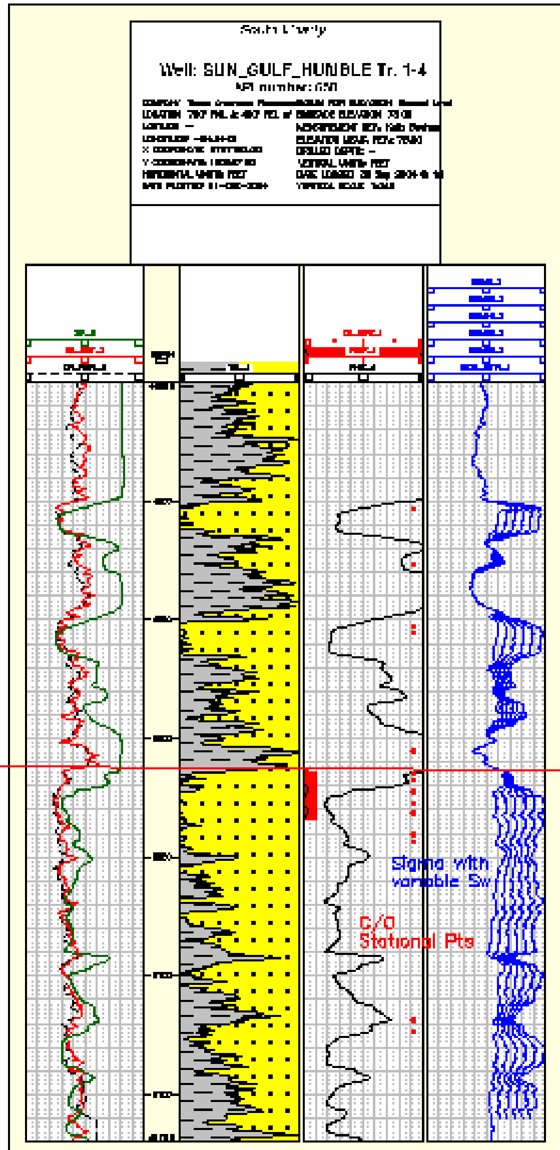



PIPELINE
FIELD
Wells
BM
61
2000
0
2000
4000
Feet

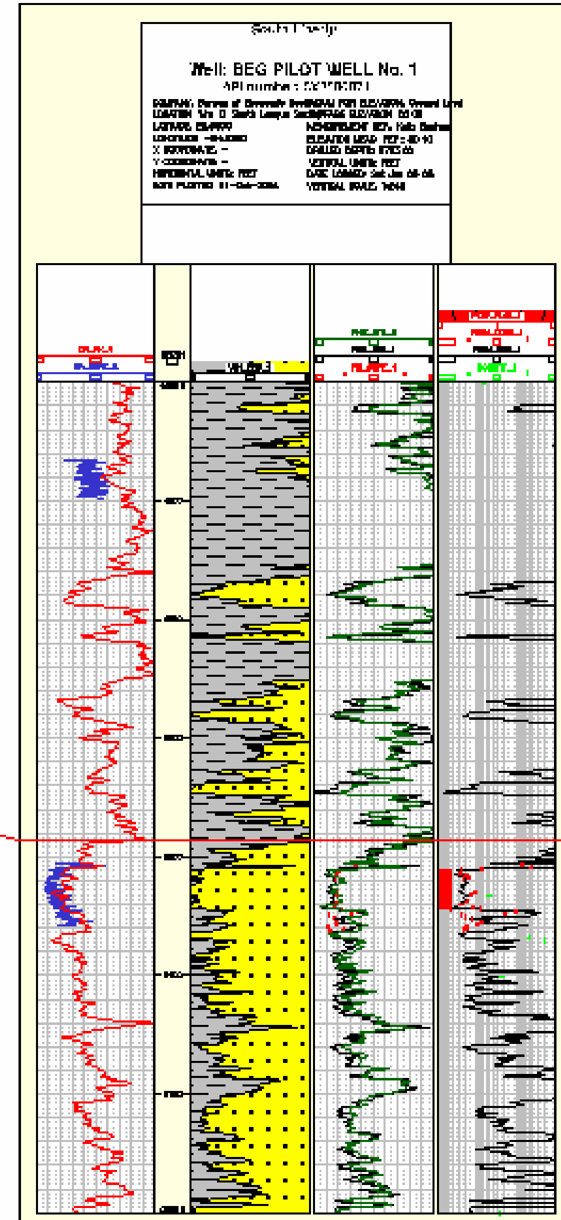
STRUCTURE CROSS SECTION

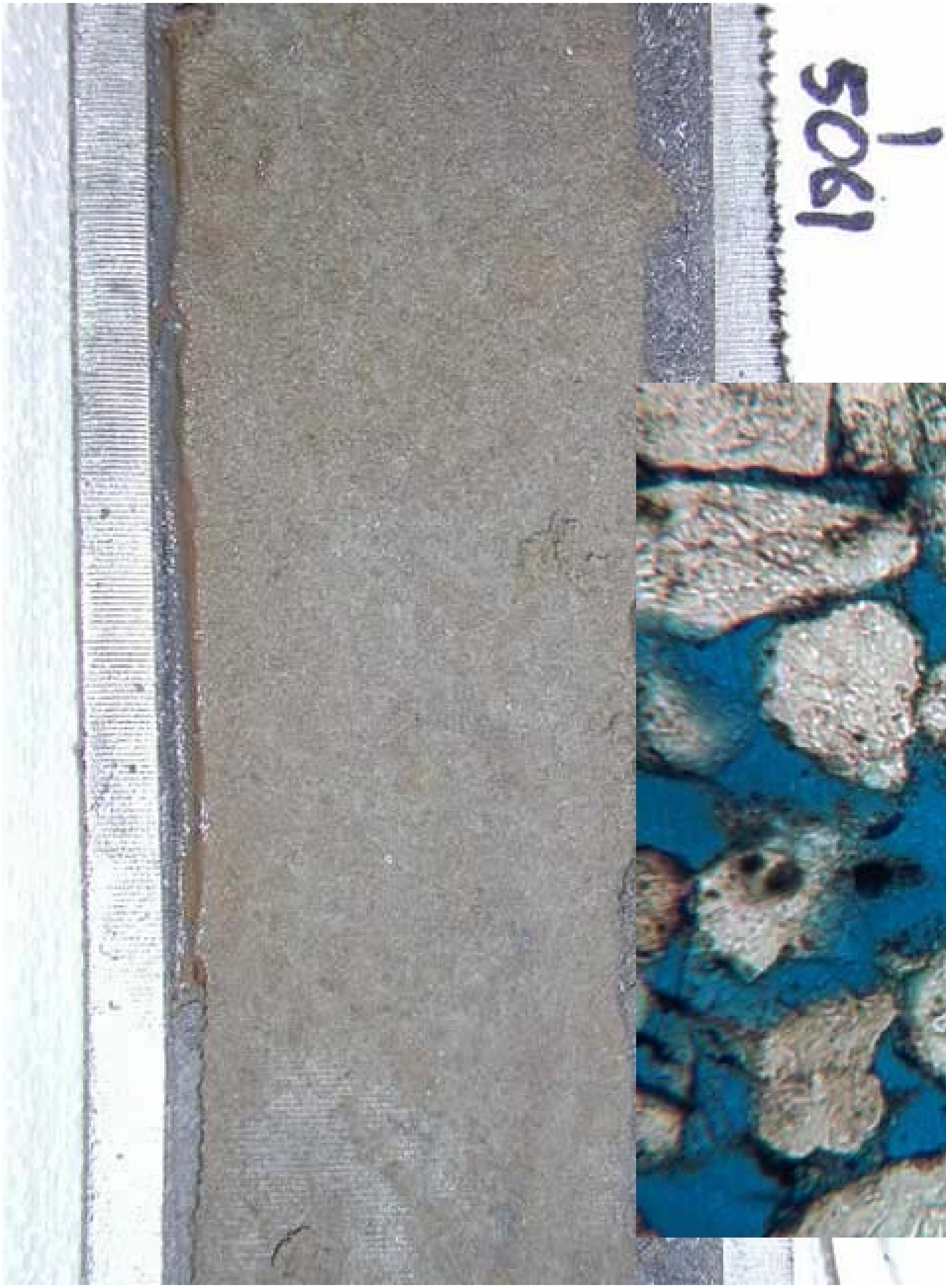


Observation Well



Injection Well





Core has been slabbed while still frozen, and samples cut for petrophysical, petrographic, and geochemical analysis

Composition of gas (v. %) obtained from the Frio Formation before and after CO2 injection

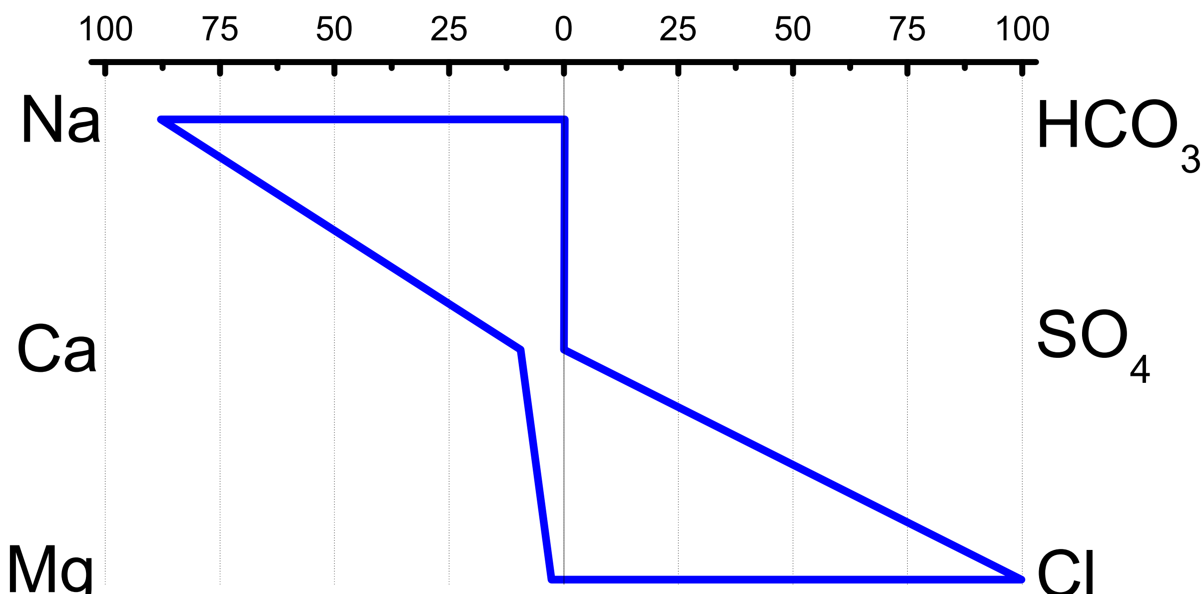
Gas	Injection well [1]	Monitoring well [2]	well [3]
He	0.008	0.012	ND
H_2	0.040	0.30	0.191
Ar	0.042	0.061	ND
CO_2	0.31	0.22	96.8
N_2	3.86	2.28	0.037
CH_4	93.8	96.9	2.94
C_2H_6+	1.92	0.13	0.005

1 "C" before CO_2 injection, 04FCO2-102
2 "B" after injection, 05FCO2-110
3 "C" after injection, 10/13/04 @ 20:37

Y. Kharaka, USGS

Brine Composition

04FCO2-218 (monitoring well; pre injection)



pH = 6.7; TDS = 93,800 mg/L

Y. Kharaka, USGS

Frio scenario

Assumptions

- Sources of Co2 available – refineries & coal power plant
- 8000 tons per day to be injected at maximum
- One well injection…?
- Assume EOR & storage to gain credits
- Objective: to design intermediate project & M&V scheme to demonstrate commercial EOR project
- Stacked target aquifers

Site description

- Mature oilfield – compartmentalised fault blocks with no evidence for connection across faults
- Weather risk for seasonal flooding in valley & 10-year storms at site
- High permeability 2 Darcy
- Contaminated aquifer from produced water (higher salinity)
- Regional 60-70m thick shale pinching out updip
  - Not fractured from current evidence
- Salt dome could provide a leakage route

Reservoir

- Immature arkosic sand
- 30% porosity
- Poorly compacted
- High K – 2D
- NaCl brine

Regulation constraints

- Can not impact underground aquifers

Risk Register

Risk	Specific issues	Consequences	Mitigation
Leakage along pre-existing abandoned wells		Leakage to atmosphere Groundwater contamination – CO_2, HC, heavy metals Wetlands vegetation at risk	Workover
Unknown wells		Leakage to atmosphere Groundwater contamination – CO_2, HC , heavy metals Wetlands vegetation at risk	Workover
Fault leakage	Straight to atmosphere. Very small surface footprint	No basements Leakage to atmosphere Groundwater contamination – CO_2, HC , heavy metals Wetlands vegetation at risk	?????
Salt dome flank		Leakage to atmosphere Groundwater contamination – CO_2, HC, heavy metals Wetlands vegetation at risk	?????
Residential areas	No basements – too wet	Asphyxiation	Co2 monitors in houses

Well completions

- Follow standard practice per Texas rule book

Monitoring

- pH changes in surface waters
- Need quantification of leaks for credits
- Surface very difficult to monitor – high surface water, high vegetation
- Monitor groundwater up- & down-gradient in major aquifer at 30m depth, not at surface
- Monitor in existing oil wells

Monitoring scheme

- Baseline
  - Geologic model and reservoir simulation
  - hydrogeology
  - hydrogeochemistry in dynamic system,
  - 3D seismic for identifying faults and devise geological model
  - Well identification & completions
- Initially in reservoir, utilising existing wells

Monitoring scheme

- Monitoring in shallow aquifer, deep aquifer immediately above regional aquifer
  - Alkalinity
  - Cation changes (Fe)
  - Tracers
  - Sensitivity…?
- Seismic could monitor losses into overlying aquifers, if leaks were big enough
- Cross-hole seismic to monitor movement in reservoir and possible leakage
  - Noise & reproducibility
- Oil wells – measure annular pressure
  - Needs setting up

Monitoring scheme

- How long to monitor?
  - When well injection declines to ambient pressure
  - At Frio this will be relatively short
  - May need longer monitoring
- Buoyancy – need small column height so could use 4D seismic to monitor this
  - Stacked injection at several heights
  - Also improve solubility and mineral trapping through fast migration and mixing

ffshore Production and Onshore Falling Water Levels in the Gippsland Basin Australia

Ninety mile beach - Victori

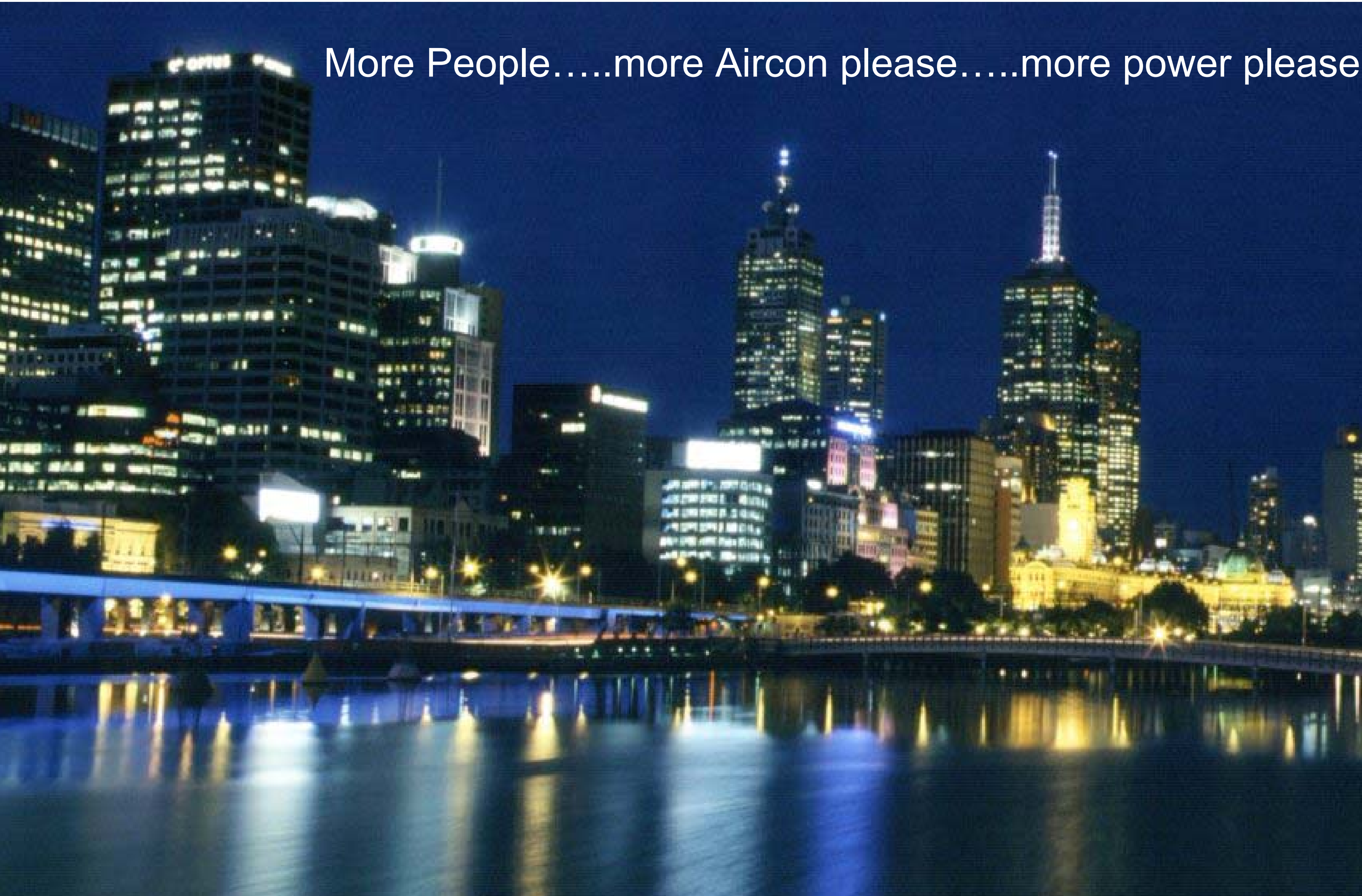
Bill Koppe Monash Energy
Jim Underschultz CSIRO
Barry Hooper CO2CRC

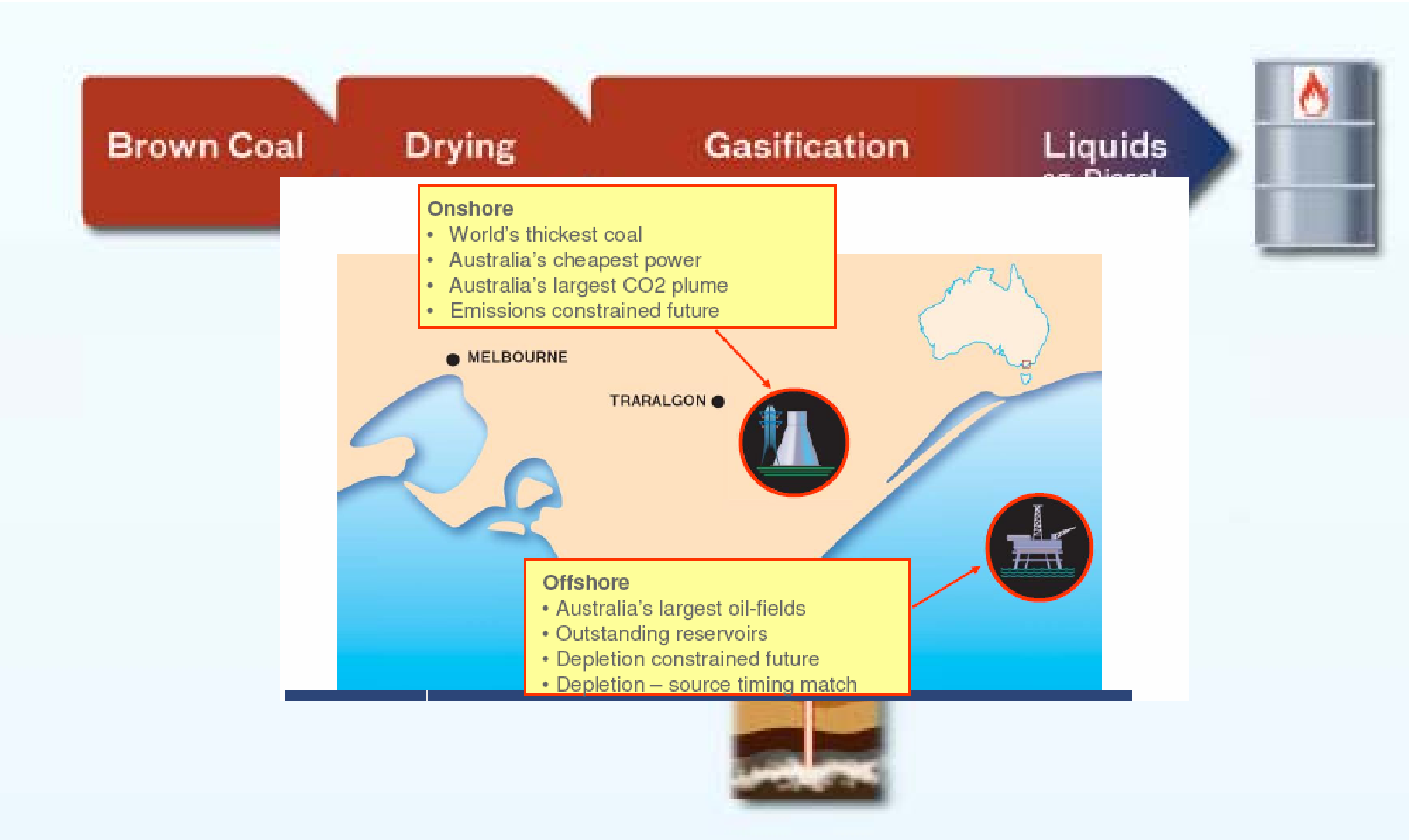
monash energy

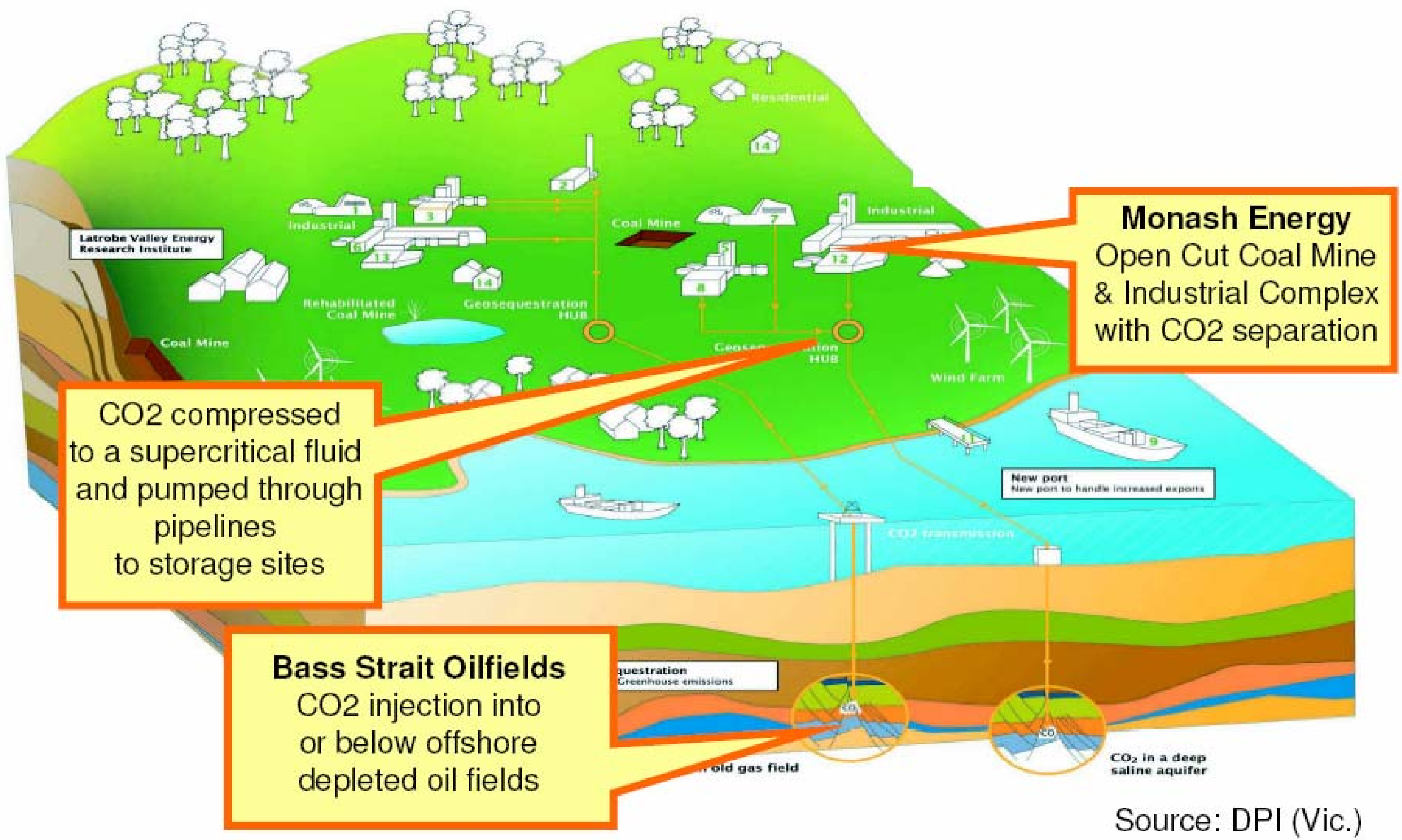
CO2CRC

CRC for Greenhouse Gas Technologies

CSIRO




Brown Coal
Drying
Gasification
Liquids
Onshore
• World's thickest coal
• Australia's cheapest power
• Australia's largest CO2 plume
• Emissions constrained future
MELBOURNE
TRARALGON
Offshore
• Australia's largest oil-fields
• Outstanding reservoirs
• Depletion constrained future
• Depletion – source timing match



Source: DPI (Vic.)

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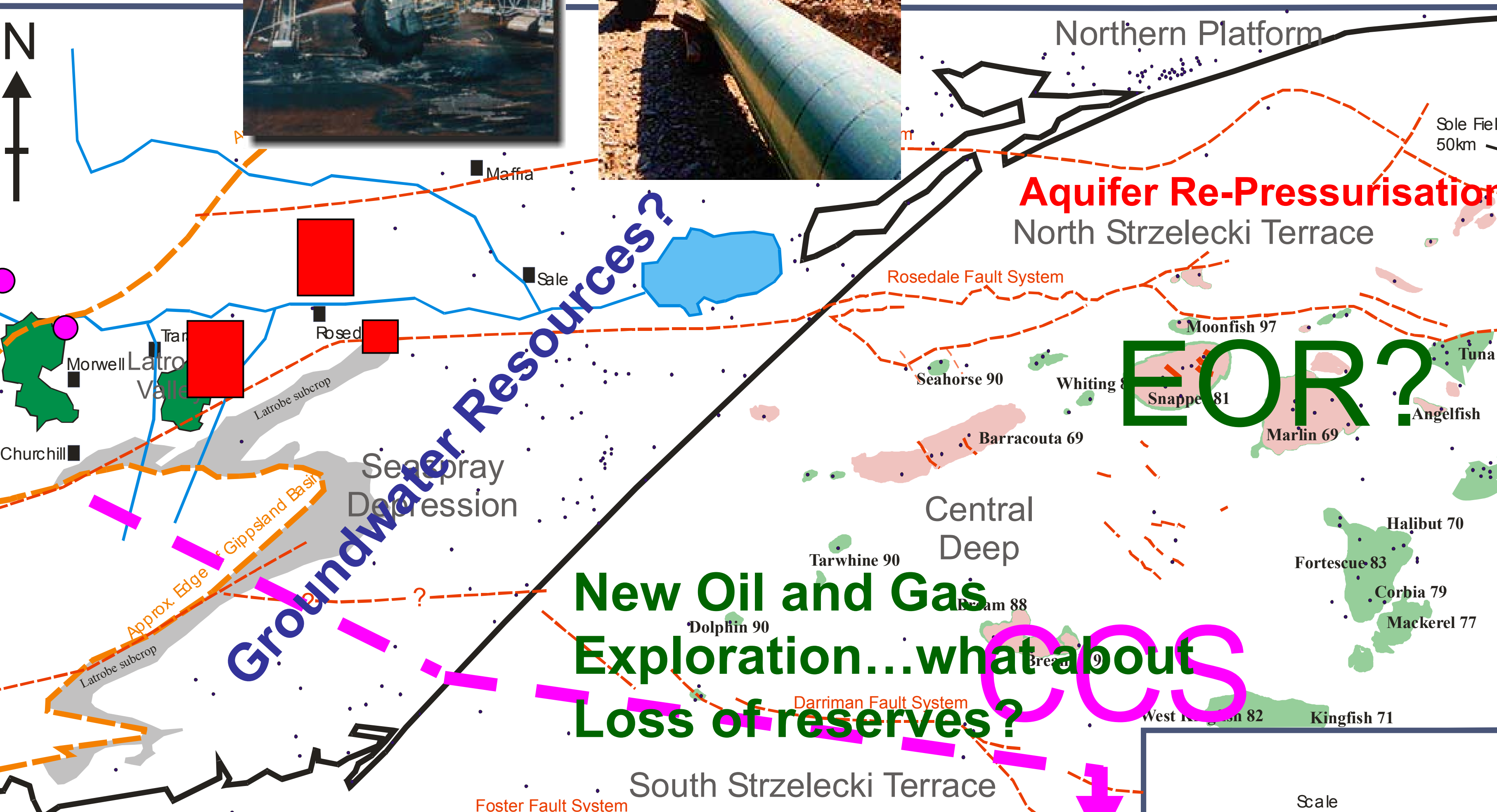
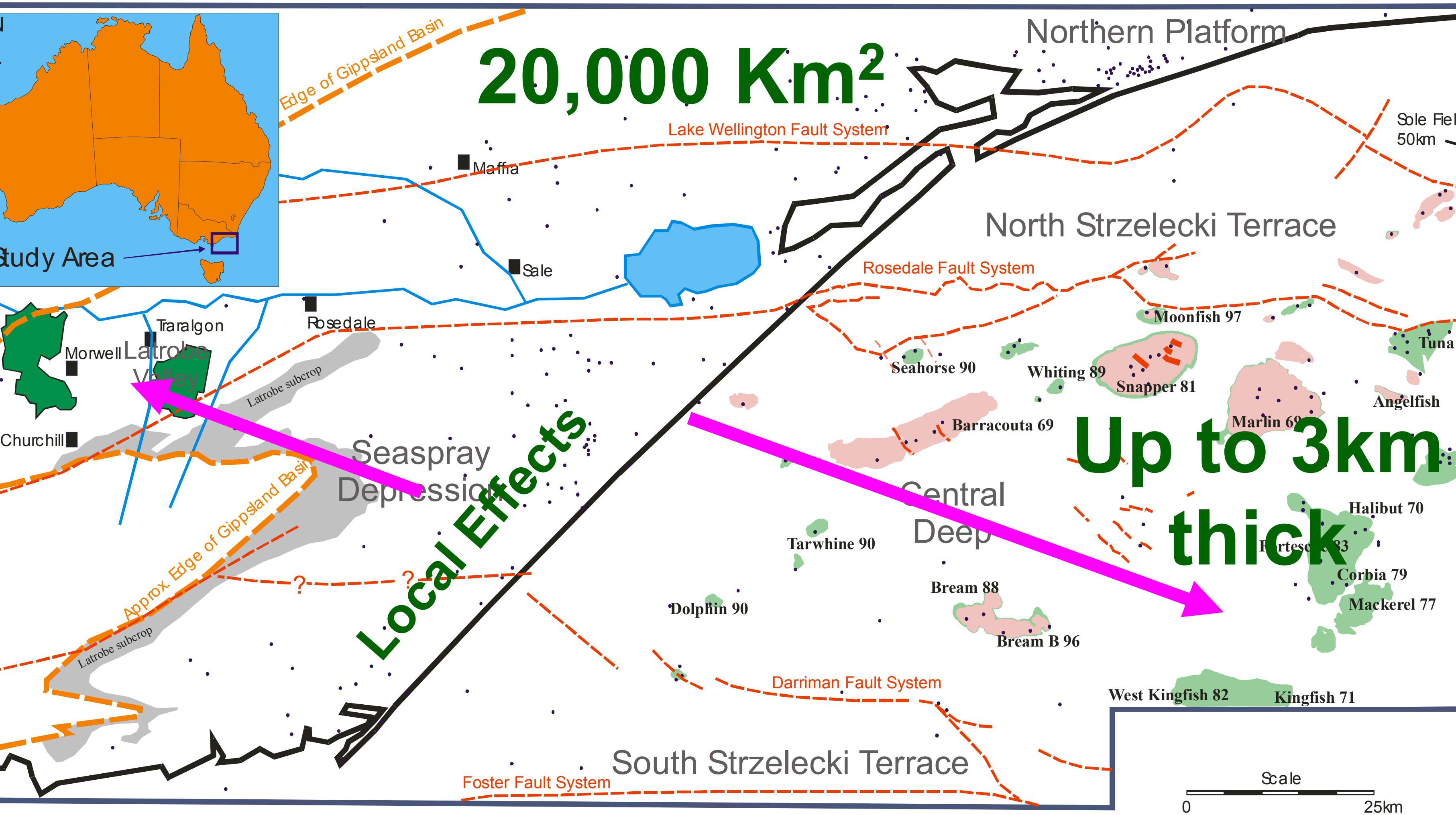
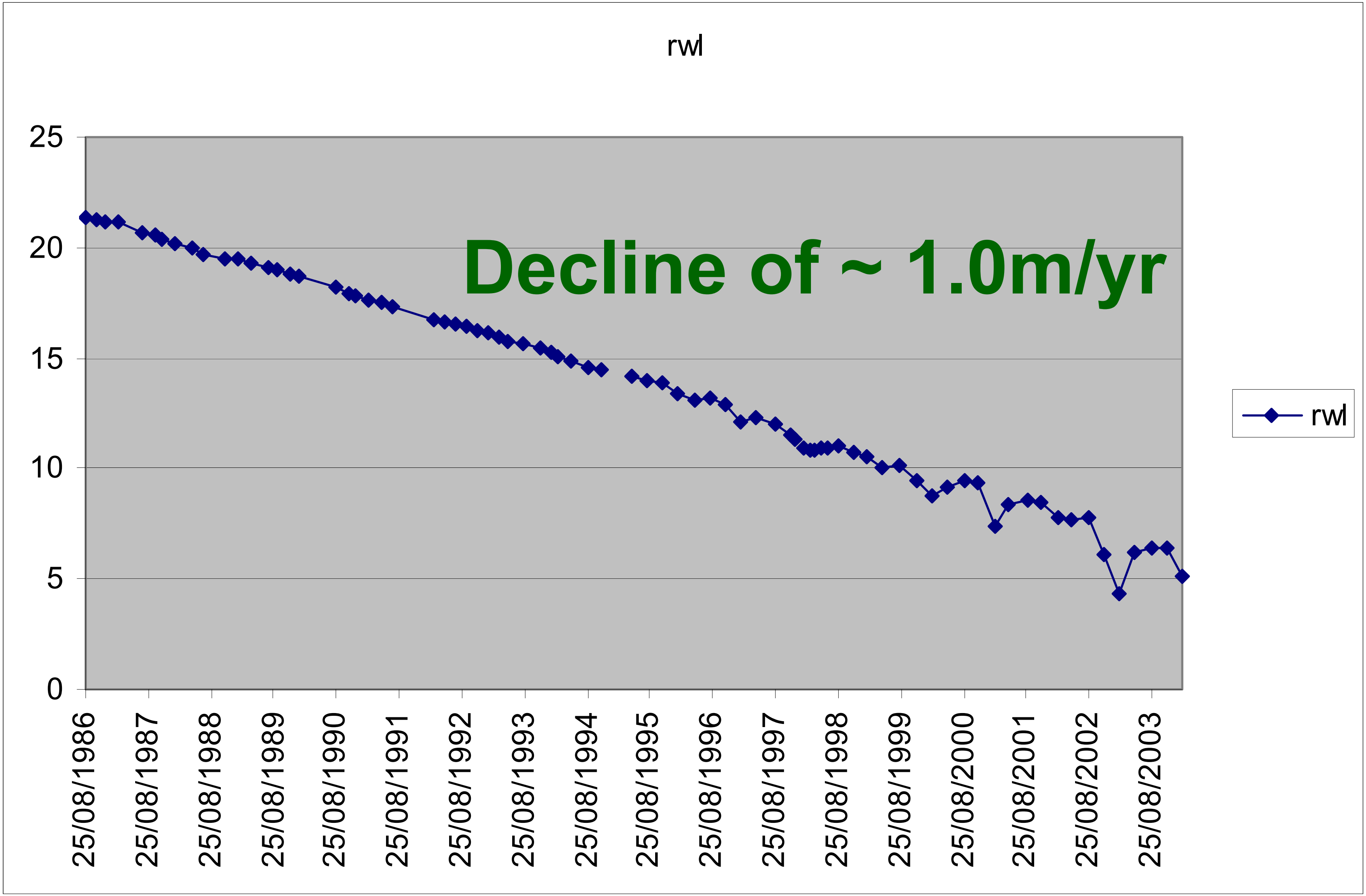



20,000 Km²
Up to 3km thick
Local Effects
Study Area
Edge of Gippsland Basin
Approx. Edge of Gippsland Basin
Lake Wellington Fault System
Rosedale Fault System
Darriman Fault System
Foster Fault System
Northern Platform
North Strzelecki Terrace
South Strzelecki Terrace
Seaspray Depression
Central Deep
Latrobe Valley
Latrobe subcrop
Maffra
Sale
Rosedale
Traralgon
Morwell
Churchill
Moonfish 97
Seahorse 90
Whiting 89
Snapper 81
Tuna
Angelfish
Marlin 69
Barracouta 69
Halibut 70
Corbia 79
Mackerel 77
Tarwhine 90
Bream 88
Bream B 96
Dolphin 90
West Kingfish 82
Kingfish 71
Scale
0
25km


rwl
Decline of ~ 1.0m/yr
25
20
15
10
5
0
25/08/1986
25/08/1987
25/08/1988
25/08/1989
25/08/1990
25/08/1991
25/08/1992
25/08/1993
25/08/1994
25/08/1995
25/08/1996
25/08/1997
25/08/1998
25/08/1999
25/08/2000
25/08/2001
25/08/2002
25/08/2003
rwl

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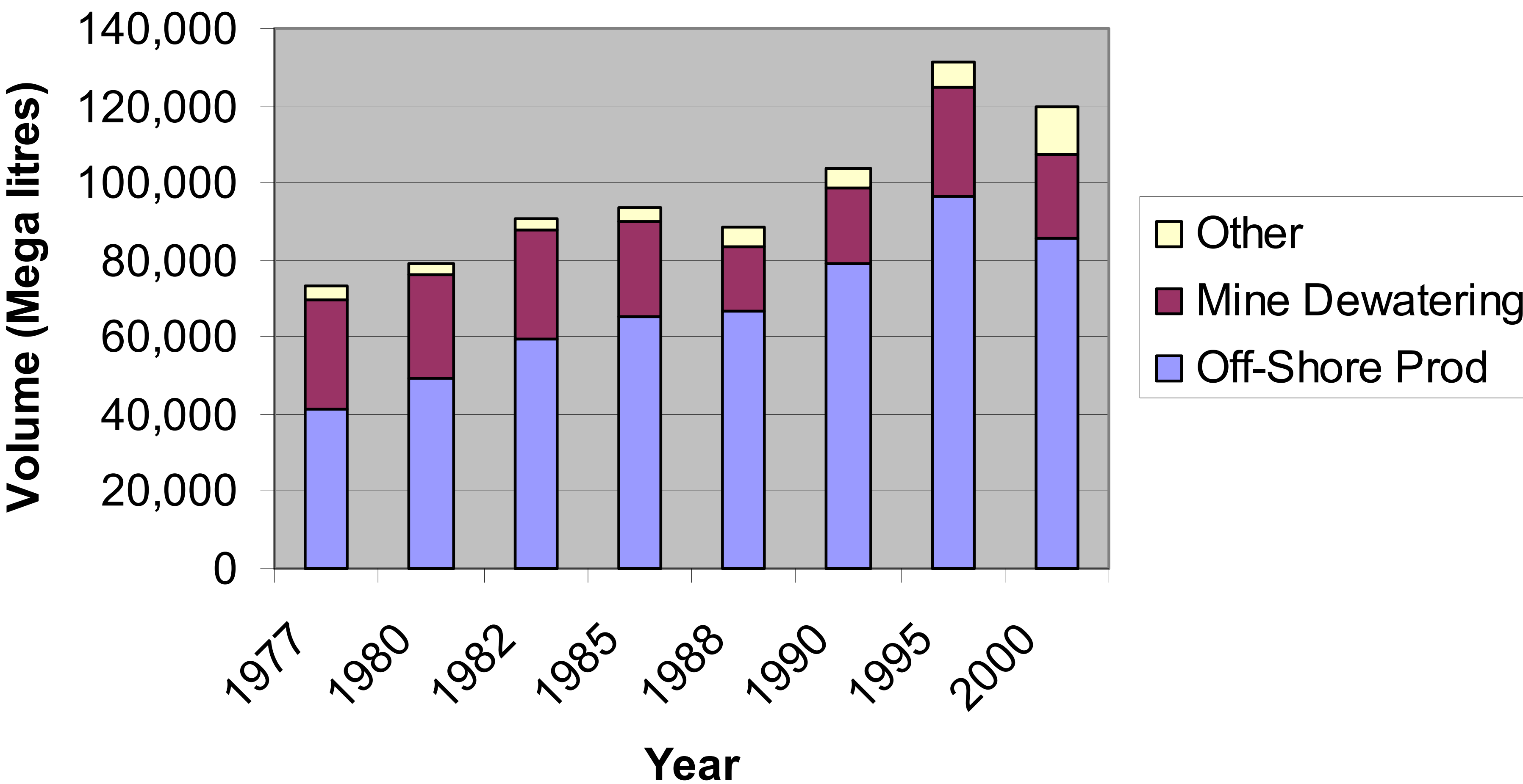
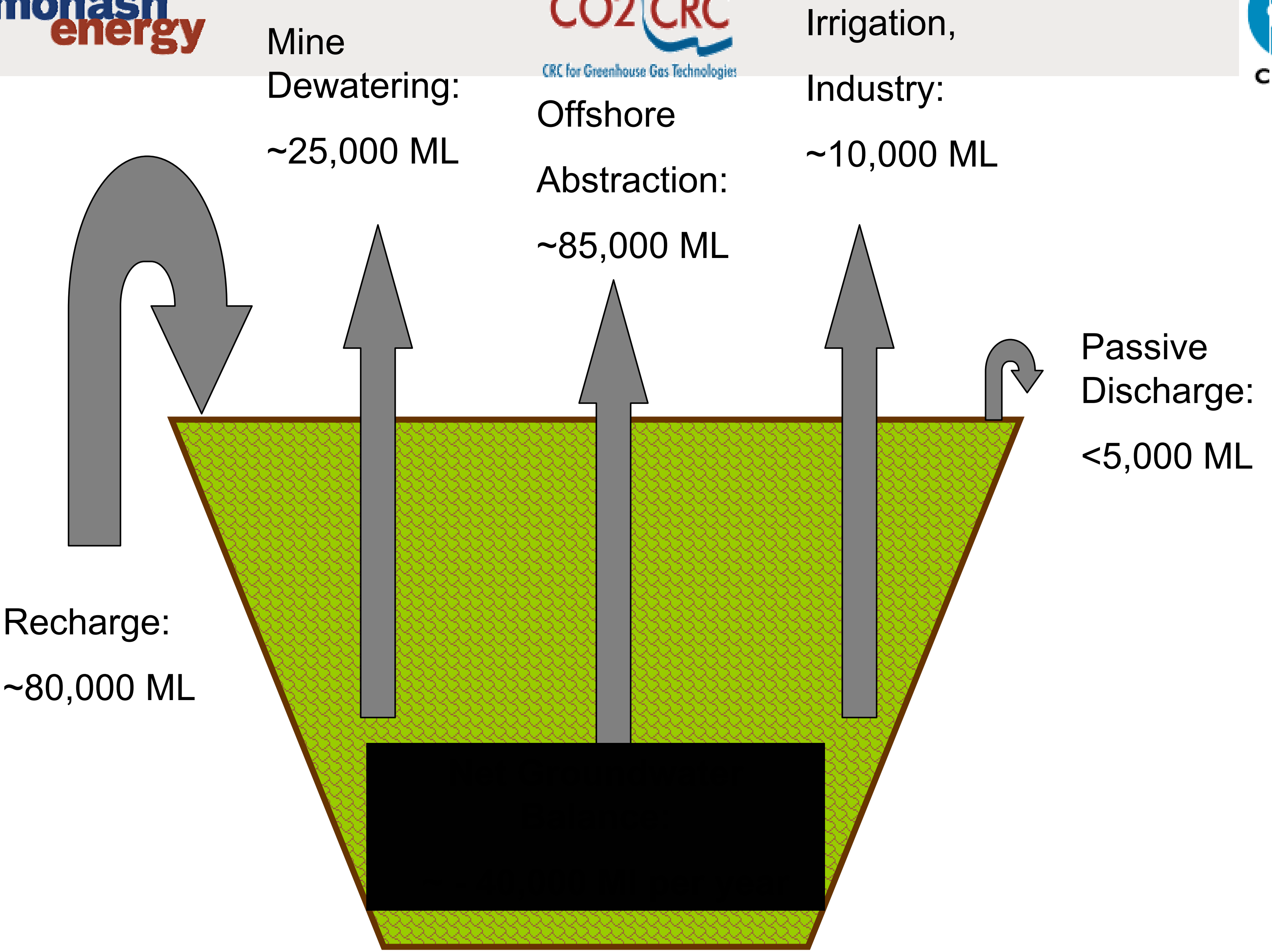
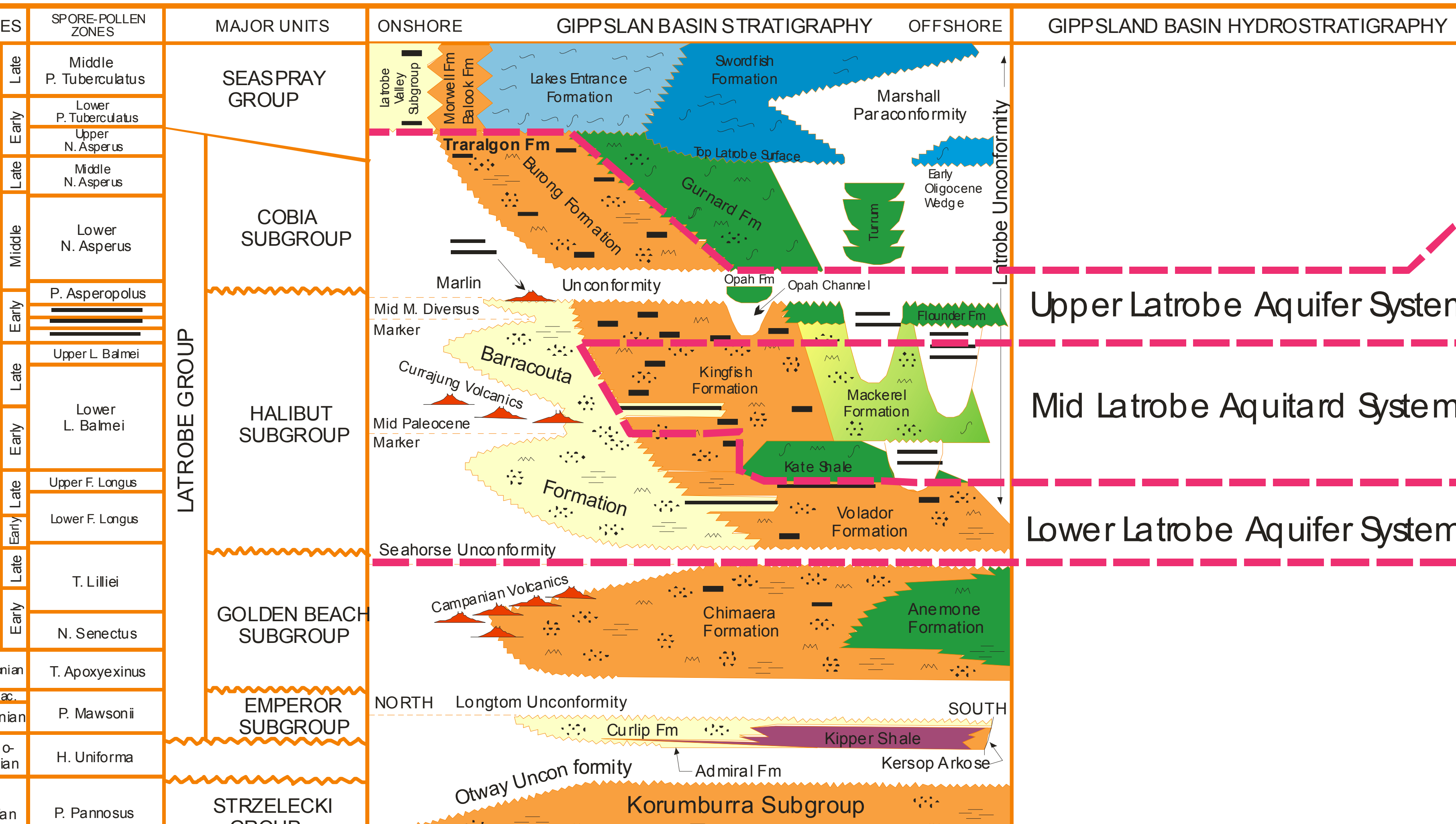
Gippsland Basin Fluid Extraction

