3rd MONITORING NETWORK MEETING

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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, CO2CRC
Susan Hovorka, Bureau of Economic Geology
Nick Riley, British Geological Survey
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IEAGHG Monitoring Network, Melbourne, Australia

31st October 2006

Third meeting of the International Monitoring Network for Geological CO_2 Storage

October 30 – November 2, 2006

Meeting report

Organised by IEA Greenhouse Gas R&D Programme and CO_2CRC

Rendezvous Hotel, Melbourne, Australia

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Monitoring and Verification Network Meeting
Melbourne, Australia
31st October 2006

1. INTRODUCTION

The third meeting of the monitoring and verification network met in Melbourne, Australia over 3 days in October and November 2006. The meeting's objective was to provide an integrated set of monitoring and verification (M&V) guidelines to encourage further public, regulatory and technical community discussion for wide scale deployment of CCS technology. The objectives were realised by addressing the questions:

- What is the framework of a Monitoring, Evaluation, Reporting and Verification (MERV) protocol for wide scale CCS deployment?
- How do we provide assurance of storage integrity through well, seal and containment monitoring technology?

The meeting brought together national and international government regulatory agencies, non-government organisations and Monitoring and Verification (M&V) technical communities in an intensive series of workshops. It was followed by a field visit by train to the site of the CO2CRC Otway Basin Pilot Project (OBPP) in South West Victoria.

The third Monitoring Network Workshop built on the material presented and discussed at the first two meetings held in Santa Cruz, California 2004 and Rome 2005. These meetings had a principle focus of bringing together, through presentation and discussion, both the regulatory groups involved in setting monitoring programmes associated with CO_2 storage and those projects that are implementing such programmes in different environments.

- The inaugural meeting of the Monitoring Network demonstrated that there is a large tool box of monitoring techniques that can be applied to both surface and sub-surface monitoring of CO_2.
- The second meeting focused on what were the monitoring requirements and how would they be defined with respect to risk and regulatory requirements.
- The third Monitoring meeting further enhanced the dialogue of regulatory and technical integration, with joint development of Monitoring, Evaluation, Reporting and Verification (MERV) guidelines.

2. WORKSHOP ATTENDEES

The meeting was attended by 62 delegates from 10 countries (Appendix 2). The delegates represented Australian and North American regulators, international industrial operators and geological researchers from Australia, Europe, Japan and North America.

3. WORKSHOP PROGRAMME

The programme and agenda for the meeting are included in Appendix 1. The meeting was preceded by a workshop on the regulatory needs for monitoring, evaluation, reporting and verification (MERV), which involved presentations from regulators and researchers and a facilitated discussion on the design of MERV protocols. The Monitoring Network meeting was divided into a series of sessions, which focussed on specific topics within the area of monitoring and verification:

Session 1 - Plenary

Session 2 - Monitoring Issues: Wells and Seals

Session 3 - Containment and Integration

Session 4 - The Latrobe Valley case study

Session 5 – Discussion

Session 6 – Otway Basin Pilot Project Site visit.

4. SESSION 1: PLENARY

4.1 Introduction of Minister – Peter Cook

Mr Theophanous is minister for energy industries and resources, and has been advocating clean energy technologies for many years.

4.2 Minister's opening address – The Honourable Theo Theophanous, Minister for Resources

Climate change is a political issue and requires political solutions – technical, economic and social solutions are not enough. Mr Theophanous welcomed delegates to the meeting and recognised the importance of the Otway Basin Pilot Project, both to Victoria and Australia, as well as internationally.

A regulatory and legislative regime will be needed for CCS implementation and Mr Theophanous welcomed the dialogue undertaken yesterday between network delegates and Australian regulators.

Australia produces 1.5% of global greenhouse gas emissions, although it has only 0.4% of global population. If countries such as Australia do not take the lead, we can not expect other countries, such as China, to act. The Stern Review is important because it places emphasis on the economic costs of climate change; £3.68 trillion was estimated as global cost of unmitigated climate change. Immediate action will cost only 1% of global GDP. Many impacts were outlined.

The Victorian government believes action should therefore be taken now. One action is investigating potential for CCS as one technical option, which could save 25% of global emissions. AUS$103.5 m has been allocated to R&D on clean energy technologies. Mr Theophanous was pleased to announce the AUS$5bn Monash project to transform brown coal into diesel with CCS – this is biggest of its type in the world.

How do we bring the technology to market? This requires a market for carbon. Victoria developed a model for an emission trading scheme, accessed via the web, a cap and trade model.

Renewable energy sources are important and Victoria is keen to introduce renewable energy, to grow from 4% current production to a target of 10%, including wind- and solar-based production.

4.2.1 Questions & answers

What impact would an Australian ETS have on the price of electricity? Model developed by all state jurisdictions excluding federal government. It included economic modelling, which predicted price increases of around AUS$30 pa for a typical household during first 10 years, increasing to AUS$50 thereafter. However this does not include external environmental impacts arising from climate change.

Do you think current stakeholder dialogue is enough or will more environmental impacts be needed before real action is taken? Debate has been more intense recently. Victoria's 10-year drought has helped to focus the debate and could be due to melting glaciers, which have shifted winds that have previously brought Victoria's normal rainfall. This is a symptom of climate change and an ETS could help to mitigate this. We can look to the

international agreements on ozone protection and CFC reductions as a hope that such agreements can be achieved.

What do you see as the next step in 20 years for Victoria? If re-elected, we will move to implement the ETS at last on a state basis, if not at federal level and will address energy efficiency through mandating.

4.3 IEAGHG overview on network activities – John Gale, IEAGHG R&D

Congratulations were given to CO2CRC for taking the opportunity to gain benefit of the delegate's attendance for a peer-review of the Otway Basin pilot project.

An overview of IEAGHG's network support in six networks was presented, on both capture and storage (capture, oxyfuel, biofixation, risk assessment, monitoring and well bore integrity).

A large number of monitoring techniques have been developed and this has led to the online monitoring selection tool being developed by BGS.

Only a few CO_2 storage demonstration projects have been instigated so far but more research projects are coming. So far, no evidence of leakage has been observed. Selected projects Weyburn, Sleipner, Rangely (where CH_4 microleakage is biologically converted to CO_2) were briefly reviewed. It was concluded that we can not define a generic leakage rate.

A storage facility should be designed for zero leakage. Wellbore integrity and performance assessments are being developed. Remediation strategies have been estimated to cost around $0.1 per tonne, estimated from an IEAGHG study. Ecosystem impacts currently being reviewed by BGS.

IEAGHG will develop briefing papers, information sheets and topical reports – which aim to develop positive but unbiased messages on CCS safety and environmental impacts.

Charles Christopher, BP – CO_2 is less dense than surrounding fluids therefore wants to migrate upwards. It was recognised very early on that monitoring was very important. The CCP project had 2 aims: reducing capture costs and establishing safe storage. Therefore, technologies were reviewed. 4D seismic is a good method but has minimum detection limits reducing its usefulness for verifying stored volumes. Key issues are both technical and non-technical and include:

Technical issues:

- What are method sensitivities?
- Which methods do we use in what environments?
- How long do we need to monitor?

Non-technical issues:

- Who is the audience?
- Do they understand technologies?
- How does this understanding influence people's opinions of storage?

An example of gas storage was presented close to Houston and a project in California is planning to store CO_2 store under Los Angeles, including pipelines through LA.

Questions:

How do you address perceived risks within communities? Comparative risk assessments is very difficult. Difference may be due to voluntary nature of some risks.

4.4 CO2CRC Otway Basin Pilot Project Organisation – Peter Cook

An introduction to CO2CRC was provided: started research into CCS in 1998, now has a budget of AUS$140m over 7 years and 100 researchers, through to 2010. The need to implement clean energy technologies is increasingly being recognised by coal industry and power industries. Many government initiatives have been launched and CO2CRC is collaborating internationally e.g. Frio project. New Zealand part of CO2CRC (a Kyoto signatory). CO2CRC needs to engage more with power companies.

CO2CRC has three strands: capture, storage and pilots and demonstration projects, with the aim of assessing scope for CCS across the Asia-Pacific region and to encourage new commercial opportunities.

Several Australian projects were reviewed:

- Monash Project – AUS$5bn brown coal to diesel with CO_2 storage offshore.
- Hazelwood post-combustion capture will be retrofitted at brown coal power station.
- Zerogen project in Queensland to assess storage potential.
- Oxyfuels project
- Fairview CO_2 ECBM project.
- Gorgon project is a large LNG project with 4Mt CO_2 pa due to start in 2010 or later.

The Otway Basin Pilot Project was briefly introduced. The Gippsland Basin has forty years of oil production with an estimated 6Gt of storage capacity. In contrast, the Otway Basin is mainly offshore with limited gas resources, divided into a series of fault blocks, which contain a number of gas fields. One advantage of the Otway Basin is the availability of cheap CO_2. The storage target is a depleted gas field – both owned by CO2CRC. The original concept was to separate CO_2 from CH_4, but now planning to inject all the gas, though planned 97% CO_2 injection within 12 months. Baseline seismic and fluid geochemical surveys have been undertaken.

The management structure of the project was explained. CO2CRC Pilot Projects Ltd takes on liabilities for the injection and monitoring project. Participating companies have collectively agreed to underwrite the excess risks and provision operating committees.

The total cost for the Otway Basin Pilot Project is AUS$30m with an extra AUS$10m for the planned capture plant. An outline schedule was presented with a new well planned for February 2007 and injection planned for mid-2007.

Questions

How do you manage knowledge generated by such a large project? This is very challenging to get information published and a recognised area for future improvement.

Was the Site chosen for availability of CO_2 source rather than as a good CO_2 storage project? How good is the site for storage? Correct. It was never designed to be a future large-scale project. Faults are thought to be good sealing faults since they have retained natural gas and will be injecting into a depleted gas field. There is lots of focus on geomechanical issues.

Could Otway provide opportunities to study fault-controlled leakage pathways? Agreed but prefer that Otway didn't leak to build confidence. It does give opportunities to monitor across faults.

Did the field contain any CO_2 originally? No.

What phase is CO_2 in the mixed CO_2/CH_4 injection stream? CO_2 will be supercritical, based on phase modelling. It should be possible to monitor the CO_2 even with the presence of residual CH4.

5. SESSION 2 – WELL-BASED MONITORING

5.1 Keynote: Well-based monitoring – overview presentation of wells for monitoring – Rick Chalaturnyk

The purposes of monitoring are multiple, including fine-scale processes, operational issues and regulatory requirements. Well-based monitoring is a big component of many CO_2 EOR projects. Measurements include injection pressure and temperature, stream composition, and injection rates. Downhole pressure measurements can include: real-time gauges (electronic or low resolution), fibre optic systems, bubble tubes.

Well based geophysical logs can include – cement evaluation, saturation, resistivity, dual sonic, VSP, geochemical sampling and passive seismic.

To optimise monitoring one needs to be very aware of the specific well completions and geometries. Well geometries could include multilaterals in overlying aquifers. The locations and numbers of wells are very important.

Different monitoring levels can be recognised: operational, verification and environmental

Examples of deployment:

An example was presented of casing conveyed pressure and temperature measurements of reservoir and bottomhole pressures, in a horizontal well with both reservoir and internal production pressures. Sensors were cemented in place. Temperatures monitor cement hydration. Pressure tests can affect casing materials. During drilling through the end-plug, immediate communication between reservoir and internal production pressures can be observed.

An example of integrated permanent installations of geophones, pressure and temperature transducers and other monitoring equipment was presented. The Penn-West CO_2-EOR pilot project will inject 35tons CO_2 per day, in an inverted 5-spot well pattern. Remedial cement squeezing was required in a monitoring well. Three pairs of P-T gauges, 8 geophones and 2 fluid sampling ports were installed. Pressure sensors can monitor well completion processes. When the well pressures dropped below reservoir pressures, an influx of reservoir fluids occurred, which caused a small channel to form during cementing, which allowed fluid escape at 7litres per minute. Remediation involved a tubing punch, which could be monitored using the installed pressure gauges.

Questions:

Were there any issues during cementing around instrument cables? No, we used armoured cables and could reciprocate during completion to around half a pipe.

5.2 Overview of well-based monitoring approaches at the Frio2 project – Susan Hovorka

A search for a site to demonstrate storage within the Gulf of Mexico identified the Frio site. Principal objectives of Frio2 are to determine storage permanence (residual saturation, CO_2 solution), to evaluate post-injection monitoring and to develop novel monitoring tools (such as tubing conveyed seismic array).

At the end of the Frio1 project attempts to produce CO_2 when the well was opened did not produce any CO_2 due to residual saturation. The well was swabbed, and a weak gas lift with a water to gas ratio of 13,600 to 1 was achieved. CO_2 was produced at 0.17 tons per hour and it was therefore concluded that the risk of leakage was small.

An overview of the geology at Frio was presented: The reservoir comprises Oligocene fluvial & reworked sandstones with a porosity 24%, 4.4-2.5 mD. The reservoir is mineralogically heterogeneous which controls permeability. In Frio2, it is planned to maximise geochemical interactions rather than force breakthrough.

Reservoir modelling was used to design a monitoring programme but reservoir heterogeneity caused a lot of uncertainty in permeability prediction, with consequences for monitoring frequencies and durations. Injection and observation wells were 30 m apart with wells instrumented with U-tubes. Cross-well seismic was used to monitor fluid migration.

Fluid geochemistry in the monitoring well was observed during the injection well shut-in. Temperature variations also indicated CO_2 plume movement, which cools formation. Fluid sampling also identified CO2 breakthrough in the monitoring well.

Question: Was the lack of production at end of Frio1 due to CO_2 movement updip? No, CO_2 was residually trapped.

5.3 Early geochemical and geophysical results from Frio2 – Barry Friefeld

Instrumentation at Frio includes a seismic source in the injection well, hydrophones (7 above packer, 17 below top of packer, in and below the perforation interval) in the monitoring well, a U-tube sampler in both wells and P&T sensors. Not all hydrophones worked following installation.

Preliminary results indicate a 1.5ms delay in arrival time following arrival of CO_2. The seismic source and PT sensors interfered with each other. Very early travel time delays (much less than expected) were observed which enabled both spatial and temporal changes due to CO_2 arrival to be detected.

A re view of the U-tube experiments was presented. The objective is to sample fresh fluids, both brine and supercritical CO_2 need to be sampled at in situ conditions (to minimise degassing) to quantify the gas: water ratio. Tracer experiments demanded almost one sample per hour. Wireline sampling was used for baseline and post-injection monitoring but was found not to be suitable for injection geochemical monitoring. Gas lift sampling was considered since it was difficult to recover downhole conditions, disturb flow-field and control sample rates. The U-tube technology was described. 52 litres of sample recovered with both phases recovered at a rate of 1 sample per 70 minutes.

Liquid samples were analysed for aqueous geochemistry, pH (showed a reduction to pH3.8), and tracers. Gas samples for CD_4 tracers and other samples. Results from Frio1 indicated some atmospheric contamination to gas compositions.

Tracer tests included CD4, perfluorcarbon, Kr Xe tracers. Xe, Kr tracers indicate rapid CO_2 solution since arrived at the same time as the CO_2.

Multi-function completions, and fibre optic based sensors will be important.

A distributed thermal perturbation sensor (DTPS) – distributed temperature sensor coupled with a heater was described. By comparing measured temperatures over time it is possible to see changes in heating as flow occurs.

Further refinements will include integration of monitoring technologies, with installation of duplicate U-tubes to sample both gas and liquid which will be engineered for simplicity and robustness.

Questions:

How do you factor in the reservoir heterogeneity in the interpretation of tracer arrival times? Geophysical measurements provide an "integration" along the flowpath.

Do you engage non-specialists? Yes, walk them through the whole process.

How do you communicate results to media? This requires careful management and coordination.

5.4 Logging techniques for CO_2 saturation and well integrity evaluation – Laurent Jammes

Performance and risk management are fundamental and requires a clear risk treatment plan. Risk management requires site characterisation and modelling. Risk treatment requires monitoring. Monitoring objectives are variable and include performance control and risk control (containment, contamination), as well as dynamic model calibration.

Well-based monitoring techniques were reviewed:

CO_2 saturation can be monitored using time-lapse density (gamma), based on photon emission, with measurement in a number of detectors. The sensitivity depends on the porosity and formation fluid density. Time-lapse neutron-neutron porosity, infers H_2 atoms from neutron scattering by H_2 in the pores, could be used for CO_2 saturation measurements with potential selectivity for CO_2/CH_4.

Neutron capture cross-section measurements (neutron-gamma), measuring gamma rays emitted following a neutron burst, are dominated by chlorine which measures the brine chlorine content. This was used at Frio1. In saline waters large differences are observed due to CO_2 concentration.

Neutron inelastic scattering, produced following fast neutron interactions with gamma rays, can be used to measure the C/O ratio. It is selective to CO_2/CH_4, CO_2/brine and possibly CO_2-rich phase and dissolved CO_2 (though the latter maybe too small).

Resistivity is also very useful: the well casing acts like a large electrode, with the current returning to the surface. It is sensitive to cement resistivity and dissolved CO_2 content. It involves two steps: measures current drop across the formation and then the casing resistivity is measured.

Cross-well electromagnetic surveys can be used to monitor the saturation distribution and monitor the injection front and CO_2 plume. Attempts at Frio were not successful, since the changes in resistivity were small and the wells were too close together and consequently, changes were below the signal to noise ratio.

Sonic logs are sensitive to the CO_2/brine ratio, although it is difficult to measure CO_2 saturations above 50%.

Downhole fluid analyser, based on IR gas analyser, are under development. H_2O and CO_2 peaks overlap in the near IR, so need to remove the water before analysis can take place.

Well integrity evaluations can be made using a variety of tools. Calliper measurements use a multifinger calliper tool with 24-60 fingers. Cement evaluation tools were identified since cement slurry displacement problems can occur for a variety of reasons. Sonic acoustic wave measurements are the classical method but recently ultrasonic tools are used. The key challenges for cement evaluation are being able to discriminate cement, liquid and gas, requiring an estimation of acoustic impedance behind the borehole wall. This works well with traditional cements but newer, lighter cements or contaminated cements have lower acoustic impedance which can be confused with water. To get around this, ultrasonic is combined with flexural impedance analysis of casing to distinguish cement density. Finally an isolation scanner can image the interface between the formation and cement to estimate casing eccentricity and cement debonding.

In summary, well measurements can complement other techniques and can provide accurate local measurements. However they need validation and demonstration in CO_2 environments. Additional possibilities when access to wells is available could include installing permanent sensors, sampling and cross-well and well-to-surface surveys.

When designing a monitoring programme it is important to answer the following questions:

- What do I want to monitor
- What properties can I measure?
- What variations can I measure?
- What techniques can I use?
- Sensor specification
- Location of sensors
- Measurement interpretation

Questions:

Can we install complex instrumentation and accurately locate your position? Possibly, but not too familiar with this.

5.5 Time-lapse well logging to monitor the injected CO_2 in Nagaoka Project – Daniji Tanase

The Nagaoka project is located at a gas field in a Miocene to Quaternary sequence with an anticlinal structure. Injection was into a 15° dipping target reservoir at ~1100m depth, in early Pleistocene sediments, at 2km from the crown of the anticline. A total of 10405 t of CO_2 was injected at an injection rate of 20-40t per day, with monitoring and simulations. Three deviated observation wells surround the injection well.

Site characterisation involved coring, cuttings analysis, logging, pump tests, step-rate tests and laboratory-based analyses of cores. Fluid samples were also taken.

A large earthquake occurred following well completion and subsequent FMI and CBL logging indicated no damage.

CO_2 was detected by cross-well seismic between the wells at various times during and following injection, and bottom hole P&T were measured in all observation wells. Continuous passive microseismic monitoring was performed.

Advanced well logging was repeated 31 times during the experiment. Changes observed include decreases in P-wave velocity, and neutron porosity and an increase in resistivity. Repeat surveys allow mapping of breakthrough with time. This can be combined with fluid sampling to calibrate logging responses to provide estimates of CO_2 saturation. Repeat borehole logging also allows comparison between estimates of porosity between different techniques (neutron and NMR). Spinner tests monitored flow within the borehole.

Future plans include continued post-injection monitoring, fluid sampling and logging of the injection well, and interpretation of 3D seismic. The simulations will be history-matched with this additional data.

Questions/comments:

This experiment provides an opportunity to identify data precision and accuracy with the repeated logging techniques used.

Did you use USIT for determining CO_2 effects of cement integrity? See presentation by Ziqui Xue in session 3 .

5.6 Discussion – focus on how well-based monitoring fits within the MERV discussion on Monday, its importance relative to injection phase and post-operational phase – Chair, Kevin Dodds

It was suggested that dynamic monitoring will be needed for CO_2 storage and is not often practised in the oil & gas industry.

Resistivity images are very powerful in showing the CO_2 plume. Ideally, permanently installed arrays of resistivity measurements would be very useful. But how would this be developed? This is an opportunity to bring additional groups who are using ERT for pollution studies. This needs more than one well which has significant cost implications and is therefore unlikely to be used widely for large projects due to costs. However, in a large project, observation wells may be more possible (for example, Gorgon has 2-3 observation wells).

Regulators would like to be able to monitor plume migration as this will be important to many communities.

It was suggested that if enough pilots are done, numerical simulations can be verified which will reduce the need for lots of detailed monitoring. It was countered that simulations will still need to be validated against monitoring data.

With commercial projects, we must have confidence that we can monitor where a CO_2 plume is located. It will not be possible to monitor plume migration in large commercial projects with wells. Imaging is useful to build confidence. In contrast, models have inherent

assumptions and experience suggests that heterogeneities add a level of unknown complexity that is difficult to predict. The models need to be verified on a regular basis.

In Texas, for Futuregen projects, site selection is trying to avoid wells to minimise leakage risks. Public concern is focussed on water supply which requires monitoring of aquifers. Seismic may not be suitable for monitoring for leakage. In contrast in Alberta there are many wells so instrumentation is not a problem.

A new offshore well is AUS$50m in Australia, so need to maximise all existing wells and any instrumentation will require additional tubing and provides more risks for leakage. How can we extrapolate well data to the reservoir scale? Does this require future technological development? Some techniques can be upscaled already.

We need to determine the workflow between EOR and industrial scale CO_2 storage projects. Different monitoring tools must be integrated to minimise costs as industry doesn't want to continually shoot 4D seismic. Costs are not likely to be an issue since previous estimates indicate that costs will be very small per tonne of CO_2 captured.

There is probably an issue of education for regulators who will have a mindset that comes from, for example, landfill. Would some sentinel wells that monitor pressure be sufficient? In Class 1 wells in US, and acid gas injection in Canada, the only required monitoring is for annular pressures for well integrity. All other issues are covered by modelling and simulations. If monitoring data matches modelling, then this is probably sufficient. However, at Frio, still got breakthrough slightly ahead of expectation based on reservoir modelling.

Regulators posed the following questions:

- What are we trying to protect?
- How do we monitor to show these are being protected?
- What are the performance monitoring techniques – these will go in guidelines.
- Also monitoring for risk management will not be mandated but will be for operators to decide.

Differences should be recognised between demonstration and commercial projects. Early demos will require more monitoring. Large commercial projects may require more than one well, which could be designed to act as monitoring wells in the future.

Monitoring depends on the structure: a closed trap could be much simpler (a single monitoring well could be enough) than dipping aquifers with heterogeneity, which would require more monitoring.

Regulators commented that we are funding demonstration projects that are supposed to develop monitoring techniques. What do we want to do? We can't provide monitoring to demonstrate no leakage over 1000 years. No performance standards have been defined in terms of leakage rates. We can not define leakage rates for a specific site. Regulators should be flexible and try to match different demonstrations techniques to appropriate projects.

We should separate performance standards for accounting from local HSE. These will require different monitoring and modelling projects. If you can quantify leakage below the discount rate being applied in Canada, then this is a way of paying for monitoring.

It was concluded that we need to define zones and need guidance from regulators as to what we have to protect, so we can design appropriate monitoring programmes.

6. SESSION 3: MONITORING FOR CAPROCK INTEGRITY

6.1 Overview of issues or mechanisms at play in seal integrity and identify monitoring processes or techniques that may play a role in assessment managing caprock integrity risks – David Dewhurst, CSIRO

Why do seals fail? Two types of failure were defined: capillary failure, where buoyancy pressure is greater than the capillary entry pressure and mechanical failure (fracturing faulting and reactivation). Two types of seals can be identified: cap seal and fault seal.

To calculate the seal capacity (or height of trapped column) we need to constrain wettability (contact angle) at reservoir conditions.

Seal capacity issues include: the sample size – which requires a regional geological approach and the seal geometry and lateral extent – which can introduce lithology changes, sequence stratigraphy, seismic resolution.

Characterisation of fault seals need to consider juxtaposition, seal capacity and reactivation. Fault zone properties include: cataclasis, diagenesis, clay smears and grain sliding which can influence fault strength. The juxtaposition of shales with reservoirs is important.

Fault rocks can be cemented, and can be graded by phyllosilicate content. At >40% phyllosilicate smears develop, which can have very low permeabilities, <500nD. These can be predicted by the shale gouge ratio (SGR) by estimating shale proportions from gamma logs. At SGRs greater than 20%, the fault will seal. If the framework models are inadequate then subsequent fault sealing assessments are useless. Issues requiring further study include: FSA's only account for geomechanical properties, and exclude diagenesis. Sealing is assumed to be due to clays which may not be true. Gamma ray is not very accurate. CO_2 wettability is poorly constrained.

Fault reactivation includes 3 types of shears, shear failure, extensional and intermediate differential stresses, depending on orientations to principal stresses. Reactivation risking can be mapped onto 3D seismic to identify those faults at greatest risk of reactivation.

How to account for changes in pore pressure during injection? Geomechanical modelling can be coupled to flow modelling to estimate stress changes. Passive seismic can be sued to monitor and evidence presented suggests events cluster on lager fault planes. 4D seismic can be used to monitor flow by monitoring pressure changes.

In summary, many techniques have been developed but there remain several key issues. Knowledge gaps include wettability, diffusivity, reactivation and poroelasticity. Geomechanical modelling must be integrated with microseismics and 4D seismics.

Questions

When taking pore pressures higher than lithostatic, what measurements could be needed? One idea could be leak off tests for minimum horizontal stresses

6.2 Using geochemical techniques for monitoring seal integrity – Ernie Perkins, ARC/CO_2CRC

The following definition of a seal was proposed: A very significant decrease in porosity or permeability that minimises fluid migration. Why do we need to monitor across or above the seal? To demonstrate a seal is effective.

It is a concern that CO_2 could affect seals: while this is correct, longer term reactions could prevent solution. High rock/water ratios minimise reaction, preventing CO_2 migration into the seal. Some seals are not reactive.

How to monitor seals? Look for tracers, changes in composition, isotopic fingerprinting, and reactive components. Demonstration projects and analogues can constrain these reactions. Case history of Weyburn was presented with gas composition and isotopic data.

Monitoring domains can be defined and some domains will be monitored for public confidence assurance reasons. For example, the Otway Basin Pilot project undertaking atmospheric, soil gas and monitoring in shallow wells (constrained by location). Penn West used fluid chemistry both in the reservoir and above the aquifer to provide assurance.

To determine the sampling frequency is difficult but the approach is to assume how the fluid migrates, determine migration volume and rate, and then calculate if a technique would see a leak.

Key issues are:

- How big a signal do we need?
- Where and when?
- What types of monitoring?
- Closer to storage the more spatially restricted the sample locations and the more difficult it is to obtain samples.

Questions:

The Kharaka et al paper on Frio caprock stated that buoyant force will bring CO_2 into contact with seal and that there is not enough rock to buffer the pH change. Most reaction occurs on the plume front, with little reaction within the plume due to a lack of water. Diffusion is a very slow process.

Are atmospheric and soil gas sampling offshore possible? See presentation by David Etheridge in Session 4.

6.3 Reservoir simulation and coupled geomechanics to calculate pressure and stress changes that feed into monitoring design – Lincoln Patterson, CO2CRC/CSIRO

Equations of multiphase flow were explained. Saturations and pressures are calculated. Biggest uncertainties in the simulations are porosities and permeabilities. Key monitoring therefore is pressure and saturation.

Examples of modelling approaches presented including the field at the Otway Basin Pilot Project. Modelling can be used to help define locations of monitoring and estimate velocities of migration. Modelling can be used to guide monitoring programme, including the choice and location of monitoring techniques. Modelling can be used to interpret monitoring data.

Does it matter if models are slightly different to monitored data, as long as containment is maintained?

6.4 Discussion/seals & MERV: Focus on how monitoring fits within MERV discussion from Monday, its importance relative to injection phase and post-operational phase: Chair Rick Chalaturnyk

Fault seals are a big focus in Australia but not addressed in the US. Dept of Energy is risk averse and do not want to hear about failure. Should we have projects that deliberately look at fault migration? We have analogues that can provide some answers; for example, gas storage projects in Otway and upstate New York are against faults with no evidence of leakage. However, there are some gas storage faults that are leaking. It should be recognised that there are considerable differences between CO_2 storage and natural gas storage.

How could monitoring help avoid blow outs due to fault reactivation? Techniques could include microseimics, tiltmeters and Differential GPS. To measure stresses requires well access in faults which are unlikely to be located in these areas. Strain measurements have been obtained for some North Sea fields but this is embryonic. It was felt that accuracies should be OK for stress measurements.

Fluid extraction can create microseismic events and cause ground movement and therefore by analogy CO_2 storage could create similar events. Does USDOE monitor for microseismicity? Not sure but a small number of projects can be attributed to creating microseismicity. Within UIC this is specifically addressed. Microseismic monitoring at Weyburn indicated only a few events with large pressure gradients– but this may be due to pressure relief from oil production.

Questions posed:

Should we base monitoring on risk predictions modelling?

Should fault reactivation and pathway migration be actively studied?

CO_2 acidification can cause mobilisation of metals.

Brine displacement into potable waters could be an issue. The volumes of displacement may not be significant.

How do you monitor in a large plume footprint? Utilise other wells as far as possible.

Laboratory work may be needed to study effects of pH on clays – some evidence from clay liners in landfill sites.

What is the worst case scenario? Hard to get significant leakage along fractures. 7 blowouts have occurred in EOR floods in Texas and in Wyoming.

7. SESSION 4: CONTAINMENT AND INTEGRATION

7.1 Susan Hovorka (chair) – Review of day 2

Review of key messages from Day 1

Looking forward to recommendations at the end of this workshop:

- What constitutes validation?
    - Affirmative data to validate model predictions,
    - Direct measurement of protected resources
    - What are we trying to quantify?
    - IPCC statement:

      It is very likely that the fraction of CO_2 retained is more than 99% over the first 100 years

      It is likely that the fraction of CO_2 retained is more than 99% over the first 1000 years
    - Protective of HSE criteria
    - Best possible practice: ALARP
    - Value of looking at retention not by percent
        - By mass
        - With time, by area, with pressure

- What retention can be predicted?
    - By natural analogues
    - Modelled – inputs from lab data, extrapolation of small scale observations, statistical approach
- What retention can be verified?
    - Accounting procedure
    - Point measurements
    - Integrated measurements

- Selecting the tools
    - Fit for purpose, all sites unique, select from MMV tool kit
    - Check up analogues
    - A procedure to follow that tailors test program for each site: Gateway process

- How do we set performance standards
  - Thresholds – what is action?
  - Issues of sensitivity, precision, accuracy, false assurance, false positives, need validated methods to provide public confidence

7.2 European CO_2GeoNet Research Network – Interim report: Nick Riley

The aims of the network are to integrate within the European Research Area with a joint research portfolio focussing on CO_2 migration and leakage mechanisms and impacts.

Why study leakage? Leakage is the main issue of concern amongst public, NGOs and regulators. HSE, ecosystem protection, resource & property damage, carbon credits, public & regulatory acceptance, efficacy & risks of CCS need to be compared to other climate change options.

As industrial sites are not designed to leak, we need to use natural analogues and field-based experiments.

The concept of source to pathway to target to resource was introduced.

We need to understand what is measurable. We need to be able to monitor storage security and defend unfounded leakage claims and we need be able to recognise leakage.

Terrestrial impacts: An overview of work at Latera, a collapsed caldera, was presented. Investigations of natural seeps, microbiological, invertebrate and mineralogical/geochemical responses to both CO_2 and H_2S are being undertaken. Testing of airborne remote sensing techniques raised the issue of false positives. Open-path laser trials have been undertaken.

Collaboration with University of Nottingham ASGARD facility is being undertaken to conduct experiments on plant responses to CO_2. Epidemiological and sociological studies at Ciampino are being undertaken to begin process of determining how populations may respond to natural CO_2 seeps.

Aquatic impacts: aquatic systems are more sensitive to CO_2 changes. An overview of the Laacher See region and microbiological studies was presented. Benthic chamber experiments via collaboration with RITE in a Norwegian fjord were reviewed.

Panarea video was shown which provides an introduction to shallow volcanic offshore seeps. This area will form a PhD thesis for a student at University La Sapienza Roma.

In summary, the leakage issue is a key concern for many stakeholders and should be addressed with transparency, honesty and openness. The evidence base is required to build confidence. Governments and regulators need evidence to develop appropriate regulatory framework.

Questions:

How many anomalies in remote sensing data are really due to CO_2? Still working on this but many, if not most, identified anomalies are not related to CO_2.

7.3 Walkaway VSP for CO_2 Monitoring at the Penn West Pilot, Alberta – Marcia Couelsan Crewes

The Penn West CO_2-EOR Pilot is injecting into the Cardium Formation, a sandstone and conglomerate reservoir with a potential for up-scaling to full commercial production. Approximately 70,000 wells are located within the region. CO_2 will be injected into two deviated wells at 70 tonnes per day at 20Mpa. For comparison, the average Canadian produces about 5 tonnes per year. The dominant fracture trend is NE-SW and the expected sweep will be along this trend. Although the Cardium is poor P-wave reflector but this is not a problem since looking for differences in 4D surveys.

The monitoring well is equipped with and array of 8 geophones. A review of the Vertical Seismic Profile (VSP) process was presented. Advantages of VSP include higher frequency bandwidth than surface seismic, which leads to increased resolution, provides correlation between the surface and depth, and provides indexed well logs. VSP can be used to improve surface seismic processing (velocities, Q estimation and anisotropy), and allows for passive seismic. A comparison of VSP with surface seismic with higher resolution and corresponding well indicates S waves are more sensitive to pressure changes and could be a useful future data source.

VSP is used in a time-lapse mode to monitor flood and look for leakage in the overburden. The first survey was acquired in December 2005, and the second is planned for early 2007. A change in P-wave velocity and fluid composition is expected to increase the Cardium Formation as reflector. There are several challenges to time-lapse VSP. One example is non-repeated shots which can introduce very strong artefacts in difference datasets. Finite difference models were used to investigate the effects on non-repeated shots, and repeatability issues. Seismic noise can be caused by geological heterogeneities. Increases in amplitudes in the Cardium Formation were observed in the models as a result of the CO_2 flood. Travel time increases at the base of the reservoir show a systematic increase of 0.2 ms.

In conclusion, shot repeatability is very important. P-wave amplitudes have increased and comparisons of datasets indicate excellent repeatability. Walkaway and 3D VSP are critical to imaging thin reservoirs and formations where surface seismic does not show any changes.

Based on the experiences at Penn West, a proposed approach for monitoring would be:

- Instrument entire wells with geophones to monitor overburden
- Install geophone arrays in several wells
- Potentially instrument in production and injection wells
- Increased integration between geophysical and geochemical monitoring.

Questions:

Did amplitudes increase below Cardium? Effects of data processing (cross-equalisation processing was not done) introduce artefacts.

Are there advantages of a seismic source generating fewer S-waves? Possibly, but not sure how available these are.

Need a baseline shot at fixed location? Yes, need to ensure exact repeat locations are used.

Repeatability can be affected by weather conditions? Yes see a static shift due to frozen ground or wet ground.

Is aspiration to ensure similar ground conditions as it will change waveform? Yes need to be careful with this.

Is cross-equalisation almost essential for looking at subtle effects? Yes, this is very important.

How much CO_2 was injected by the time of the repeat surveys? ~15000-25000 tonnes can be estimated.

7.4 Field investigation results after the Mid Niigata pref. Earthquake at the Nagaoka injection site – Ziqiu Xue

Main objectives of this study are to detect CO_2 breakthrough and CO_2 movement through formation pressure monitoring. Time-lapse well logging was reviewed.

Following the start of injection on July 7th, 2003, an earthquake occurred on October 23rd, 2004, after ~9000 tonnes of CO_2 had been injected. The epicentres were very close (~20km) to the site with magnitude 6.8 recorded at 10 km. Following the earthquake, CO_2 injection was stopped and pressure systems automatically shutdown.

No damaged was observed in any of the site infrastructure including the liquid CO_2 tank, injection and observation wells, and pipelines. Some damage was sustained on the access road. Some sand liquefaction and small fractures were observed at the surface close to observation wells.

Following the earthquake, cement bonding, induction, sonic and neutron logging and cross-well seismic (comparing differences in waveform), formation water by Cased hole dynamic tester (CHDT) were all performed. No difference was observed in the pressure decay curves indicating no additional fracture reactivation or formation damage. No correlation between injection rate and microseismics was observed. CBL logging indicated no damage to cements above and below the formation. SUIT also confirmed no damage observed at formation level. No anomalies were observed on sonic, induction or neutron logs. Similarly cross-well seismic tomography indicated that no CO_2 leakage into the caprock had occurred.

Cased hole dynamic tester (CHDT) detected changes in resistivity in specific strata within the Zone 2 injection zones. The biggest changes were due to high (99%) CO_2 concentrations displacing the water, below this zone large amounts of CO_2 have been dissolved into the water. Concentrations of Ca, Mg and Fe also increased in waters in this zone.

In summary, no differences in drawdown curves indicate the integrity of reservoir was maintained following the earthquake. Cement bond logs and detailed well logging indicated that well integrity had been maintained. Cross-well seismic also confirmed CO_2 containment.

Question:

In Japan, are there any design requirements built-in to well design? Ideally should select a safe site, but in Japan this is unavoidable. Therefore this is always considered in project designs.

7.5 Assessing the efficacy of CO_2 storage by atmospheric monitoring – David Etheridge

Why do we need to monitor the atmosphere? To verify containment and complement subsurface monitoring since the atmosphere is where climate change takes place and where health and safety impacts are likely to be seen if a leak should occur.

Atmospheric monitoring can be continuous, unattended, non-invasive, with integration across multiple points and diffusive.

Monitoring should be able to detect CO_2 concentrations, attributable to the stored CO_2 (by using isotopic signatures or tracers) and quantify the leaks (transport and dispersion, CO_2 fluxes). The literature suggests that we need leakage rates of better than 0.1% globally, to ensure sustainability.

Historical variations in CO_2 and other gases at Cape Grim were reviewed. Here seasonal effects dominate CO_2 concentrations though long-term trends show increases. In the local atmosphere, baselines can show very large variations against which we need to be able to detect leaks. This can be achieved through adding tracers or using natural tracers, determine or model natural fluxes, and employ strategies based on temporal variations.

Tracers can be naturally occurring (isotopic, trace gases) or introduced (SF_6, CF_4). These require continuous high precision CO_2 analysers and flask air sampling and must be analysed in laboratories.

At Otway, baseline ocean-sourced CO_2 shows biospheric exchange over 4km fetch from the coast. Background fluxes either on tower or using flux chambers are mature technologies.

It is important to predict how potential plumes could migrate

In conclusion, atmospheric monitoring may be a regulatory requirement. Acceptable atmospheric leakage rates are just detectable with the sensitivity depending on setting and the amounts of CO_2 injected.

Questions:

What are the comparative costs to analogue well logging? This could be done (cf: Benson report) but atmospheric monitoring is likely to be cheap, since it utilises existing monitoring.

How is the leakage rate defined? It is a constant leakage rate relative to the original amount injected.

How does precipitation affect atmospheric concentration? Yes it does affect soil gas permeability and biosphere and microbiological productivity.

Could ozone be used? This would be very challenging.

7.6 Design and data needs for a facility for testing near-surface CO_2 detection – Lee Spangler

An overview of the Zero Emissions Research and Technology Centre (ZERT) was presented. The aim is to develop a site for testing near-surface monitoring techniques with known injection rates, establish detection limits, improve models of ground water-vadose zone-atmospheric dispersion models and develop a site that is accessible and available for multiple seasons/years.

The target scenario is to assume a fault leakage scenario. The site comprises a 100m perforated pipe at 2.8m depth in glacial till. Background data such as wind direction and speed, with variable wind direction was collected. Background CO_2 eddy covariance fluxes have been measured. Energy inputs were determined. The influence of low-permeability silt layers to horizontal migration was investigated. Soil textures were characterised.

Vertical injection tests were described. Soil gas sorption tubes were used to monitor tracer distribution. Large fluxes were observed over an area of 2m diameter. Ground-based hyperspectral imaging to monitor plant stress proved less useful due to the late season and lack of chlorophyll but some plants may be better suited for longer injection tests.

Resistivity measurements may be able to monitor the CO_2 plume. Isotopic measurements indicate shifts in isotopic signatures both in chambers and canopy air. A LIDAR system is being developed to monitor atmospheric CO_2 concentrations.

Conclusions are that concentration and flux measurements are probably less sensitive than ^{13}C measurements. Soil moisture and temperature are important to soil flux. Depending on the geometry of the underground source, surface fluxes may be measurable.

7.7 Wellbore integrity at Sheep Mountain: Charles Christopher

Brief updates of the experiments at the Sheep Mountain CO2 production facility were presented. Wells have been in place since the 1970s and have been exposed to wet CO_2. Tubing that was pulled after 18 years showed no corrosion. Five side wall plugs were taken, including from both formation and caprocks. CO_2 movement was observed with minor cement alteration (red colouration).

7.8 Discussions: Seismic and atmosphere monitoring and MERV requirements

Soil gas and atmospheric monitoring suggest CO_2 could migrate horizontally a along way from the injection point. This means that near-surface site characterisation is very important to define where monitoring should be placed. Atmospheric monitoring provides opportunities to monitor large areas. For example at Gippsland, site characterisation and modelling shows that CO_2 can migrate 10's km. This is a familiar problem to regulators.

Should early demonstrations bother with near-surface conditions directly above the reservoir, when CO_2 could leak a long way horizontally? This confuses people that this is where CO_2 could leak.

Soil gas measurements can also be used to identify potential migration pathways as part of site characterisation and this can contribute to an understanding of migration pathways. Analogues of gas movement in shallow subsurface exist. Near surface monitoring can also be used to determine background fluctuations and show that the CO_2 is not from the reservoir.

Atmospheric monitoring should be done in conjunction with ground-based measurements.

At ZERT, they are developing open-path lasers for permanent installation.

8. SESSION 5: LATROBE VALLEY CASE STUDY

8.1 Review of Monday Regulatory Outcomes – Mark Bonner

The regulator's role is still in its infancy and a need to build this capacity was recognised. Researchers need to educate and inform regulators. There is a need to focus the science to answer regulatory requirements. Which regulatory analogues are relevant? We will need to use existing legislation as far as possible. Regulators are sceptical about safety in an industry with a poor environmental record.

Key issues

- Key values need to be protected
- How can risks be managed or mitigated?
- What is the role of MERV?
- What is the role of standards-based MERV systems?
- What is the most chronic risk of incidents, what options are there for mitigation, remediation and/or rehabilitation?

Principles of regulation are based on; inter alia, Equity, Efficiency, Dependability, Independence, Transparency, Flexibility, and Consultation

Political realities

- It is a political judgement that ultimately defines the term "dangerous climate change".
- Scientists provide evidence for political judgements to be made.
- Many uncertain tipping points.
- We need to deliver CCS to a public that is still wondering how it all works.
- Politicians want numbers even if they are not understood.
- Key to success is the maintenance of integrity of public confidence.
- Much angst over who accepts long-term acceptability.
- Important to understand private sector risks.
- CCS intuitively offers greater benefits than disbenefits.
- Least developed countries need to slow rate of emissions growth

Our generation is focussed on stabilisation, while the next generation will be seeking absolute reductions. Low or high rates of deployment will impact other options and it should be remembered that CCS is 15-20% of required reductions. If it is going to fail, we need to know sooner rather than later. Proponents disparage other options, which should be avoided. Plenty of tools are available but we need to focus on the real needs of monitoring.

Economically, the cost of getting CCS wrong will be huge. We need to protect the integrity of emission caps for both market and environmental reasons.

There are many analogous activities from which to draw guidance in establishing regulatory approaches. However, there remains considerable confusion amongst policymakers and regulators around key issues of knowing how much knowledge is enough, monitoring capabilities, permitting of long-term storage, monitoring and liability transfer, and management of failure.

Possible approaches to standards, from political, business and social standpoints were highlighted.

The urgency of needing regulatory frameworks now was emphasised.

In conclusion, dialogue is as important as addressing the technical issues, the design basis is crucial and the regulatory approach should be flexible. Transparency and openness are very important. Learning by doing is an appropriate way forward. The long term concepts of storage are challenging for non-experts. Politicians will demand numbers and there needs to be a quantifiable end state. Are we monitoring for a market or environment – if both, compromises will be inevitable.

8.2 The Latrobe Valley CO_2 Storage Assessment

Catherine Poole outlined the Latrobe Valley feasibility study. The delegates broke out into groups to discuss issues raised by the Latrobe Valley assessment.

8.3 Breakout results: Risk evaluation and regulatory recommendations

It was identified that the locations of well, drilled in 70s, was poorly understood and that well integrity could be an issue.

Plume migration is a clear uncertainty due to a lack of existing data. This has required several modelled scenarios to be investigated, which will need verification. The controlling influence on baffles could require verification. Opportunities exist to improve models during drilling of the injection well. 3D seismic considered most appropriate monitoring tool despite trying to exclude it.

The ultimate operator is unknown – smaller operators have less familiarity with CO_2 injection and mid-size operators have more experience but less interest in storage.

Injectivity could be an issue, though current evidence indicates permeabilities are more than sufficient. Fault reactivation was identified as a possible issue.

Regulatory issues: Protecting existing oil and gas resources is currently the biggest concern for existing operators, but the overlying Kingfish field is likely to be depleted before injection starts. Currently the London Convention would exclude this project, as it is storage in an offshore saline aquifer not associated with oil and gas production.

8.4 Breakout results: M&V evaluation – Latrobe Valley recommended technologies using IEAGHG M&V tool.

The Latrobe Valley study was used as a case study to evaluate the monitoring and verification tools that could be deployed to address various MERV aims. The delegates broke out in to small groups and were asked to use the IEAGHG Monitoring Technique selection tool to facilitate their discussions.

Breakout group 2:

The following techniques were thought to be appropriate:

Well integrity: CBL, seafloor (sparker/boomer, biological) for abandoned wells

During injection, could use annular pressure and mechanical integrity.

Faults: seismic, downhole-pressures, falloff tests, microseismicity, history match in post-injection phase.

The group thought the tool was helpful but in some areas the group disagreed with the findings (e.g. downhole pH in post-closure abandoned wells).

Breakout group 3:

Quantification and storage efficiency aims were not selected. Pre-injection monitoring requires regional surface seismic to test repeatability and validate model predictions, and early repeat surveys would be needed due to the high injection rates. If the seismic survey was good, then a permanent array could be installed.

Multibeam echo sounding was selected for surface characterisation.

Discussions centred on the use of a monitoring well for microseismic monitoring – issues of location on plume path required. VSP, passive seismic, downhole chemistry could all be employed in a monitoring well.

Breakout group 4:

Issues over biological impacts on whales of repeat 3D seismic surveys were recognised.

Other identified tools included downhole fluid chemistry (may not be needed due to hydrodynamic trapping), geophysical logs, microseismic monitoring to allay fears of earthquakes with the installations of ocean bottom seismographs. Additional existing wells could be used for fluid chemistry monitoring.

The need for financial assurances was discussed.

Regarding the selection tool itself, the question was asked who was this tool meant for – do we expect the public to understand the tool? It is likely they will find and use it so the clickable explanations are very useful.

Breakout group 1:

In addition to those already listed, a need was identified to include flow rates at the wellhead. A baseline benthic survey was required. 3D seismic survey could be acquired for the baseline survey with follow-up 2D surveys which were cheaper.

Comments on the tool included the definitions of aims sometimes varied from what was assumed, for example 'leakage' and 'plume' vs. 'migration'.

9. FINAL MEETING WRAP-UP

Thanks were expressed to Kevin Dodds for the excellent organisation of this meeting. The delegates also thanked Charles Christopher for his guidance which was instrumental in setting up the network and he was wished a happy and profitable retirement.

The next meeting will be in Edmonton, with an opportunity to see Penn West and Weyburn plus many other active industry practitioners.

10. APPENDIX 1: AGENDA

Day 1 - Monday 30 October, 2006		
Regulatory Guidelines for Monitoring, Evaluation, Reporting and Verification (MERV)		
08.45 to 09.00	Introduction/Housekeeping:	Gerry Morvell, Assistant Secretary Energy Futures, Department of the Environment and Heritage.
Session 1–Keynote and NGO Perspective; Chair Gerry Morvell		
09.00 to 09.45	Keynote speech: The Climate Change Context for CCS:	Howard Bamsey, Deputy Secretary, Department of the Environment and Heritage.
09.45 to 10.15	An NGO viewpoint on CCS, Regulation and Monitoring:	Greg Bourne, CEO WWF Australia.
10.15 to 10.30 Break		
Session 2 – Further Perspectives; Chair John Gale		
10.30 to 11.00	US EPA Underground Injection Control programme: experience:	Elizabeth Scheele - US Environment Protection Agency.
11.00 to 11.30	A perspective on MERV for Australia:	Gerry Morvell, Assistant Secretary Energy Futures, Department of the Environment and Heritage
11.30 to 12.00	Insurance industry perspective:	Peter Sengupta, Zurich Global Energy.
12.00 to 12.30	Another country's experience with MERV:	Steve Cornelius, UK Department for Environment, Food and Rural Affairs.
12.30 to 13.30	Lunch	
Session 3-Technicians Upate: Chair John Gale		
13.30 to 14.15	IEA Monitoring Tool:	Andy Chadwick, British Geological Survey.
14.15 to 14.45	Goals of the OBPP monitoring programme + summary of other projects:	Kevin Dodds, CO2CRC.
14.45 to 15.00 Break		
Session 4-Facilitated Discussion on Design of MERV Protocols; Chair Gerry Morvell		
15.00 to 16.00	THEME - how to design and establish a suite of generic MERV protocols for CO_2 storage:	
Facilitated discussion: within the context of some agreed MERV objectives (which may include): • for accounting purposes within national emission inventories; • protect health, safety and environment (HSE) - existing or new regulations? • recognition within emissions trading schemes (accounting for capture, transport and injection); • assurance that sites perform effectively (frequency); • verify CO2 remains trapped in short term; and • provide a basis for predictions about behaviour in the very long term basis.		

Session 5-Facilitated Discussion On Where To From Here;Chair Gerry Morvell	
16.00 to 17.30	THEME - what are the next steps to help expedite MERV arrangements and so assist in the widescale implementation of CCS?:
Facilitated discussion: within the context of supporting the early trialling and eventual widescale deployment of CCS: • managing MERV arrangements within a CCS integrated system (pre injection (3-5 yrs); injection (5-50 years); post injection (50-200 years); and • post closure (>200 years) • MERV arrangements for RD&D today (what are the minimum regulatory arrangements for pilot projects; pre-commercial); • MERV arrangements for commercial scale projects (what are the minimum regulatory arrangements); • MERV arrangements for onshore and offshore storage (consistency?); • MERV arrangements for allowing realistic market expectations (insurers/reinsurance/financiers - risk premiums); and • How to strike a balance between regulator; technology and market.	
Close Day 1	
Dinner-Guest Speaker, Dr. Graeme Pearman-Climate Change: Risk and Opportunity. Dinner sponsored by Woodside Energy	

Day 2 - 3rd Meeting of the Monitoring Network - Tuesday 31 October, 2006		
08.15 to 08.30	Welcome and, fire briefing/safety issues;	John Gale, Kevin Dodds.
Session 1		
08.30 to 08.40	Introduction of Minister;	Peter Cook CO2CRC.
08.40 to 09.00	Minister's Speech:	The Honourable Theo Theophanous, Minister for Resources.
09.00 to 09.10	Question and Answers for Peter Cook and Minister.	
09.10 to 09.25	IEA GHG Views;	John Gale IEA GHG.
09.25 to 09.40	CO2CRC Views;	Peter Cook CO2CRC.
09.40 to 10.00	Setting stage for monitoring network discussions during Day 1 and Day 2 relative to the Regulatory Meeting on MERV. Provide overview comments about how structure and agenda for the next two days relate to MERV discussions on Monday; Rick Chalaturnyk, U.Alberta.	
10.00 to 10.30 Break		
Session 2- Monitoring Issues: Wells and Seals		
10.30 to 11.00	KEYNOTE1: WELL BASED MONITORING	Rick Chalaturnyk, U.Alberta.
11.00 to 11.30	Overview of Well-Based Monitoring Approaches at the Frio 2 Project;	Susan Hovorka.
11.30-12.00	Compatibility and Early Results of Geochemical and Geophysical Well-Based Monitoring from Frio 2;	Barry Friefeld

12.00 to 13.00	Lunch	
13.00 to 13.30	An overview of logging techniques for CO2 concentration measurements and well integrity evaluation;	Laurent Jammes, Schlumberger.
13.30 to 14.00	Time-lapse well logging to monitor the injected CO2 in Nagaoka Project;	Daji Tanase SEC Engineering Advancement Association, Japan.
14.00 to 14.30	Facilitator Discussion-Focus on discussion is how well-based monitoring fits within MERV discussion from Monday, its importance relative to injection phase and post-operational phase, etc.	
14.30 to 15.00	Report back and general discussion on well-based monitoring technologies.	
15.00 to 15.30 Break		
15.30 to 16.00	KEYNOTE 2:MONITORING for SEAL or CAPROCK INTEGRITY;	Dave Dewhurst, CSIRO.
16.00 to 16.30	Using geochemical techniques for monitoring seal integrity;	Ernie Perkins, CO2CRC
16.30 to 17.00	Reservoir simulation and coupled geomechanics to calculate pressure and stress changes that feed into monitoring design;	Lincoln Paterson, CO2CRC
17.00 to 17.30	Facilitated Discussion/Seals &MERV	
Focus on discussion is how monitoring fits within MERV discussion from Monday, its importance relative to injection phase and post-operational phase, etc.		
17.30 to 17.45	Discussion and preparation for Day 2;	Kevin Dodds, CO2CRC
Close Day 2		
Dinner sponsored by Rio Tinto		

Day 3 - 3rd Meeting of the Monitoring Network - Wednesday 1 November 2006		
Session 1-Containment and Integration		
08.00 to 08.30	Introduction review Day 2 plan fro Day 3;	Susan Hovorka, Bureau of Economic Geology, Austin
08.30 to 09.00	European "CO2 Geonet" Research Network on the geological storage of CO2-interim progress report relative to monitoring verification, ecosystem protection/responses, health and safety regulation and public perception of underground CO2 storage;	Nick Riley, BGS
09.00 to 09.30	Walkaway VSP for CO2 Monitoring at the Penn West Pilot;	Marcia Coueslan, U.Calgary.
09.30 to 10.00	Field investigation results after the Mid Niigata Pref. Earthquake at the Nagaoka injection site;	Ziqiu Xue, Research Institute of Innovative Tech for the Earth, Japan.
10.00 to 10.30 Break		

10.30 to 11.00	Assessing the long term efficacy of CO2 geological storage by atmospheric monitoring;	David Etheridge, CSIRO.
11.00 to 11.30	Design and Preliminary Data for a New Facility for Testing Near Surface CO2 Detection;	Lee Spangler, ZERT and Montana State University.
11.30 to 12.00	Discussion/Seismic and Atmosphere	
12.00 to 13.00 Lunch		
Session 2-Latrobe Valley Scenario Introduction and Break-out Sessions		
13.00 to 13.30	Review Day 1 Regulatory Outcomes;	Mark Bonner, DEH-Australian Greenhouse Office
13.30 to 14.00	The Latrobe Valley CO2 Storage Assessment;	Catherine Gibson-Poole, Australian School of Petroleum.
14.00 to 14.45	Breakout-Risk Evaluation and Regulatory recommendations;	Latrobe Valley Key risks and regulatory issues to be address by MERV.
14.45 to 15.15	Report Back Discussion	
15.15 to 15.45 Break		
15.45 to 16.15	Breakout M&V Evaluation: Latrobe valley Recommended technologies using IEA GHG M&V tool.	Session Chair: Kevin Dodds,CO2CRC.
Session 3		
16.15 to 16.45	Report Back Discussion	
16.45 to 17.00	Wrap up	
Close Day 3 IEA Dinner (1MB Adobe Acrobat pdf)		

Travel to Warrnambool

Day 4 - 3rd Meeting of the Monitoring Network - Thursday 2 November 2006
Otway Basin Pilot Project (OBPP) Site Visit

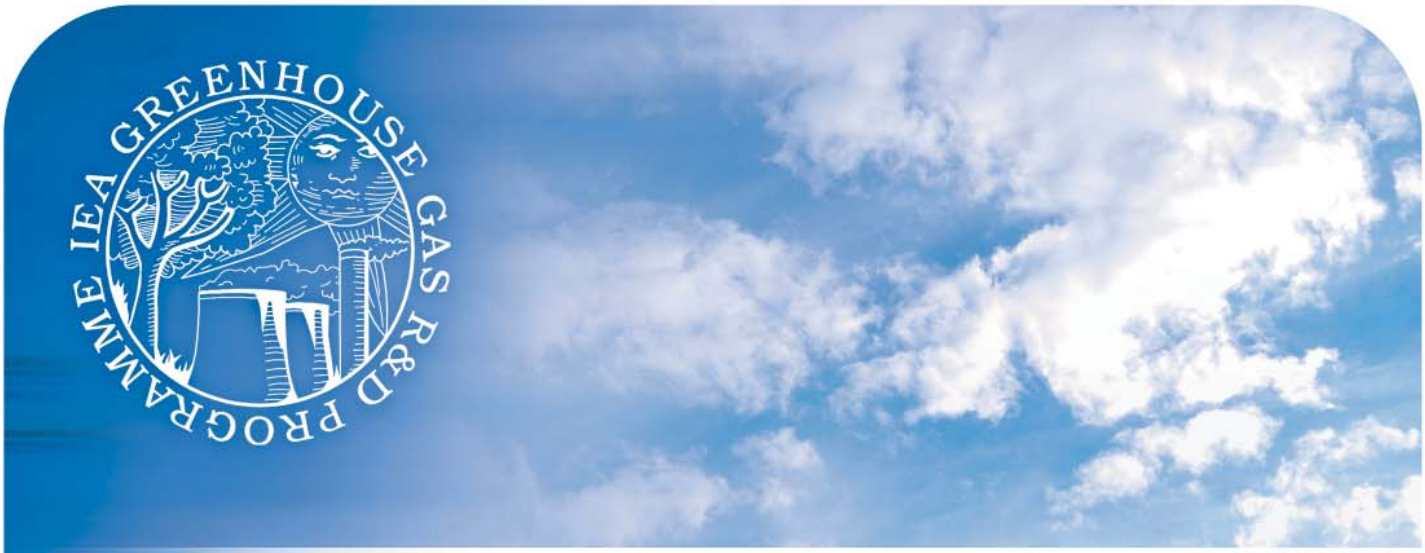
Bus tour of Otway site
This will include:
• Visit and presentation of OBPP implementation
• Geological overview of CO2 containment with reference to local outcrops
• Visit to locations of the volcanic source of the OBPP CO2
• Tour of local gas storage project
• Visit to the magnificent cliffs and coastline nearby the OBPP

Delegates will be returned to Melbourne by bus leaving 1500-1630 Nov 2nd for 3 hour travel time back to Melbourne.

11. APPENDIX 2: ATTENDING DELEGATES

No	First Name	Last Name	Organisation	Country
1	Kevin	Dodds	CO2CRC/CSIRO	Australia
2	John	Gale	IEA GHG	UK
3	Tony	Espie	BP Alternative Energy	UK
4	Nick	Riley	British Geological Survey	UK
5	Lee	Spangler	ZERT and Montana State University	USA
6	Alistair	Jones	Woodside Energy Ltd.	Australia
7	Dave	Dewhurst	CSIRO Petroleum	Australia
8	Sandeep	Sharma	CO2CRC	Australia
9	Christian	Bernstone	Vattenfall Research and Development AB	Sweden
10	Geoffrey	Ingram	Schlumberger carbon Services	Australia
11	Elizabeth	Mackie	Shell	Netherlands
12	Hirokuyi	Azuma	OYO Corporation	Japan
13	Mark	Williamson	Environmental Protection Agency	Australia
14	Ian	Wilson	Environmental Protection Agency	Australia
15	Jiro	Watanabe	Geophysical Surveying CO.Ltd.	Japan
16	Darren	Gladman	Dept. of Sustainability & Environment	Australia
17	David	Etheridge	CSIRO Marine and Atmospheric Research	Australia
18	Kate	Roggeveen	Australian Greenhouse Office	Australia
19	Anthony	Sheehan	Australian Greenhouse Office	Australia
20	Julian	Turecek	Origin Energy	Australia
21	Mark	Payne	Australian Greenhouse Office	Australia
22	Koji	Kano	Engineering Advancement Association of Japan	Japan
23	Ziqiu	Xue	Research Institute of Innovative Tech for the Earth	Japan
24	Don	White	Geological Survey of Canada	Canada
25	Daiji	Tanase	SEC, Engineering Advancement Association	Japan
26	Ernie	Perkins	Alberta Research Council	Canada
27	Andy	Chadwick	British Geological Survey	UK
28	Wendy	Hadley	Zurich Global Energy	Australia
29	Peter	Sengupta	Zurich Global Energy	Australia
30	Toshiyukki	Tosha	Geological Survey of Japan (AIST)	Japan
31	Jonathan	Pearce	British Geological Survey	UK
32	Elizabeth	Scheehle	US Environmental Protection Agency	USA
33	Alex	Zapantis	Rio Tinto Ltd.	Australia

34	Donald	De Vries	CanSyd Australia Pty Ltd.	Australia
35	Gerry	Morvell	Department of the Environment & Health	Australia
36	Simon	Race	Benfield Corporate Risk	Australia
37	Damon	Jones	EPA Victoria	Australia
38	Stephen	Cornelius	Defra	UK
39	Shiro	Ohkawa	Japan Petroleum Exploration Co., Ltd (JAPEX)	Japan
40	John	Frame	EPA Victoria	Australia
41	Bruce	Dawson	EPA Victoria	Australia
42	Susan	Hovorka	University of Texas at Austin	USA
43	Richard	McDonough	Primary industries & Resources SA	Australia
44	Cassandra	McCarthy	Australian Coal Association	Australia
45	Ian	Duncan	Bureau of Economic Geology	USA
46	Marcia	Couesaln	University of Calgary	Canada
47	Namiko	Ranasinghe	Department of Primary Industries	Australia
48	Max	Watson	CO2CRC	Australia
49	Thomas	Berly	CO2CRC	Australia
50	Peter	Cook	CO2CRC	Australia
51	Rick	Chalaturnyk	University of Alberta	Canada
52	Barry	Freifeld	Lawrence Berkeley National Laboratory	USA
53	Ashish	Datey	Schlumberger	Australia
54	Mark	Bonner	Australian Greenhouse Office	Australia
55	Clement	Yoong	DITR	Australia
56	Tim	Moore	Solid Energy	New Zealand
57	Charles	Christopher	BP	USA
58	Lincoln	Paterson	CO2CRC/CSIRO	Australia
59	Bill	Koppe	Monash Energy	Australia
60	Scott	Hargreaves	Monash Energy	Australia
61	Carmel	Anderson	CO2CRC	Australia
62	Catherine	Gibson-Poole	CO2CRC/ASP	Australia



3RD MONITORING NETWORK MEETING

Monday 30th October -Thursday 2nd November 2006
Rendezvous Hotel, Flinders Street, Melbourne, Australia.

This meeting brings together national and international government regulatory agencies, non-government organisations and monitoring and verification (M&V) technical communities.

Organised by

IEA Greenhouse Gas R&D Programme

Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

and

Australian Greenhouse Office of the Department of the Environment and Heritage

Sponsored by

Victorian Department of Primary Industry

Woodside Energy

and

Rio Tinto Ltd

Objectives

Provide an integrated set of M&V guidelines to encourage further public, regulatory and technical community discussion for wide scale deployment of CCS technology.

This objective will be realised by addressing the questions:

- What is the framework of a Monitoring, Evaluation, Reporting and Verification (MERV) for wide scale CCS deployment?
- How do we provide assurance of storage integrity through well, seal and containment monitoring technology?

Program

Monday: Regulatory Guidelines for Monitoring, Evaluation, Reporting and Verification
Tuesday: IEA M&V Network: Well Based Monitoring and Caprock Integrity
Wednesday: IEA M&V Network: Containment and Integration – Latrobe Valley Scenario
Thursday: Otway Basin Pilot Project (OBPP) Site Visit

Monday 30th October

Day 1: Regulatory guidelines for Monitoring, Evaluation,Reporting and Verification (MERV)

Australian Government
Department of the Environment and Heritage
Australian Greenhouse Office

08.45 to 09.00 **Introduction/housekeeping**
Gerry Morvell, Assistant Secretary Energy Futures, Department of the Environment and Heritage

Session 1: Keynote and NGO perspective — *Chair: Gerry Morvell*

09.00 to 09.45 **Keynote: The climate change context for CCS**
Howard Bamsey, Deputy Secretary, Department of the Environment and Heritage

09.45 to 10.15 **An NGO viewpoint on CCS, regulation and monitoring**
Greg Bourne, CEO WWF Australia

10.15 to 10.30 Break

Session 2: Further perspectives — *Chair: John Gale*

10.30 to 11.00 **US EPA underground injection control programme: experience**
Elizabeth Scheele, US Environment Protection Agency

11.00 to 11.30 **A perspective on MERV for Australia**
Gerry Morvell, Assistant Secretary Energy Futures, Department of the Environment and Heritage

11.30 to 12.00 **Insurance industry perspective**
Peter Sengupta, Zurich Global Energy

12.00 to 12.30 **Another country's experience with MERV**
Steve Cornelius, UK Department for Environment, Food and Rural Affairs

12.30 to 13.30 Lunch

Session 3: Technicians upate — *Chair: John Gale*

13.30 to 14.15 **IEA monitoring tool**
Andy Chadwick, British Geological Survey

14.15 to 14.45 **Goals of the OBPP monitoring programme & summary of other projects**
Kevin Dodds, CO2CRC

14.45 to 15.00 Break

Session 4: Facilitated discussion on design of MERV protocols — *Chair: Gerry Morvell*

15.00 to 16.00 **THEME: how to design and establish a suite of generic MERV protocols for CO_2 storage**
Facilitated discussion, within the context of some agreed MERV objectives, which may include:
- *for accounting purposes within national emission inventories;*
- *protect health, safety and environment (HSE) - existing or new regulations?*
- *recognition within emissions trading schemes (accounting for capture, transport and injection);*
- *assurance that sites perform effectively (frequency);*
- *verify CO_2 remains trapped in short term; and*
- *provide a basis for predictions about behaviour in the very long term basis.*

Session 5: Facilitated discussion on 'where to from here?' — *Chair: Gerry Morvell*

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

Close Day 1

19:00 *Dinner sponsored by Woodside Energy*
Guest Speaker: Dr Graeme Pearman — Climate Change: Risk and Opportunity.

WOODSIDE AUSTRALIAN ENERGY

Tuesday 31st October

Day 2: 2006 Monitoring and Verification Network Meeting

08.15 to 08.30	**Welcome and fire briefing/safety issues** *John Gale*, IEA GHG R&D, and *Kevin Dodds*, CO2CRC/CSIRO

Session 1: Plenary — *Chair: Kevin Dodds*

08.30 to 08.40	**Introduction of Minister** *Peter Cook*, CO2CRC
08.40 to 09.00	**Minister's opening address** *The Honourable Theo Theophanous*, Minister for Resources
09.00 to 09.10	**Question and answers**
09.10 to 09.25	**IEA GHG overview on network activities** *John Gale*, IEA GHG R&D
09.25 to 09.40	**CO2CRC Otway Basin Pilot Project organisation** *Peter Cook*, CO2CRC.
09.40 to 10.00	**Setting stage for monitoring network discussions** *Rick Chalaturnyk*, University of Alberta
10.00 to 10.30	*Break*

Session 2: Well-based monitoring — *Chair: Kevin Dodds*

10.30 to 11.00	**Keynote: well-based monitoring - overview presentation of wells for monitoring** *Rick Chalaturnyk*, University of Alberta
11.00 to 11.30	**Overview of well-based monitoring approaches at the Frio 2 project** *Susan Hovorka*, Bureau of Economic Geology
11.30 to 12.00	**Early geochemical and geophysical Results from Frio 2** *Barry Friefeld*, Lawrence Berkeley National Laboratories
12.30 to 13.00	*Lunch*
13.00 to 13.30	**Logging techniques for CO_2 saturation and well integrity evaluation** *Laurent Jammes*, Schlumberger.
13.30 to 14.00	**Time-lapse well logging to monitor the injected CO_2 in Nagaoka Project** *Daiji Tanase SEC*, Engineering Advancement Association, Japan
14.00 to 15.00	**Discussion: focus on how well-based monitoring fits within MERV discussion from Monday, its importance relative to injection phase and post-operational phase (Chair: Kevin Dodds)**
15.00 to 15.30	*Break*

Session 3: Monitoring for caprock integrity — *Chair: Rick Chalaturnyk*

15.30 to 16.00	**Overview of issues or mechanisms at play in seal integrity and identify monitoring processes or techniques that may play a role in assessment managing caprock integrity risks** David Dewhurst, CSIRO
16.00 to 16.30	**Using geochemical techniques for monitoring seal integrity** Ernie Perkins, Alberta Research Council/CO2CRC
16.30 to 17.00	**Resevoir simulation and coupled geomechanics to calculate pressure and stress changes that feed into monitoring design** Lincoln Paterson, CO2CRC/CSIRO
17.00 to 17.30	**Discussion/seals & MERV: focus on how monitoring fits within MERV discussion from Monday, its importance relative to injection phase and post-operational phase (Chair: Rick Chalaturnyk)**
17.30 to 17.45	**Discussion and preparation for Day 3** Kevin Dodds, CO2CRC/CSIRO

Close Day 2

19:00 *Dinner sponsored by Rio Tinto*

Wednesday 1st November

Day 3: 2006 Monitoring and Verification Network Meeting

Session 4: Containment and Integration		*Chair: Susan Hovorka*
8:00 to 8:30	**Containment & integration** Introduction Review Day 2 Plan for Day 3 *Susan Hovorka,* Bureau of Economic Geology	
8.30 to 9.00	**European "CO_2 GeoNet" Research Network on the geological storage of CO_2 - interim progress report relevant to monitoring, verification, ecosystem protection/responses, health and safety, regulation and public perception of underground CO_2 storage** *Nick Riley,* British Geological Survey	
9.00 to 10.00	**Walkaway VSP for CO_2 monitoring at the Penn West Pilot, Alberta** *Marcia L. Couëslan Crewes,* University of Calgary	
9:30 to 10:00	**Field investigation results after the Mid Niigata pref. earthquake at the Nagaoka injection site** *Ziqiu Xue,* Research Institute of Innovative Technology for the Earth, Japan	
10.00 to 10.30	*Break*	
10:30 to 11:00	**Assessing the efficacy of CO_2 storage by atmospheric monitoring** *David Etheridge,* CO2CRC/CSIRO	
11:00 to 11:30	**Design and data for a facility for testing near surface CO_2 detection** *Lee Spangler,* ZERT and Montana State University	
11:30 to 12:00	**Discussions: Seismic and atmosphere monitoring and MERV requirements (Chair: Susan Hovorka)**	
12.00 to 13.00	*Lunch*	
Session 5: Latrobe Valley Case Study		*Chair: Kevin Dodds*
13:00 to 13:30	**Review of Monday Regulatory Outcomes** *Mark Bonner,* Director Technology Futures, Department of the Environment and Heritage	
13:30 to 14:00	**The Latrobe Valley CO_2 Storage Assessment** *Catherine Gibson-Poole,* CO2CRC/ASP	
14:00 to 14:45	**Breakout: Risk evaluation and regulatory recommendations — Latrobe Valley key risk and regulatory issues to be addressed by MERV**	
14:45 to 15:15	**Report back discussion**	
15.15 to 15.45	*Break*	
	Breakout: M&V evaluation — Latrobe Valley recommended technologies using IEA GHG M&V tool **Report back discussion** **Wrap-up session** *Kevin Dodds,* CO2CRC/CSIRO	
Close Day 3		

17:45	Proceed to Southern Cross Railway Station by Tram (see map)
18:35	Train leaves for Warrnambool

Thursday 2nd November

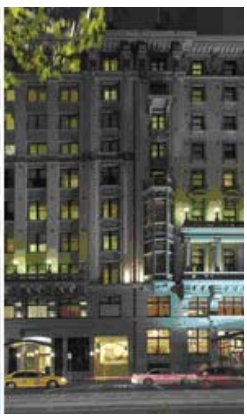
Day 4: Otway Basin Pilot Project (OBPP) Site Visit

08.00 to 18.15	**Bus tour of Otway site** Leader Maxwell Watson, CO2CRC/Australian School of Petroleum *This will include:* • *Visit to locations of the volcanic source of the Otway Basin Pilot Project CO_2* • *Geological overview of CO_2 containment with reference to local outcrops* • *Visit and presentation of Otway Basin Pilot Project implementation* • *Tour of local gas storage project* • *Visit to the magnificent cliffs and coastline nearby the Otway Basin Pilot Project*

	Quest Apartments Accommodation Assigned– Breakfast Packs in Room
8:00	Leave Warrnambool. Group to assemble at bus at 7:45
	10 – 15 minute drive to Stop 1
8:15 to 8:30	**Stop 1: Tower Hill.** Drive through Tower Hill. This is the best place to view volcano and volcanic deposits. The group will be addressed in the buses, discussing the source of the natural CO_2 that is to be injected into the Naylor structure.
	30 minute drive to Stop 2
9:00 to 9:45	**Stop 2: Boggy Creek Production Facility.** A brief pause to observe the Buttress-1 well location (source of CO_2), then arrive at a CO_2 production facility operated by BOC. Neil Evans of BOC will address the group for 15 - 20 minutes. A further ½ hour is then available for questions and a drive in the buses around the site before heading to the next stop.
	15 minute drive to Stop 3
10:00 to 10:30	**Stop 3: Otway Basin Pilot Project injection well and monitoring well site.** Corner of Soda's Lane from Dances Rd. The group will assemble in the back of the Dumsney's property; future location of CRC 1. CO2CRC Pilot Project Manager Sandeep Sharma will address the group for 15 minutes.
	15 minute drive to Lunch Stop
10:45 to 11:45	**Lunch Stop (early lunch): Boggy Creek Pub.** Sandwiches and finger food. Sandeep Sharma and other CO2CRC Otway Basin pilot Project members available for questions.
	30 minute drive to Stop 4
12:15 to 1:10	**Stop 4: Twelve Apostles.** A chance to appreciate the reservoir/seal concept in geosequestration. If time and tide permits the group will walk down the Gibson Steps onto the beach and can see the seal-reservoir relationship.
	20 minute drive to Stop 5
1:30 to 2:15	**Stop 5: Iona Gas Storage Facility**. This will be a similar process to the stop at the CO_2 plant with a 15 minute talk by TruEnergy followed by questions.
	2 hour drive to Stop 6 (inland route i.e. no Great Ocean Road)
4:15 to 4:45	**Stop 6: Anglesea Coal Mine and Power Plant.** This will be a stop on the side of the road to view the scale of a brown coal mine and power station. The group can get out and look around for ~20 minutes.
	1 ½ hours drive to Melbourne
6:15	Arrive in Melbourne, Rendezvous Hotel.

Day 4: Otway Basin Pilot Project (OBPP) Site Visit

Further Information...



Location & Transport

1. Rendezvous Hotel, Melbourne
2. Southern Cross Station
3. Telstra Dome
4. Melbourne Convention Centre
5. Melbourne Exhibition Centre
6. Crown Entertainment Complex
7. Southbank Promenade
8. Australia on Collins
9. Flinders Street Station
10. Chinatown
11. Federation Square
12. Melbourne Aquarium

Australian Government

IEA GHG R&D Programme
CCS Monitoring Network
30 October 2006

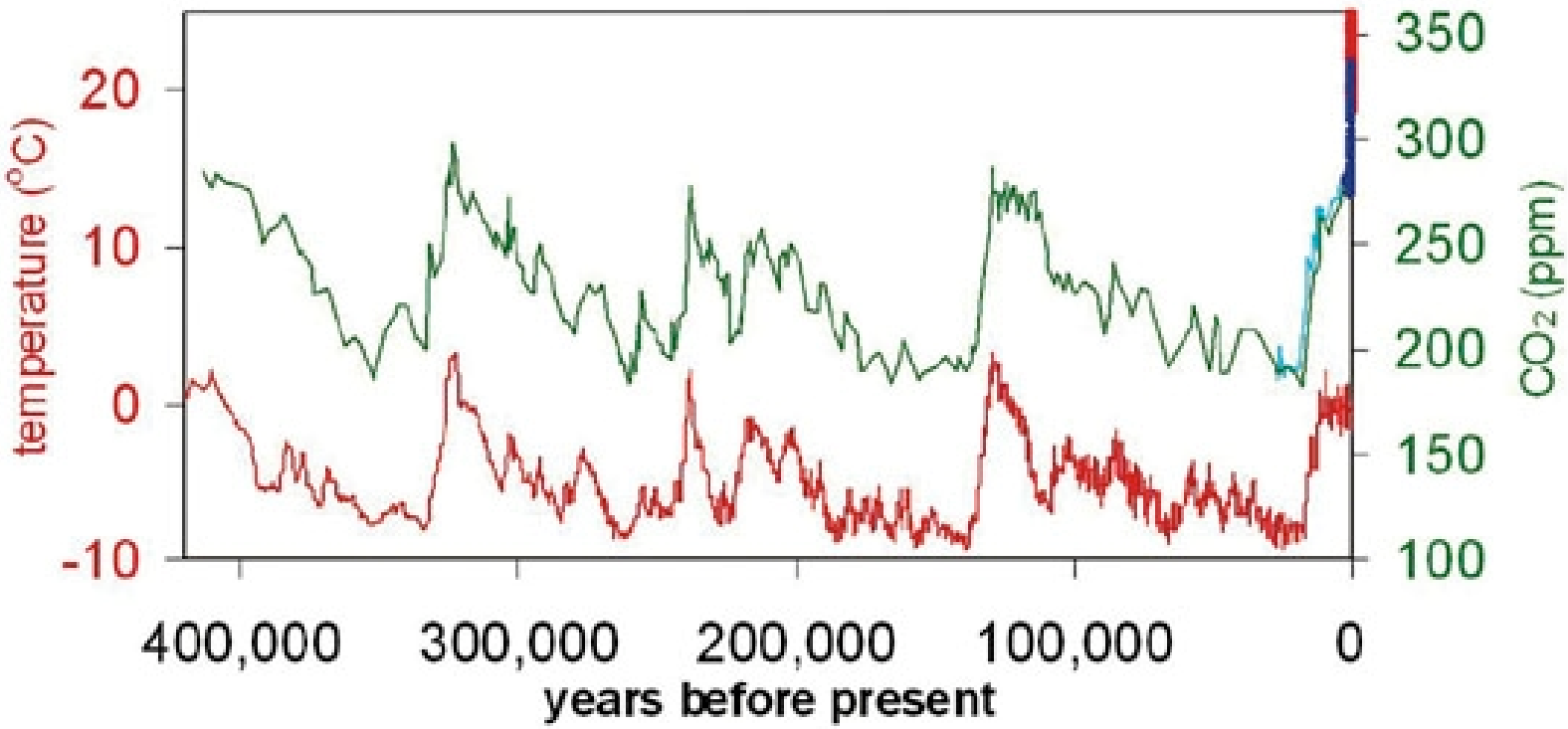
Long-term climate change:
challenges, opportunities, cooperation

Howard Bamsey

Australian Greenhouse Office
Department of the Environment and Heritage

Australian Government

CO_2 & temperature: last 420,000 yrs



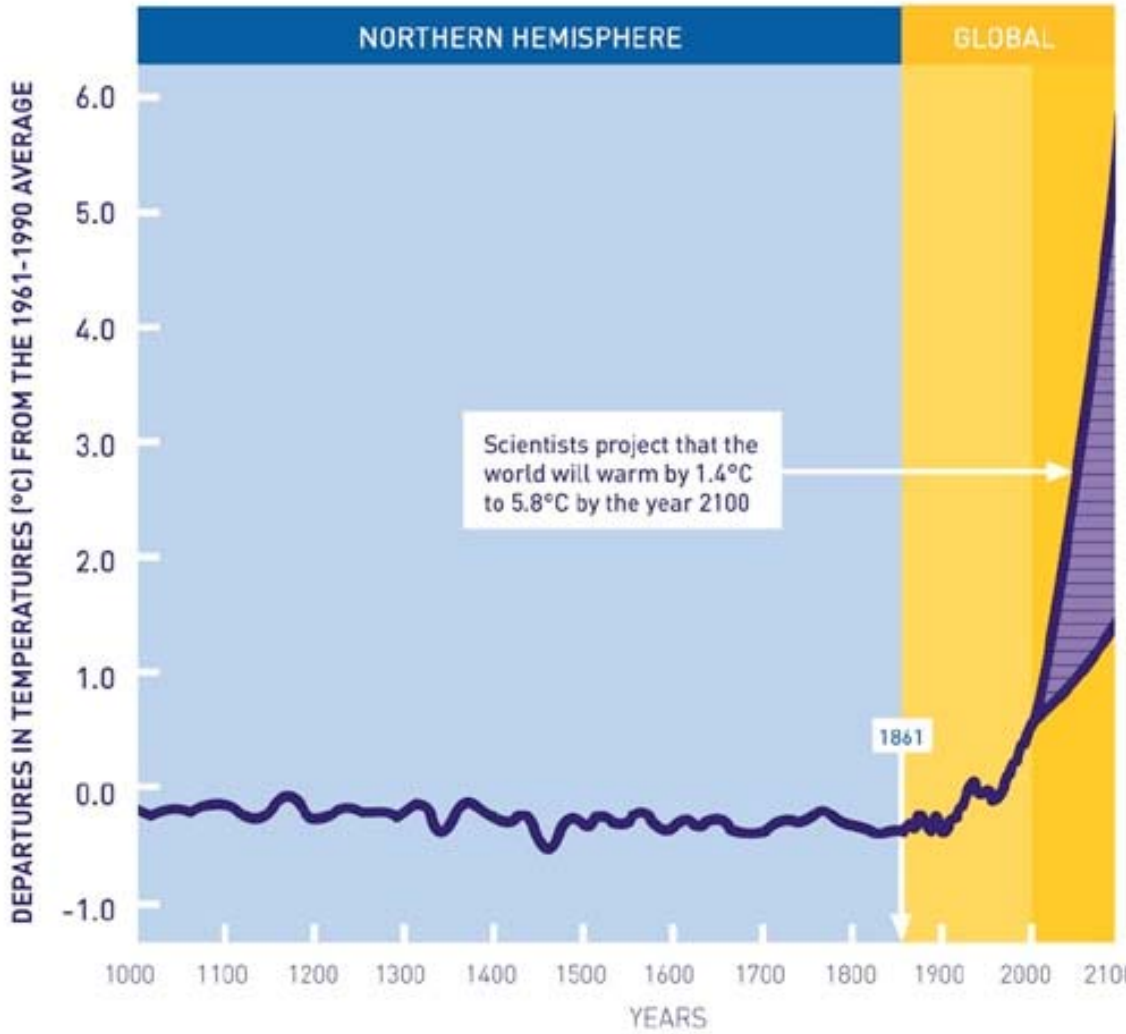
Temperature and CO_2 concentrations from the Vostok ice core in Antarctica.

Current global atmospheric concentrations of CO_2 (~ 380ppm) are the highest in the last 420,000 years.

Source: IPCC TAR 2001

Australian Government

Forward projections show potentially severe consequences

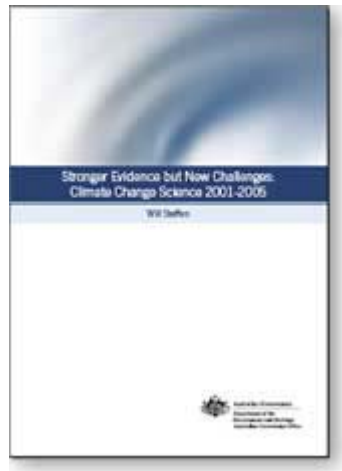


Source: Adapted from IPCC TAR, 2001

Australian Government

Firming science

- Earth warming beyond natural variability.
- Impacts observable.
- Stronger evidence of human influence. Consequences: climate, sea-level rise, ocean acidification.
- New focus: defining and timing of ‘dangerous’ climate change.



Australian Government

Growing public concern

Global Views 2006 – Australians surveyed:

- 68% - global warming a critical threat.
- 68% - we should take action now even if significant costs.
- 87% - improving the global environment is *the* top foreign policy goal.

Source: Chicago Council on Global Affairs; Lowy Institute for International Policy, 2006

Australian Government

Projected energy use

- World demand for energy to rise.
  - Almost 60% higher in 2030.
  - 85% of this increase to be sourced from fossil fuels.

- Related emissions to rise marginally faster.
  - 60% increase in CO_2 emissions in 2030.

Source: IEA World Energy Outlook, 2004

Australian Government

Multi-track approaches at all levels

Physical action required

- Limit climate change by limiting emissions.
  - Energy sector:
    - Energy efficiency, renewables, other low emission technologies such as CCS (i.e.. No one solution).
  - Other sectors.
- Prepare to adapt to a warmer climate.

Australian Government

Multi-track approaches at all levels

Global cooperation required

- Broad global response and commitments (global problem affecting all, but not equally).
- Must accommodate different local circumstances.

Australian Government

Australia has a big stake in an effective global response

Costs of climate change and adaptation	Costs of emissions reductions
• Increased severe weather events – storms and bushfires • Impacts on water supply and agriculture • Reduced biodiversity and risks to tourism • New health risks	• Risk to competitive advantage in abundant fossil fuel. • Large investment needed in new technologies and infrastructure • Business restructuring – regional adjustments

Australian Government

Long-term global cooperation

- Greater cuts required.
- Unlikely to see a long-term version of Kyoto without change in architecture.
- Needs to accommodate all emissions and all national needs.

Australian Government

UNFCCC Dialogue on long-term action

- Established Dec 2005.
- Non-binding, open dialogue:
  - Advancing development goals in a sustainable way
  - Addressing action on adaptation
  - Realising the full potential of technology
  - Realising the full potential of market-based opportunities
- To run for two years, over four workshops.

Australian Government

UNFCCC Dialogue on long-term action

- First workshop: May 2006, Bonn.
- Recognition of:
  - increasing global energy demand;
  - ongoing role of fossil fuels;
  - need for a range of actions; and
  - need for climate change policies to be considered in a sustainable development context.

Australian Government

UNFCCC Dialogue on long-term action

- Second workshop: Nov 2006, Nairobi:
  - sustainable development; and
  - market-based opportunities.

- Axis between global and national strategies.

Australian Government

UNFCCC Dialogue on long-term action

- Third workshop: early 2007.
  - Adaptation.
  - Realising the full potential of technology.
- Final workshop: late 2007.
  - Overarching and cross-cutting issues.
  - Proposals for further actions and approaches.
- Report to UNFCCC late 2007.

Australian Government

Long-term global cooperation

UNFCCC – COP12 and COP/MOP2

- Initial negotiations towards new commitments for Kyoto's developed country parties.
- Role of CCS, including under Clean Development Mechanism

Australian Government

Long-term global cooperation

Asia Pacific Partnership

- US, Japan, China, South Korea, India and Australia
- Climate change, energy security and air pollution
- Economic development and poverty reduction
- Industry partnerships; taskforces; projects

Australian Government

Long-term global cooperation

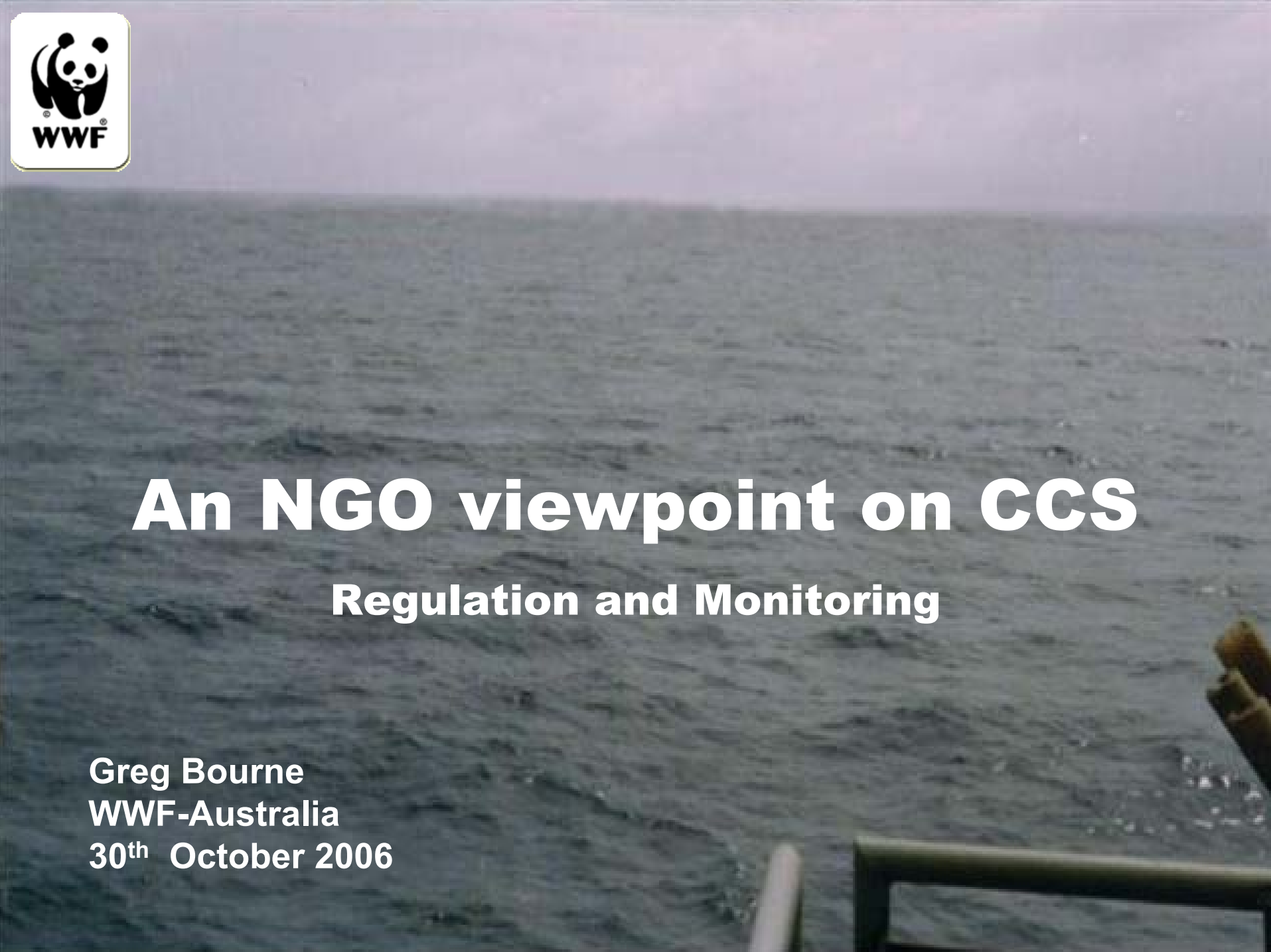
G8+ Dialogue on Climate Change, Clean Energy and Sustainable Development

- Initiative of G8 Gleneagles Summit, July 2005
- Focus on:
  - deployment of clean technologies;
  - incentives for large-scale private investment;
  - new model for cooperation between developed and developing countries; and
  - adaptation.

Australian Government

Conclusion: CCS Monitoring context

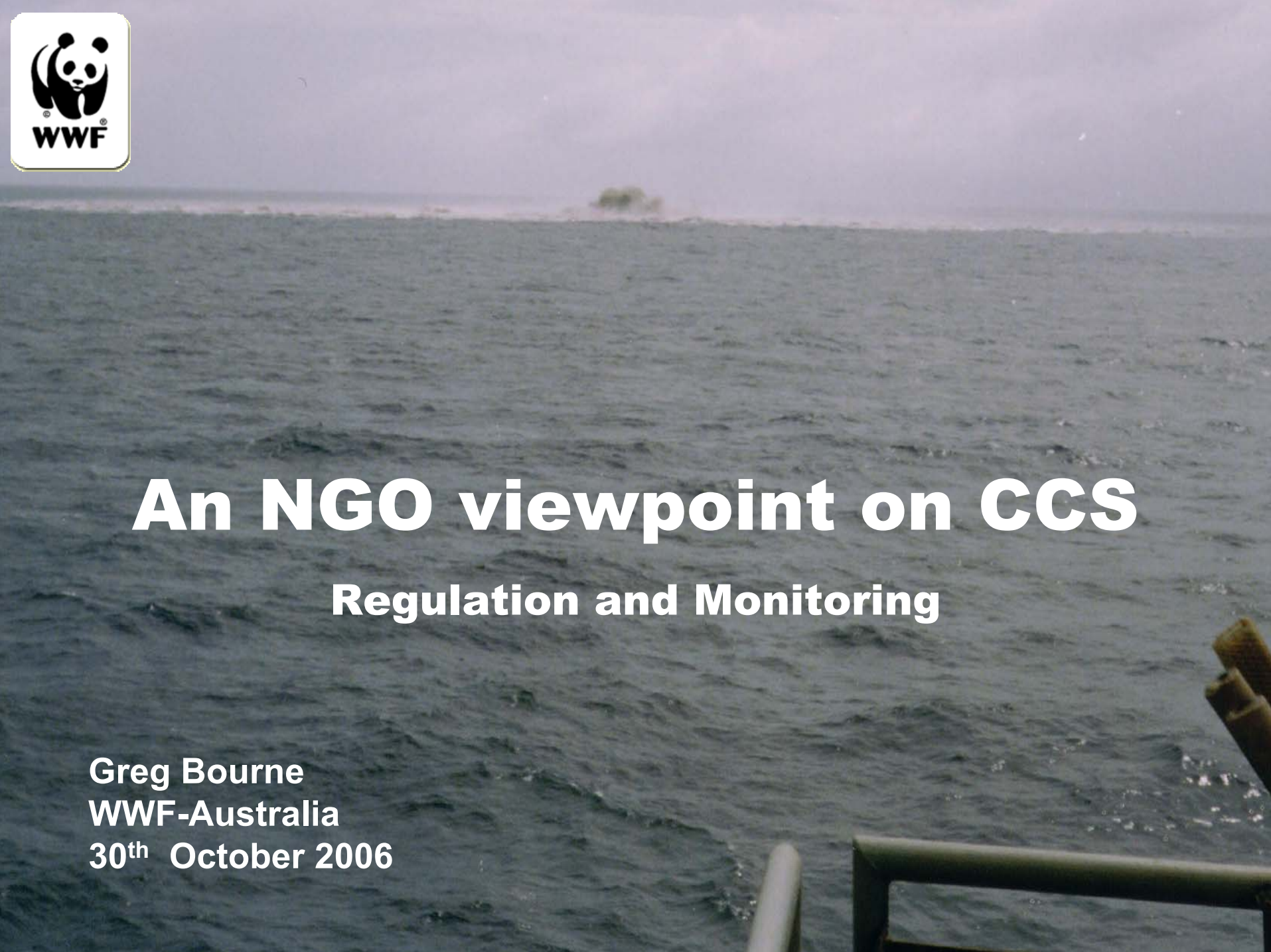
- Must act now, including on CCS.
- MERV critical for all CCS stakeholders.
- Certifiable evidence of CO_2 behaviour for:
  - public safety and confidence
  - credibility in carbon markets;
  - ownership and liability issues;
  - greenhouse accounting; and
  - management of the environment and resources.



An NGO viewpoint on CCS

Regulation and Monitoring

Greg Bourne
WWF-Australia
30th October 2006



An NGO viewpoint on CCS

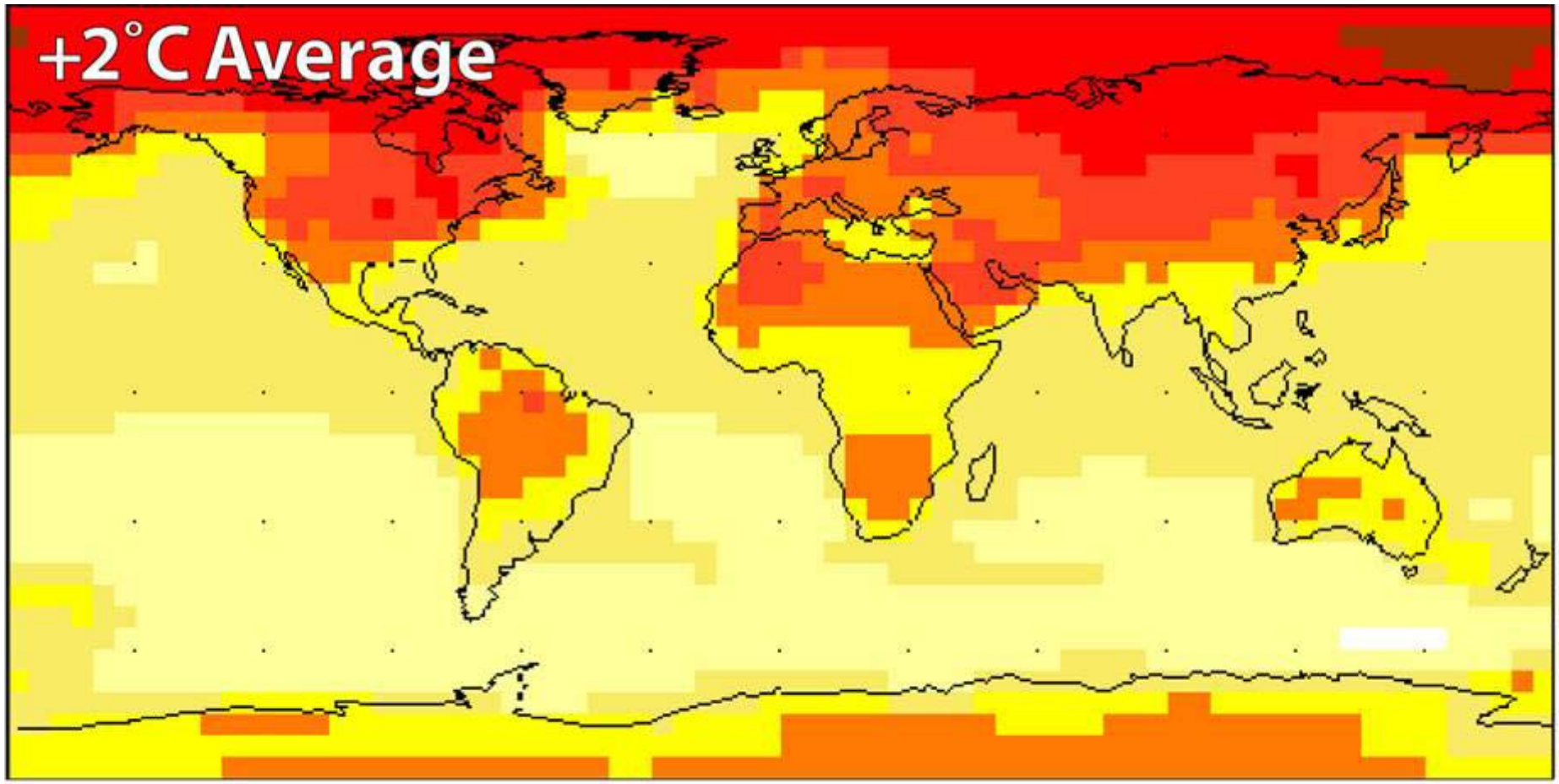
Regulation and Monitoring

Greg Bourne
WWF-Australia
30th October 2006

Don’t get it wrong!

Climate Change and ways forward!

What does this mean for global temperatures?

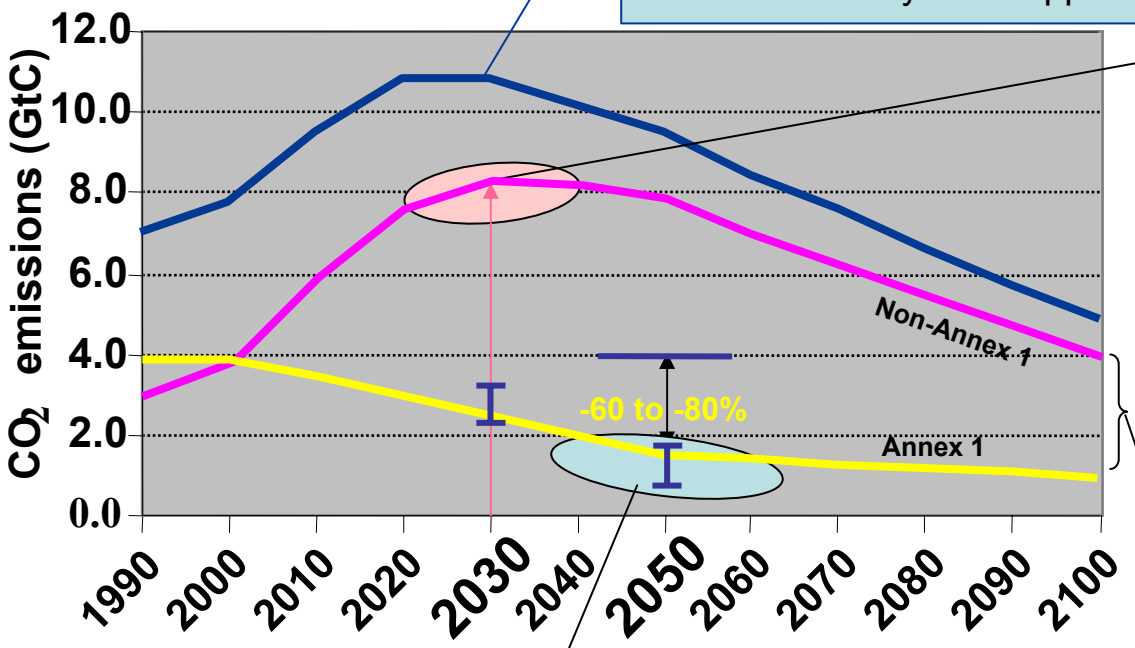


Approximate annual mean surface temperature distribution for global increase by 2˚C

0 1 2 3 4 (˚C)

Note: Employed linear pattern scaling method as implemented in the SCENGEN model (by Wigley et al.).
The displayed pattern is the average of the default set of models, namely CSM (1998), ECHAM3 (1995), ECHAM4(1998), GFDL(1990), HADAM2(1995), HADAM3(2000).
The pattern has been derived for a temperature increase of 2˚C above 1990 in a transient run with emission scenario IPCC SRES B2. Note that the equilibrium temperature pattern for a 2˚C increase above pre-industrial levels will be quantitatively different, although qualitatively similar.

A Projection of Emissions Pathways for the Developed and Developing Worlds



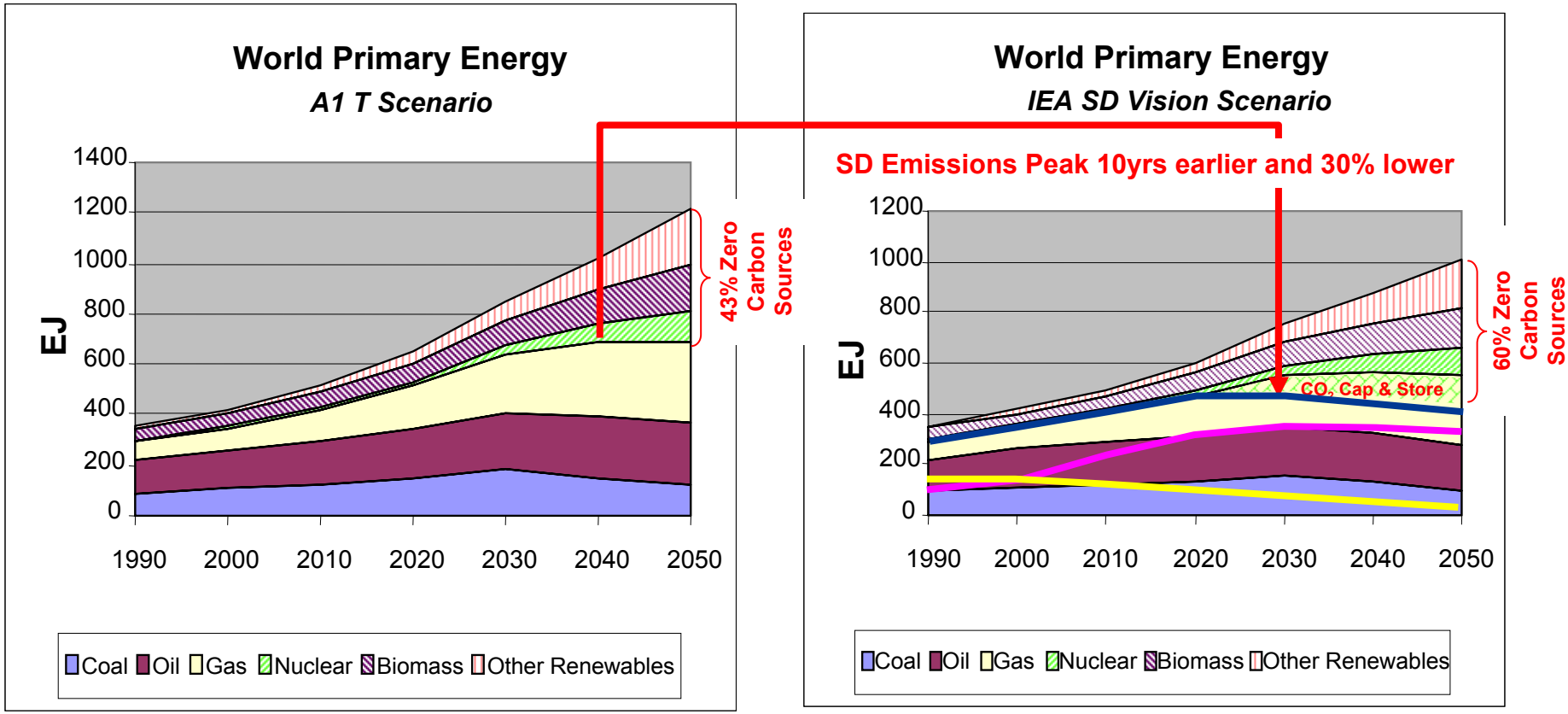
CO_2 emissions pathway needed to stabilise at 550 ppm (WRE550) or more likely at 450 ppm

Developing world emissions grow as they "catch up" then need to diminish from ~2030

Developed and developing worlds converge on some combination of emissions/capita and emissions/GDP while contracting their emissions

Developed world needs to reduce emissions **60 ~ 80%** by ~2050 starting now!

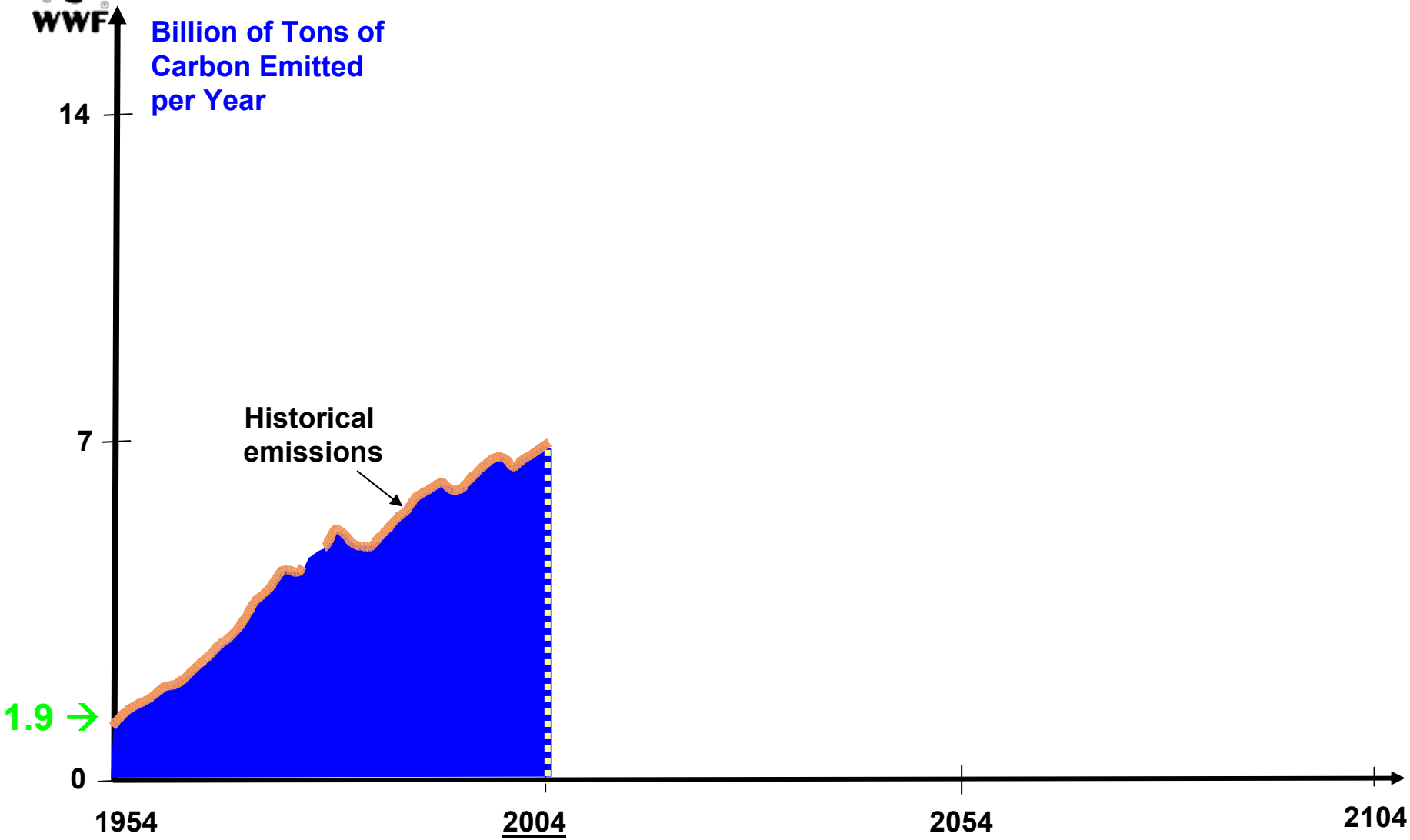
Energy Demand Grows – How Much Emissions?



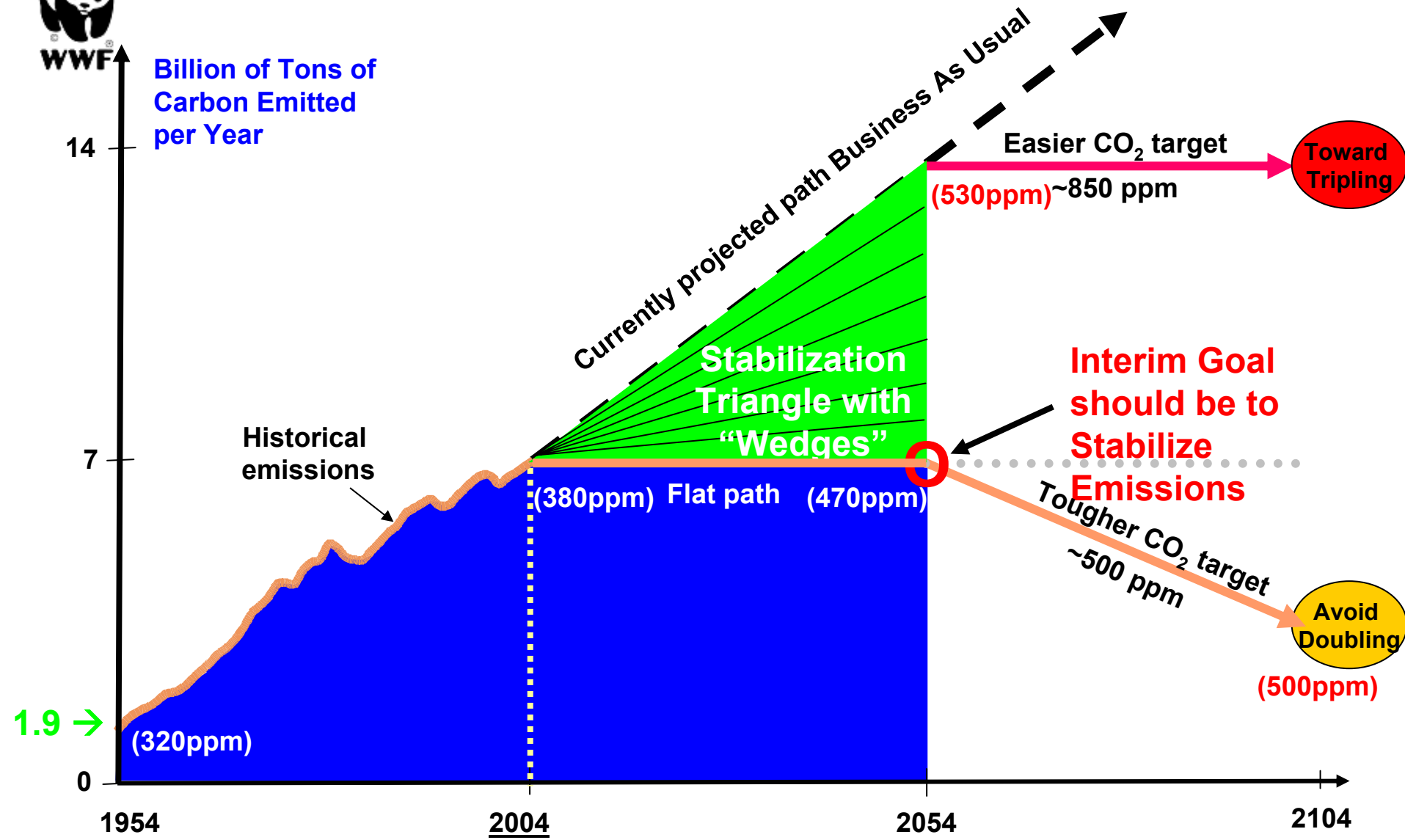
Source: Energy to 2050 Scenarios for a Sustainable Future IEA 2003

Emissionless Energy portfolio

Past emissions



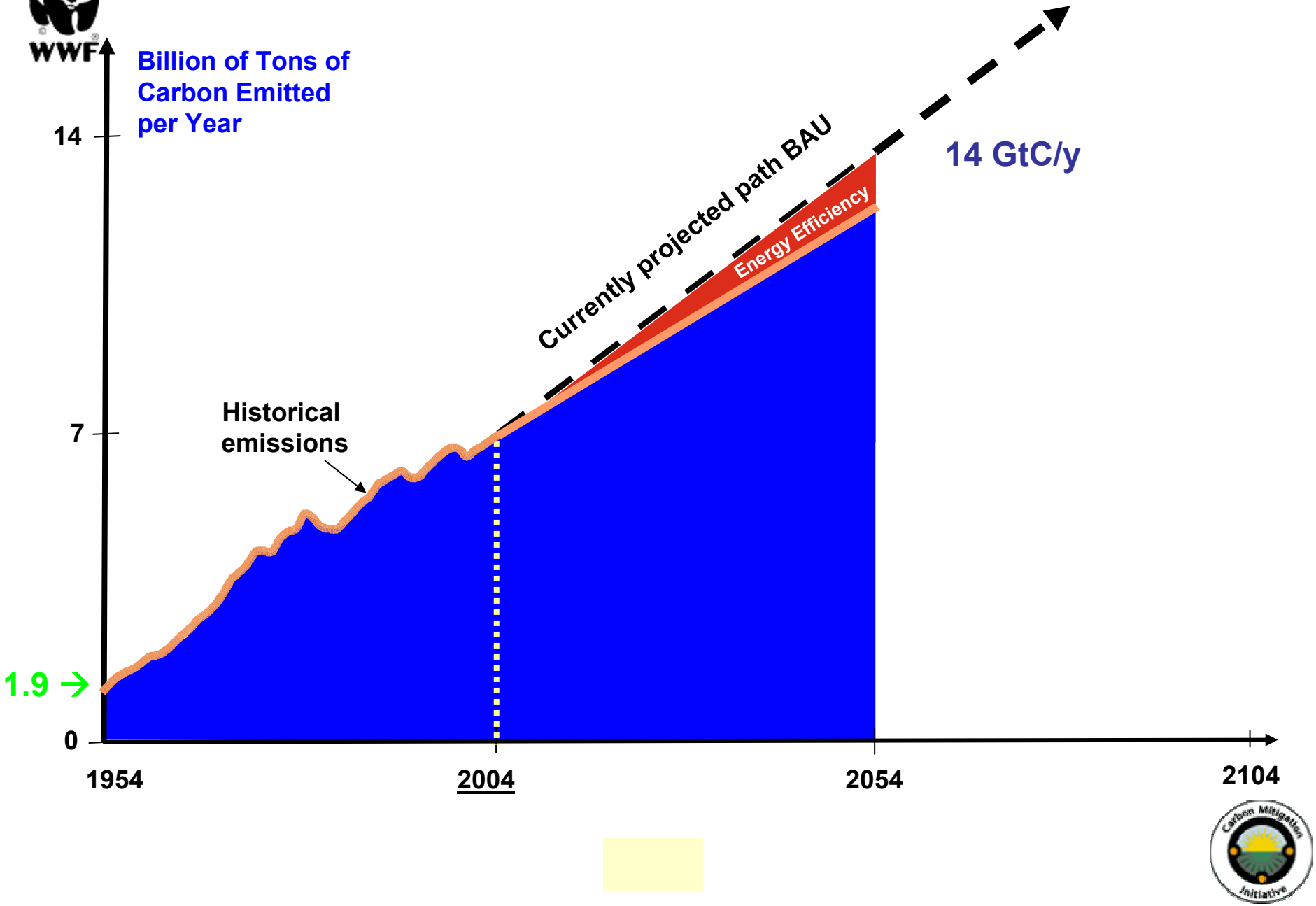
Avoid doubling* or inexorably towards tripling*



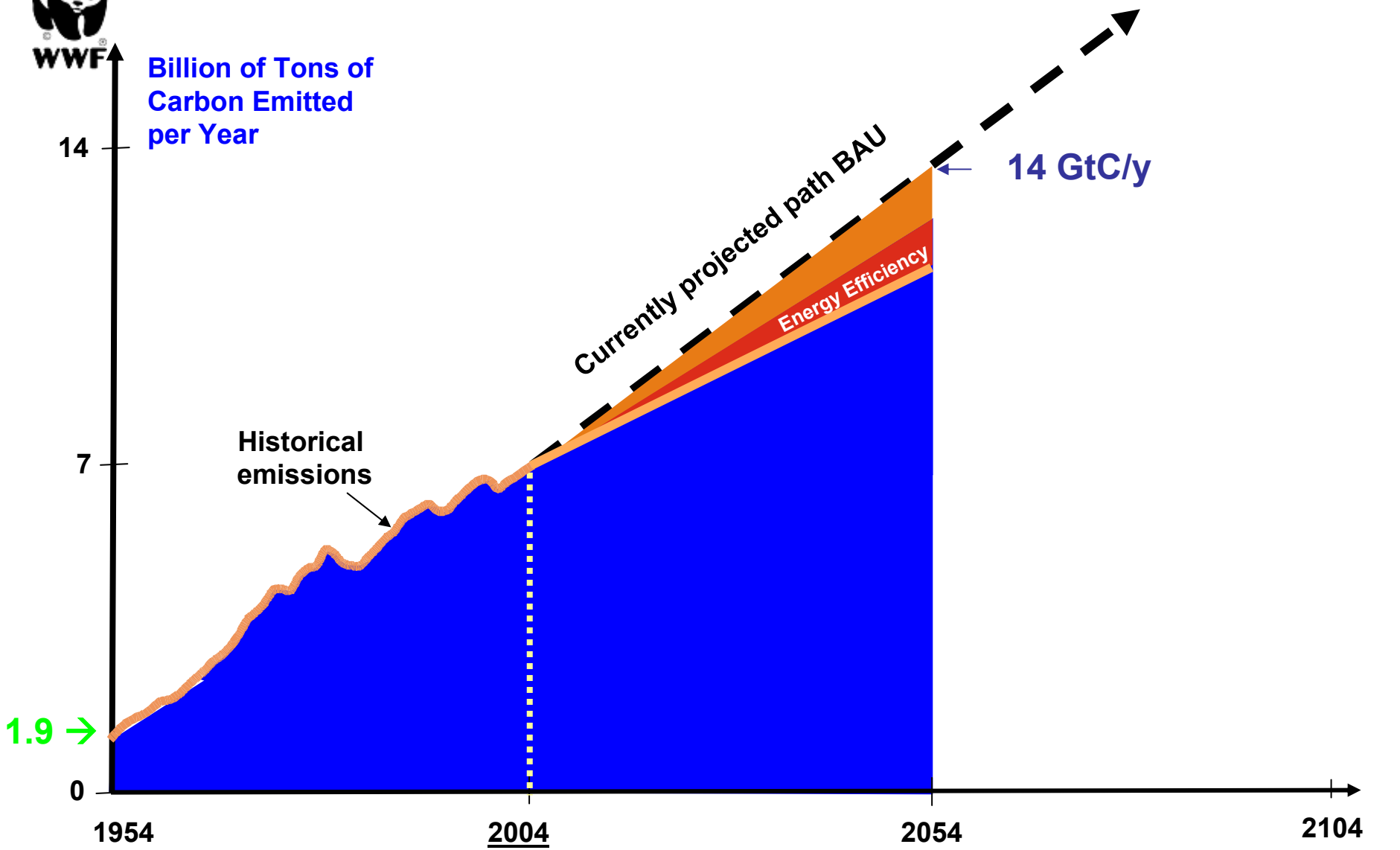
*

- Atmospheric CO_2 concentration Pre Industrial **~275 ppm** Double **550 ppm** Triple **825 ppm**
- With current knowledge of "climate sensitivity" and **BAU** implies **+3°C** by 2100

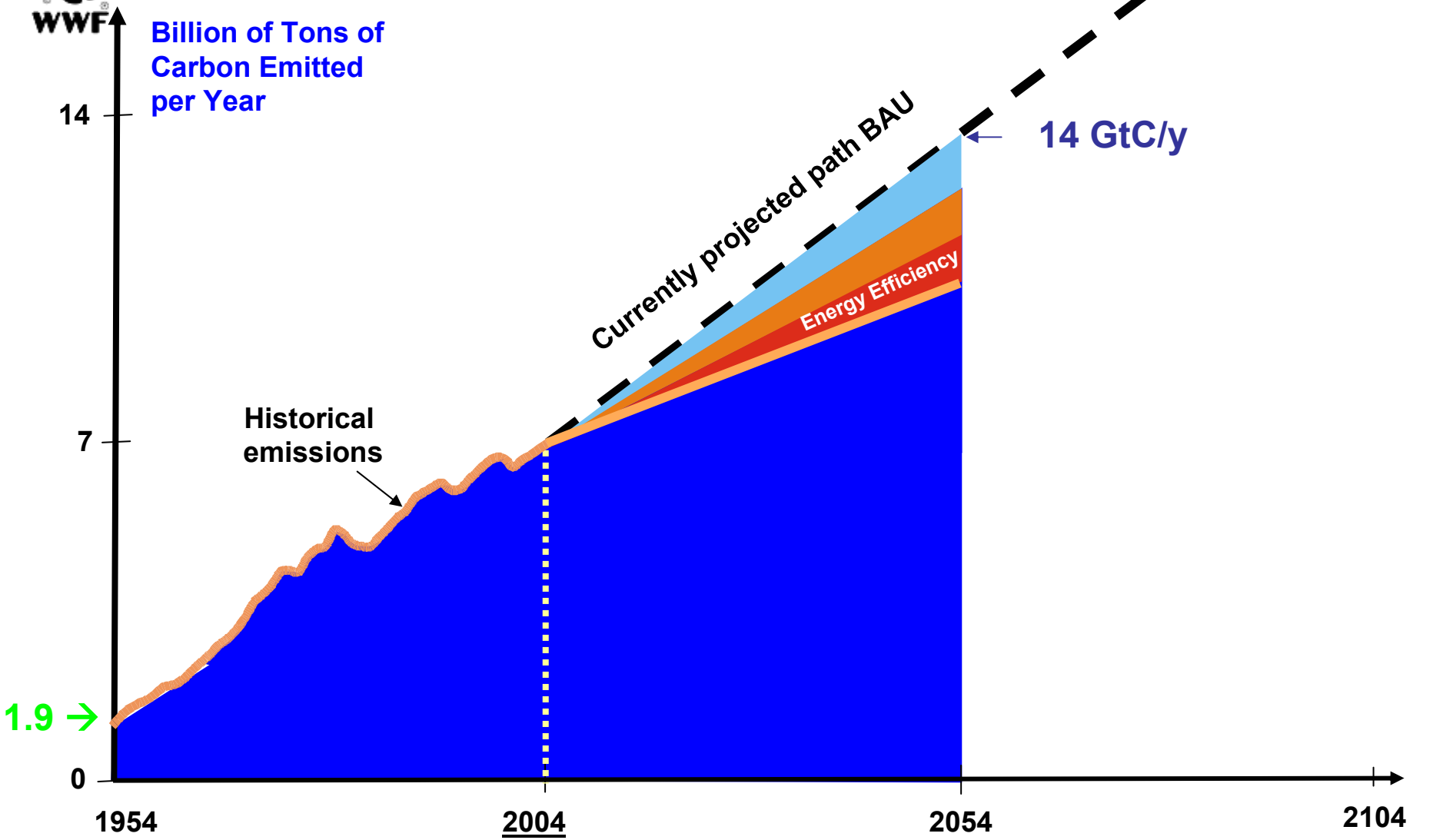
Driving in wedges reduces emissions from BAU



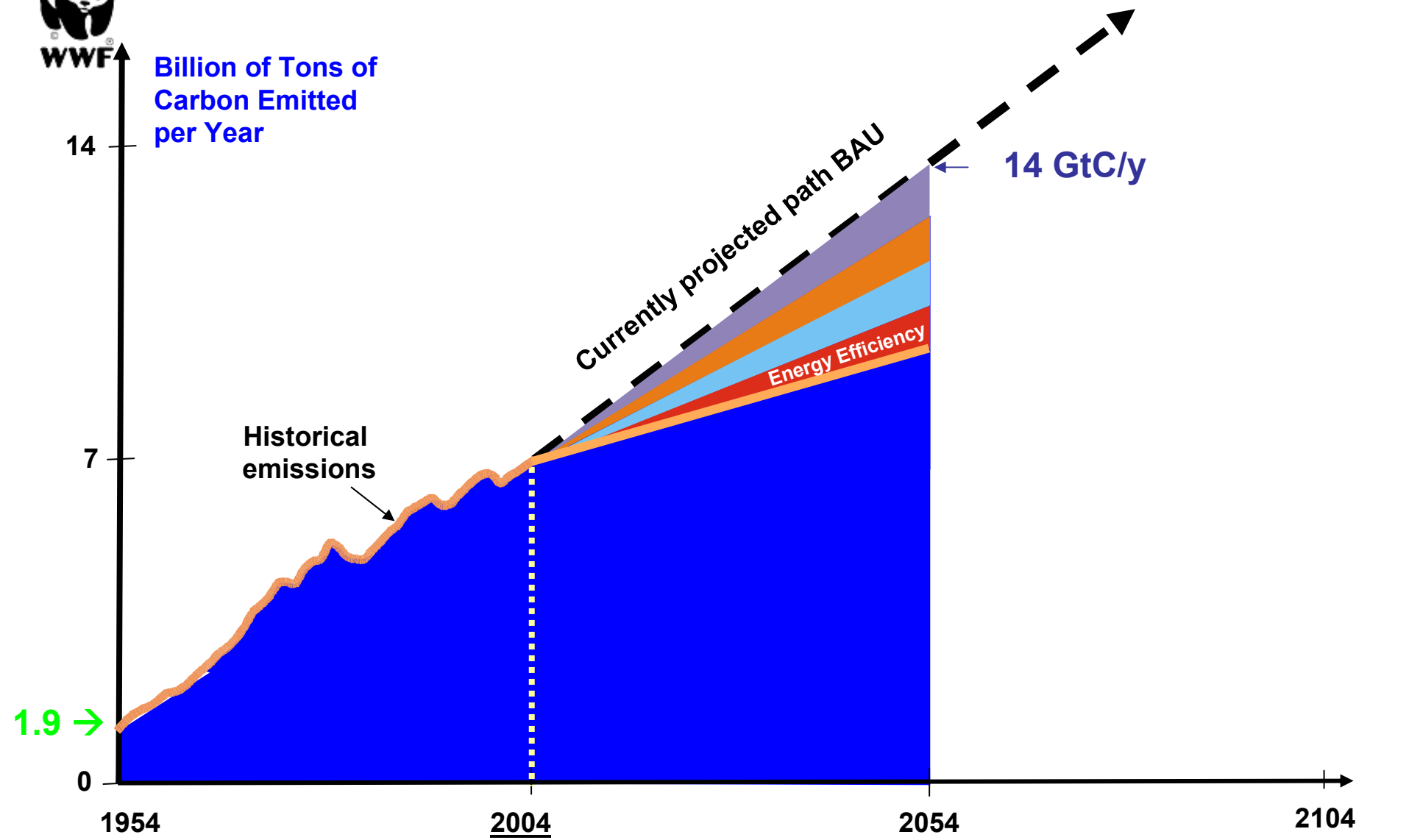
Start with energy efficiency measures



Introduce according to preference order



The more wedges the better



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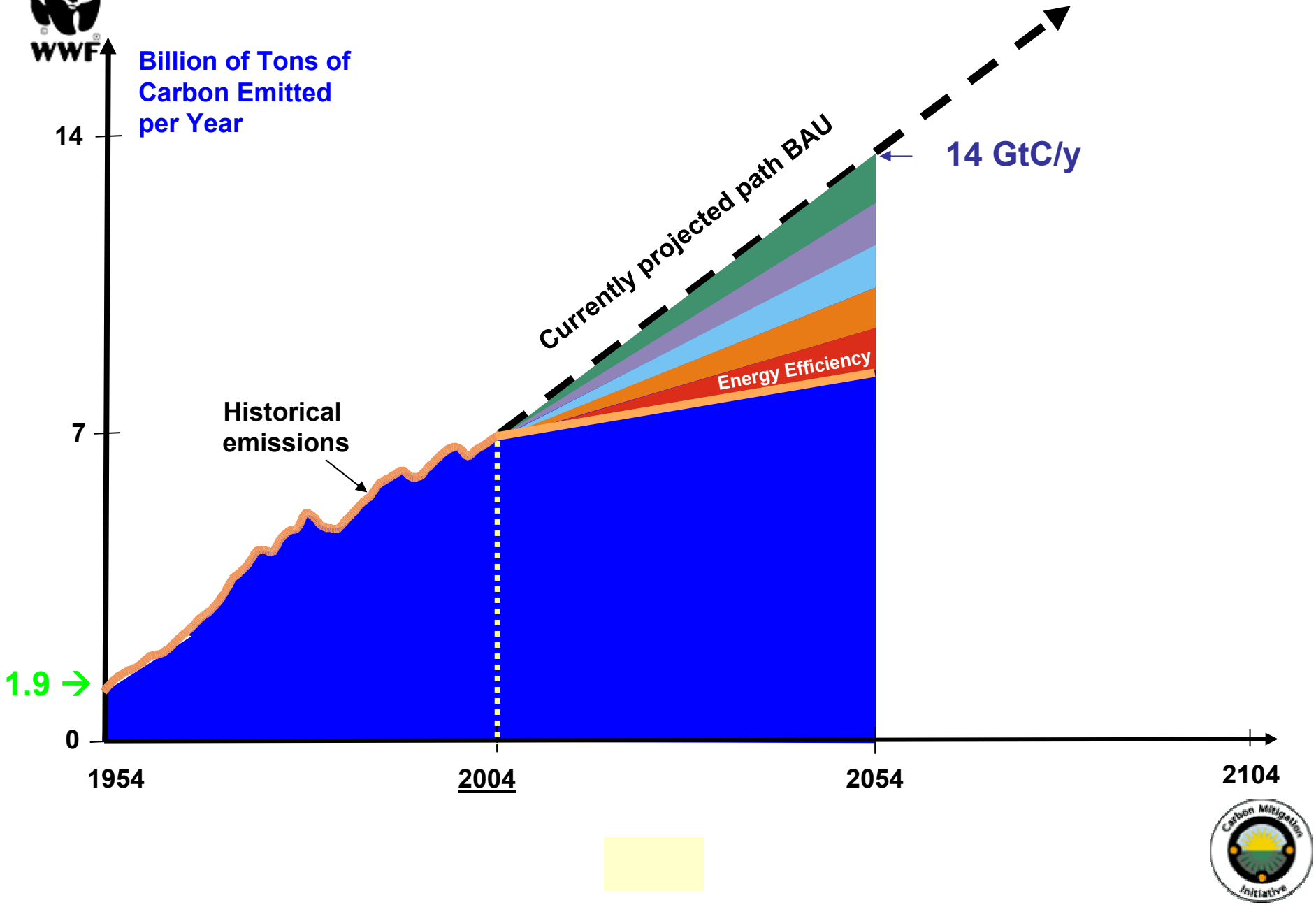

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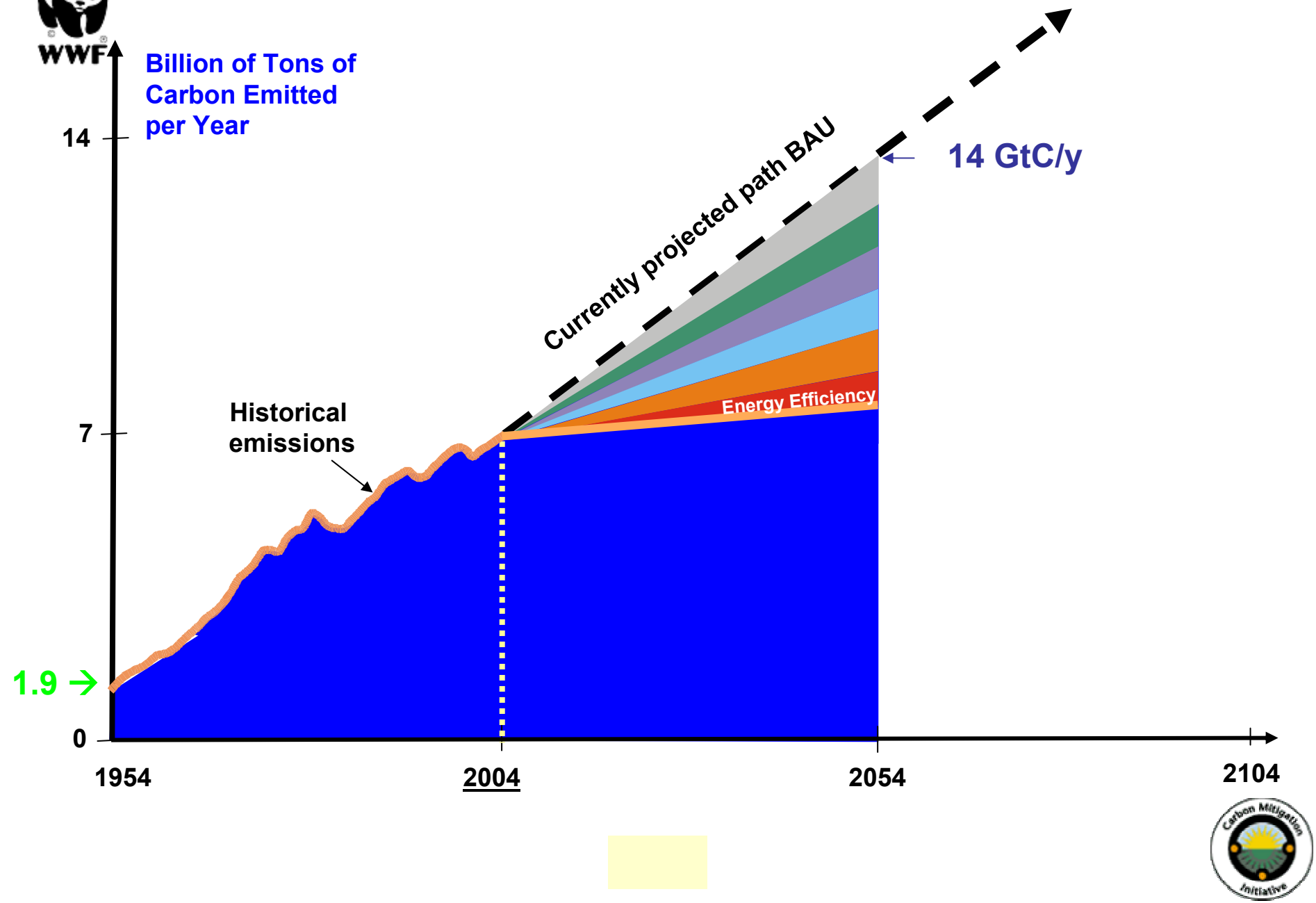
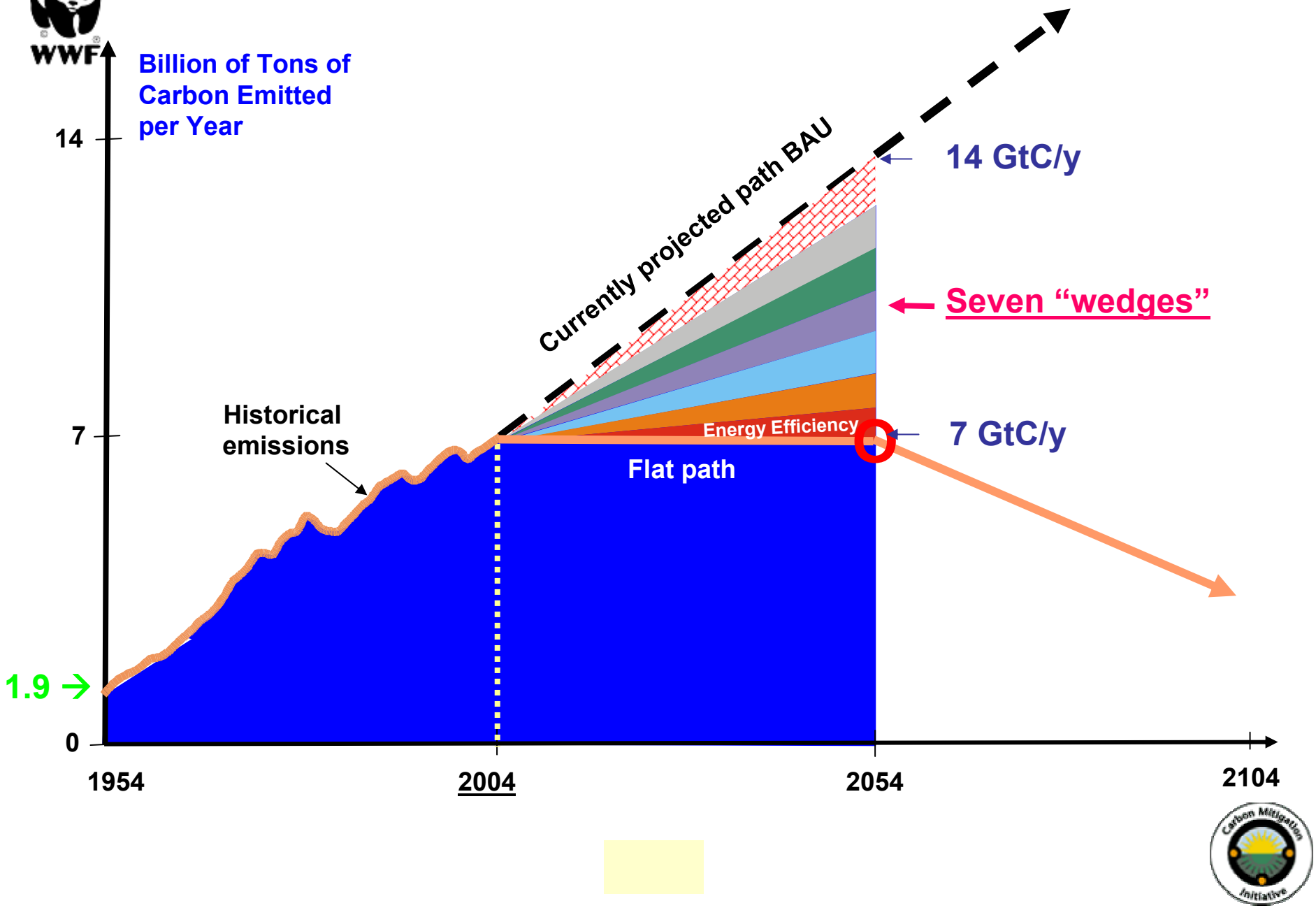
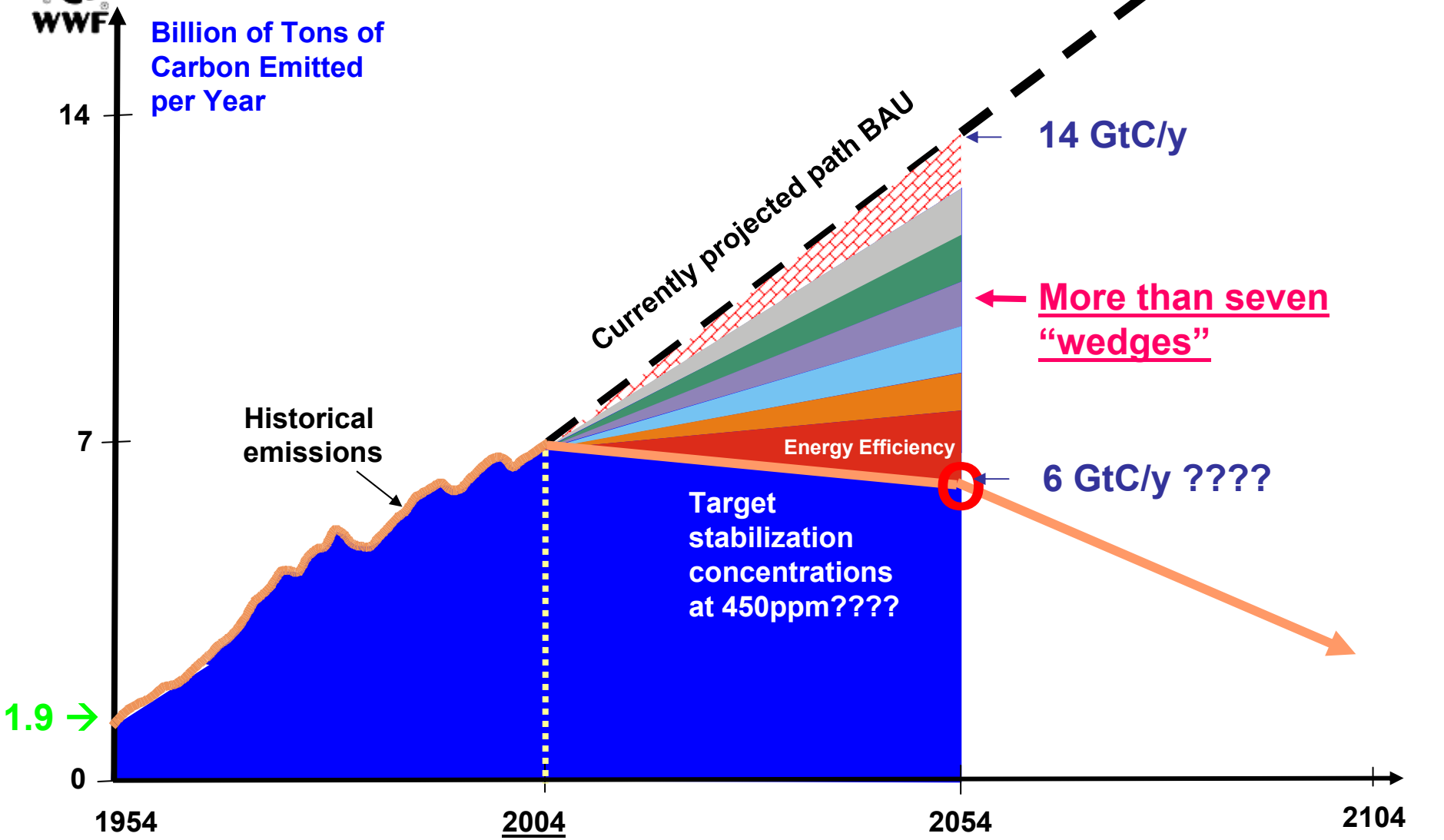


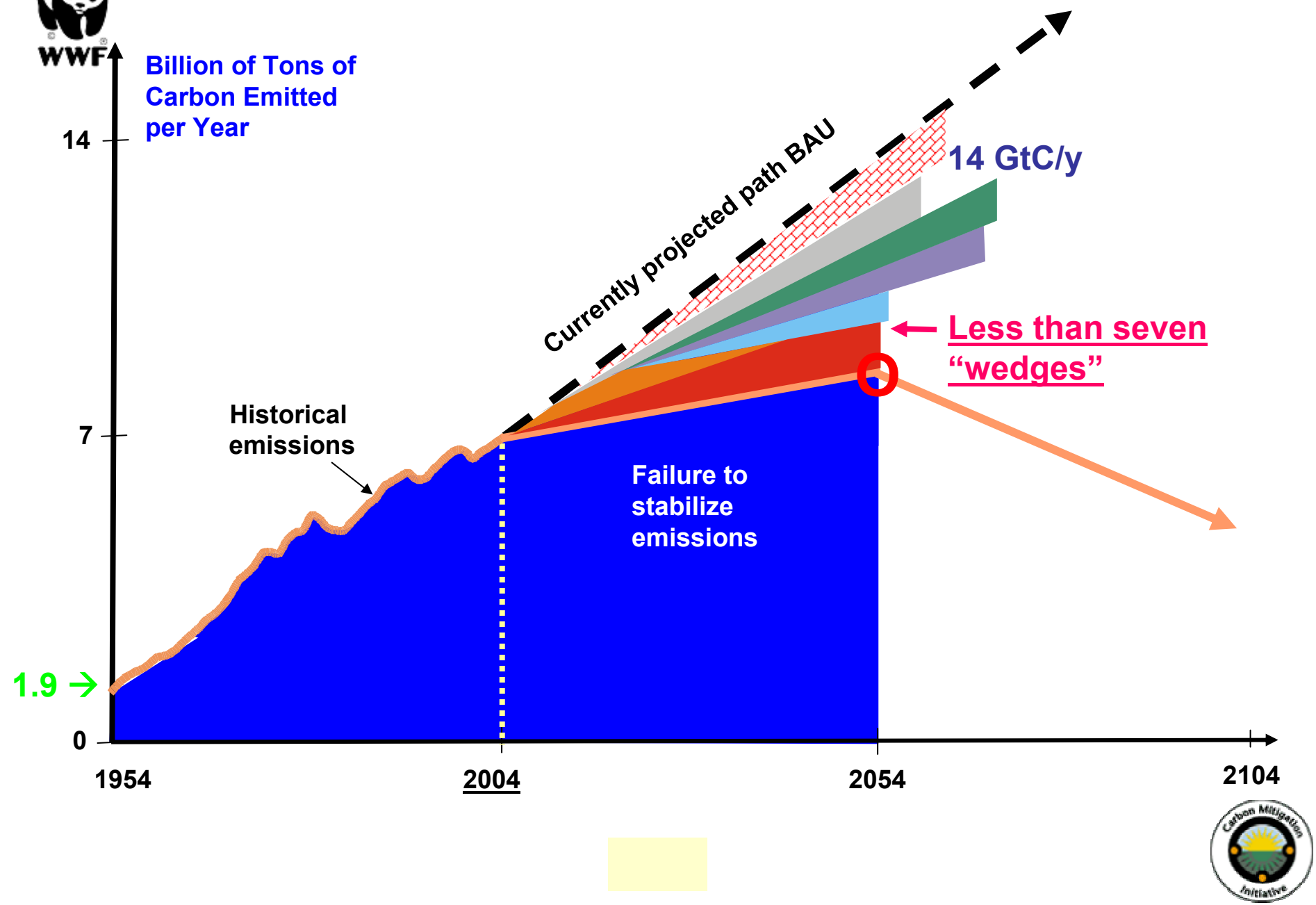
Need 7 standard wedges to stabilize at 500ppm



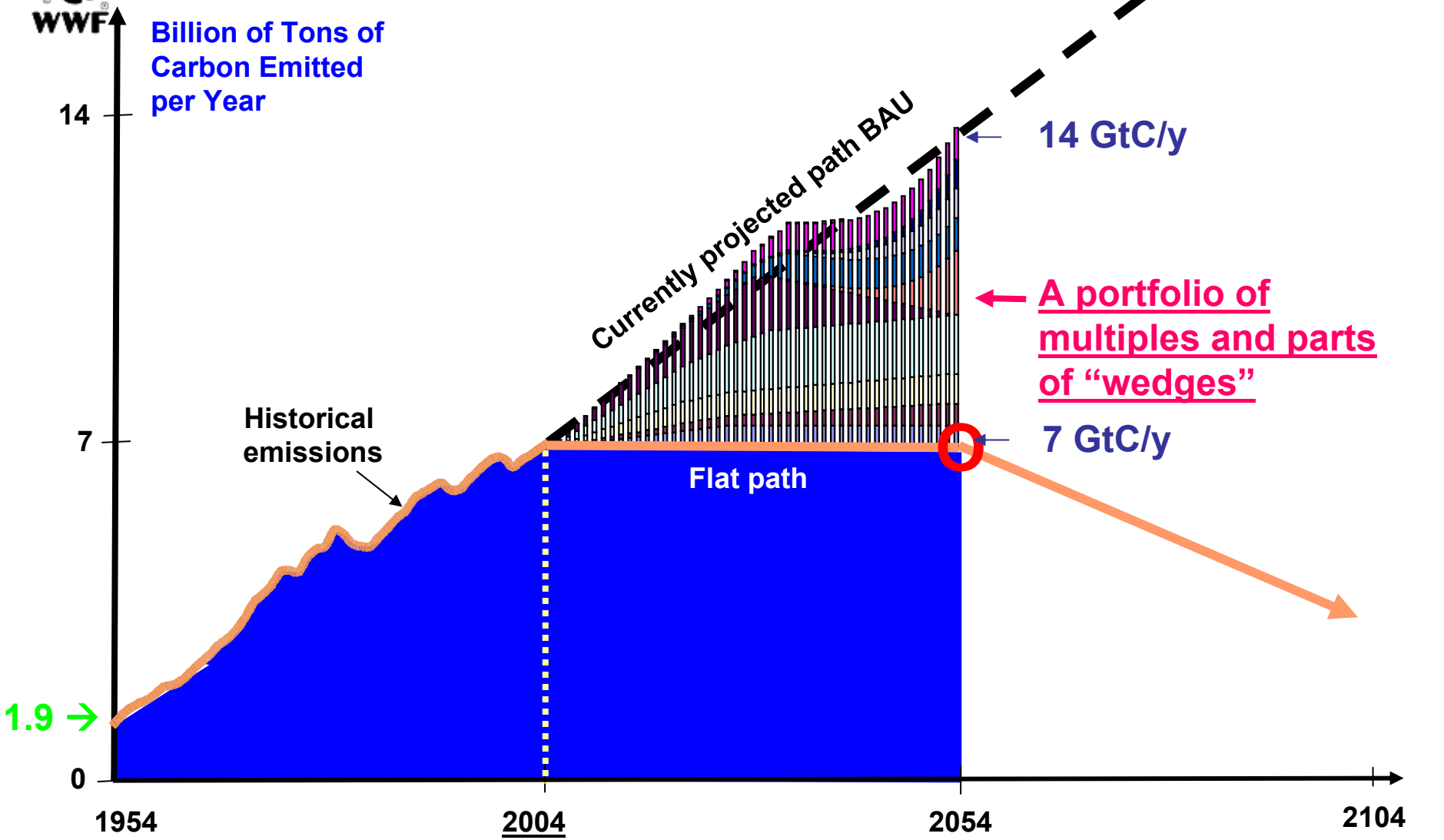
Need more than 7 wedges to stabilize at 450ppm



Delays lead to Failure to Stabilize



It's actually a complex portfolio of solutions



WWF working across the network on a portfolio

- **The context is a world growing from 6.5bn – 9bn people by 2050**
  - With demands for brand new energy in new locations and
  - Huge investments in old energy in old locations
- **There are no "Magic Bullets". "green", "brown" or "black"**
  - Setbacks are as likely as Breakthroughs. Tooling up the world's economy for a New Energy Paradigm takes time – and "The Will" - which is not yet there!
- **There are complex interactions between potential solutions**: eg
  - Advocating **too much biofuels** implies landclearing or converting productive food lands and brings on the GMO debate!
  - Advocating **too much hydropower** takes us beyond WCD criteria and implies loss of HCV biodiversity catchments!
  - **Ruling out** possible contributions from Gas and Carbon Sequestration implies higher contributions from biofuels, hydropower, renewables and so on!

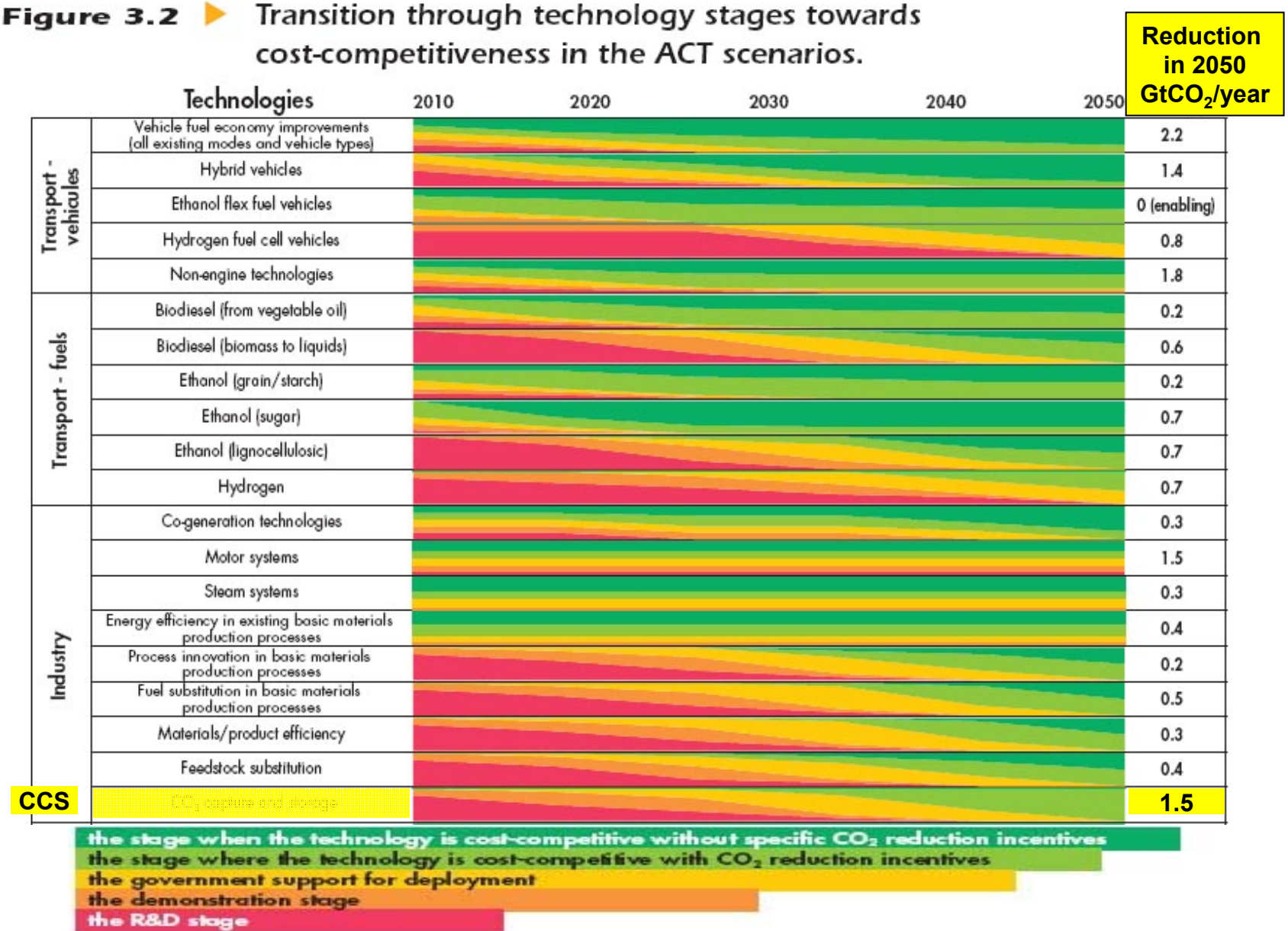
WWF working across the network on a portfolio

- **A drive for Energy Efficiency is really important**
  - It can slow or stop growth of emissions in the developed world BUT
  - Only slows the rate of growth of emissions in the developing world
- **A drive for Renewables is really important**
  - **Concurrent introduction of technologies is essential**
- **A drive for more Gas may be really important**
  - WWF may need to advocate for more “sensible” exploration and production of gas to displace coal where the emissions are not sequestered!
- **Knowing if CCS will work at scale is critical**
- **The initial Portfolio Mix indicates there is sufficient coverage if and only if**
  - **The World acted as One NOW and**
  - **there are more breakthroughs than setbacks**

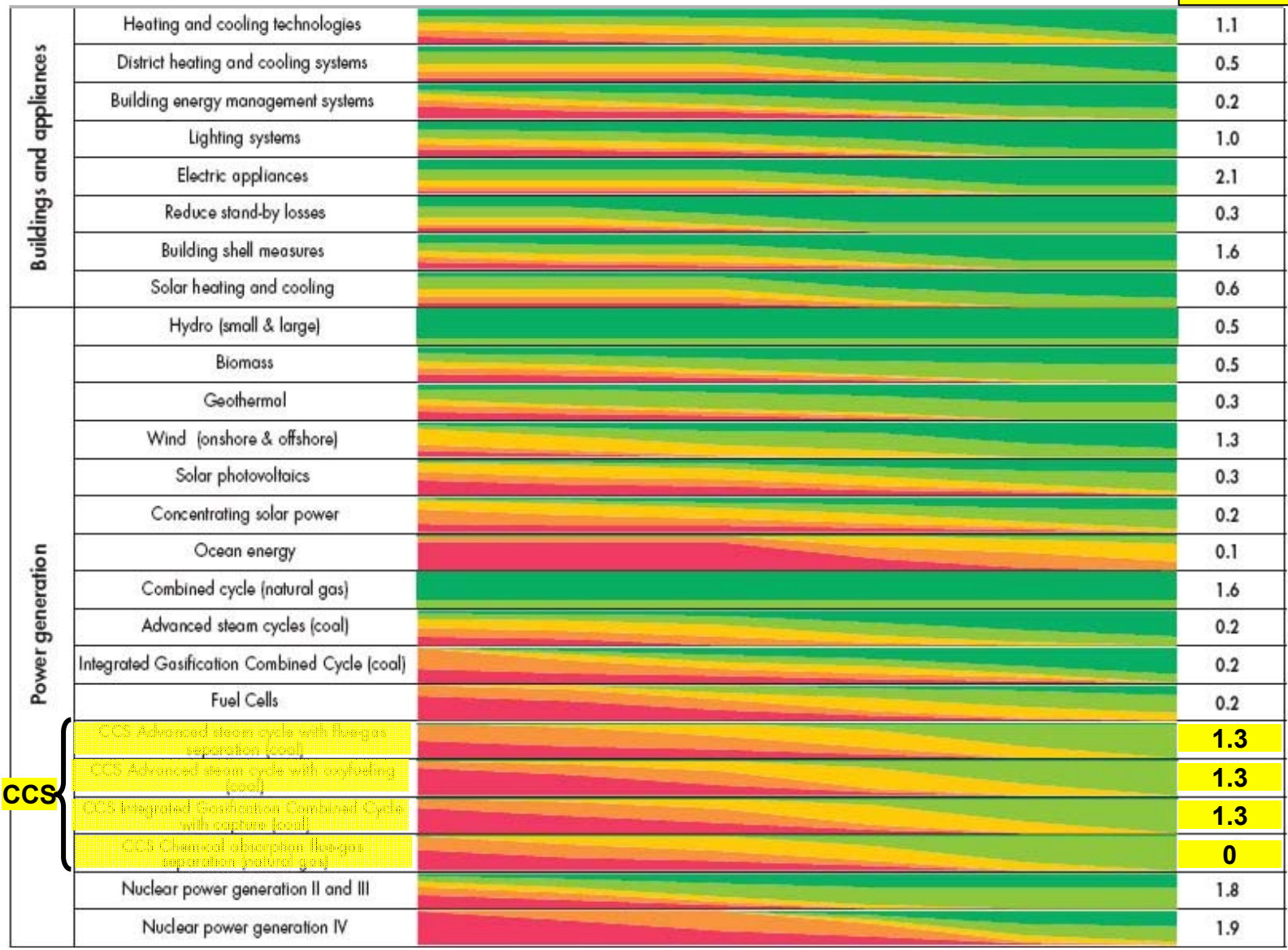
IEA Portfolio Mixes

IEA Energy Technology Perspectives 2006 – Scenarios and Strategies to 2050

Figure 3.2 ▶ Transition through technology stages towards cost-competitiveness in the ACT scenarios.