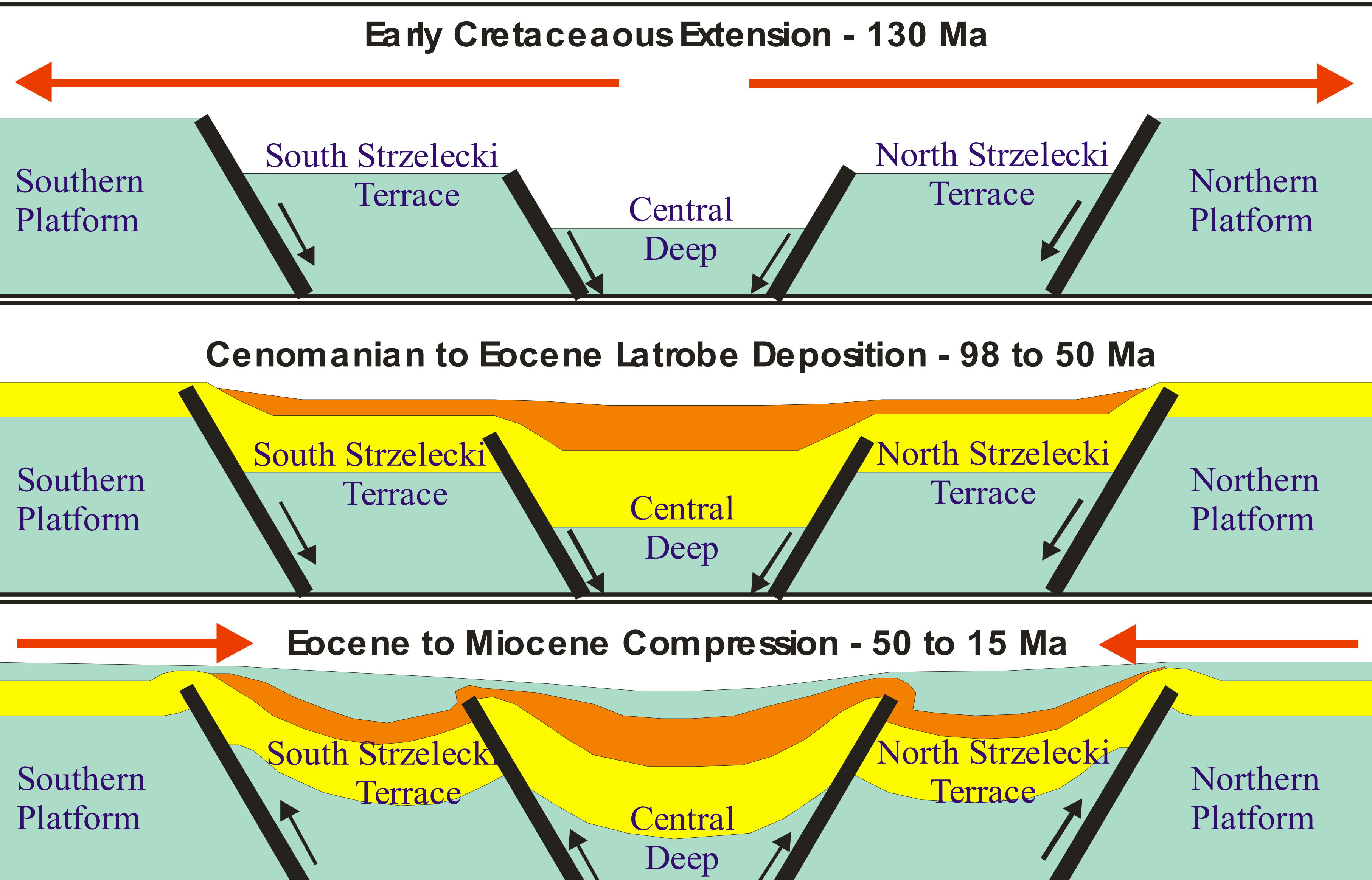



Mine
Dewatering:
~25,000 ML
Offshore
Abstraction:
~85,000 ML
Irrigation,
Industry:
~10,000 ML
Passive
Discharge:
<5,000 ML
Recharge:
~80,000 ML
[redacted]

Statigraphic Nomenclature

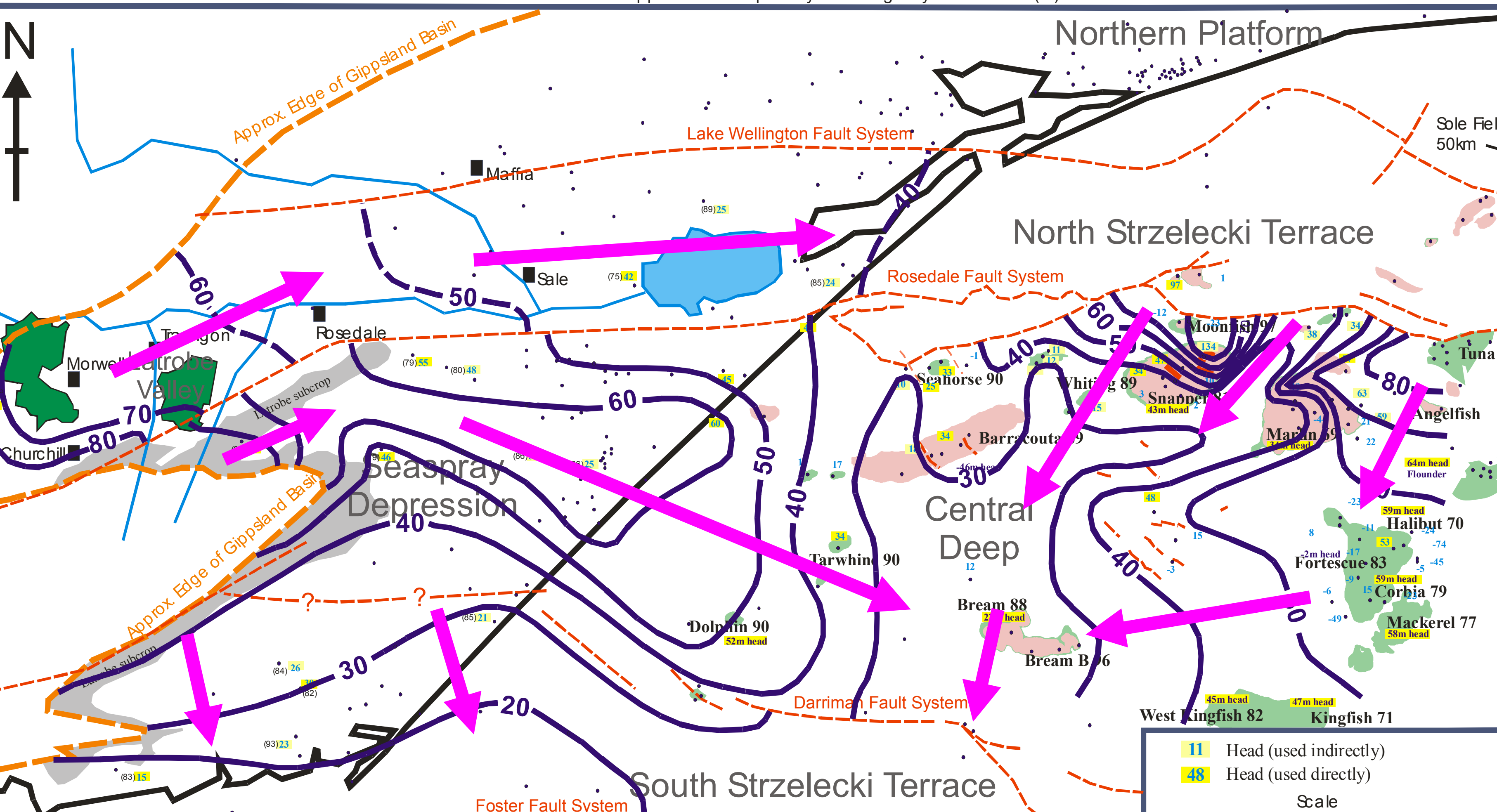


Schematic Basin Formation and Fill



Pre-Human Groundwater System (Head mSS

Upper Latrobe Aquifer System - Virgin Hydraulic Head (m) Distribution



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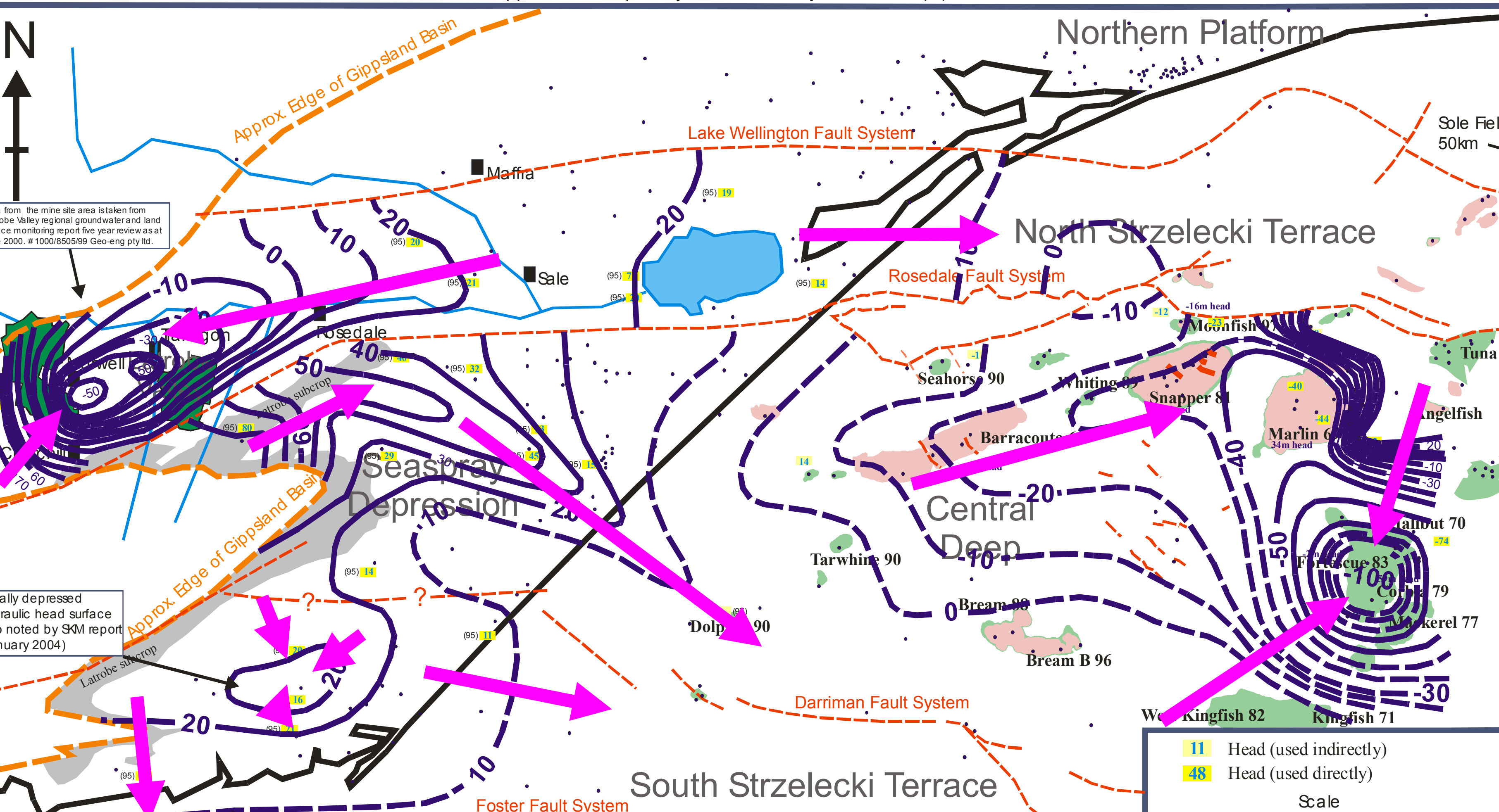
Mid 1990's System (Head mSS)

Upper Latrobe Aquifer System - Inferred Hydraulic Head (m) Distribution for mid 1990's



A. Into Oil Traps

- CO_2 migrates into traps either soon after depletion or as EOR; limited lateral migration
- CO_2 confined to trap structures; smaller pore volumes available
- Well defined reservoirs
- Multiple well access to containment
- Immediate production well – CO_2 contact
- Both wells and seismic represent early CO_2 monitoring options

B. Deep Below Oil Traps

- CO_2 migrates into traps well after production – decades or centuries of migration
- Torturous migration path; larger pore volumes available, residual gas trapping
- Shale and coal bed barriers to migration
- Limited well access to plume
- Deferred production well – CO_2 contact
- Seismic only early CO_2 monitoring option, wells may be P&A'd when plume arrives

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CO2CRC

CRC for Greenhouse Gas Technologies

CSIRO

Regulatory and Risk Assessment Workshop Summary

- **Project Risks**

  Water

  - Competing needs (depletion)
  - Contamination
  - Flow direction (re-pressurization)

  Pipeline

  - Land to offshore
  - Existing lines fit for CO2 ?

  Wells

  - Current wells can accept Co2 ?
  - Requirements to re-engineer ?

Regulatory and Risk Assessment Workshop Summary

- **Project Risks**

  Faults

  - Repressurization : fault integrity
  - Lower pressure limits

  Seals

  Sea Floor Stability

Regulatory and Risk Assessment Workshop Summary

Regularatary Risks

Liability

Multiplayers/stakeholders

Long term legislation weak

Long term CO2 commitment

Native Title

Parks/Water reserves

Public acceptance

- Migration out of basin
- Public education

Effectiveness of managing NGOs

Selling “whole package”

- **Regularatary Risks**

Selling

- “whole package”
- Integration of State/Federa
- Offshore/Onshore Regs

How to make transition from

“oil producers” to “CO2 Disposal”

Does coal do it ? How ?

Regulatory and Risk Assessment Workshop Summary

- **Monitoring Issues**

  Sea floor leakage

  KPI – transition of liabilities

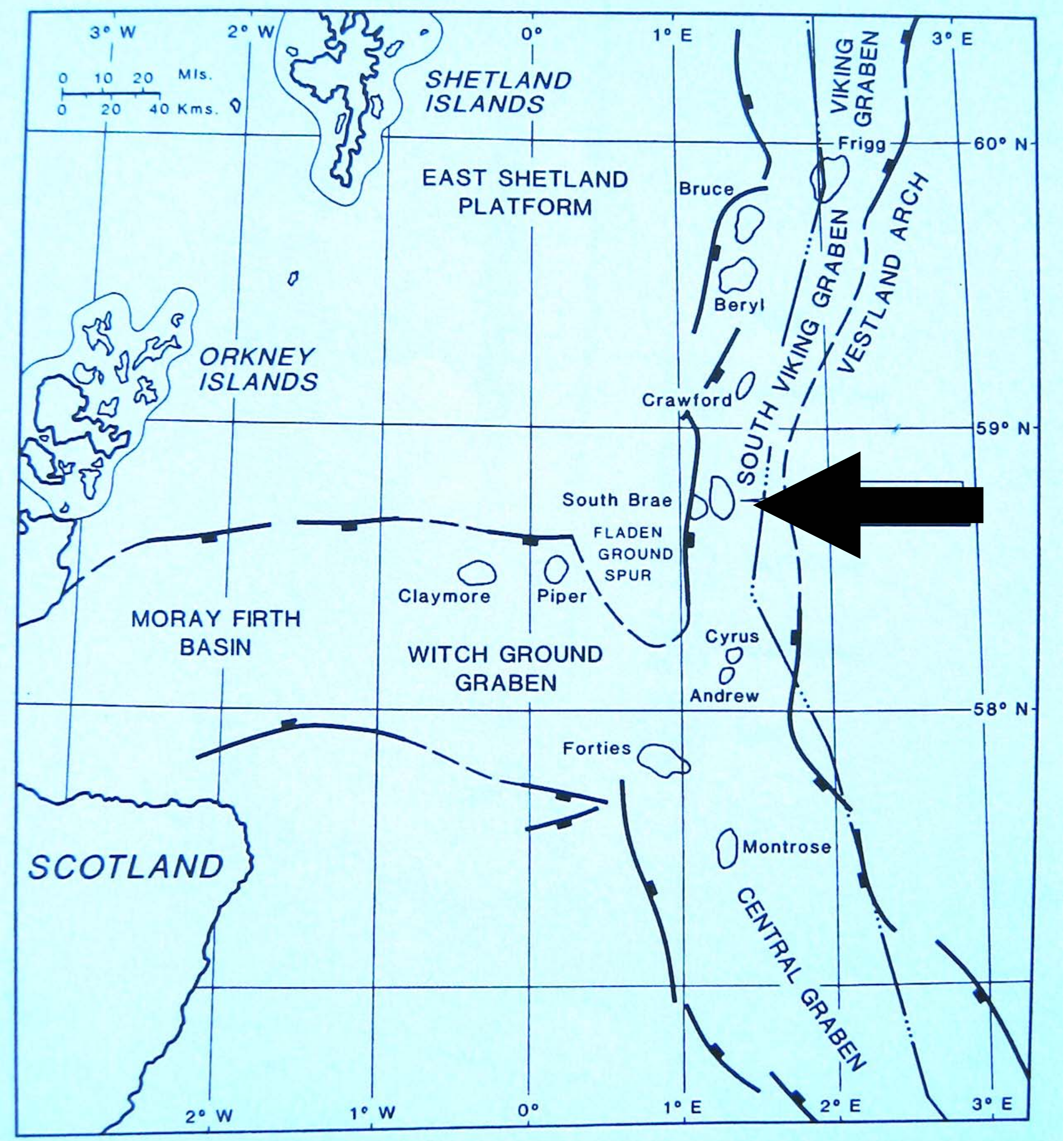
  Teams Transition of ownership

  - Oil---Coal..Government ?
  - Suitability of facilities
  - Liability of platforms transferred ie North sea problems
  - Safe abandonment

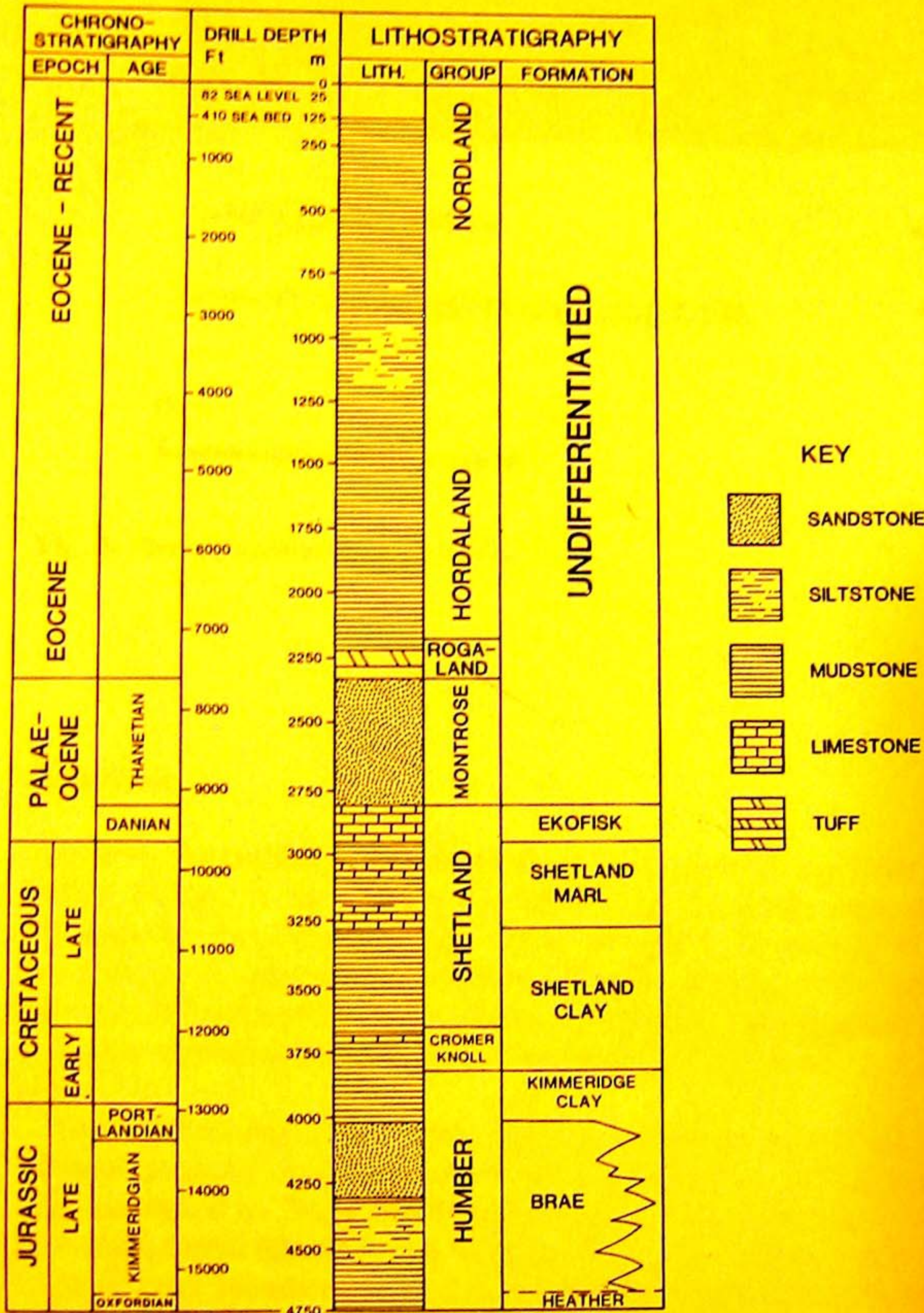
IEA GHG M&V Workshop Rome 2005

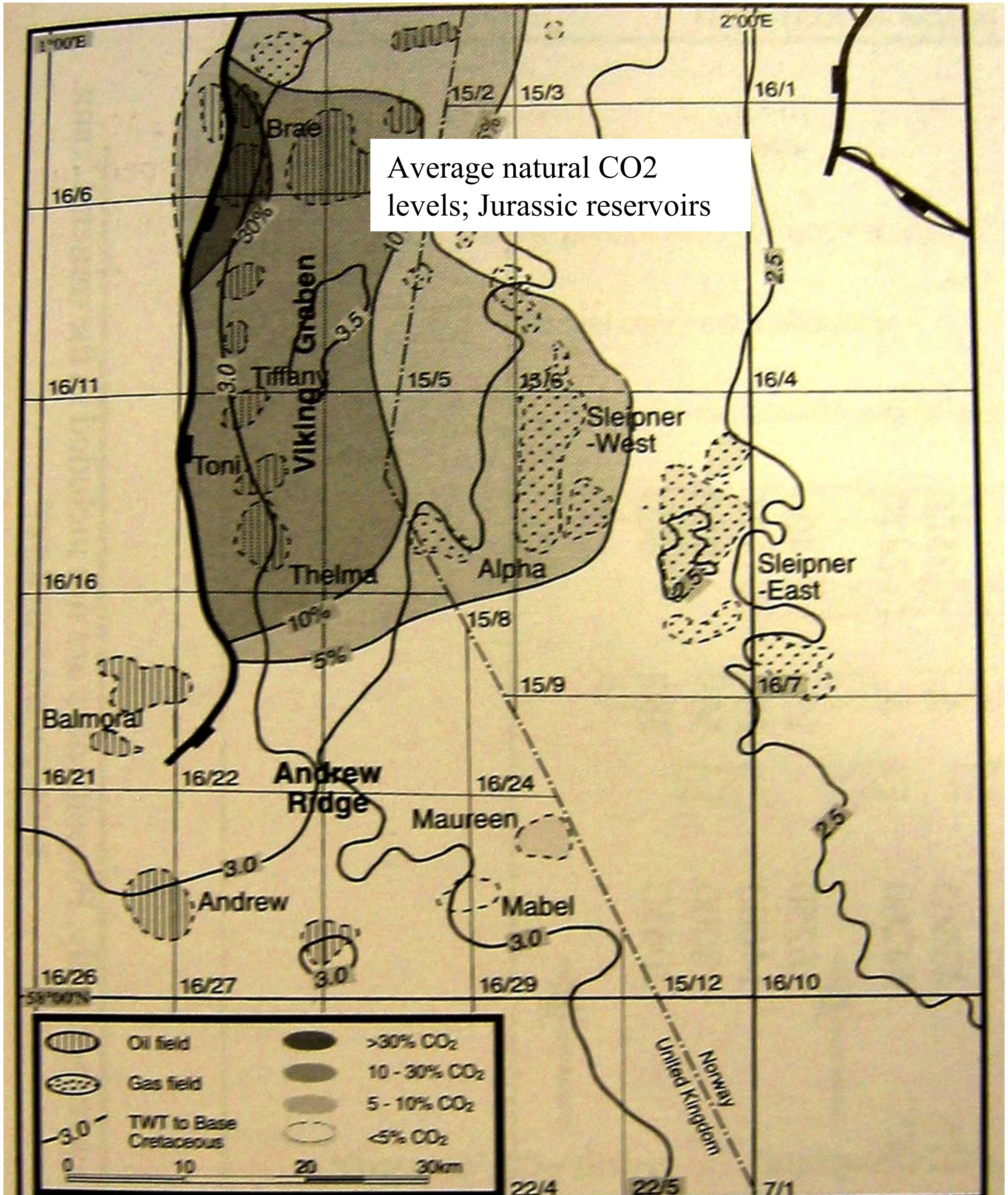
Scenario

Viking Graben; N. Sea

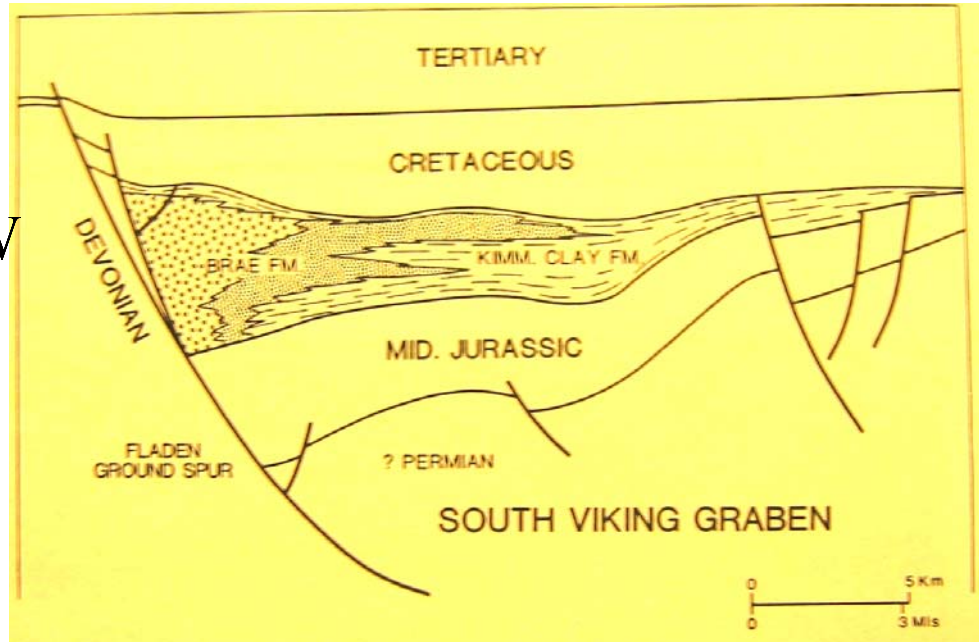


3° W
2° W
0°
1° E
3° E
0 10 20 Mls.
0 20 40 Kms.
SHETLAND ISLANDS
VIKING GRABEN
Frigg
60° N
EAST SHETLAND PLATFORM
Bruce
Beryl
SOUTH VIKING GRABEN
VESTLAND ARCH
ORKNEY ISLANDS
Crawford
59° N
South Brae
FLADEN GROUND SPUR
Claymore
Piper
MORAY FIRTH BASIN
WITCH GROUND GRABEN
Cyrus
Andrew
58° N
Forties
Montrose
SCOTLAND
CENTRAL GRABEN
2° W
1° W
0°
1° E
2° E
3° E


CHRONO-STRATIGRAPHY
EPOCH
AGE
DRILL DEPTH
Ft
m
LITHOSTRATIGRAPHY
LITH.
GROUP
FORMATION
82 SEA LEVEL 25
410 SEA BED 125
EOCENE - RECENT
EOCENE
PALAE-OCENE
CRETACEOUS
LATE
EARLY
JURASSIC
LATE
THANETIAN
DANIAN
PORT-LANDIAN
KIMMERIDGIAN
OXFORDIAN
NORDLAND
HORDALAND
ROGA-LAND
MONTROSE
SHETLAND
CROMER KNOLL
HUMBER
UNDIFFERENTIATED
EKOFISK
SHETLAND MARL
SHETLAND CLAY
KIMMERIDGE CLAY
BRAE
HEATHER
KEY
SANDSTONE
SILTSTONE
MUDSTONE
LIMESTONE
TUFF


Average natural CO2 levels; Jurassic reservoirs
Brae
Viking Graben
Tiffany
Toni
Thelma
Alpha
Sleipner -West
Sleipner -East
Balmoral
Andrew Ridge
Maureen
Andrew
Mabel
Norway
United Kingdom
Oil field
Gas field
TWT to Base Cretaceous
>30% CO2
10 - 30% CO2
5 - 10% CO2
<5% CO2
0 10 20 30km

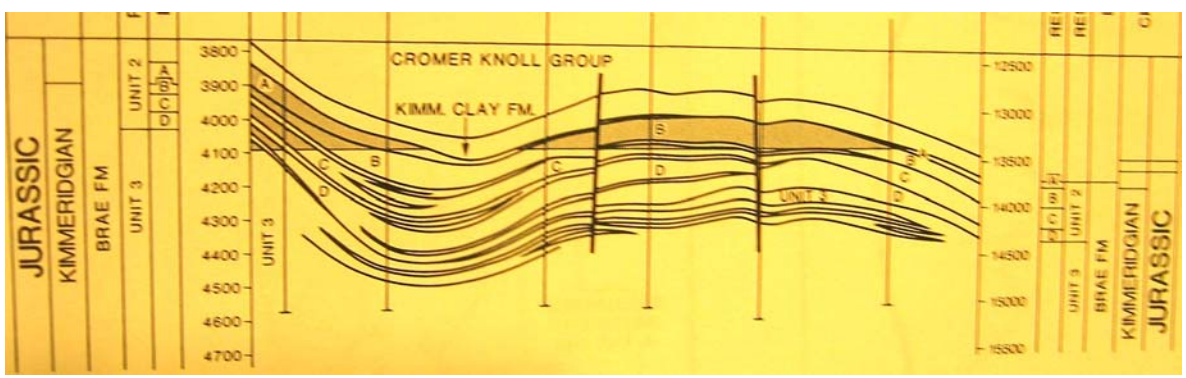
W



TERTIARY
CRETACEOUS
DEVONIAN
BRAE FM
KIMM. CLAY FM.
MID. JURASSIC
FLADEN
GROUND SPUR
? PERMIAN
SOUTH VIKING GRABEN
0
5 Km
0
3 Mls

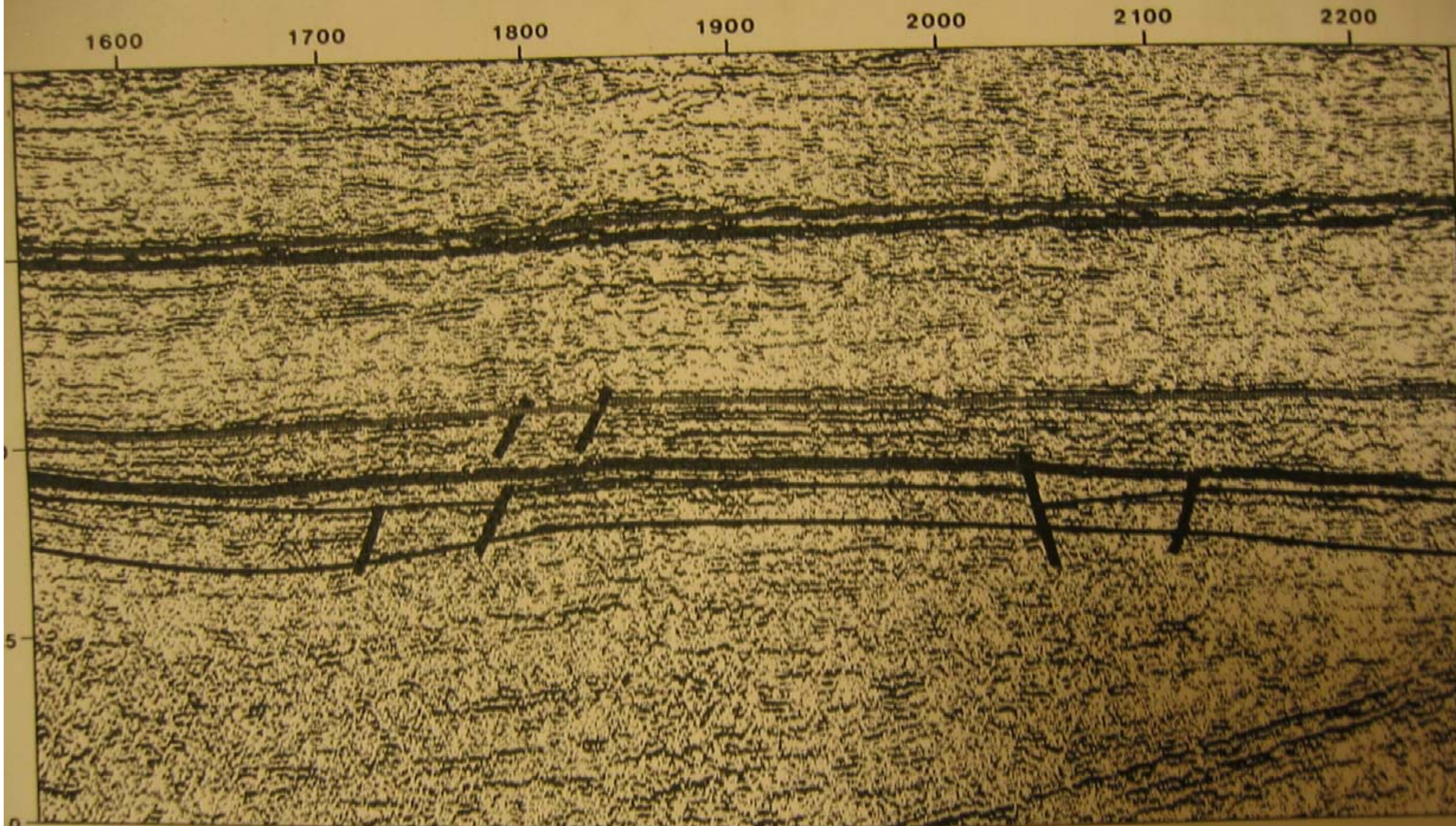
E

W



JURASSIC
KIMMERIDGIAN
BRAE FM
UNIT 2
UNIT 3
A
B
C
D
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
CROMER KNOLL GROUP
KIMM. CLAY FM.
UNIT 3
12500
13000
13500
14000
14500
15000
15500
UNIT 2
UNIT 3
BRAE FM
KIMMERIDGIAN
JURASSIC

E



TOP EKOFISK | TOP TOR | TOP HERRING

TOP KIMMERIDGE CLAY FM. | TOP RESERVOIR | BASE RESERVOIR (?)

0

Trap	
Type	Combination; Structural 3 way dip & stratigraphic
Depth to crest (U Jurassic)	3980 m (13 058 ft)
Oil–water contact	4090 m (13 418 ft) ± 3m
Gross oil column	*c.* 110 m (361 ft)
Pay zone	
Formation	Brae Formation sandstones
Age	Late Jurassic (Kimmeridgian/ Portlandian)
Thickness	125–250 m
Net/gross	Average 0.8, range 0.4–0.98
Porosity	Average 16%, range 12–23%
Hydrocarbon saturation	85–90%
Permeability	11–1200 md
Hydrocarbons	
Oil gravity	0.83 gm cm^{-3} at 60°F/1.0 bar (38.5° API)
Oil type	Significant CO_2 and H_2S, undersaturated, volatile
Gas/oil ratio	1813 SCF/STB
Bubble point	4900 psia
Formation volume factor	1.97 rb/STB at 7250 psia
Formation water	
Resistivity	0.032 ohm m at 250°F
Salinity	70 000 ppm
Reservoir conditions	
Temperature	250°F
Pressure	7250 psig (original)
Pressure gradient in reservoir	0.27 psi/ft
Field size	
Area	45 km^2 (11 120 acres)
Recoverable oil and gas	300 MMBBL/0.57 TCF
Drive mechanism	Aquifer plus water injection
Production	
Anticipated first oil	1Q 1992
Anticipated daily production	113 000 BOPD
Development scheme	Steel jacket, drilling and export facilities for oil and gas
Number/type of wells	30 wells, 21 producers, 9 injectors

Viking Graben Scenario

EOR in a North Sea Oilfield

Risk Register

- Relevance of impurities on leakage hazards
- Impact on neighbouring fields
- Impact on faults
- Seismic activity
- Distinguishing natural methane from CO_2 seepage – lack of baseline data
- Exploration wells provide potential pathways
- High T, P, sour gas impact on instrumentation
- Accounting for recycled CO_2 – credits etc

Risk Elements Containment

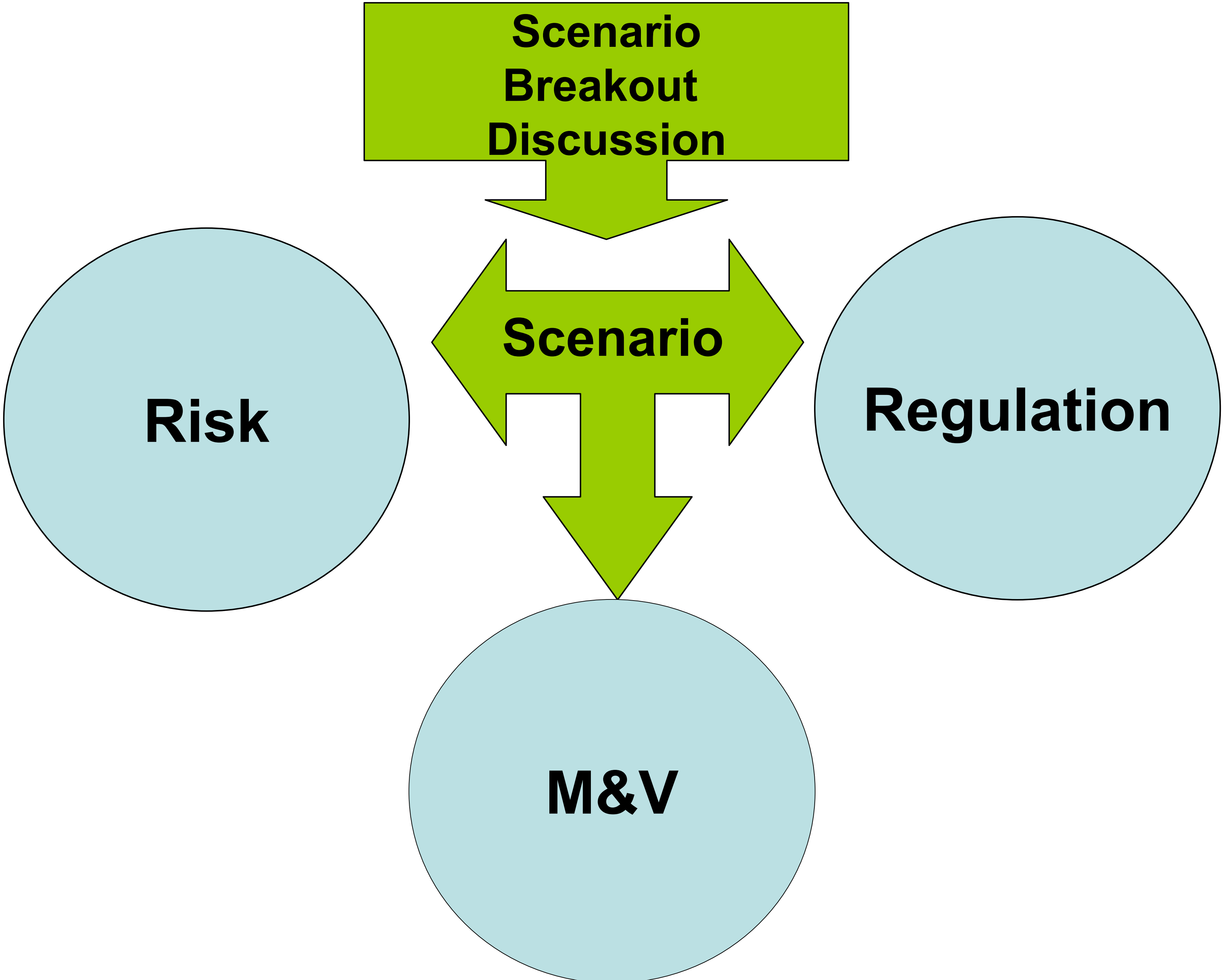
- ***Leakage Through Faults***
  - ***(but not to surface?)***
- ***Leakage Through Wells***
  - ***exploration & production***
  - ***well damage***
- ***Long term climate change***
  - ***(ice bergs) ?***
- ***Exceeding Spill Point***
  - ***Direction***
- ***Earthquake***

Risk Register for External Environment

- Categories of regulatory interest
  - Climate change effectiveness
    - National emissions reporting
  - Eco-system protection
    - chronic seepage
  - Local HSE
    - acute short term releases
  - Impact on other natural resources
  - Monitoring requirements for post-closure stewardship
    - Operational and post-closure
- NGO interests
  - Adverse public perception

Basis for Monitoring Programme

- Accurate seismic monitoring
- Identification of injected CO_2
  - Isotopic monitoring, organic chemical fingerprinting
  - Characterisation of shallow interval fluids and geology
  - Regional flow model
- Consider seabed seepage monitoring
- Wellbore monitoring
  - Operational
  - Post-closure requirements
- CO_2 inventory
- Long term stewardship
  - Passive wellbore tools ???


Scenario
Breakout
Discussion
Scenario
Risk
Regulation
M&V

COAG suggested for purposes of M&V provides to a regulatory framework:

- *Provide for the generation of clear, comprehensive, timely and accurate information effectively*
- *Responsibly manage environmental, health, safety and economic risks*
- *Ensure that set performance standards are being met*
- *Determine to an appropriate level of accuracy*
  - *–the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of fugitive emissions.*

Consequently the goals of monitoring framework is to provide

- *A comprehensive set of information from direct measurements and remote sensing of the process of storage*
- *Appropriately document the complete storage process within the following tasks:*
  - *–Safely transport CO2 from source to sink;*
  - *–Safely inject CO2 into subsurface reservoirs;*
  - *–Safely store CO2 in the subsurface; and*
  - *–Safely abandon facilities and restore sites.*

Verification at each stage is critically important to achieve public and stakeholder satisfaction that the CO2 has been removed permanently from the surface environment.

Process of Scenario Evaluation

- **Scenario Context**
  - **Guidance from Leader only**
- **Risk Register**
  - **Risk - Specific Issues-Consequences-Mitigation**
  - ***Consider consequences for all stakeholders***
  - ***Consider subsurface to surface***
  - ***Consider phases,***
- **Regulatory**
  - ***Don't get tangled with legal aspects***
  - ***Define possible, sensible framework that will verify performance at each stage***
  - ***Address risks***
  - ***Give thought to liabilities, short term, long term, abandonment.***
  - ***Define possible KPIs…one sentence***
- **M&V Program**
  - ***Should address risk and regulatory environment***
  - ***Should have eye on economic but complete***
  - ***Should be generic and high level, unless illustrative***

Risk Elements
Effectiveness

- *Lack of Capacity*
- *Reduced Injectivity*
- *Inadequate Source*
- *Groundwater Displacement*
- *Regulatory Change*
- *Stakeholders Reject or Oppose Project*
- *Poor Public Perception of Other Projects*
- *Sub-Surface Biological Concerns*
- *Lack of Regulations*
- *Licensing/Ownership/Liability/Insurance*

Scenarios

- **Acid-gas Canada**

-

- **Gippsland Australia**

-

- **Frio Texas**

- **Mullet**

Scenario 1. Gippsland, Aus

Coal onshore, offshore storage, active hydrodynamics?

• Kevin Dodds	CO2CRC/CSIRO Australia
• Ernie Perkins	CO2CRC Australia
• Bill Koppe	Anglo Coal Australia
• Alan Rezigh	ConocoPhillips
• Massimo Angelone	ENEA
• Sergio Persoglia	OGS
• Fedora Quattrocchi	INGV
• Gianfranco Galli	INGV
• Gianluca Patrignani \	Snamprogetti div. Aquater/RISAMB
• Brent Lakeman	Alberta Research Council Inc.
• Hubert FABRIOL	BRGM
• Don White	Geological Survey of Canada
• Daiji Tanase	Engineering Advancement Association of Japan
• Scott Imbus	Chevron Energy Technology Co.
• Tim Dixon	UK DTI

Scenario 2. Mullet, Europe

Deep 4km, offshore, European consequences

• Nick RILEY	British Geological Survey
• Tony Espie	BP
• Malcolm Wilson	Energy INET
• Fabio Moia	CESI S.p.A.
• Francois KALAYDJIAN	IFP
• Roberto Bencini	INGV
• Barbara Cantucci	INGV
• Johannes Petrus van Dijk	ENI Div. Exploration & Production
• Neeraj Gupta	Battelle
• K. MICHEL	BRGM
• Hiroyuki Azuma	Oyo corporation
• Arthur Wells	U.S. Department of Energy
• Pascal Winthaegen	TNO
• Anhar Karimjee	US EPA

Scenario 3. Acid Gas, Canada

Regulatory environment is mature…is it adequate ?

• Rick Chalaturnyk	University of Alberta
• Don Lawton	University of Calgary
• Dan Ebrom	BP
• Ernesto Bonomi	CRS4
• Yann Le Gallo	IFP
• Antonella Cianchi	INGV
• Janpieter van Dijk	Eni E&P Division
• Umberto Fracassi	INGV
• Hideki Saito	Oyo Corporation
• Bernard BOURGEOIS	BRGM
• Ola Eiken	Statoil
• Anne-Marie Thompson	Natural Resources Canada
• Laurent Jammes	Schlumberger

Scenario 4. Frio US

Mature regulatory environment Answers looking for the questions ?