IEA Portfolio Mixes



ca 16% wedges come from CCS

We have a limited “carbon budget” to stay below a 2° C rise

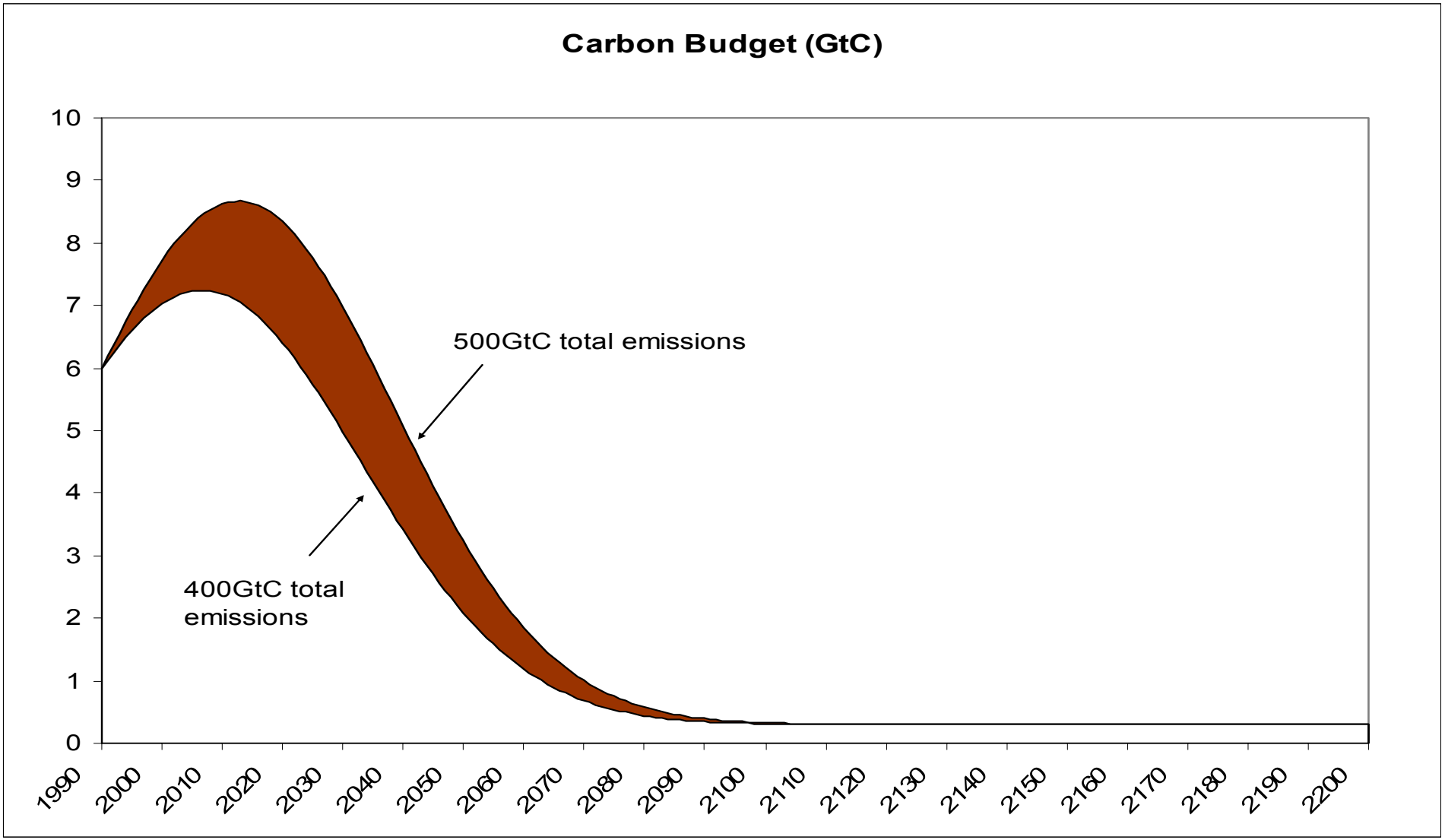


Figure 1: The annual carbon emissions range in GtC available for energy based on a total budget of between 400GtC and 500GtC taken out to 2200.

Carbon Sequestration – Key Issues

- CCS should not be considered a “silver bullet” it may work well at “coal” scale it may not!
  - The proposed pilot at Hazelwood 50t/day CCS is **1/500th** of full scale
- If CCS works well it will play perhaps 15-20% of the emissions reductions possibilities – i.e. it is but one of the portfolio solutions.
- If it is going to work we need to know as soon as possible.
- If it is going to fail at scale, we need to know that fact even sooner so that alternative solutions can be accelerated.
- Ocean and Marine sequestering are not considered suitable by WWF. (stability over millennia and acidification)
- Permanence, liability, property rights, monitoring, public confidence are all key issues which must be addressed.

Storage Monitoring

Out of sight is not out of mind! (c.f. Asbestos, Nuclear Waste, Toxic Stockpiles)

- Maintenance of integrity is critical for public confidence pre decision to sequester, during sequestration, post closure of “waste dump”. (c.f. Leachates, Cadmium, Mercury, CrF_6).
- Four types of maintenance philosophy.
  - Maintain on fail — **No Way**
  - Maintain on schedule — **Yes**
  - Maintain on condition (**Monitoring**) — **Yes**
  - Maintain on risk assessment (probability x impact) — **Yes**
- **Geo-mechanical monitoring will be critical and will give the early signals of success or failure of the site**
- Transparency to the public is critical to any successful adoption
  - There are large risks of “outrage” curtailing trials and full scale CCS

Regulatory Requirements

- A **Strategic Environmental Assessment** should be carried out before a “scale” (eg 1 million tonnes per annum) CCS goes ahead.

- Pilot and Demo projects should have EIAs prior to commencement and given that they may well lead to full scale CCS the SEAs should be commenced immediately.

- Speed is of the essence. The State/Nation should bear much of the initial costs/risks for the Research, Development and Demonstration phases and should “insure” the public at large.

Three Key Risks

- **Geotechnical**
  - **Will the reservoirs "take" continuous injection over decades without geo-mechanical failure**
  - **Remember that most oilfields have extraction and injection going on simultaneously**
  - **For CCS there will be injection with no extraction – stresses will rise –will the strain be contained or how will it be released?**
- **Public acceptability**
  - **CCS has the potential to be really beneficial but**
  - **Its failure mode at scale may well be because of the NIMBY response**
  - **Do not expect that locating CCS in areas that have mining activity already will be acceptable – breaches threaten families**
- **Not everyone is going to be helpful**
  - **Proponents of other wedges will be disparaging**
  - **Some NGOs environmental and social are opposed to CCS**
  - **NIMBYism is alive and well everwhere – just beneath the surface**

Don’t get it wrong!

wwf.org.au

US EPA Experience: Climate and Underground Injection Control

Elizabeth Scheehle
U.S Environmental Protection Agency
Climate Change Division, Office or Air and Radiation

October 30, 2006

Overview

- US Climate Perspective: Policy, Storage Capacity and Effectiveness, and Accounting
  - Elizabeth Scheehle, Climate Change Division, Office or Air and Radiation

- Underground Injection Control Program: Regulatory process for Geologic Sequestration
  - Lee Whitehurst, Underground Injection Control Program, Office of Water

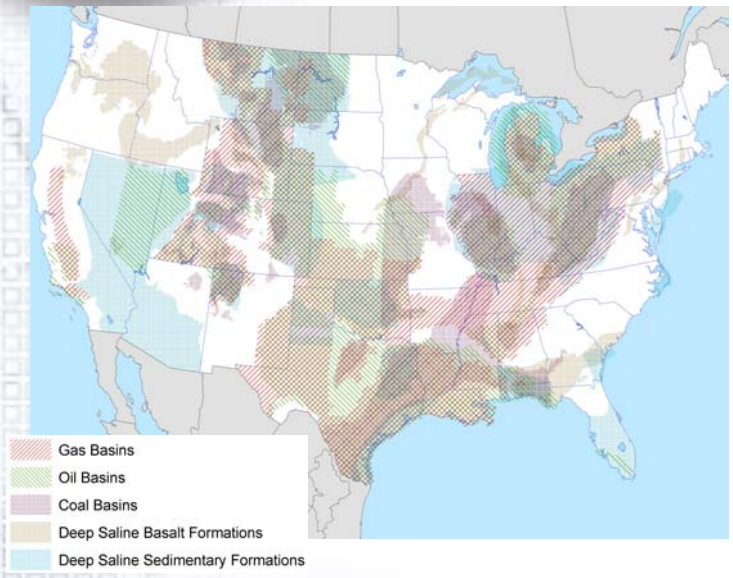
Three Elements of US Climate Policy

1. **Slowing the growth of emissions**
   - Reduce GHG emissions intensity (tons/$GDP) by 18% from 2002 - 2012 through voluntary programs
     - Energy STAR, methane, SmartWay Transport, etc.

2. **Advancing climate science and technology**
   - Annual investment of $5.5 billion in climate change research and technology, focus on long-term R&D

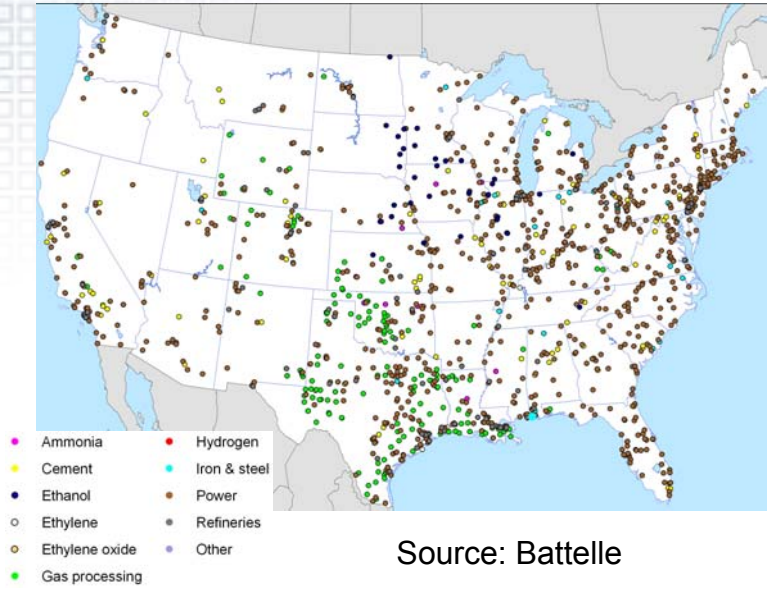
3. **Enhancing international cooperation**
   - Reaffirm U.S. commitment to the UNFCCC
   - Emphasize U.S. commitment to mutual goals of sustainable development and economic growth

CO_2 Storage Capacity in the US



3,900+ $GtCO_2$ Capacity within 230 Candidate Geologic CO_2 Storage Reservoirs

- 2,730 $GtCO_2$ in deep saline formations (DSF) with perhaps close to another 900 $GtCO_2$ in offshore DSFs
- 240 Gt CO_2 in on-shore saline filled basalt formations
- 35 $GtCO_2$ in depleted gas fields
- 30 $GtCO_2$ in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 $GtCO_2$ in depleted oil fields with potential for enhanced oil recovery (EOR)



Source: Battelle

1,715 Large Sources (100+ $ktCO_2/yr$) with Total Annual Emissions = 2.9 $GtCO_2$

- 1,053 electric power plants
- 259 natural gas processing facilities
- 126 petroleum refineries
- 44 iron & steel foundries
- 105 cement kilns
- 38 ethylene plants
- 30 hydrogen production
- 19 ammonia refineries
- 34 ethanol production plants
- 7 ethylene oxide plants

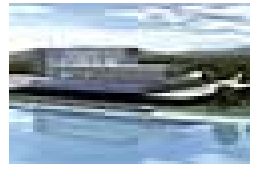
Geologic Sequestration

- Geologic Sequestration has the potential to significantly reduce GHG emissions
  - DOE is the lead agency invested in R&D (e.g. Regional Partnerships, FutureGen)
  - EPA is responsible for permitting and greenhouse gas inventory
- Regulatory framework is essential, given the potential scale of the technology and need for public acceptance
  - EPA is working with DOE, with a focus on risk assessment and to ensure R&D supports regulatory development
- OAR (Climate Change Division) & OW (Underground Injection Control Program) are collaborating to support technology development and provide the regulatory framework
  - Identify data gaps, jointly fund research, organize conferences, collaborate with DOE and other agencies, and communicate with stakeholders, NGOs, and the public

Current Efforts

- DOE leads U.S. efforts on R&D and deployment
  - Carbon Sequestration Leadership Forum
  - Regional Sequestration Partnerships
    - Phase 1 completed (characterization)
    - Phase 2 underway (25 small pilots)
    - Phase 3 planned (several large pilots)
  - FutureGen
  - Core R&D

- Commercial projects
  - Sleipner (Norway), Weyburn (Canada), In Salah (Algeria)
  - Several under development in the U.S. and abroad



- EPA will be able to gather information from US and international activities to answer those key technical questions and determine appropriate regulatory action
  - Monitoring requirements
  - Area of Review
  - Well construction

Key Technical Questions

- Do we fully understand the storage mechanisms and their effectiveness?
- Will CO_2 leak?
  - What are the probabilities and impacts of leakage?
  - How would $C0_2$ leakage affect water supplies?
  - Could CO_2 releases impact human health and/or the environment?
  - Will large-scale CO_2 injection induce seismicity, cause fluid displacement, or effect regional ground water pressure/flow?
- Can we monitor and verify subsurface CO_2?
- Can we permit wells, develop long-term monitoring and closure requirements based on our current level of understanding?

Answering these questions are key to permitting, inventory, and ensuring projects are safe and effective

Greenhouse Gas Inventory

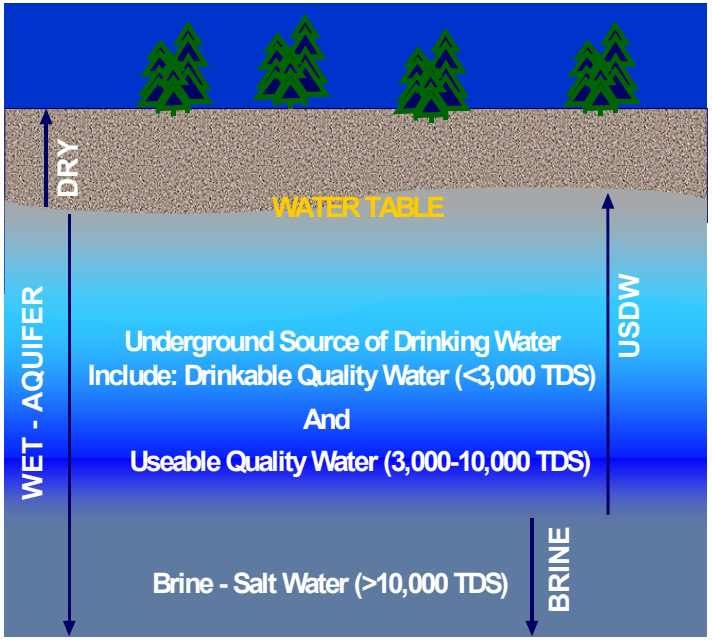
- Inventory estimates emissions and sinks
  - Reductions accounted for at capture site
  - Fugitive emissions throughout the capture, transport, injection, and recycling.
  - Emissions from subsurface to surface also counted
    - Relies on effective monitoring program to detect emissions to the atmosphere or vertical migration that will inform potential future emissions
  - Reductions associated with EOR without monitoring information will not be considered
    - Assumption: 100% emitted without monitoring data

EPA Regulatory Development Goals

- Protect human health and the environment
- Ensure that decisions are cost-effective and fully protective
- Conduct high quality scientific, economic, and policy analyses at early stages so that decision makers are well informed
- Apply new and improved methods to protect the environment
  - build flexibility into regulations from the very beginning
  - create strong partnerships with the regulated community vigorously engaging in public outreach and involvement
  - use effective non-regulatory approaches

UIC Program
General Overview

- SDWA requires EPA to develop minimum federal regulations for state and tribal Underground Injection Control (UIC) Programs to ***protect underground sources of drinking water***
- USDW are defined as aquifers or portions of aquifers that:
  - have sufficient quantity of ground water to supply a public water system and
  - contain fewer than 10,000 mg/l or ppm total dissolved solids



- 33 states have primary enforcement authority (primacy); EPA directly implements the program in 10 states; 7 split programs
- Primacy States can be more stringent than the minimum federal regulations
- KEY CONCEPT: SDWA provides EPA and States with flexibility to establish effective Class II oil and gas programs (Section 1425)

UIC Program:
More Key Concepts

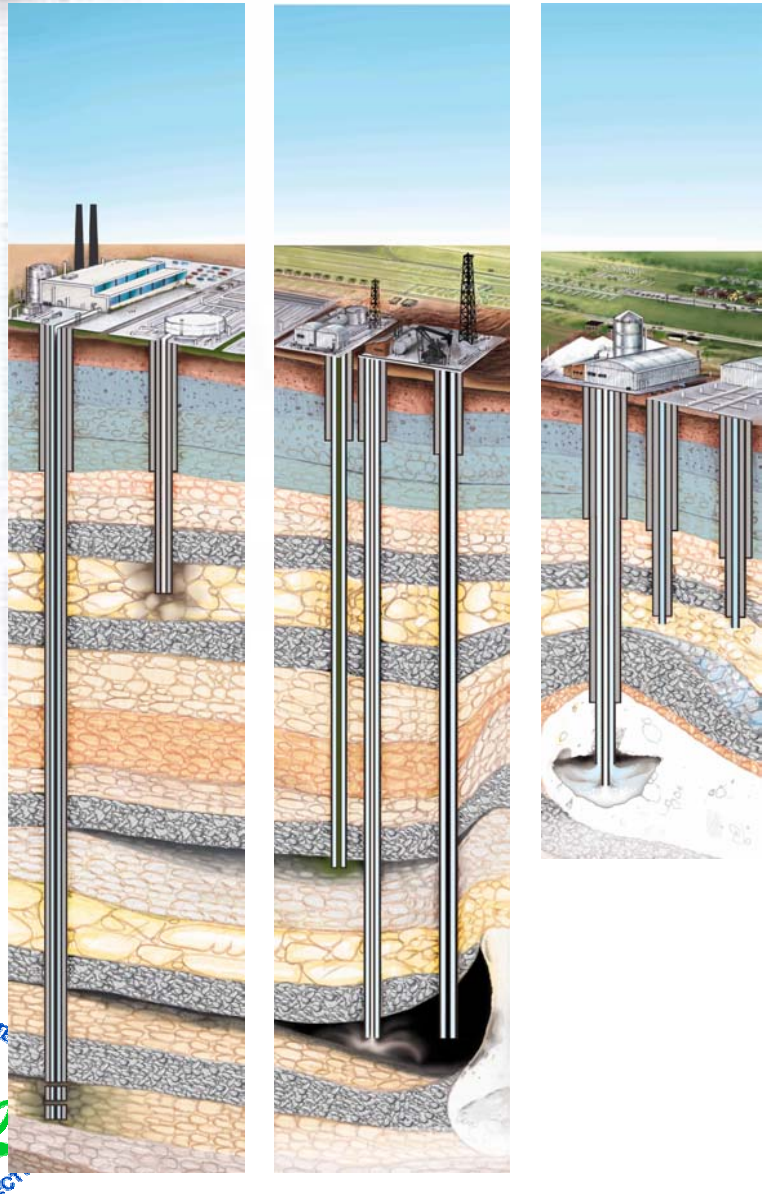
- **Safe Drinking Water Act (SDWA)**
  - UIC Program regulates underground injection of ALL fluids – liquid, gas, or slurry
  - Program covers injection of wastes and commodities (e.g. liquid hydrocarbons, water)
  - Only federal exemptions for natural gas storage and specific hydraulic fracturing
  - Therefore, EPA believes that the UIC program provides existing framework for CCS technologies

Main Objective of the UIC Program Regulations

- Protect underground sources of drinking water from waste injection practices by requiring;
  - Proper well sitting
  - Adequate well construction
  - Careful well operation and monitoring

UIC WELL CLASSES

Class I Class II Class III

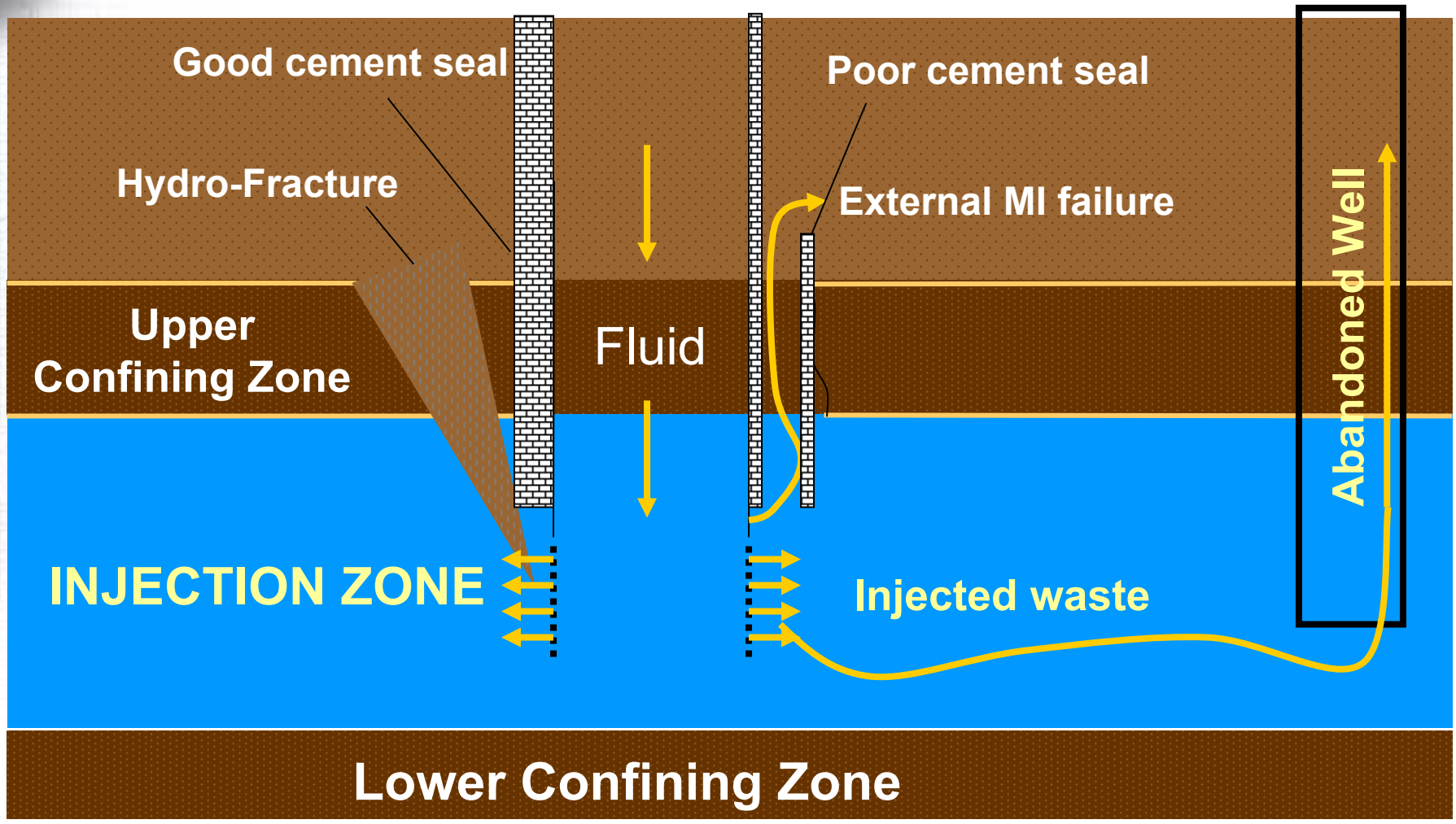


Class V

Requirements for Wells

- Class I requirements have very strict waste isolation requirements;
- Class II requirements are based on "effectiveness" in protecting USDWs;
- Class III requirements are variable depending on the type of mining operation;
- For the most part, Class V wells have two basic requirements;
  - Prohibition of endangerment;
  - Operators must submit inventory information.

Fluid Migration Pathways



Not to scale

UIC Regulations

- The UIC regulations address:
  - Well Siting (geologic studies, Area of Review)
  - Construction (casing, cement)
  - Monitoring and Testing
  - Proper Closure (also financial responsibility for post–closure care)

- The regulations specifically address the potential fluid migration pathways

Monitoring and Testing Requirements

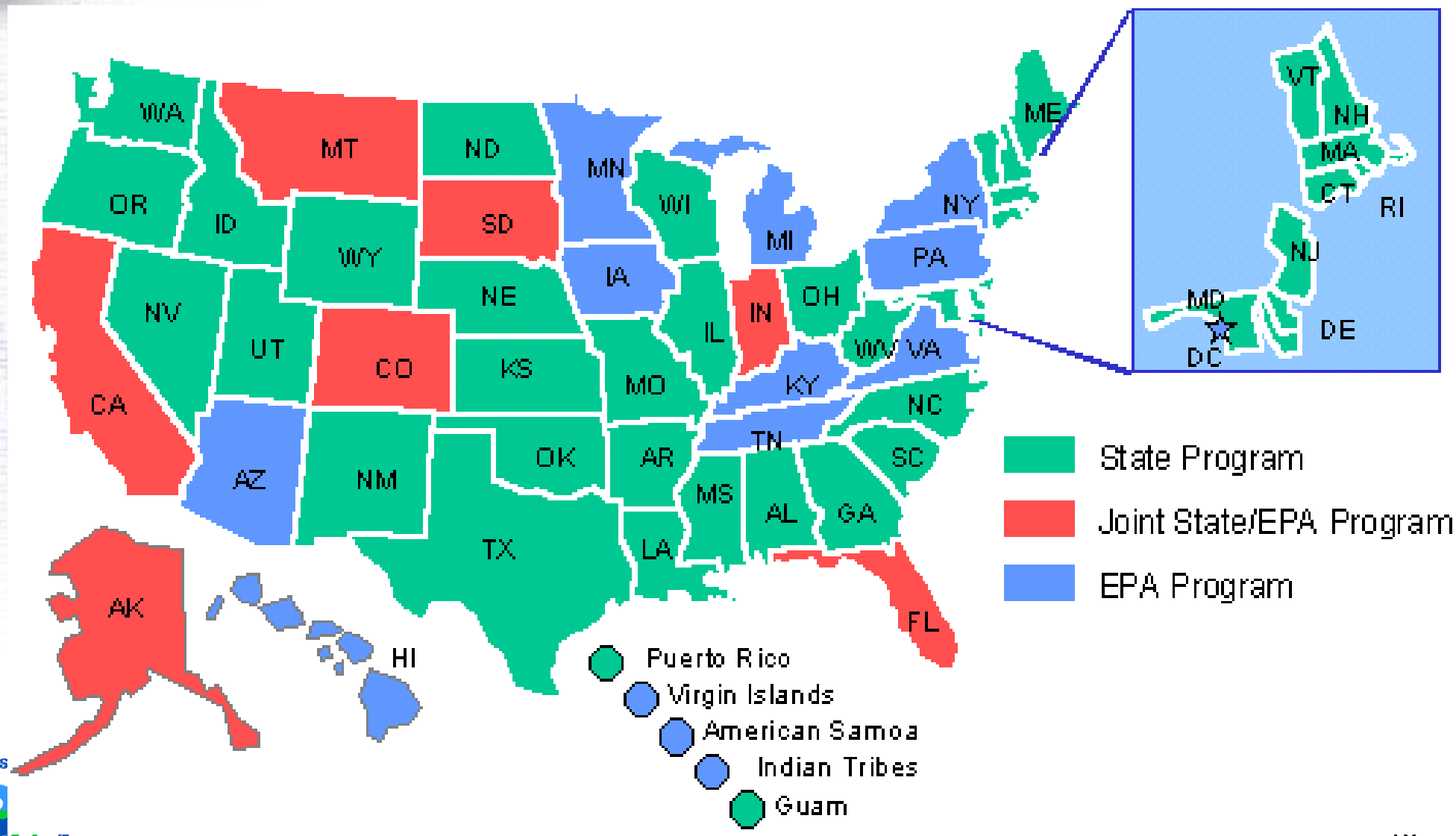
- Monitor pressure, volume, and temperature of injected fluids
- Conduct Mechanical Integrity Tests (MITs)
- Monitor ambient ground water quality for the presence of injected fluids

- *CO_2 geosequestration may bring up new considerations for monitoring requirements*

State Primary Enforcement Authority (Primacy)

- Law encourages states to seek "primary enforcement authority" for the UIC program
  - EPA provides grants to states to assist them with this responsibility (grants are based on each state's population, land area, and well inventory)
- Depending on the well types being regulated, states have to meet specific minimum federal requirements or demonstrate that their programs are "effective"
- States' requirements can be, and often are, more stringent than minimum federal requirements
- EPA is responsible for implementing the UIC program when a state chooses not to, or is unable to obtain federal approval (this is the case in 17 states for all or part of the program, and for all tribes)

Current Primacy Picture



UIC Injection Authorization

Two Ways to Obtain Authorization to Inject

1) Authorization by Permit
   - Individual permits - mostly for Class I wells and oil and gas production related disposal wells;
   - Area permits - for multiple wells that have the same sitting and operational characteristics, mostly for enhanced recovery and solution mining wells;
   - General permits: for wells with similar characteristics but with different owners.

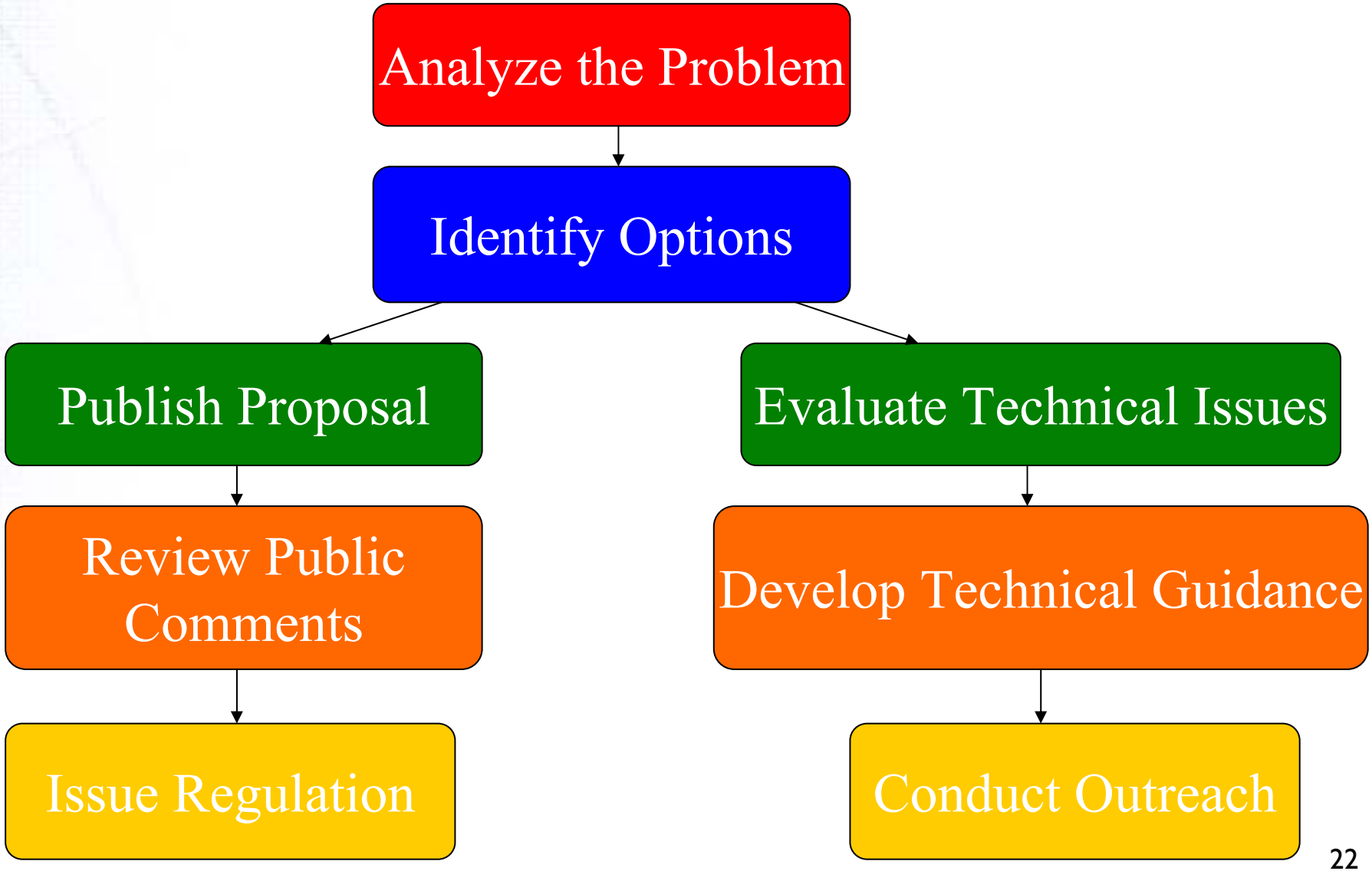
2) Authorization By-Rule
   - Allowed for certain well type;
   - Mainly because of the lower risk they present to USDWs.

- EPA is recommending that all CO2 injection projects be authorized by permit.

EPA Efforts: Geologic Sequestration Workgroup

- Collaborative efforts on CCS started by EPA Office of Air and Radiation (OAR) and Office of Water in early 2004
- Internal EPA Geologic Sequestration Workgroup formed including 30 members from HQ Offices, EPA Regions and Labs (August 2004)
- Initial focus on technical and regulatory issues, risk assessment, communication and outreach

Role of an EPA Workgroup



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- Protect human health and the environment
- Ensure that decisions are cost-effective and fully protective
- Conduct high quality scientific, economic, and policy analyses at early stages so that decision makers are well informed
- Apply new and improved methods to protect the environment
  - build flexibility into regulations from the very beginning
  - create strong partnerships with the regulated community vigorously engaging in public outreach and involvement
  - use effective non-regulatory approaches

Key Technical Issues

- Site characterization for CO2 injection well projects including geology, geochemistry, and geohydrology
- "Area of Review" to determine locations of abandoned wells or other conduits for leakage
- Well construction and plugging and abandonment procedures for well closure
- Predicting fate of CO_2 (modeling and analytical tools)
- Monitoring and verification

EPA Efforts: 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.
- LBL International Symposium on Site Characterization for CCS
  - March 20-22, 2006 in Berkeley, CA
  - Technical papers covering geologic considerations, construction, monitoring, geochemistry, and public acceptance

EPA Future Regulatory Role

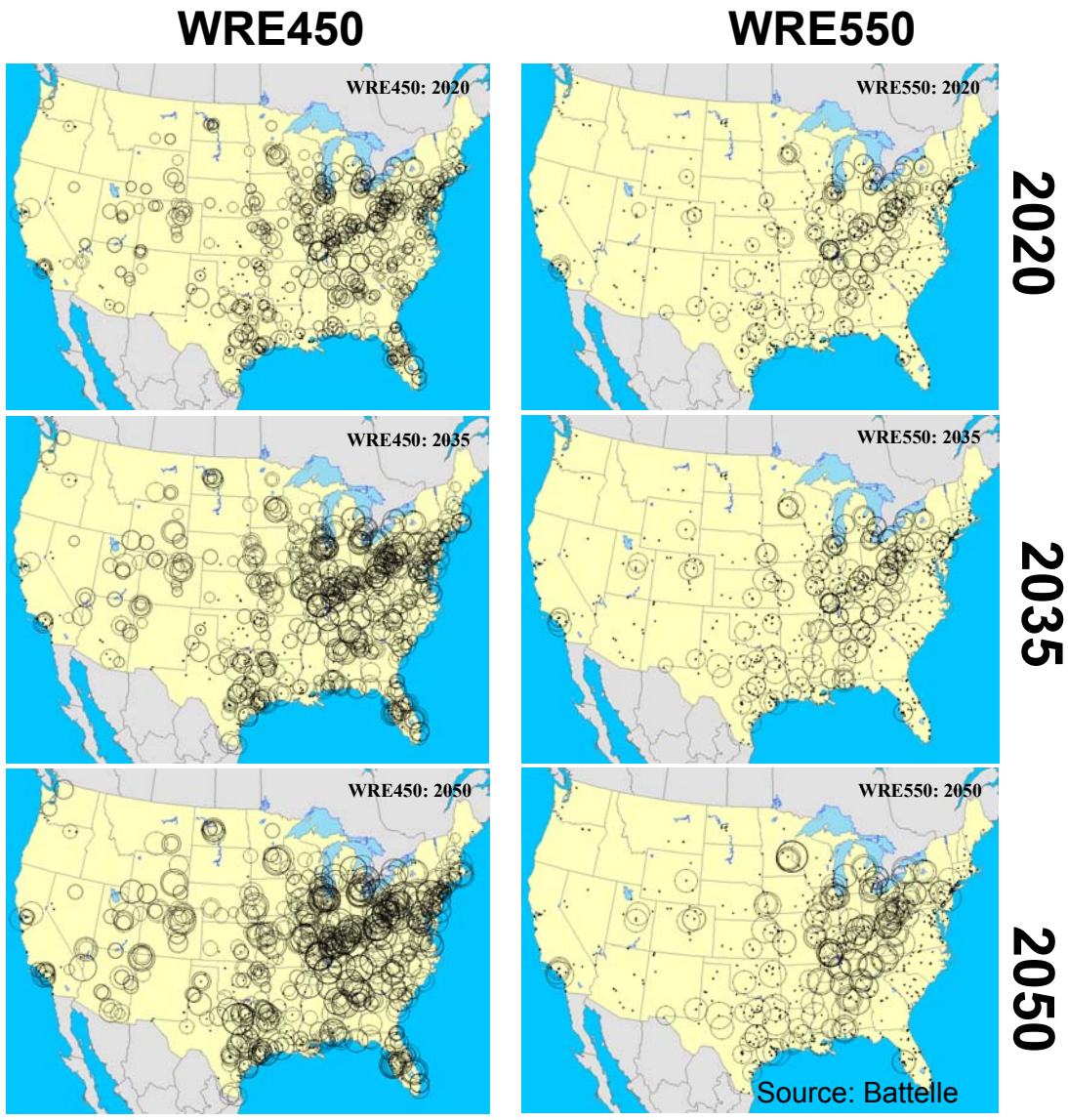
- All regulatory agencies have an important role to play in building public confidence that CCS can be implemented safely and effectively
- But, as the findings from the workshops indicate, some uncertainties with respect to the potential risks of CCS and monitoring technologies still may exist
- *However*, we have a regulatory framework and years of technical experience with underground injection
- Our goal is to use that expertise, focus on near-term implementation issues, and collaborate with DOE, states, industry, and academia to ensure success

Class V Experimental Technology Guidance for CO2 Injection

- Purpose is to assist writing permits for short-term DOE CCS pilot carbon dioxide injection projects.
- Stresses flexibility to ensure safety during the data gathering phase of developing GS technologies
- Includes considerations for the appropriateness of injection sites, Area of Review, well construction, operation, monitoring, and site closure
- Final draft is being distributed for comments; EPA expects to finalize in the coming months
- Information gathered during the pilot projects will inform any regulatory approach for the long-term commercial projects anticipated by 2012

Potential U.S. Deployment

- Could be massive:
  - 1,000s of power plants and industrial facilities capturing CO_2
  - 1,000s of miles of dedicated CO_2 pipelines
  - 100s of millions of tons of CO_2 being injected into the subsurface annually



EPA's Reason to Stay Involved:

Protect Public Health

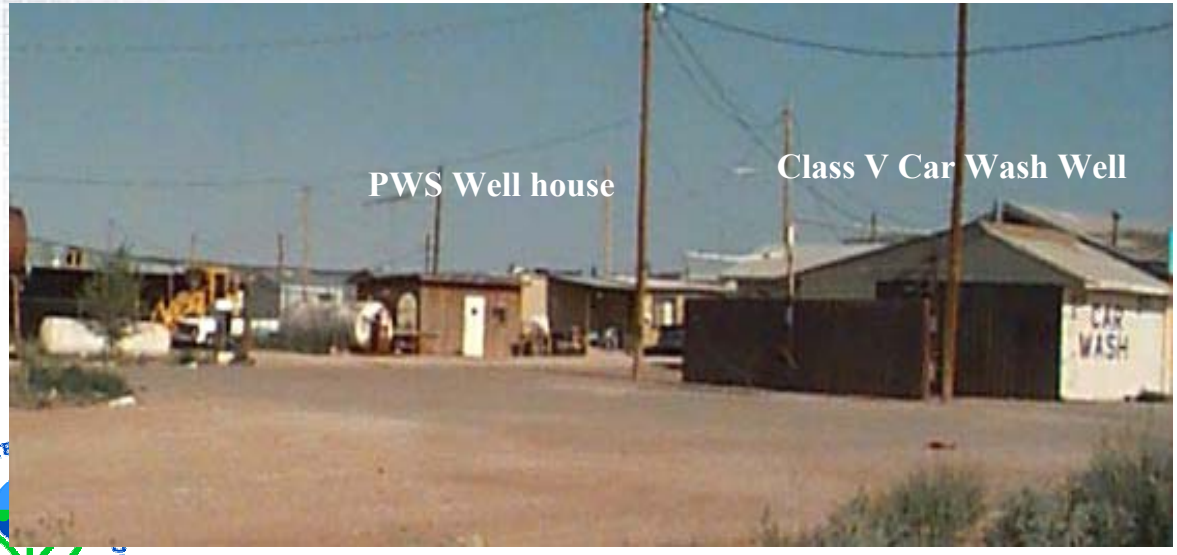
- Nature of some injected fluids may pose a risk to ground water quality and public health if managed improperly.
- Deep Class I and Class II wells must be properly sited, operated and constructed to avoid contaminating USDWs.

Class V Wells:

Are numerous & may be in close proximity to PWS or private wells;

Inject a wide range of fluids;

Inventory, location & injectate data is incomplete.



Summary

- U.S. is uniquely positioned to support global efforts to facilitate deployment of CCS
  - DOE R&D and Regional Sequestration Programs continue to provide data through demonstration projects
  - EPA's UIC program provides an existing framework and demonstrates safe underground injection of a variety of fluids
- EPA is currently evaluating technical and regulatory issues along with accounting approaches for national inventories
- EPA has identified practical questions with respect to site characterization and monitoring, and is evaluating the need, timing, and data requirements for regulatory development

Final Thoughts

- EPA shares your enthusiasm for CCS technologies which could address harmful climate change
- All Groups – the international community, states, industry, academics - can provide positive contributions to CCS efforts
- Participation by, and outreach to the public, in all arenas, will be ***critical*** to the success of CCS
- USEPA will continue to be an active participant

IEA GHG R&D Programme
CCS Monitoring Network
30 October 2006

Monitoring, Evaluation, Reporting and Verification: Towards an Australian Strategy

Gerry Morvell
Energy Futures Branch Head
Australian Greenhouse Office
Department of the Environment and Heritage

Australian Government

Relevance of Today

- Collaboration is key
- High level principles for CCS related MERV
- Current Australian investment in CCS projects

Australian Government

Australian Perspectives

- National
  - Market leader in CCS
  - Permitting / approvals
  - MERV conditions
  - Post site closure
  - Otway Basin Pilot Project

Australian Government

Australian Perspectives

- International
  - Carbon Sequestration Leadership Forum
  - IEA / CSLF partnership
  - London Convention / Protocol
  - UNFCCC Clean Development Mechanism

Australian Government

Australian Context for CCS

- Australia is a small contributor to global emissions
- Energy intensive economy - fossil fuel energy supply
- CCS potential ~125MtCO_2 per annum
- Closely integrated energy-climate change policy framework
- Energy White Paper identifies Australia should be a market leader in CCS
- Investment in science is underpinned by *Backing Australia's Ability*
- LETDF - CCS integral to most fossil fuel projects

Australian Government

Australian Policy Framework

- Council of Australian Governments (COAG)
  - Ministerial Council on Mineral and Petroleum Resources
- Agreed regulatory principles – high level
- Consistent legislation across Australia
- Offshore CO_2 storage legislation
  - London Convention
  - Model Legislation on Access and Property Rights

Australian Government

CCS – MERV Framework

- Objectives
- Integrated and complex systems
- All components and phases require MERV
- Lower risks through site selection and MERV

Australian Government

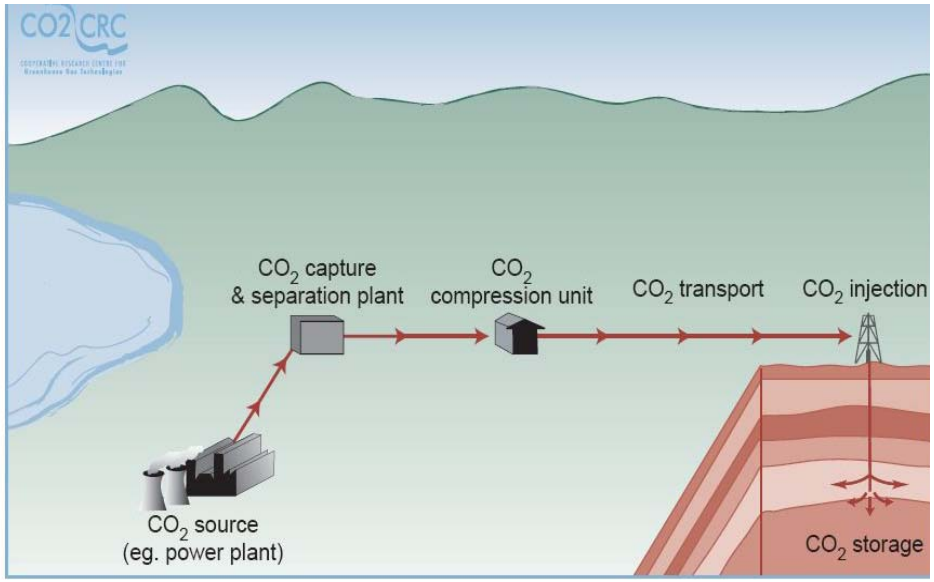
MERV Objectives

- For resource management
- For accounting purposes within national emission inventories and transboundary issues
- To protect health, safety and environment (HSE)
- For accurate recognition within abatement incentive schemes
- For public assurance that sites perform effectively (meets a suite of defined standards)
- To verify CO_2 remains trapped in short term
- Provide a basis for predictions about behaviour in the very long term basis.

Australian Government

CCS Phases

- Capture
- Transport
- Injection
- Storage
  - Pre-injection
  - Injection
  - Post injection
  - Post storage site closure



Australian Government

Conclusions

- Early stages of dialogue
- Important to keep this open and realistic
- Objectives based regulation
- Legitimacy of abatement reliant on MERV
- Public acceptability reliant on MERV
- Ease of transfer of property rights and ownership reliant on MERV

Australian Government

Regulatory Guidelines for Monitoring, Evaluation, Reporting and Verification

Stephen Cornelius
Defra – Climate Energy: Science Analysis

3rd meeting of the IEA Monitoring Network
Melbourne, 30 October 2006

defra
Department for Environment Food and Rural Affairs

Overview

- Carbon Capture and Storage in the EU Emissions Trading Scheme (EU ETS)
- Second EU Climate Change Programme (ECCP II)
- Task Force on UK Regulation of Carbon Capture and Storage

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CCS in the EU Emissions Trading Scheme

- UK recognises potential value of CCS for GHG reduction
  - nationally and internationally
  - G8 and EU initiatives
  - Legal and regulatory barriers e.g. London Convention / Protocol

- UK encourages use of market-based mechanisms to reduce GHG emissions

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CCS in the EU ETS: Why?

- EU ETS
  - World's first large-scale CO_2 emissions trading system
  - started January 2005
  - 25 countries, 6 sectors, ~12000 installations,

- Incentivise CO_2 reductions

- Should incentivise CCS

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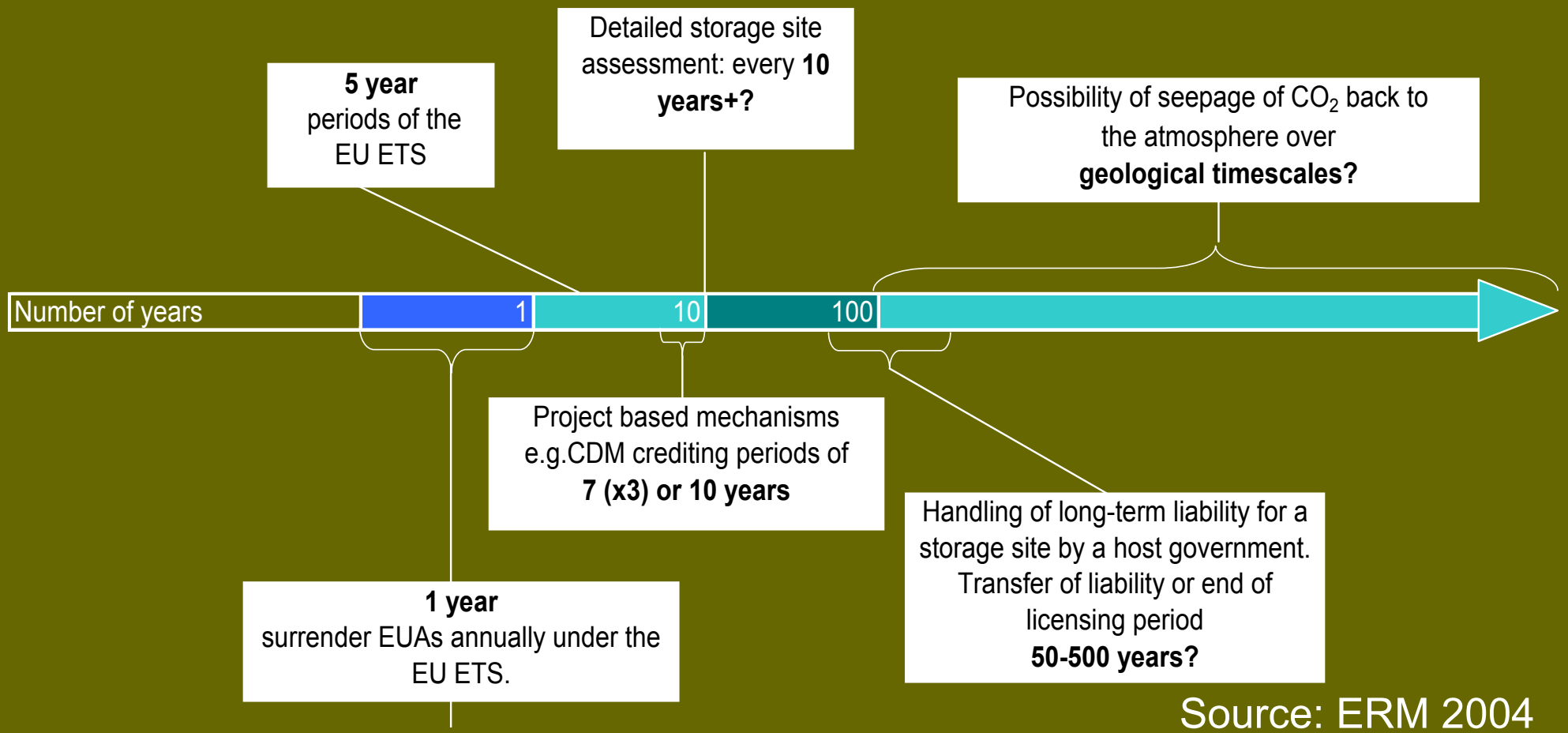
Global risks in GHG trading (permanence)



Source: ERM 2004

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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 for M&R…..subject to approval by EC….CCS CO2 can be subtracted from emissions of installations…."

- **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, and Alstom
  Norwegian Government, UK DTI, UK Defra, EC DG Env and DG Res
  IEA GHG

- Commissioned ERM and DNV for study

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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

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EU ETS: Recent Developments

- European Commission drafting revised M&R guidelines for the EU ETS (final publication 31 December 2006)

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Overview

- CCS in the EU Emissions Trading Scheme (EU ETS)
- EU Climate Change Programme (ECCP)
- Task Force on UK Regulation of Carbon Capture and Storage

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European Climate Change Programme

A Working Group on geological CCS was set up under ECCP II to explore carbon dioxide capture and geological storage as a mitigation option by:

1. reviewing the potential, economics and risks of CCS

2. identifying regulatory needs and barriers and exploring the elements of an enabling regulatory framework for the development of environmentally sound CCS;

3. identifying other barriers that could impede the development of environmentally sound policies to advance CCS, and policies to enable the development of environmentally sound CCS.

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European Climate Change Programme

The WG recommends that, during 2007, the Commission produces a Communication outlining the major EU policy choices for CCS, accompanied (where necessary and appropriate) by a proposal for an EU CCS regulatory framework. Those policy and regulatory frameworks should be in place as soon as possible (before 2012) and the Commission should identify which elements of those frameworks should be elaborated at an EU level, in accordance with the principle of subsidiarity.

The Commission is requested to address:

1. Permitting of geological storage sites, including risk management, site selection, operation, monitoring, reporting, verification, closure and post-closure;
2. Liability for leakage from storage sites during operation and post-closure;
3. Clarification of the role of CCS under EU legislation, in particular concerning waste and water, and propose appropriate amendments;
4. The recognition of CCS projects in the EU Emissions Trading Scheme;
5. The need and possible options for incentivising CCS in a transitional period;
6. The status of CCS projects under rules and guidelines for State Aid.

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Overview

- CCS in the EU Emissions Trading Scheme (EU ETS)
- EU Climate Change Programme (ECCP)
- Task Force on UK Regulation of Carbon Capture and Storage

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Task Force on UK Regulation of CCS

- *A Strategy for Developing Carbon Abatement Technologies for Fossil Fuel Use* (UK CAT strategy) – June 2005
  - Action 8: Lead in preparing the national and international regulatory frameworks and market systems

- Cross-Government task force set up
  - DTI, Defra, HM Treasury, Crown Estates, Environment Agency
  - initial meeting of the steering group 5 May 2006

- Stakeholder workshop (industry) 20 October 2006
  - Another broader based workshop likely to be held November

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CCS Regulatory Task Force – terms of reference

High level aims

To facilitate and regulate the development and use of CCS as one approach in a portfolio of measures to tackle the challenge of climate change and ocean acidification. In order to help achieve this, to remove uncertainties for industry and regulators relating to the regulatory regimes and processes involved in CCS, and to ensure the environmental integrity of CCS activities.

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CCS Regulatory Task Force – terms of reference

Specific aims

To clarify existing regulation and its application, to identify any gaps and the need for new regulation, and to develop new regulation as required, in the following areas:

- Licensing of CO_2 storage sites and activities offshore
- Decommissioning and abandonment of storage facilities
- Long-term liabilities for abandoned CO_2 storage sites
- Licensing and regulation of onshore facilities, including CO_2 capture

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CCS Regulatory Task Force – international links

The work of the Task Force will take direct account of the work of the North Sea Rim Task Force on the Storage of CO_2 in the North Sea which has been agreed by Ministers from the UK and Norway. It will also take account of the developments in the international marine treaties (London Convention/Protocol and OSPAR).

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CCS Regulatory Task Force – working groups

Offshore

1. Licensing of CO_2 storage sites, activities and transportation offshore
2. Conditions for abandonment of storage sites, and long-term liabilities for CO_2 storage

Onshore

3. Enabling/facilitating capture and capture-ready power plant. Licensing of onshore transportation facilities and re-licensing of existing infra-structure for CO_2 transport
4. A fourth working group was later added, to look at the issue of licensing onshore storage sites.

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Next Steps of the UK CCS Task Force

- Further informal consultations
- Agreement in HMG on alternatives to pursue
- Consultation prior to legislation
- Legislative process
- Enactment & ‘doing’
- Review and evaluation

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MERV – immediate needs in the UK

- Six projects declared
  - Timescales for investment decisions
- Want clarity on
  - What should the CO_2 monitoring programme look like?
  - Where should the CO_2 monitoring programme be recorded?
- Who should be responsible for assessing the CO_2 monitoring programme?

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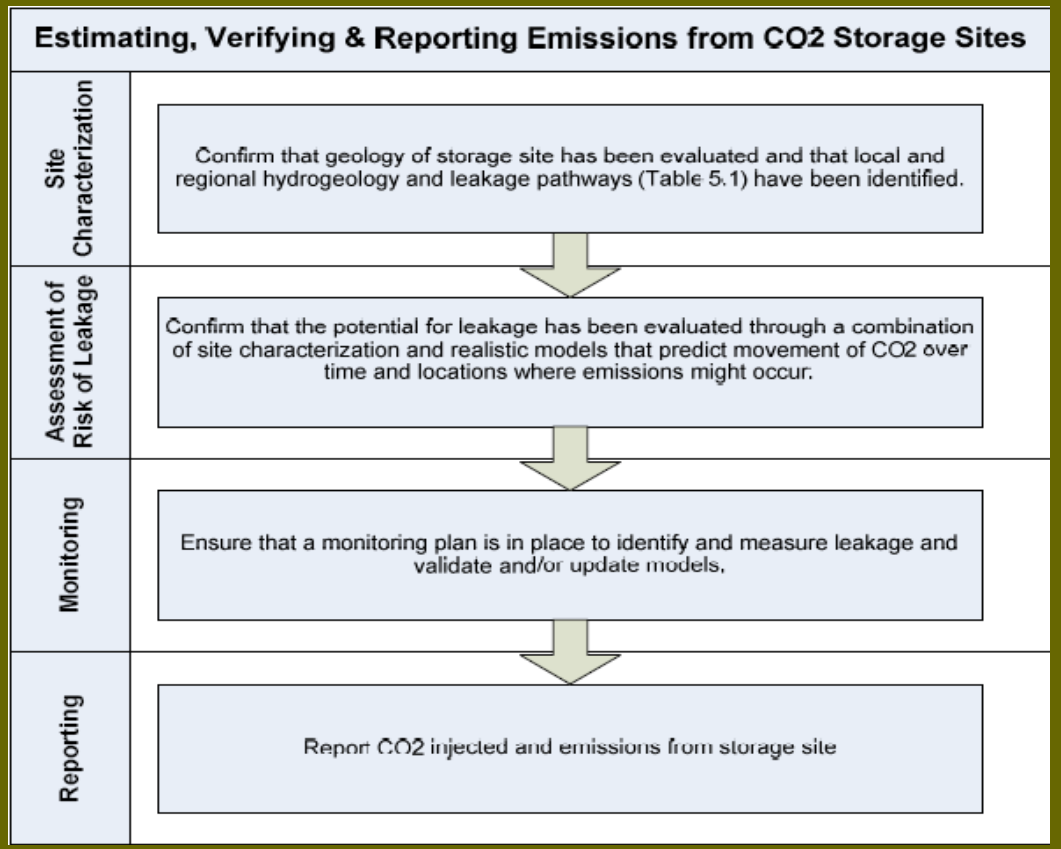
UK MERV Consistent with International



IPCC 2006 GHG Inventory Guidelines

- Site characterisation
- Risk assessment
- Risk management (monitoring)
- Risk management (reporting)

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Dr J. Bradshaw

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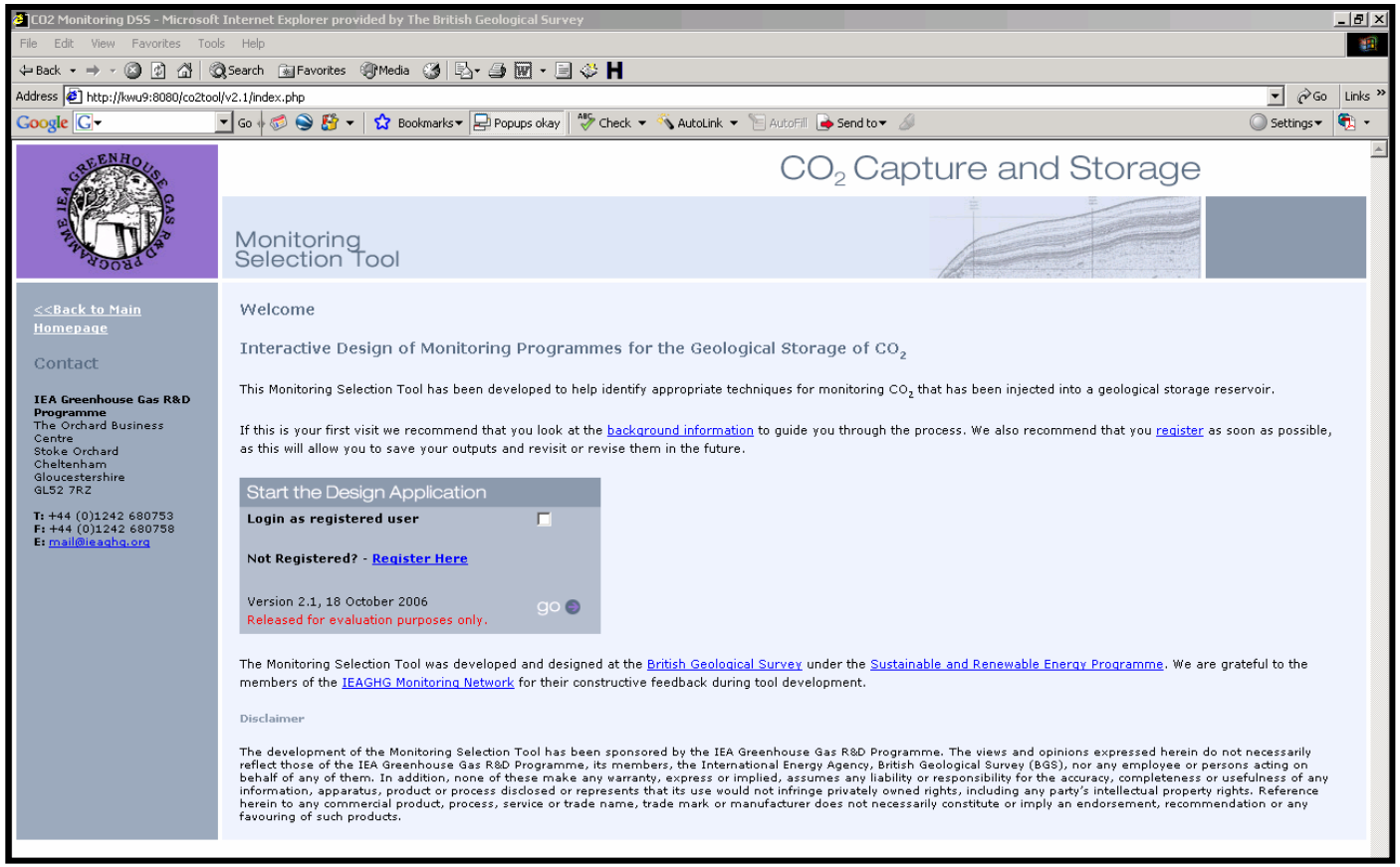
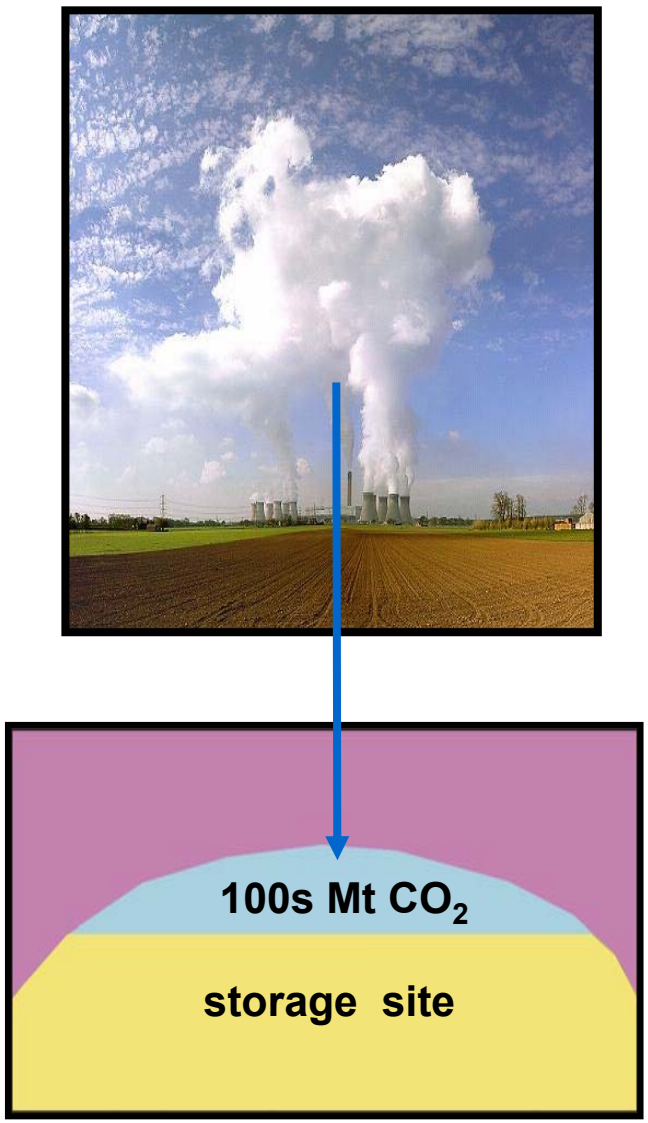
Department for Environment
Food and Rural Affairs

A web - based CO_2 storage monitoring selection tool



Why Monitor?



1. FIT FOR PURPOSE

- Image & track CO_2 in the subsurface
- Verify *in situ* mass of CO_2
- Quantify leakage rates

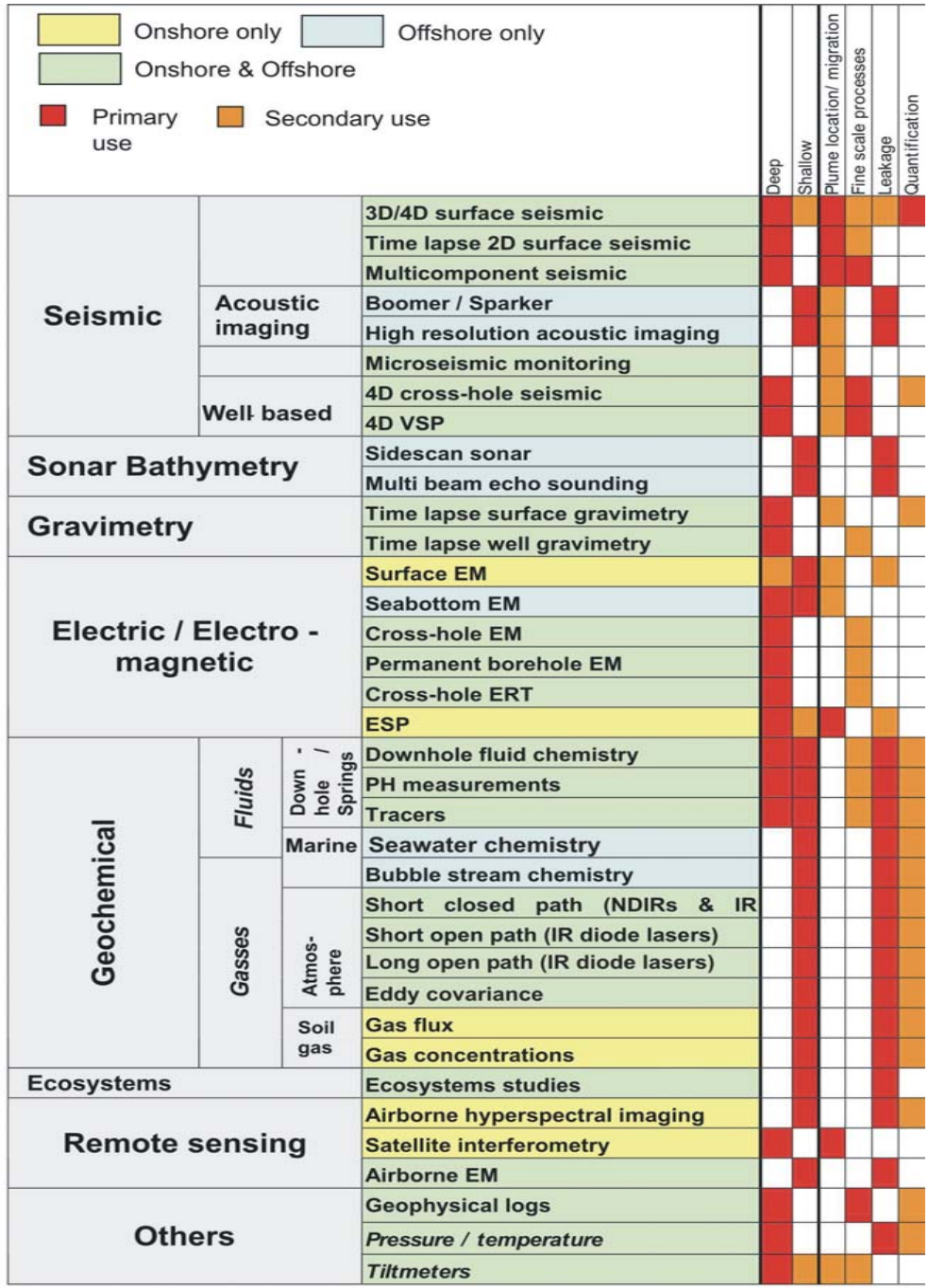
2. SAFETY

- Early warning of leakage
- Potential health/ecological impacts

UNDERSTANDING PROCESSES

- Site characterisation
- Show site is currently performing as expected
  - Identify & remediate non-conformances
- Constrain predictions of long-term site behaviour
  - Calibrating flow simulations
- Enable site closure

Available techniques ……



Need to assess & rationalize

1. Define generic storage site

- Onshore / offshore
- Reservoir depth / type
- CO_2 amount (rate / duration)
- Surface conditions (wooded, agricultural, urban, protected)

2. Define project stage

- Pre-injection (baseline), injection, post-injection, post-closure

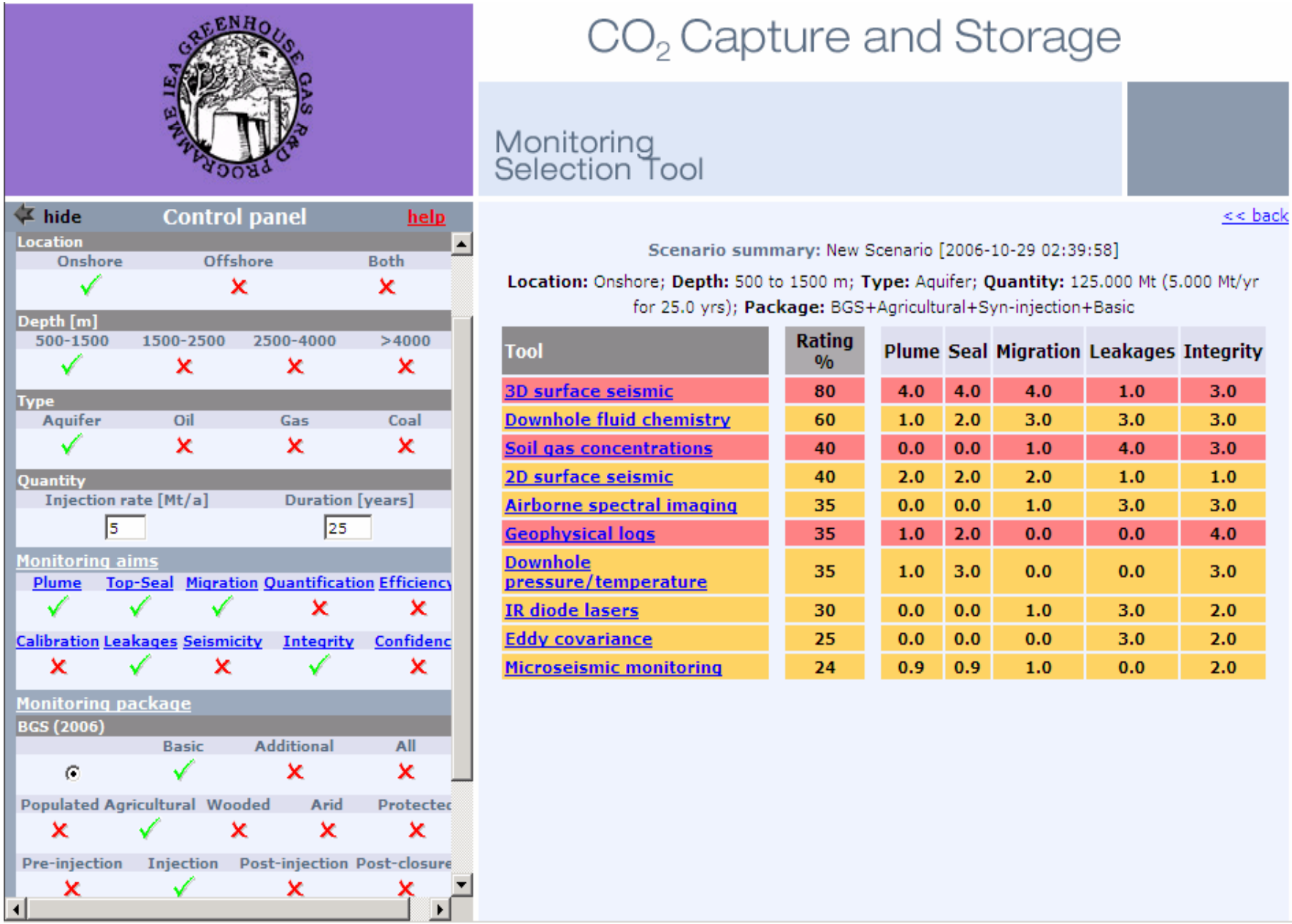
3. Set output options (filters)

- Basic package (fit-for-purpose, conformance)
- Additional package (research, complementarity, non-conformance)
- All

4. Define Monitoring Aims

- Plume imaging (reservoir)
- Topseal integrity
- Well integrity
- Induced seismicity
- Migration in overburden (>25 m depth)
- Quantification *in situ*
- Storage efficiency
- Calibrating flow simulations
- Leakage detection and measurement
- Public confidence (early projects)

Tool output



Tool	Rating %	Plume	Seal	Migration	Leakages	Integrity
3D surface seismic	80	4.0	4.0	4.0	1.0	3.0
Downhole fluid chemistry	60	1.0	2.0	3.0	3.0	3.0
Soil gas concentrations	40	0.0	0.0	1.0	4.0	3.0
2D surface seismic	40	2.0	2.0	2.0	1.0	1.0
Airborne spectral imaging	35	0.0	0.0	1.0	3.0	3.0
Geophysical logs	35	1.0	2.0	0.0	0.0	4.0
Downhole pressure/temperature	35	1.0	3.0	0.0	0.0	3.0
IR diode lasers	30	0.0	0.0	1.0	3.0	2.0
Eddy covariance	25	0.0	0.0	0.0	3.0	2.0
Microseismic monitoring	24	0.9	0.9	1.0	0.0	2.0

Tool Summary

Ranking list of suitable technologies

Knowledge - base of CO_2 monitoring technologies
Library of case-studies, range of settings

N.B. Not prescriptive
Site specific circumstances can override generic rankings

Tool development history

Monitoring technology assessment and knowledge base:
Andy Chadwick, Gary Kirby, Jonathan Pearce (BGS)

Software programming and web implementation:
John Rowley, Gareth Williams (BGS)

Internal review:
John Gale, Angela Manancourt (IEAGHG)

External review:
AN Others

Version 1.0 IEAGHG internal review
Version 2.0 GHGT-8 Trondheim June 2006
Version 2.1b IEA Monitoring Workshop Canberra October 2006

Changes V2.0 to 2.1b (following external review)

- Improved Welcome text
- Improved log-in explanation
- Improved Help text for monitoring aims
- Explained units (metric/SI)
- Altered descriptions of tools scores & 'traffic light' colours
- Implemented storage scenario save/save-as and delete functions, check maximum number of allowed scenarios
- Checked all web links
- Checked back buttons are available everywhere
- Added direct access to techniques descriptions

- Reviewed scores on techniques
- Rationalised site conditions / project stage filters
- Added two new techniques (headspace gas and bubble detection)
- Updated case-studies
- Updated technique descriptions (inc. maturity, qualitative costs)

Formal responses to all feedback comments to be placed on tool website

Future developments (?)

Maintenance

- Tool descriptions
- Case-studies
- FAQ
- Ranking review (user feedback)

Additions/Enhancements

- Aims weightings
- CO_2 impurities
- Improve land-use algorithm
- *Well numbers/spacings*
- *Reservoir/overburden geology*
- *Trap type*
- *Monitoring repeat frequency*
- *Costs*

[Implement as ‘Advanced’ options]

3rd IEA Greenhouse Gas Research and Development Program Monitoring and Verification Network Meeting

Regulatory Requirements Day 1

Application of M&V to Regulatory Requirements: Using OBPP as a Model

Kevin Dodds, Sandeep Sharma

Acknowledgement

Carmel Anderson, Milovan Urosevic, Don Sherlock, Brian Evans, Anton Kepic, Max Watson, Allison Hennig, Jim Underschultz, Claus Otto, Linda Stalker, Ernie Perkins, Peter Van Ruth, Tony Siggins, David Etheridge, Ray Leuning

Cooperative Research Centre

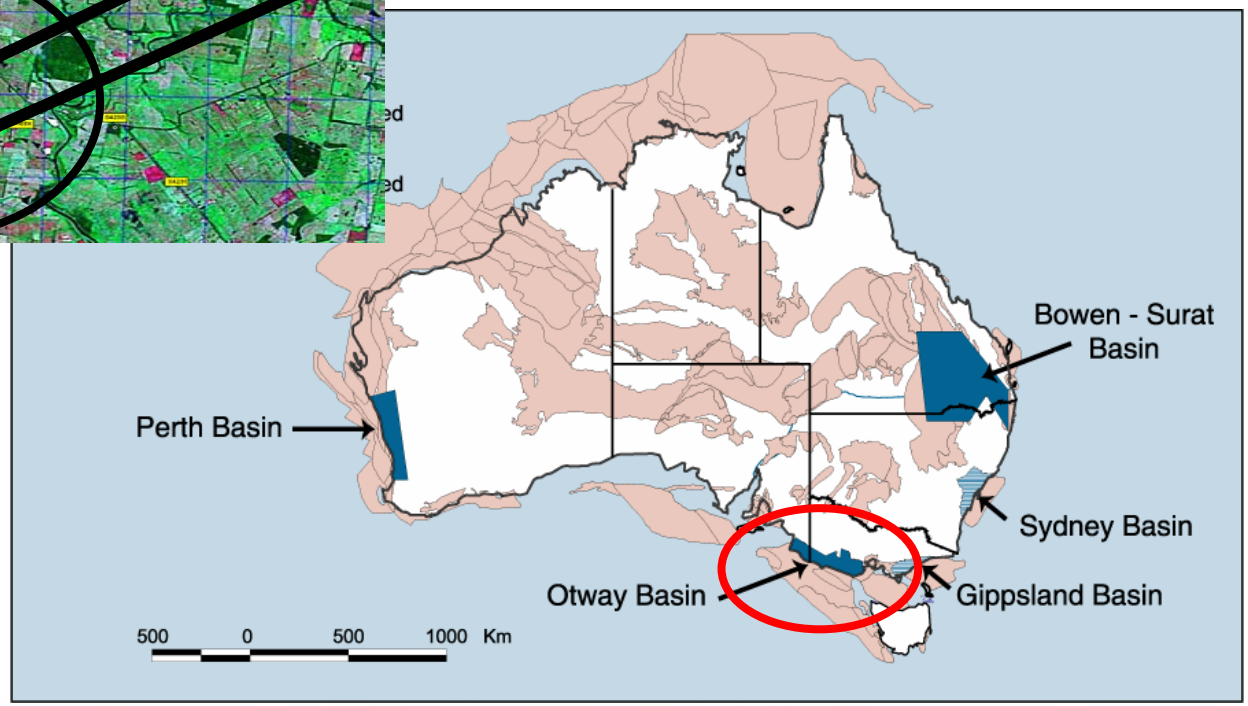
for Greenhouse Gas Technologies (CO2CRC)

Kevin.Dodds@CSIRO.au

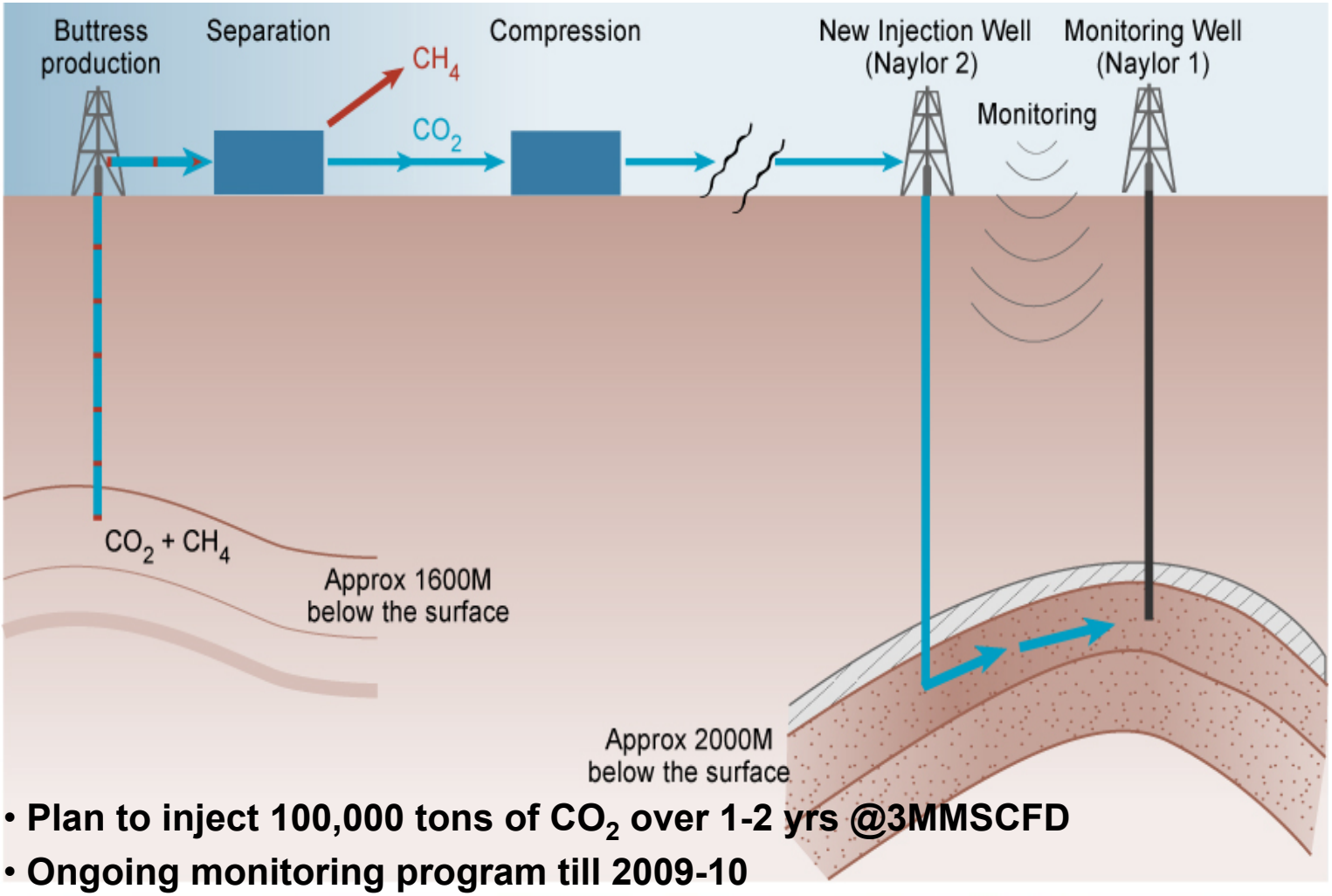
Overview

1. Context
2. M&V Drivers
3. OBPP implementation Phases
4. Monitoring and Verification Domains

Otway Basin Pilot Project - OBPP

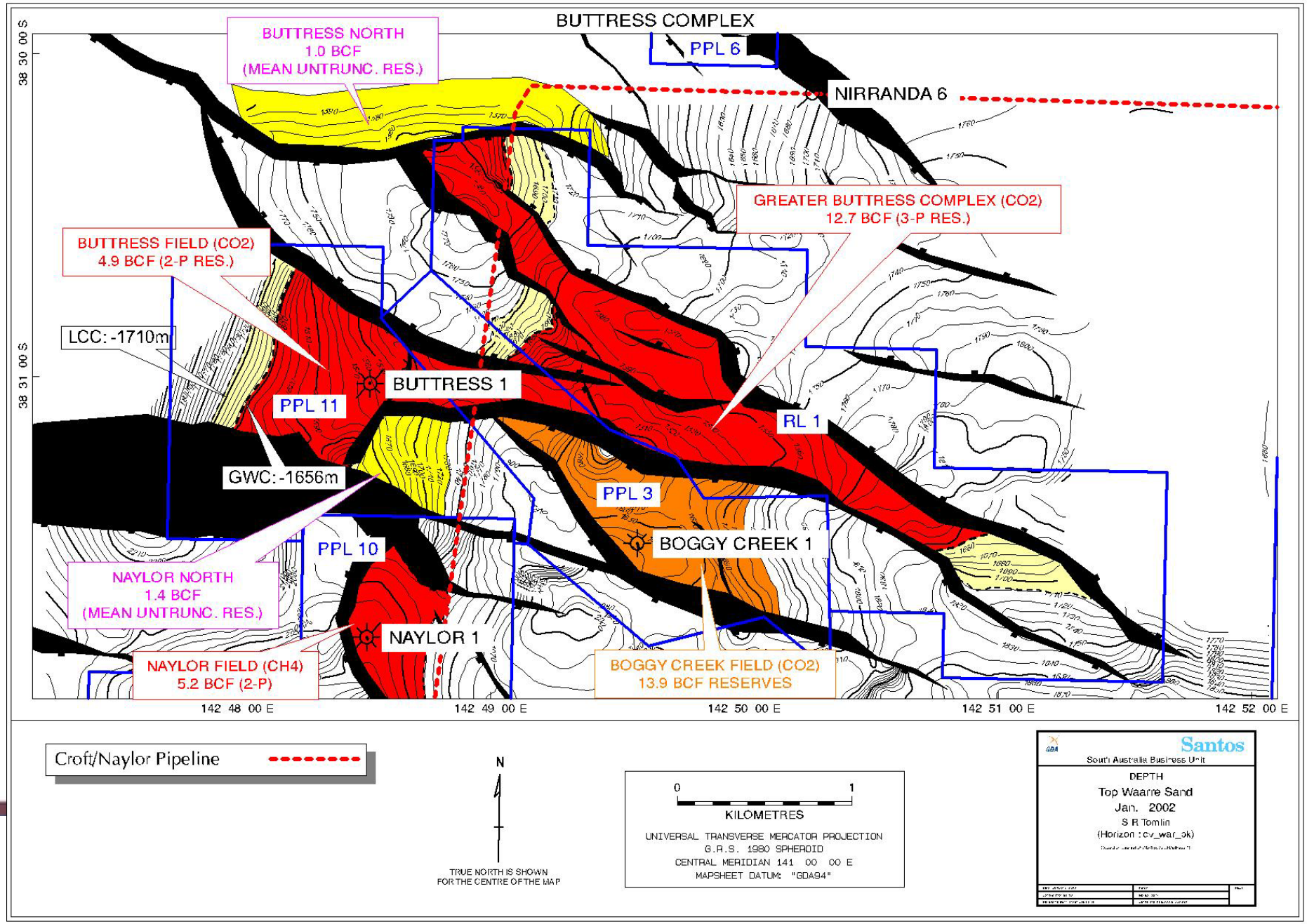


Conceptual Representation of the Pilot Project



- Plan to inject 100,000 tons of CO_2 over 1-2 yrs @3MMSCFD
- Ongoing monitoring program till 2009-10

Structure Map - OBPP Fault Distribution



M&V Drivers

CCS is not an exploration or development project !

It has a completely different set of questions that need answering

Site Risk Assessment

Regulatory Framework

Public Acceptance

Carbon Credits Validation

Non-Technical Challenges

Regulatory

- No existing regulation for geo-sequestration.
- Not permissible under existing petroleum legislation

Organisational

- CRC not an operating entity
- Not all CRC participants able to shoulder operational liability
- Providing for long term monitoring requirements

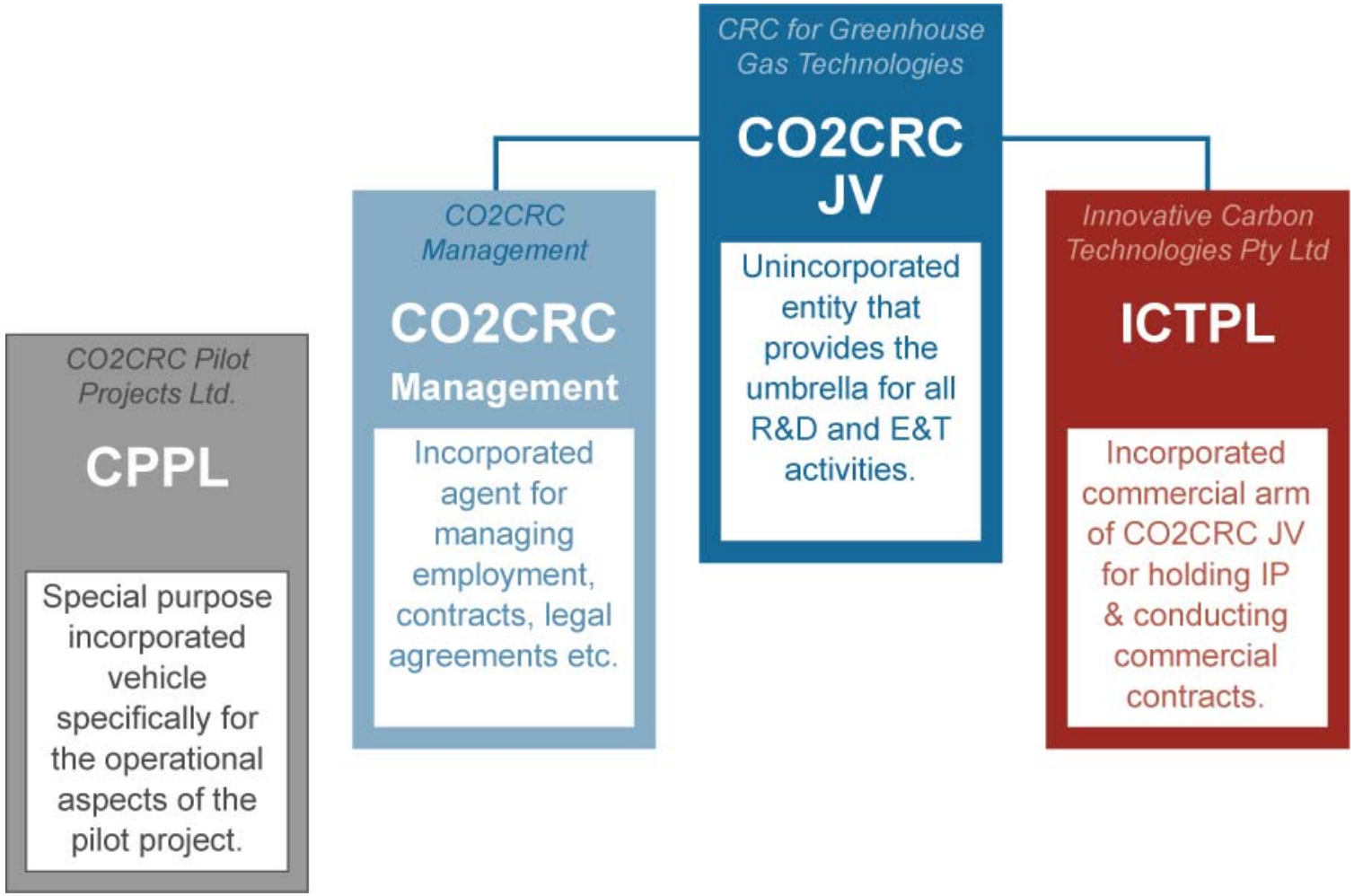
Liability Management

- Research Project: Operational Liability not offset by project NPV.
- Need for a solution to long term liability.

Community

- First of its kind with no national precedent
- Mixed reports in media

Special Company for Project Execution



Community Consultation

- Formal program to engage with and brief the community early – starting Jan 05
  - key landholders
  - Shire and neighbouring councils
  - the local media
- Informing via email and offering briefings to:
  - local State Upper and Lower House MPs
  - NGOs (eg WWF, ACF)
  - State and Federal ministers through their Departments
- Invited Mayor and Planning Manager to CRC technical Symposium
- Formal briefing to shire and public
  - Public info packs distributed to 1200 households
  - Advertisements run in local papers
  - Public meeting with state regulators held on Feb 12,06 – others planned
- Social research in community perception

OBPP "Regulatory" Phases and Scope

- **Regulation under a combination of the Victorian Petroleum and RD&D provision of the Victorian Environment Protection Act.**
- **Phase 1 (Pre-injection) and 1A (Injection): Petroleum and EPA**
  - Safely produce, transport and inject processed CO_2 into the sink structure for 1- 2 yrs (2006-2009)
    - ➢ Engineering design for plant and injection well and operations to be compliant with good oilfield practices.
    - ➢ Establish monitoring baselines and models for to monitor CO_2 plume movement
    - ➢ Monitor plume behaviour and compare v.s.model predictions
- **Phase 2 (Post Injection Monitoring and Closure): Petroleum and EPA**
  - Achievement of KPI's set with the EPA through monitoring activities. (2009-2010)
  - Safe closure of all wells as per regulation and site restoration
- **Longer Term Monitoring for Public Assurance : EPA**
  - **Phase 3 (Post Closure) and Phase 4 (Long Term)**

OBPP Risk Assessment History

- Construction of risk register
- Qualitative RA at time of Evaluation of Assets
  - Planning and pre-implementation risks
  - Implementation risks
  - Long-term storage risks
    - Leakage to surface from reservoir
    - Leakage to surface via wells
    - Leakage into potable water aquifers
- First pass QRA-containment
  - Post-static and pre-dynamic modelling
- Latest QRA-containment
  - Post dynamic modelling
- Next QRA
  - Post Buttress well-testing, Naylor logging, well-location selection
- **No other pilot site had full QRA undertaken prior to injection**

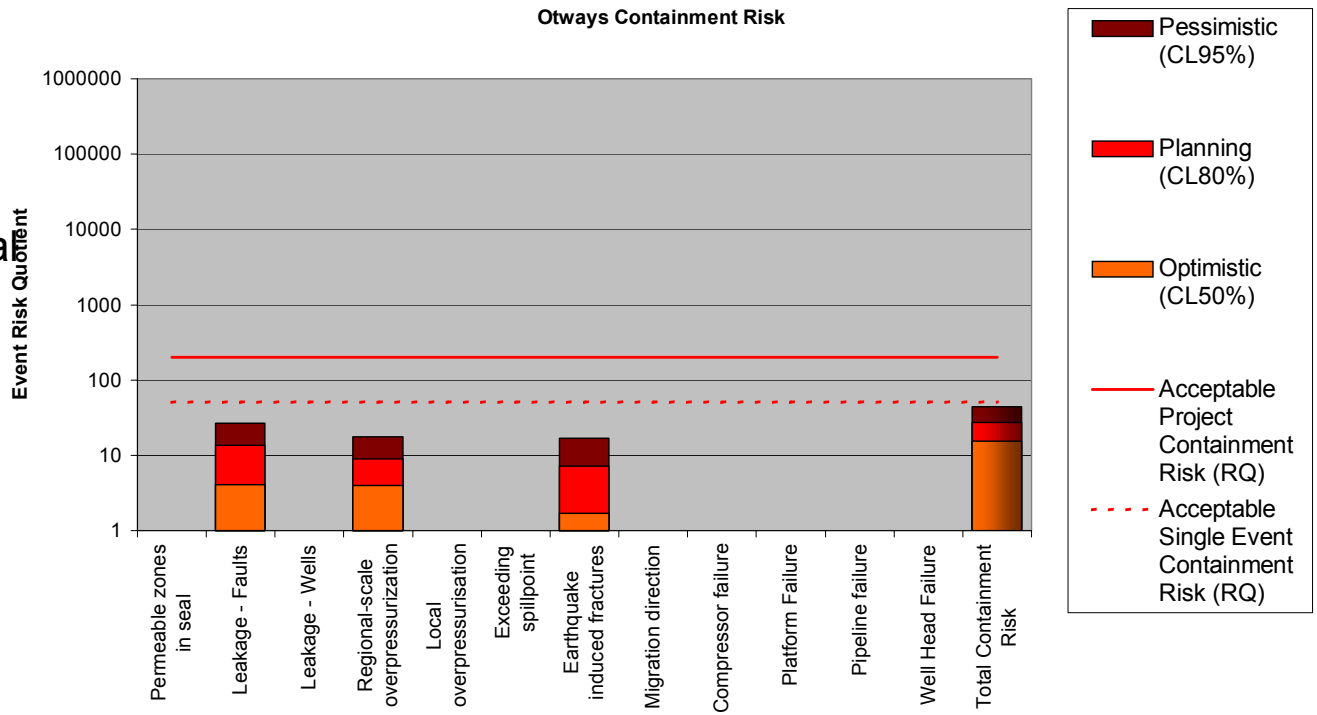
QRA: Confidence in Proposed Site

Quantitative Risk Assessment (QRA)

- Considered both natural and man-made risk events.
- "Expert Panel" based approach

Risk Management

- Adherence to established operational procedures and standards
- Comprehensive Monitoring program



The Otway Site is appropriate for a Pilot

- Deep injection far below any useable water sources
- Favourable geology to keep the CO2 trapped
- Established oil and gas operations in the area

Technical/Operational Challenges

- Site characterisation
- Constraints from existing wells – size and condition
- Quantification of risk → research
- Monitoring and Verification:
  - Sub surface detection and imaging of plume in the presence of residual gas→ geophysical and geochemical research
  - Modelling and long term interactions → research
  - Null measurements (soil, atmosphere)
- Other Constraints
  - Budget inflexibility : Funded through grants
  - Industry Resource shortage : Cost and Schedule creep

Key Monitoring Objectives

- Confirm conduct all tasks safely and to the satisfaction of all stakeholders.

Assurance Monitoring (no leakage)

- Soil and atmospheric measurements to confirm non leakage/seepage of injected Co2.
- Hydrogeological monitoring to ensure no leakage of CO_2 into the overlying aquifers

Storage Integrity Monitoring (predicted behaviour)

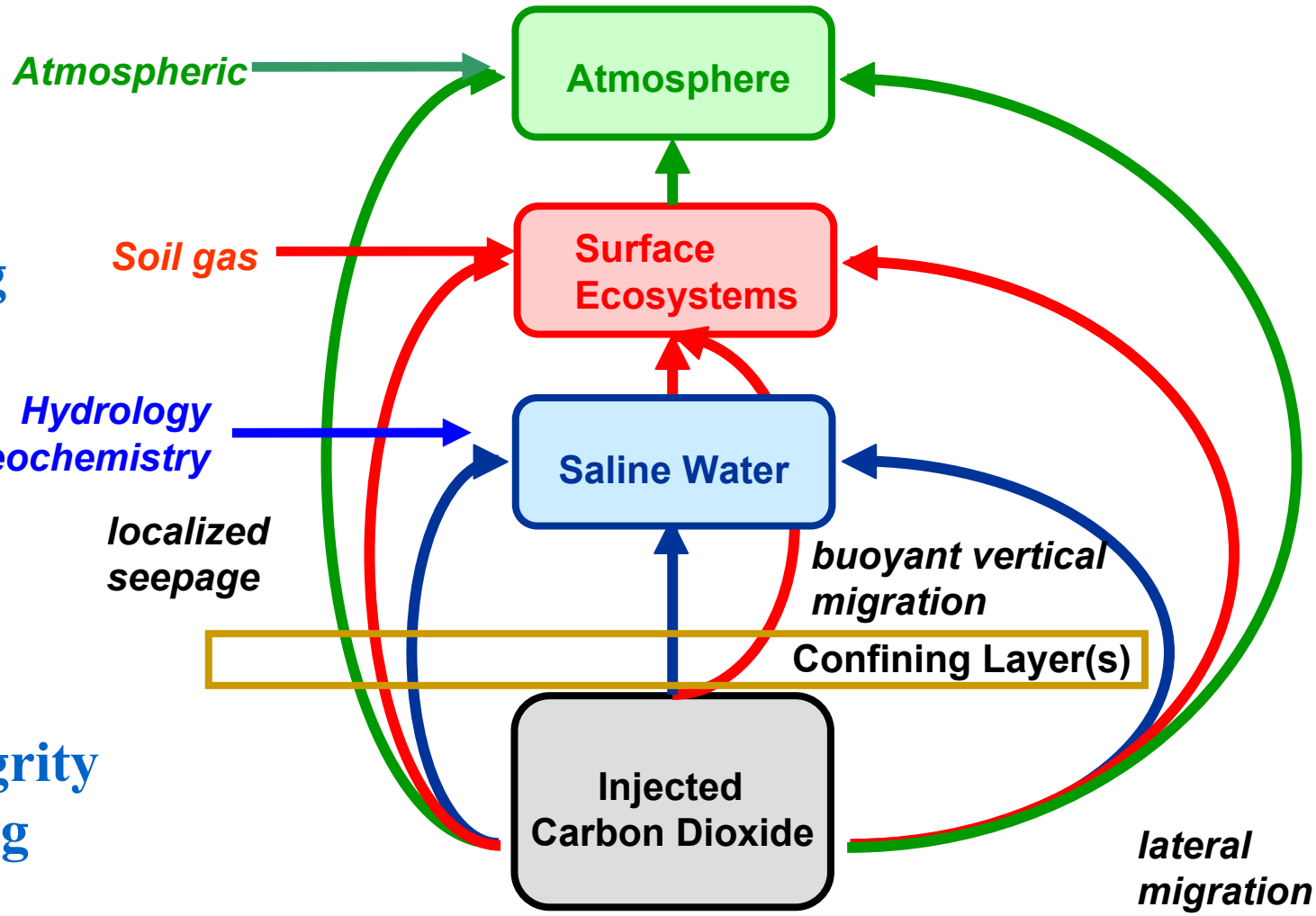
- Monitor the injected CO_2 plume to :
  - Validate migration paths - geophysics
  - Validate migration times - geochemistry
  - Validate likely shape - reservoir properties
  - Validate geomechanical integrity - dynamic behaviour

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 & VSP	micro Seismic	Water Wells	Atmospheric	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										

Monitoring Domains



Modified from: http://web.princeton.edu/sites/cmi-aquifers/

Modified from: http://web.princeton.edu/sites/cmi-aquifers/

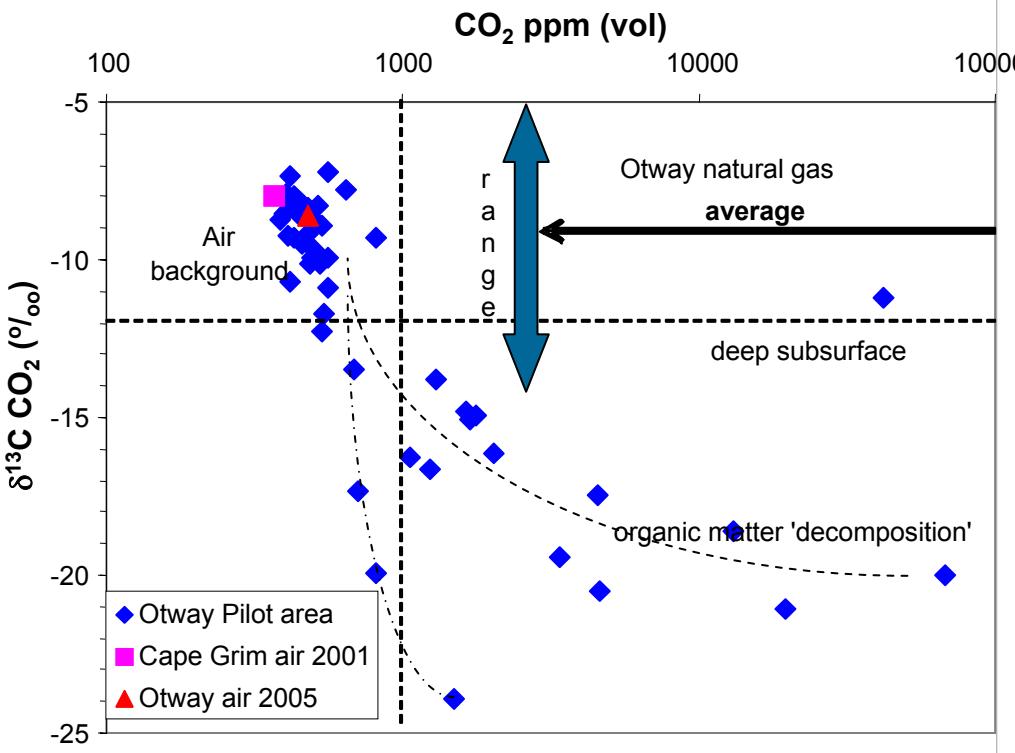
Atmospheric Monitoring and Verification

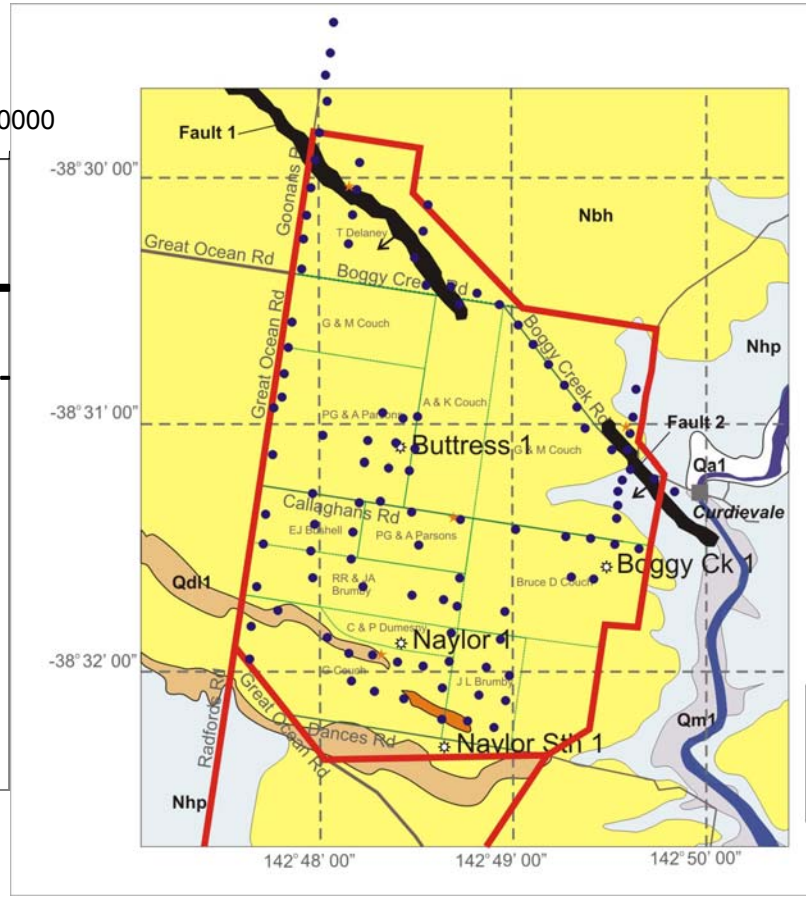
To detect, attribute and quantify CO_2 emissions to the atmosphere

- **Measurements of CO_2 concentration (continuous)**
- **Measurements of other gases and isotopes (including tracers)**
- **Measurements of CO_2 fluxes**
- **Interpretation with transport and dispersion models**
- **Integration with subsurface work - soil, hydro, geochemistry….**

Soil Gas Sampling

Monitor gas compositions in the soil to order to define near surface CO_2 movement.

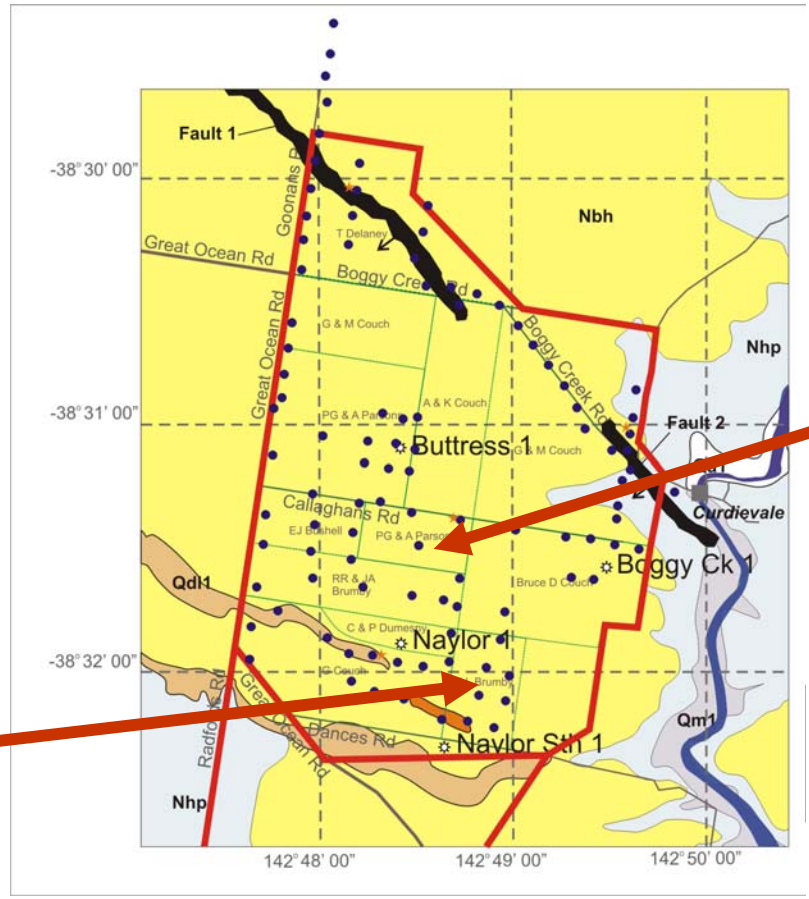




Atmospheric Monitoring

Monitor CO_2 in the atmosphere and define the sources

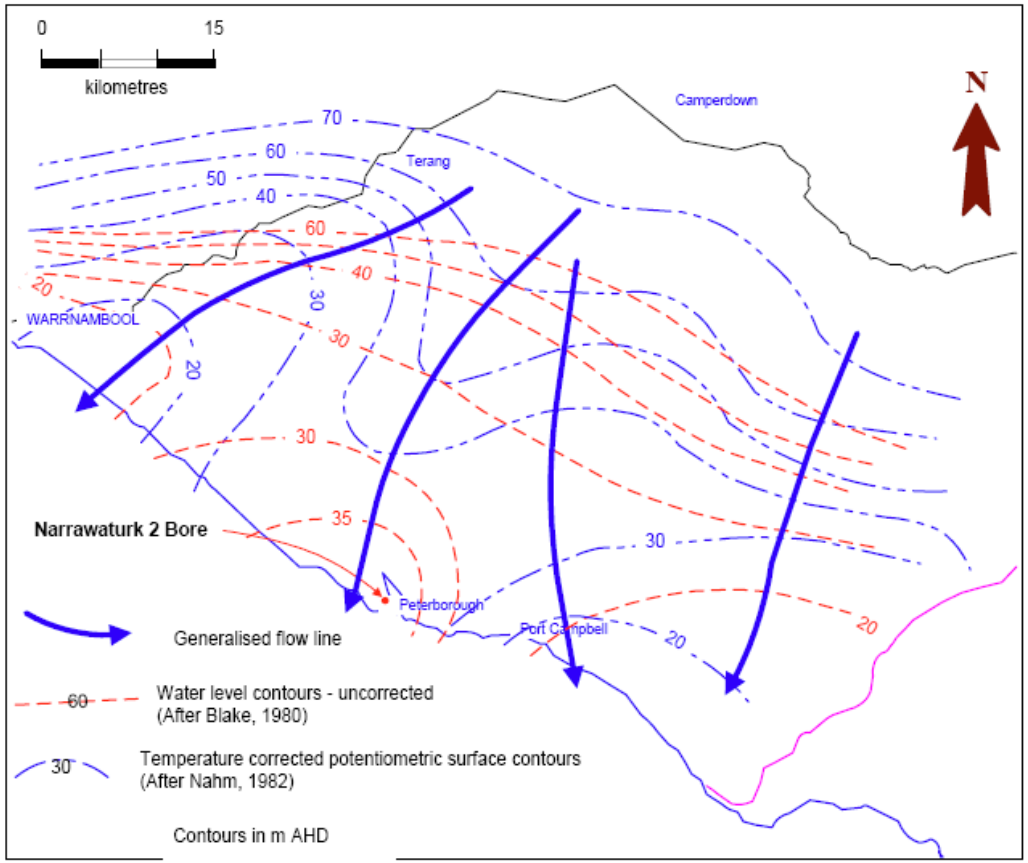
Flux Tower



Lo-Flo*

Hydrological Areal Model

- A network of pressure monitoring to provide assurance of no leakage
- An increased understanding of where the long term potential end points for dissolved CO_2 may be
- Demonstrated preservation of existing resources (water, soil and air) and hence compatibility of CCS with existing environment
- And an increased understanding of the requirements and calibration of a long-term sentinel monitoring system



Storage Integrity
Reservoir Geochemical Monitoring

Sample and analyze reservoir fluids in order to monitor CO_2 movement in the reservoir.

Project Tasks

- **Baseline fluid and gas samples to be taken and analyzed using U-Tube developed in collaboration with LBNL.**
- **Regular fluid and gas samples to be taken and analyzed until CO_2 break through occurs.**
- **Inject various tracers with the CO_2 stream and monitor their composition variations in the reservoir.**

Standard and Unique Technology

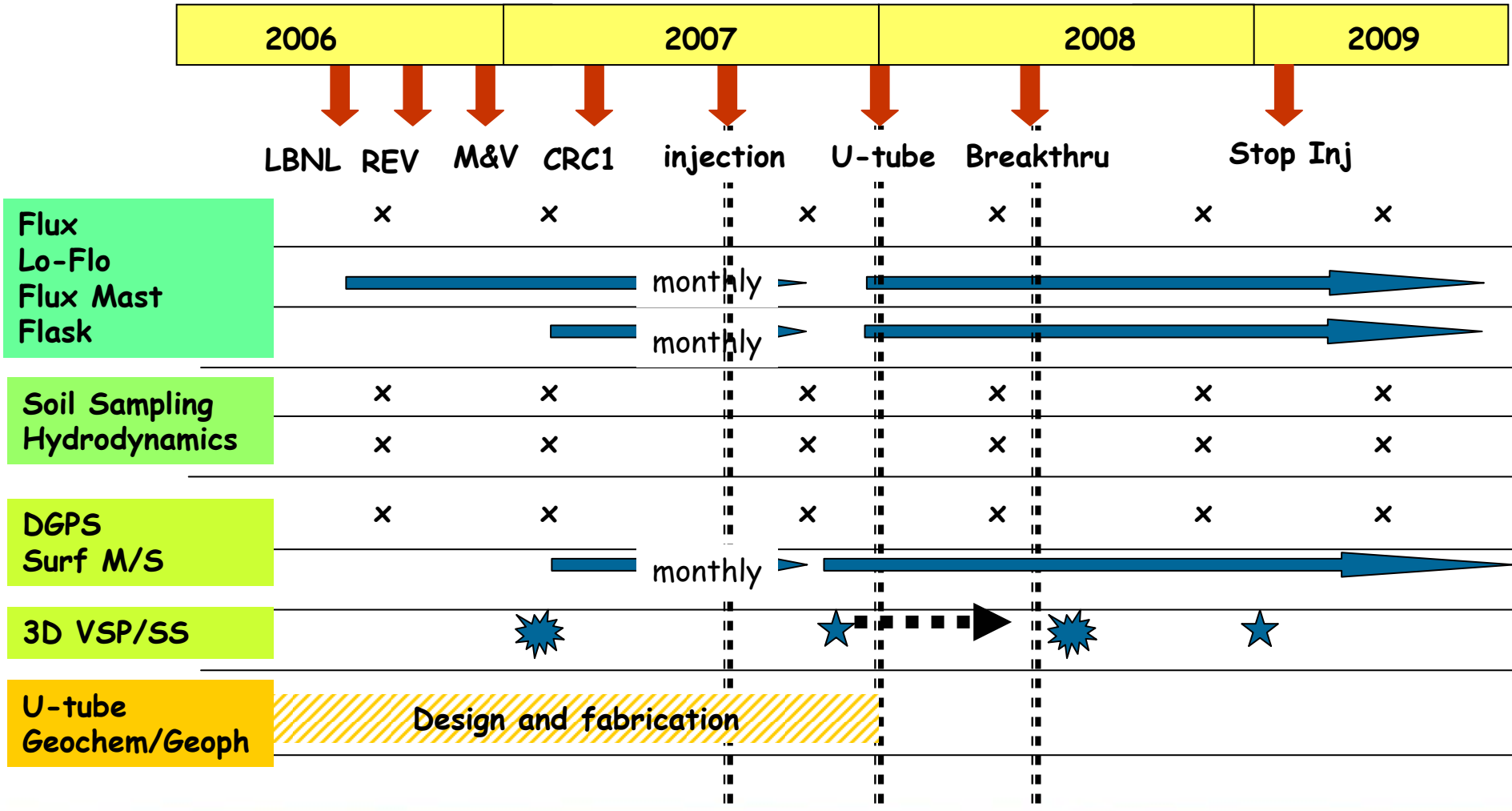
- **SF_6 Can be transported in gases and liquids**
- **CD_4 tracer Important for depleted methane gas reservoirs**

(will be tested in FRIO-2)

Integrity Monitoring : Surface & Borehole Geophysics

- Existing 3 D seismic is pre-production and of good quality. Some velocity anomalies to be validated in monitoring well through VSP.
- Goals
  - Monitor movement of CO_2 plume in depleted Gas field
- Approach
  - Re-process existing PSDM
  - 3DVSP and Surface seismic– mapping of areal changes
  - Borehole Seismic – Vertical and Walkaway Imaging and AVO
  - AVO analysis and fracture orientation
  - Elastic inversion and saturation.
- Timing
  - #1 : Pre-injection
  - #2 : Prior breakthrough (3 m injection start)
  - #3 : end 2008/9 : several months after stopping injection

Schedule


2006
2007
2008
2009
LBNL
REV
M&V
CRC1
injection
U-tube
Breakthru
Stop Inj
Flux
Lo-Flo
Flux Mast
Flask
monthly
monthly
Soil Sampling
Hydrodynamics
DGPS
Surf M/S
monthly
3D VSP/SS
U-tube
Geochem/Geoph
Design and fabrication

OBPP Implementation Phases
EPA Transition Criteria

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

KPI's Per Phase

Phase	Key Performance Indicator (KPI)
1	**1.** Establish injection and migration models and uncertainties
1A	**2.** Environmental impacts within State set guidelines for noise, emissions etc. (SEPP) **3**. Injection/Migration within model prediction bounds
2	**4.** Verified stable plume within model prediction bounds a) Measurements show no evidence of CO_2 beyond secondary containment in sink wells b) Air Samples collected over deep water wells show no evidence of tracers. c) Air samples collected over sink site shows no evidence of injected CO_2 **5.** Appropriate decommissioning certificate from authorities
3	**6.** No evidence of injected CO_2 over 2 yrs ? a) Air Samples collected over deep water wells show no evidence of injected CO_2 b) Air samples collected over sink sites show no evidence of injected CO_2
4	**7.** No evidence of injected CO_2 over 2 yrs ? a) Air Samples collected over deep water wells show no evidence of injected CO_2

Site and Monitoring Technologies Overview

	Geological Data Availability		Baseline data	Reservoir Geochem	Geo-physics	Ground water monitoring		Soil Gas	Atmos	Contain-ment Risk Ass. prior to project start
	Regional	Reservoir				Hydrology	Geochem			
West Texas	✓	Largely confidential		very limited	limited					
Alberta Basin	✓	limited		very limited						
Sleipner	✓	limited	limited		✓					
Weyburn	✓	Largely confidential	✓	✓	✓	✓	✓	limited		
Frio	✓	✓	✓	✓	✓	limited	limited	limited		
Japanese	✓	✓	✓		✓					
Proposed OBPP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

3rd International Monitoring Network Workshop

John Gale

IEA Greenhouse Gas R&D Programme

Rendezvous Hotel

Melbourne, Australia

31st October – 2nd November 2006

Building Confidence in CCS

- To move the technology forward to implementation we need to:
  - Identify technical barriers
  - Identify ways of addressing these barriers
- Provide information on what we know to build confidence
  - Transparent and open manner

Research Networks

CAPTURE

- International Network for CO_2 Capture
- Oxy-fuel Combustion Network
- International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

IEA GHG Networks

STORAGE

- Risk Assessment Network
- Monitoring Network
- Well Bore Integrity Network

Monitoring Network

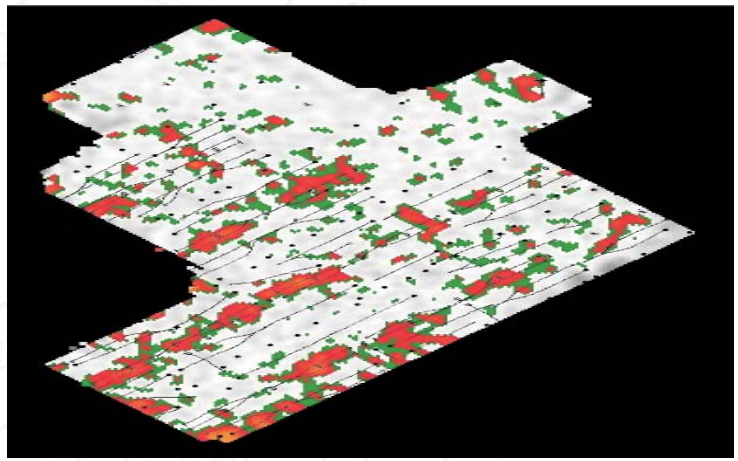
- Identified that we have a large number of techniques to use
  - Need a suite of techniques
- Strong positive messages to convey
- Developed the Monitoring Selection Tool as a way of communicating this message
  - Better than a static report
  - Intend to maintain the status of the tool

Monitoring Activities

- Only a few projects are injecting commercial scale volumes of CO_2 (e.g. 1 Mt/CO_2/y)
  - Sleipner, Weyburn, Rangely, In-Salah,
- Many are research projects that will inject 100's to 1000's tonnes CO_2
  - Frio, West Pearl Queen, CO2SINK, OBPP
- Can only draw firm conclusions on evidence for leakage from the large scale projects

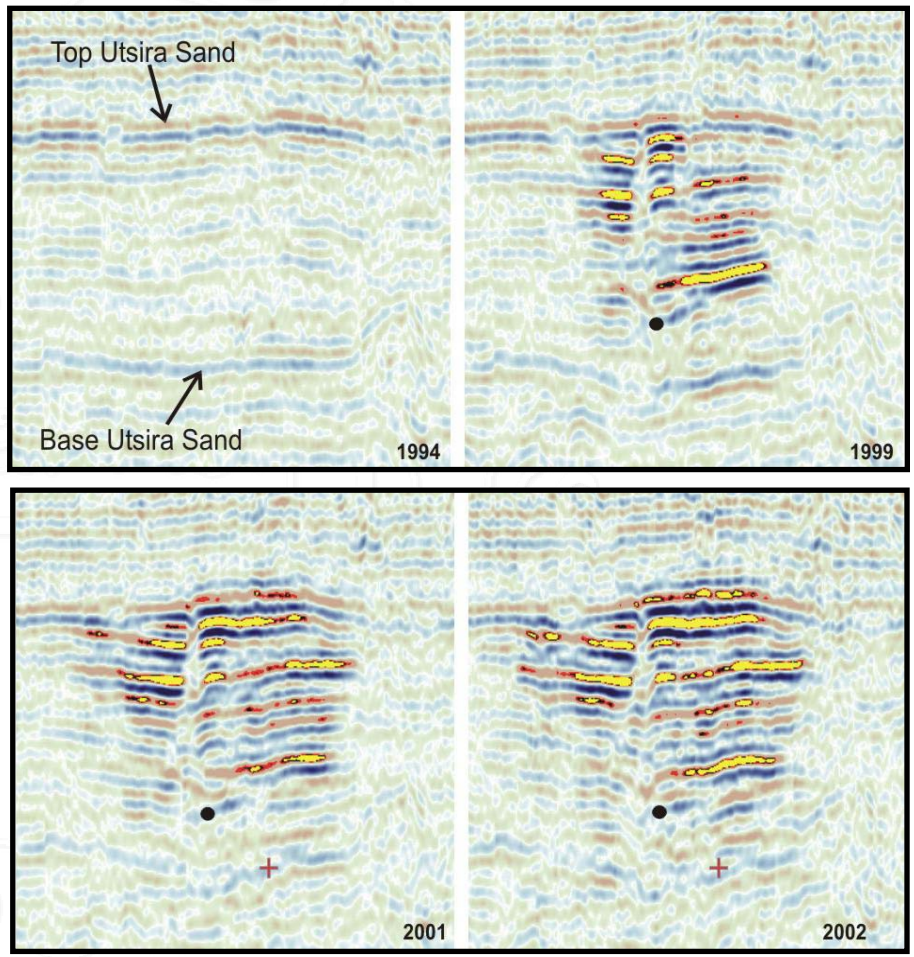
Weyburn

- Presence of CO_2 within oil field identified using seismic surveying
- Soil gas sampling used to measure leakage of CO_2 to the surface
- No evidence of surface leakage after 3 years of CO_2 injection



Sleipner

- Injected CO_2 accumulating under cap rock
- CO_2 can be monitored with seismic surveying
- No evidence of migration out of the reservoir after 8 years of injection



Rangeley

- 1 Mt/y CO_2 injected for 25 years
- Surface monitoring has identified possible CO_2 leakage
- The average winter CO_2 flux is 0.302 g $m^{-2}day^{-1}$ or 170 t/y,
  - But it is likely that some or all of CO_2 is converted biogenically in soil from CH_4 seepage
  - Therefore actual figure is <170 t/y
  - Annual leakage rate of <0.01%/year
- Arboreal measurements do not indicate any changes in plants ecosystems since injection began
  - Cast further doubt on leakage data

Summary of Monitoring Experience

- No firm evidence from any of the large scale projects that leakage is occurring
- Cannot determine a generic leakage rate

How Safe is CCS?

- Design storage facility for zero leakage
  - Site characterisation
- Monitoring programme
  - Current results indicate zero leakage during operational phase
- Well bore integrity?
  - Some uncertainties but developing our knowledge
- Performance assessments
  - Predict long term fate of injected CO_2
- Remediation strategy
  - IEA GHG study recently completed to begin to address this issue

Environmental impacts of CCS?

- CO_2 capture
  - Initial study underway
    - Need further work
- Onshore storage
  - Reported at this meeting
- Offshore storage
  - Initial study to identify issues/gaps in knowledge underway

Confidence Building

- Bring results from network and study activities together:
  - Briefing papers
  - Information sheets
  - Topical Report
- Aim to deliver positive (but unbiased) messages on CCS safety/environmental impact

CO2CRC

3RD MONITORING NETWORK MEETING

Minister's Opening Address

The Honorable Theo Theophanous,
Minister for Resources

CO2CRC and the Otway Basin Project

Peter Cook, CO2CRC

Chief Executive

Cooperative Research Centre

for Greenhouse Gas Technologies (CO2CRC)

The Context to CCS in Australia

- The CRC (initially APCRC, now CO2CRC) started CCS research in Australia in 1998. In 2003 it was given new funding. It now has a bubget of around A$140 million over the 7 years and has 100 researchers involved
- In past 3 years, a very major increase in interest by government, industry and community.
- Many government initiatives, including funding:
  - LETDF
  - AP6
  - CSLF
  - Energy Paper
  - Government Geosequestration Inquiry
- Industry initiatives

  Coal 21

It is now time to deliver!

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CO2CRC Core Participants:

Australian Government

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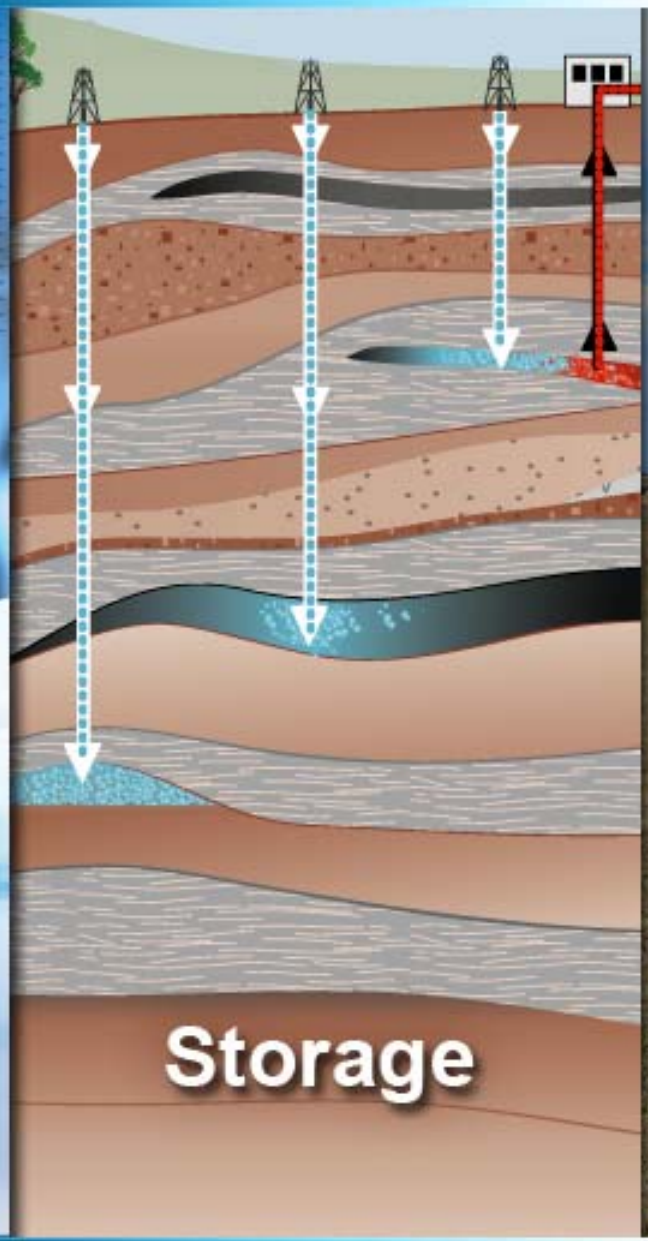


CO2CRC

Strategic Intentions

- ***Contribute to cutting CO_2 emissions from major stationary sources by undertaking leading R&D into CO_2 CCS technologies;***
- ***Decrease commercial risk by demonstrating the practical application of CCS technologies, to cut CO_2 emissions;***
- ***Develop new opportunities for decreasing CO_2 emissions in an economically and environmentally sustainable manner, by assessing the scope for the application of CCS in a range of geographic, technical and commercial settings in Australia, New Zealand and elsewhere in the Asia-Pacific region;***

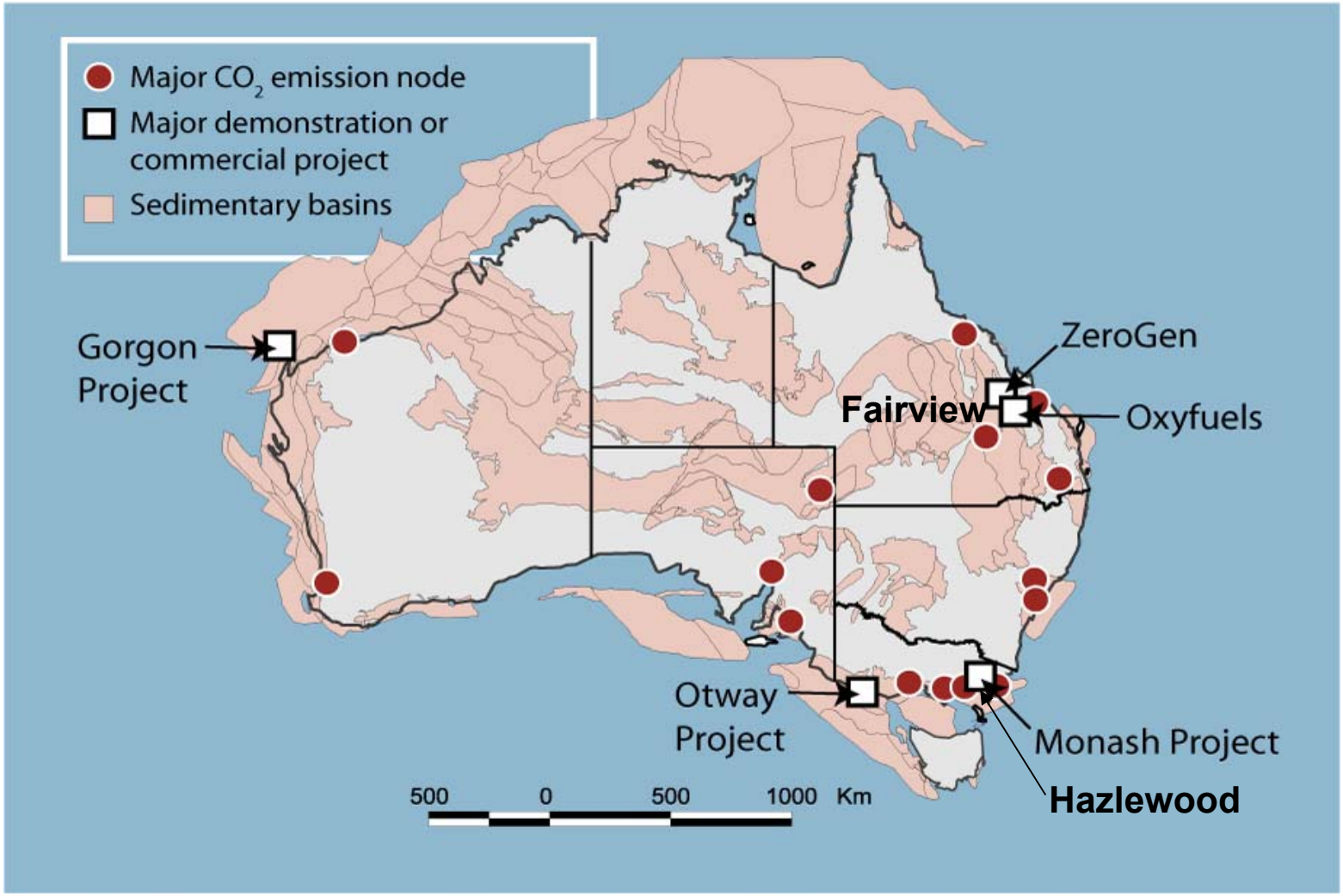
CO2CRC

Strategic Intentions *continued…*

- ***Contribute internationally* to the development and global uptake of CCS technologies through participation in international programs and collaboration with leading international research and development groups;**
- ***Strengthen CCS technology uptake through technology transfer and the development of new commercial opportunities;***
- ***Meet the needs of industry and government for quality graduates and well trained staff, by offering outstanding education and training in greenhouse gas technologies.***

CO2CRC

There are a number of CCS projects proposed for Australia, including several announced in the last few days under LETDF



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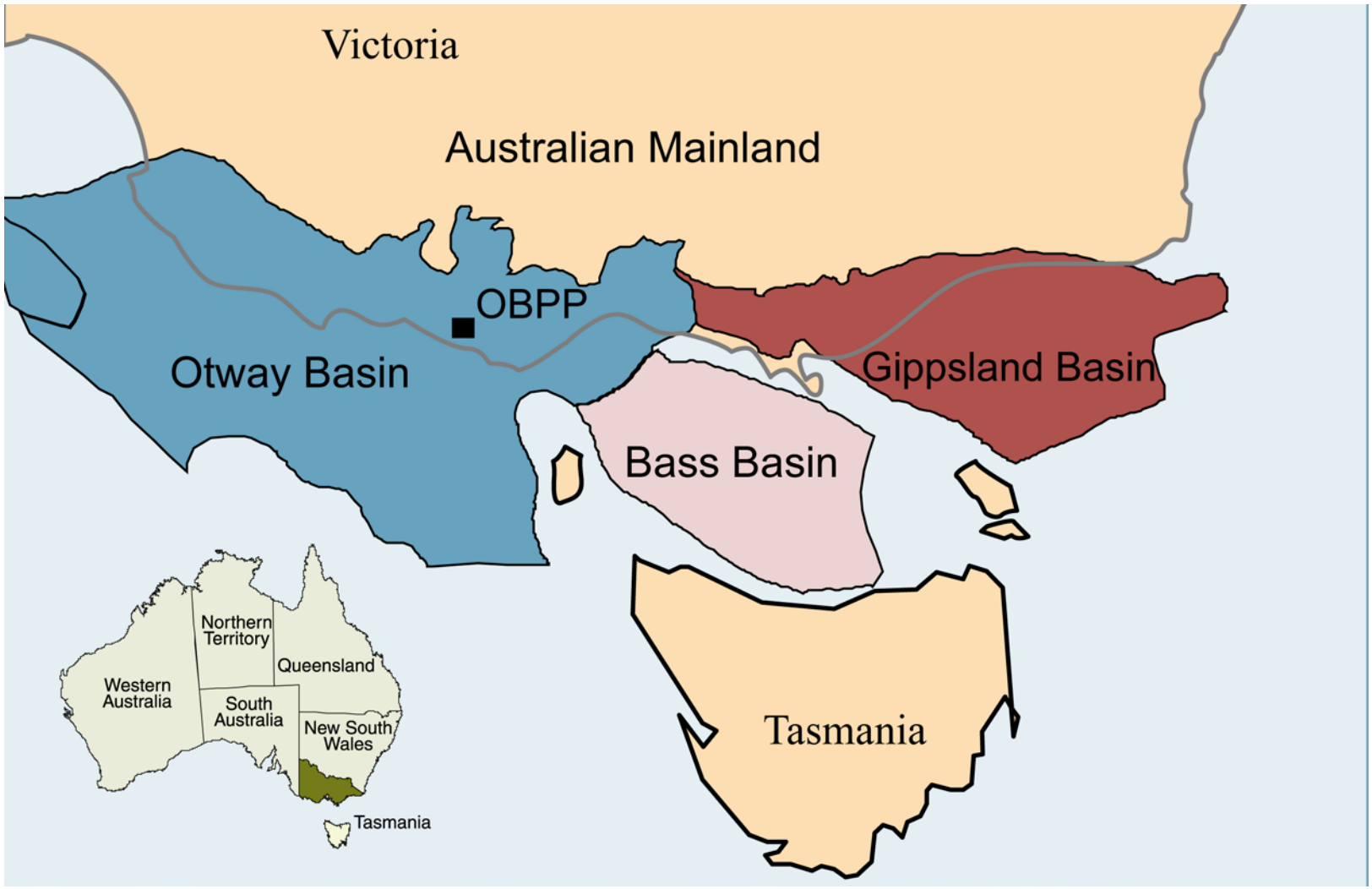
Otway Basin Project

Dr Peter Cook
Chief Executive
Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

CO2CRC

Sedimentary Basins in the Victorian Region



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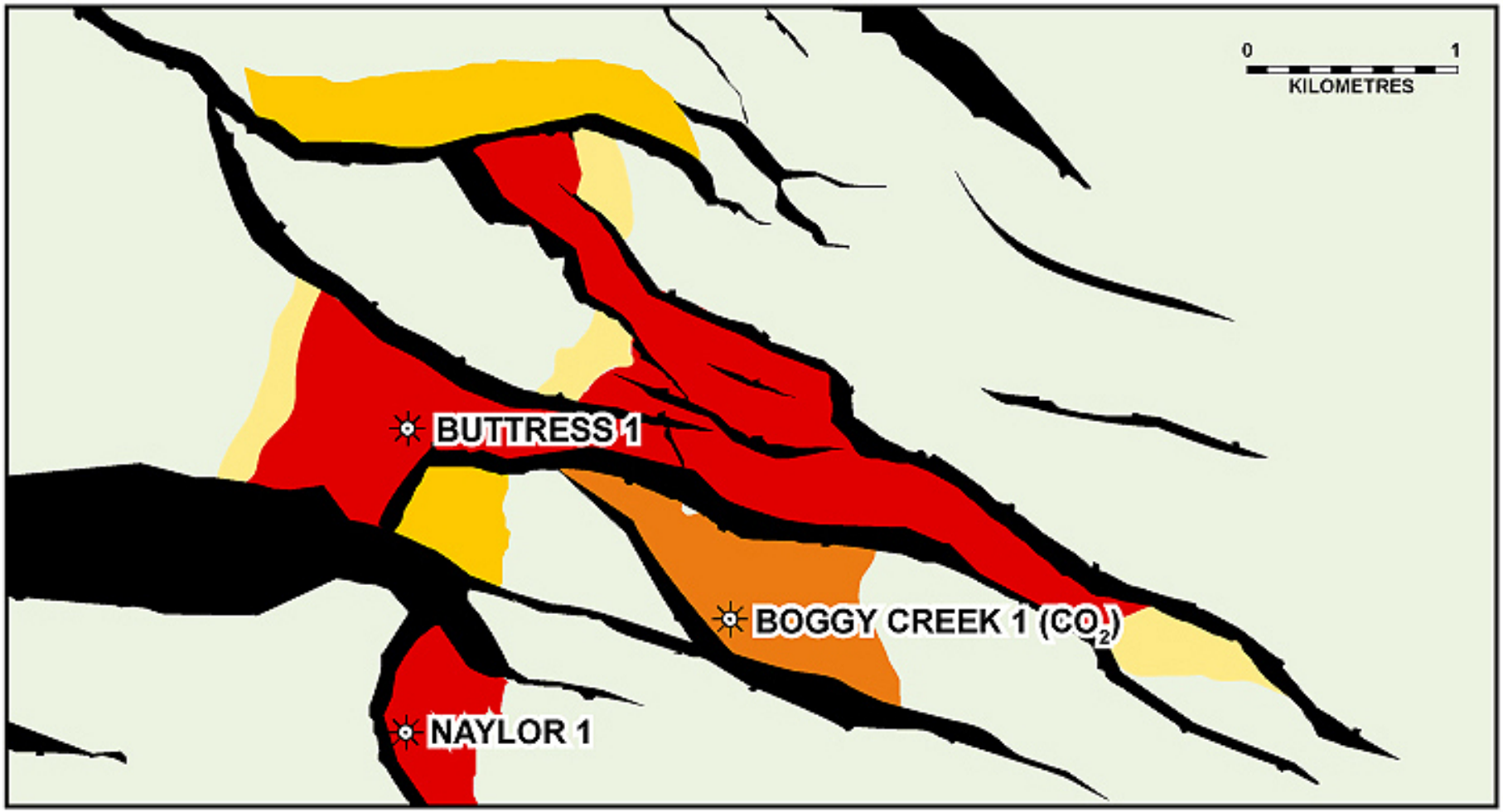
Sealing Faults in the vicinity of the Pilot Project



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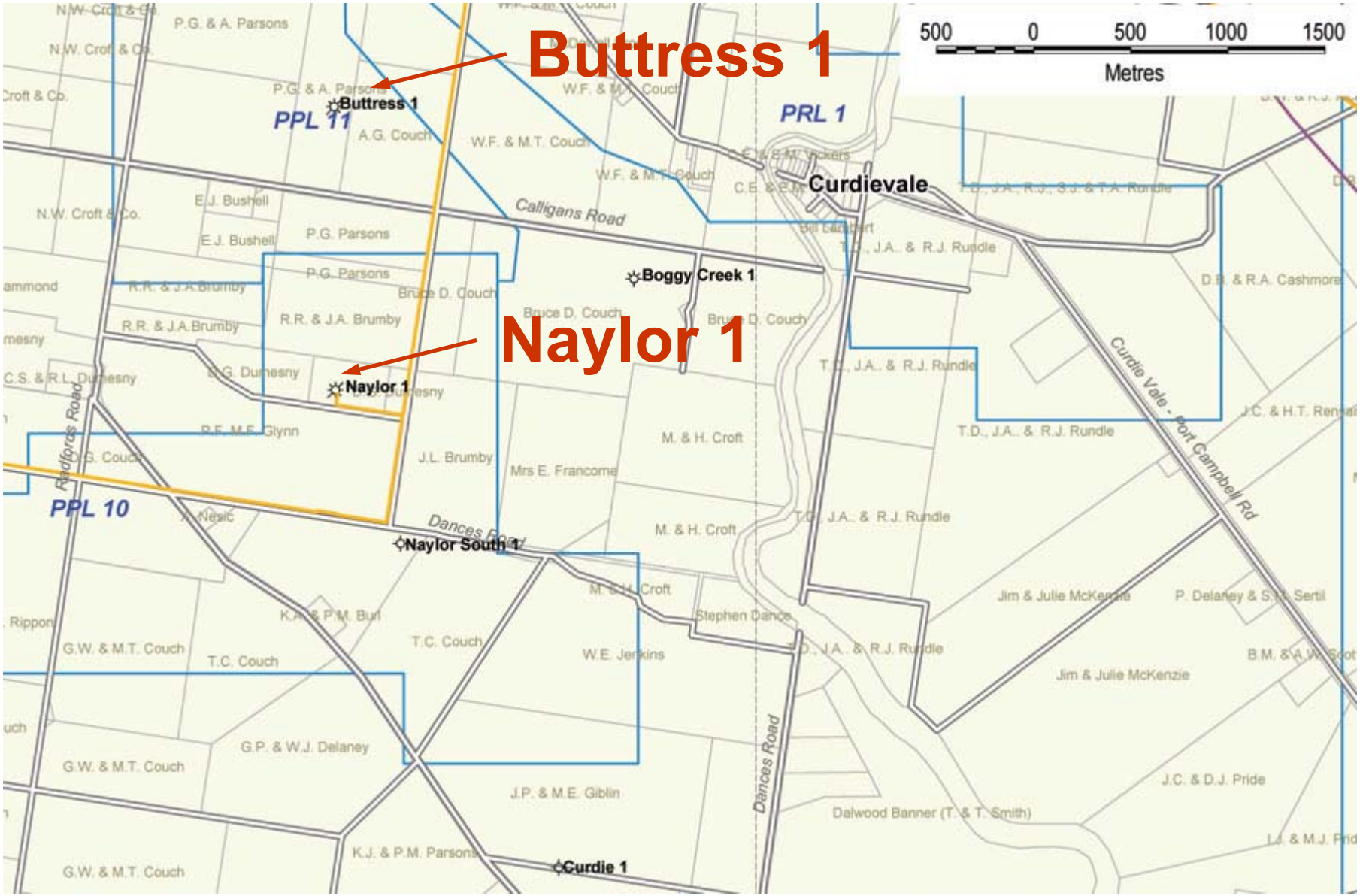

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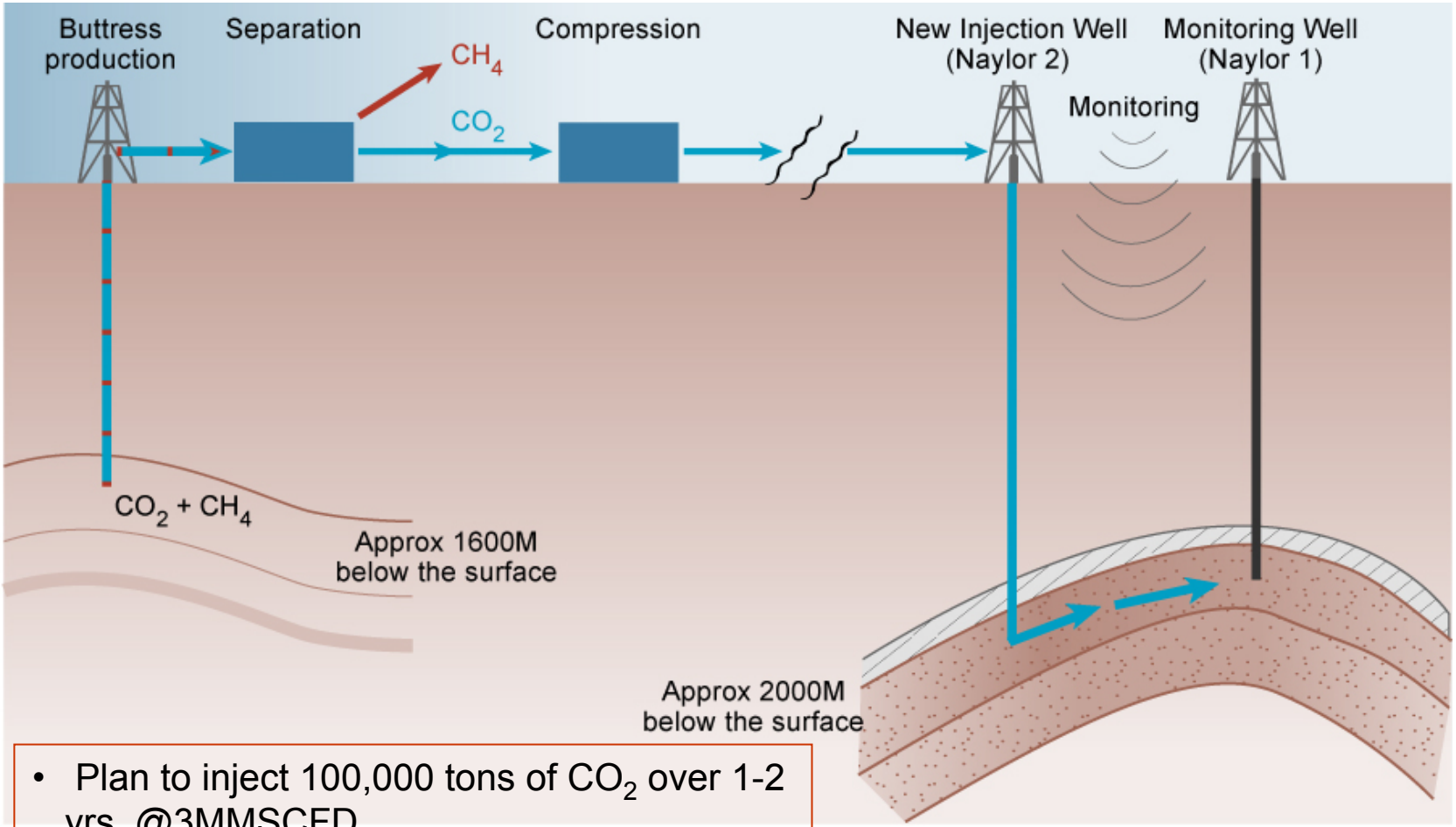
The Otway Basin Project



- Plan to inject 100,000 tons of CO_2 over 1-2 yrs @3MMSCFD
- Ongoing monitoring program till 2009

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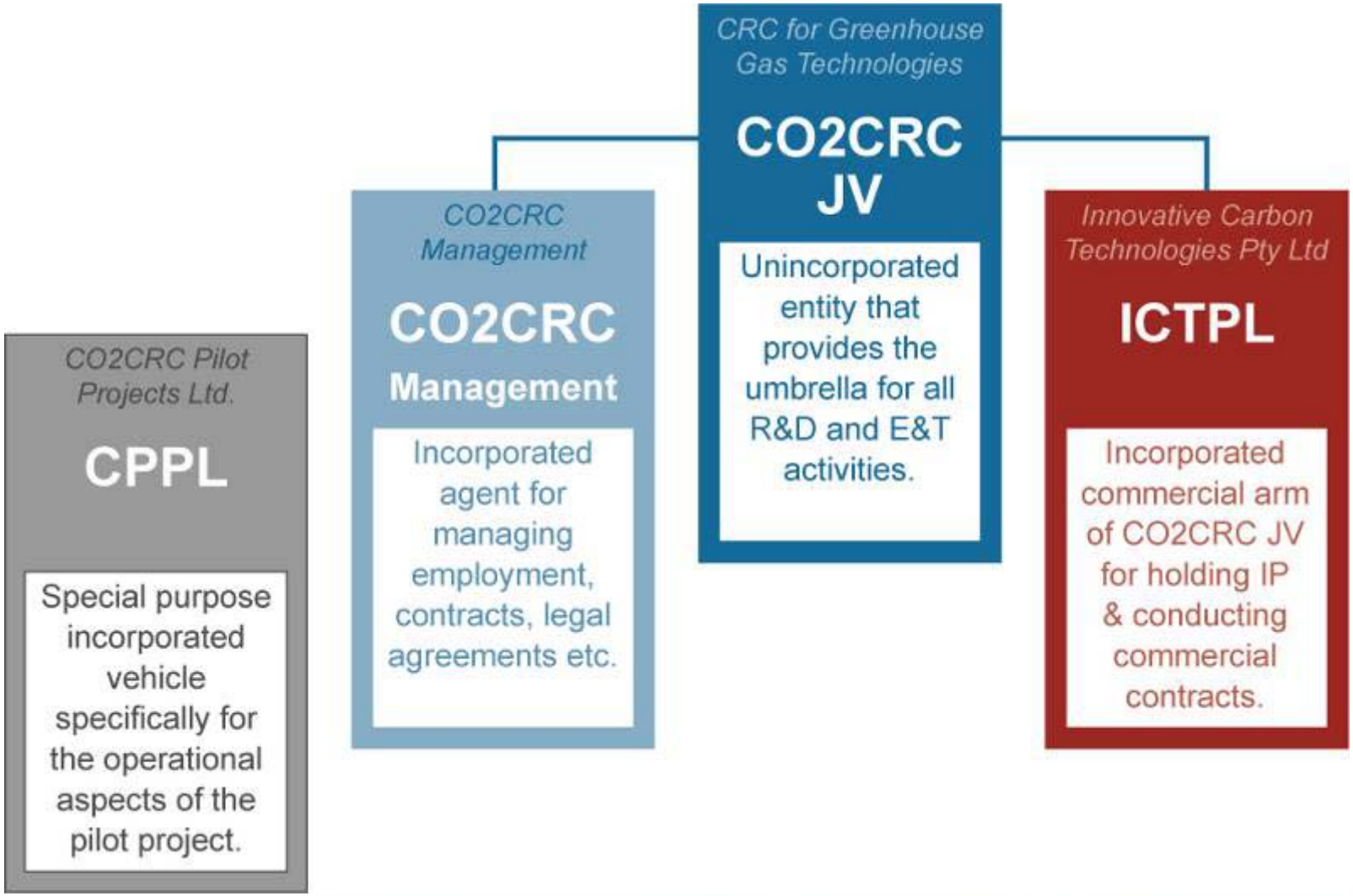
Water sampling was recently conducted by Dirke Kirste and Ernie Perkins in the pilot project region. Samples have been sent to the United States for analysis, May 2006.

Preparing equipment for seismic surveys in the OBPP region, May 2006.

Buttress #1 Well, flare pit for the gas testing process, June 2006.

The structure of CO2CRC & related entities



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Companies in CO2CRC Pilot Project Ltd (CPPL)

Current Members

bhpbilliton

Schlumberger

ANGLO AMERICAN

Chevron

RIO TINTO

SOLID ENERGY
Coals of New Zealand

WOODSIDE
AUSTRALIAN ENERGY

xstrata
coal

Anticipated Members

bp

Financial Supporters

CO2CRC

Australian Government
Australian Greenhouse Office

Victoria
The Place To Be

AusIndustry

ACARP
Australian Coal Association Research Program

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Research Organisations Involved in Otway Basin Pilot Project

Australian Government
Geoscience Australia

curtin
University of Technology
Western Australia

THE UNIVERSITY OF ADELAIDE
AUSTRALIA

Alberta Research Council

CSIRO

Institute of GEOLOGICAL & NUCLEAR SCIENCES Limited

Lawrence Berkeley National Laboratory

process group

CANSYD
AUSTRALIA

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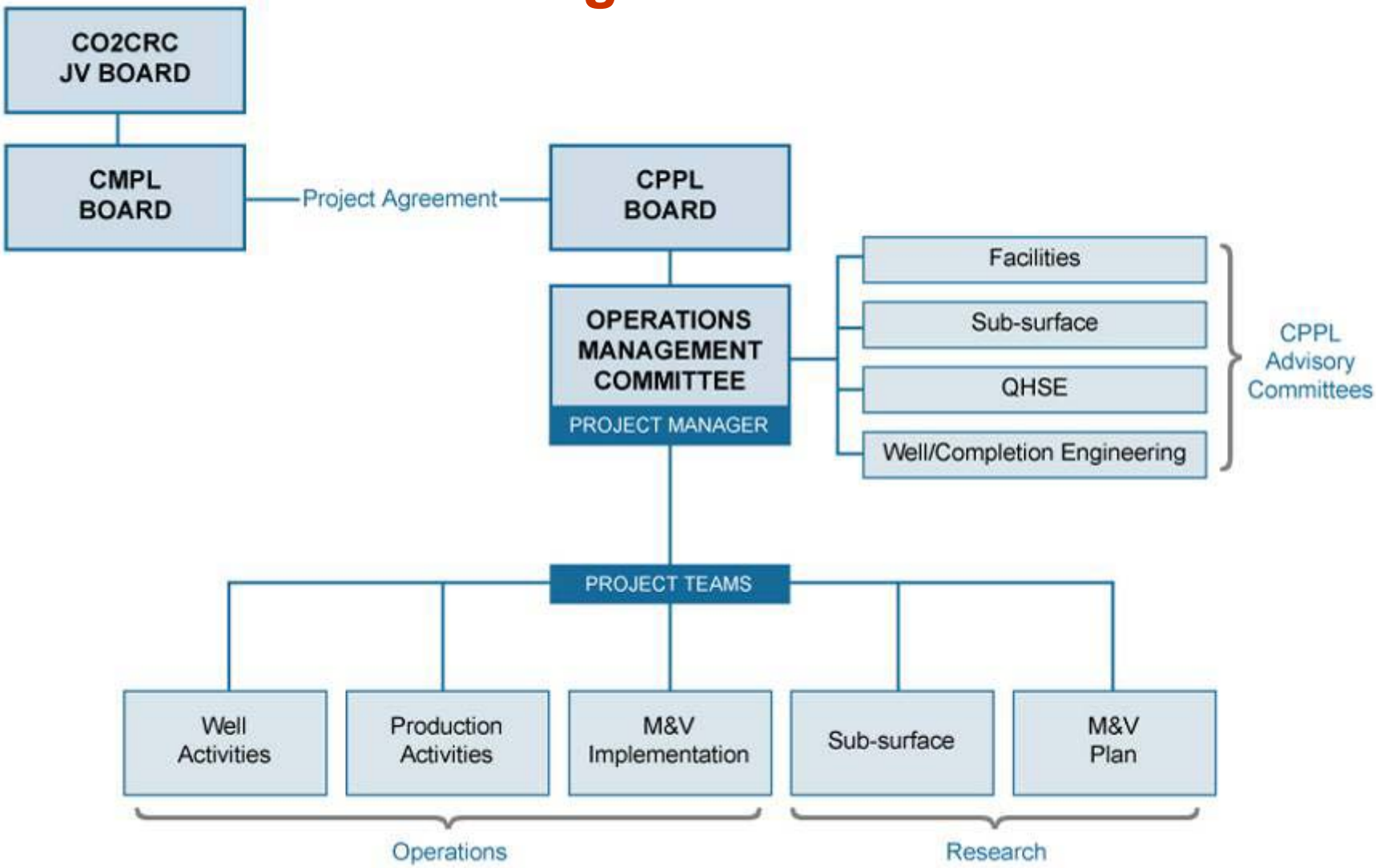
CPPL Organisational Chart



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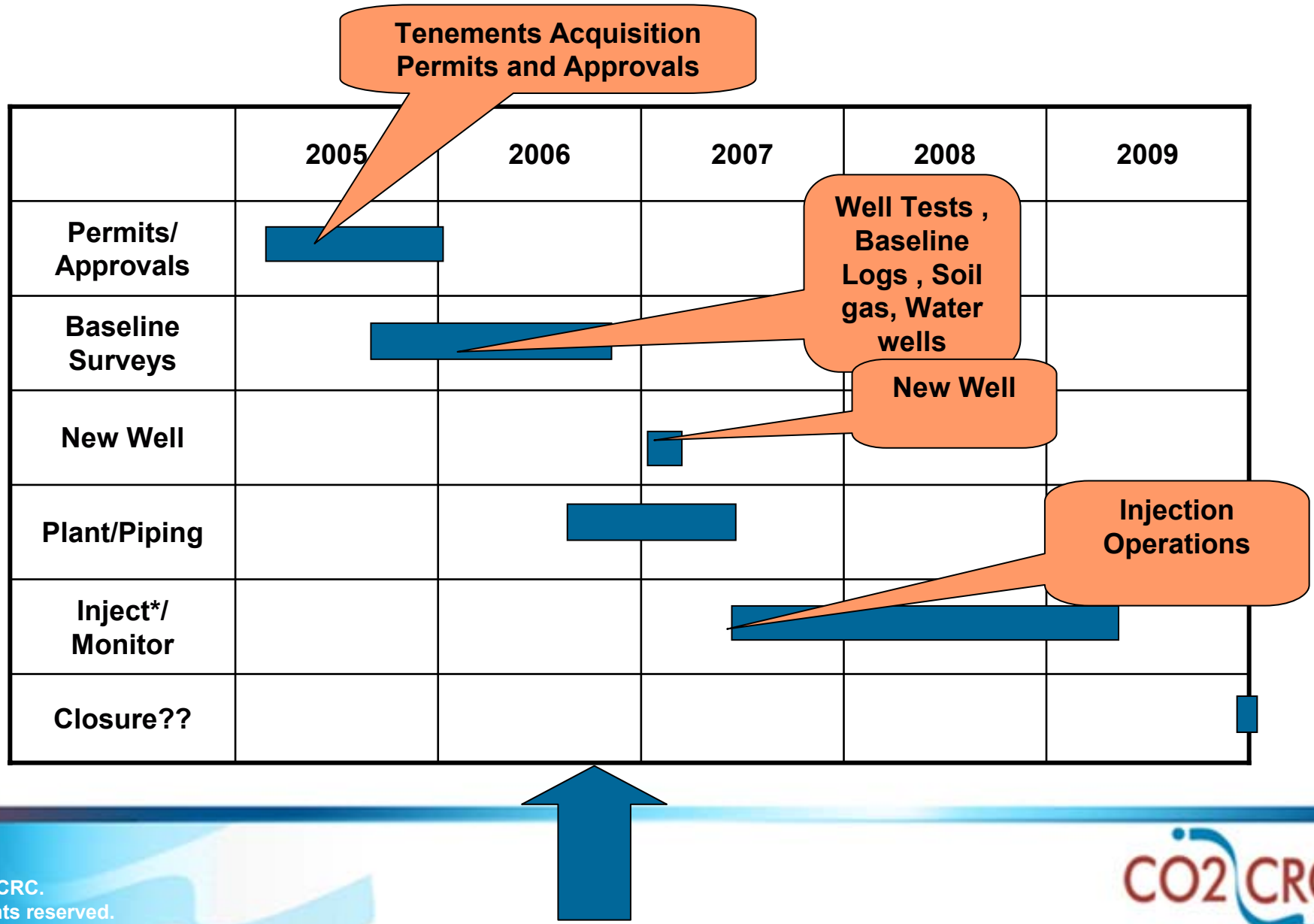
Project Timelines



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CO2CRC Core Participants:

Australian Government

Geoscience Australia

RIO TINTO

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3RD MONITORING NETWORK MEETING

Our thanks to the following sponsors

The Australian Greenhouse Office

The Victorian Government

Rio Tinto

Woodside Petroleum

University of Alberta

Rick Chalaturnyk
Petroleum Geomechanics Research Group
Department of Civil and Environmental Engineering
University of Alberta

Well-Based Monitoring

IEA MONITORING and VERIFICATION NETWORK Meeting
2006
Melbourne, Australia

Organised by
IEA Greenhouse Gas R&D Programme,
Cooperative Research Centre for Greenhouse Gases (CO2CRC)
The Australian Greenhouse Office and
Department of Industry, Trade and Resources

Outline

- Workshop Objectives and Wells
- Well-based Options
- Case History of Challenges in Deploying Well based Monitoring
- Summary

Purpose of Monitoring…..

- To "truth" or validate the predictive capability of the simulators
- To validate the physics of the storage process
- To mitigate uncertainty associated with reservoir parameters
- To identify and validate different categories of storage mechanisms in geological horizons
- To correlate operational issues with aquifer and caprock response, trigger contingency plans and mitigation activities
- To satisfy regulatory requirements.

Wellhead Measurements

- Measurement variables can include:
  - Injection pressure and temperature
  - stream composition
  - injection rates
  - pressures developed in surface casing vents (SCVP)
- These measurements used:
  - for managing safe well operating conditions,
  - determining the boundary conditions for input into flow models,
  - as indicators of changes in downhole conditions, and
  - as indicators of annular leaks in the wellbore.

Downhole Pressure Measurement

- Memory Gauges
- Real-Time Gauges
  - Electronic (e.g. quartz, high resolution)
  - No downhole electronics (lower resolution)
- Fibre Optic Systems
- Bubble Tubes (Capillary Tubes)

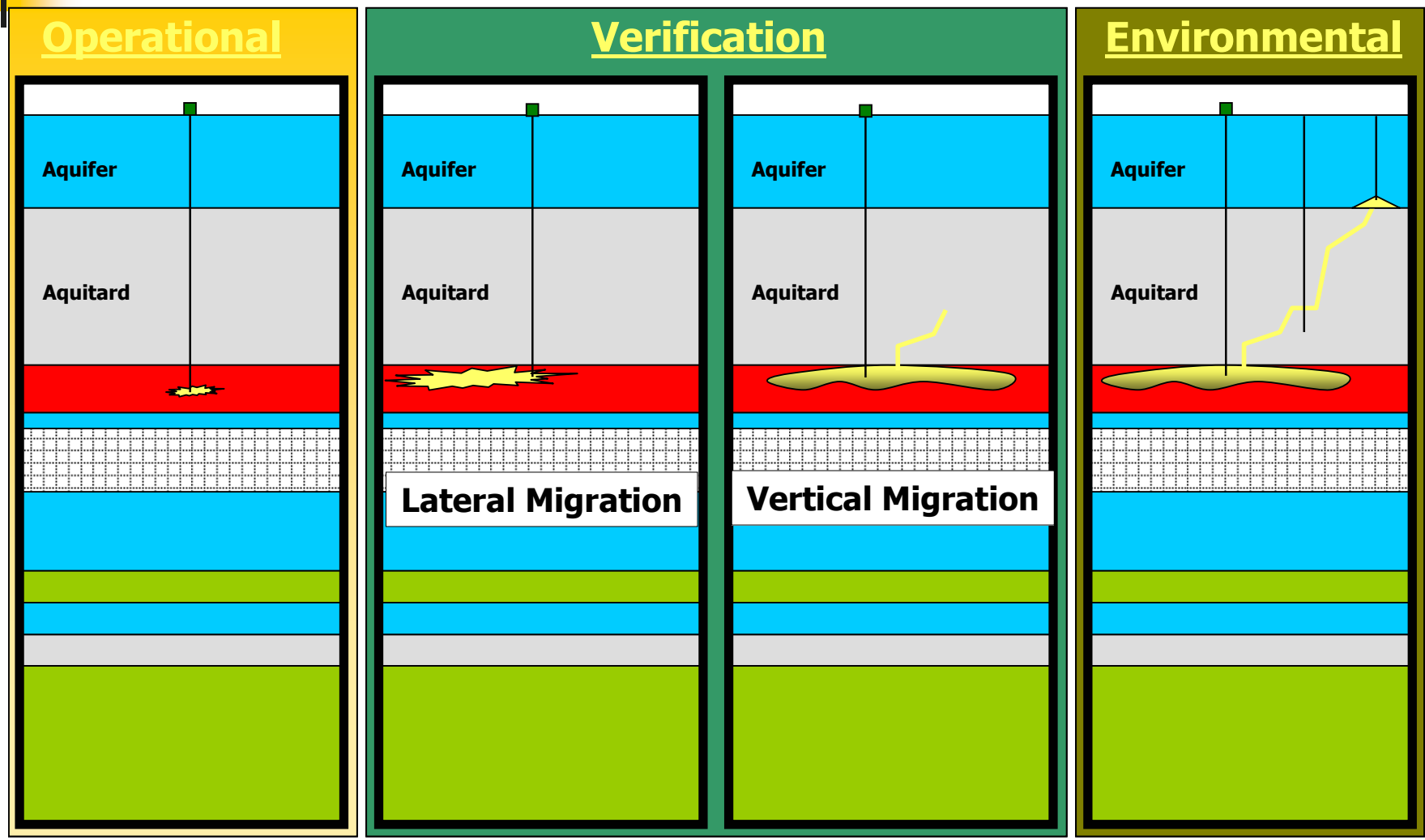
Access for Geophysical Logs

- Openhole
- Cased Hole
  - Cement evaluation
  - Saturation
  - Resistivity
  - Dual Sonic
  - VSP
  - Geochemical Sampling
  - Passive Seismic

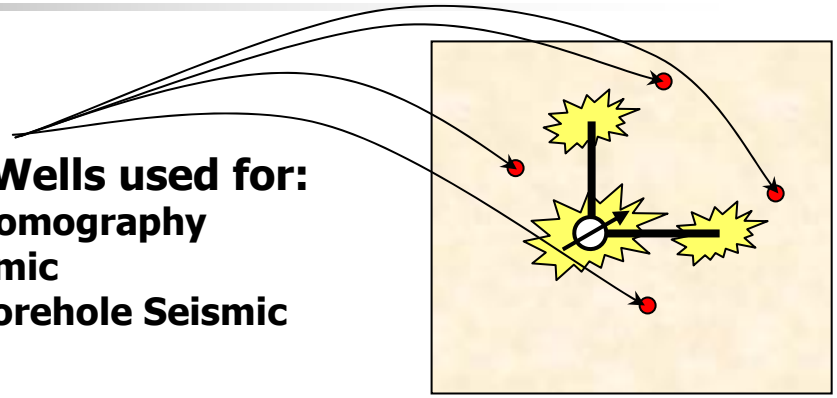
Integrated Monitoring Programs * Philosophy

- Operational Monitoring
  - Governed by existing regulations based on well classification
- Verification Monitoring
  - Primarily aimed at assessing spatial and temporal distribution of CO2 (..it goes where its supposed to go and stays where its supposed to stay!)
  - Staged implementation based on risk level
- Environmental Monitoring
  - Primarily aimed at monitoring when verification monitoring establishes deviation from expected behavior

Examples of Monitoring Levels



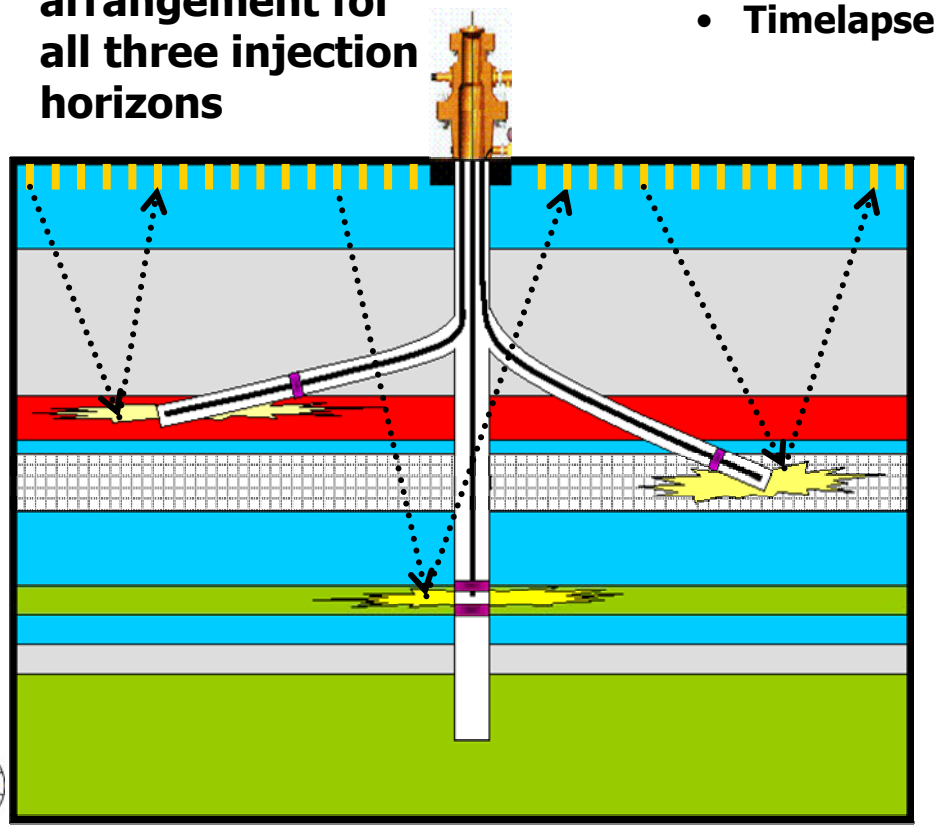
Multiple Storage Horizons: Multiple Monitoring Scenarios



Observation Wells used for:

- **Cross Well Tomography**
- **Passive Seismic**
- **Timelapse Borehole Seismic**

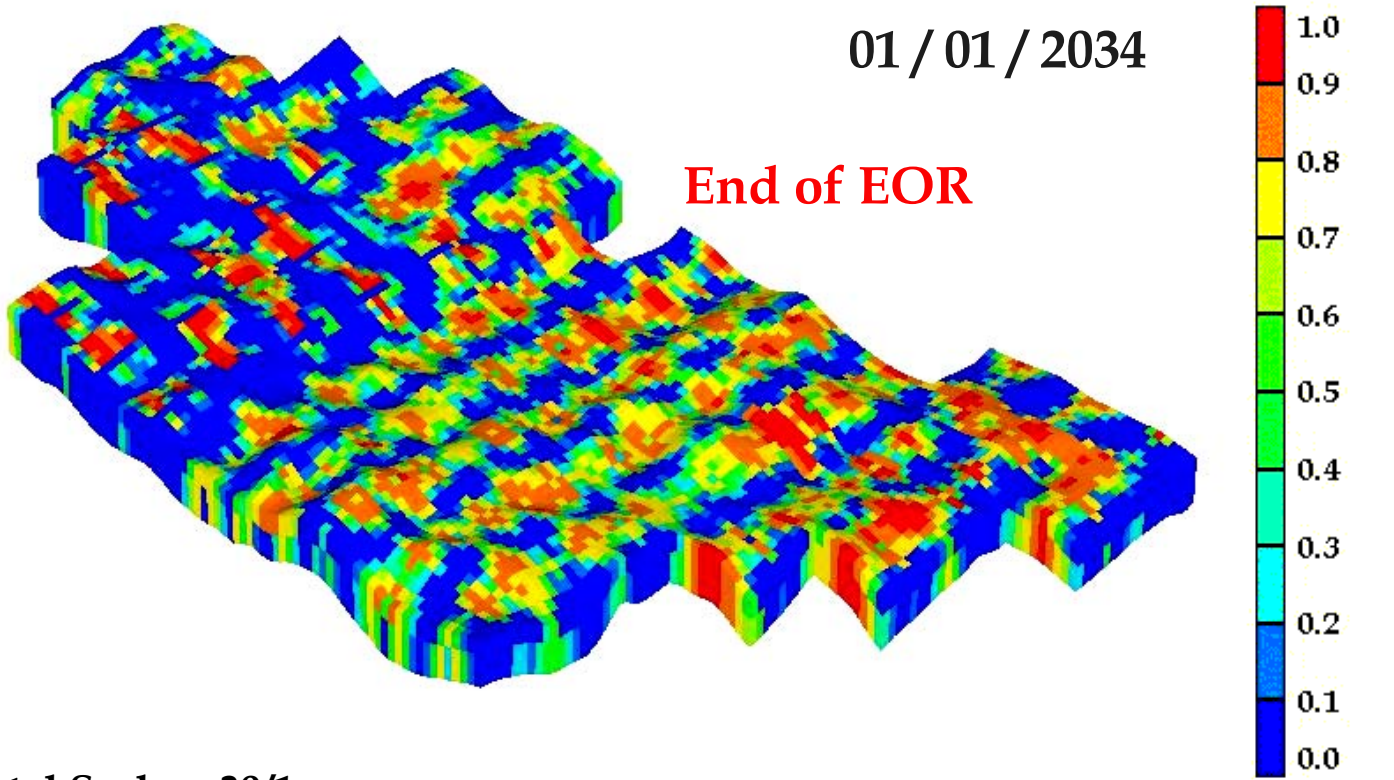
3D geophone arrangement for all three injection horizons



- Effective use of observation wells
- Allows evolution in installation of observation wells
- Detailed characterization only required for one regional area

Numbers of Observation or Monitoring Wells?

75 Pattern Reservoir Simulation from IEA Weyburn Monitoring and Storage Project – Law, ARC

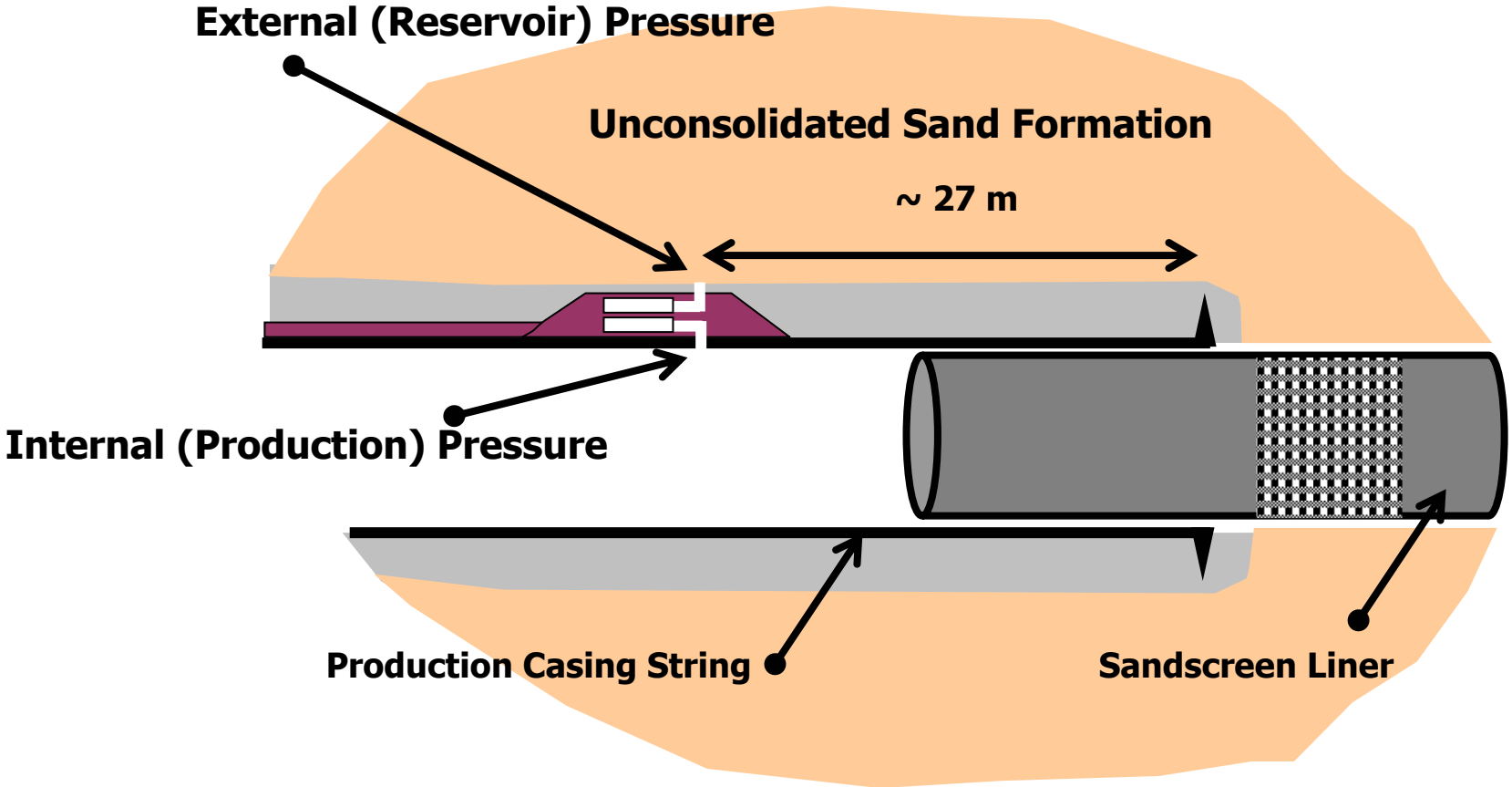


Vertical/Horizontal Scale = 30/1

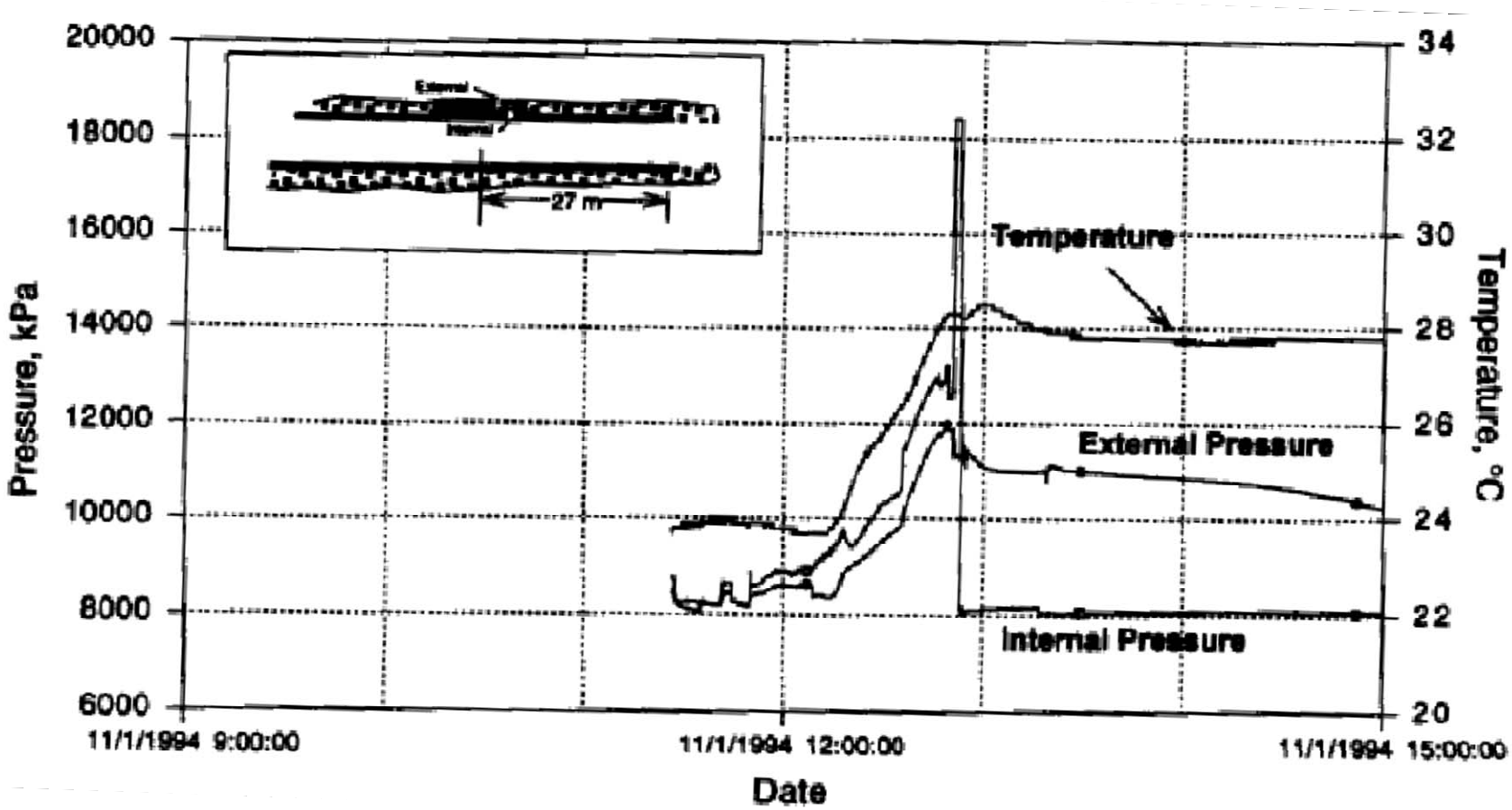
Examples of Deployment in Wells

- Casing Conveyed pressure and temperature gauges for reservoir and bottomhole measurements
- Integrated permanent installation of geophones, pressure/temp gauges and downhole fluid sampling ports

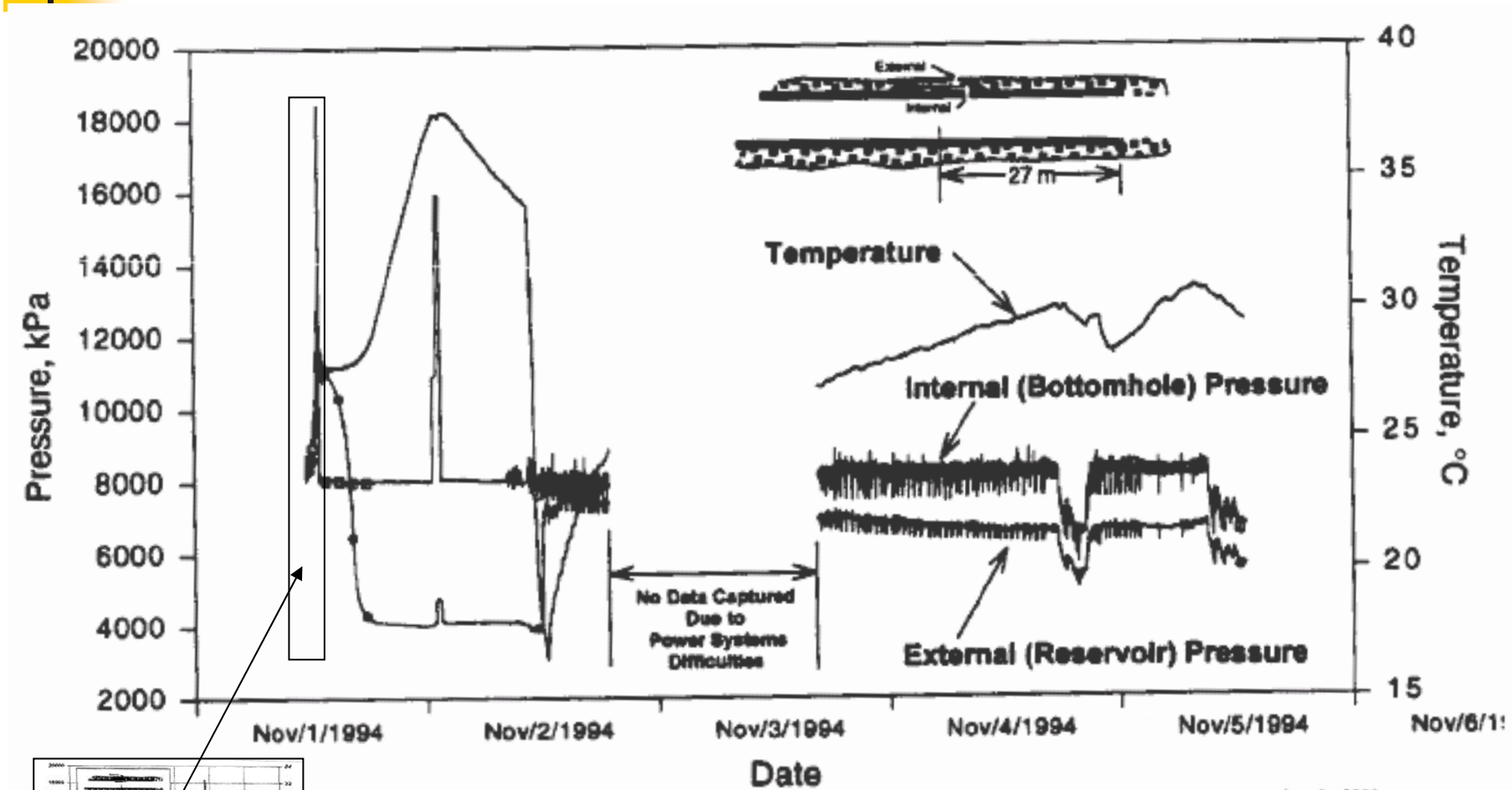
Casing Conveyed Pressure and Temperature Gauges

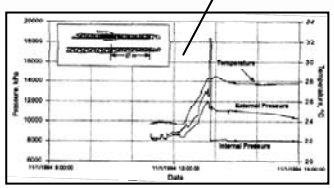


Pressures during Installation and Cementing



Response during Cement Hydration and Drilling of Horz.





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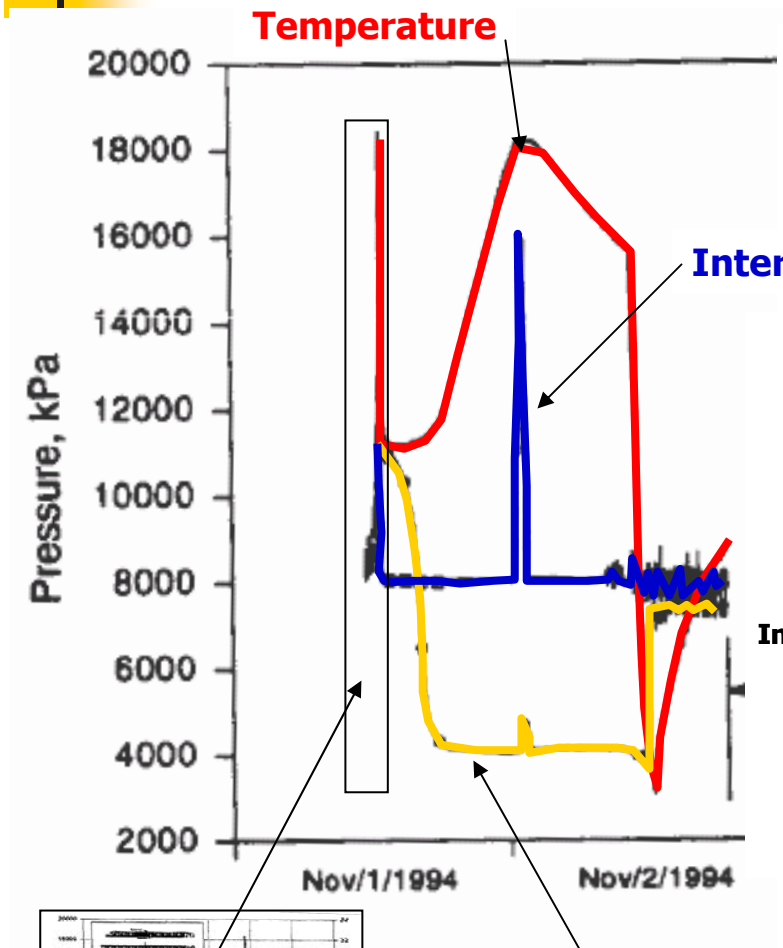
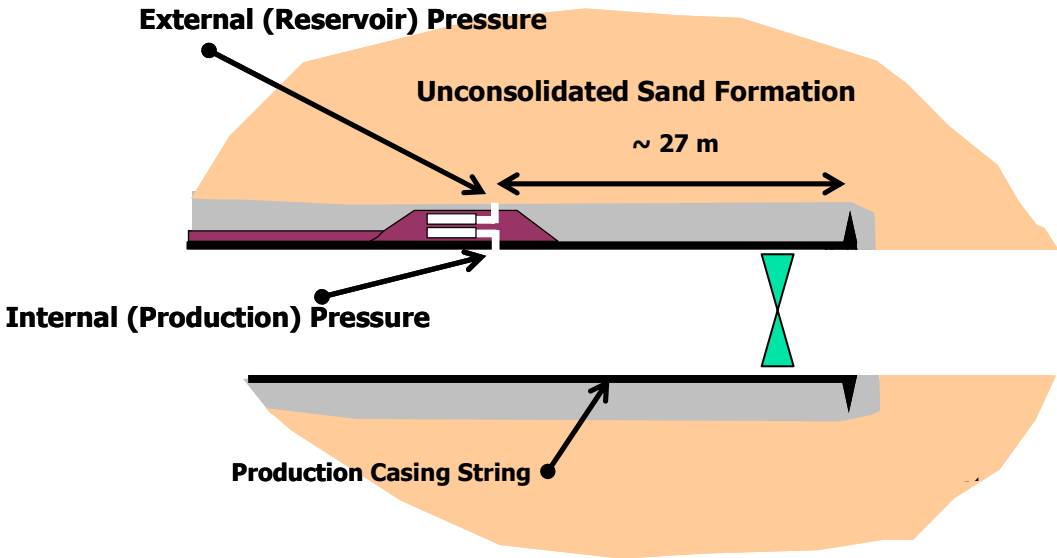
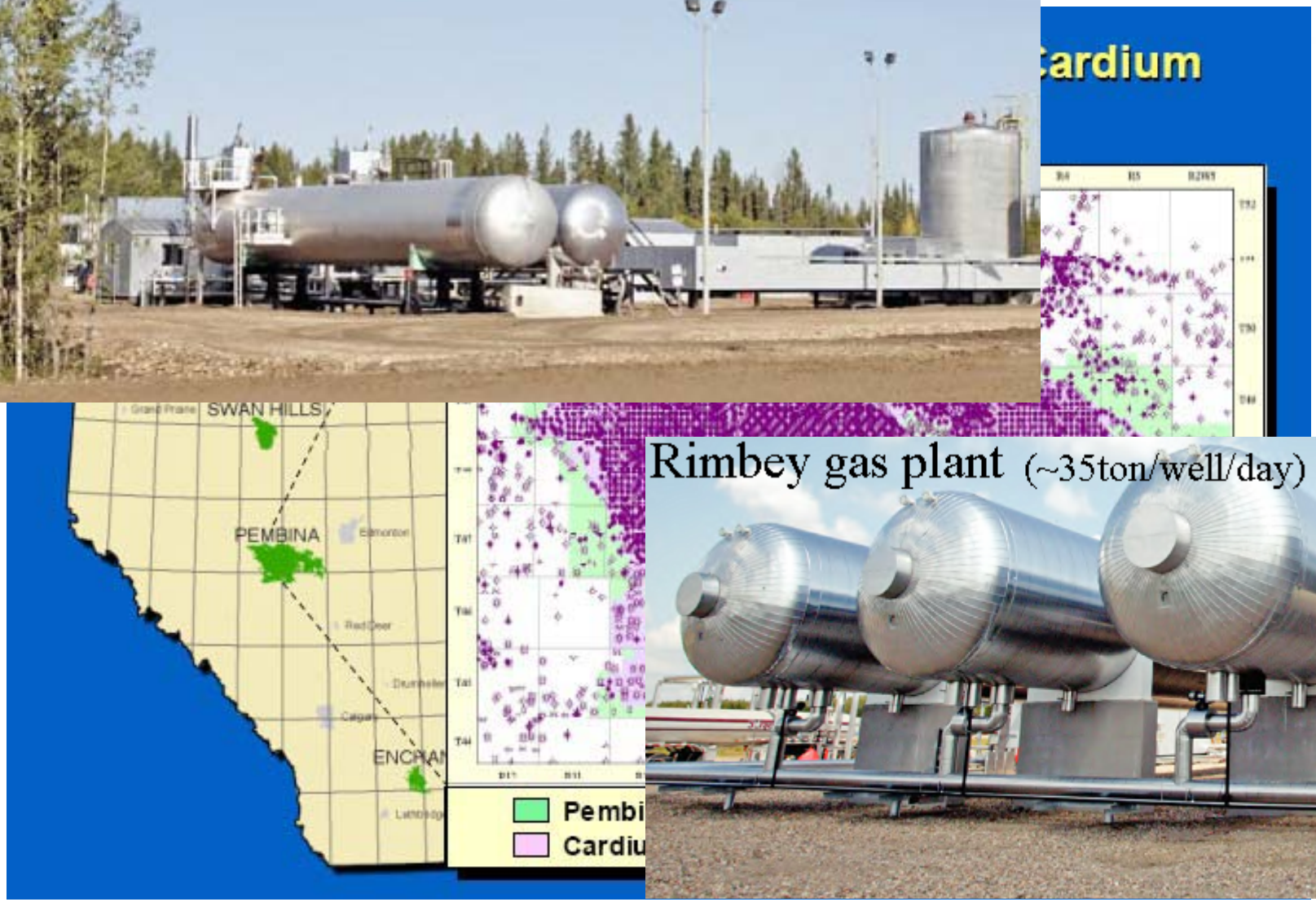
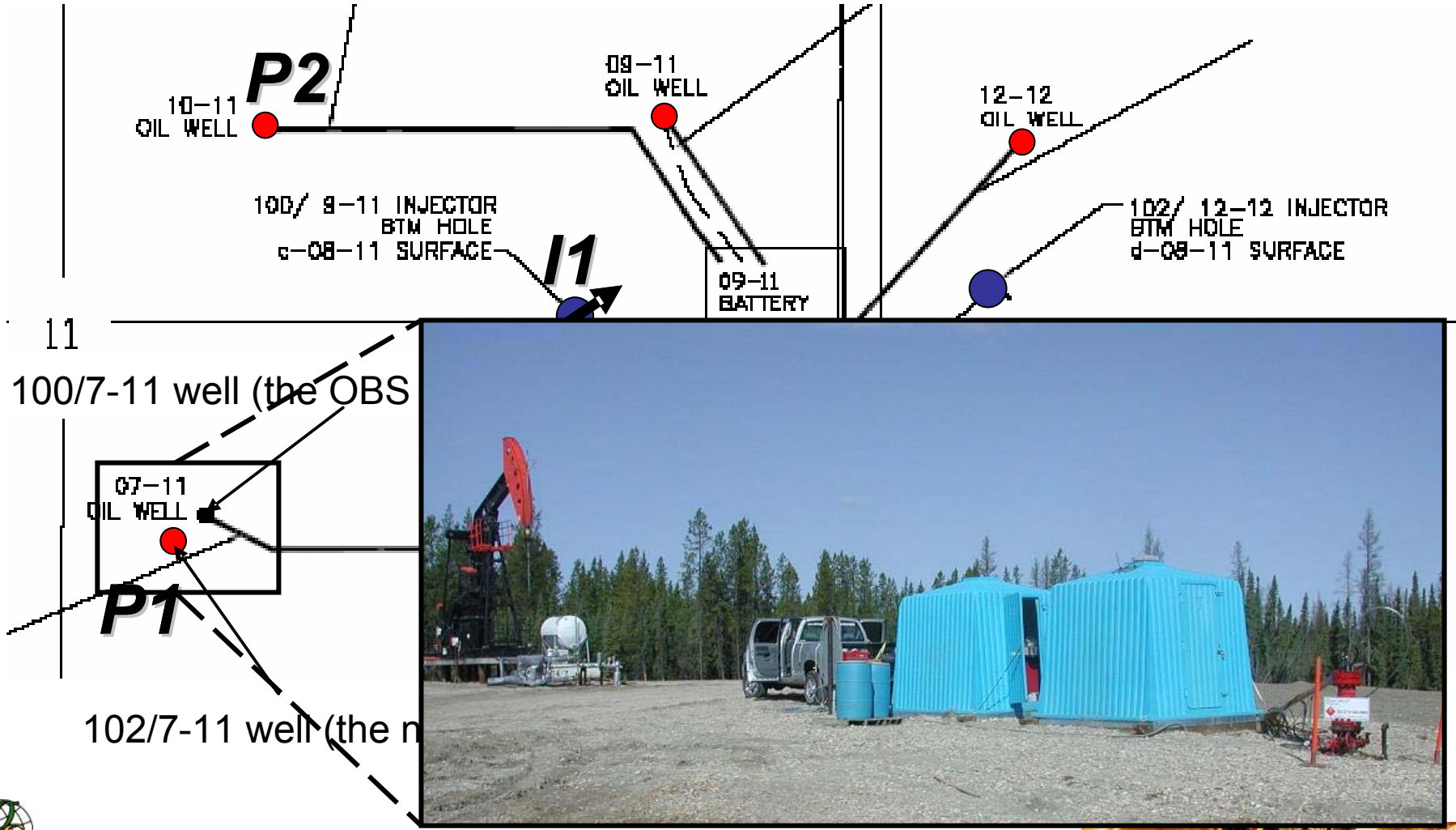




Penn West CO2-EOR Pilot



Pennwest CO2-EOR Pilot
6 Producers, and 2 injectors



Observation Well Specifications

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

Geology and Design C

2 downhole fluid sampling ports

8 phone Geophone string

3 pairs of pressure/ temperature gauges

Ground Surface

0

1023

1.4

Shale

1599

1619

1619.5

1622

1630.5

1637.2

Lower Cardium Sandstone

1360
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
1620

8 Geophone String. Bottom phone at 1640 mD and phone spacing is 20 m.

Fluid Sampling Port #2 at 1622 mD. Port located within Upper/Middle Cardium SST

Two (2) pressure/temp. gauges at 1610 mD. In the middle of the Cardium Zone.

Two (2) pressure/temp. gauges at 1621 mD.

Two (2) pressure gauges at 1602 m

g Port #1

Port located within rk zones where

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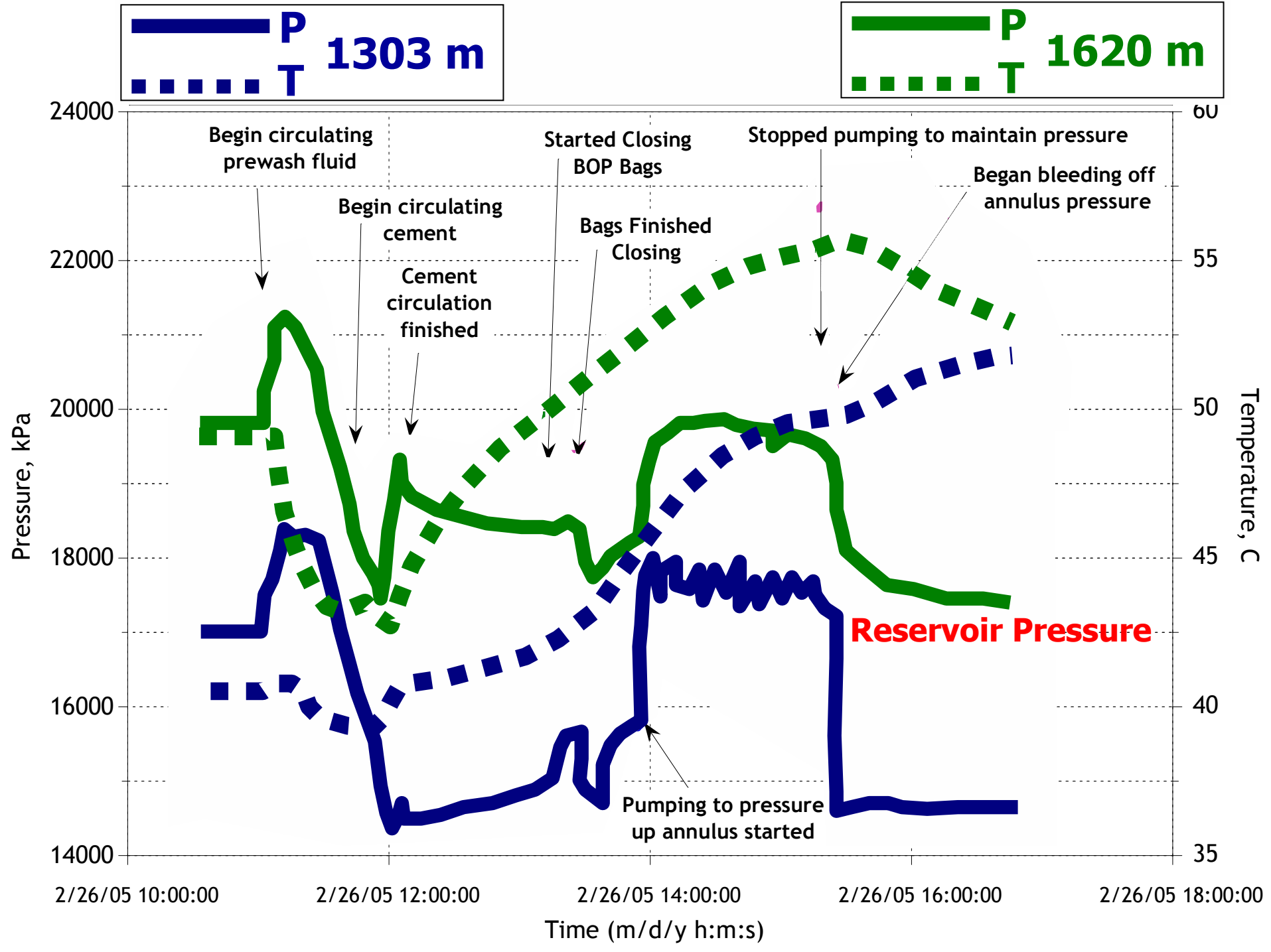
Top a

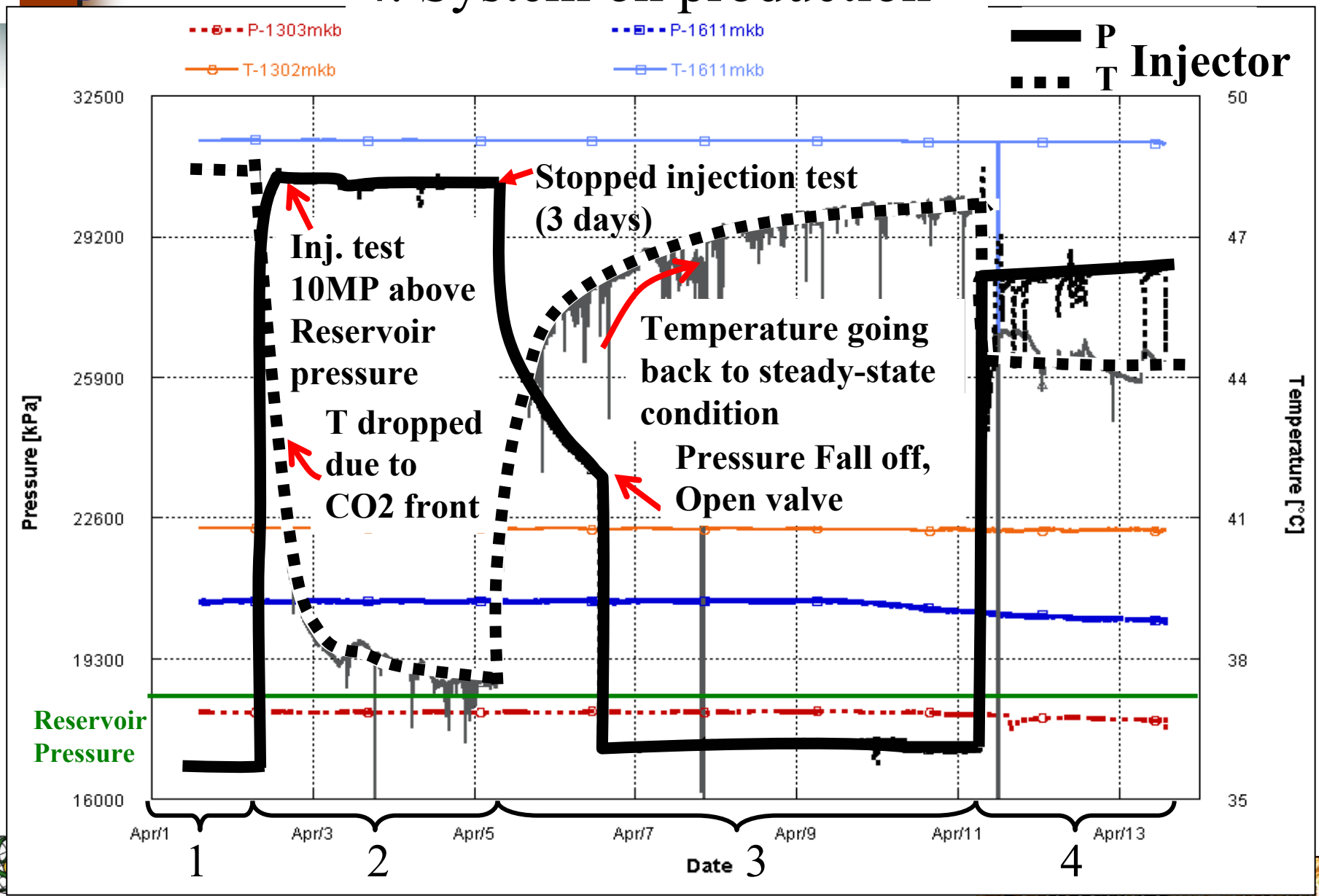

P
T
1303 m
P
T
1620 m
Begin circulating prewash fluid
Begin circulating cement
Cement circulation finished
Started Closing BOP Bags
Bags Finished Closing
Stopped pumping to maintain pressure
Began bleeding off annulus pressure
Reservoir Pressure
Pumping to pressure up annulus started
24000
22000
20000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

HYDRIL
DANGER

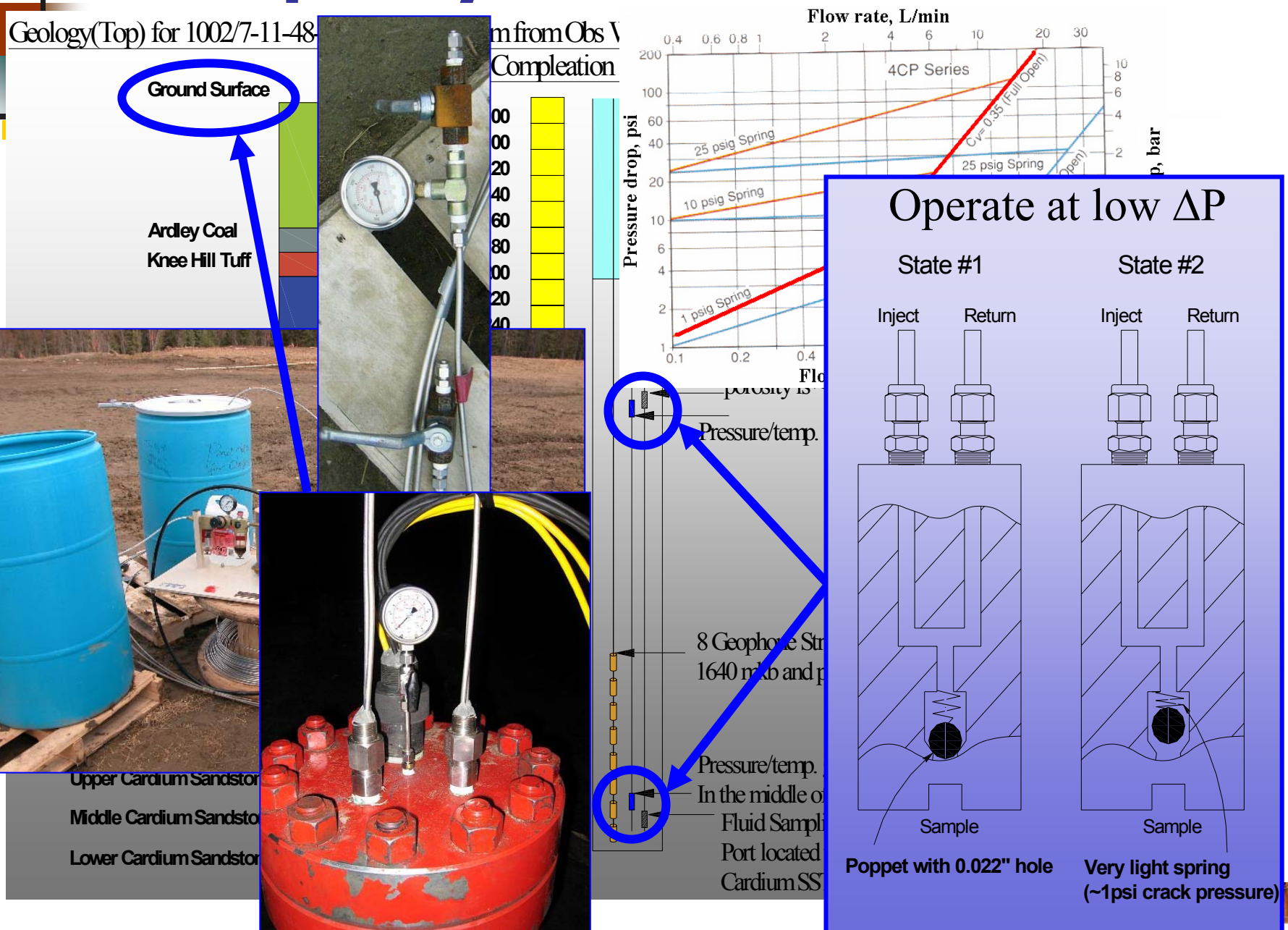
SHELL TX2

Early PT reading in Observation and Injection V

4. System on production

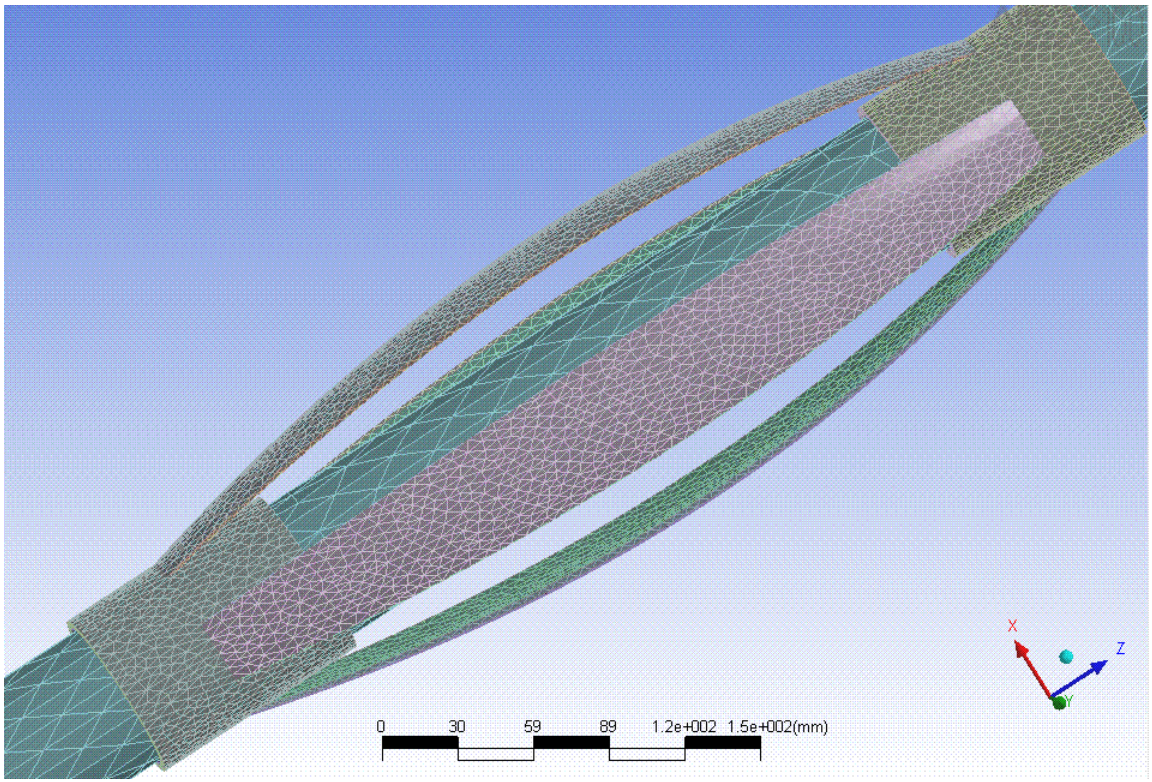


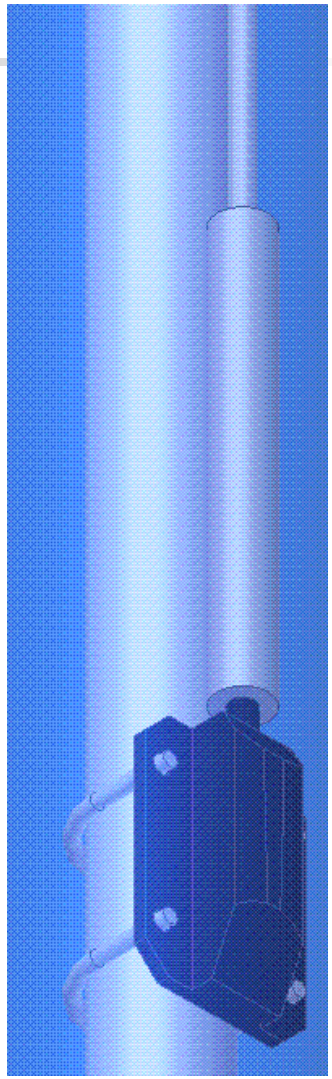
Fluid Sample System

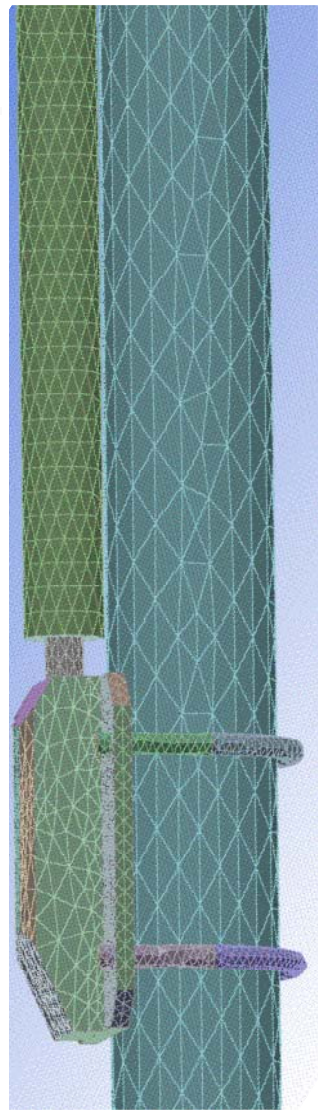


Fluid S ocol

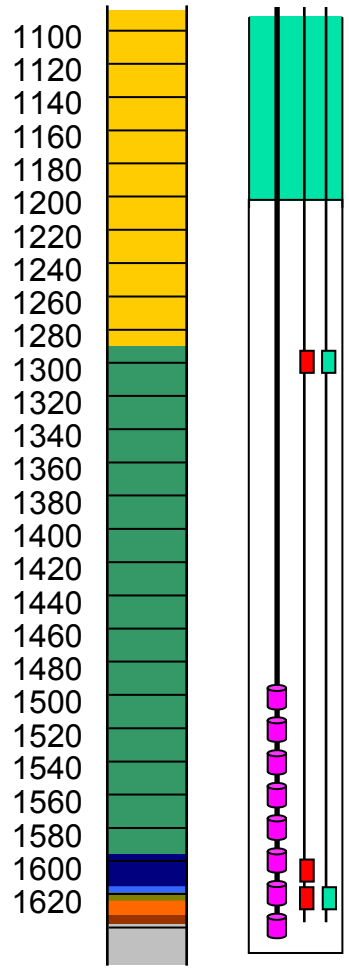
Complex Flow Modeling

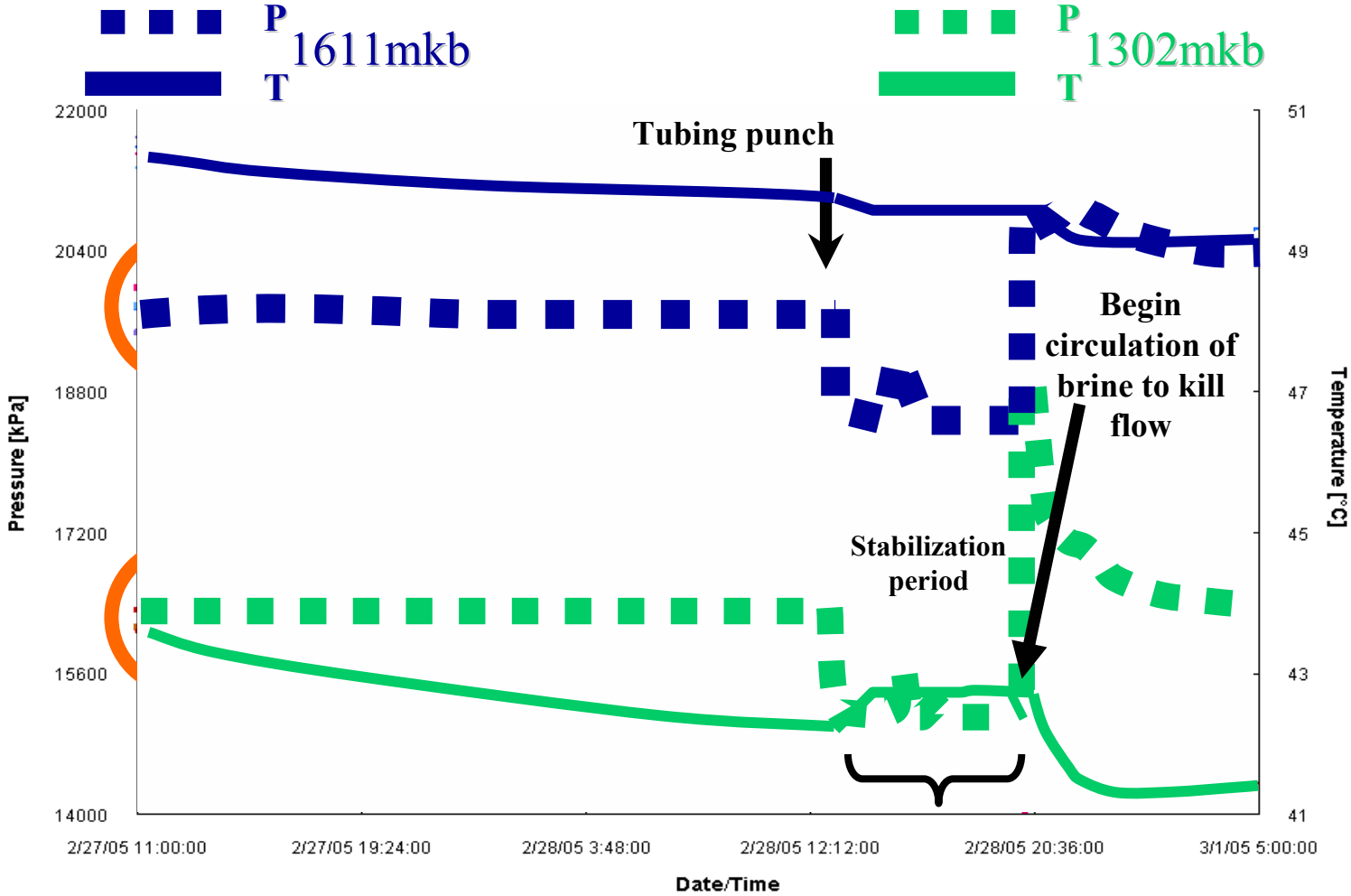






Wellbore Completion
Feb 27 to Mar 1





University of Alberta

Rick Chalaturnyk
Petroleum Geomechanics Research Group
Department of Civil and Environmental Engineering
University of Alberta

Well-Based Monitoring

IEA MONITORING and VERIFICATION NETWORK Meeting
2006
Melbourne, Australia

Organised by
IEA Greenhouse Gas R&D Programme,
Cooperative Research Centre for Greenhouse Gases (CO2CRC)
The Australian Greenhouse Office and
Department of Industry, Trade and Resources

Site Selection

- size of the injection zone, to confirm that it is large enough to volumetrically hold all of the injected acid gas over the project lifetime;
- stratigraphic and structural traps that may affect the ability to contain the acid gas;
- thickness and extent of the overlying confining layer (top seal);
- location and extent of the underlying or lateral bounding formations;
- folding and faulting as well as fractures in the area, and an assessment of seismic (tectonic) risk;
- rate and direction of the natural flow system, to assess the potential for migration of the injected acid gas;
- permeability and heterogeneity of the injection zone;
- chemical composition of the formation fluids (water for aquifers, oil or gas for reservoirs);
- formation temperature and pressure;
- analyses of formation and caprock core (if available); and, finally,
- a complete and accurate drilling history of offsetting wells within several kilometers of the injection well, to identify any wells or zones that may be impacted by the injected acid gas.

Environmental Concerns

- In addition to the above technical requirements, the regulatory agencies require that environmental concerns must be addressed, such as injection-formation suitability, wellbore integrity, operating parameters (to ensure formation and well integrity) and optimization of the injection space, which is considered to be a limited resource

Completion and Logging Requirements

- identification of all geological zones using logs and/or cores;
- isolation by cement of all potential hydrocarbon-bearing zones and shallow potable groundwater aquifers;
- confirmation of hydraulic isolation and cement integrity by a full-length casing log;
- injection through tubing, and filling of the annulus with a corrosion-inhibiting fluid; and
- installation of safety devices both above the ground and in the wellbore to ensure that failure of any component in the system does not result in environmental damage. If the injection pressure drops for any reason, the well is automatically shut-in, to prevent acid gas backflow.

Integrity of Host Formation and/or Reservoir

- Potential migration pathways from the injection zone to other formations, shallow groundwater and/or the surface.
- To avoid diffuse gas migration through the caprock pore space, the difference between the pressure at the top of the injection aquifer or reservoir and the pressure in the confining layer must be less than the caprock threshold displacement pressure.
- To avoid migration through fractures, the injection zone must be free of natural fractures, and the injection pressure must be below a certain threshold to ensure that fracturing is not induced. The maximum bottomhole injection pressure is set by regulatory agencies at 90% of the fracturing pressure in the injection zone.
- If injection takes place into a depleted oil or gas reservoir, the avg. reservoir pressure should not exceed the initial pressure.

Annual Reporting

- all workovers done on the injection well, including reasons and results;
- any changes in injection equipment and operations;
- changes in performance, including cause, remedial actions and results;
- overall performance;
- results and evaluation of monitoring, including:
  - pressure surveys
  - corrosion protection
  - fluid analyses
  - logs
- representative composition and formation (Z) factor for the injected fluid;
- monthly volumes of injected fluid at STP and hours of injection;
- amount (tones) of injected sulphur and carbon dioxide;
- maximum and average daily injection rates for each month;
- average and maximum wellhead injection pressure and average temperature;
- plots versus time of relevant parameters (e.g., rate, pressure, temperature)

Monitored Decision Approach to Geologic Storage Verification

- Planned approach to decision making over time that draws on long-term field measurements for input, with planned analysis of the measurements and appropriate contingent actions
- Recognizes uncertainties in the geological storage system and making design/operational decisions with the knowledge that planned long-term observations and their interpretation will provide information to decrease the uncertainties, plus providing contingencies for all envisioned outcomes of the monitoring program.

Framework of Approach

- ”the inevitable uncertainty involved in fundamental design assumptions, the conception on which the design is based is often no more than a crude working hypothesis”. (Terzaghi, 1948)
- The monitoring results combined with their analysis or interpretation serve to support the hypotheses of storage processes or aid in improving our predictive capabilities.
- Monitoring, its frequency, longevity, and scope is part of the approach, as are the evaluations of the monitored results and actions to be taken based on the evaluations.
- It includes routine or operational monitoring and analysis and actions for special circumstances such as unanticipated reservoir response to injection of CO2.
- The interaction of environmental regulations, legal concerns, limited financial resources, operational performance and both current and future regulatory requirements are best managed using the monitored decision approach.

Systematic Approach to Planning Monitoring Programs

- Definition of project conditions
- Technical questions to be answered
- Prediction of mechanisms that control behavior
- Parameters to be measured and role in answering technical questions
- Magnitude of change expected in parameters
- Select instrumentation and monitoring approaches/systems
- Instrument / monitoring locations

CO_2 Storage in Geologic Environments

New results From Frio Pilot site

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

Funded by
DOE NETL

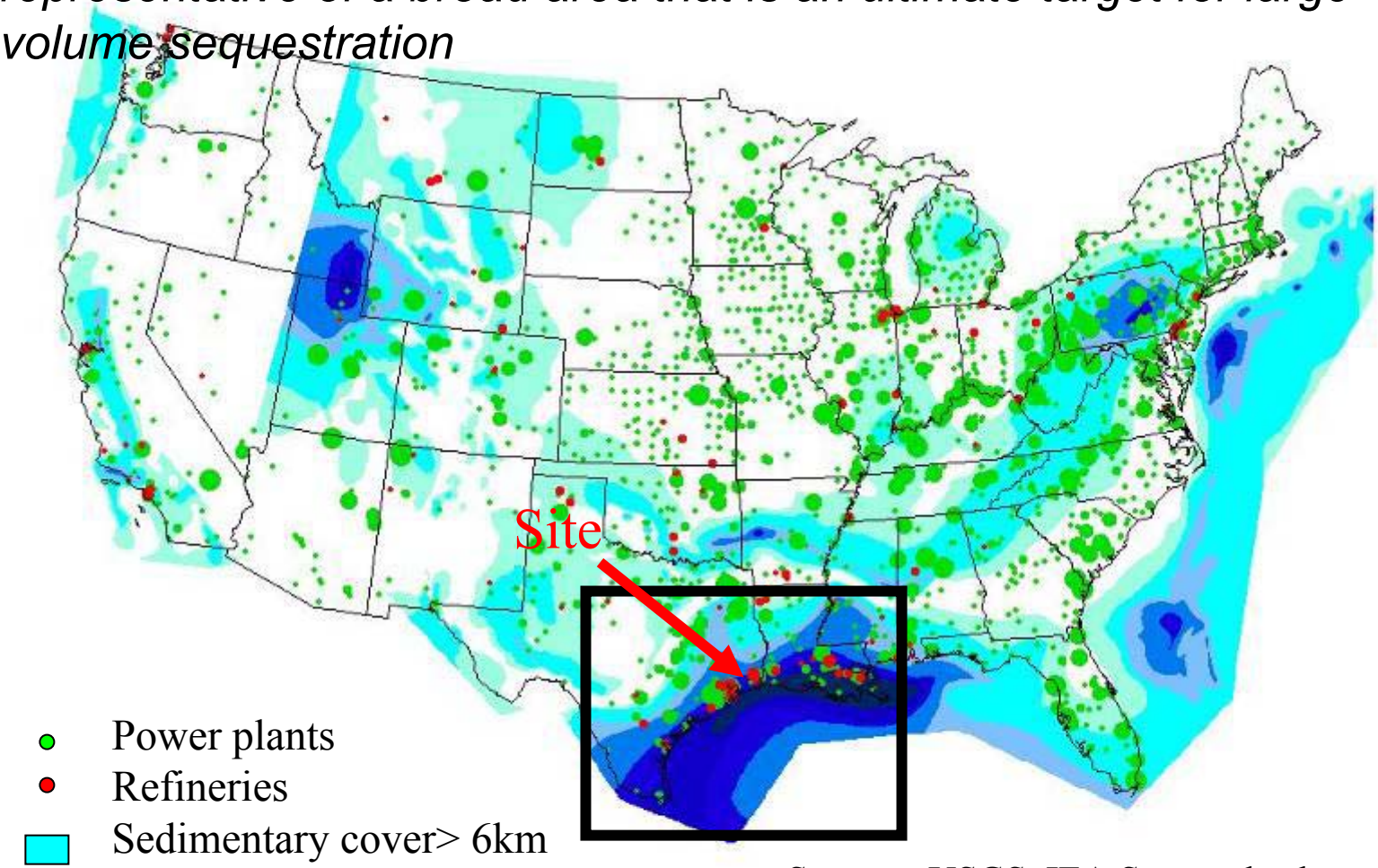
IEA GHG MERV
workshop
October 31, 2006

Frio II Brine Pilot Research Team

- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, Jeff Kane, Andrew Tachovsky, Abhijit Mukarjee, Tip Meckel;
- Lawrence Berkeley National Lab, (Geo-Seq): Larry Myer, Tom Daley, Barry Freifeld, Rob Trautz, Christine Doughty, Sally Benson Paul Cook, Duo Wang, Ray Solbau
- Schlumberger: John Tombari, T. S. Ramakrishna,
- Oak Ridge National Lab: Dave Cole, Tommy Phelps, Phil Szymcek Sandia Technologies: David Freeman, Kirk De long, Dan Collins, USGS: Yousif Kharaka, Evangelos Kakauros, Jim Thordsen, Gill Amsen
- Praxair: Glen Thompson
- Australian CO2CRC (CSIRO): Jim Unders[illegible],
- Core Labs: Paul Martin and others
- MIT Jonathan Ajo-Franklin

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

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.

Frio 1 October 2004 – January 2006

- **(1) high-quality characterization prior to injection,**
- **(2) numerical modeling integrated with all phases of the project,**
- **(3) cross-comparison of multiple types of measurements,**
- **(4) use of wireline logs for monitoring plume movement,**
- **(5) data collection focused on selected azimuths,**
- **(6) above-zone monitoring for leakage**

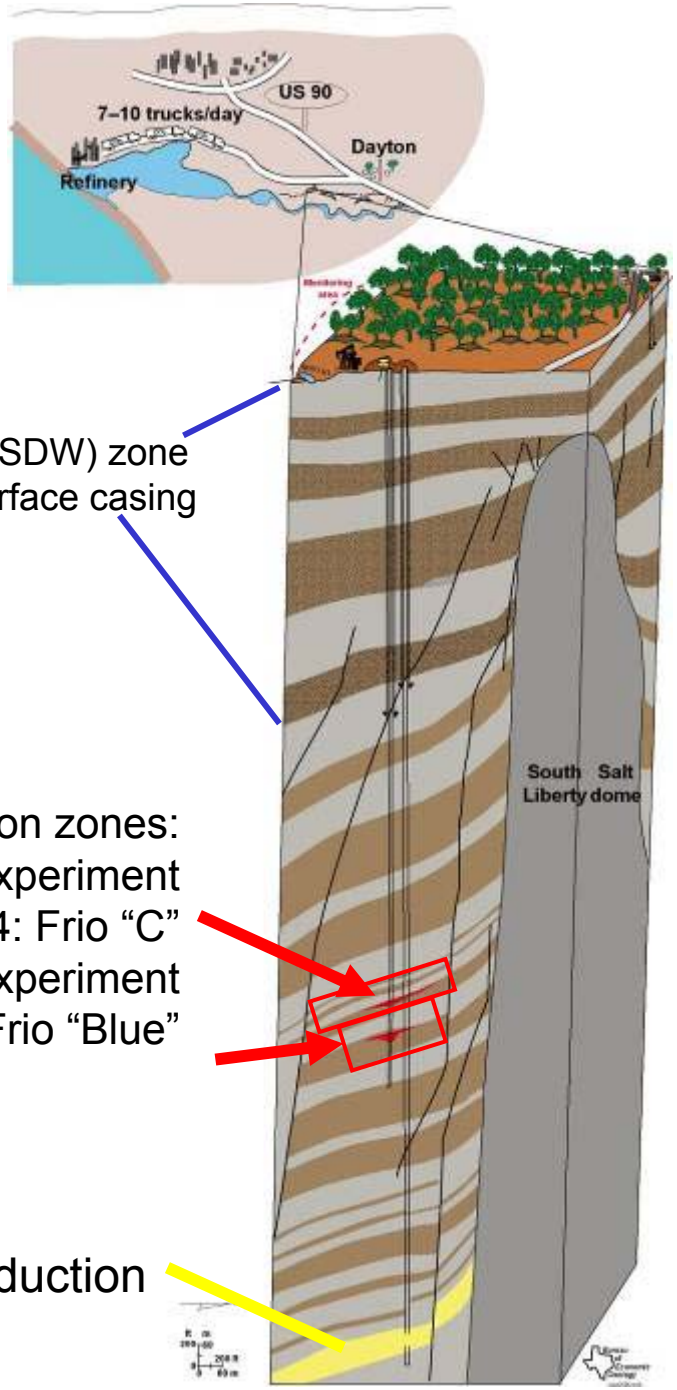
Frio 2 September 2006 – December 2007

- **Storage permanence – quantifying residual saturation and dissolution**
- **Post- injection monitoring under stable conditions**
- **Novel tool – tubing-conveyed seismic array**

Production Test – end of Frio 1

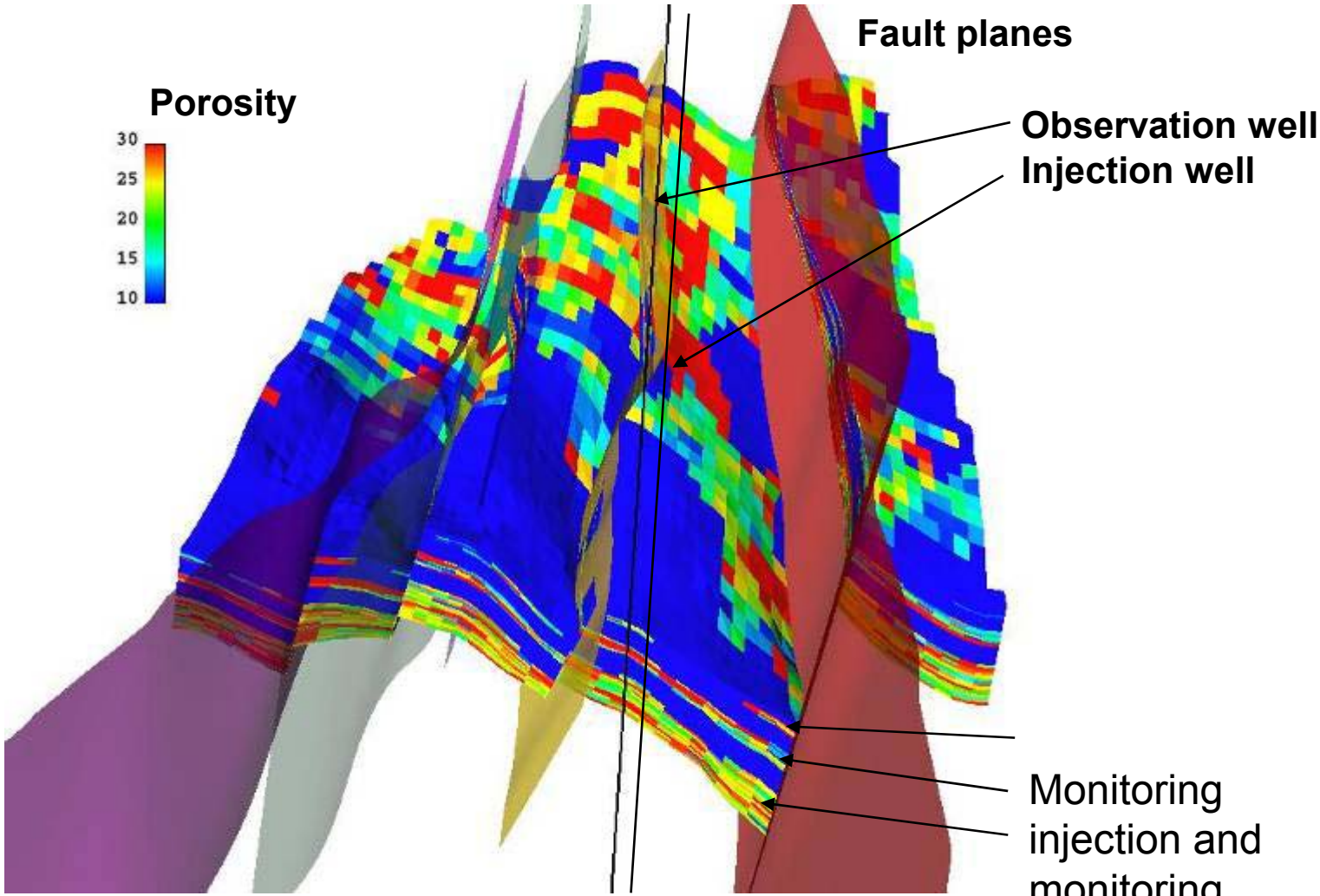
- Produced CO_2 from the “C” sand in the injection well at month 16 after the end of injection.
- Wellbore filled with gas-phase CO_2, with atmospheric pressure at wellhead. Brine at 100 m = approximate original pressure in zone, no flow of gas or brine.
- Swabbing the well to produce brine decreased pressure about 14 bars well produced brine and CO_2 under weak gas lift
- The ratio of water to gas was 13,600 to 1
- CO_2 was produced at an average of 0.17 tons/hour, but the rate did not decline during the one day production period.
- Post injection leakage risk small

Frio Brine Pilot Site two test intervals



- Injection intervals: mineralogically complex Oligocene fluvial and reworked fluvial sandstones, porosity 24%, permeability 4.4 to 2.5 Darcys
- Steeply dipping 11 to 16 degrees
- Seals – numerous thick shales, small fault block
- Depth 1,500 and 1657 m
- Brine-rock system, no hydrocarbons
- 150 and 165 bar, 53 -60 degrees C, supercritical CO_2

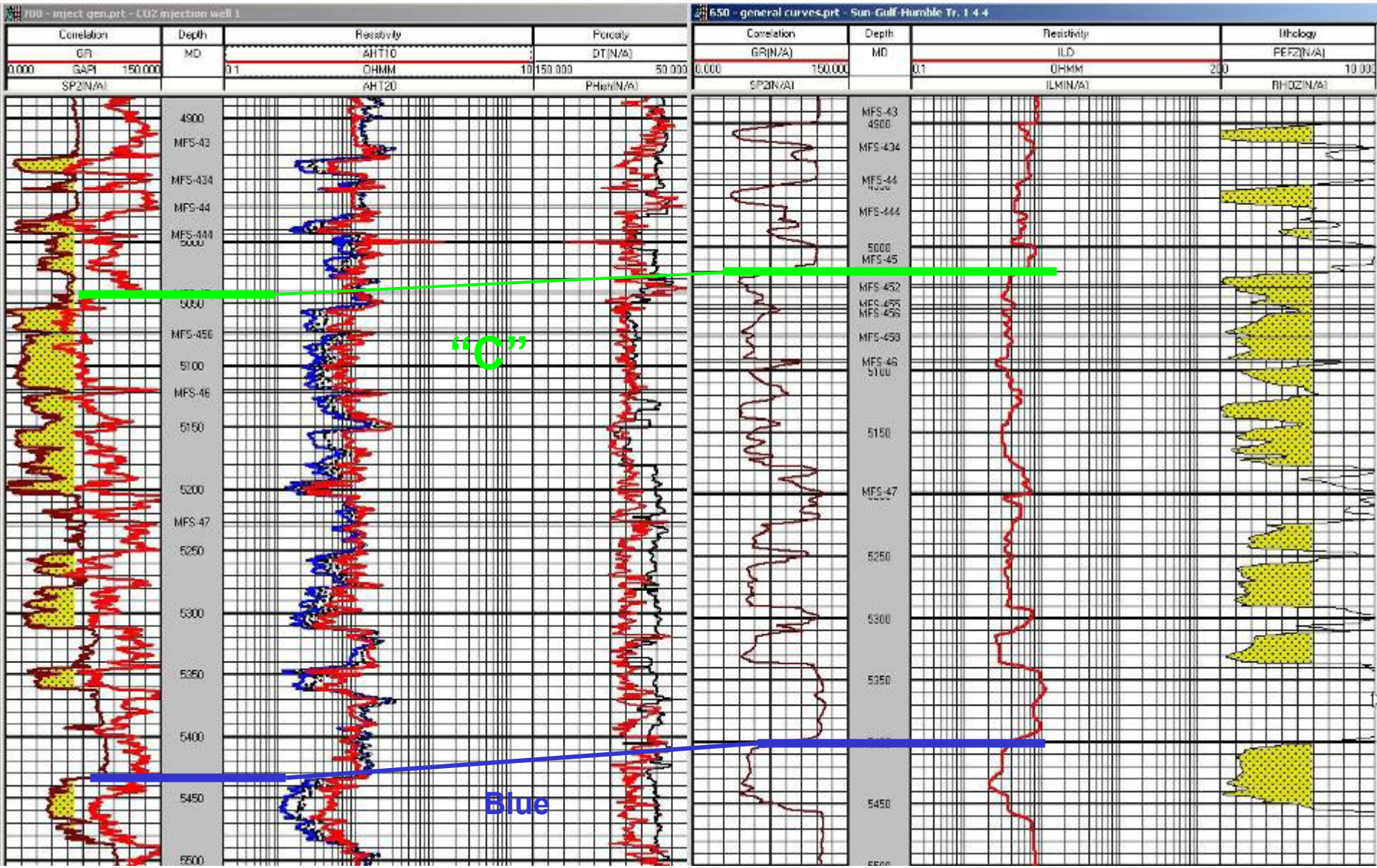
High Quality Characterization Prior To Injection



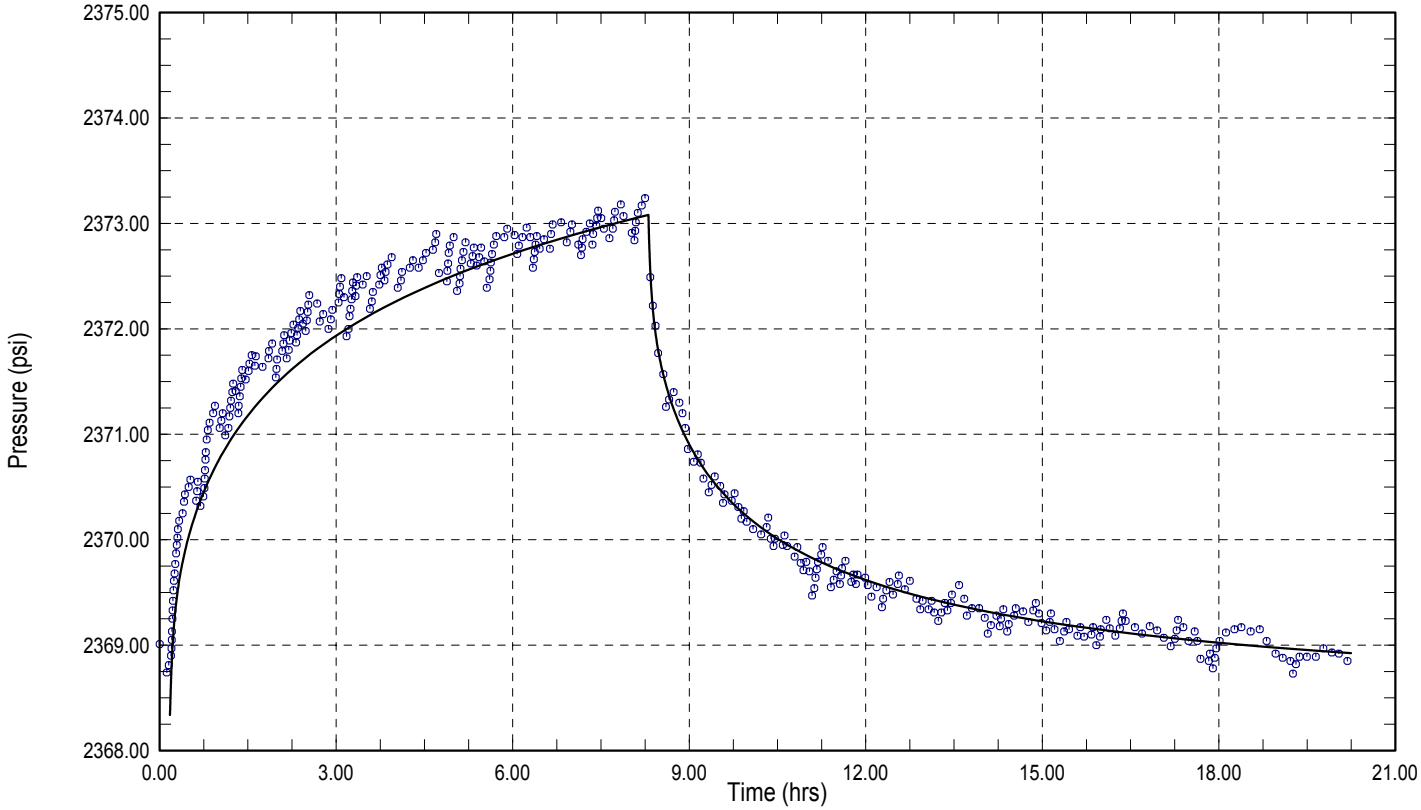
Knox, Fouad, Yeh, BEG

Injection Well

Observation Well



Hydrologic Characterization Prior to CO_2 injection

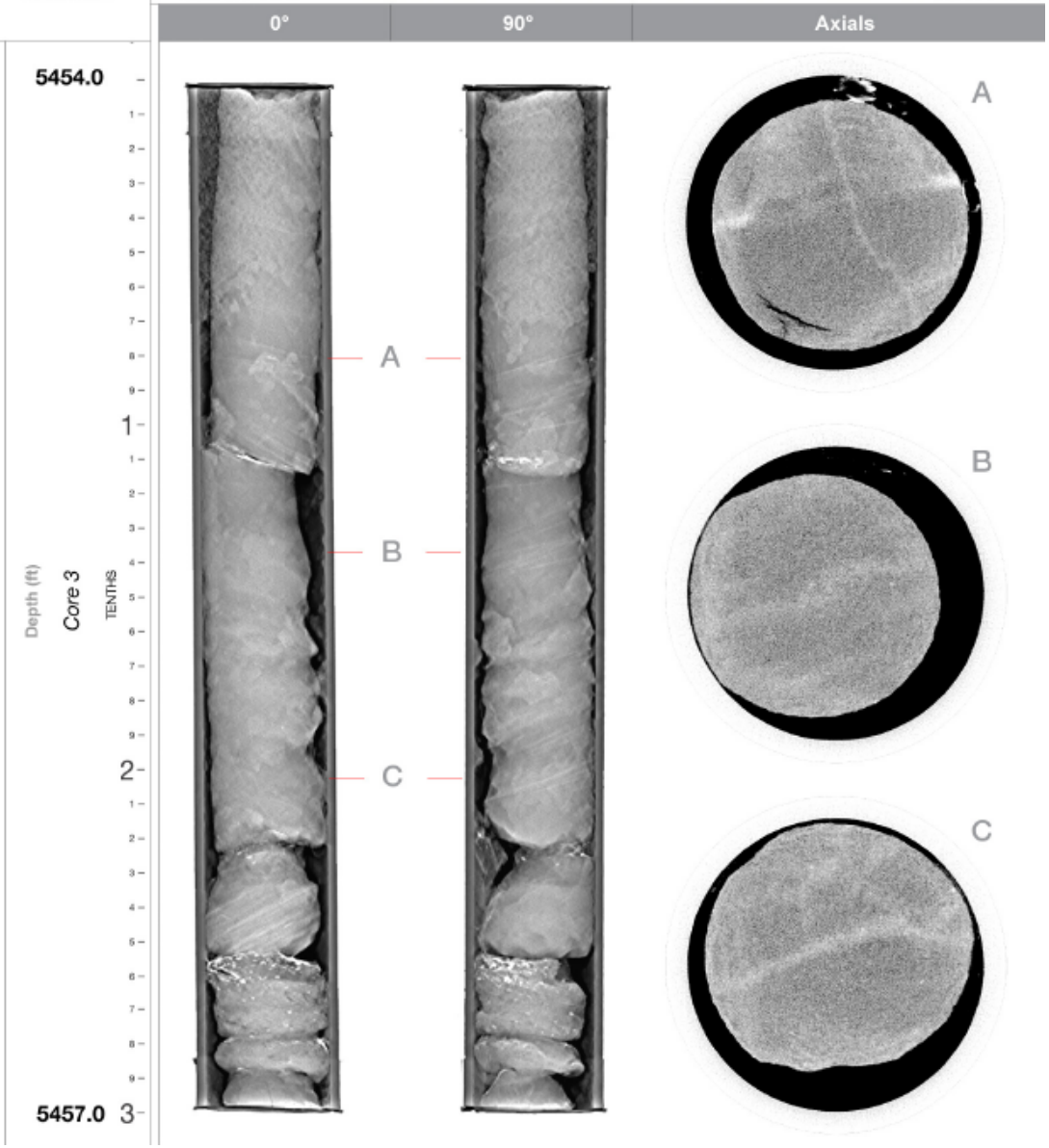


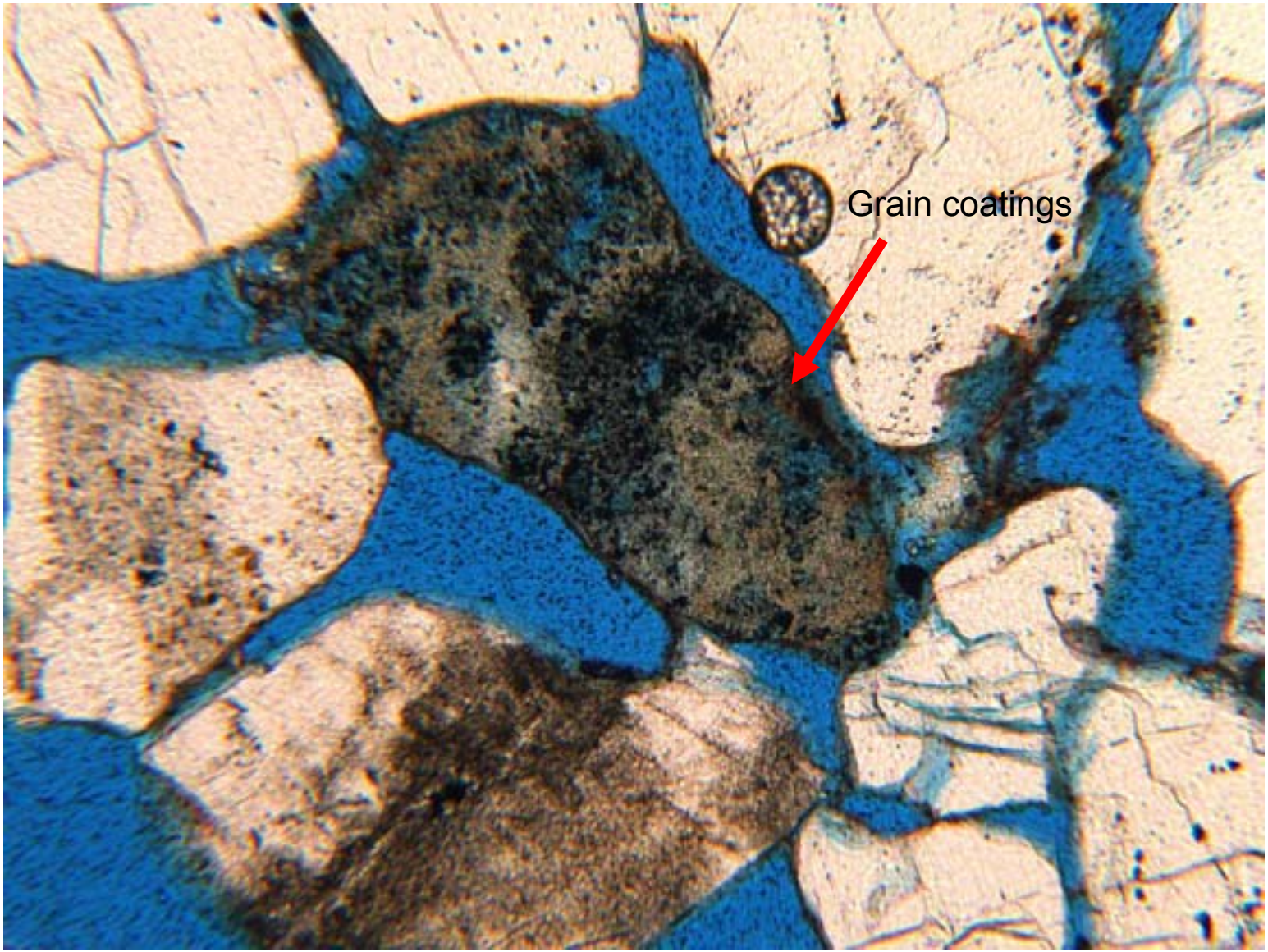
Dan Collins, Sandia Technologies

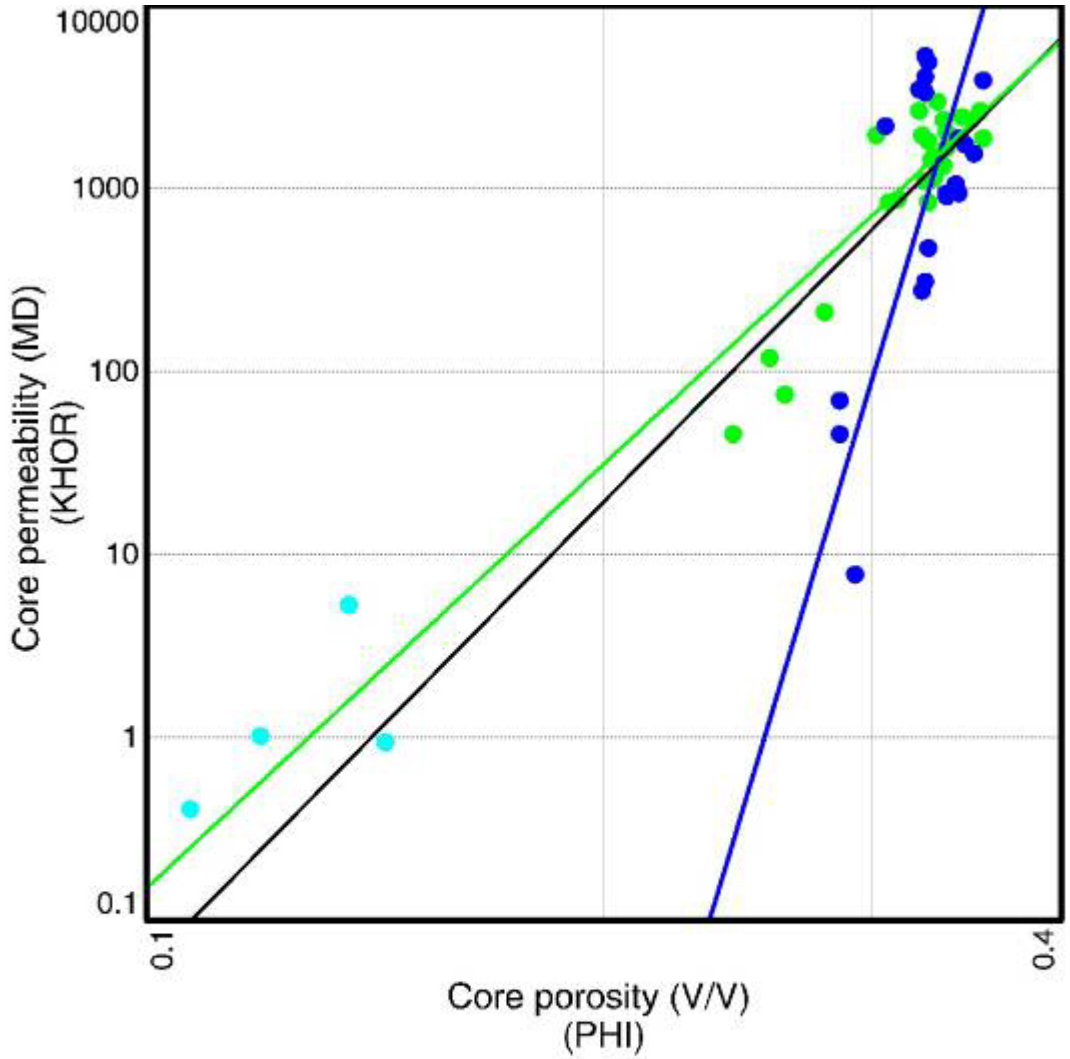
BEG

Pilot No.1 Well
Liberty County, Texas

File No.: HOU-040470 Date: June 9, 2004




Grain coatings
5mm



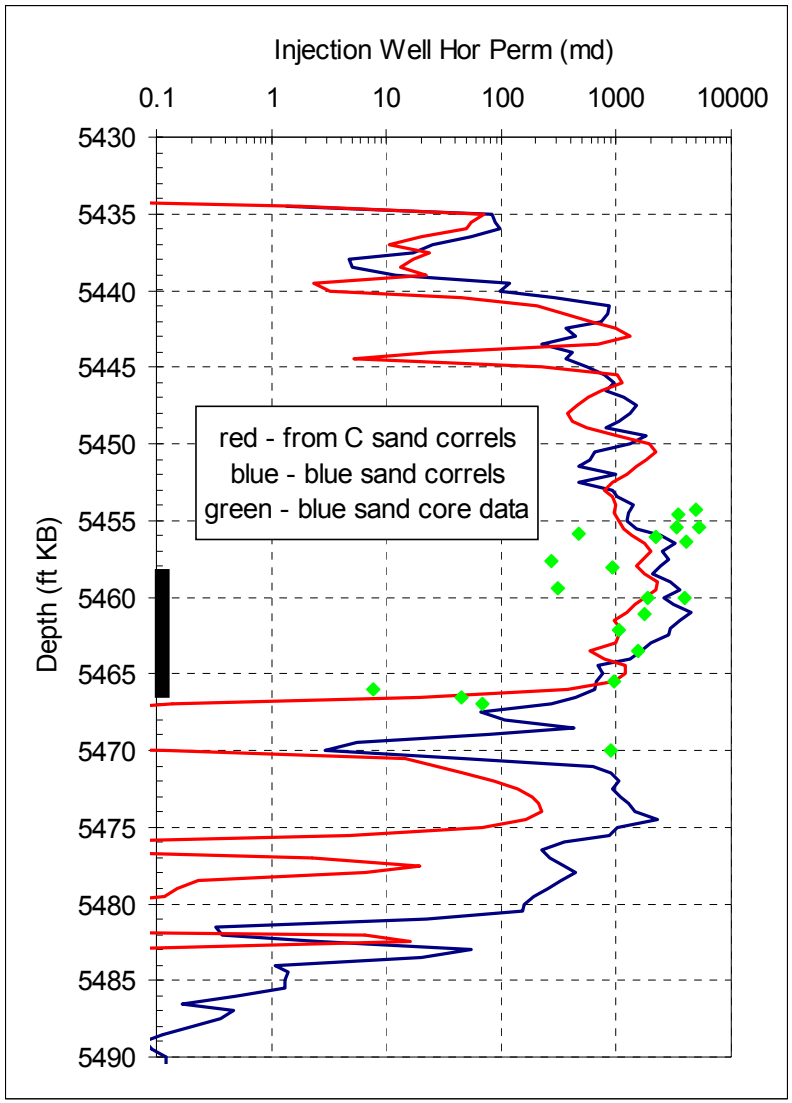
Color: Shale above "C" sand is cyan,
"C" sand is green and "Blue" sand is blue

Regression lines:

All core data	KHOR = 10**(7.17855 + 8.42626*log10(PHI))
Blue sand core data only	KHOR = 10**(16.3931 + 27.6299*log10(PHI))
"C" sand (with shale above) core data only	KHOR = 10**(6.87305 + 7.69593*log10(PHI))

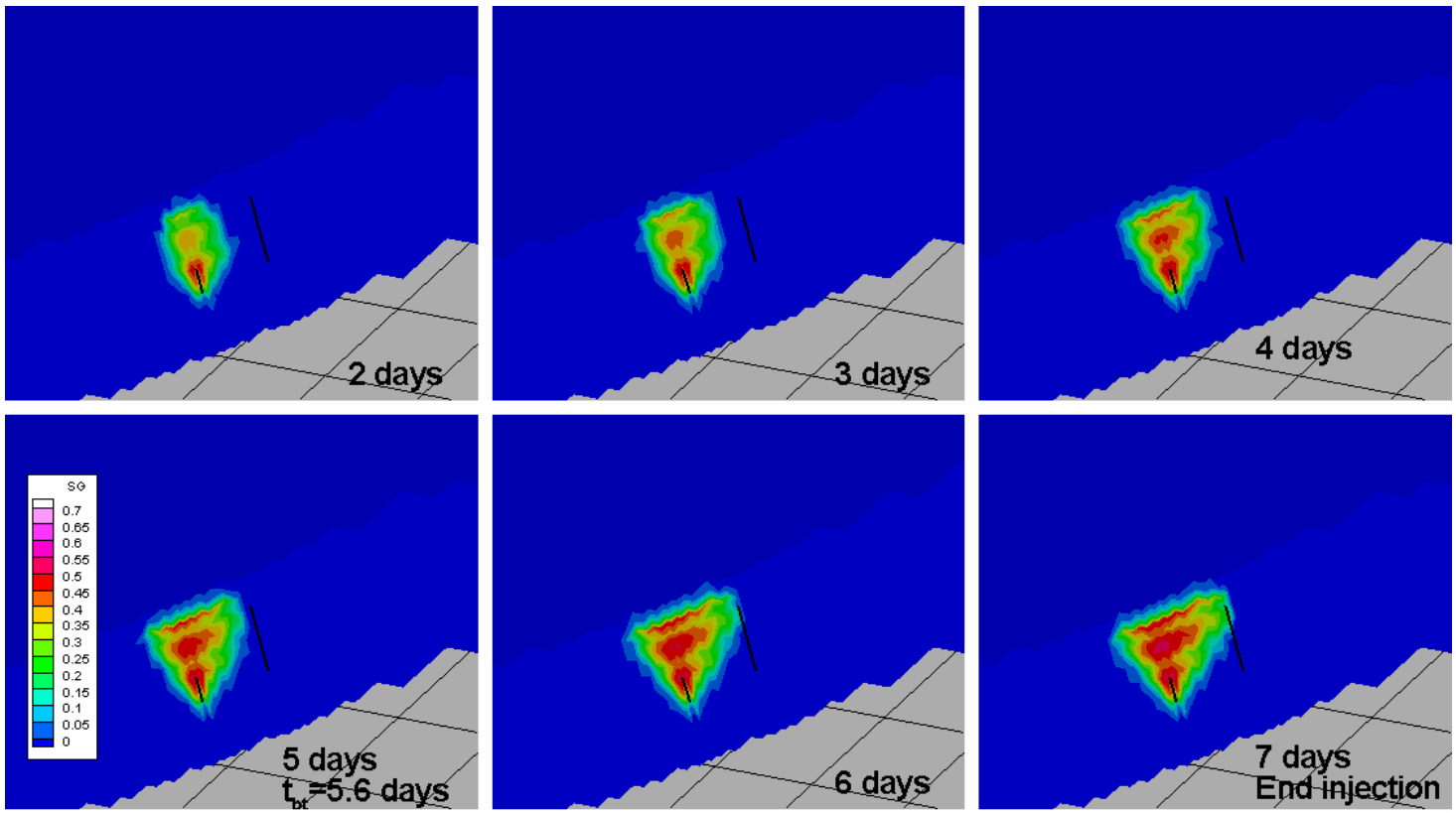
Jeff Kane, BEG

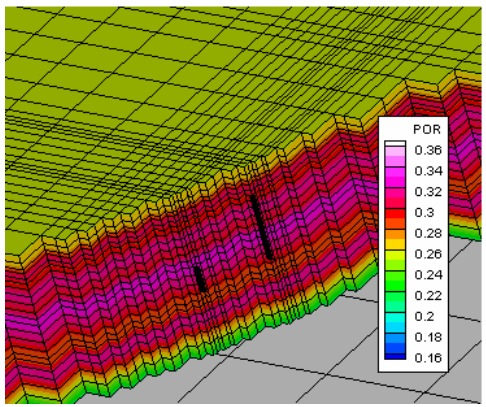
Uncertainly in Permeability Profiles



- Red curve used for preliminary model (June 2006)
  - Note low permeability at 5445 ft, CO_2 plume is trapped below it
- Blue curve used for current model (Sept 2006)
  - Permeability at 5445 ft not low enough to stop CO_2 plume's upward movement

Christine Doughty LBNL





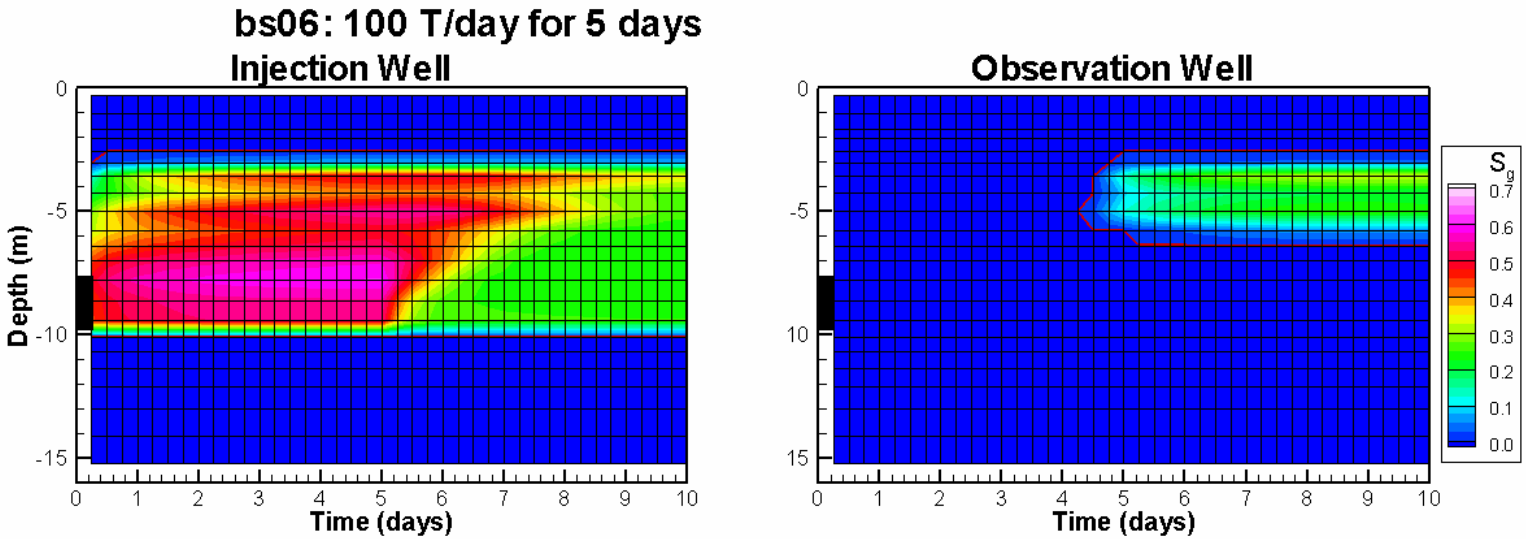
BS08 (Sept 25, 2006)

Porosity and permeability from core-correlated injection-well log

Usual anisotropy

$S_{lr} = 0.2$

TOUGH2, Christine Doughty LBNL

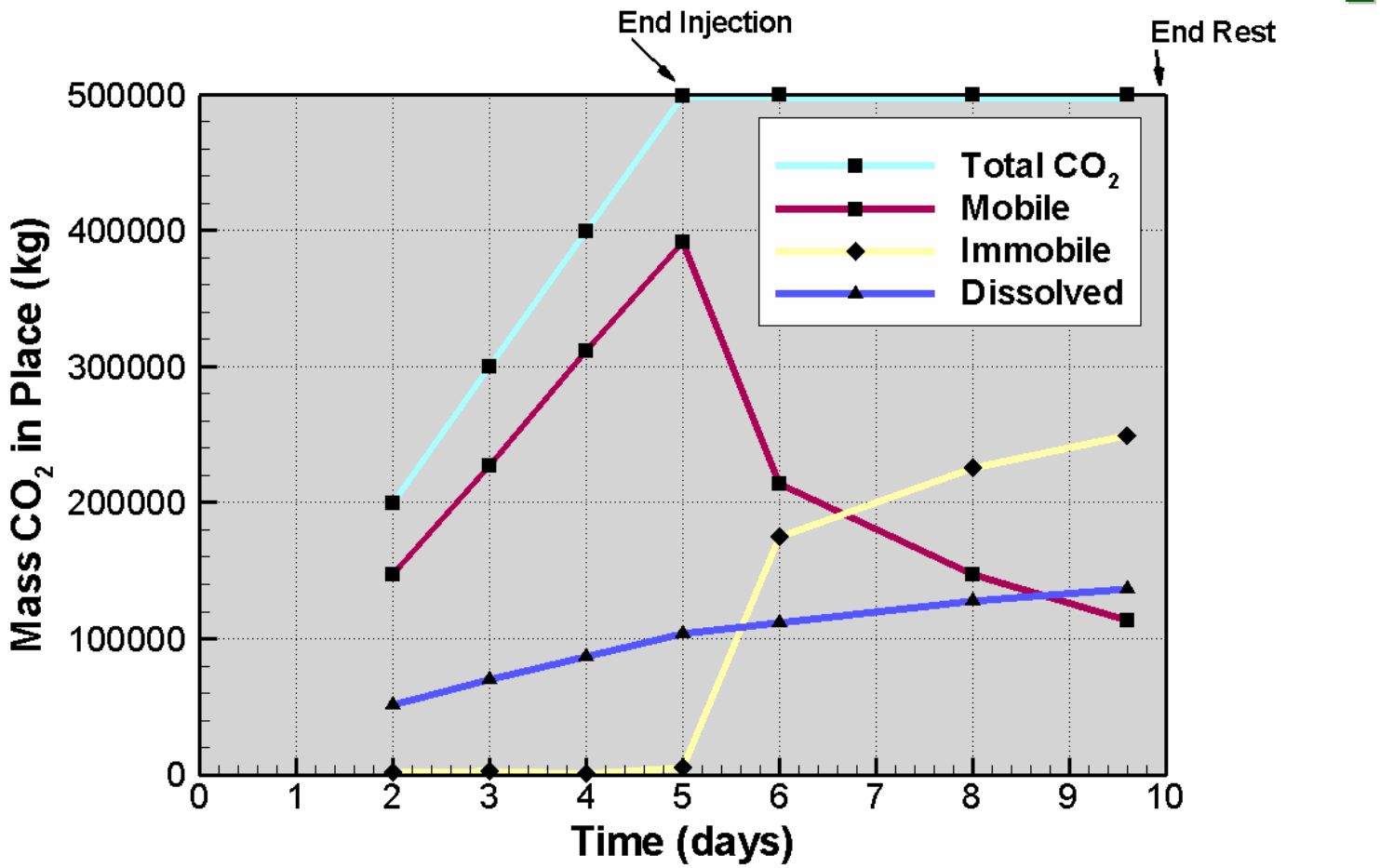


Christine Doughty LBNL

Summary of Modeled CO_2 Arrival Times

Case	Porosity and Permeability	S_{lr}	t_{bt} (hrs)	Comments
BS06 (June 2006)	C sand	0.3	89 (3.7 days)	Low k_v at 5445 ft keeps plume low, earlier arrival
BS08 (Sept 25, 2006)	Blue sand	0.2	134 (5.6 days)	High k_v allows plume to move upward more, up dip less, later arrival
BS09 (Sept 25, 2006)	Blue sand	0.3	120 (5.0 days)	S_{lr} variation has about a one-half day effect
BS10 (Sept 26, 2006)	Blue sand $k_v/k_h \leq 0.1$	0.2	91 (3.8 days)	Low k_v keeps plume low, earlier arrival
BS11 (Sept 26, 2006)	Blue sand $k_v/k_h \leq 0.1$	0.3	83 (3.4 days)	S_{lr} variation has about a one-half day effect

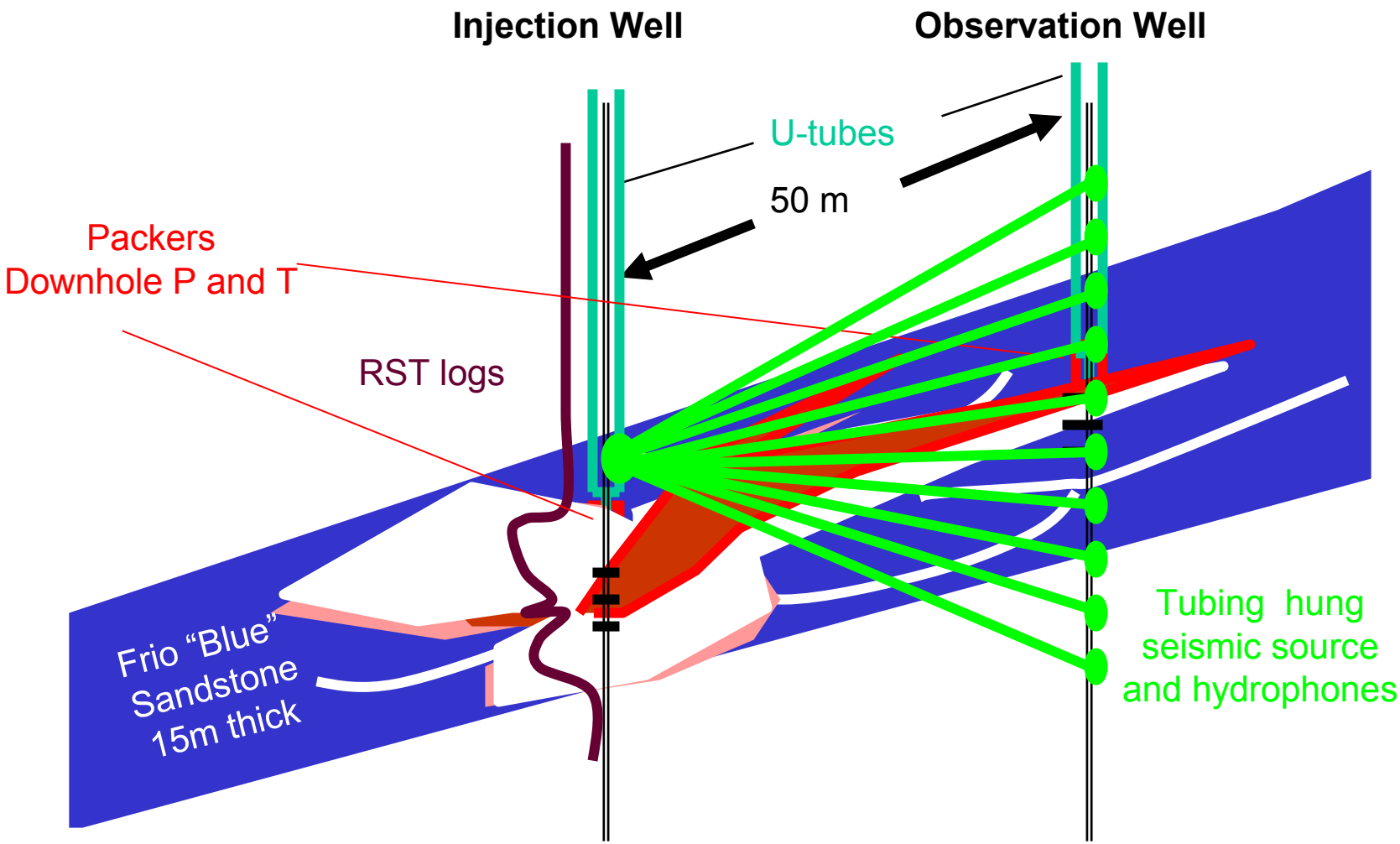
Modeled evolution of phases of CO_2



Frio 2 Monitoring Techniques Selected

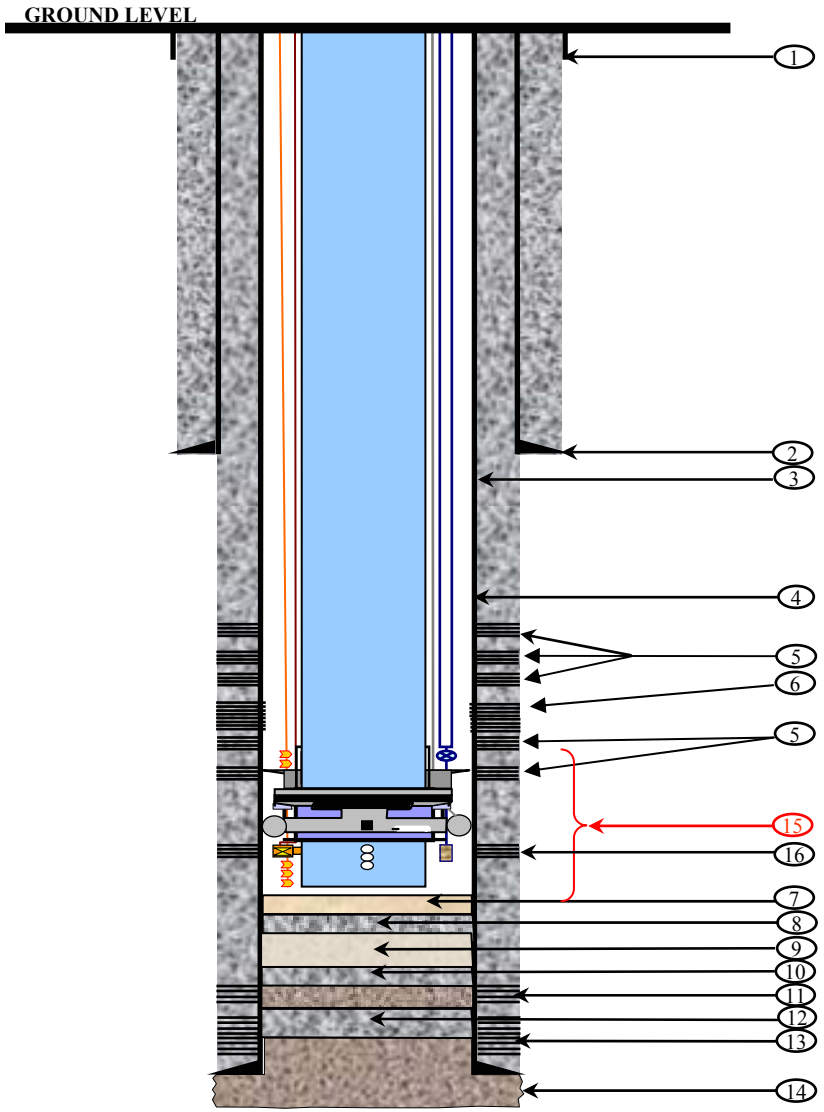
- Injection zone characterization – core analysis, open and cased hole logs, single phase hydologic testing
- RST logs: CO_2 saturation change with time – pressure and temperature change with depth
- Downhole Panex gages: pressure and temperature
- U-tubes – tracer gas and aqueous transport and gas and aqueous chemistry
- Tubing-conveyed cross-well seismic array

Monitoring Design Frio 2



Observation Well
Frio Brine Pilot Test
Sun Gulf Humble Fee Tract 1,Well #4
Frio II Anticipated Completion Well Schematic - September 2006
Observation Well #4

All depths reference RKB
KB = 12.7' above LMCF
G.L= 65'



COMPLETION DETAIL

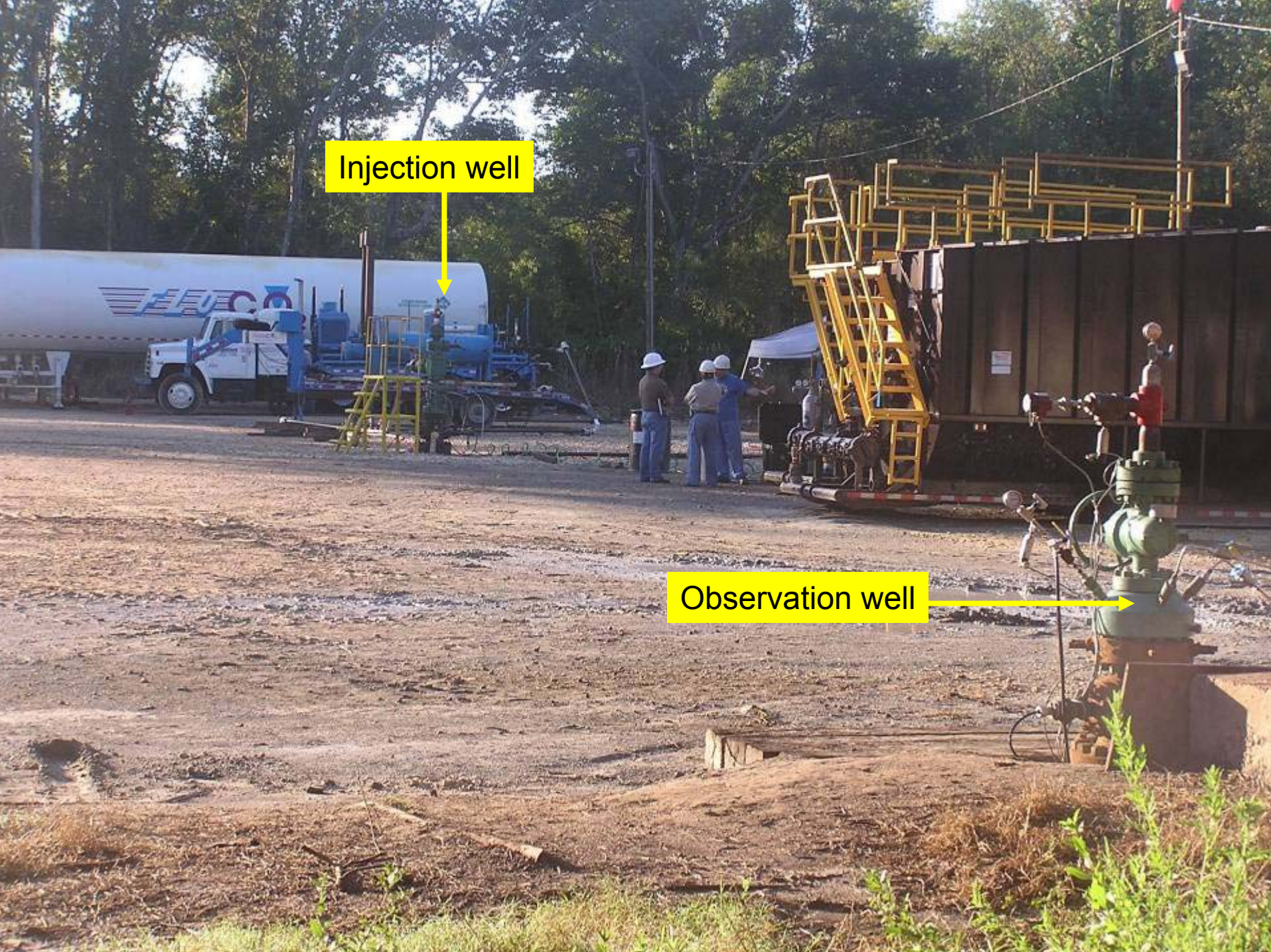
1. Conductor Pipe:
2. Surface Casing: 10-3/4" Set from surface to 2,040' (1952).
3. Protection Casing: 5-1/2" Set from surface to 8,964' (1952).
4. Estimated top of cement @ 4,591' to 4,791'
5. Squeeze Perforations:
   - 5,189' to 5,192' (8/12/2006)
6. Squeezed production perforations: 4,954' to 4,962' w/ 4 spf, 60 degree phasing, .28" entry holes, and 19" penetration. Cemented 5/26/2006 with 50 sks cement.
7. Top of sand fill: 5,885
8. Cement Plug: 6,129'to 6,327' (8/01/2003). Class H, 23 sacks.
9. Drilling Mud Plug: 6,327' to 7,931' (8/01/2003). 10.6-ppg.
10. Cement Plug: 7,931' to 8,414'(7/31/2003). Class H, 57 sacks.
11. Abandoned Perforations: 8,489' to 8,501' (7/31/2003).
12. Plug Back Total Depth: 8,600'
13. Abandoned Perforations: 8,810' to 8,914'
14. Total Depth Drilled: 9,516'

* Casing testing performed 7/27/2004 confirmed a leak in the 5-1/2" casing between 5,184' & 5,215'. The injection rate into the leak was 10 gpm at 1,100 psi.

15. Downhole completion consisting of: TAM Inflatable Packer (5,395.9' to 5,398.9') and inflate line, w/pass through sub on top of packer (top of sub at 5,392.6'), LBL Seismic Hydrophone Array from 5,343' to 5,516', Panex P&T Gauge at 5,409' and LBL Stainless Steel U-Tube Sampler below packer (filter at 5,417.4'). Perforated tail pipe from 5,410.8' to 5,453.3' and blank pipe to re-entry guide at 5,518.9'.
16. Sampling Perforations: Frio Blue Sand
17. Test Interval: 5,405' to 5,435 feet w/ 4 spf, 60 degree phasing, .28" entry holes, and 19" penetration.

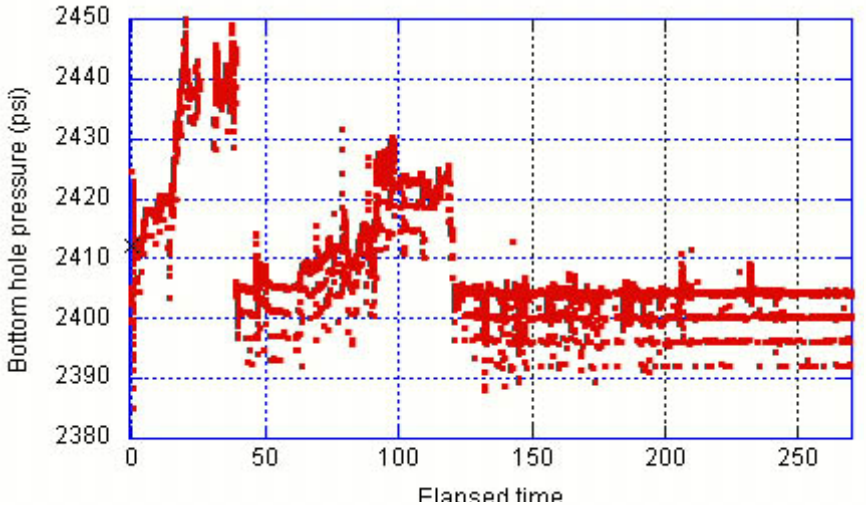
Sandia Technologies, LLC
6731 Theall Road, Houston, TX 77066
Tel: (832) 286-0471 Fax: (832) 286-0477

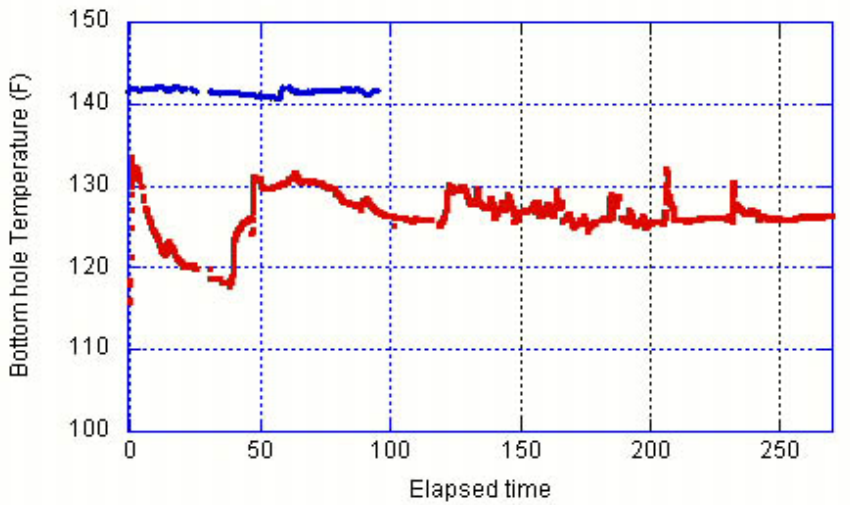
Drawn by: drf | Date: 09/23/2006 | *Drawing not to scale*

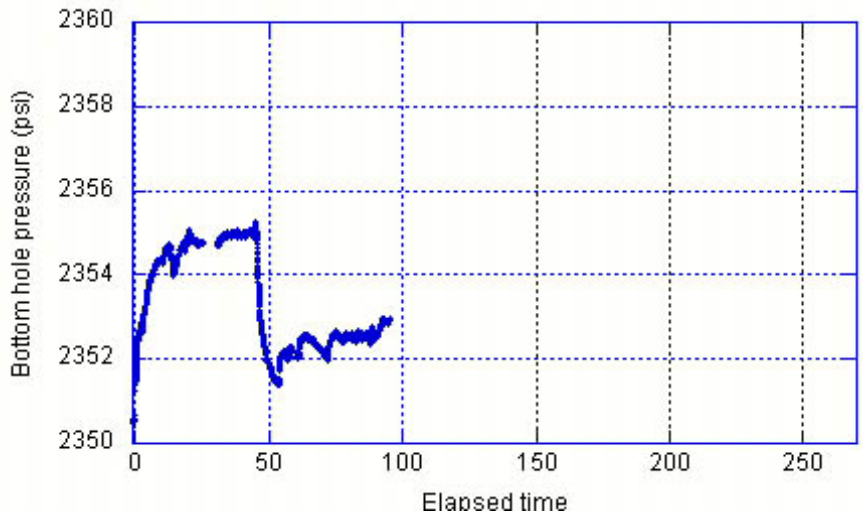

Injection well
Observation well

ENERGY
A.B.

Sample Bottom-Hole data







(Pressure Fall-off Test CO2 pump repair)

Real Time Data Acquisition - Frio Brine Pilot - C02 Injection Project

Select Options and then choose graph or data

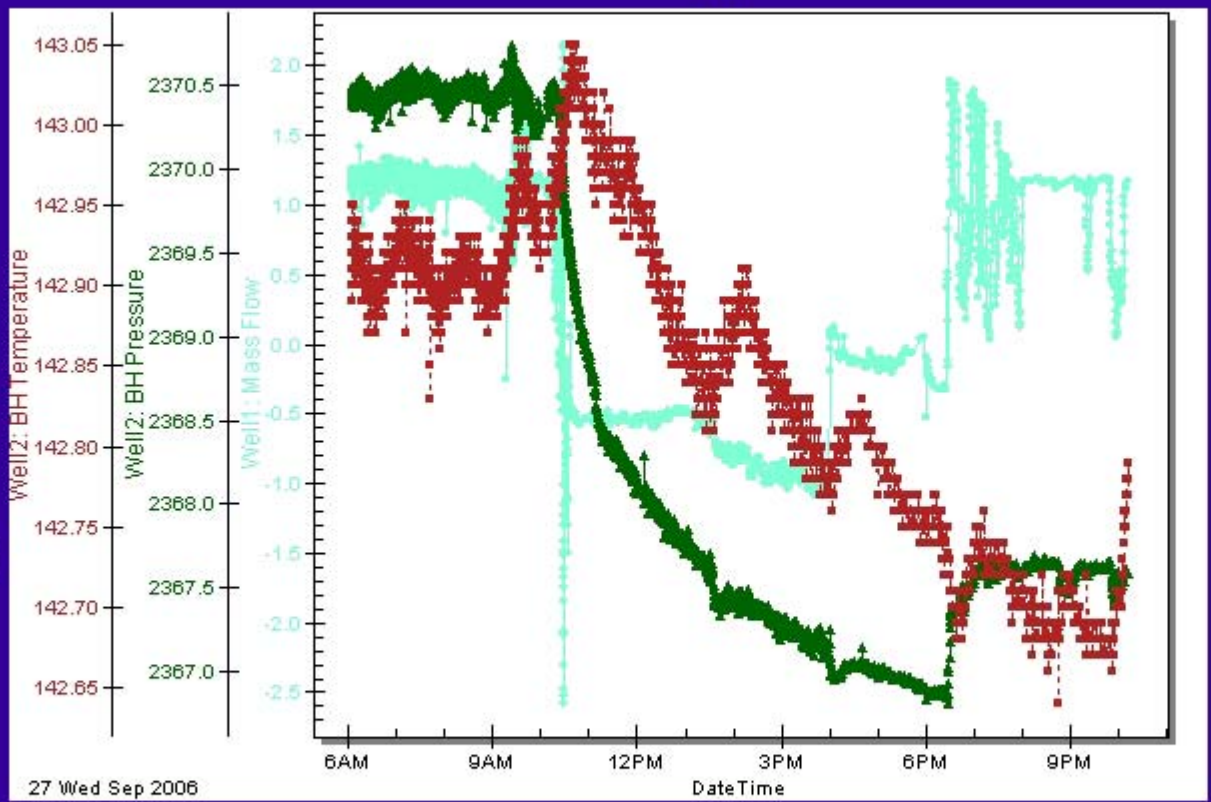
DateTime Range From: 9/27/2006 6:05:09 AM To: 9/27/2006 11:59:09 PM Output: Graph Refresh

Injection Well (1)

- [ ] BH Pressure
- [ ] BH Temperature
- [ ] Tubing Pressure
- [ ] Tubing Temperature
- [ ] Casing Pressure
- [ ] Injection Paker PSI
- [x] Mass Flow
- [ ] Mass Total Flow
- [ ] Flow Temp
- [ ] Density

Observation Well (2)

- [x] BH Pressure
- [x] BH Temperature
- [ ] Tubing Pressure
- [ ] Tubing Temperature
- [ ] Casing Pressure
- [ ] Observation Pkr Pressure
- [ ] Site Barometric Pressure



Go to Main Page

Real-time Downhole Pressure and Temperature Monitoring

Real Time Data Acquisition - Frio Brine Pilot - C02 Injection Project

Select Options and then choose graph or data

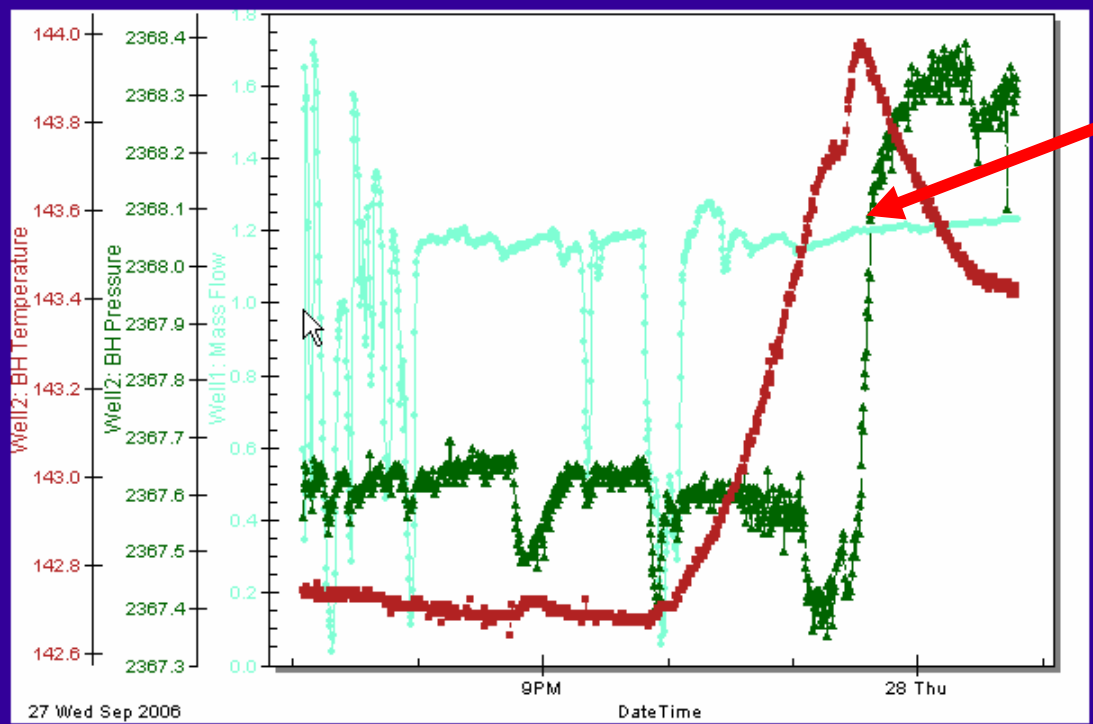
DateTime Range From: 9/27/2006 7:05:09 PM To: 9/28/2006 12:59:09 PM Output: Graph Refresh

Injection Well (1)

- [ ] BH Pressure
- [ ] BH Temperature
- [ ] Tubing Pressure
- [ ] Tubing Temperature
- [ ] Casing Pressure
- [ ] Injection Paker PSI
- [x] Mass Flow
- [ ] Mass Total Flow
- [ ] Flow Temp
- [ ] Density

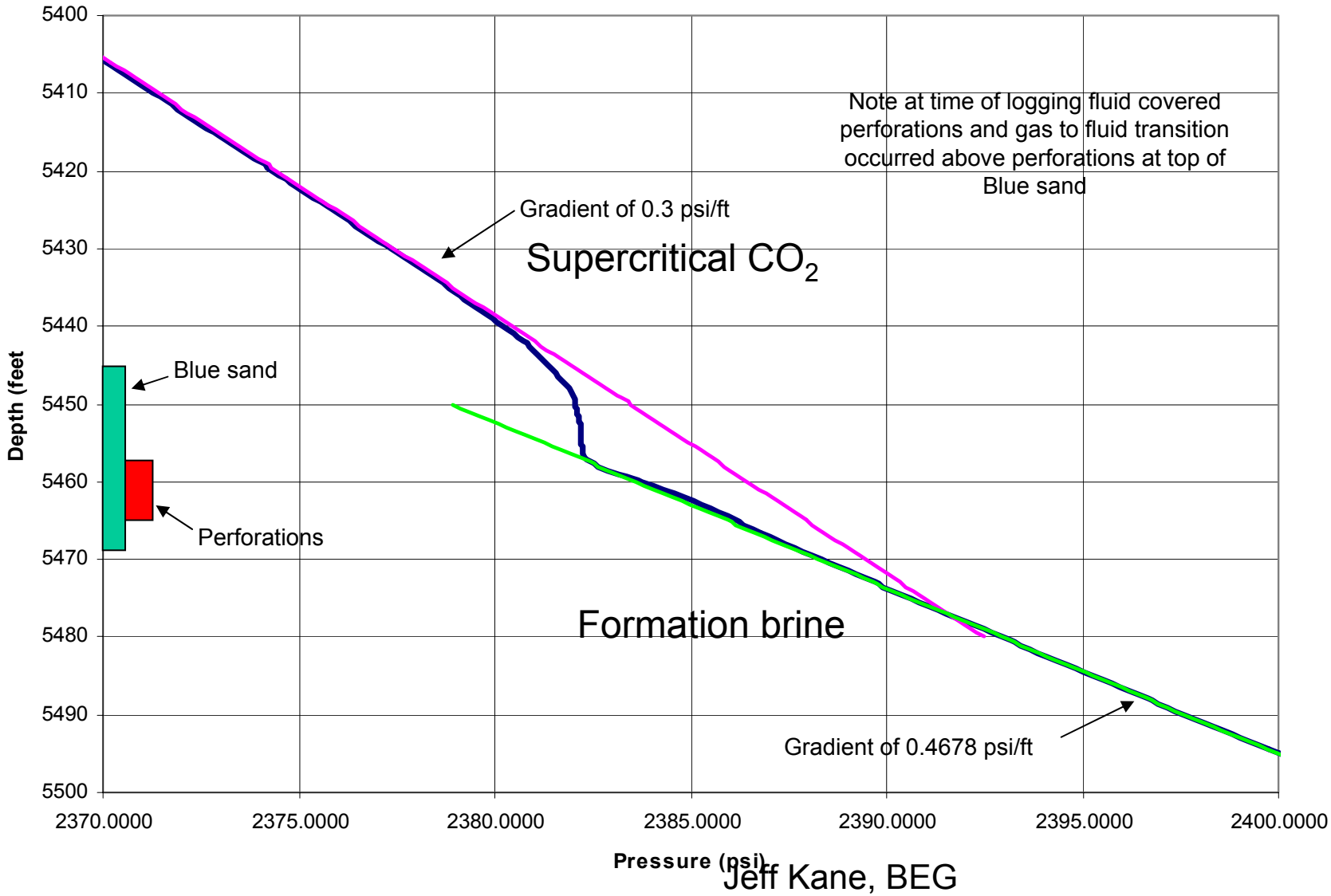
Observation Well (2)

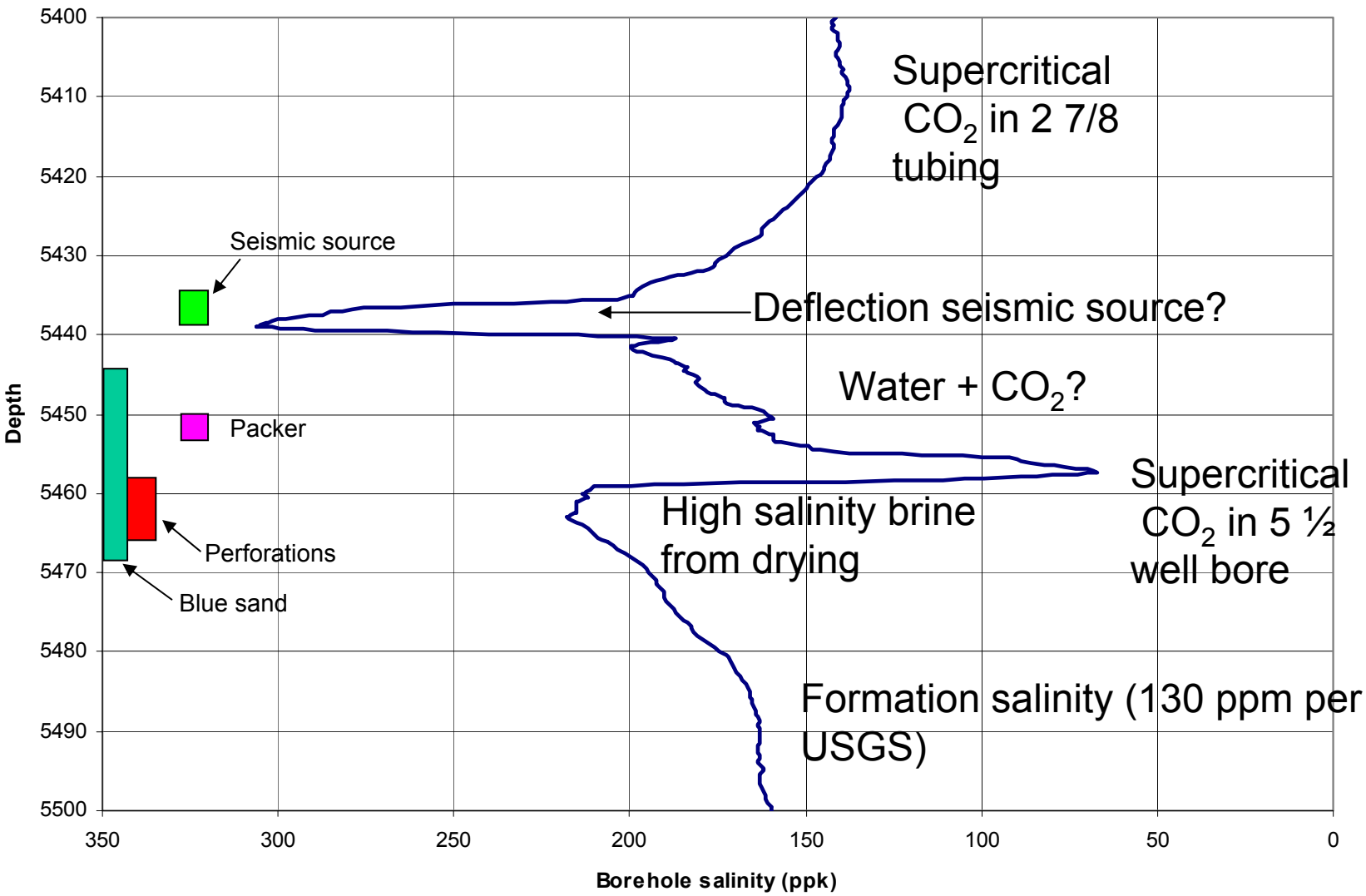
- [x] BH Pressure
- [x] BH Temperature
- [ ] Tubing Pressure
- [ ] Tubing Temperature
- [ ] Casing Pressure
- [ ] Observation Pkr Pressure
- [ ] Site Barometric Pressure

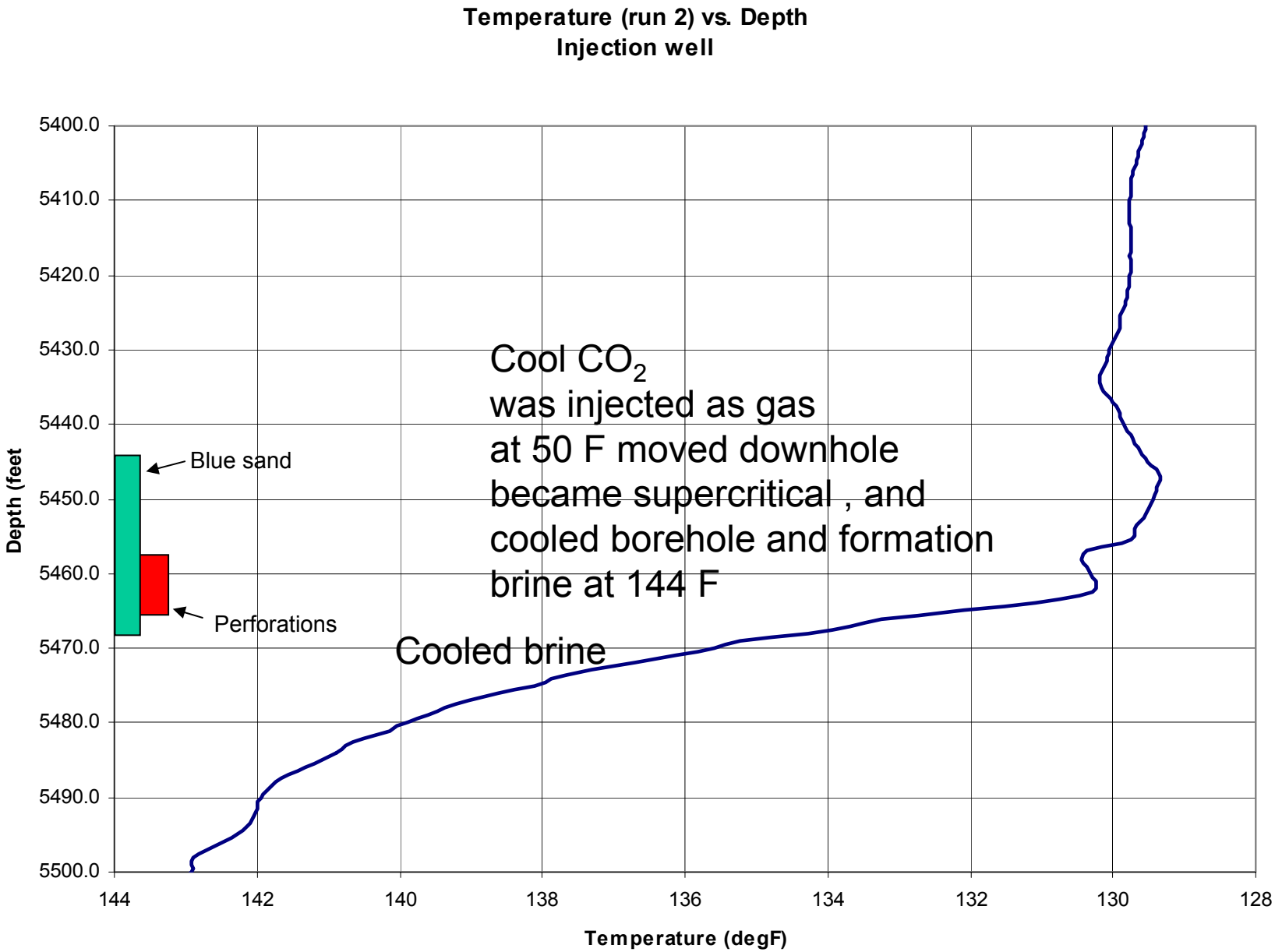


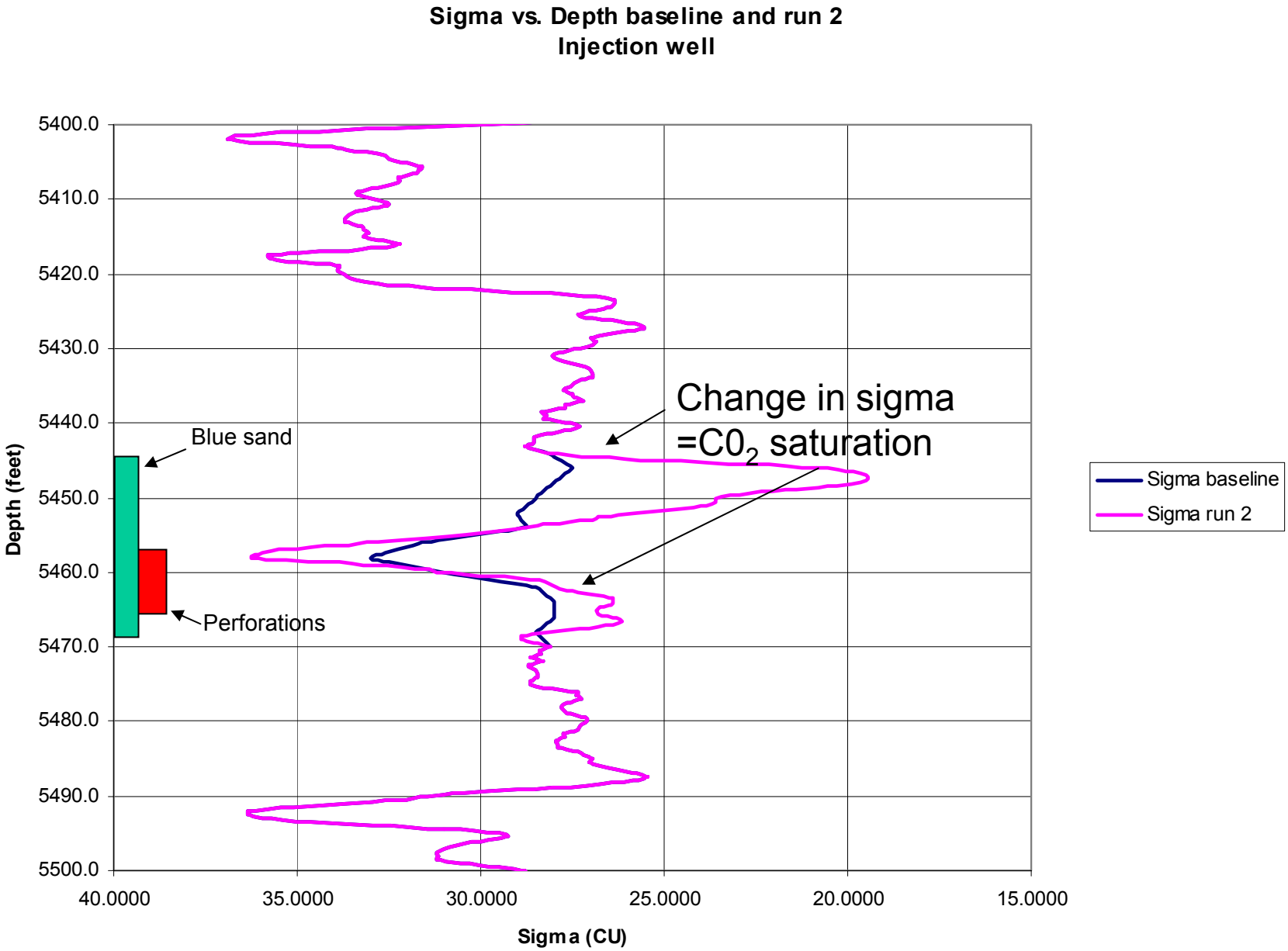
CO_2 breakthrough

Go to Main Page

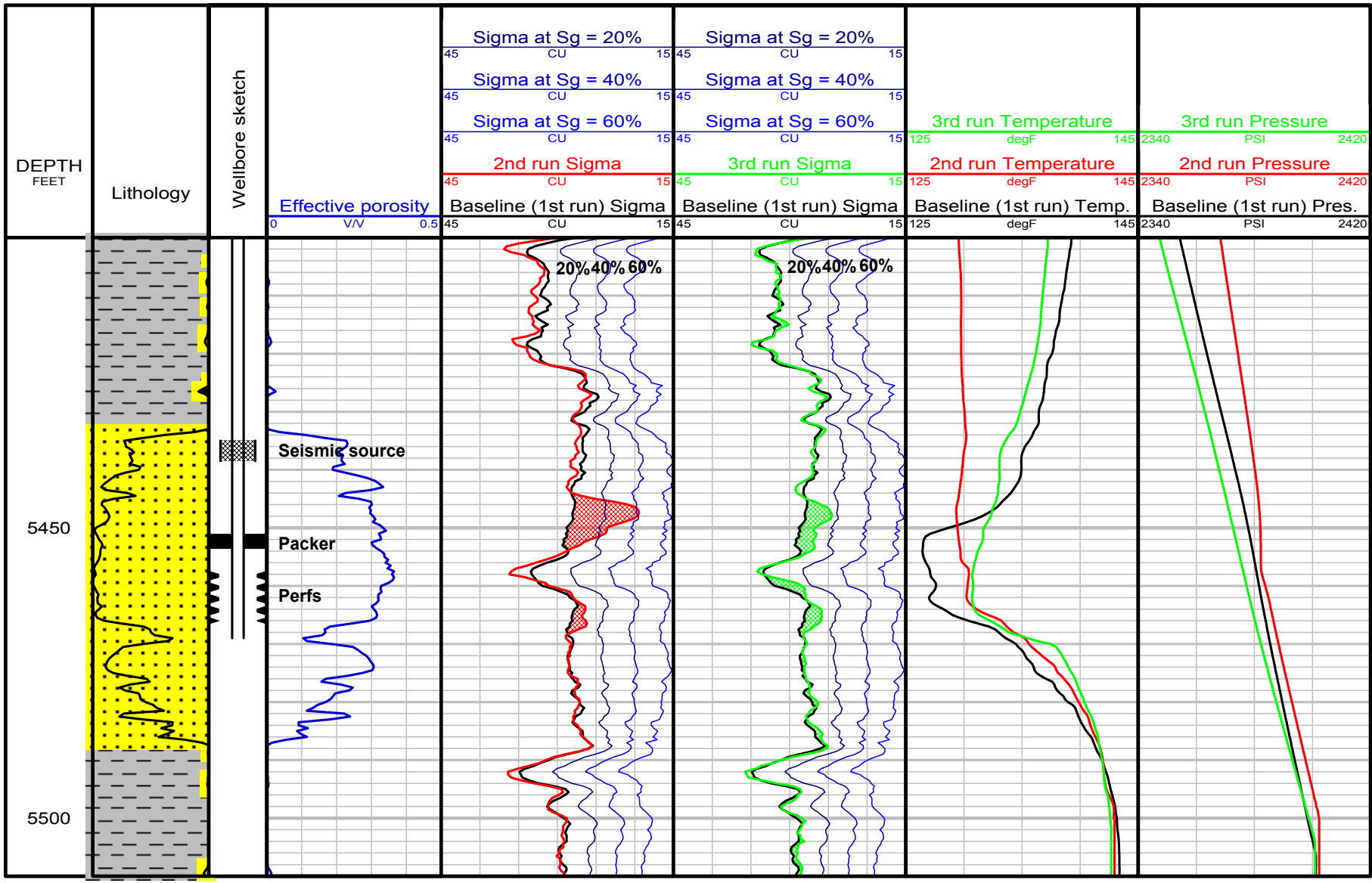

Pressure (run 2) vs. Depth
Injection well
Depth (feet
5400
5410
5420
5430
5440
5450
5460
5470
5480
5490
5500
2370.0000
2375.0000
2380.0000
2385.0000
2390.0000
2395.0000
2400.0000
Pressure (psi)
Note at time of logging fluid covered perforations and gas to fluid transition occurred above perforations at top of Blue sand
Gradient of 0.3 psi/ft
Supercritical CO_2
Blue sand
Perforations
Formation brine
Gradient of 0.4678 psi/ft
Jeff Kane, BEG


Apparent borehole salinity (run 2) vs. Depth
Injection well
Depth
5400
5410
5420
5430
5440
5450
5460
5470
5480
5490
5500
350
300
250
200
150
100
50
0
Borehole salinity (ppk)
Seismic source
Packer
Perforations
Blue sand
Supercritical CO_2 in 2 7/8 tubing
Deflection seismic source?
Water + CO_2?
High salinity brine from drying
Supercritical CO_2 in 5 ½ well bore
Formation salinity (130 ppm per USGS)

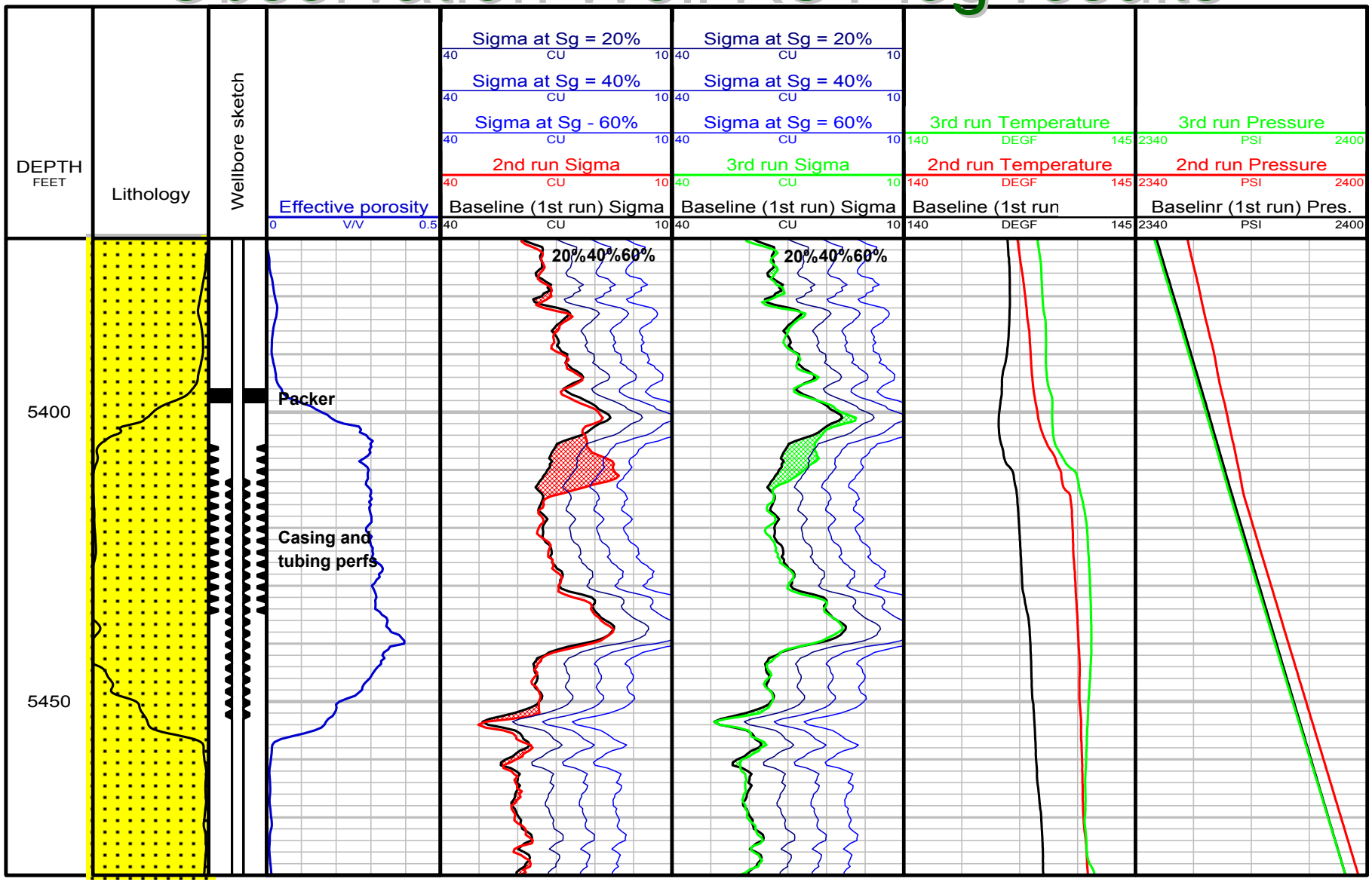

Temperature (run 2) vs. Depth
Injection well
Depth (feet
5400.0
5410.0
5420.0
5430.0
5440.0
5450.0
5460.0
5470.0
5480.0
5490.0
5500.0
144
142
140
138
136
134
132
130
128
Temperature (degF)
Blue sand
Perforations
Cool CO_2
was injected as gas
at 50 F moved downhole
became supercritical , and
cooled borehole and formation
brine at 144 F
Cooled brine

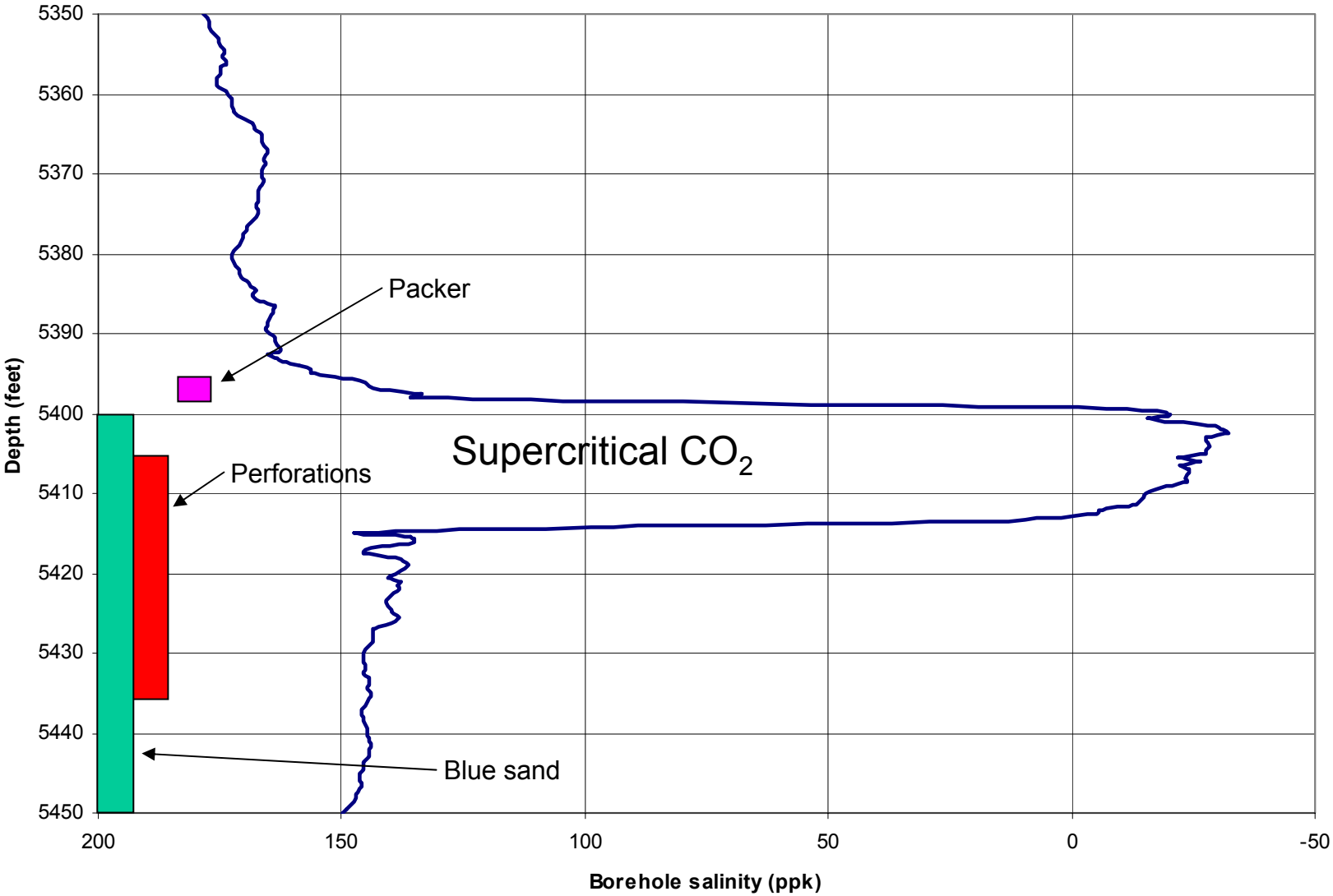

Sigma vs. Depth baseline and run 2
Injection well
5400.0
5410.0
5420.0
5430.0
5440.0
5450.0
5460.0
5470.0
5480.0
5490.0
5500.0
Depth (feet)
Blue sand
Perforations
Change in sigma
=C0$_2$ saturation
40.0000
35.0000
30.0000
25.0000
20.0000
15.0000
Sigma (CU)
Sigma baseline
Sigma run 2