• Susan Hovorka	Bureau of Economic Geology
• Charles Christopher	BP Americas
• Richard Rhudy	EPRI
• Kate Roggeveen	Australian Greenhouse Office
• Giuseppe Girardi	ENEA
• Salvador Rodriguez	IFP
• Sonia Topazio	INGV
• Lombardi Salvatore	University "La Sapienza of Rome"
• Maria Teresa Mariucci	INGV
• Jonathan Pearce	British Geological Survey
• Akio Sakai	Japex
• Paitoon Tontiwachwuthikul	University of Regina, Canada
• Christian Bernstone	Vattenfall Utveckling AB
• Angela Manancourt	IEA GHG
• John Gale	IEA GHG

Risk Elements
Containment

- ***Permeable Zones in Seal***
- ***Leakage Through Faults***
- ***Leakage Through Wells***
- ***Regional Over-Pressurisation***
- ***Local Over-Pressurisation***
- ***Exceeding Spill Point***
- ***Earthquake***
- ***Migration Direction***
- ***Compressor Failure***
- ***Platform Failure***
- ***Pipeline Failure***
- ***Well-Head Failure***

Risk Elements Effectiveness

- *Lack of Capacity*
- *Reduced Injectivity*
- *Inadequate Source*
- *Groundwater Displacement*
- *Regulatory Change*
- *Stakeholders Reject or Oppose Project*
- *Poor Public Perception of Other Projects*
- *Sub-Surface Biological Concerns*
- *Lack of Regulations*
- *Licensing/Ownership/Liability/Insurance*

Regulatory Environment

Players

- Private – NGO – Indigenous
- Government – State – National – International
- Need to balance deal across the spectrum
- Identify issues and reconcile

Constraints

- Environment, petroleum, offshore, onshore
- Law of Ocean

Definitions

- How CO2 defined, how injected
- Saline formations…van use ocean salinity a benchmark

Considerations for Regulatory Environment

- Storage
  - Leakage to surface through reservoir path
  - Leakage to surface through wells during monitoring
  - Leakage to surface post decommissioning
  - Leakage into potable water supply

Considerations for Regulatory Environment

Project Phases

- Phase 1 : Pre Injection and Injection related activities

KPIs

- Phase 2 : Post Injection but pre-closure related activities

KPIs

- Phase 3 : Post Closure Monitoring. How the ownership will pass from Operator to another entity (expected to be a Govt. entity)

KPIs

- Phase 4 : Long term monitoring.

Responsibilities ?

Considerations for Regulatory Environment

- Production Risk
  - Data Acquisition
  - Plant and processing
  - Gas Transportation
  - Drilling Risk
  - Injection Risk
  - Personal Risk
  - Decommissioning

M&V Addressing Regulatory & Risk Questions

Monitoring and Verification

- M&V framework including frequency of monitoring
- Trigger points to identify anomalies per phase
- Baseline establishment
- KPI's to define transition points to a different monitoring regime (move from 1 phase to another)
- Contingency planning for monitoring responses outside uncertainty bands
- Roles and Responsibilities

Gorgon Development – LNG with CO_2 Storage

Scott Imbus, Chevron Energy Technology Co.
(On Behalf of the Subsurface Technical Team)

Presentation Outline

Project Overview

Environmental Issues

Greenhouse Gas Management Strategy

Geology of Barrow Island

Injection & Trapping Simulation

Well Issues

Monitoring Options

Feedback from Monitoring Network Group?

Further Information: www.gorgon.com.au

Managing our Environment "Environmental Impact Statement / Environmental Review and Management Programme"

Project Overview -1

Gorgon Development: Chevron (50%, Operator), Shell (25%) and ExxonMobil (25%)

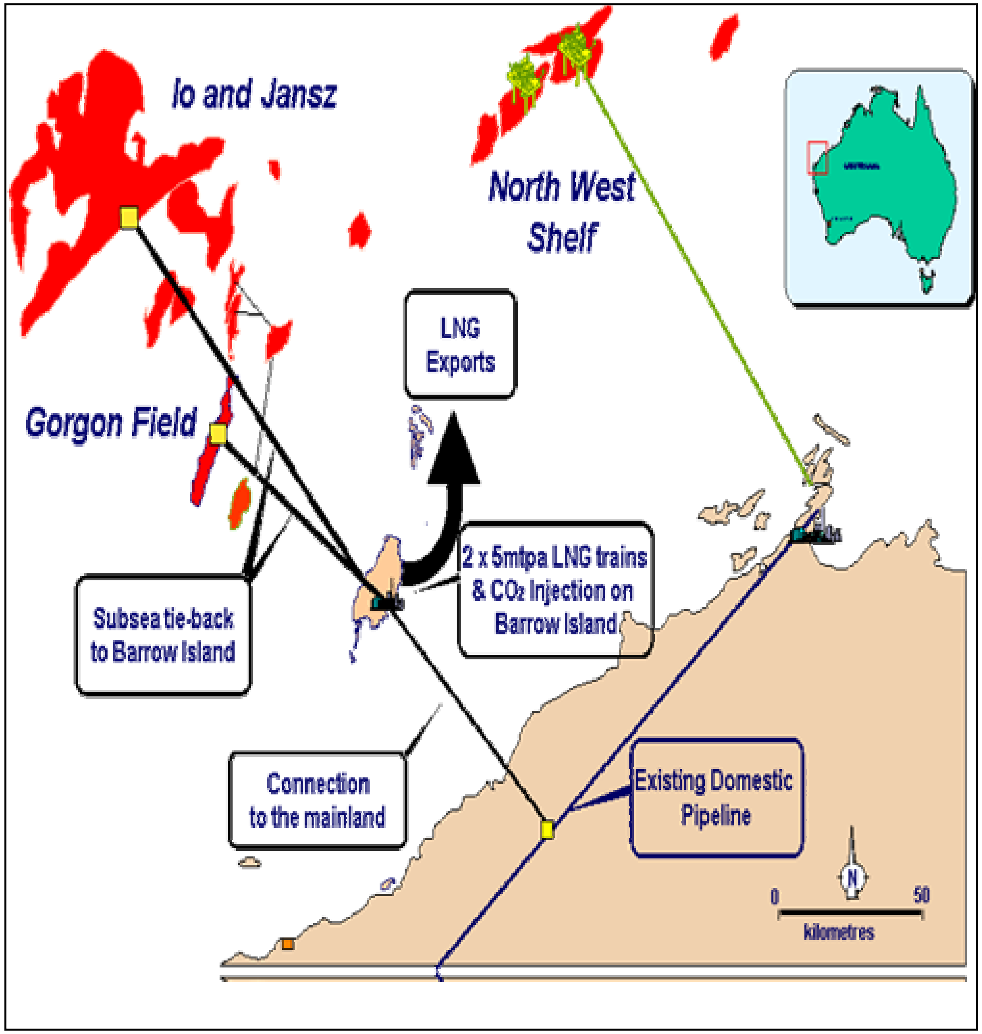
Greater Gorgon Area ~ 40 Tcf Resource (25% Australian)

Gorgon Area Gas ~12.9 Tcf (9.6 Tcf Proven)

Co-Development of Gorgon Gas (~14%) CO_2 + Jansz Gas (<1%)

Screening Process for Processing / LNG Plant Location and Suitable Reservoirs

Barrow Island Optimal Site for Economic and Technical Reasons



Project Overview - 2

Gorgon Gas Field Wells and Subsea Installation

Feed Gas to Barrow Island (70km sea + 14km land)

Gas Processing (CO_2 Rejection via a-MDEA)

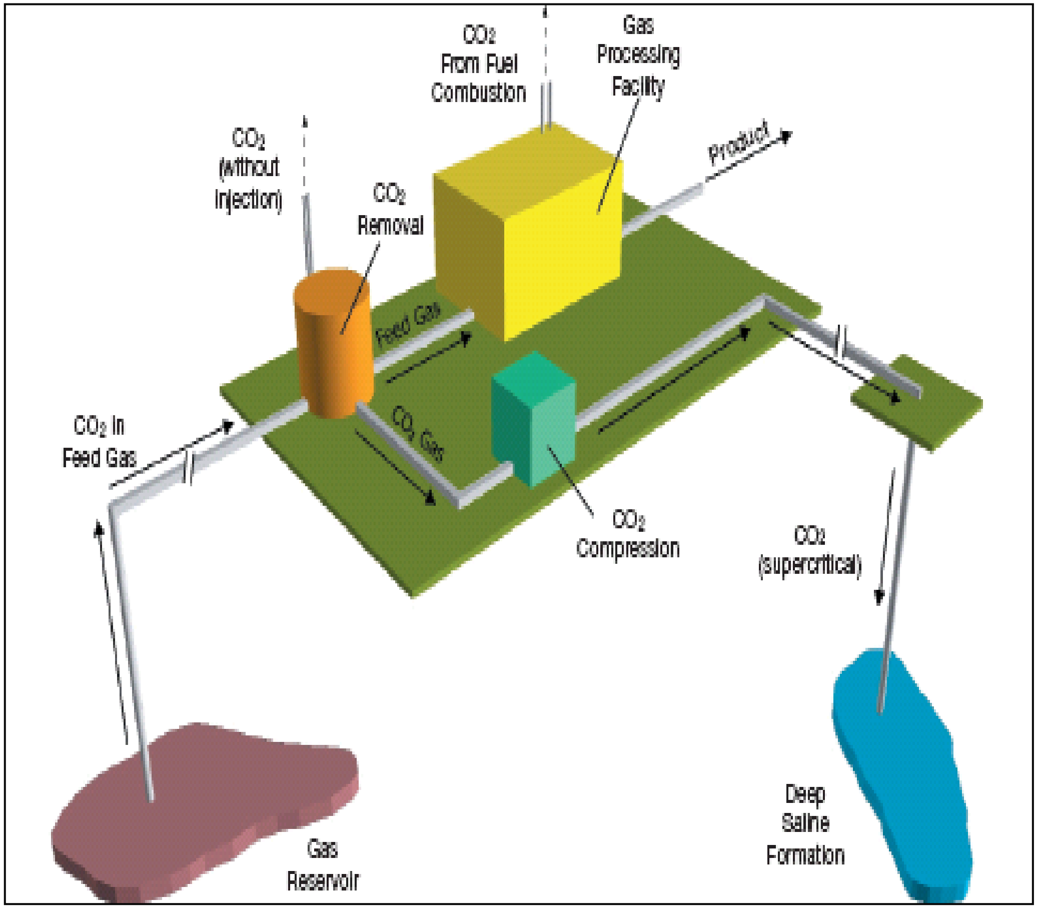
LNG + Dom Gas Export (10 MPTA) + Condensate

Injection of Captured CO_2 into Dupuy Fm.

First LNG Cargo (mid 2010)

Final Investment Decision (mid 2006)

Development Investment ~AU$11B



Environmental Issues

Barrow Island is a “Class A Nature Reserve” but has been Under Oil Production for ~ 40 yrs.

Land Take Restrictions (<300Ha), Flora/Fauna Protection and Invasive Species Control (Quarantine)

Gas Processing / LNG Facilities Selected to Avoid Sensitive Areas

Injection Site Avoids Sensitive Areas Whilst Optimizing Performance and Avoiding Vulnerable Features

Greenhouse Gas Management Strategy

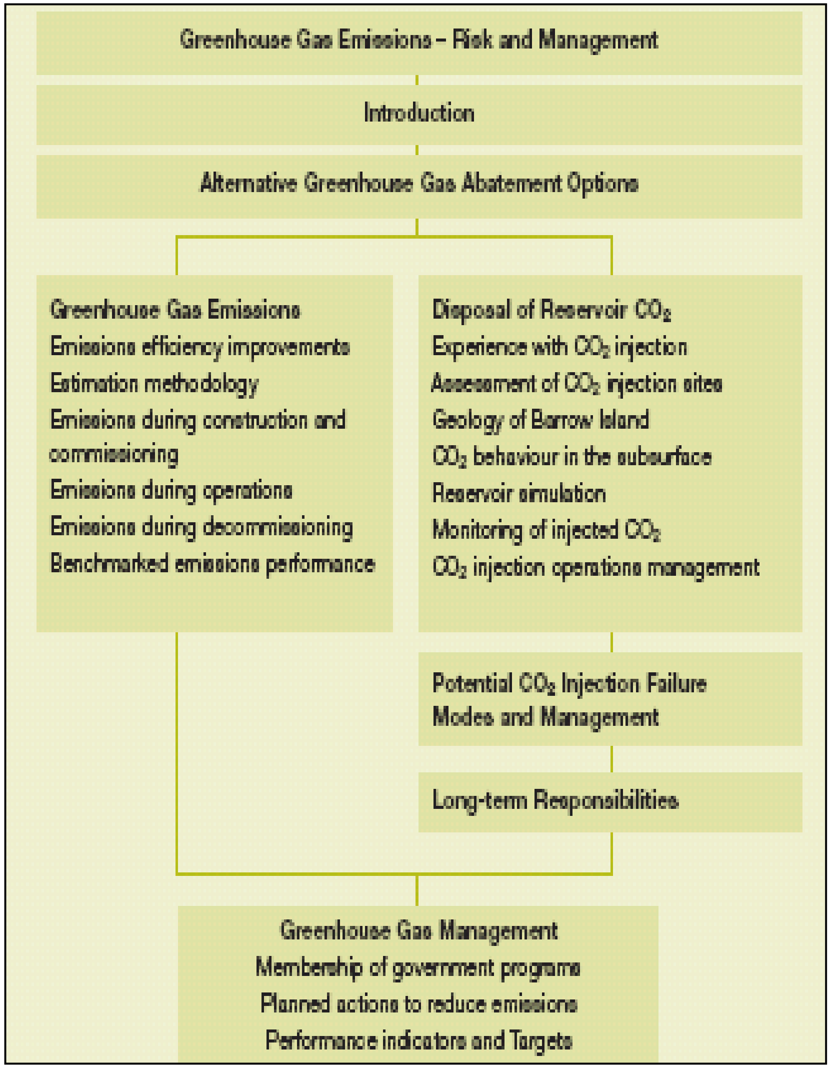
Major Elements Include: Efficiencies in Extraction, Avoiding Fugitive Emissions, gas Processing Efficiencies and CO_2 Storage

"Develop a project to re-inject the removed CO_2 into the Barrow Island Dupuy saline reservoir, unless it is technically infeasible or cost-prohibitive."

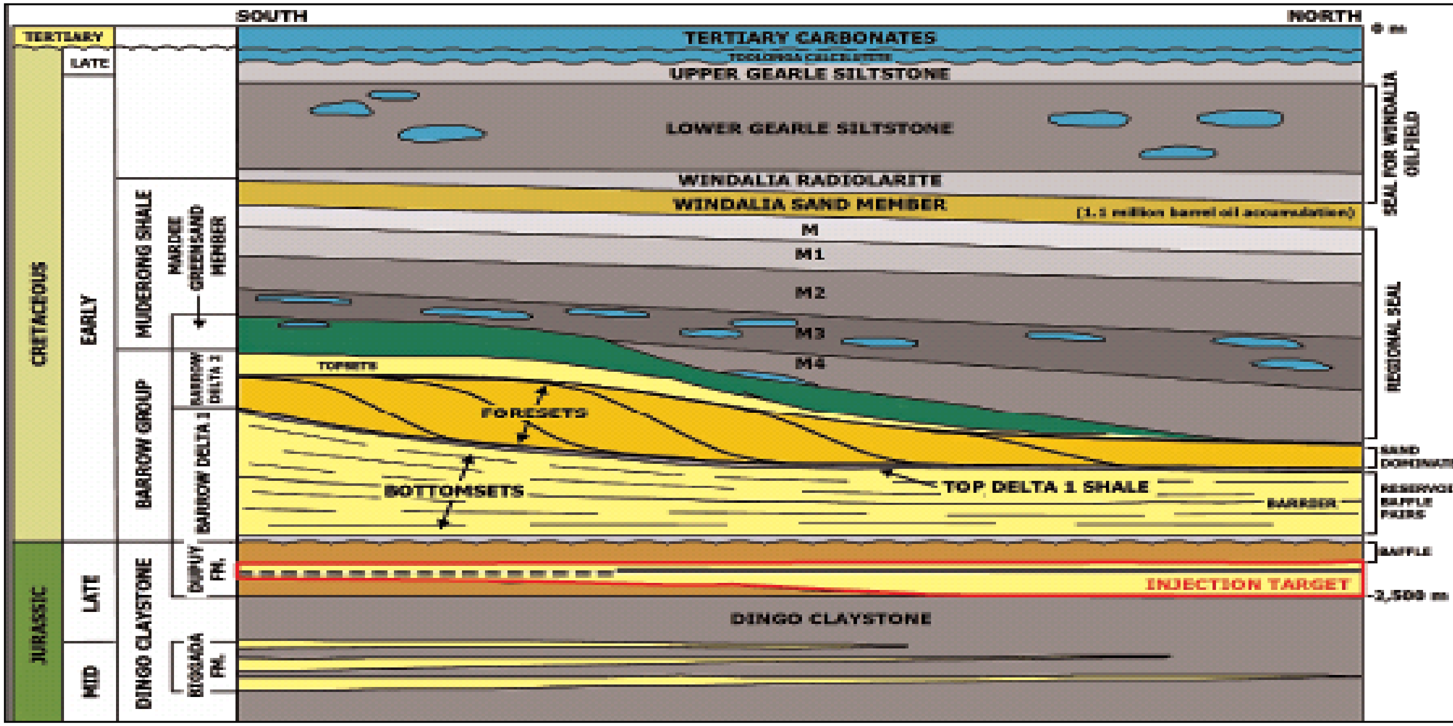
Proposed Injection into Dupuy Fm. Will Reduce Project GHG by 40% (From 6.7 to 4.0 MTPA) (250Mcf/day)

Key CO_2 Storage Issues Include Geologic Characterization, CO_2 Movement and Trapping, and Monitoring.

Leverage CO_2 Injection Experience and R&D Results (e.g., CO2CRC)



Geology of Barrow Island



Lower 2/3 Dupuy Fm. Injection Target (Late Jurassic Sandstone)

Low to Medium Permeability with Abundant Baffles (Vertical & Lateral)

Sealing Strata at top Dupuy with Additional Shallower CO_2 Sinks (Barrow Group Aquifer) and Regional Seals (e.g., Muderong & Gearle)

Injection & Trapping Simulation

2 Injection Centers with Up to 7 Lateral Wells; Injection into Lower 2/3 Dupuy

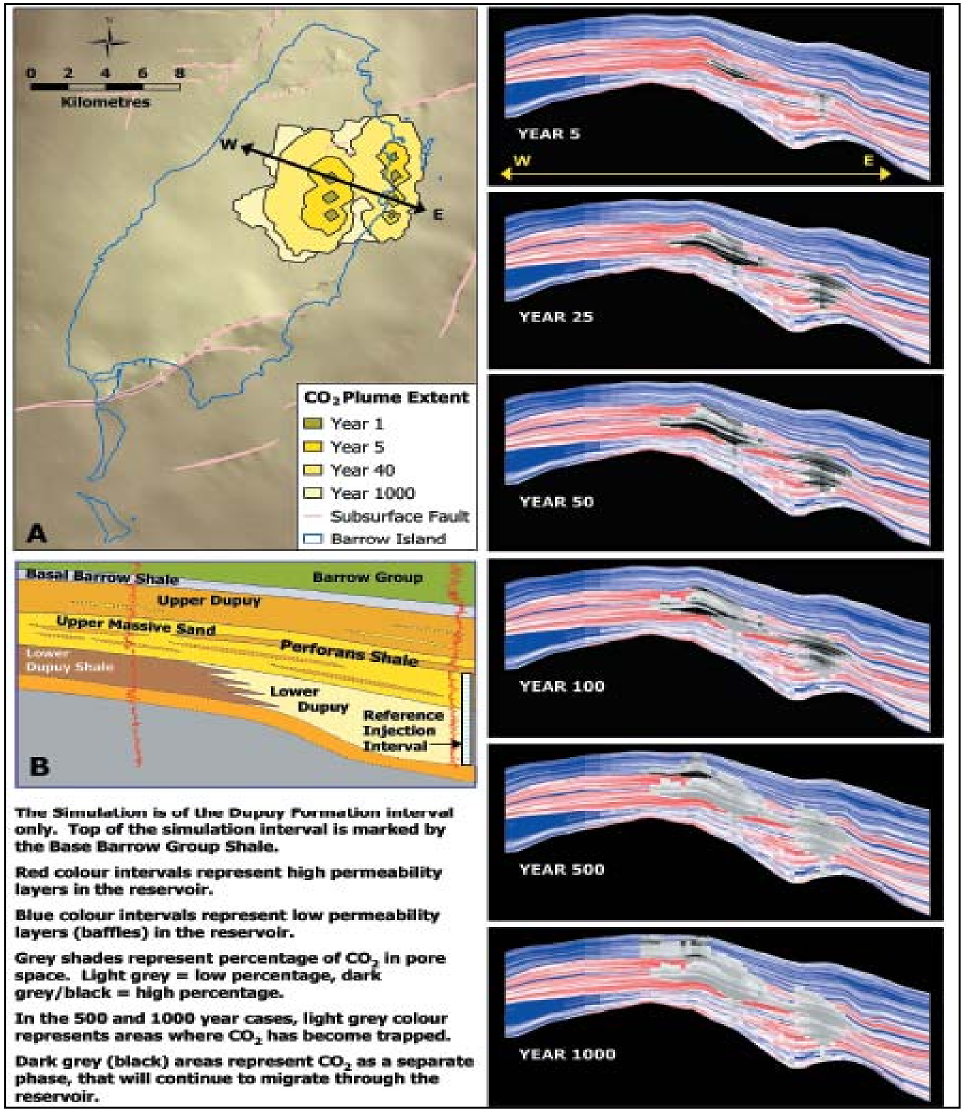
Permeability Distribution Prevents Rapid Vertical and Lateral Migration

Pressure Field Peaks at ~30 yrs.

Major Mechanisms Likely to Trap most CO_2 Within 1000 yrs.

Aerial Extent of Plume Increases Slowly After 40 yrs. (Operational Phase)

Plume Avoids Major Faults but does Intersect Wells



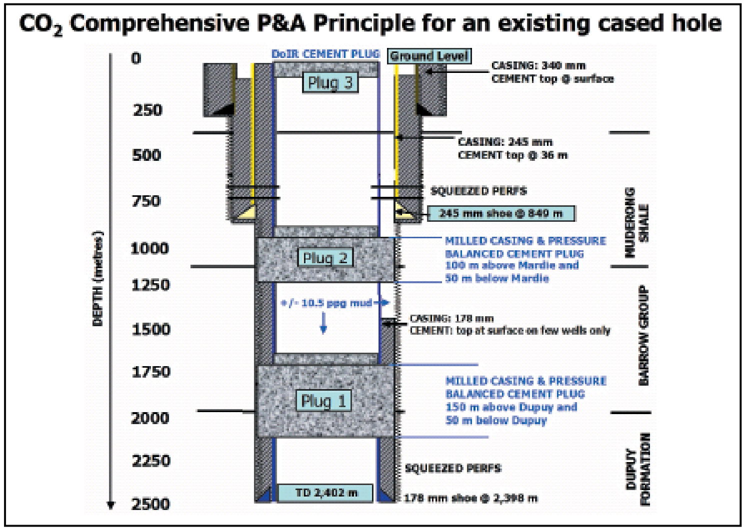
Well Issues

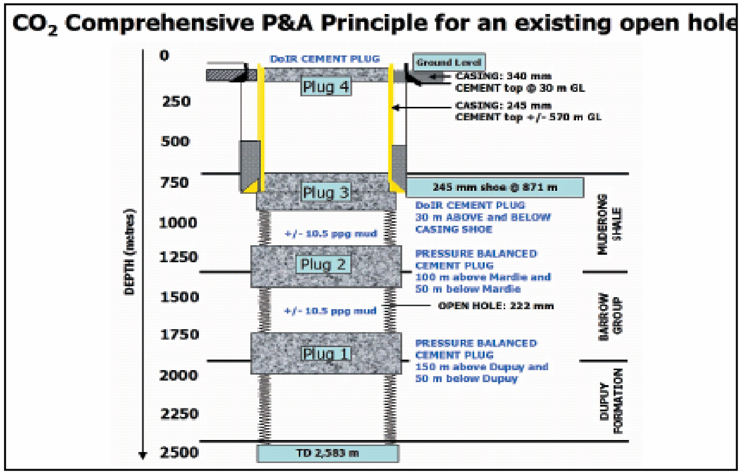
27 Wells Penetrating the Dupuy Fm. w/ 2 Over 40 yr. plume and Additional 3 Over 1000 yr. Plume

Assessment of Service in CO_2-Rich Environment w/ Ranking of High, Moderate and Low-Risk Based on Remedial Ability

Development of Decommissioning and Remedial Plan (Reactive Strategy)

Design of New Wells





Monitoring Options

Issues:

Geology / Geography

- Onshore & Offshore Plume
- Near-Surface Karst
- Structure / Stratigraphy
- Rock Properties

Deviation from Simulations

- High Permeability Layers
- Down Dip Migration
- Wells
- Faults & Fractures

Monitoring Solutions:

Injection Rate Metering and Pressure Measurements

HES – Oriented Surveillance for Leak Detection

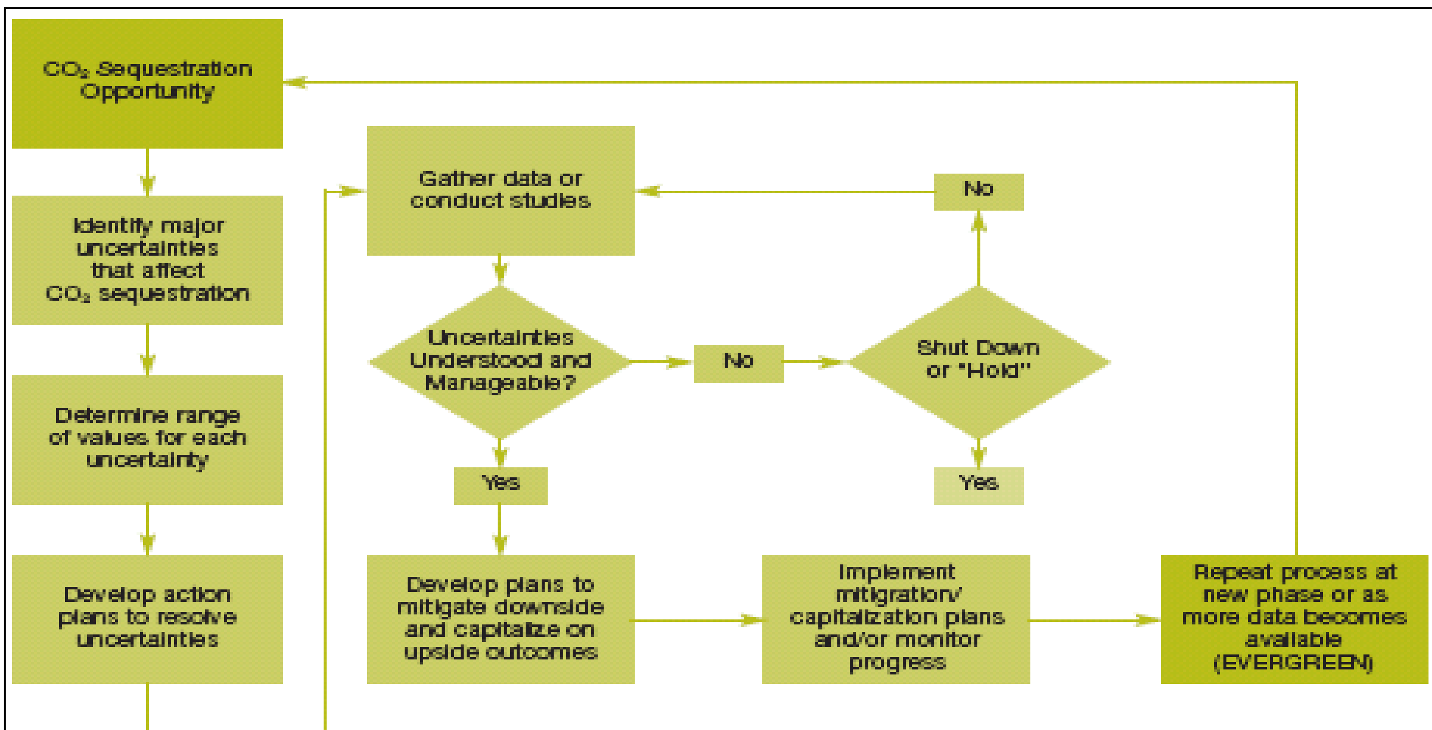
Verification Via Seismic Surveys and / or Observation Wells Supplemented by:

- Conventional Wireline Logs to Detect CO_2 Migration at Wells or Up Wellbore
- Geochemical Analysis of Formation Waters

Uncertainty Management

Potential Failure Modes: Leakage from Surface Injection Facilities, Migration Events, Reduced Injectivity, Earthquakes, Environmental Impacts

Workshop to Assess "Safeguards, Mitigation or Management Measures" and "Residual Risk"



Feedback from Monitoring Network Group?

Considerations:

- Environmental – Class A Nature Reserve; Adjacent Reserves
- Geography – Sea / Land Boundary
- Geology – Shallow Karst; Multiple Sinks / Seals
- Simulation Results – Unexpected Migration
- Presence of Wells – Condition; Remediation Strategy

Options:

- Seismic (Image Quality; Minimize Impact)
- Observation Wells (Sampling/Analysis; Sensors; Tracers)
- Shallow Subsurface (Shallow Imaging & Wells)
- Atmospheric (Soil Gas, Flux, Near Surface LS, Remote)

The Gorgon CO_2 Subsurface Team

Seb Leigh	Team Lead
Graeme Beacher	Geologist
Jeroen Brentjes	Petrophysicist
Aaron Burt	Geologist
Jon Cocker	Geophysicist
Matthew Flett	Reservoir Engineer
Randy Gurton	Reservoir Engineer
Fiona Koelmeyer	Petroleum Engineer
Robert Lawrence	Geophysicist
Jason McKenna	Geophysicist
Terrell Tankersley	Geologist
Joann Williams	Production Engineer

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
www.bgs.ac.uk

CO_2GeoNet Activities in monitoring geological storage

Jonathan Pearce - British Geological Survey

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

NATURAL ENVIRONMENT RESEARCH COUNCIL

Outline

- Outline of CO_2GeoNet
- Overview of monitoring research objectives
- Progress
- Joint research activity plans
- Summary

A Network of Excellence

- Align & harness national research programmes
- Jointly develop / share knowledge & research infrastructure
- Durable integration resulting in co-dependence & standardisation
- Provide training for the next generation of researchers
- Provide advice for Europe on CO_2 storage R&D
- Engage and collaborate with major non-EU R&D programmes & research centres

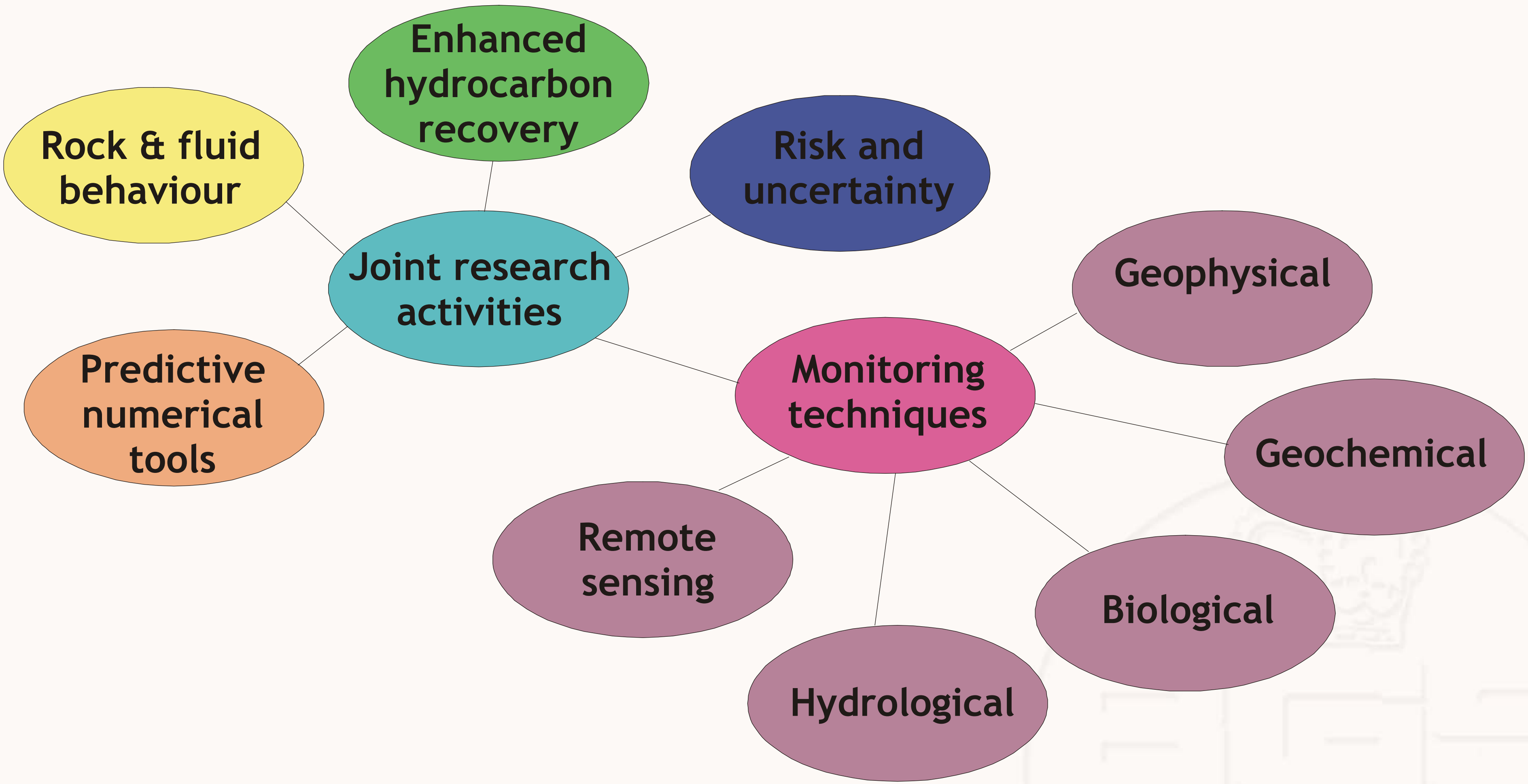
13 Partners

- Denmark
  - Geological Survey of Denmark and Greenland –GEUS
- France
  - Bureau de Recherches Geologiques et Minieres- BRGM
  - Institute Francais du Petrole –IFP
  -
- Germany
  - Federal Institute for Geosciences and Natural Resources –BGR
- Italy
  - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale-OGS
  - Università di Roma “La Sapienza” -URS
- Netherlands
  - Netherlands Organisation for Applied Scientific Research –TNO
- Norway
  - Norwegian Institute for Water Research –NIVA
  - Stiftelsen Rogalandsforskning-RF
  - SINTEF Petroleumsforskning AS –SPR
- UK
  - Natural Environment Research Council-British Geological Survey-BGS
  - Heriot-Watt University –HWU
  - Imperial College of Science, Technology and Medicine-IMPERIAL

CO2 GeoNet

Resourcing

- Launched April 2004
- Budget over 5 years
- EC Contribution - €6million
- Network Partners and external funding - €3million
- Beyond 2009 the Network will be funded independently of the EC


Enhanced hydrocarbon recovery
Rock & fluid behaviour
Risk and uncertainty
Joint research activities
Geophysical
Predictive numerical tools
Monitoring techniques
Geochemical
Remote sensing
Biological
Hydrological

Why do we need to monitor CO_2?

- Effectiveness as a greenhouse gas mitigation technique
  - Verifying volumes stored for “credits” – within IPCC and European ETS.
- Local health & safety during injection
- Local environmental impacts post-closure
  - Leakage mechanisms
  - Offshore ecosystems in seabed and seawater
  - Onshore ecosystems (microbiological, invertebrate and vertebrate)
  - Humans

CO_2GeoNet objectives for monitoring research

- Currently no guidelines exist on how a CO_2 storage site should be monitored.
- CO2GEONET is a key forum to develop such guidelines based on knowledge from the different monitoring techniques and sites.
- Actively complements demonstration projects.
- Focussed on process research and technique development.

Progress

- Inventories completed 2004-05
  - Review of partner capabilities and current research
- 3 'quick start' JRAs were approved in December 2004
  - Maintaining continuity of soil-gas monitoring at Weyburn
  - Seismic attribute analysis of Sleipner data
  - Seismic pushdown from pre-stack data
- Gaps and opportunities for co-operation identified
- Gaps addressed through proposals, which were independently evaluated.

Summary of inventories

	JRA4-1 (WP16)	JRA4-2 (WP17)	JRA4-3 (WP18)	JRA4-4 (WP19)	JRA4-5 (WP20)
	Geophysical	Geochemical	Biological	Hydrological	Remote sensing
Number of tools currently applied	23	17+	0	1	(1)
Number of new tools for future application	7+	6+	34	13	27
Number of collaborations inside network	7	6	2	6	3
Number of collaborations outside network	10+	15	11	10	28

Themes for monitoring research

- Monitoring migration through caprocks and the overburden.
- Monitoring the potential impacts of near-surface leaks on both marine and terrestrial ecosystems.
- The use of industrial, experimental and natural sites as test facilities for developing monitoring technologies.

JRAs which include monitoring

JRA	Joint research activities (Months 13-30)	Coord-inator	Partners	Months
JRAP-2	Creation of a conceptual model of gas migration in a leaking CO_2 analogue	URS	BGS, OGS	18.1
JRAP-3	Development of advanced seismic modelling capabilities	BGS	OGS, SPR, TNO	3.9
JRAP-4	Ecosystem responses to CO_2 leakage - model approach	BGS	URS, OGS, BGR, NIVA, BRGM,	26.2
JRAP-5	Geochemical monitoring for onshore gas releases at the surface	URS	BGS, BGR, BRGM	14.4
JRAP-8	Monitoring of submarine CO_2 fluxes and ecological impact	BGR	NIVA, OGS, URS	12.3
JRAP-10	Testing remote sensing monitoring technologies for potential CO_2 leaks	BGS	URS, OGS, Imperial	9.7
JRAP-12	Application of Tracers for Monitoring CO_2 Storage	HWU	GEUS	14.6

Deliverables

- Development of CO_2GeoNet and European test facilities.
- Development of monitoring guidelines and best practise.
- Improved understanding of gas migration processes in the overburden.
- Methods to assess the potential impacts of a CO_2 leak on ecosystems.
- Improved seismic modelling capabilities

Creation of a conceptual model of gas migration in a leaking CO_2 analogue

- Combine shallow (ground penetrating radar) and deep (seismic) geophysics, geochemistry (gas, fluid) & mineralogy
- Use naturally leaking systems
  - Probably Ciampino
- Contribute to the development of monitoring protocols for leaking sites

Development of advanced seismic modelling capabilities

- Use Sleipner seismic dataset to evaluate advanced techniques:
  - Quantify signal attenuation and velocity dispersion
  - Understand CO_2 saturation distributions

- Comparative modelling trials of 2D algorithms incorporating elastic, porous, layered and anisotropic media to models of Sleipner plume

BGS
BGR
BRGM
GEUS
HWU
IFP
IMPER
NIVA
OGS
RF
SPR
TNO
URS

Ecosystem responses to CO_2 leakage

- Development and testing of techniques to monitor the potential impacts of a leak on terrestrial or marine ecosystems

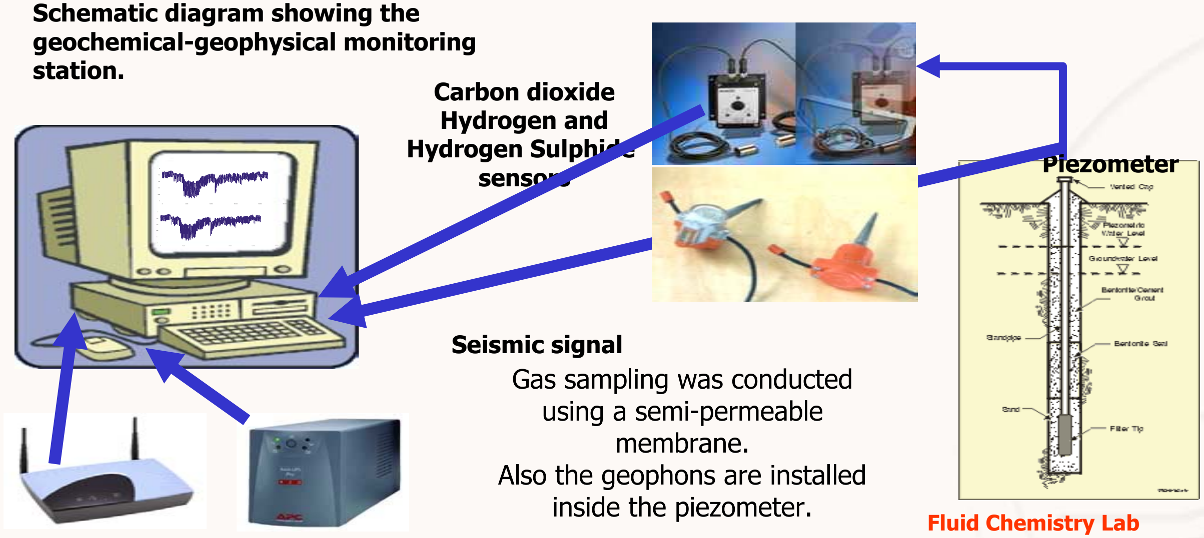
- Identify appropriate indicator species
- Develop monitoring protocols
- Add environmental data layers to storage GIS for North Sea

BGS
BGR
BRGM
GEUS
HWU
IFP
IMPER
NIVA
OGS
RF
SPR
TNO
URS

JRAP5 Geochemical monitoring for onshore gas releases at the surface

- Building on Nascent and Weyburn soil gas work
- Provide supporting data on defining detection limits in areas with large natural background fluctuations
- Test different monitoring technologies
- Refine low-cost automatic monitoring technologies

Schematic diagram showing the geochemical-geophysical monitoring station.

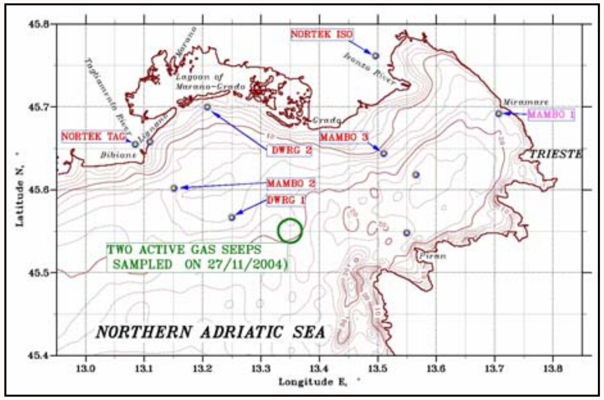


Fluid Chemistry Lab
Earth Science Department – University of Rome "La Sapienza"

CO2 GeoNet

Monitoring of submarine CO_2 fluxes and ecological impact

- Feasibility study of automatic sampling and detection of offshore gas releases.
- Initial testing in Gulf of Trieste, using OGS meteo-oceanographic buoy.
- Supported by laboratory experiments on mussels and modelling of CO_2 seabed behaviour.