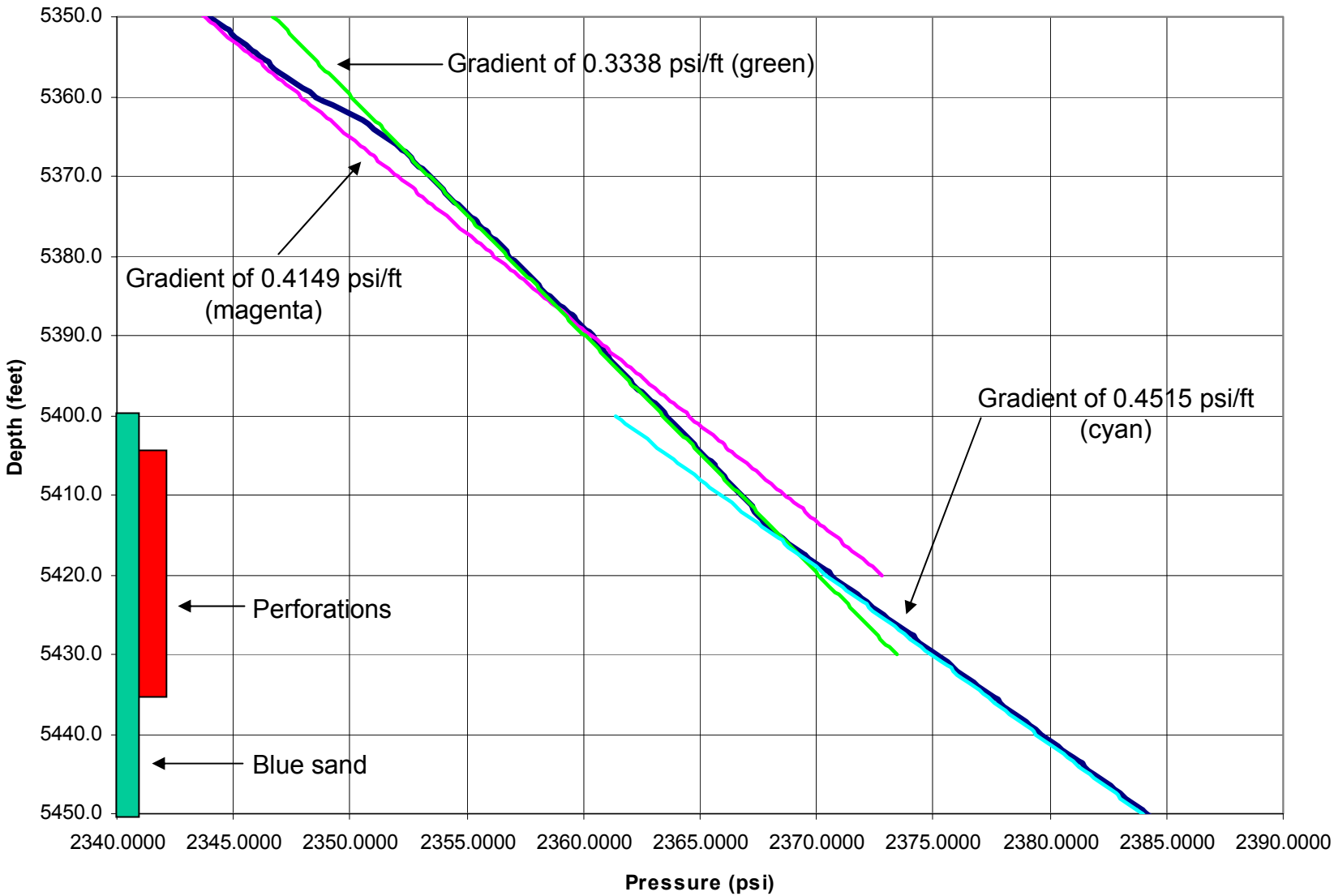
Injection Well RST runs baseline, 2, 3



Observation Well RST log results




Apparent borehole salinity (run 2) vs. Depth
Observation well
Depth (feet)
5350
5360
5370
5380
5390
5400
5410
5420
5430
5440
5450
200
150
100
50
0
-50
Borehole salinity (ppk)
Packer
Perforations
Supercritical CO_2
Blue sand


Pressure (run 2) vs. Depth
Observation well
Gradient of 0.3338 psi/ft (green)
Gradient of 0.4149 psi/ft (magenta)
Gradient of 0.4515 psi/ft (cyan)
Perforations
Blue sand
Depth (feet)
Pressure (psi)
5350.0
5360.0
5370.0
5380.0
5390.0
5400.0
5410.0
5420.0
5430.0
5440.0
5450.0
2340.0000
2345.0000
2350.0000
2355.0000
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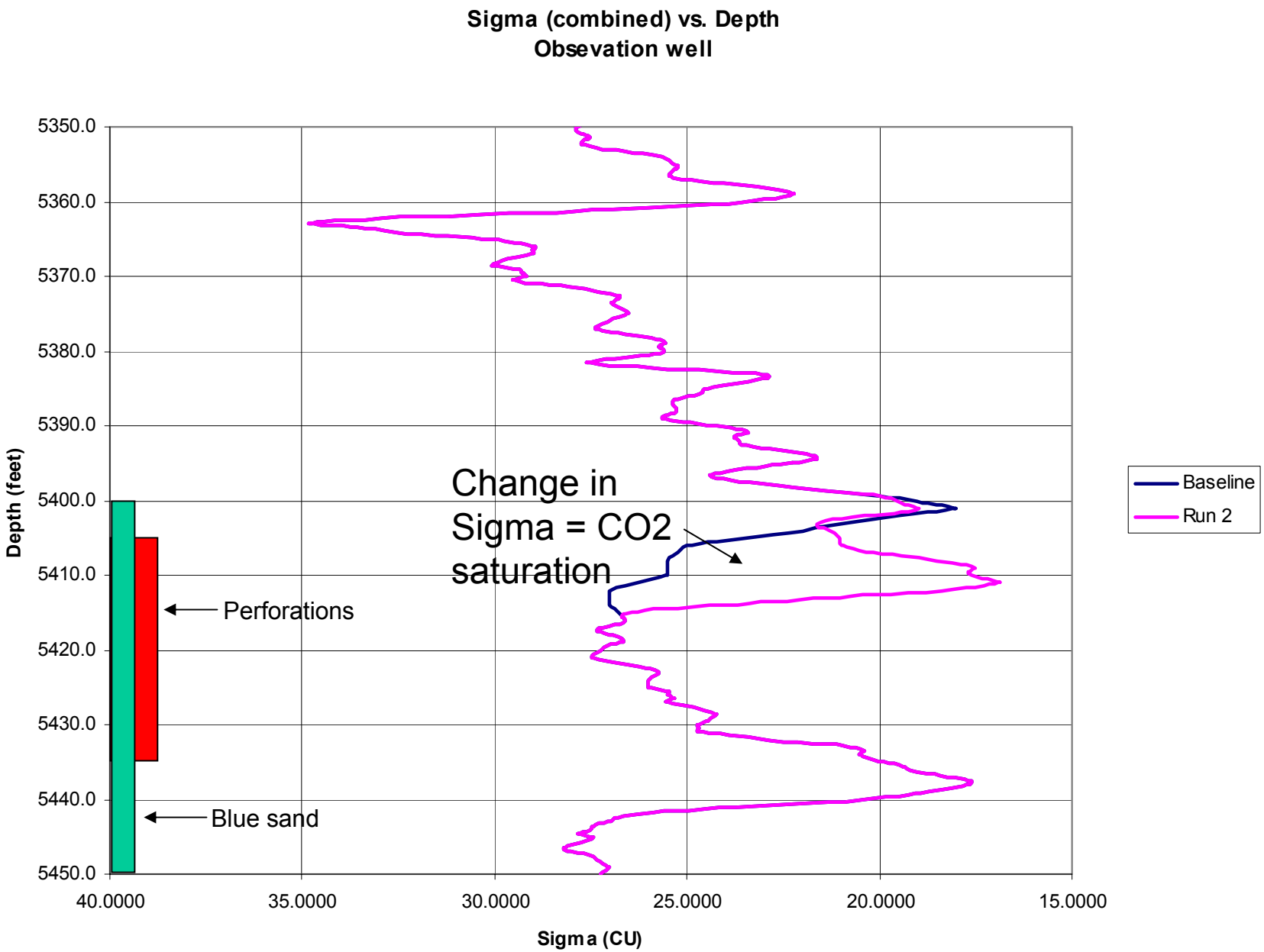
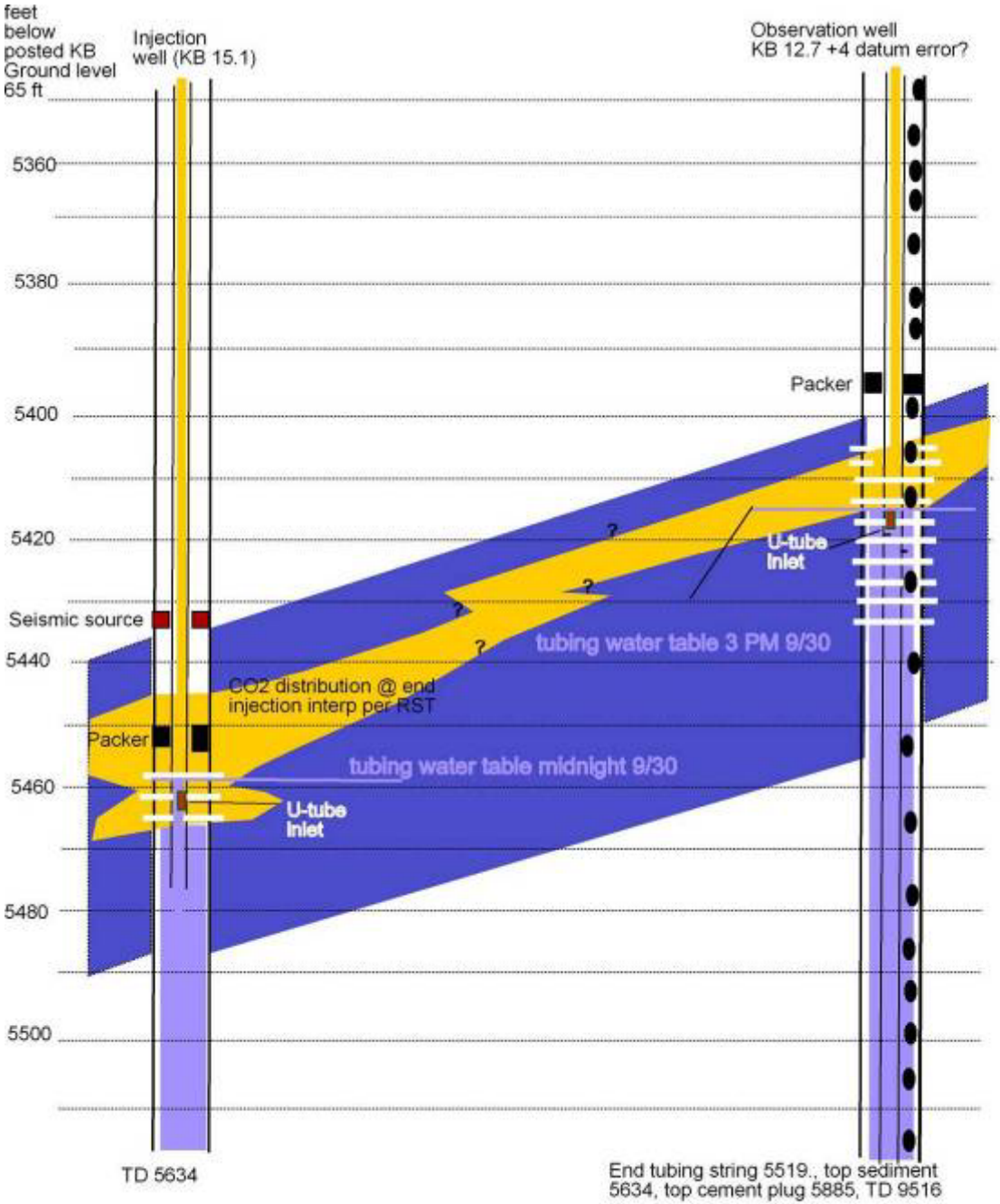
2385.0000
2390.0000


Sigma (combined) vs. Depth
Obsevation well
Depth (feet)
5350.0
5360.0
5370.0
5380.0
5390.0
5400.0
5410.0
5420.0
5430.0
5440.0
5450.0
40.0000
35.0000
30.0000
25.0000
20.0000
15.0000
Sigma (CU)
Change in Sigma = CO2 saturation
Perforations
Blue sand
Baseline
Run 2



Well completion and inferred CO_2 distribution at end injection, based on RST log response and compatible with well production performance

Inferred CO_2 distribution

Blue sandstone

Water-filled wells

Receivers

Frio 2 Preliminary Results

- **Storage permanence – quantifying residual saturation and dissolution**
- **Post- injection monitoring under stable conditions**
- **Novel tool – tubing-conveyed seismic array**

Frio II Brine Pilot: Preliminary results of combined well-based geophysical and geochemical monitoring methods

Barry Freifeld and Tom Daley
Lawrence Berkeley National Laboratory

Yousif Kharaka
United States Geological Survey

October 31, 2006
IEA GHG 3rd Meeting of the Monitoring Network

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- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, Jeff Kane, Andrew Tachovsky, Abhijit Mukarjee, Tip Meckel;
- Lawrence Berkeley National Lab, (Geo-Seq): Larry Myer, Rob Trautz, Christine Doughty, Sally Benson Paul Cook, Duo Wang, Ray Solbau
- Schlumberger: John Tombari, T. S. Ramakrishna,
- Oak Ridge National Lab: Dave Cole, Tommy Phelps, Phil Szymcek
- Sandia Technologies: David Freeman, Kirk De long, Dan Collins,
- USGS: Evangelos Kakauros, Jim Thordsen, Gill Amsen
- Praxair: Glen Thompson
- Australian CO2CRC (CSIRO): Jim Underschultz,
- Core Labs: Paul Martin and others
- MIT Jonathan Ajo-Franklin

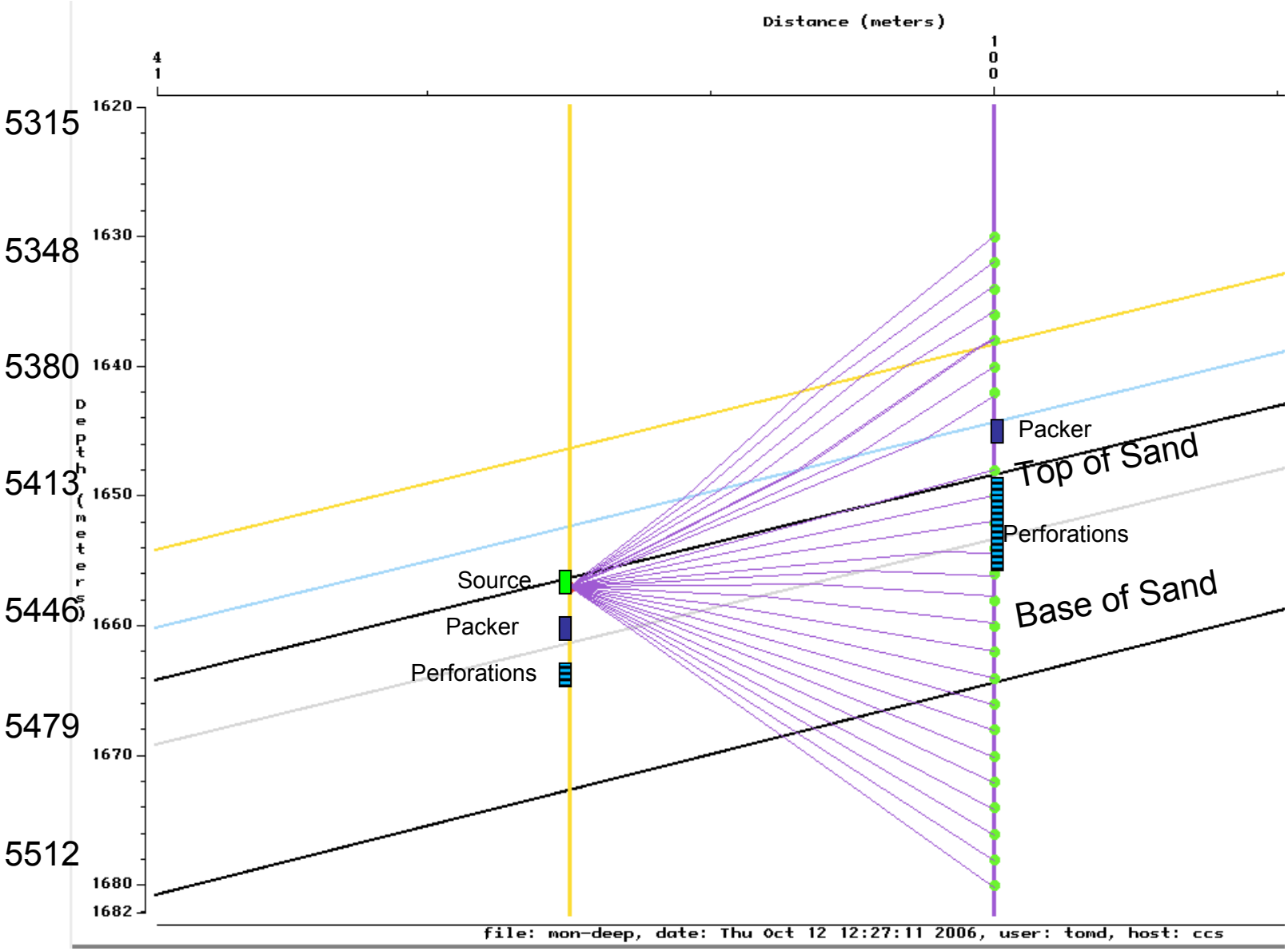
- **U.S. DOE/NETL provided the funds to make it possible**

Combined Well-based Geophysical/Geochemical Monitoring

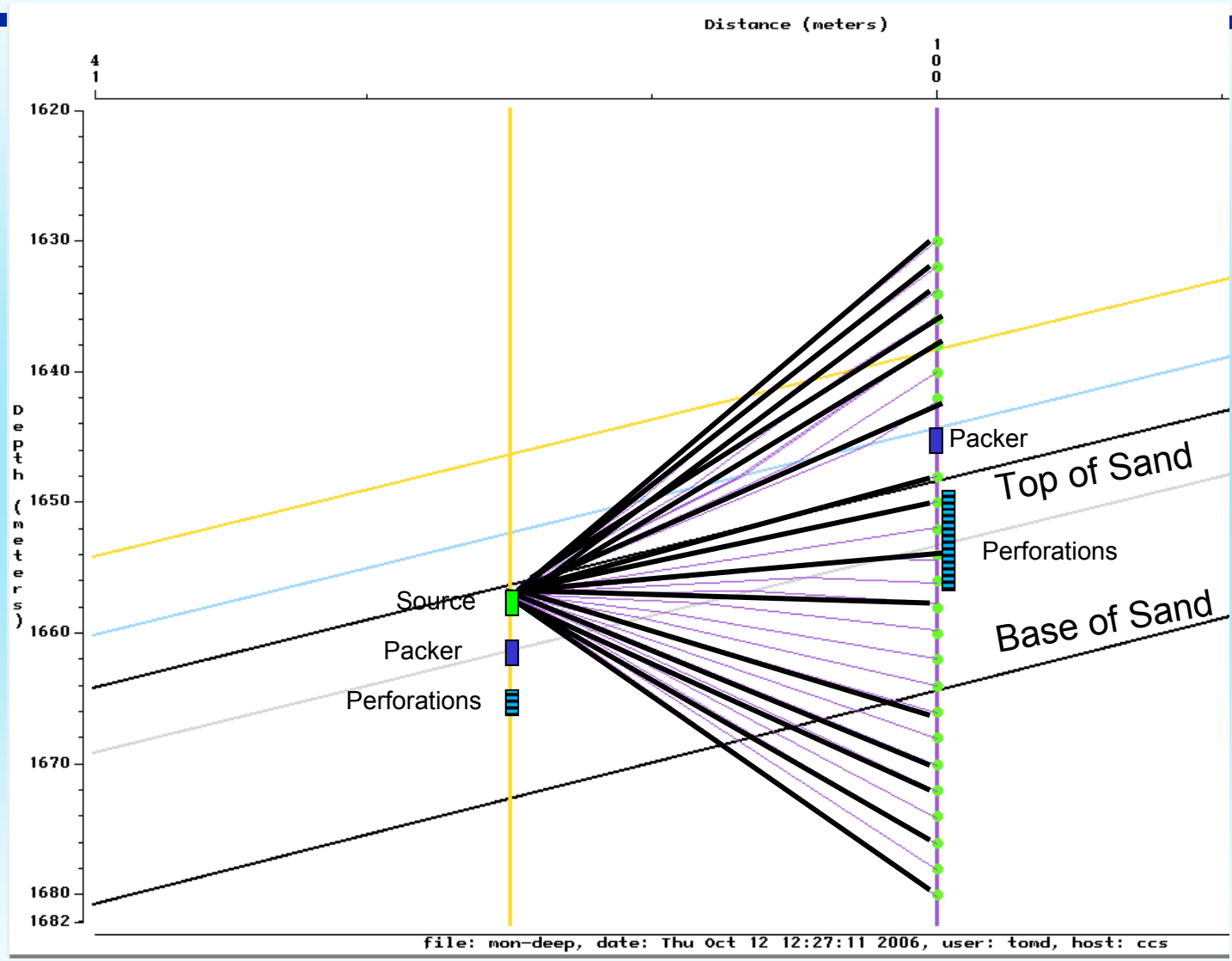
Frio II utilized

- —Seismic source in injection borehole
- —Hydrophones in observation borehole
- —In each perforated interval
  - U-tube sampler
  - Pressure/Temperature sensor

Frio II Seismic Monitoring (As Installed Sep. 2006)
Source: 1657 m (5437 ft) Sensors1630-1680 m (5349-5512 ft) with 6 m gap



Frio II Seismic Monitoring (As Installed Sep. 2006)
Source: 1657 m (5437 ft) Sensors1630-1680 m (5349-5512 ft) with 6 m gap



Injection Well Equipment

Packer

Seismic Source

CO2 Injection tubing

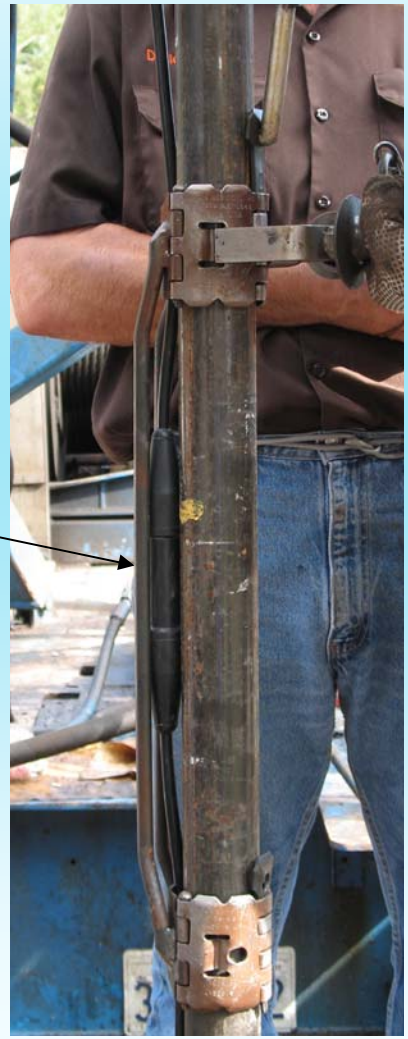
Collocated U-Tube and Seismic Source

Installation of U-tube and Seismic Source on 2 3/8” tubing

Rolls of tubing for U-tube

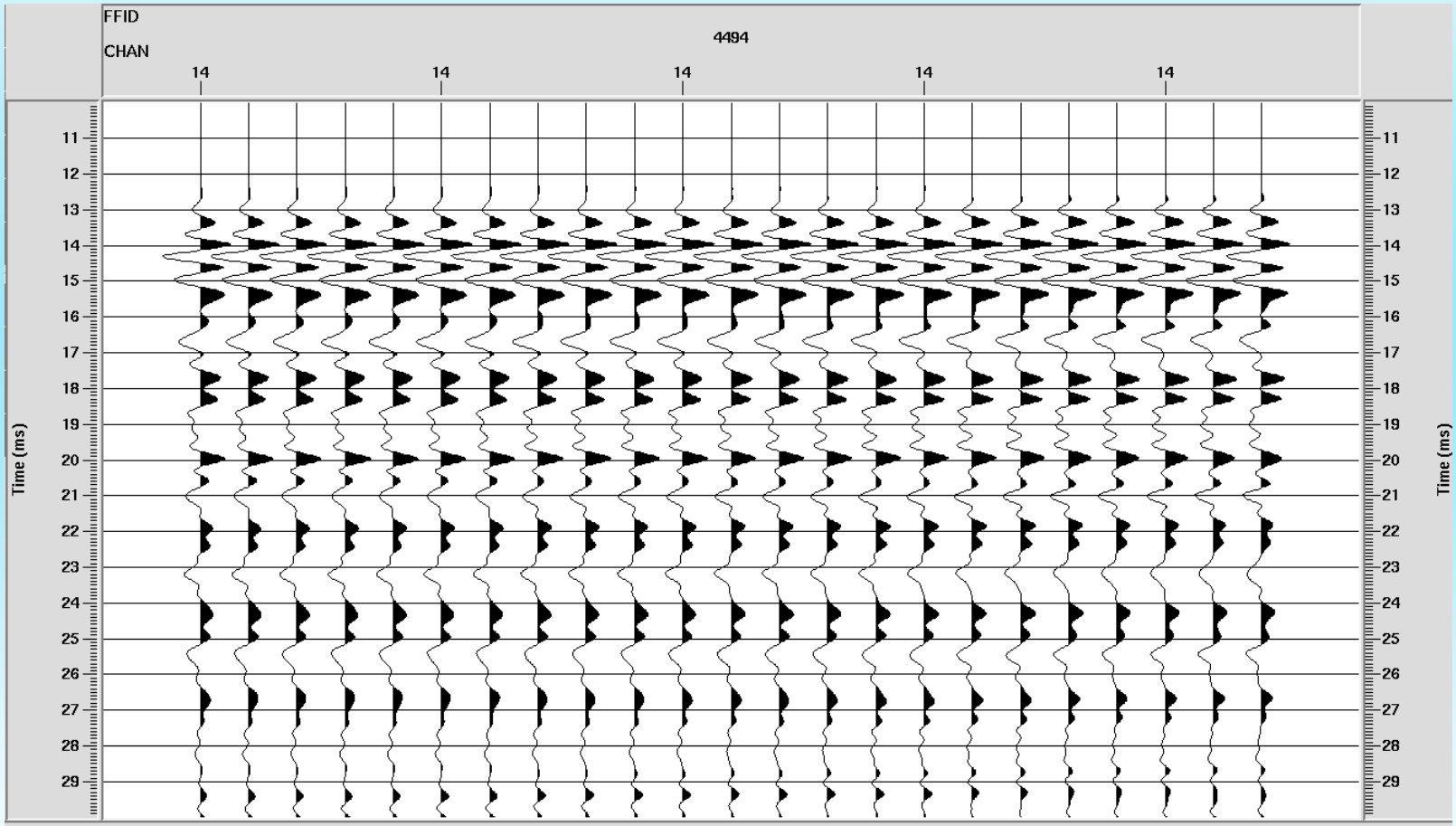
Seismic Sensor (Hydrophone) Inside Protective Clamp

Hydrophone



Pre Injection Monitoring Channel 14 One recording every 2.5 minutes

Clock Time (1 Hour total)

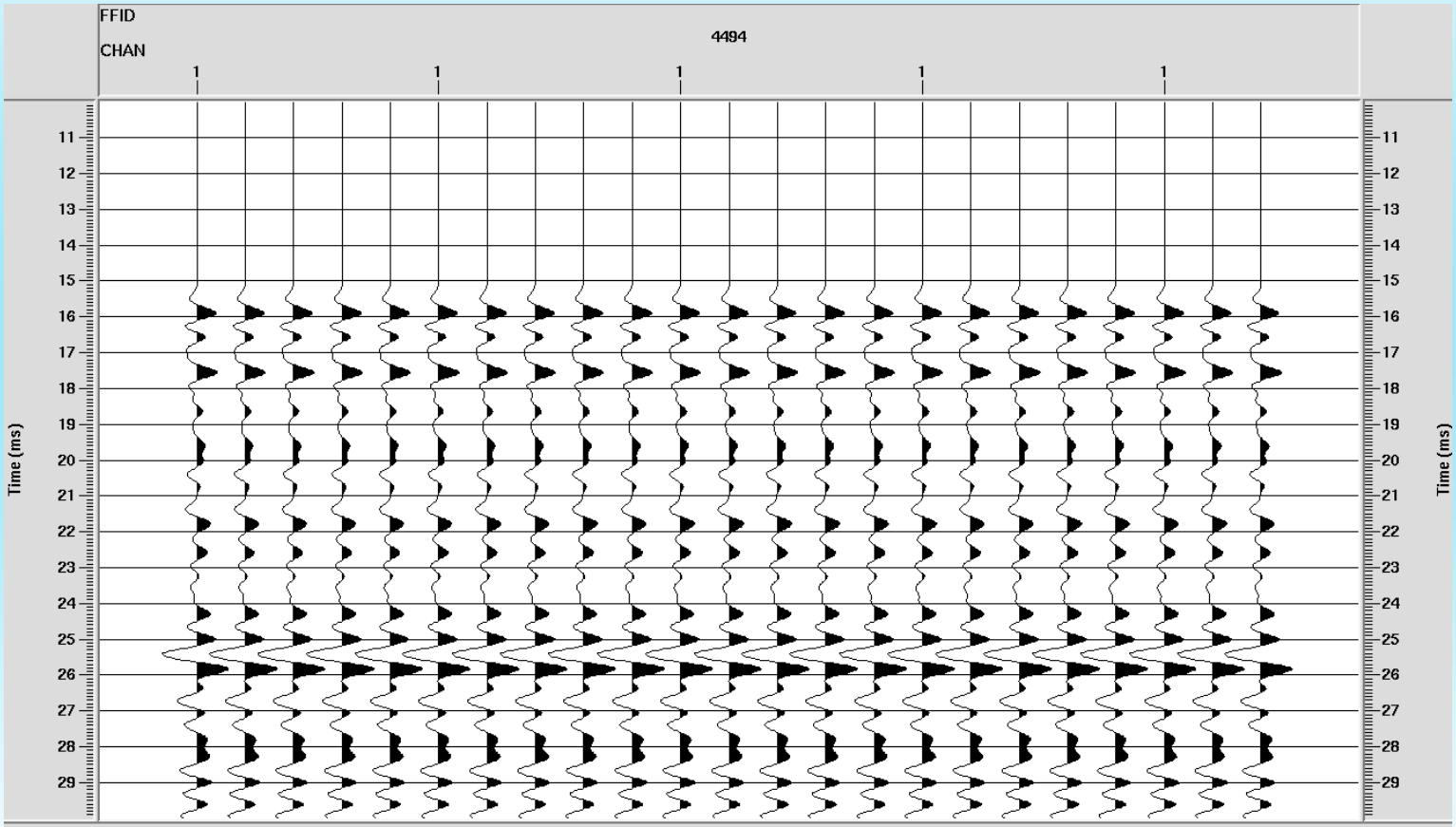


Record time (ms)

Note: Expected Change due to CO2 ~ 1.5 ms

Channel 1 (Bottom) PreInjection

Clock Time (1 Hour total)

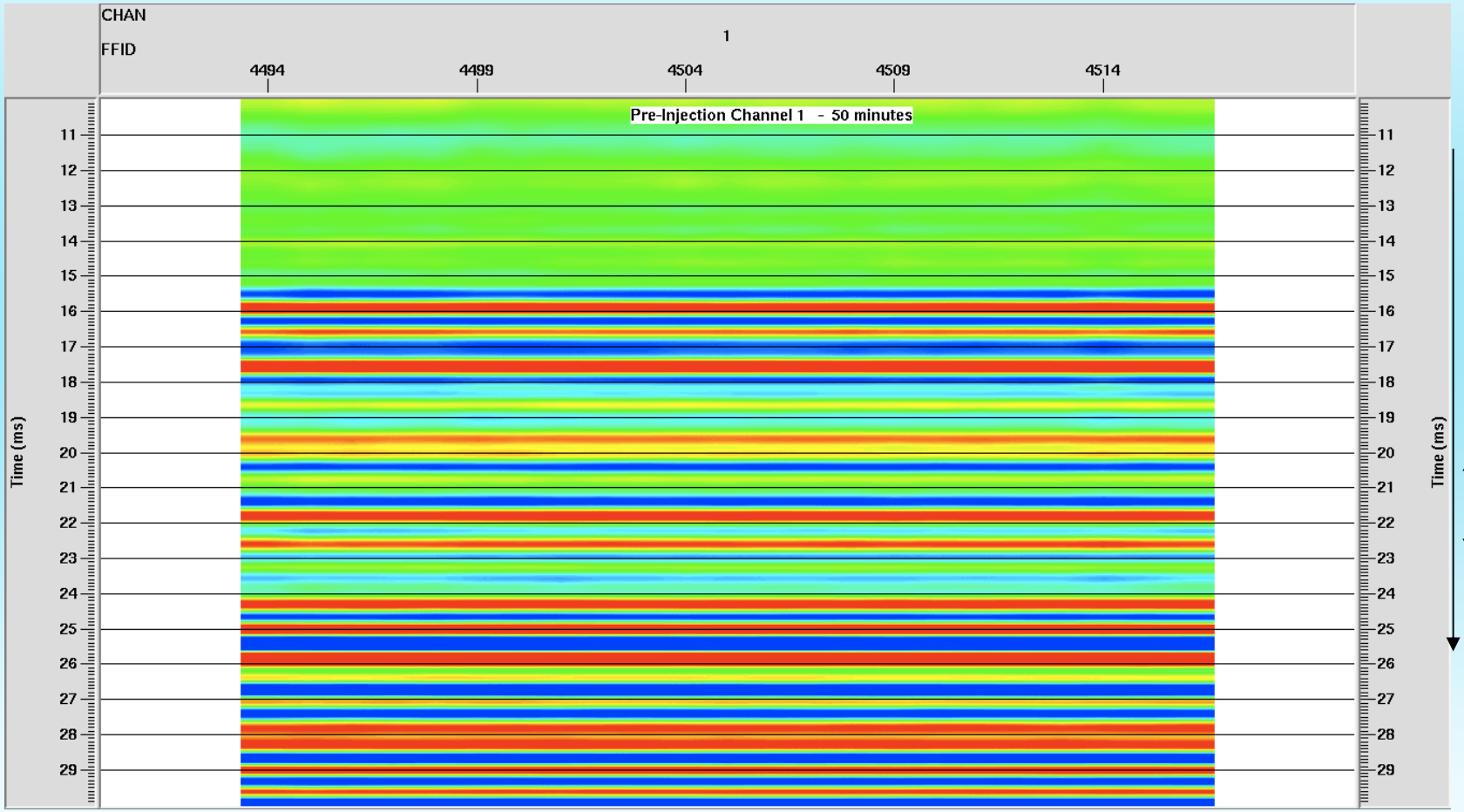


Record time (ms)

Note: Expected Change due to CO2 ~ 1.5 ms

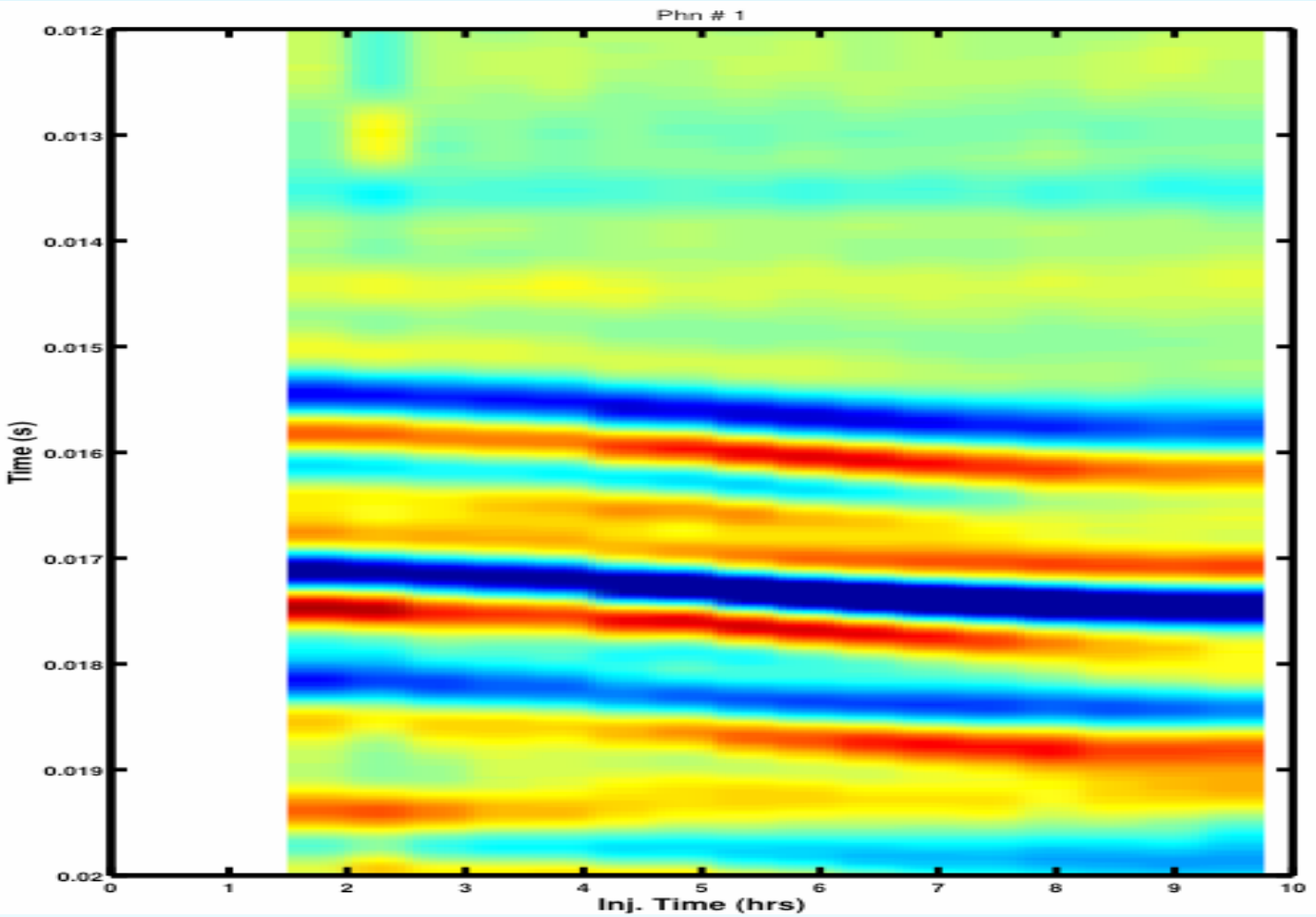
Channel 1 (Bottom) PreInjection Color Amplitude Display

Clock Time (1 Hour total)



Note: Expected Change due to CO2 ~ 1.5 ms

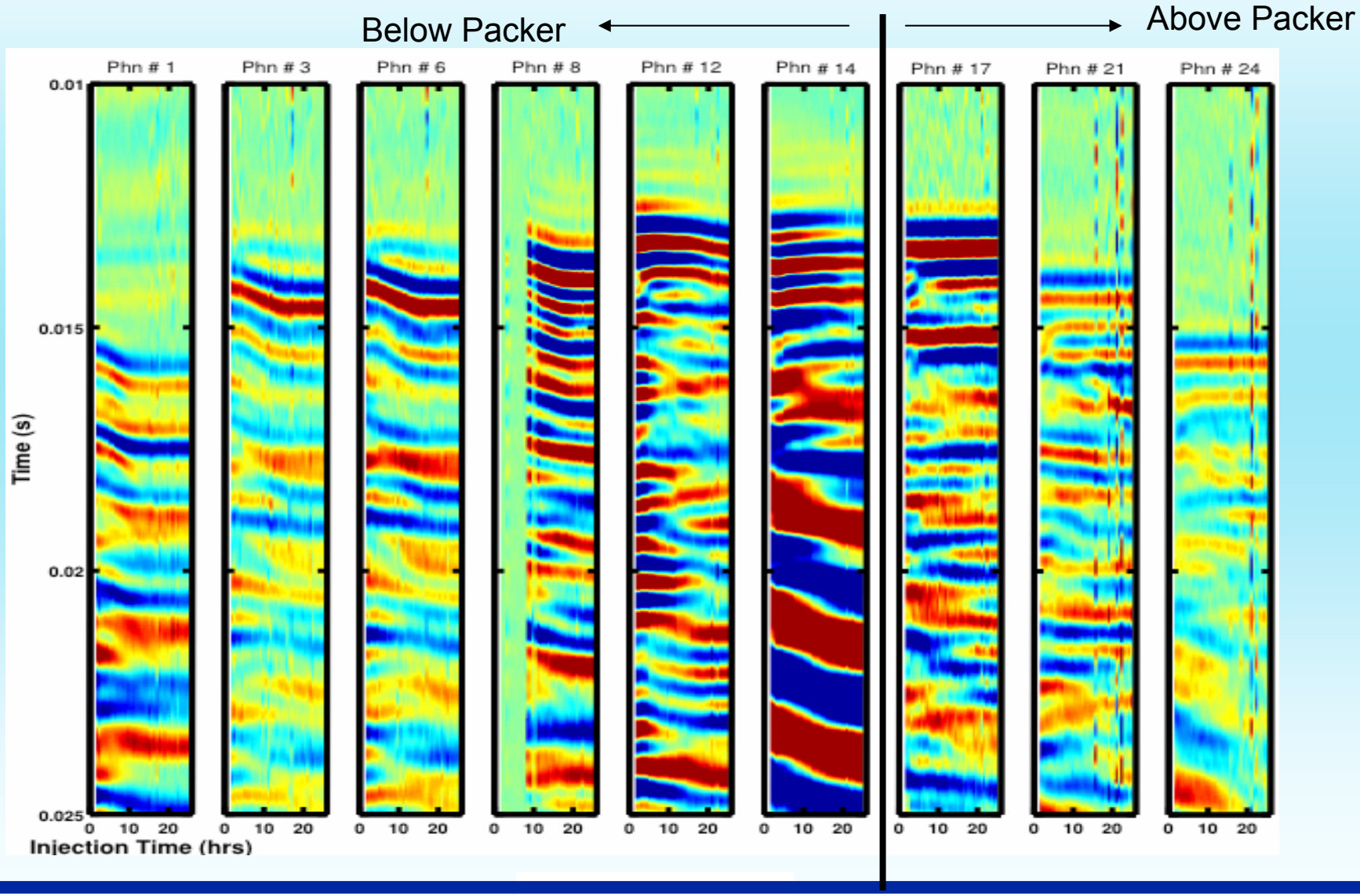
Channel 1 (Bottom)



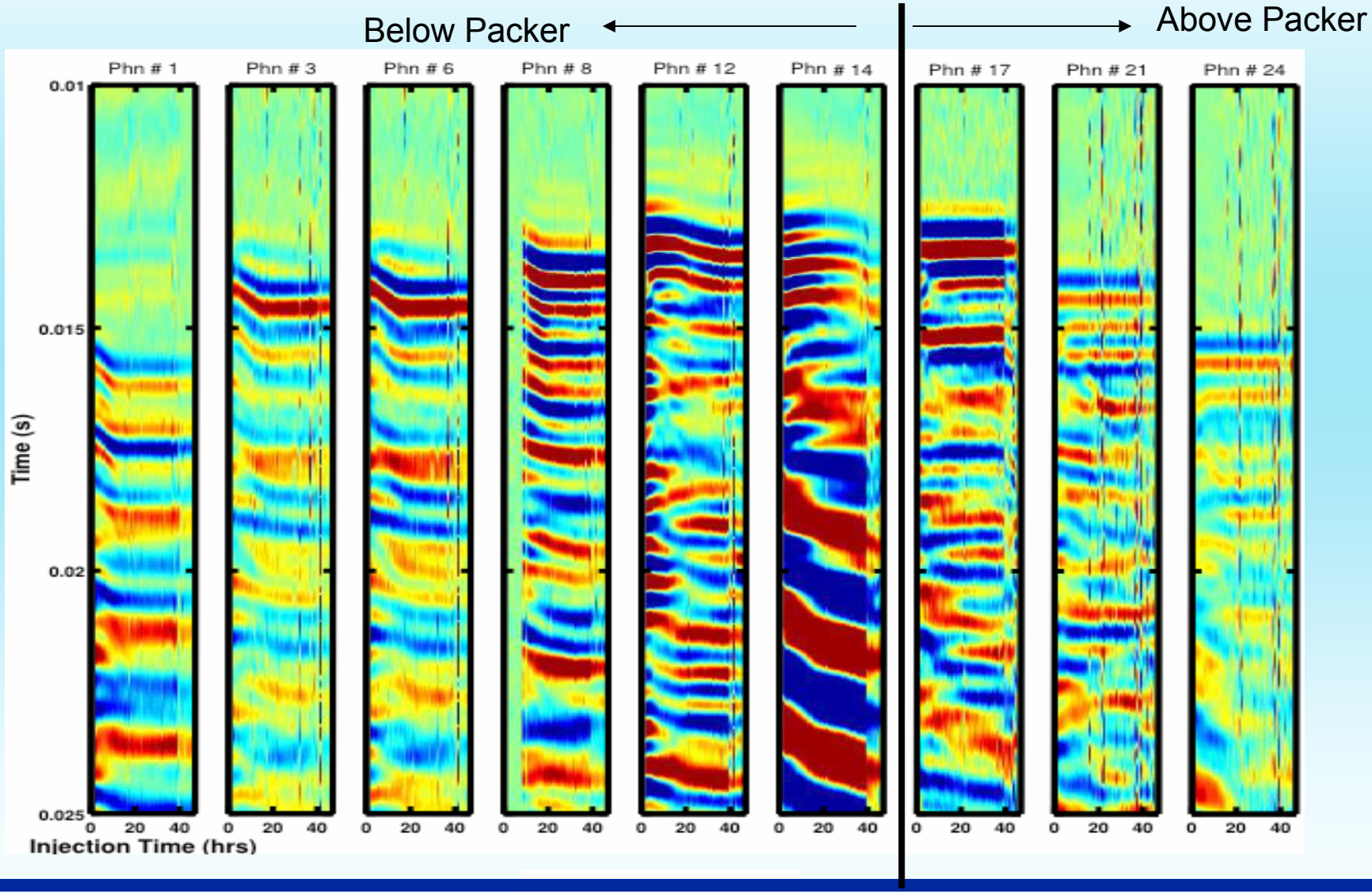
Record time (ms)

Clock Time (10 Hours total)

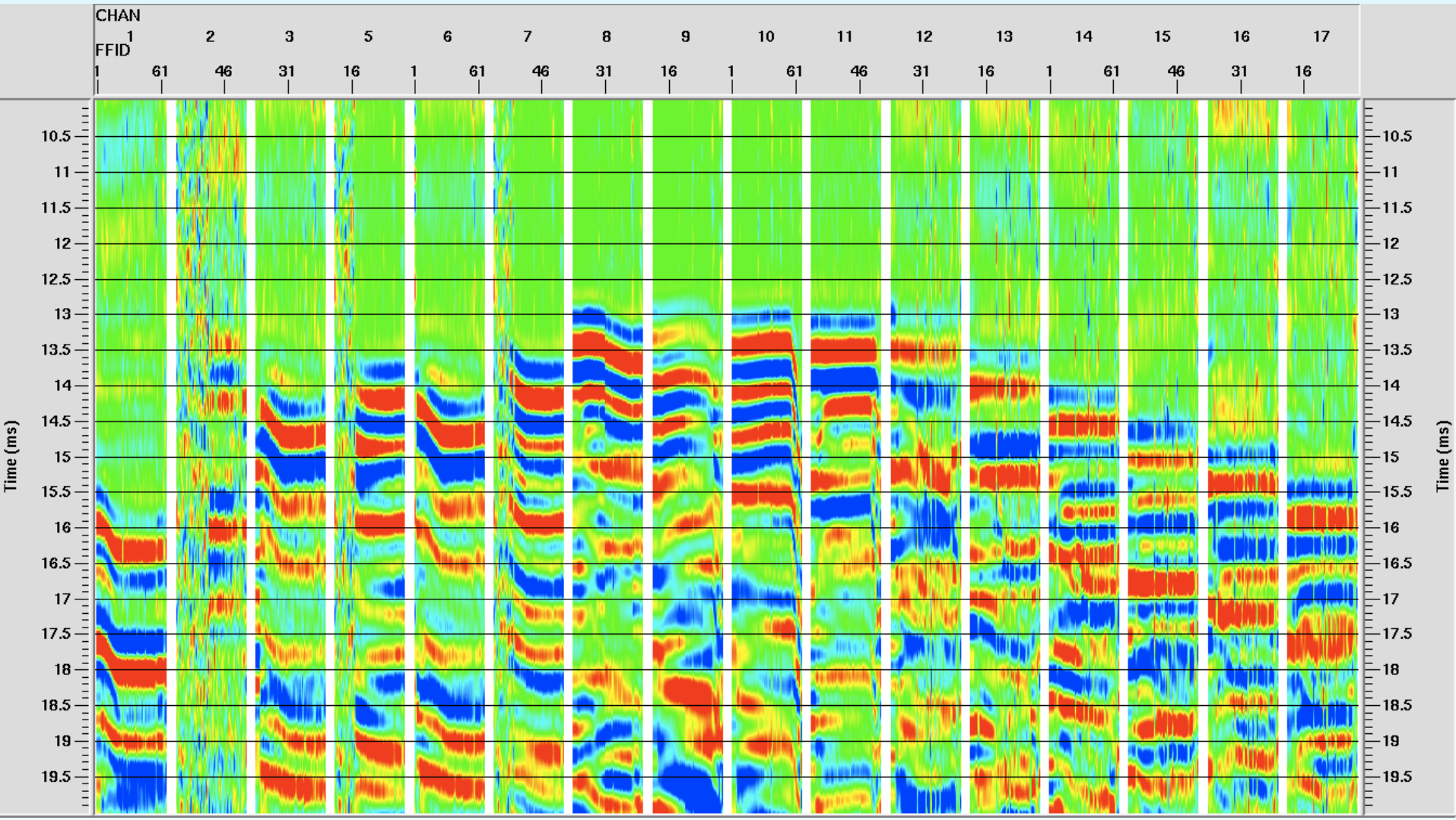
9 Channels 25 Hours



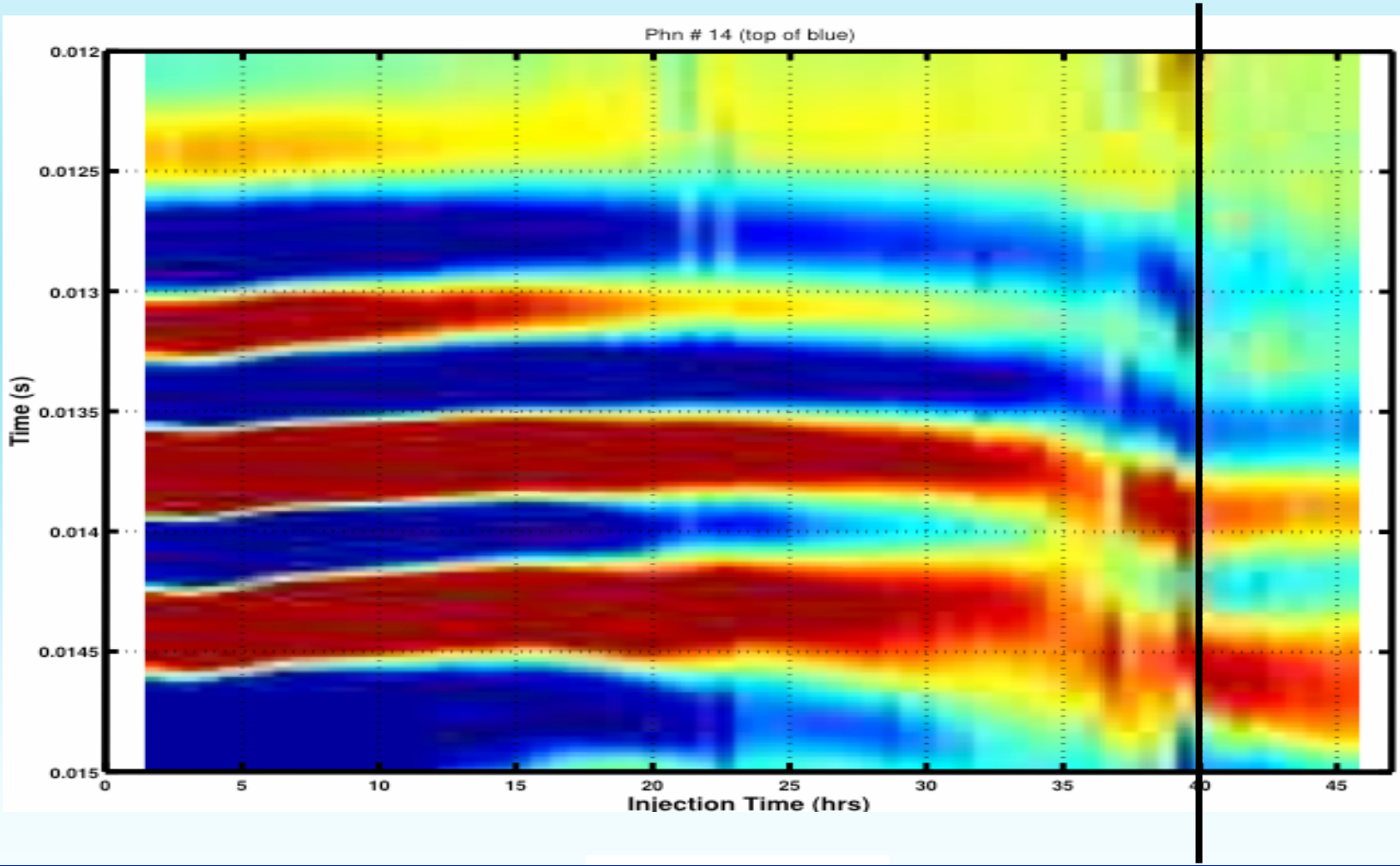
9 Channels 45 Hours



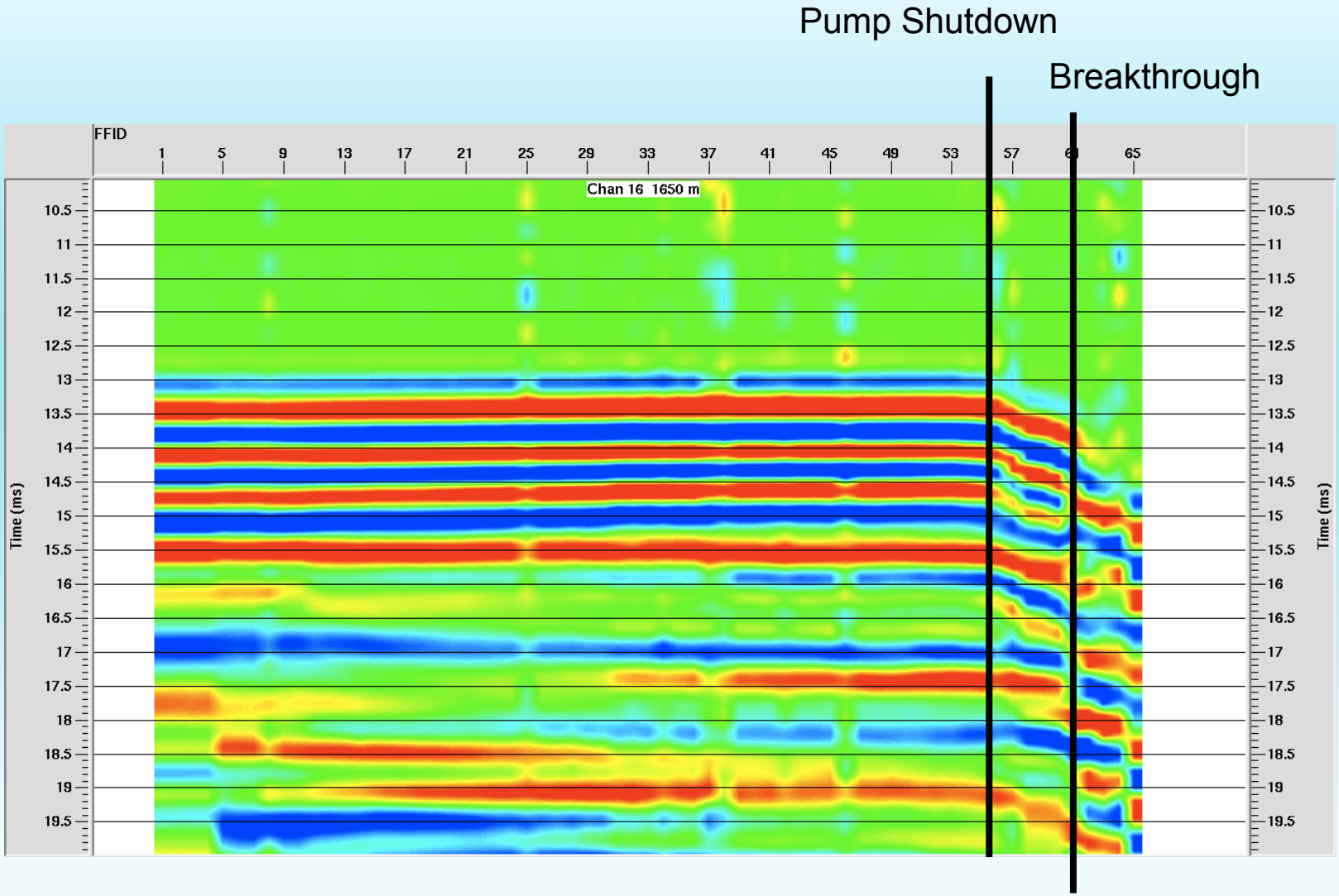
All Channels - 60 Hours



Channel 14 (Top of Sand) 45 Hours



Sensor 1650 m (5413’) Top Sand



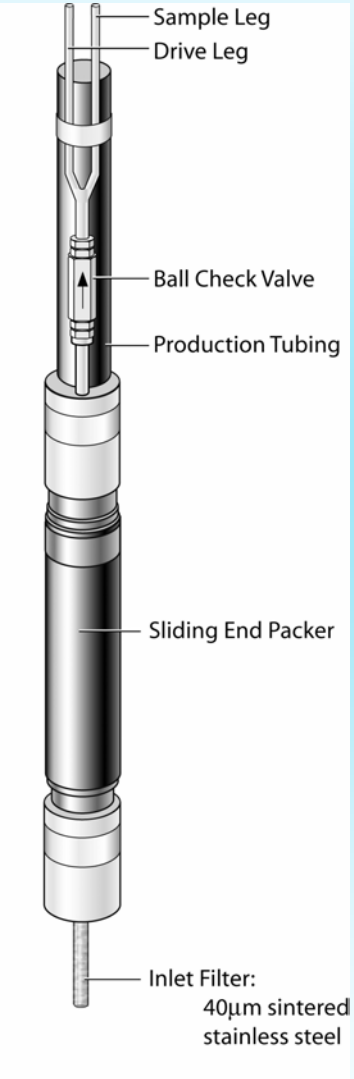
Geochemical Sampling Requirements for Frio I & II Pilot Study

- Minimal perturbation to flow field
- Sample recovery of sufficient volume to introduce fresh fluid to wellbore
- Multiphase constituents preserved and representative of downhole conditions
  - —Brine/supercritical CO_2
  - —No degassing
- Quantify brine/CO_2 ratio
- High frequency (hourly?) for assessment of CO_2/tracer arrival at observation well

Sampling Technologies Considered and Rejected

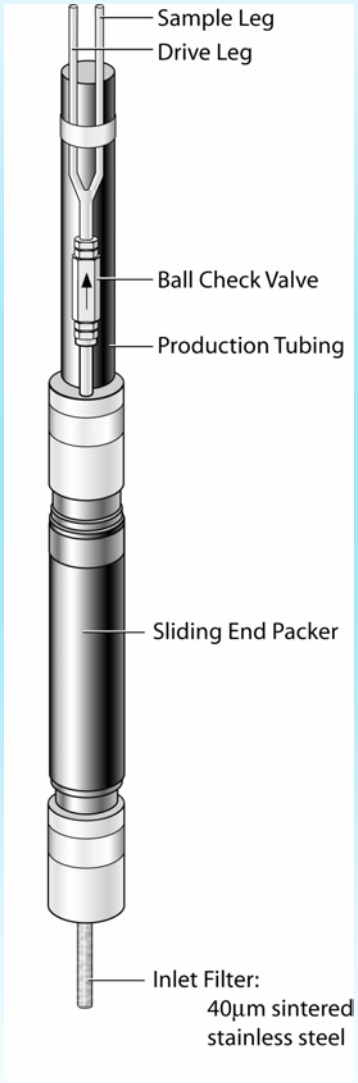
- **Downhole wireline sampling** (used for baseline/postinjection monitoring)
  - Expensive
  - Small sample size (other method needed to introduce fresh fluid to wellbore)
  - Difficult/risky to perform as 24/7 operation
- **Gas lift**
  - Hard to control lift rate
  - Perturbation to flow field
  - Difficult to recover downhole conditions
- **Submersible pump**
  - Not applicable to multiphase fluids
  - Interference with seismic
  - Perturbation to flow field

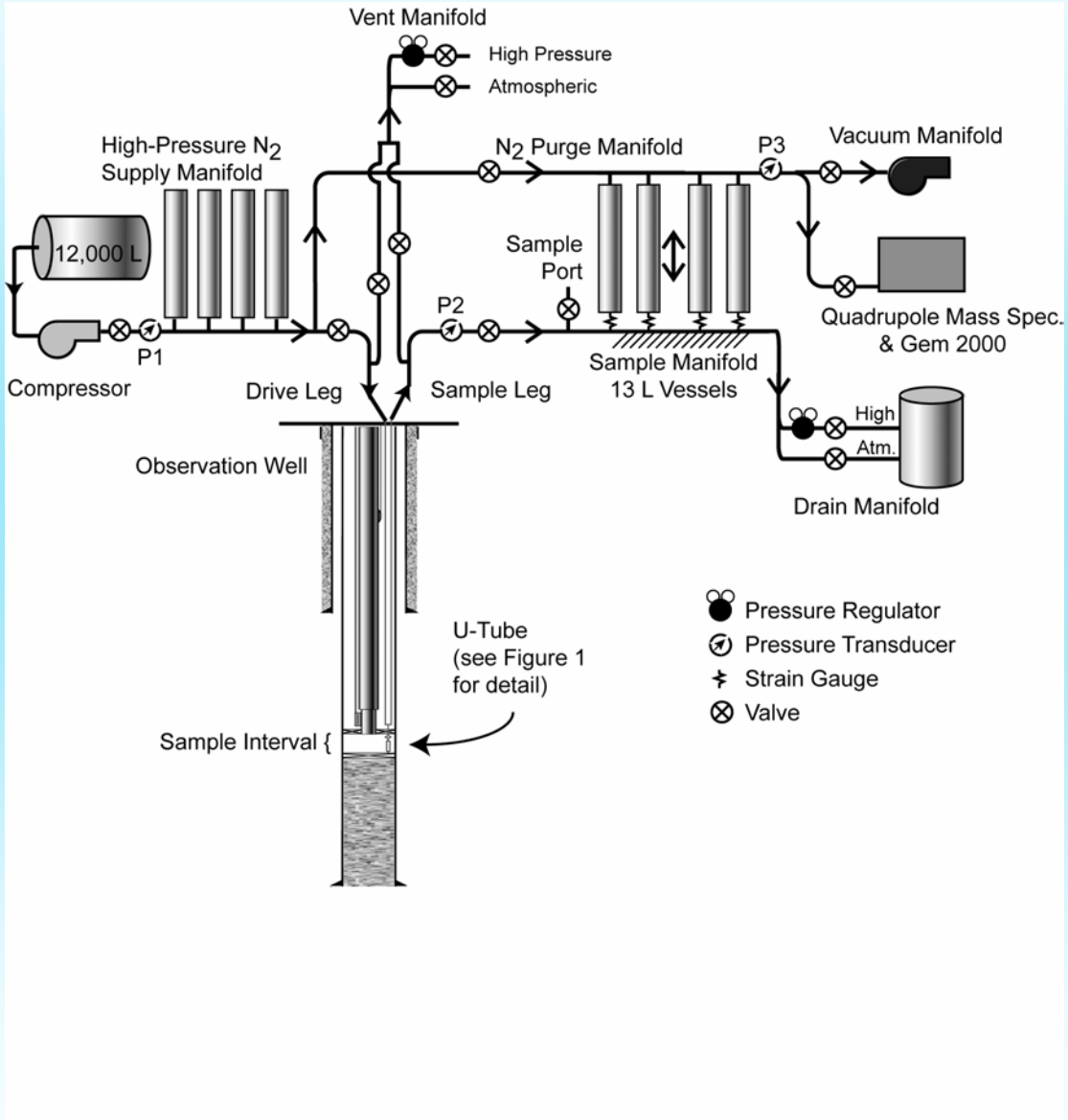
New Sampling Methodology based on old technology—U-Tube Sampling



- Large volume samples -52 liters
- No degassing
- High purity – no contamination from air
- Collection of multiphase fluids
- High frequency ~70 minute cycle time

New Sampling Methodology based on old technology—U-Tube Sampling

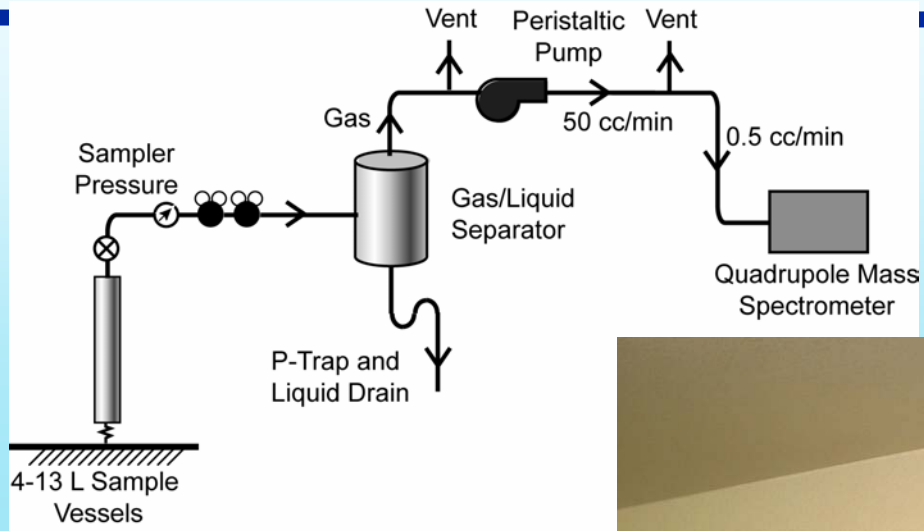


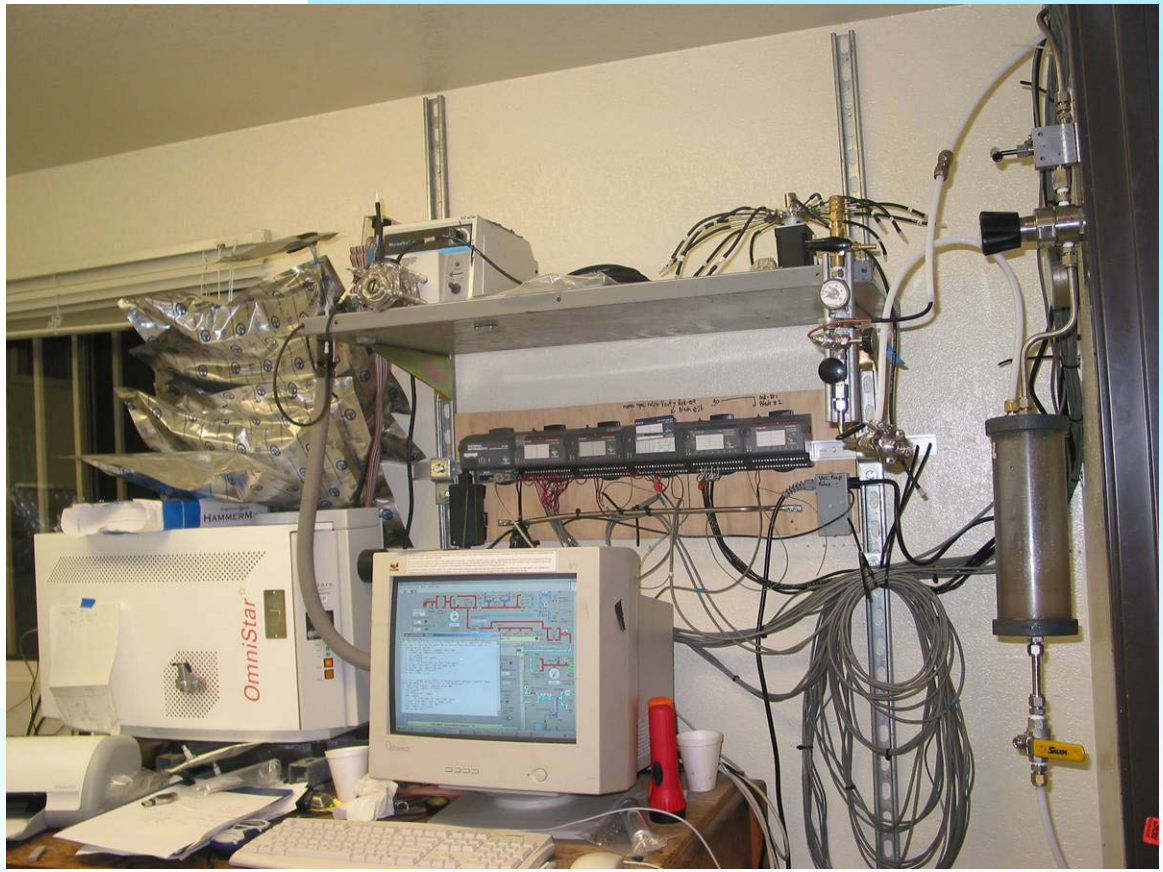


Frio II Geochemical Sampling

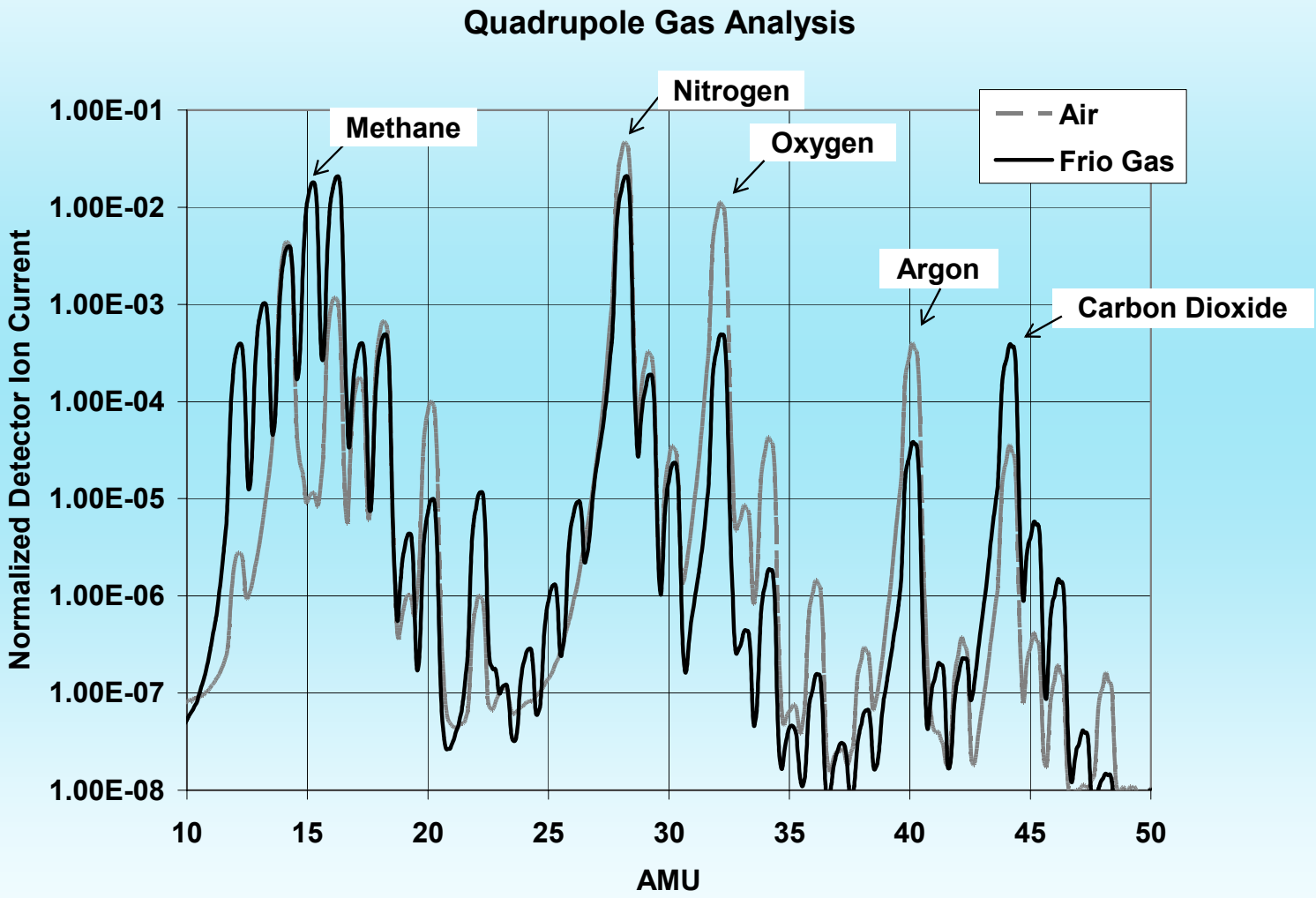
- On-line high pressure pH, EC
- Liquid samples for
  - Aqueous chemistry (USGS)
  - PFT/Difluoro- Dibromo-methane tracers (ORNL/UT)
  - Fluorescein tracer (LBNL)
- Gas samples for
  - CD_4 Tracers (CO2CRC)
  - Quadrupole Mass Spectrometer Analysis
    - CO_2/CH_4
    - $Kr/Xe/SF_6$ Tracers (LBNL)

Gas Analysis—Quadrupole Mass Spectrometer

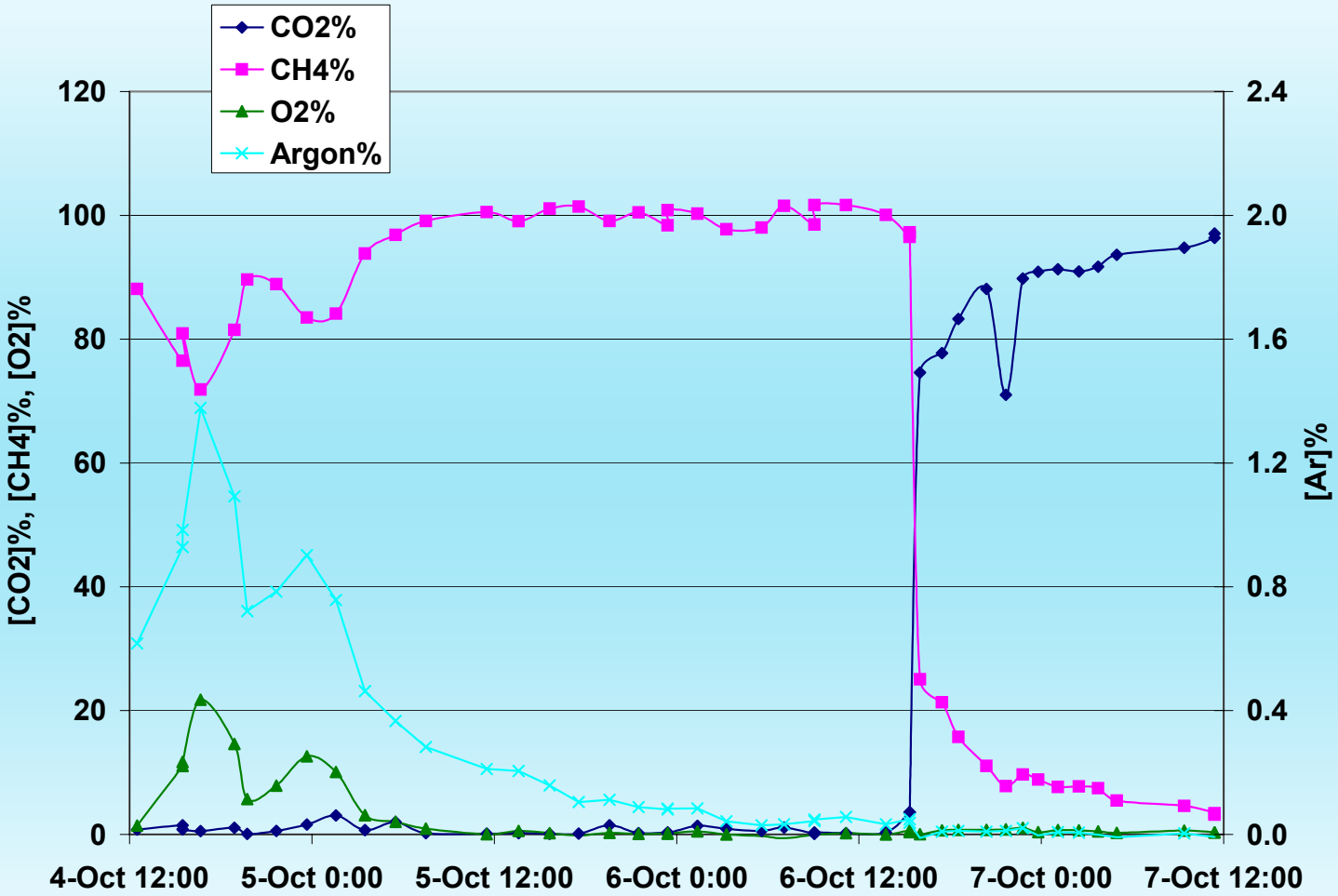




Mass Spectrometer Data

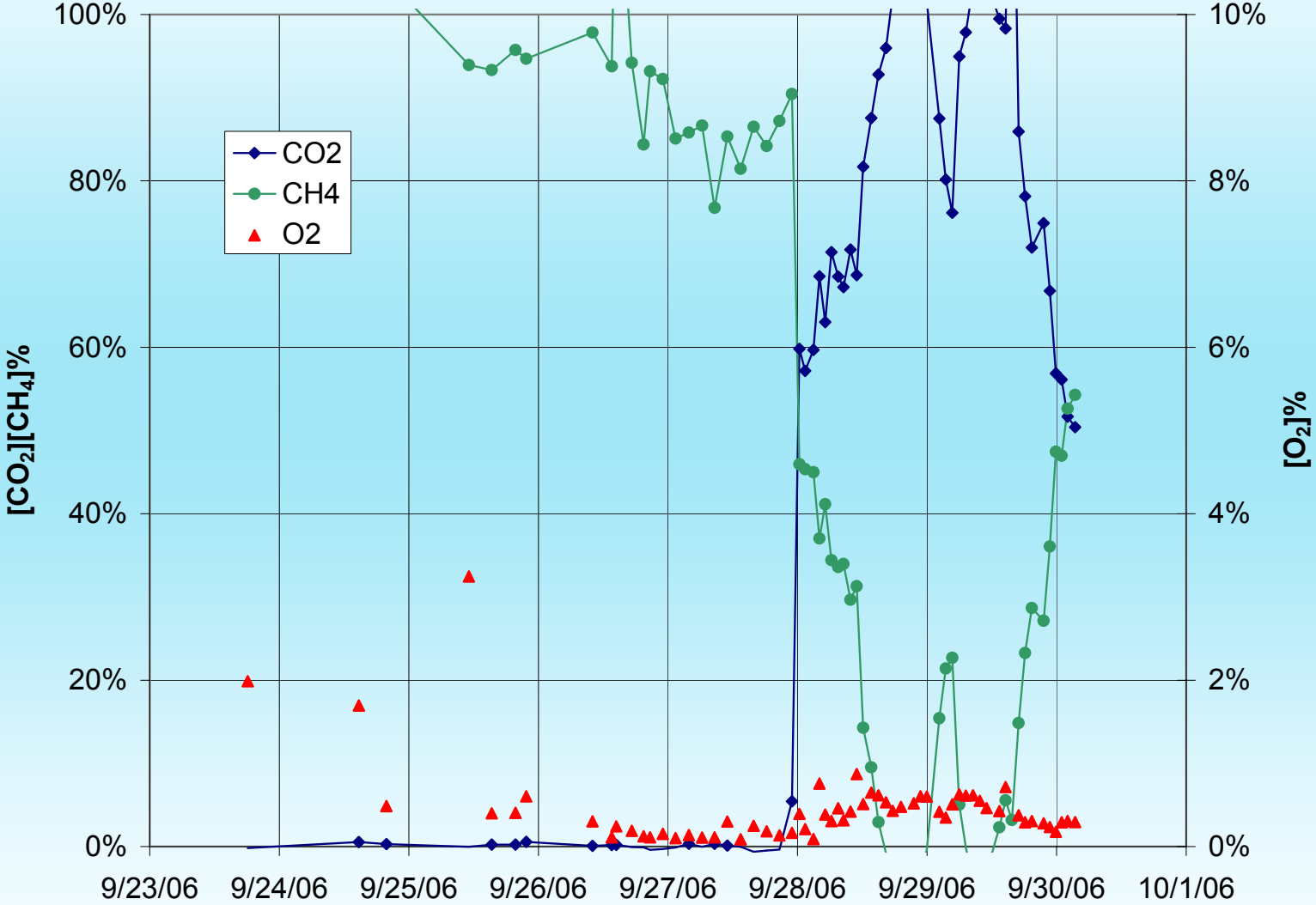


Results from Frio I

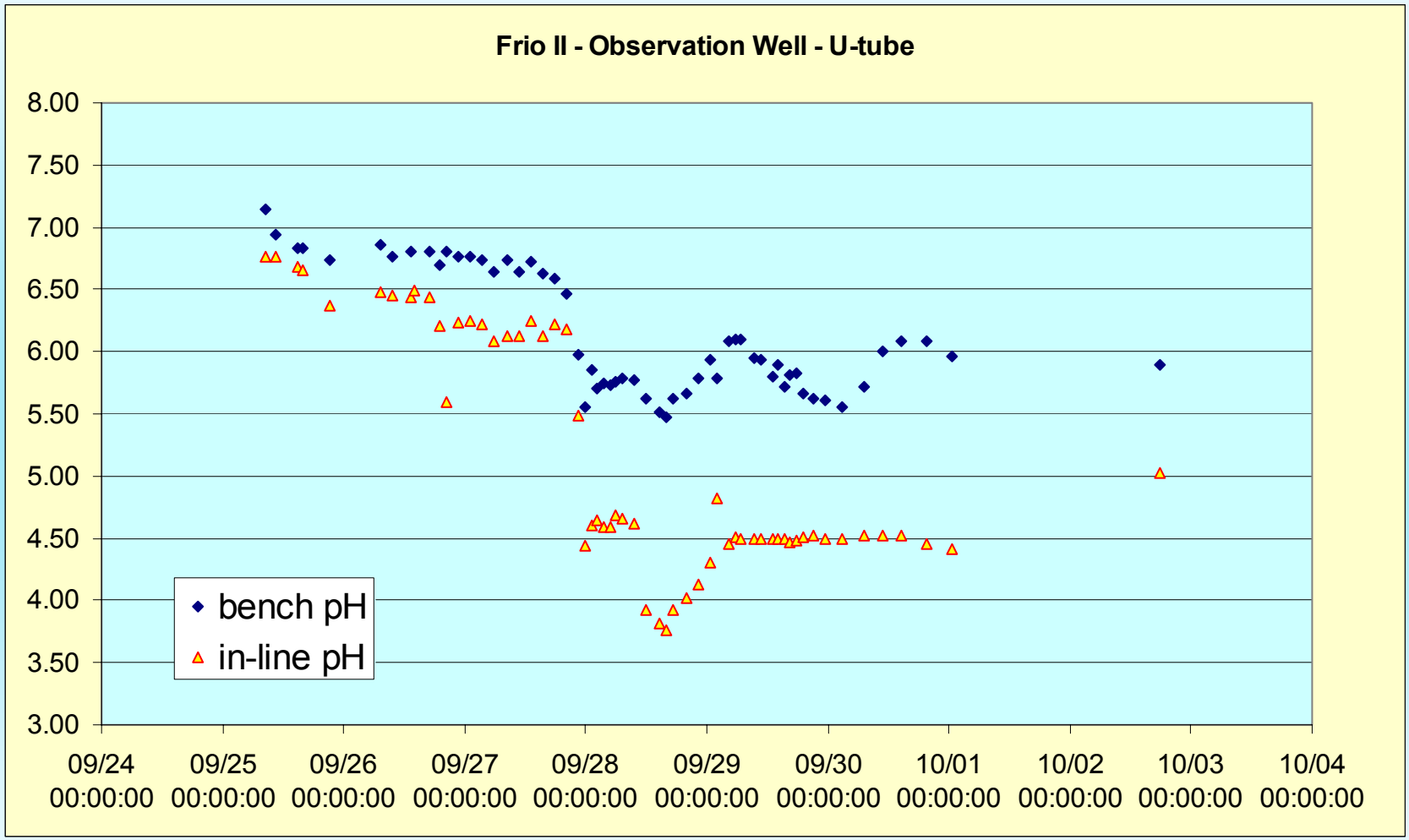


Ref: Freifeld, B. M., et al., (2005), The U-tube:
A novel system for acquiring borehole fluid samples from a deep geologic CO2 sequestration experiment, J. Geophys. Res., 110, B10203, doi:10.1029/2005JB003735.

Results from Frio II

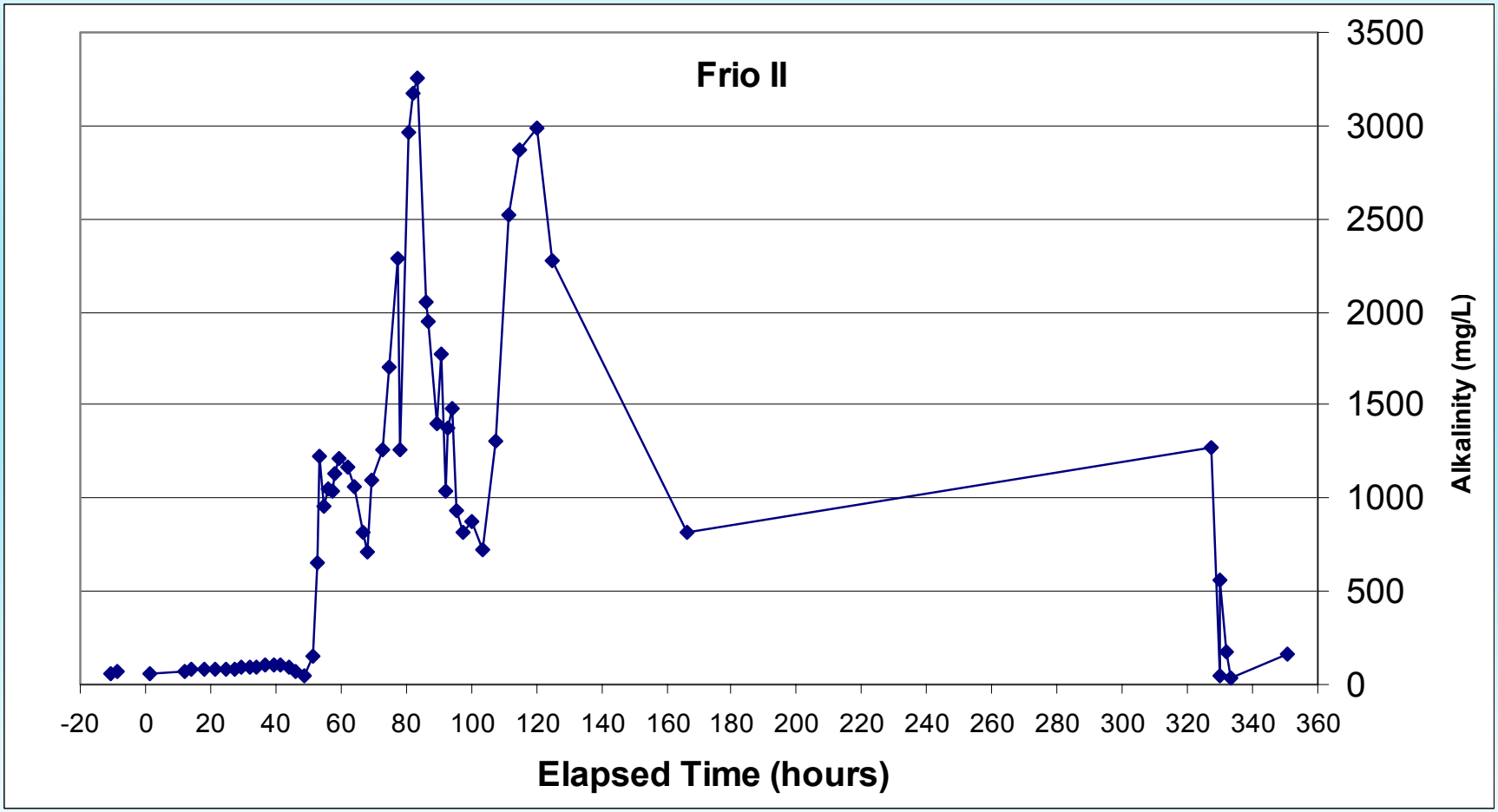


High Pressure/Bench pH Measurements



preliminary

Frio II Alkalinity

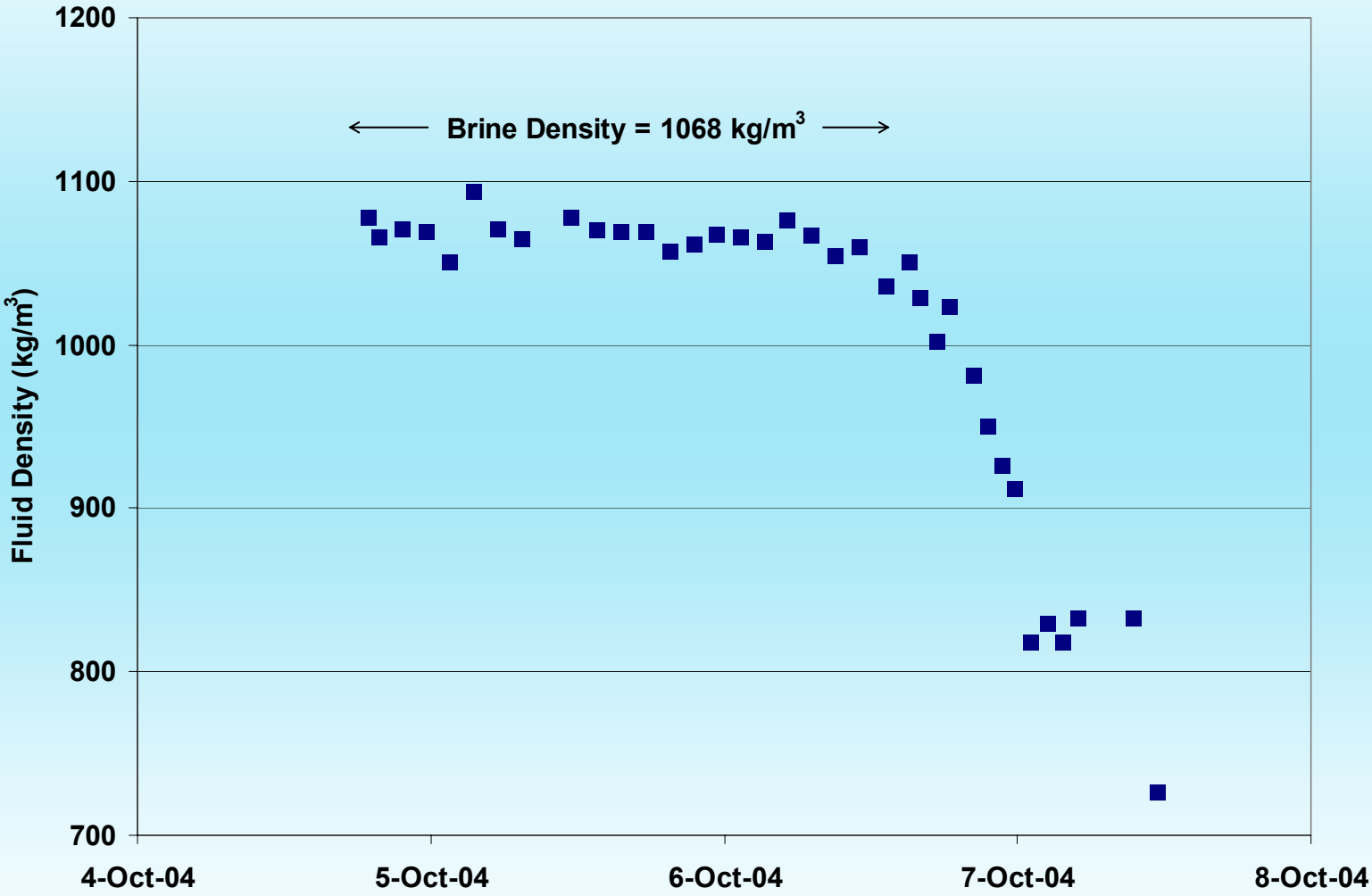


Determination of Sample Fluid Density

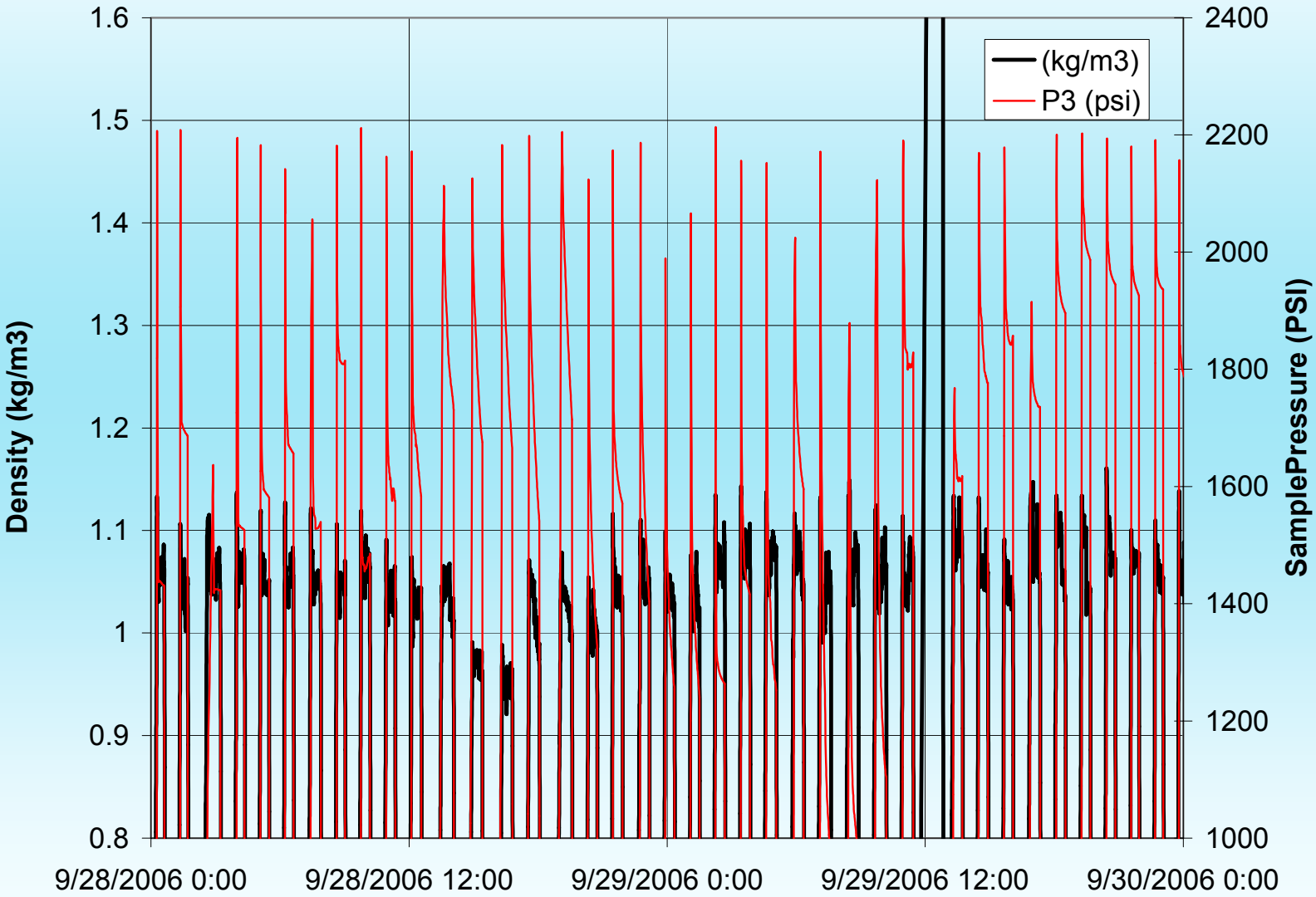
Sliding Sleeves

Strain Gages

Frio I Sample Density



Frio II Sample Fluid Density

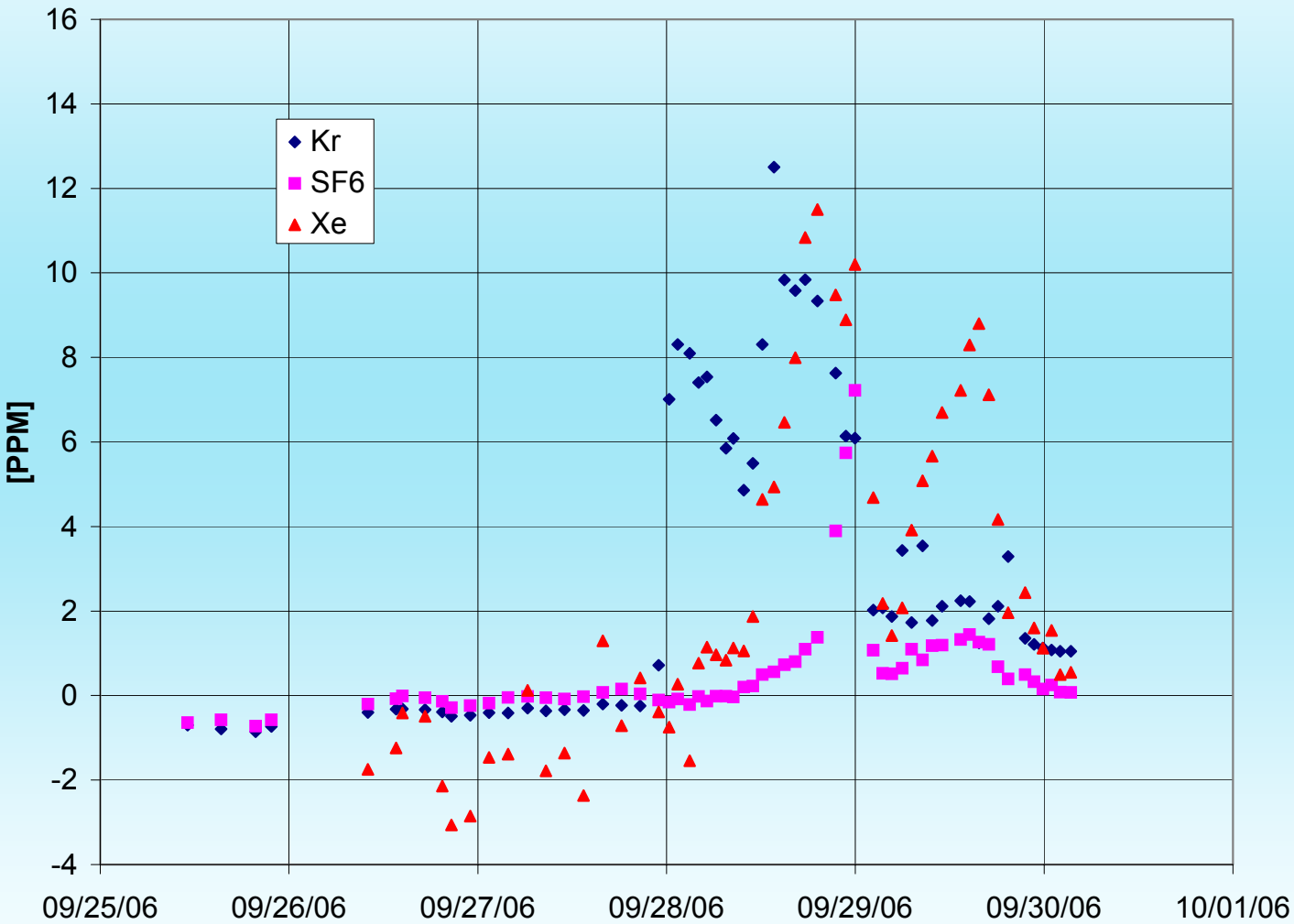


Tracer Testing

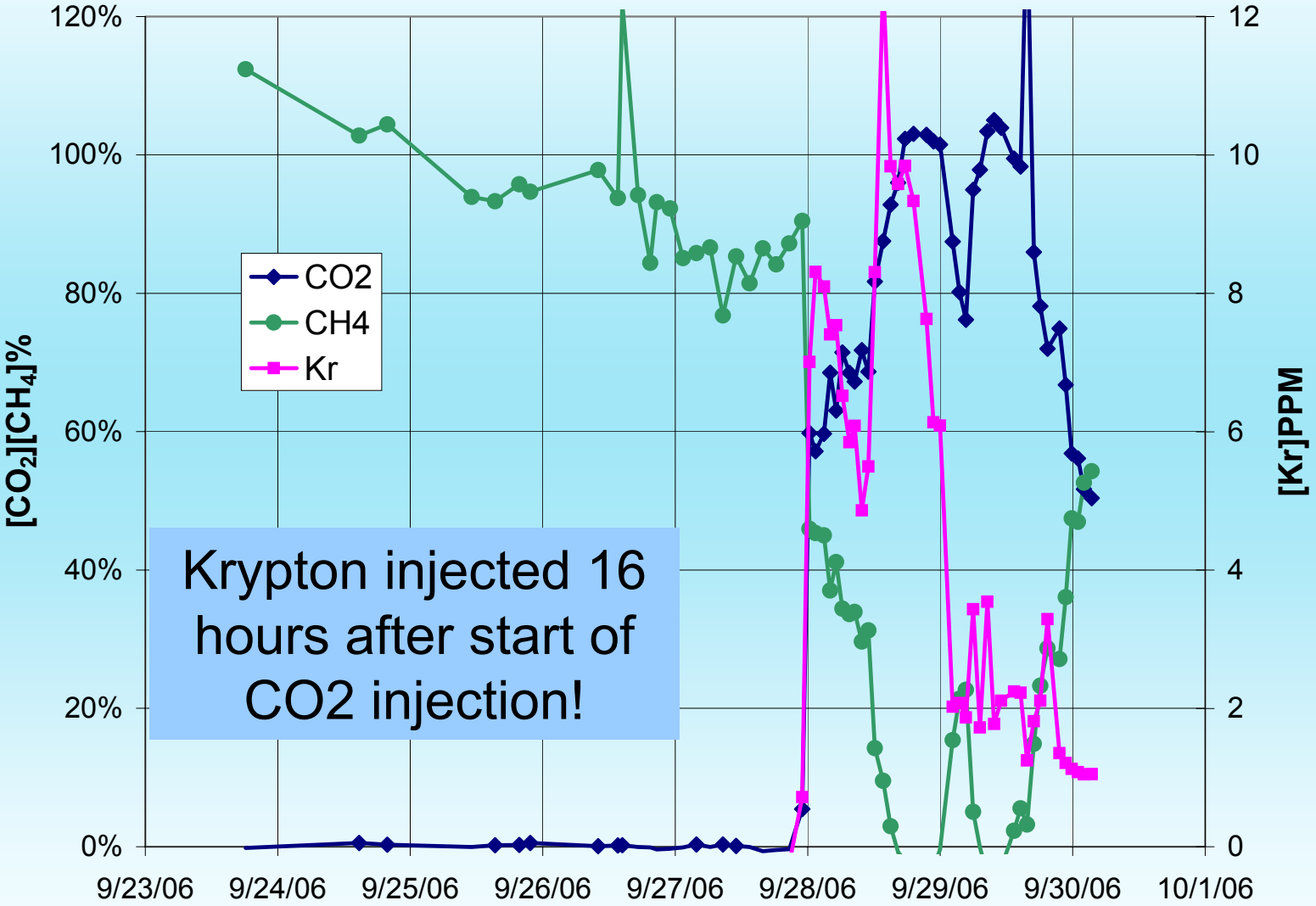
Tommy Phelps, Phil Szymcik –ORNL
High pressure piston pumps
for Perfluorocarbon Tracers

Jim Underschultz –CSIRO Petroleum
collects isotubes for CD_4 analysis

Frio II Results-Evidence of Rapid CO_2 Dissolution



Frio II Results-Evidence of Rapid CO_2 Dissolution



What does the future hold for well-based methods?

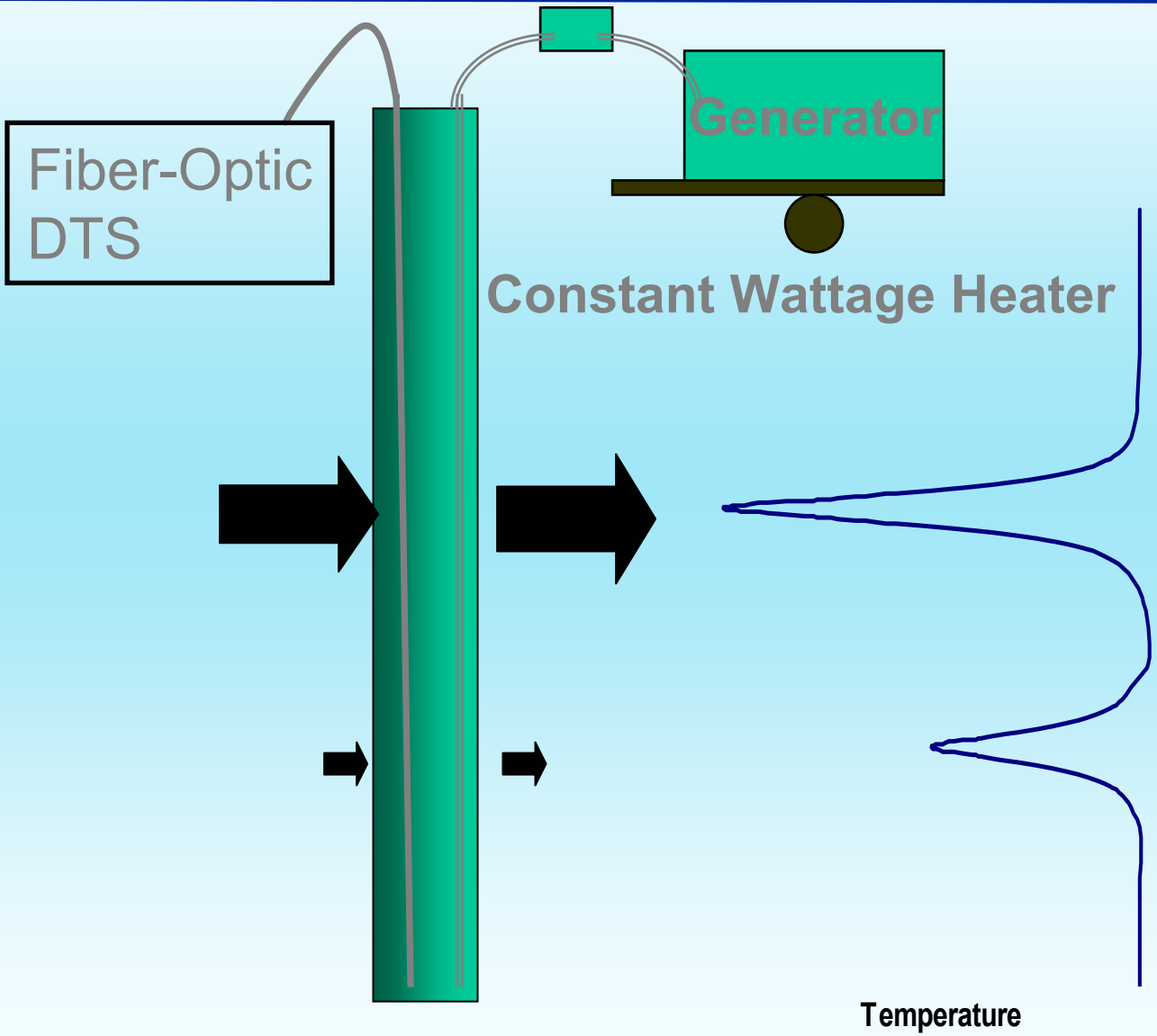
- Multiple completions in each borehole
- Multifunction completions
  - —Electrical
  - —Seismic
  - —Hydrologic/Geochemical sampling
  - —???
- Fiber-optic based sensors
  - —Distributed Temperature Sensors
  - —Down-hole geochemical measurements
  - —Advective flux measurement
- Vigilence required to incorporate technologies from other fields as they develop

Example of technology not yet applied to monitoring CO_2—DTPS

- Application—monitoring of conditions at Yucca Mountain Nevada, USA for High-Level Radioactive Waste storage
- Completion consists of:
  - —4 U-tube samplers
  - —Distributed Thermal Perturbation Sensor (DTPS)

- Similarity to M&V CO_2 sequestration
  - —Regulatory driven activity aimed at waste isolation
  - —Long-duration monitoring(~100 yrs)
  - —Economic drivers—high well cost⇒sparse data Therefore need to maximize data from a single wellbore

Distributed Thermal Perturbation Sensor

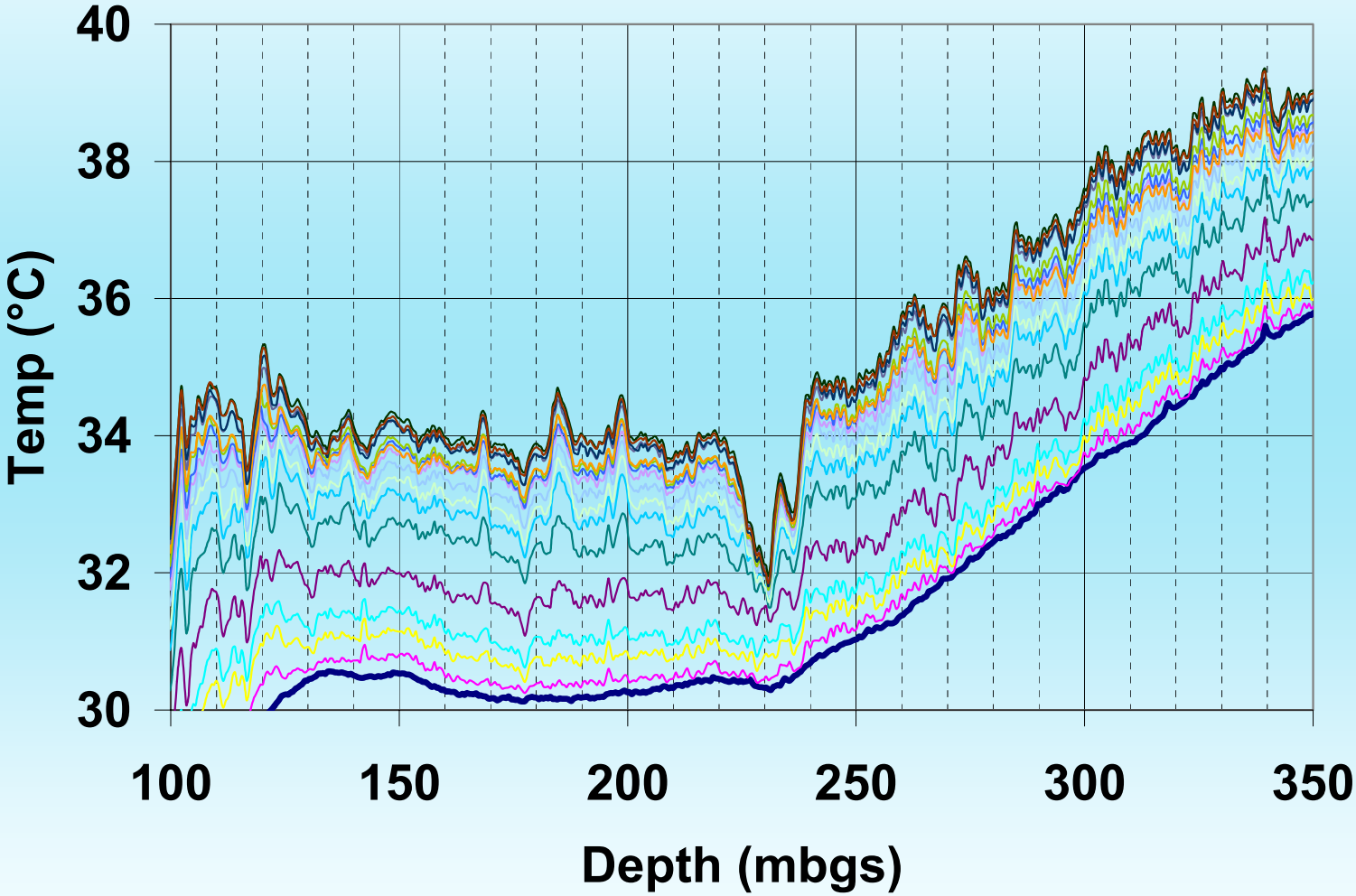


Installation of DTPS with 4 U-tubes

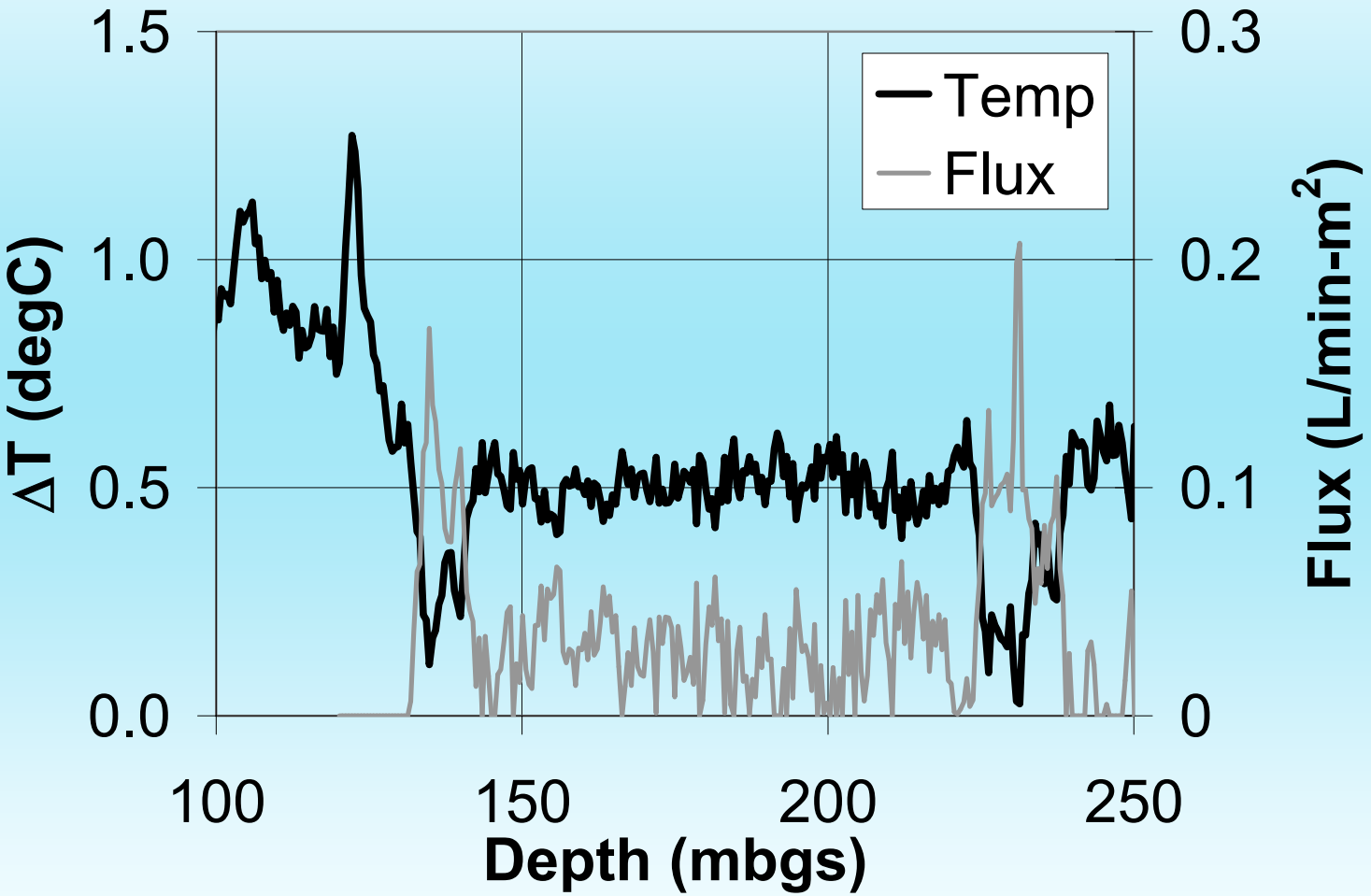
Getting U-tube Ready for Deployment

Low Tech Installation

DTPS Heating Data



Data Converted into Advective Flux



Frio II Lessons Learned

- Integration between monitoring technologies is key to success
- Time-lapse seismic cross-hole worked!!!
- Sample fluid location has a large impact on what is measured
  - —Borehole fluid≠formation fluid
  - —Two U-tubes (shallow and deep) should be located to collect samples biased towards gas and liquid
- Do not limit yourselves to “accepted” modalties and methodologies for M&V
- Engineer for simplicity and robustness- Future U-tube deployments will be simpler.

Lessons learned continued

- For pilot scale (scientific) testing all critical processes/parameters need to have a clearly designated technical lead
- Expect the unexpected
  - —Early breakthrough
  - —No breakthrough
  - —All points in between

Logging Techniques for CO_2 Saturation & Well Integrity Evaluation

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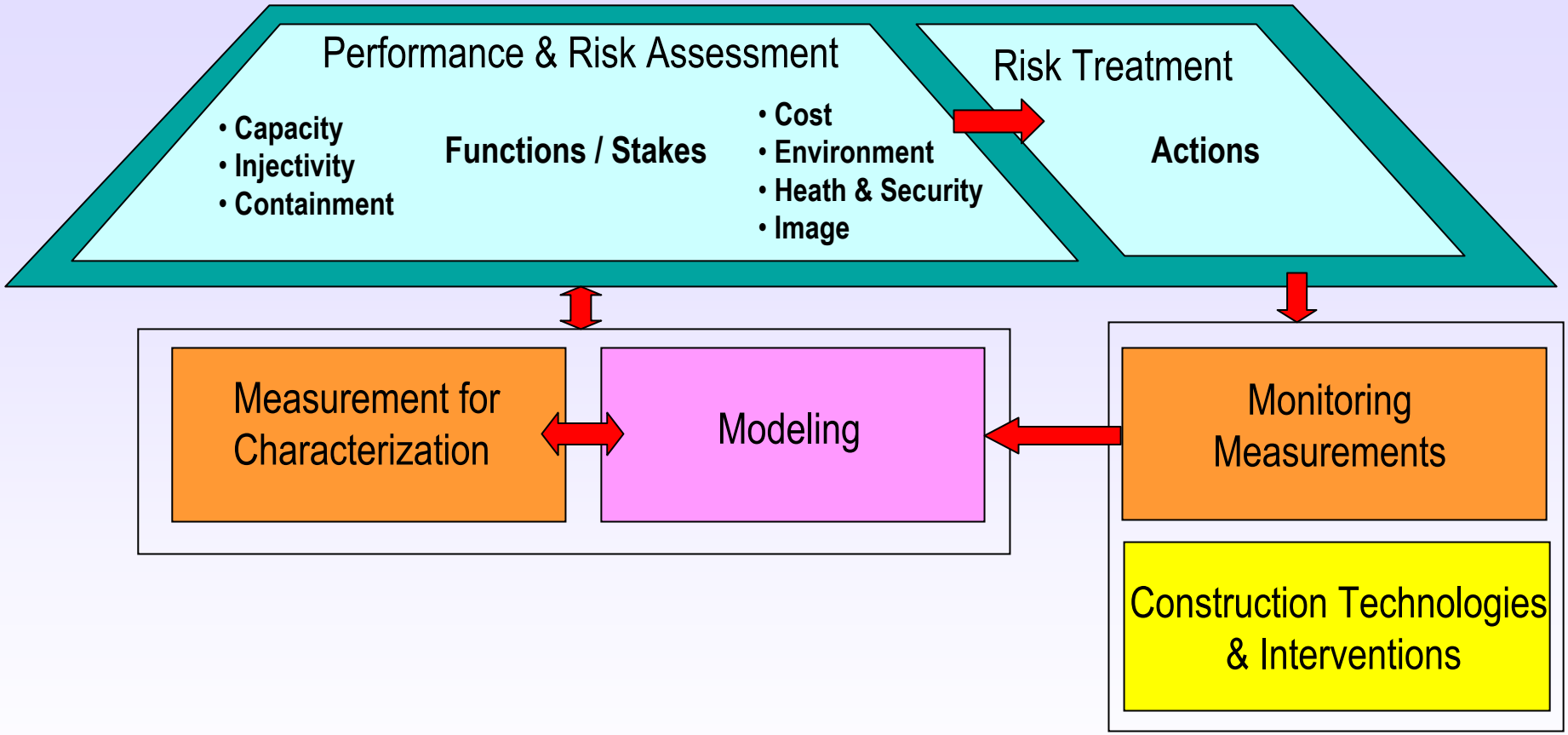
Laurent JAMMES
IEA-GHG Monitoring Network
Melbourne
November 1st, 2006

Schlumberger

Performance & Risk Management for CO2 Storage



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Monitoring Objectives

- **Performance Control**
  - Injection efficiency
  - CO2 in place – displacement & trapping
  - Sealing
- **Risk Control**
  - Containment losses
  - Contamination (shallower aquifers…)
  - Releases on surface - accumulation

Dynamic modeling calibration for reliable long-term prediction of CO2 fate

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Well Monitoring Techniques

- CO2 Saturation Measurements
  - Nuclear
  - Electrical
  - Sonic
  - Sampling
- Well Integrity Evaluation
  - Calipers (corrosion)
  - Electromagnetic (corrosion)
  - Sonic (cement)
  - Ultrasonic (corrosion & cement)

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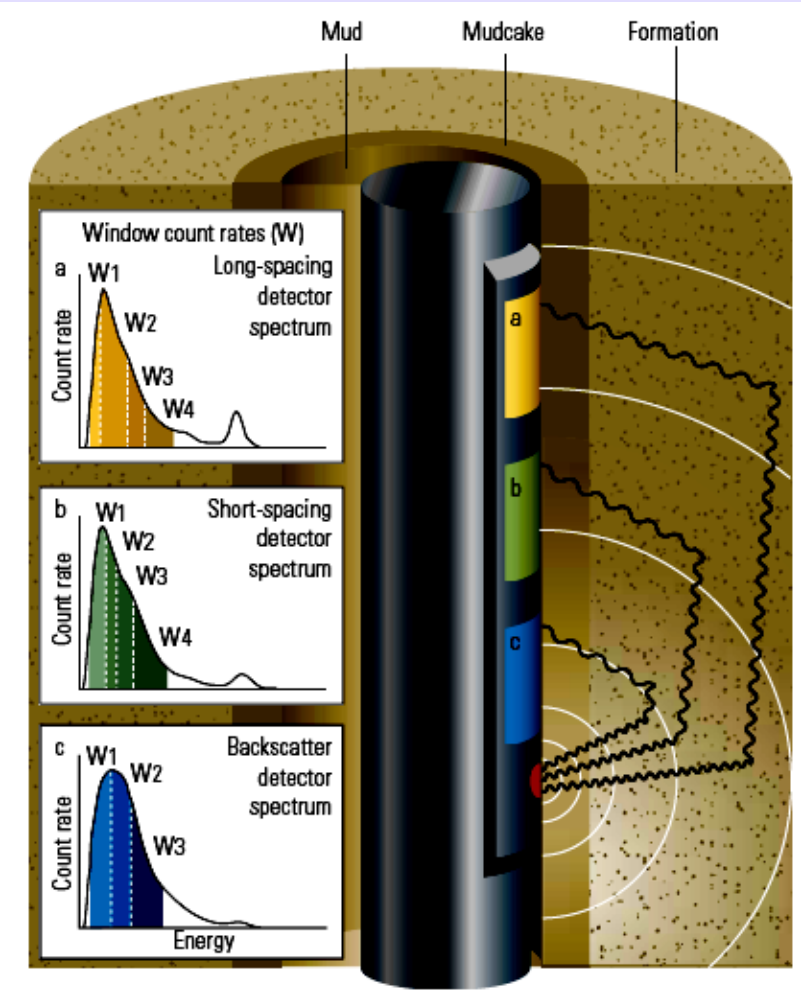
Density

Gamma – Gamma

$$N = No \cdot \exp(-\mu\rho x)$$



N: counting rate for a detector at a distance x from the source
x: source-detector spacing
ρ: density

$$\rho_b = \Phi_D \cdot \rho_f + (1 - \Phi_D) \cdot \rho_{ma}$$

Φ_D: density porosity

Time-Lapse Density Measurement

Baseline: ρ_b

Measurement: ρ_{b1}

$$S_{CO_2} = \frac{1}{\Phi}\left(\frac{\rho_b - \rho_{b1}}{\rho_{ff} - \rho_{CO_2}}\right)$$

Measurement sensitivity depends on Porosity and formation fluid / CO2 Density contrast

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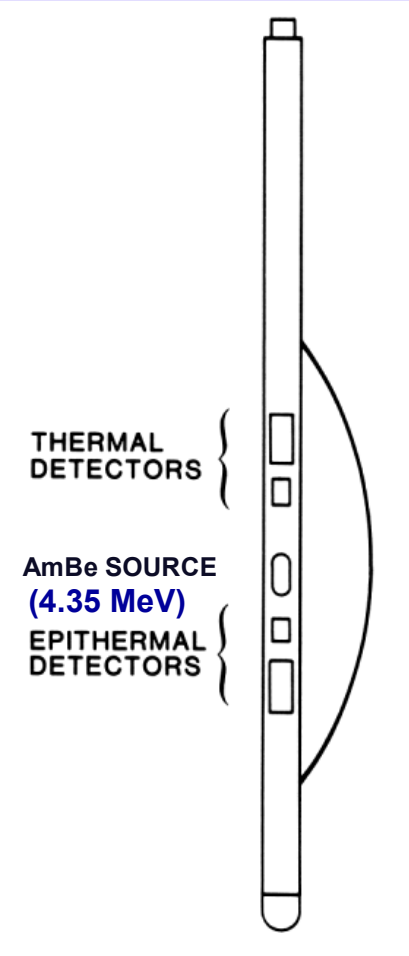
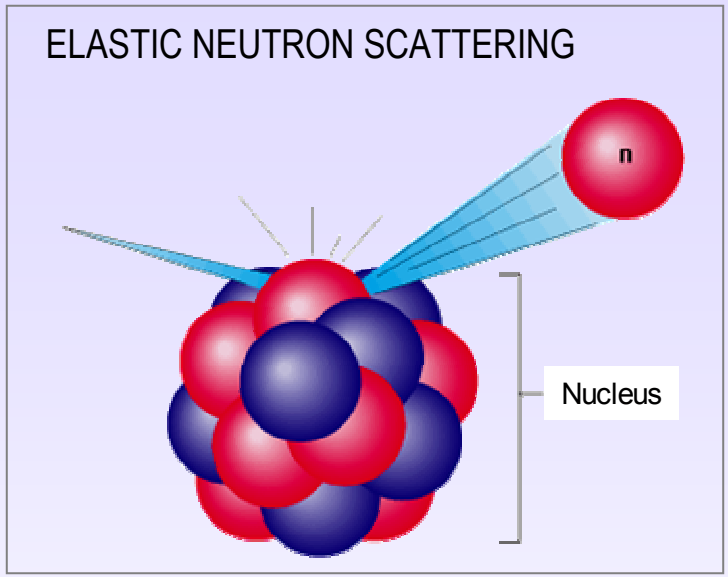
Neutron porosity

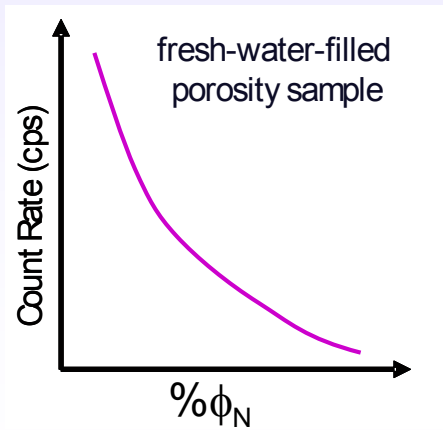
Neutron – Neutron





The scattering of neutrons by Hydrogen is very efficient in reducing the neutron energy

The Hydrogen Index HI, or quantity of Hydrogen atoms in the pore space, is inferred from detector count rate ratio



Time-Lapse Neutron Porosity Measurement

Baseline: Φ_N

Measurement: Φ_{N1}

$$S_{CO_2} = 1 - \frac{\Phi_{N1}}{\Phi_N}$$

Selectivity to CO_2/H_2O (brine)

Potential Selectivity to CO_2/CH_4 (Φ_N is due to H)

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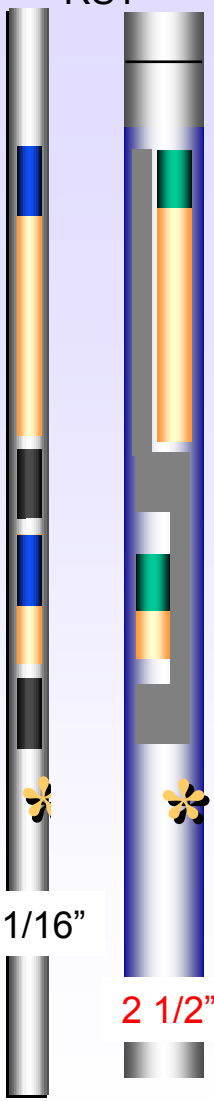
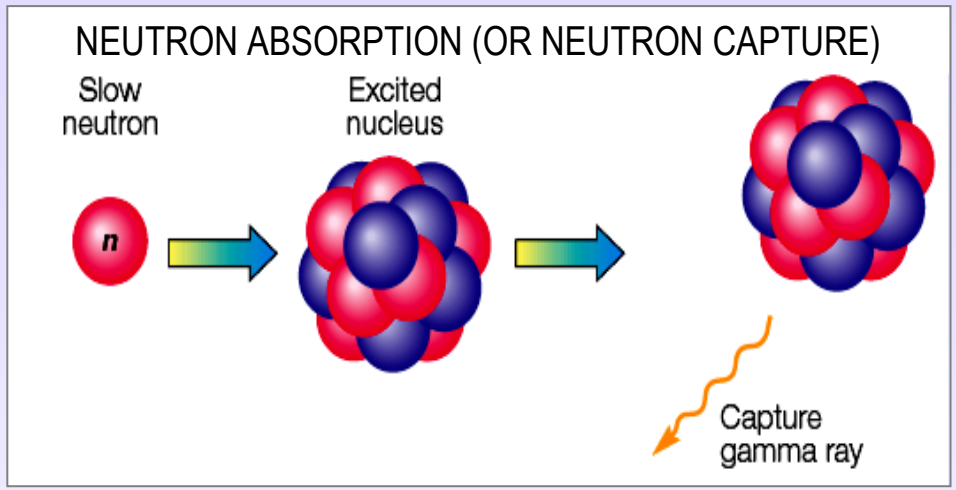
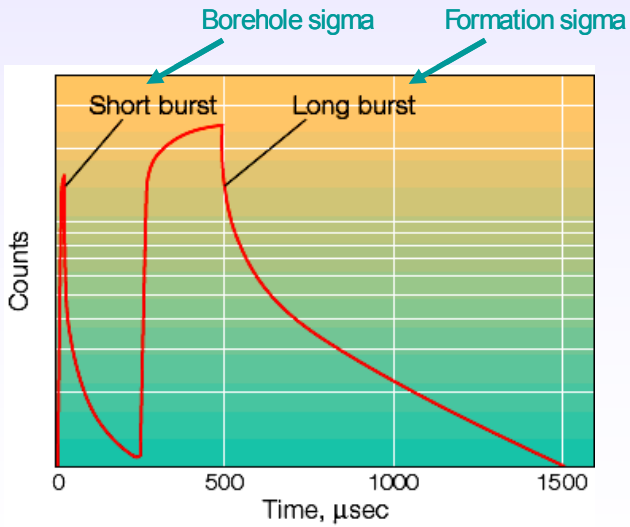
Neutron Capture Cross-Section Neutron – Gamma

RST







SIGMA: is a measure of how fast the thermal neutrons are captured, which is a process mainly dominated by **chlorine**.

[chlorine] α [brine]

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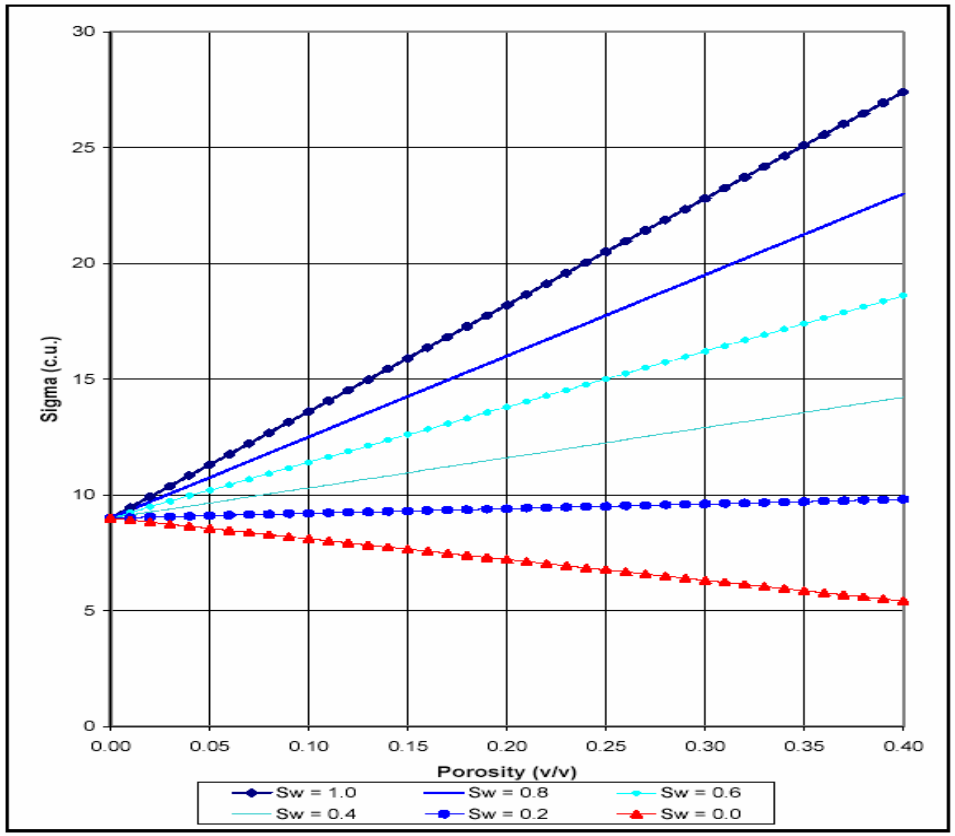
Neutron Capture Cross-Section

- CO2 and Water Σ values
  - CO2 (0.3 c.u.)
  - Water (55 c.u.) (@ 93,000 ppm)
- X-plot Porosity – Σ
  - For different Water (CO2) Saturations



Selectivity to CO_2/brine (H_2O)

(*) Sakurai et al. , SPWLA 46th – June 26-29th - 2005

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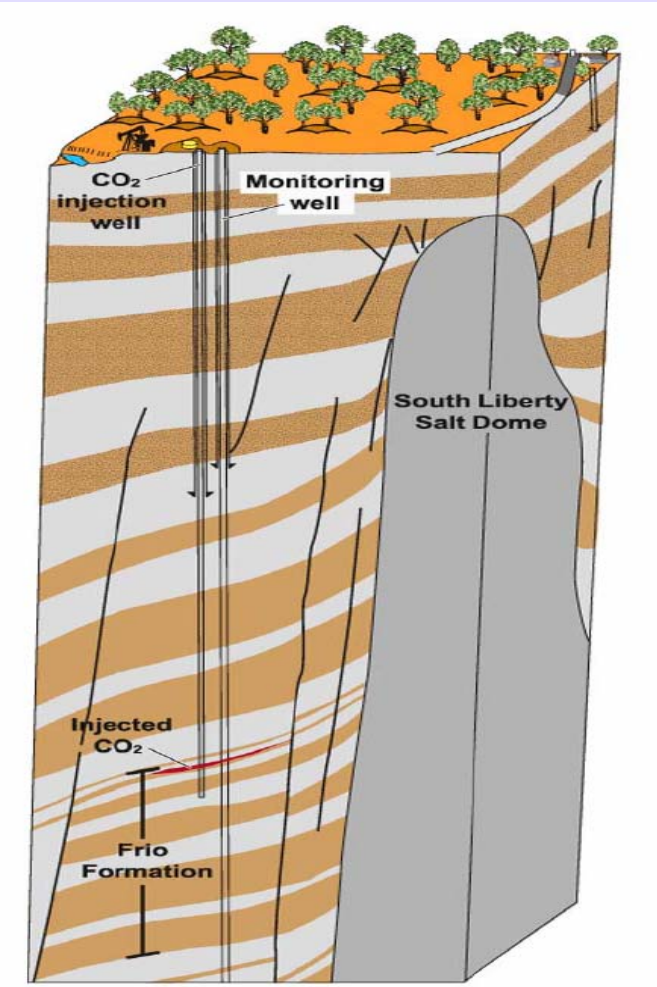
CO_2 Monitoring Using RST – Frio Experiment



- Injection started on Oct 4th 2004, stopped on Oct 14
- 1,600 t/CO_2 injected

- Target: Frio formation (~5000 ft deep)
- Sandstone
- High Salinity: 93,000 ppm
- High Porosity: 32-35 p.u.
- High Permeability: 2.5 Darcy (air)
- Injector-Monitoring well spacing: 100ft

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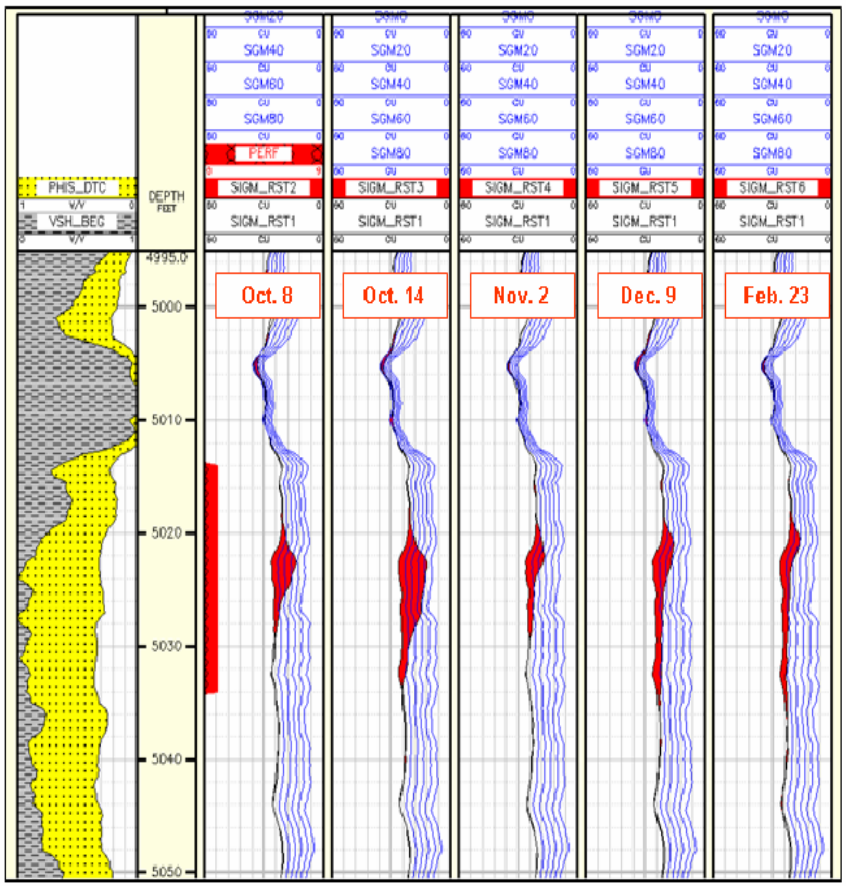
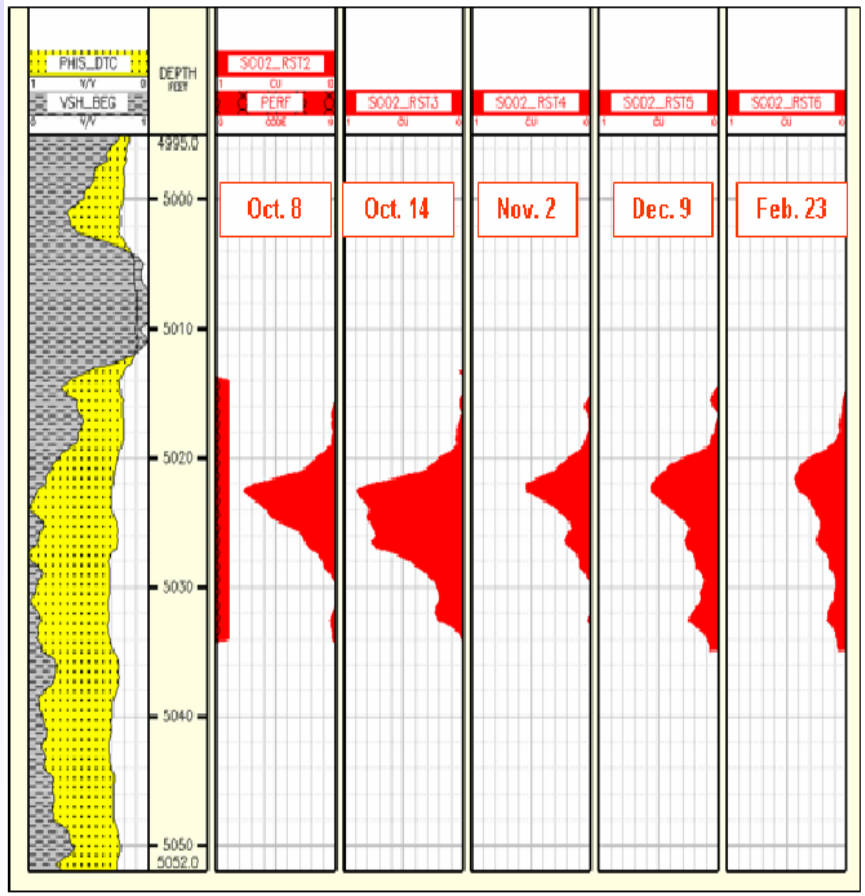
Monitoring Using RST in Frio – Σ Measurement

CO_2 Injection : Start – Oct 4th / Stop - Oct 14th



Time-Lapse Σ Measurements



Time-Lapse CO_2 Saturations

(*) Sakurai et al. , SPWLA 46th – June 26-29th - 2005

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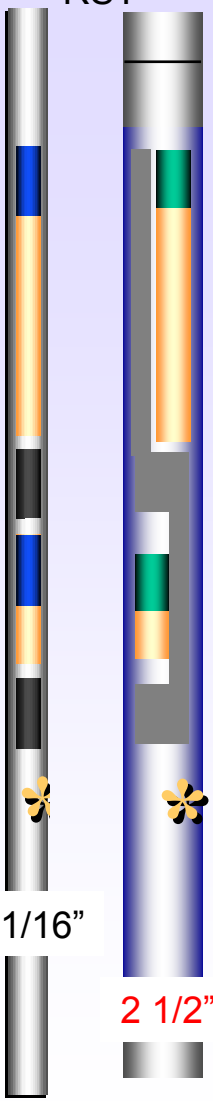
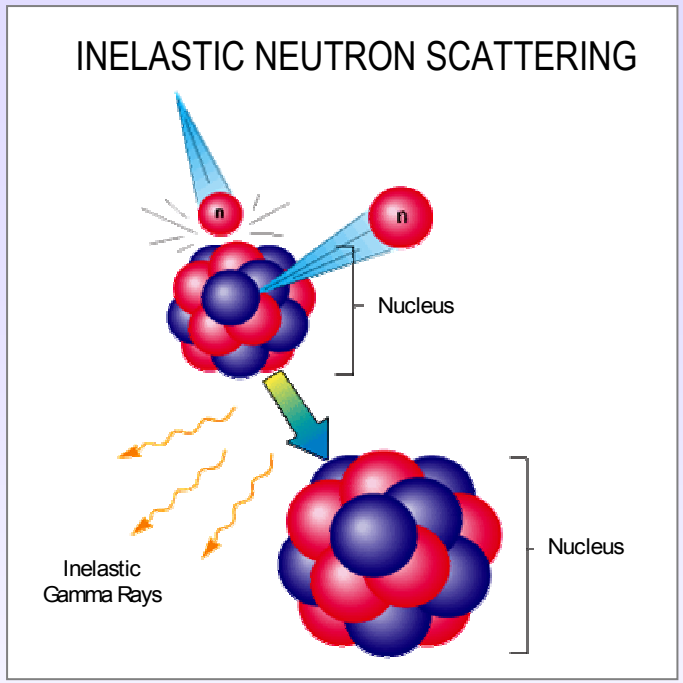
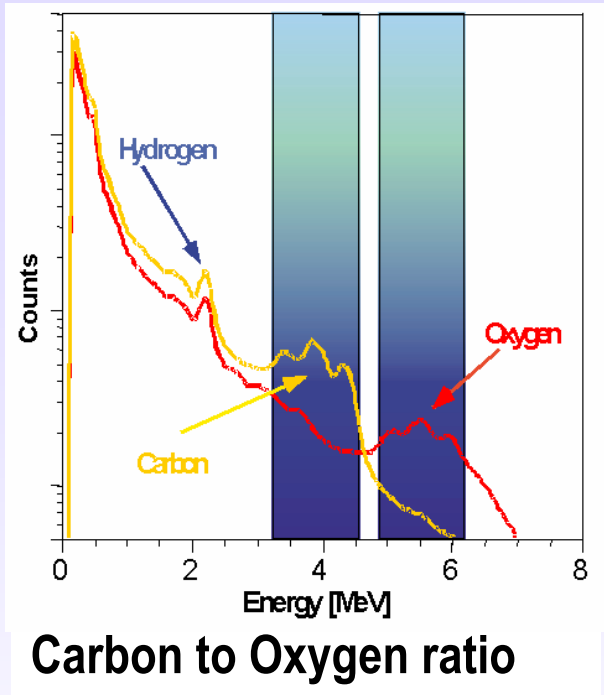
Neutron Inelastic Scattering

Neutron - Gamma

RST







Carbon to Oxygen ratio

- Inelastic Spectra in CO_2 and Water
- Two different C/O ratio
  - Elemental Yields (accurate but low statistics)
  - Windows Ratio (less accurate, more precise)

Selectivity to CO_2/CH_4
Selectivity to CO_2/brine (H_2O)
Measures CO_2 rich-phase **and** dissolved CO_2

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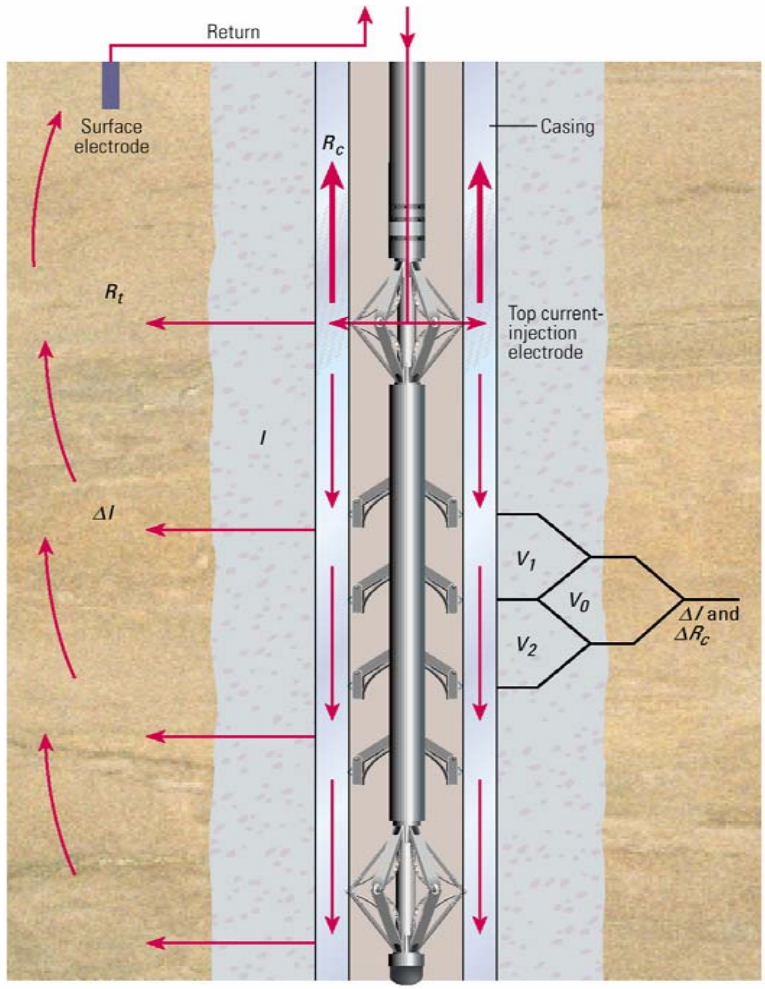
Resistivity



Casing acts like a large electrode. Current returns to surface similarly to a Laterolog tool.