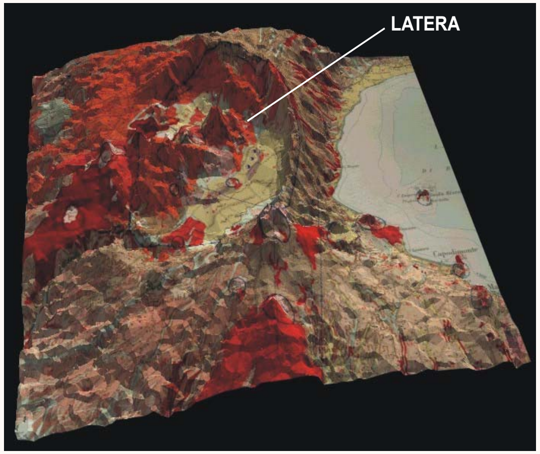


Monitoring of submarine CO_2 fluxes & ecological impact

Video clip with the divers in the Gulf of Trieste

Testing remote sensing monitoring technologies for potential CO_2 leaks

- Testing airborne and satellite-based remote sensing
- Use a naturally leaking site as test case
- Data will be calibrated against soil gas data



GeoNet

Applications of tracers for monitoring CO_2 storage

- Develop and test tracers, both inert gases and water soluble
- Perfluorocarbons, SF6 and He at ppm levels
- Two test sites: K12B EGR site (NL) and Ketzin (DE)

K12B (NL)	Ketzin (DE)
Offshore depleted gas field	Onshore saline aquifer
Deep (3000 m)	Shallow (600 m)
Low permeability	High permeability
Work plans	
First tracer injection at K12B on March 1st (1 kg in 10 min).	Determination of optimum concentration of water tracers
Limited sampling until breakthrough	Modelling fate / transport of tracers
Modelling in Petrel and Eclipse	Analysis of samples from observation wells
	reservoir simulation of CO2 / tracer

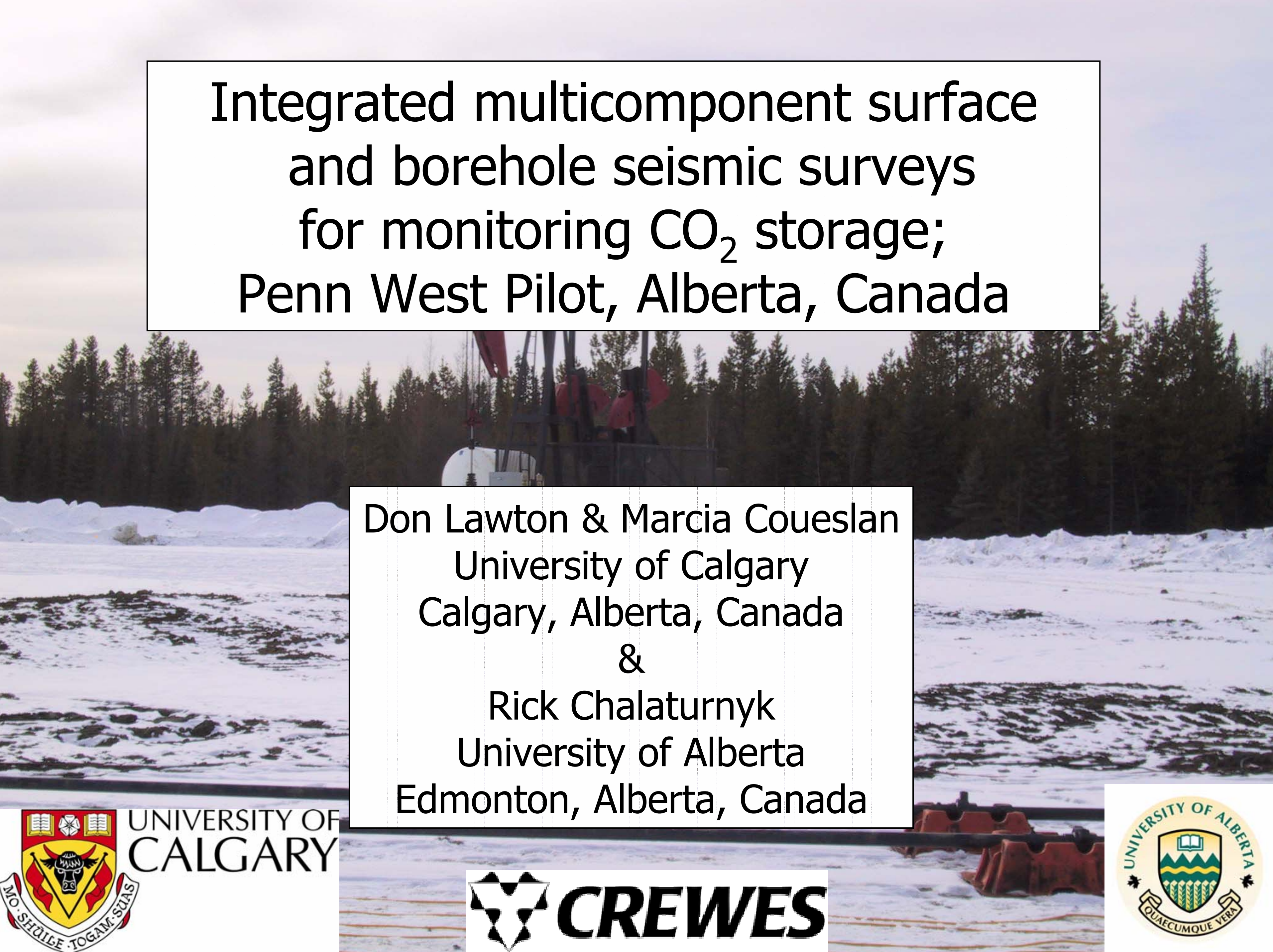
Summary

- Bring together institutes and researchers across Europe

- Develop and test new monitoring techniques
  - Onshore and offshore
  - Deep and shallow monitoring

- Long-term aim to develop test facilities
  - Laboratory, field-scale, industrial and natural sites

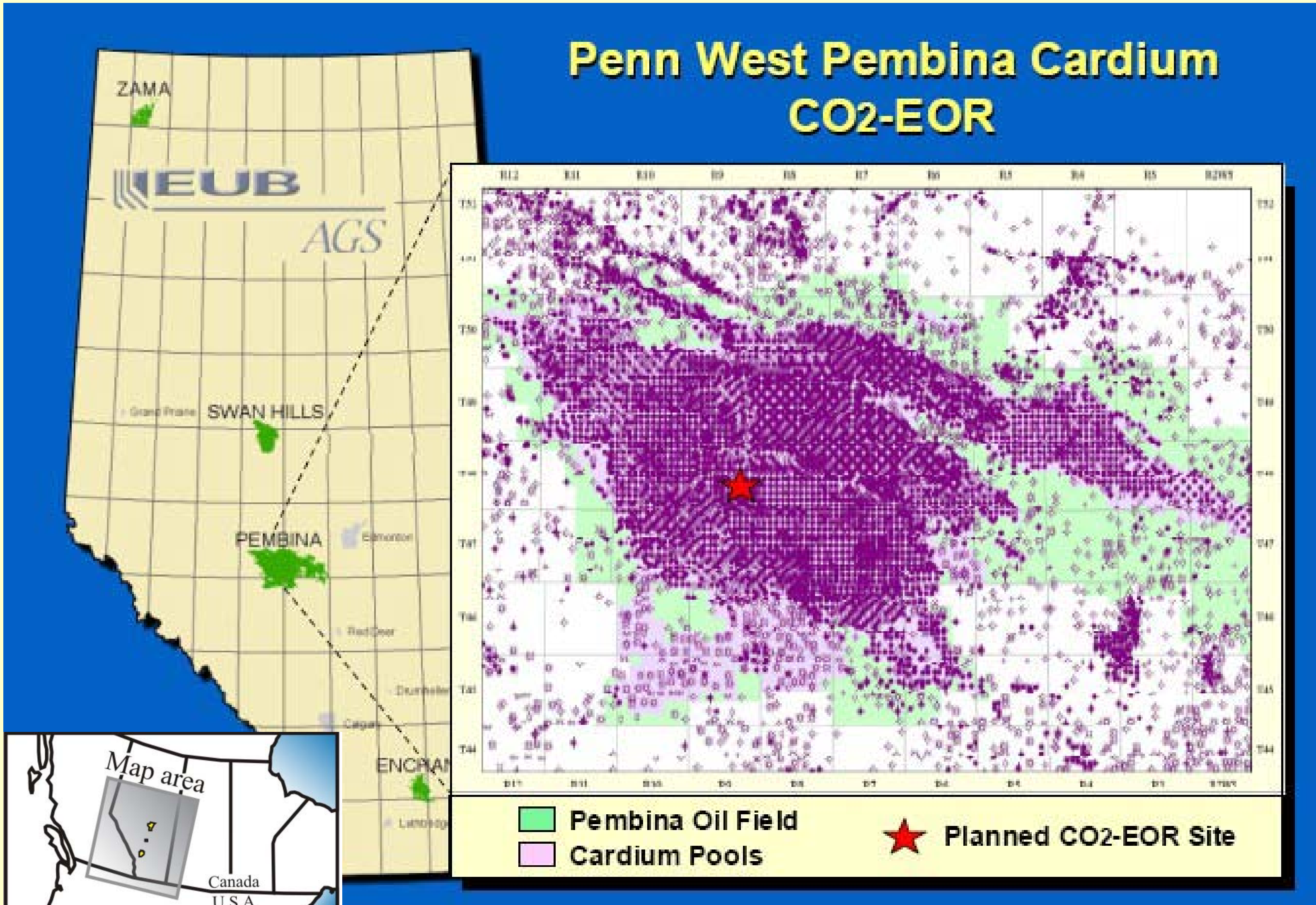
www.co2geonet.com



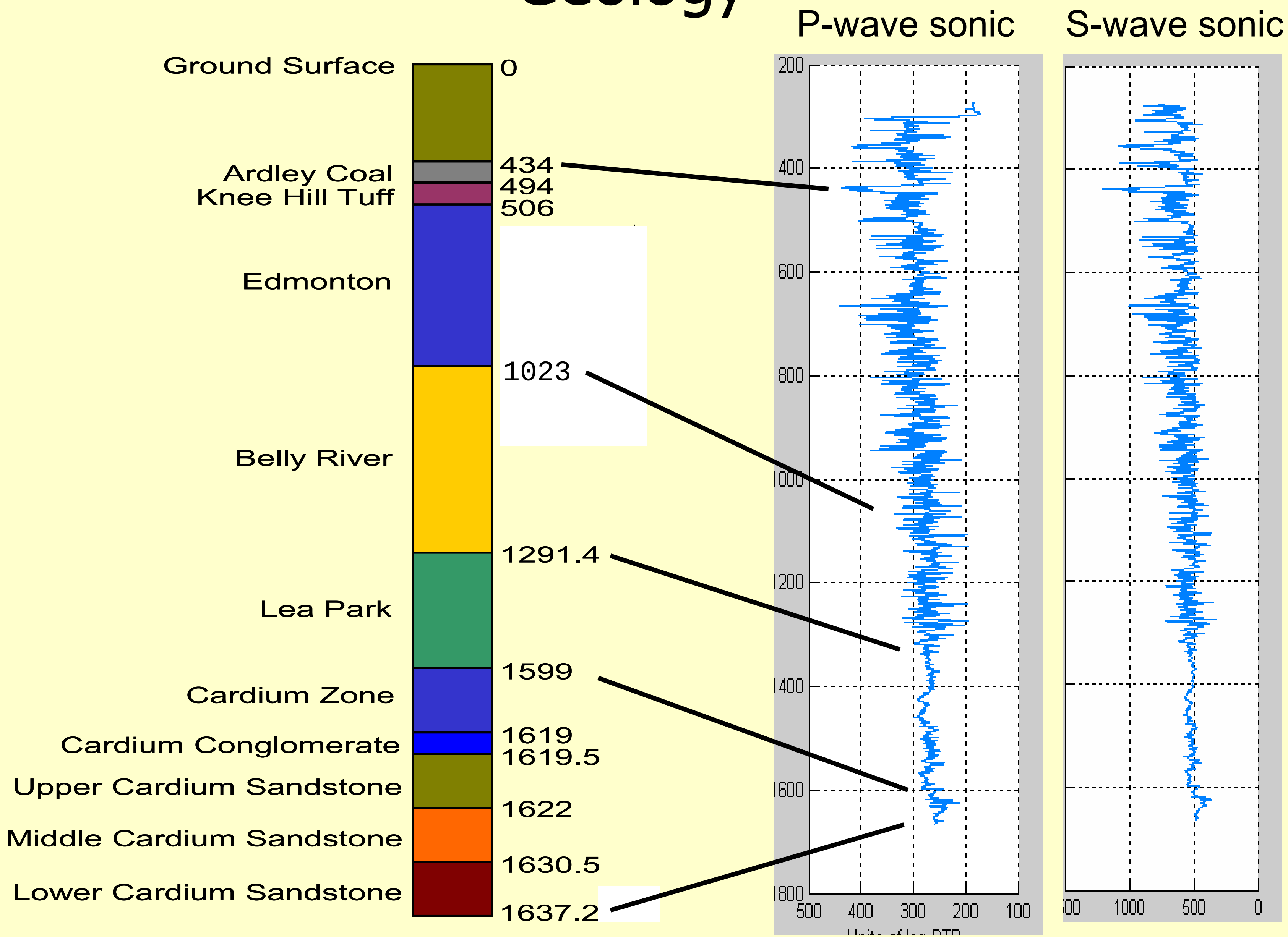
Integrated multicomponent surface and borehole seismic surveys for monitoring CO_2 storage; Penn West Pilot, Alberta, Canada

Don Lawton & Marcia Coueslan
University of Calgary
Calgary, Alberta, Canada
&
Rick Chalaturnyk
University of Alberta
Edmonton, Alberta, Canada

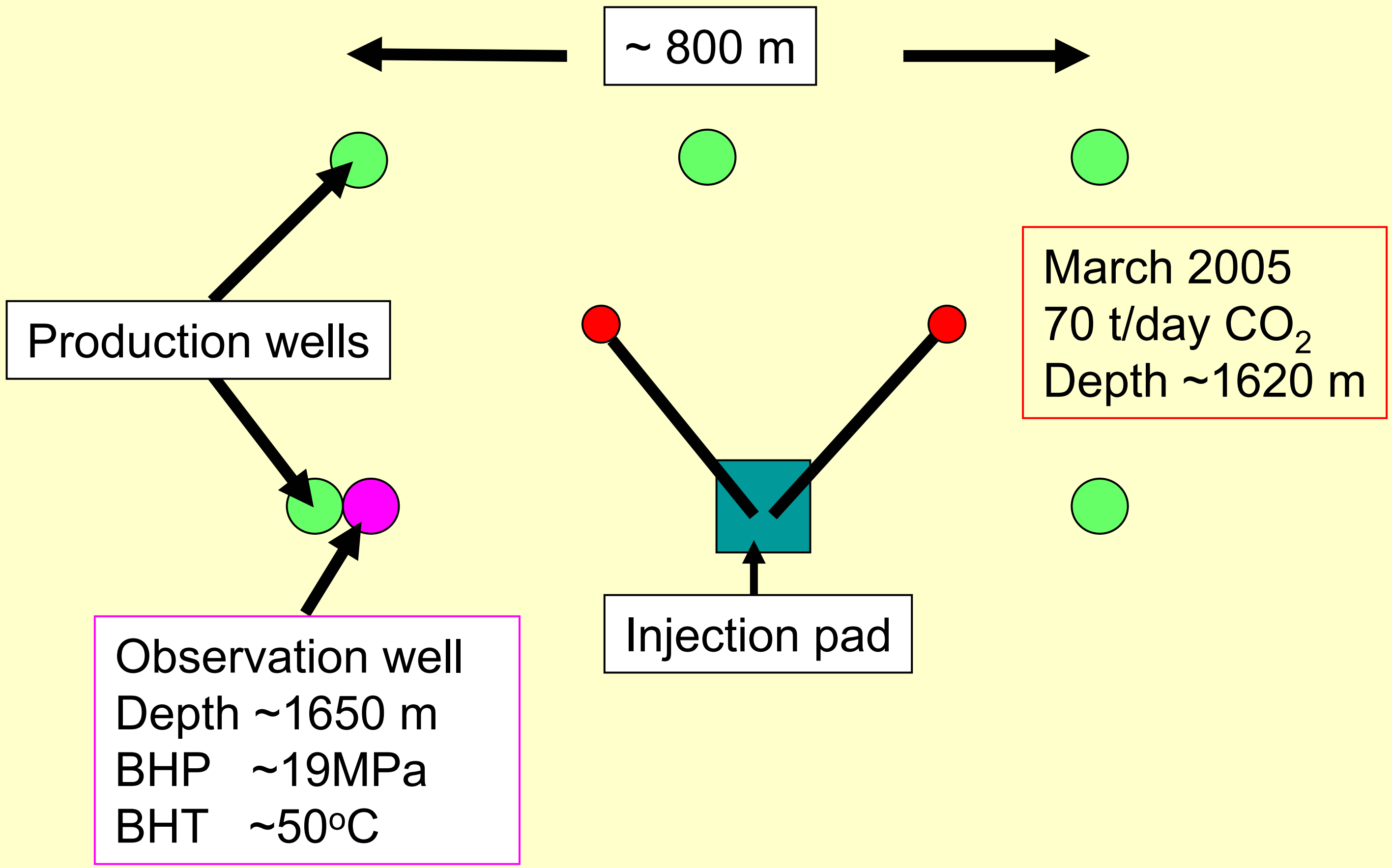
Penn West Petroleum CO_2-EOR Pilot



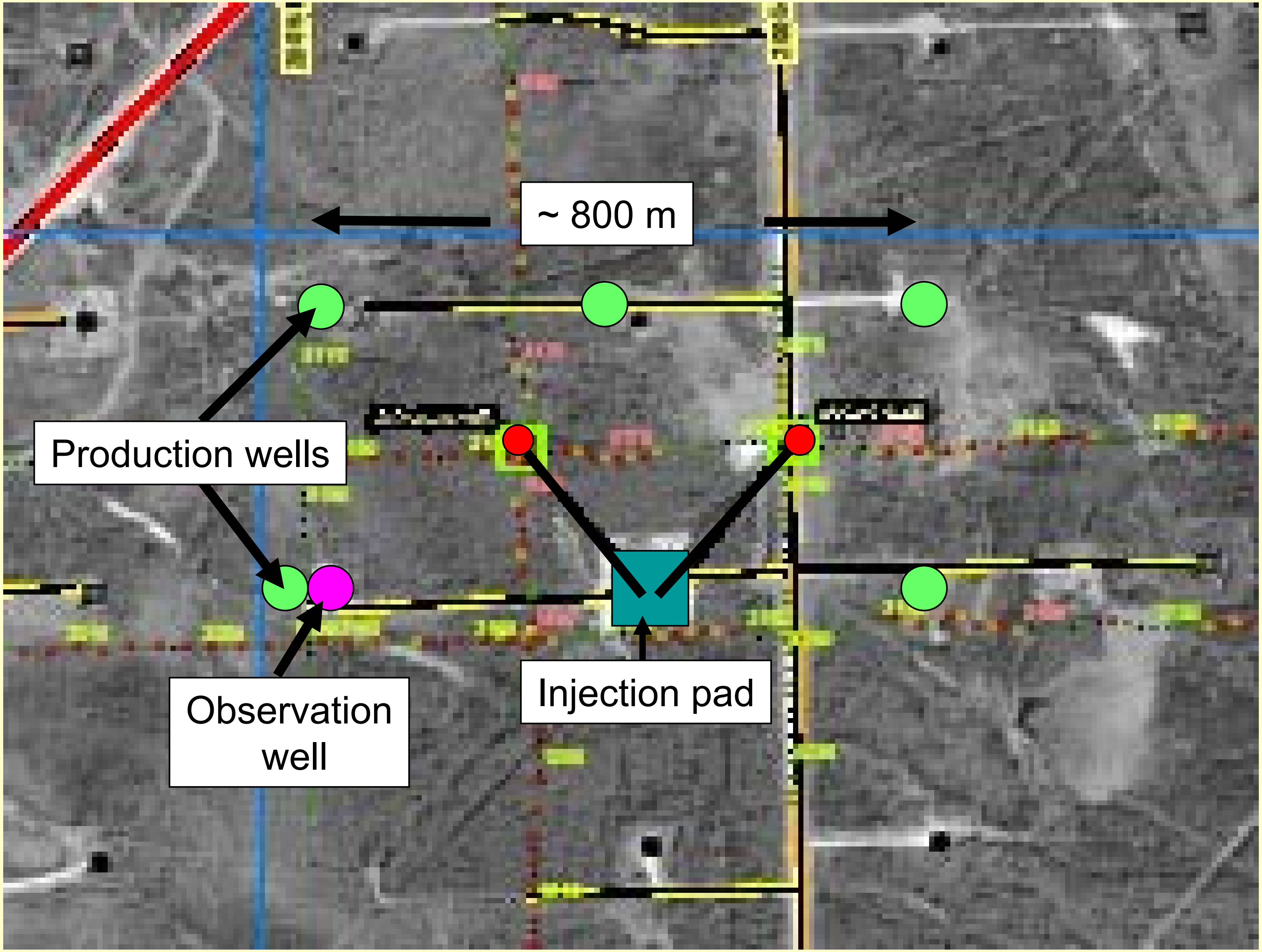
Geology


P-wave sonic
S-wave sonic
Ground Surface
Ardley Coal
Knee Hill Tuff
Edmonton
Belly River
Lea Park
Cardium Zone
Cardium Conglomerate
Upper Cardium Sandstone
Middle Cardium Sandstone
Lower Cardium Sandstone
0
434
494
506
1023
1291.4
1599
1619
1619.5
1622
1630.5
1637.2
200
400
600
800
1000
1200
1400
1600
1800
500
400
300
200
100
1000
500
0

Penn West CO_2- EOR injection pilot



Penn West CO_2- EOR injection pilot



Penn West CO_2 M&V Program

Baseline Studies

- EUB Data Retrieval (LS)
- EUB Data Retrieval (RS)
- Well Analysis (LS)
- Well Analysis (RS)
- Baseline Geology (Local Scale=LS)
- Baseline Geology (Regional Scale=RS)
- Baseline Hydrogeology (Local Scale)
- Baseline Hydrogeology (Regional Scale)
- Baseline 2D Surface Seismic & VSP
- Instrumentation of the Deep Monitor Well
- Drilling of the 3 to 5 Shallow Monitor Wells
- Monitoring of Existing Local Water Wells
- Soil Gas and Casing Gas
- Chemistry Water Prod. Primary Recovery
- Core and Reservoir & Fluids Analyses
- Well Tests
- Rock Physics
- Well Log Suites
- Wellbore Integrity
- Baseline Modelling

Continuous Monitoring

- Monitoring data Penn West
- Geochemistry at Production Wells
- Pressure & Temperature Deep Monitor Well
- Passive Seismic

Discrete Monitoring

- Time-lapse VSP and surface seismic survey
- Casing Gas & Soil and Gas Sampling
- Fluids from Shallow Monitor Wells
- Fluids from Deep Monitor Well
- Well Testing and Tracers

Continuous Integration

- Reservoir Modeling
- Geochemical Modelling
- Integration Continuous-Discrete Monitoring
- Post-Pilot Program
- Final Reporting
- Contingency Plans
- Project Management

4D seismic applications in CO_2 storage

GOAL

Reservoir characterization

geometry
impedance ($I = \rho V$)
petrophysical properties
(λ, μ, ρ)

↓

high effort 3D surveys
(expensive)

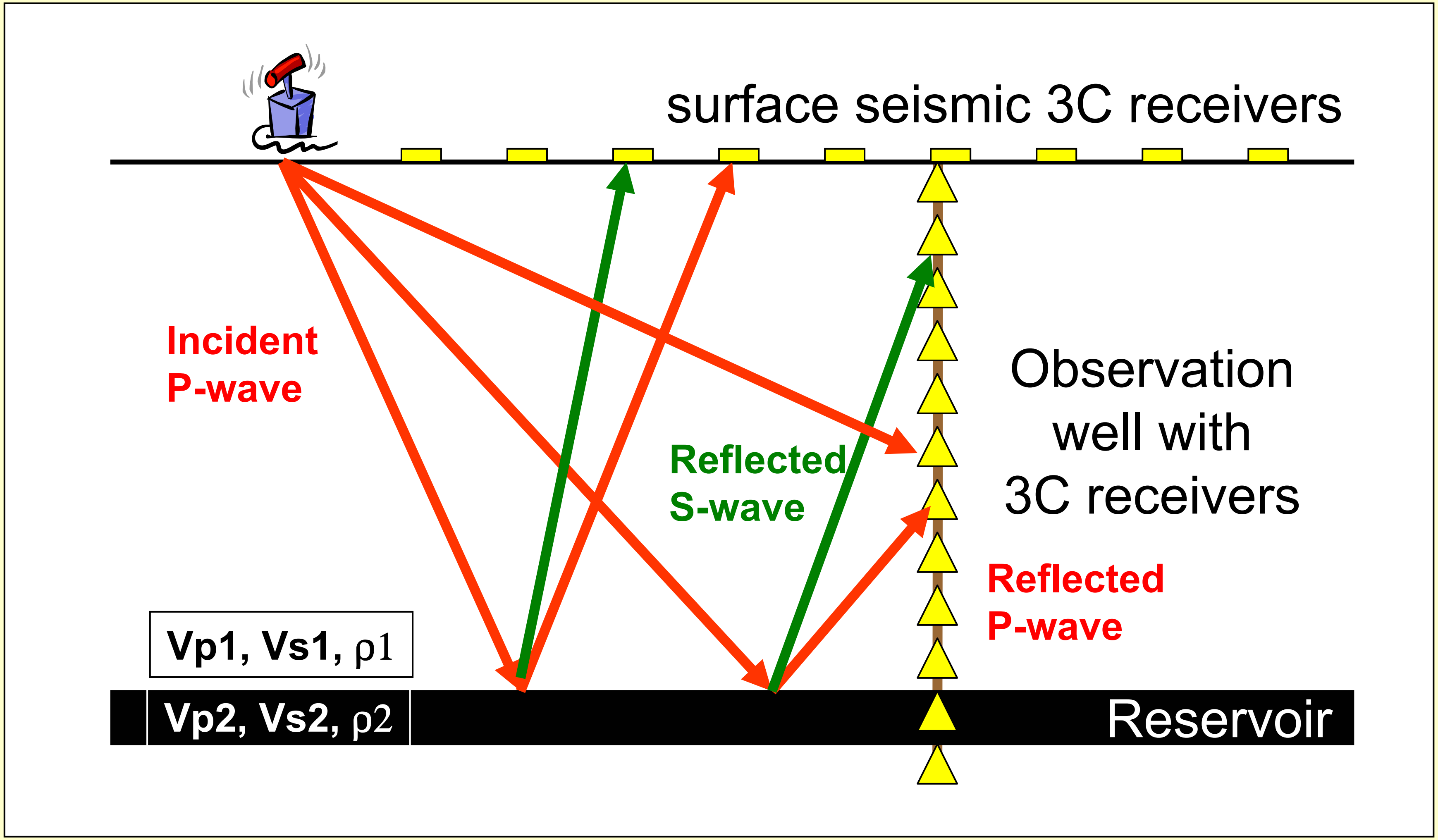
Reservoir monitoring

fluid substitution
pressure changes
$\Delta I = (\Delta V \Delta \rho)$
$\Delta\lambda$, $\Delta\mu$, $\Delta\rho$

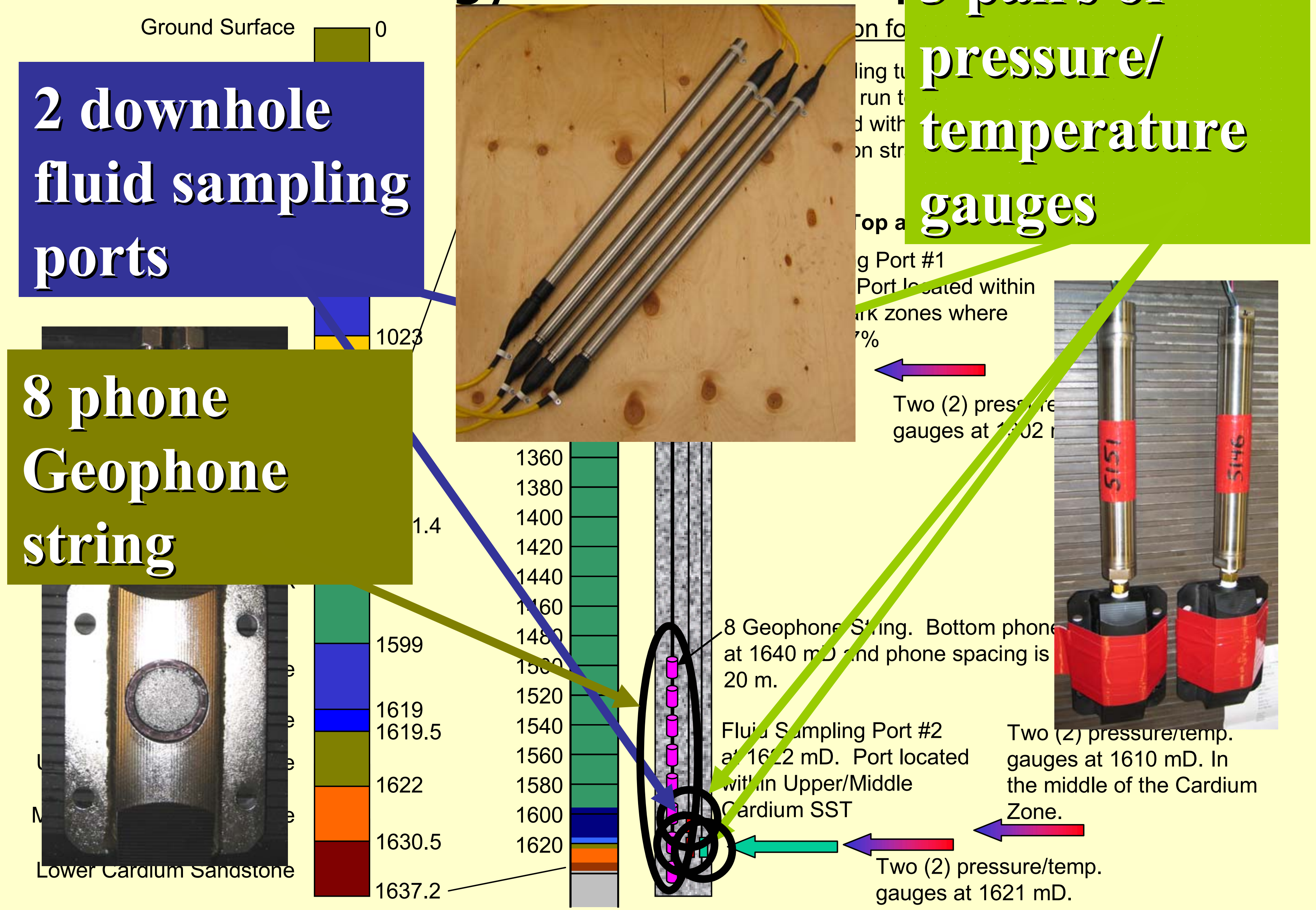
↓

2D, 2.5D or
low effort 3D surveys
(cheaper)

Multicomponent surface seismic & VSP



Geology and well comp

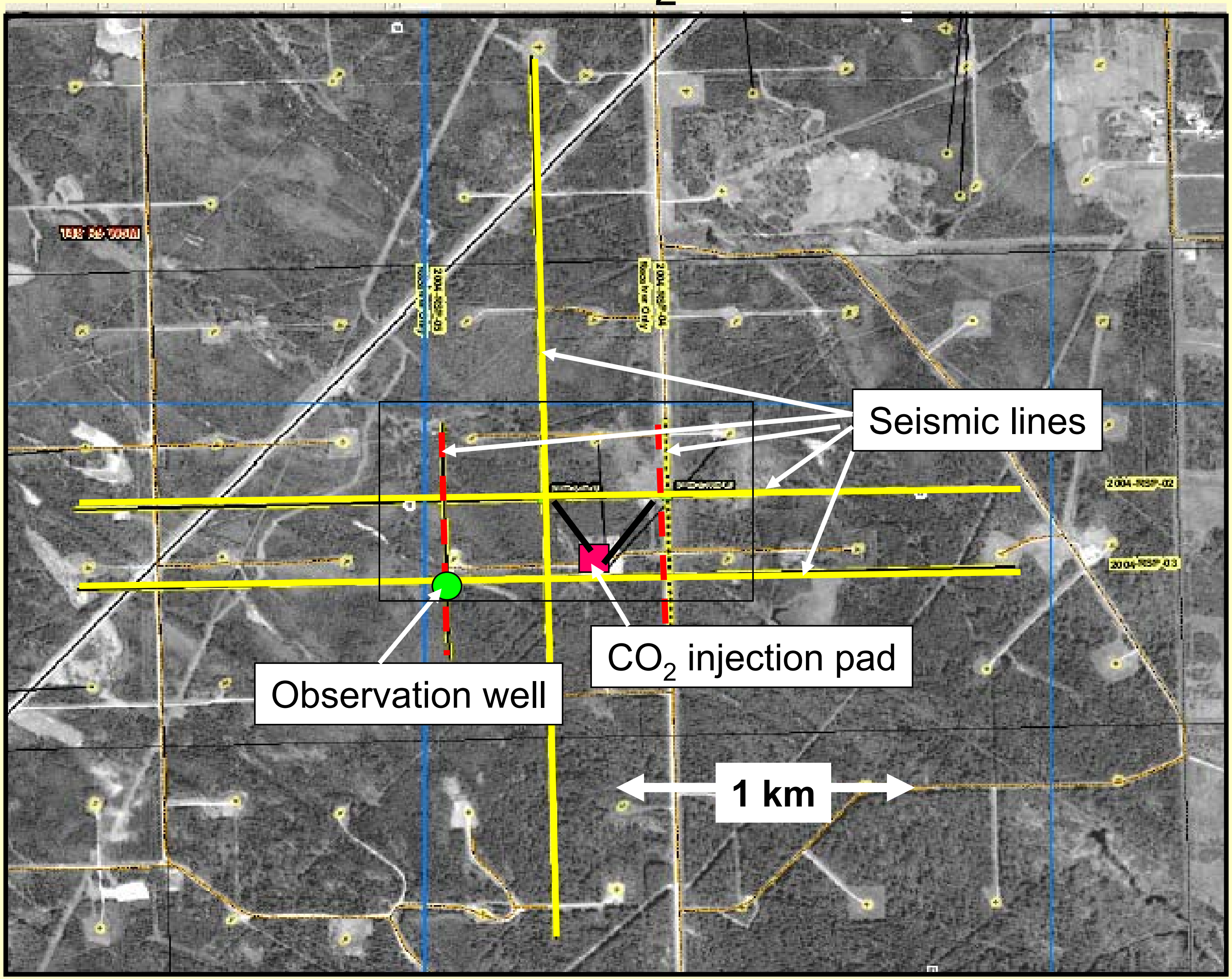



BRANDETTE
RIG #19
B.W.RIG

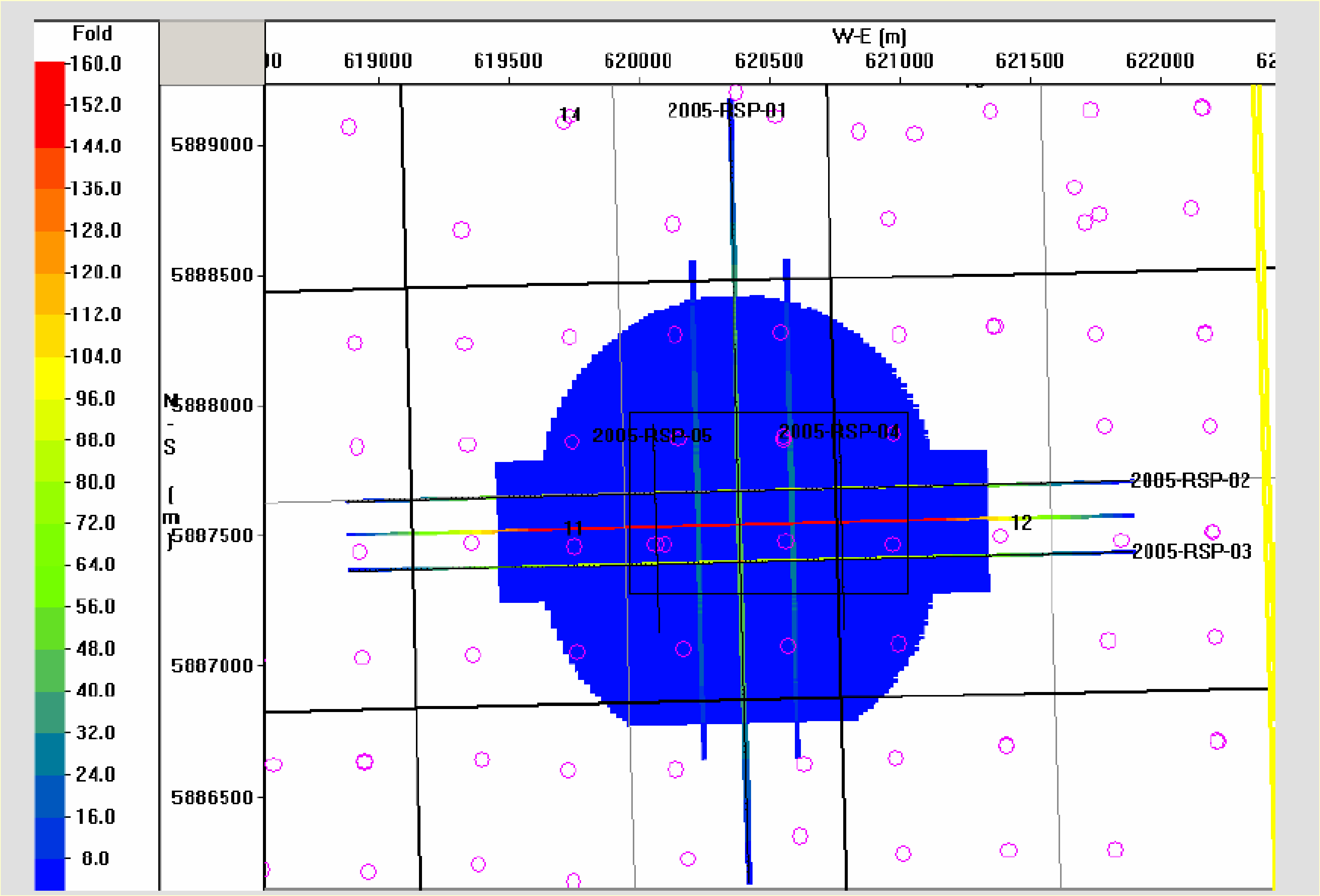

BRANDETTE
RIG #19


BRANDETTE

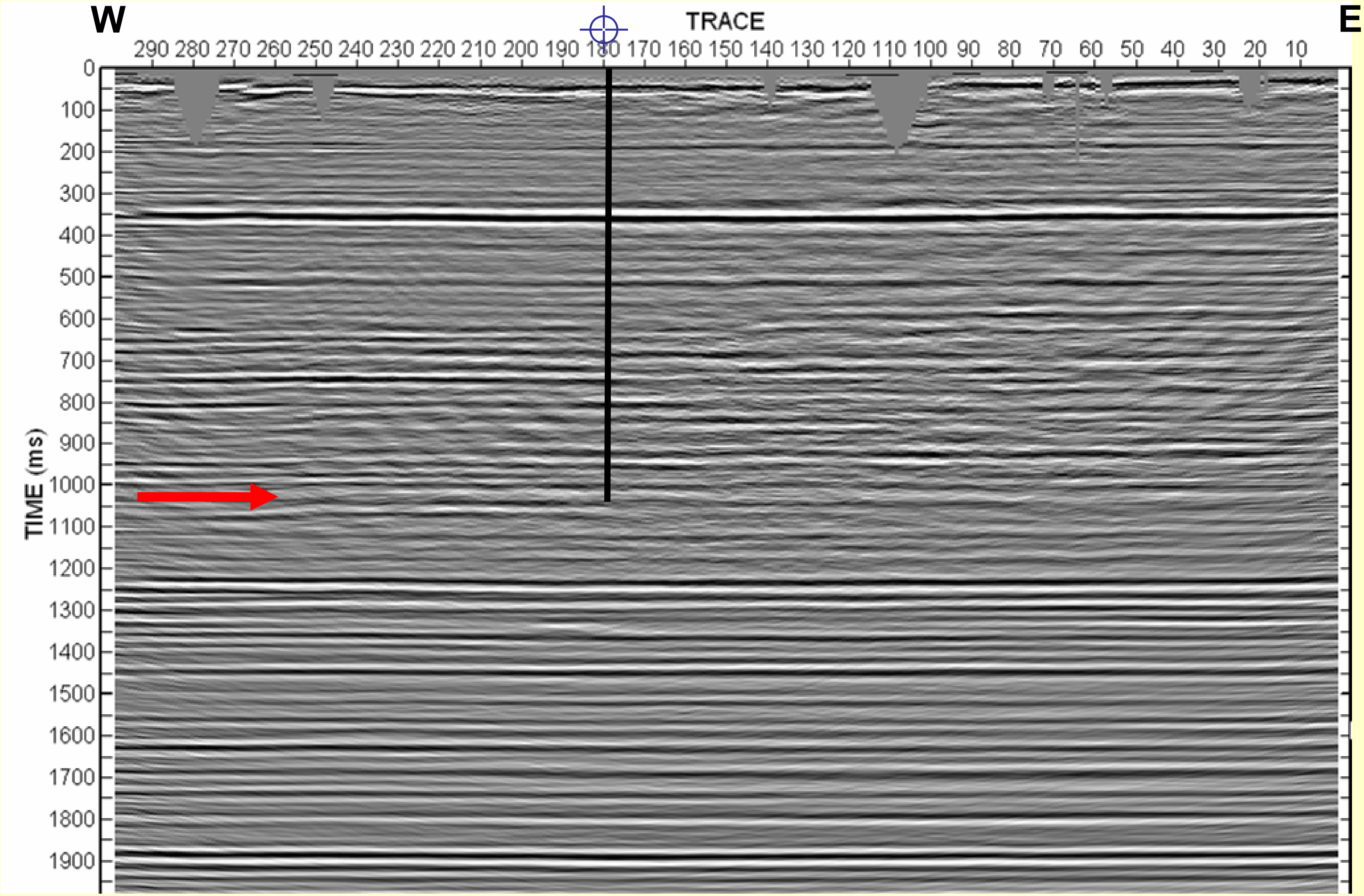
Penn West CO_2 EOR Pilot



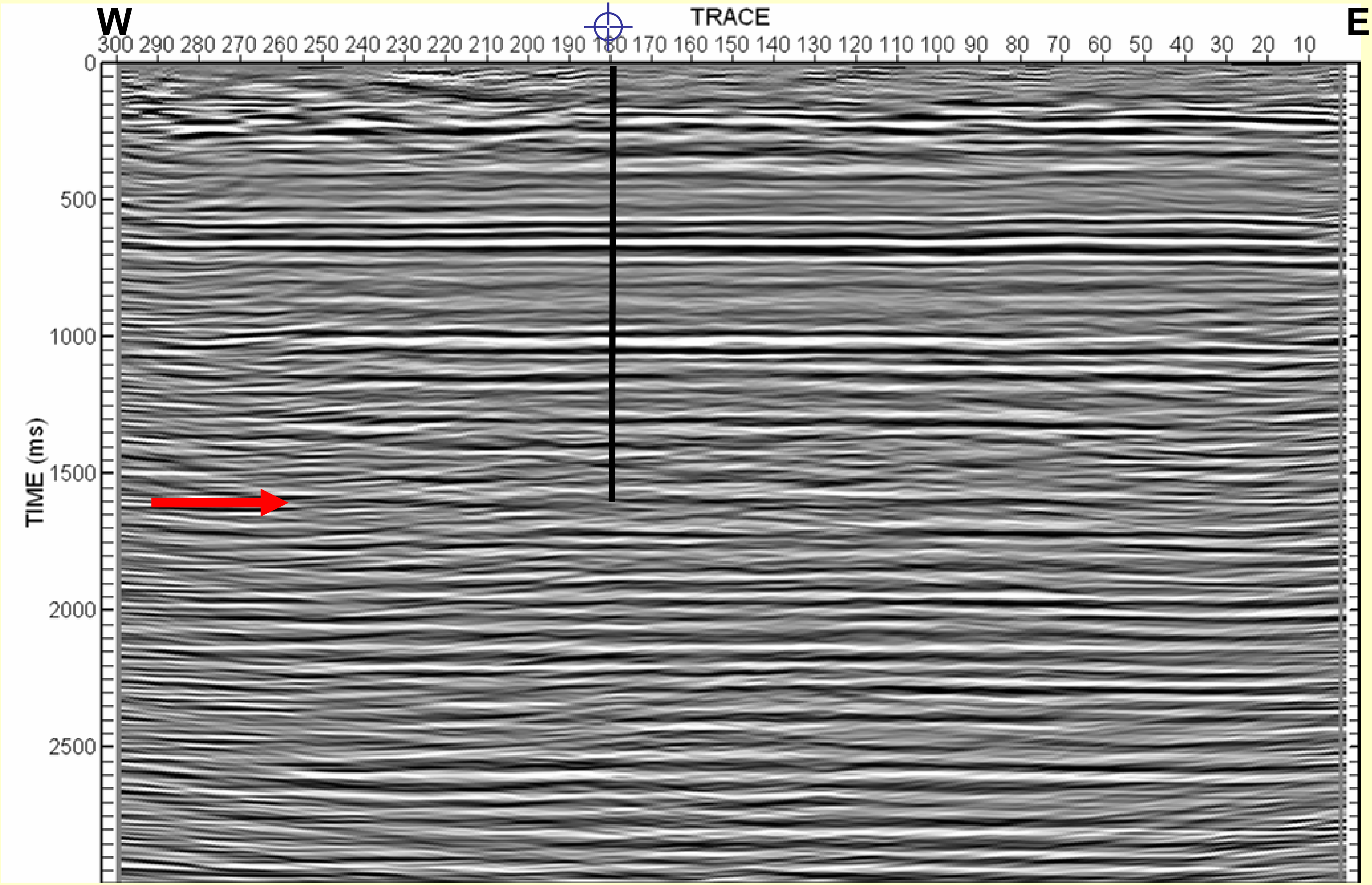
Penn West CO_2 EOR Pilot: P-P fold



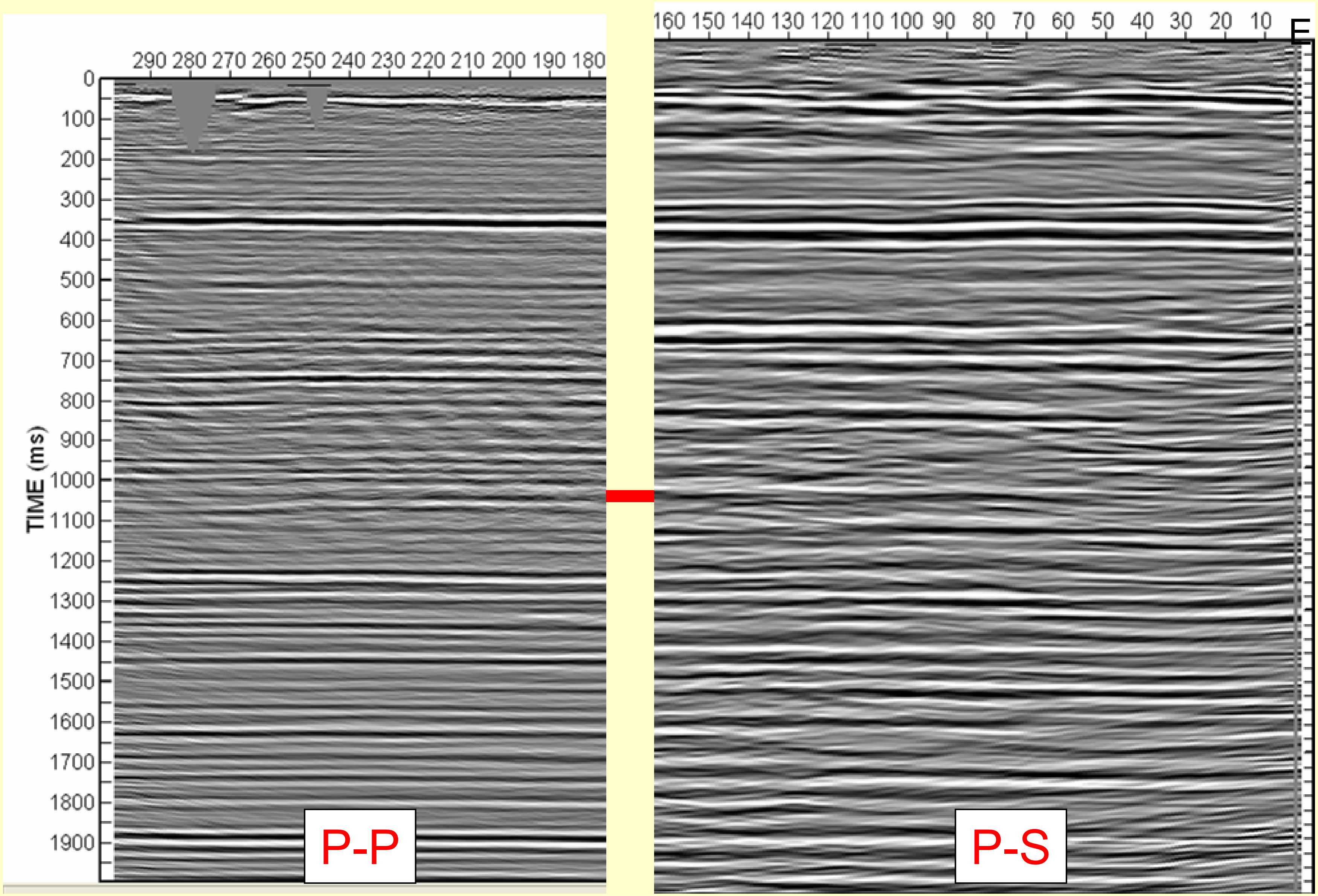
Line 3 migrated P-P section



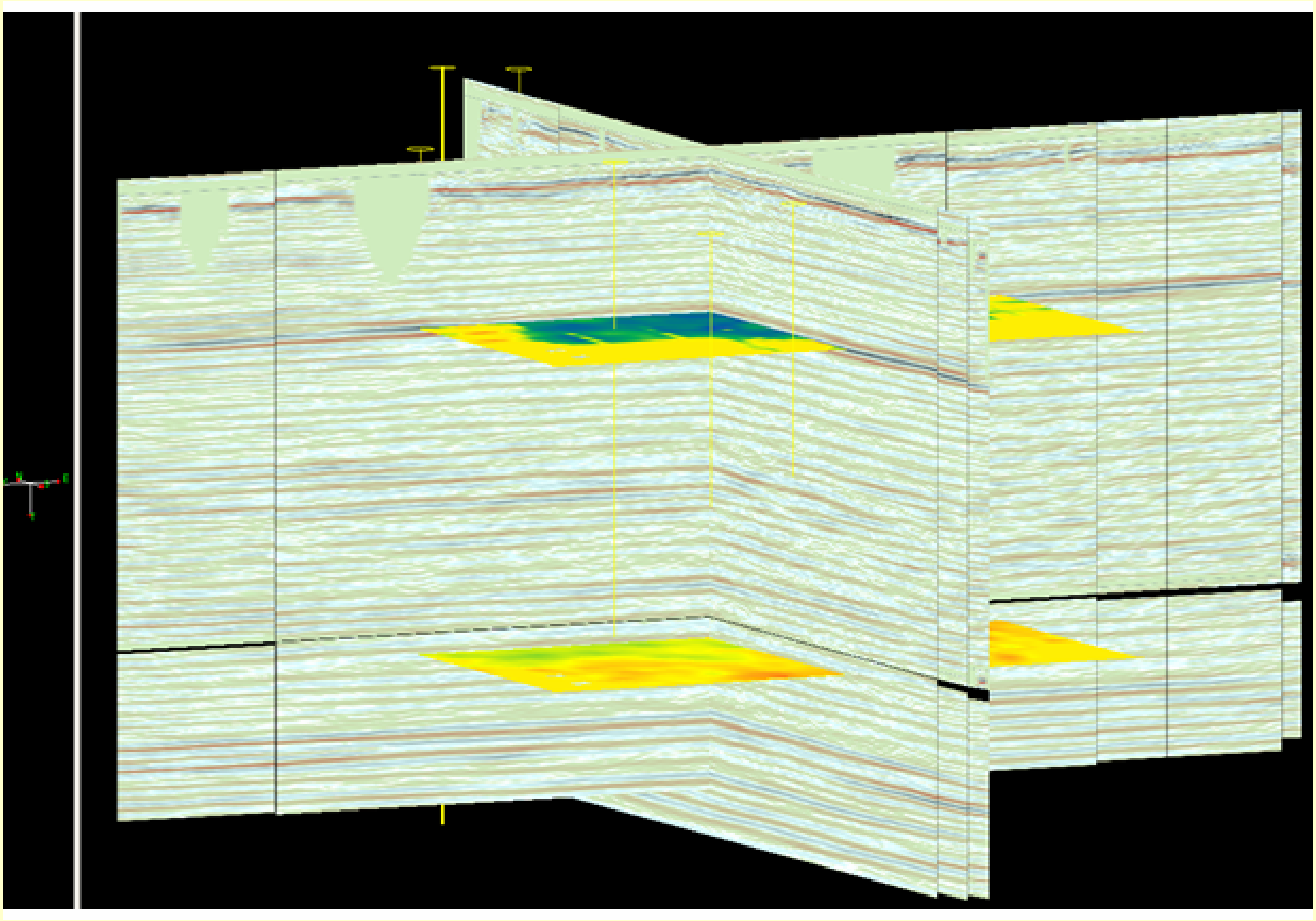
Line 3 migrated P-S section



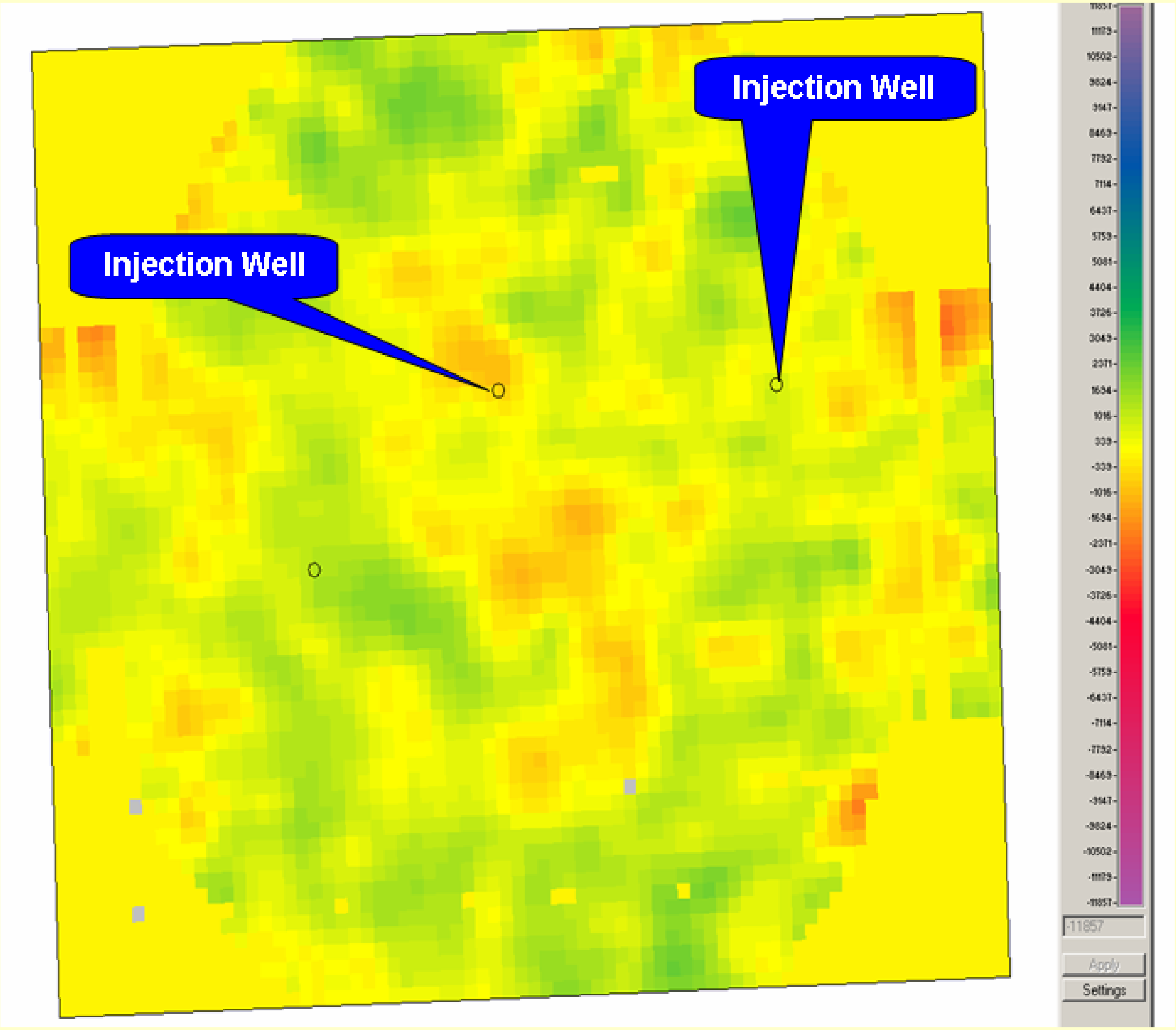
Line 3 P-P & P-S correlation



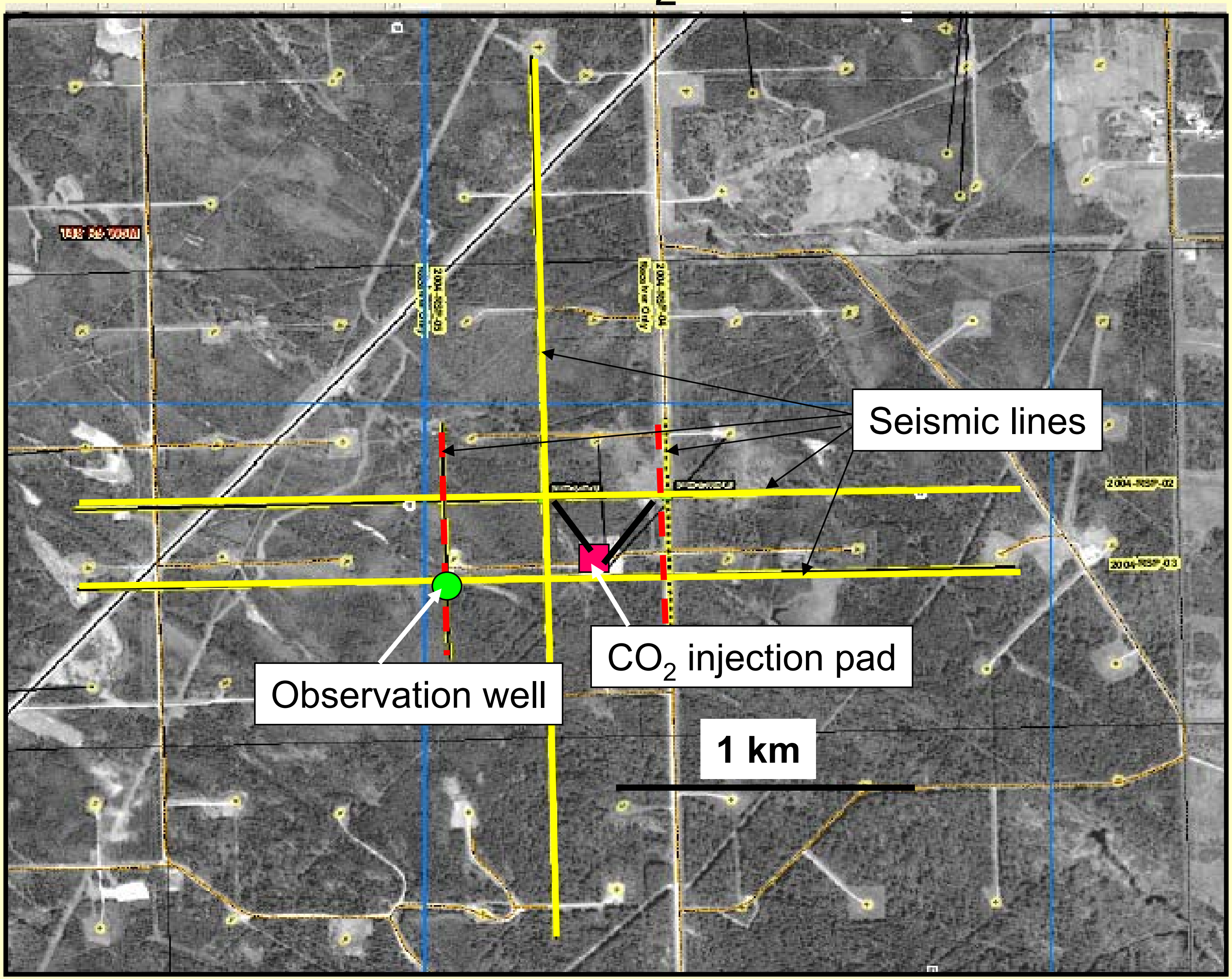
3D volume display [P-P]



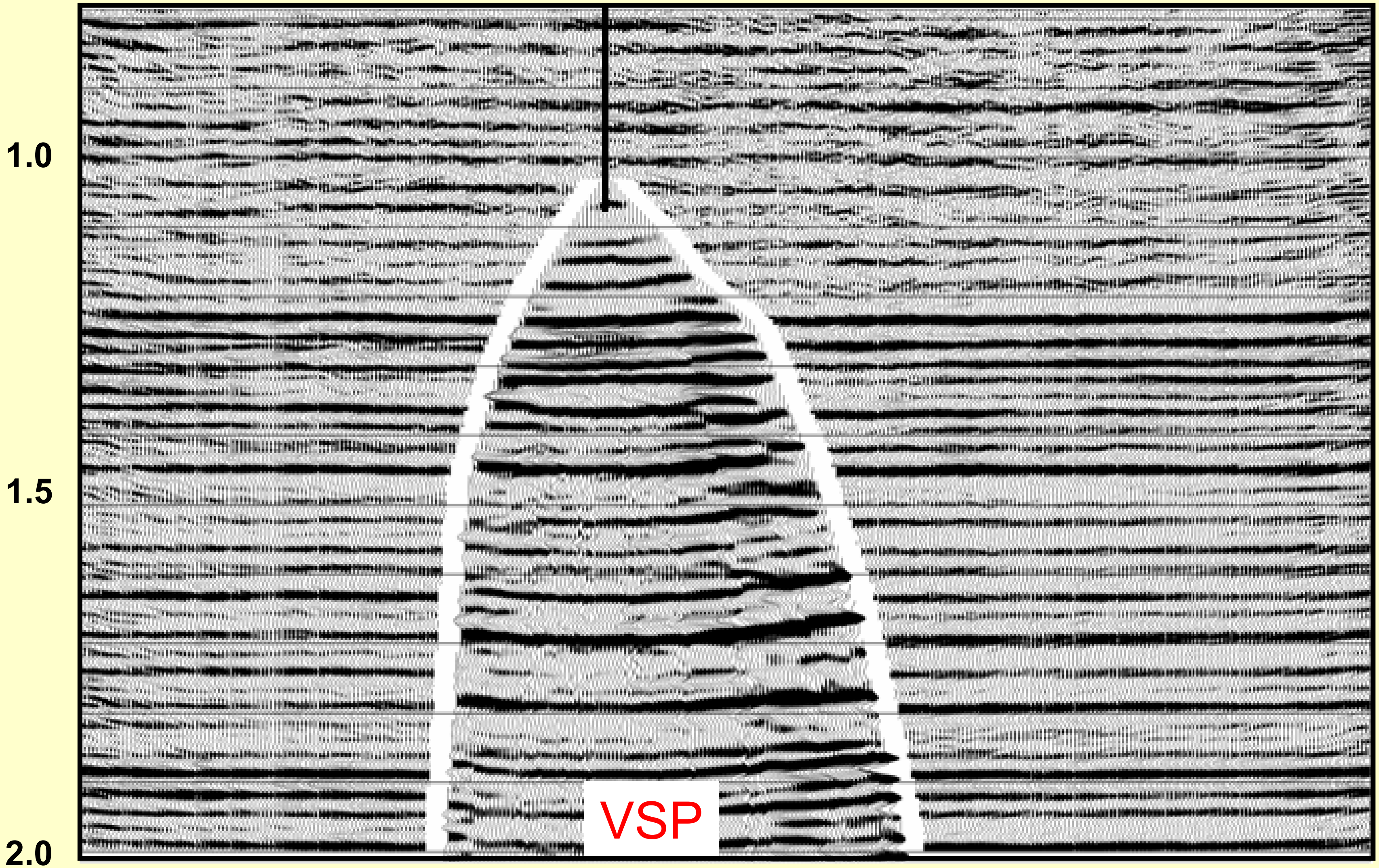
Time slice at reservoir level



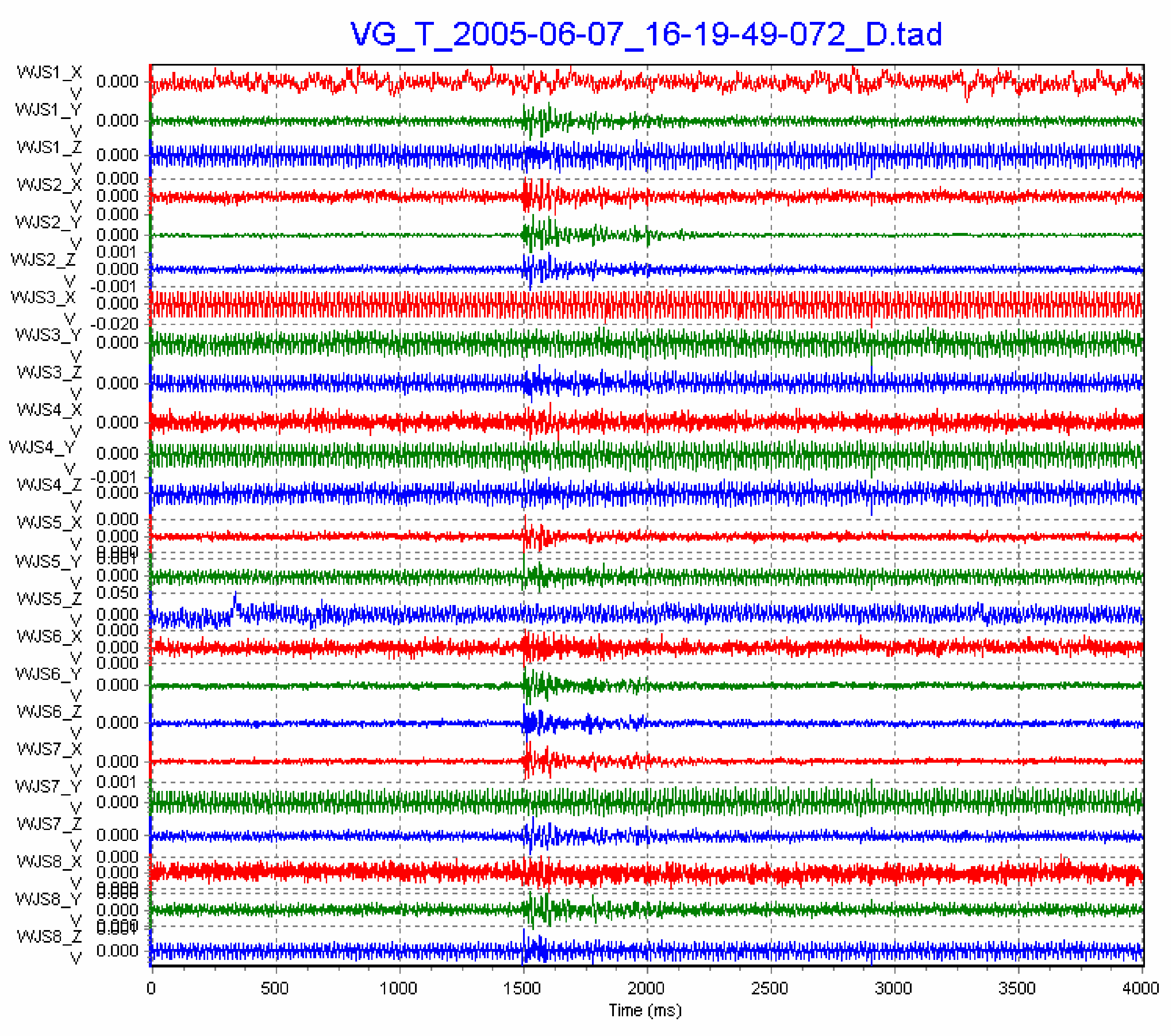
Penn West CO_2 EOR Pilot



Line 3 surface seismic + VSP



Passive seismic record



Discussion

Baseline survey

- sparse 3D survey
- cheaper than full 3D
- multicomponent
- weak reservoir delineation
- targeted at 4D

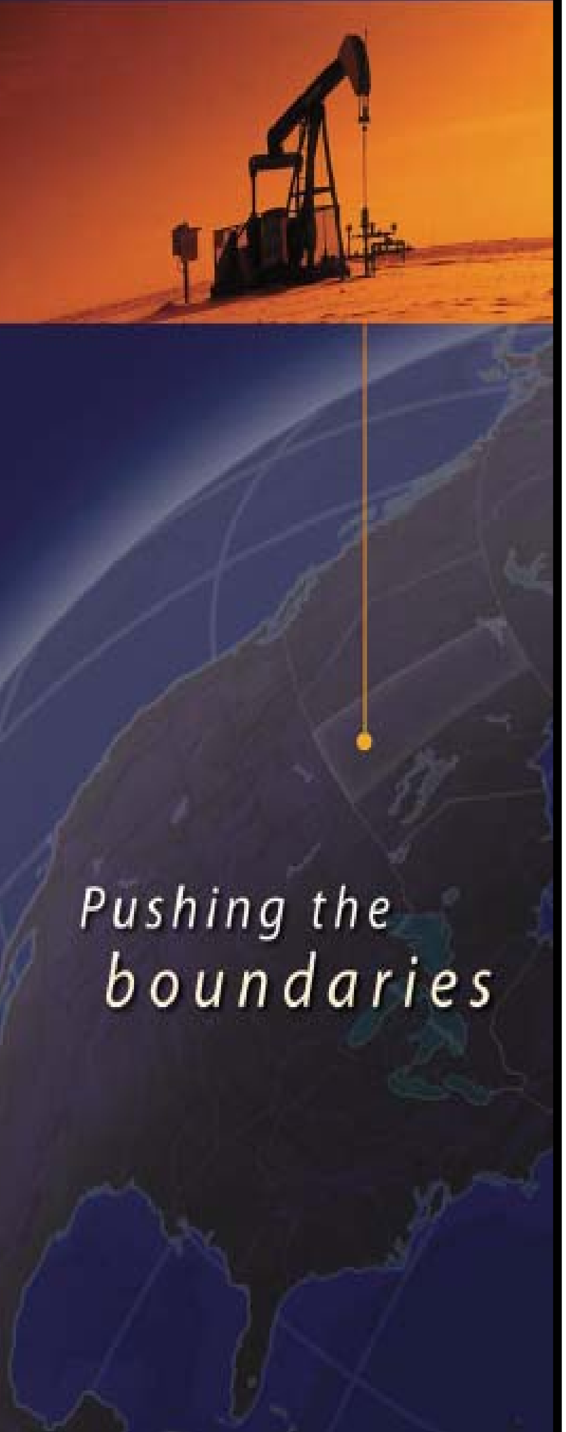
Observation well

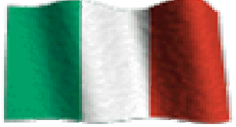
- capital cost up front
- ‘free’ timelapse VSP’s
- enables passive monitoring
- sampling for leakage
- in-situ PT measurements

Acknowledgements

- Alberta Energy Research Institute [AERI]
- Natural Resources Canada [NRCan]
- Penn West Petroleum Ltd
- Schlumberger Canada
- Bill Gunter (ARC); Stefan Bachu (AGS)

“Fieldwork”





Rome, Italy

2nd Meeting of the Monitoring Network

ptrc

Petroleum Technology Research Centre

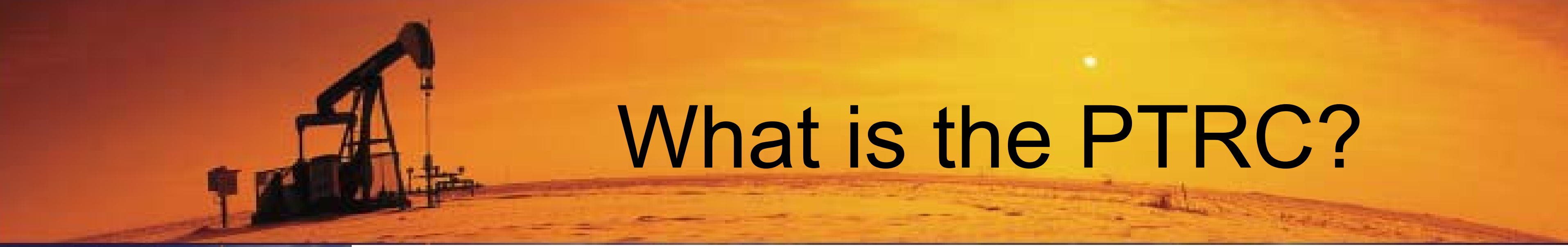
Based in Regina, Saskatchewan, Canada

Presenter: Malcolm Wilson

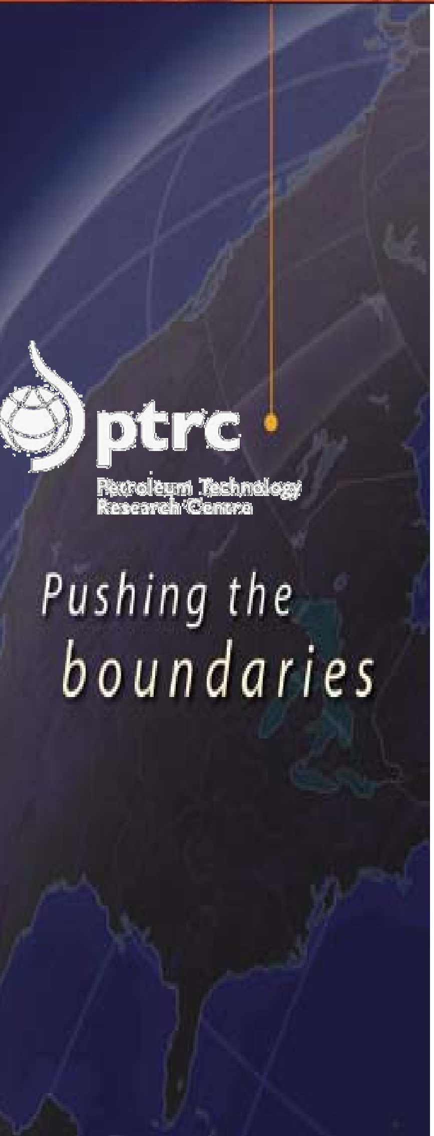
CO_2 Management Program Director

October 5, 2005

"Results and New Directions of the IEA GHG Weyburn CO_2 Monitoring and Storage Project"



What is the PTRC?



- ➢**Established in 1998**
- ➢**Non-profit**
- ➢**Government and industry funded**
- ➢**World leader in geological storage and enhanced oil recovery**
- ➢**Reduce greenhouse gases while assisting producers in recovery and production**
- ➢**Brings people together**
  - ➢**Industry, government and researchers**

IEA GHG Weyburn CO_2 Monitoring and Storage Project

Leading the World in Carbon Storage Technology

Quick Facts:

- *IEA Weyburn CO_2 Monitoring and Storage Project* started injection Sept. 15, 2000
- The largest, full-scale, in-the-field scientific study in the world involving CO_2 storage
- Divided into 2 phases – each lasting 4 years
- Status:
- **Phase I** ($40 million)
  - Recently completed with HUGE success

IEA GHG Weyburn CO_2 Monitoring and Storage Project

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Pushing the boundaries

Who's Involved?

Natural Resources Canada

ENCANA

European Commission

NETL

Saskatchewan Industry and Resources

AERI

- **8 Industry Sponsors**
  - BP, Chevron, Dakota Gasification Co., Engineering Advancement Association of Japan, Nexen Canada, SaskPower, Total and TransAlta Utilities Corp.
- **Numerous Research Organizations**
  - Canada, U.S. and international

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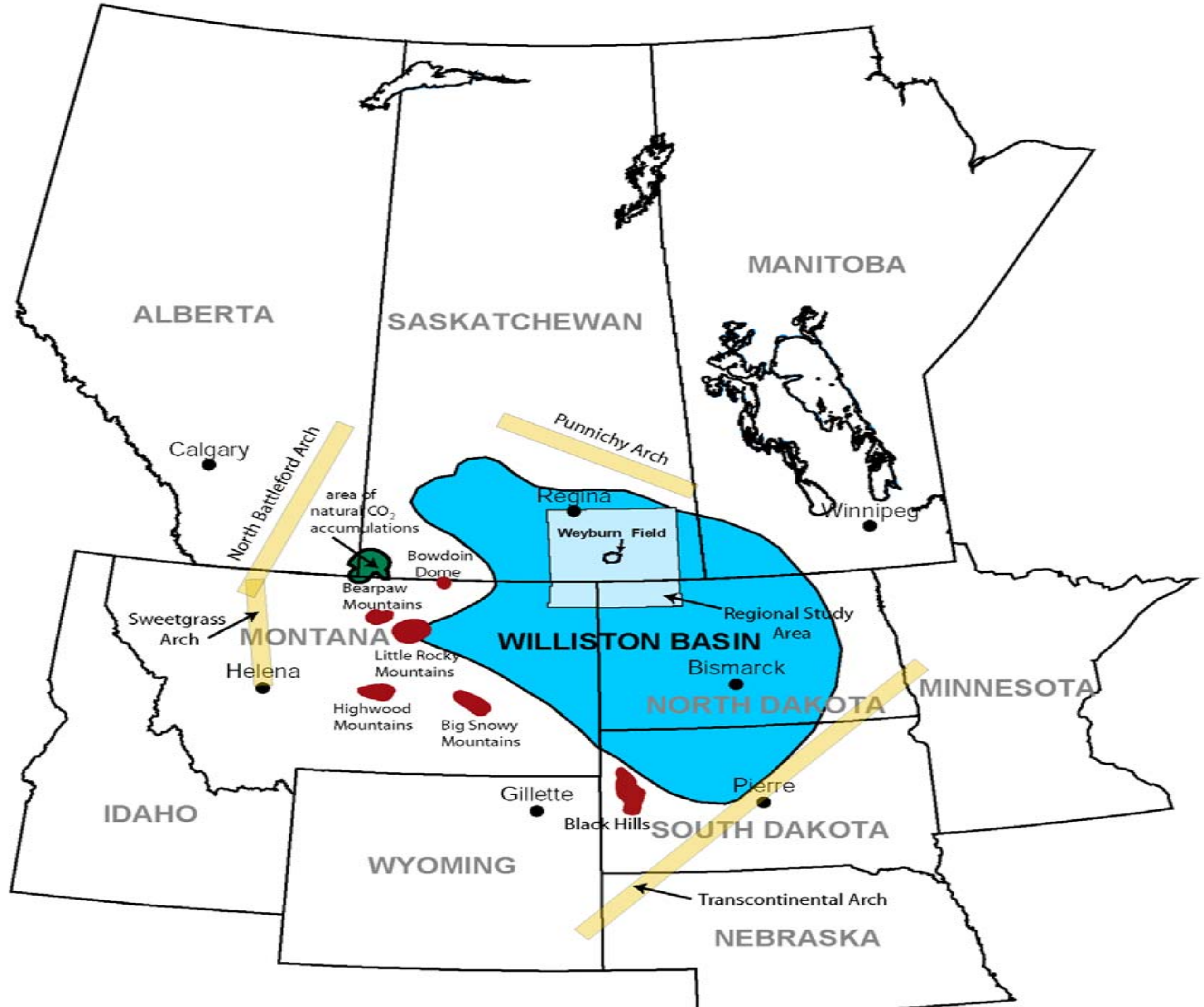
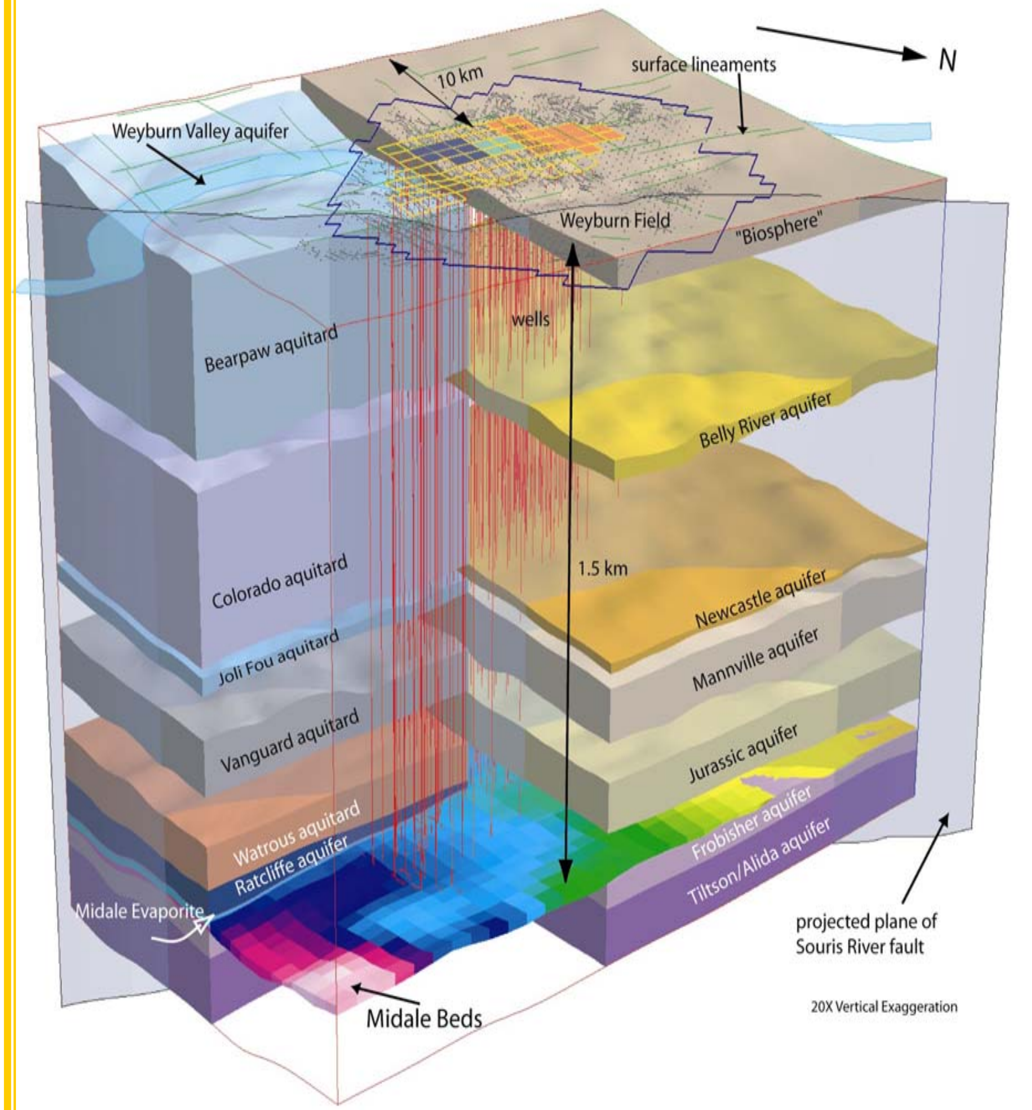


Weyburn Geological 3D Model

- Areal extent 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system
  - Lithology
  - Hydrogeological characteristics
  - Faults
- Can be tailored for different RA methods and scenario analyses



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Phase I Results

- **CO_2 reduction**
  - 5000 tons/day of CO_2 stored in ground
  - More than 5 million tons already injected
  - Project's storage potential
    - 30 million tons of CO_2
- **Oil increase**
  - Additional 13,000 bbl/day
  - Project's oil production potential
    - 130 million additional barrels

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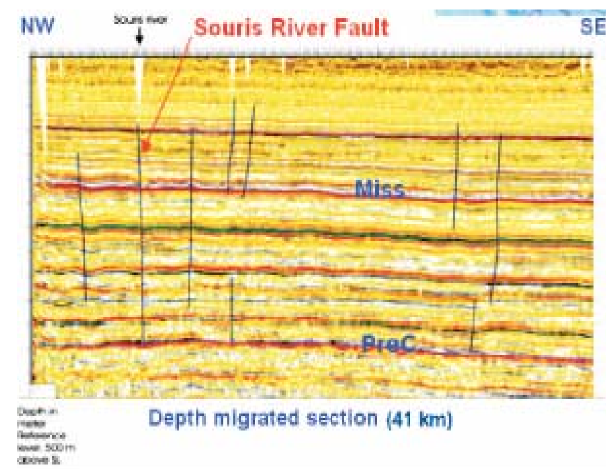
Monitoring Techniques

- **4D, 3C surface seismic**
- **4D, 9C surface seismic**
- **3D, 3C vertical seismic profile (VSP)**
- **Cross-well seismic**
- **Geochemical sampling analysis**
- **Tracer injection monitoring**
- **Conventional production data analysis**
- **Passive seismic**



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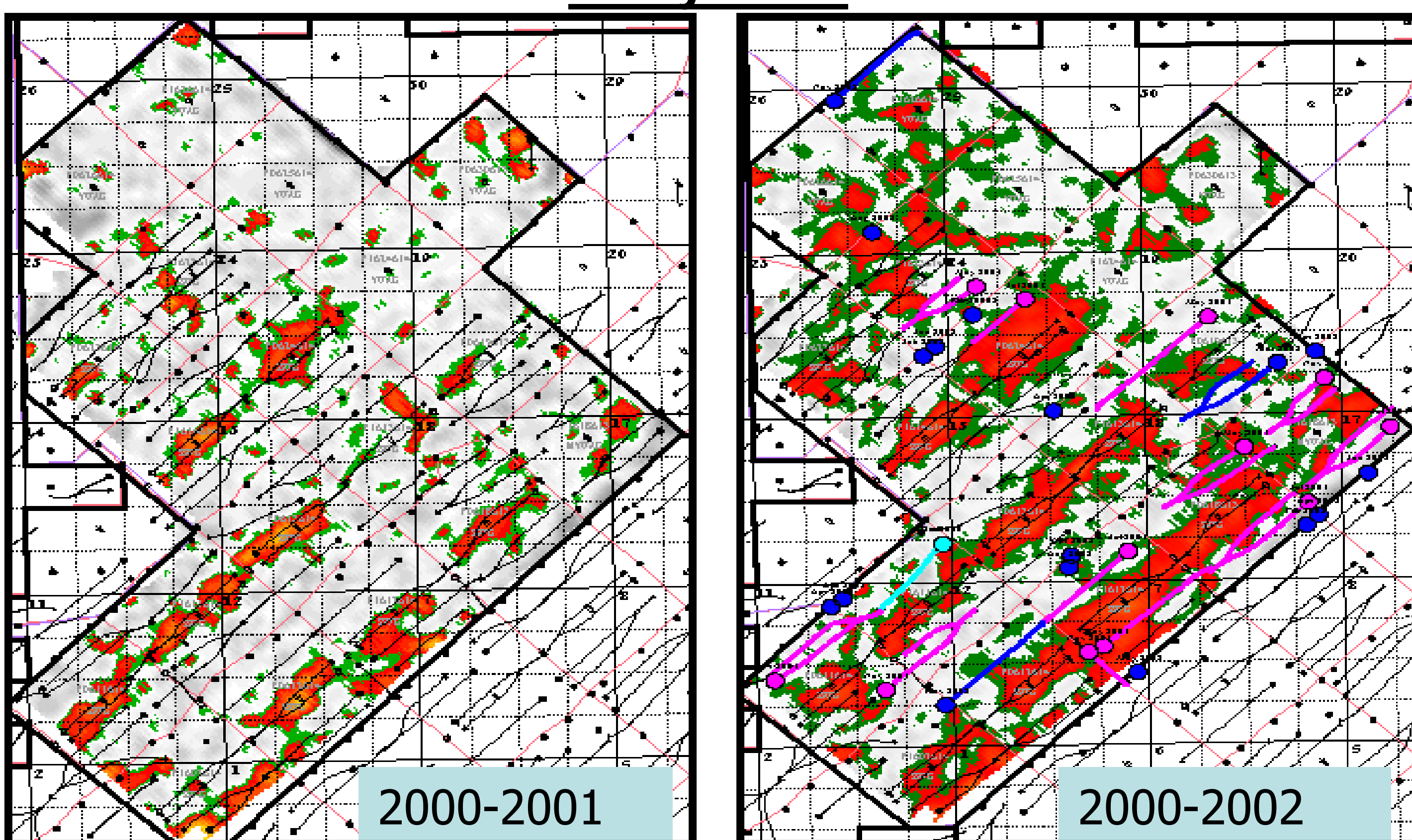
4D-3C Time-Lapse Seismic Surveys vs. Baseline Survey (Sept. 2000)

Marly Zone



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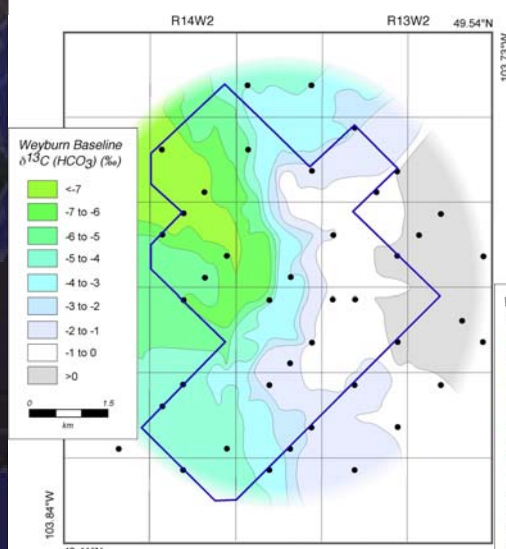
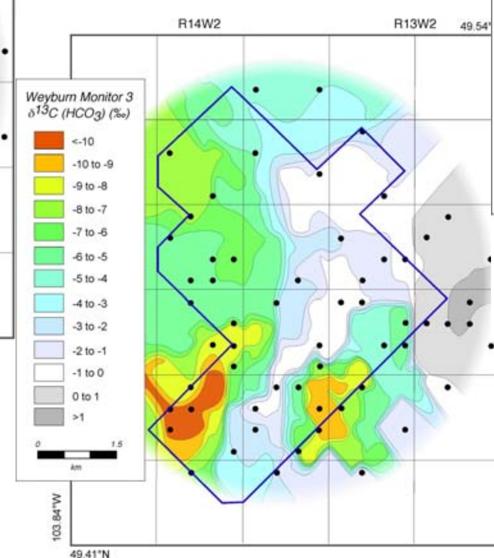
Injected CO_2 Dissolution

$\delta^{13}C_{HCO3}$ in produced fluids

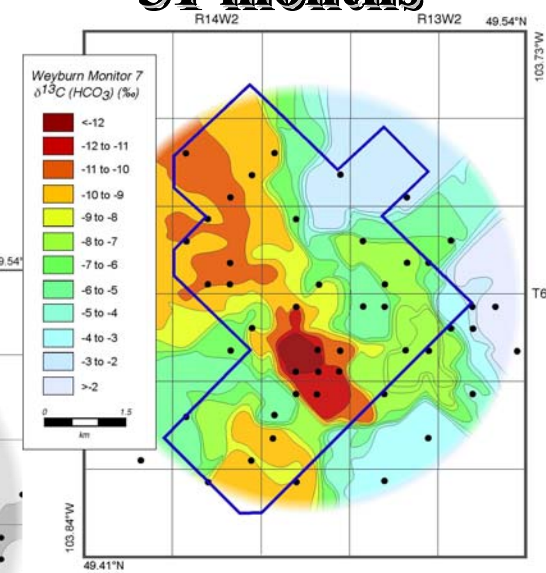
Pre-injection



12 months



31 months



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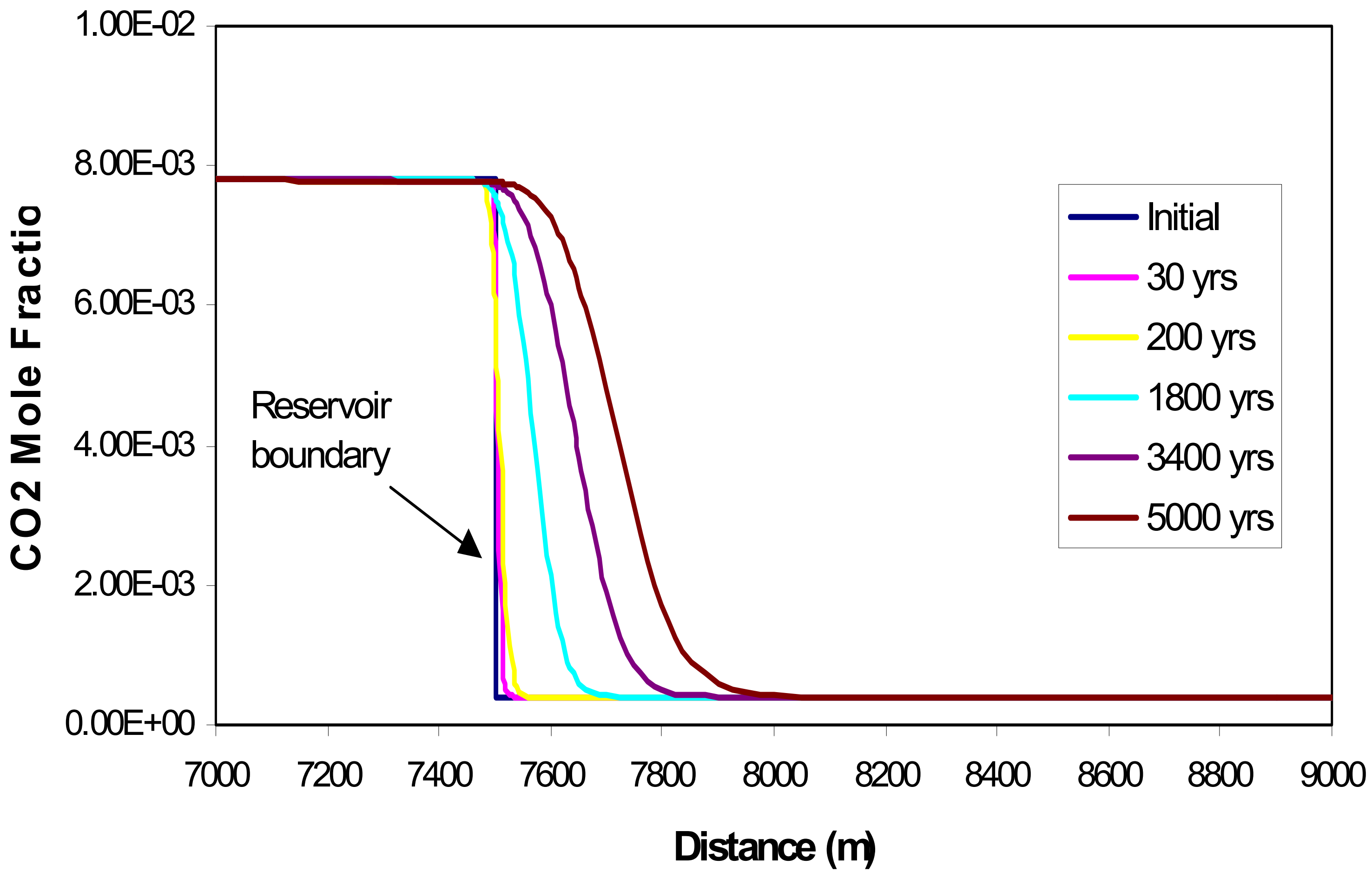
CO_2 Movement in Reservoir Plane



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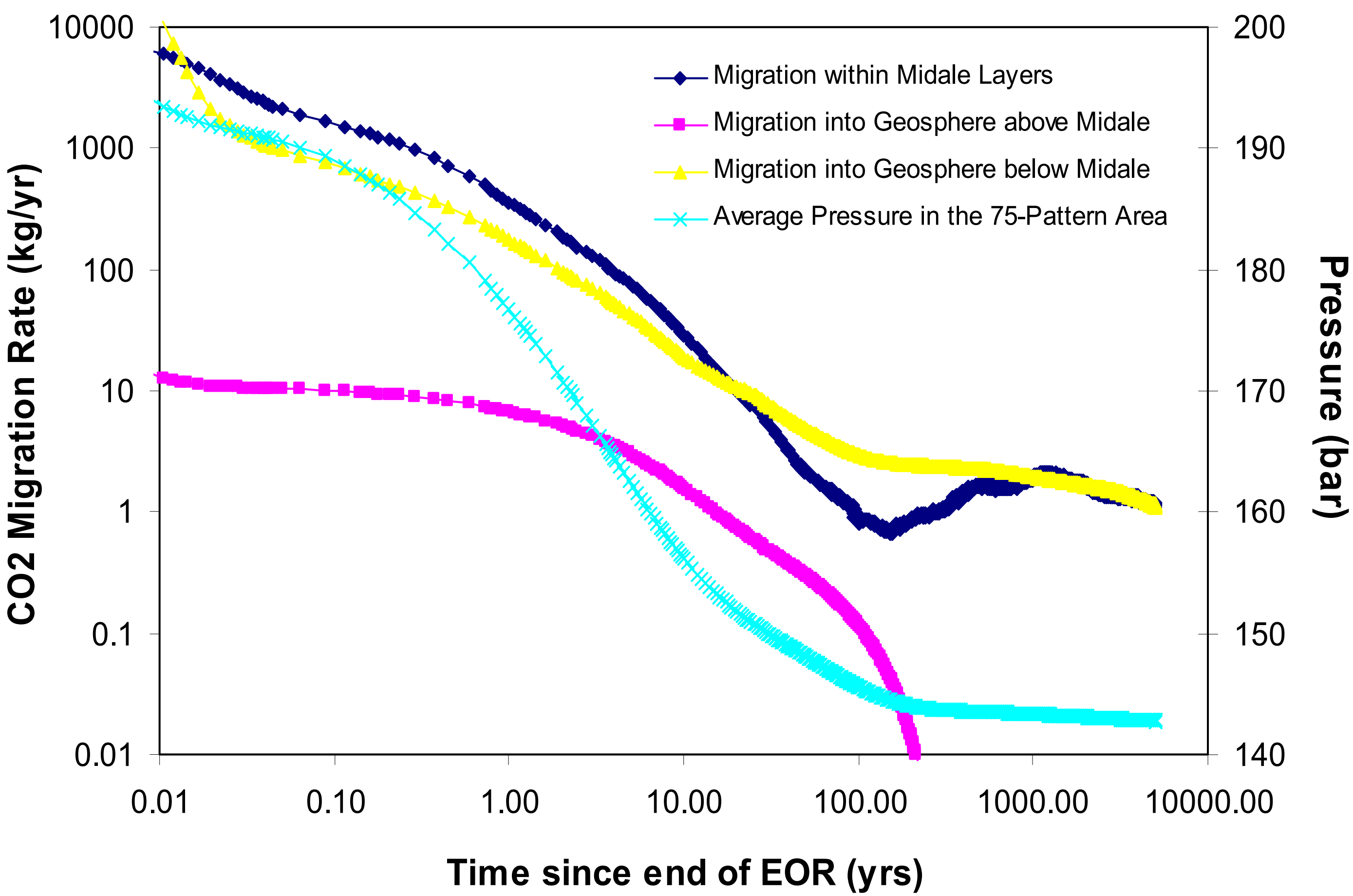
CO_2 Migration Rate



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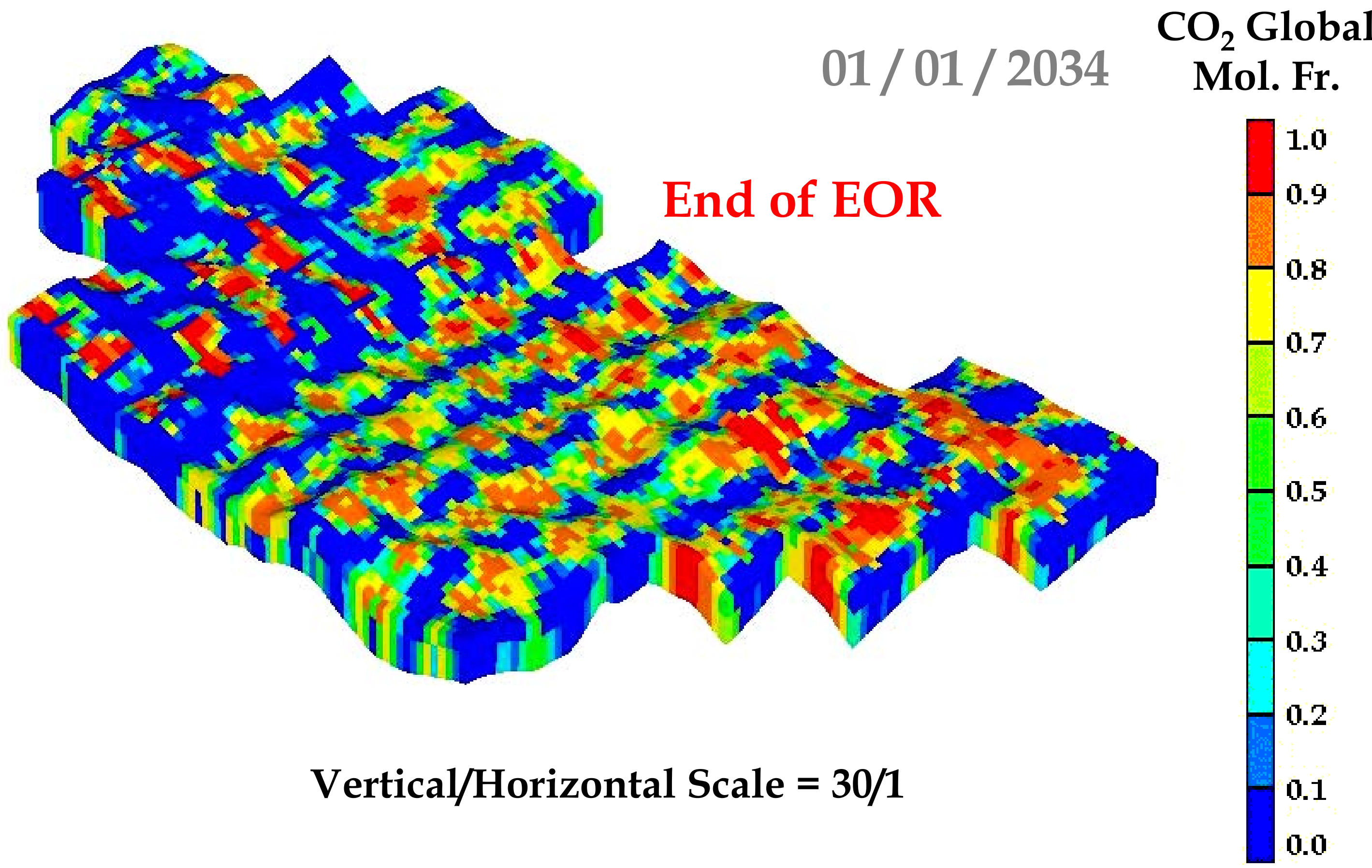
75 Pattern Simulation Model and Results