Rt = K * ΔV / ΔI

First step: ΔI = (V1-V2)/Rc

Second step: I' = (V1-V2)/Rc

Time-Lapse Resistivity Measurement

Baseline: R_t

Measurement: R_{t1}

$$S_{CO_2} = 1 - \left(\frac{R_t}{R_{t1}} \right)^{1/2}$$

Measurement & Interpretation Issues:

Sensitivity to cement resistivity

Effect of dissolved CO2 on brine resistivity:

CO2 ↗ Rw ↘

Effect of Water in Supercritical CO2

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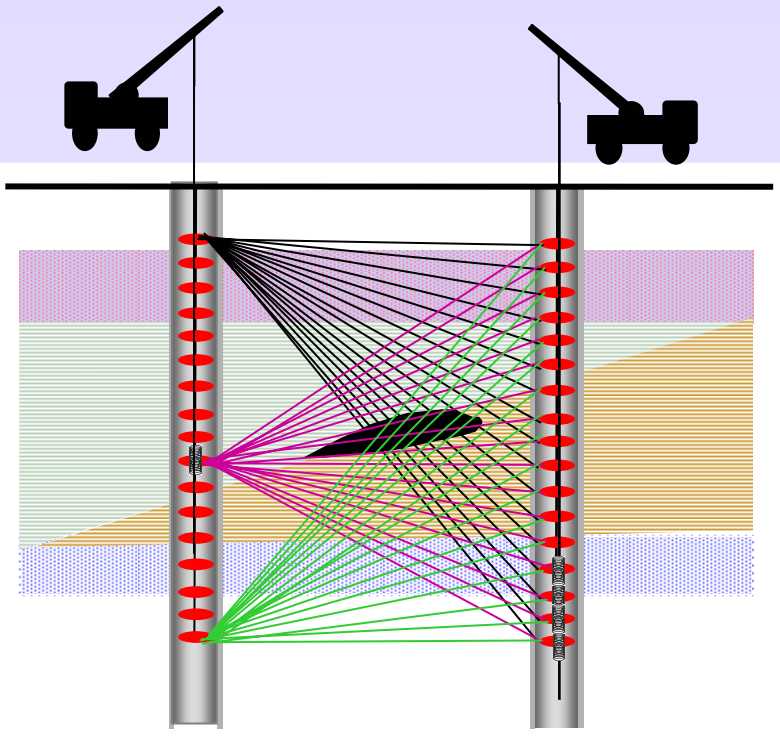
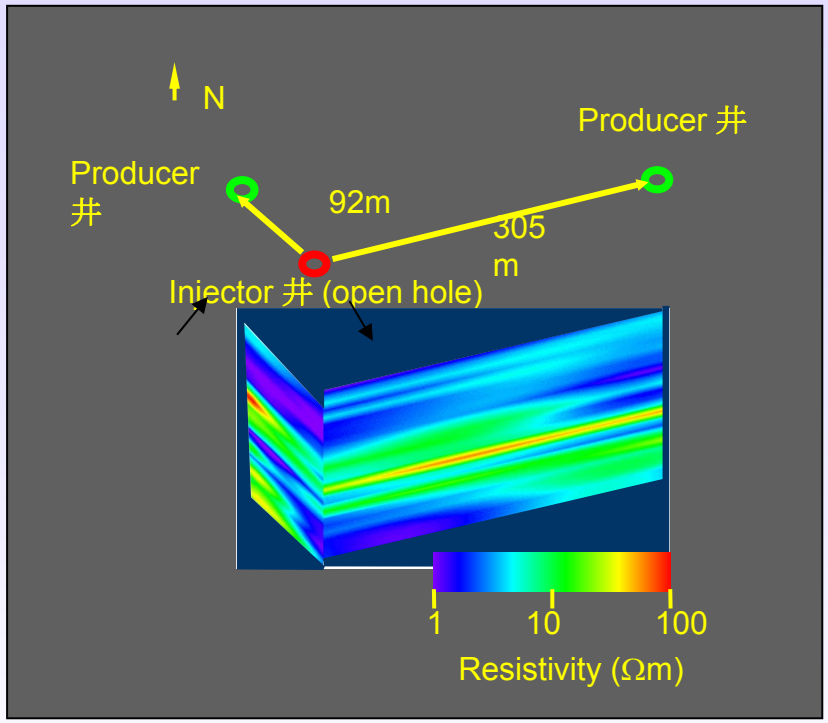
X-Well EM Surveys





- Saturation Distribution
- Monitoring of Injection front & CO2 Plume

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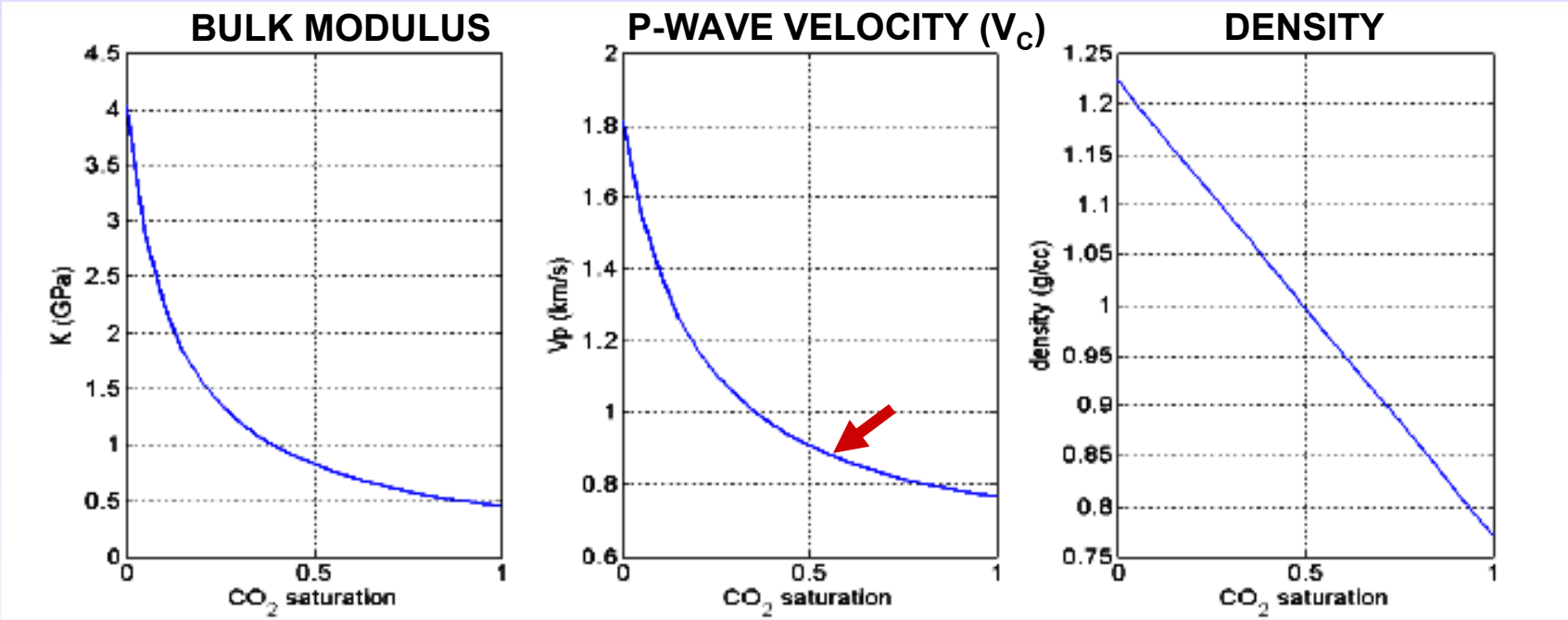
Sonic



$\Delta V_P \sim 10$ %

Batzle-Wang equations with modified parameters were used for calculations. T = 57°C, P = 6750 psi, [NaCl] = 300 000 ppm (brine)

Selectivity to CO_2/brine

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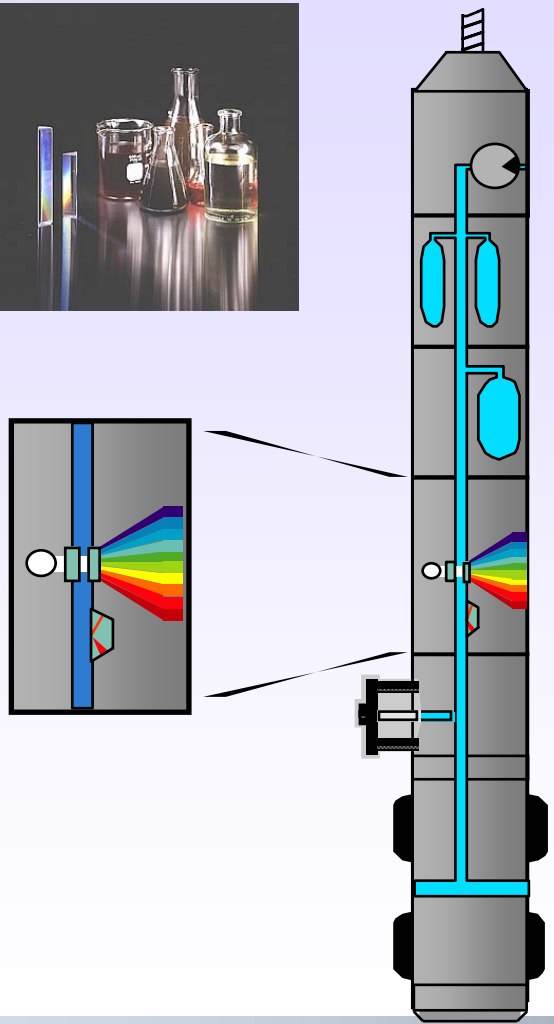
Downhole Fluid Analyser – CO2 Concentration



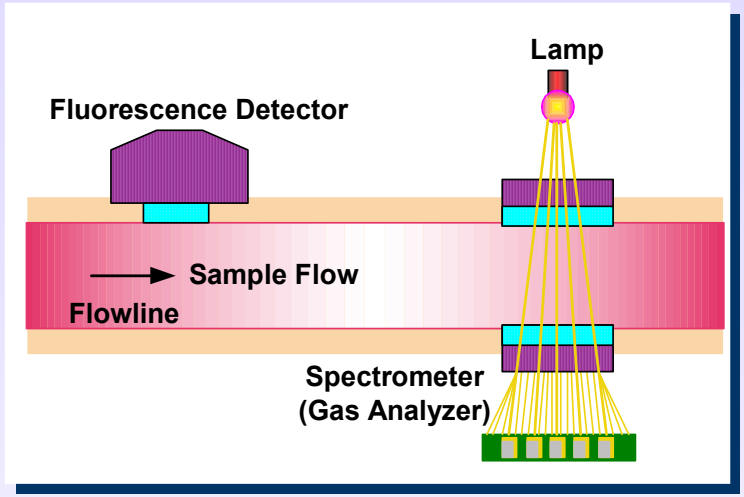
Pumpout module

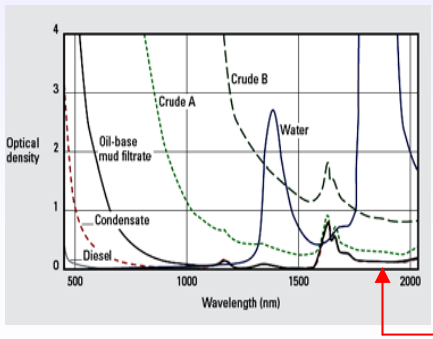
Multisample module(s)
(Six 450cc samples)

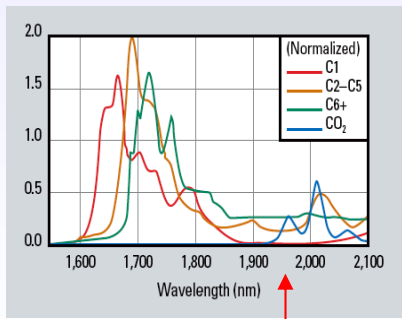
OFA/CFA

Single probe module

Packer module







H_2O and CO_2 peaks overlap in the Near-IR region

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Well Monitoring Techniques

- CO_2 Saturation Measurements
  - Nuclear techniques
  - Electrical
  - Sonic
  - Sampling
- Well Integrity Evaluation
  - Calipers (corrosion)
  - Electromagnetic (corrosion)
  - Sonic (cement)
  - Ultrasonic (corrosion & cement)

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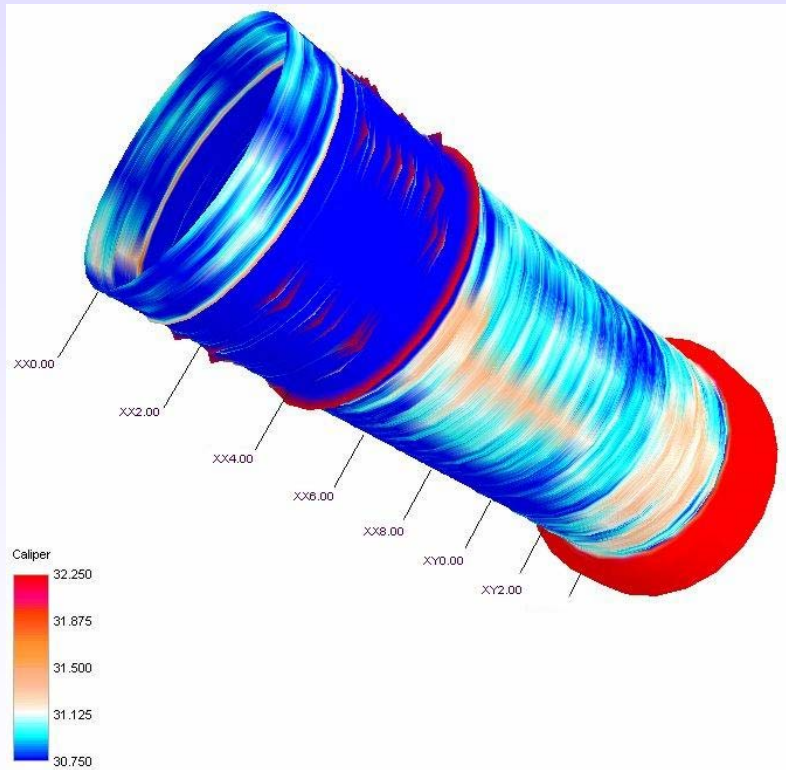
Well Integrity – Caliper Measurements (Corrosion)

Multifinger Caliper

Casing/tubing inside diameter

24 to 60 fingers



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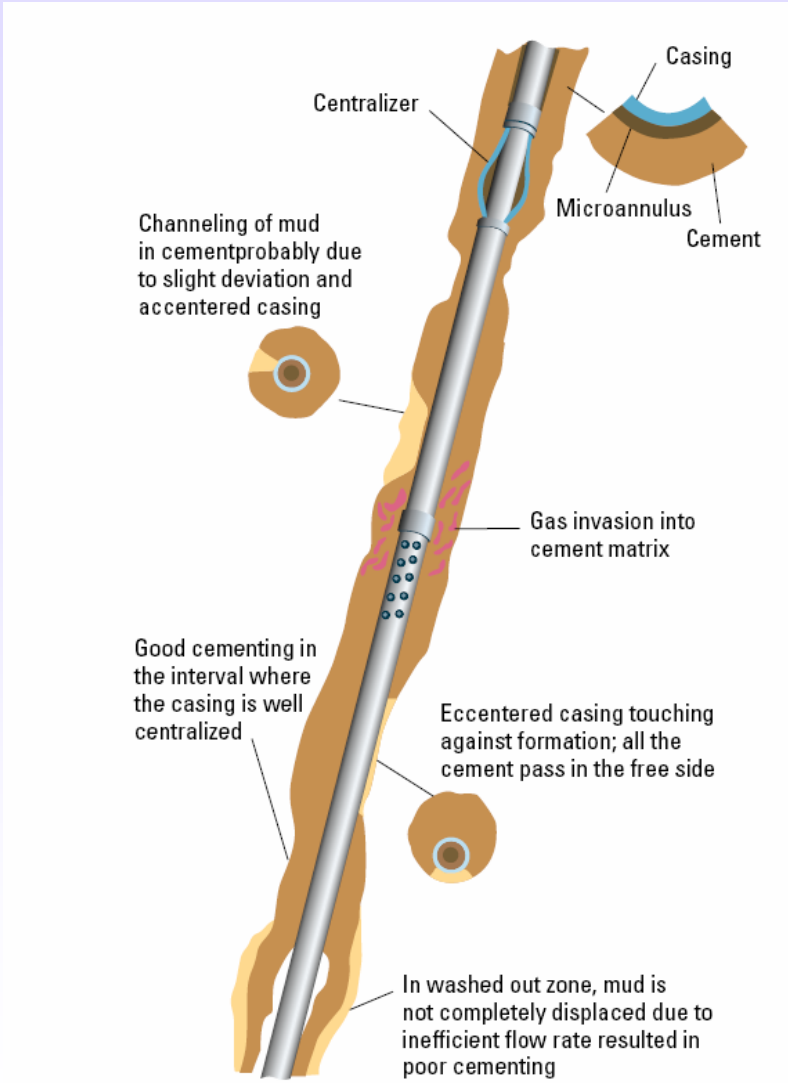
Cement Slurry Displacement Problems



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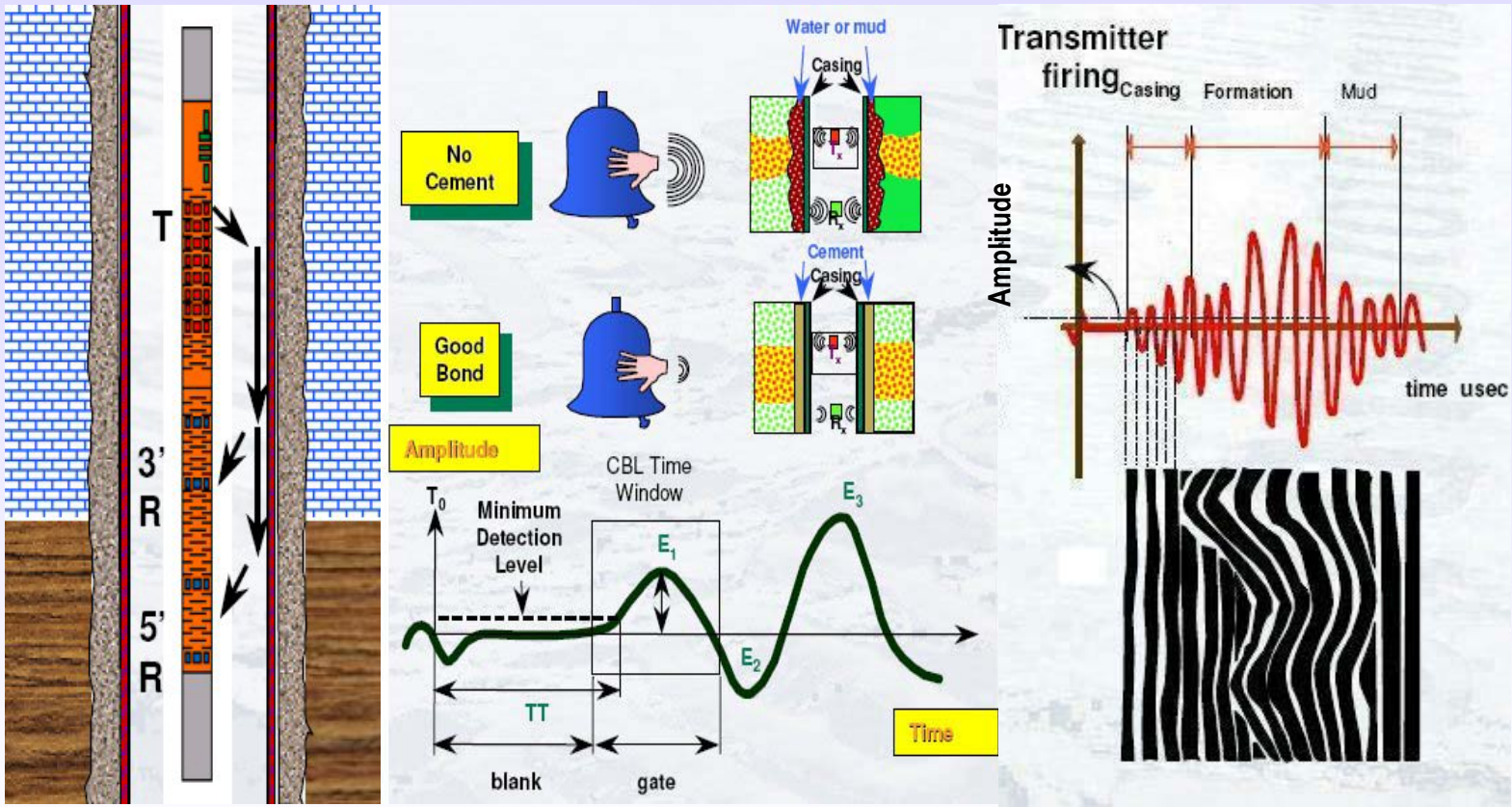
Sonic Cement Bound Evaluation



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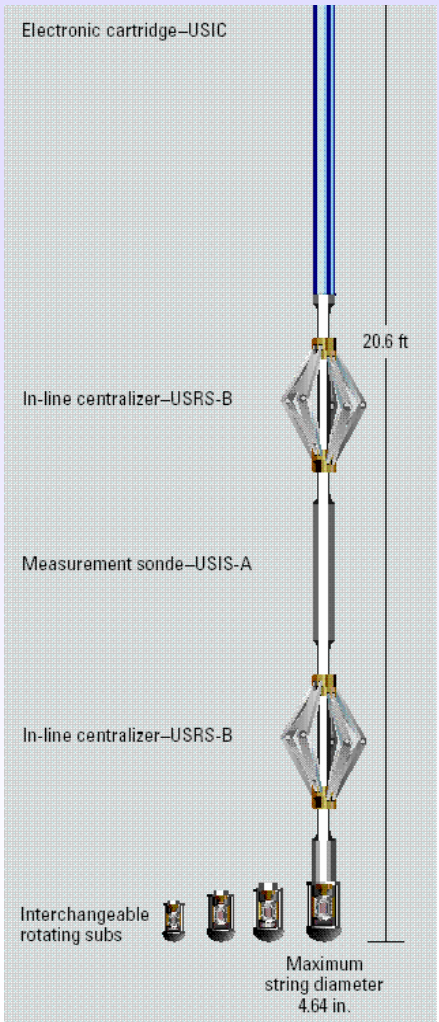
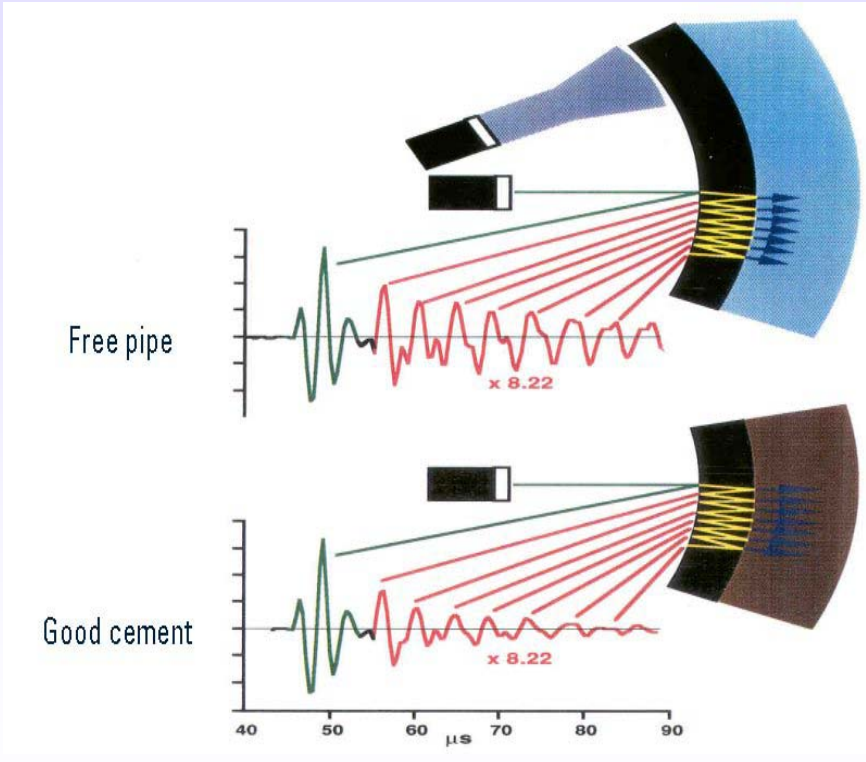
UltraSonic

Pulse Echo Imager



The resonance technique



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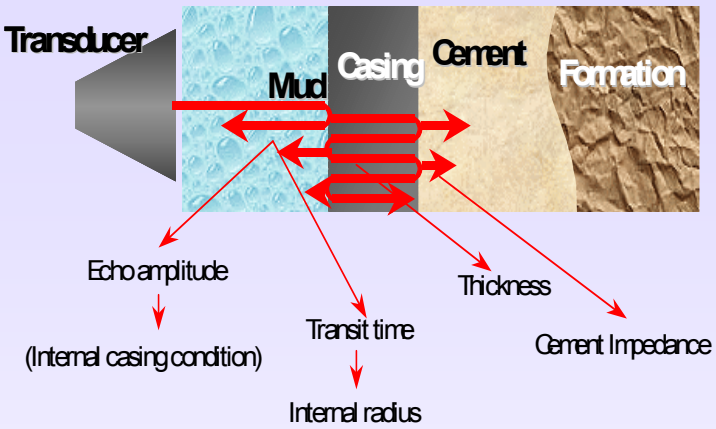
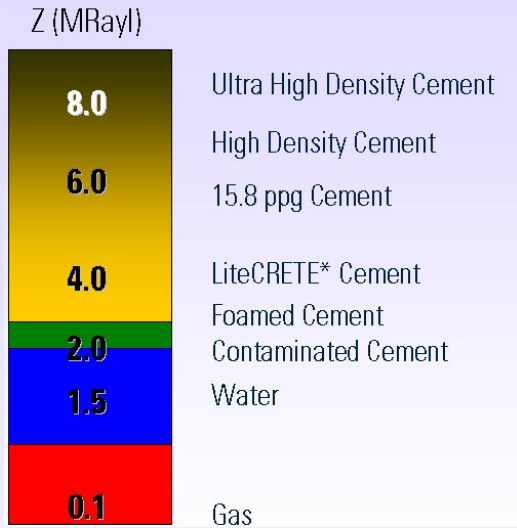
Measurements



- **Internal Casing Condition**
- **Internal Radius**
- **Casing Thickness**
- **Cement Impedance**



Tool Characteristics

Casing OD	4.5 - 13.375 in.	Sampling:	
Casing thickness	0.17 - 0.59 in. (4.5-15 mm)	-Azimuthal	5-10 deg.
Acoustic Impedance	0-10 Mrayl	-Vertical	0.6”- 6”
Max. deviation	No limit	Maximum mud weight	
Logging speed	400 to 3200 ft/hr	- WBM	16 lbm/gal
		- OBM	11.6 lbm/gal*

(*) Depends on composition, temperature and pressure.
Good logs can be obtained in up to 1560 kg/m3 (13 lb/gal) and sometimes up to 1917 kg/m3 (16 lb/gal)

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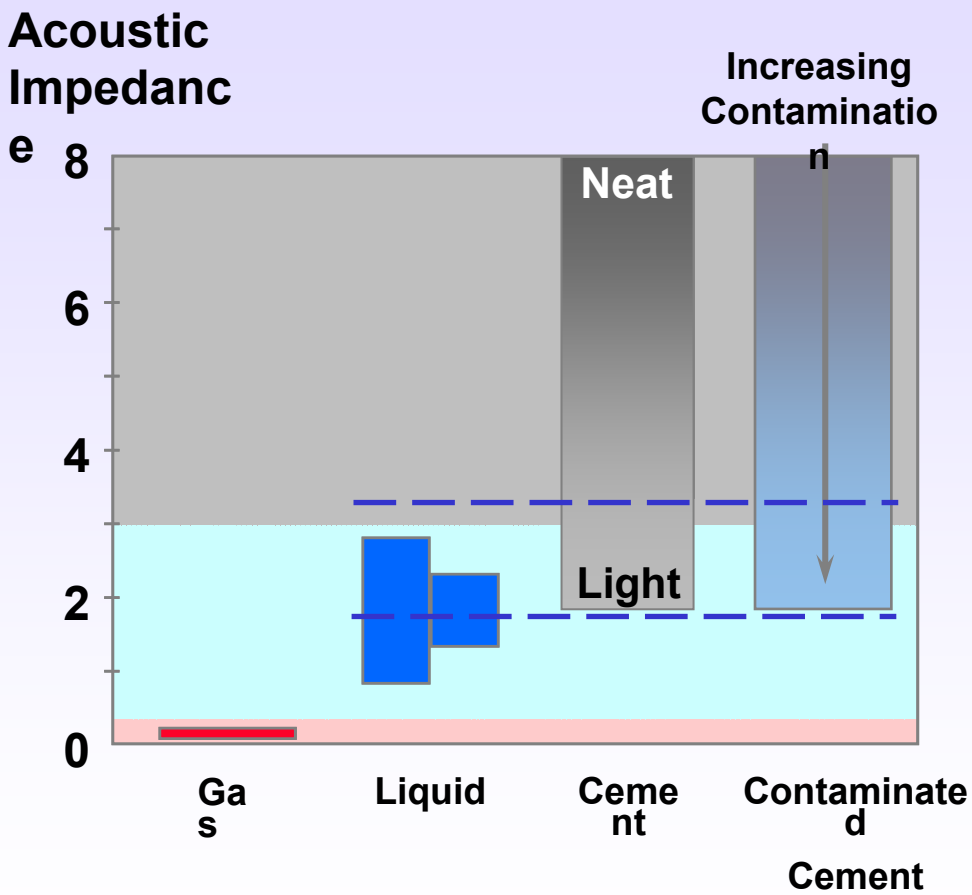
Cement Evaluation Challenges

- Discriminate
  - Cement
  - Liquid
  - Gas



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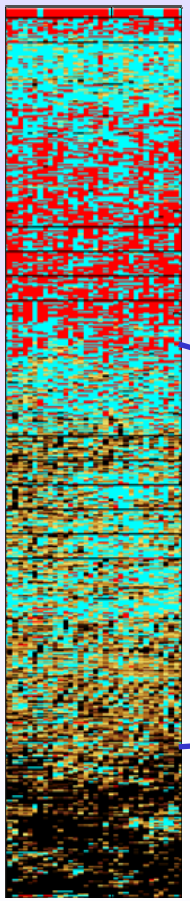
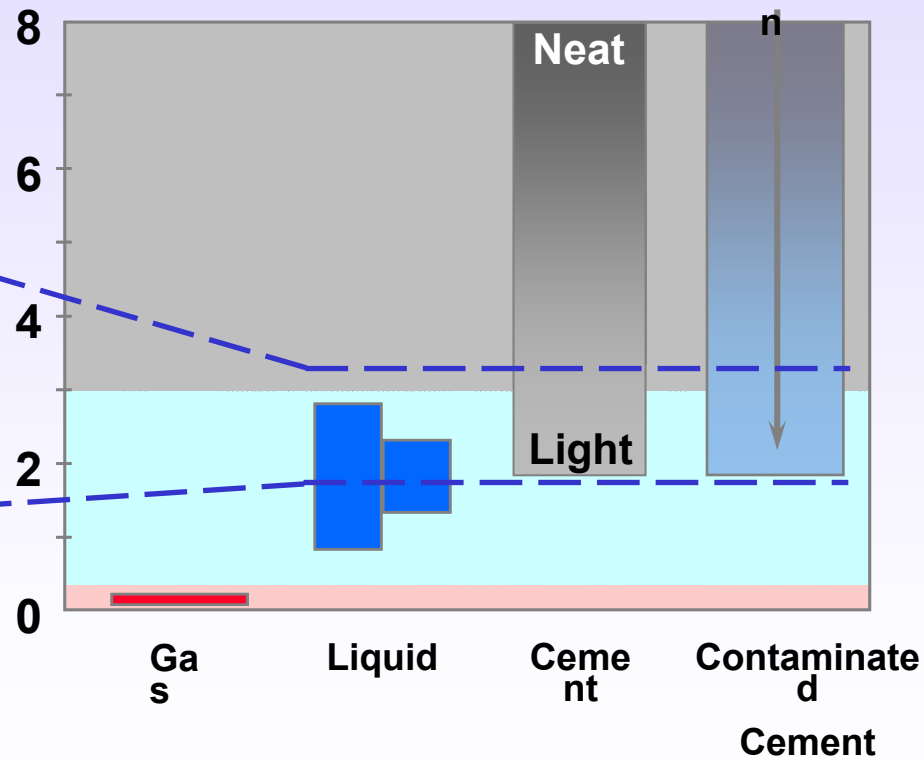
Cement Evaluation Challenges



USIT

Acoustic Impedance



LiteCrete bond quality unclear

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Imaging Behind Casing - principle

- Combine USI (ultra sonic imager) measurement:
  - Excitation of thickness mode of the casing
  - Single transducer (Tx/Rx)configuration measuring resonance and decay of thickness mode
  - Inversion for the acoustic impedance immediately behind the casing
- with FWI (flexural wave imager) measurement:
  - Excitation of flexural mode of the casing
  - Pitch-catch configuration (one Tx, two Rx) measuring flexural attenuation
  - Due to leakage, image may reveal up to third interface (formation/double string)

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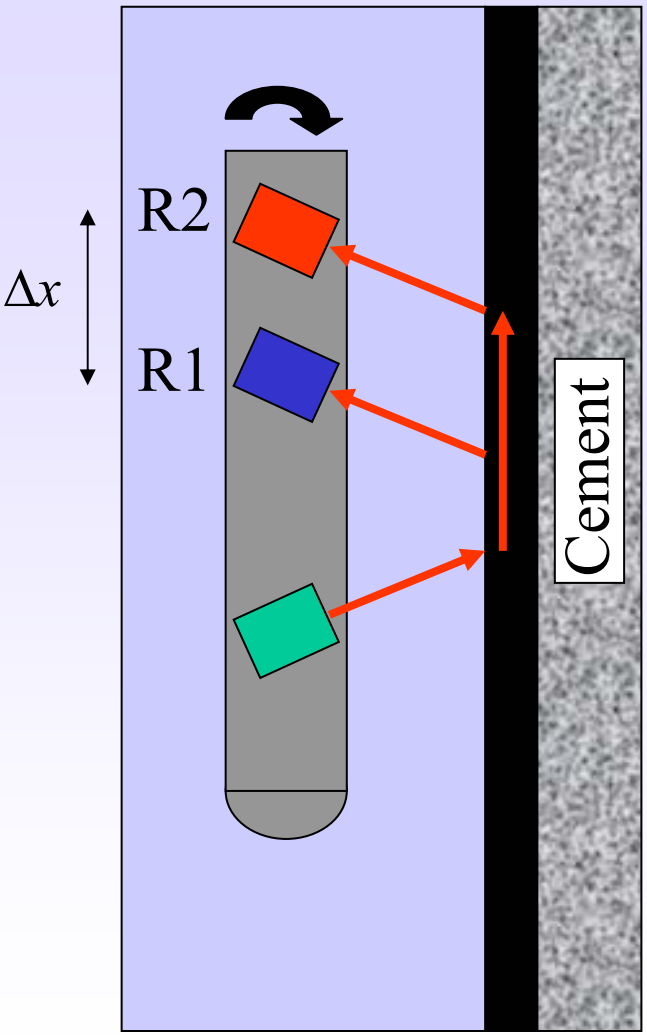
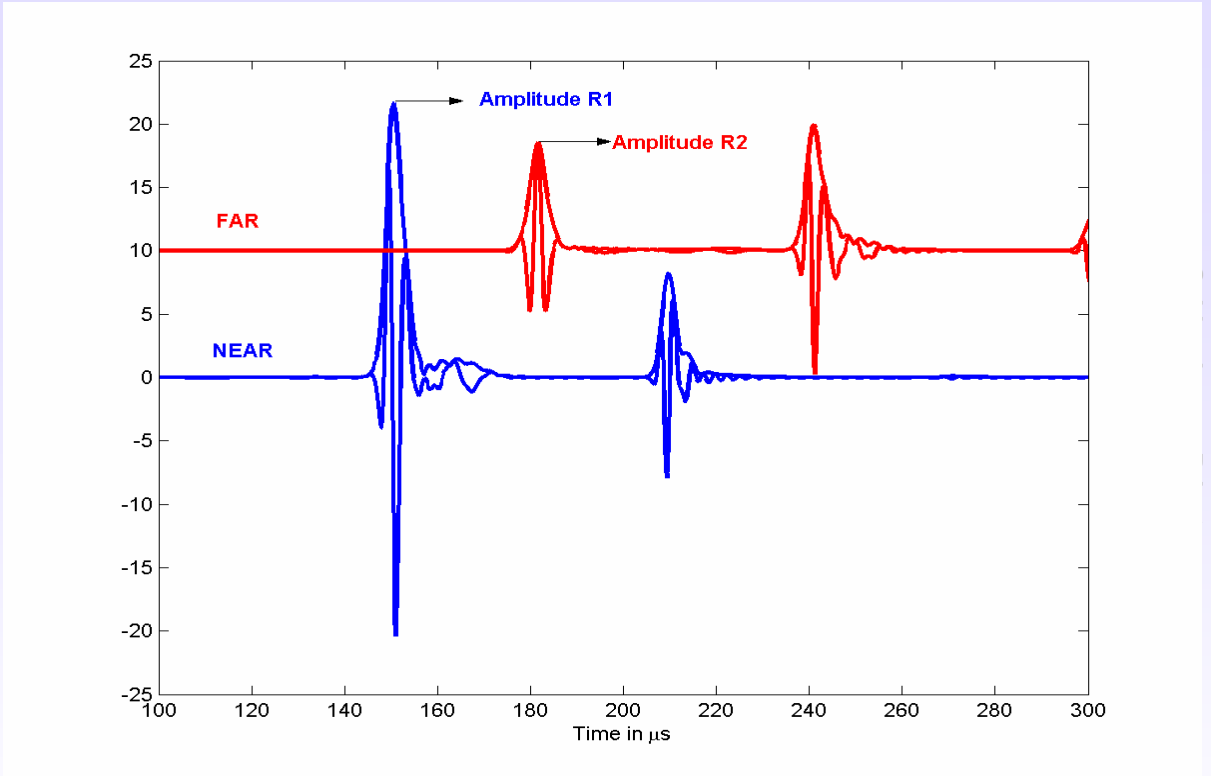
Imaging Behind Casing

Flexural Mode

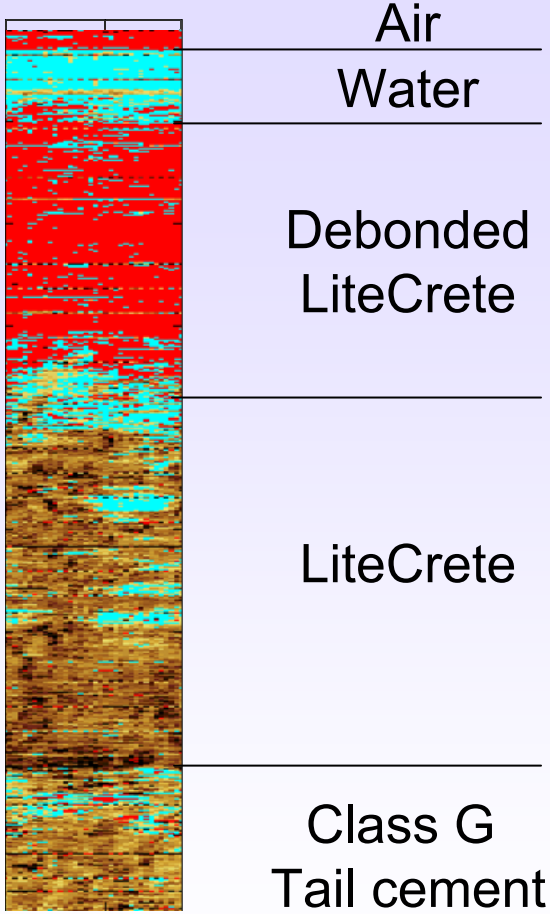


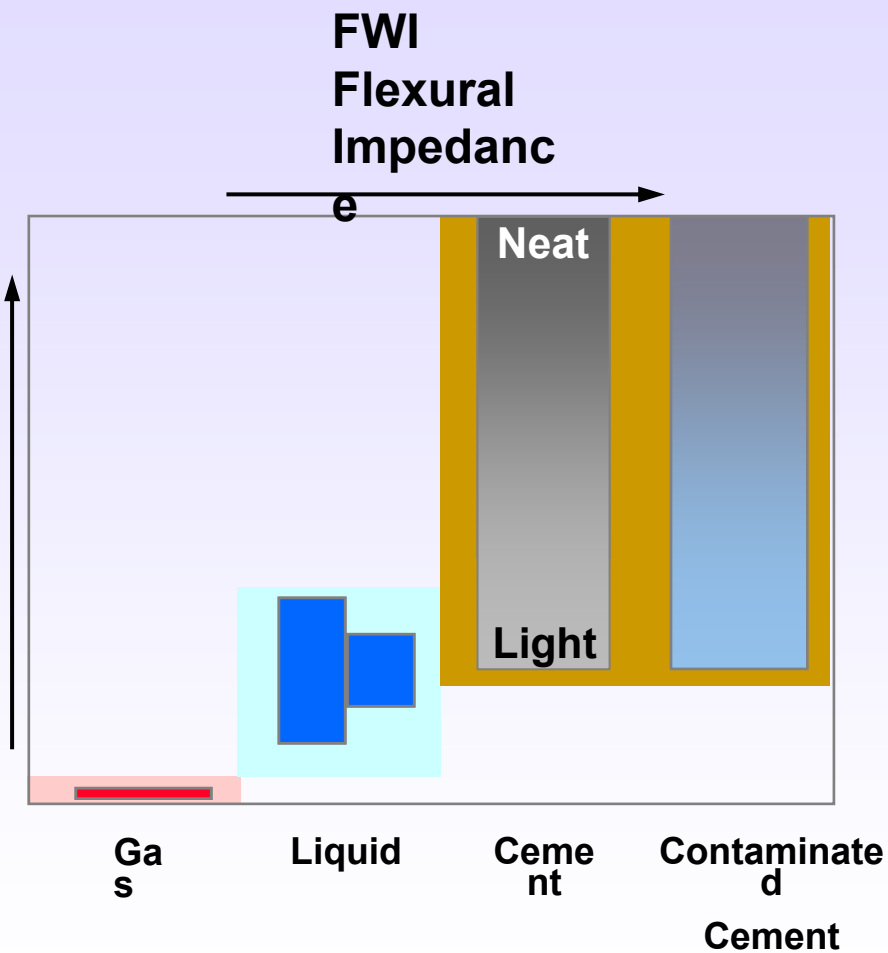


$$\alpha = \frac{20}{\Delta x(cm)} * Log_{10}\left[\frac{AmplitudeNear}{AmplitudeFar}\right] \quad dB/cm$$

Schlumberger

Imaging Behind Casing





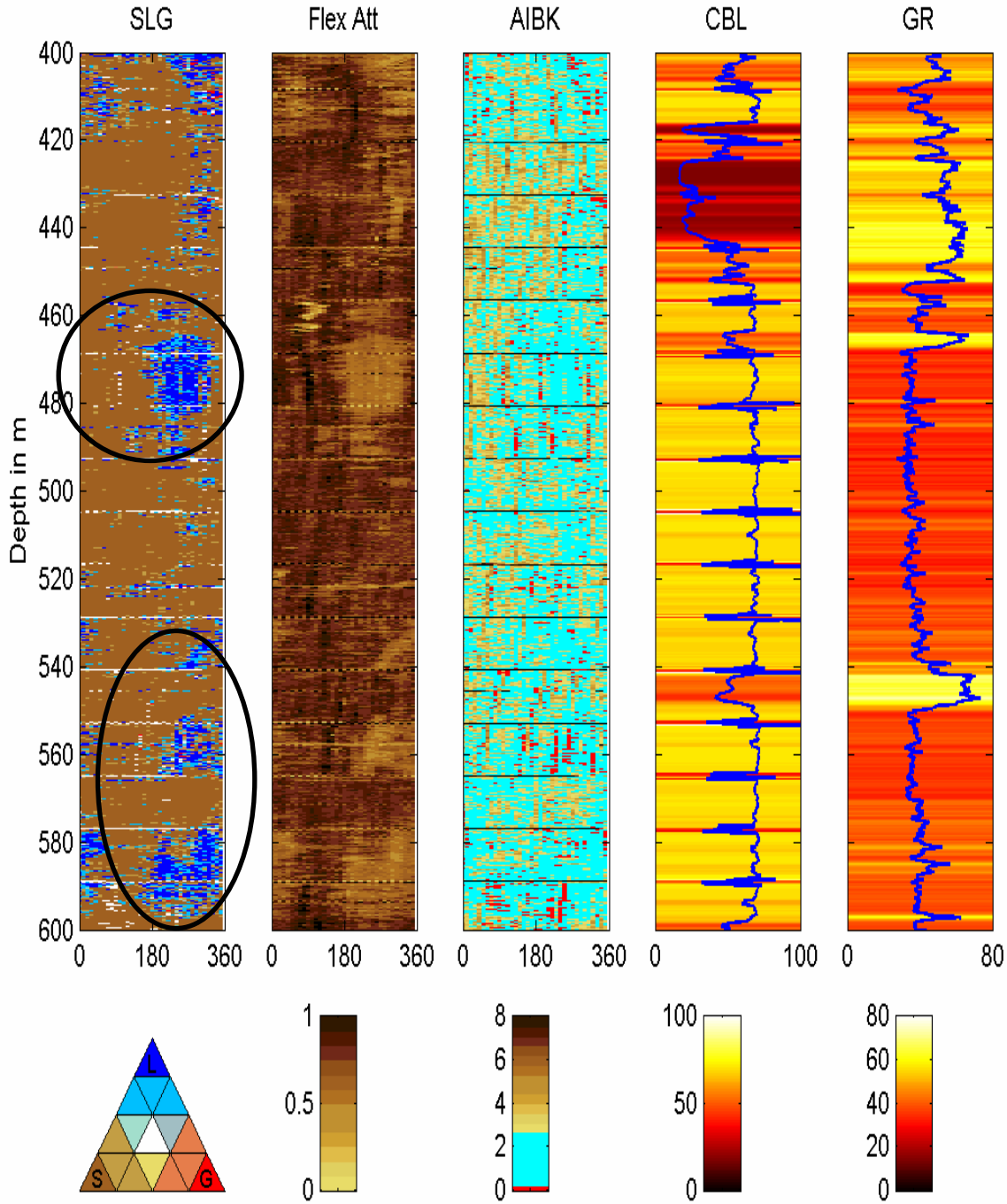
Cement
Water
Gas

Schlumberger Private

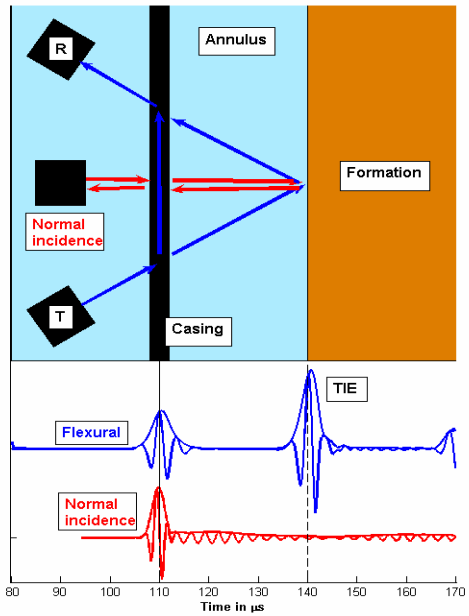
Example:

Channeled section in LiteCRETE cement

Not identified by USIT and CBL!



Isolation Scanner: Third Interface Echo

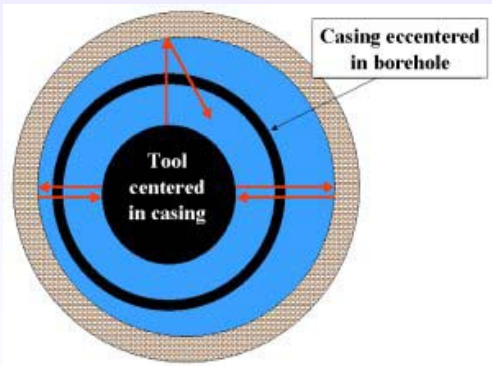


- Strong TIE from Flexural Wave
- ΔT independent of T-R Spacing
- ΔT = F(Annulus thickness, Wave Velocity)

Known Velocity ⟺ Cement Thickness

TIE not always possible:

- Casing Eccentering
- Attenuation of annulus material
- Not enough acoustic contrast
- Large Hole/ Washouts



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Conclusion

- Wells provide access to the reservoir!
- Well measurements complement geophysical monitoring techniques by providing accurate local evaluation of properties
- Validation and demonstration of measurement techniques is still needed, which requires tool response characterization in CO2 environment
- Availability of wells also allows
  - Installing permanent sensors (P,T, microseismicity…)
  - Sampling
  - Performing X-Well or Well-to-surface surveys

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Questions for Designing a Monitoring System

What do I want to monitor?	CO_2 displacement, leak…
What property change can I monitor?	P, CO_2 Saturation, Resistivity
What variation am I considering?	
What measurement technique can be used?	Seismic, EM, Nuclear…
What should be my sensor specifications?	Accuracy / Precision
Where should I place my sensor?	Surface, Obs. Well (Permanent, Logging…)
For how long?	Operation phase, surveillance
How can I deploy it?	
How can I interrogate it?	
How can I interpret the measurement?	

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Questions?

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Time-lapse well logging to monitor injected CO_2 in an aquifer at Nagaoka

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

1: Engineering Advancement Association of Japan (ENAA)

2: Geophysical Surveying Co., Ltd.

3: Research Institute of Innovative Technology for the Earth (RITE)

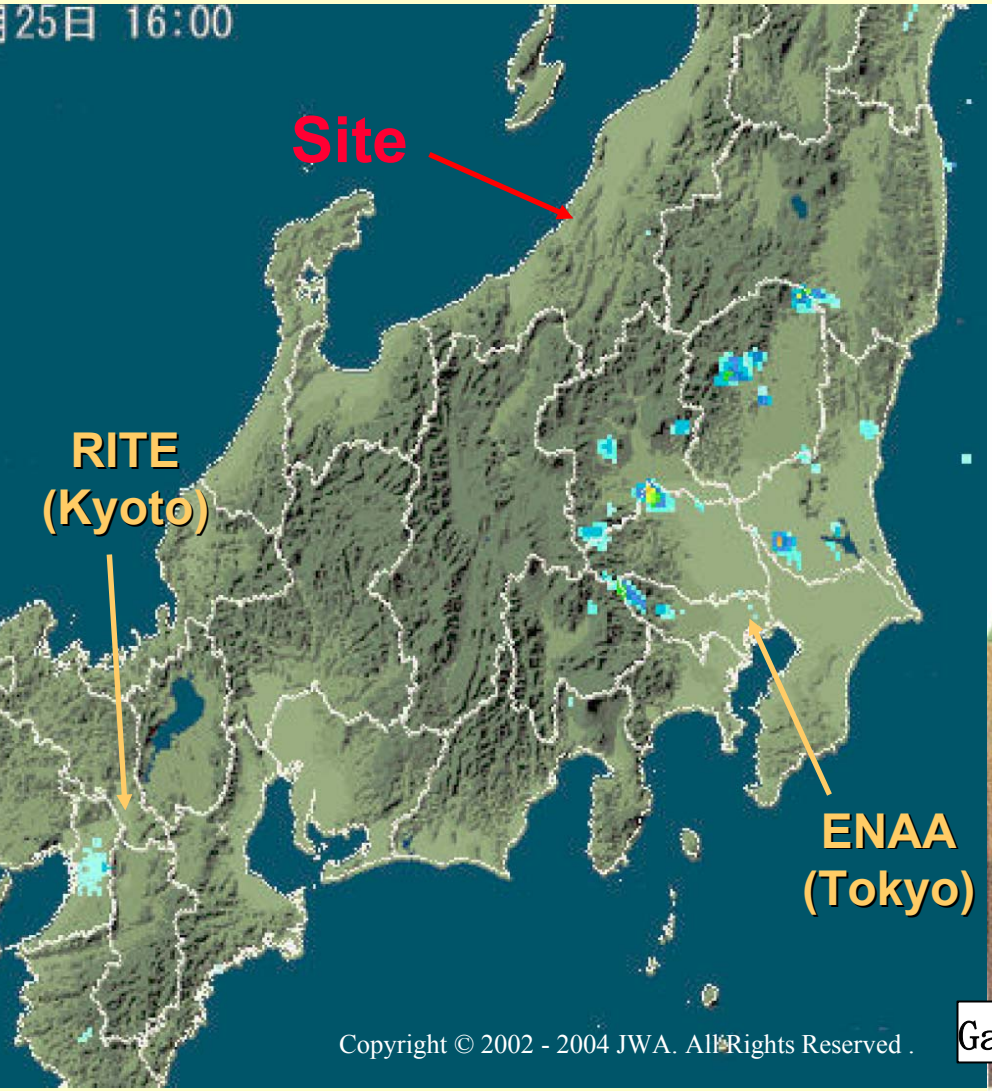
4: Oyo Corporation

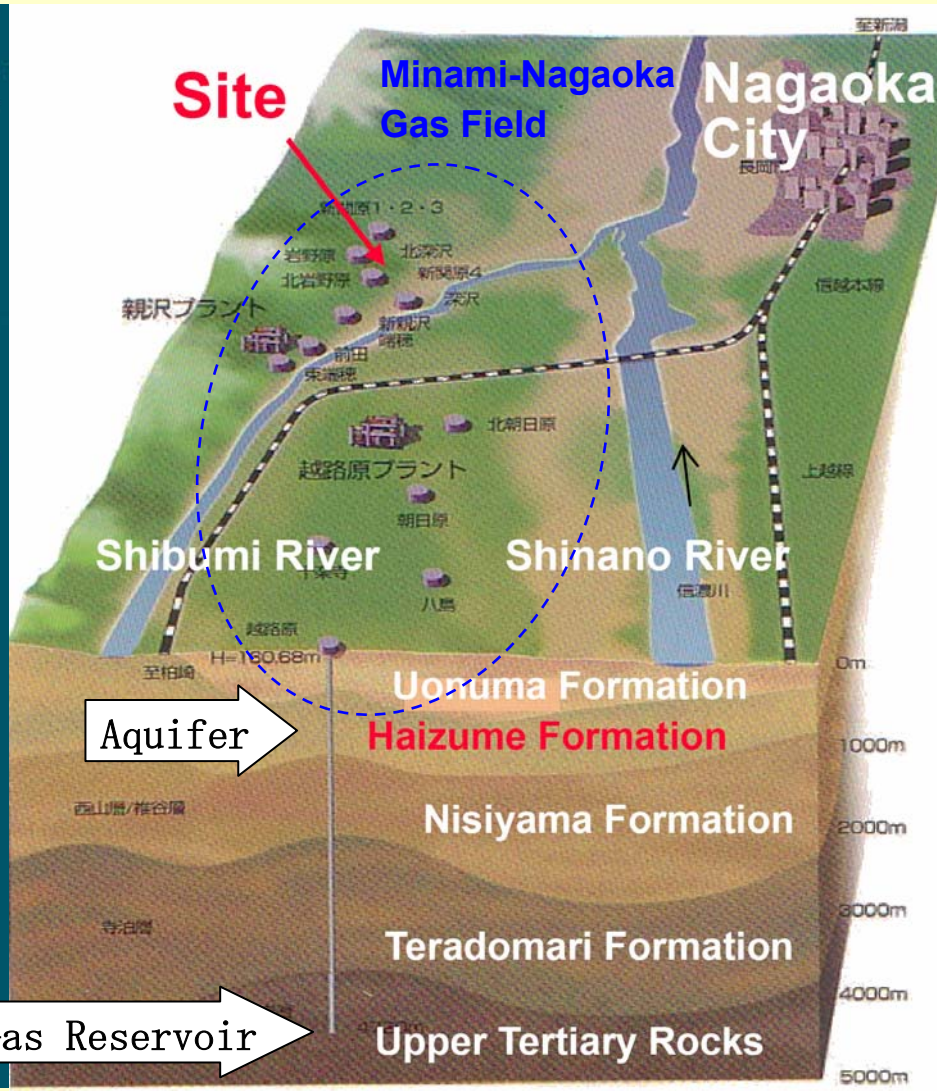
3rd MEETING of the MONITORING NETWORK

October 30 - November 2, 2006

Overview

Location and Geology



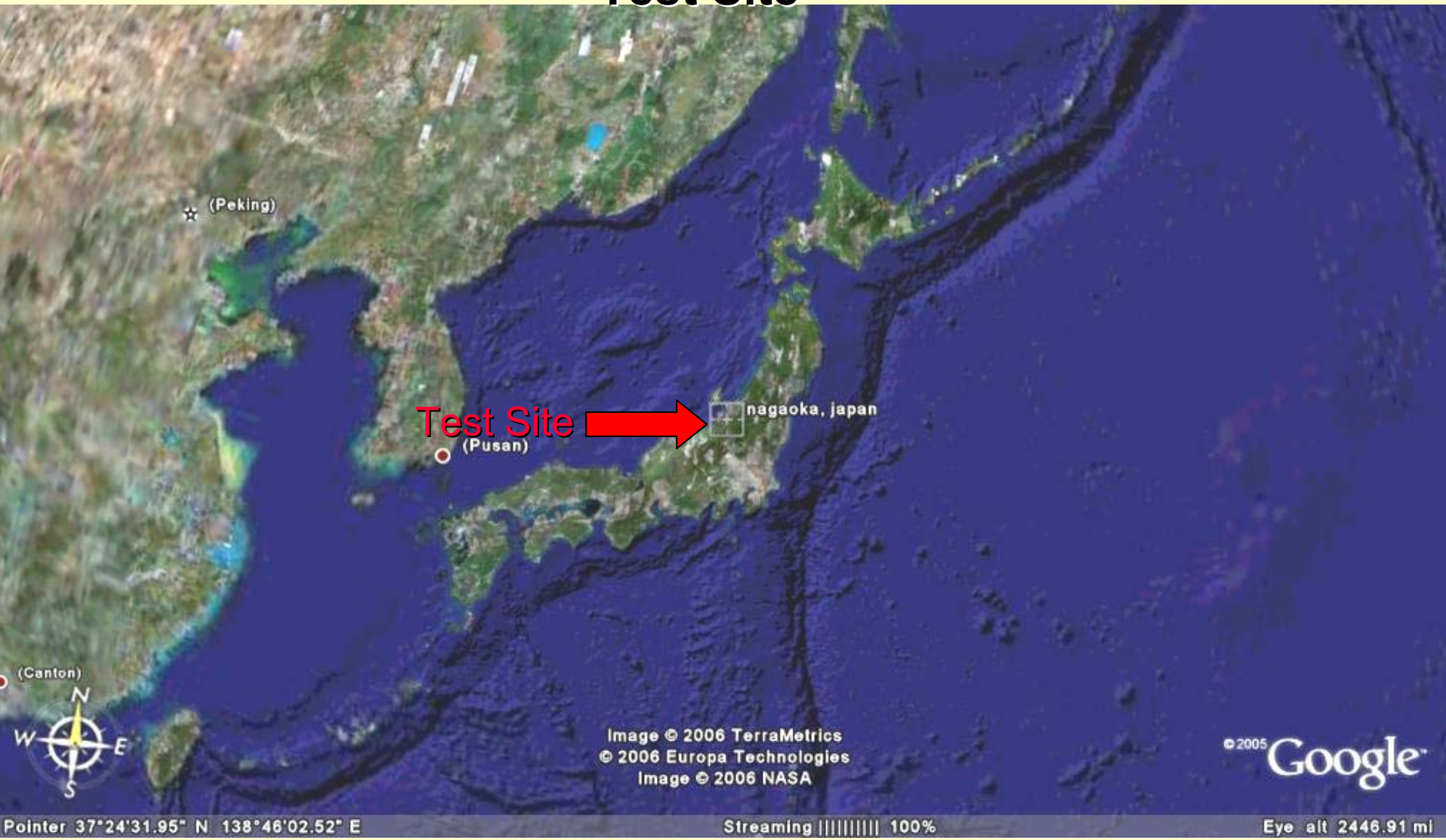


Chronicle of Nagaoka Project

- **FY2000 : Site Selection ・・・South Nagaoka Gas Field**
- **Drilling of Wells, Well logging and Test of Core Sample**
  - ✧ FY 2000 : Injection well (IW-1) drilled
  - ✧ FY 2001 : Two observation wells (OB-2, OB-3) drilled
  - ✧ FY 2002 : One observation well (OB-4) drilled
- **FY 2002 – 2003 : Construction of the Facilities**
- **FY 2003 – 2004 : Injection of CO_2 ・・・10,405t**
- **FY 2002 – present :Monitoring of CO_2**
- **FY 2000 – present : Simulation Study**
  - ✧ FY 2000 – 2002 : Simulation prior to the injection start
    ・・・Optimum arrangement of CO_2 monitoring etc.
  - ✧ FY 2003 - present : History matching simulation after the injection start
    ・・・ Long-term CO_2 behavior anticipation
- **FY 2007 – Blockage of Wells**

Overview

Test Site

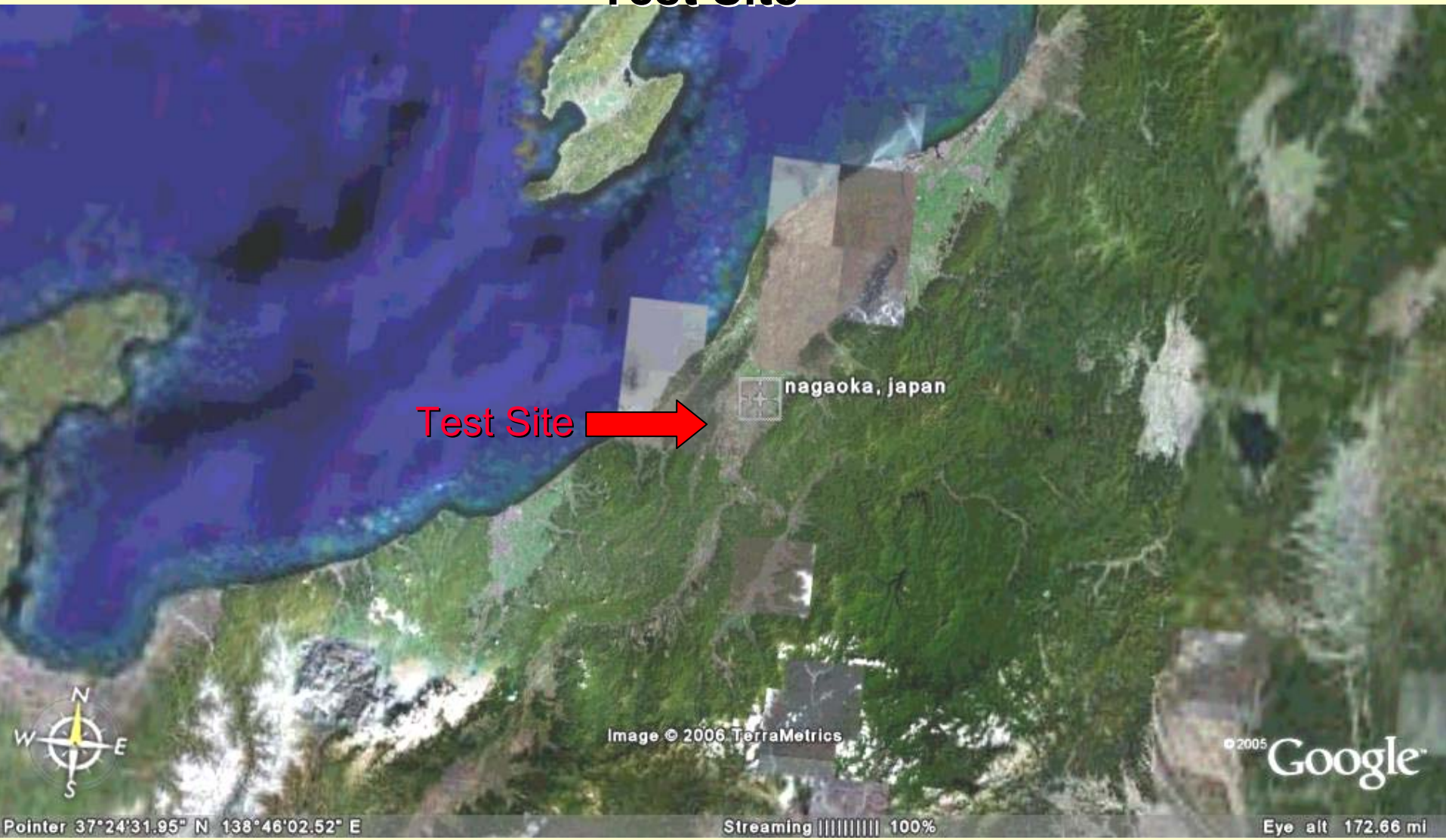


Overview

Test Site

Overview

Test Site



Overview

Test Site

Overview

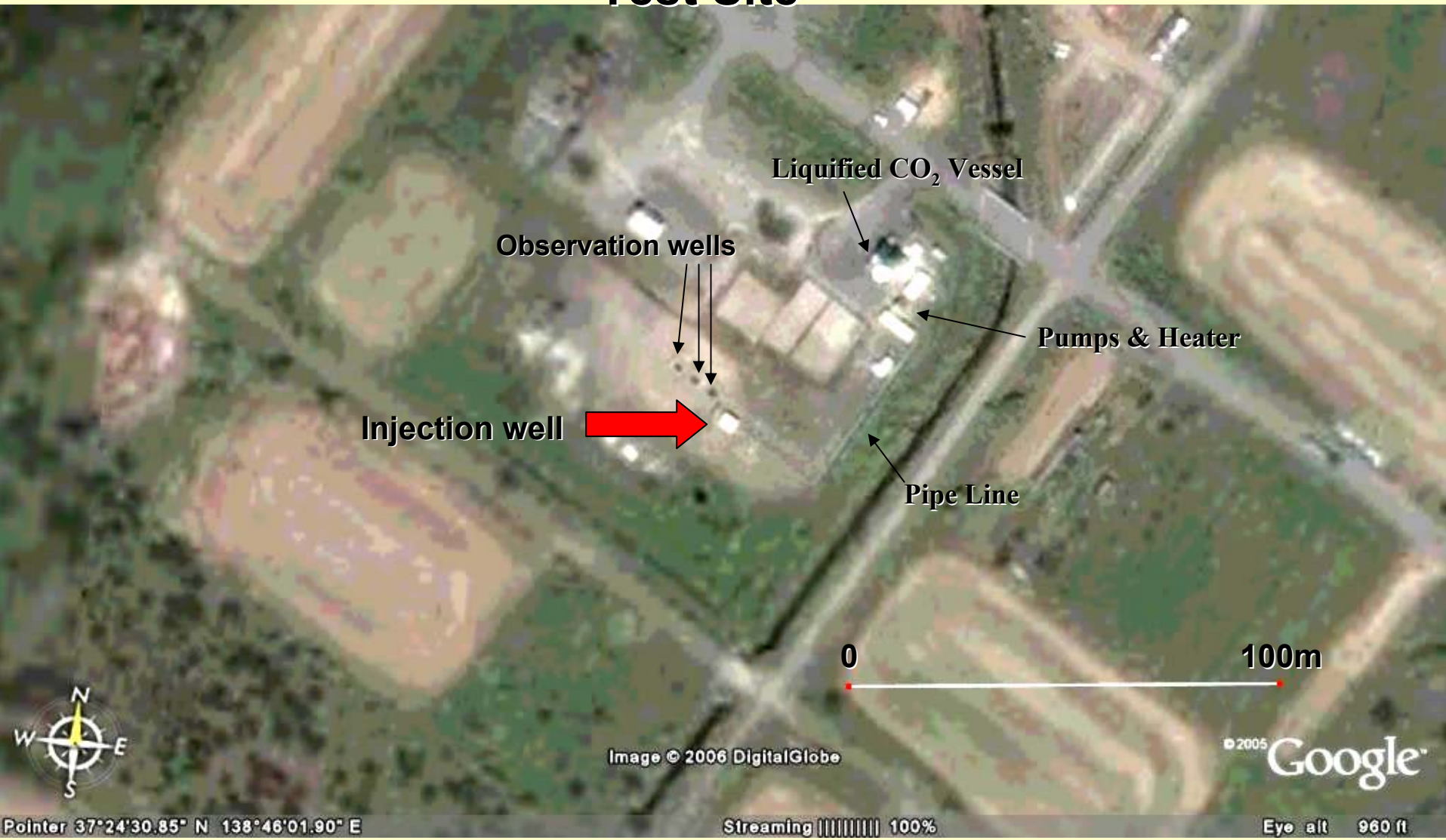
Test Site

Overview

Test Site

Overview

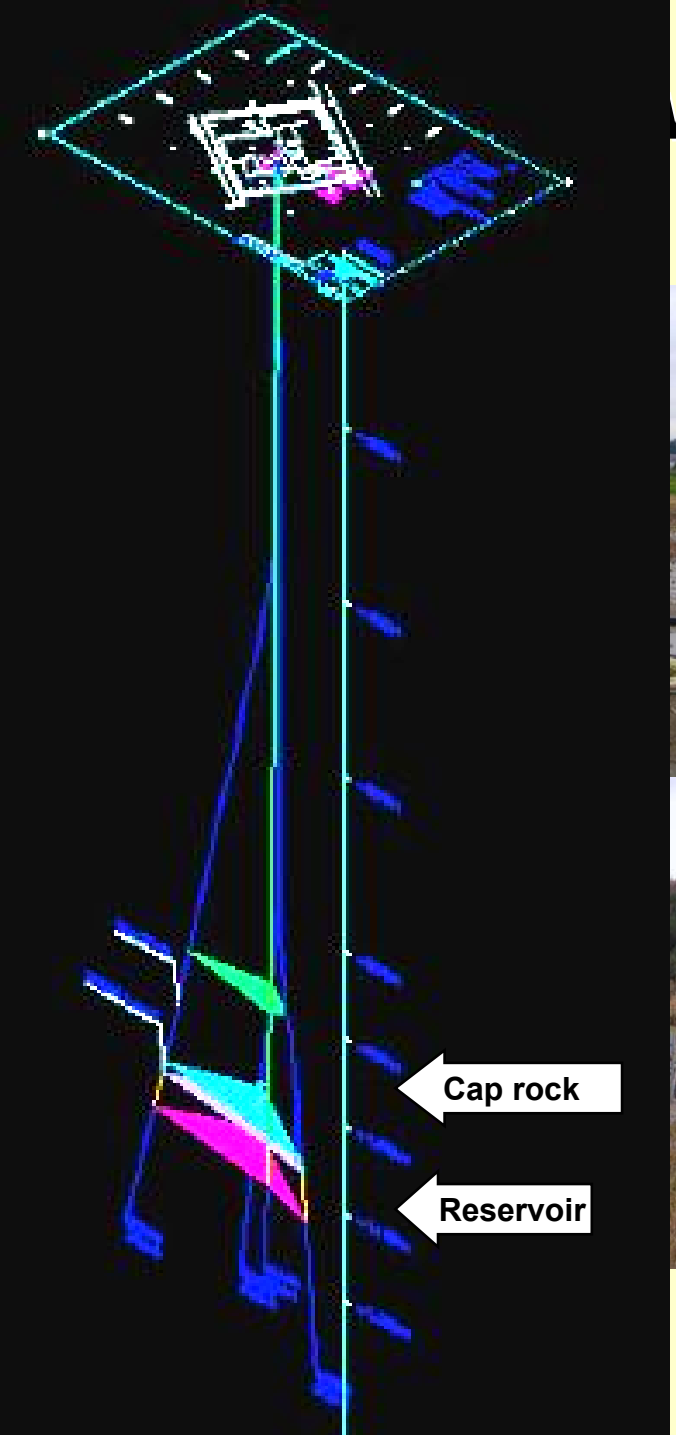
Test Site

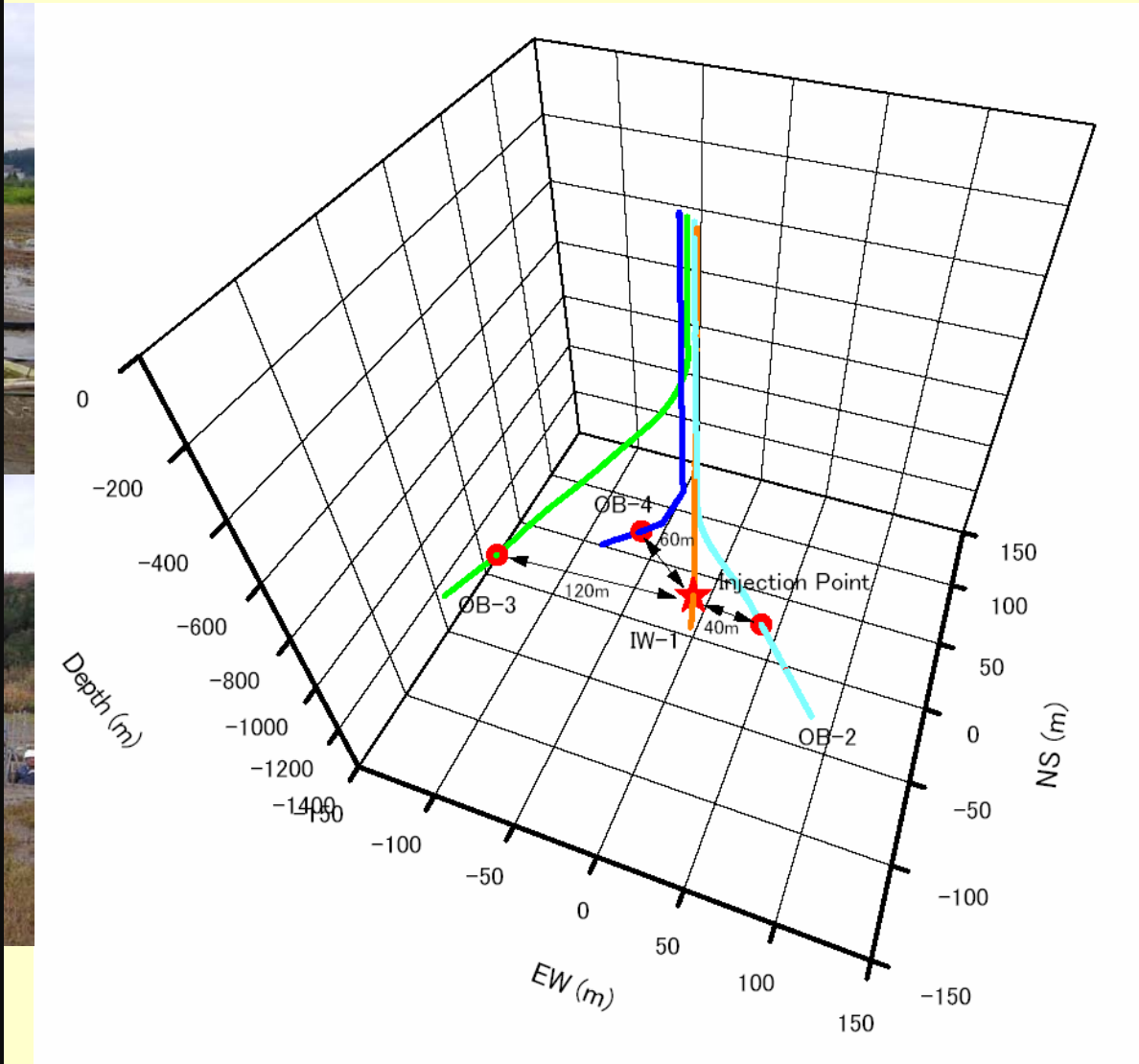


Well Configuration

Injection well : IW-1

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

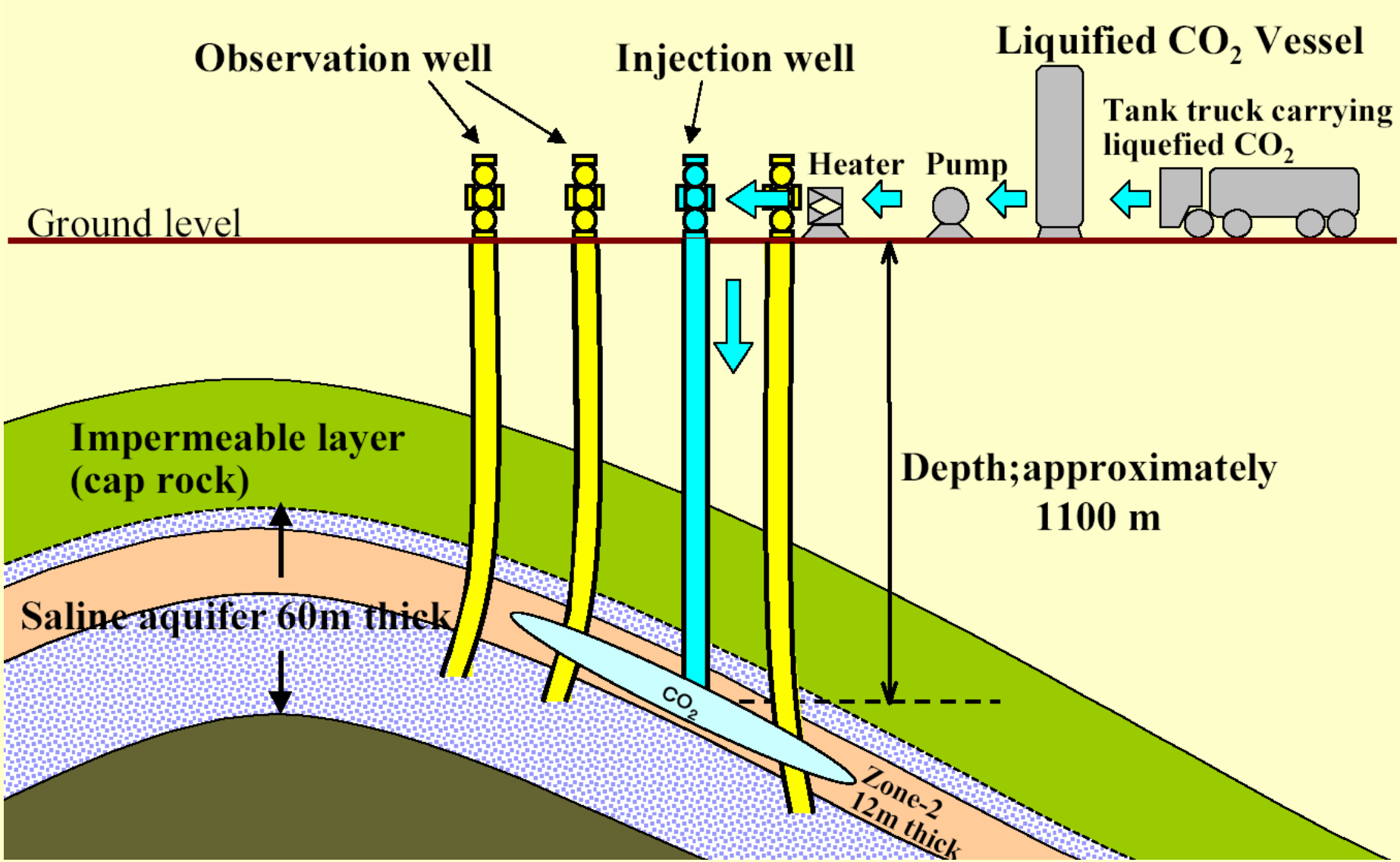




Main Features of CO_2 Injection

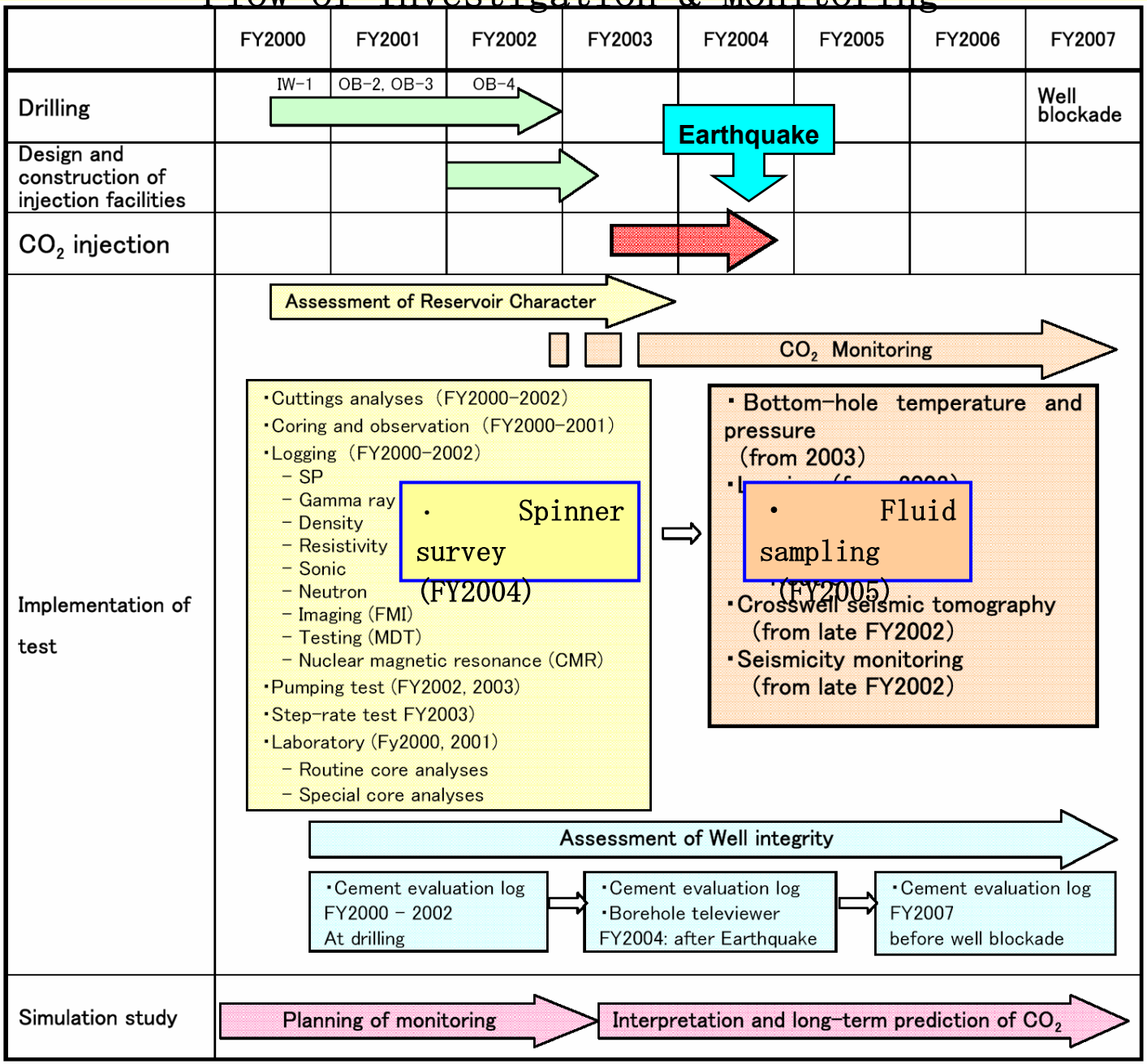
- Reservoir: Aquifer of 1,100m deep
- Duration of Injection: About 18 months
- Injection started on 7 July 2003, ended 11 January 2005
- Total Amount of CO2 : 10,405 t
- Injection Rate: 20 - 40t /day
- CO_2 Phase: kept to be Supercritical
- Injection Pressure
  - Well Head 6.6 - 7.4 MPa
  - Well Bottom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

Sketch of Injection



Overview

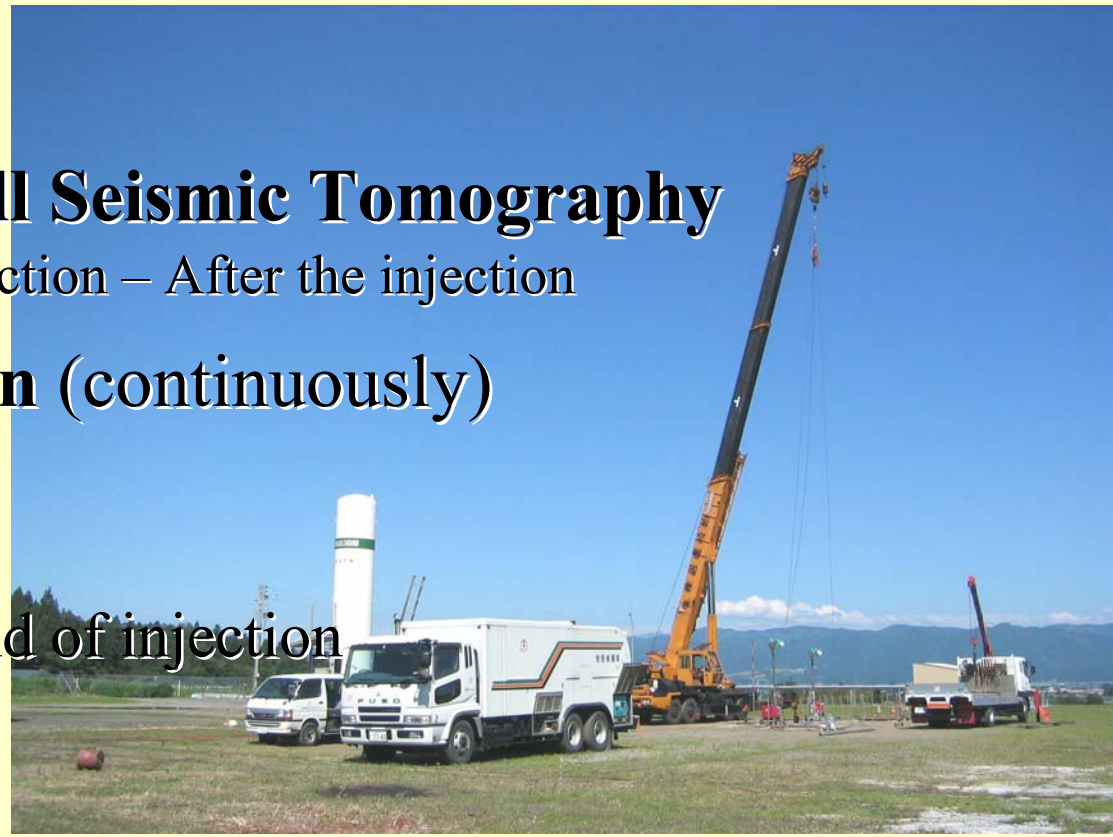
Flow of Investigation & Monitoring



Monitoring

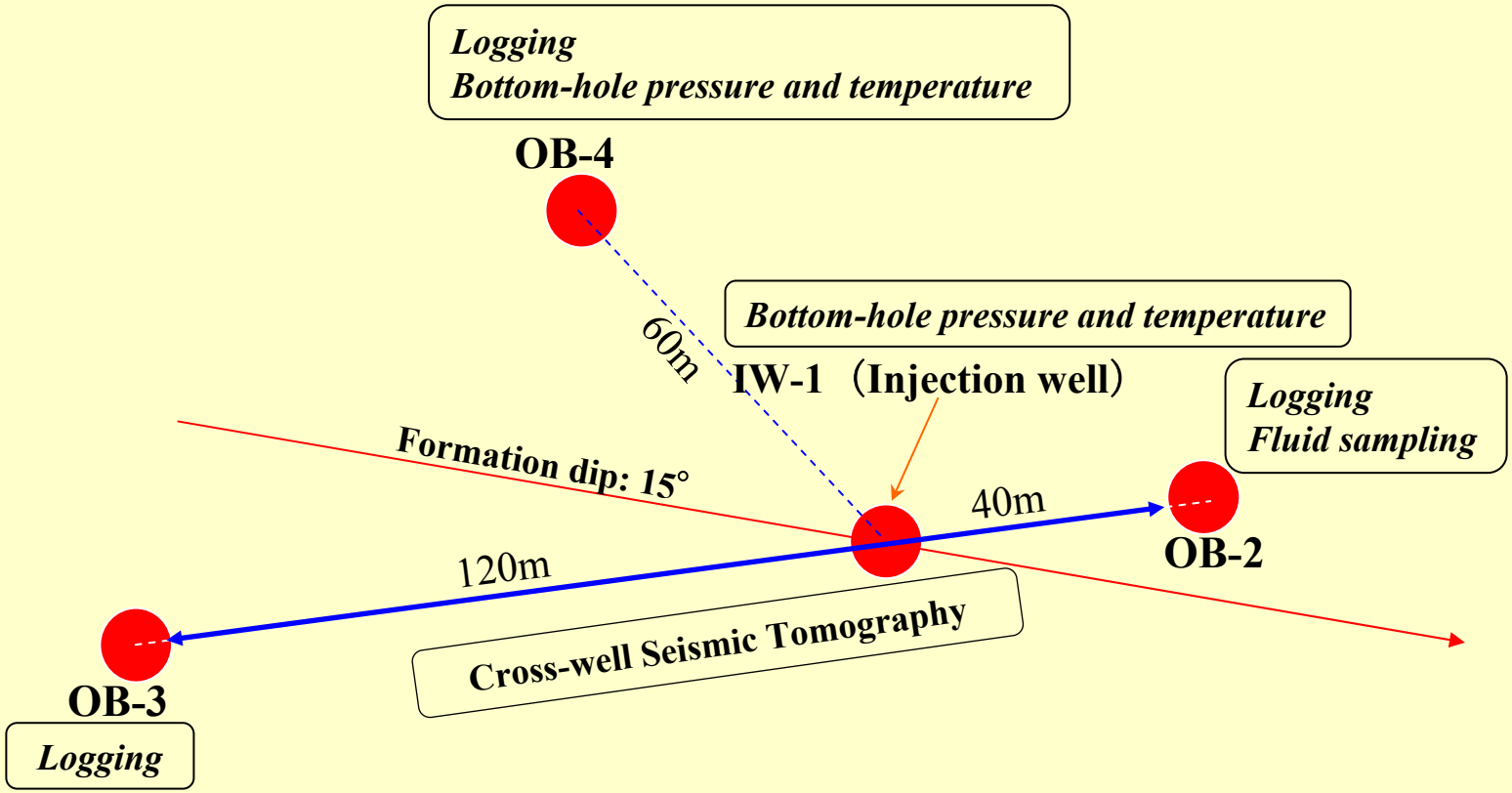
- **Pressure & Temperature Measurement**
  - Continuously at well bottom and well head)
- **Time-lapse Logging**

  (Baseline + 22 times during injection +8 times after the end of injection)
  - Induction Log
  - Neutron Log
  - Acoustic Log
- **Time-lapse Cross-well Seismic Tomography**
  - Six times : Before the injection – After the injection
- **Seismicity observation** (continuously)
  - Micro earthquake
- **Fluid Sampling**
  - 11 months after the end of injection



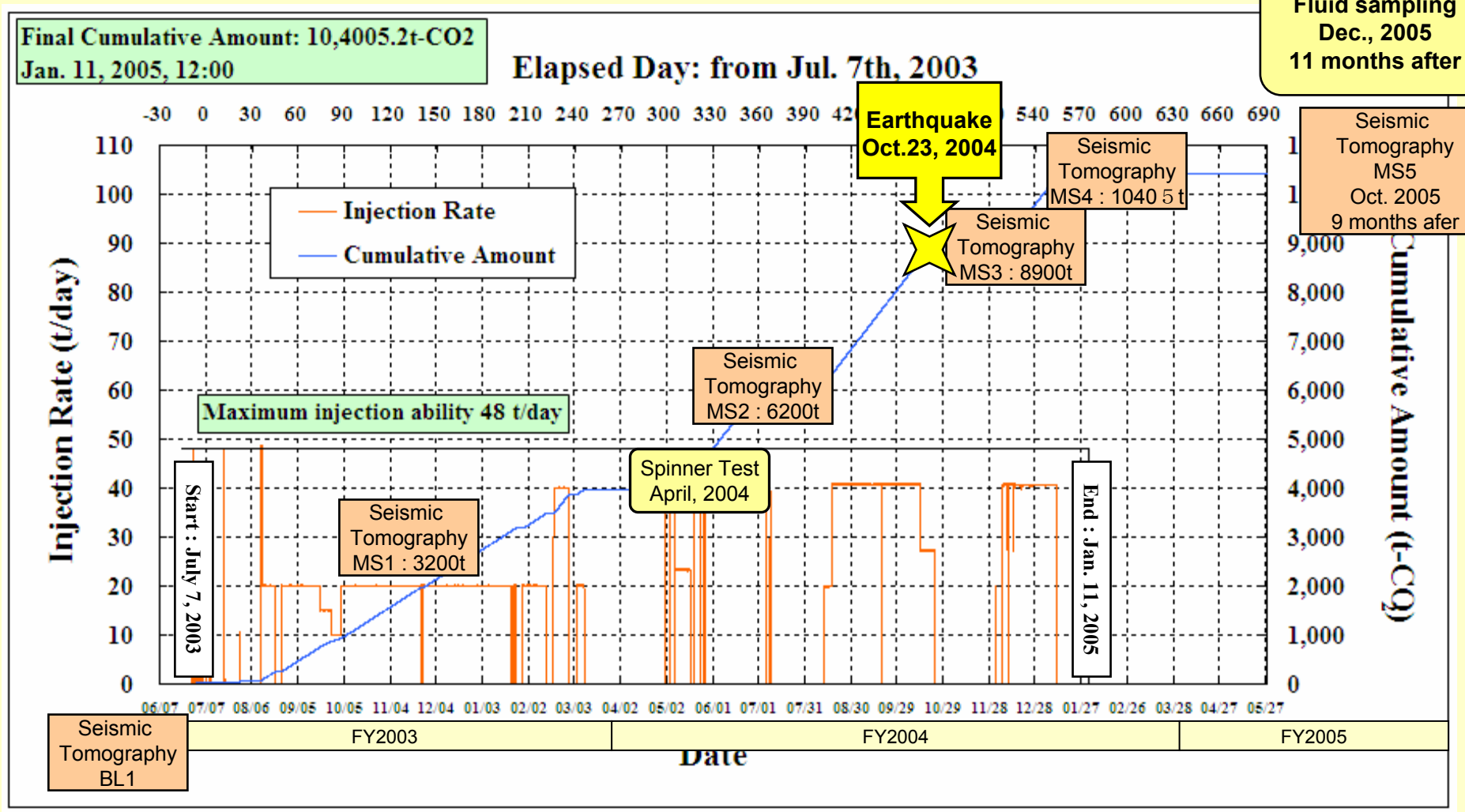
Well Configuration

Arrangement of Wells at Reservoir Level



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

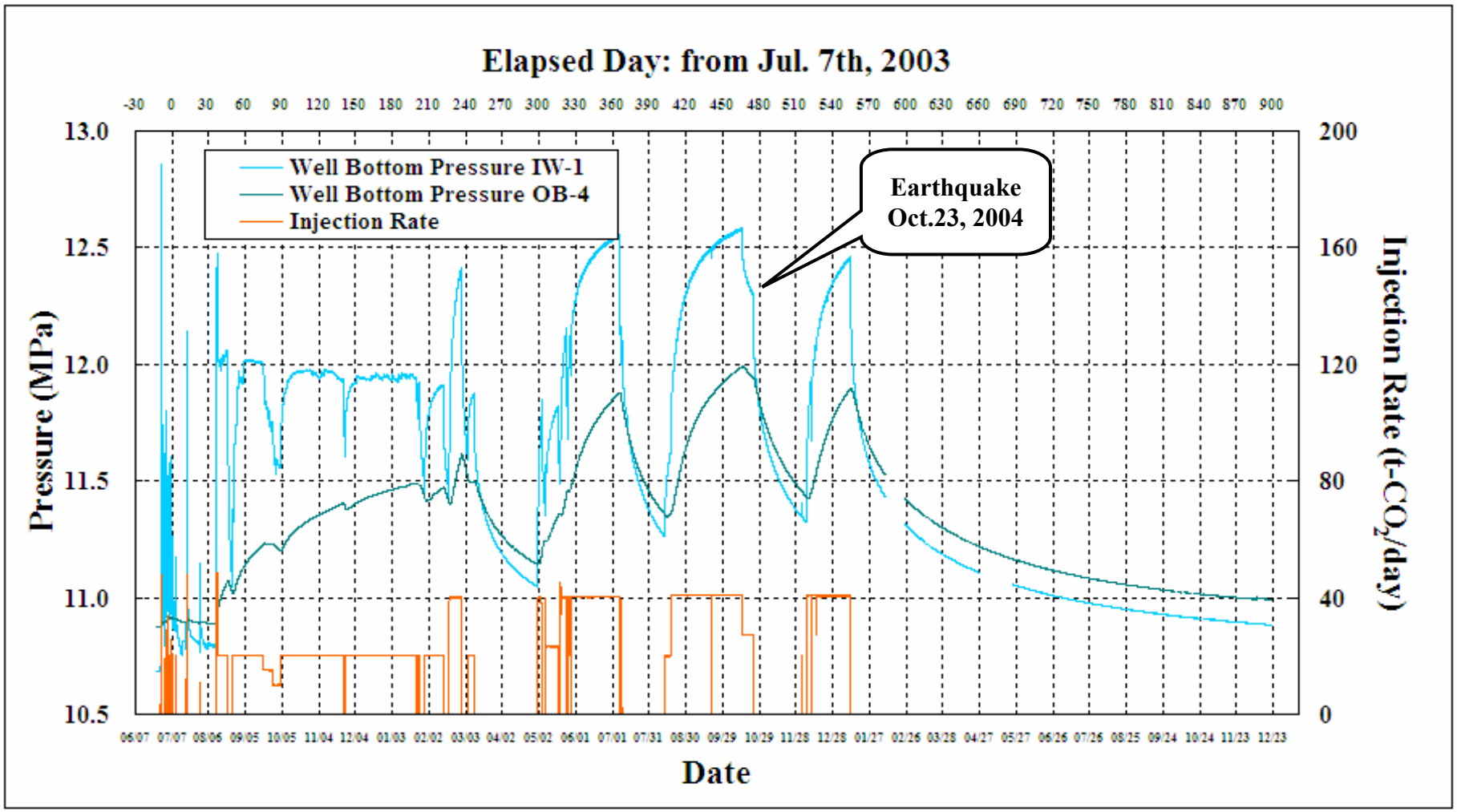
Progress of Injection and Monitoring



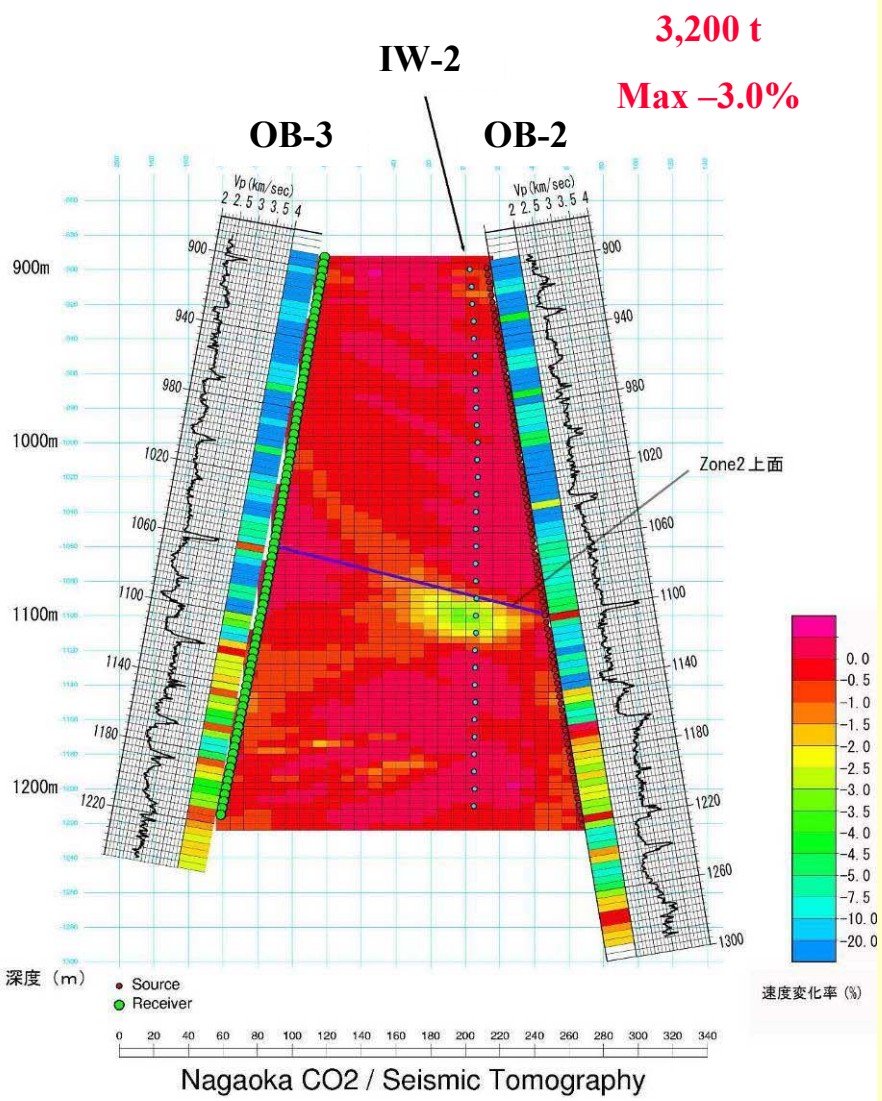
Pressure & Temperature Measurement

Seismicity Observation

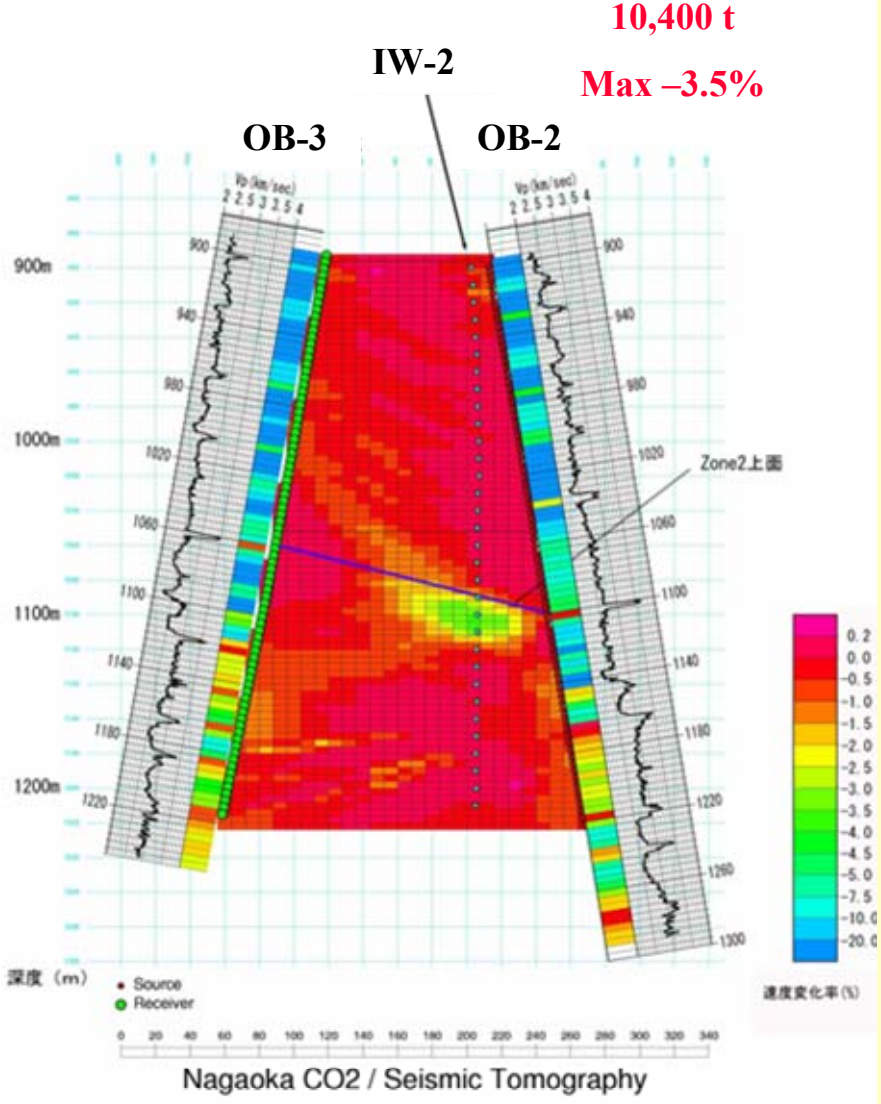
Pressure Measurement



Time-lapse Crosswell Seismic Tomography



MS1/BLS



MS4/BLS

Time-lapse Well Logging

- Improved Understanding of the CO_2 Movement in the Porous Sandstone Reservoir
- Breakthrough time (the arrival of injected CO2)

Liquified CO2 Vessel

Logging Unit

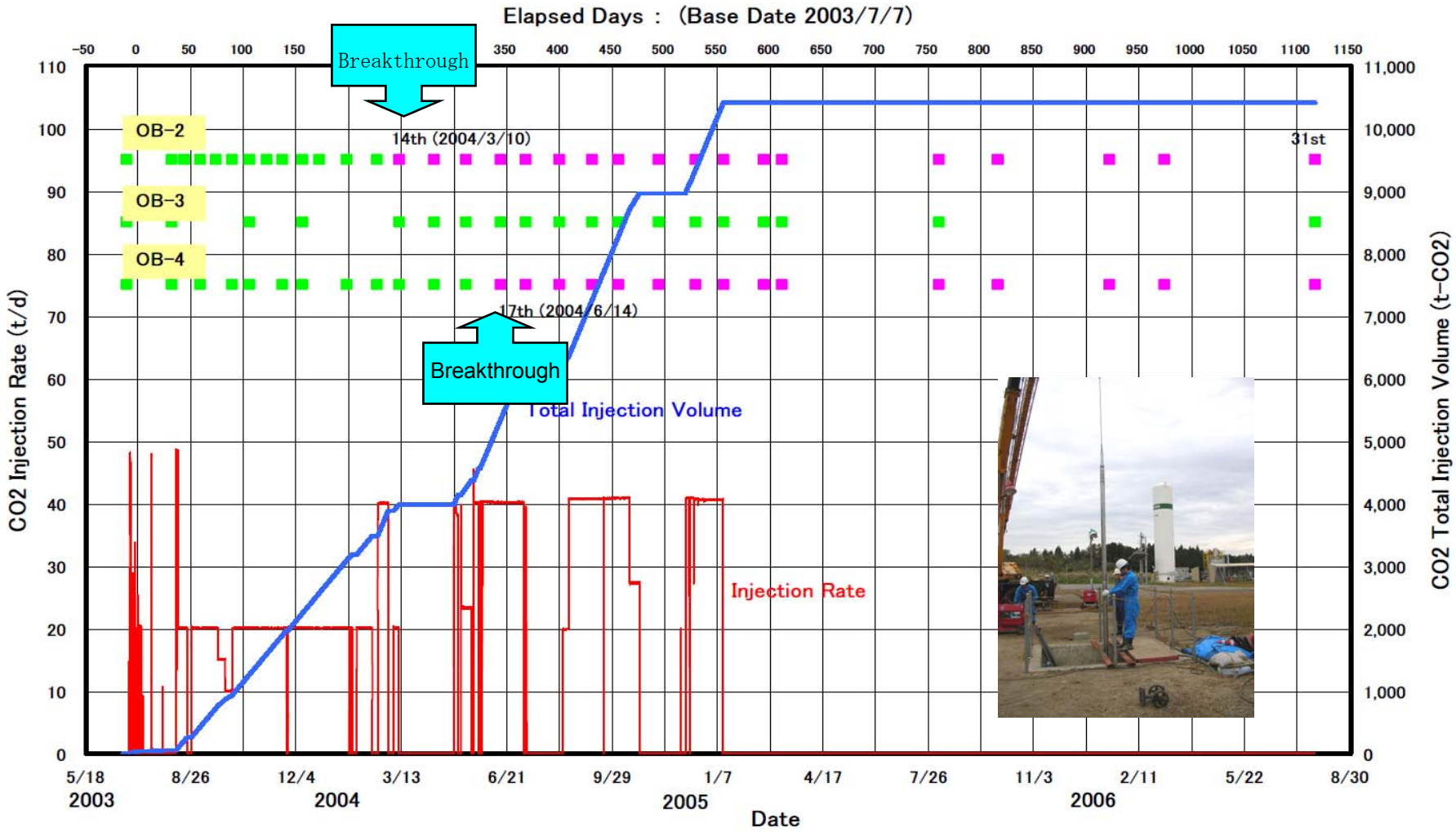
OB-2

OB-3

OB-4

IW-1

Time-lapse Well Logging



CO_2 Breakthrough at OB-2

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

17th logging on June 14

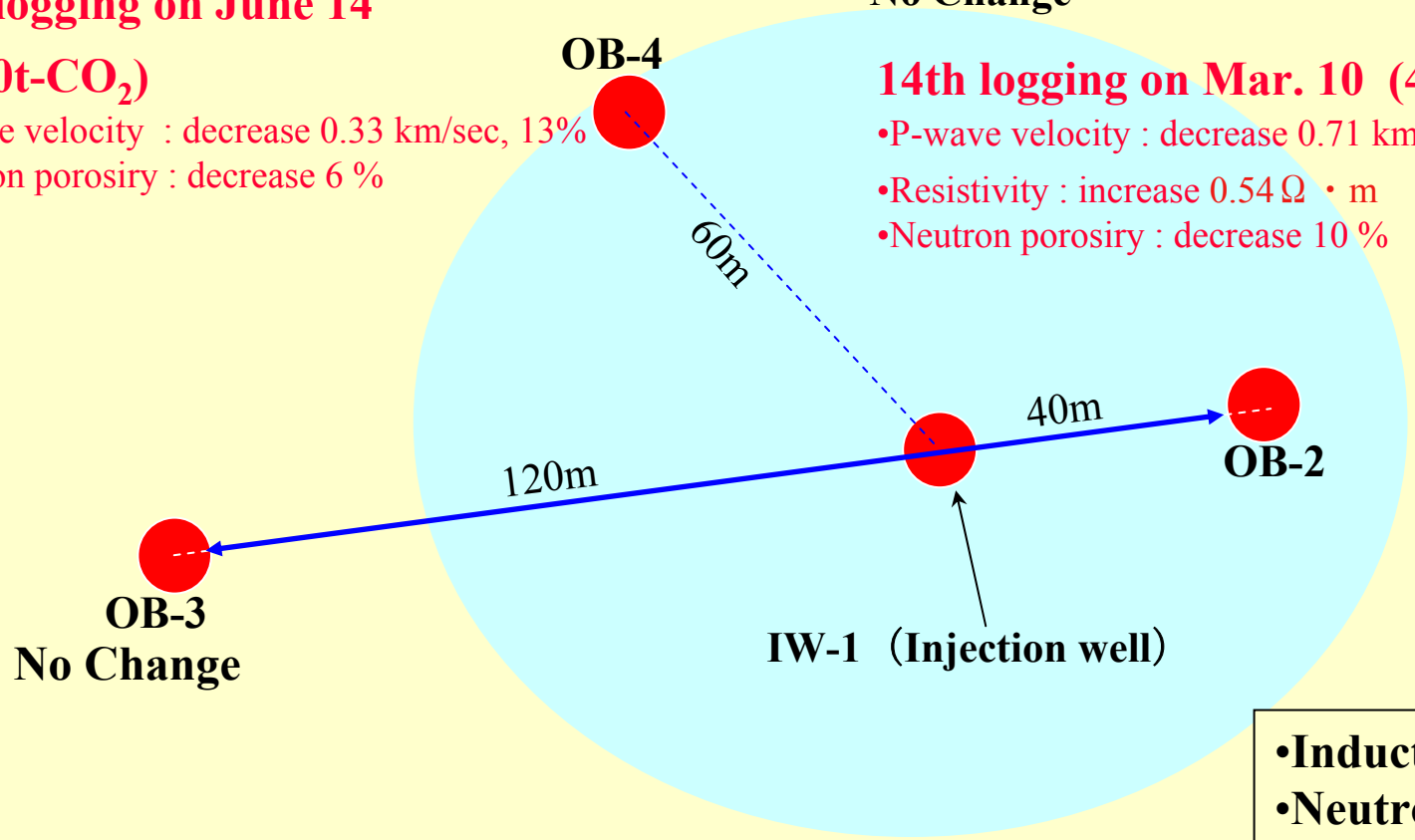
(5,400t-CO_2)

- P-wave velocity : decrease 0.33 km/sec, 13%
- Neutron porosiry : decrease 6 %

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

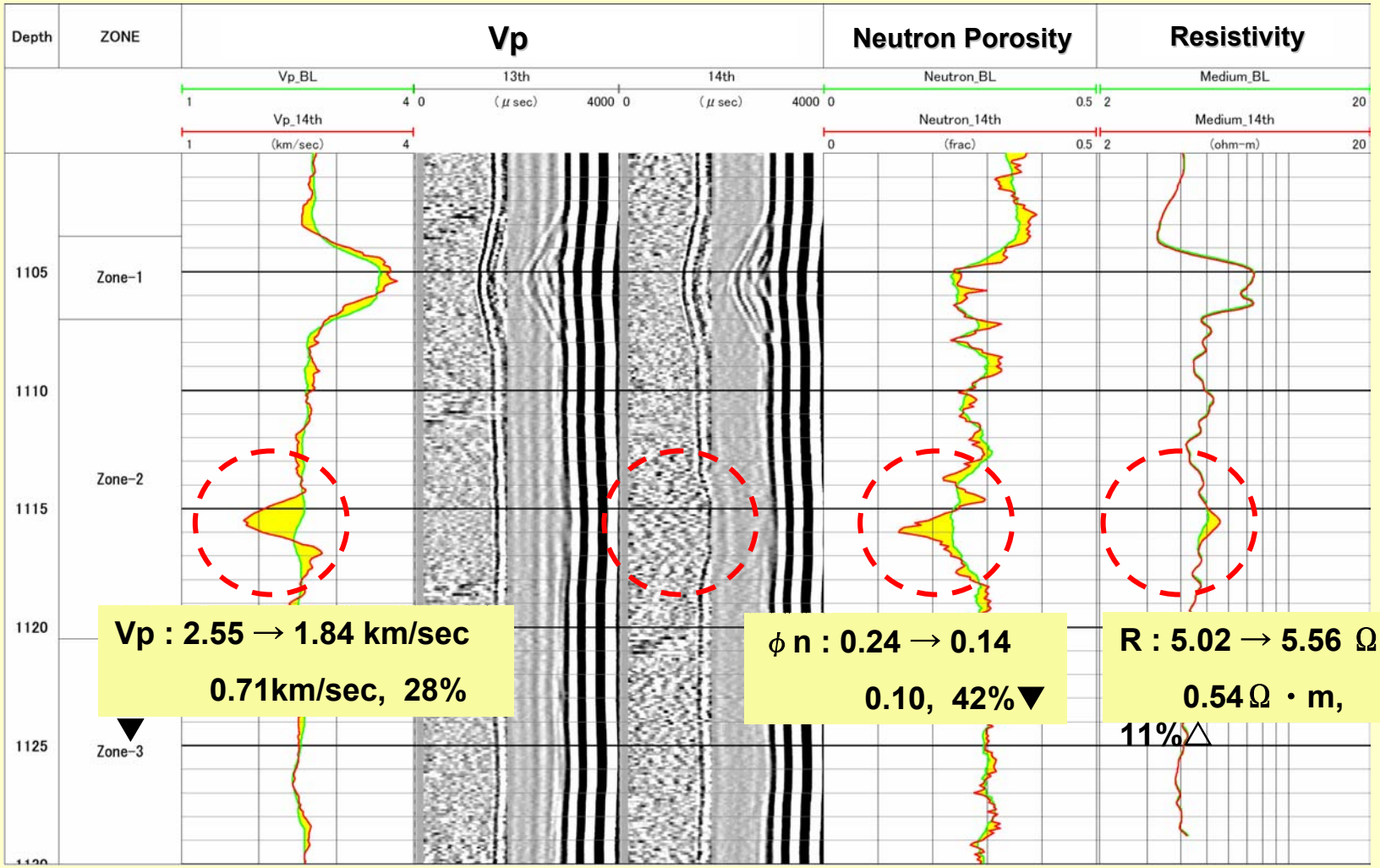
14th logging on Mar. 10 (4,000t-CO_2)

- P-wave velocity : decrease 0.71 km/sec, 28%
- Resistivity : increase 0.54 Ω・m
- Neutron porosiry : decrease 10 %



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

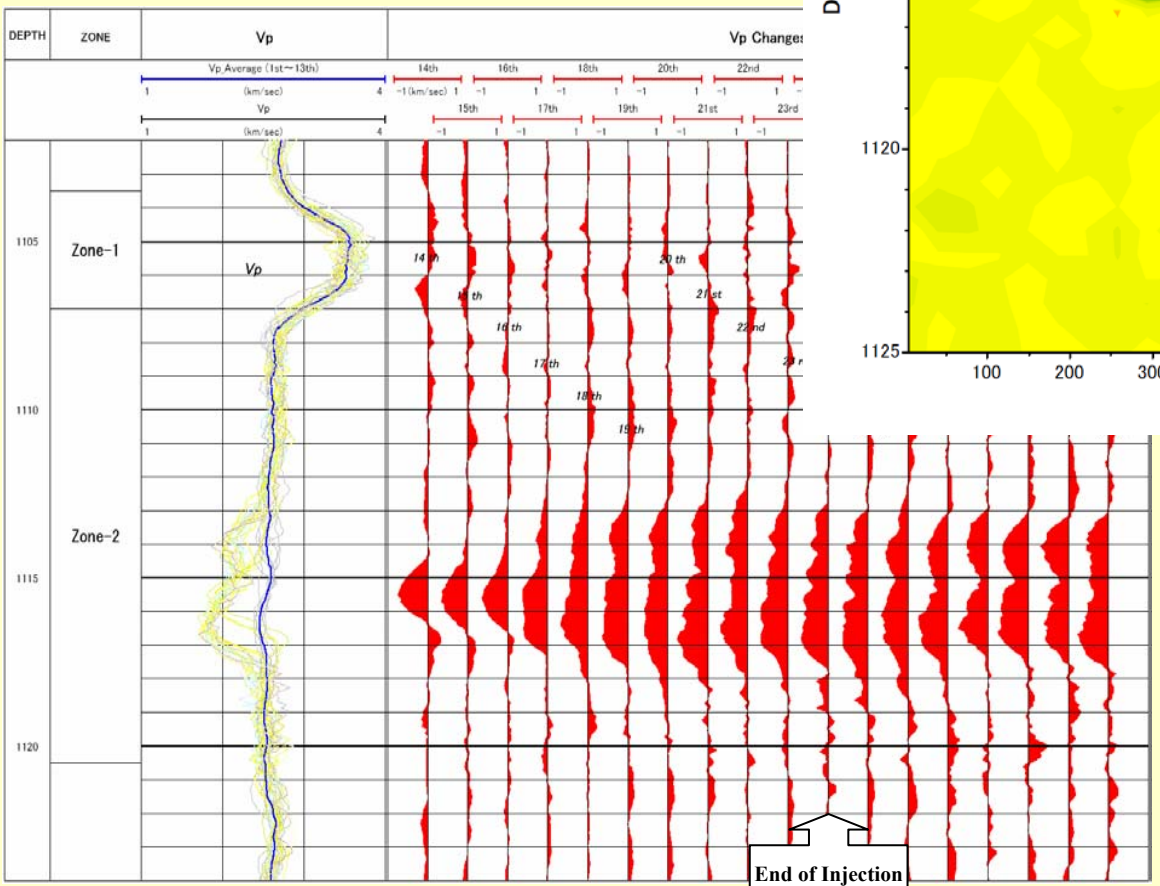
CO_2 Breakthrough at OB-2

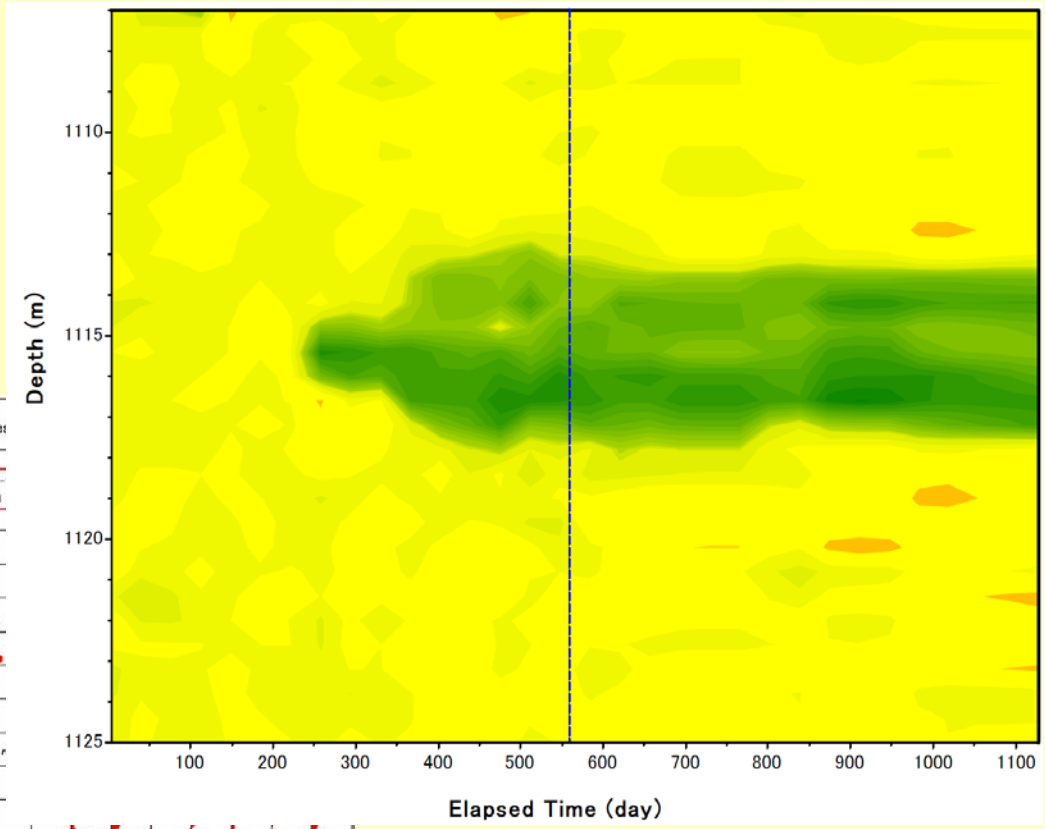


Feb. 12. 2004 → Mar. 10. 2004

Time-Lapse Well Logging

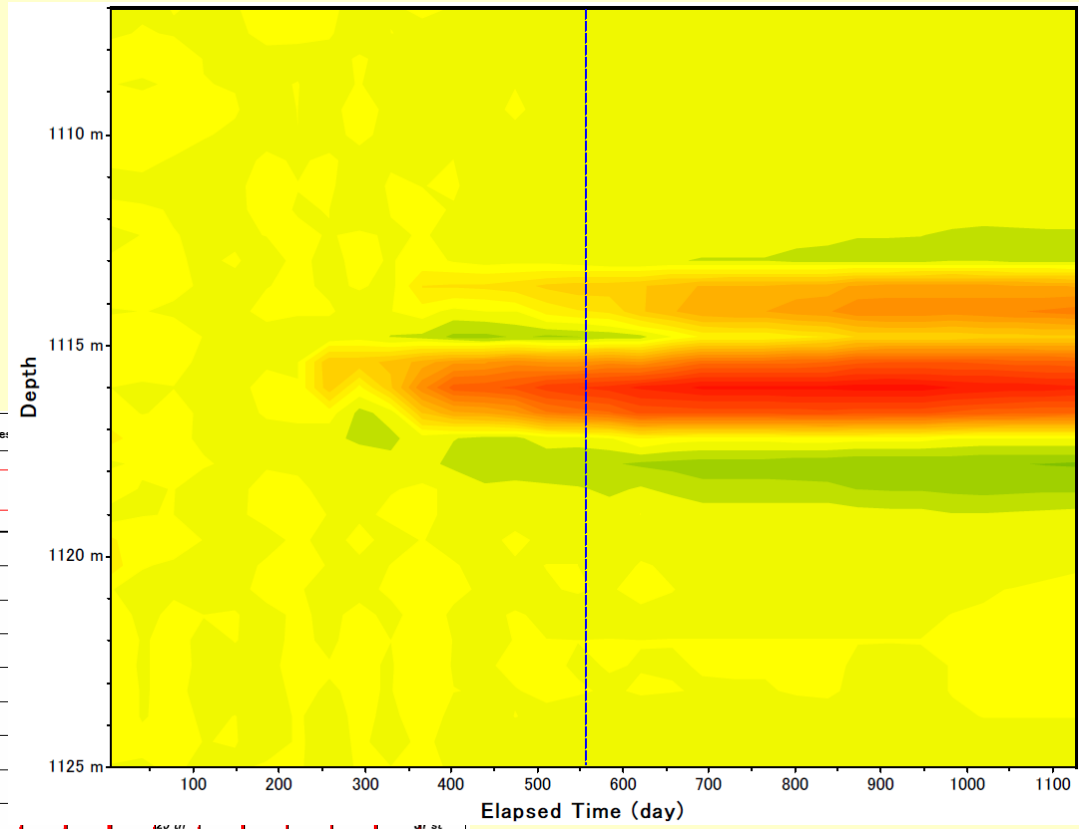
Well Logging Result :OB-2 (Vp)

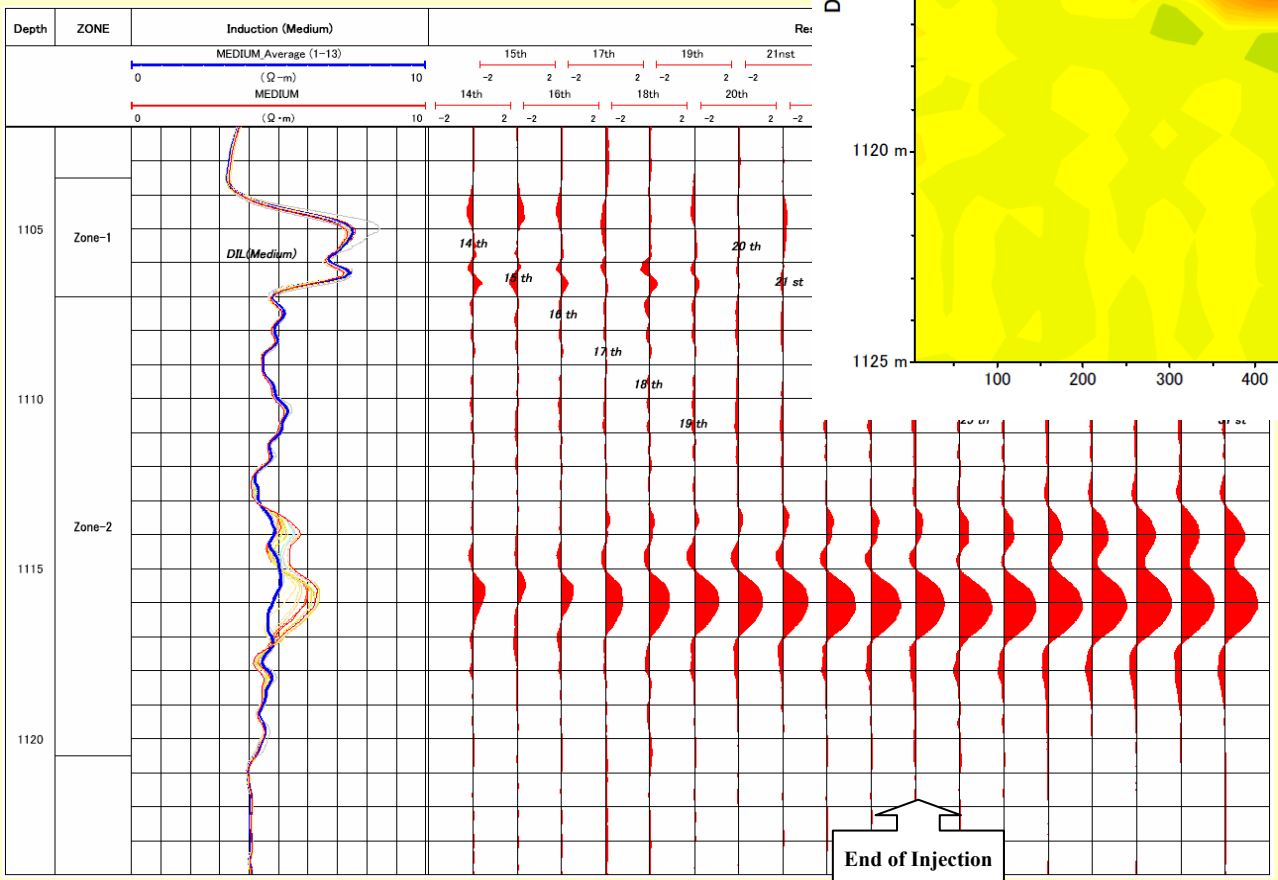




Time-Lapse Well Logging

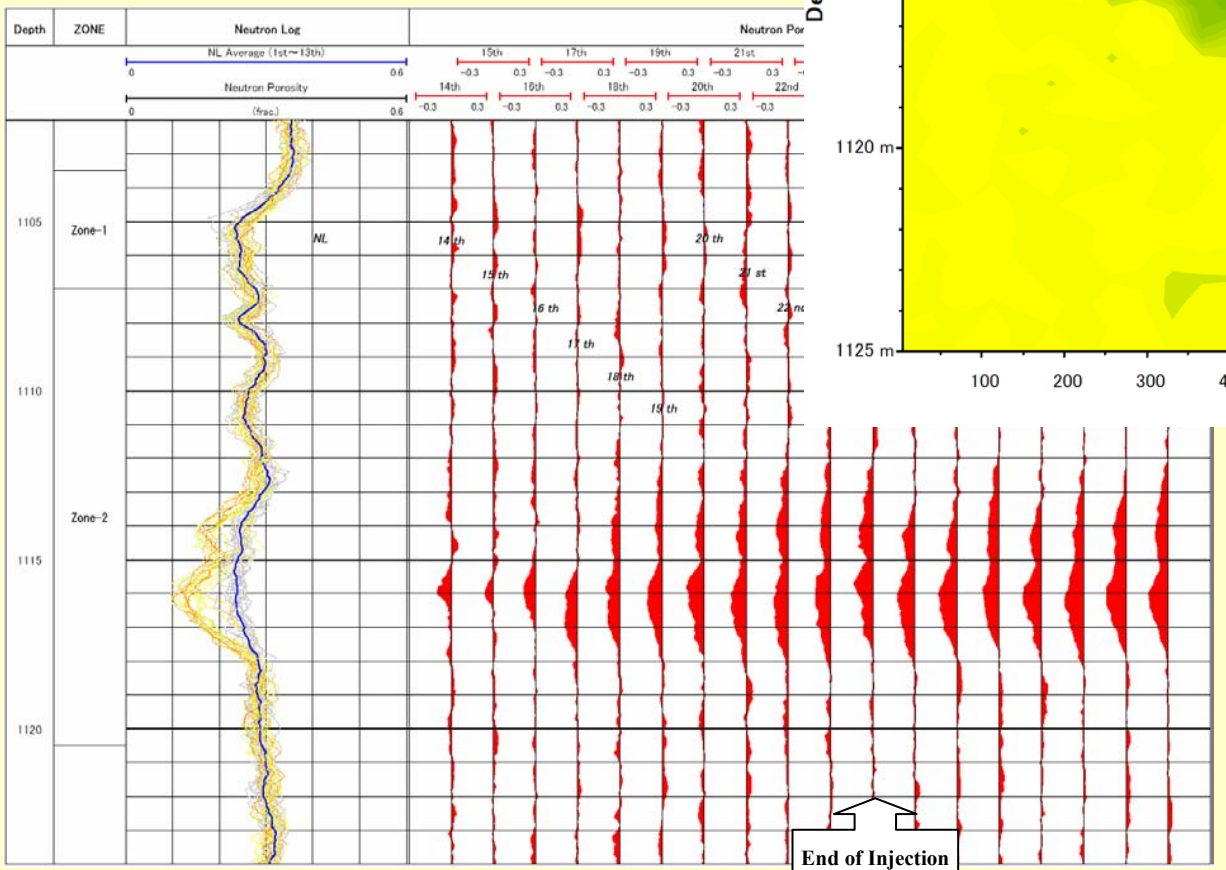
Well Logging Result :OB-2 (resistivity)

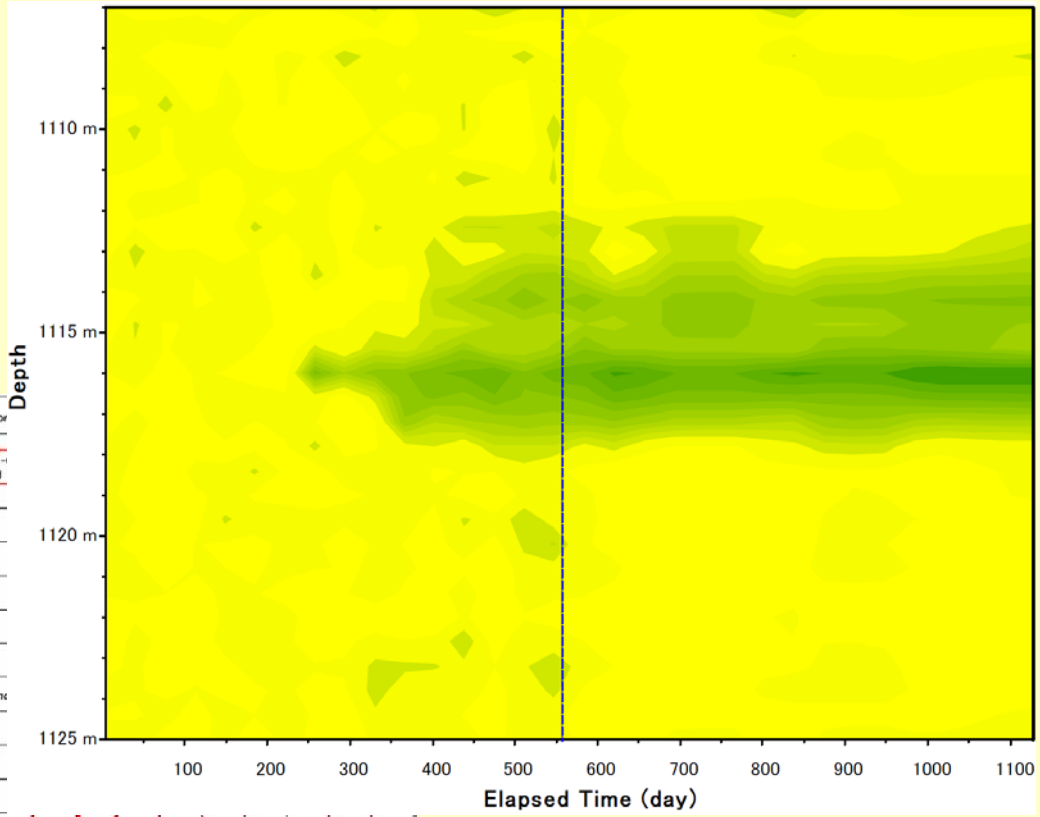




Time-Lapse Well Logging

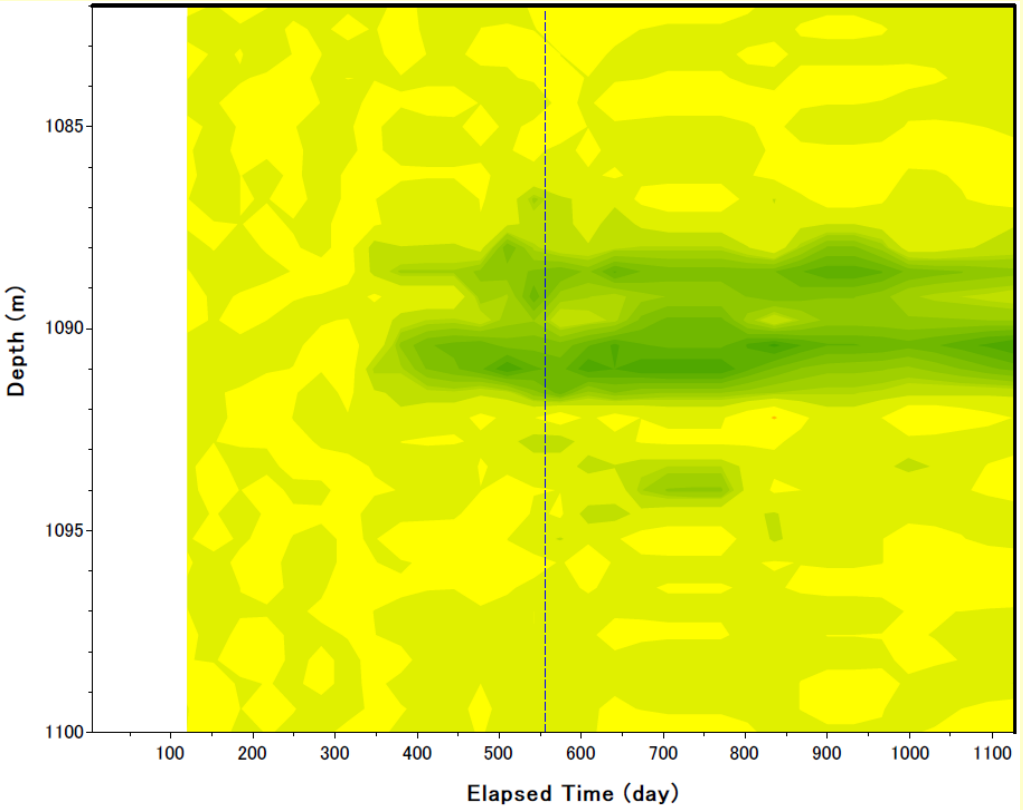
Well Logging Result : OB-2 (Neutron porosity)

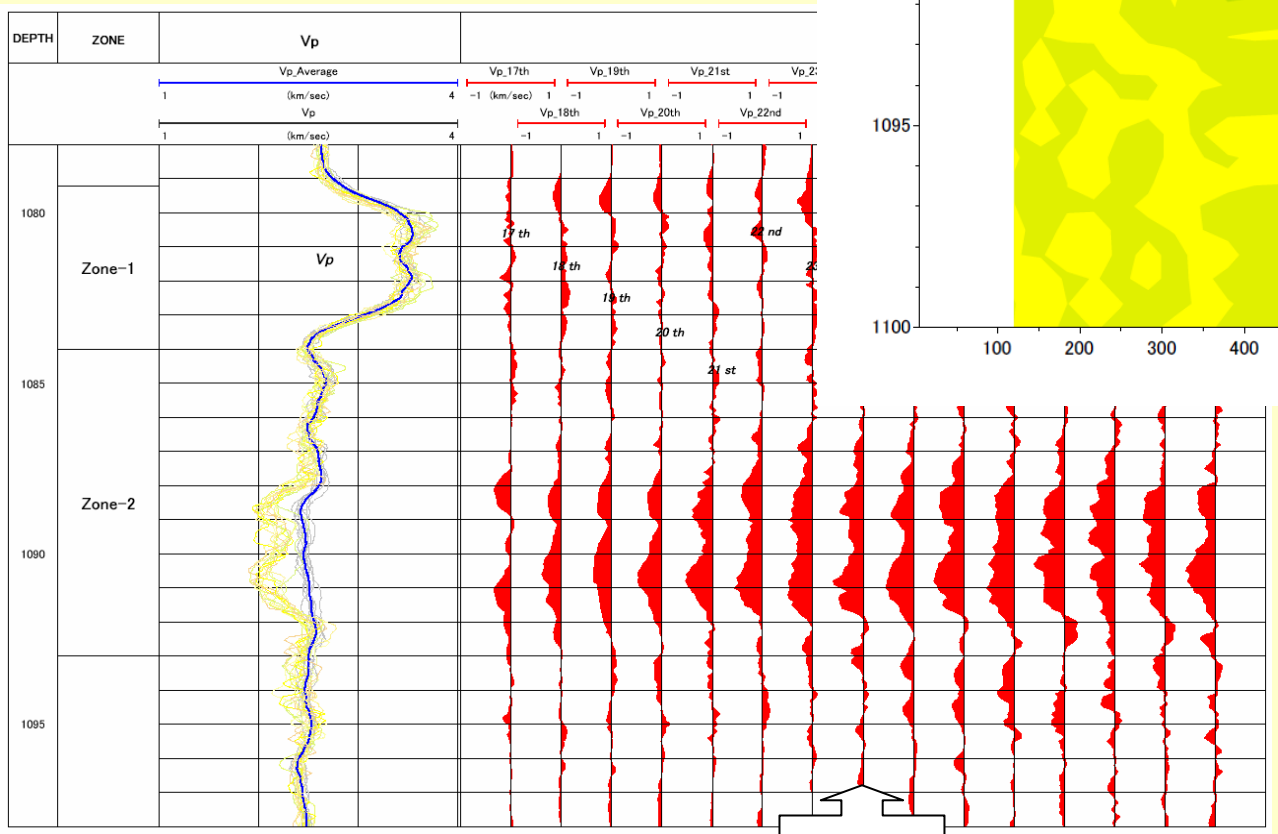




Time-Lapse Well Logging

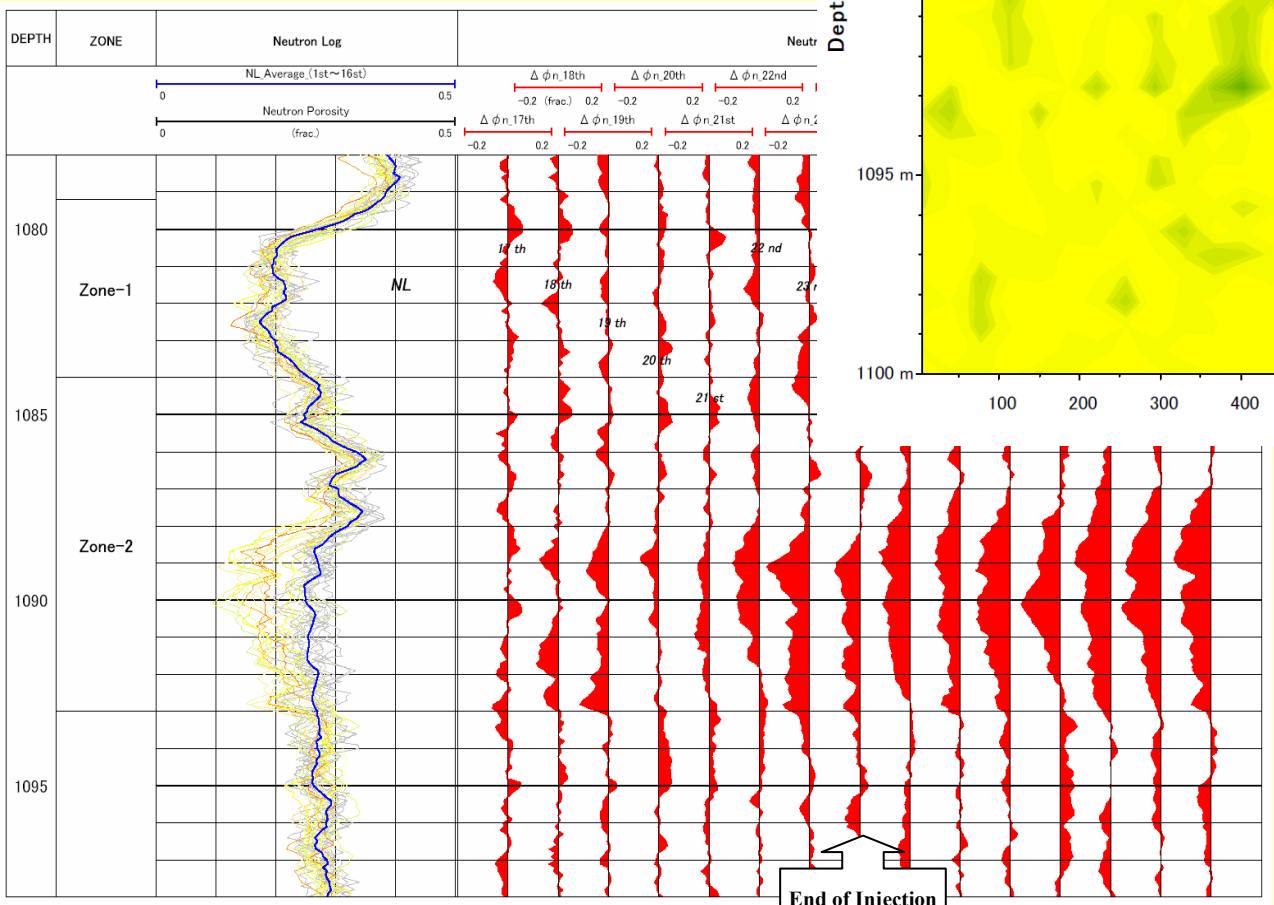
Well Logging Result :OB-4 (Vp)

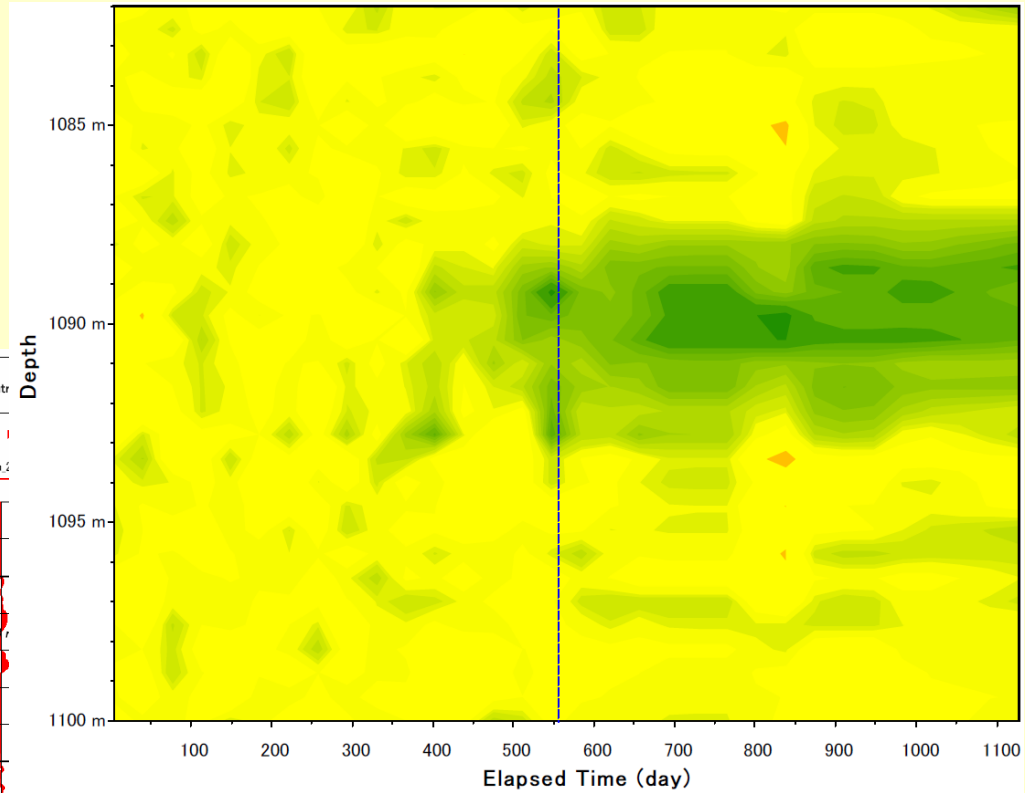




Time-Lapse Well Logging

Well Logging Result :OB-4 (Neutron porosity)





Time-Lapse Well Logging

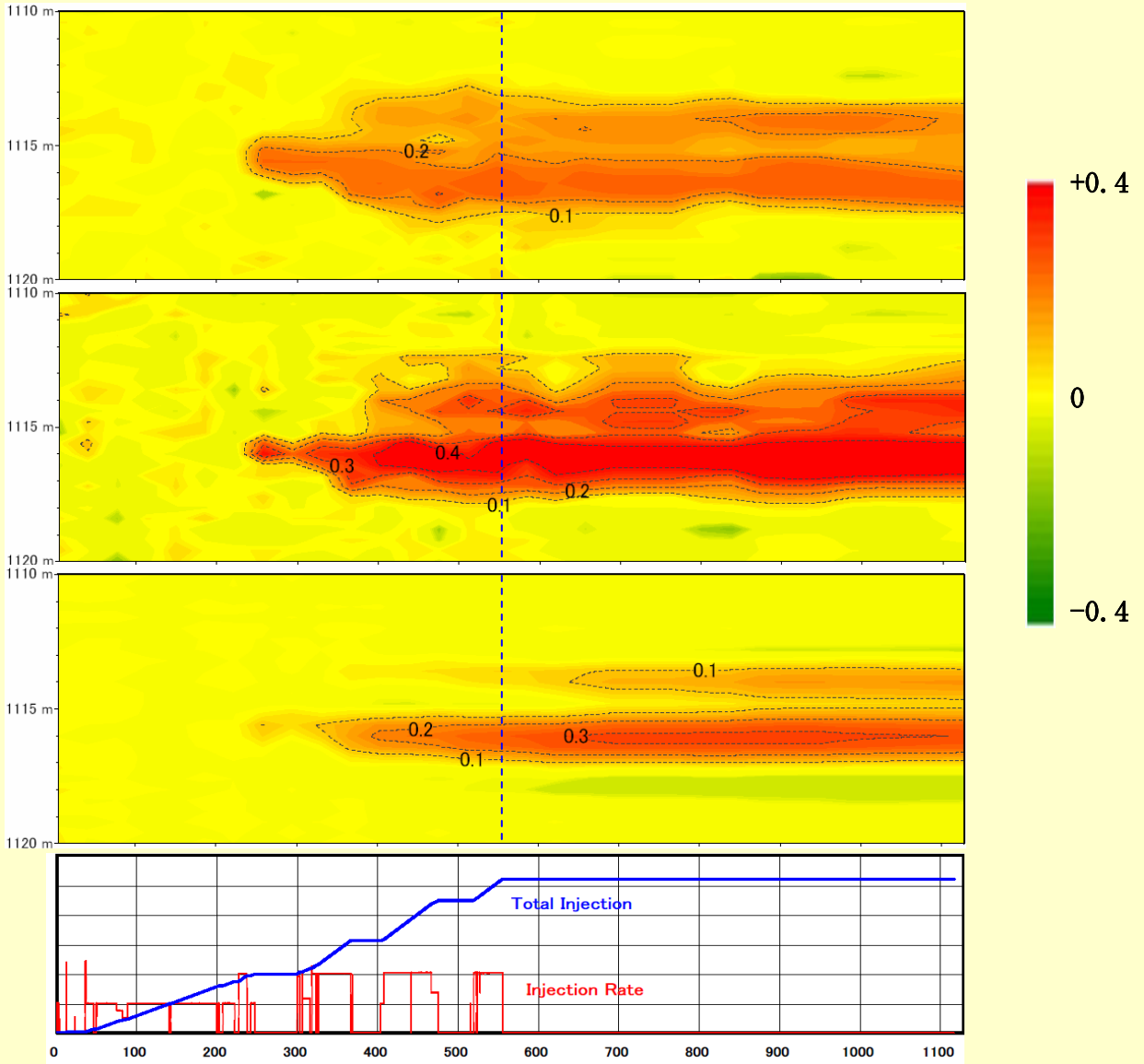
Change of values (OB-2)

Vp

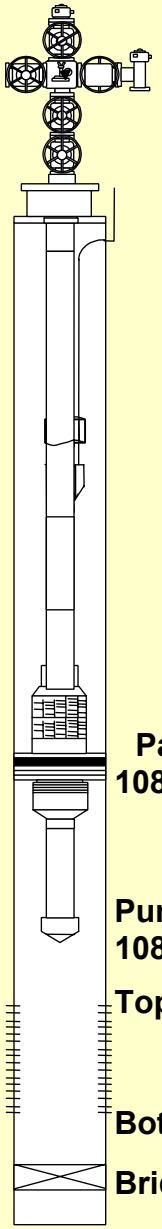
Neutron porosity

Resistivity

CO_2 injection



Spinner (flow meter) Test



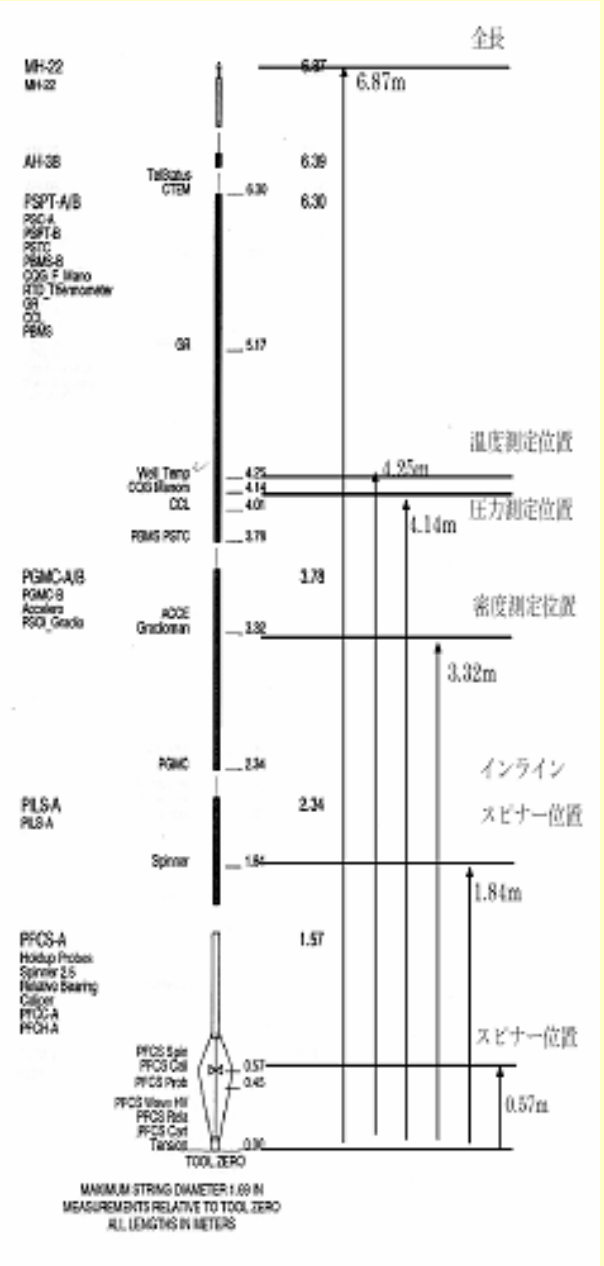
Packer
1081.84m

Pump out plug Bottom
1085.72m

Top 1093m

Bottom 1105m

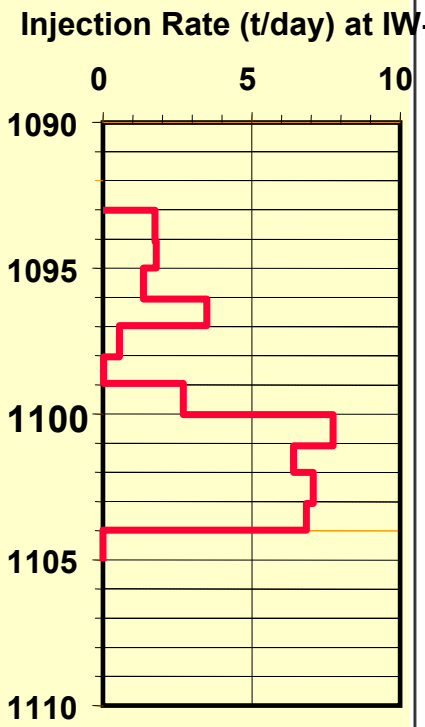
Bridge Plug 1113m

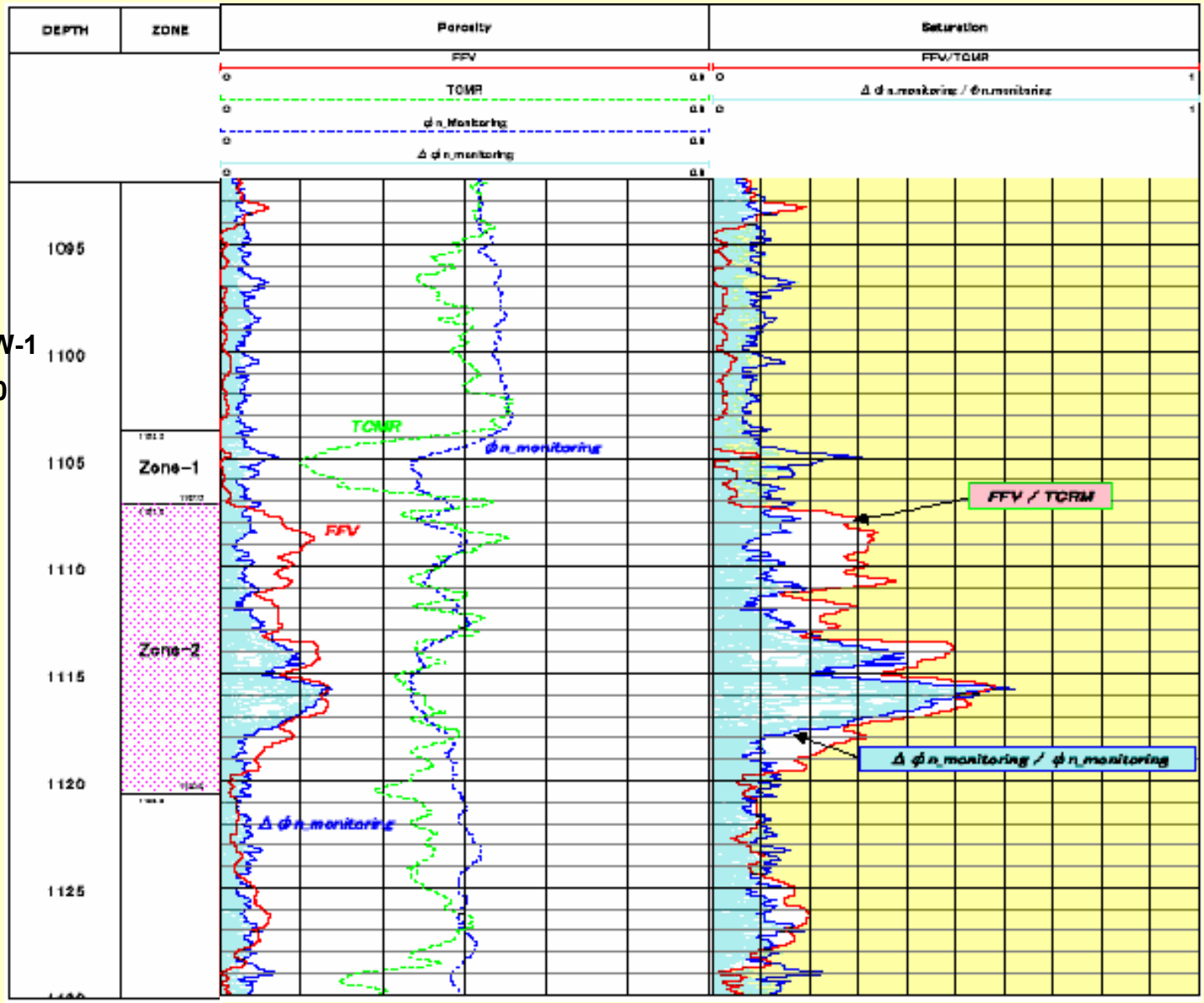


PLT Tool

Flow Meter Injection Rate and Logging Result

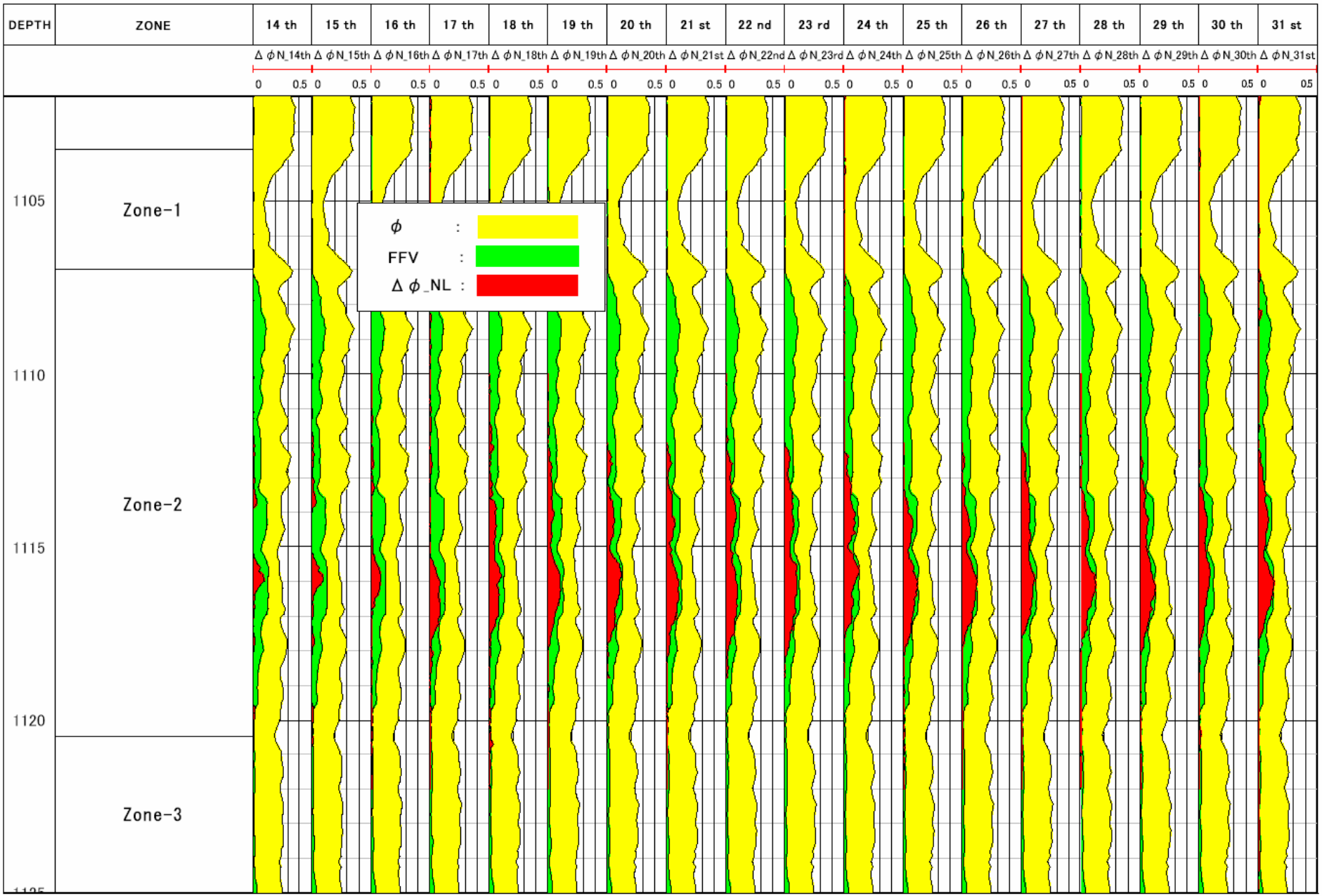
Change of Neutron Porosity (Δ Φn) and FFV at OB-2



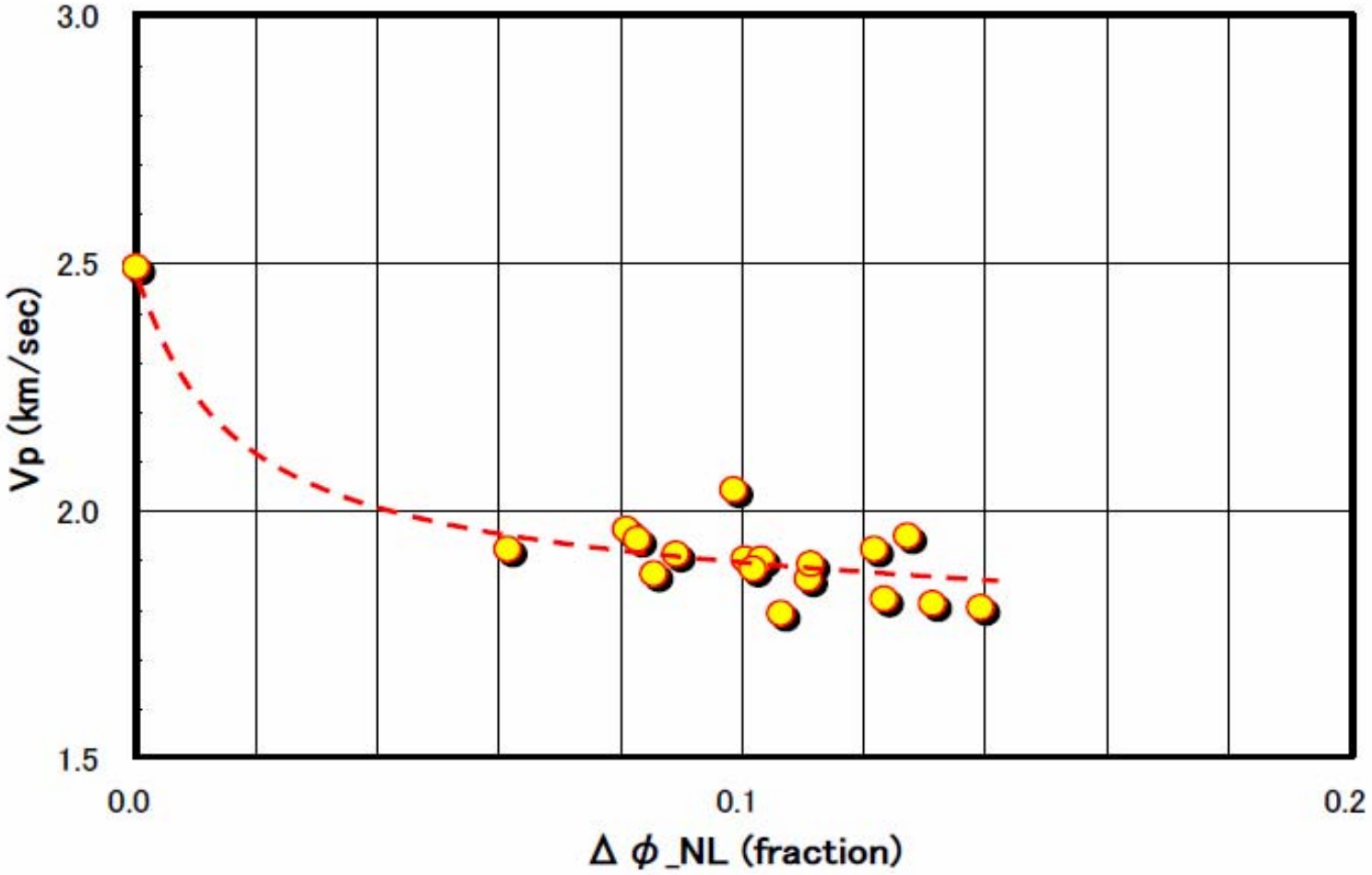


Time-Lapse Well Logging

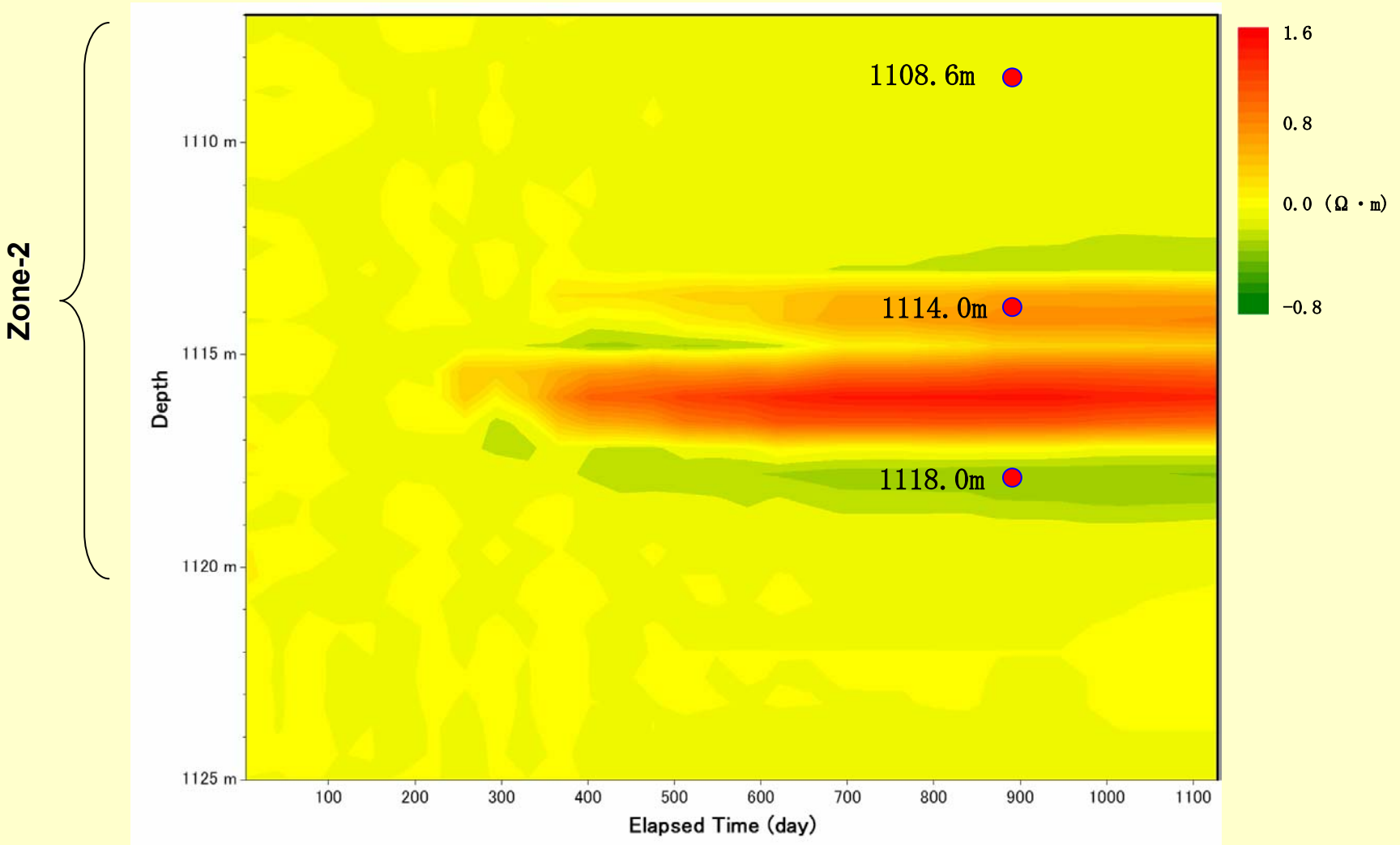
Change of Neutron porosity and NMR Result (OB-2)



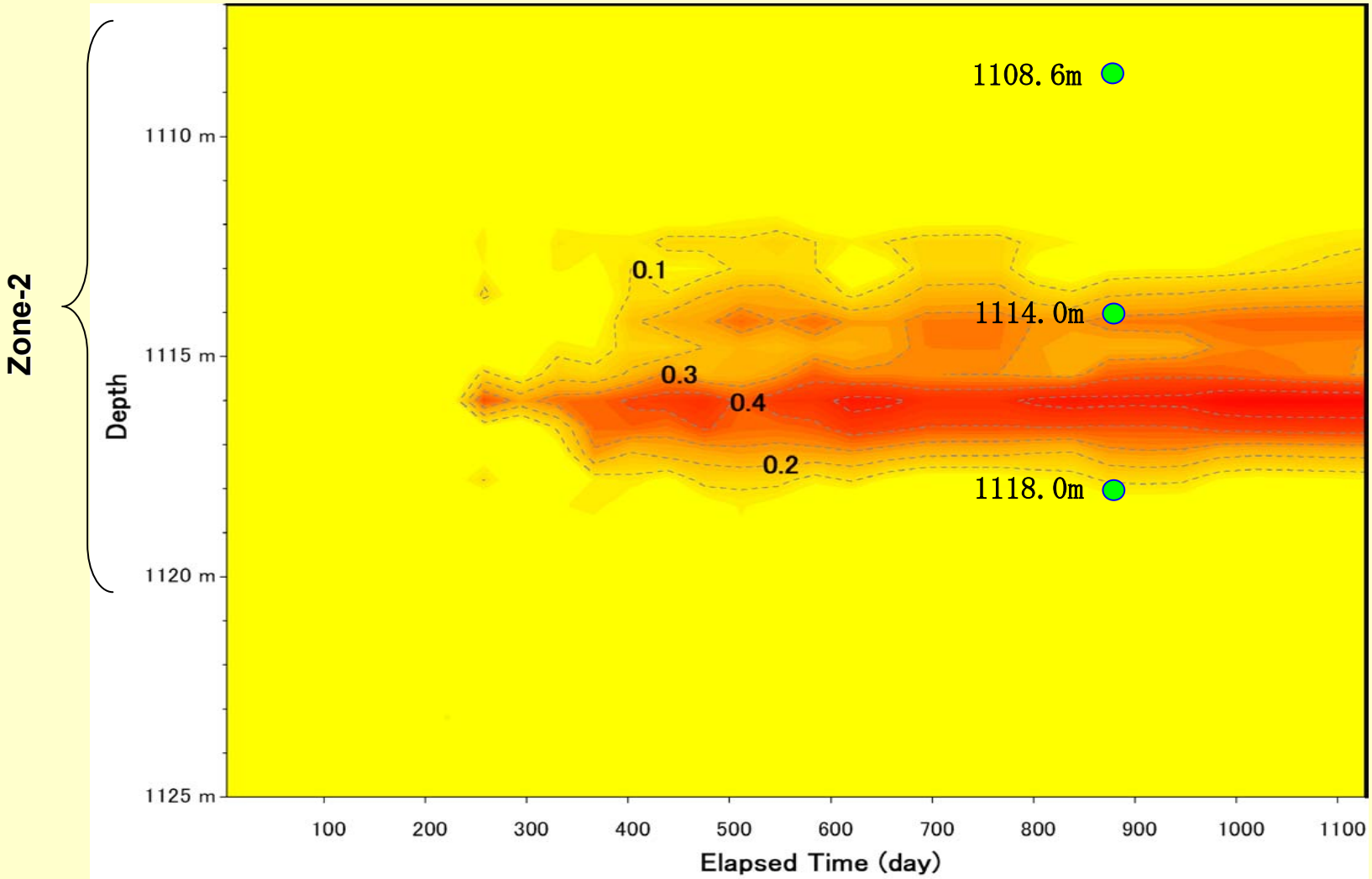
P-Wave Velocity Response (OB-2 : 1,116m)



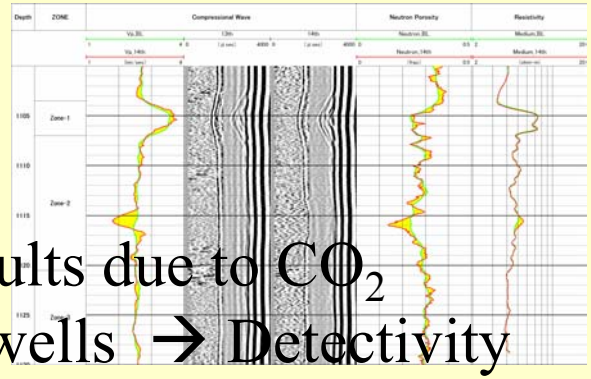
Change of Resistivity at OB-2 and Sampling Points



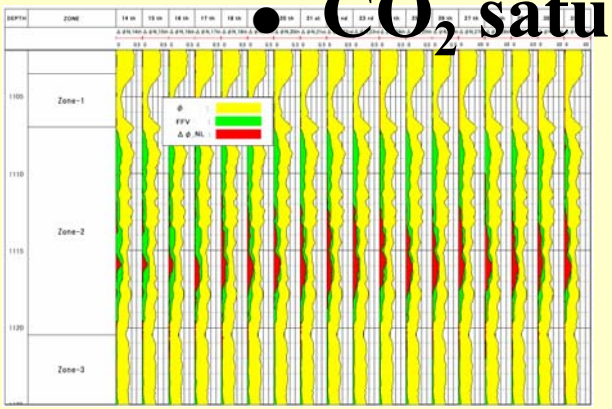
History of CO_2 Saturation at OB-2 and Sampling Points

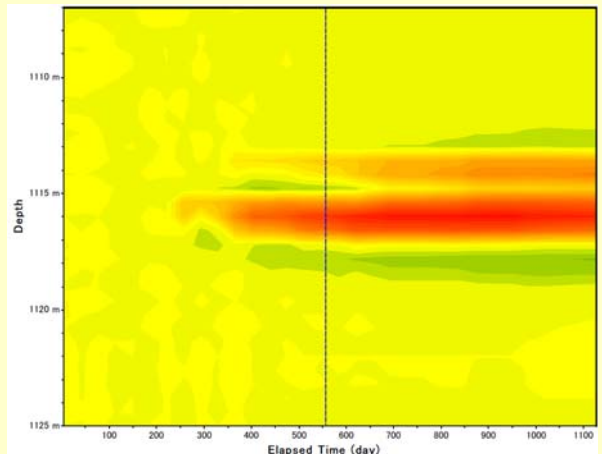


Conclusion



- **CO_2 Breakthrough**
  - Responses in the well logging results due to CO_2 breakthrough at two observation wells → Detectivity of CO_2 leakage
- **Observation after Breakthrough**
- Long-term behavior of CO_2 learned from time-lapse well logging.
- **CO_2 saturation**

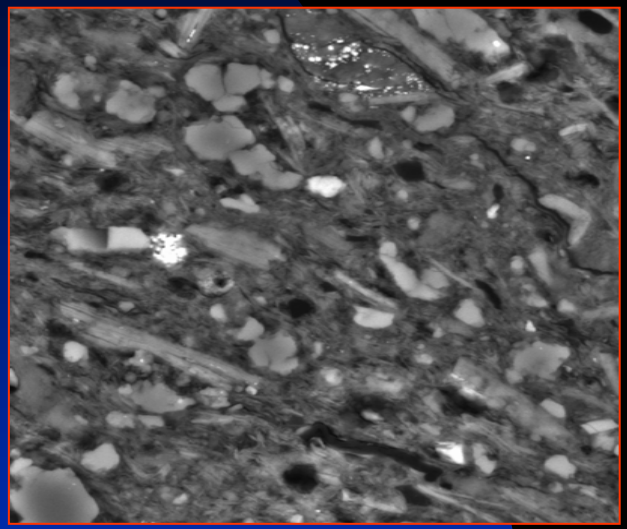
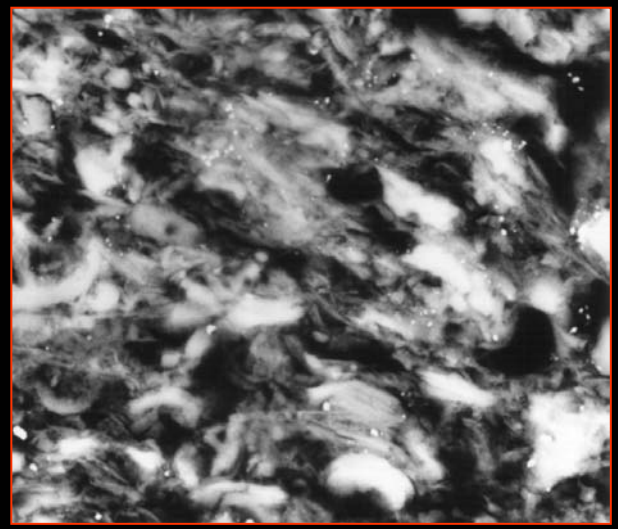
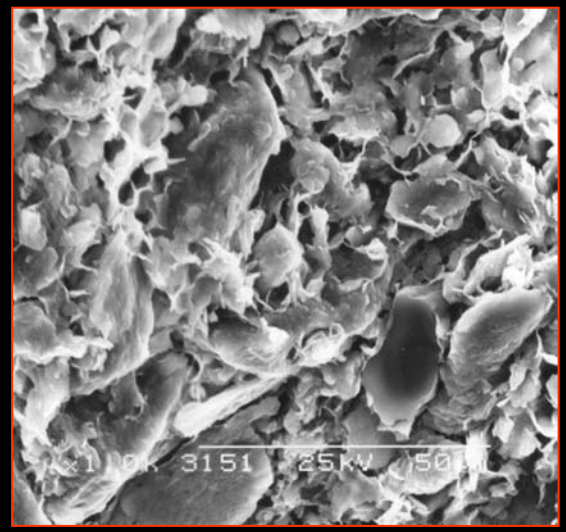




Future Study Plan

- **Additional data acquisition:**
  - **Follow-up monitoring (BHP measurement, time-lapse logging, and crosswell seismic tomography) will be continued till 2007.**
  - **Fluid sampling by CHDT at the injection well IW-1.**
  - **Logging at the injection well IW-1 (RST or NL).**
    - **Injecting water into the injection well and run logging tool in it to measure the residual CO2 saturation in an aquifer.**
  - **Interpretation of time-lapse 3D seismic data is underway.**
- **History-match simulation incorporating these additional data is expected to improve our understanding of CO_2 distribution.**

Seals and CO_2:
Techniques and Issues

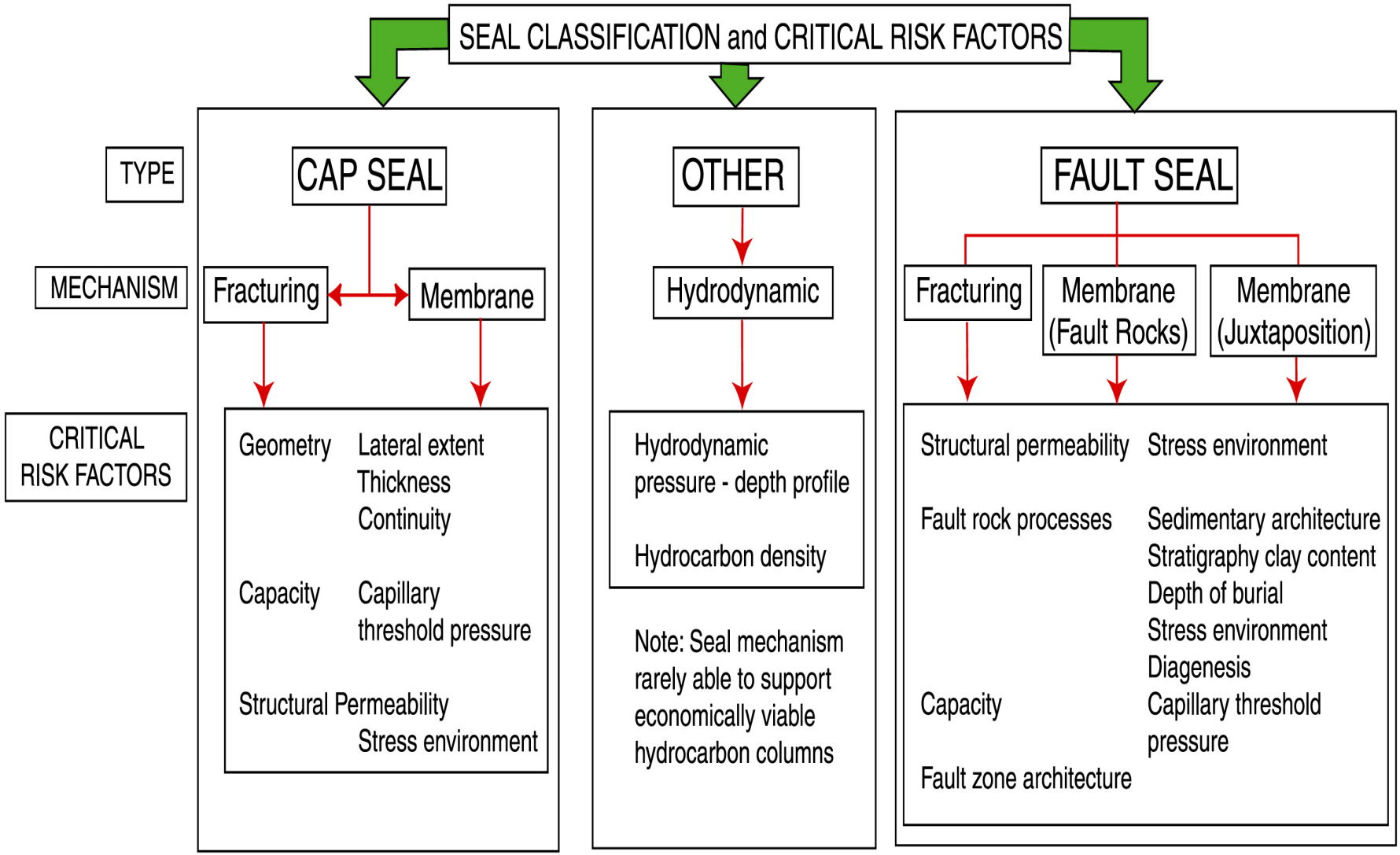
Dave Dewhurst

CSIRO Petroleum

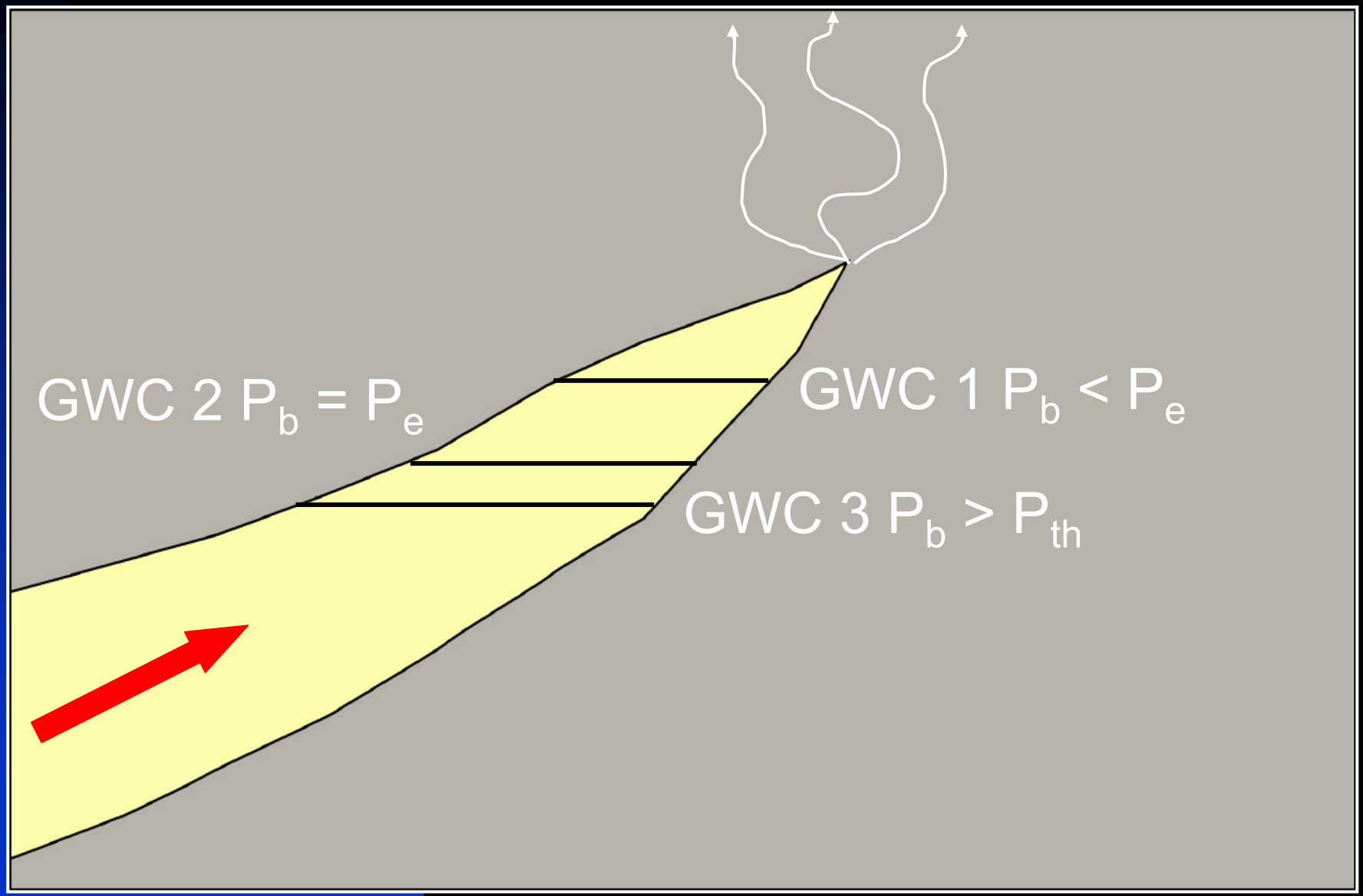
Why do Seals Fail?