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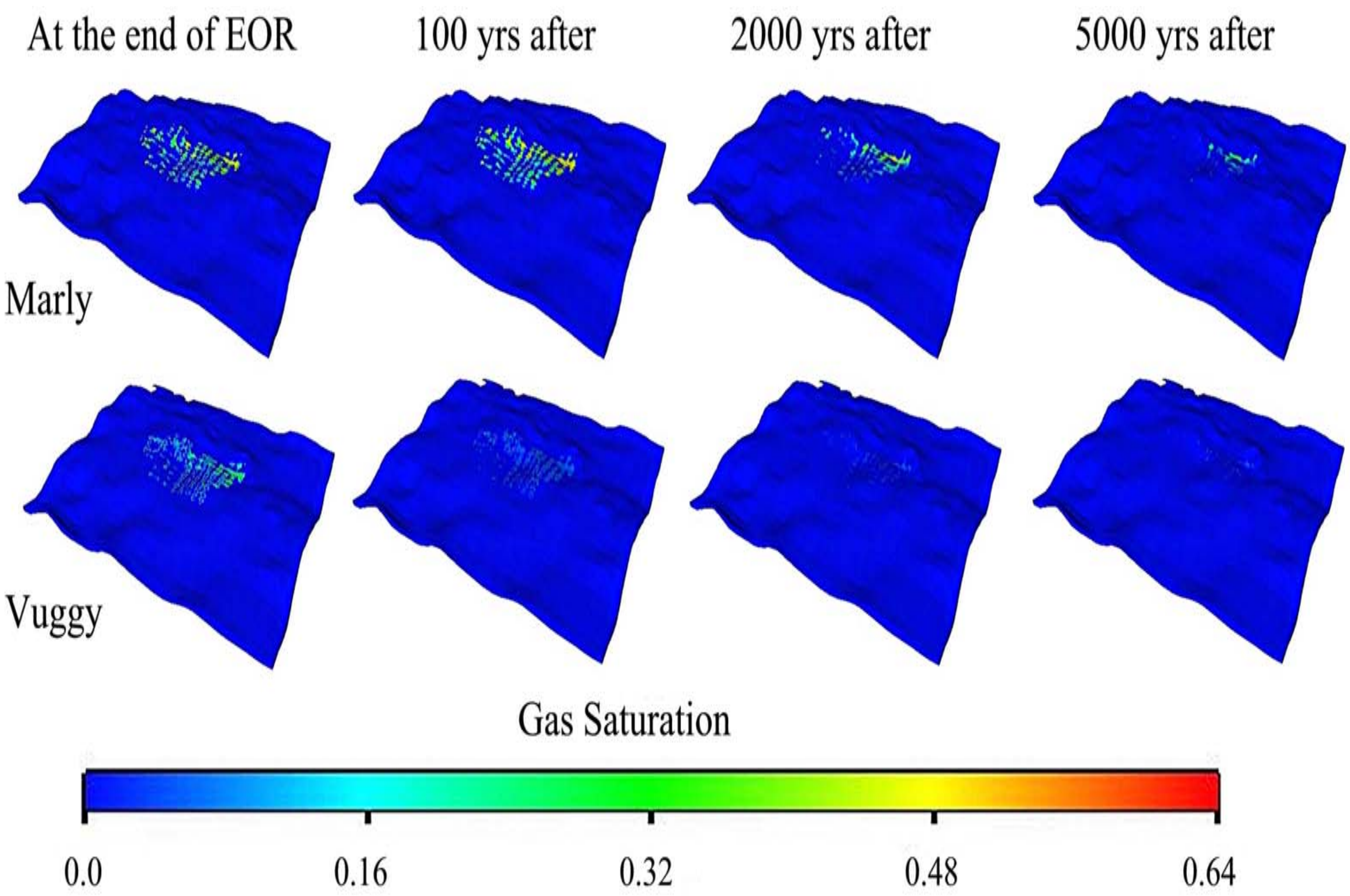
Gas Saturation With Time



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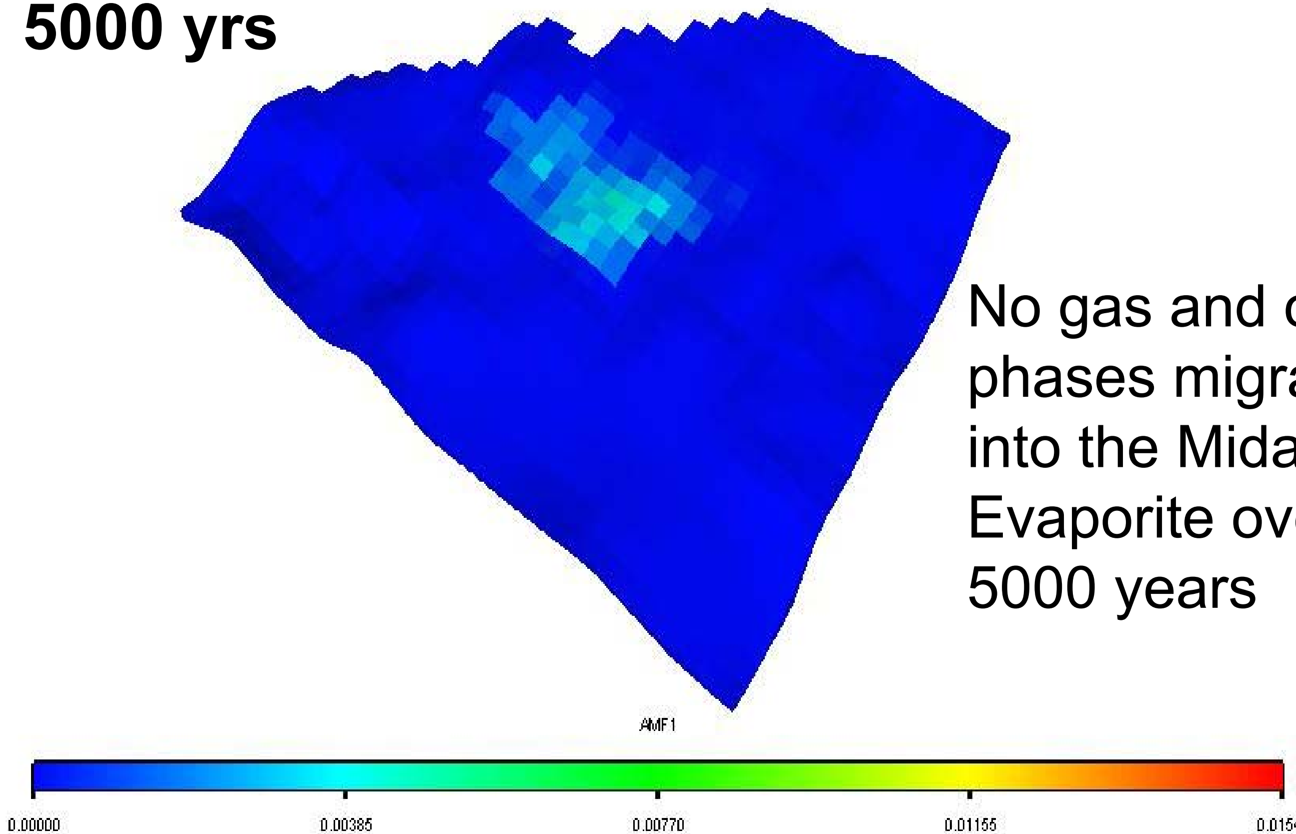
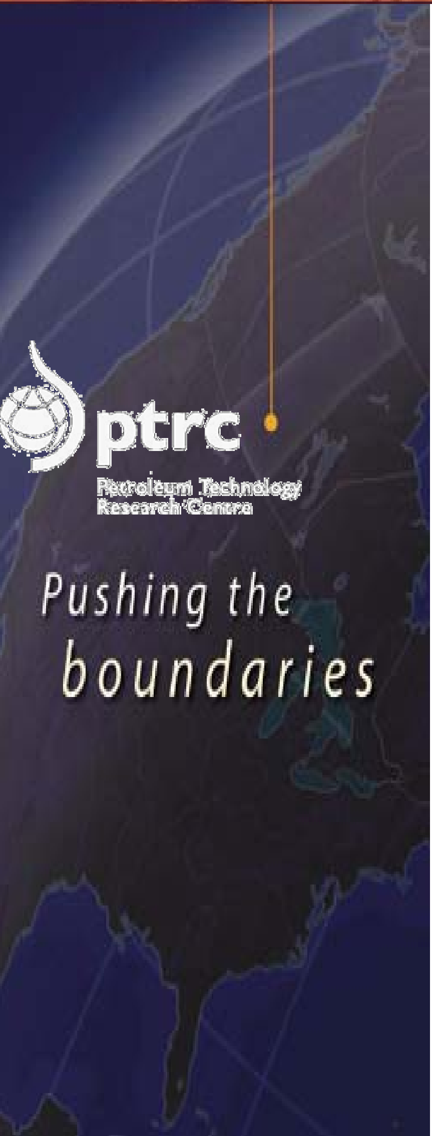
Element of Risk: CO_2 Aqueous Concentration in Midale Evaporite

5000 yrs



No gas and oil phases migrate into the Midale Evaporite over 5000 years

IEA GHG Weyburn CO_2 Monitoring and Storage Project



Phase II

Project Objectives:

- Build on the success of the IEA GHG Weyburn CO_2 Storage and Monitoring Project (Phase I)
- Complete the development of the necessary technical and operating information for guiding regulatory policy
- Foster the creation of a conducive business environment
- Facilitate public outreach and acceptance
  - Enable large-scale applications of commercial, EOR-based CO_2 Geological Storage Projects as early as possible

IEA GHG Weyburn CO_2 Monitoring and Storage Project

Phase II

Six Themes

Theme 1 – *Geological Integrity (Site Selection)*

Theme 2 – *Wellbore Injection & Integrity*

Theme 3 – *Storage Monitoring Methods*

Theme 4 – *Risk Assessment; Storage and Trapping Mechanisms, Remediation Measures, Environment, Health and Safety*

Theme 5 – *CO_2 Storage Performance Optimization*

Theme 6 – *Data Management/Grid Computing for Worldwide Information Sharing*

IEA GHG Weyburn CO_2 Monitoring and Storage Project

Phase II

Wellbore Injection & Integrity

- Complete the parameterization of wellbore integrity
- Compile a list of remediation activities that could be applied and include scoping level cost estimates
- Describe current well abandonment technology trends (new cements, alloys, plugs, cementing practice, etc) and how they may impact future abandonment requirements
- Conduct Cased-Hole Dynamic Testing
    - Log can be used to test behind casing pressure and formation fluids. In un-perforated zones, establish pressures and mobile fluids to look for CO_2 migration out of zone
- Document safe practices of normal CO_2 EOR operations on well-bore integrity and geomechanics and produce summary report

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IEA GHG Weyburn CO_2 Monitoring and Storage Project

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Pushing the boundaries

Phase II

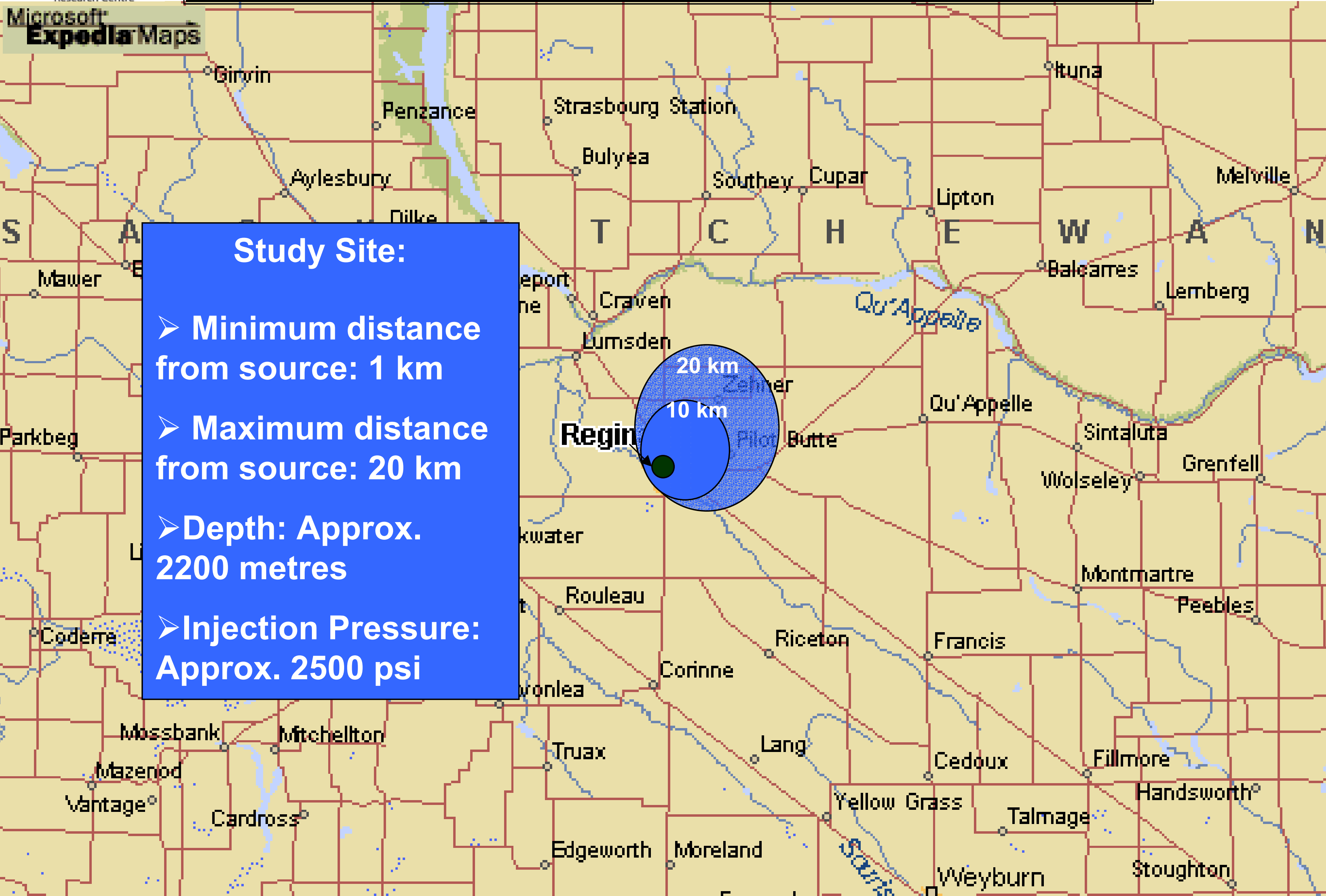
Storage Monitoring Methods

- Include in the Best Practices Manual conclusions on applications and limitations of subsurface and surface monitoring methods
- Characterize the accuracy of monitoring technologies for quantitatively predicting the location and volume-in-place of CO_2
- Coupled with the simulation supporting Risk Assessment, determine the monitoring technologies needed as a function of time and estimated risk
- Participate in EnCana's 2005 4-D seismic program
- Conduct in situ time-lapse well logging to verify and constrain the results from seismic and other monitoring approaches
- Continue with passive seismic program and determine from the interpretation results the merits of this monitoring method
- Verify predictions through spinner surveys and selective drilling, coring and logging of vertical slim holes to determine CO_2 distribution

Proposed Saline Aquifer Project

Study Site:

- Minimum distance from source: 1 km
- Maximum distance from source: 20 km
- Depth: Approx. 2200 metres
- Injection Pressure: Approx. 2500 psi



Proposed Saline Aquifer Project

ptrc
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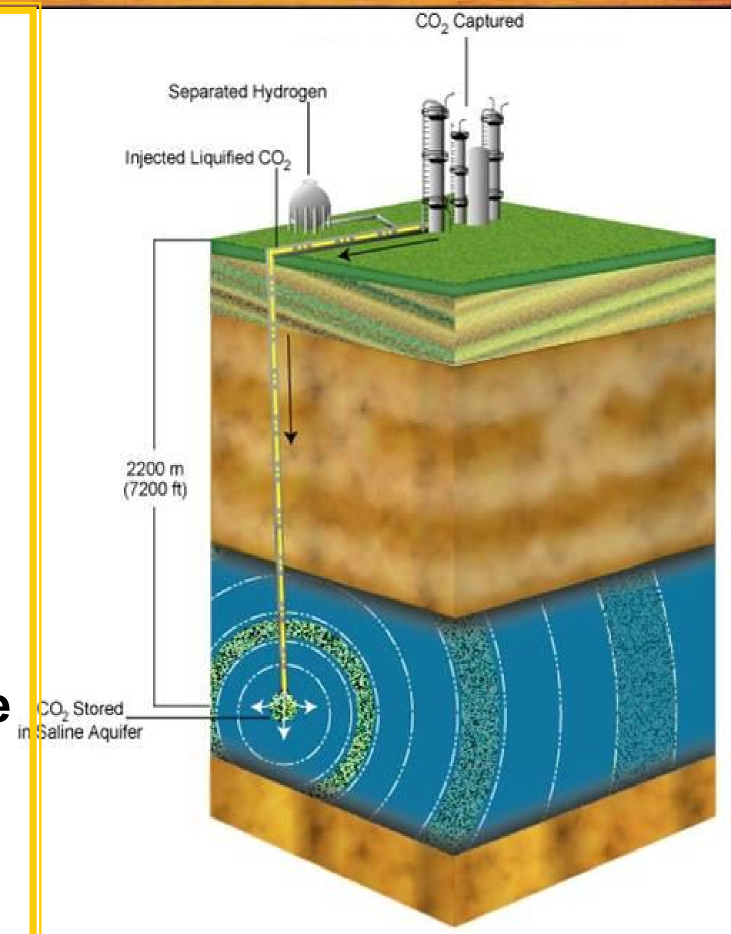
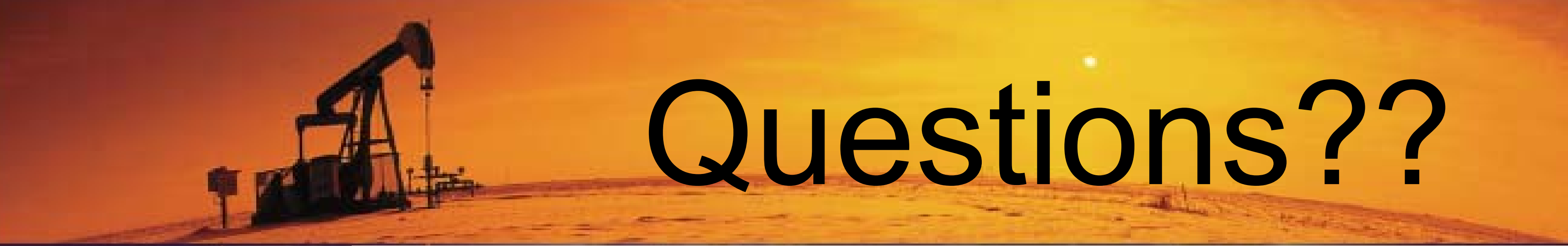
Pushing the boundaries

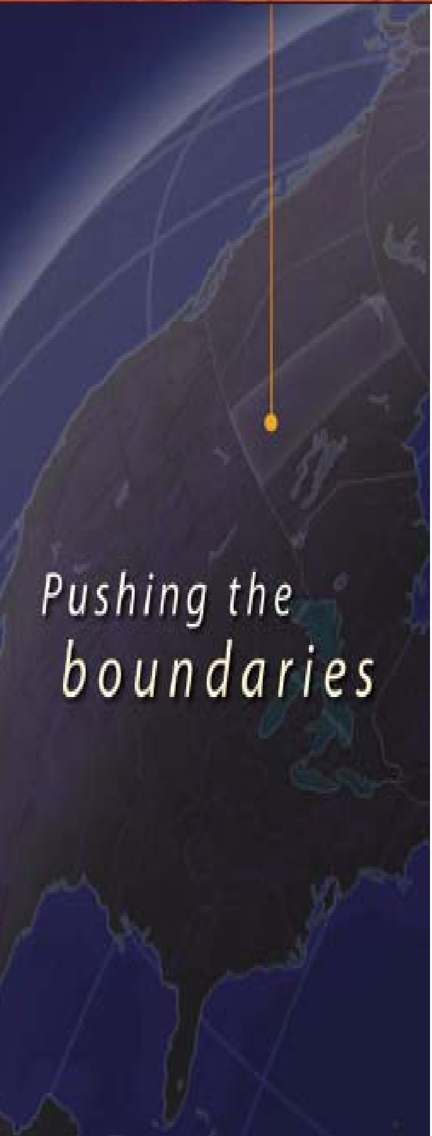
Overview:

- Potential of high purity source
    - Approx. 100,000 tons/day
- Palaeozoic injection
    - Possibly multizone
- Existing potash mine injects approx. 6,000 cubic metres/day
    - Virtually no pressure response
- Monitoring program to be determined



Questions??





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Research Centre

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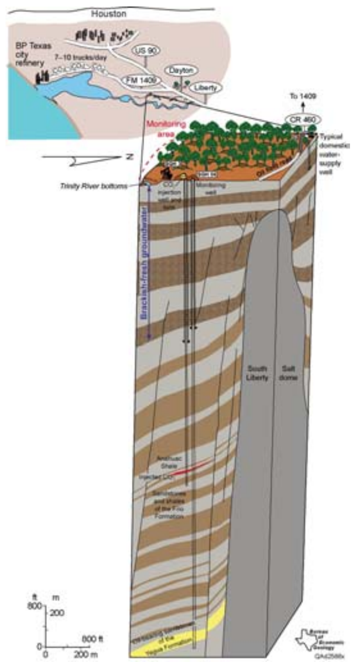
MONITORING NETWORK MEETING ROME 2005



TRACER, SHALLOW AQUIFER, DIRECT $C0_2$ FLUX, AND GEOPHYSICAL SURVEY RESULTS FROM THE FRIO BRINE SEQUESTRATION SITE, TEXAS

Field Participants: NETL: Art Wells, Rod Diehl, Grant Bromhal, Brian Strazisar, Denny Stanko, Sheila Hedges, Dennis Stanko
WVU: Tom Wilson, Henry Rauch
CSM: Ron Klusman
BEG: Seay Nance

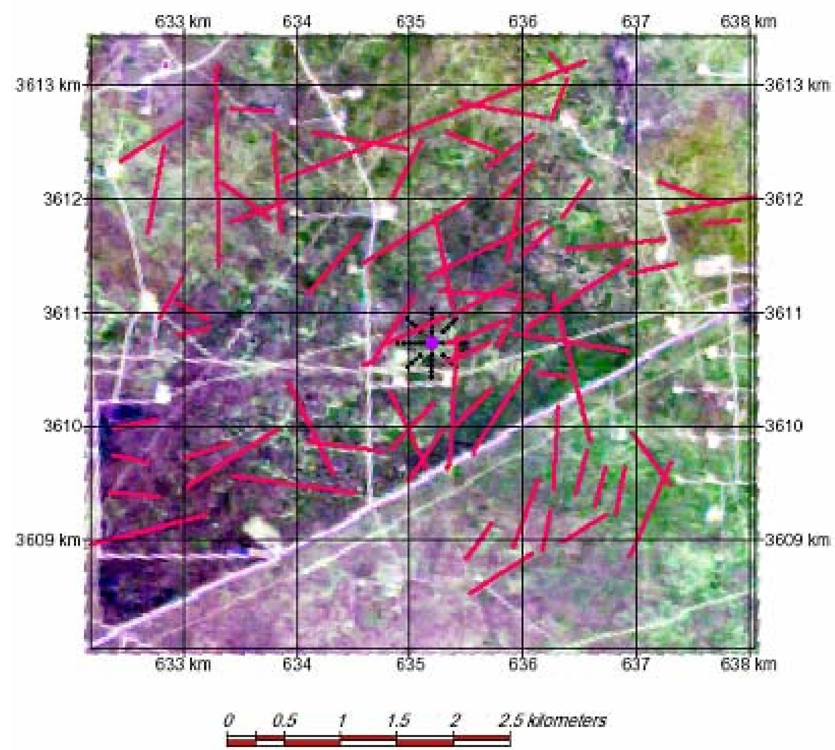
COMPREHENSIVE MONITORING "SEQURE" TECHNOLOGIES

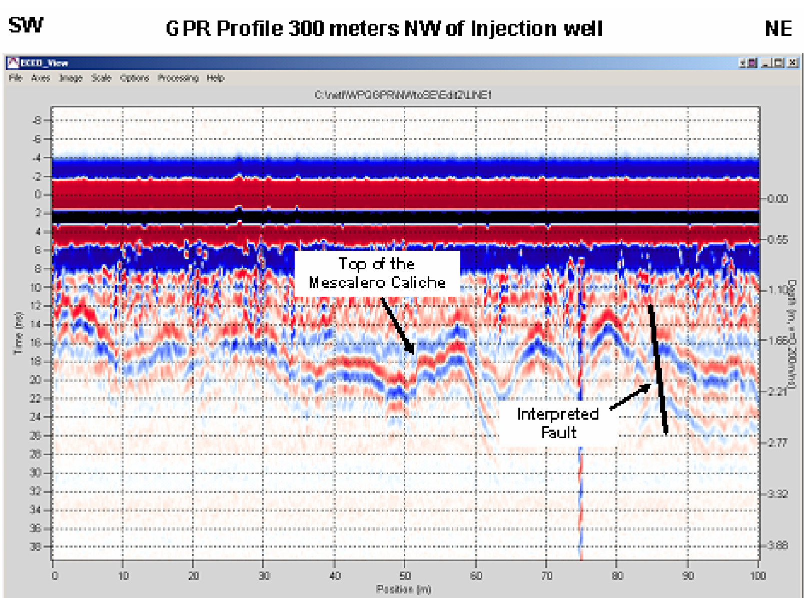
SUITE OF MONITORING TECHNOLOGIES

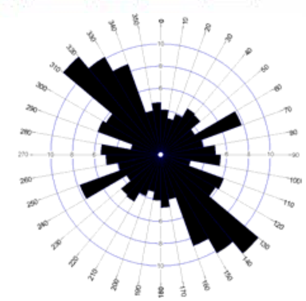
- CO_2 TRACERS WITH SOIL-GAS MONITORING
- DIRECT CO_2 FLUX AND METHANE / RADON IN SOIL-GAS MONITORING
- SHALLOW WATER AQUIFER CHEMISTRY MONITORING
- AIRBORNE MAGNETOMETRY SURVEYS AND RADIOMETRY/METHANOMETRY/ETHANOMETRY (TO FIND ABANDONED WELLS AND EVALUATE LEAKAGE POTENTIAL)

TECHNICAL APPROACH
GEOPHYSICAL SURVEY (Tom Wilson, WVU)

- Provide Location/Evaluation of Monitoring Sites
- Remote Sensing for Lineaments and Geologic Features: Satellite and Aerial Photography
- Ground Based Measurements: Ground Penetrating Radar, Seismic Surveys







Perfluorocarbon tracers were injected with the carbon dioxide.

- 3 Different Tracers at the Well Head as 2 12-Hour Slugs and 1 6-Hour Slug, Over a Week
- Soil Monitoring with Adsorbent Packets (CATS) Placed in Monitoring Pipes in a Matrix around the Injection Well

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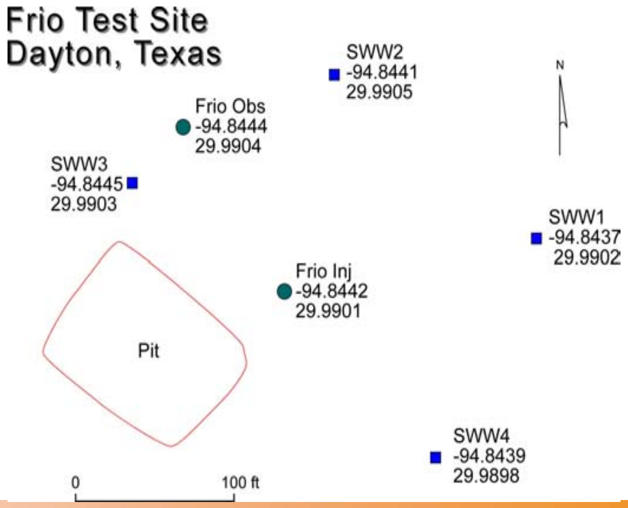
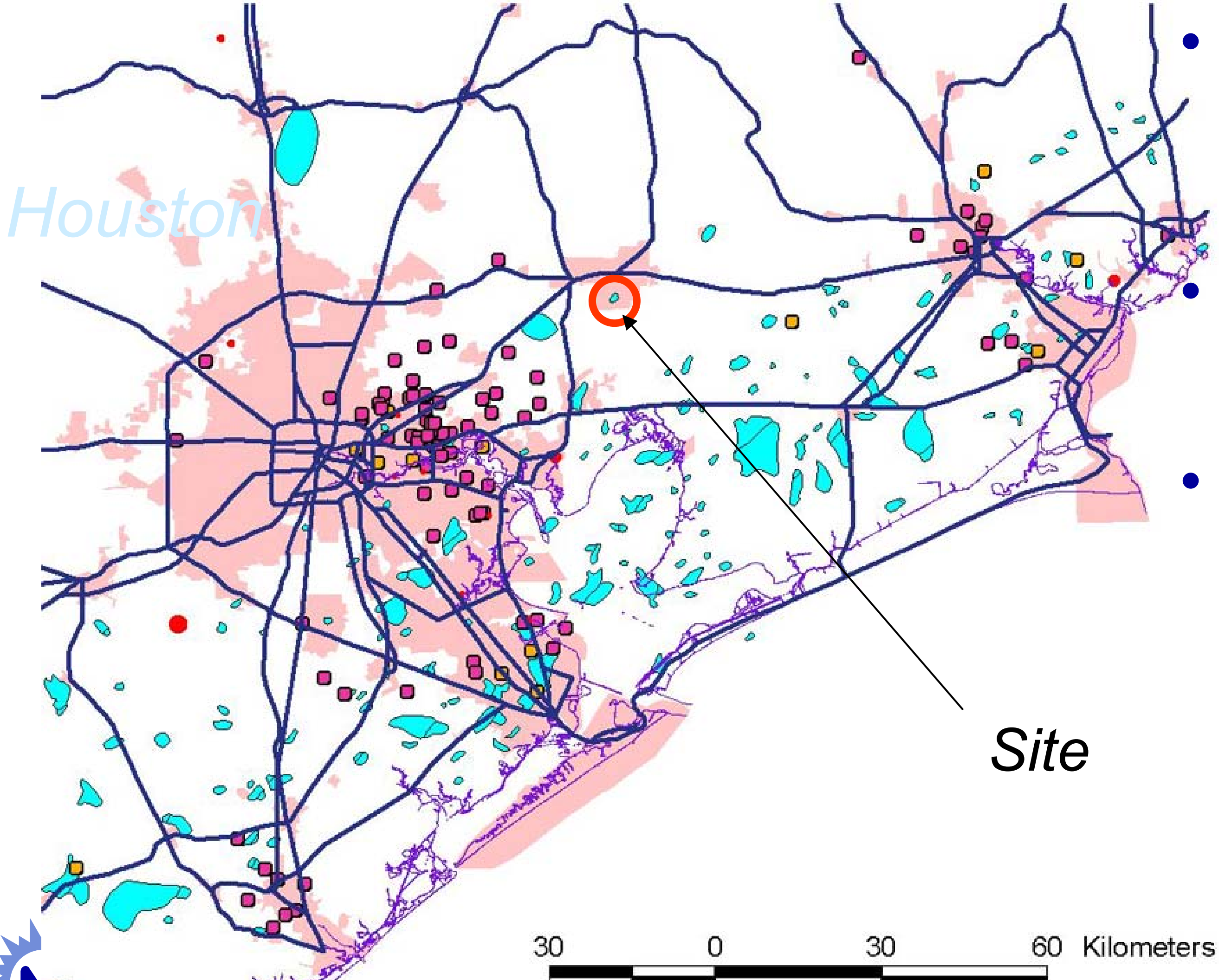
MONITORING AT WATER WELLS

SHALLOW WATER AQUIFERS: (Grant Bromhal, Sheila Hedges, Henry Rauch, Seay Nance)

- **Determine Chemical Activities for Tested Solute Species for Equilibrium Carbon Dioxide Partial Pressures Associated with Each Sampled Well Water**
- **Pre- and Post-Injection Studies Compared**
- **Monitoring of 4 Water Wells at Frio**

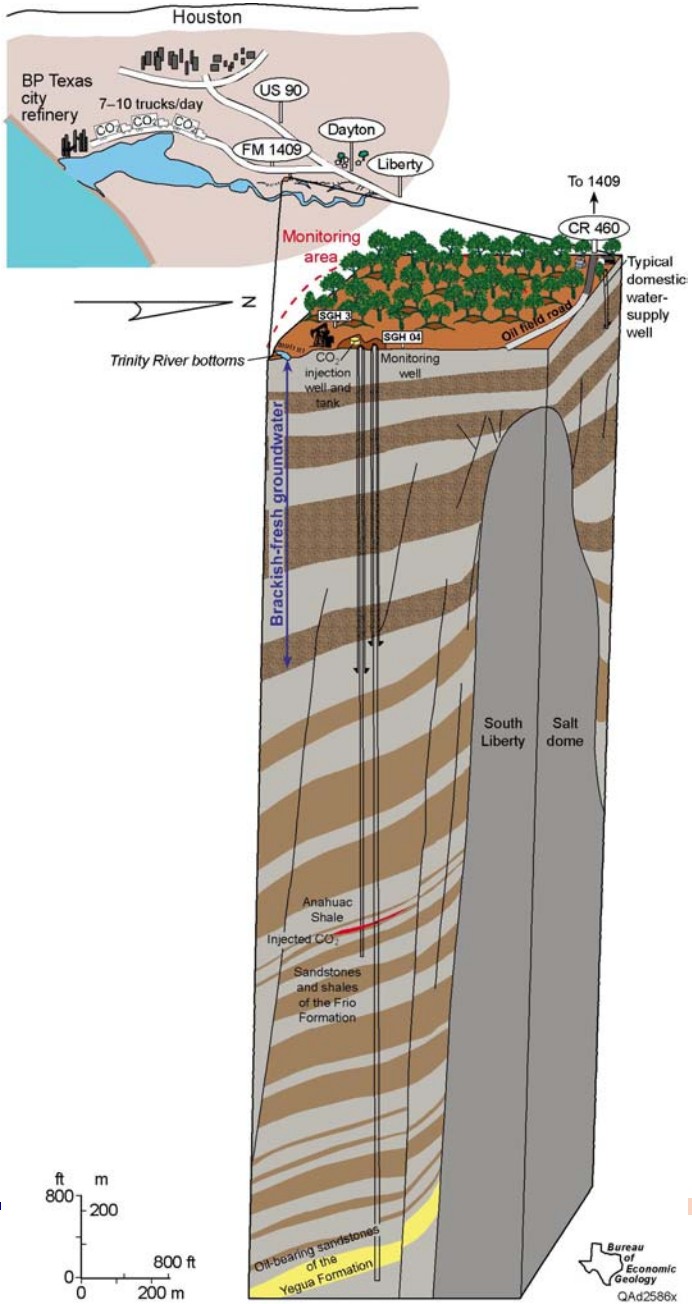


FRIO BRINE SITE



- 50-year-old oil field in the Yegua and Frio Formations
- Operator is a small independent
- Flank of a salt dome, steep dips, fault bounded compartments

Frio Project

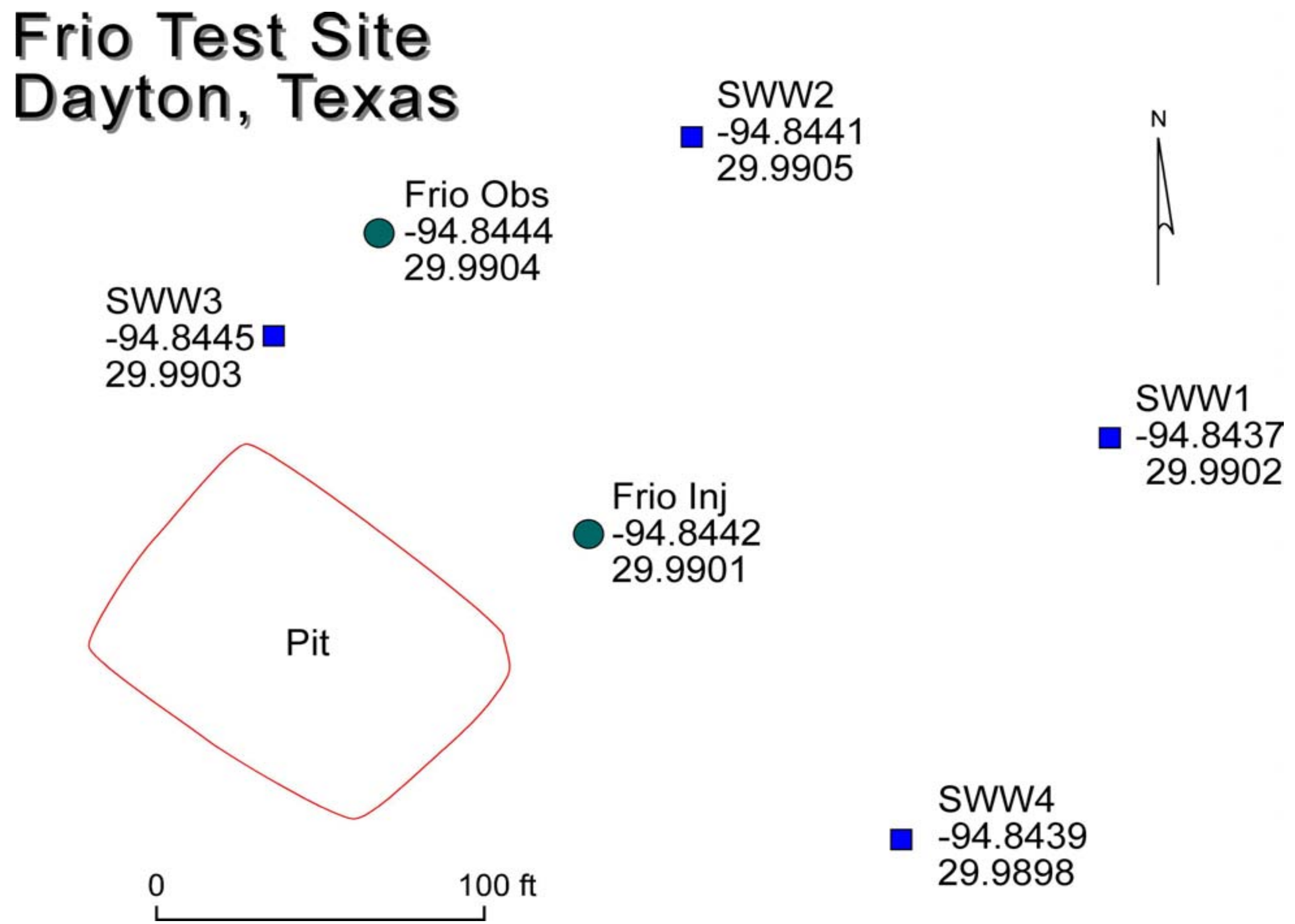


- **Collaboration with the University of Texas- Texas Bureau of Economic Geology**
- **3,750 tons of food-grade CO_2 was trucked from the BP Texas City refinery and be injected 5000 feet deep into the Frio formation over a period of a few weeks**

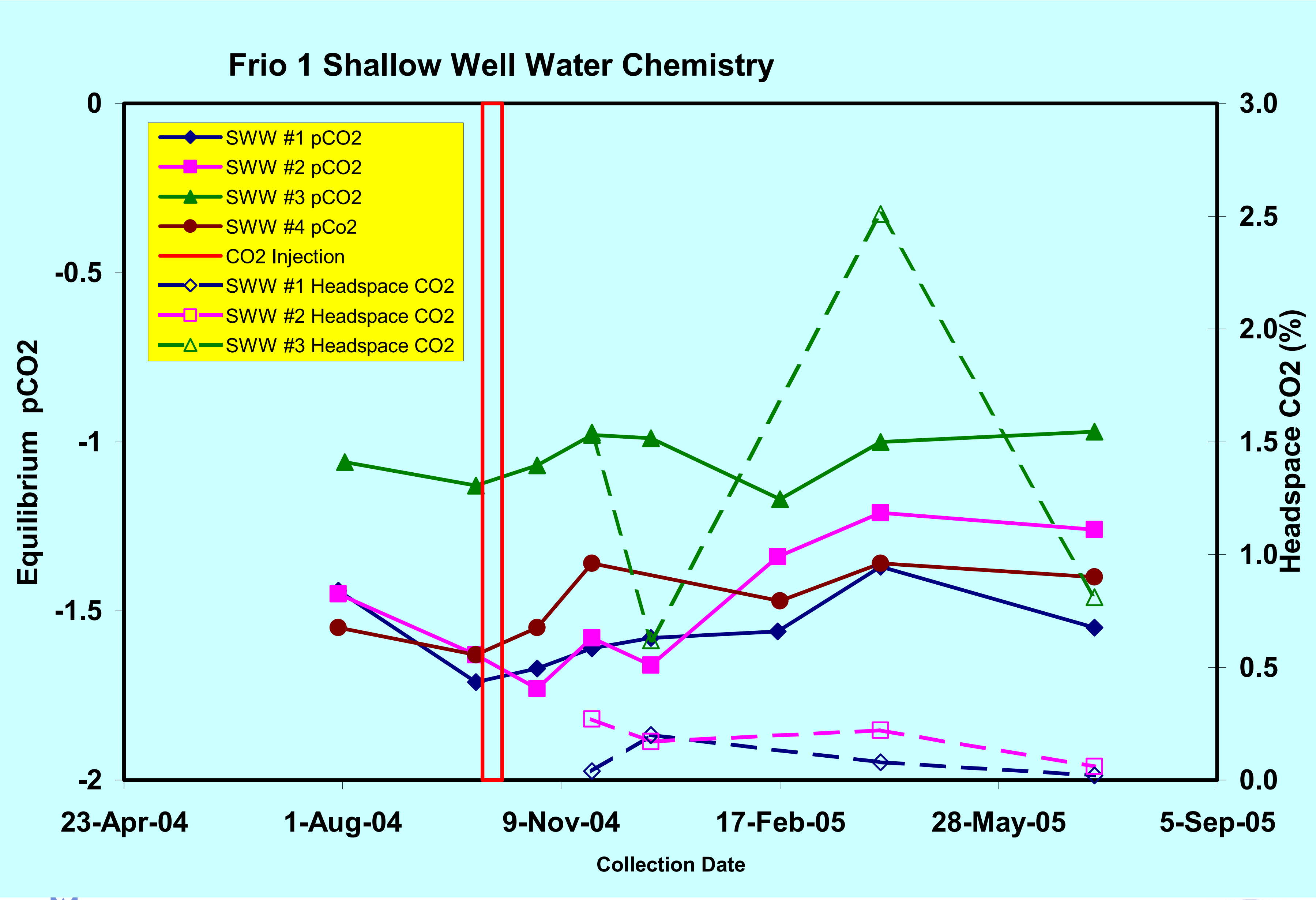
FRIO SITE SWAP AREAS

Van with Tracer Syringe Pump Near Injection well Head

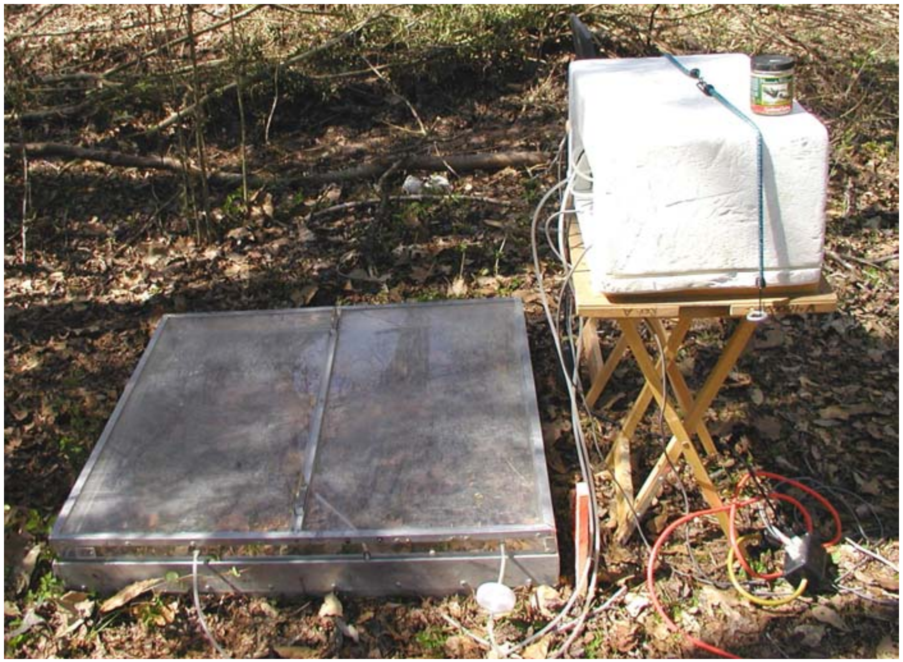
Frio test site map showing CO_2 gas injection well and water monitoring wells

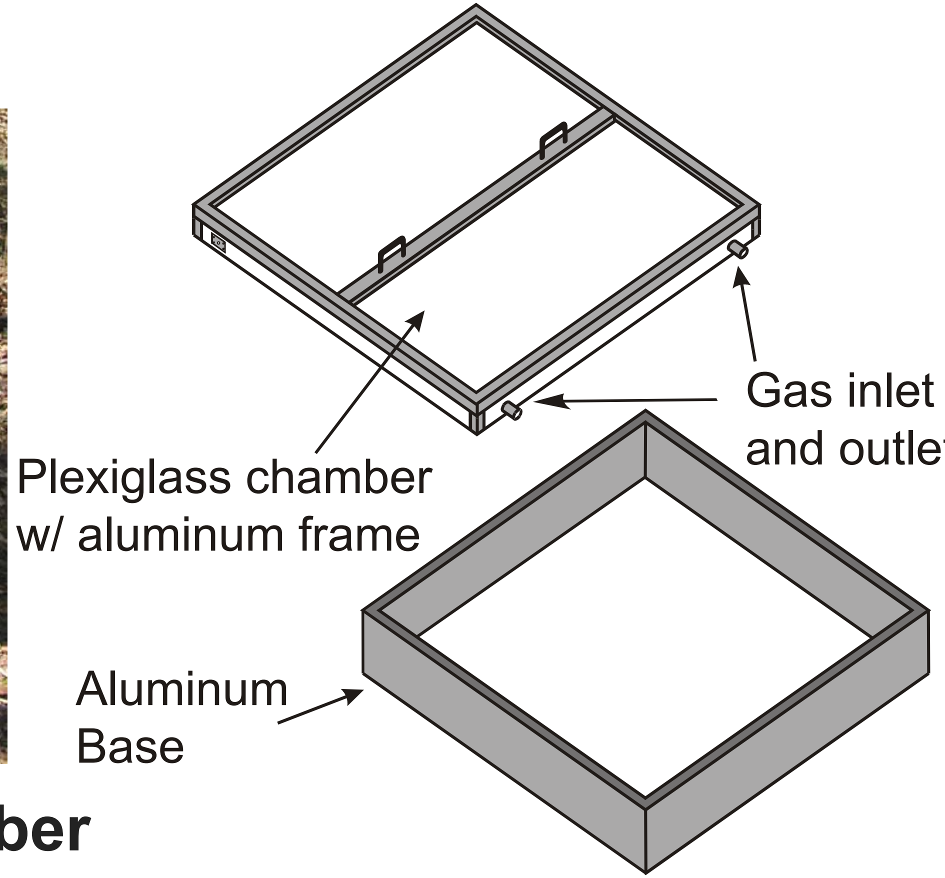


SEAY NANCE (BEG) PURGING A MONITORING WATER WELL AT FRIO


Frio 1 Shallow Well Water Chemistry
SWW #1 pCO2
SWW #2 pCO2
SWW #3 pCO2
SWW #4 pCo2
CO2 Injection
SWW #1 Headspace CO2
SWW #2 Headspace CO2
SWW #3 Headspace CO2
Equilibrium pCO2
0
-0.5
-1
-1.5
-2
Headspace CO2 (%)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
23-Apr-04
1-Aug-04
9-Nov-04
17-Feb-05
28-May-05
5-Sep-05
Collection Date

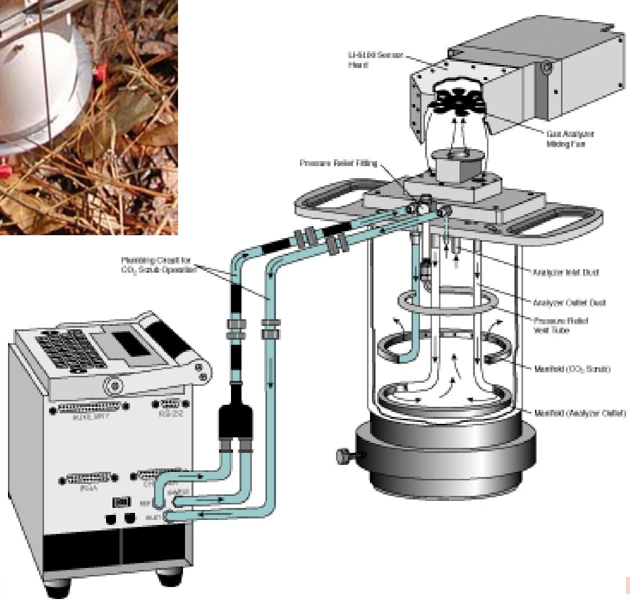
CO_2 Soil Flux Measurements – "homemade" instrument





- **One meter square chamber**
- **Gas circulated between chamber and infrared detector**
- **Rate of CO_2 concentration change used to calculate flux**

CO_2 Soil Flux Measurements – commercial instrument



- Four inch diameter cylindrical chamber
- Infrared detector head located on top of chamber
- CO_2 scrubbing allows multiple experiments in short time and avoids CO_2 build-up in chamber

Soil Gas Sampling

- Depth profile of soil-gas up to 1 meter
- CO_2 and CH_4 concentrations
- CO_2 stable isotope ratio ($\delta^{13}C$)

CO_2 Stable Isotopes

$$\delta^{13}C = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} \times 1000$$

- **Result expressed as "per mil" or ‰**
- **Biological processes generally favor ^{12}C, leading to isotopically "light" CO_2 (strongly negative $\delta^{13}C$)**
- **$\delta^{13}C$ for CO_2 in soil gas help identify the source of CO_2**

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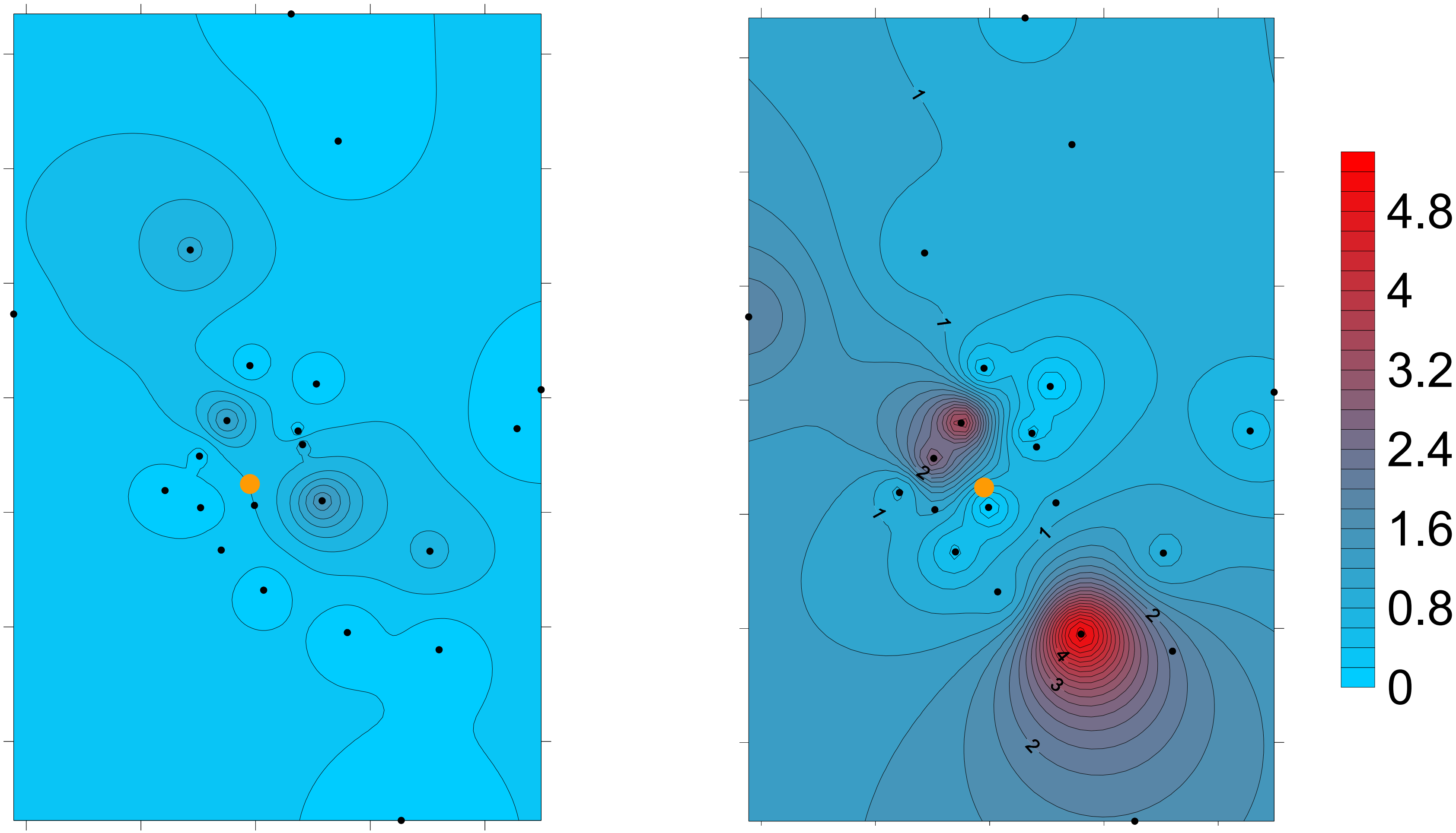
Soil Gas Radon Measurements

- CO_2 can act as a carrier gas bringing Radon to the surface
- Radon easily detected due to alpha decay
- Radon – “indicator” of CO_2 movement to the surface

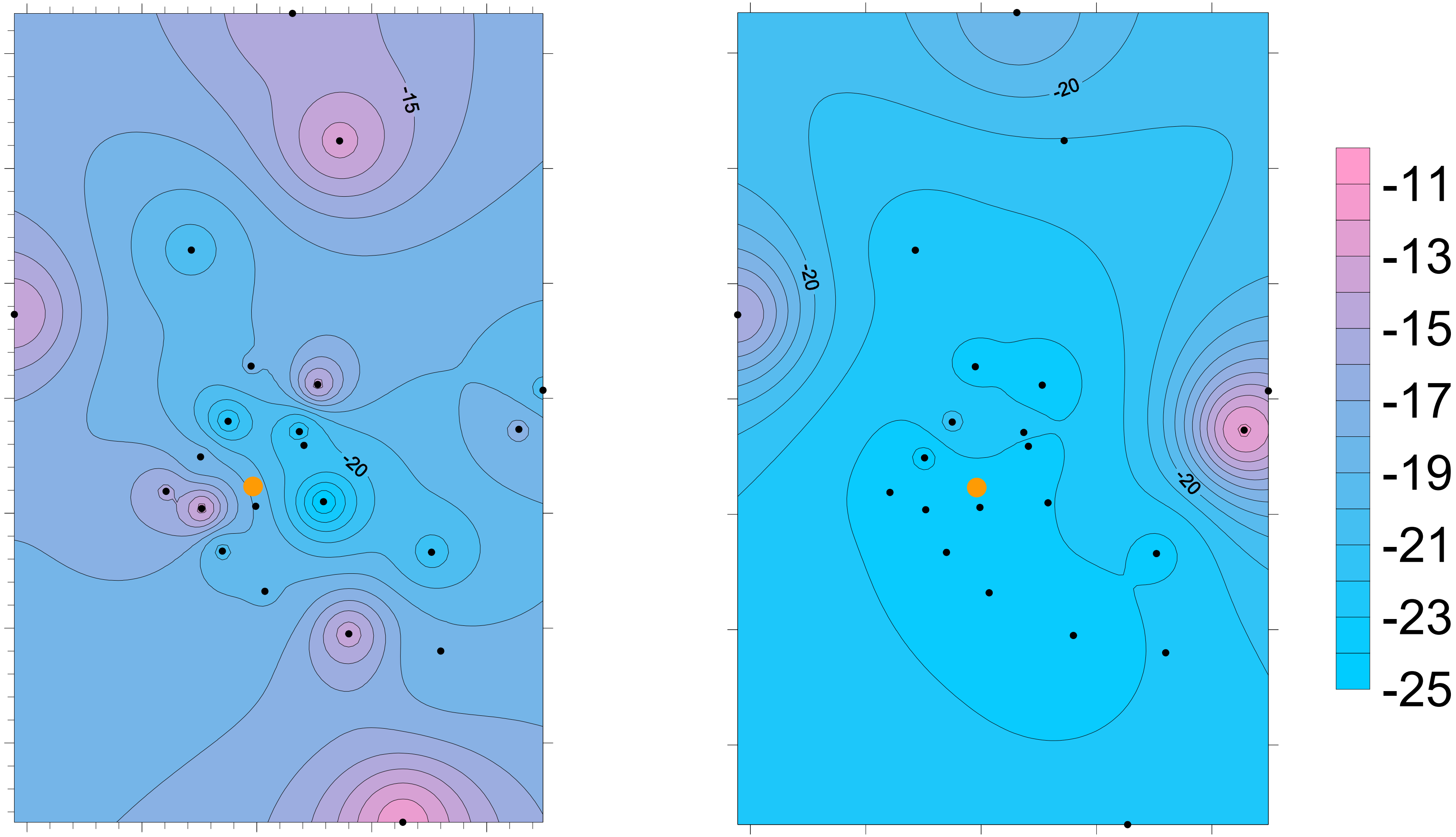
Frio Site

Frio Site soil gas CO_2 at 30 cm (%)



Pre-injection **Post-injection**

Frio site – $\delta^{13}C$ of CO_2 at 30 cm



Pre-injection **Post-injection**

TRACERS USED AT FRIO

PFTs	Mol. Wt.	Abbreviations
Perfluoro-ethylcyclohexane	400	PECH
Perfluoro-1,2-Dimethylcyclohexane	400	PDCH
Perfluoro-Dimethylcyclobutane	300	PDCB

- Completely Miscible with Carbon Dioxide
- Non-Toxic
- Non-Flammable
- Non-Explosive
- Non-Radioactive
- Non-Corrosive
- Detection Limits of 10 Parts per Quadrillion in Soil-Gas or Air

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TRACER MONITORING LOCATIONS

- **Immediate Vicinity of the Injection Well Pad**

  --- Highest Concentration of Monitors

  --- Tracer in Soil-Gas Depth Profiling Arrays (2)

- **Adjacent to Active, Inactive and Abandoned Wells**

  --- High Potential Leakage Sources

  --- Associated NETL Programs in Remote Sensing for Abandoned Wells and Cement Degradation Studies

TRACER MONITORING LOCATIONS

- **Geologic Features that Might Represent Leakage Pathways to the Surface**

  --- Fault Zones with Surface Expression

  --- Outcroppings

  --- Hydrocarbon Seeps

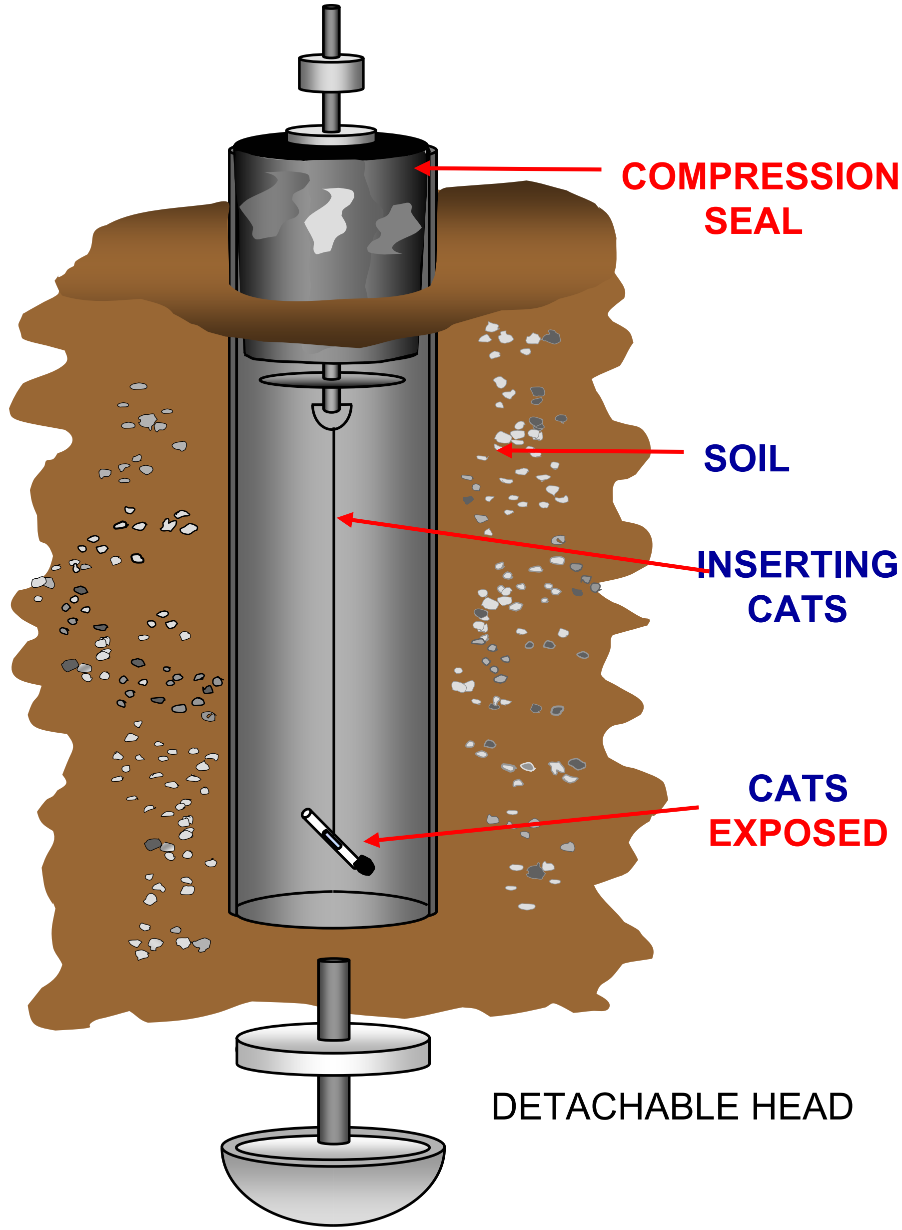
- **Geometric or Statistically Meaningful Scatter Patterns Emanating From the Injection Well**

  --- Representative Sampling at 34 "Sectors"

  --- Limitations: Heavily Forested Terrain, Swamps, Permission to Place Monitors

DETACHABLE HEAD PENETROMETER FOR SOIL-GAS MONITORING

- Pound steel pipe with detachable head one meter into ground
- Detach head with narrower pipe
- Lower CATS into the pipe
- Seal pipe at top with a compression fitting stopper
- CATS are replaced as sets: one week apart initially to months apart later in the study



Van with Tracer Syringe Pump Near Injection Well Head

Testing Soil Permeability

SOIL-GAS MONITORING LOCATION S AT FRIO

TRACER MONITORING SCHEDULE AT FRIO

DATE	PFT MONITORING	CO2 INJECTION	TIME
Aug. 19, 2004	Place CAT Set 1		
Oct. 2, 2004	Remove CAT Set 1		
Oct. 4, 2004		Start of CO_2 Injection	11:34am
Oct. 5, 2005	Inject Tracer 1 (PECH)		12 Hour Injection (7am to 7pm)
Oct. 6, 2005	Placed CAT Set 2	Breakthrough at Monitoring Well	3:45pm (Breakthrough)
Oct. 7, 2005		End of First CO_2 Injection Period	11:45am
Oct. 8, 2005		Start of Second CO_2 Injection Period	6:13pm
Oct. 11, 2005	Inject Tracer 2 (oPDCH)		12 Hour Injection (7am to 7pm)
Oct. 12, 2005	Remove CAT Set 2		
Oct. 13, 2005	Inject Tracer 3 (PDCB)		6 Hour Injection (6:00pm to 12:00am)

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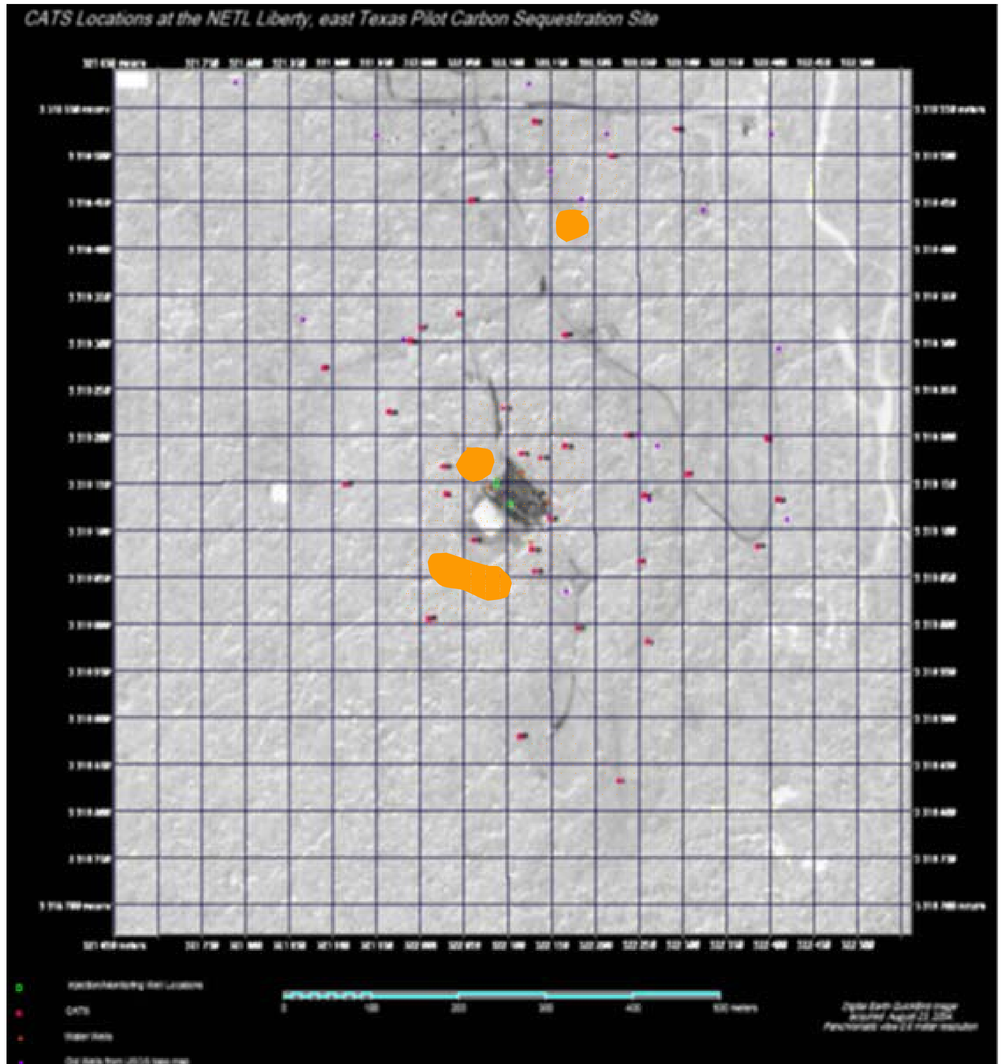
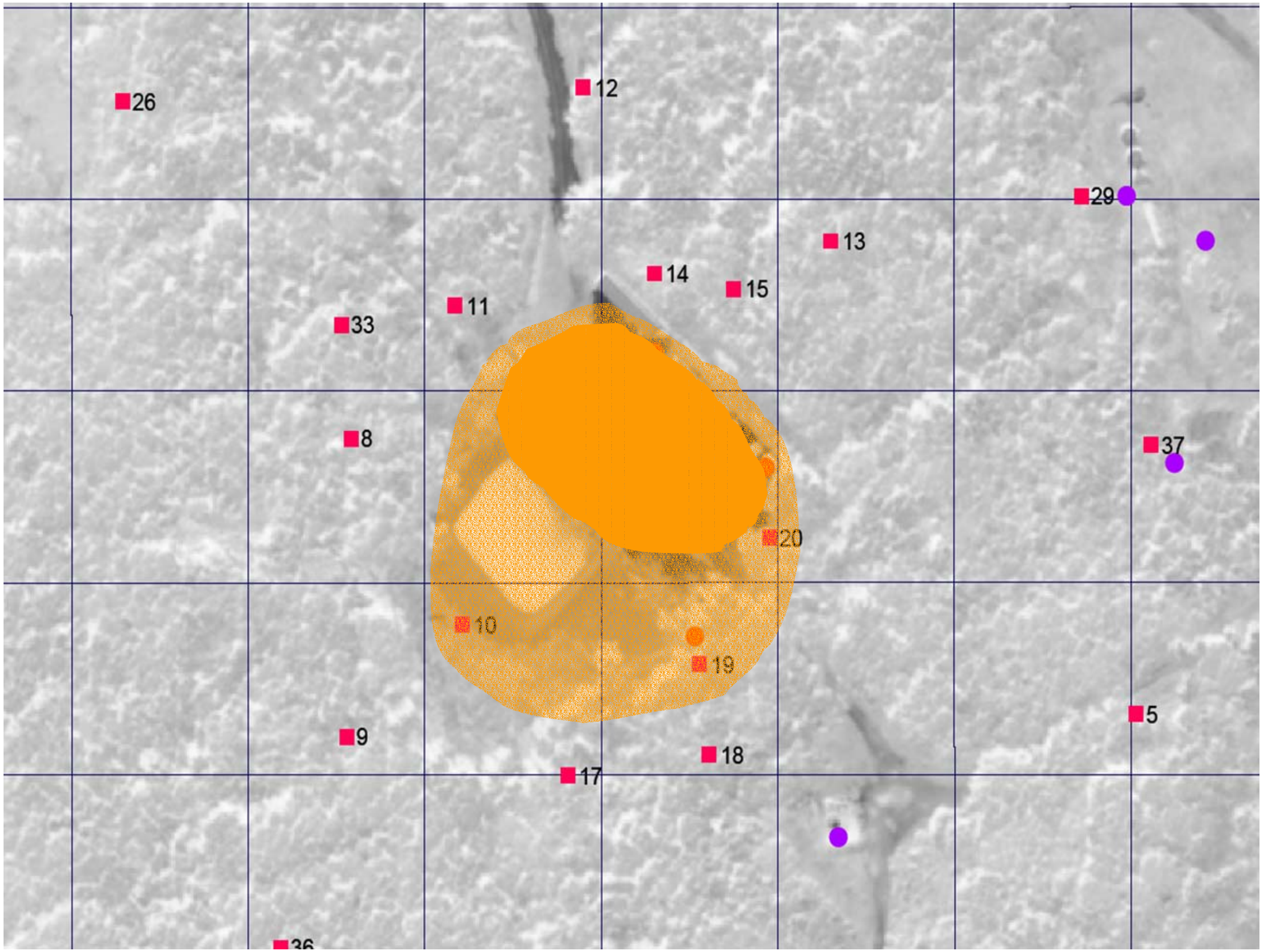
TRACER MONITORING SCHEDULE AT FRIO

DATE	PFT MONITORING	CO2 INJECTION	TIME
Oct. 14, 2004	Place CAT Set 3	End of Second CO_2 Injection Period	2:30pm
Nov. 17/18, 2004	Remove CAT Set 3 Place CAT Set 4		
Feb. 24/25, 2005	Remove CAT Set 4 Place CAT Set 5		
April 20/21, 2005	Remove CAT Set 5 Place CAT Set 6		

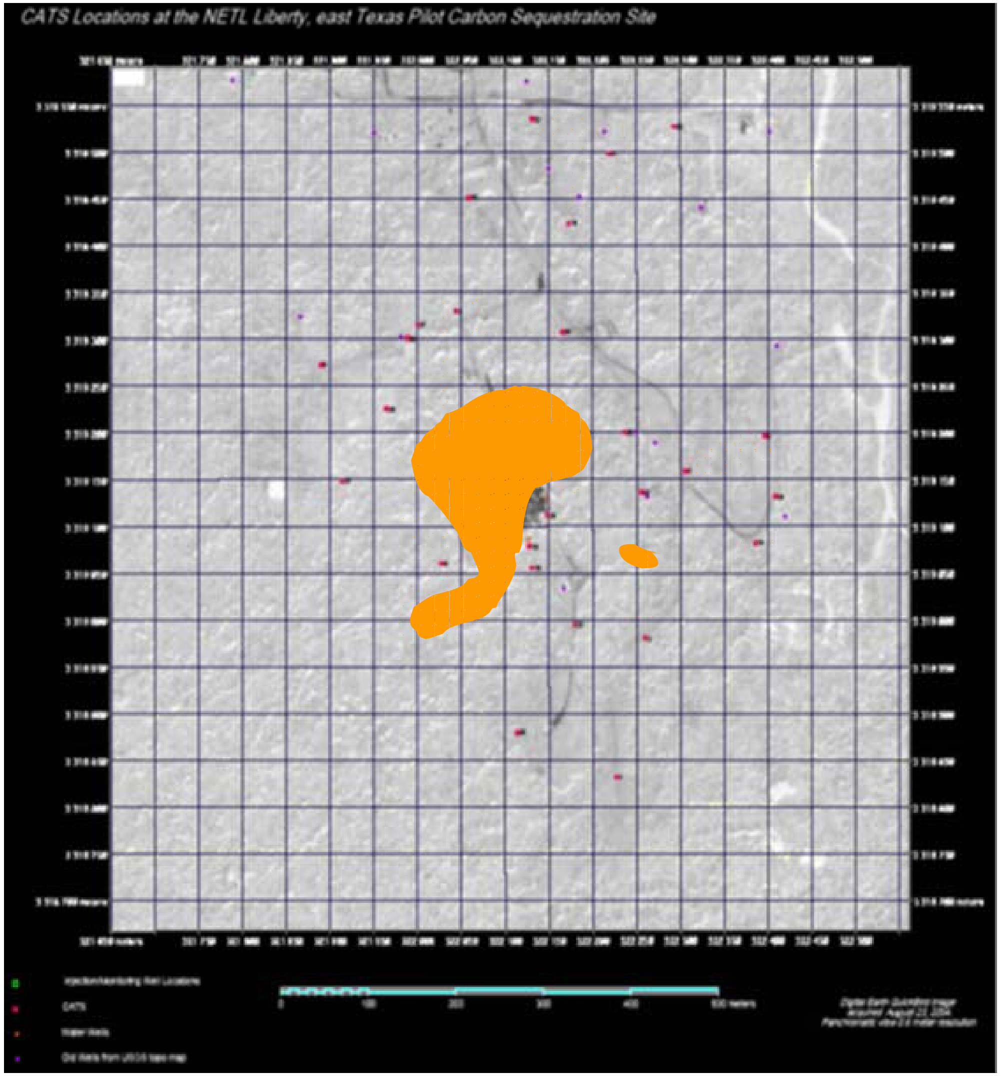
FRIO CAT SET 2: PECH CONCENTRATIONS



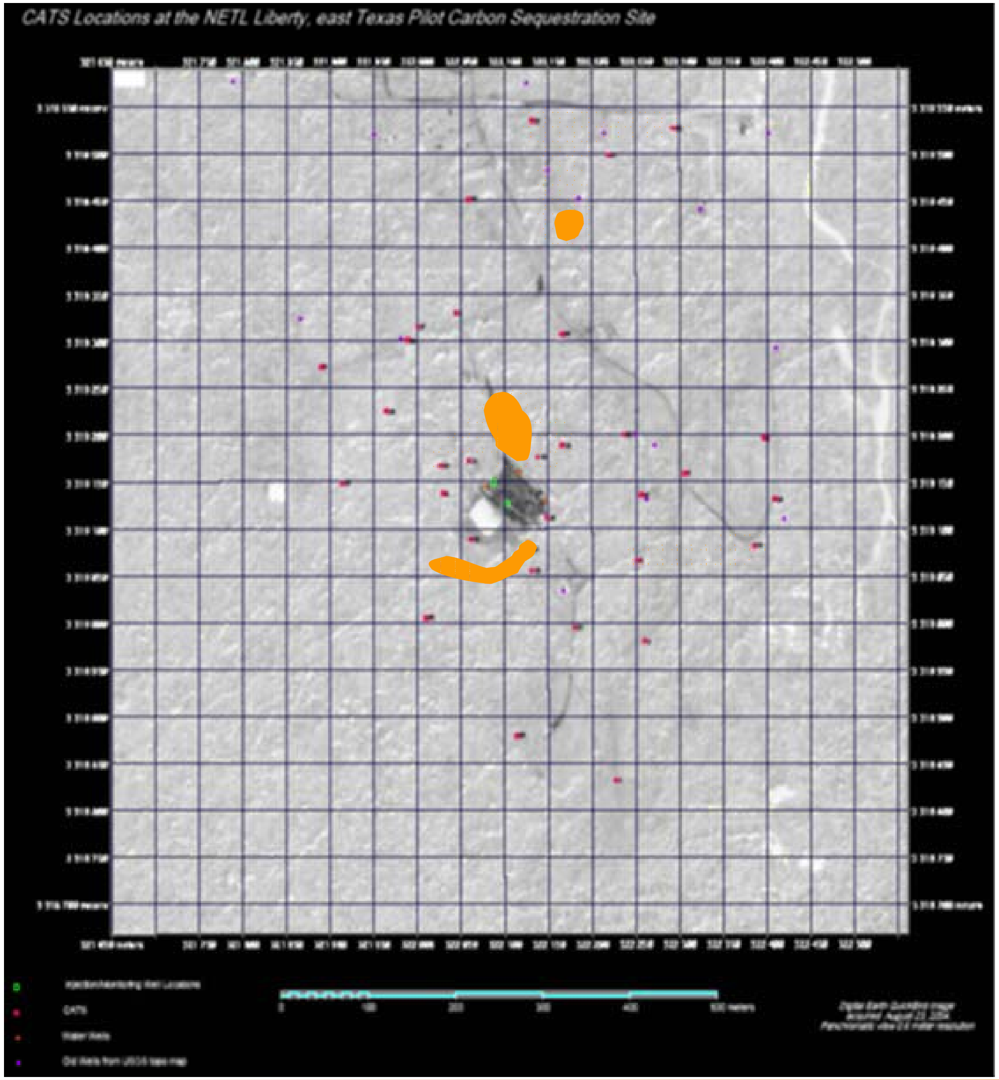
FRIO CAT SET 2: ATMOSPHERIC PECH CONCENTRATIONS



FRIO CAT SET 3: PDCB CONCENTRATIONS



FRIO CAT SET 4: PDCB CONCENTRATIONS



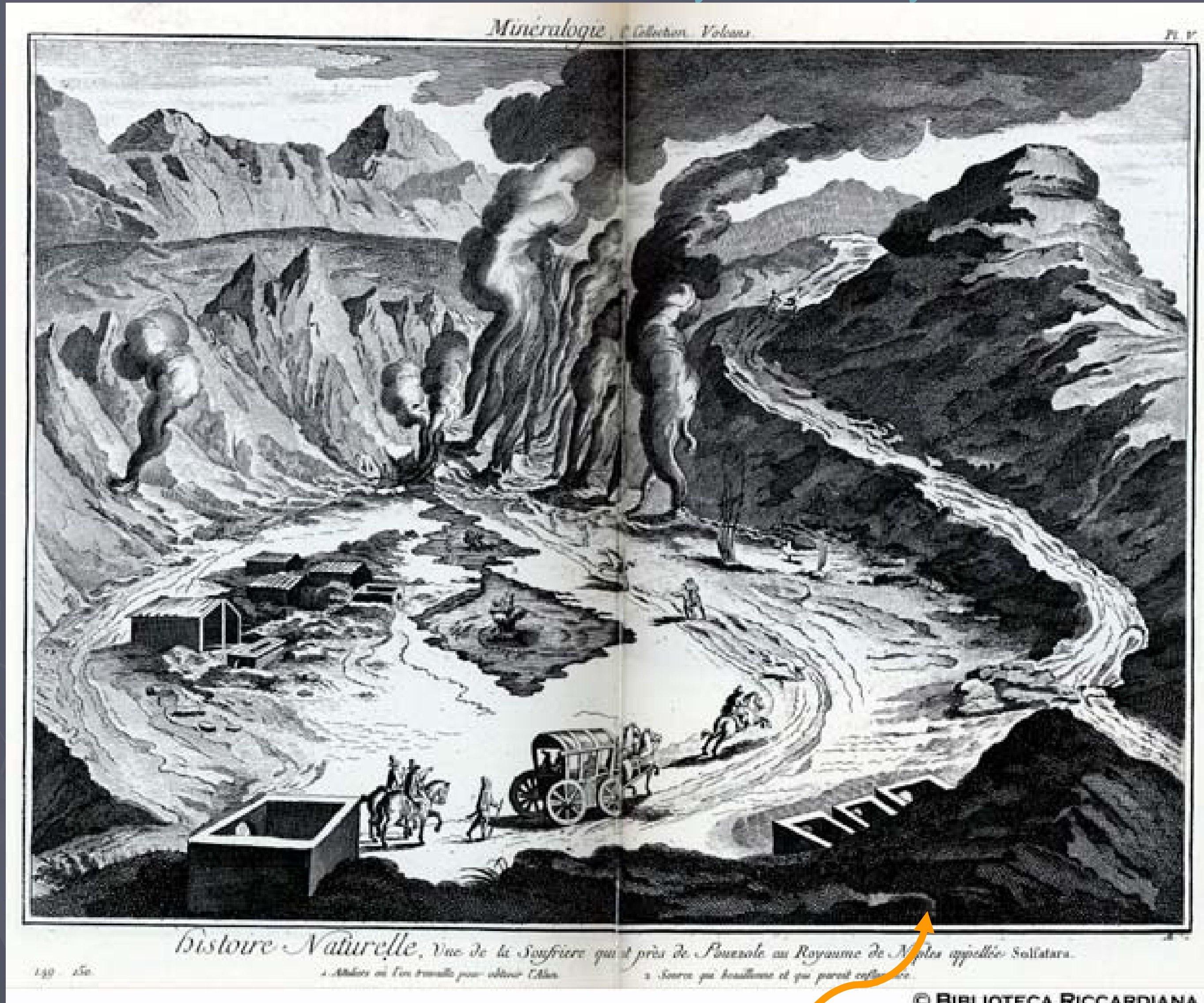
SUMMARY OF CONCLUSIONS FROM NEAR SURFACE MONITORING AT FRIO

- **The Location of Tracers Found in Soil-Gas Remained Relatively Constant between CAT sets, and Between Tracers.**
- **The Overall Total Concentrations of Tracers in Soil-Gas Declined After November 2004.**
- **The Calculated Partial Pressures of CO_2 in Water Well Samples were also Highest Immediately After CO_2 Injection.**
- **No Evidence of CO_2 Flux was Observed with Direct Surface Monitoring. Isotopic Ratios were Characteristic of Biogenic and Atmospheric Sources. The Post-Injection Survey was Conducted in February When Soil-Gas Tracers and Well Water CO_2 were Low.**

THE CAMPI FLEGREI CO_2 ANALOGUE

Voltattorni N., Pizzino L., Cinti D., Galli G., Mastino F., Piccolini L., Quattrocchi F.

1719 image

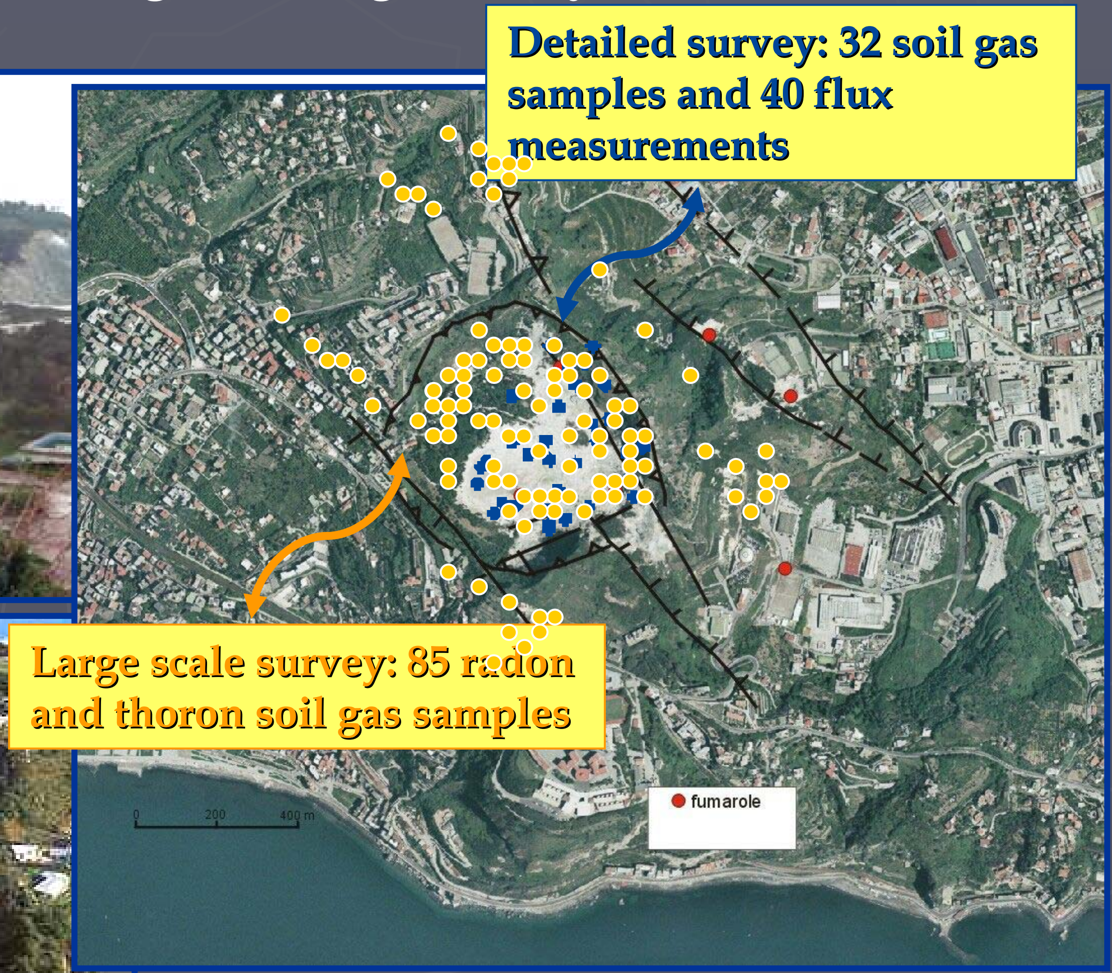

Minéralogie, Collection Volcans
Pl. V
Histoire Naturelle, Vue de la Soufriere qui est près de Pouzzole au Royaume de Naples appellée Solfatara.
149 . 150.
1. Attelier où l'on travaille pour obtenir l'Alun.
© BIBLIOTECA RICCARDIANA

1768 image

1770 image

1800 image

- **Solfatara volcano is located in the central part of Phlegraean fields caldera (Naples, southern Italy).**
- **It is characterized by intense and diffusive fumarolic and hydrothermal activity confirming that magmatic system is still active.**



The bradyseism phenomenon in the Phlegraean fields

During 1982-84 the earth's surface rose by a total of 1.80 metres. This phenomenon is called ***bradyseism*** related to the elastic response of the shallow crust to increasing pressure within a shallow magma chamber.

The "*macellum*" (Temple of Serapide, I century a. c.)

General settings

Campi Flegrei caldera is the result of two large collapses related to the Campanian Ignimbrite and to the Neapolitan Yellow Tuff eruptions.

The Campi Flegrei magmatic system is still active and it is affected by NW-SE and NE-SW faults (typical of the Campanian Plain).

Fumaroles and thermal springs occur in different sectors of the caldera. In particular, fumarolic activity occurs along the coast south of Pozzuoli and in the Mofete area and concentrates in the Solfatara area.

Main goals

Geochemical investigations were performed in the Solfatara and surrounding areas (*Pozzuoli, Cuma-Cigliano, Agnano, Bagnoli* e *Astroni*) in order to:

- **evaluate CO_2, H_2S, CH_4, radon and helium degassing phenomena;**
- **emphasise the origin of the discharging fluids;**
- **quantify the various degree of the gas-steam-rock interaction;**
- **quantify geochemical processes accounting for their final chemical features.**

Work done

Soil gas surveys:

- ✓ areal survey: n° 85 radon and thoron measurements all over the Campi Flegrei area.
- ✓ detailed survey (Solfatara area): n° 32 soil gas (CO_2, CH_4, He, H_2S, O_2 and N_2)samples collected and analysed in the laboratory and the same number of radon measurements performed in loco.
- ✓ flux measurements: n°32 gas (CO_2, Rn, CH_4, He, H_2S, O_2 and N_2) flux measurements in the Solfatara area.

Work done

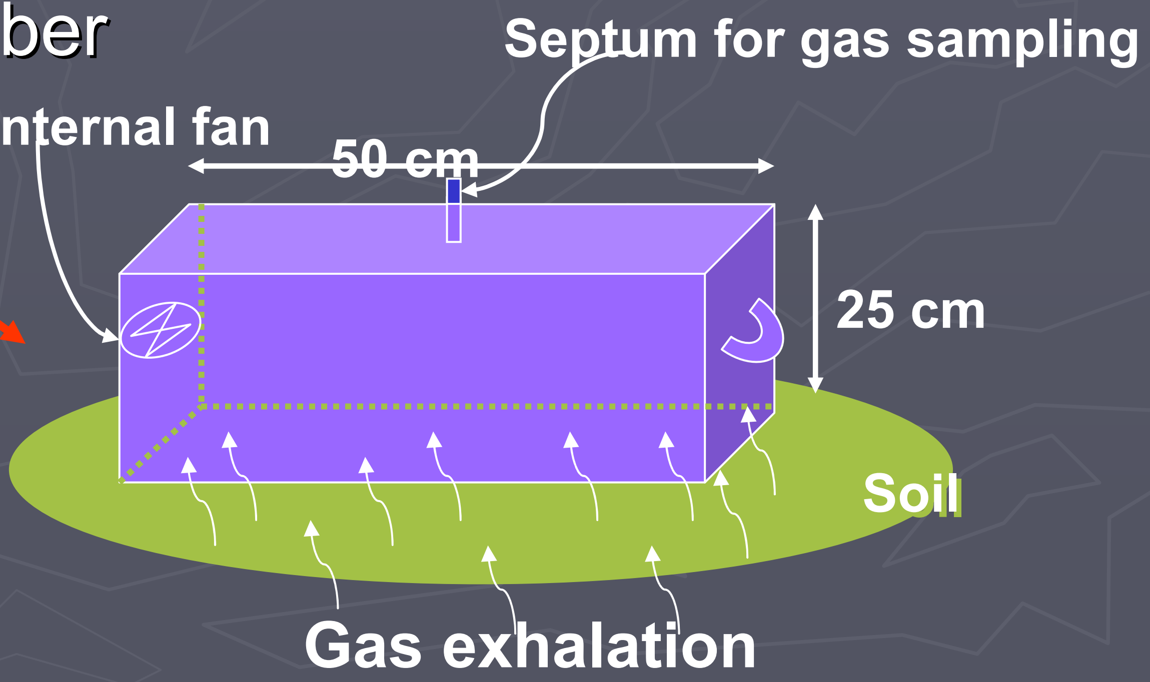
Groundwater survey: n°35 sampling points (springs and wells).

Performed analysis:

- **physic-chemical parameters (pH, Eh, electrical conductivity);**
- **HCO_3 content (by nitration);**
- **H_2S and NH_4 content (colorimetric methods);**
- **total CO_2 content (ion-selective method);**
- **major and minor elements (ionic chromatography);**
- **^{222}Rn content (g spectrometry);**
- **trace elements (ICP);**
- **dissolved gases (CO_2, CH_4, H_2S, O_2, N_2)**
- **stable isotopes (^{18}O, D, ^{13}C).**

field instruments

- Durridge portable radon detector
- 1m stainless steel probe fitted with a brass valve for collecting soil gases
- Metallic containers for storing soil gases
- Portable gas chromatographer
- Accumulation chamber



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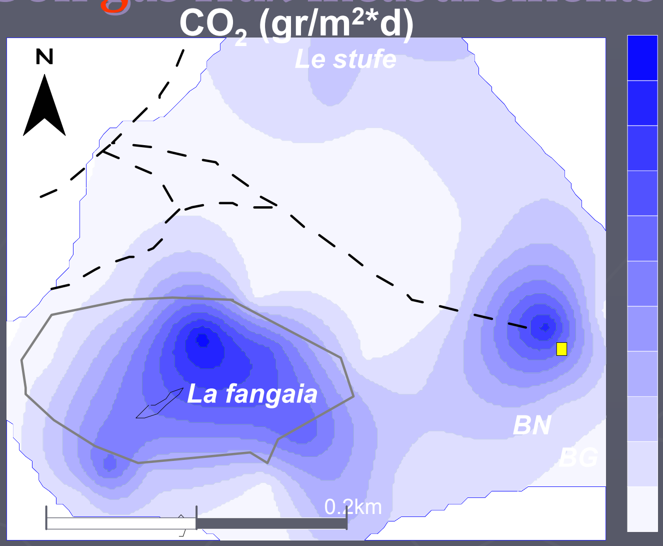
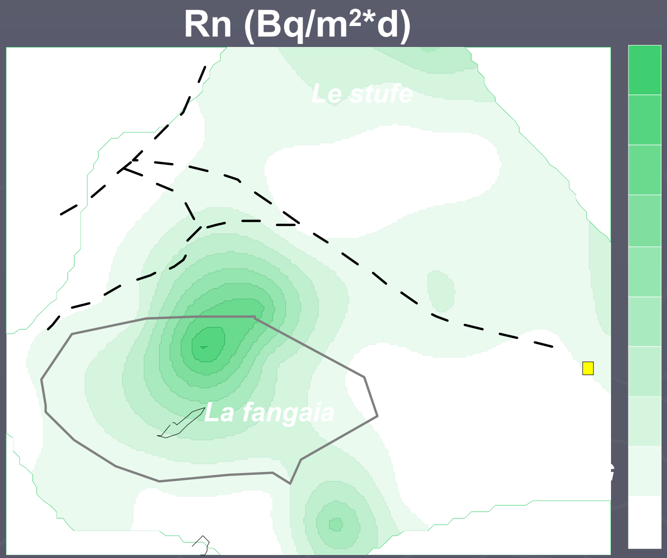
Soil gas flux measurements in the inter crater sector of Solfatara area

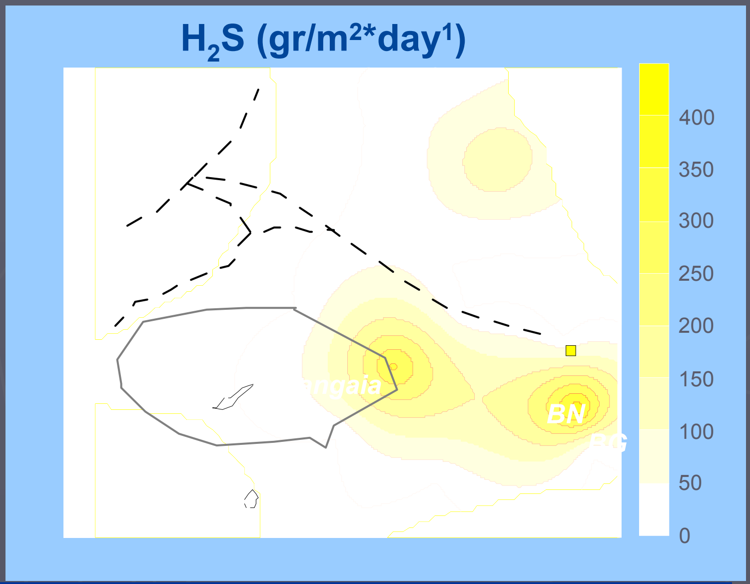




The results, carried out during 2002 summer, show that the whole area discharges between 1200 and 1500 tons of CO_2 a day.