- Capillary Failure
  - Buoyancy Pressure > Capillary Entry Pressure
- Mechanical Failure
  - Fracturing (tensile/shear)
  - Faulting
  - Reactivation
- Presence/Efficiency at time of Charge
  - Alteration, post charge.

SEAL CLASSIFICATION and CRITICAL RISKS

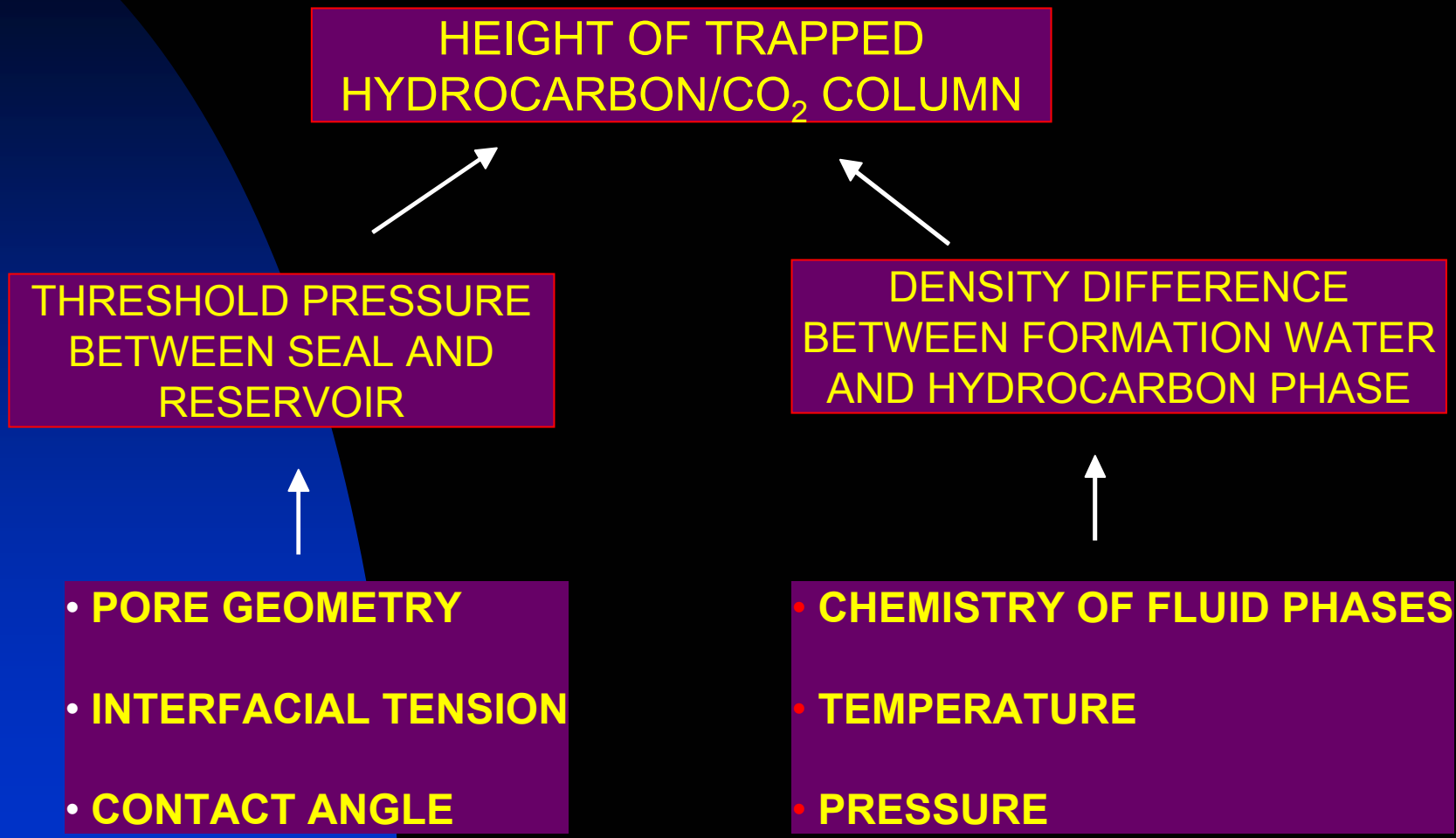


Capillary Failure



Courtesy John Kaldi, CO2CRC

SEAL CAPACITY



Courtesy John Kaldi, CO2CRC

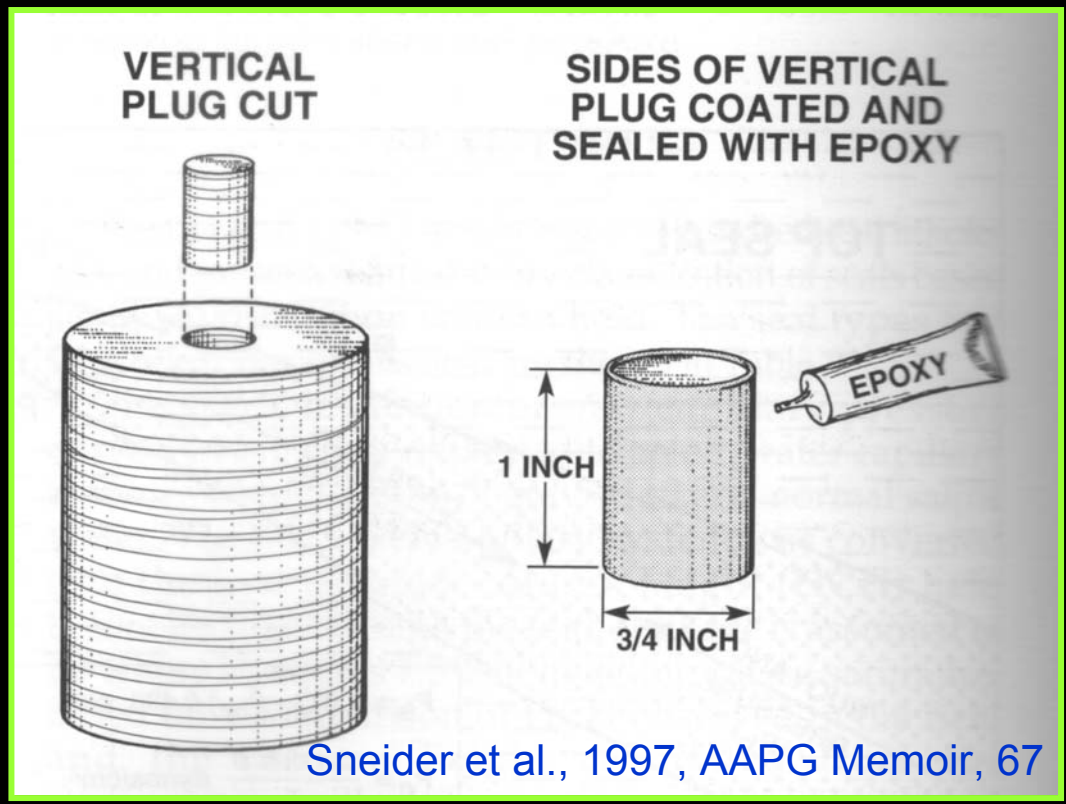
Evaluation of Seal Capacity

- Mercury Porosimetry.
- Allows estimation of P_{th} from:

$$P = \frac{2\sigma Cos\theta}{r}$$

σ = Interfacial tension

θ = Contact angle



Sneider et al., 1997, AAPG Memoir, 67

Calculating Seal Capacity

$$(P_{th})_{b/CO_2} = (P_{th})_{a/m}\left(\frac{\sigma_{b/CO_2} Cos\,\theta_{b/CO_2}}{\sigma_{a/m} Cos\,\theta_{a/m}}\right)$$

Air-mercury contact angle = 140°

Air-mercury interfacial tension = 480 dyne/cm

CO_2-brine contact angle = ??

CO2-brine IFT = Reasonably constrained

Need CO_2 wettability at reservoir conditions

CSIRO

Calculating Seal Capacity

$$H_{\max} = \left(\frac{P_{th}(seal) - P_{th}(res)}{0.433(\rho_w - \rho_{CO_2})} \right)$$

CSIRO

Seal Capacity Issues

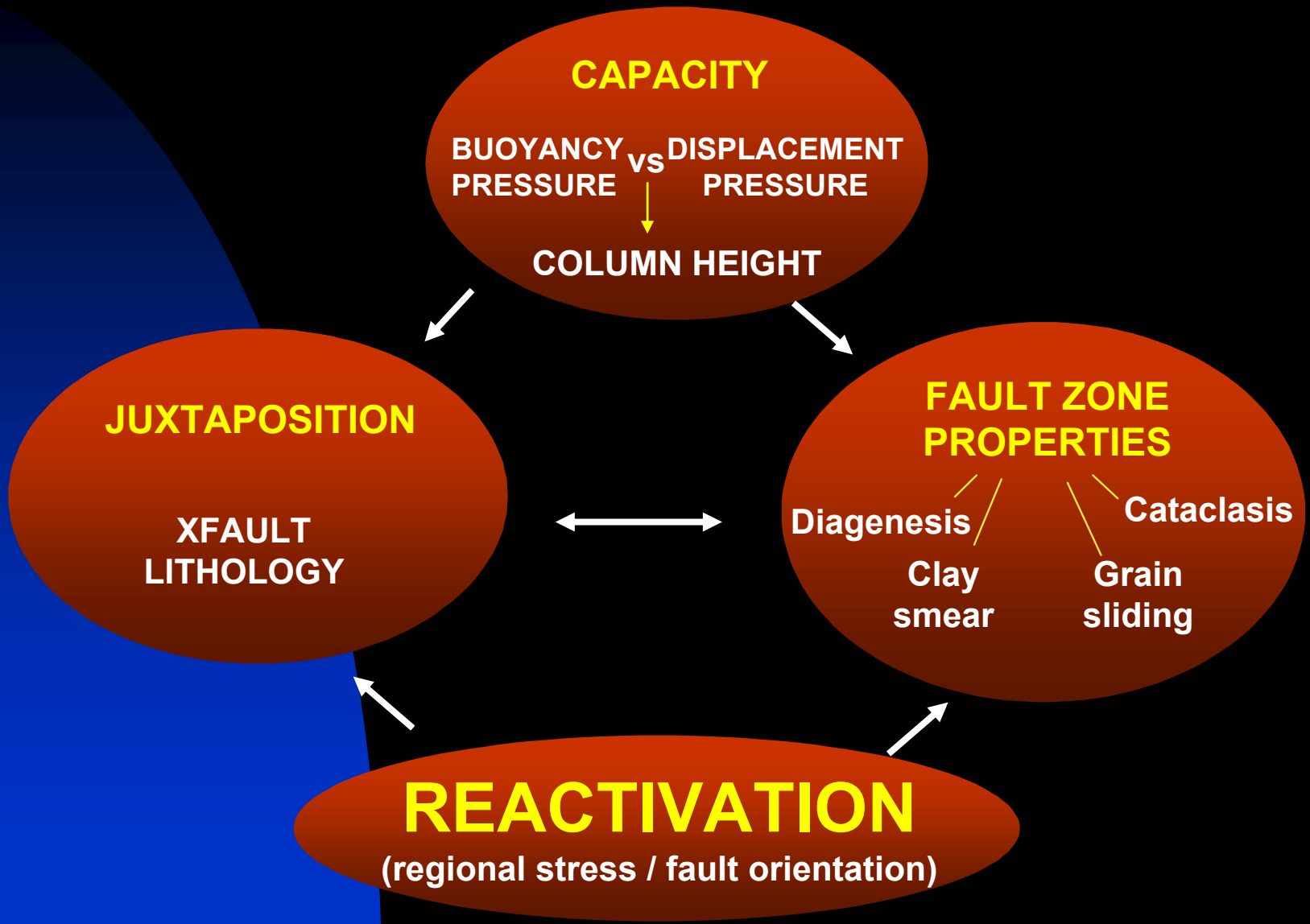
Sample size, representative? Use regional geology.

Geometry, lateral extent

- lithology changes, how to predict away from well
- sequence strat relation to shale properties embryonic
- seismic resolution

Wettability of CO_2 – not well constrained how physically interacts with rocks

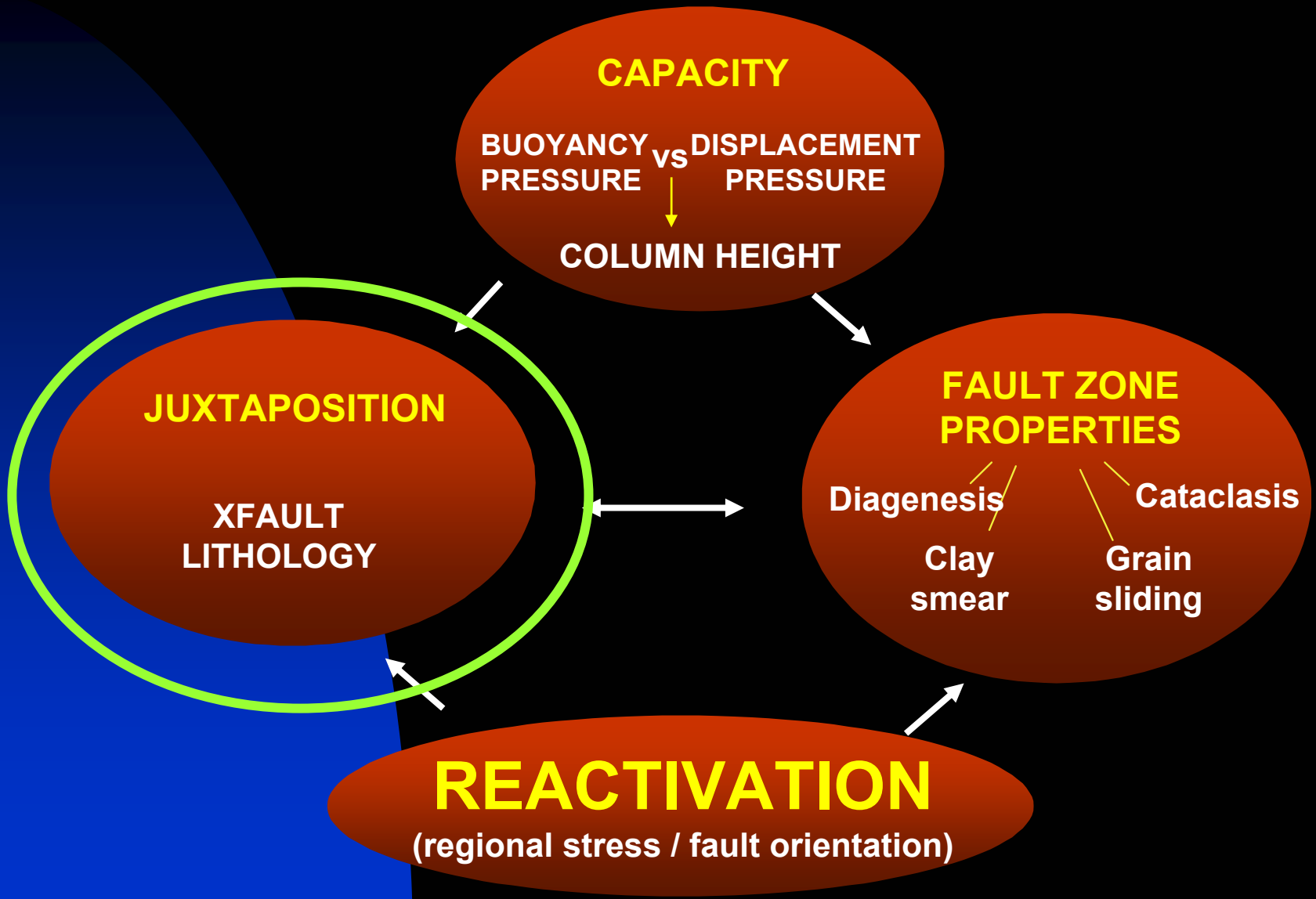
FAULT SEAL RISK



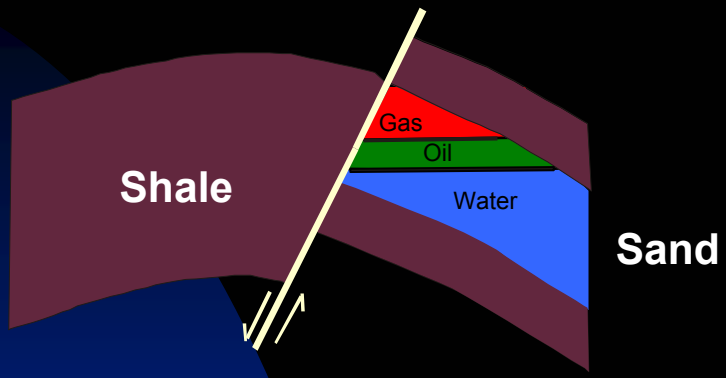
FAULT SEAL APPROACHES

- **Fault Plane Mapping**
  - ALLEN DIAGRAMS
- **Fault Rock Processes**
  - SHALE GOUGE RATIO (SGR)
  - MICROSTRUCTURAL CHARACTERIZATION
- **Pressure Data**
  - PRESSURE COMPARTMENTS
- **Stress Analysis**
  - TRIAXIAL TESTING
  - RISK OF REACTIVATION
  - GEOMECHANICAL MODELLING

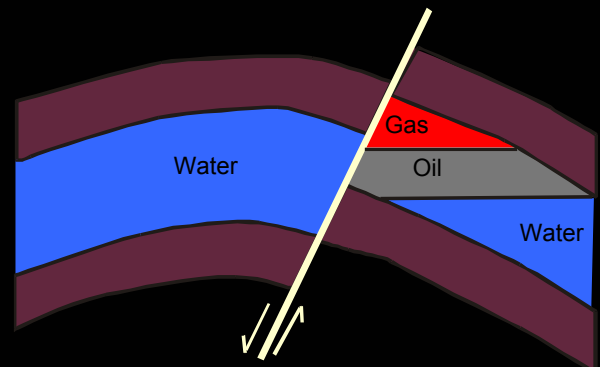
FAULT SEAL RISKS



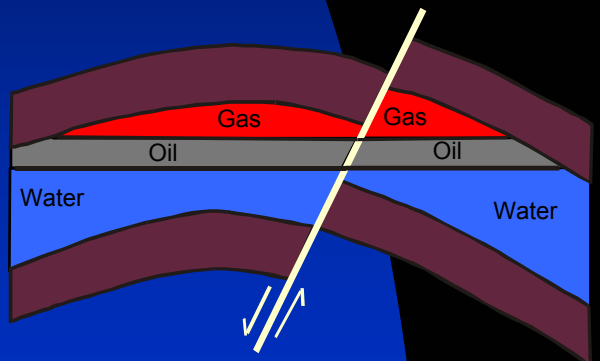
Juxtaposition Situations



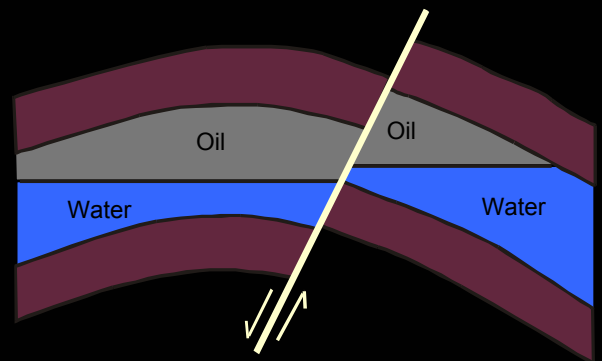
1) Sand juxtaposed opposite shale.



2) Sand juxtaposed opposite sand.



3) Common GOC and HWC across the fault.

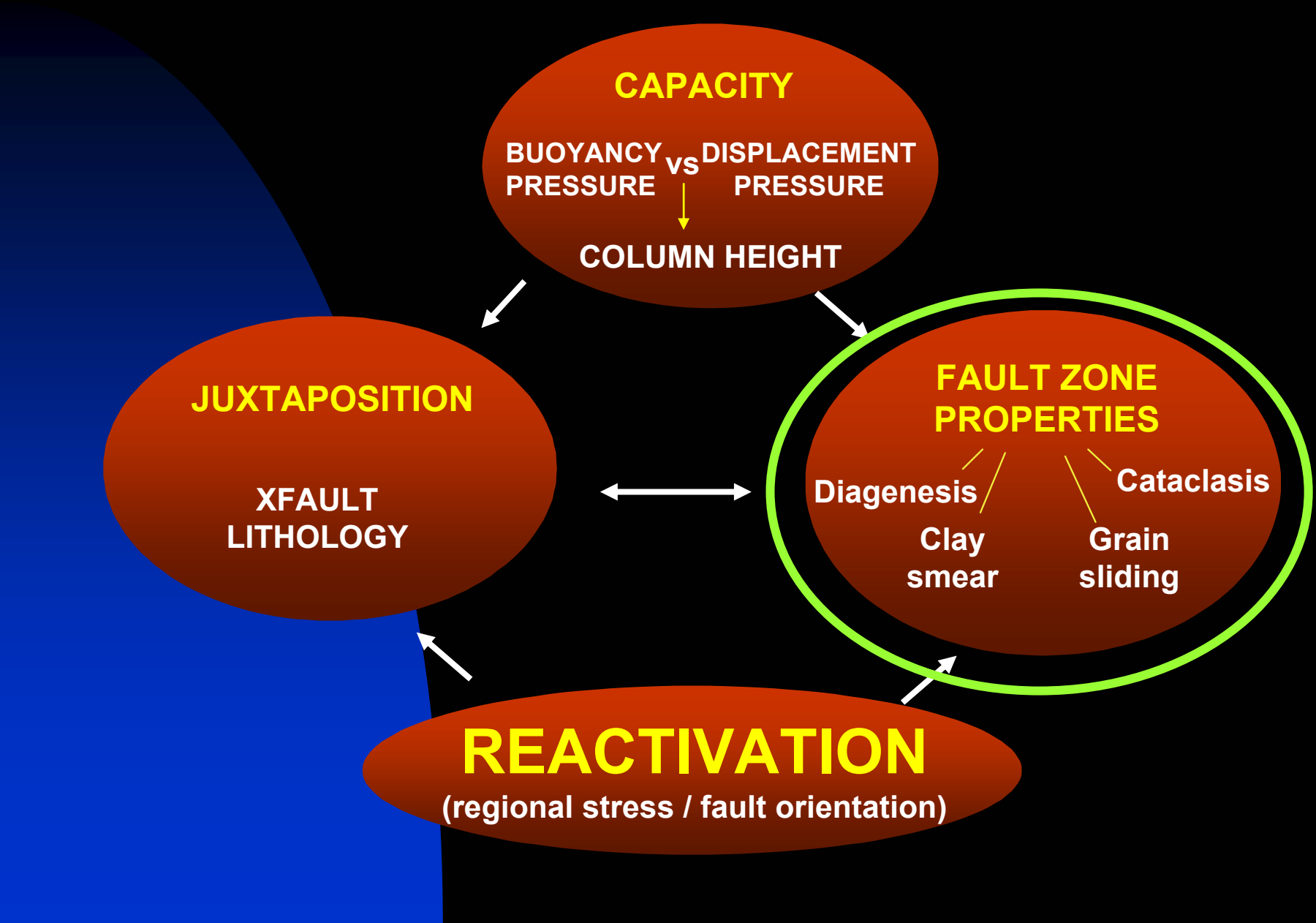


4) Different OWC across the fault.

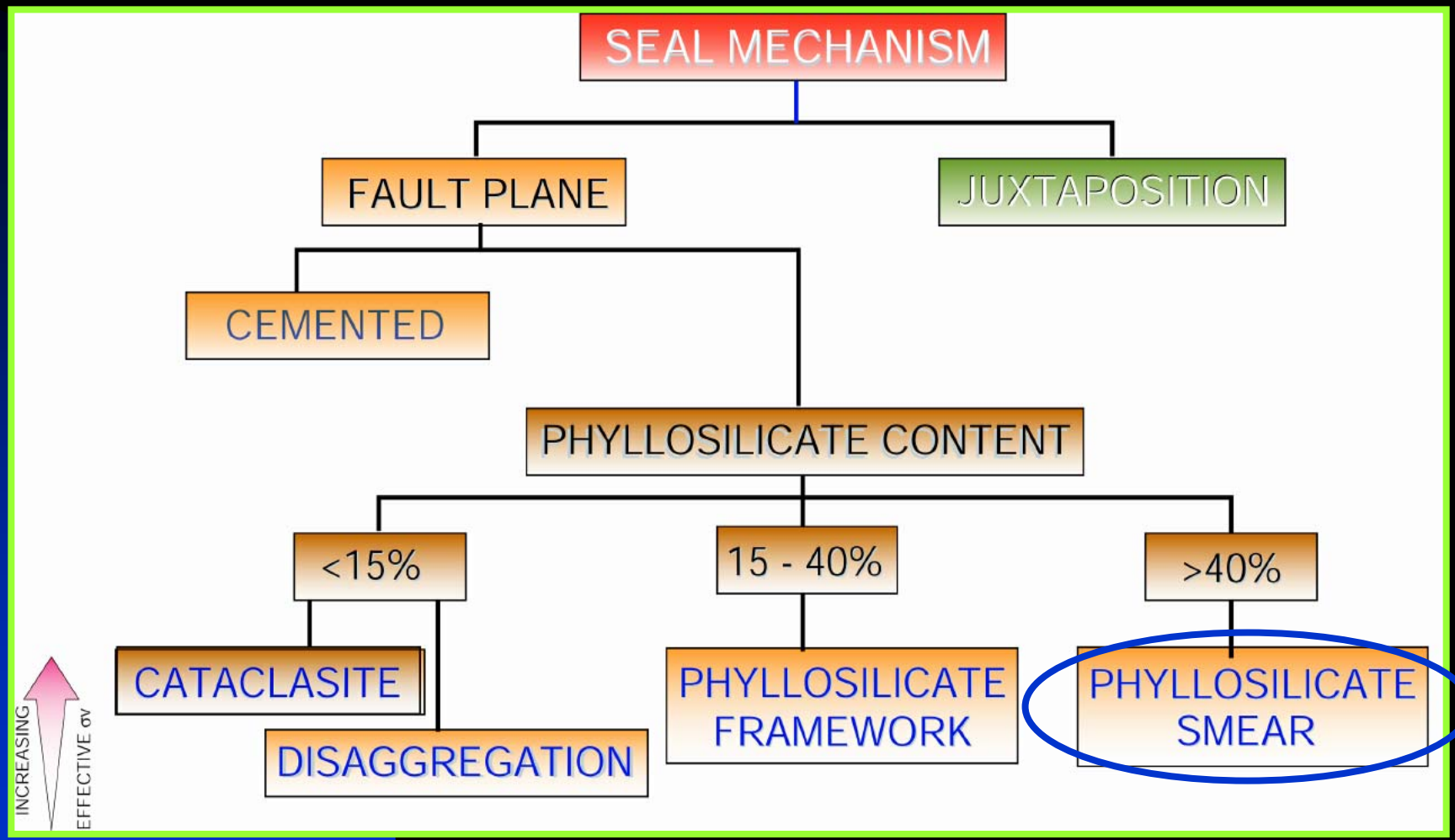
After Smith (1980)

Slide courtesy of John Kaldi, CO2CRC

FAULT SEAL RISKS

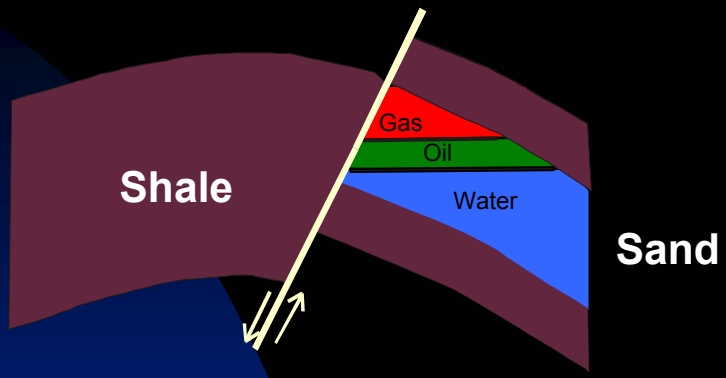


Fault Rock Types



After Fisher and Knipe, 1998

Juxtaposition Situations



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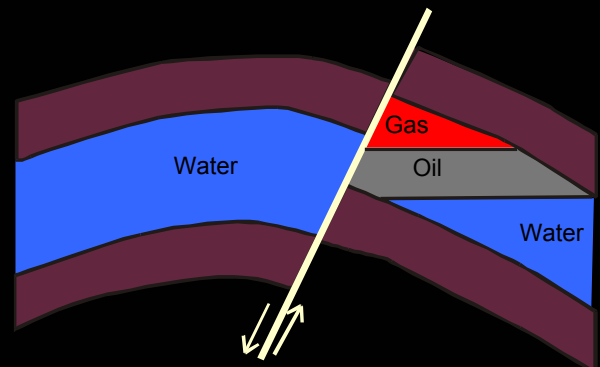
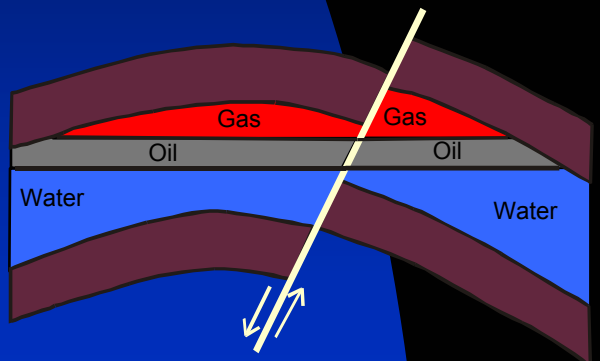
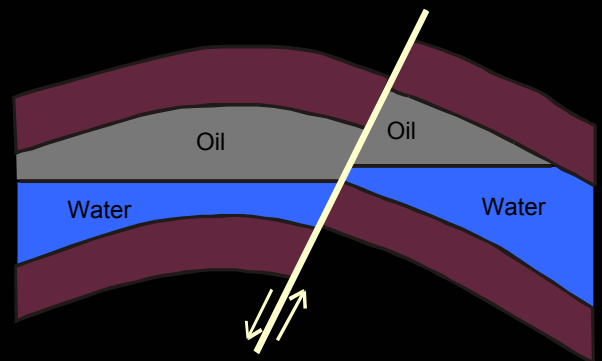


2) Sand juxtaposed opposite sand.



3) Common GOC and HWC across the fault.

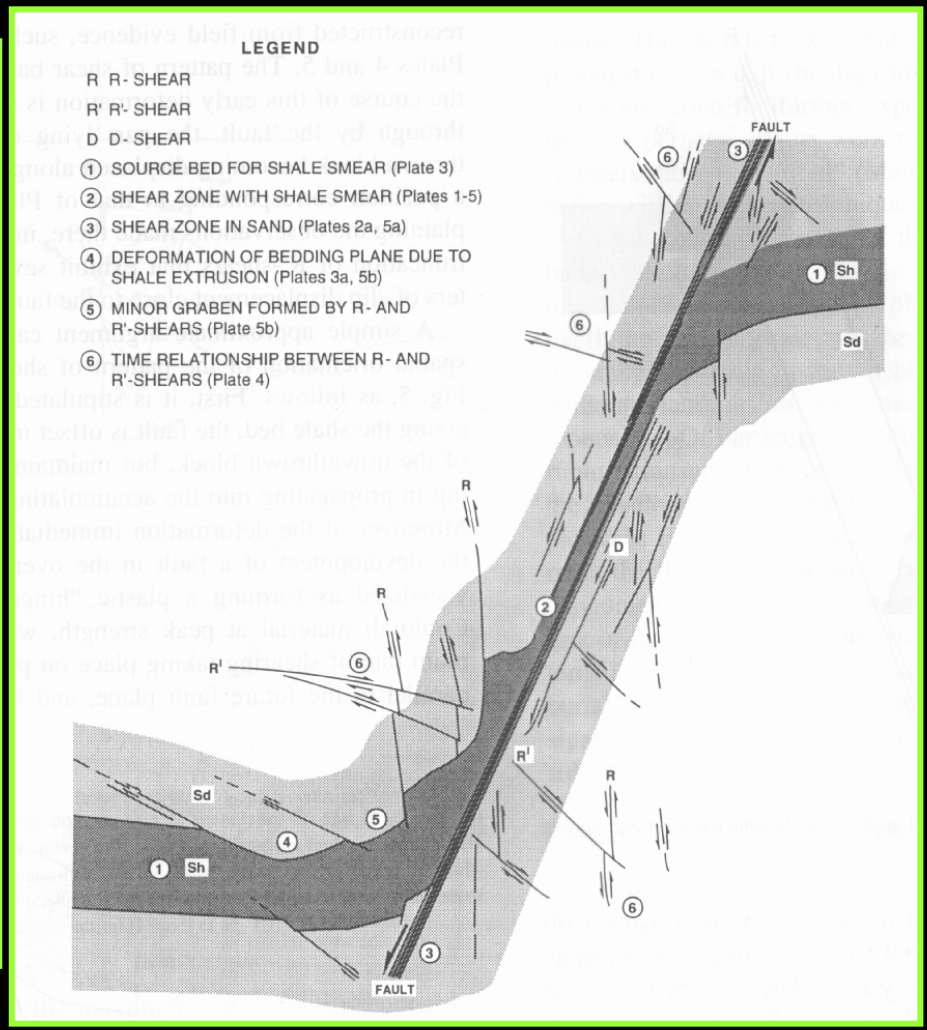


4) Different OWC across the fault.

After Smith (1980)

Slide courtesy of John Kaldi, CO2CRC

Clay Smears



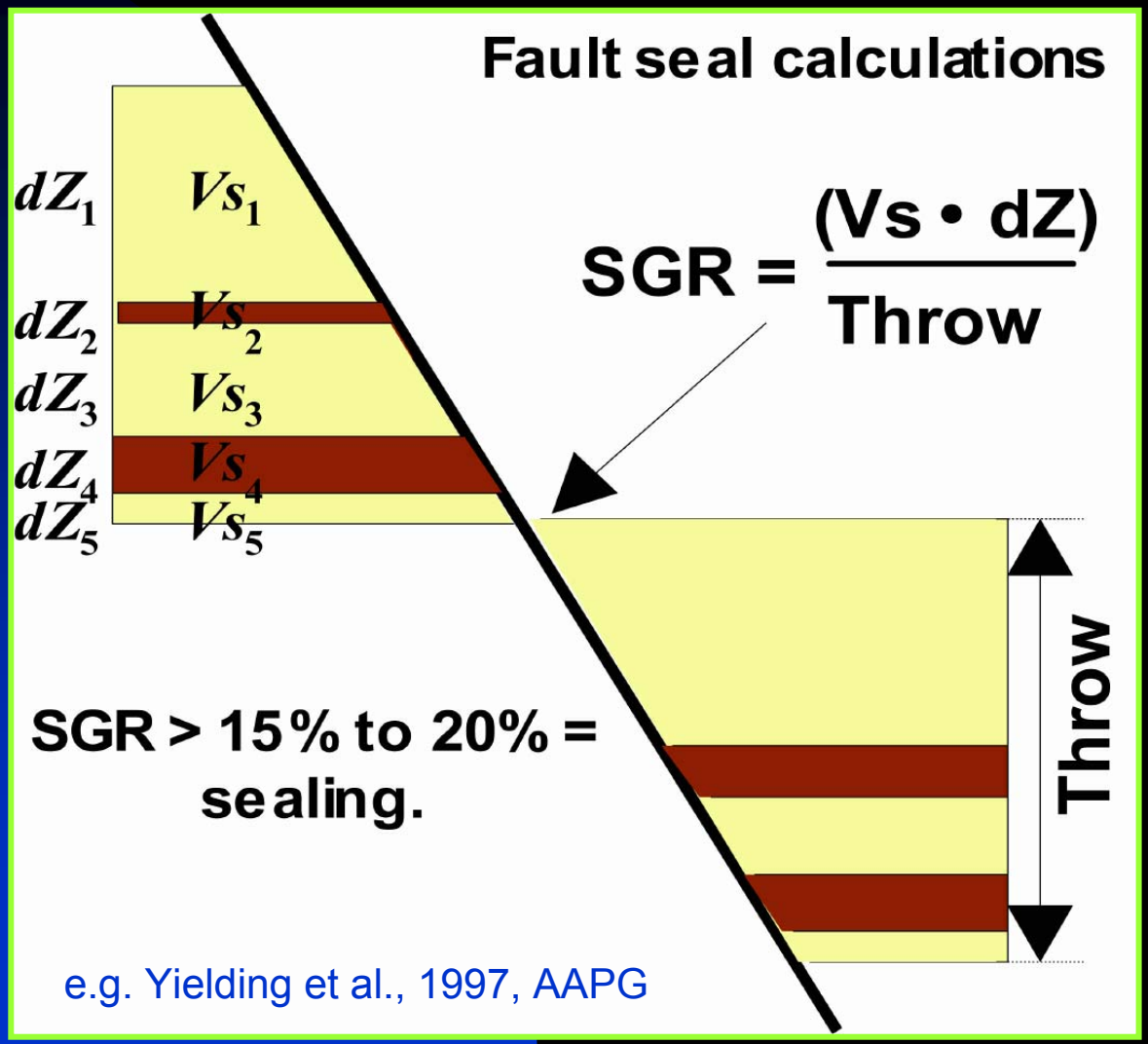
Lehner and Pilaar, 1997, NPF 7

Clay Smears

- Form in sediments with clay content > 40%
- Smearing of adjacent host lithologies into fault zone
- In ductile clays/shales – shearing or injection
- In brittle shales – abrasion smears.
- Perm often < 500 nD, P_{th} = 2000 to >10,000 psi.
- Common in clastic sedimentary sequences

Can be predicted through various methods.

Predicting Clay Smear : Shale Gouge Ratio



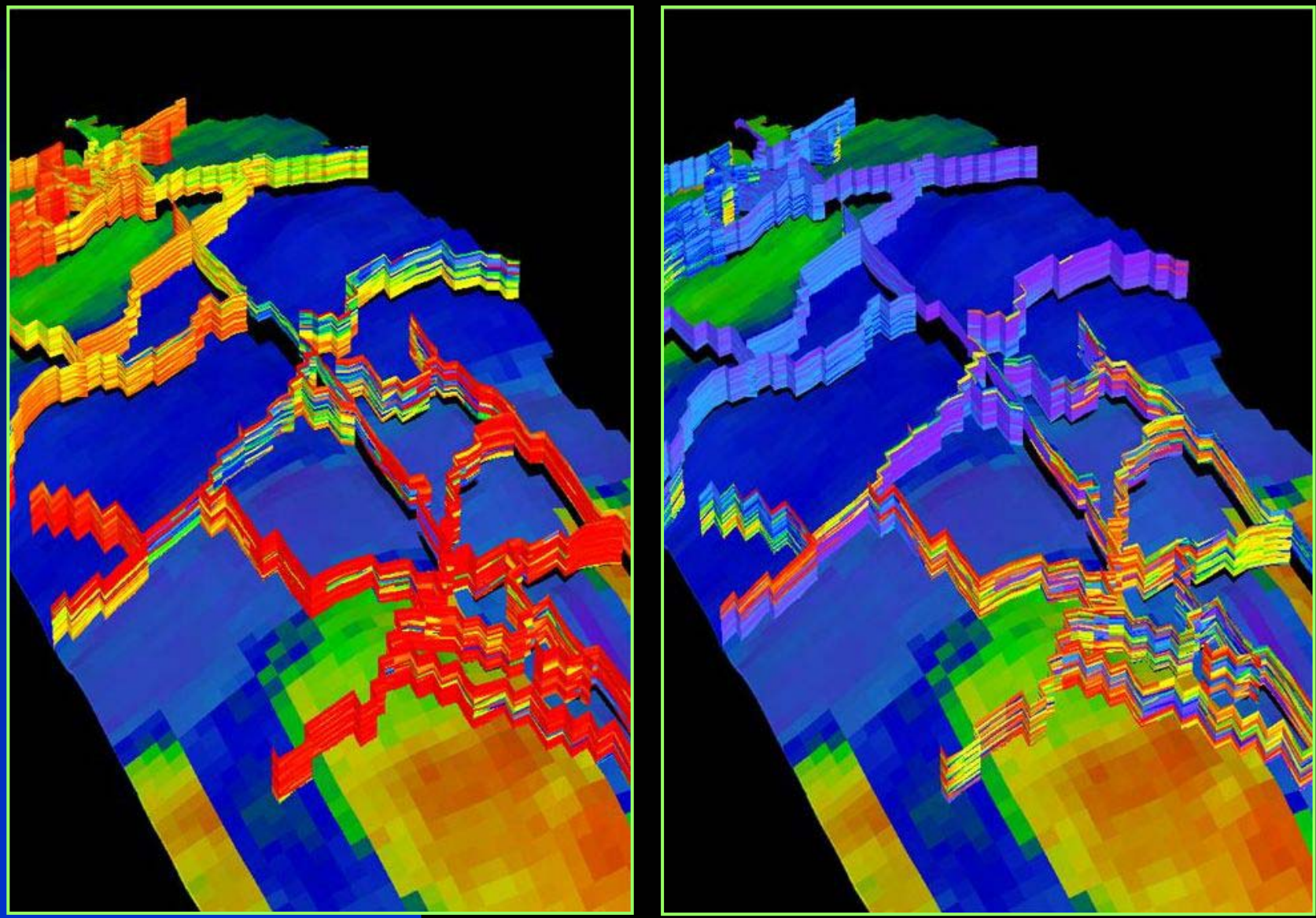
SGR can be calibrated to column height by using either

1.field pressure data

or

2. laboratory-based analyses of immiscible fluid breakthrough

SGR 3D Projection

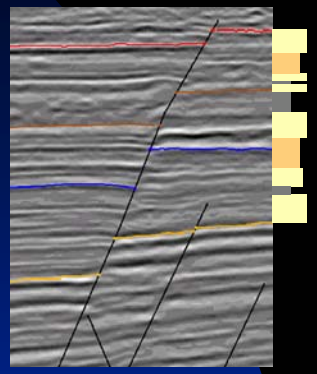


Courtesy Julian Strand, CSIRO Petroleum

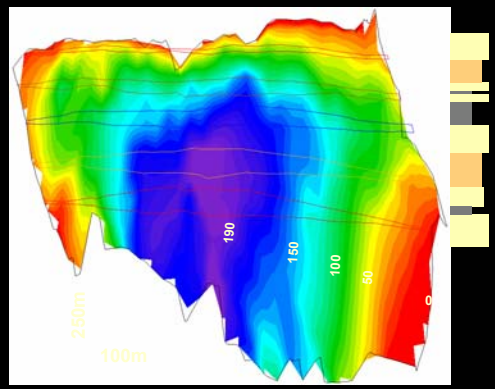
FAULT SEAL ANALYSIS

WORKFLOW

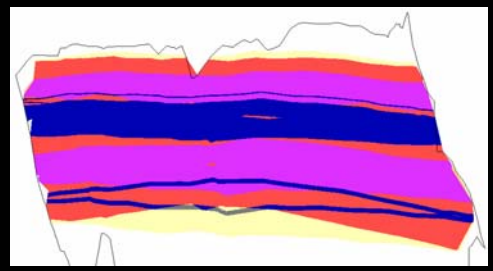
Seismic interpretation

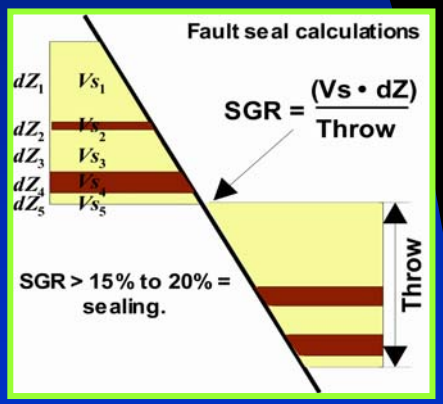


Fault surface map

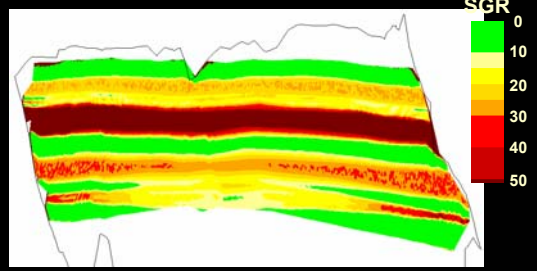


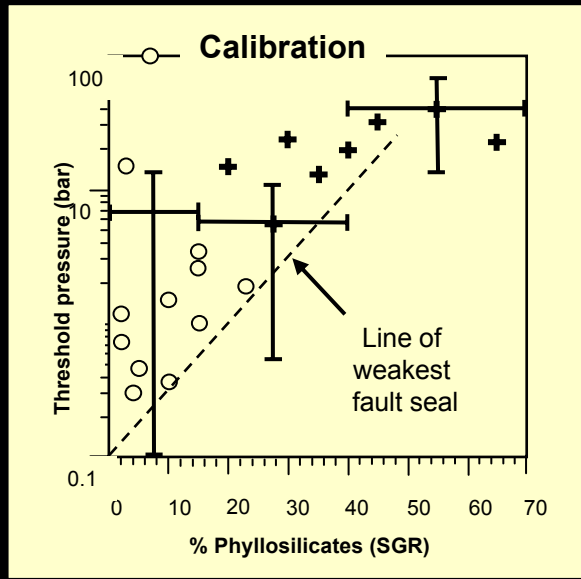
Across fault juxtaposition maps





Fault seal potential maps





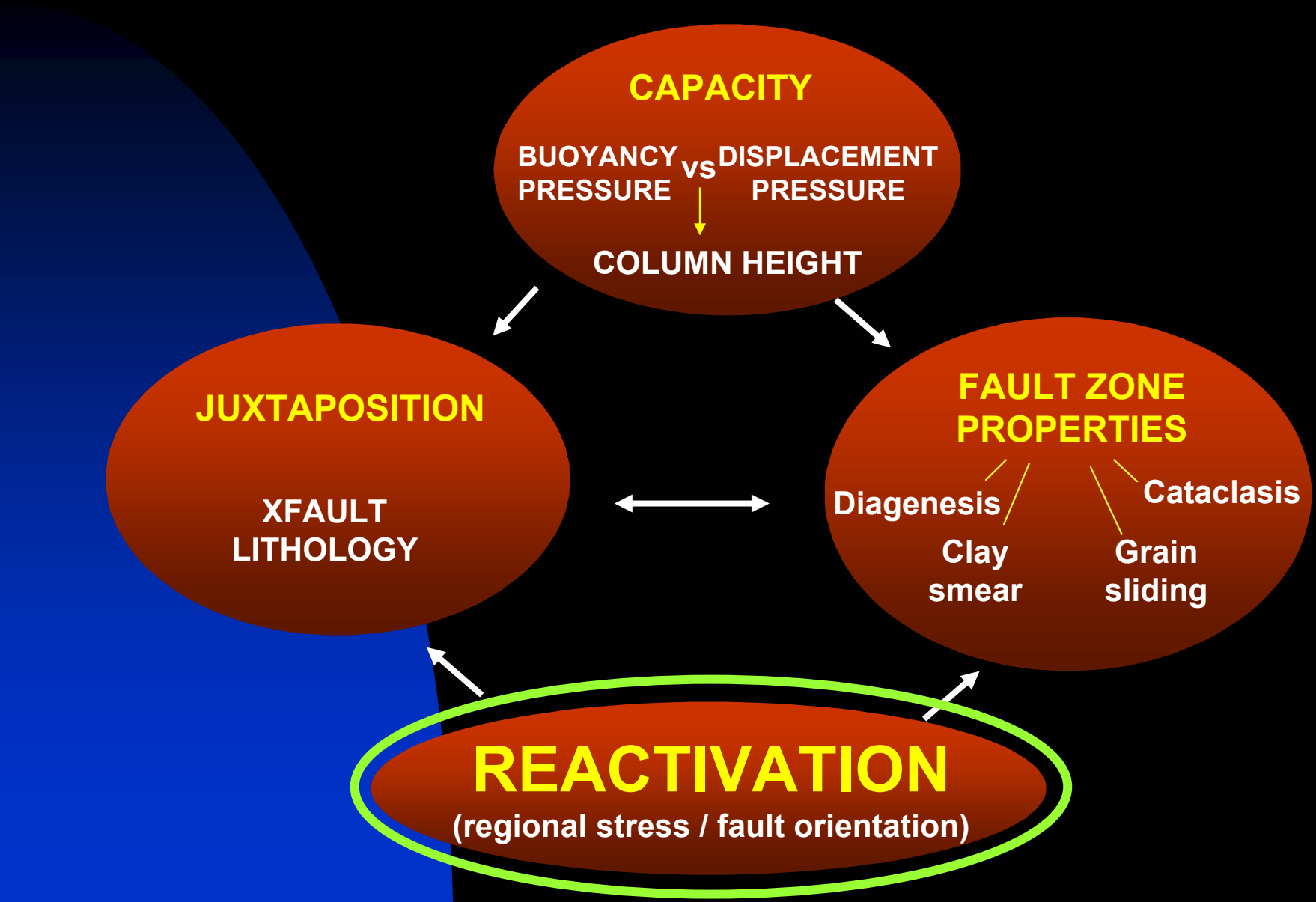
IF FRAMEWORK MODEL INADEQUATE SUBSEQUENT FSA MEANINGLESS.

Courtesy of Wayne Bailey, CSIRO Petroleum (ex)

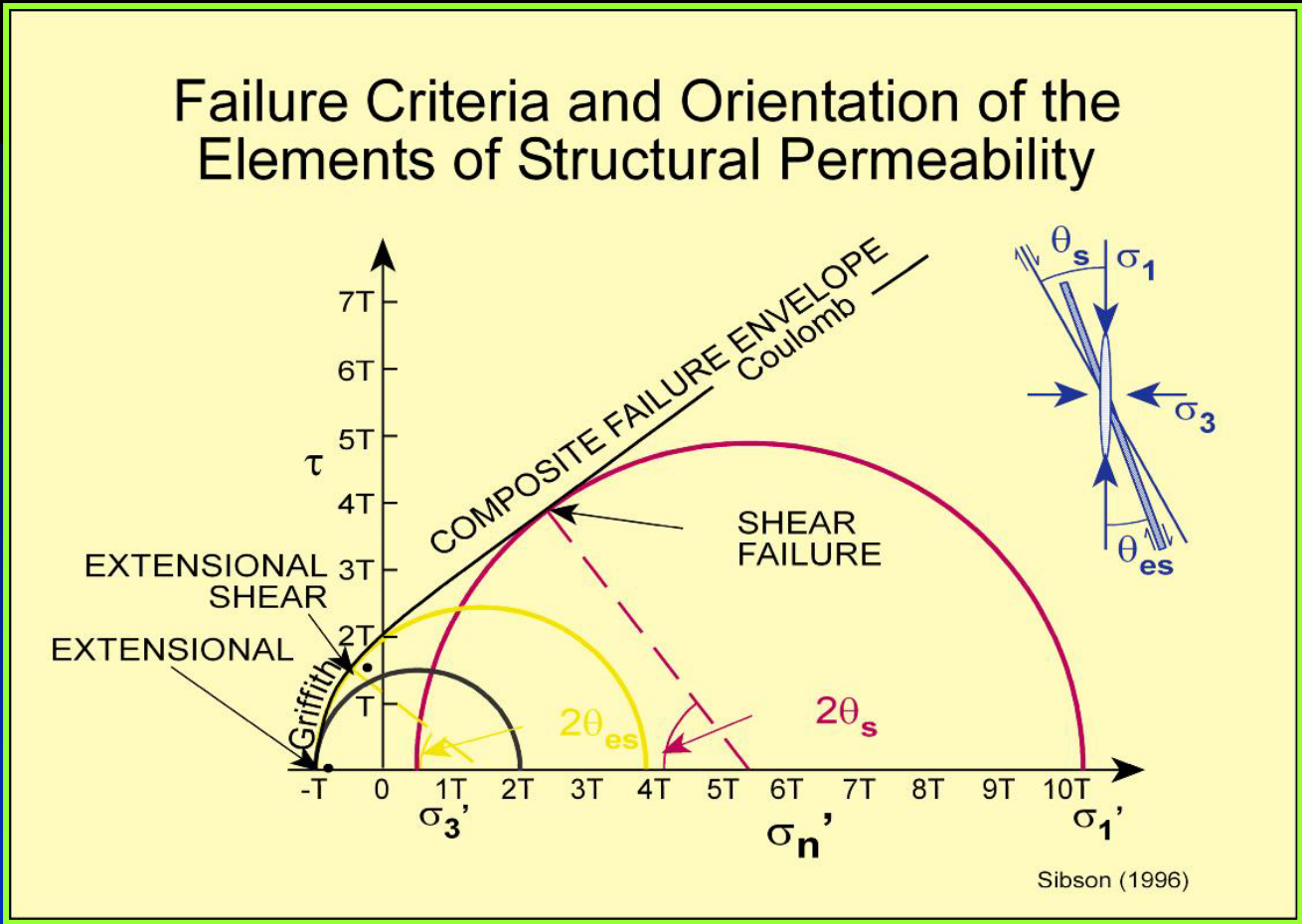
Issues with Fault Capillary Seal Methods

- Mechanical incorporation of material only
  - No account of diagenetic changes
- Assumes all sealing is due to clays
- Assumes V_{clay} from gamma-ray is accurate
- CO_2 wettability not well understood yet
- Microstructural/lab-based approaches
  - Scale, representative, continuity etc

FAULT SEAL RISKS



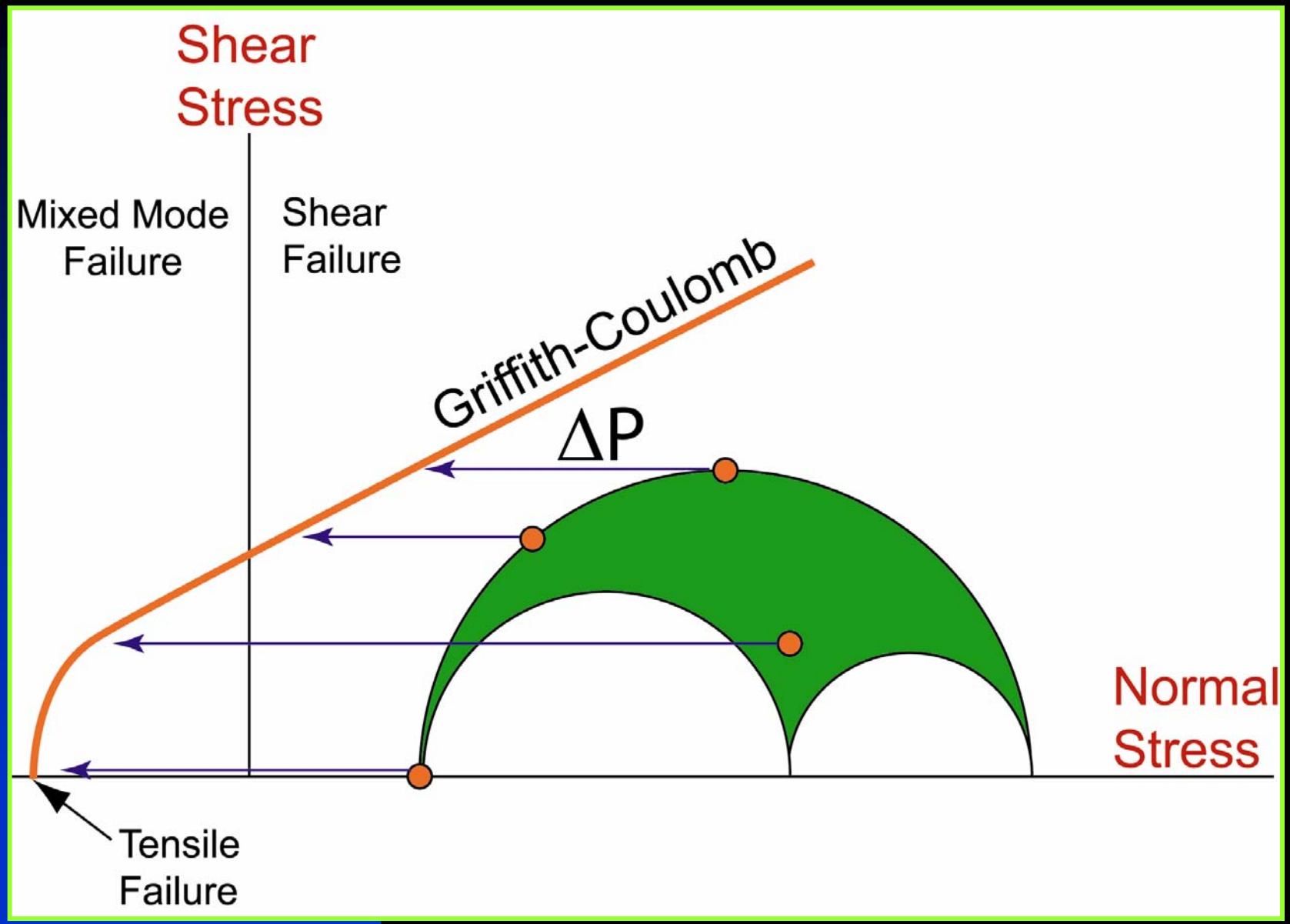
Reactivation Risking



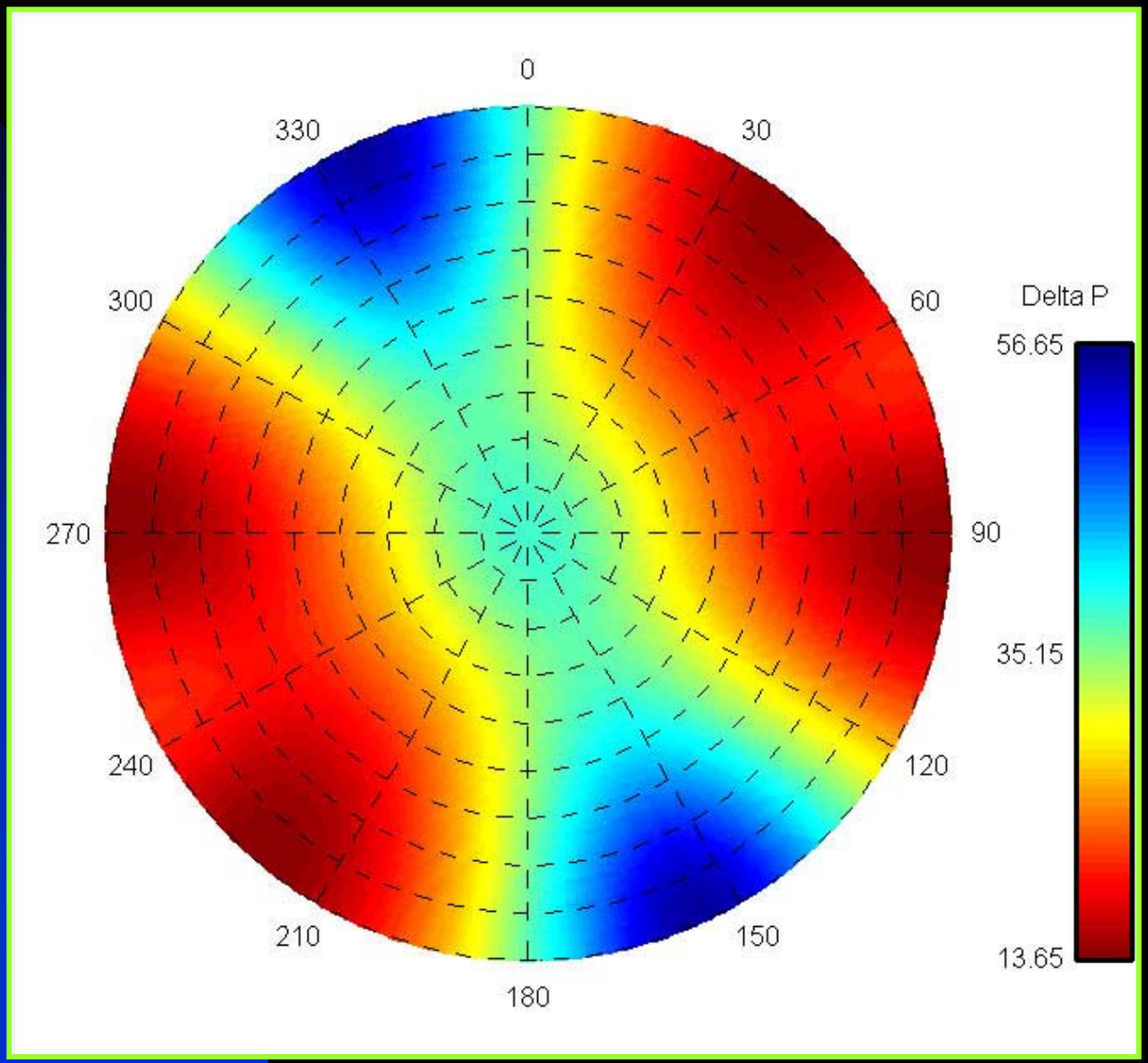
- Different fracture types form at various angles to principal stress planes
- Forms basis for assessing reactivation risk for pre-existing faults/fractures

Courtesy of Richard Hillis, ASP.

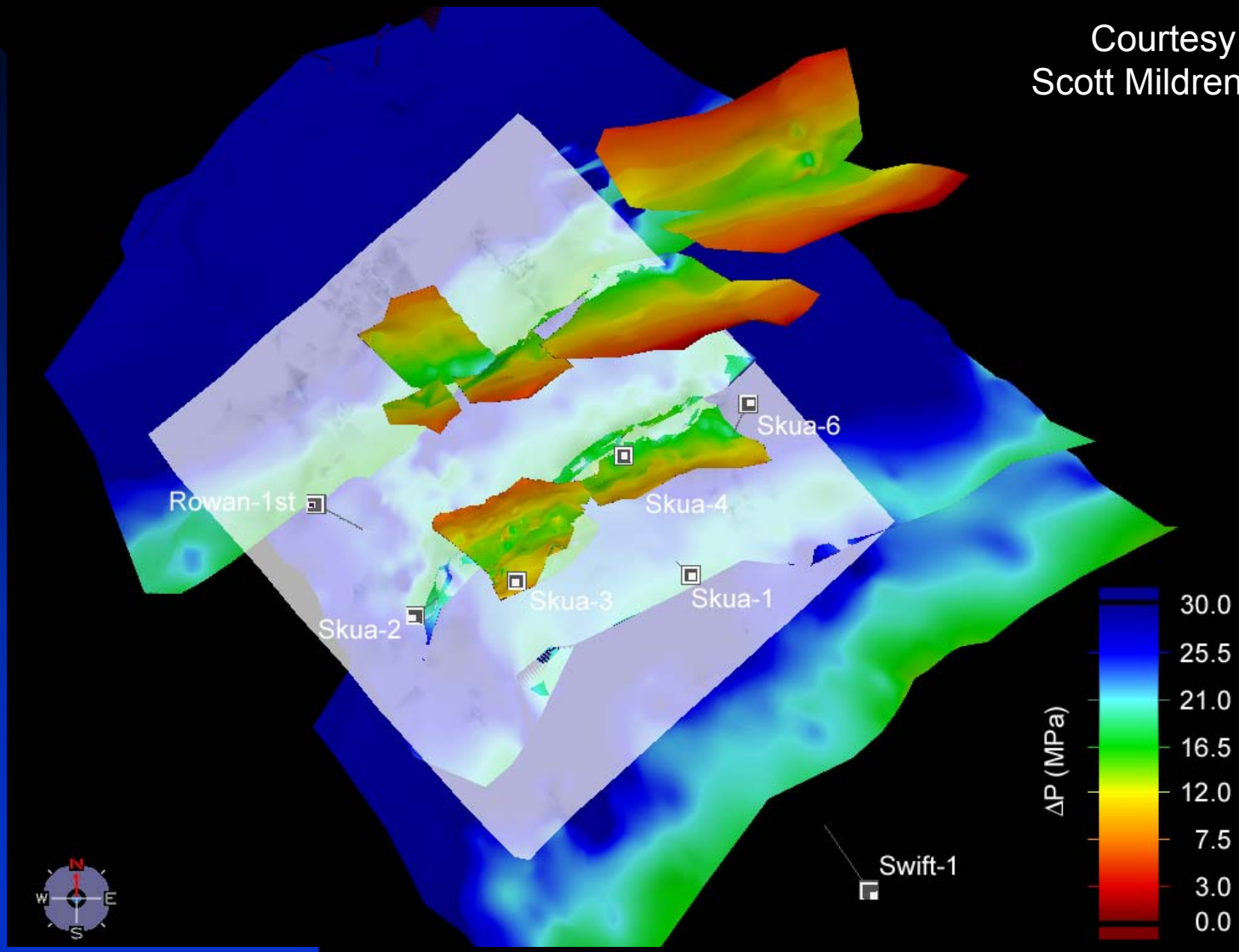
Reactivation Risking



Reactivation Risking



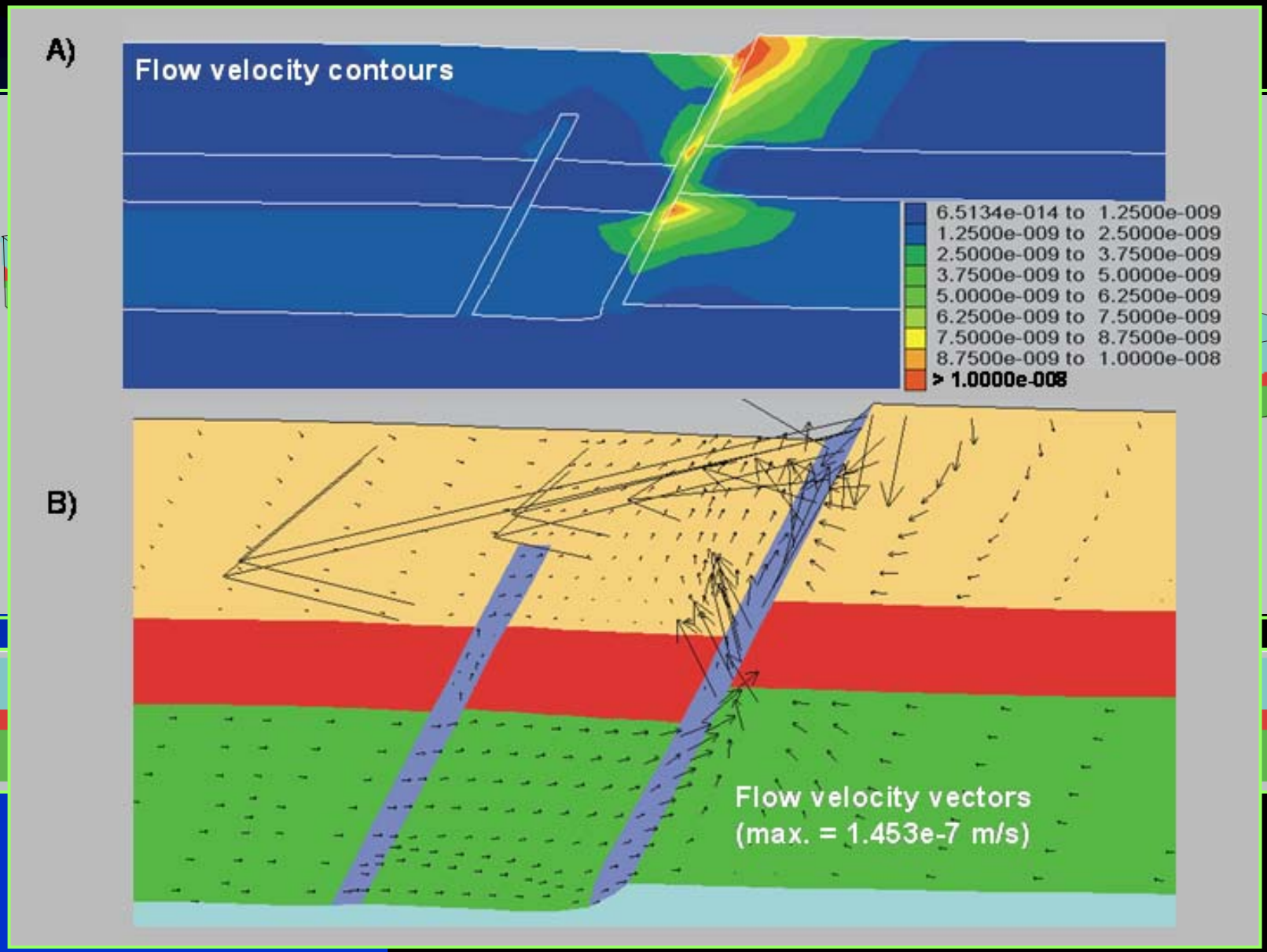
Reactivation Risking



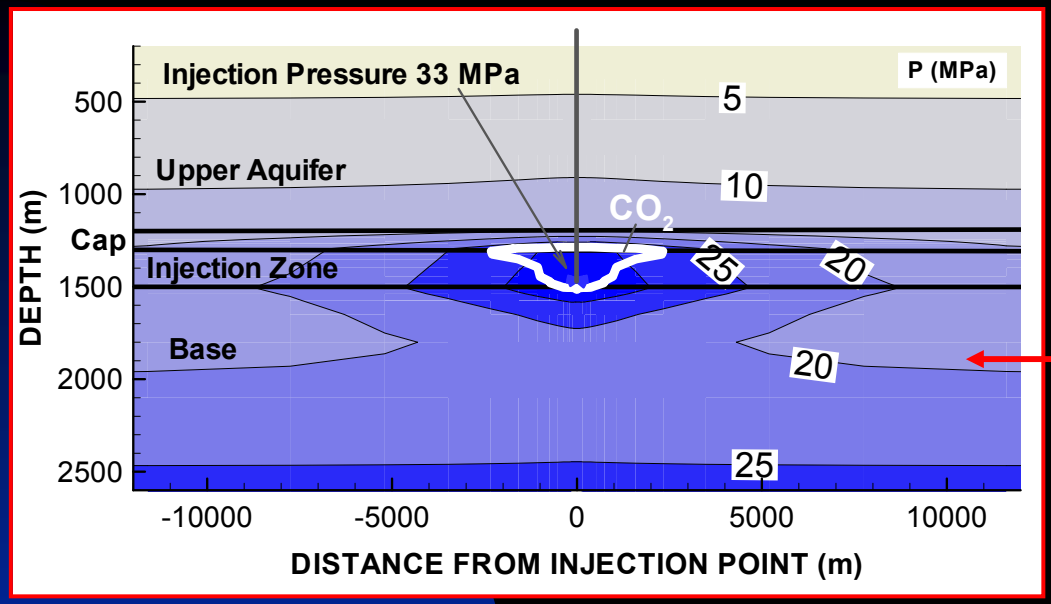
Issues with geomechanical approaches

- Treats faults as discrete entities
- Stress field rotation near faults
- Generally 2D analyses
  - stress is 3D, intermediate stress can influence failure
- How to account for P_p changes with injection
  - poroelasticity issues not well understood in practice.
- Fault size issues
- Geomechanical modelling may aid understanding.

Geomechanical Modelling



Geomechanical Modelling



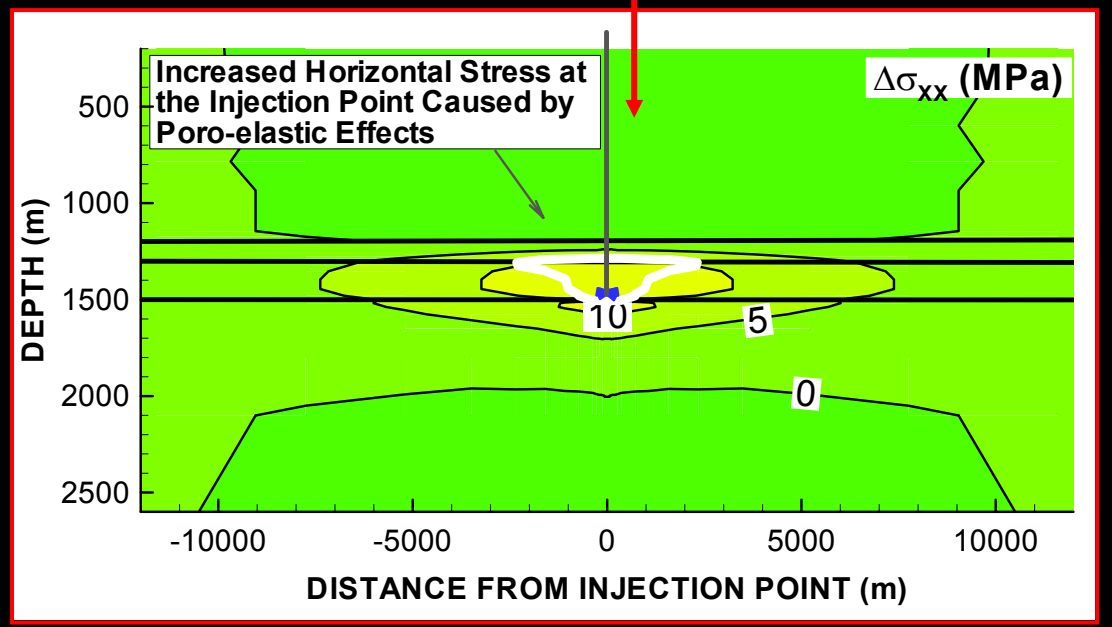
Coupled mechanical-fluid flow modelling (TOUGH-FLAC) of CO_2 injection

P_P Distribution

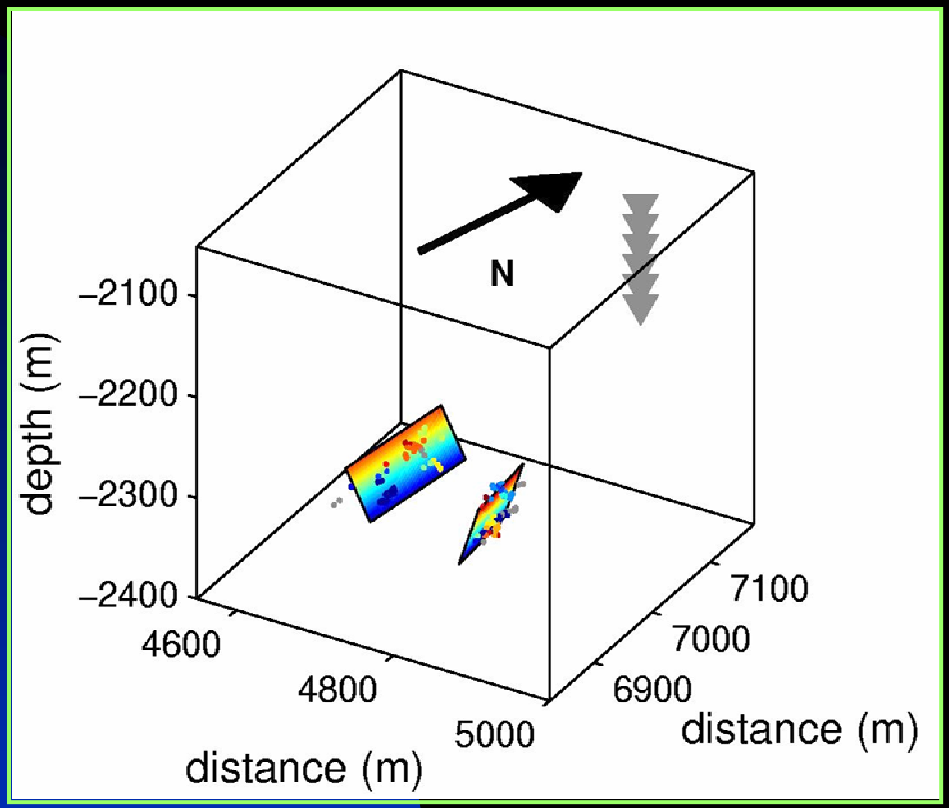
Stress change

From Rutqvist and Tsang, 2002, LBNL.

Issues – input properties, complexity of mechanical layering and faulting for meshing.



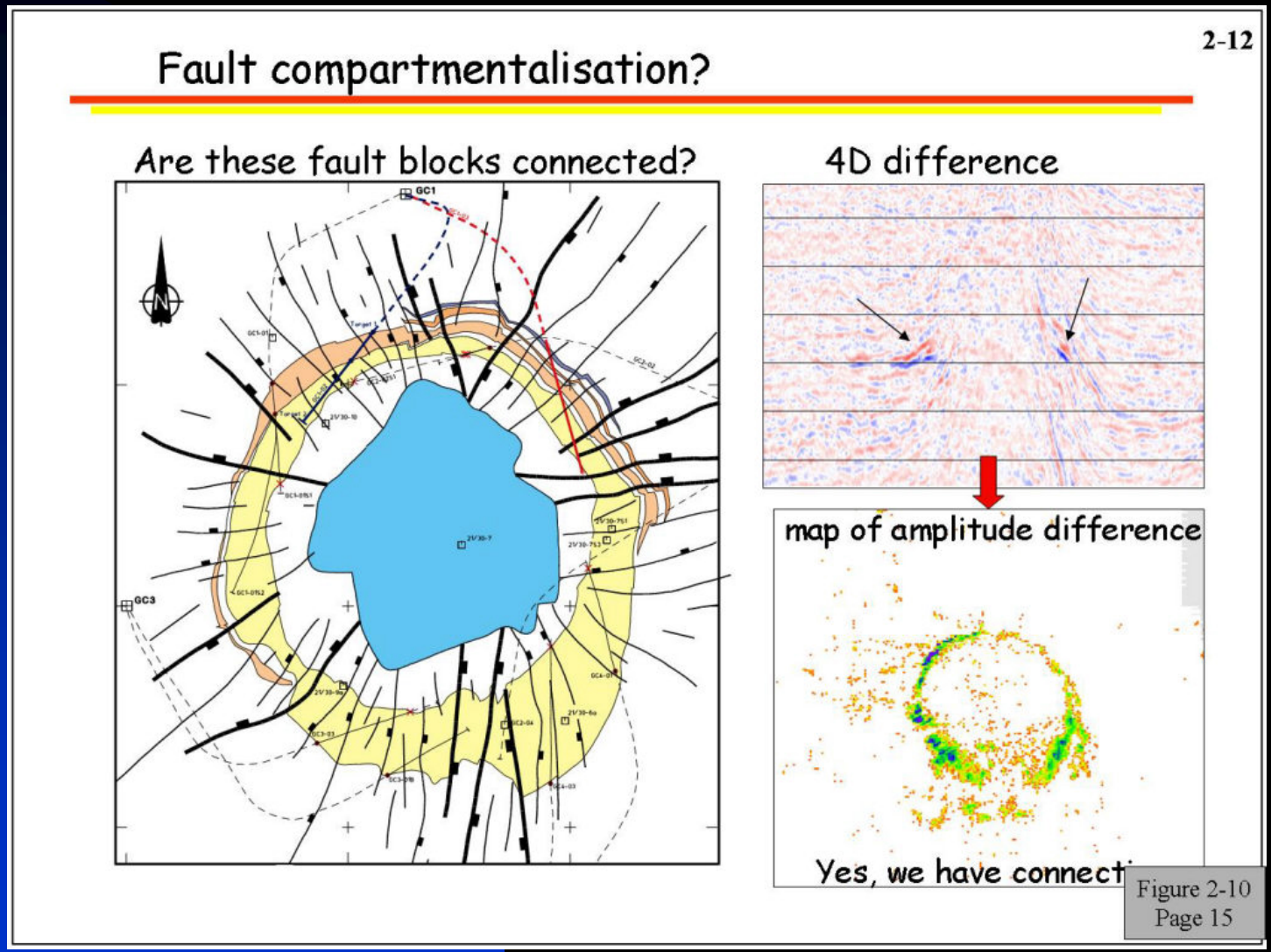
Microseismics



- Passive seismic monitoring during production
- Resolved location of clusters onto steeply dipping faults
- Data can ground truth geomechanical models

Courtesy Mike Kendall, University of Bristol

4D Monitoring



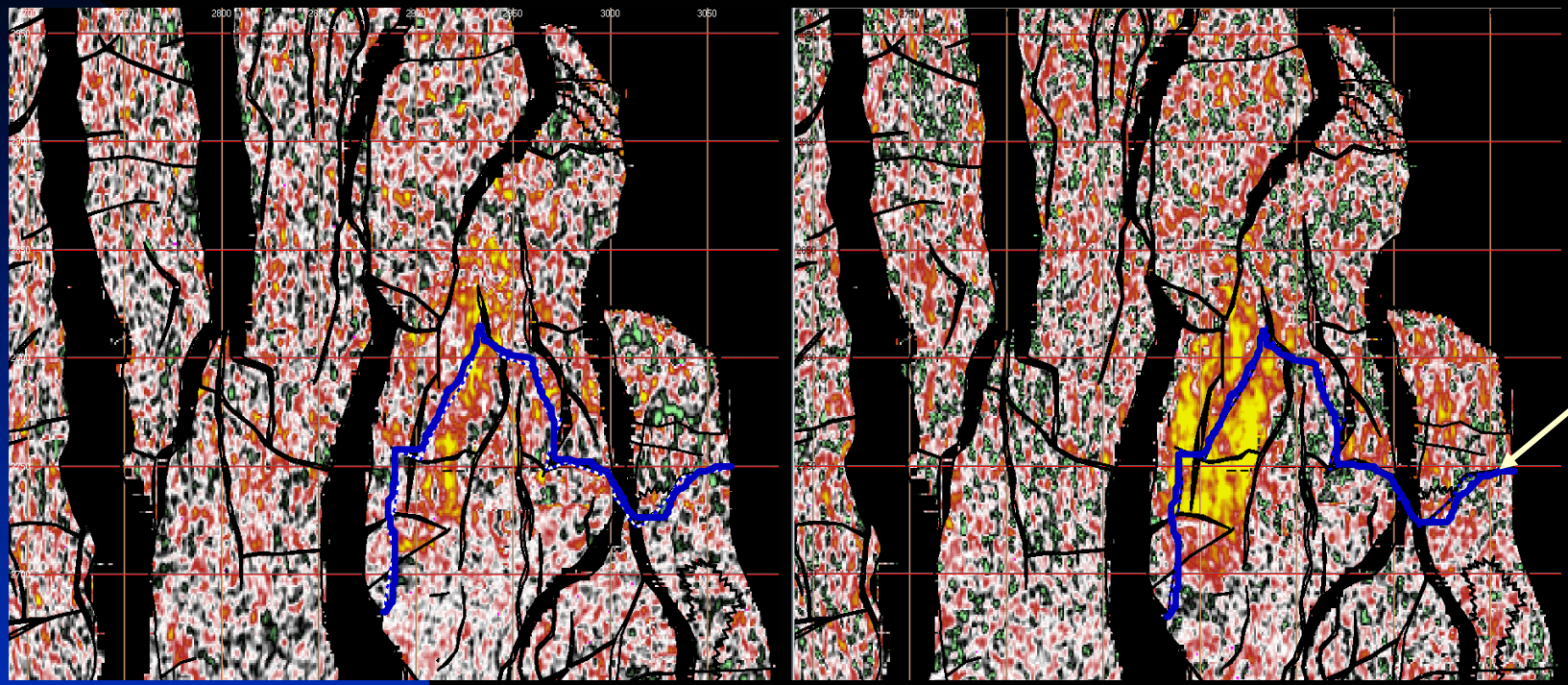
Issue: Often considerable overburden response rather than reservoir

Shale behaviour not well constrained

From Rodney Calvert, Shell, SEG Distinguished Lecturer

4D Monitoring

Estimated saturation and pressure changes at top Cook interface



Saturation changes **Pressure changes**

- 27% of remaining reserves in this segment has been produced in 1996
- Notice that pressure anomaly crosses the OWC and terminates close to faults
- Observed pore pressure increase in the segment is 50-60 bar

Courtesy of Martin Landrø, NTNU, & Statoil

Summary

- Many techniques - lots of issues/uncertainties
- Critical knowledge gaps:
  - Wettability
  - Reactivation & Poroelasticity
  - Diffusivity
- Critical methods aiding in understanding subsurface processes and monitoring:

Geomechanical modelling, microseismics and 4D and their integration. Currently embryonic in oil industry but growing rapidly.

Using Geochemical Techniques For Monitoring Seal Integrity

Ernie Perkins

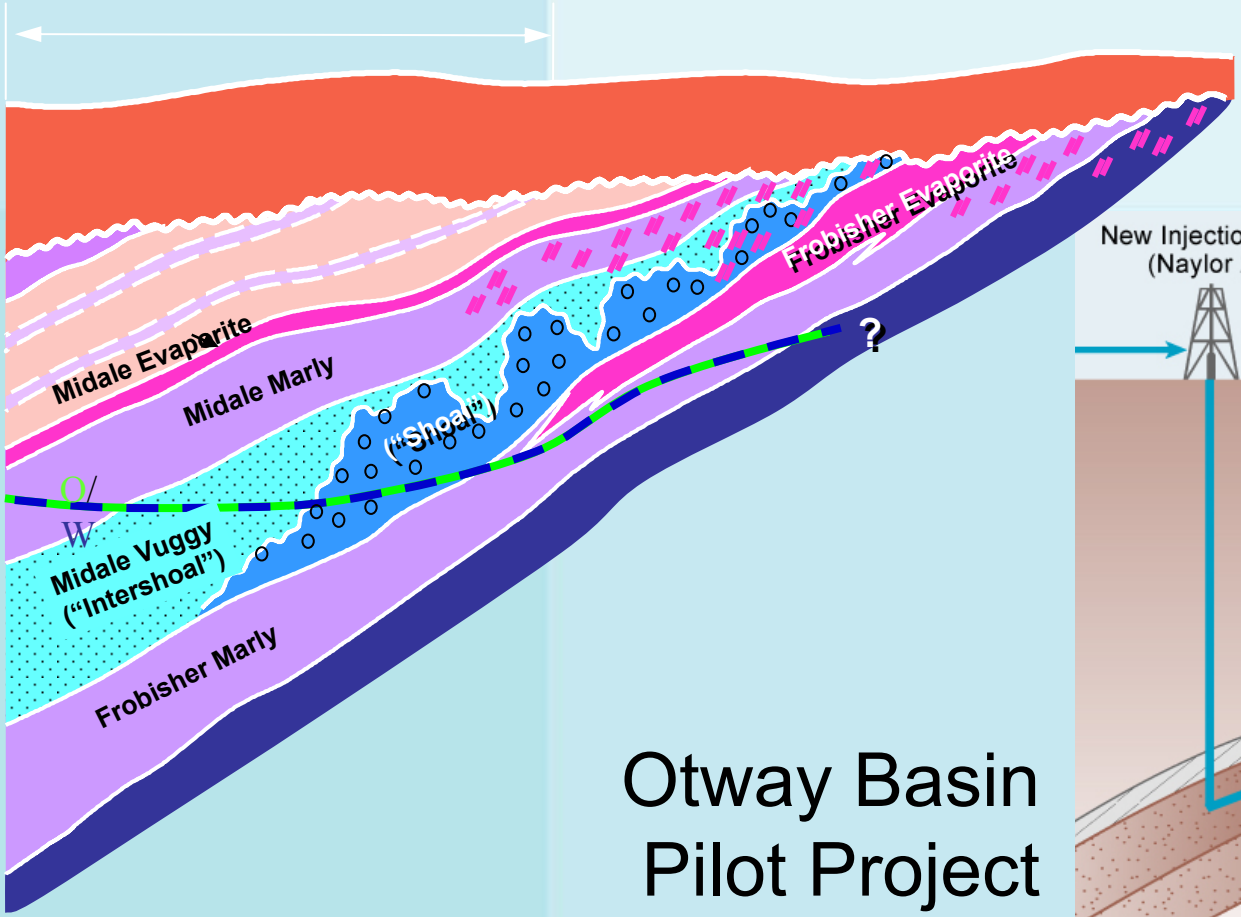
Alberta Research Council
CO2CRC

What is a seal?

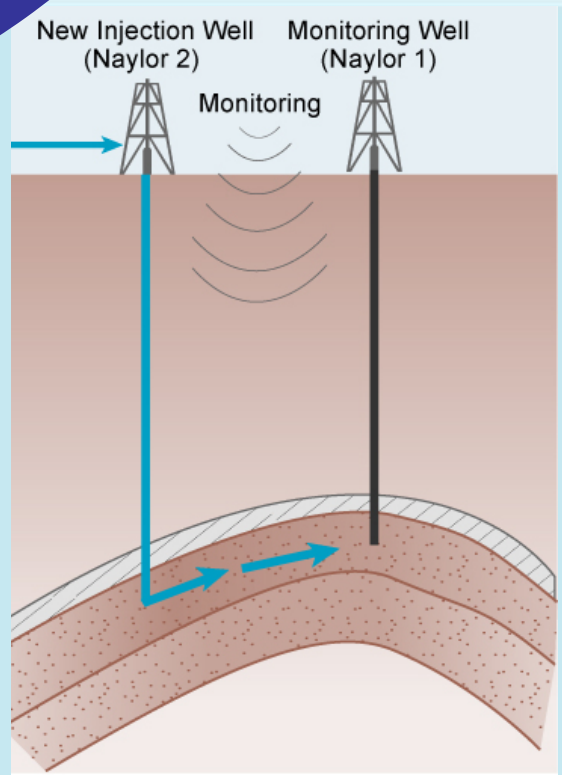
- A very significant decrease in the porosity and/or permeability which minimizes or eliminates fluid migration in a particular direction.

Seal Examples

Weyburn



Otway Basin
Pilot Project



Why monitor across (above) the seal?

- A concern that the seal may not be “effective” and fluids may migrate out of the primary zone
  - by matrix diffusion,
  - around an incomplete seal,
  - through fractures/faults,
  - along poor bonding between well bore cement and seal.
- A concern that the effectiveness of a seal may be decreased through geochemical reactions between CO_2, formation waters and the rock matrix.

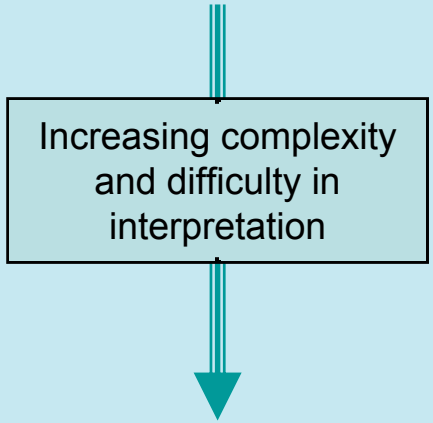
What limits geochemical changes of a seal?

- The location of the injected CO_2 is in the storage zone, not the seal.
- There will be high rock to water ratios – the rock controls what happens.
- Some seals are not reactive (or the mineralogy is similar to the storage zone and the fluids are already in equilibrium).

How would migration across a seal be recognized?

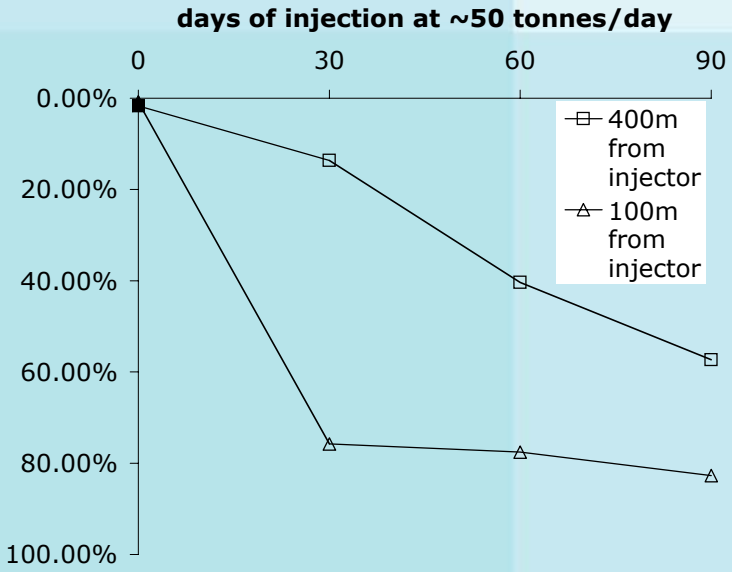
Sample and compare to baseline surveys and modelling (above and below seals), observe if there are …

- changes in amount and/or composition of gas (CO_2 increase?)
- the presence/absence of Tracers
  - Natural and injected.
    - Inert ions, noble gases, isotopes, CD_4, PFCs, SF_6, …
- changes in concentration of reactive components
  - E.G. Calcium, TIC, …, including isotopes

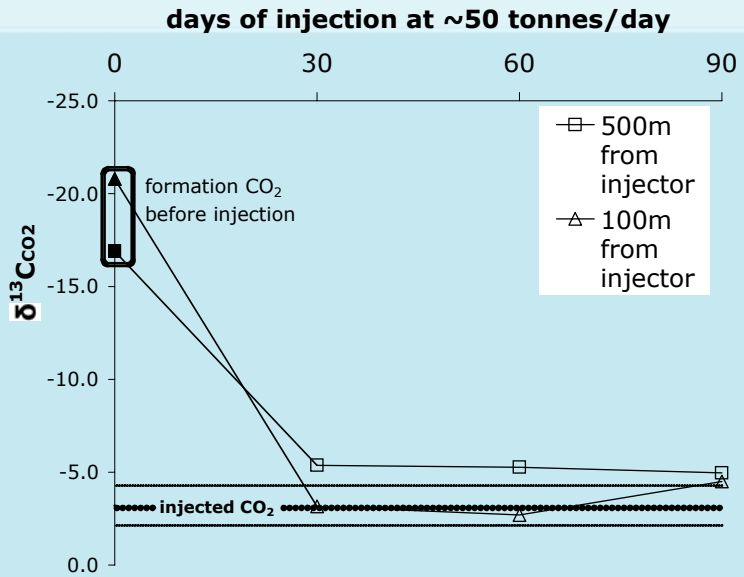


If changes are observed above a seal, they should be similar to changes observed in storage pilots and in EOR (e.g. Frio, Weyburn, Penn West, …)

Example of changes in the reservoir (Weyburn)



Gas composition



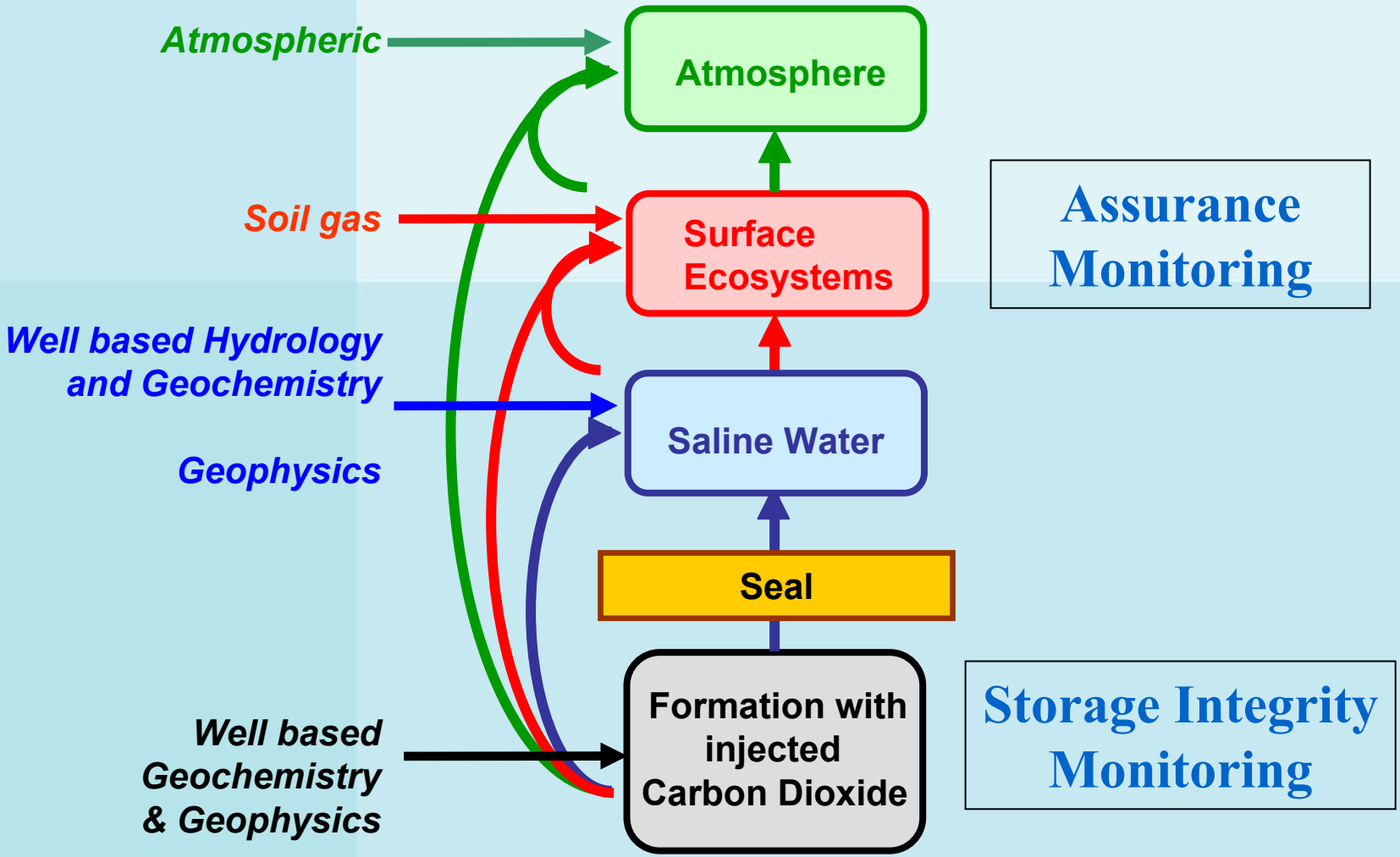
Gas isotopic composition

Seal effectiveness must be addressed "upfront" through

- appropriate geological and engineering site assessment and selection process,
- preliminary detailed reservoir & geochemical modelling.

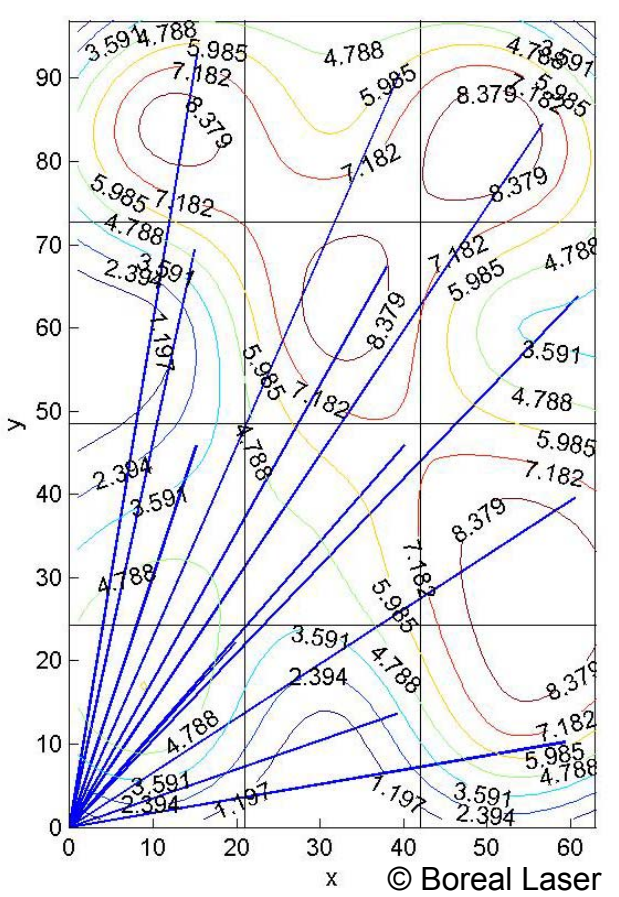
And are monitored through an ongoing sampling program.

Monitoring Domains



Modified from: http://web.princeton.edu/sites/cmi-aquifers/

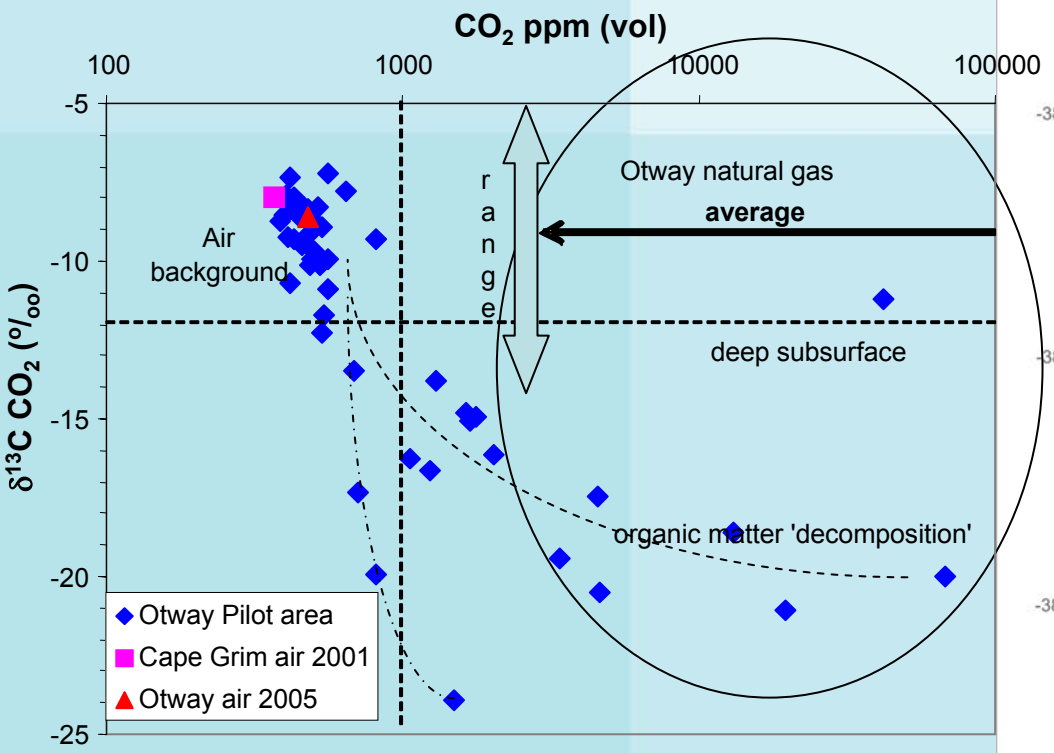
Atmospheric Monitoring Penn West



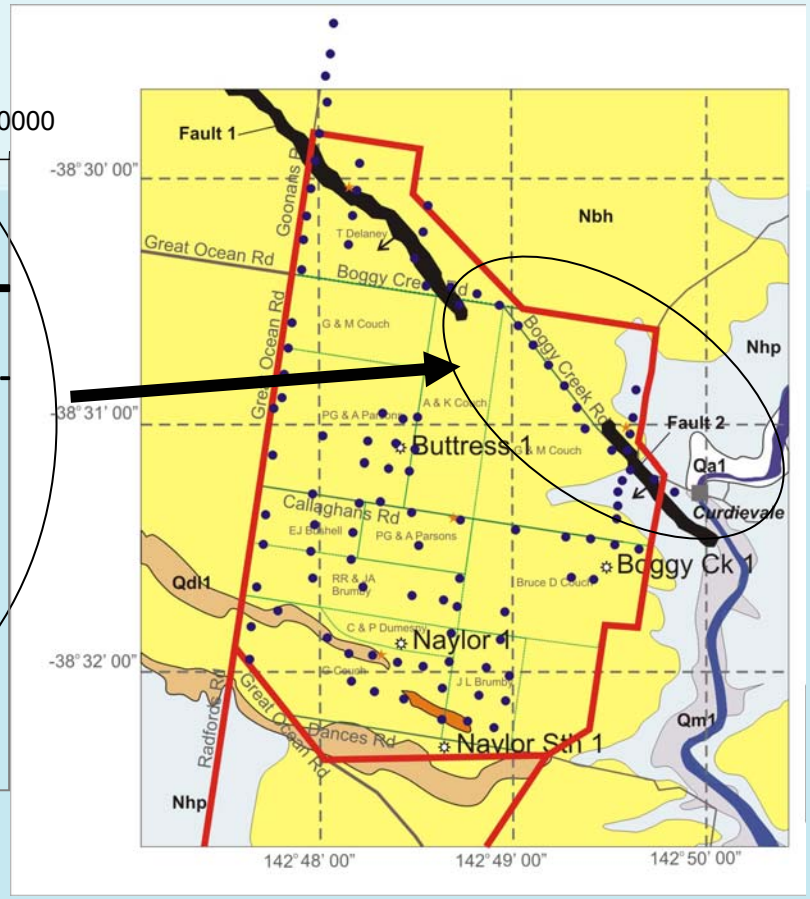
Isomap of concentration

- Baseline atmospheric for both CO_2 and CH_4 at Penn West site.
- Absorption based measurement combined with plume reconstruction
- Equipment and software from Boreal Laser.

OBPP Soil Gas Sampling:



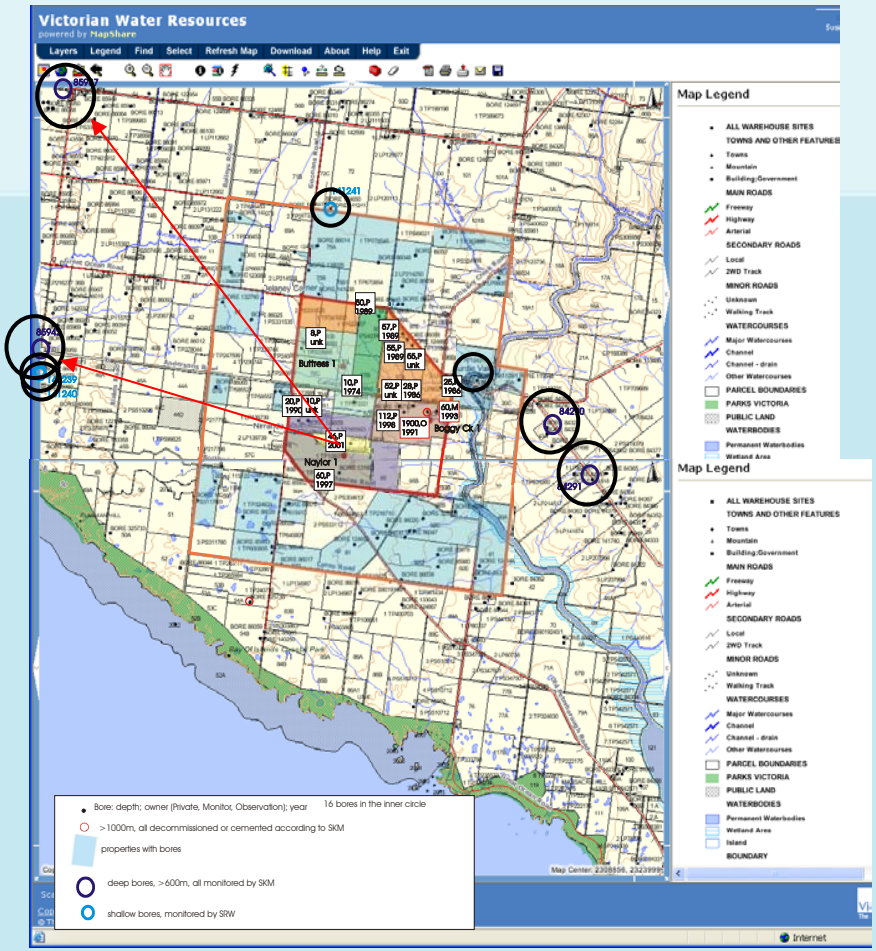
First Sampling Trip Results



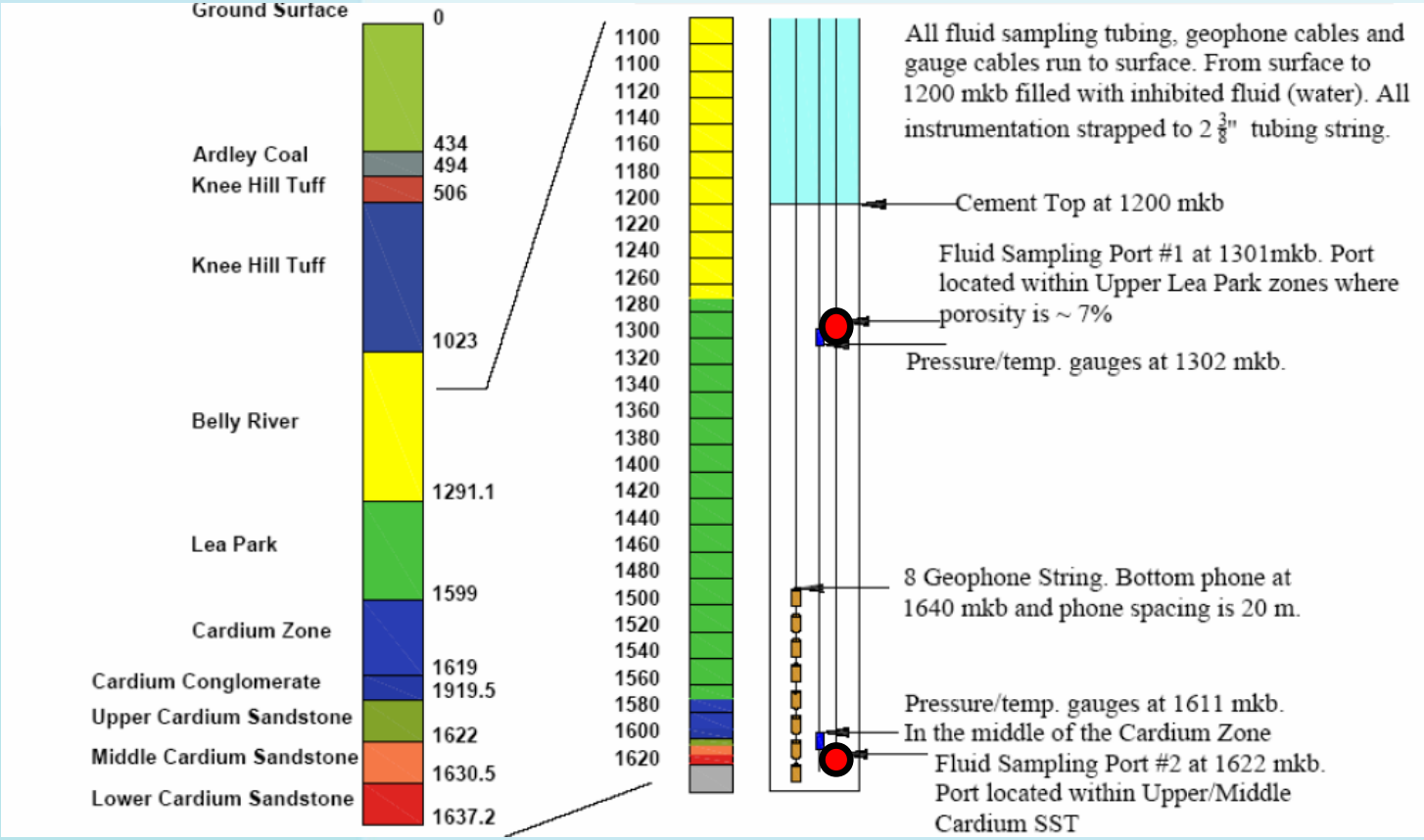
Otway Basin Pilot Project

Ground Water Monitoring Otway Basin Pilot Program

- Privately owned bores
  - Shallow, primarily for:
    - Garden water
    - Dairy sluice
    - Stock
- Monitoring Wells
  - Owned by state and local governments
  - Deep, primarily for water resource monitoring and management.



Monitoring Fluid Compositions across zones – Penn West



Sampling Frequency

Difficult to determine but …

- Assume how fluid will migrate out of zone.
- Based on questionable assumptions, determine migration rate and volume.
- Calculate when a sample would “see” the leak.
- Sample at a higher frequency.

Practical answer - manpower availability, resource limitations, regulatory requirements, weather, site access and funding will control the sampling frequency.

Key issues for assurance monitoring

- How big of signal is needed before it can be seen?
- Where (and when) should the samples be taken?
- What type(s) of monitoring should be undertaken?
- The closer to the storage zone, the more spatially restricted the sample locations become, and the more difficult it is to obtain samples!

End statement

- Assurance monitoring will be a necessary part of any GHG storage program.
- The existing research programs are addressing the key issues - progress is being made but there is more to do.

Reservoir simulation and coupled geomechanics to calculate pressure and stress changes that feed into monitoring design

Lincoln Paterson

CO2CRC/CSIRO

IEA 3rd Monitoring Network Meeting 2006

Outline

- Equations for multiphase flow.
- Example of reservoir simulation.
- Monitoring with 4D seismic.
- Patchy saturation.
- Equations for coupled geomechanics.
- Coupled geochemistry.
- Conclusions.

Equations for multiphase flow

$$\phi \frac{\partial S_1}{\partial t} - \frac{\partial}{\partial x_i}\left[k_{ij} \frac{k_{r1}}{\mu_1} \left(\frac{\partial p_1}{\partial x_j} + \rho_1 g \frac{\partial z}{\partial x_j} \right) \right] = 0$$

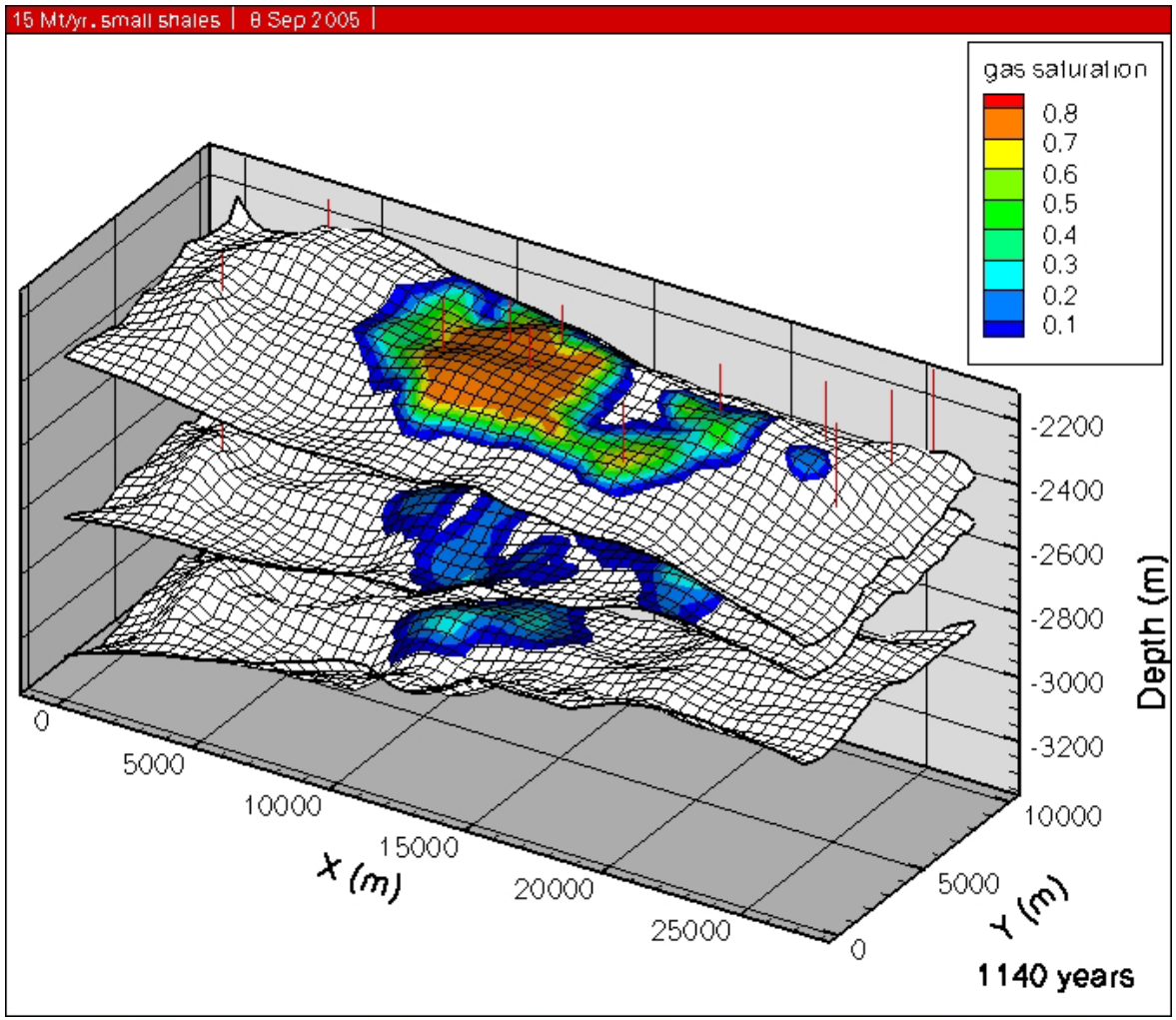
$$\phi \frac{\partial S_2}{\partial t} - \frac{\partial}{\partial x_i}\left[k_{ij} \frac{k_{r2}}{\mu_2} \left(\frac{\partial p_2}{\partial x_j} + \rho_2 g \frac{\partial z}{\partial x_j} \right) \right] = 0$$

$$S_1 + S_2 = 0$$

$$p_2 - p_1 = p_c(S_1)$$

Reservoir simulation solves for pressure *p* and saturation *S*

Reservoir simulation: Gippsland Basin



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Monitoring wells to measure pressure

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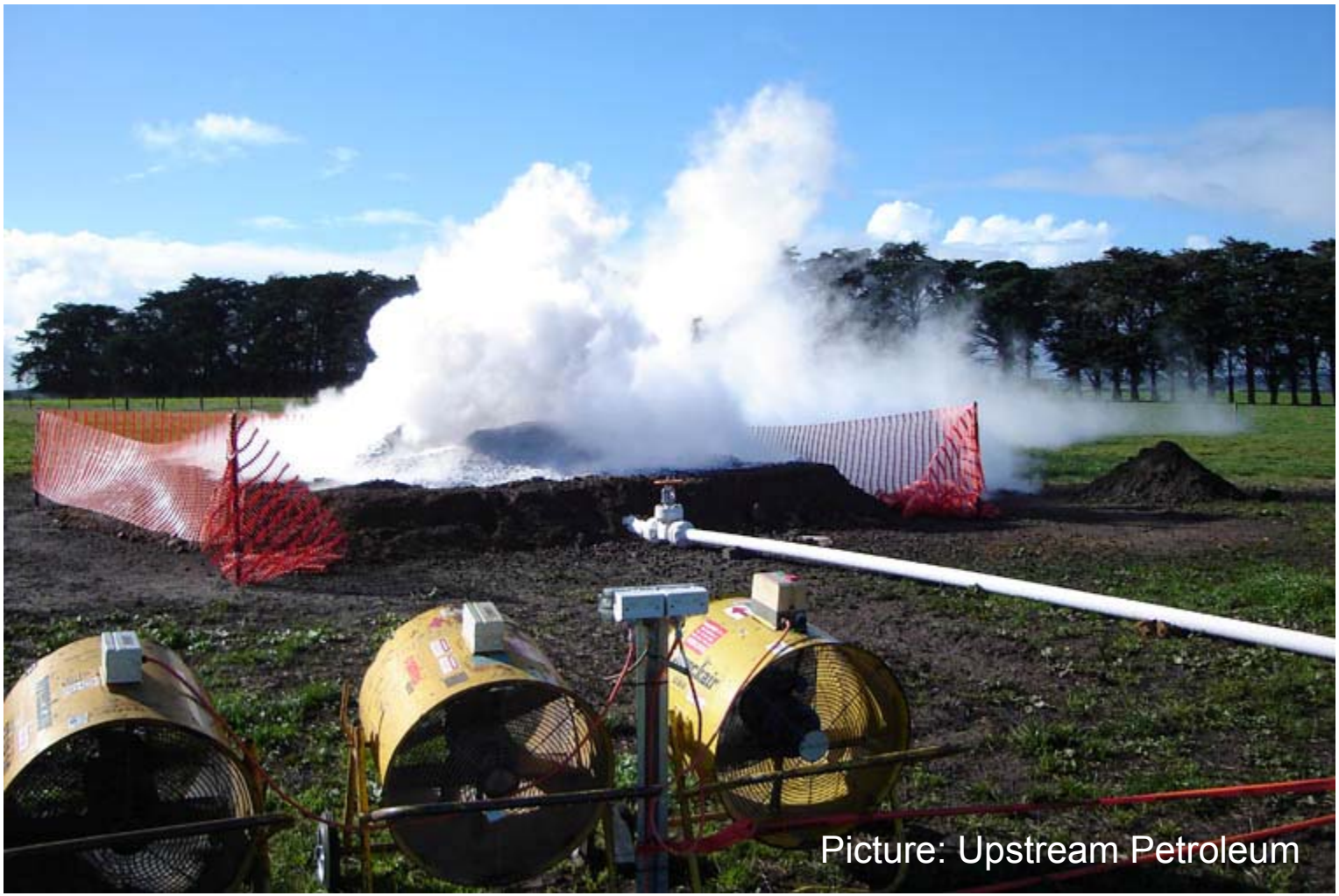
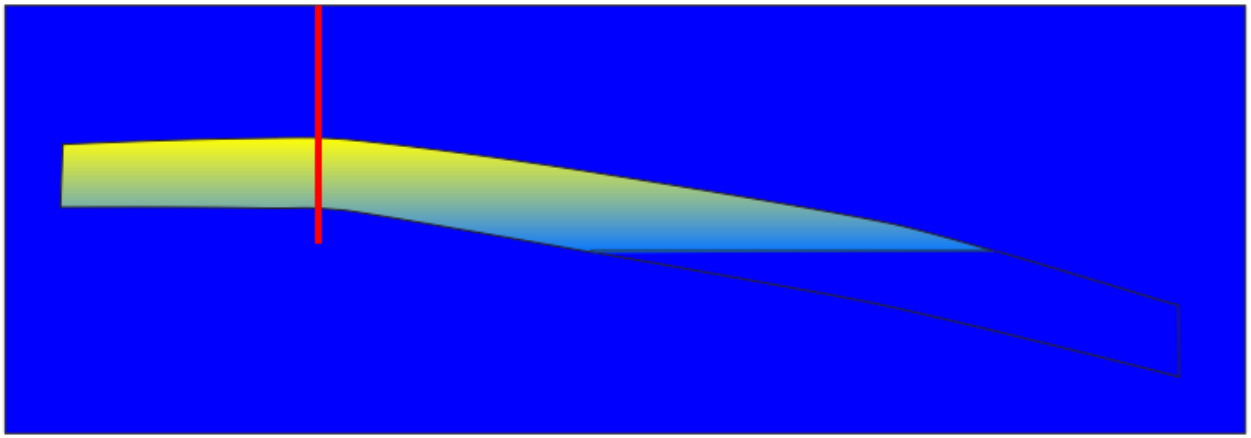
Short-term controlled CO_2 release

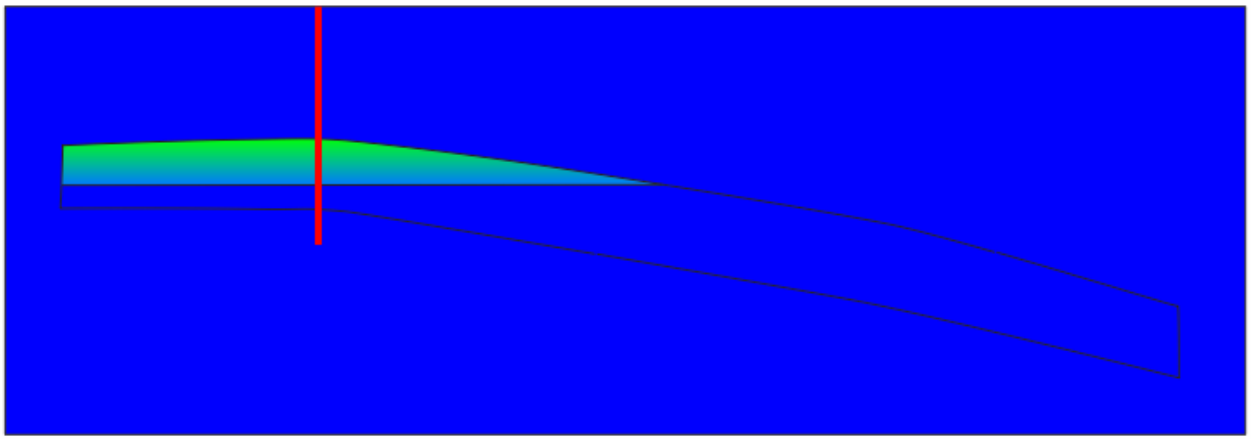


Otway Basin Pilot Project: Naylor depletion

Initial methane in-place

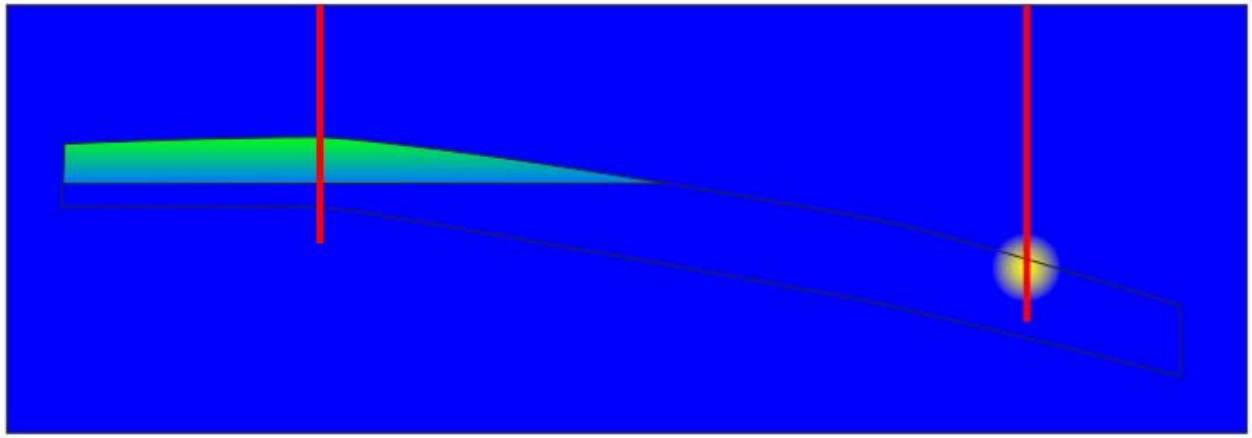


After production

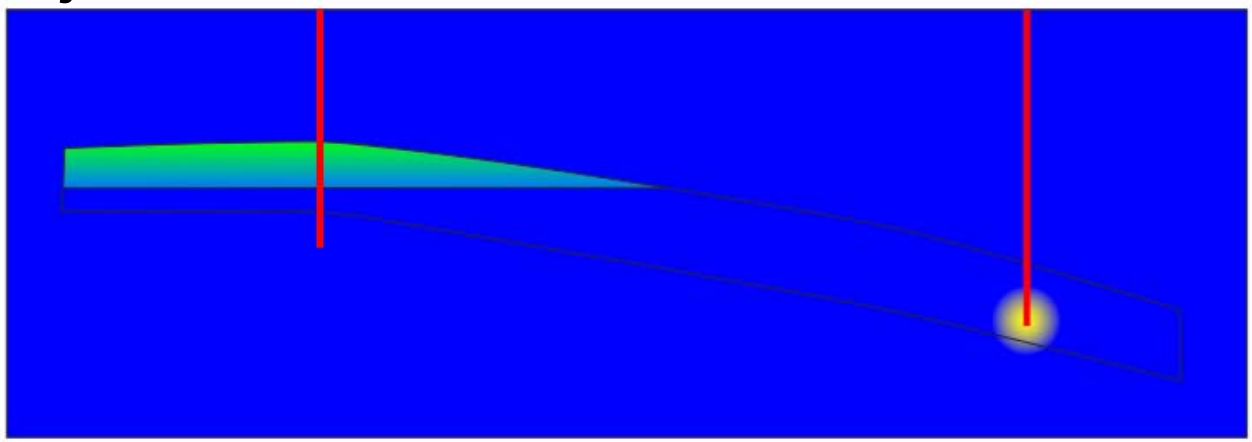


Otway: Start of CO_2 injection

Injection at top

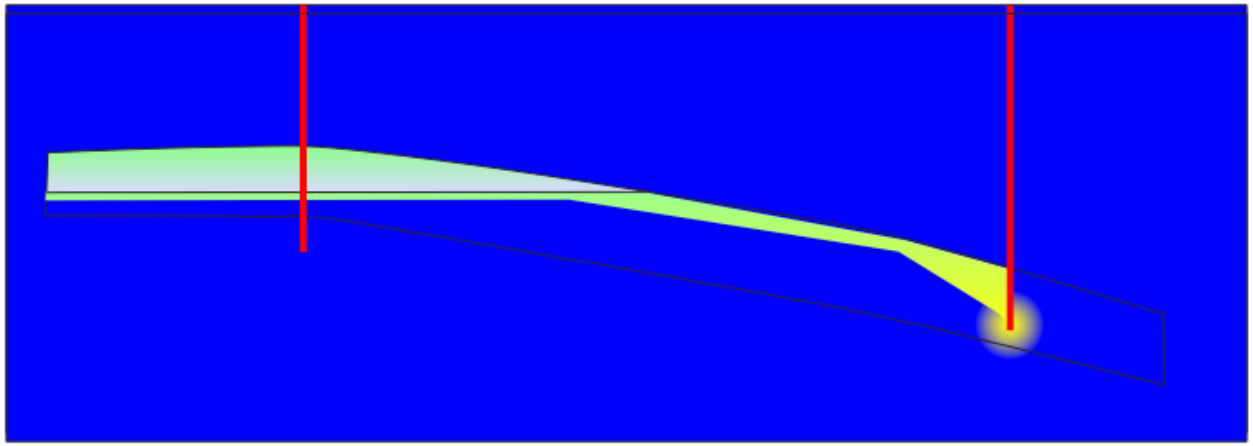


Injection at bottom

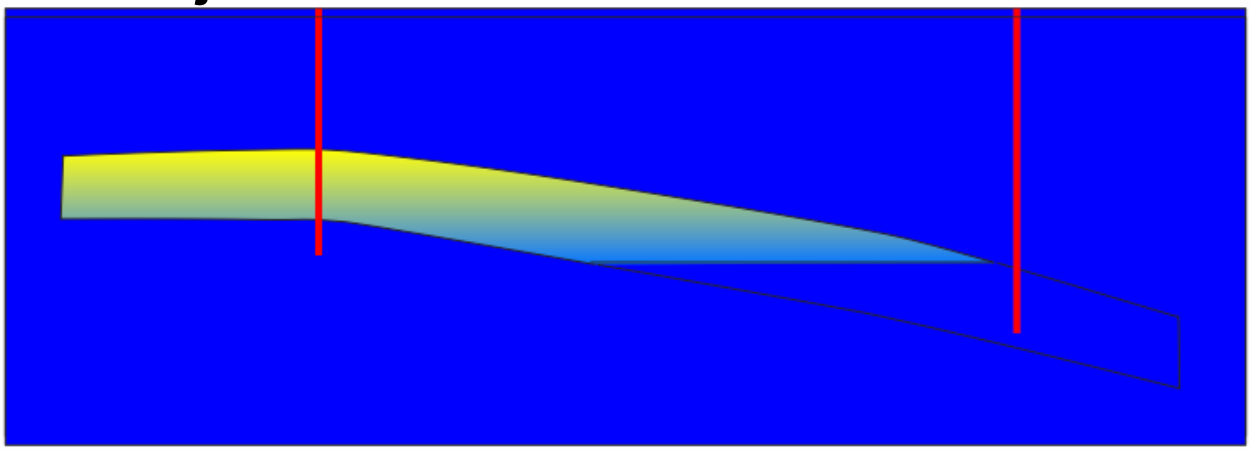


Otway: During and after CO_2 injection

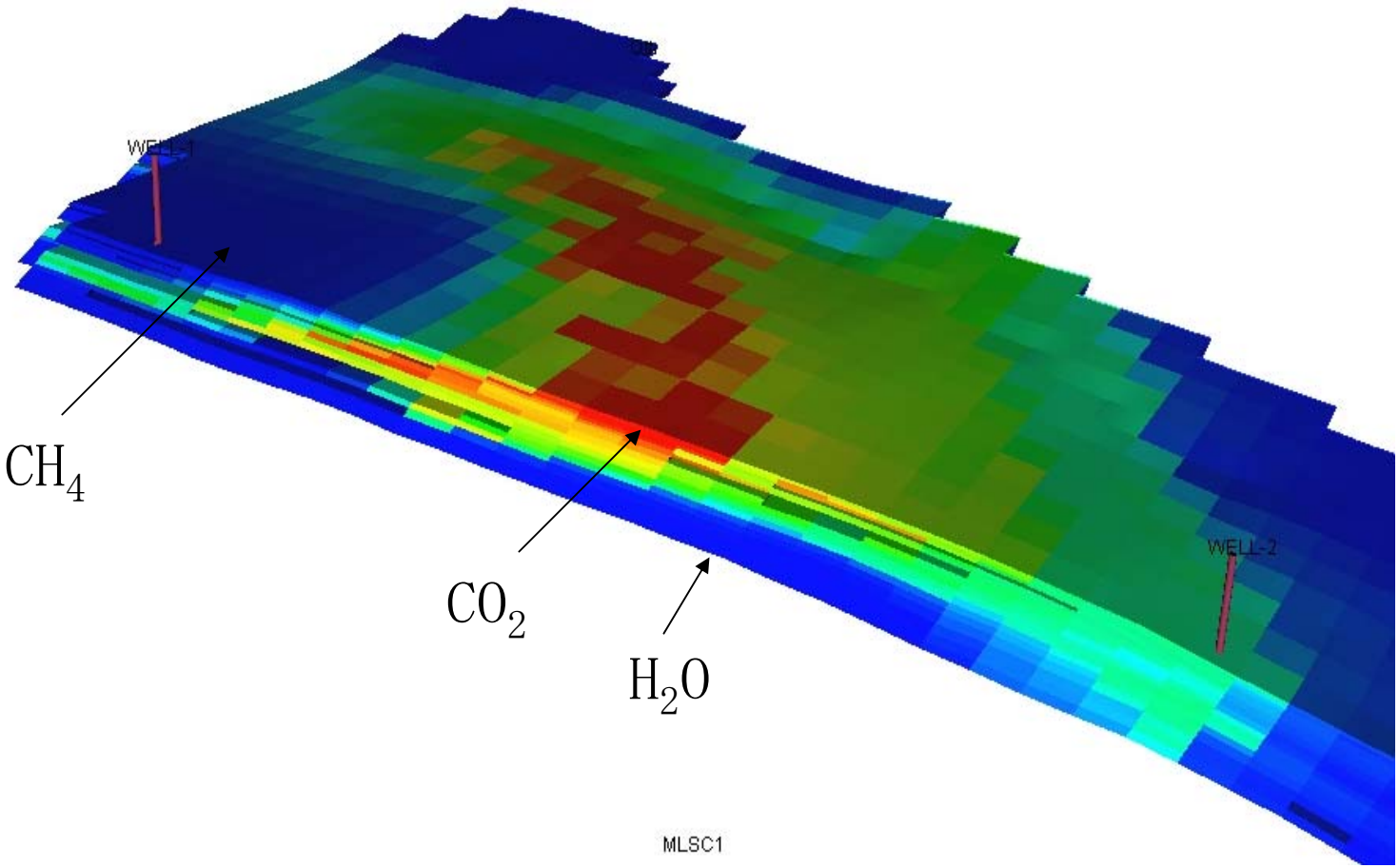
During injection



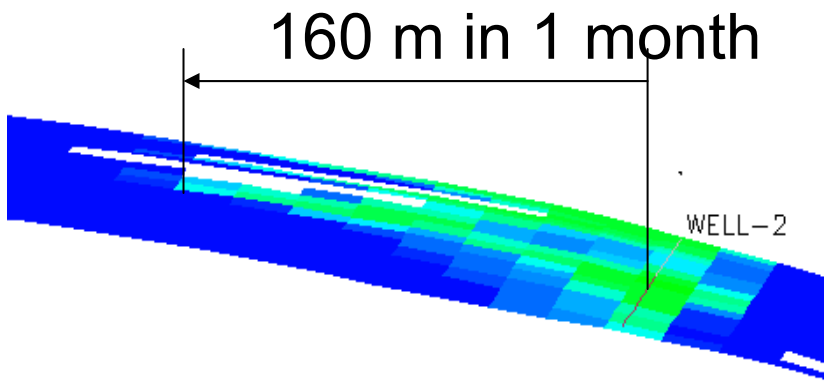
After injection

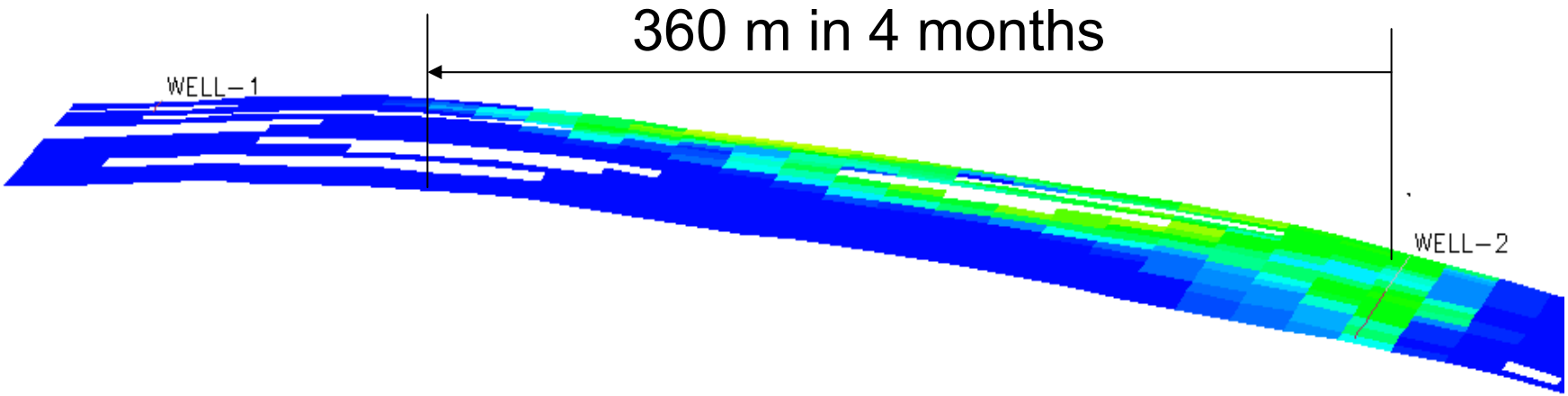


Otway: Reservoir simulation during injection

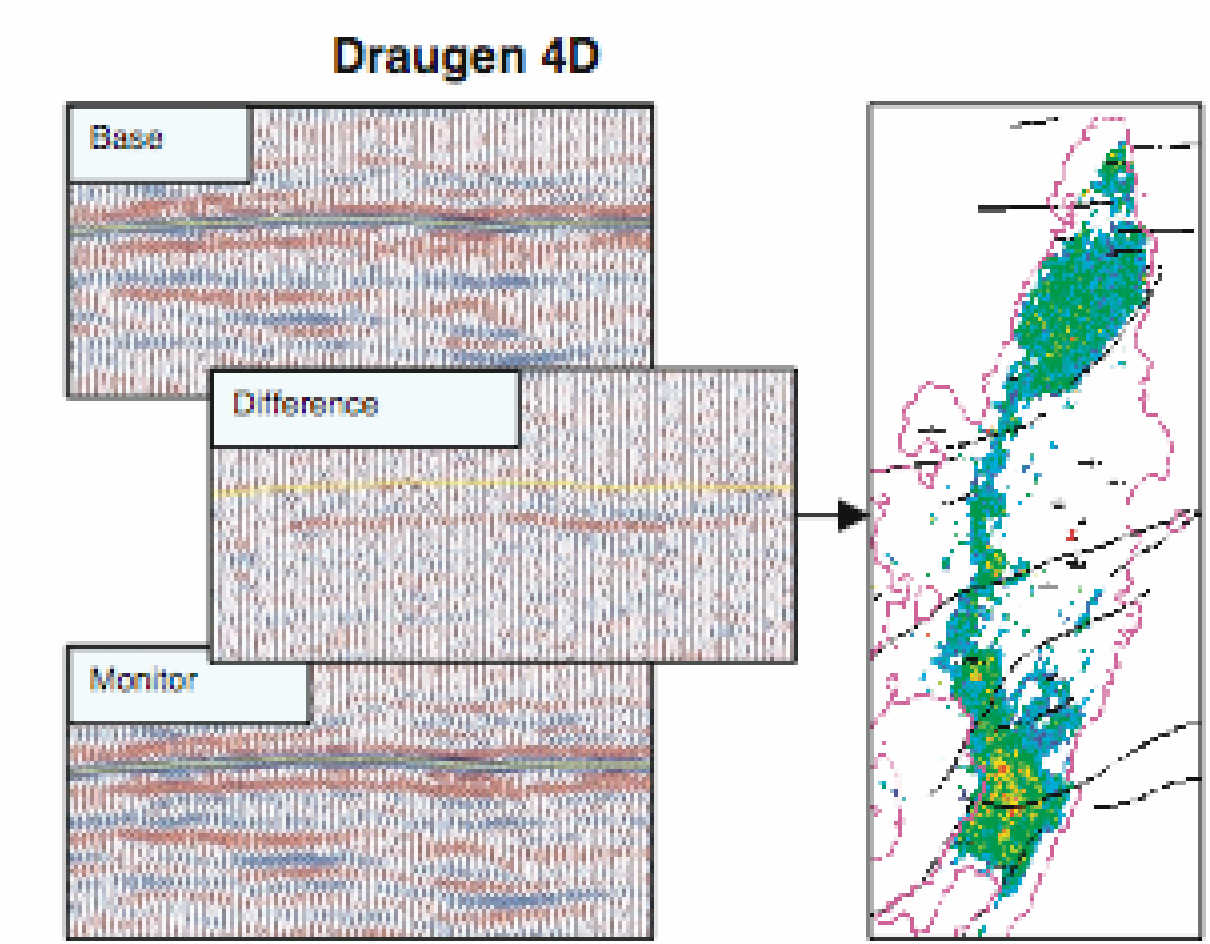


Otway: Migration velocity





4D seismic using difference between images



Source: R. Calvert (2005) Geophys. Prosp. 53, p.161

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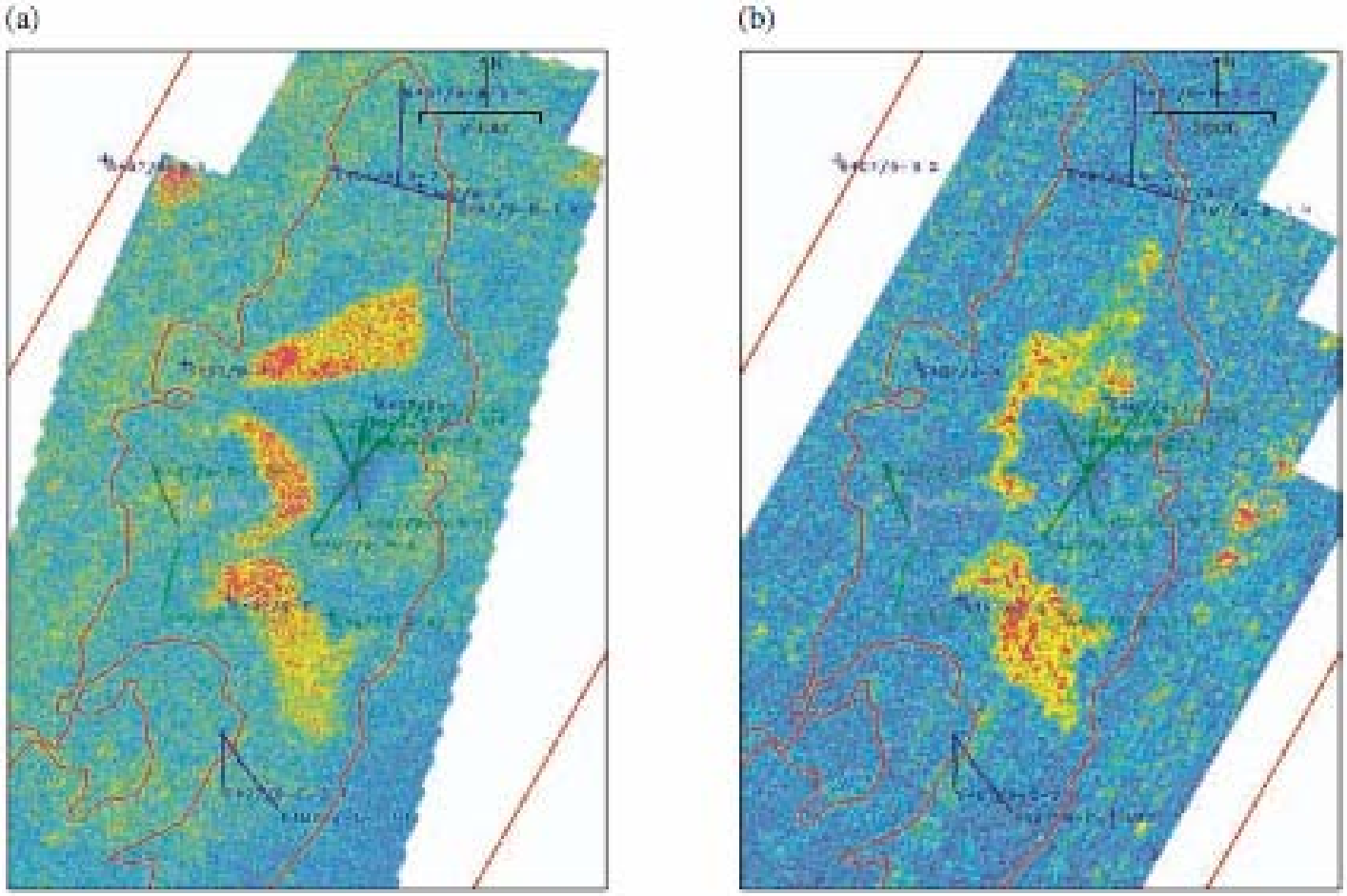
Modelled and measured 4D flood water



Source: R. Calvert (2005) Geophys. Prosp. 53, p.161

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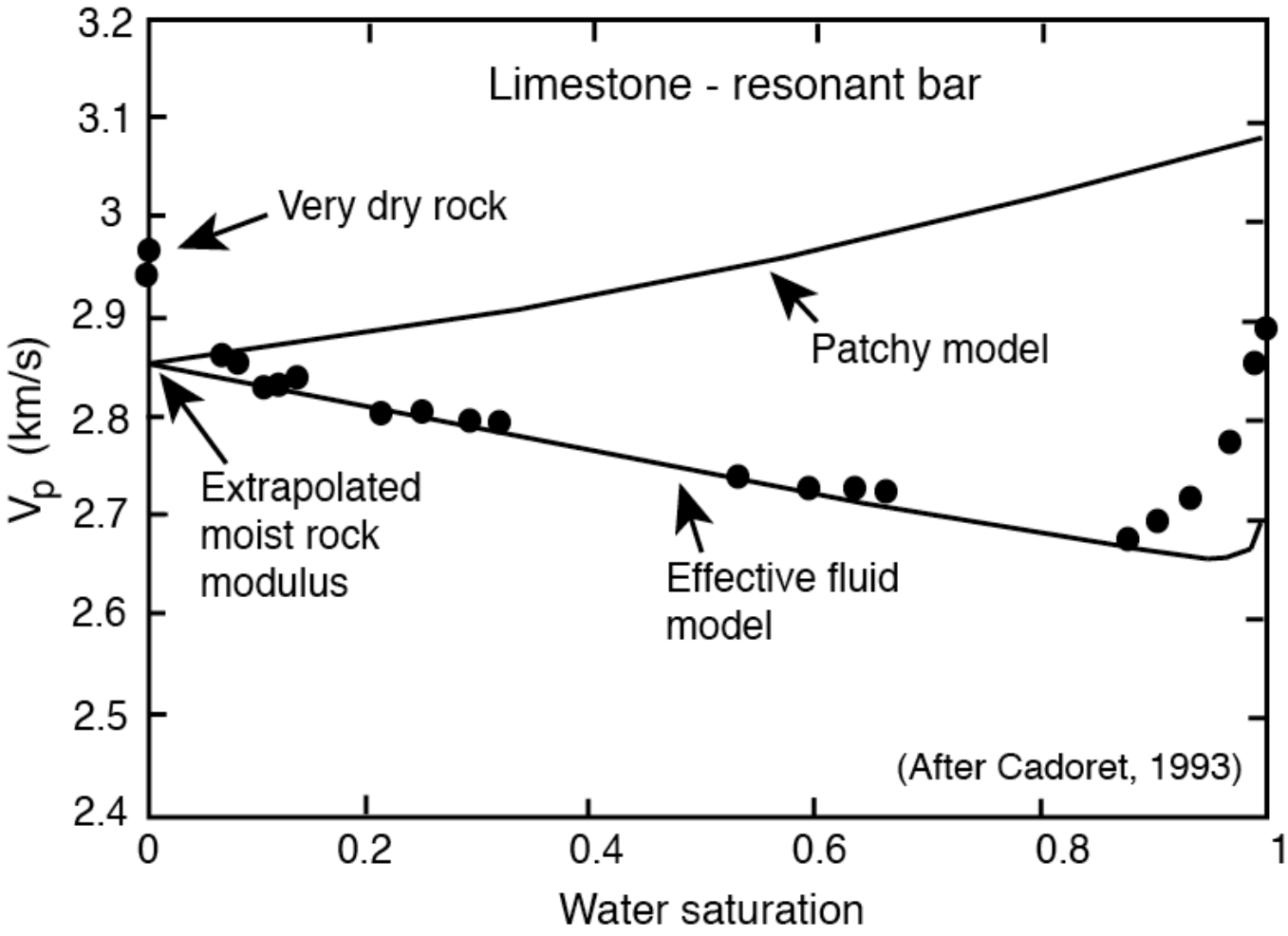
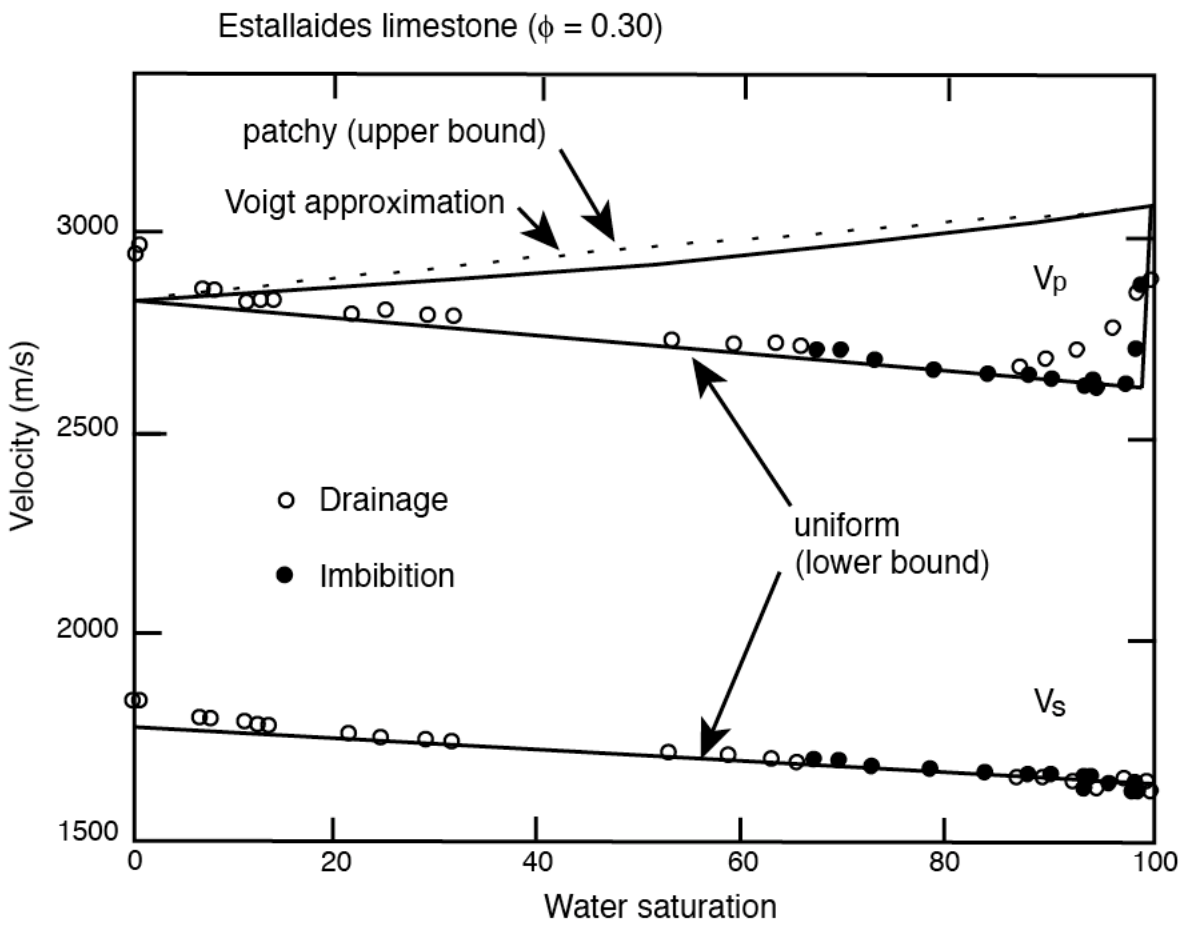
Mapping from acoustic velocity to saturation



Partial saturation: P and S waves



Equations for coupled geomechanics

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0$$

$$p = -\alpha M \varepsilon_{kk}$$

$$\sigma_{eff} = \sigma - p\mathbf{I}$$

$$\sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij} - \alpha p \delta_{ij}$$

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\nabla^2 \left(\sigma_{kk} + \alpha \frac{1-2\nu}{1-\nu} p\right) = 0$$

Can couple pressure *p* from reservoir simulation

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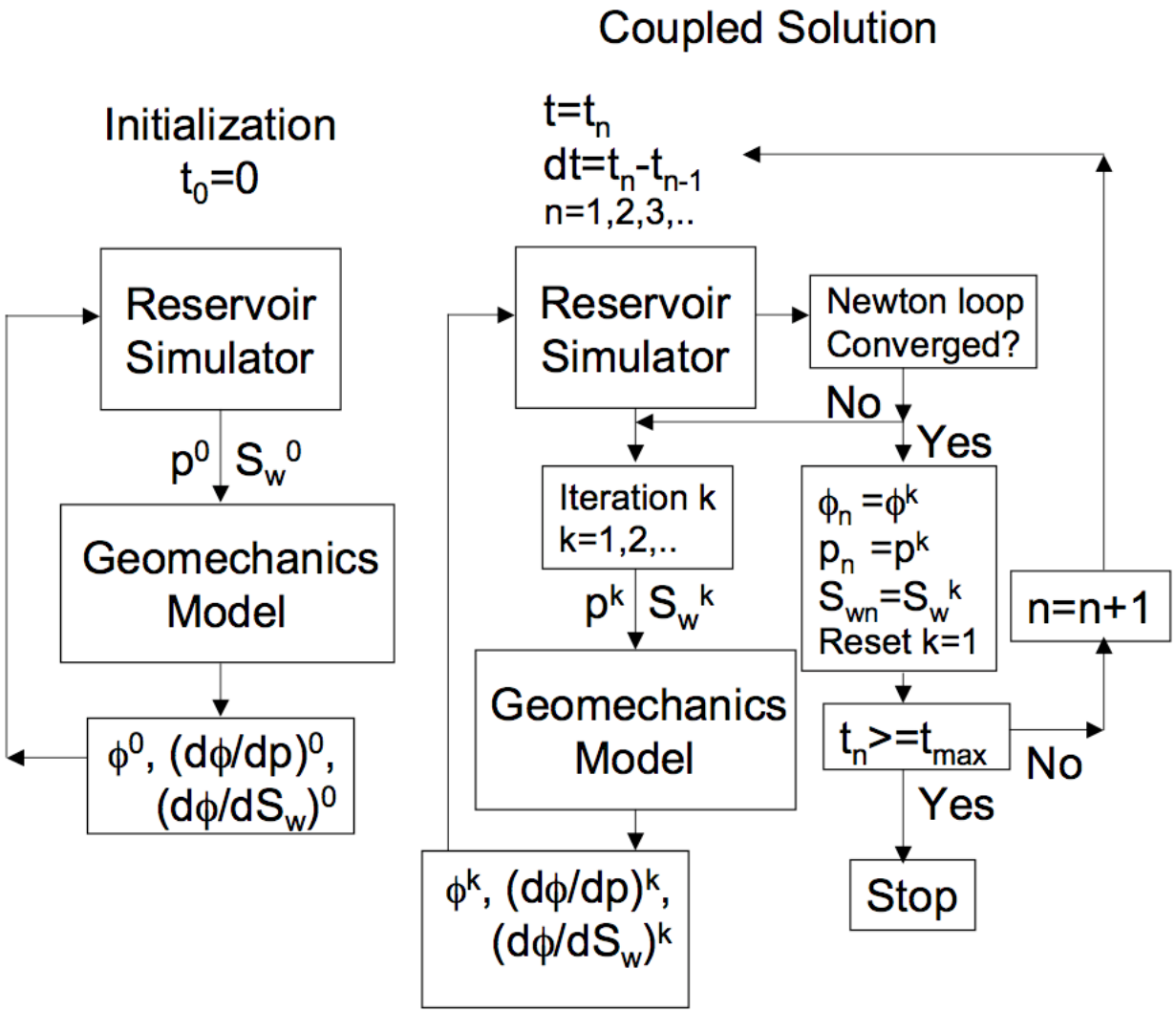
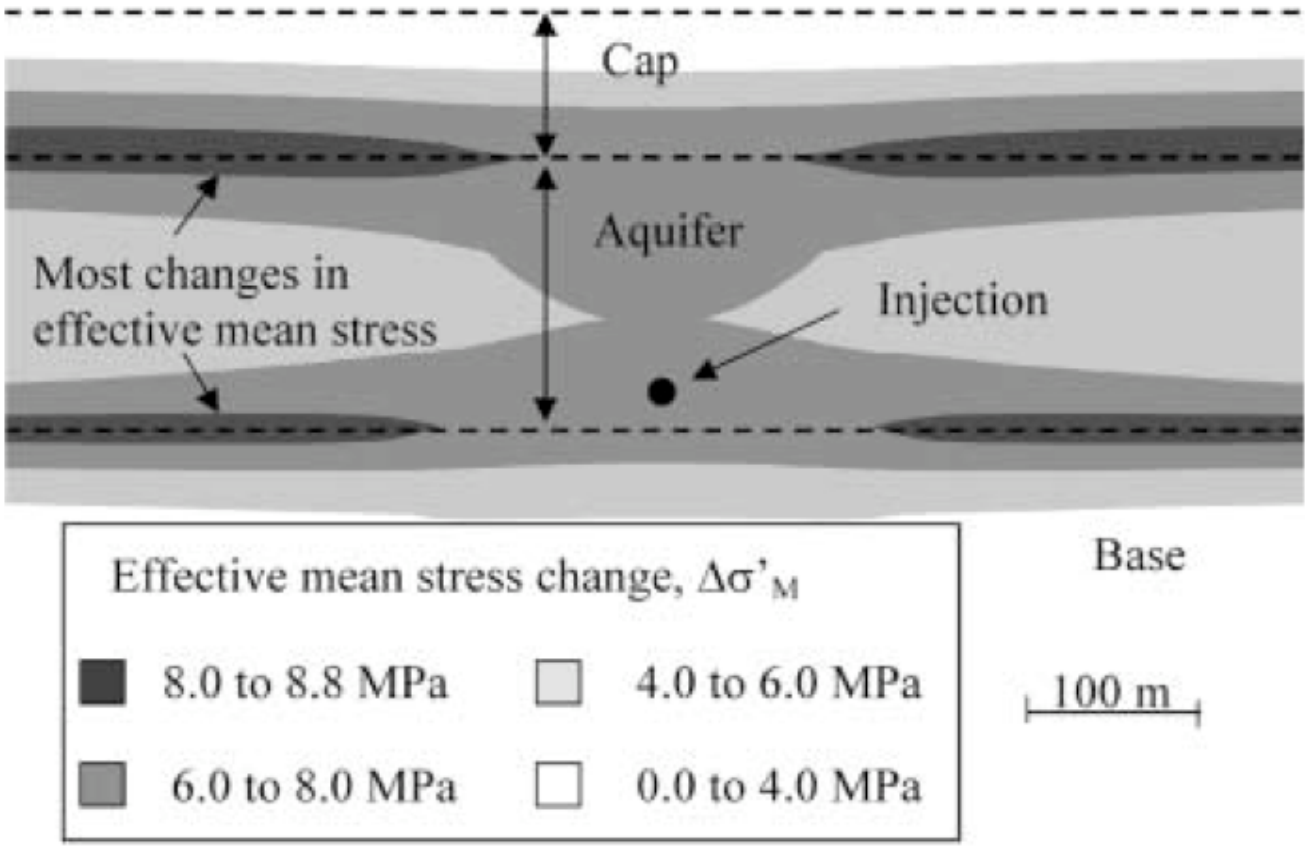
Flow chart (Thomas et al, SPEJ, Dec 2003)



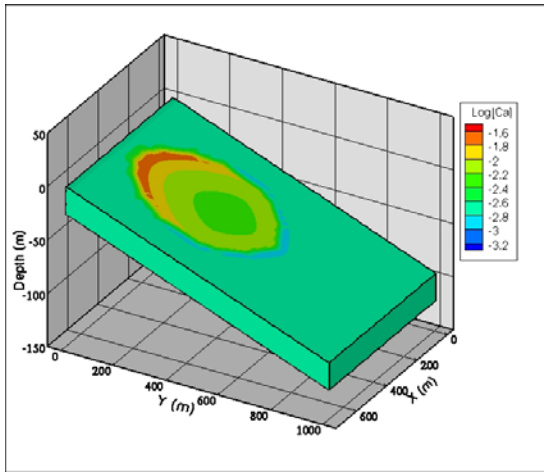
Example: Distribution of effective mean stress

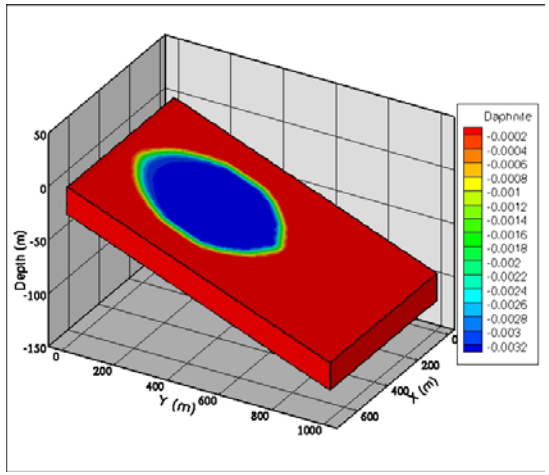


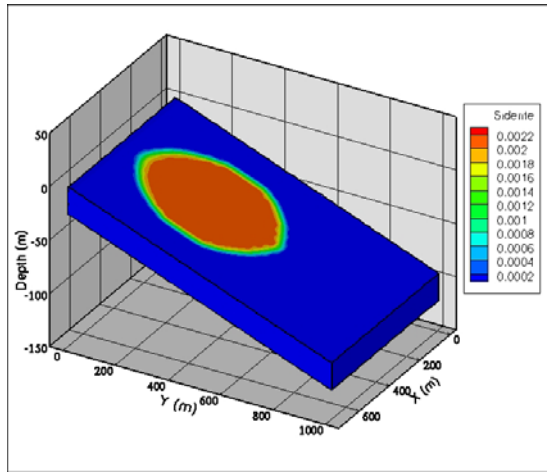
Source: J Rutqvist and C-F Tsang (2002) Environmental Geology, 42, 296-305.

Otway: Coupled geochemistry

Changes after 3 years (injection up to 18 months), based on a simplified geometry.







$Log_{10}[Ca^{2+}]$ Daphnite Siderite

Dissolution and precipitation leads to seismic velocity changes.

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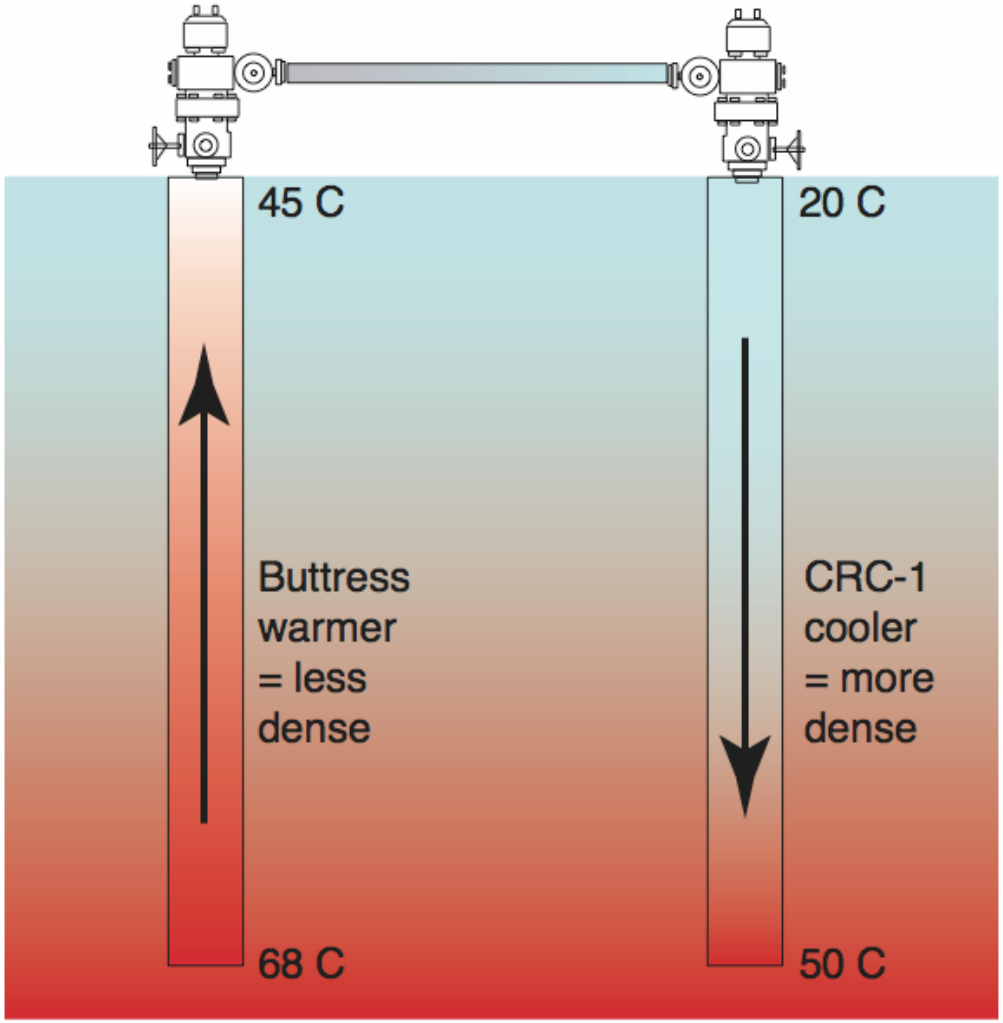
Thermal effects during production and injection



4D seismic challenges

- Surface seismic resolution is limited, may be > 25 m at surface, downhole seismic is better.
- Quantitative mapping from acoustic velocity to fluid saturation can be difficult, especially where there is patchy saturation.
- Velocity depends on pressure through changes in effective stress on the solid matrix.
- Velocity can change as stiffness of the solid matrix changes due to dissolution and precipitation of minerals.

Conclusions

- Reservoir simulation can be used to guide monitoring, assisting in the choice and location of monitoring approaches.
- Reservoir simulation can be used to help interpret monitoring results, including coupled geomechanical and coupled geochemical effects.
- Pressure response is a good indicator of CO_2 migration, sealing and containment.

CO2CRC Core Participants:

Australian Government

Geoscience Australia

RIO TINTO

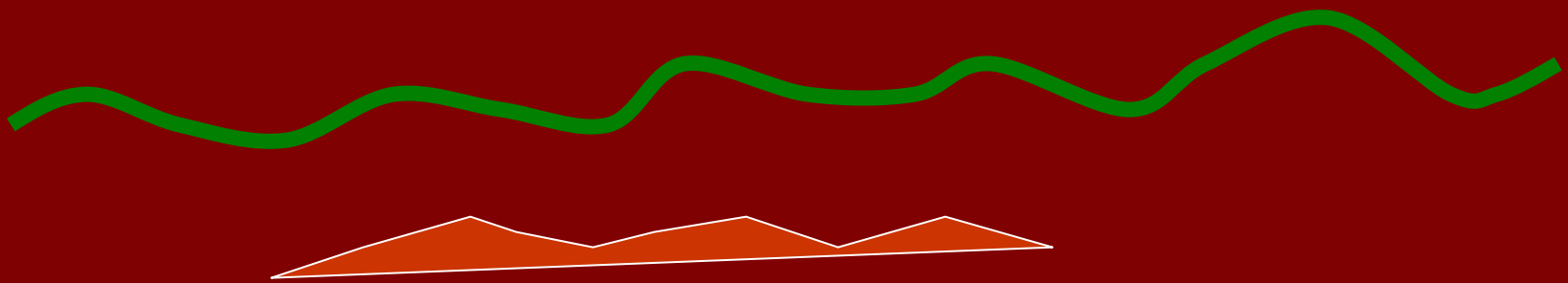
Schlumberger

UNSW

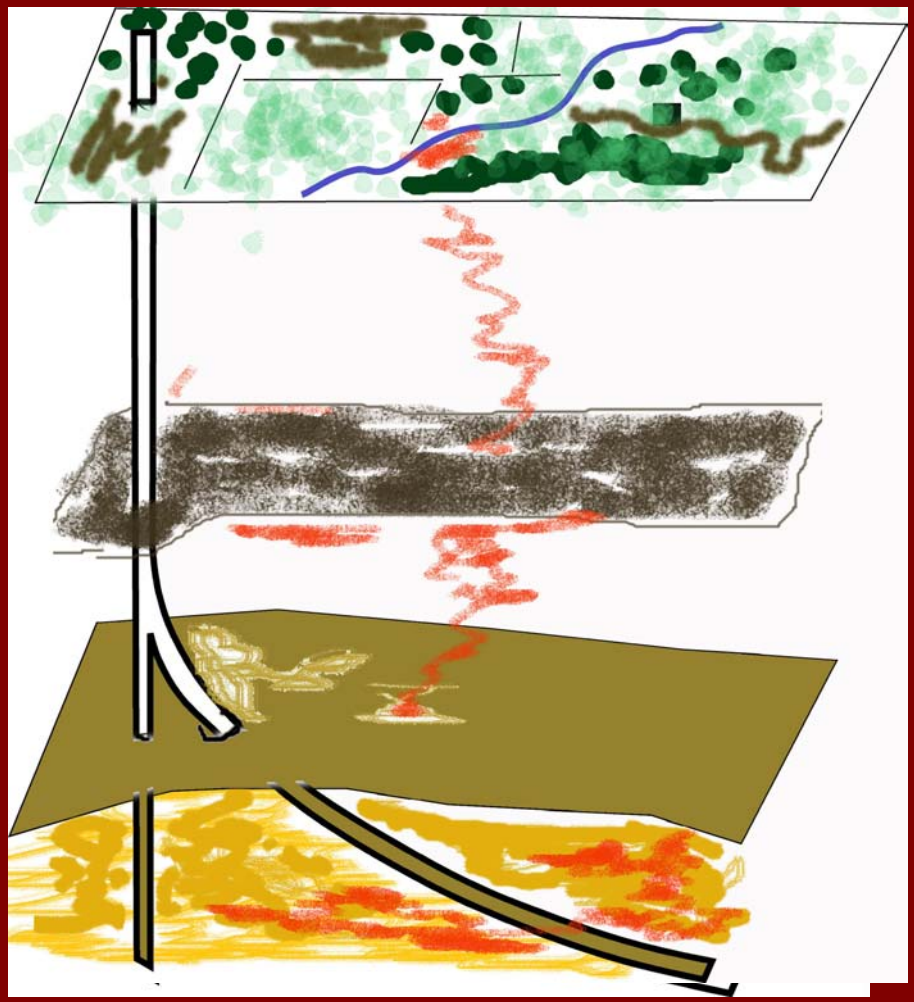
Containment and Integration

Review Day 2

Plan Day 3



Changing Scales of Monitoring



- Well based techniques
- Seals
- Seismic techniques
- Land surface techniques

Day 2 Highlights

- Minister Theo Theophanous: Take action now to hand over to next generation a world in repair, or leave a them a damaged world
- Peter Cook: confidence building - prescribing knowledge as an antidote to specific pubic concerns – Australia and CO2 CRC project list
- Charles Christopher – reminder of what is not done – call for technologies that answer questions that those outside the CCS community required to be answered - demonstrate that storage is safe

Day 2 Highlights continued

- Rick Chalaturnyk: technical needs: validate simulation, physics of storage, correct reservoir parameters, measure caprock integrity, triggers for contingencies. Use of wells –pressure response interpretation, well completion as an issue
- Myself – news from Frio II – specific goals set for experiment
- Barry Freifeld – deploy tools that successfully collected data relevant to goals
- Laurent Jammes: Monitoring planning list: what do you want to monitor, what properties will change, what tool, sensor sensitivity, where, how, when to deploy, how to integrate, how to interpret

Day 2 Highlights continued

- Daiji Tanase: very detailed time lapse logging program comparing logging tool response to CO_2 arrival at Nagaoka. CO_2 monitoring is a dynamic process compared to oil field assessment.
- Dave Dewherst – crash course in seals from hydrocarbon experience – confidence in tools – data needs: wettabilty of CO_2; poroelastic behavior, diffusion of CO_2 into caprock
- Ernie Perkins – containment by multiple seals, containment by limited availability of water.
- Lincoln Patterson; Reservoir simulation and geomechanics – importance of pressure in monitoring

Day 3 preview

- Nick Riley - Monitoring strategies considered by European projects
- Marcia Coueslan- walkaway VSP
- Ziqui Xue – Nagaoka earthquake
- David Etheridge – atmosphere
- Lee Spangler – near surface

Thinking about recommendations leaving this workshop

- What constitutes validation?
  - Affirmative and negative data – show that the (model) predictions are correct
  - Direct measurement of protected resources – air and water

What does success of MERV look like: what retention in zone should we attempt to quantify?

- IGCC

> For large-scale operational CO_2 storage projects, assuming that sites are well selected, designed, operated and appropriately monitored, the balance of available evidence suggests the following:
>
> - It is very likely the fraction of stored CO_2 retained is more than 99% over the first 100 years.
> - It is likely the fraction of stored CO_2 retained is more than 99% over the first 1000 years.

- Protective of HS&E, water, atmosphere
- Best possible practice: As low as reasonably practical
- Value of looking at retention not by percent:
  - by mass
  - With time, by area, with pressure

Thinking about recommendations leaving this workshop

- What retention can be predicted?
  - By natural analog
  - Modeled
    - Inputs from lab data, extrapolation of small scale observations, statistical approach
- What retention can be verified?
  - Accounting procedure
    - Point measurements
    - Integrated measurements

Selecting the tools

- Fit to purpose, all sites unique, select from MMV tool kit
- Check up analog
  - A procedure to follow that tailors test program to the patient at hand. Gateway process.
- How do we set performance standards
  - If standard is exceeded – what is action?
  - Issues of sensitivity, precision, accuracy, false assurance, false positives: reduced public assurance if measurements are not Evaluated Reported and performance Validated

Synergy or non-overlap of various MERV goals

- For HS&E
  - Acute exposure, water damage, failure to benefit atmosphere
- For greenhouse gas inventory accounting
- Public acceptance
- Regulatory compliance

Early experiments/demonstations – early implementation – mature implementation

European Research Network of Excellence on the Geological storage of CO_2.

Interim progress report relating to monitoring, verification, ecosystem protection/responses, health & safety, regulation and public perception of underground CO2 storage.

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IEA GHG 3rd Monitoring & Verification meeting
Melbourne, Australia Oct 2006

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NATURAL ENVIRONMENT RESEARCH COUNCIL

Talk Structure

Introduction & acknowledgements
What is “CO2 GeoNet”?
Why study leakage?
Joint Research Portfolio
Terrestrial settings
Aquatic Settings
Conclusions

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Introduction & acknowledgements

What is “CO2 GeoNet?”

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EUROPEAN COMMISSION
Community Research

European Research Network Of Excellence on Geological CO_2 storage

13 Research 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
International Research Institute Stavanger-IRIS
SINTEF Petroleumsforskning AS –SPR

UK
Natural Environment Research Council-British Geological Survey-BGS (Co-ordinator)
Heriot-Watt University –HWU
Imperial College of Science, Technology and Medicine-IMPERIAL

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The European Commission has pioneered in supporting CO_2 storage research since the early 1990's

NATURAL ENVIRONMENT RESEARCH COUNCIL

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Joint Research Portfolio

WORK PACKAGES months 13-30	JRAP-1	Cap rock seal capacity for CO2 storage
	JRAP-2	Creation of a conceptual model of gas migration in a leaking CO2 analogue
	JRAP-3	Development of advanced seismic modelling capabilities
	JRAP-4	Ecosystem responses to CO2 leakage - model approach
	JRAP-5	Geochemical monitoring for onshore gas releases at the surface
	JRAP-6	Integrating risk assessment tools for CO2 storage performance assessment
	JRAP-7	Interaction of CO2 with host rocks: experiments and models
	JRAP-8	Monitoring of submarine CO2 fluxes and ecological impact
	JRAP-9	Seal properties database
	JRAP-10	Testing remote sensing monitoring technologies for potential CO2 leaks
	JRAP-11	Unlithified seal deformation
	JRAP-12	Application of tracers for monitoring CO2 storage
	JRAP-13	CO2 storage in virgin seams and in coal seams stimulated by UGC
New WPs months 25-42	JRAP-14	Reactions between CO2 and borehole infrastructure
	JRAP-15	Enhanced Oil Recovery From Depleted Oil Reservoirs Through CO2 Storage
	JRAP-16	Geological Models, Heterogeneity Catalogue and Scale-relations
	JRAP-17	Feasibility of geophysical methods as a tool to detect migration pathways of CO2 in the shallow subsurface
	JRAP-18	Monitoring near surface leakage and its impacts
	JRAP-19	Development of a low cost alert system for the CO2 Storage, based on active and passive seismics

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Why study leakage?

Leakage from geological storage is the main issue of concern with NGOs, the public, government and regulators

Health & Safety
Ecosystem protection
Resource/property damage
Carbon credits
Public & Regulatory Acceptance
Efficacy and risk of CCS compared to other climate management options

As industrial CCS sites are designed not to leak we need to study natural analogues and conduct deliberate exposure experiments in order to learn what we can measure above baseline conditions.

Source → Pathway → Target → Response

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We need to be able to demonstrate what is, and what is not measurable and distinguishable from baseline conditions with regard to context, timing, processes, fluxes, doses and responses

If we claim that a storage site is secure- we need to be able to demonstrate that this is indeed the case, beyond reasonable doubt.

If it is wrongly claimed/perceived that a storage site is leaking- then we need to be confident that we can rely on an evidence base to revoke such claims

We also need to be able to recognise leakage, should such an unlikely event occur, in order to manage risk, address public & stakeholder concerns/interests and fulfil regulatory obligations.

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Terrestrial Settings

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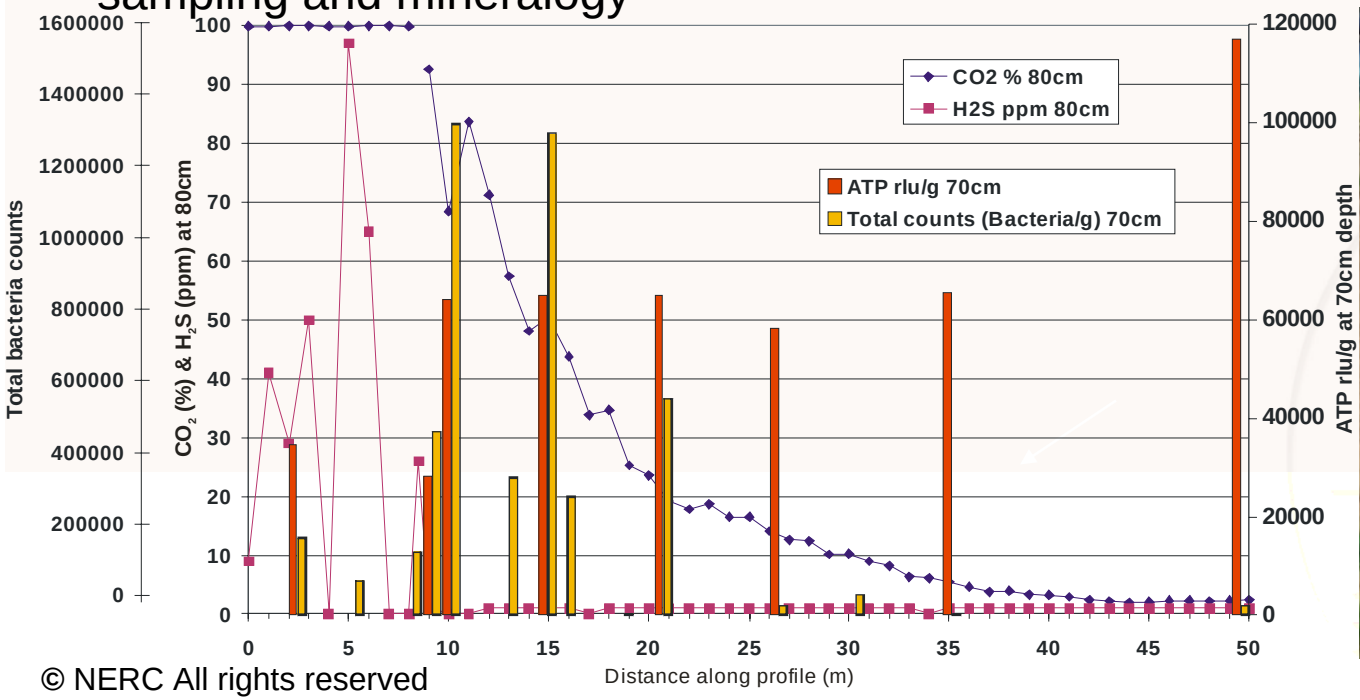
Latera

- Latera, Italy
- CO_2 seepages (with other gases) – volcanic origin
- Previously studied in BGS-led NASCENT project
- Ecological study – botany, microbiology (diversity), ecotoxicology together with gas sampling and mineralogy



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Latera

Botanical assessment

Cleaning before soil sampling for microbial analysis

Soil sampling for chemical and microbiological analysis

Ecotoxicology – Worm sampling

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Latera

- White = Casi B12
- Red = Thermal
- Green = NDVI May
- Yellow = Orthophoto
- Cyan = Hyper B 41
- Magenta = NDVI Oct

Fixed wing & helicopter acquired remote sensing

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Latera- Open path infra-red laser

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Controlled terrestrial injection site

- CO2 GeoNet collaboration with Nottingham University - **Artificial Soil Gassing and Response Detection(ASGARD)** site. Started in Spring 2006.

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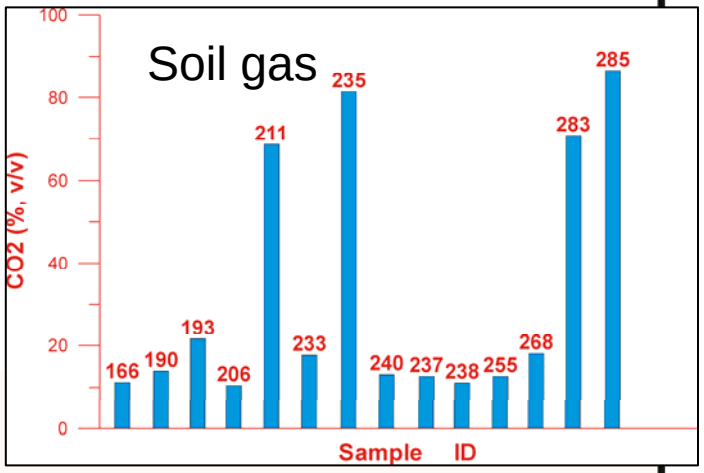
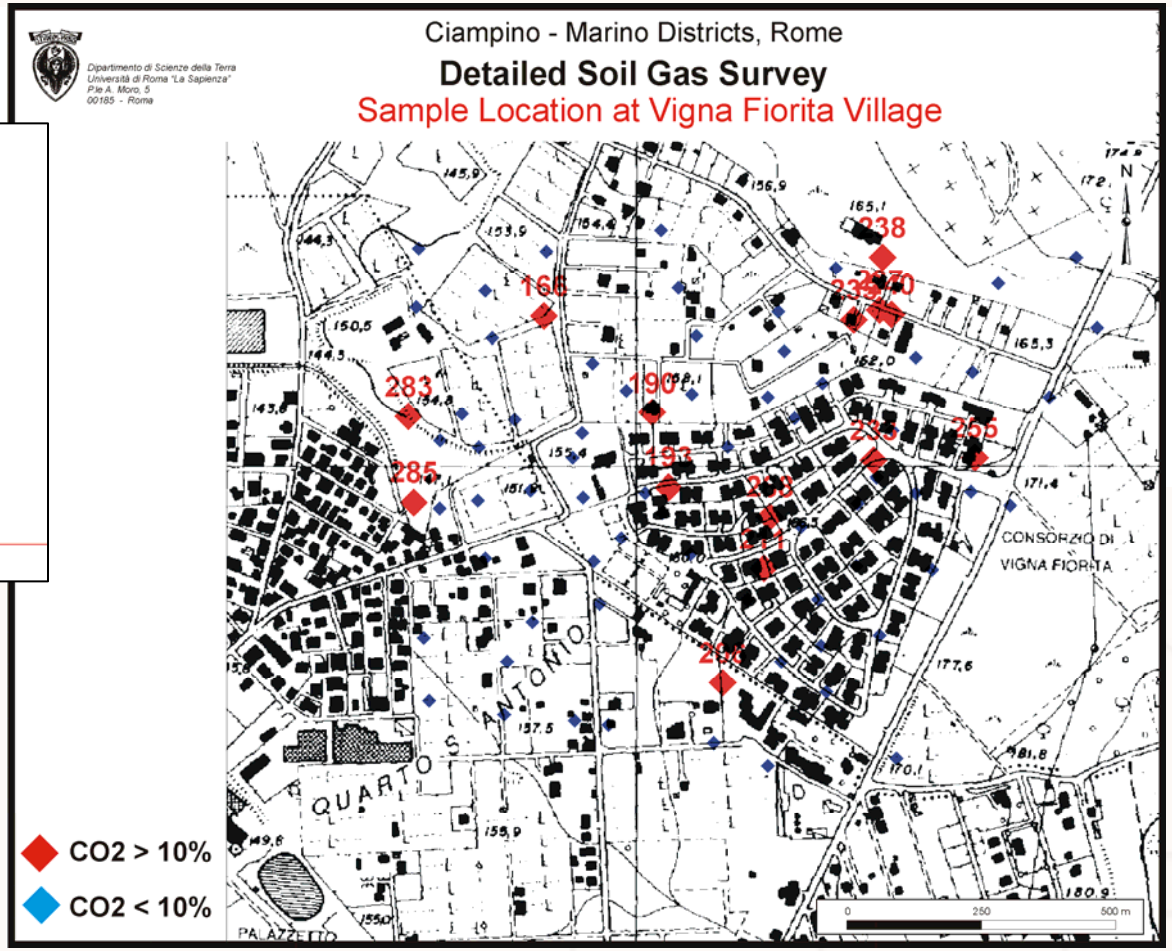
Ciampino



Presentations to, and interviews with, residents about living with CO_2 leakage and evaluation of their perceptions of CCS



Epidemiological studies- is there an epidemiological signature associated with long term exposure to raised CO_2 levels?

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Aquatic settings

Aquatic organisms are much more sensitive to CO_2 than terrestrial ones!

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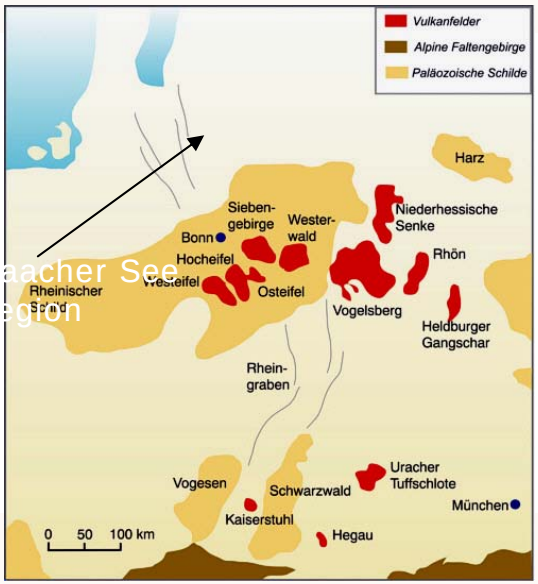
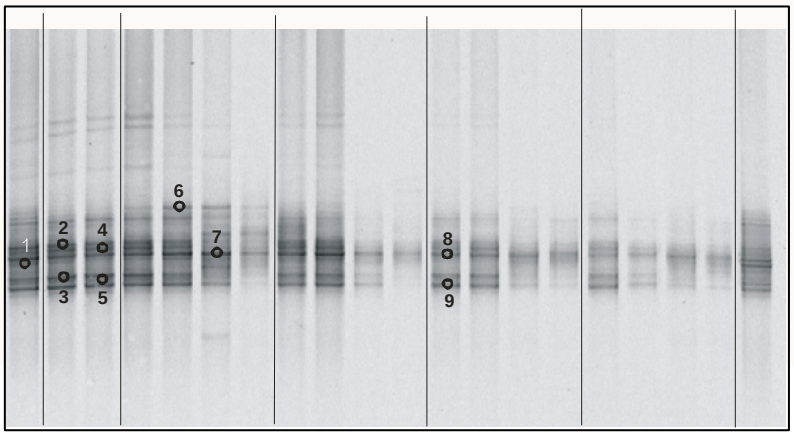


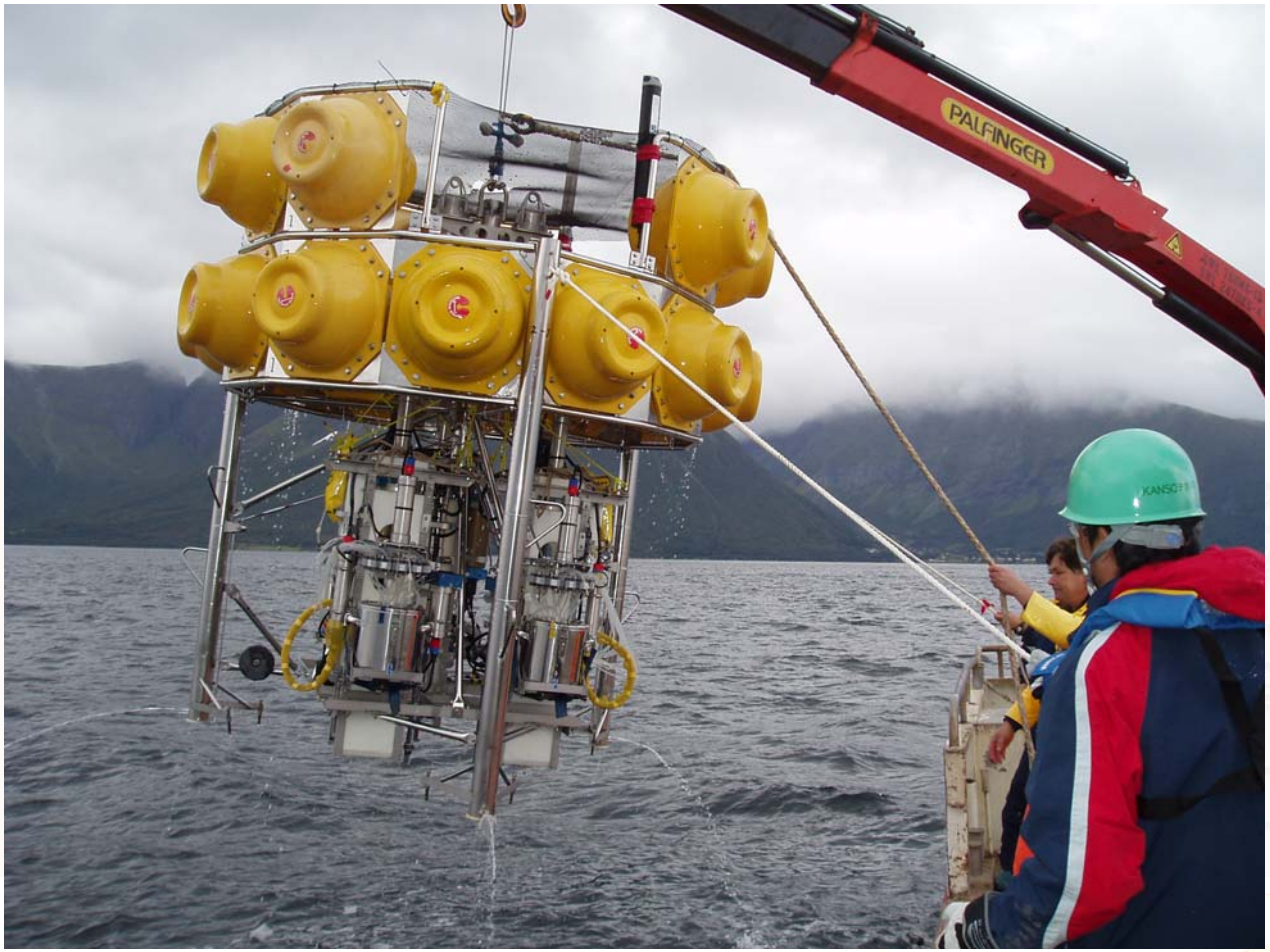
CO_2 gas bubbles, mainly in the eastern lake sector



Fingerprinting of the diversity of microorganisms in environmental samples analysed via Gel electrophoresis (DGGE).

GeoNet
C All rights reserved

Marine ecosystem experiments



(courtesy of NIVA & RITE)

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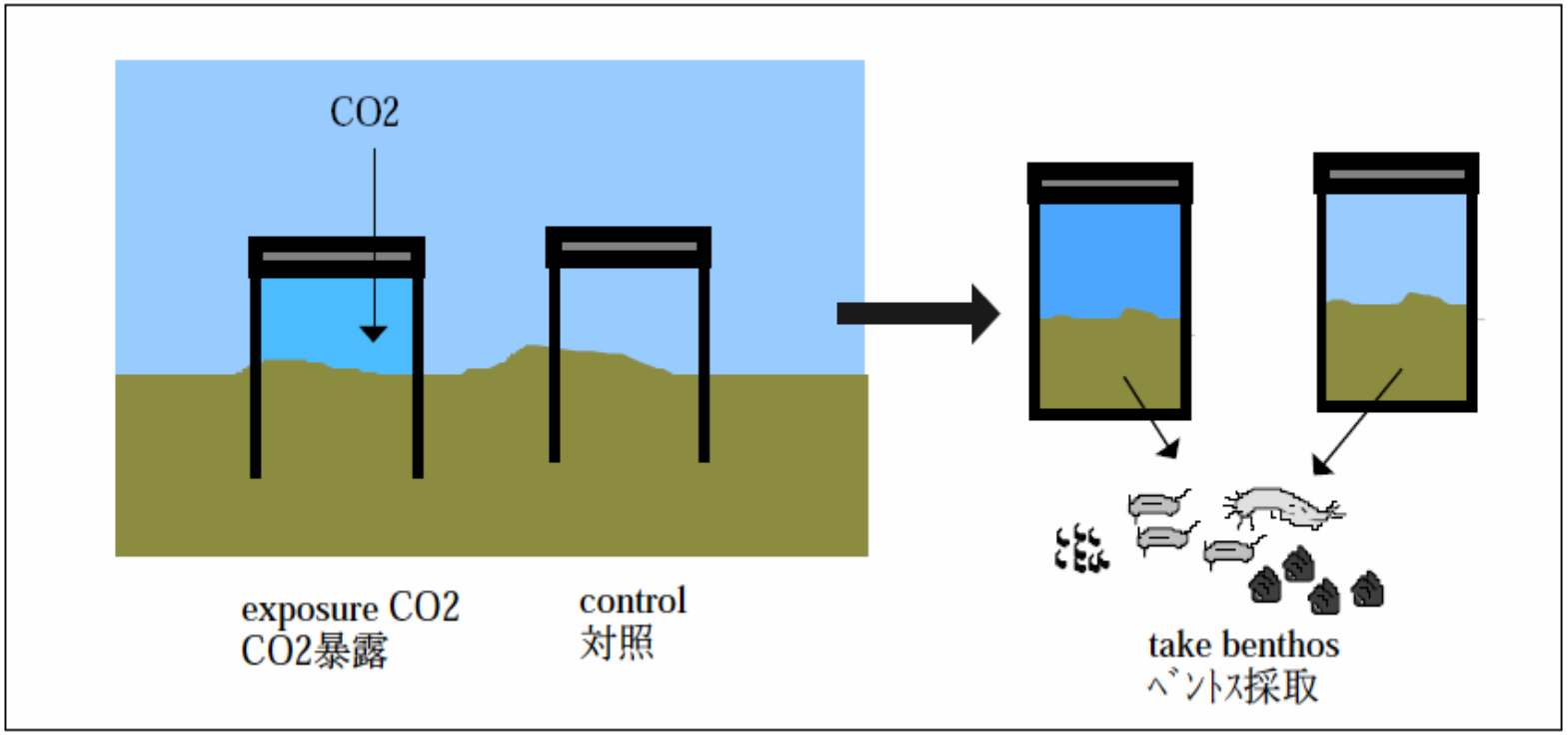
1. Offshore

In situ Benthic Chamber Experiment to assess the effects of CO_2 on deep-sea benthic fauna (NIVA and RITE, Japan with Network input for analyses)



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Aeolian Islands (South Tyrrenian sea – Sicily - Italy)

Video courtesy of Giorgio Caramanna, University of Rome

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Conclusions

- The leakage issue will not go away by ignoring it, or “playing it down”.
- Honesty, transparency, and openness is key to building trust
- Fact can become fiction and myth reality- clarity of communication is essential
- Evidence base is required to build stakeholder confidence
- Governments and regulators need the evidence base so they can develop an appropriate and wise policy/regulatory framework for CCS
- Operators need to be able to protect themselves and stakeholders from risk

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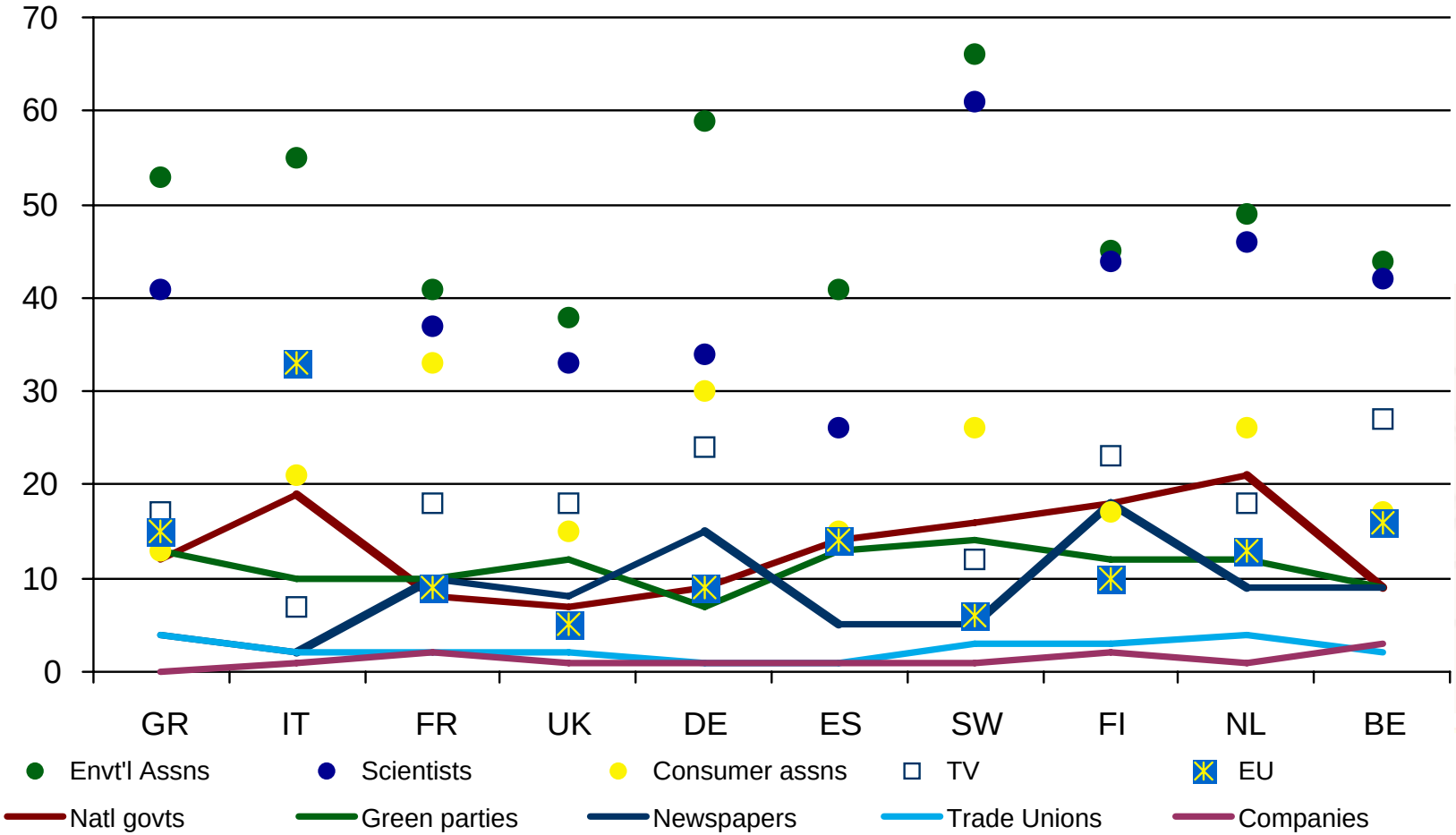
Who does the public trust regarding information on environmental issues?



(after Reiner et al 2006)

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Walkaway VSPs for CO_2 Monitoring at the Penn West Pilot, Alberta, Canada

Marcia Couëslan & Don Lawton, University of Calgary
Mike Jones, Schlumberger Canada

Outline

- Introduction
- Field Background
- VSP Data & Processing Highlights
- Time-lapse Surveys
  - The Challenges
  - The Results
  - The Supporting Evidence
- Conclusions
- Acknowledgements

Introduction

The Penn West Project is

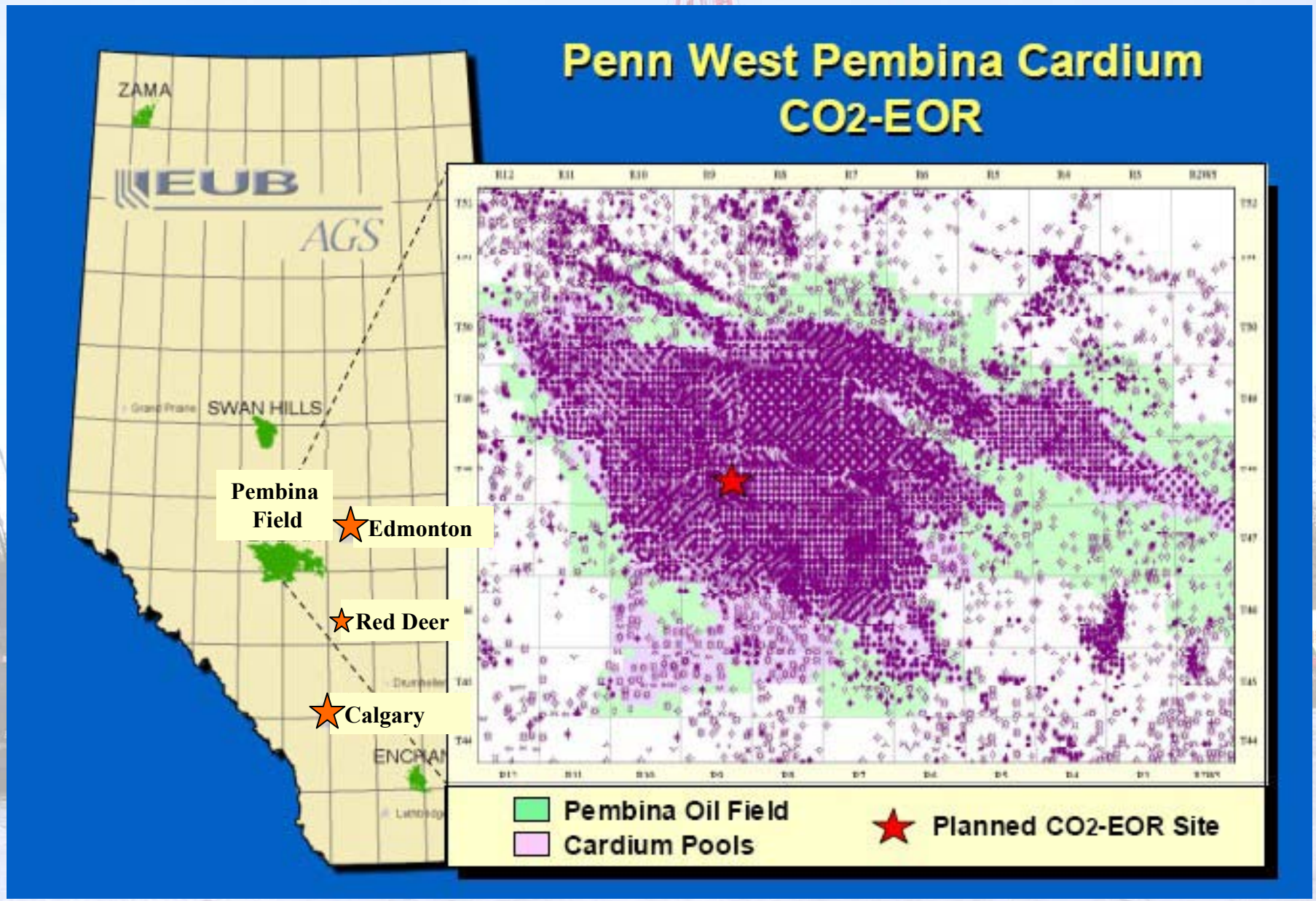
- A pilot project that injects CO_2 into the reservoir for EOR and sequestration purposes.

- Uses an innovative surface and borehole seismic program that has been designed to monitor injected CO_2.

Project Background

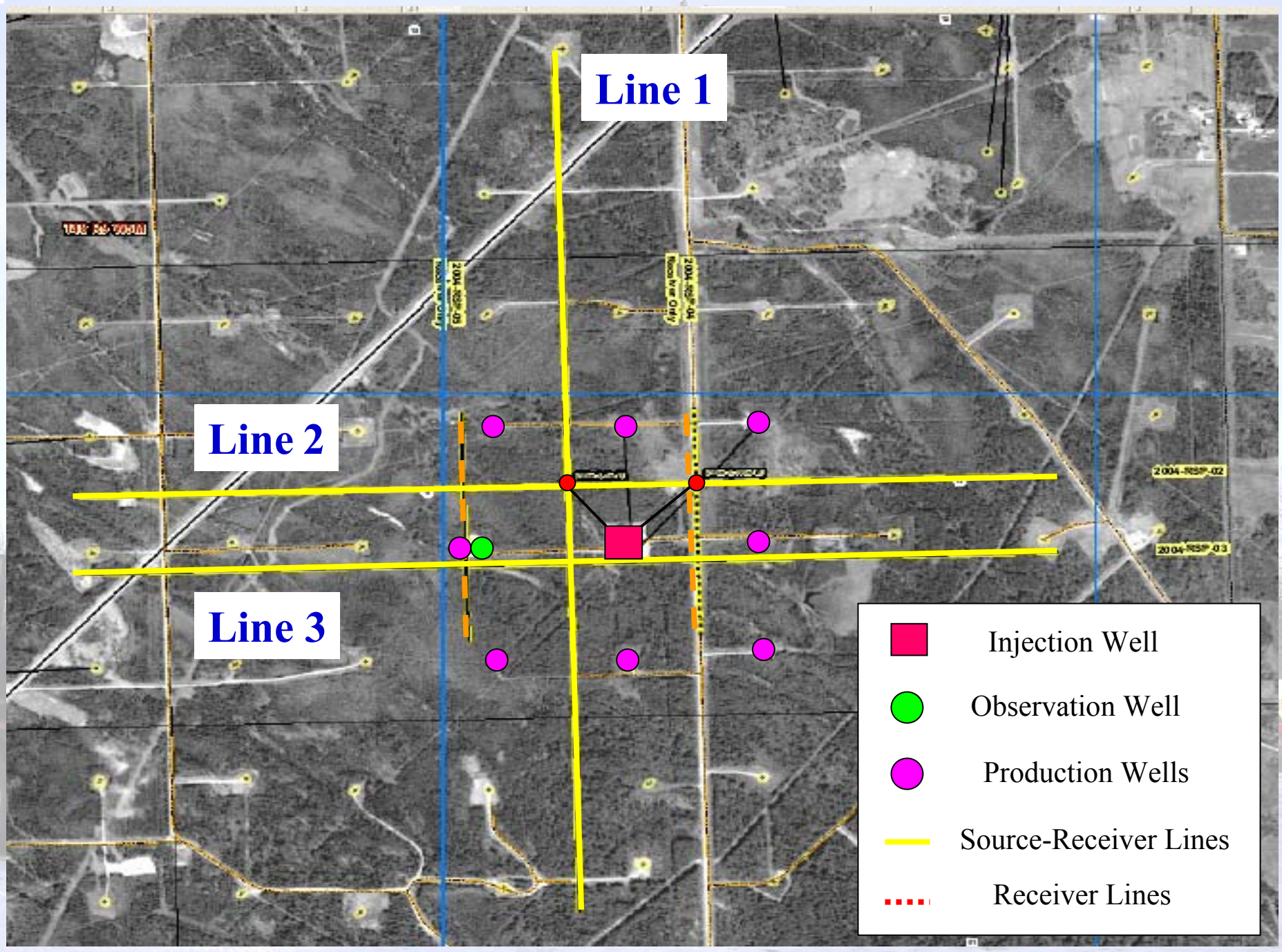
- Site selection was based on
  - Wanted a sandstone reservoir that would contrast with the carbonate reservoir at the Weyburn CO_2 Injection Project
  - Relatively easy site access
  - Potential to upscale the project for full commercial production

Project Background



Project Background

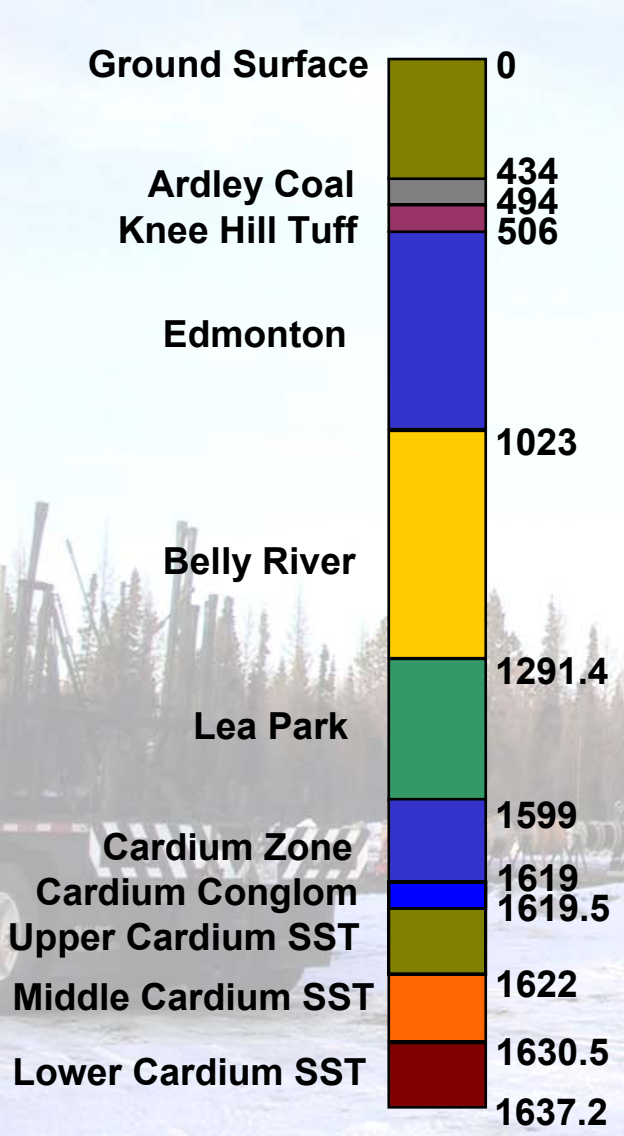
- CO_2 injection for EOR and sequestration
- CO_2 is deliver by tanker truck from a gas plant 50 km away
- Supercritical CO_2 is injected
  - At a rate of ~ 70 tonnes/day at ~ 20 MPa
- The average Canadian produces ~5 tonnes of CO_2 per year

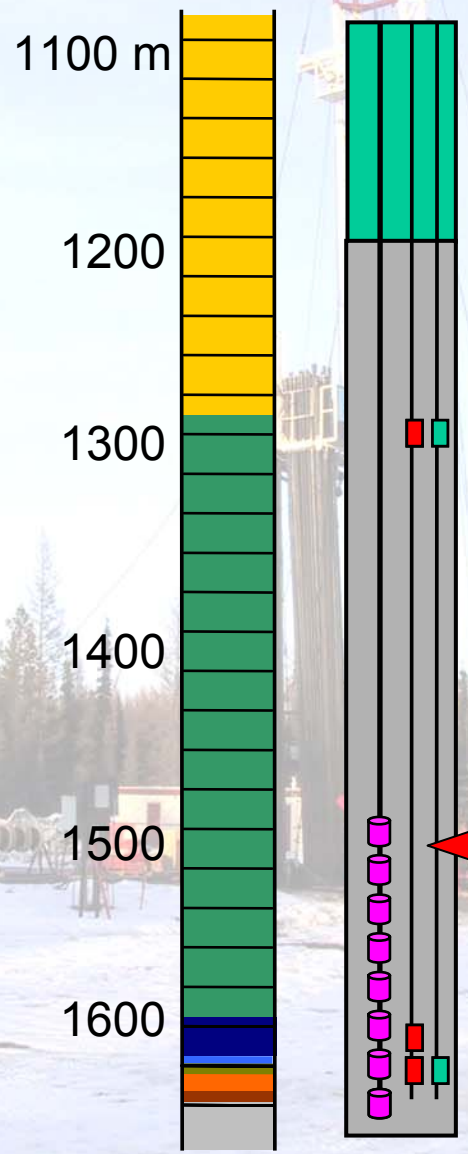

Line 1
Line 2
Line 3
Injection Well
Observation Well
Production Wells
Source-Receiver Lines
Receiver Lines

Project Background

- Monitor well equipment was installed in February 2005
  - 8 geophone arrays
  - 6 pressure/temperature sensors
  - 2 fluid sampling ports
- Baseline seismic survey was acquired in March 2005
- CO_2 injection commenced the next week

Project Background





Cement Top at 1200 m

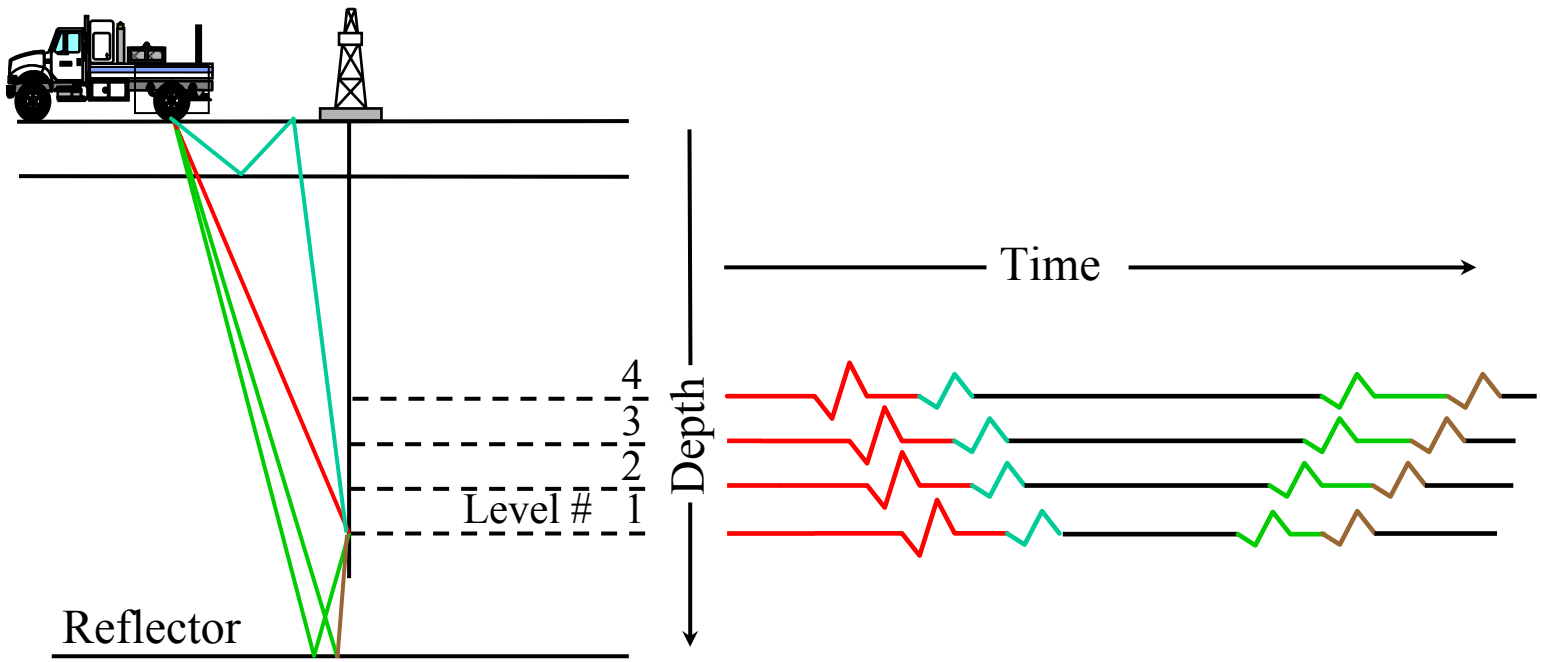
8 geophone array, from
1500 to 1640 m
at a 20 m spacing

Courtesy of Rick Chalaturnyk
University of Alberta

Advantages of Fixed VSP Array

- Higher frequency bandwidth than surface seismic data
  - Results in higher vertical and horizontal resolution near the monitor well
- Provides a correlation between the time indexed surface seismic and the depth indexed well logs
- Information gained from the VSP can be used to improve surface seismic processing
  - Velocities, Q Estimation, anisotropy analysis
- Allows for passive seismic monitoring

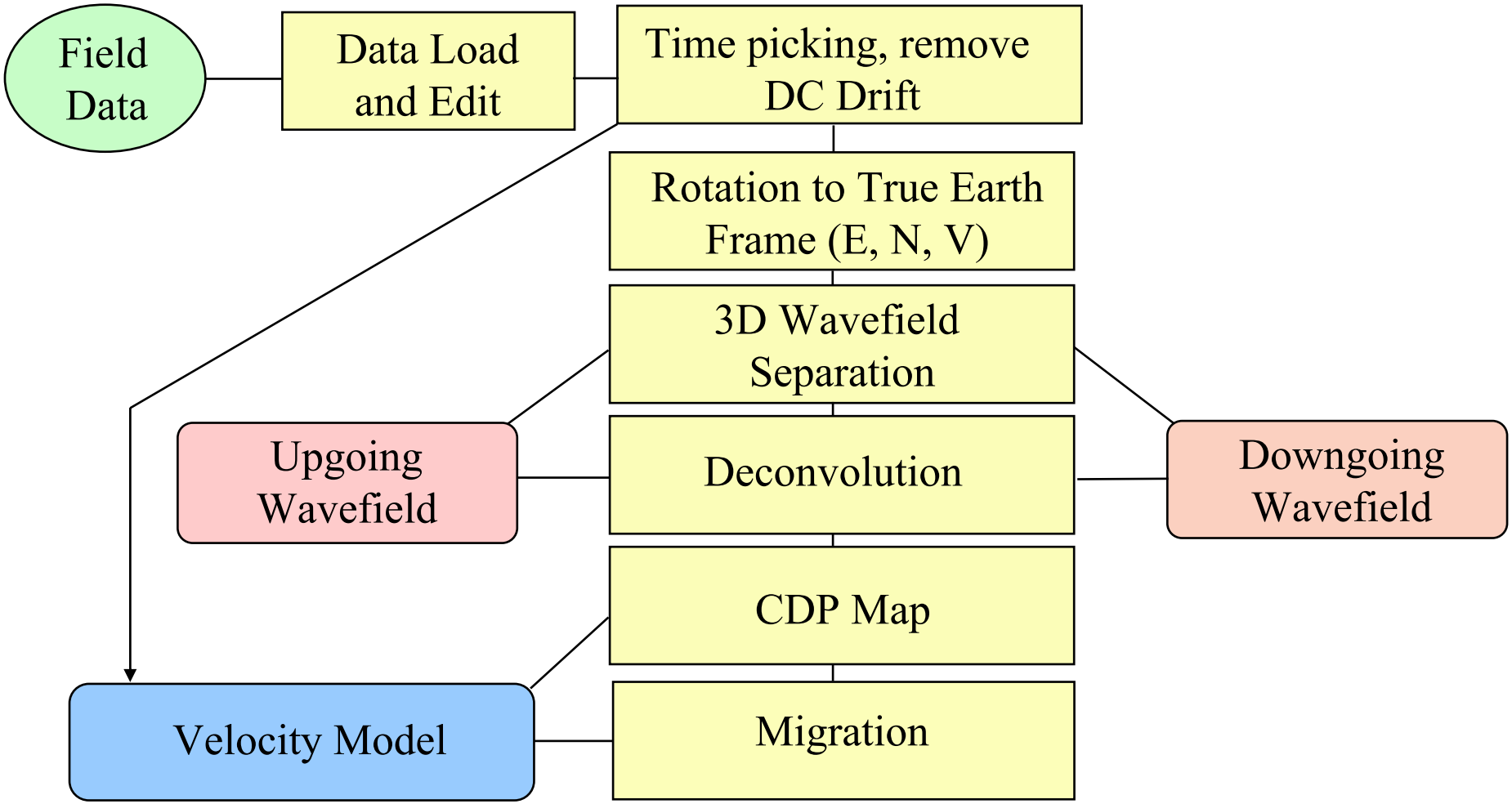
VSP Recording



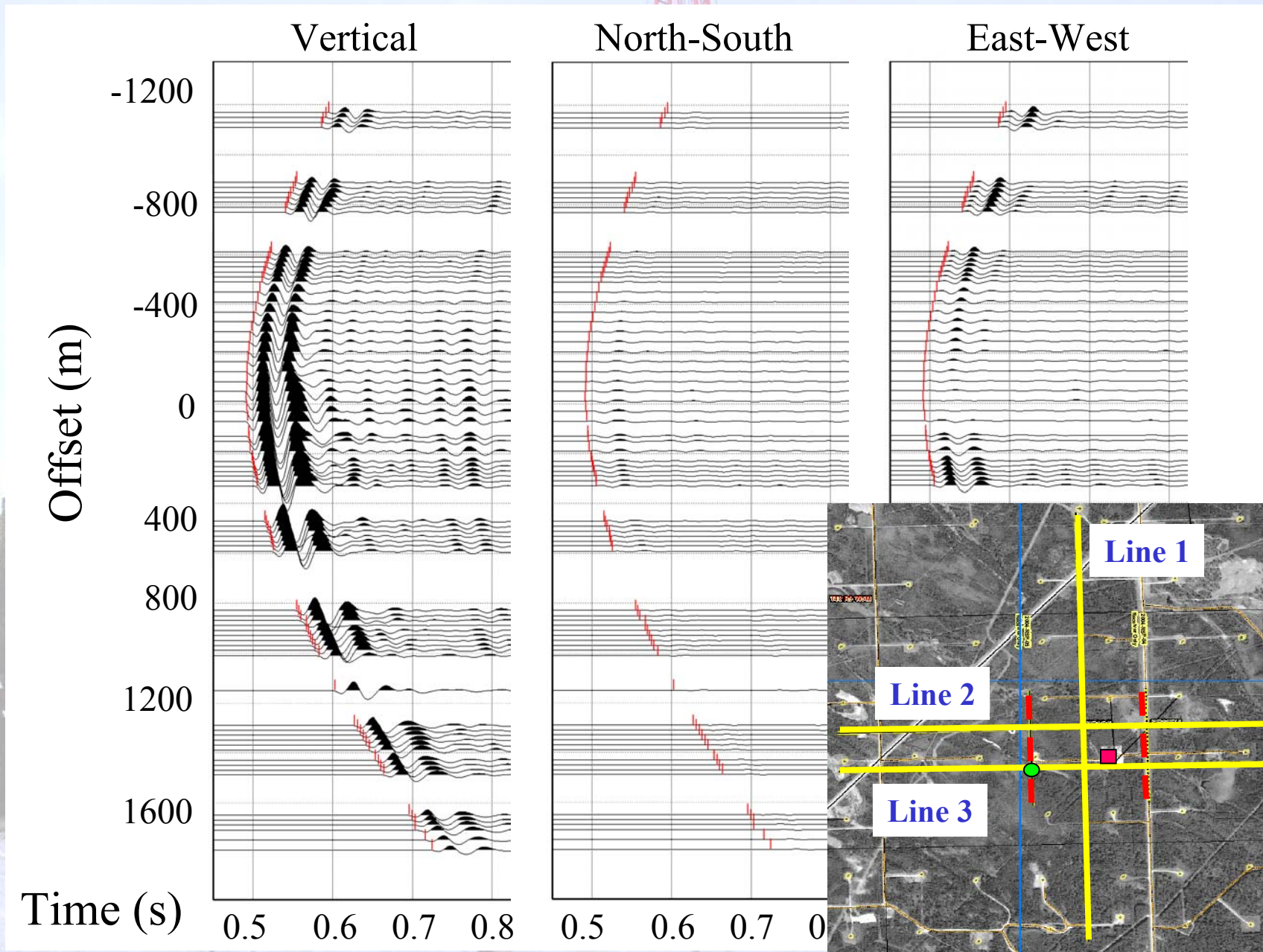
Downgoing direct arrival energy
Downgoing multiple
Reflected upgoing P
Converted upgoing S

Courtesy of Schlumberger

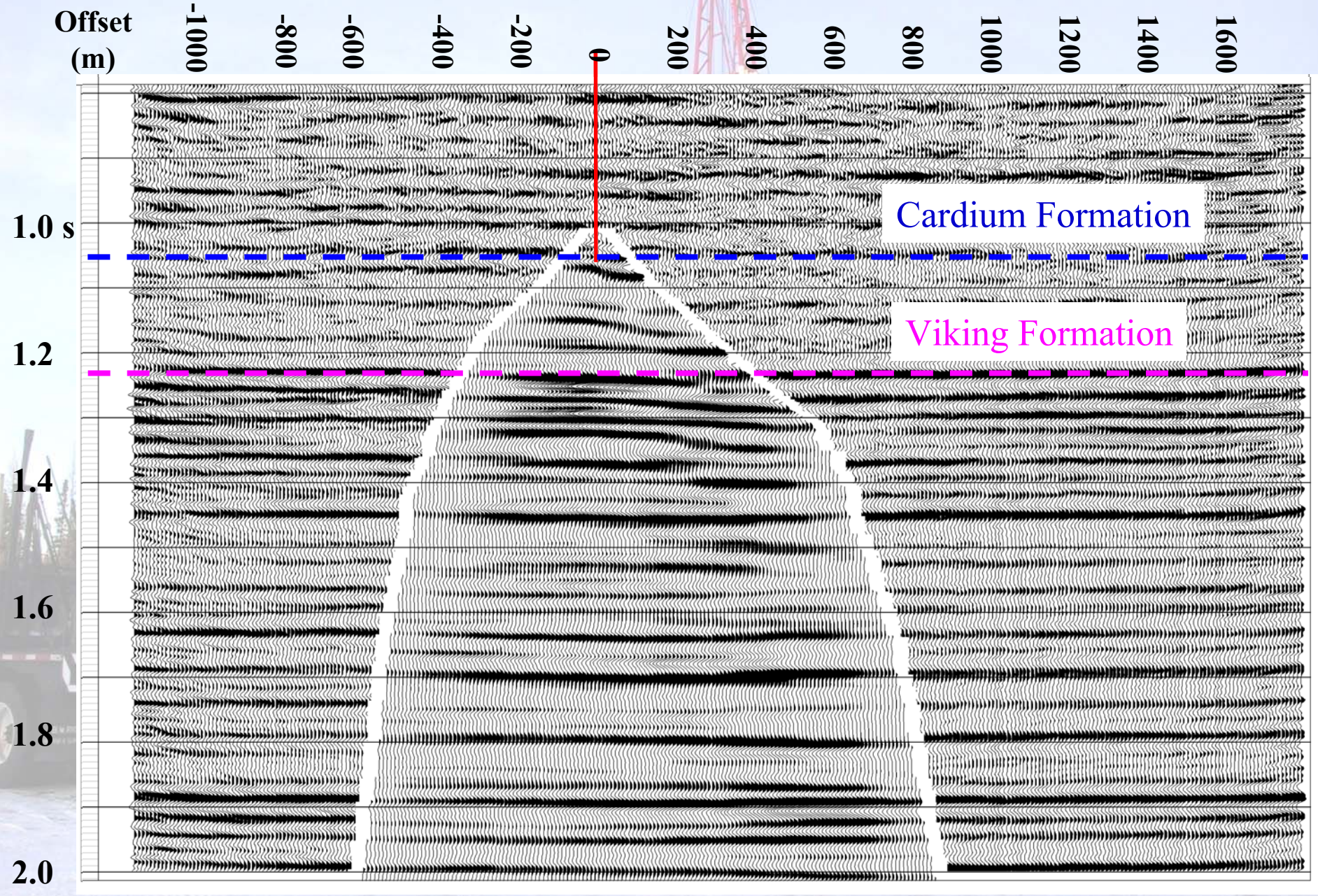
Processing Flow



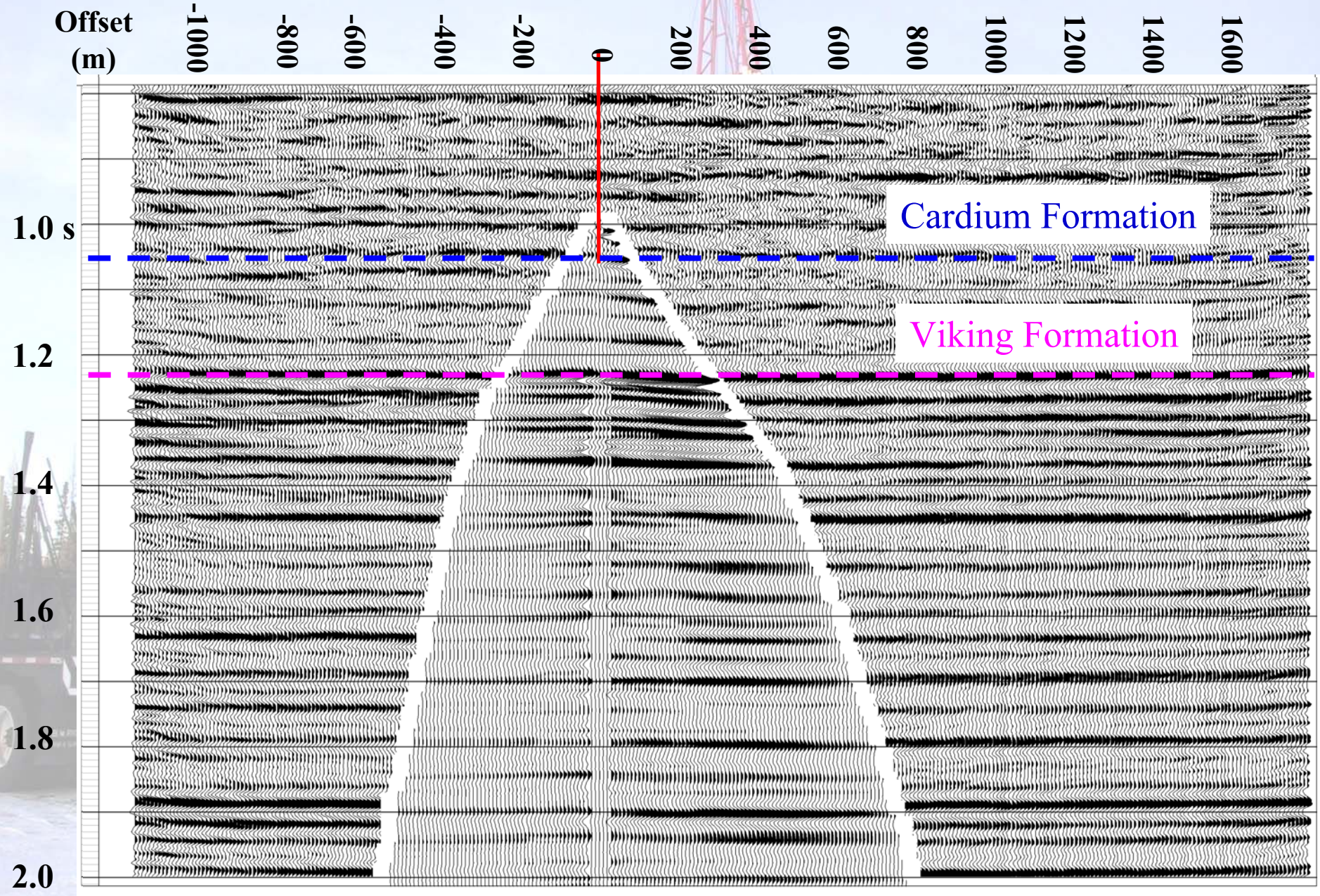
Line 3 Rotated Data Components



Line 3: PP Surface Seismic & VSP



Line 3: PP Surface Seismic & S-VSP



Time-lapse Surveys

- Time-lapse surveys are required
  - To monitor the CO_2 flood in the reservoir
  - To look for leakage pathways in the overburden
- First monitor survey was acquired in December 2005
- Expect to acquire a second monitor survey in early 2007

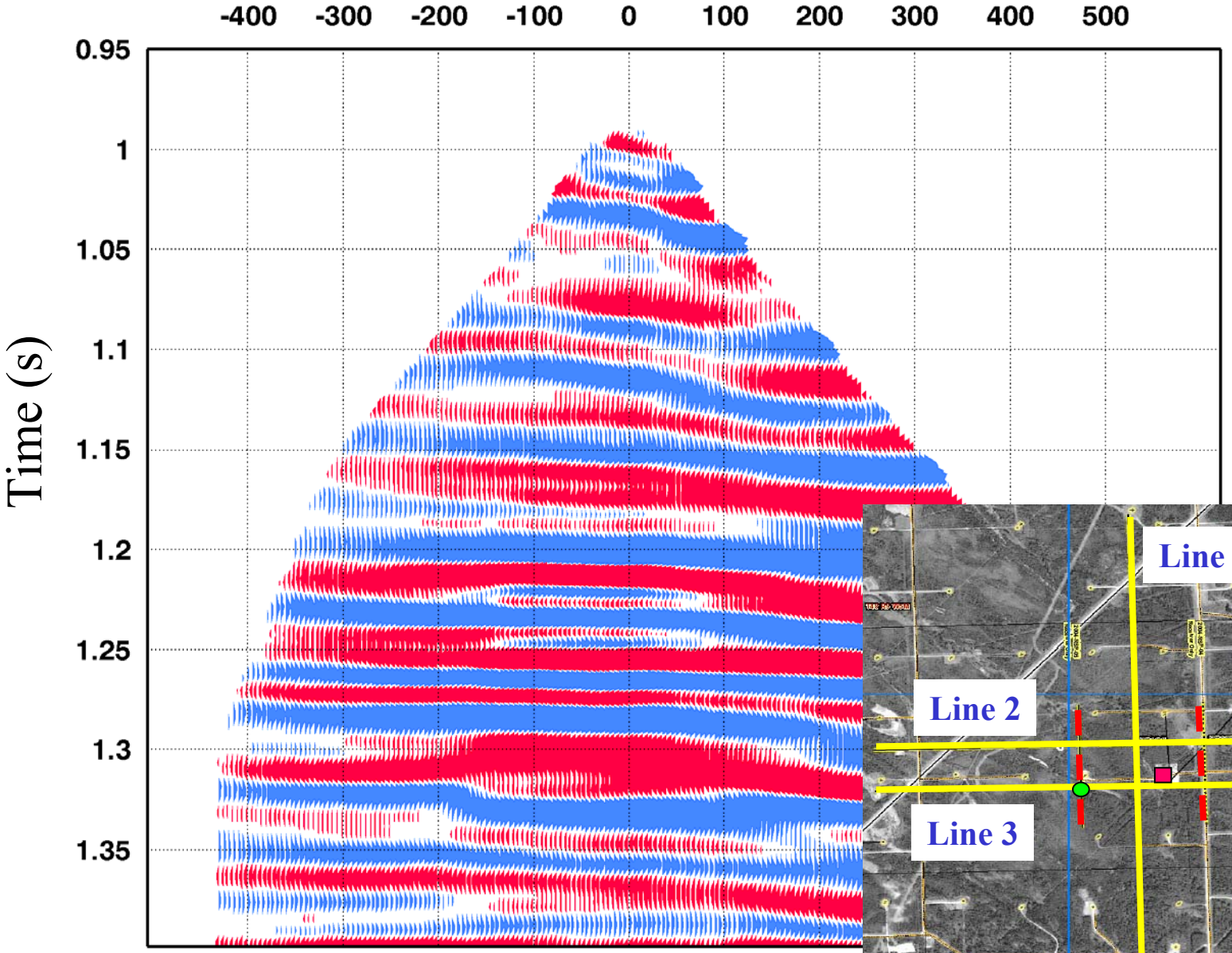
Time-lapse Surveys

- Properties expected to change:
  - P-wave velocity at the reservoir
  - Fluid composition as the CO_2 is injected
- Expected seismic response:
  - Increased travel times
  - Change in reservoir amplitudes
- Geophone array is fixed
  - Can be used to calibrate source variability and overburden travel times between the surveys

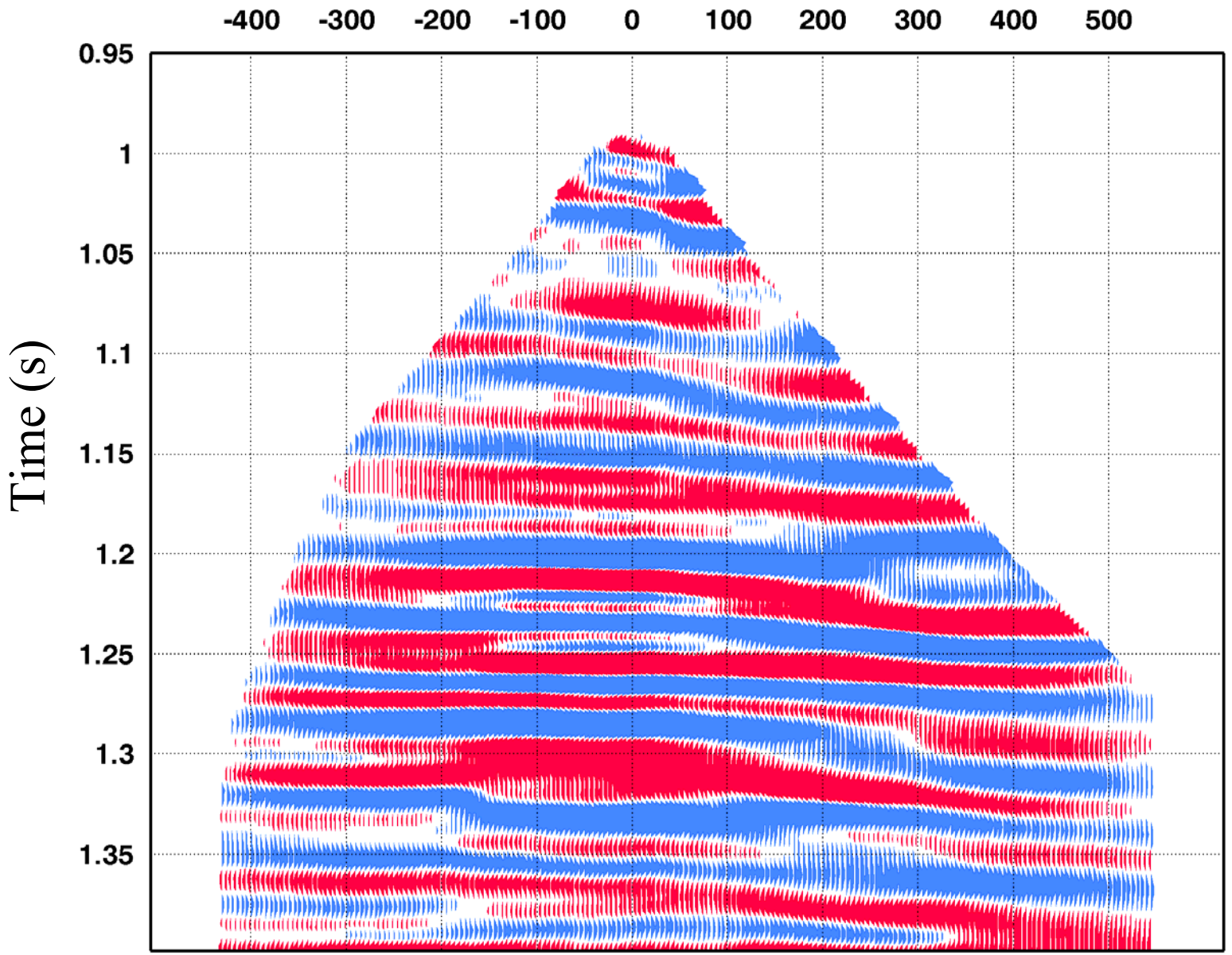
The Challenges

- Bulk time shifts between surveys
- Non-repeated shots
  - Non-repeated source-receiver geometry
  - Noisy shots from survey to survey
- Changes to the processing flow or algorithms

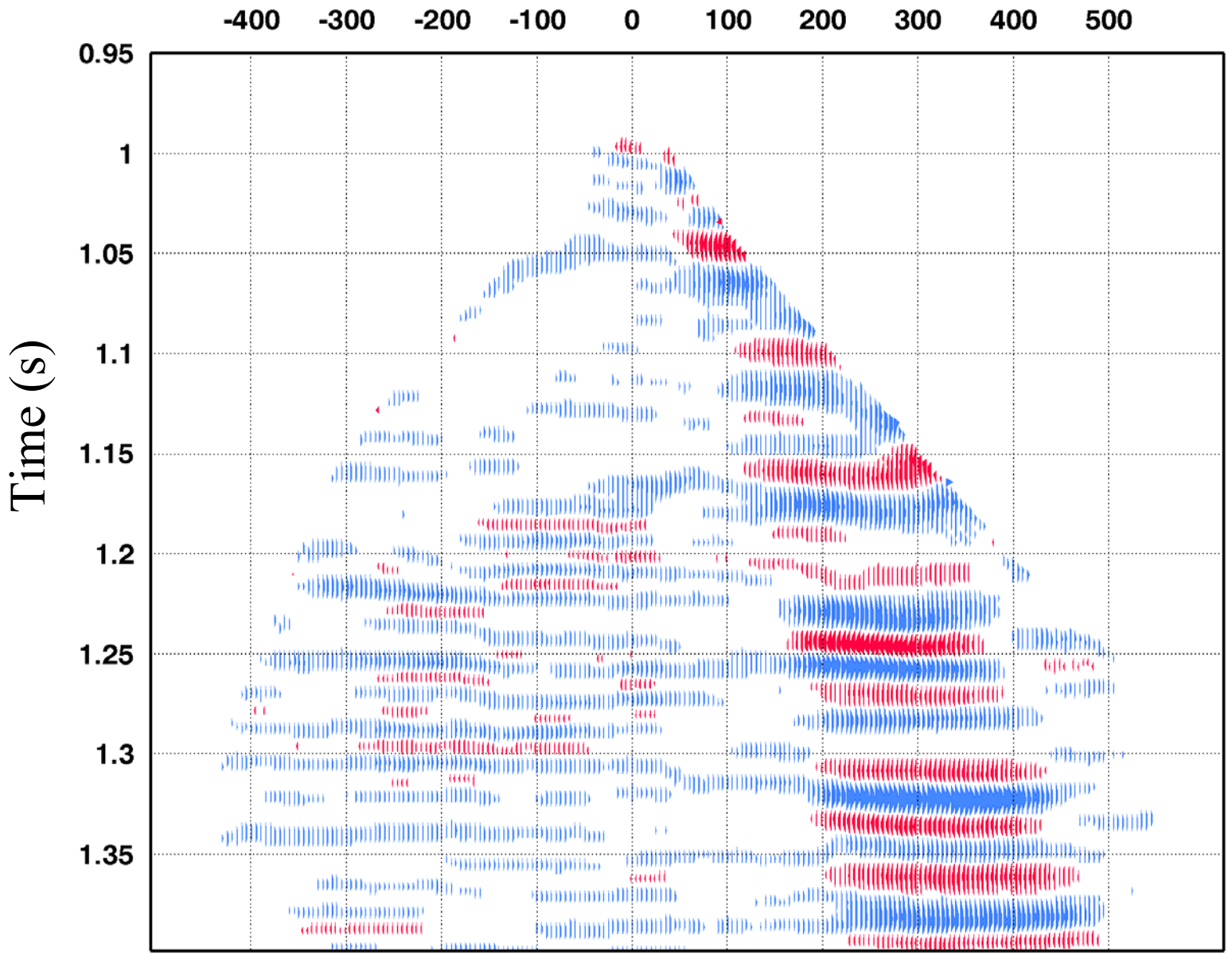
Line 2 All Shots: Baseline



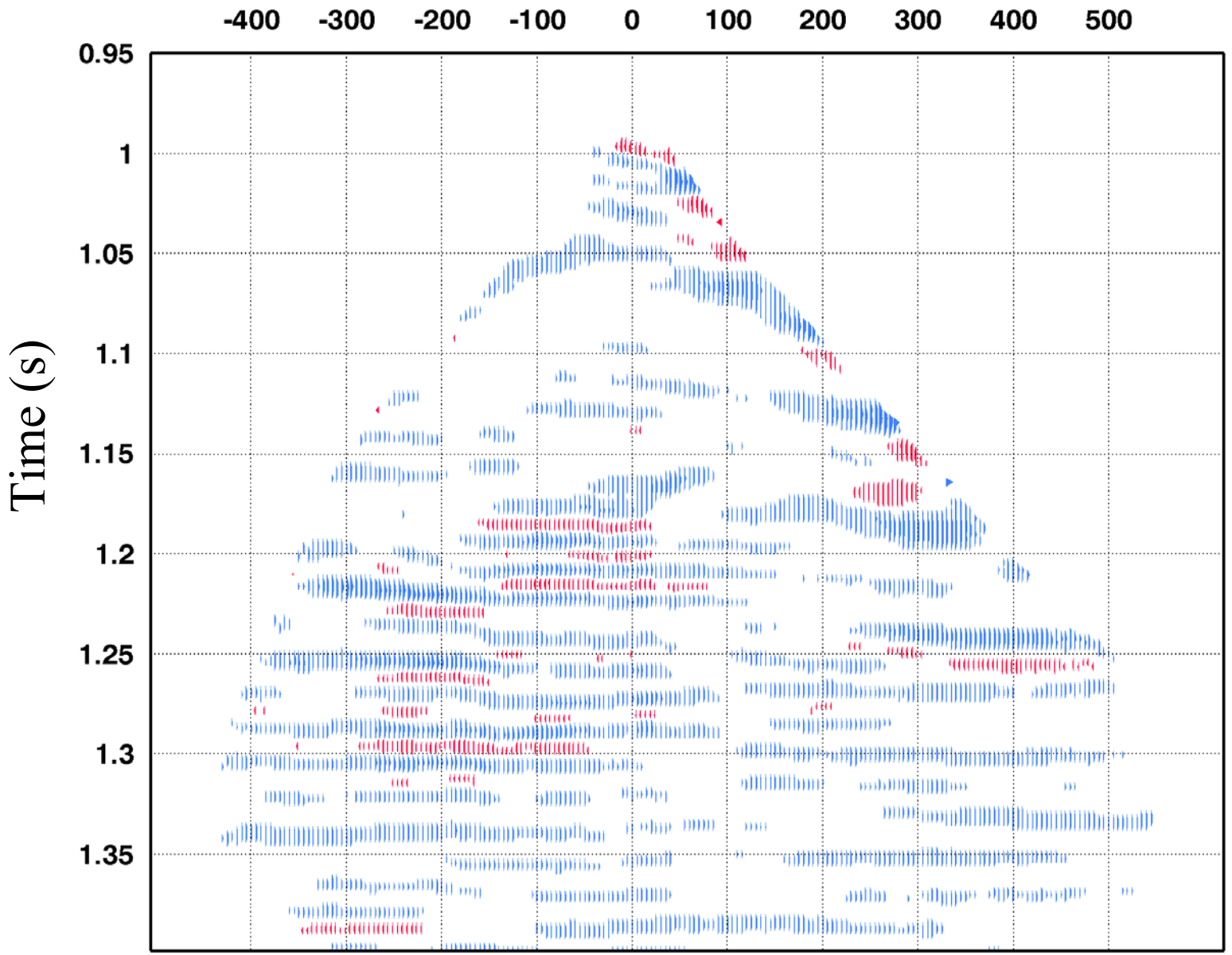
Line 2 All Shots: Monitor



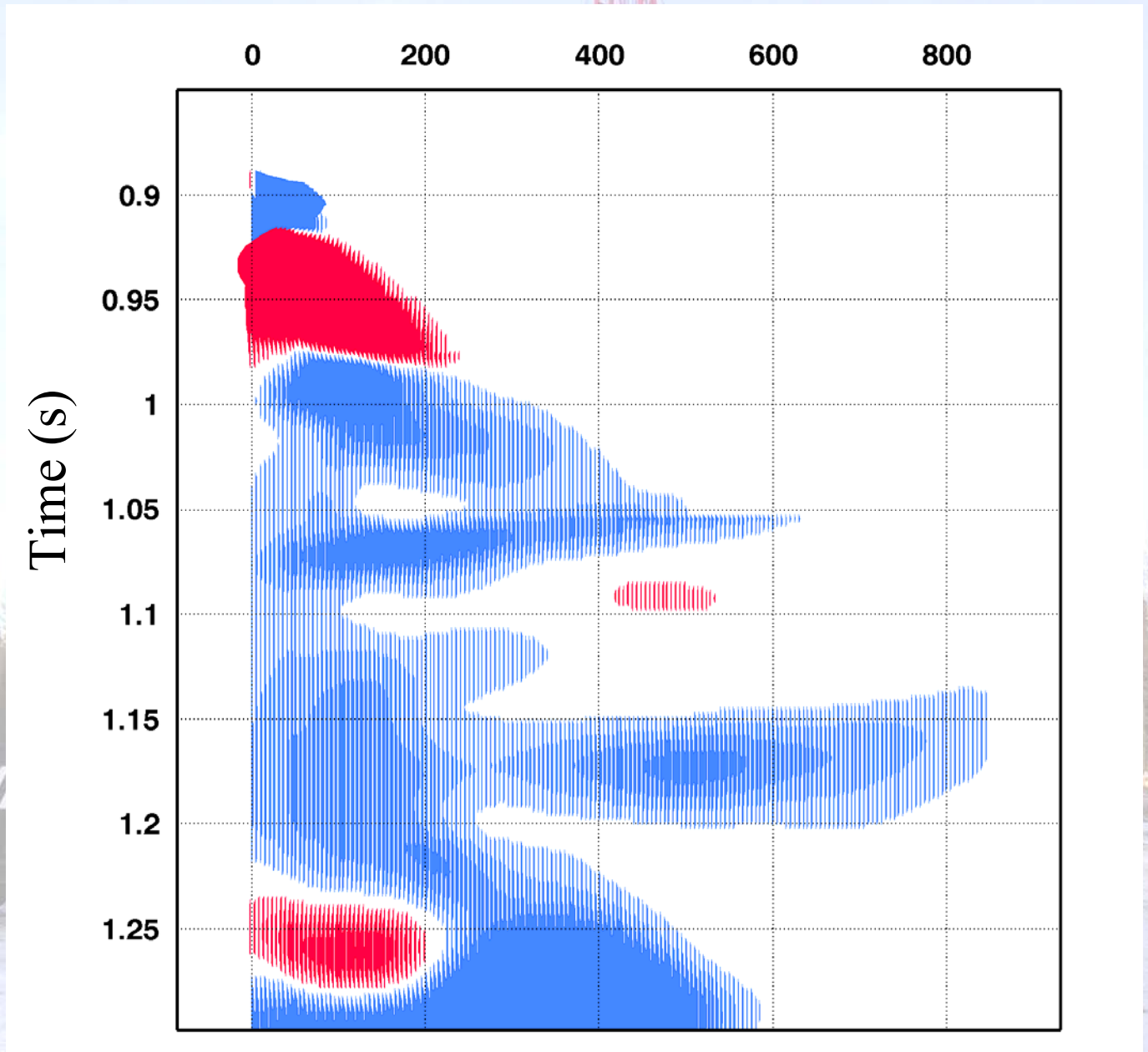
Line 2 All Shots: Difference



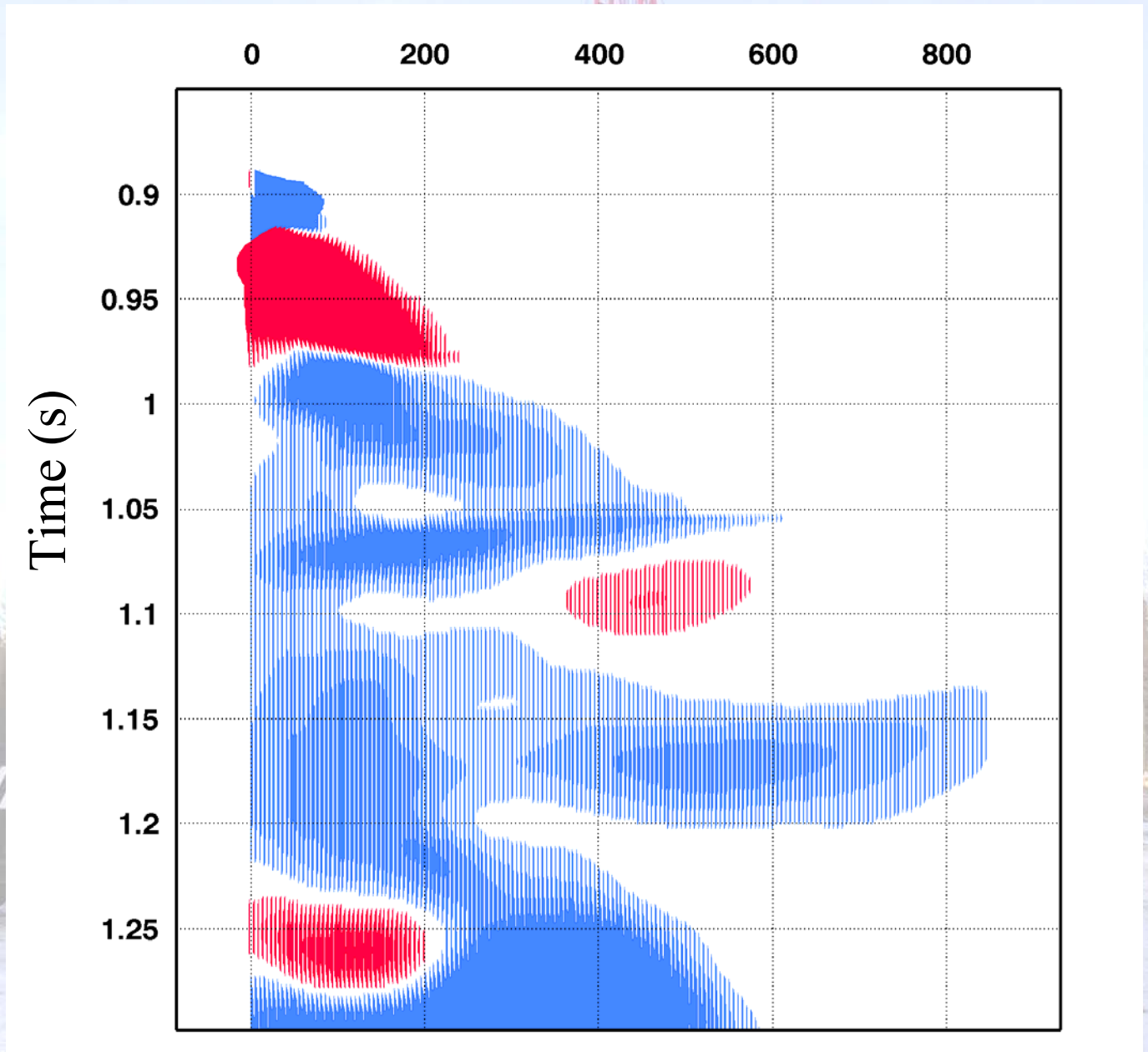
Line 2 Repeated Shots: Difference



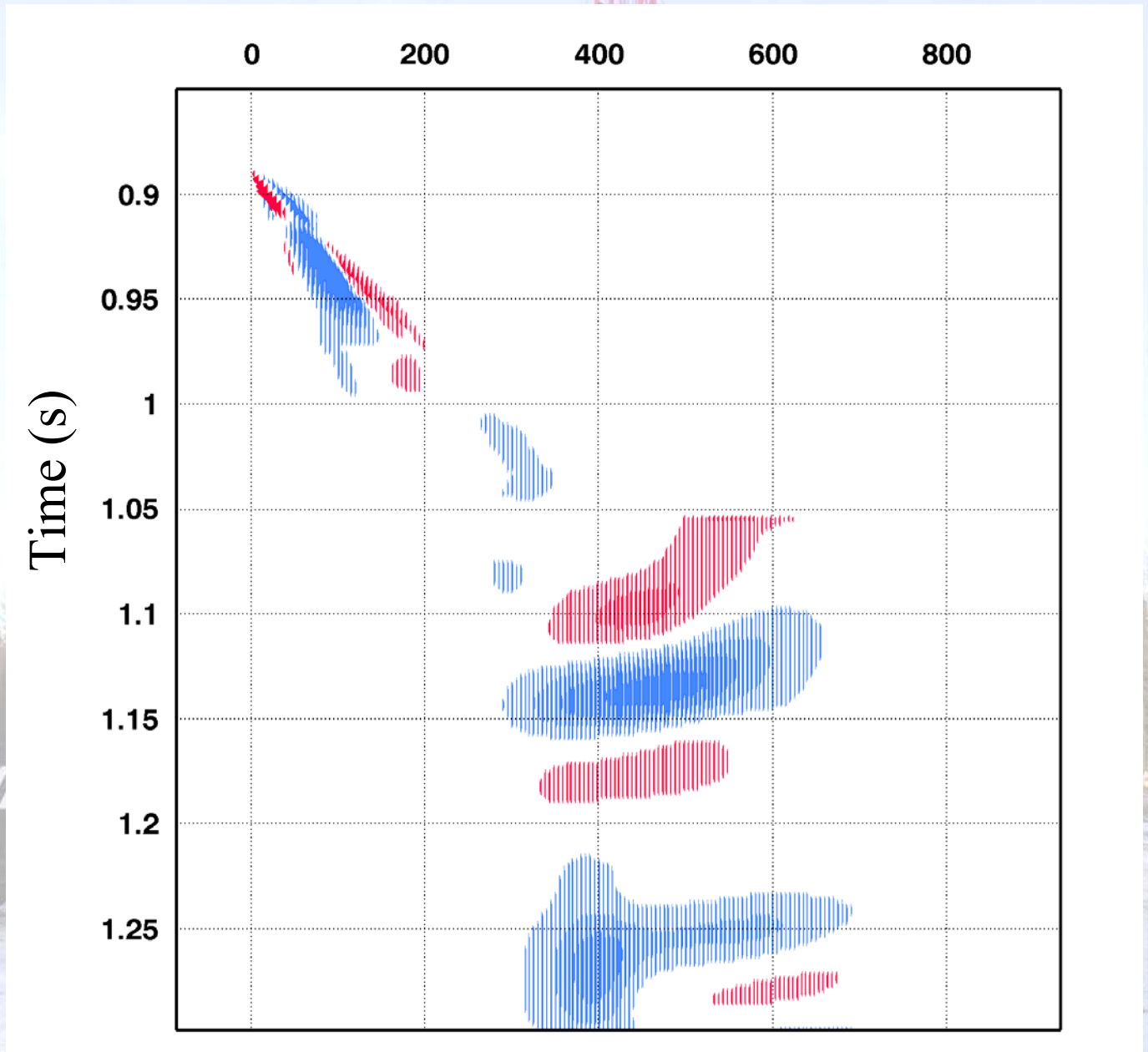
Finite Difference Modelling: Baseline



Finite Difference Modelling: Monitor



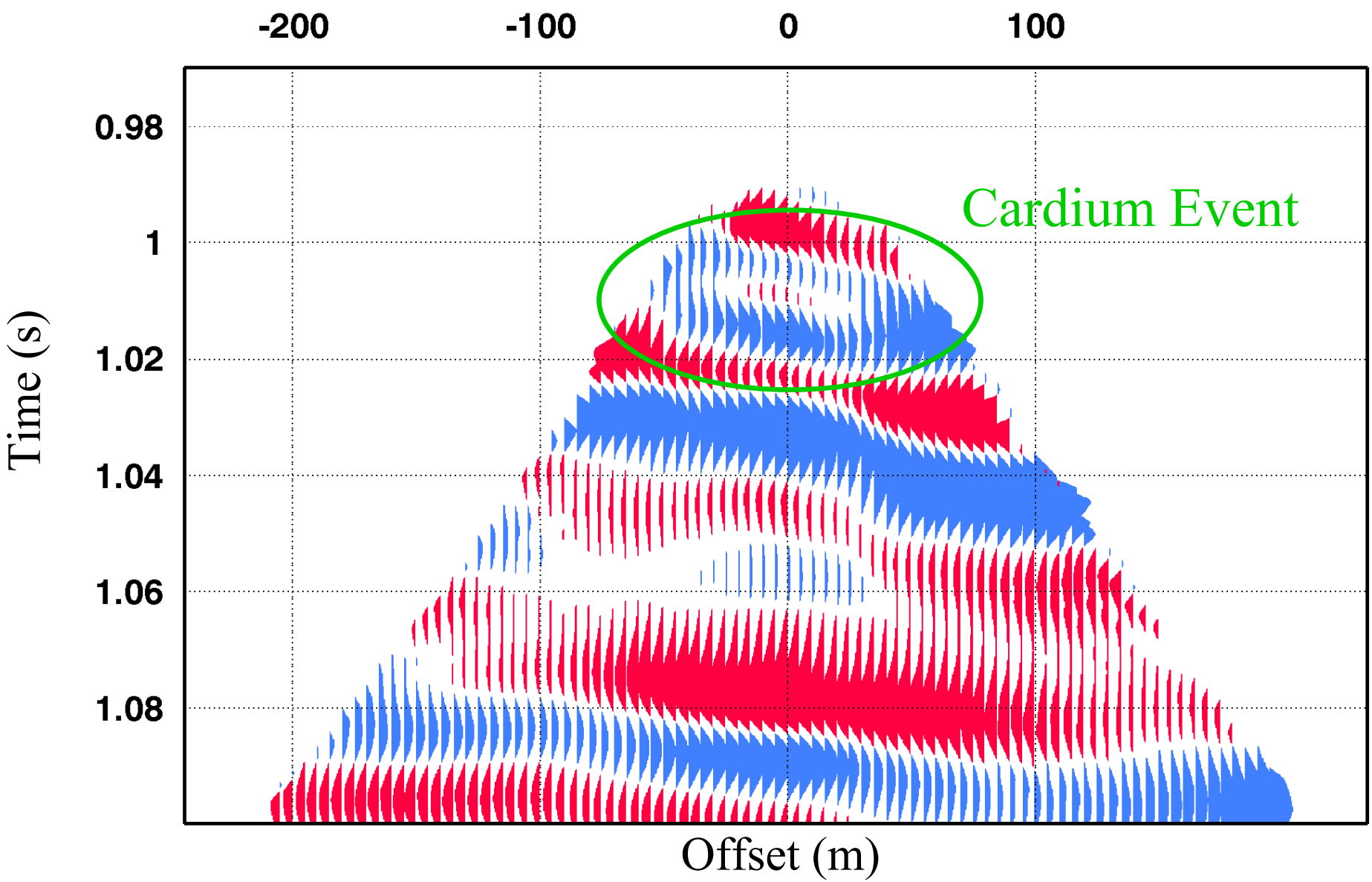
Finite Difference Modelling: Difference



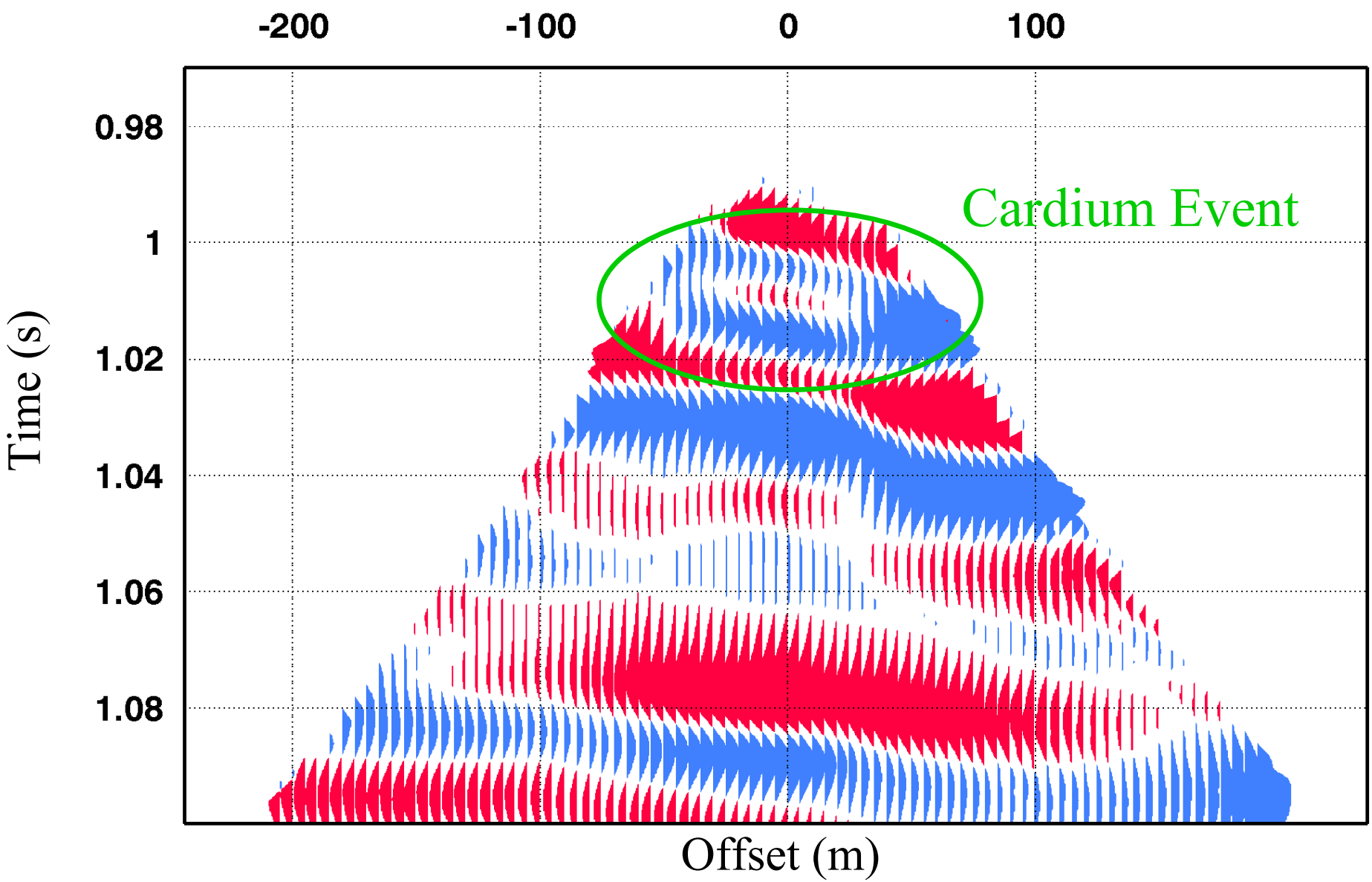
Why Is Repeatability Important?

- Repeatability is affected by source-receiver geometries, consistency of the source signature, and shot-generated noise
- Seismic noise is often caused by subsurface heterogeneities
- Repeating source-receiver geometries allows the noise to the replicated and differenced away

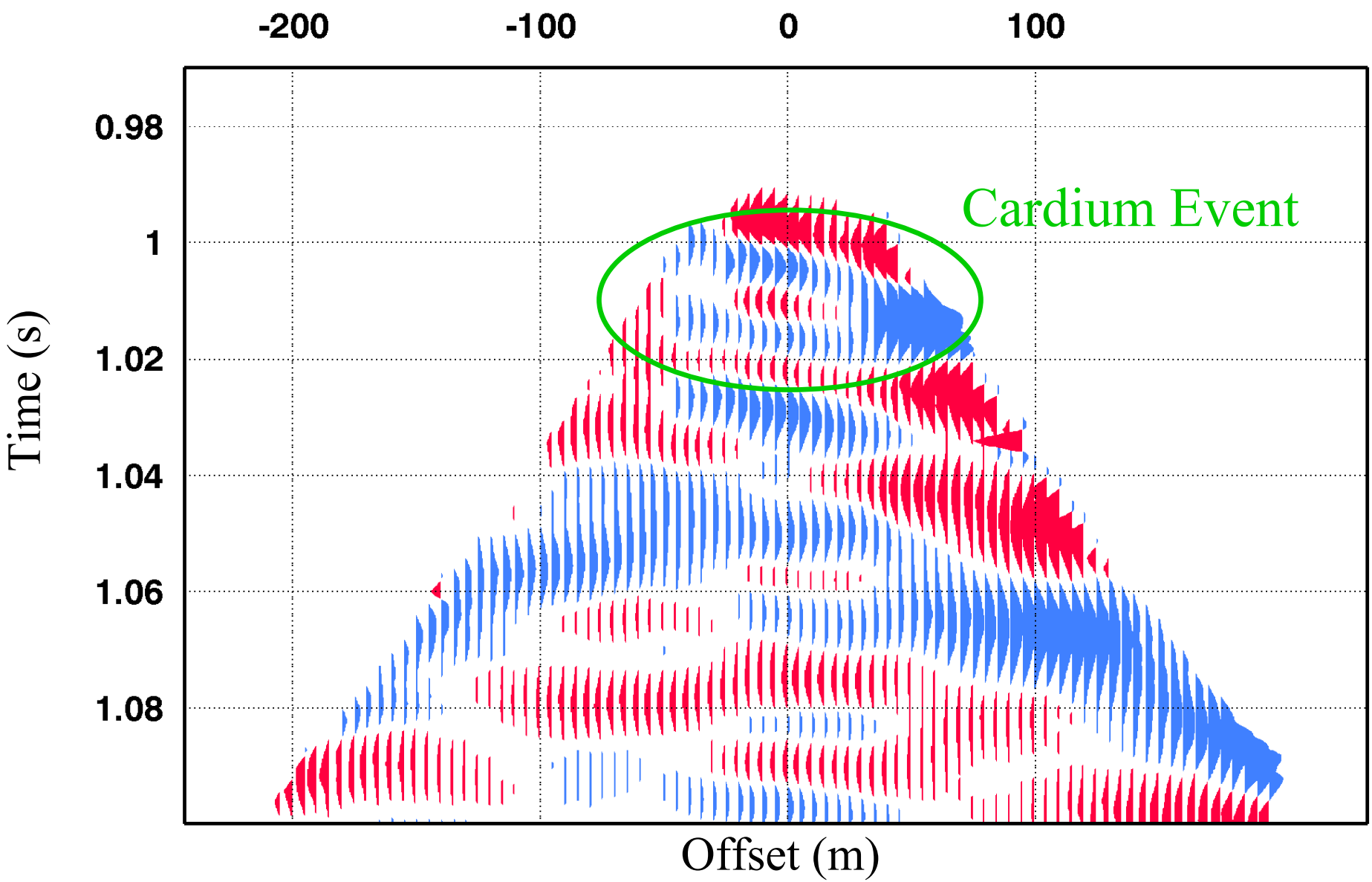
P-wave Results Line 2: Baseline



P-wave Results Line 2: Monitor



P-wave Results Line 2: Difference



The Supporting Evidence

- Amplitude increases correlate directly to the Cardium event
- Excellent data repeatability
  - Seismic traces, amplitude & phase spectra
- Small time shifts in the crosscorrelations
  - Travel times at base of the reservoir show a systematic increase of 0.2 ms

Conclusions

- Shot repeatability is extremely important
- P-wave amplitudes at the Cardium on Line 2 have increased since the baseline survey
- Comparison of the datasets, amplitude & phase spectra, and crosscorrelations indicate an excellent tie between surveys
- Use of walkaway or 3D VSPs will be critical for imaging thin reservoirs that are not resolvable with surface seismic data

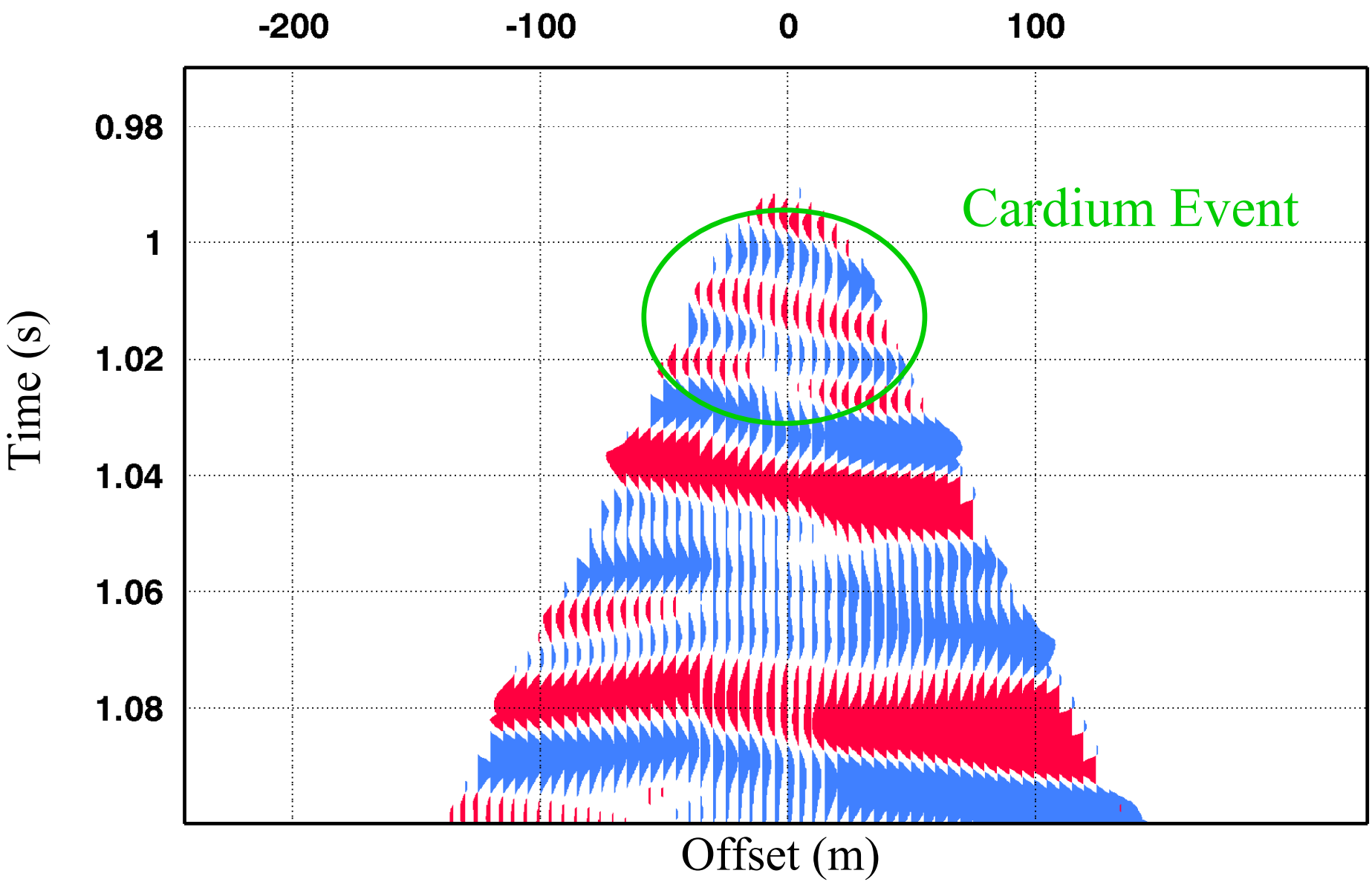
Discussion

- Instrument entire well with geophones
  - Will provide high resolution images of the reservoir and overburden around the well
- May want geophone arrays in several wells in the field
  - Merge the volumes for laterally extensive coverage
- Potentially instrument production or injection wells
- Increased integration between geophysical and geochemical monitoring

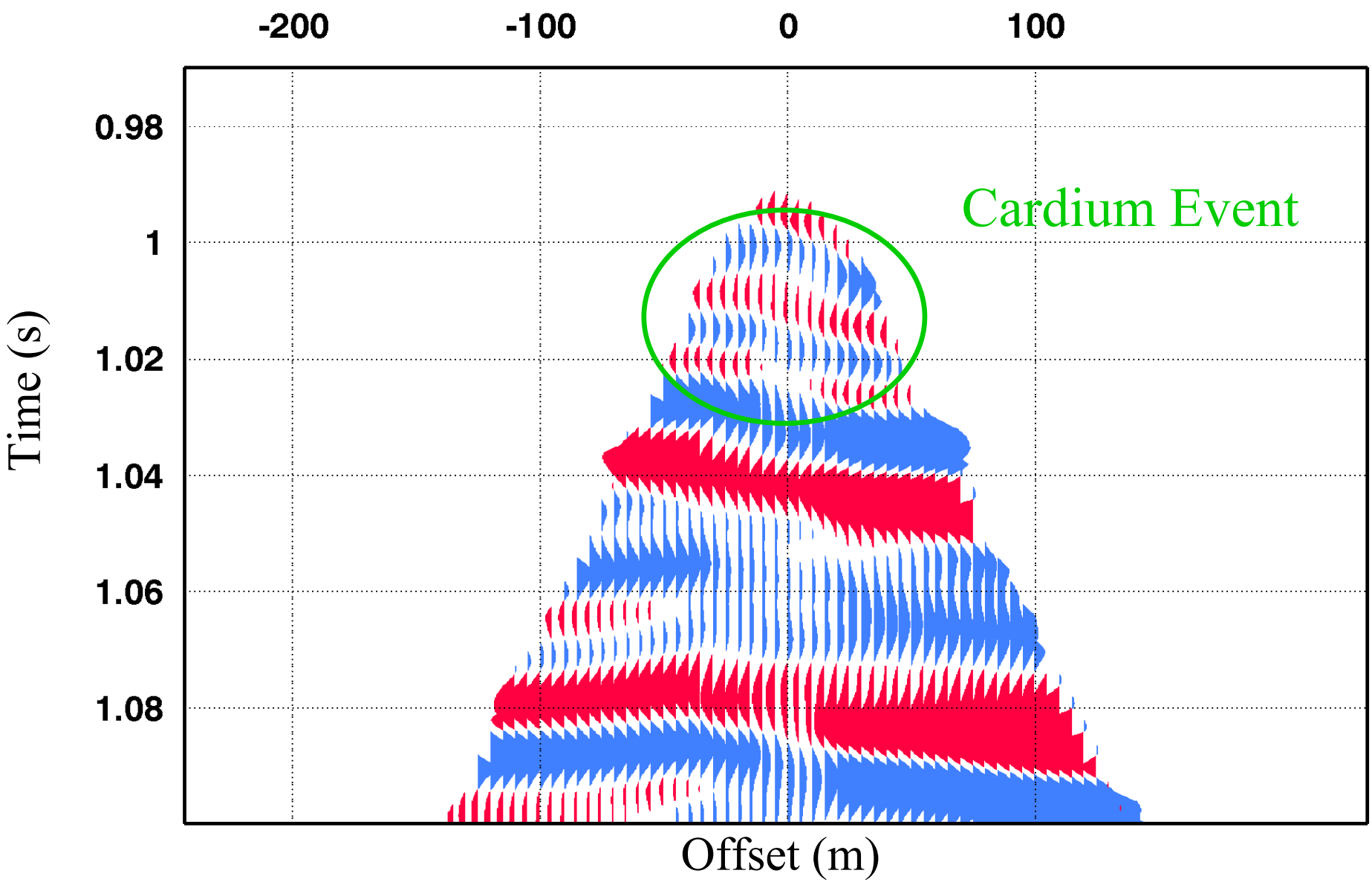
Acknowledgements

- Scott Leaney and Schlumberger Canada
- Alberta Energy Research Institute (AERI)
- Western Economic Diversification (WED)
- Natural Resources Canada (NRCan)
- CREWES sponsors for financial support
- Penn West Petroleum

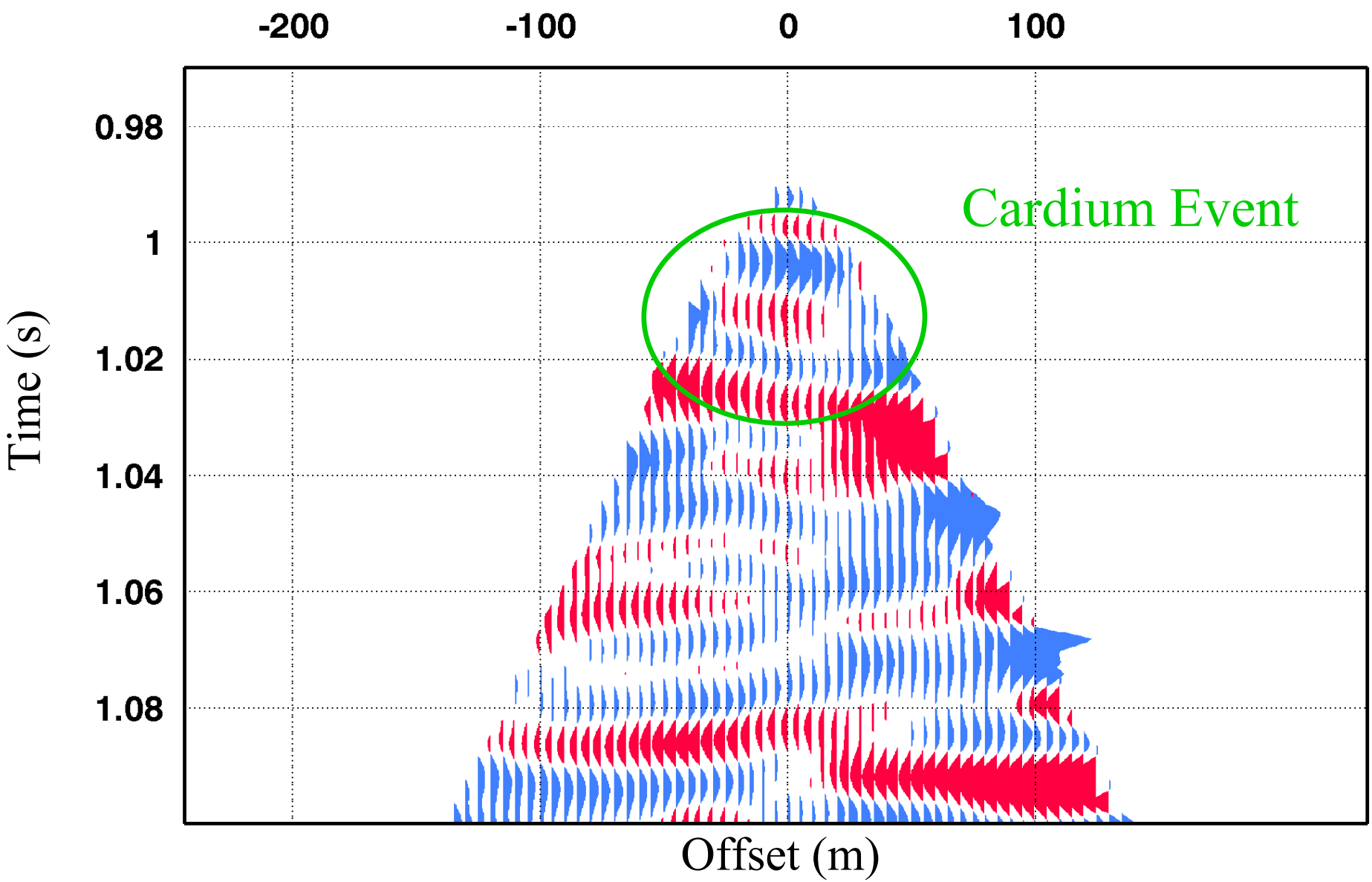
S-wave Results Line 2: Monitor



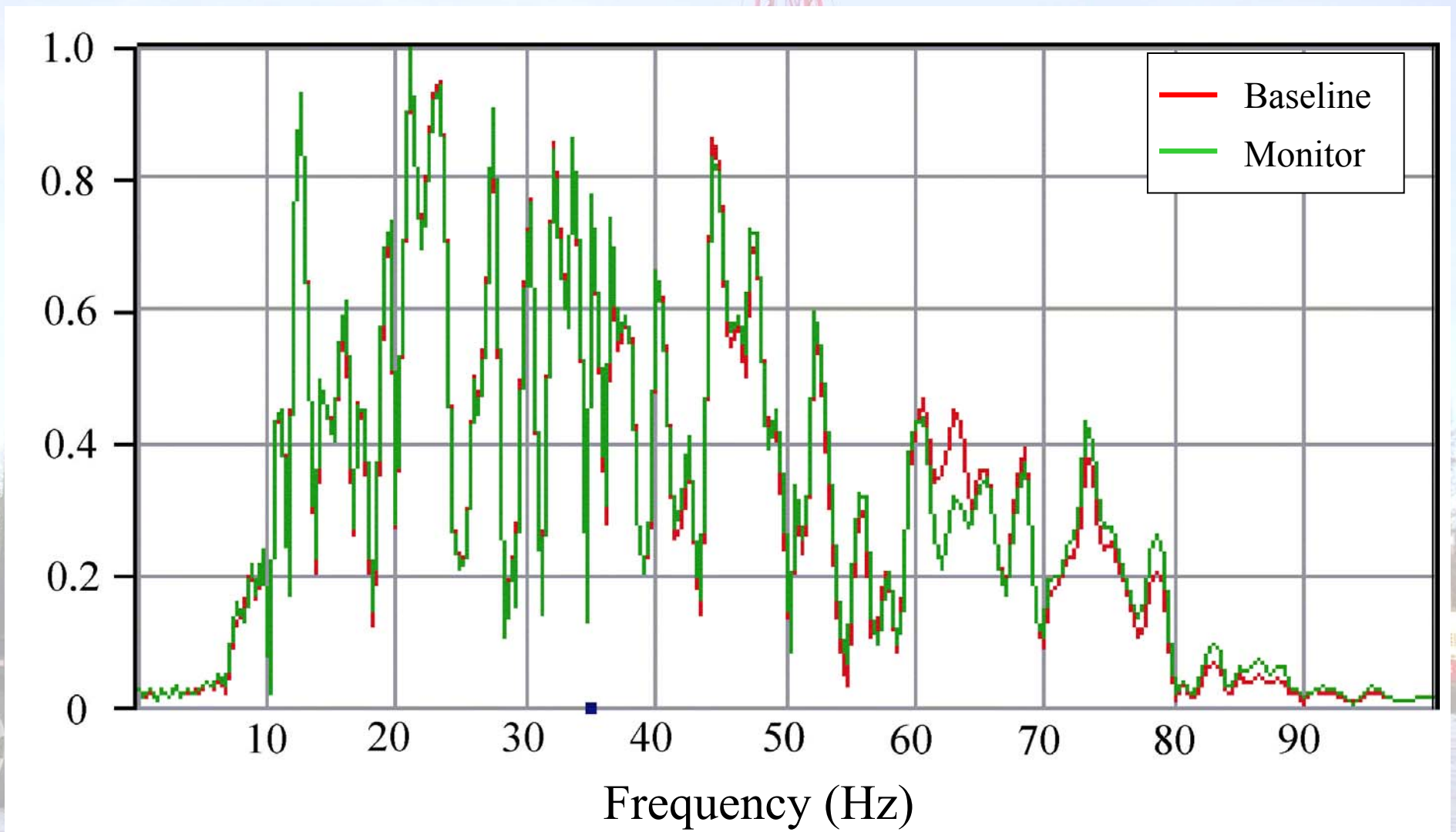
S-wave Results Line 2: Baseline



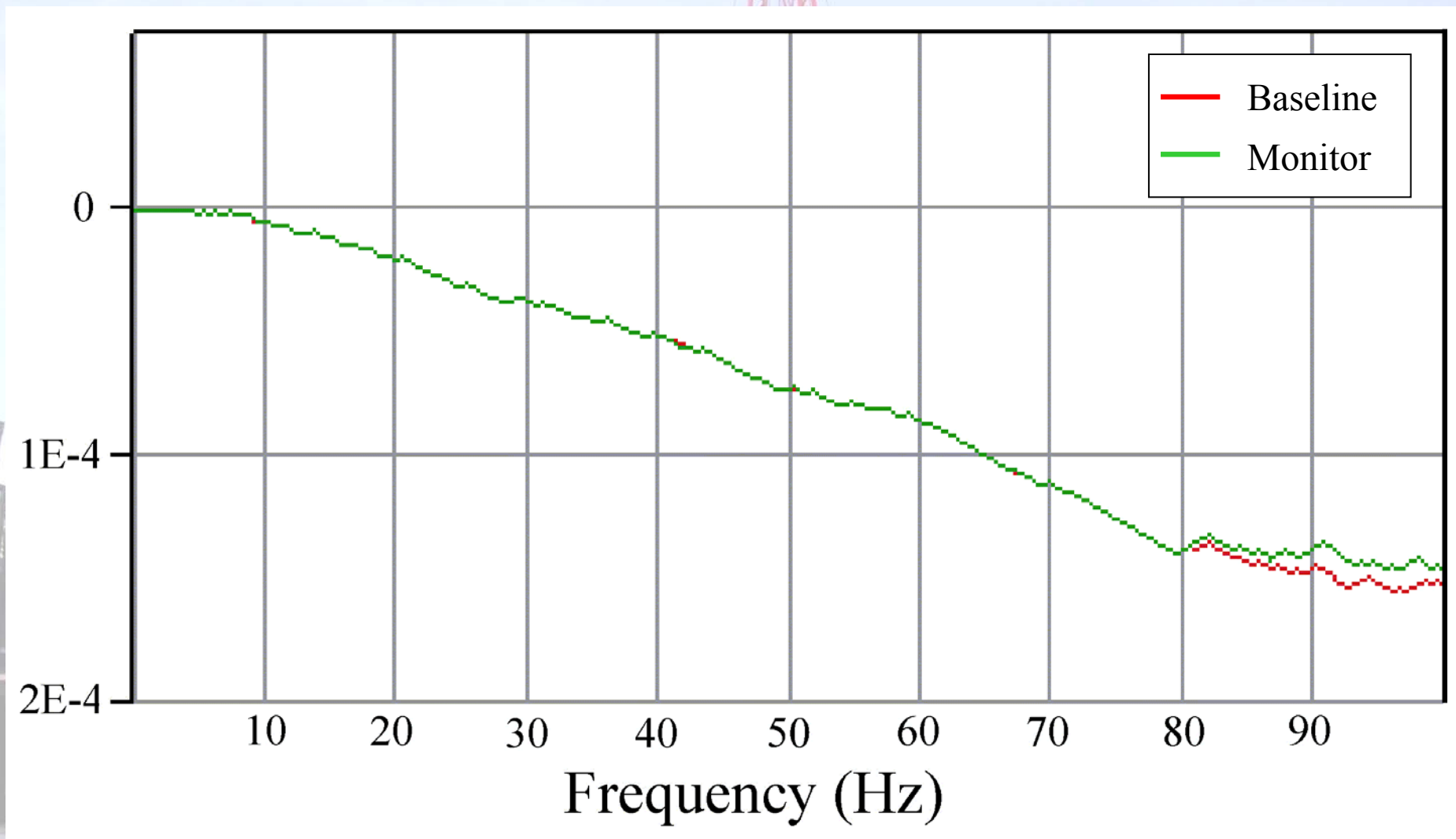
S-wave Results Line 2: Difference



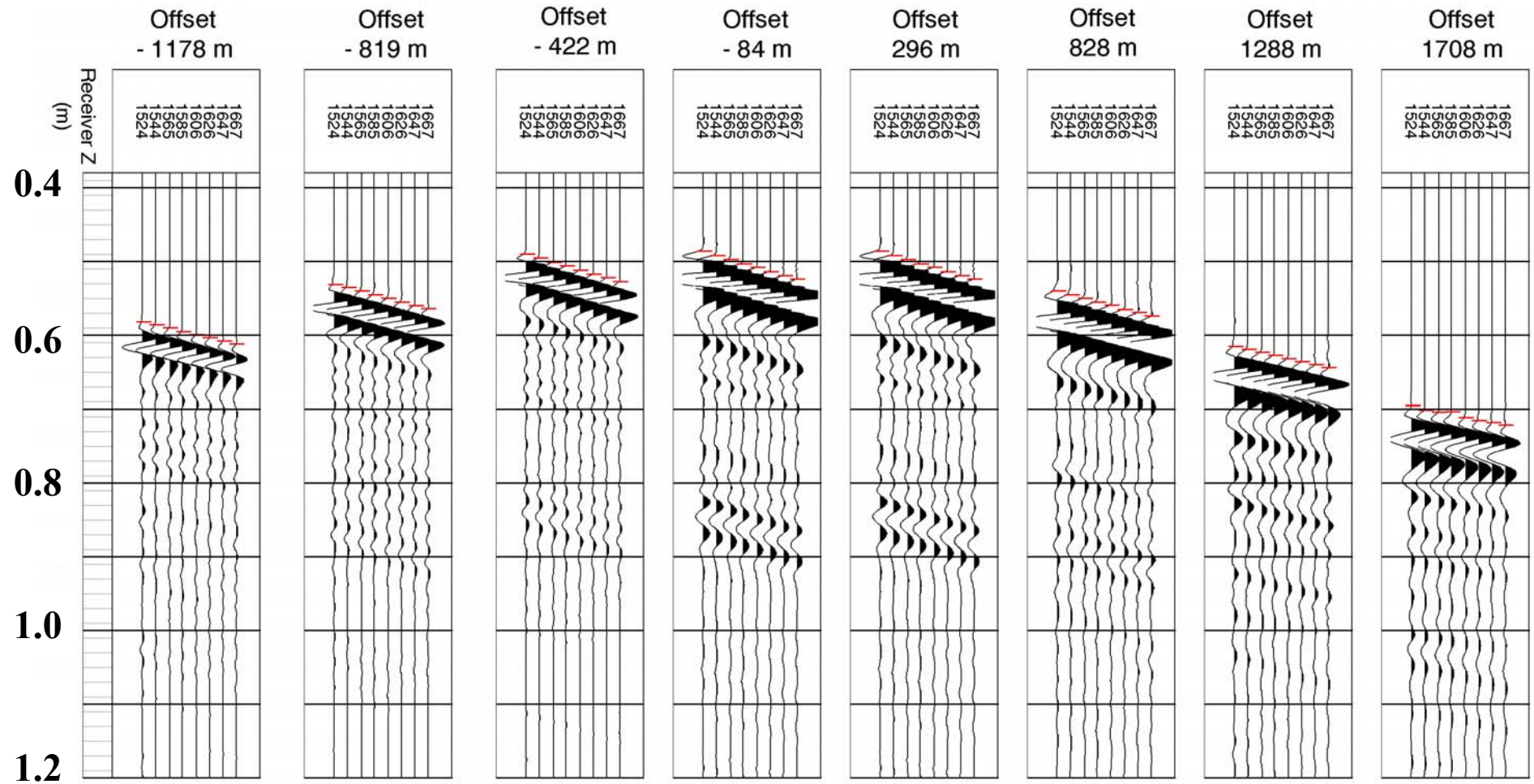
Comparison of Amplitude Spectra



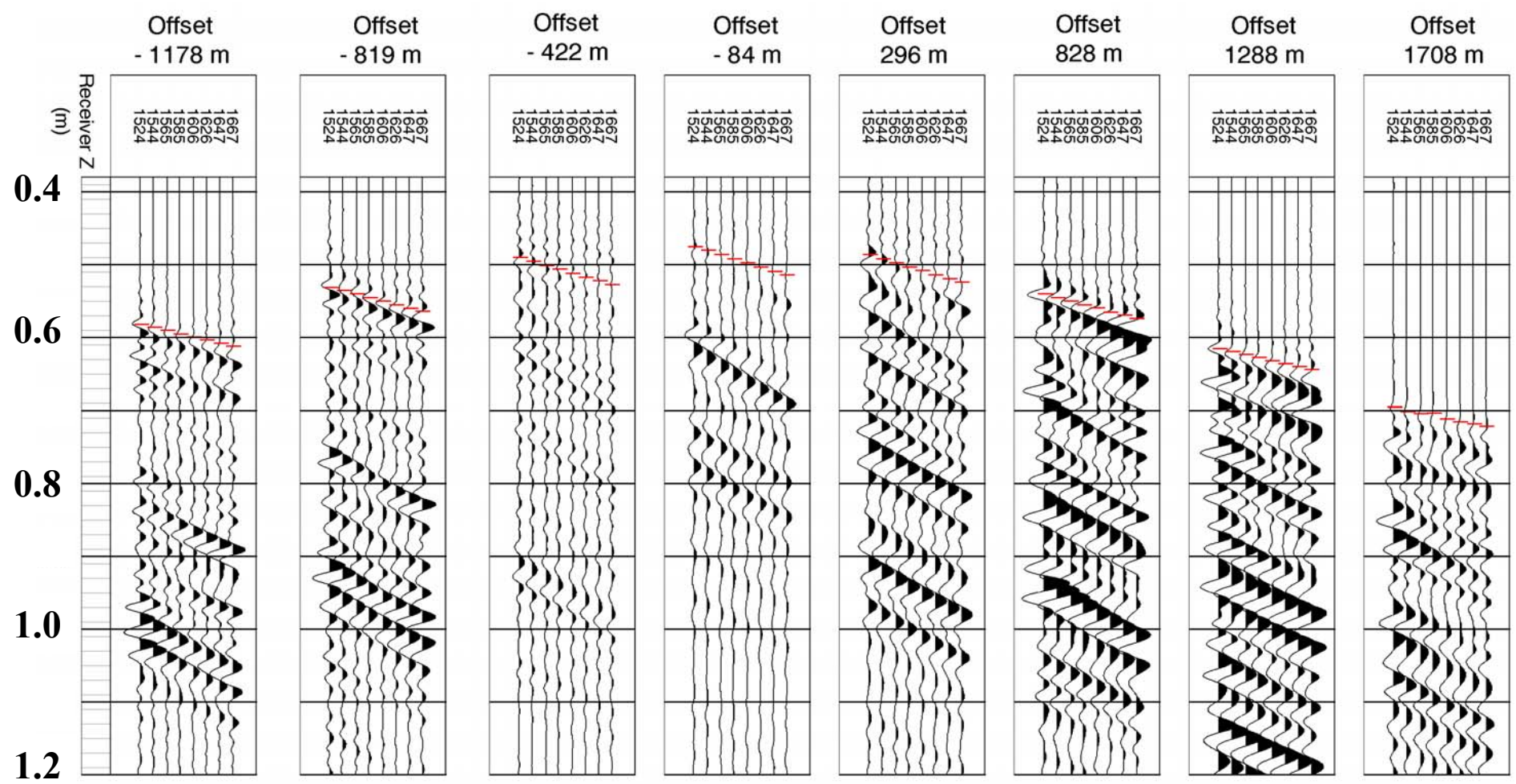
Comparison of Phase Spectra



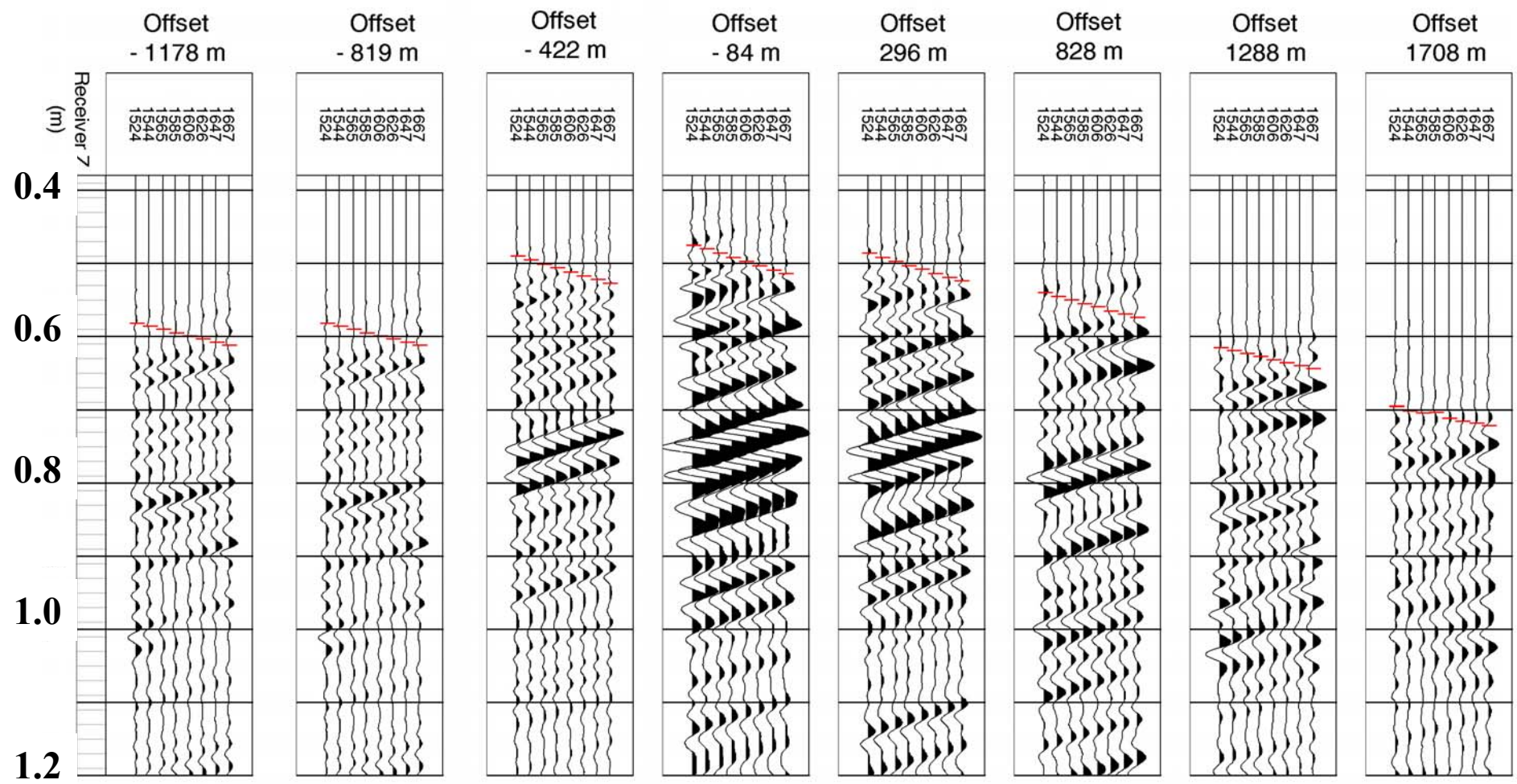
3D Wavefield Separation: Downgoing P



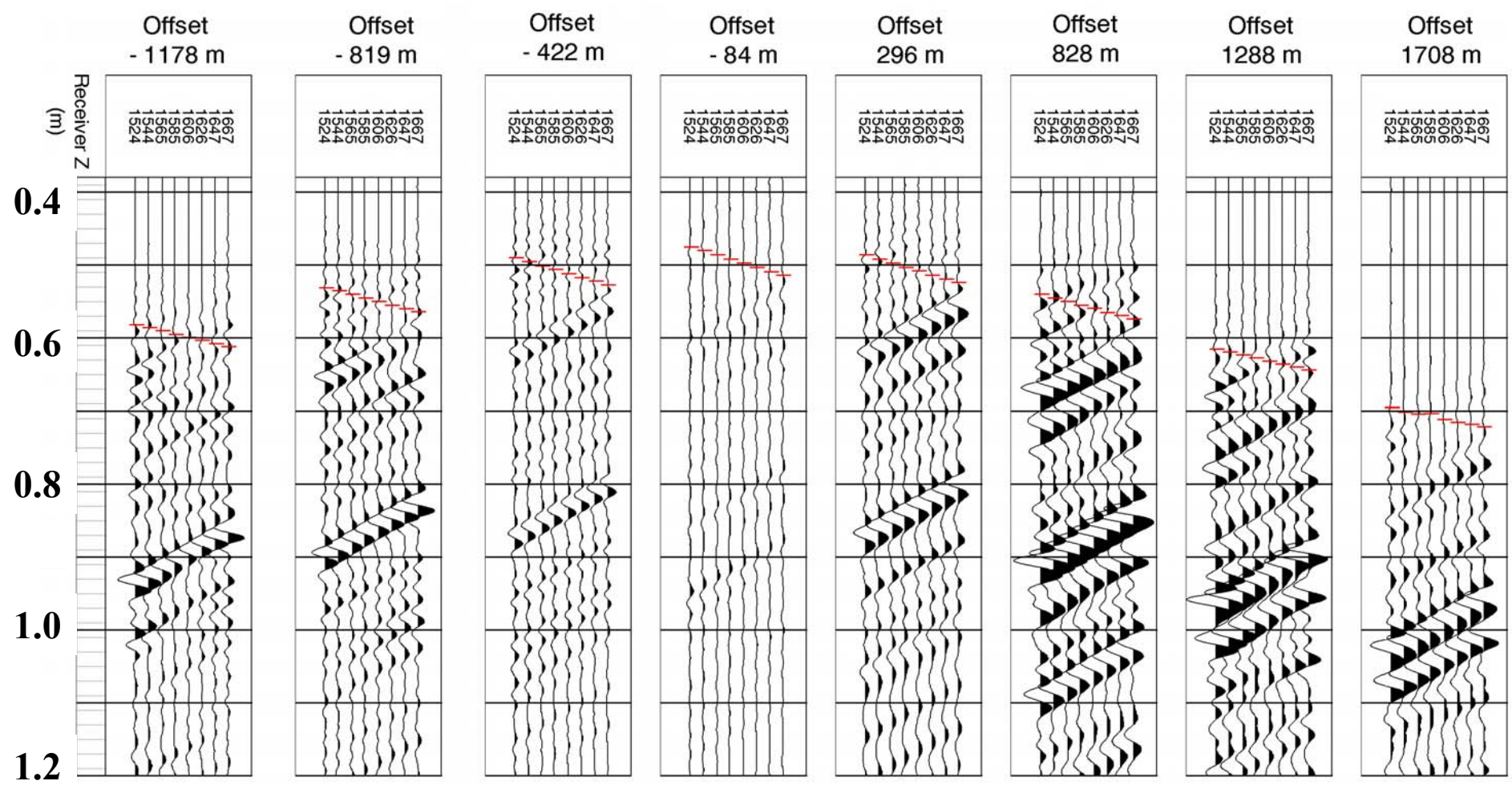
3D Wavefield Separation: Downgoing S



3D Wavefield Separation: Upgoing P



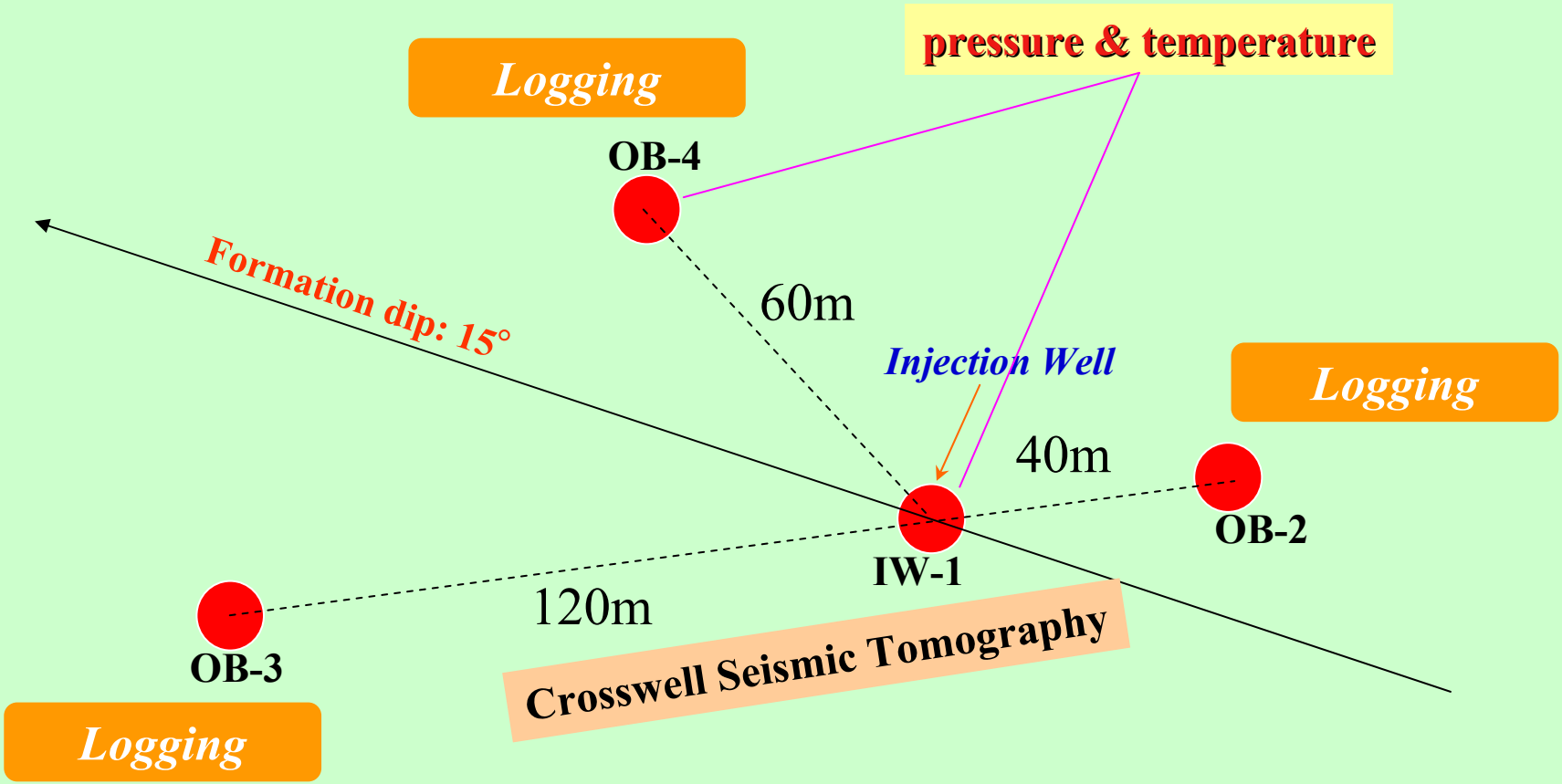
3D Wavefield Separation: Upgoing S



Field investigation results after the Mid-Niigata Pref. Earthquake at the Nagaoka injection site

*Ziqiu Xue, Daiji Tanase, Jiro Watanabe, Hiroyuki Azuma and Saeko Adachi-mito

Geophysical Monitoring of CO_2



Objectives of time-lapse well logging and pressure measurement

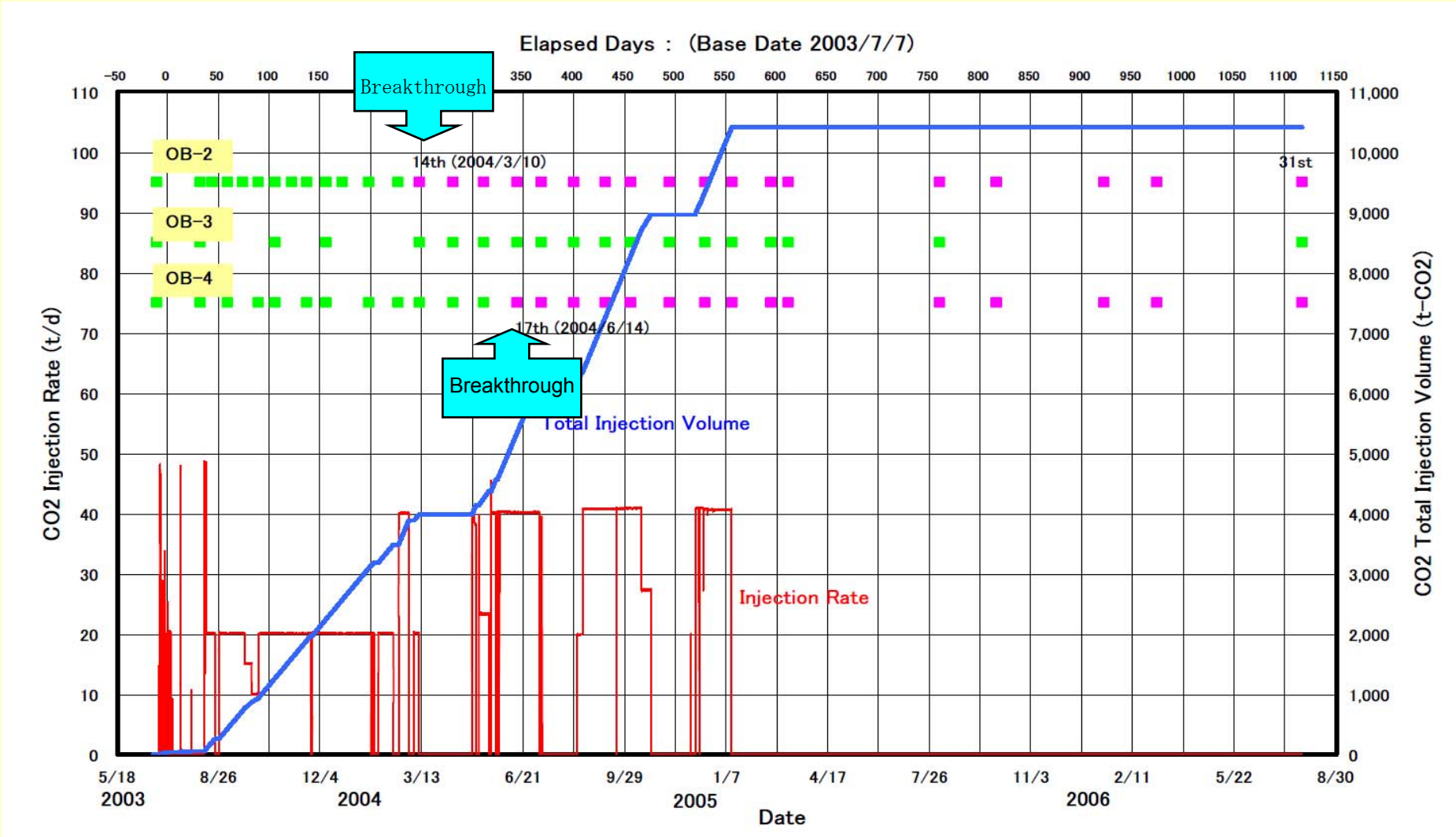
- **CO_2 breakthrough time (*calibrating geological model*)**
- **CO_2 movements after breakthrough & formation pressure buildup disappeared (*driving force and long term behavior prediction*)**

Trapping Mechanism

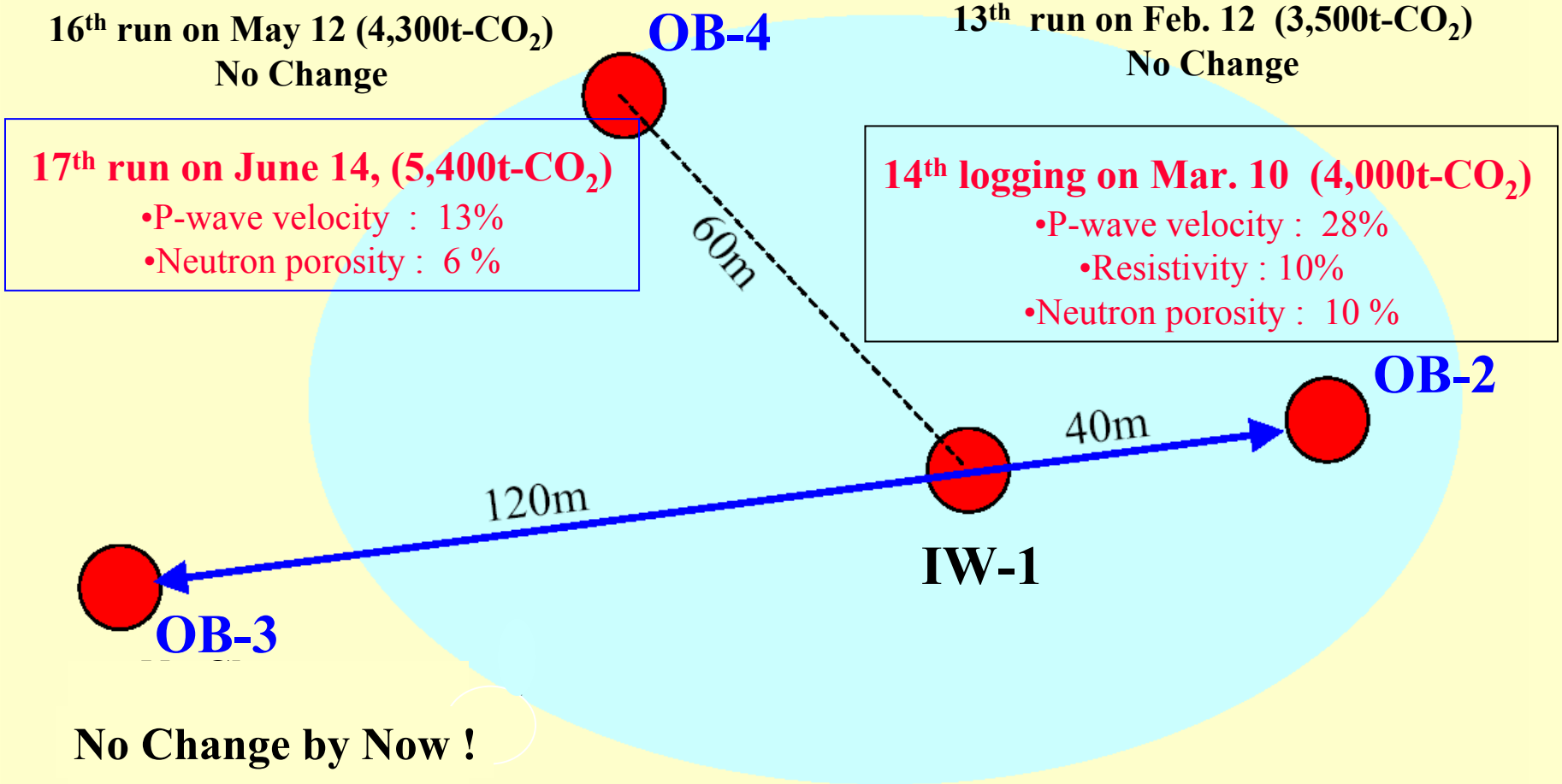
- **Formation pressure measurements at injection well and one of the three observation wells**

(pressure buildup due to the low permeability, decay curves for permeability (single-phase) and relative permeability (two-phase) estimations)

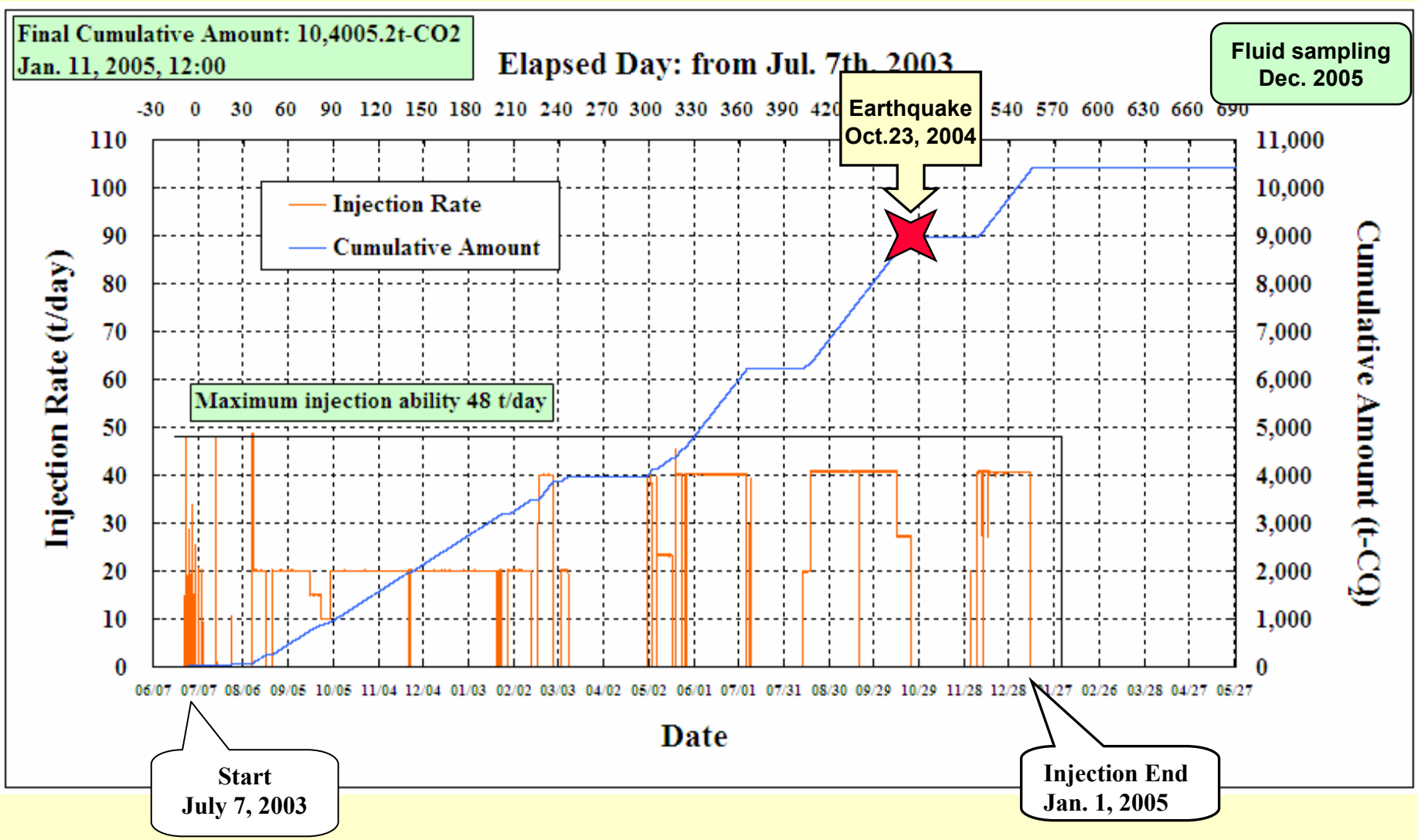
Time-lapse Well Logging



CO_2 Breakthrough time

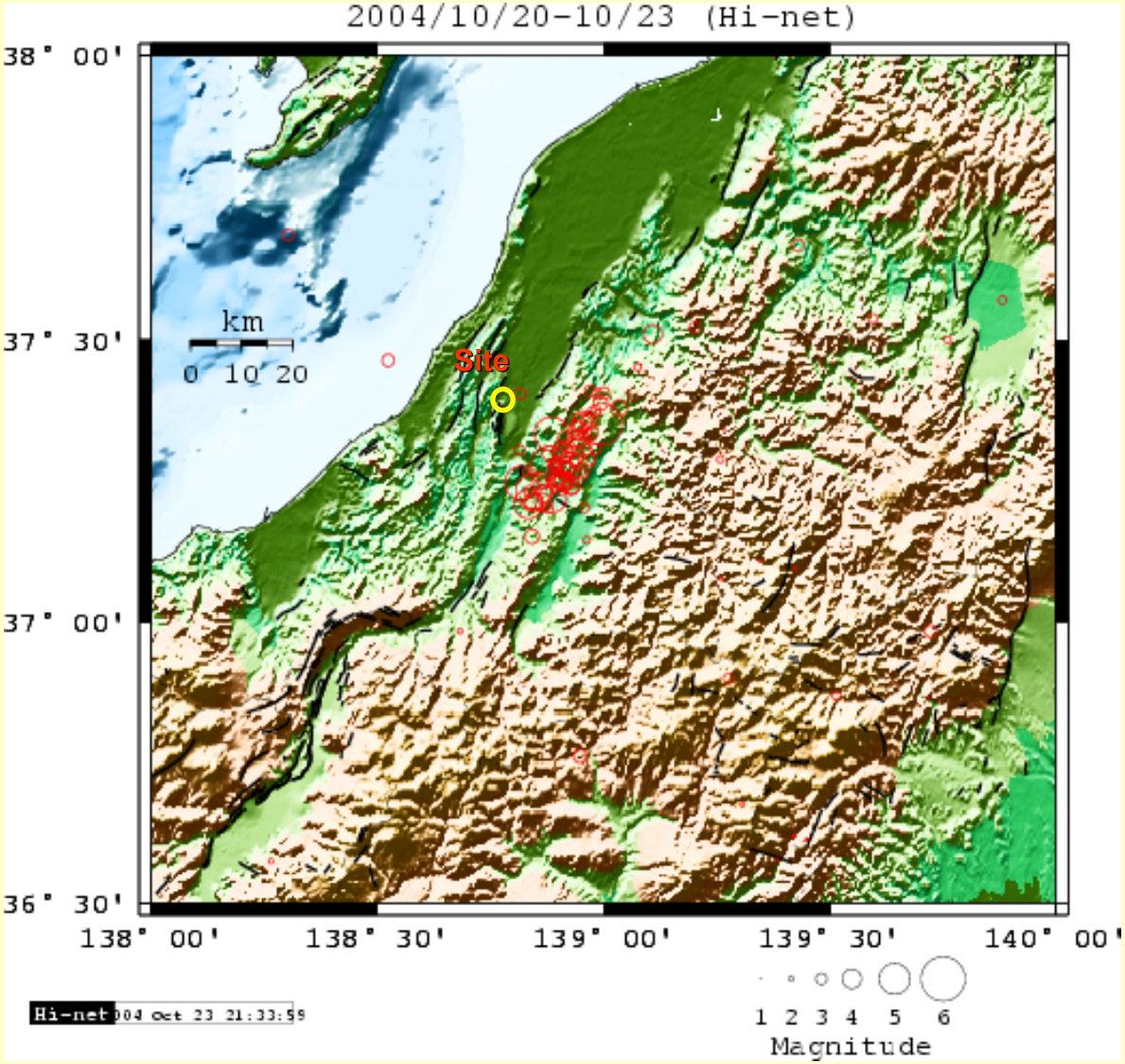


History of the CO_2 Injection at Nagaoka



The Mid-Niigata Prefecture Earthquake in Oct. 2004

Date : 23 Oct. 2004
Time: 17:56
Mag.: 6.8 (JMA)
Depth : 10 km



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Field Investigations after the Mid-Niigata Earthquake

- Cement Bond Logging
- Induction, Sonic & Neutron Loggings
- Crosswell Seismic Tomography

- Collecting data around the injection site, comparing differences in waveforms

- Formation water sampling by CHDT*

Liquid CO_2 Tank

Diameter: 3.8 m
Height : 18 m

No Damages !