- *Radon flux: mean value 18000 Bq/m²*d*

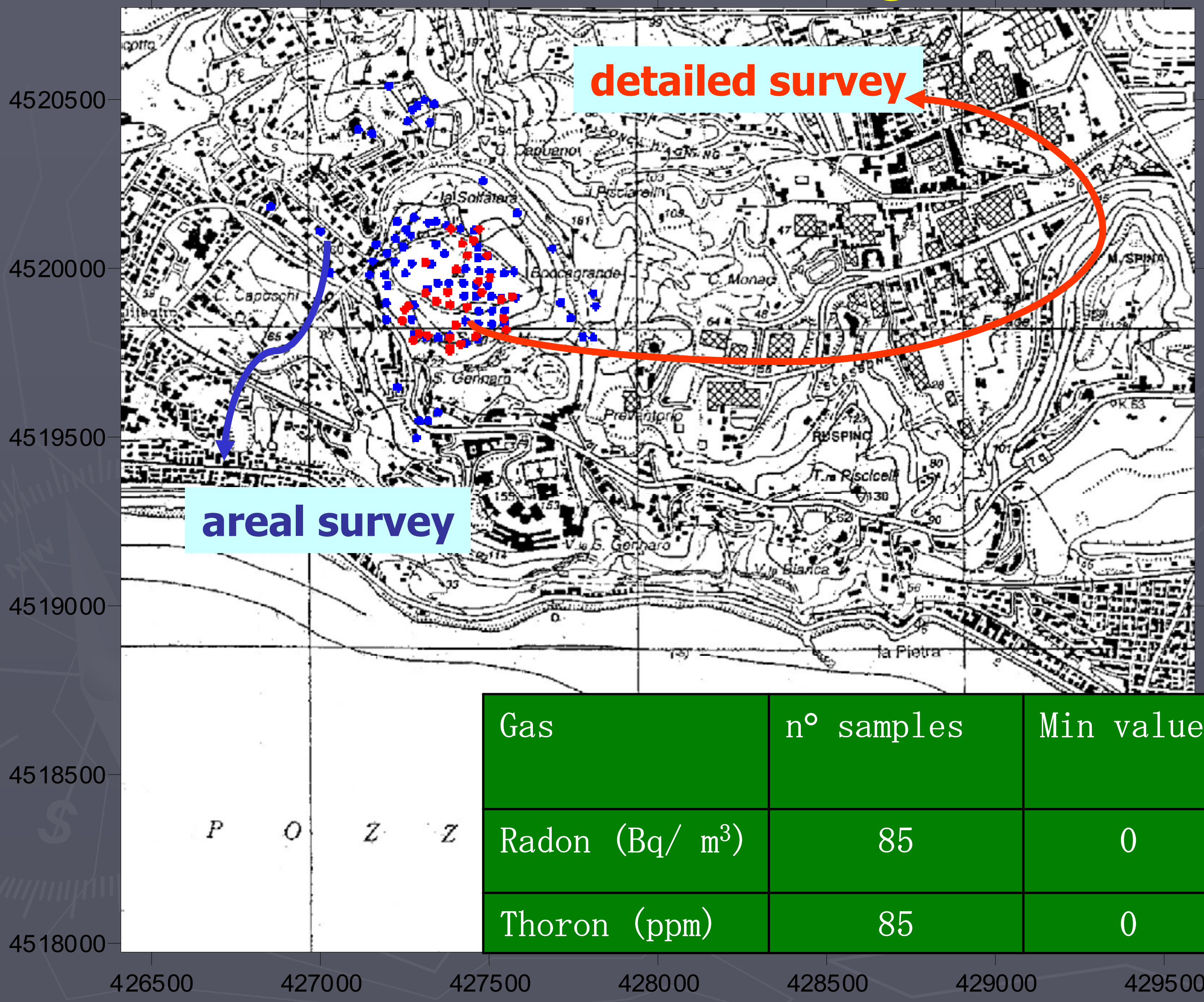
The Solfatara area (Phlegraean fields, Naples)



*H_2S flux measurements highlighted local anomalous spots (values > 100 gr/ m²*d)*

•Within the mouth of the main fumarole, there are salts contained in the vapor condense among which REALGAR (AsS), CINABRO (HgS) and arsenic trisulphide (As_2S_3) which give a yellow-reddish color to the surrounding rocks

Soil gases sampling sites



Main statistics

Gas	n° samples	Min value	Max value	Mean
Radon (Bq/ m^3)	85	0	42000	4984,89
Thoron (ppm)	85	0	19600	3360,96

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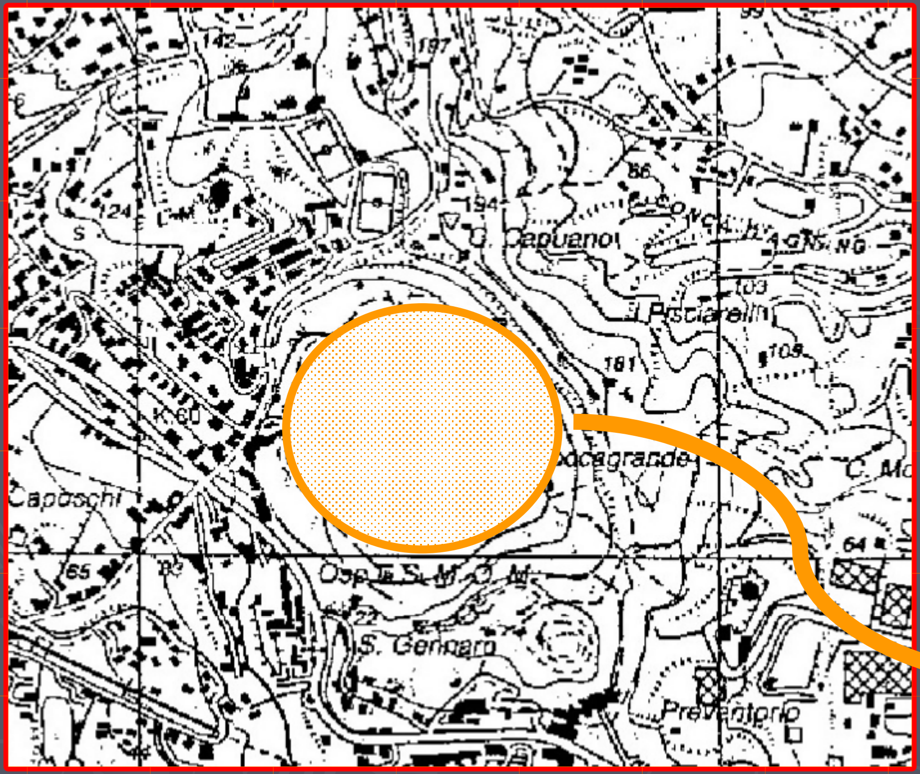
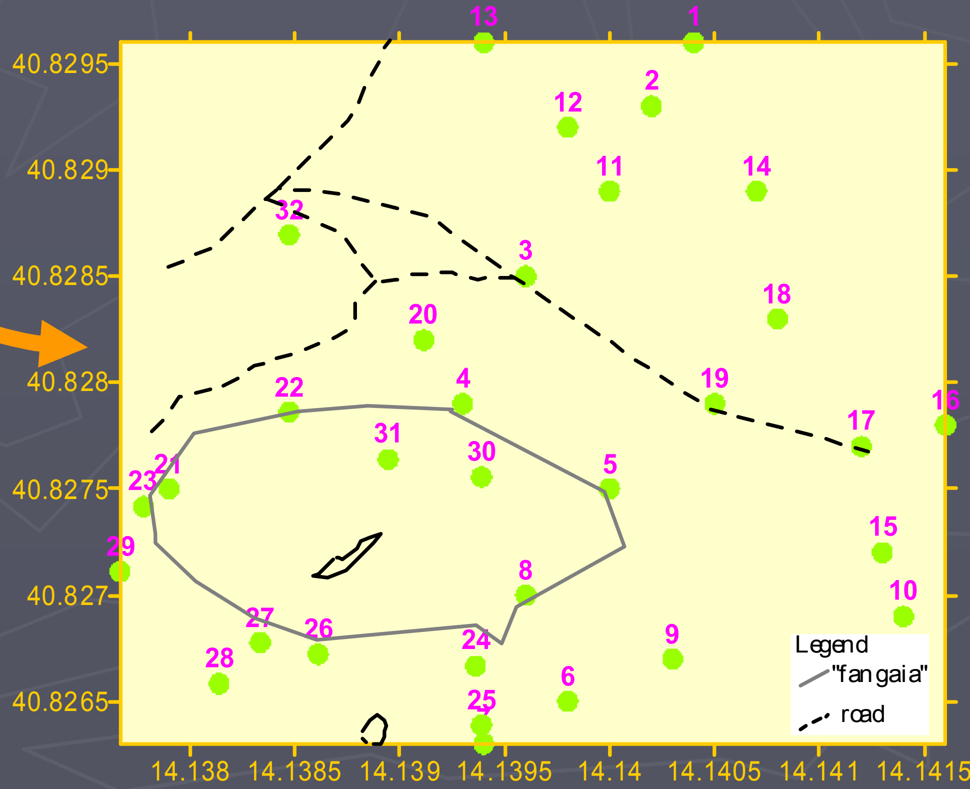
Detailed survey





Main statistics

Flux data

Gas	n° samp.	Min value	Max value	Mean
CO_2 (gr/ $m^2{}_*d$)	32	83.3	5287.20	1127.32
CH_4 (mgr/ $m^2{}_*d$)	32	0	1524.96	361.49
H_2S (gr/ $m^2{}_*d$)	32	0	390.24	28.34
Rn (Bq/ $m^2{}_*d$)	32	0	92763.87	18234.52

Soil gas concentrations

Gas	n° samples	Min value	Max value	Mean
CO_2 (%, v/v)	32	0.0038	7.26	3.89
CH_4 (ppm)	32	0	165.51	85.10
H_2S (%, v/v)	32	0	2.62	0.52
Rn (Bq/ m^3)	32	0	33767	5504.44
He (ppm)	32	0	9.048	3.5152

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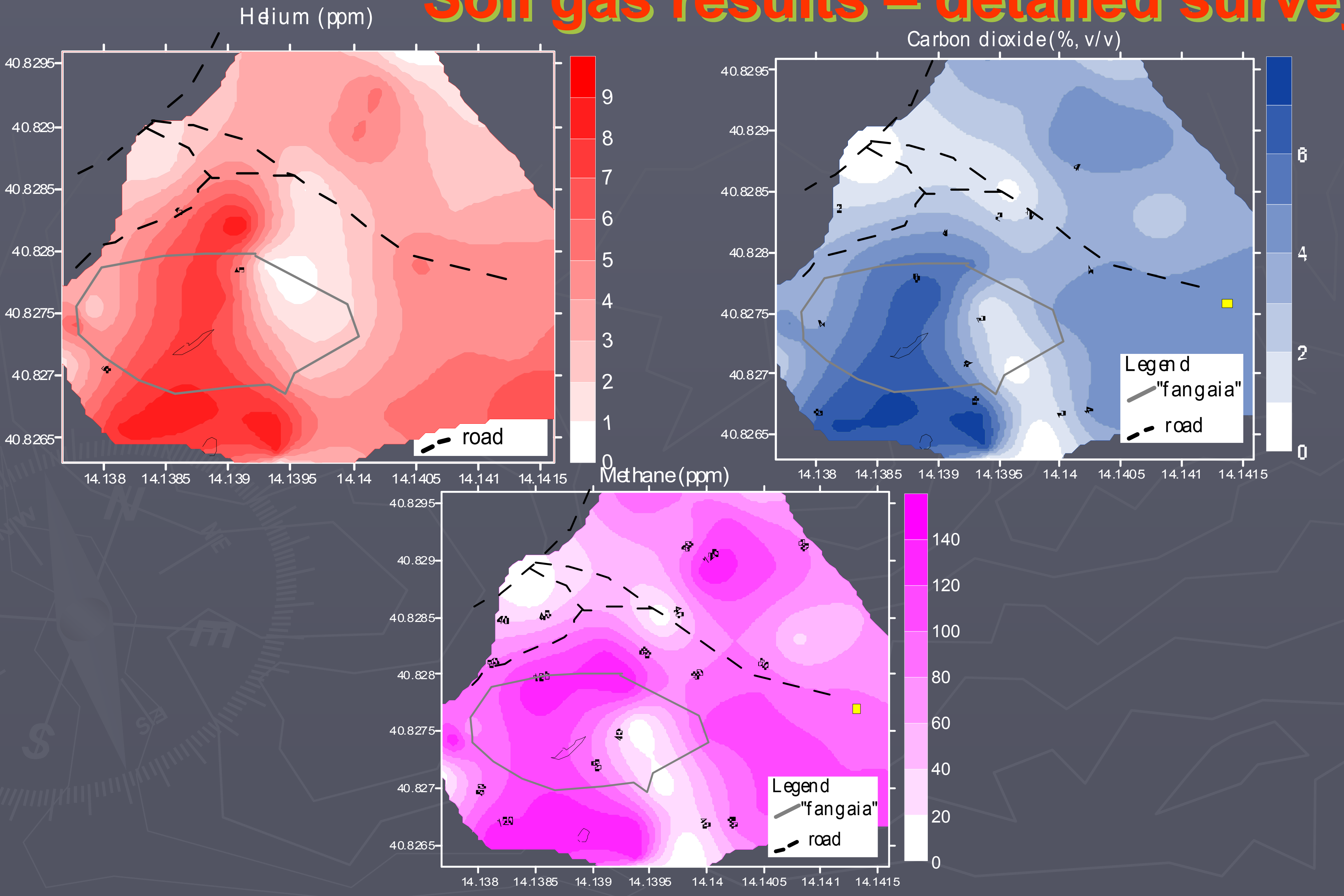
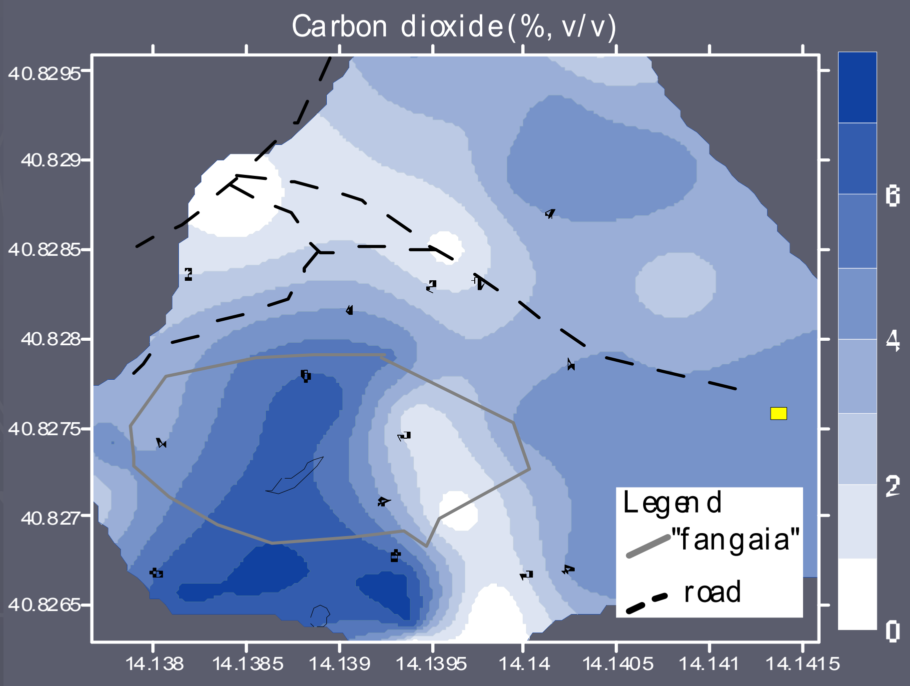
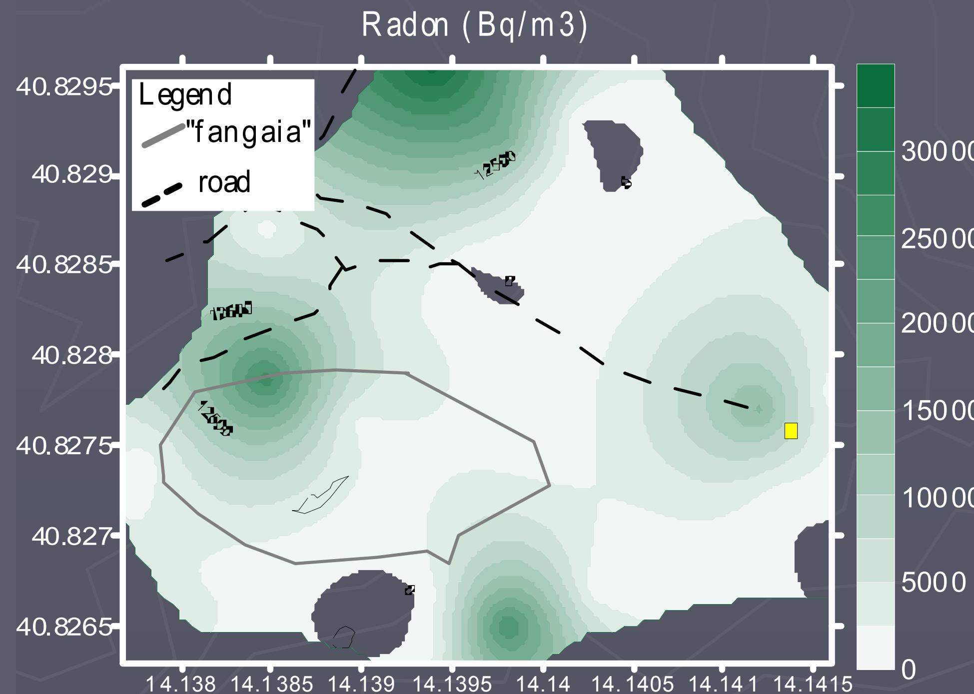
Soil gas results – detailed survey

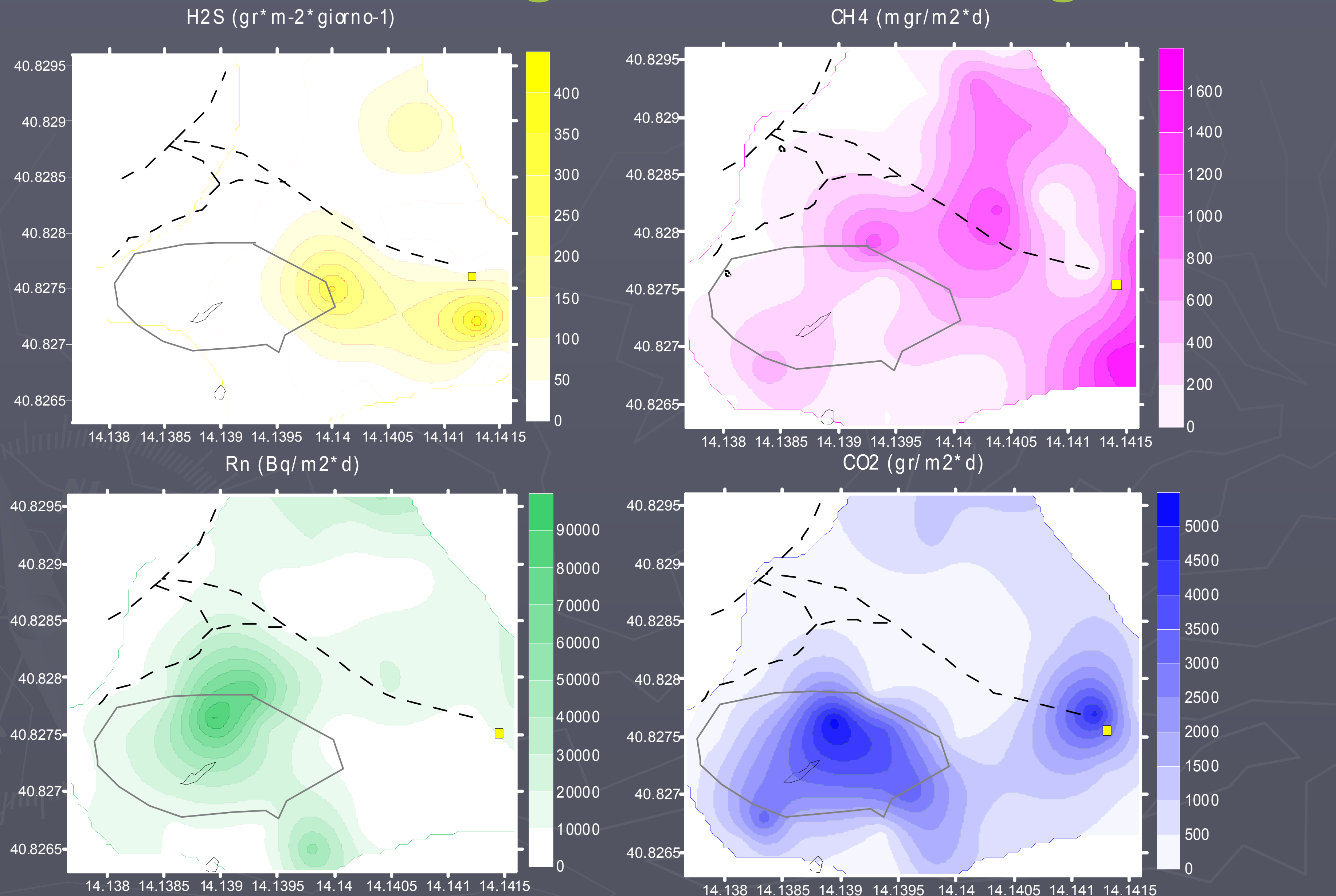


Soil gas results – detailed surve





Soil gas results – flux gas survey



Gas surveys - **Conclusions**

- Results from soil gas samples analysed both in the field and in the laboratory are in agreement with gas flux results. Local trends are very similar, although soil-gas concentrations show a more diffusive distribution, as it was reasonable to suppose.

- Gas flux distribution highlighted a clear correspondence between gaseous emanation and local tectonic: in particular, radon and carbon dioxide have a dominant flux in a NE-SW direction and, in a lesser extent, in a E-W and a NW-SE directions.

- These directions are in agreement with regional extensional tectonic and with transverse structures considered as transfer faults along which the main regional volcanoes are located (Acocella *et al.*, 1999).

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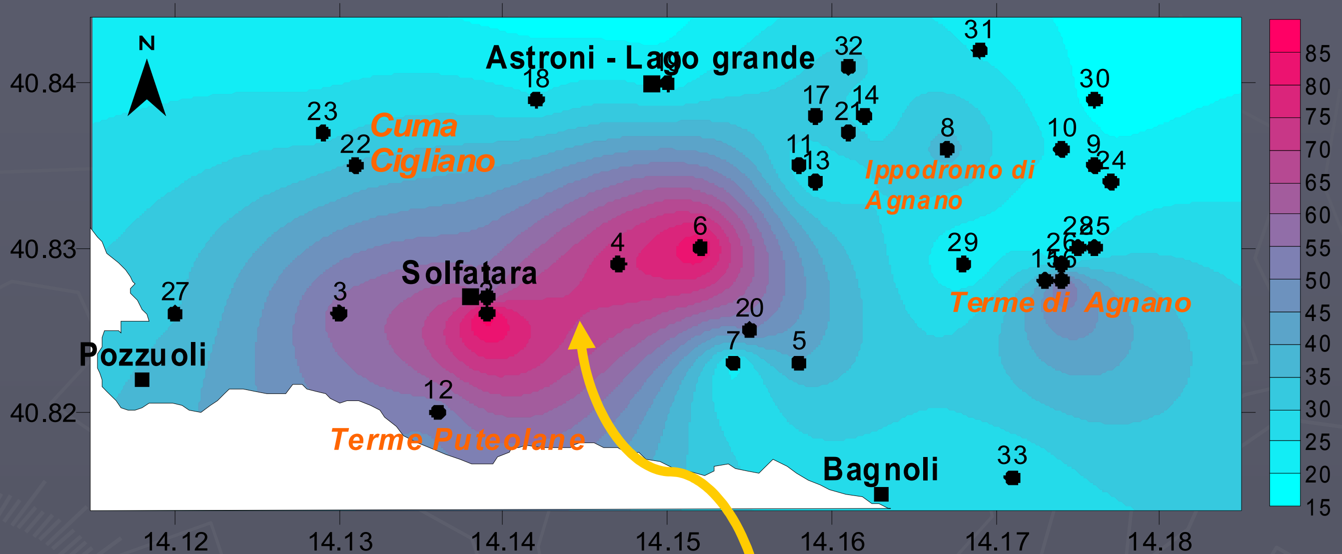
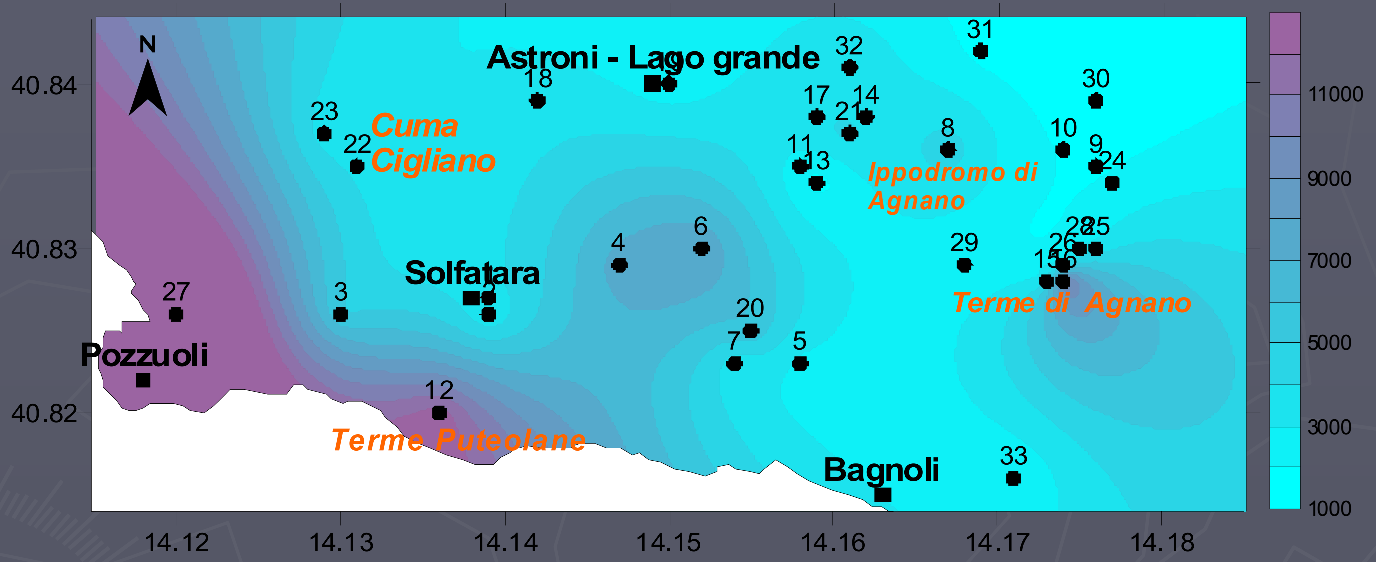
Water results – temperature (°C)



Hottest areas (high thermalism) are connected directly to magmatic chamber

Water results - electrical conductivity (µS/cm)



Highest electrical conductivity values are in proximity of the coast suggesting sea water mixing phenomena:

- **Terme Puteolane :12000 mS/cm**
- **Tempio Serapide: 20000 mS/cm**

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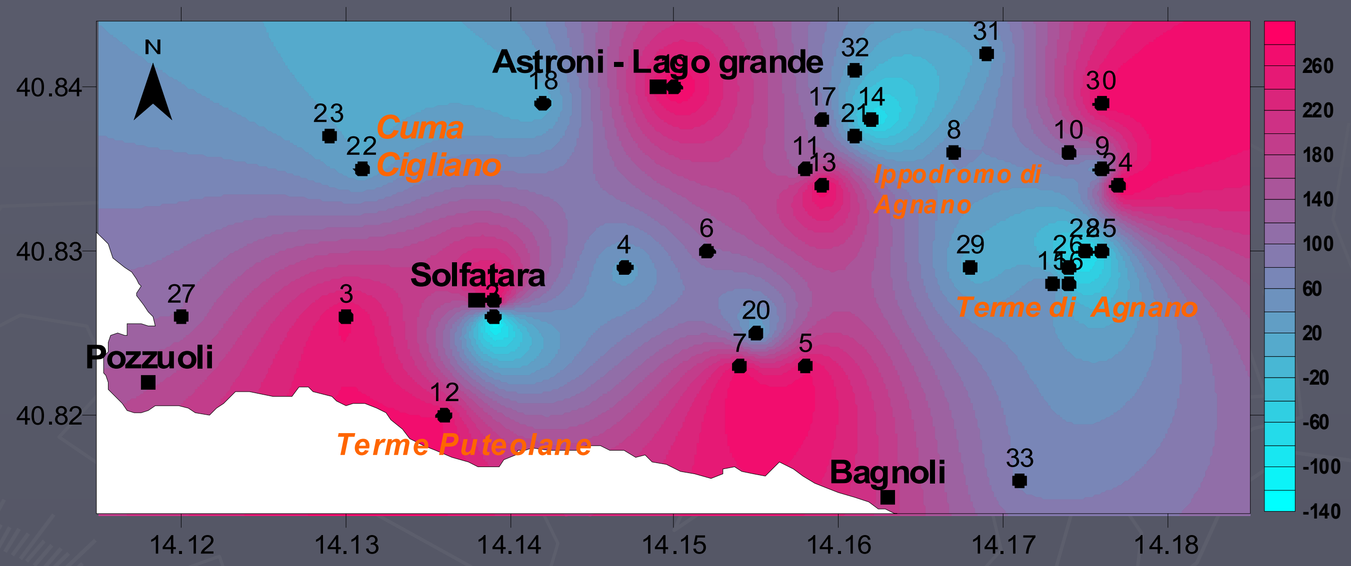
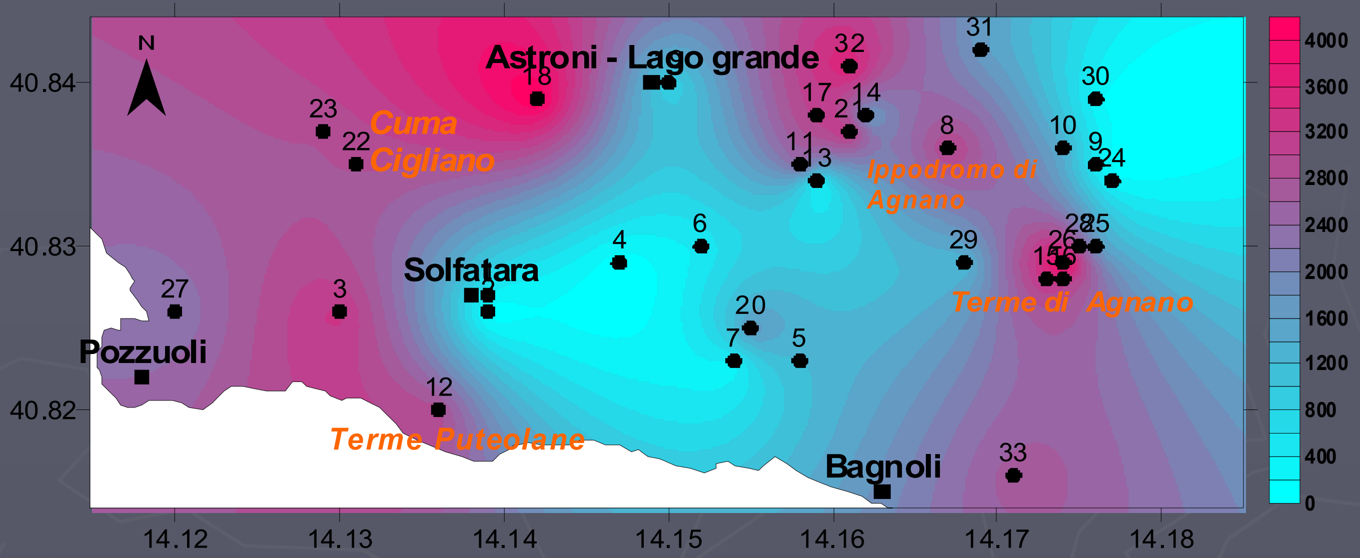
Water results – redox potential (Eh)



<u>- Negative values</u> highlight three well defined areas characterised by highest H_2S values: Solfatara area, Agnano spa/race-course, Cuma/Cigliano area.

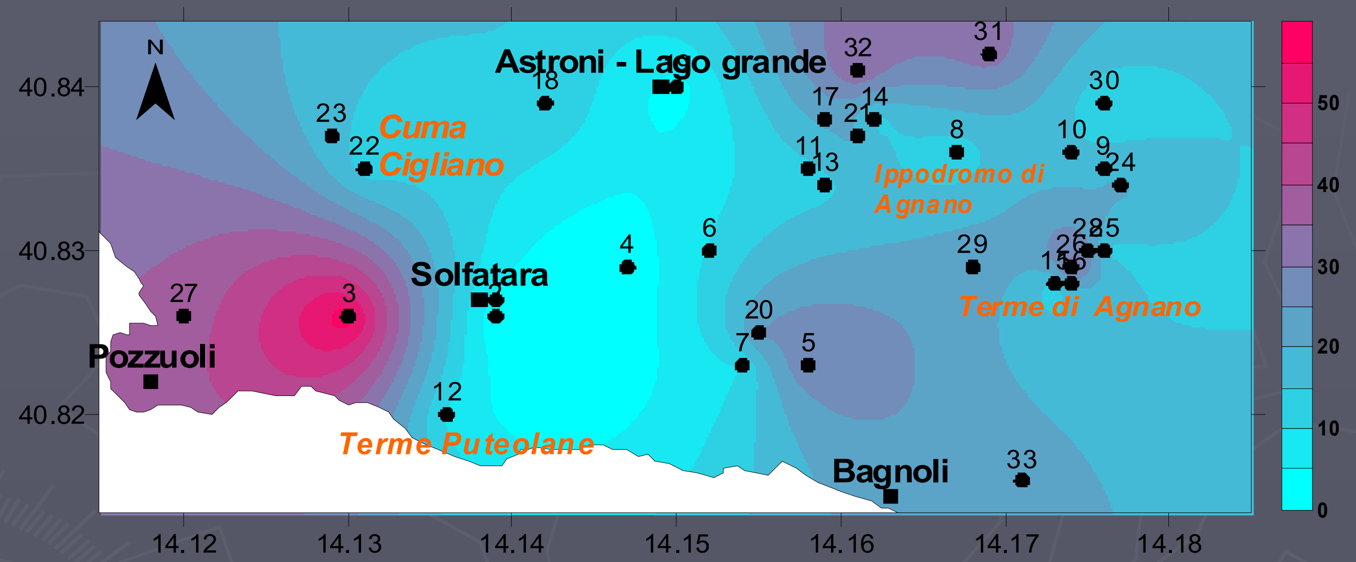
<u>- Positive values</u> could be due to the sea water influence (along the coast), to the presence of superficial waters and/or to the absence of fractures that control CO_2 flux.-

Water results - total CO_2 content (ppm)



- <u>Total CO_2 content is the amount of all dissolved carbonatic species</u> (CO_2+HCO^-_3+CO^{--}_3).
- Highest values are in the Agnano spa/race-course, Cuma/Cigliano area and along the Coast.
- In the Solfatara area, steam dilutes CO_2 and H_2S content except in the “fangaia” zone.

Water results – radon distribution (Bq/l)



Radon is random distributed and there is, apparently, any correlation with the other species: it is possible to distinguish some anomalous spots where CO_2 content is low suggesting “stripping” effects.

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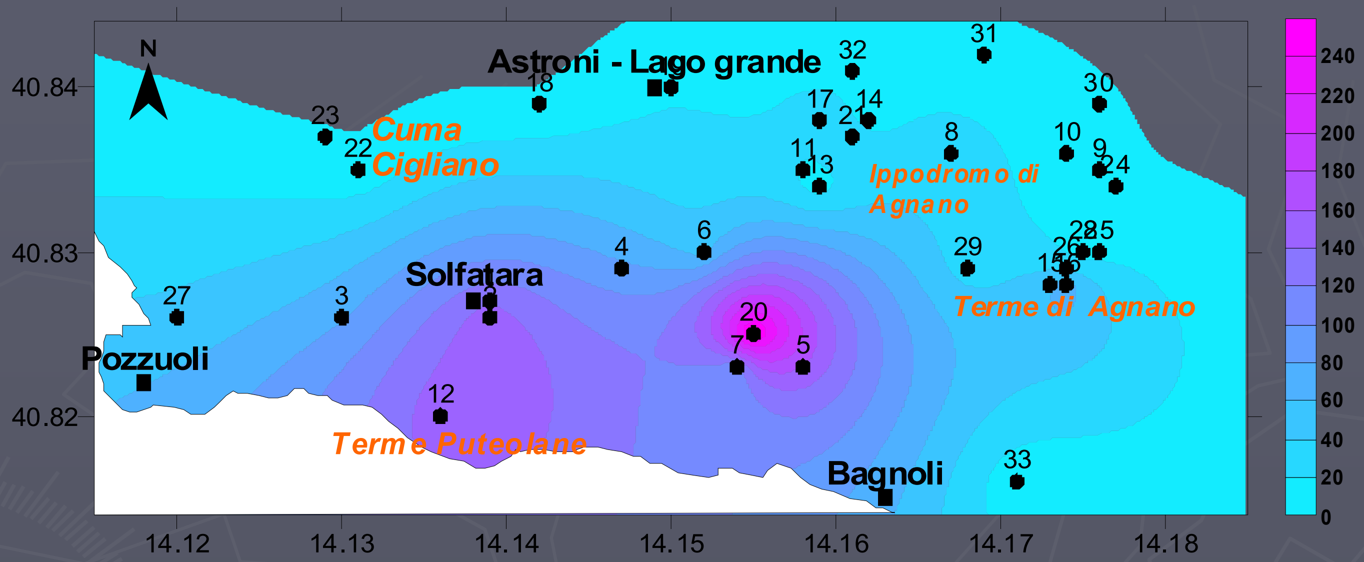
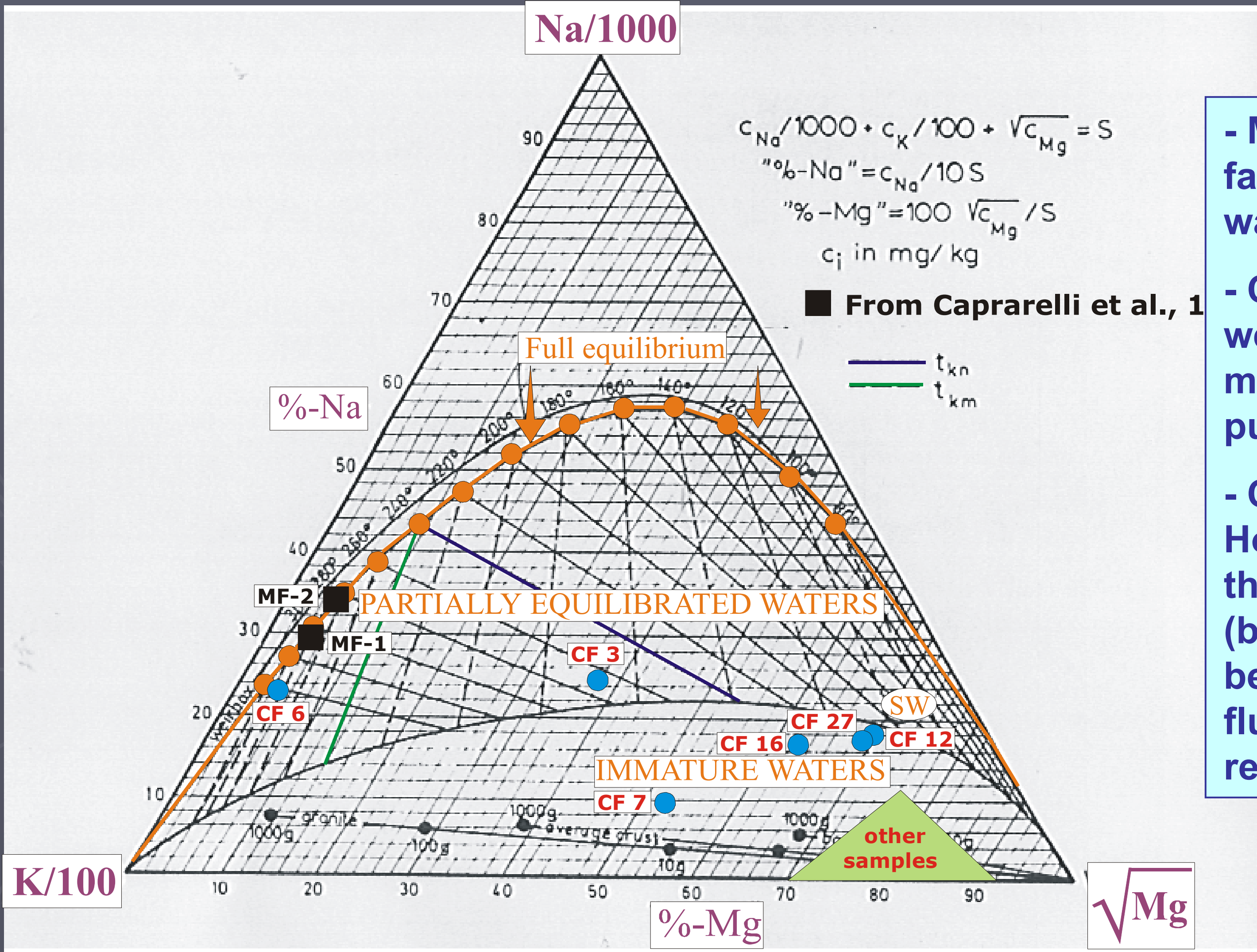
Water results – H_3BO_3 distribution (ppm



Boron is mobilised in volcanic areas: B content is directly correlated with high temperature.

Water results – Giggenbach diagra

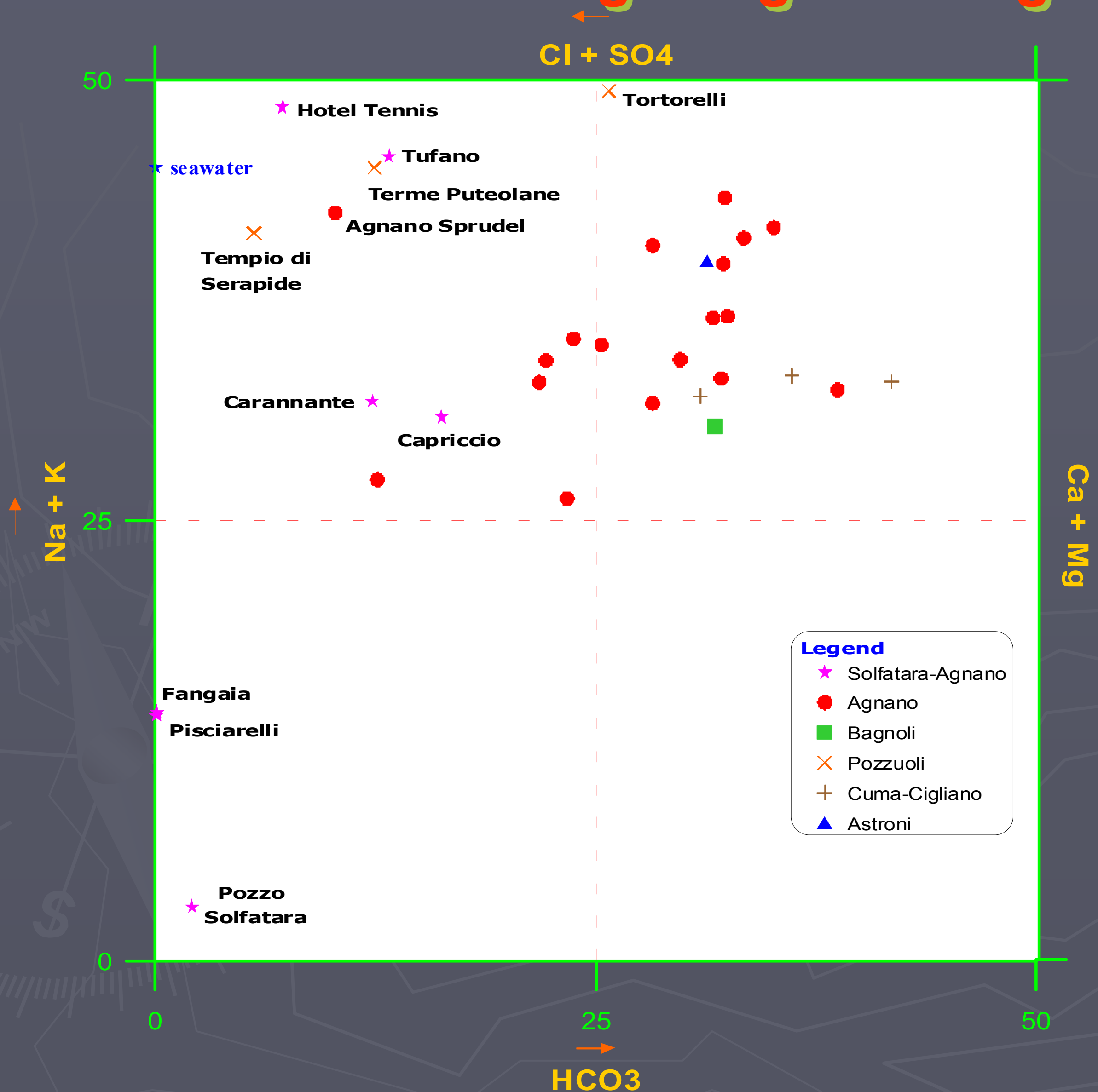


- Most part of samples fall in the "immature waters" area excepting:

- CF3 sample (Tortorelli well): mixing between a mature water and a pure term (end-member)

- CF6 sample (Tennis Hotel) that is close to the deep end-member (brines): equilibrium between circulating fluids and rocks in the reservoir.

Water results - Ludwig-Langelier diagram



It is possible to distinguish four main chemical families:

1. **Solfatara-Agnano family: interaction between superficial waters and acid and reducing gases.**
2. **Agnano family: interaction between deep CO_2 and volcanic rocks.**
3. **Cuma-Cigliano family: high CO_2 content.**
4. **Pozzuoi area: mixing between sea-waters and deep brines.**

Conclusions (1)

The Ludwig-Langelier diagram highlighted four different chemical groups:

1) **Na-Cl waters**: in this group we find the samples Hotel Tennis, Tufano, Carannante and Capriccio (belonging to the Solfatara-Agnano family), Puteolane and Serapide (belonging to the Pozzuoli family), as well as some samples of the Agnano family (Agnano sprudel). These waters are characterized by a very high electrical conductivity (up to 20 mS/cm) and high discharge temperatures (up to 85°C, as in the Hotel Tennis well). The only exception is represented by the Tufano well, being less mineralized (electrical conductivity equal to 3 mS/cm) and colder (temperature of 22.4°C) with respect to the above mentioned samples.

The origin of these waters may be due to :

- a huge mixing with seawater for the samples located along the Tyrrhenian coast (Tempio di Serapide and Terme Puteolane)
- various degrees of mixing between cold shallow aquifers and hot deep brines (Agnano-Solfatara area)
- mixing between deep brines and shallow steam-heated aquifers (Hotel Tennis).

Conclusions (2)

2) **Na-HCO$_3$ waters**: in this group we find the bulk of the waters belonging to the Agnano family, samples located in the Cuma-Cigliano, Astroni and Bagnoli areas, and the Tortorelli well of the Pozzuoli family.

All samples show relatively high saline contents (values of electrical conductivity ranging from 2 to 5 mS/cm) and temperatures spanning from 18 to 57°C).

The origin of these waters may be due to the interaction of CO$_2$-rich fluids with the young vulcanites cropping out extensively in the area. In some cases (Tortorelli sample) the high temperature and the very peculiar chemical features (very low content of Ca and Mg, high bicarbonate content and alkaline pH) are due to the interaction between gas, steam and shallow clayey strata, with precipitation of carbonatic species at the permeability interfaces and cationic exchange processes.

Conclusions (3)

3) **Sulphate-acid waters**: in this group we find samples of the Solfatara-Agnano area (Fangaia and Pisciarelli). These waters shows electrical conductivity values of 3-8 mS/cm and very high discharges temperatures (57-74°C). They are typical acid waters (pH = 2) whose origin is due to the dissolution of steam and reducing gases into shallow aquifers; the sulphate signature is due to the oxidation of the H_2S.

4) **Ca-SO_4 waters**: this chemistry is showed only by the Pozzo Solfatara sample, located inside the homonymous volcano. This water shows an electrical conductivity value of 3 mS/cm and a discharge temperature of 89°C, the hottest in the area. Its chemistry may be due to the mixing between hot steam and reducing gases and Ca-SO_4 rich fluids.

……TO BE CONTINUED