Injection Well

Observation Wells

CO_2 Pipeline

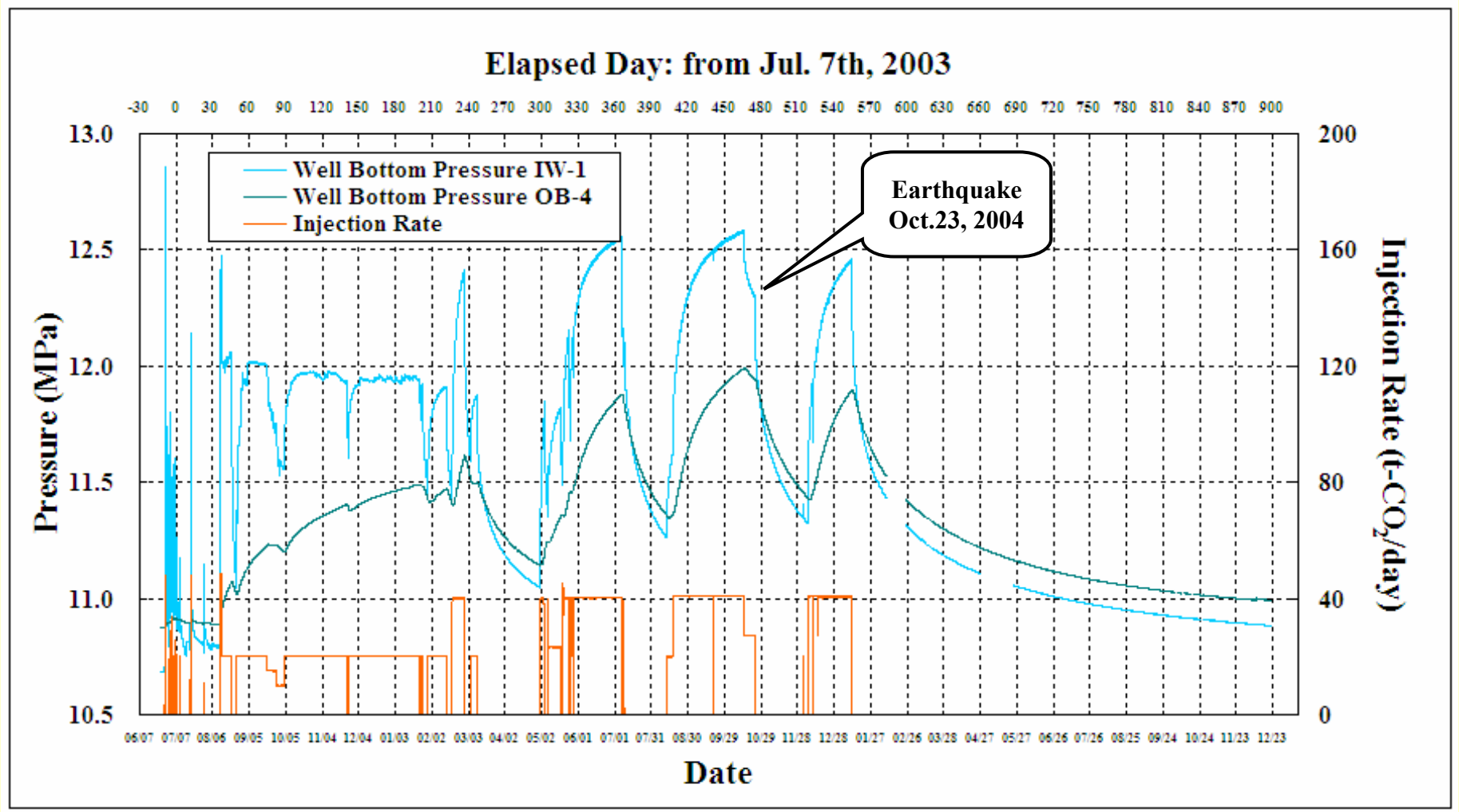
CO_2 Injection Site

Damages at the access road to the injection site

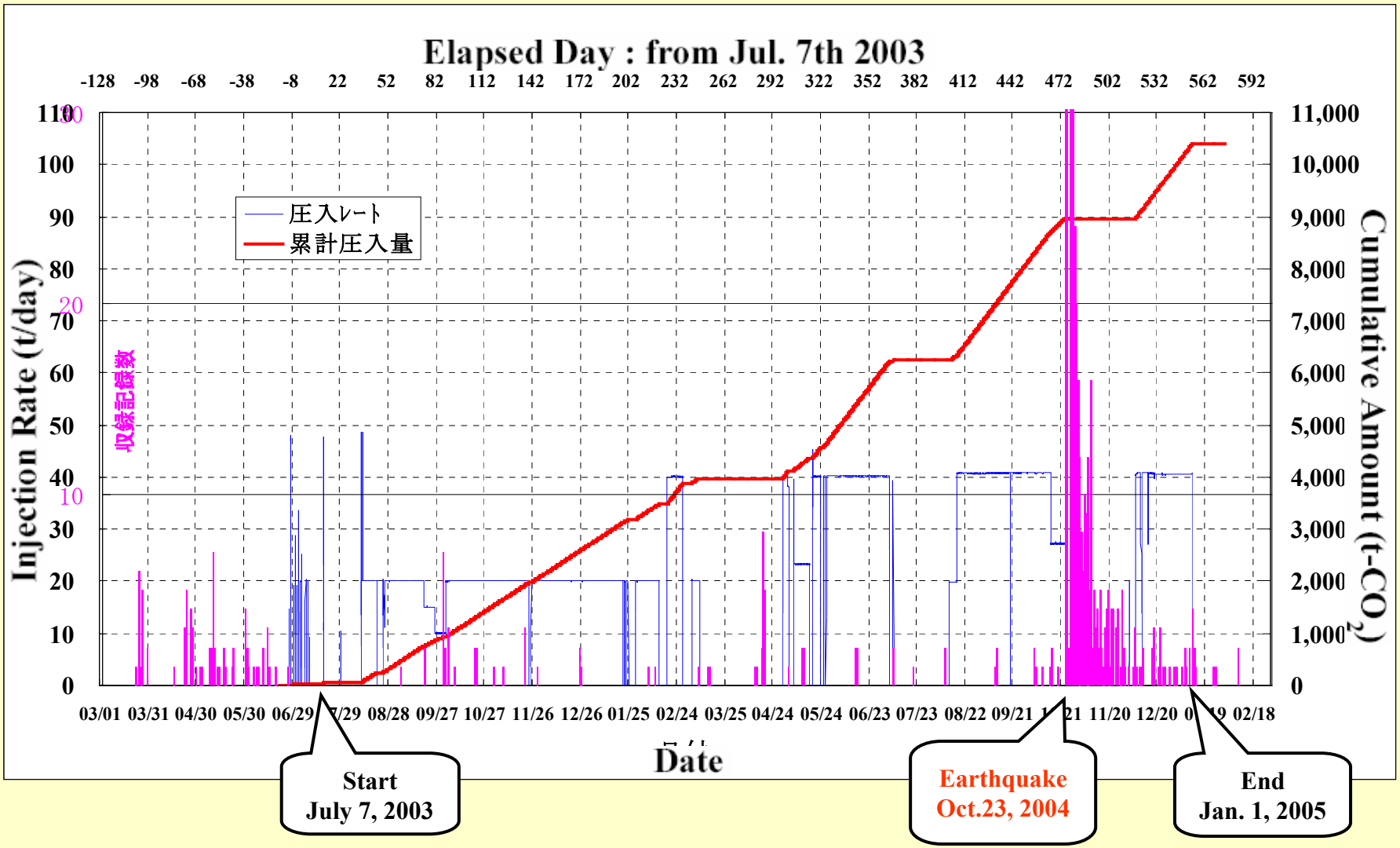
After the Earthquake (Oct. 25, 2004)

After the Earthquake (Oct. 25, 2004)

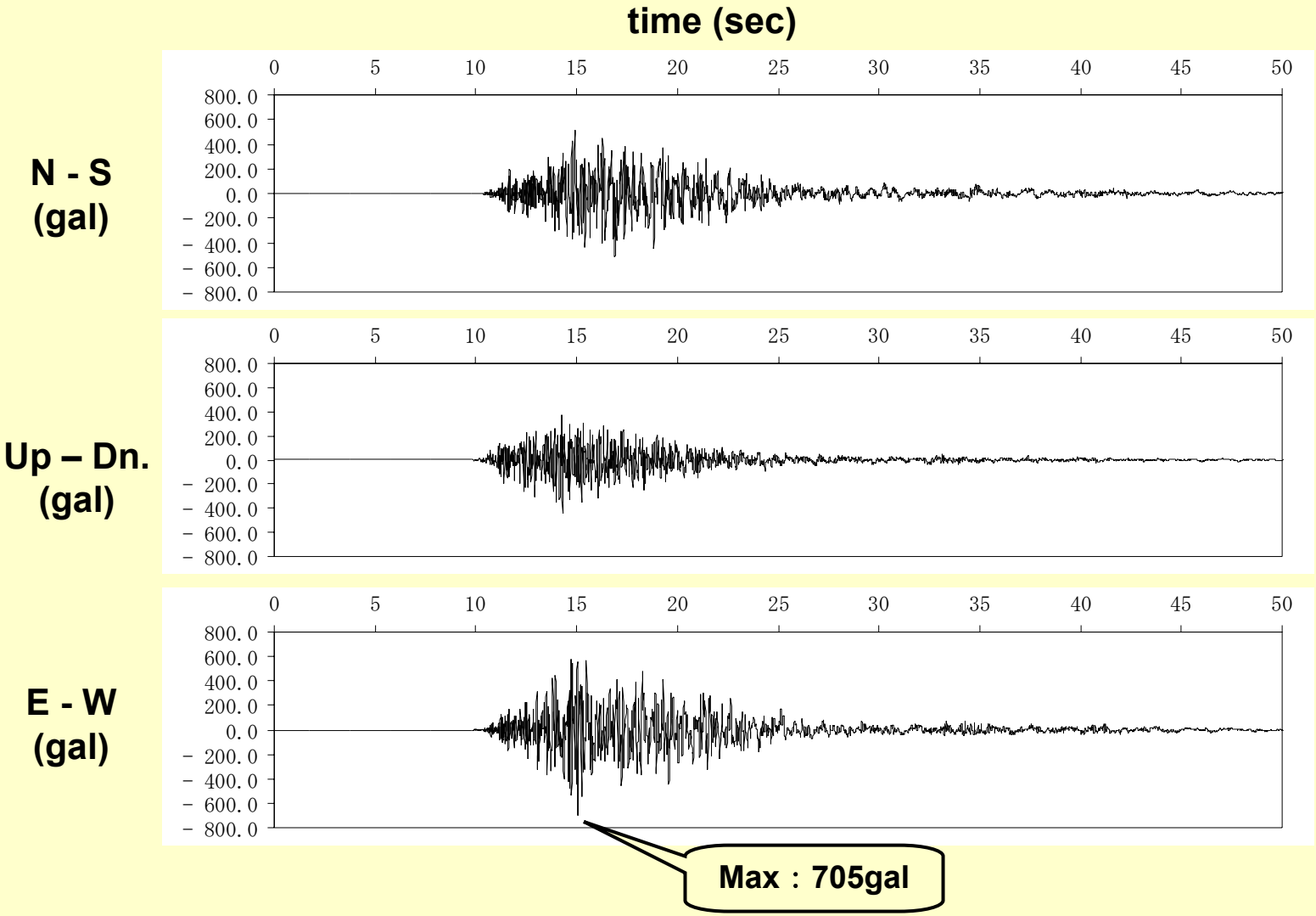
Formation Pressure Measurements



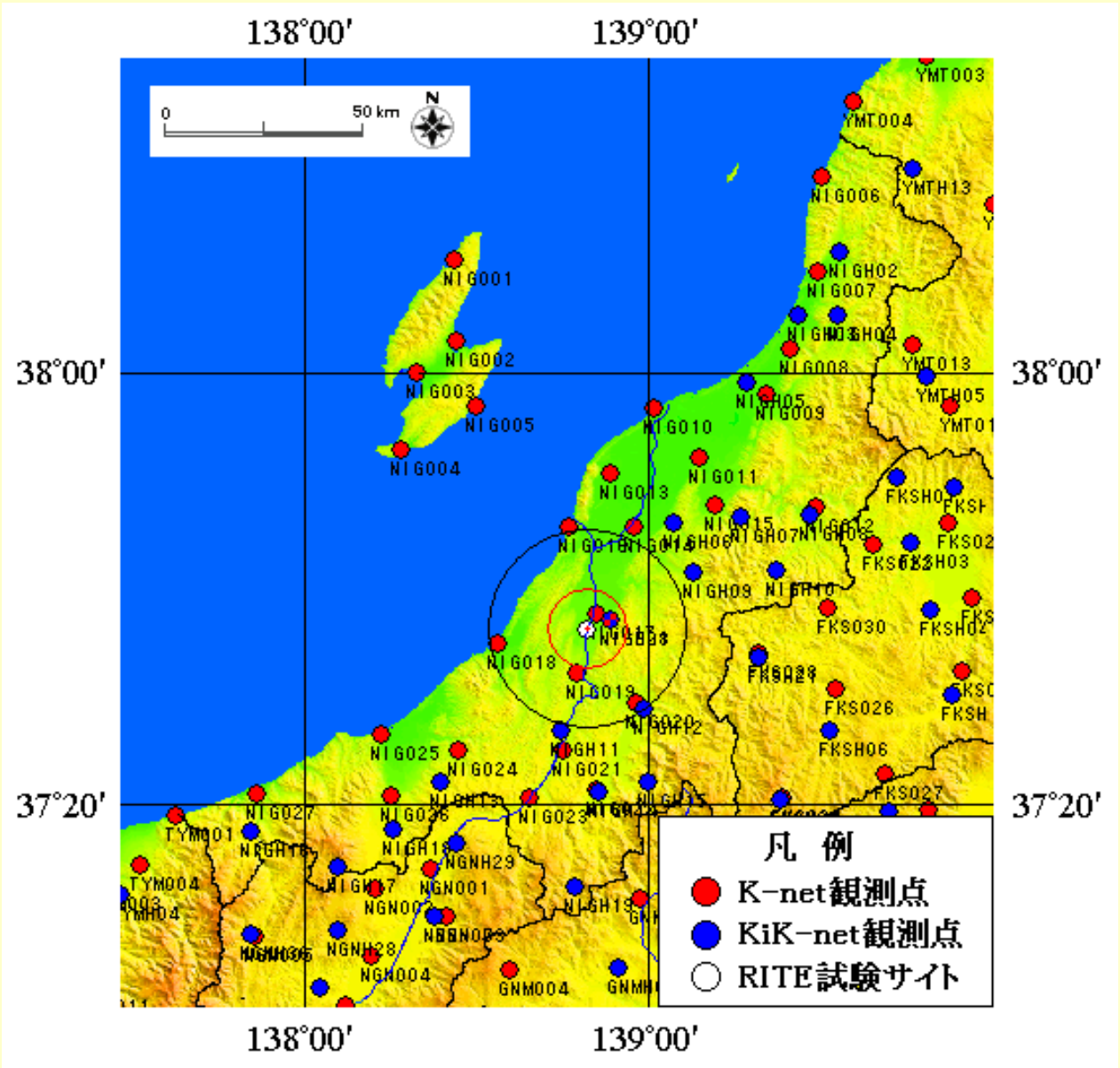
Seismicity Observations



Record of the Mid-Niigata Prefecture Earthquake 2004/10/23 17:56 M6.8 at Nagaoka

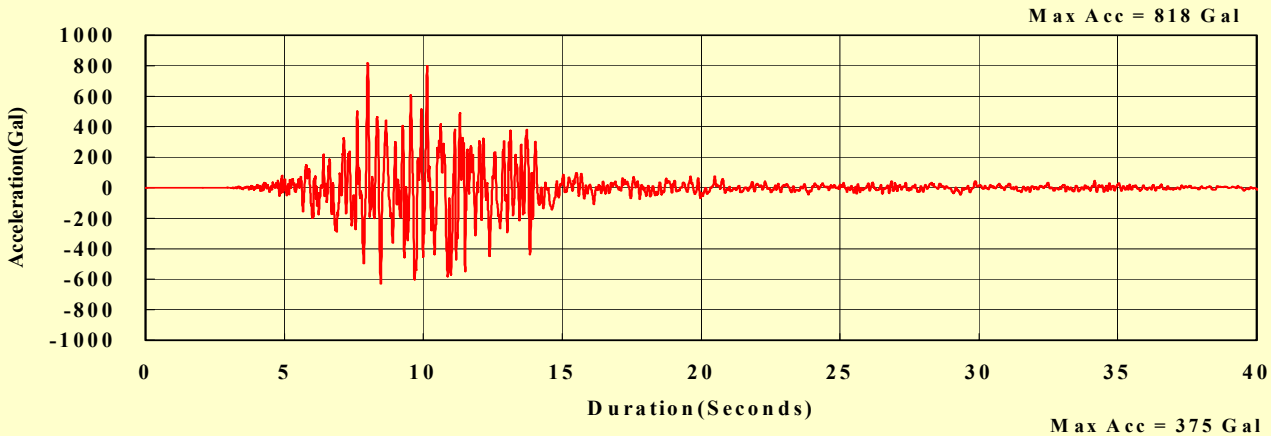


Earthquake Observation Stations around Niigata Prefecture

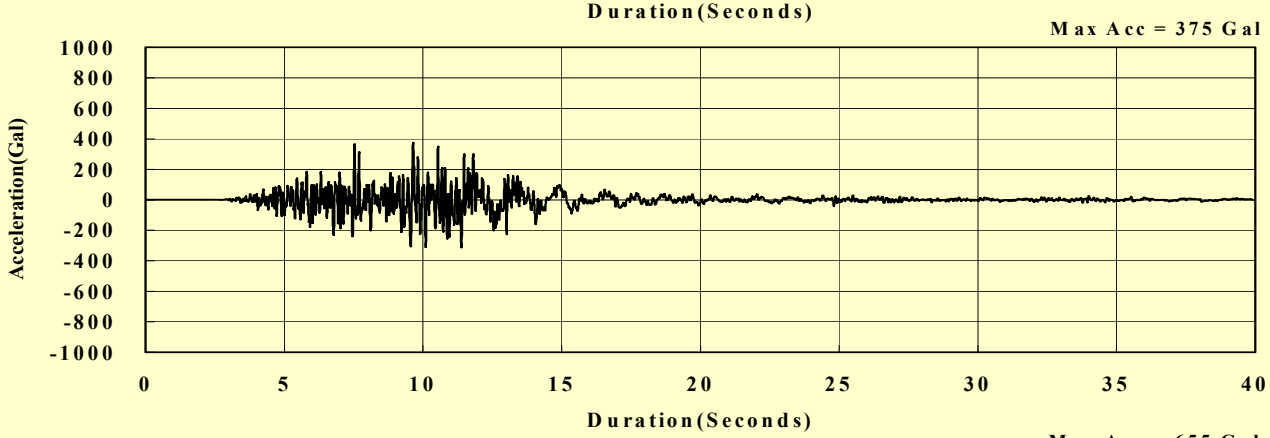


KiK-net, NIGH01: 10km away from the injection site

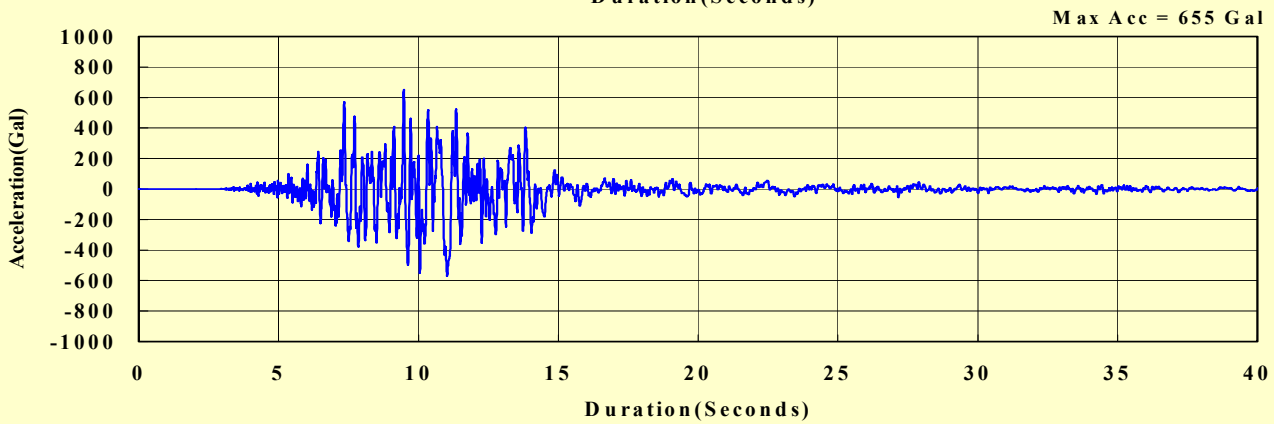
N - S (gal)



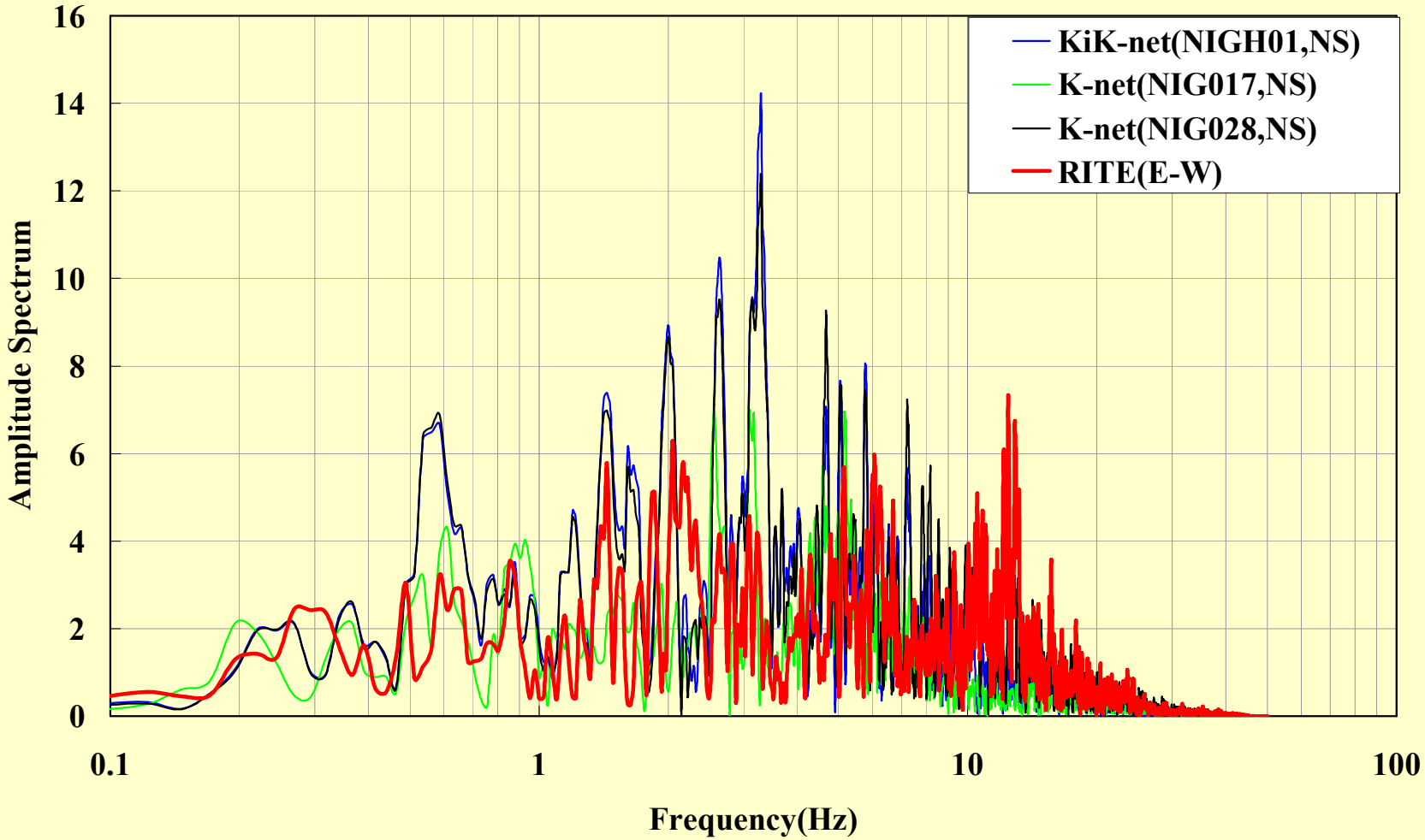
Up – Dn. (gal)



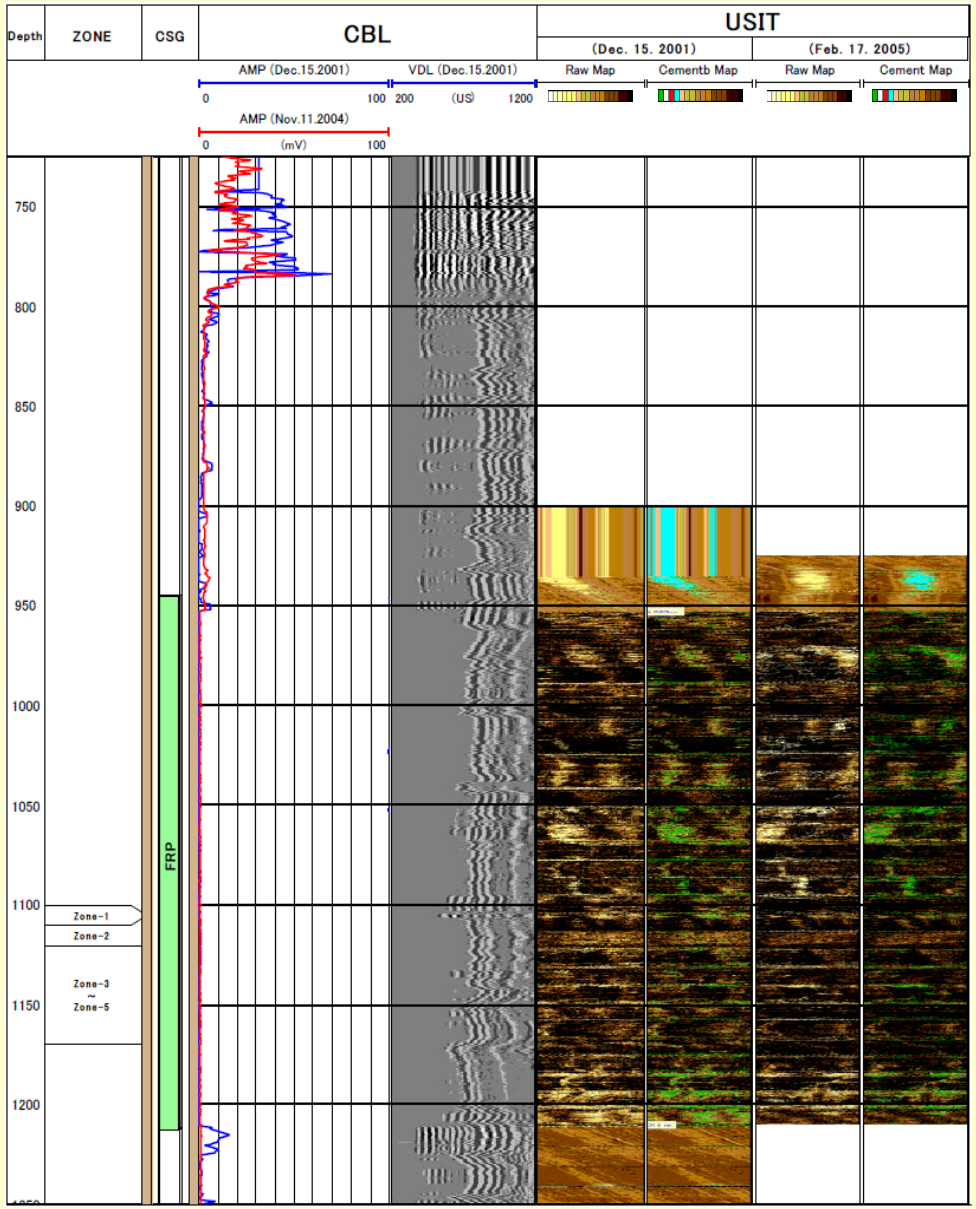
E - W (gal)



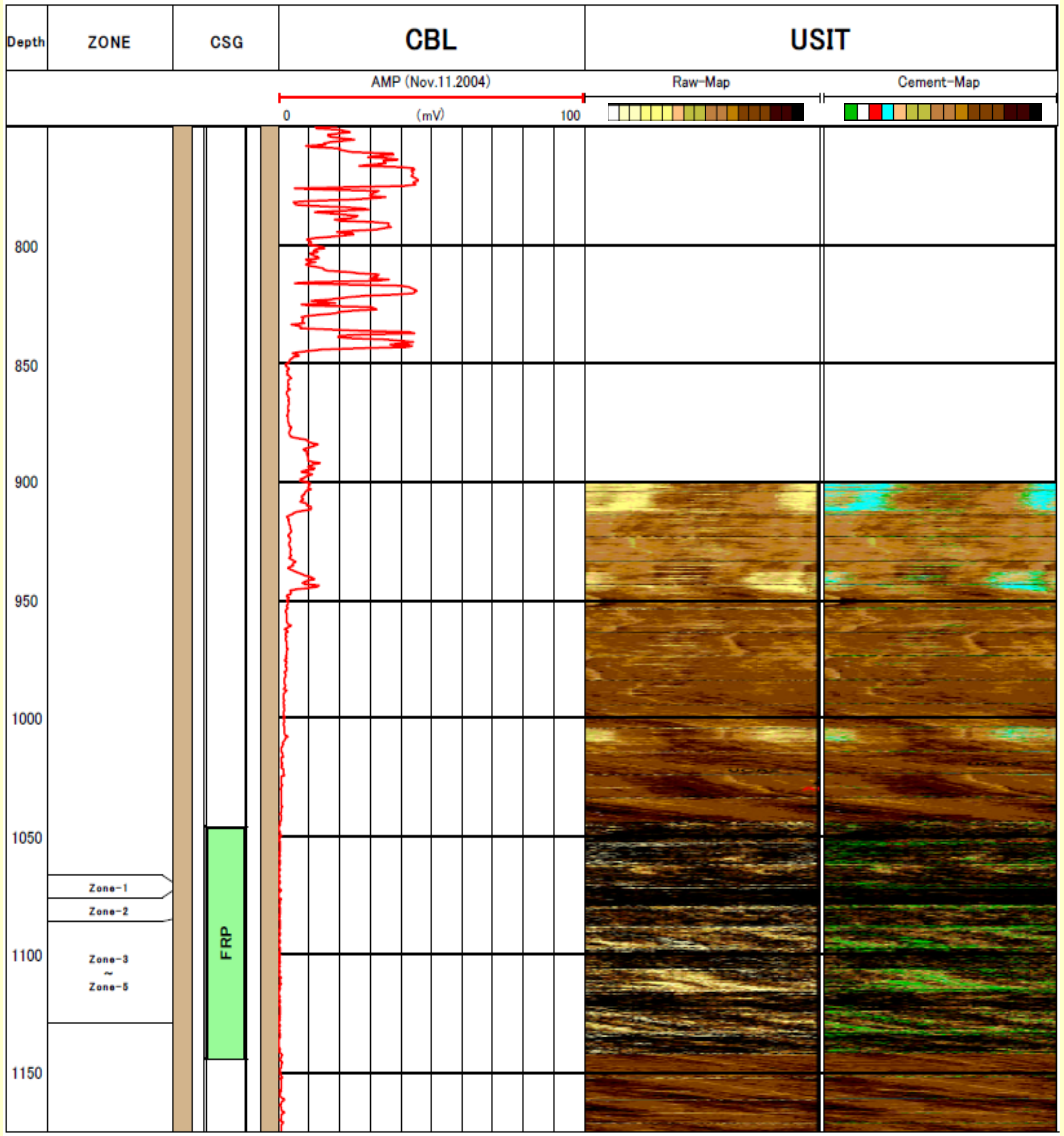
Fourier's Spectral Analysis (4 points)



OB-2 USI/CBL


Depth
ZONE
CSG
CBL
USIT
(Dec. 15. 2001)
(Feb. 17. 2005)
AMP (Dec.15.2001)
VDL (Dec.15.2001)
Raw Map
Cementb Map
Raw Map
Cement Map
0
100
200
(US)
1200
AMP (Nov.11.2004)
0
(mV)
100
750
800
850
900
950
1000
1050
1100
1150
1200
FRP
Zone-1
Zone-2
Zone-3
~
Zone-5

OB-3 USI/CBL


Depth
ZONE
CSG
CBL
USIT
AMP (Nov.11.2004)
Raw-Map
Cement-Map
0
(mV)
100
800
850
900
950
1000
1050
1100
1150
Zone-1
Zone-2
Zone-3
~
Zone-5
FRP

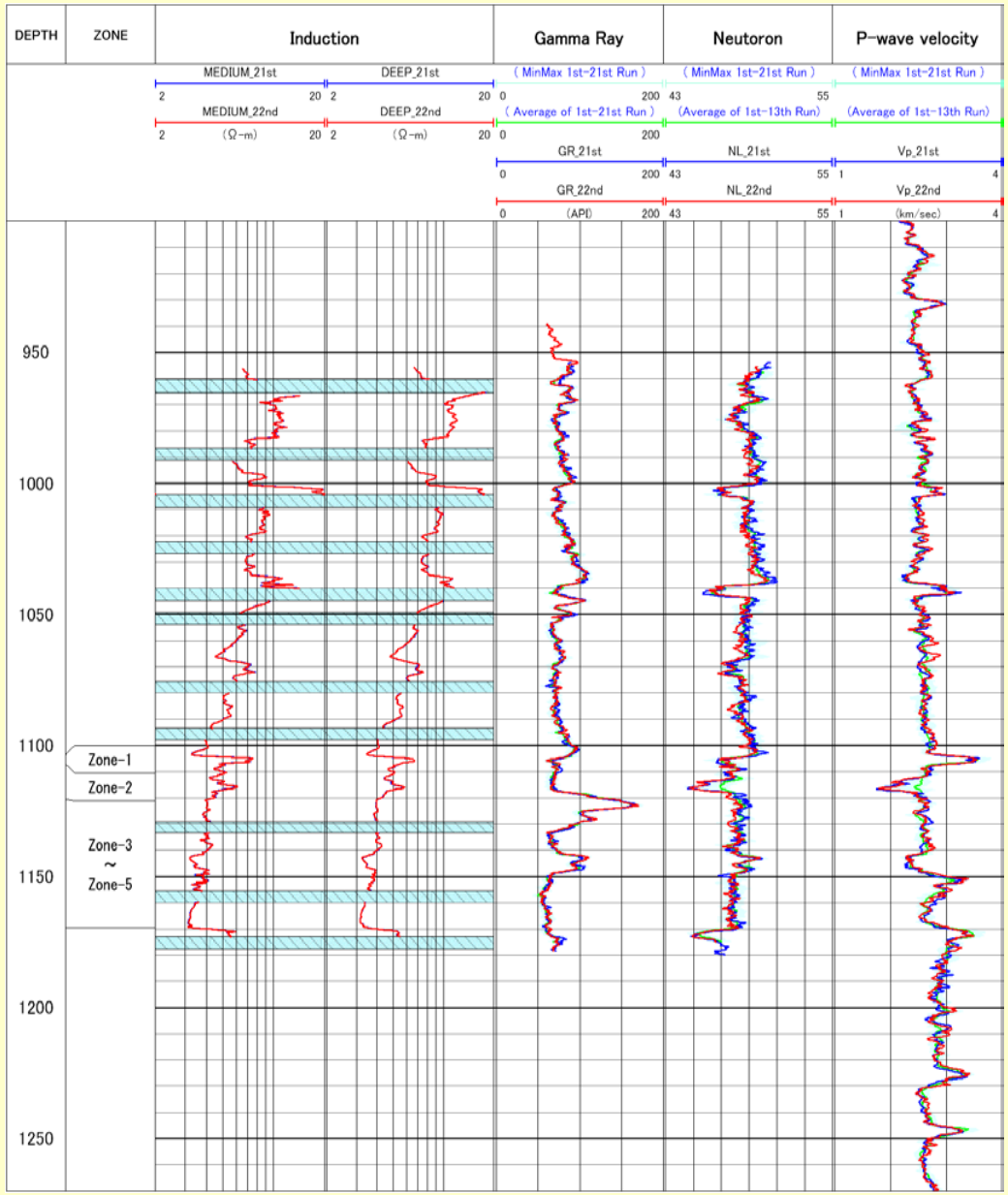
OB-2

Well Logging Results
Before & after the Earthquake

Blue line: 21st run, Oct.4-5 2004

Red line: 22nd run, Nov.11-13 2004

Earthquake: Oct. 23 2004

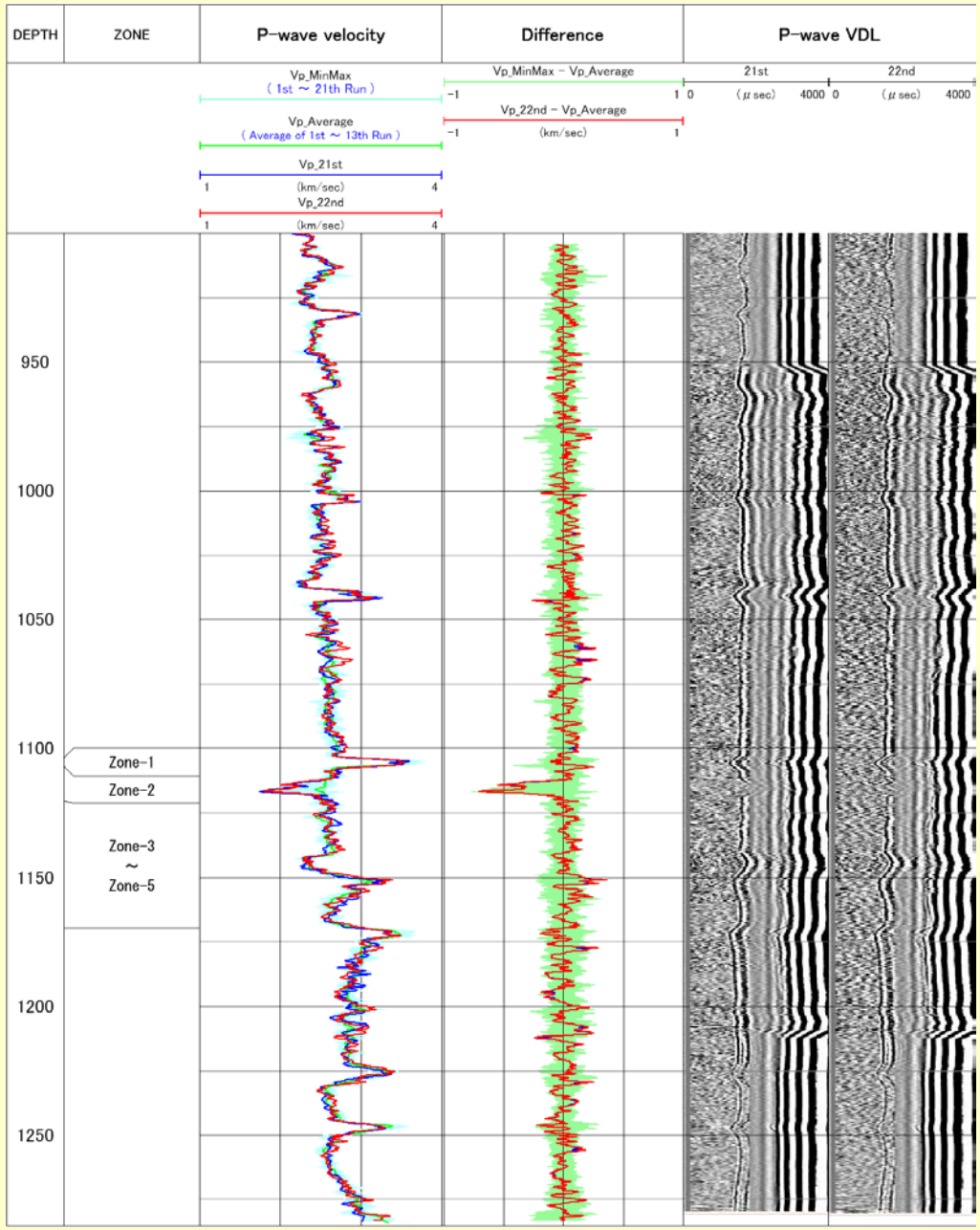


Sonic P-wave Velocity at OB-2

Blue line: 21st run, Oct.4-5 2004

Red line: 22nd run, Nov.11-13 2004

Earthquake: Oct. 23 2004

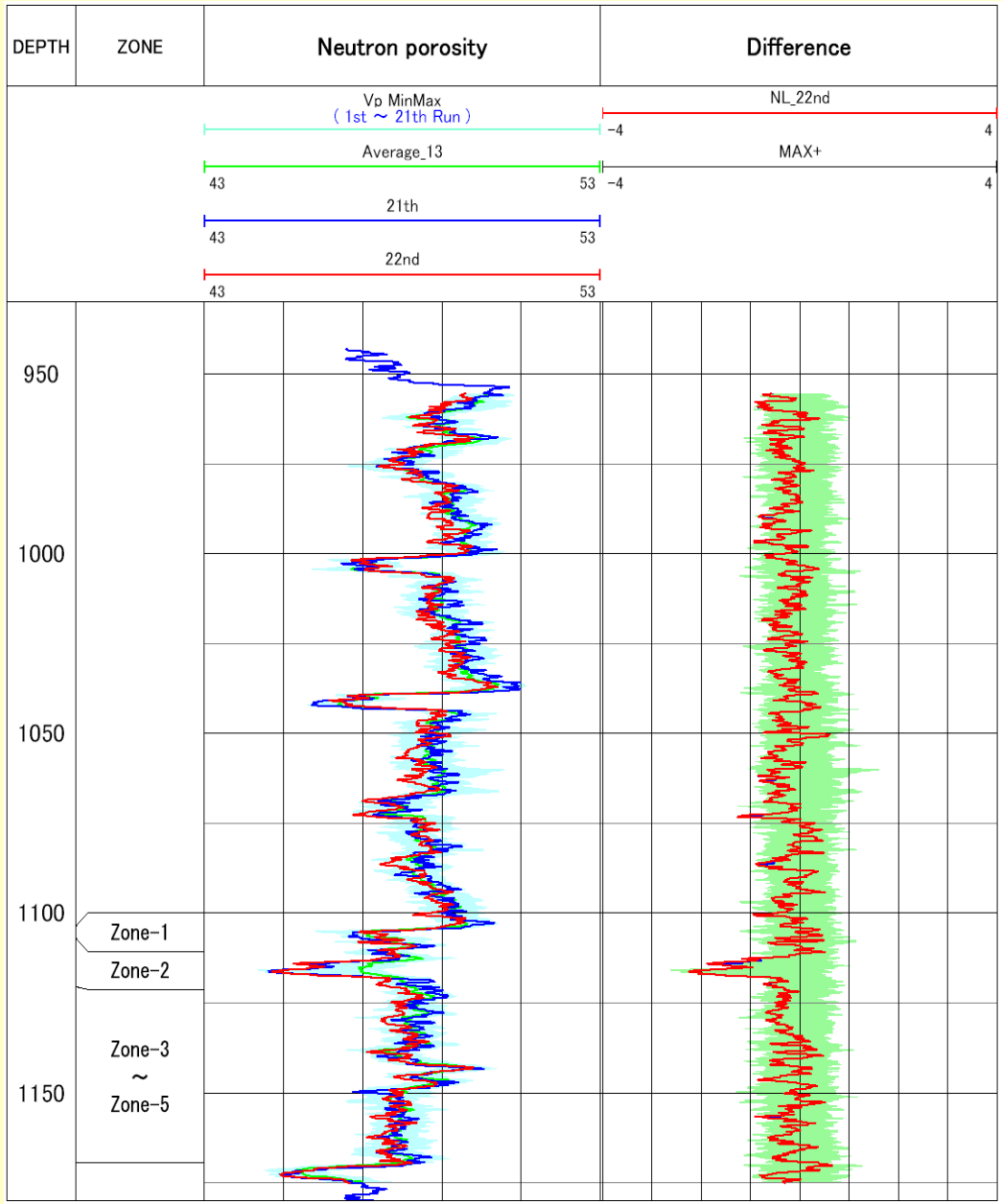


Neutron Porosity at OB-2

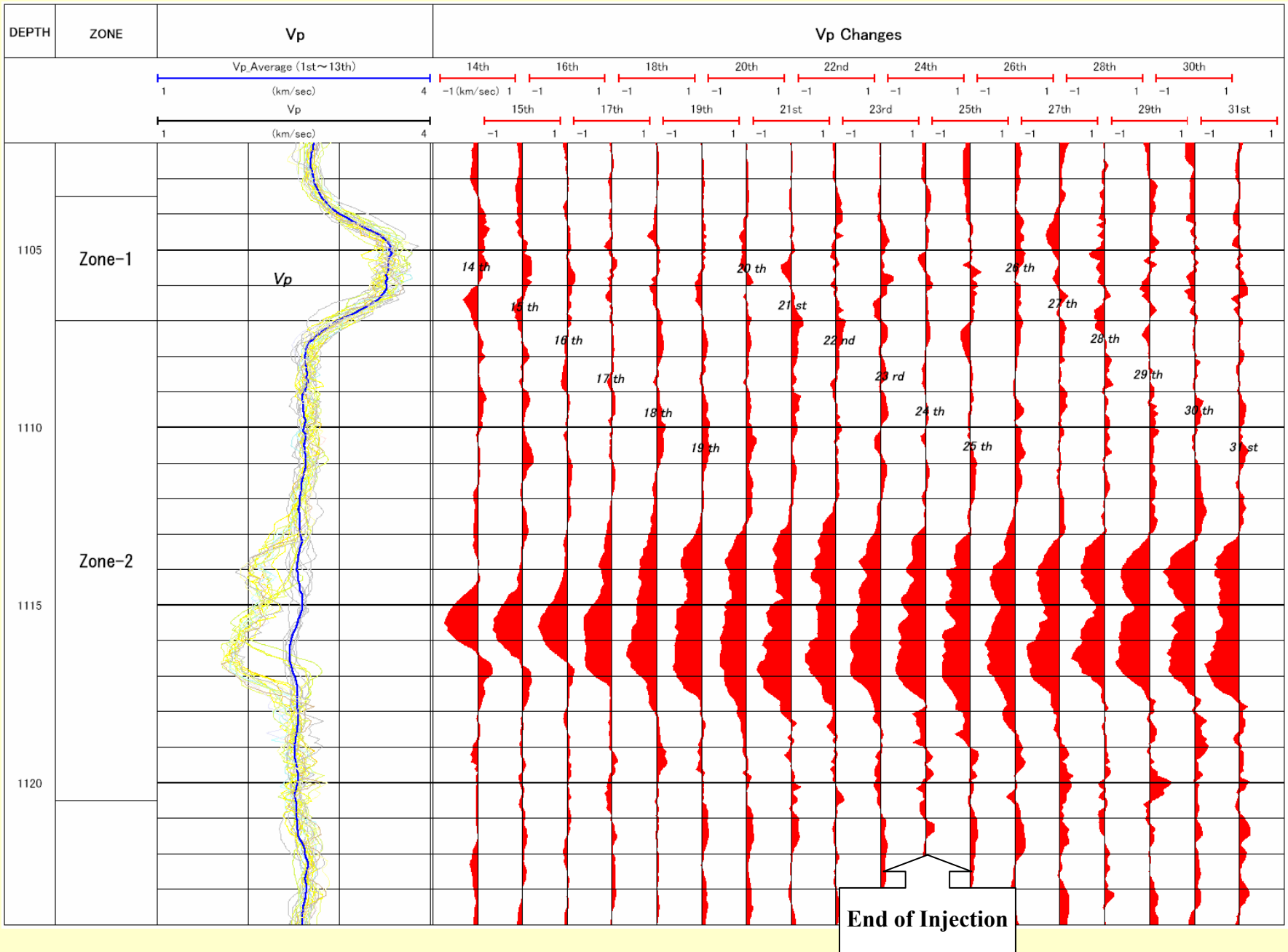
Blue line: 21st run, Oct.4-5 2004

Red line: 22nd run, Nov.11-13 2004

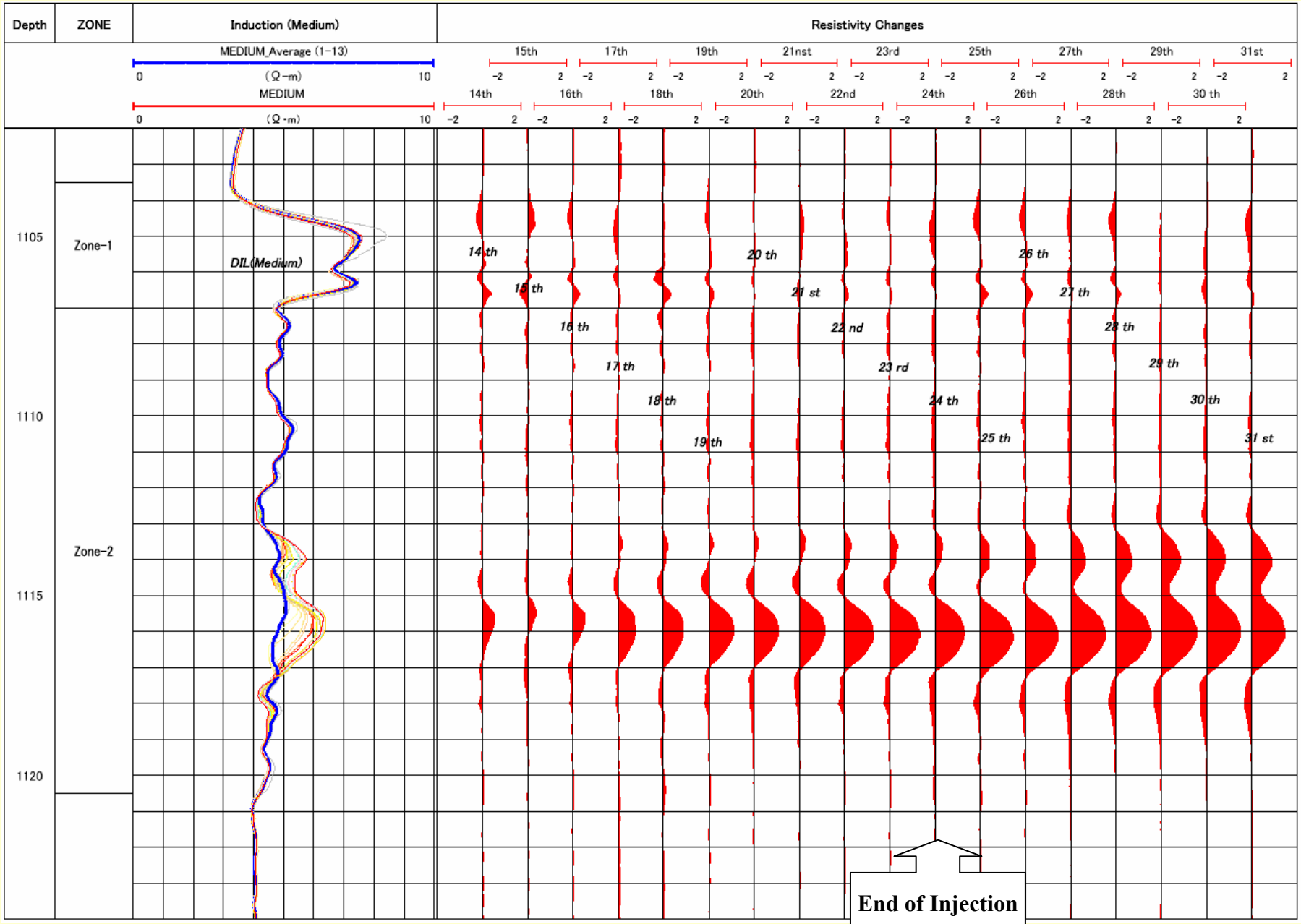
Earthquake: Oct. 23 2004



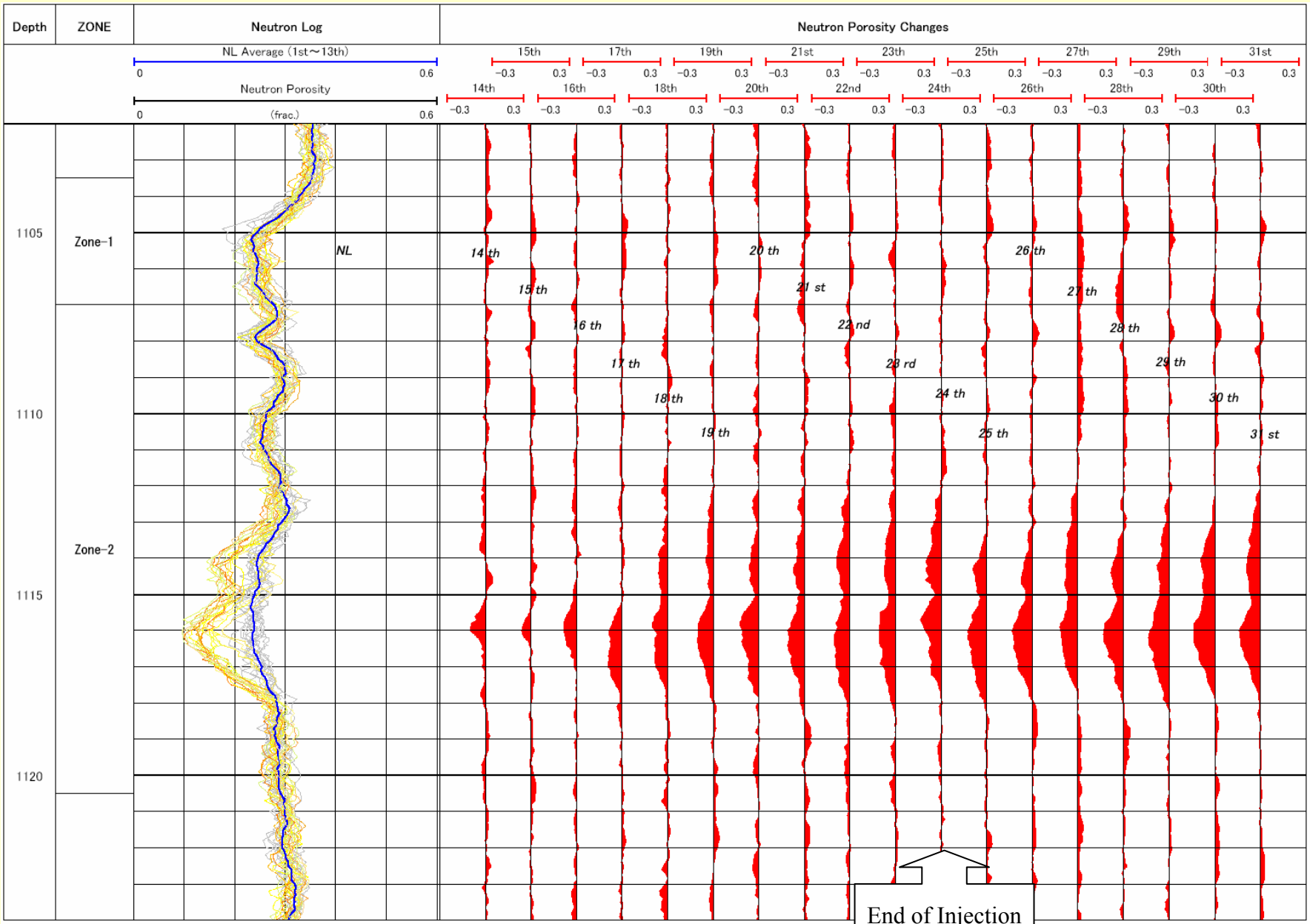
Sonic Logging @OB-2 (Vp)



Induction Logging @OB-2 (resistivity)

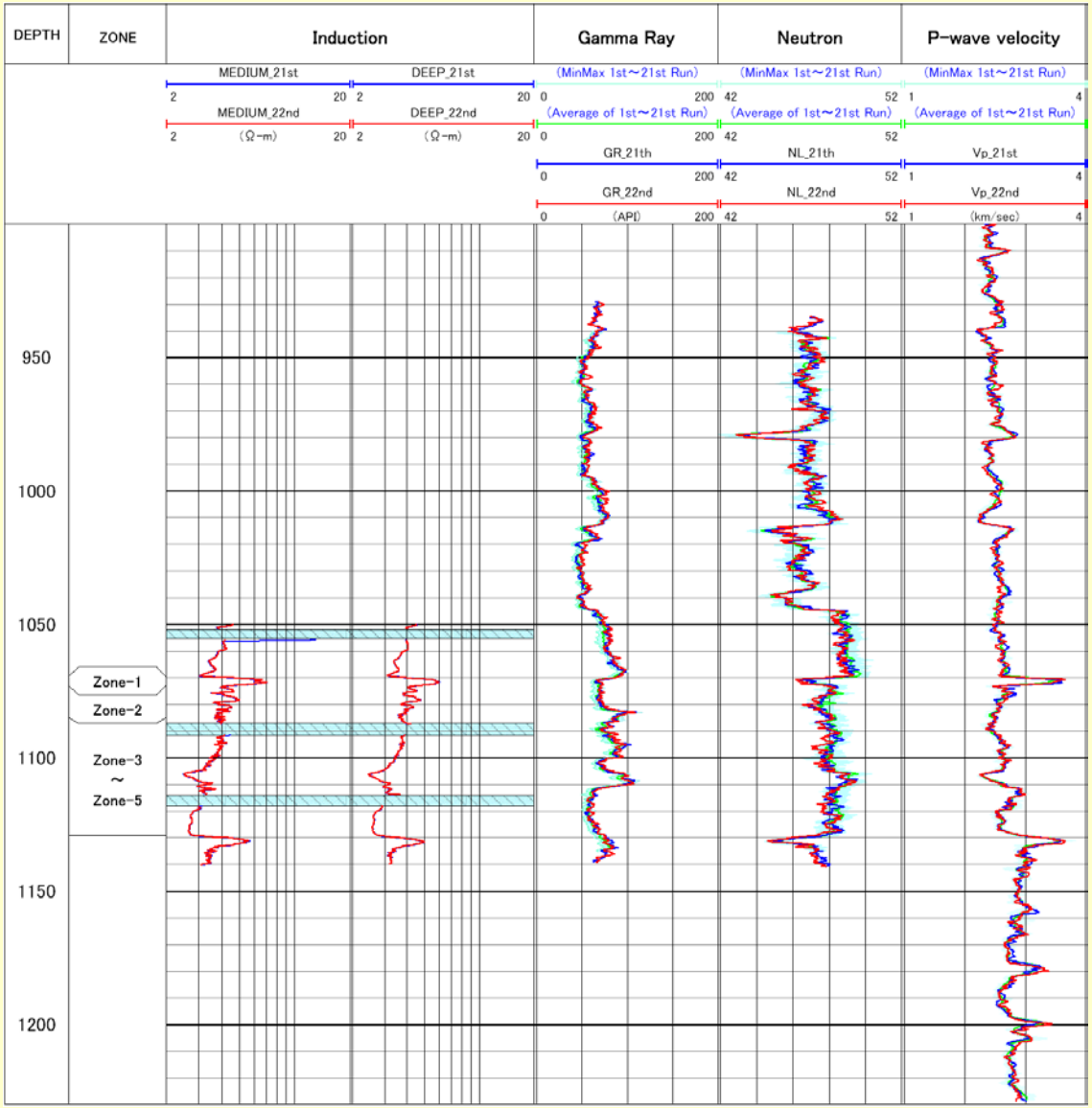


Neutron Logging @ OB-2 (Neutron porosity)



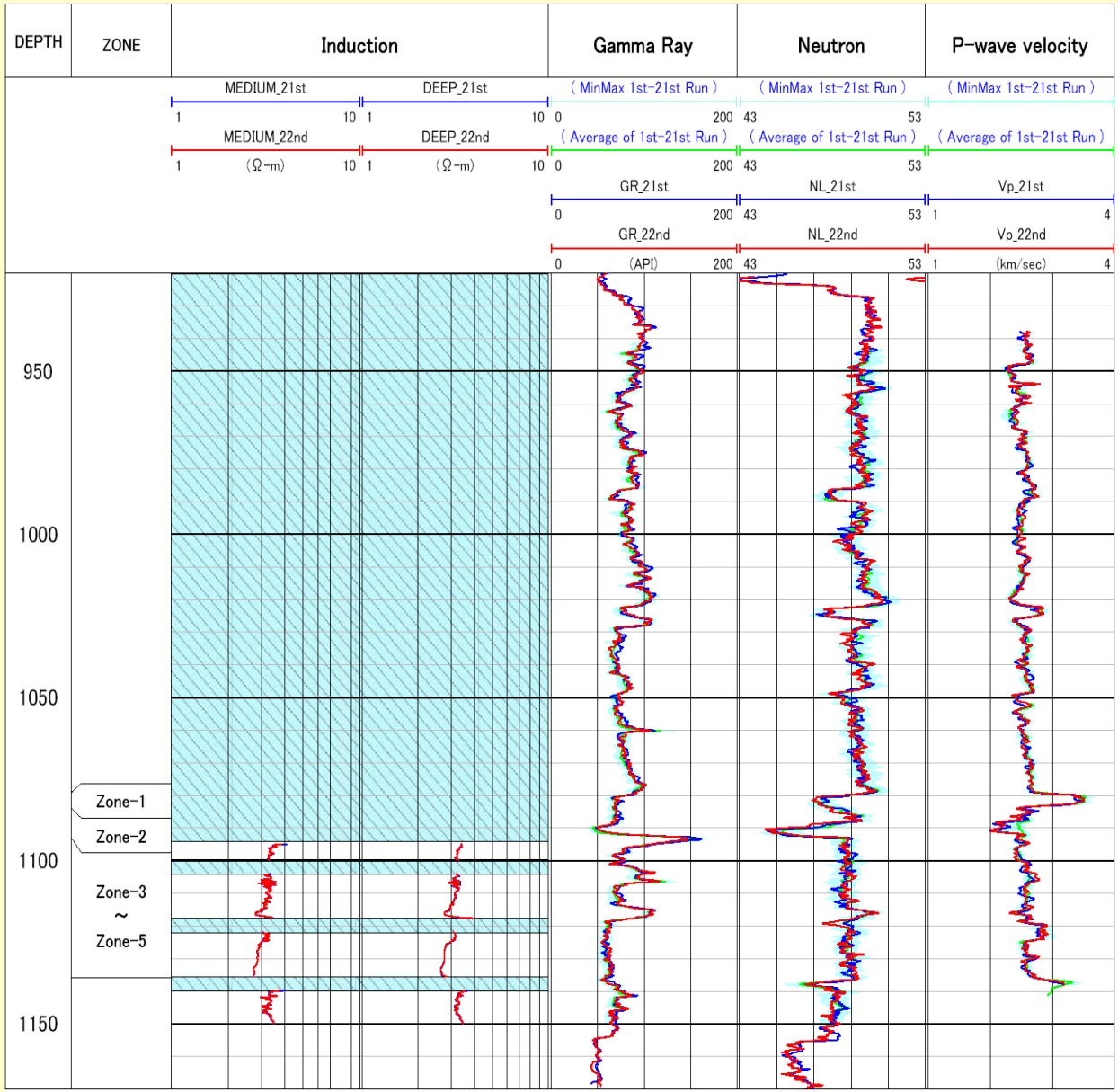
Well Logging Results Before & after the Earthquake

OB-3

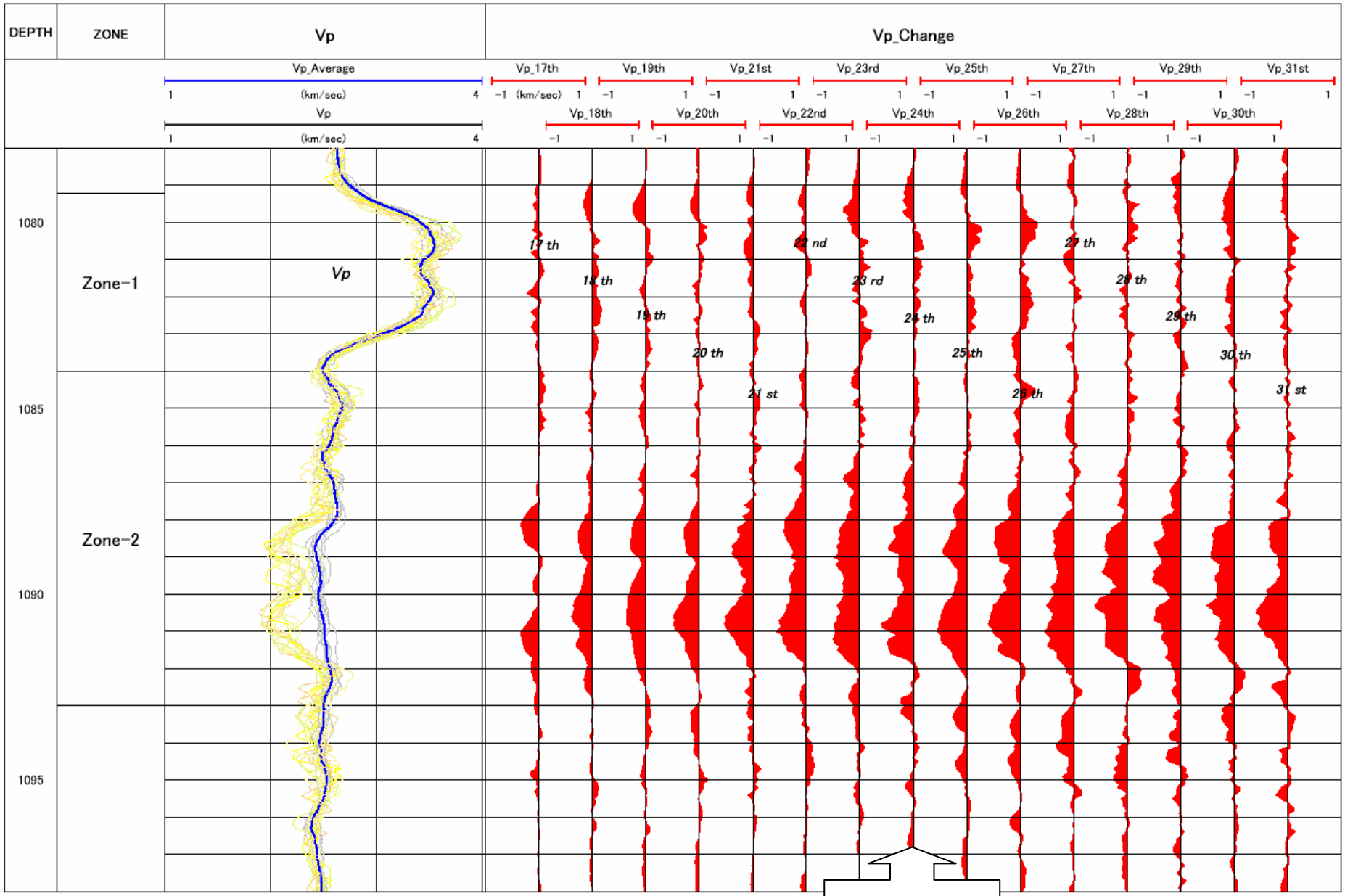


Well Logging Results Before & after the Earthquake

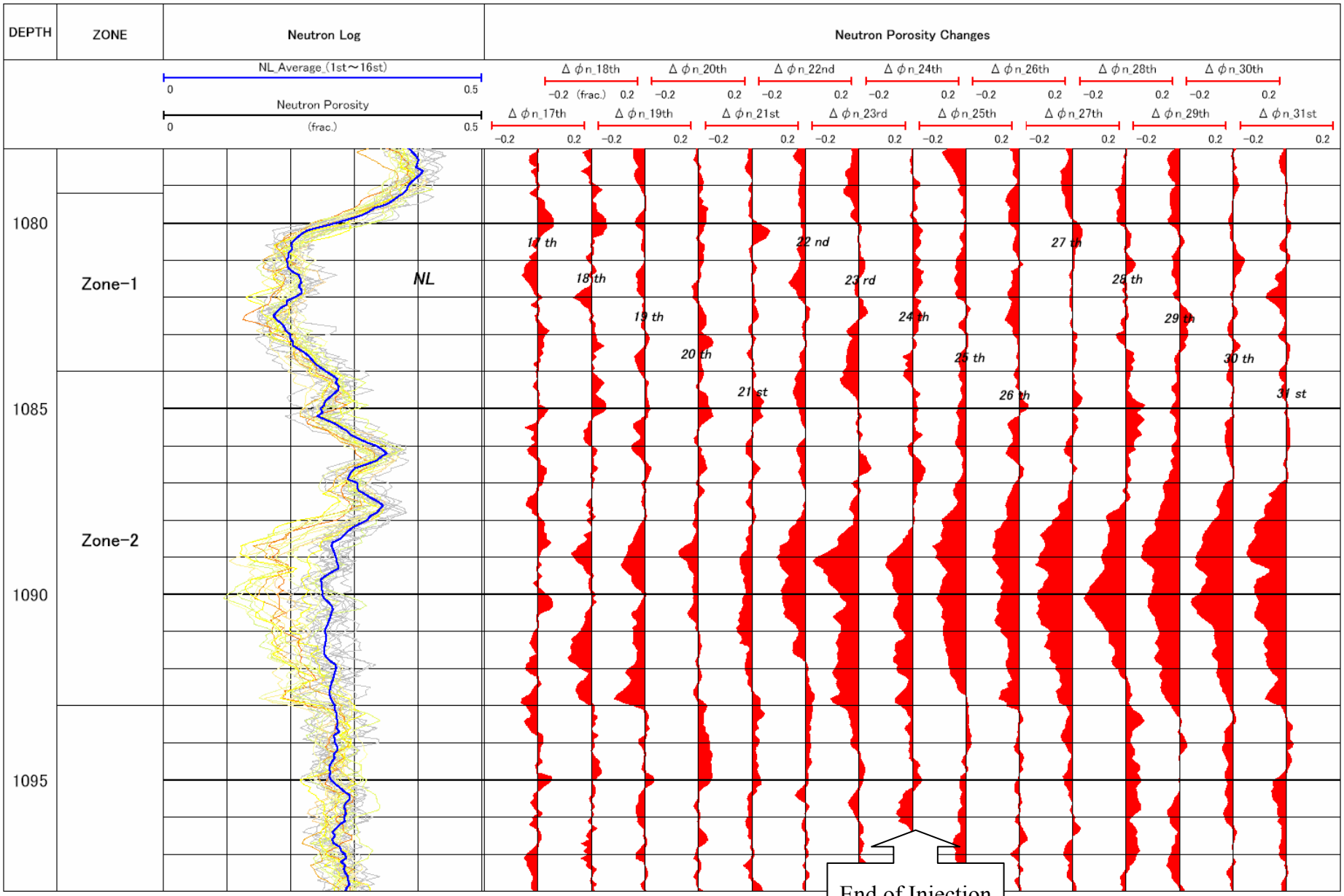
OB-4



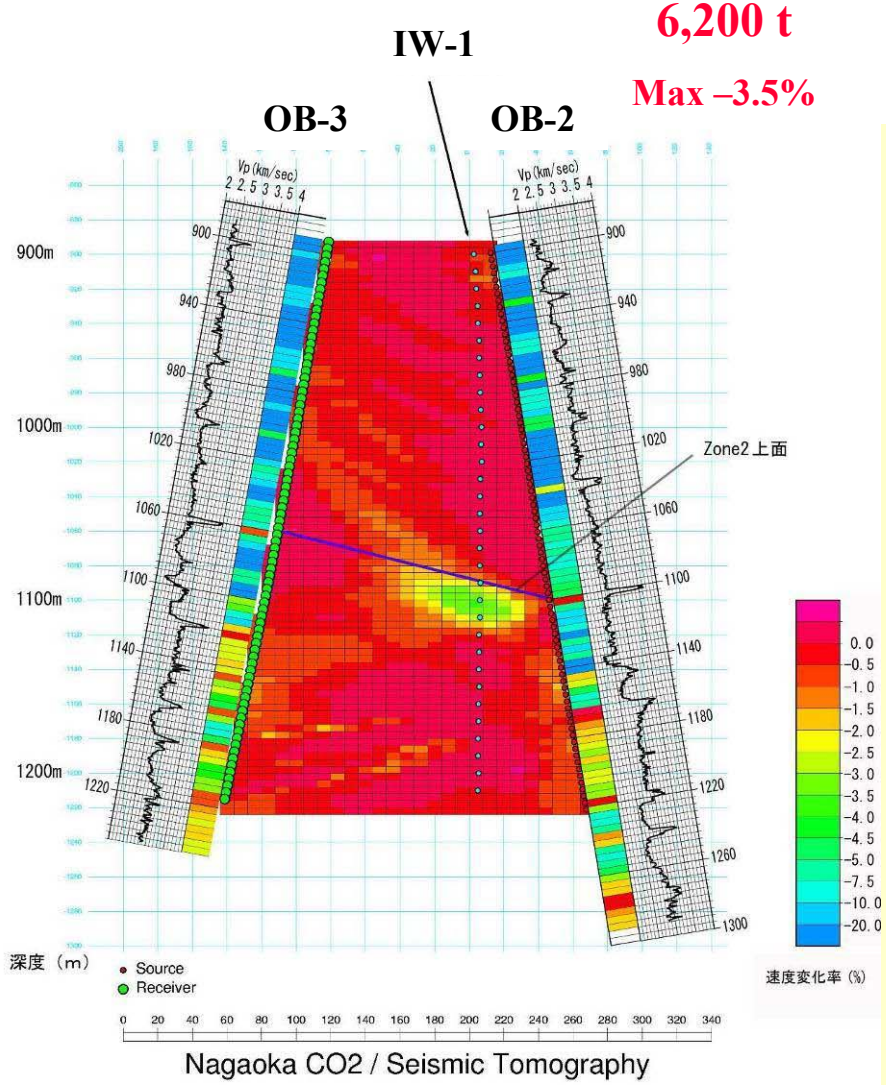
Sonic Logging @OB-4 (Vp)



Neutron Logging @OB-4 (Neutron porosity)

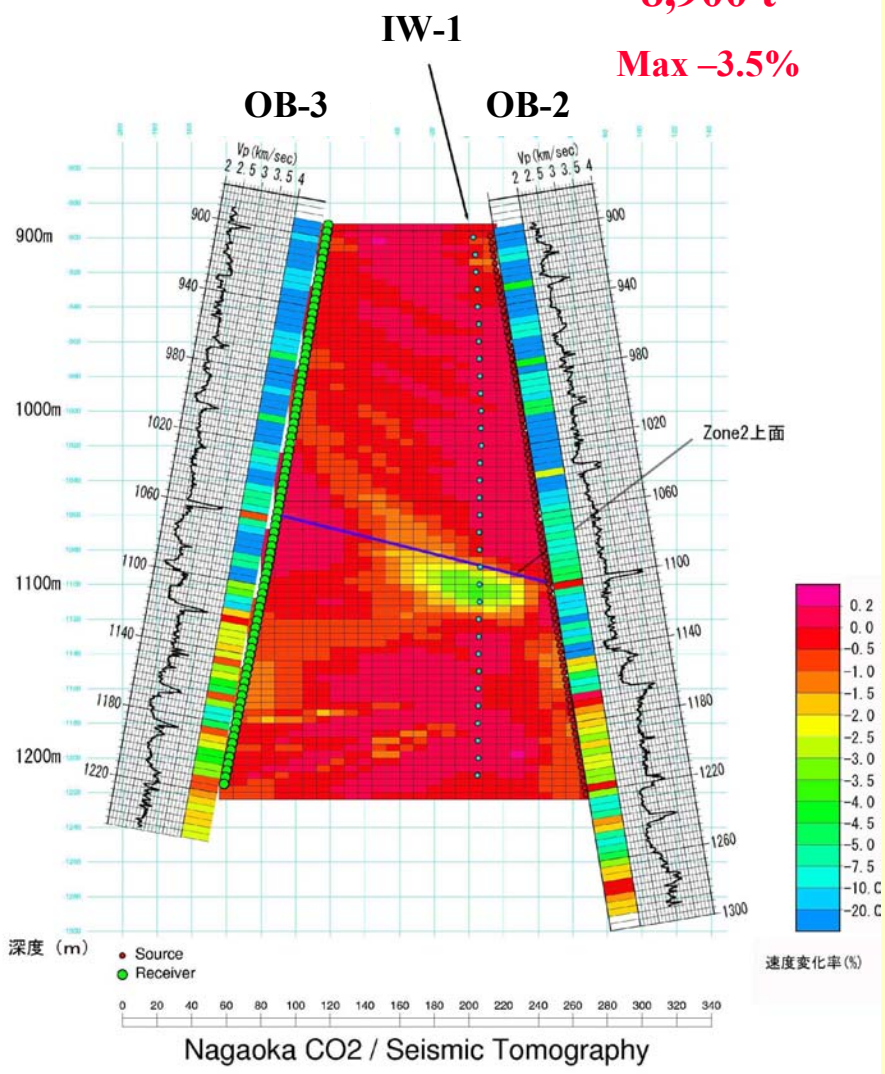


Before the Earthquake



MS2/BLS

After the Earthquake



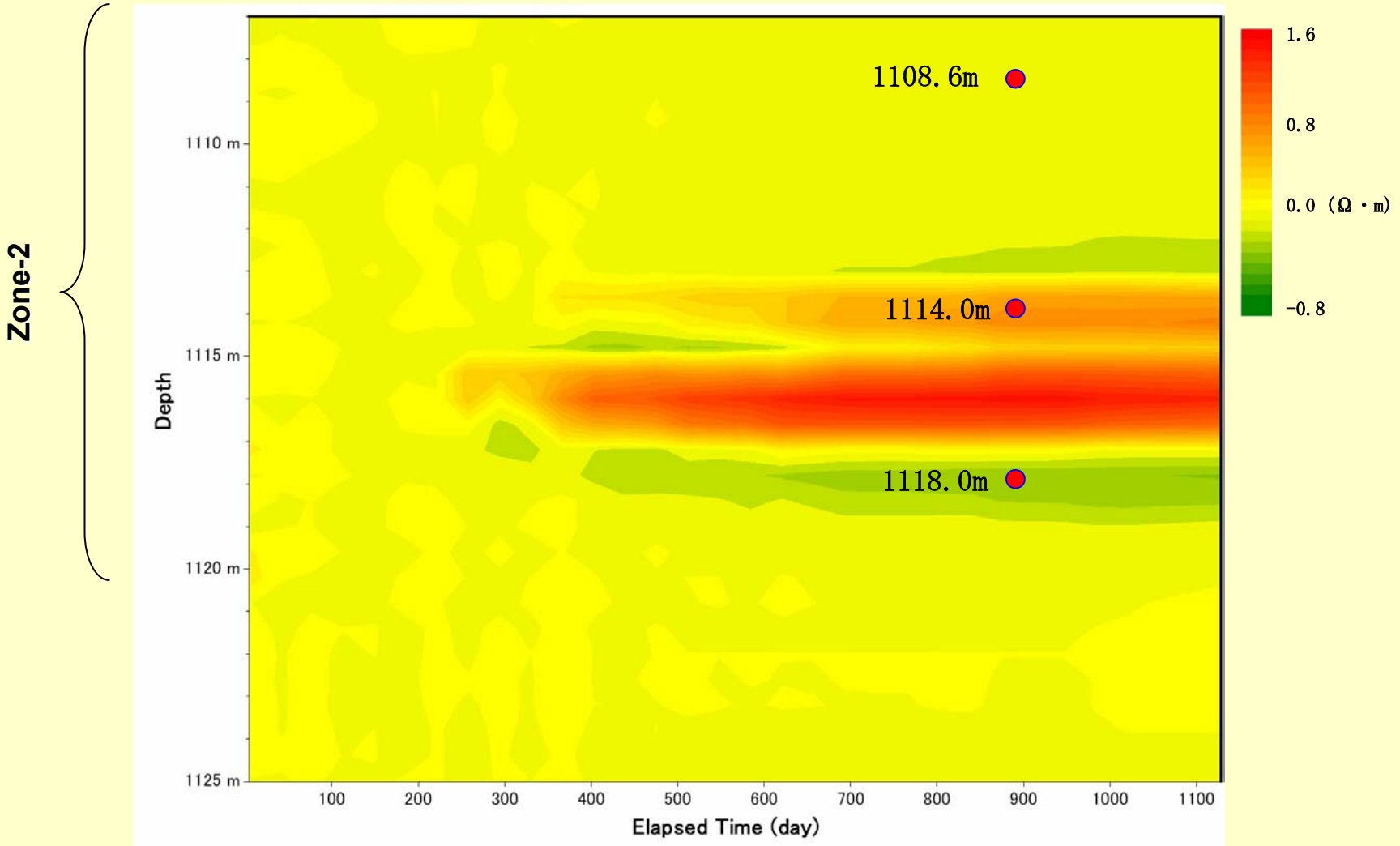
MS3/BLS

Fluid sampling

CHDT*(Cased Hole Dynamic Tester)

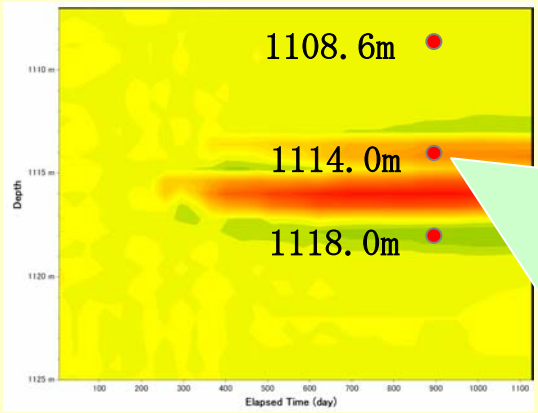
Fluid sampling

Resistivity Changes at OB-2 and Sampling Points



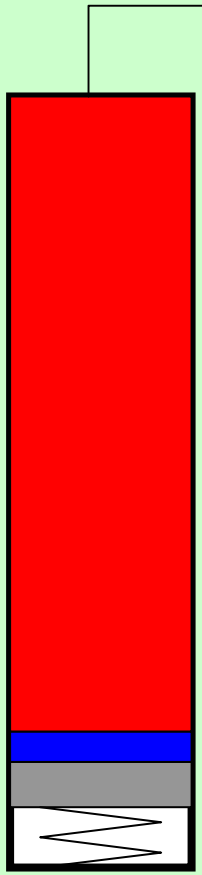
Fluid sampling

OB-2 1114m : Mostly free CO_2



Gas:
≒3,500ml

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



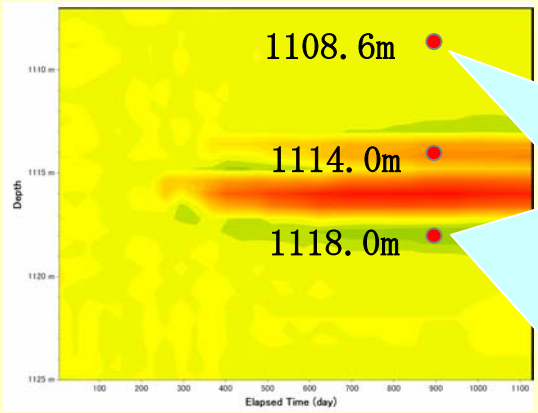
Gas composition

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

Sample Chamber
(volume 3,786ml)

Fluid sampling

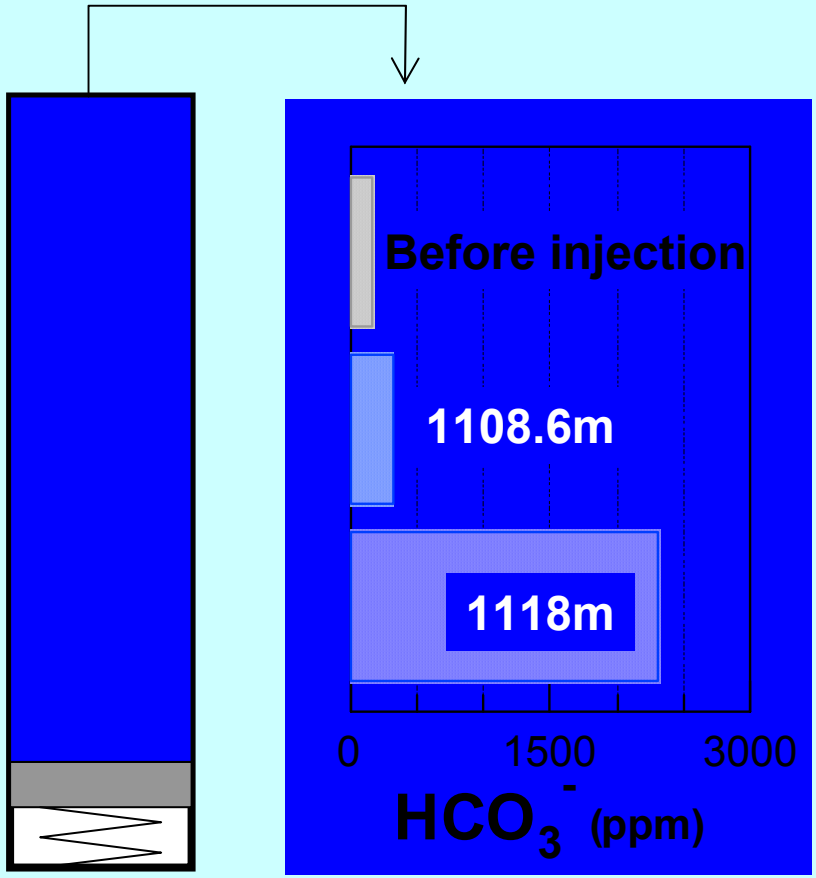
OB-2 1108.6m & 1118m : Water



At 1118m, formation water rich in dissolved CO_2.

Gas:
None

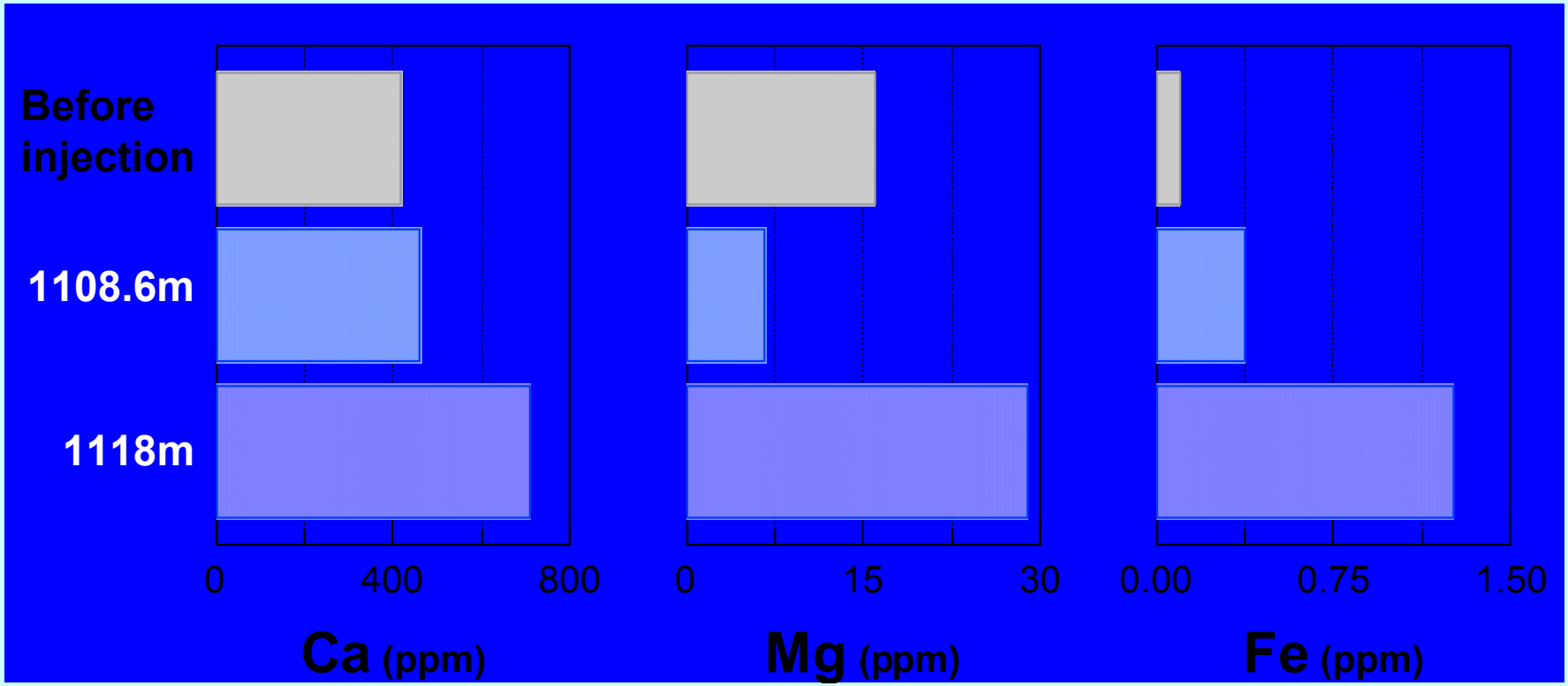
Water:
3430ml
-3540ml
(Contamination <1%)



Sample Chamber
(volume 3,786ml)

Fluid sampling

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



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

Summary of the Field Surveys

- **No differences between drawdown curves between usual shut downs and the emergency shut down.**
  → ***Integrity of the reservoir***
- **No anomalies in the CBL results.**
  → ***Integrity of boreholes***
- **No anomalies in well logging results.**
  → ***Integrity of CO_2 containment***
- **No anomalies in crosswell tomography result.**
  → ***Integrity of the aquifer & CO_2 containment***

Assessing the long term efficacy of CO_2 geological storage by atmospheric monitoring

David Etheridge[1,2], Ray Leuning[1,2] and Kevin Dodds[3,2]

1 CSIRO Marine and Atmospheric Research, Aspendale and Canberra, Australia

2 CRC for Greenhouse Gas Technologies, Canberra, Australia

3 CSIRO Petroleum Research, Kensington, Australia

CSIRO

CO2CRC

The need to monitor the atmosphere

- Verify the containment of CO_2 storage
- The atmosphere is where CO_2
  - causes greenhouse climate change
  - can impact on health and safety
- Complement subsurface monitoring

correspondence

Nature **433**, 683 (17 February 2005); doi:10.1038/433683b

Emissions control needs atmospheric verification

E. Nisbet, 2005

Attributes of atmospheric monitoring

- Continuous, unattended
- Not invasive
- Integrates across multiple point or diffuse emissions
- But is it too late if a leak is detected?

Atmospheric M and V hierarchy

		Atmospheric quantities required		
Aim	Concern/purpose	CO_2 concentrations	Other gas concentrations, isotopes, tracers	Transport and dispersion - CO_2 fluxes
Detect leak	Air quality, HS and E, public acceptance, inform project operators	*		
Attribute leak	Regulatory matters, public acceptance, inform project operators	*	*	
Quantify leak	Effectiveness of GH gas control, carbon accounting and trading	*	*	*

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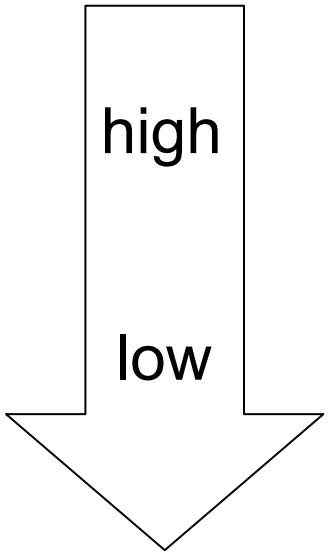
CO2CRC

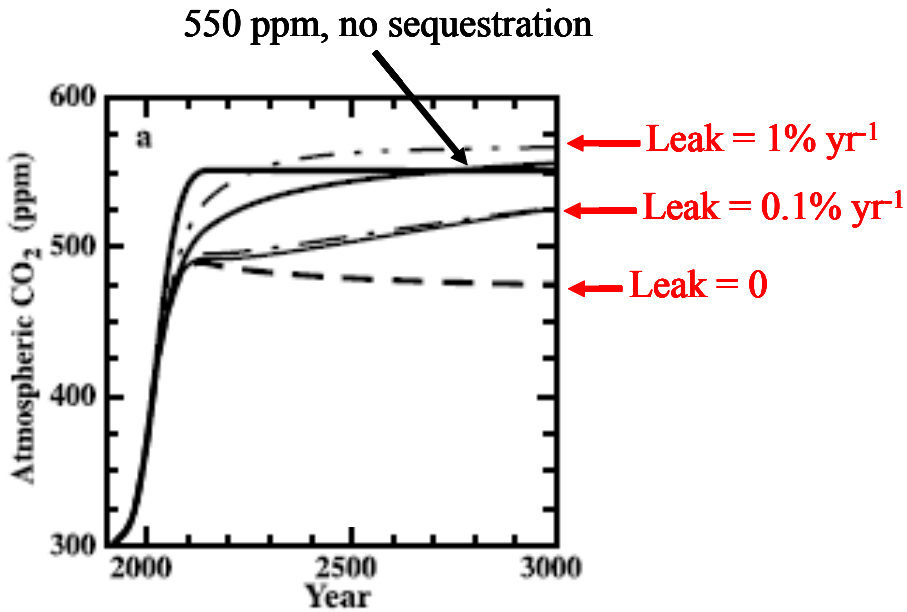
What rate of leakage is acceptable?



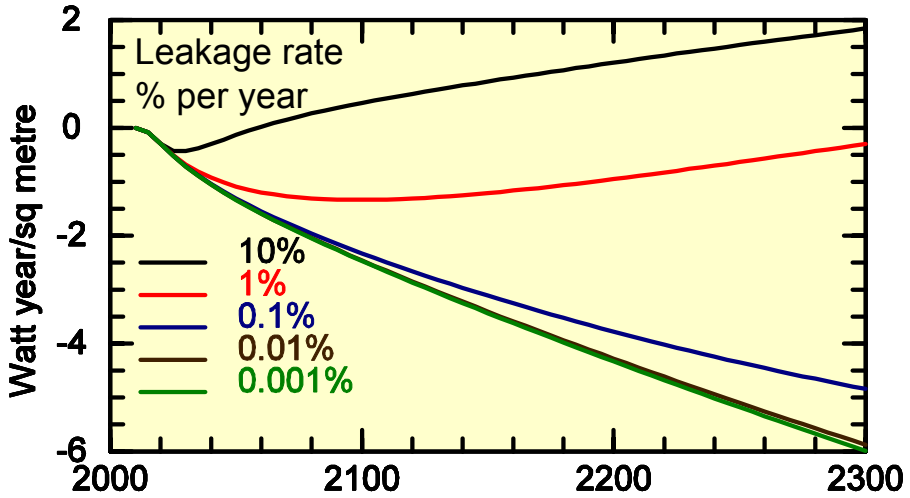
- HS and E requirements
- GHG mitigation requirements
- Geological expectations

…….but estimates are always > zero

Global leak rate scenarios



Future global CO_2 (Haughan and Joos, GRL 2005). Sequester 30% more CO_2 than 550 ppm case; Energy-CO_2 cost = 20%.



Future radiative forcing by CO_2 (I. Enting, Greenhouse 2005). Capture 1 GtC/yr 2010-2020 at 90% efficiency; Energy-CO_2 cost = 30%.

Leakage of 1% /yr provides short term mitigation

0.1% /yr or less is required for sustainability

Could this be verified by atmospheric techniques?

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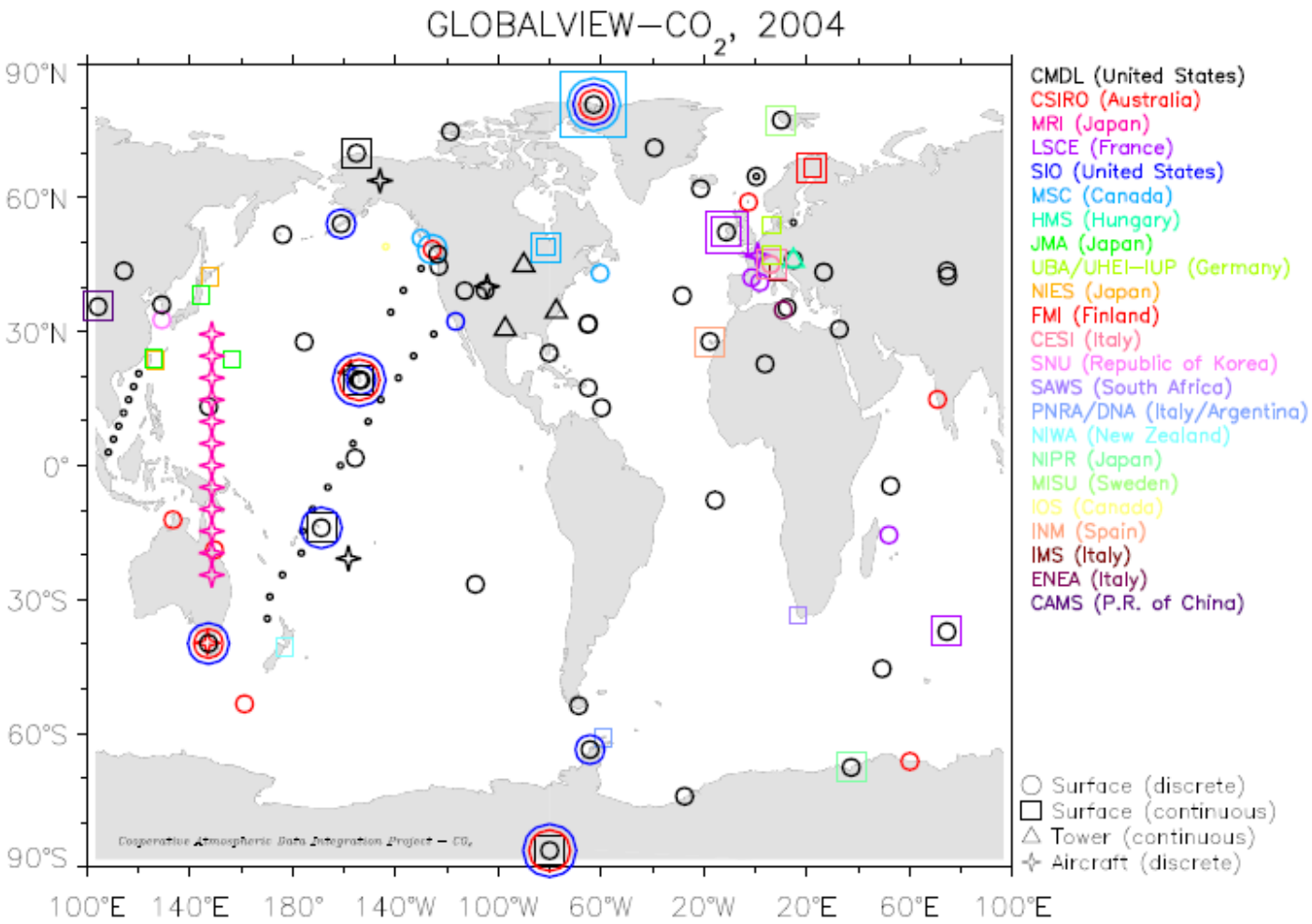
CO2CRC

CO_2 (and associated gases) in the atmosphere-
global baseline monitoring



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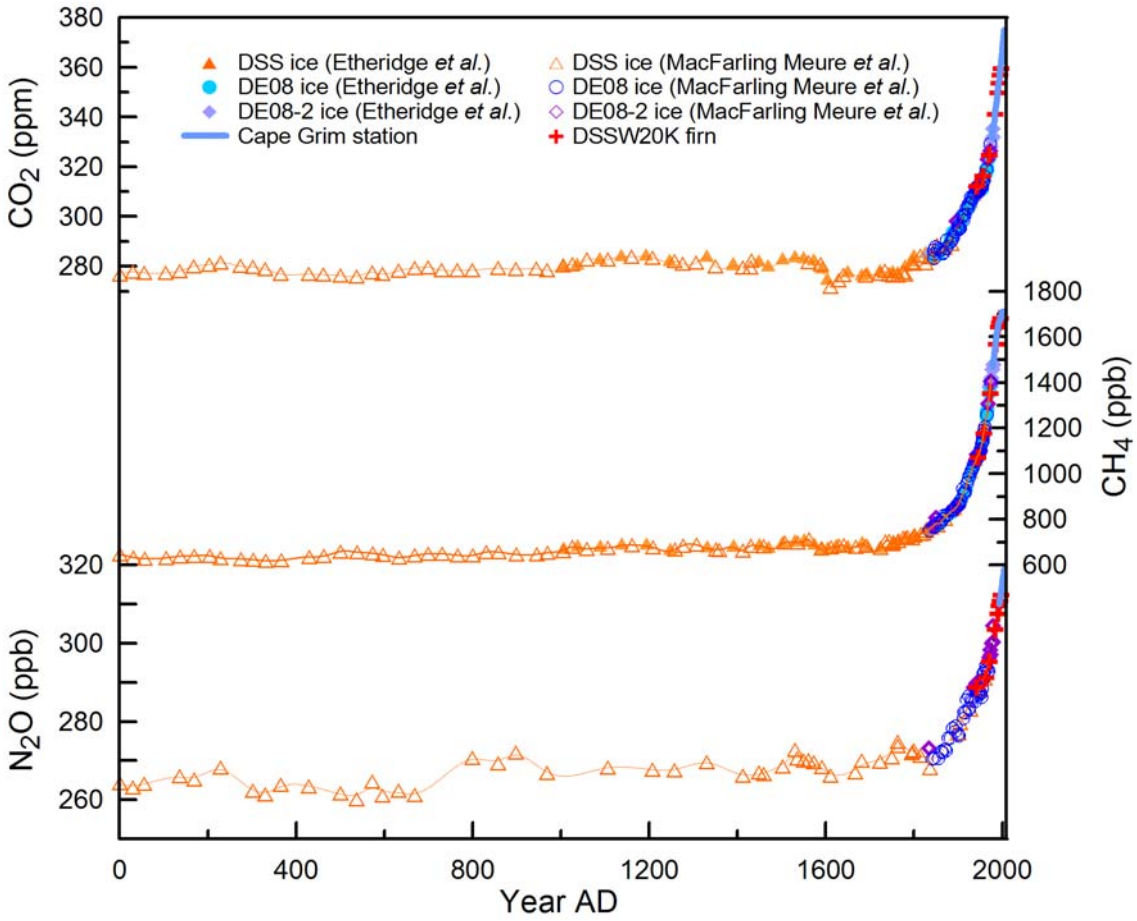
CO2CRC

Global CO_2, CH_4 and N_2O past 2000 years-
from Cape Grim baseline station (1978+) and Antarctic ice



MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A. and Elkins, J. *Geophysical Research Letters*, 2006.
Etheridge, D. M., Steele, L. P., Francey, R. J., and Langenfelds, R. L. *Journal of Geophysical Research,* 1998.
Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J. M., and Morgan, V. I. *Journal of Geophysical Research*, 1996.

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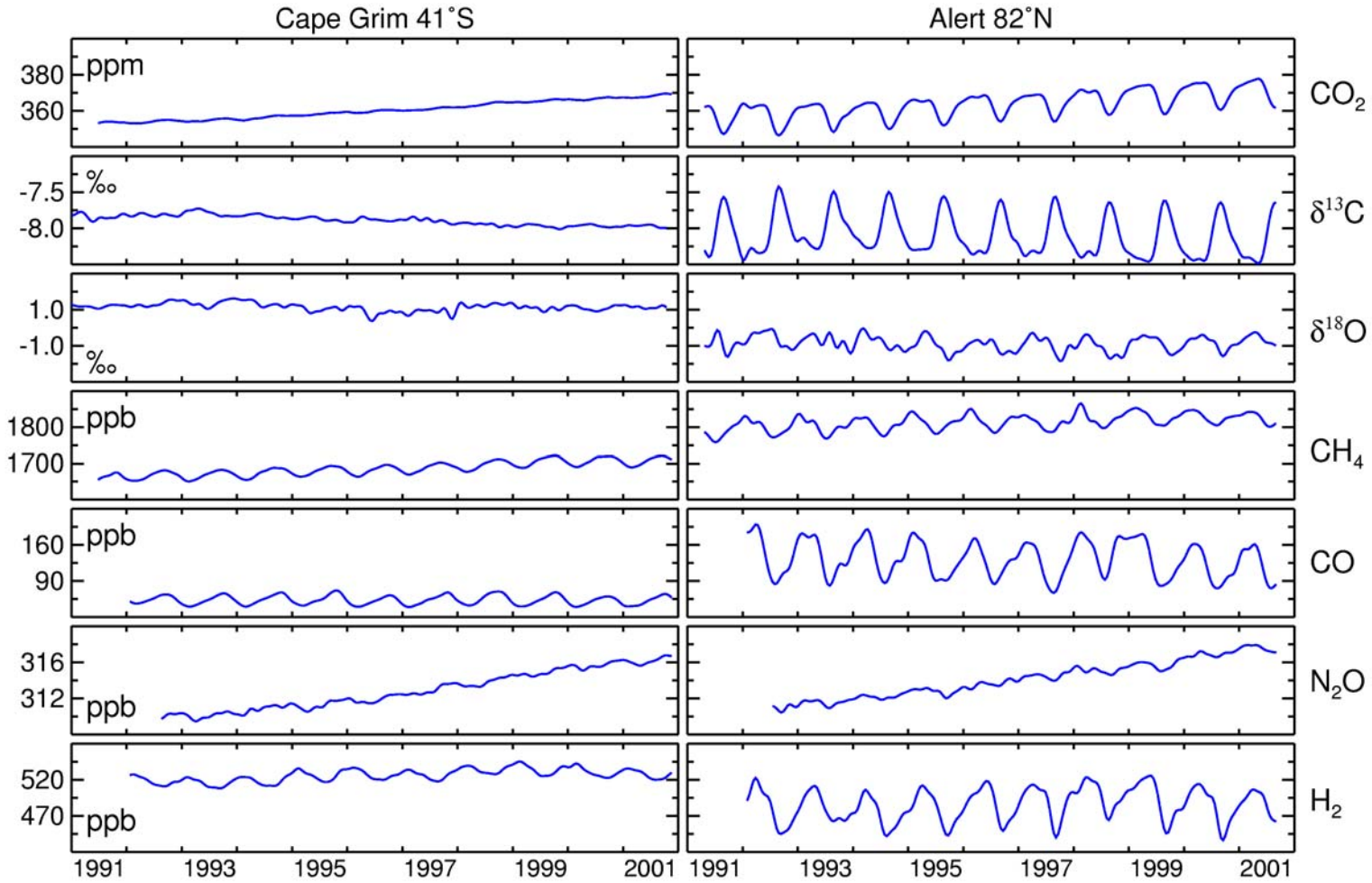
CO2 CRC

Past decade - background atmosphere



Data: CSIRO Marine and Atmospheric Research and Bureau of Meteorology

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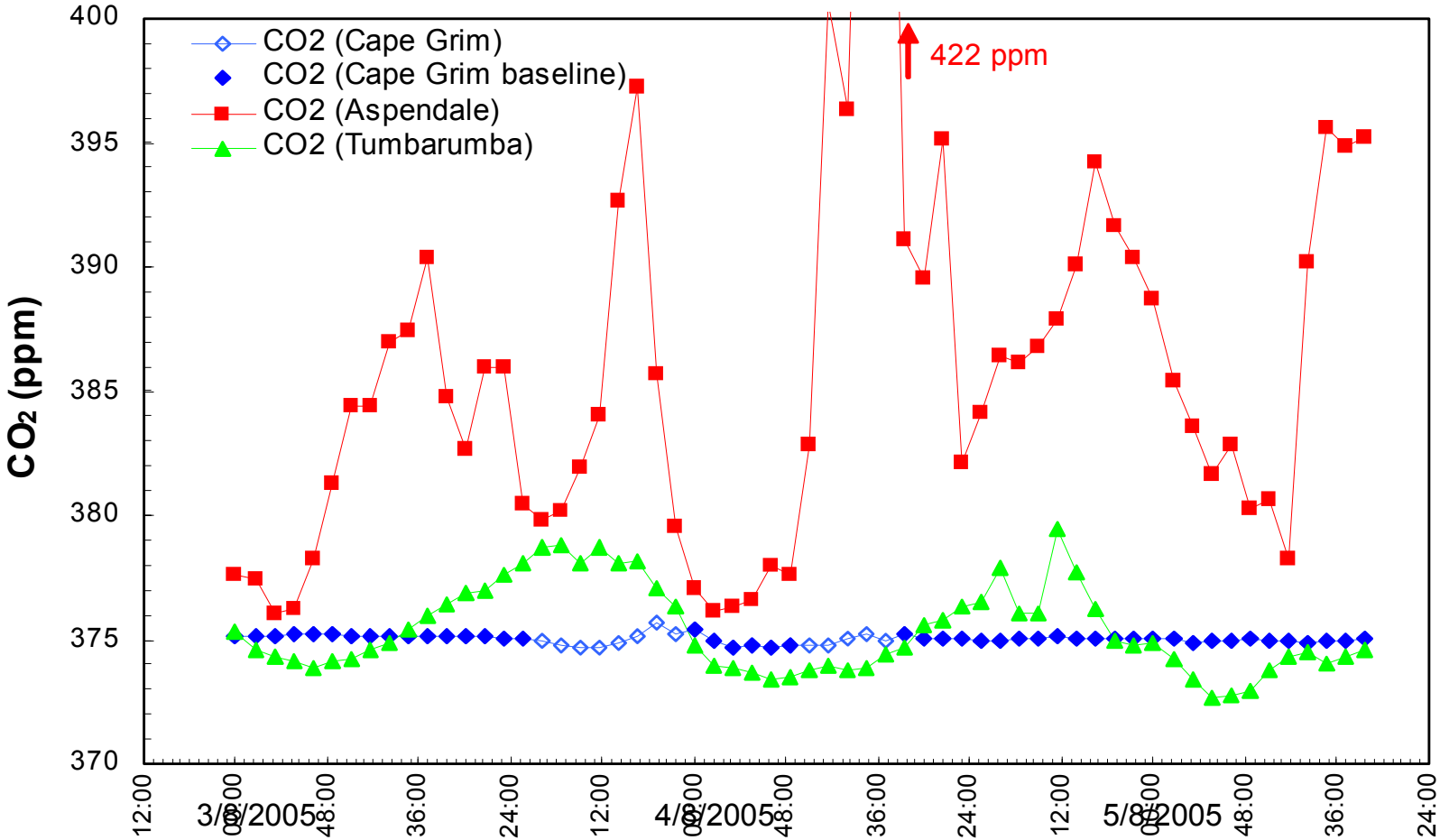
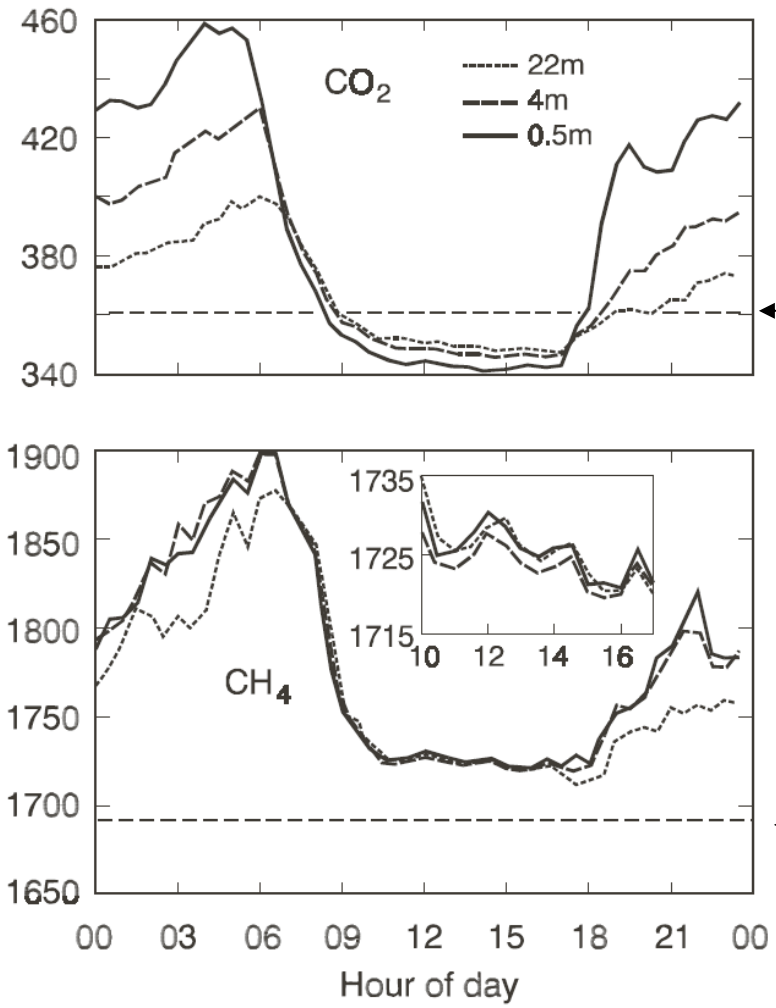
CO2 CRC

CO_2 in the local atmosphere



Data: CSIRO Marine and Atmospheric Research and Bureau of Meteorology

CO_2 and CH_4 in the rural atmosphere



← background (Cape Grim)

← background (Cape Grim)

Griffith, Leuning, Denmead, Jamie,
Atmospheric Environment, 2002

How to differentiate these variations from possible leaks

- Baseline record - before, during, after injection
- Tracers - added
- Tracers - natural
- Measure natural fluxes and determine residual
- Model natural fluxes and determine residual
- Statistical strategy based on different temporal characteristics
- Atmospheric transport- dispersion and back trajectories

"Tracers" to discriminate CO_2 storage leak from:

	Naturally occurring	Introduced with fluid
Terrestrial biology	$^{13}CO_2$, $^{14}CO_2$	SF_6, CF_4
Biomass burning	CO	SF_6, CF_4
Fossil fuel burning	CO, $^{14}CO_2$	SF_6, CF_4
Livestock CH_4 cf displaced CH_4	$^{13}CH_4$, $^{14}CH_4$	
Geological-natural	Radon?	SF_6, CF_4
Geological-facilities	?	SF_6, CF_4

Concentration measurements

Continuous, in situ, high precision CO_2, linked to network and international standards - LoFlo analyser system

Flask air sampling for isotopes, tracers, CH_4….measurements back in laboratories

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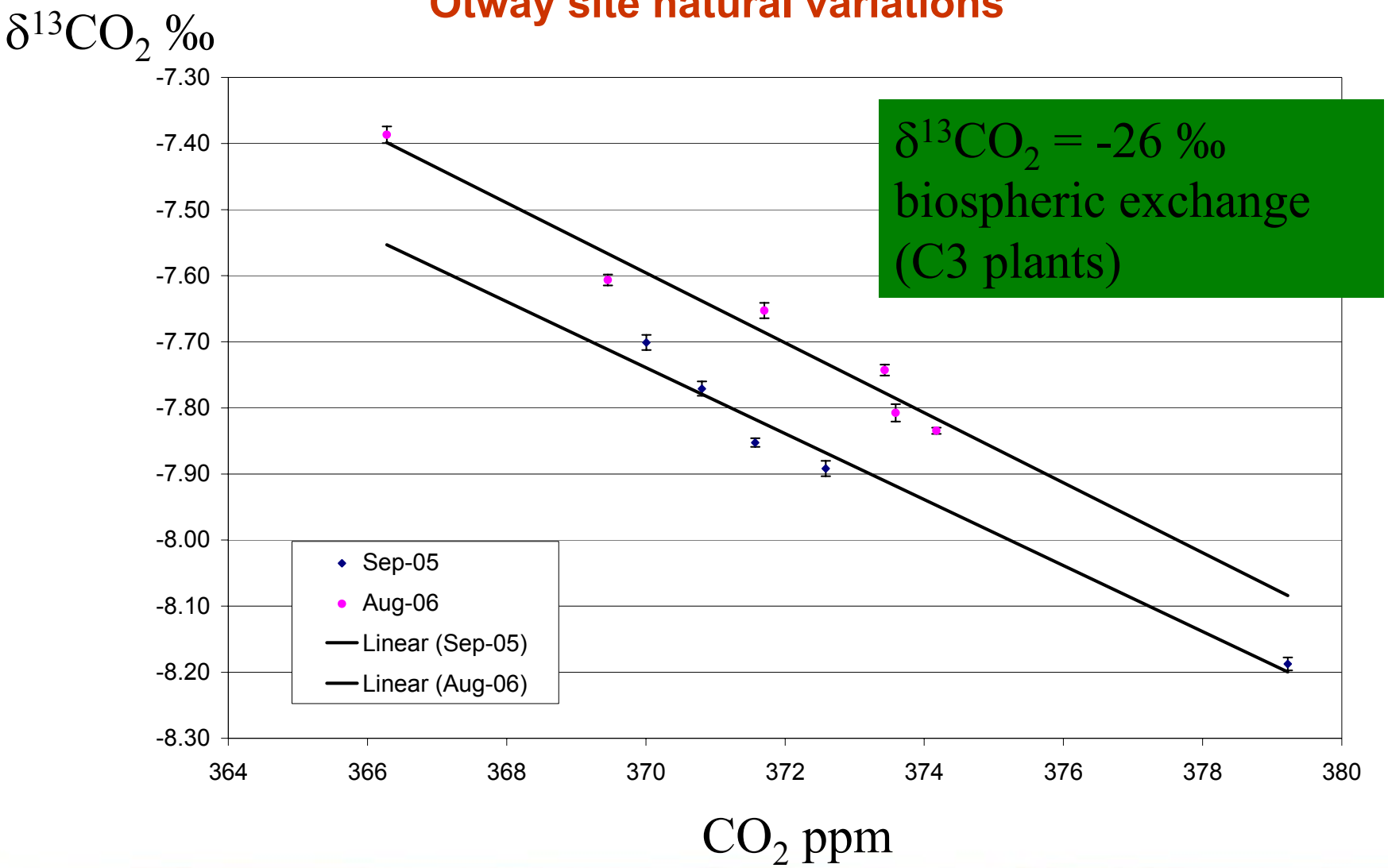
CO2CRC

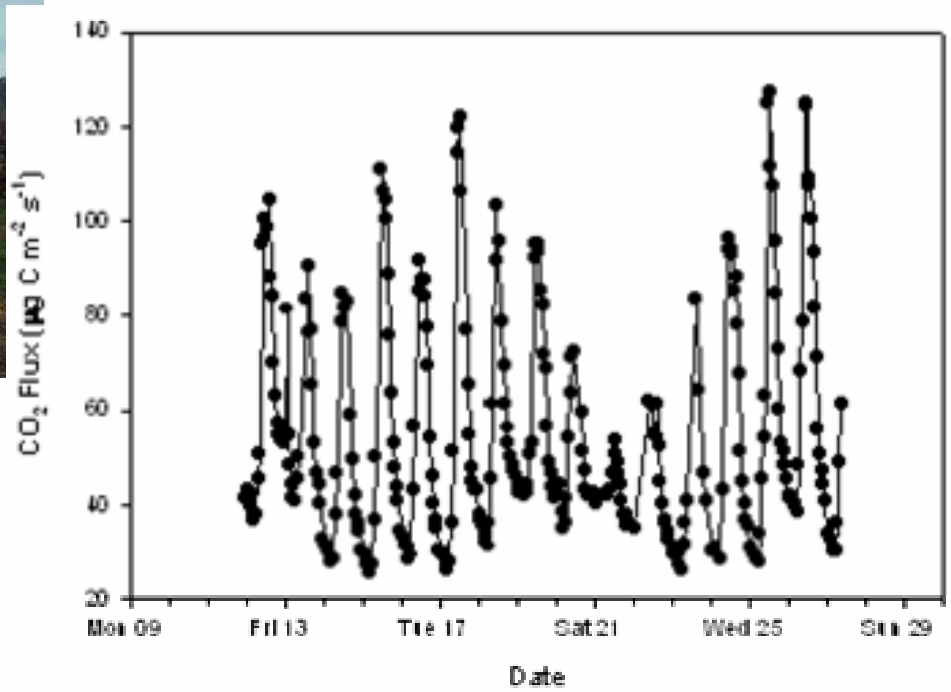
Measured CO_2 variations and $\delta^{13}CO_2$ signature- Otway site natural variations



CSIRO

CO2CRC

Flux tower and flux chamber



Images: R. Leuning Data: M. Meyer
CSIRO Marine and Atmospheric Research

CSIRO

CO2 CRC

Statistically differentiate natural signal and leakage signal

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L19403, doi:10.1029/2005GL024281, 2005

An improved strategy to detect CO_2 leakage for verification of geologic carbon sequestration

J. L. Lewicki,[1] G. E. Hilley,[2] and C. M. Oldenburg[1]

Received 2 August 2005; revised 26 August 2005; accepted 14 September 2005; published 15 October 2005.

[1] The long-term storage of CO_2 must be verified to ensure the success of geologic carbon sequestration projects. To detect subtle CO_2 leakage signals, we present a strategy that integrates near-surface measurements of CO_2 fluxes or concentrations with an algorithm that enhances temporally- and spatially-correlated leakage signals while suppressing random background noise. We assess the performance of this strategy using synthetic CO_2 flux data sets and modeled surface CO_2 leakage. These simulations provide a means of estimating the number of measurements required to detect a potential CO_2 leakage signal of given magnitude and area. Results show that given a rigorous and well-planned field sampling program, subtle surface CO_2 leakage may be detected using the algorithm; however, leakage of very limited spatial extent or exceedingly small magnitude may be difficult to detect with a reasonable set of monitoring resources. Citation: Lewicki, J. L., G. E. Hilley, and C. M. Oldenburg (2005), An improved strategy to detect CO_2 leakage for verification of geologic carbon sequestration, *Geophys. Res. Lett.*, *32*, L19403, doi:10.1029/2005GL024281.

1. Introduction

[2] One strategy to mitigate potential climate change associated with elevated atmospheric CO_2 concentrations is the sequestration of anthropogenic CO_2 in deep geologic formations [e.g., *International Energy Agency*, 1997; *et al.*, 2003], within which a potentially small CO_2 anomaly may be hidden.

[4] We present a strategy that integrates near-surface measurements of CO_2 with statistical analysis to enhance properties of the data that are associated with leakage, while reducing random background contributions. Using a suite of synthetic CO_2 flux data sets and modeled CO_2 surface leakage from a flow and transport simulator, we investigate various combinations of sampling and analysis approaches to optimize leakage detection and quantification while minimizing the number of measurements. We discuss implications for geologic carbon storage verification and other studies where detection of a small anomalous signal within background noise is required.

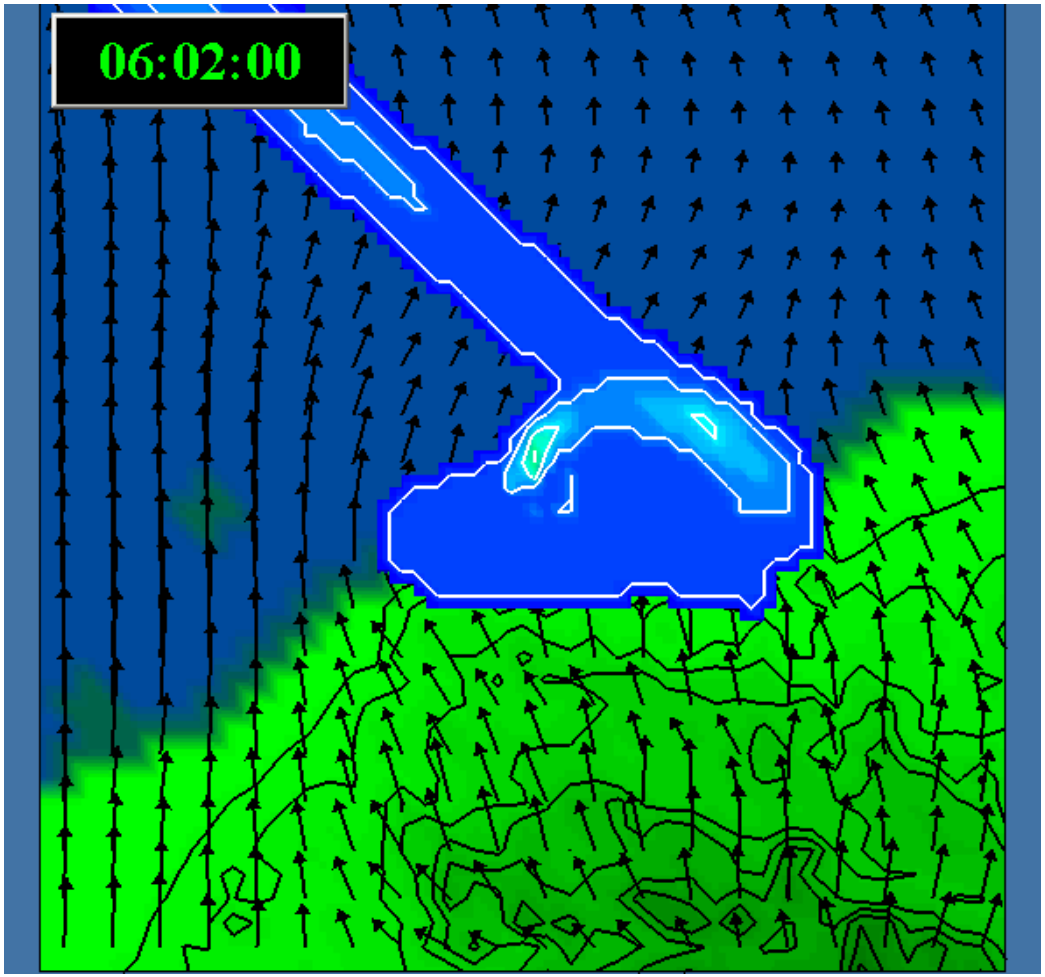
2. Methods

[3] Our filtering method exploits several contrasting properties of near-surface CO_2 fluxes and concentrations derived from natural background processes versus those from CO_2 leakage. First, the production of CO_2 by background processes (e.g., soil respiration) is highly spatially heterogeneous, resulting soil CO_2 fluxes and concentrations are therefore poorly correlated on moderate to large spatial scales (e.g., ≥5 m) [e.g., *Hoyan et al.*, 2000; *Xu and Qi*, 2001; *Lewicki et al.*, 2003]. In contrast, CO_2 derived from leakage along e.g., a well bore or fault should be relatively

CSIRO

CO2CRC

Take advantage of atmospheric transport



TAPM
(The Air
Pollution Model,
CSIRO)

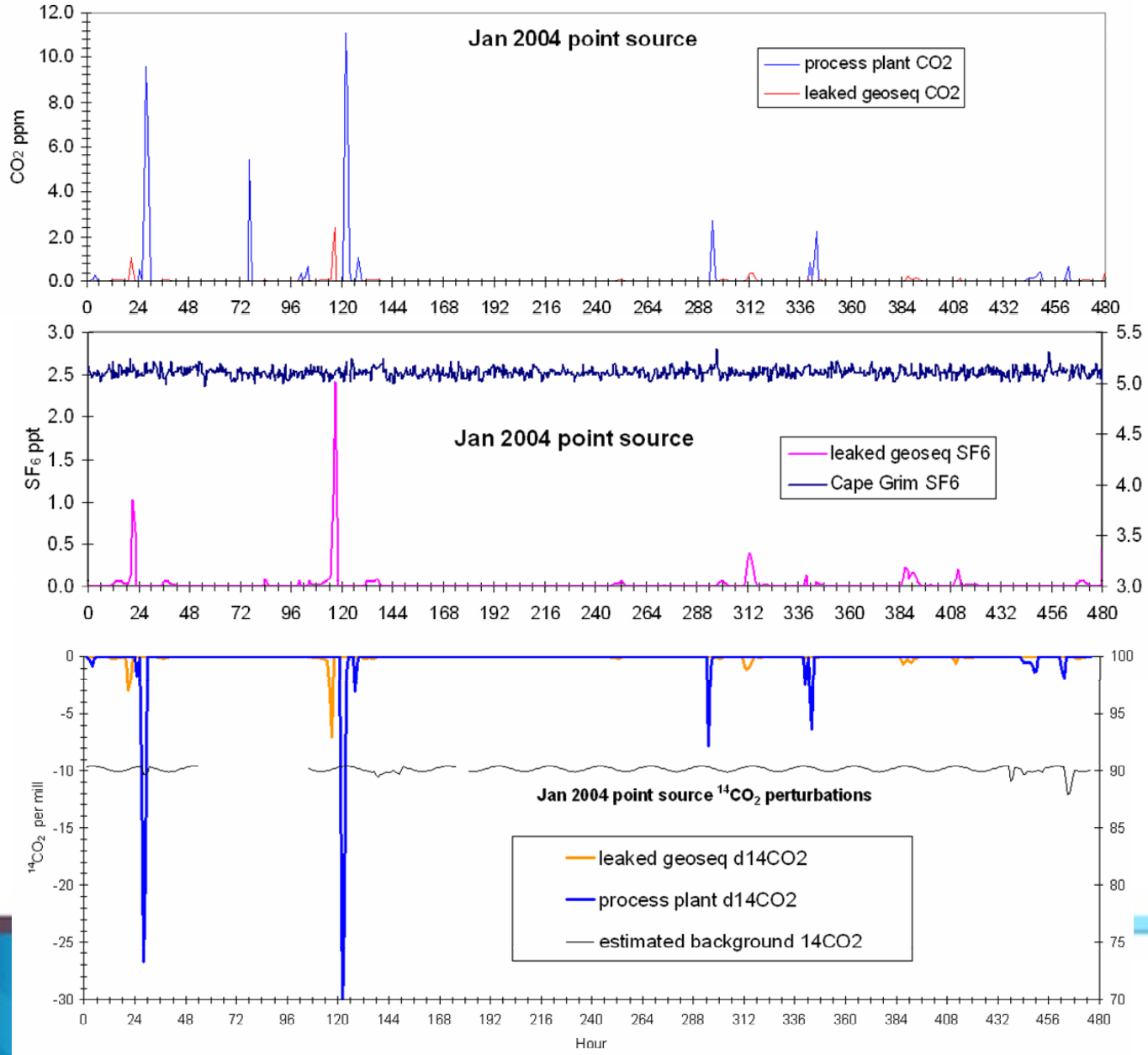
Simulated plume for region of Barrow Island, NW Australia

CSIRO

CO2 CRC

Simulated concentration perturbations

CO_2 and tracers at Otway



700 m from point release at Otway site

1000 t CO_2/yr (~1%/yr of Otway 0.01%/yr Gorgon)

TAPM simulation using actual winds

SF_6 tracer introduced at 1 micromolar

$^{14}CO_2$ based on natural occurrences, not introduced

Conclusions

- Verification of CO_2 storage by atmospheric monitoring will be appropriate for health and safety, public acceptance, carbon accounting and regulatory needs
- Small leakage rates that would compromise storage are just detectable using a suite of techniques

  - concentration measurements (continuous, precise)
  - tracer measurements (continuous, precise, natural and introduced compounds)
  - flux measurements

  – transport modelling

- Detection sensitivity will depend on the setting (meteorology, land cover, other sources), amount and type of CO_2 to be injected

Zero-Emission Research & Technology Center

A collaborative involving DOE National Labs and Universities

- Montana State University
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory
- West Virginia University
- Lawrence Berkeley National Laboratory
- National Energy Technology Laboratory
- Lawrence Livermore National Laboratory

Zero-Emission Research & Technology Center

Mission: Perform technical assessments for geologic carbon sequestration

- Siting, Permitting and Insurability are all issues for geologic sequestration
- Accurate risk assessments are needed
  - The ultimate fate of underground CO_2 needs to be understood
  - Predictive modeling tools with cross validation are needed
- Monitoring and verification technologies and strategies must be developed
- Mitigation technologies and strategies should be developed to further reduce risk

Major Areas of Effort:

- **Basic Sequestration Science**
  - Geophysics and geochemistry of CO_2
  - Interaction with formation minerals and waters
- **Modeling**
  - Understanding two-phase flow
  - Reactive transport
  - Validation with experiments
  - Cross validation of models
- **MMV**
  - Development of new technologies for monitoring and mitigation
  - Assessment of technologies
  - Effective deployment of suites of technologies

A Unique Test Facility at MSU

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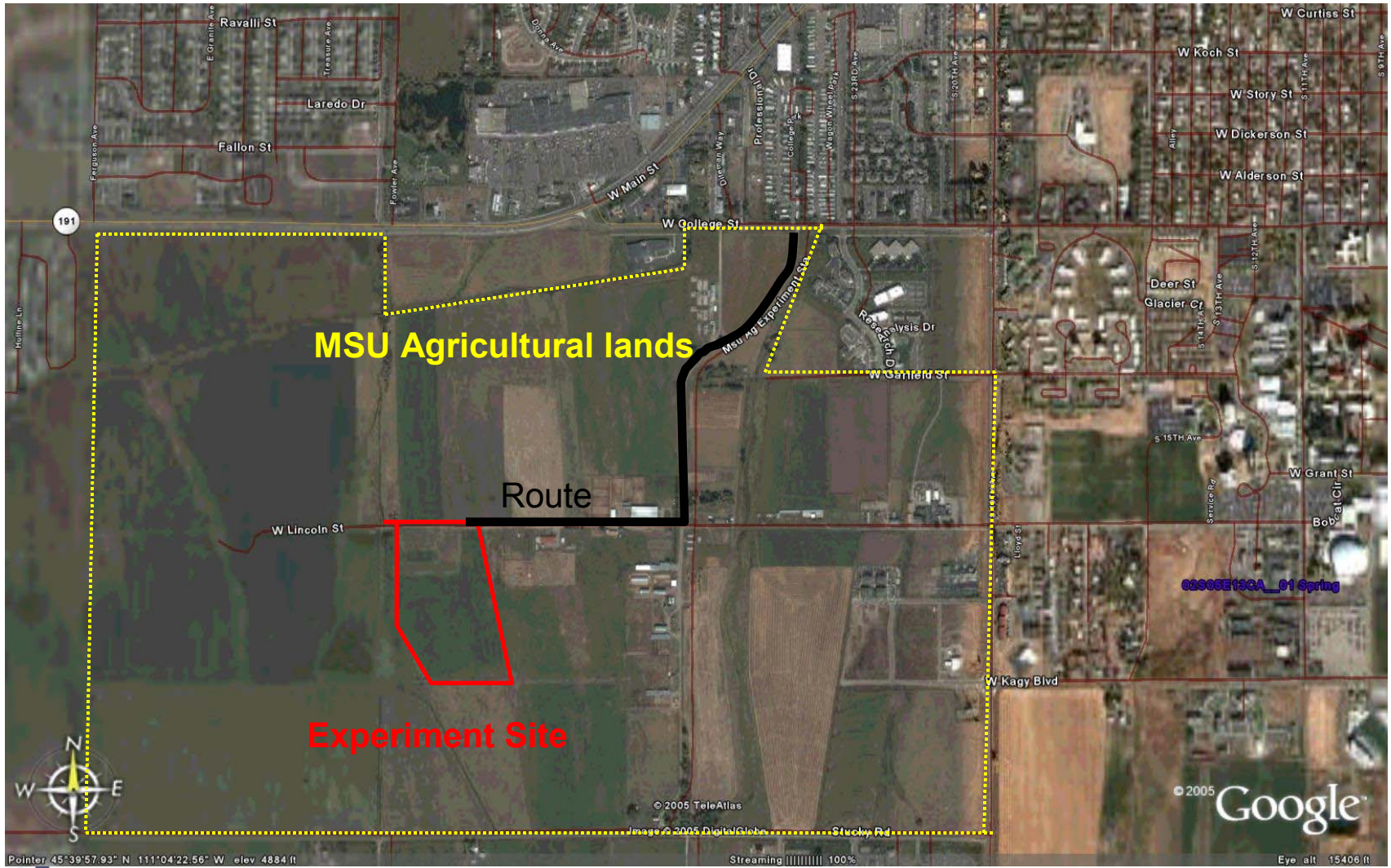

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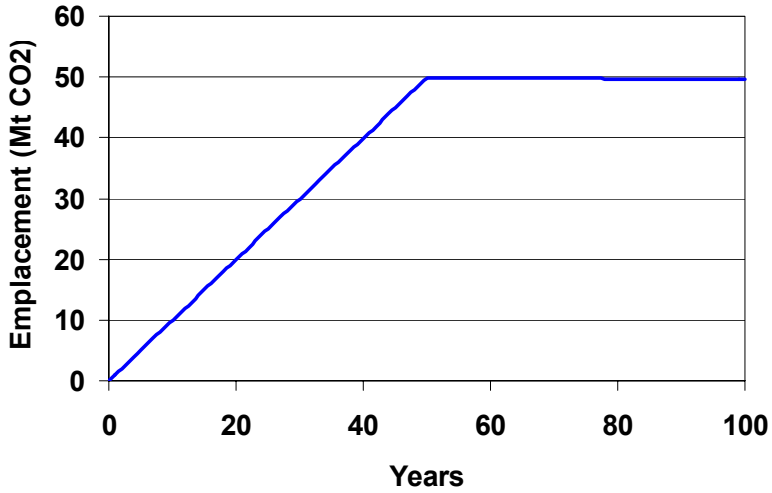
Facility Goals

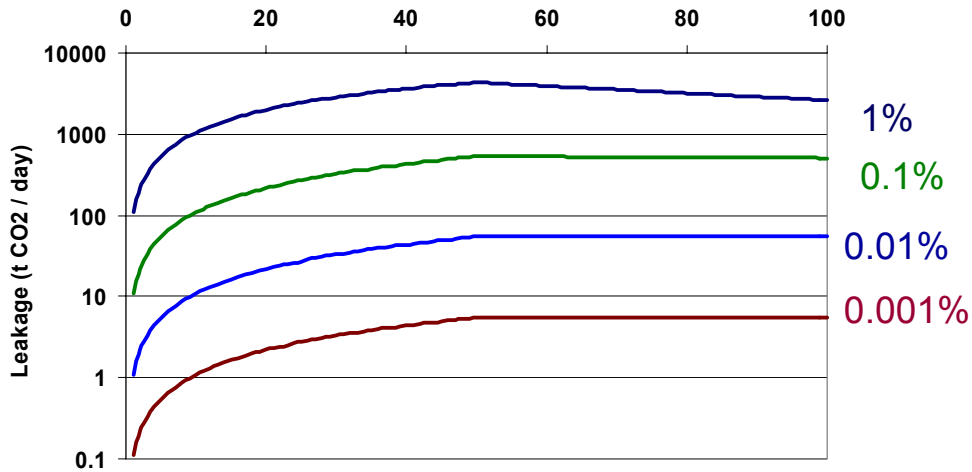
- Develop a site with known injection rates for testing near surface monitoring techniques
- Use this site to establish detection limits for monitoring technologies
- Use this site to improve models for groundwater – vadose zone – atmospheric dispersion models
- Develop a site that is accessible and available for multiple seasons / years

Scenario for Injection Rate Choice

Sally Benson

- **4 Mt/year injection ~ 500 MW power plant**
- **50 years injection**
- **3 Leakage rates**
  - 0.1%/yr. 0.01%/yr, 0.001%/year
- **2 Leakage geometries**
  - Linear fault 10*1,000 m
  - Linear fault 100*1,000 m
- **What is a meaningful rate at which to conduct the experiments?**
- **Emplacement**





Lee Spangler

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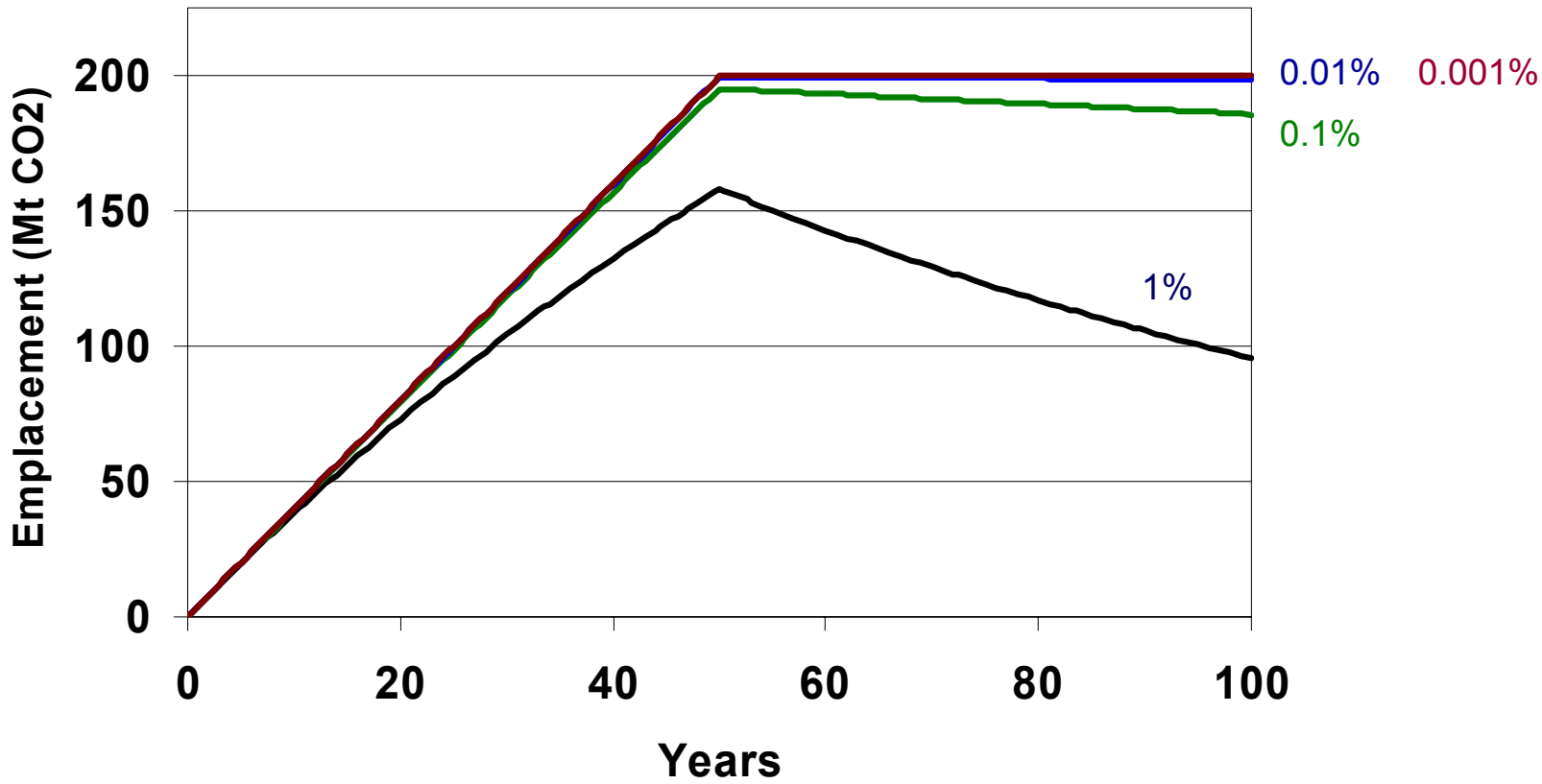
Scenario

Sally Benson



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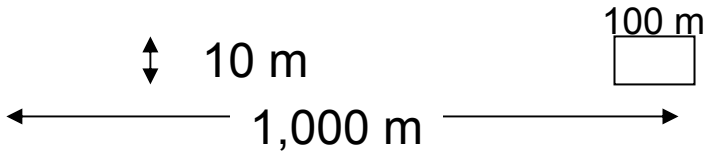
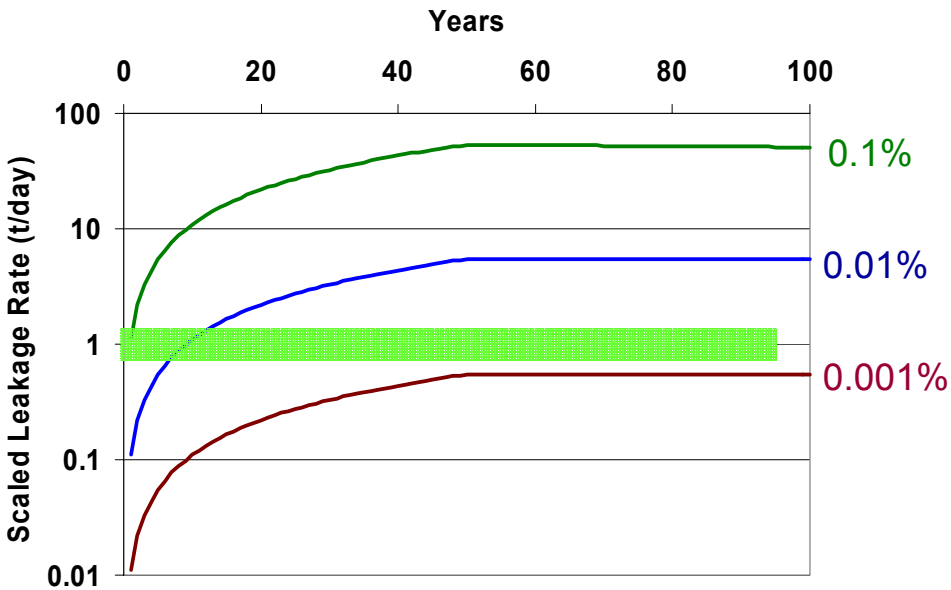
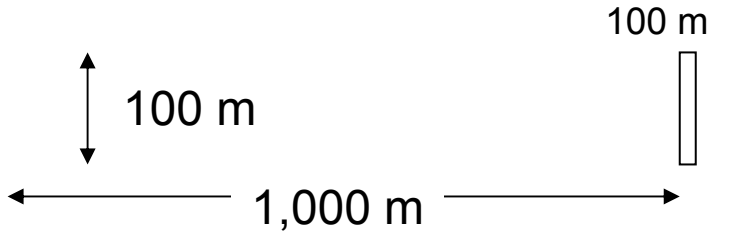
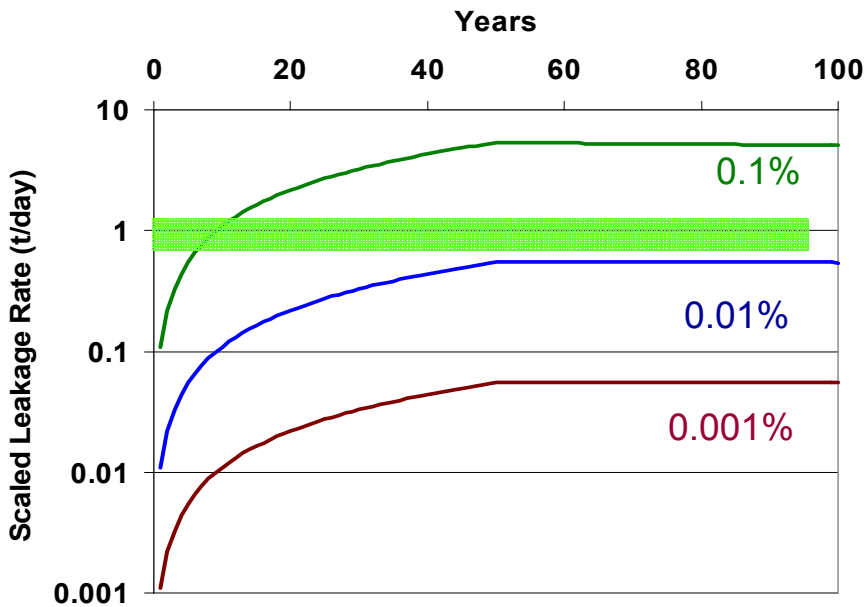
Injection Rate

Sally Benson









Scale to 1000 m leak
1,000 kg/day: 1 tonne/day

Lee Spangler

A Unique Test Facility at MSU

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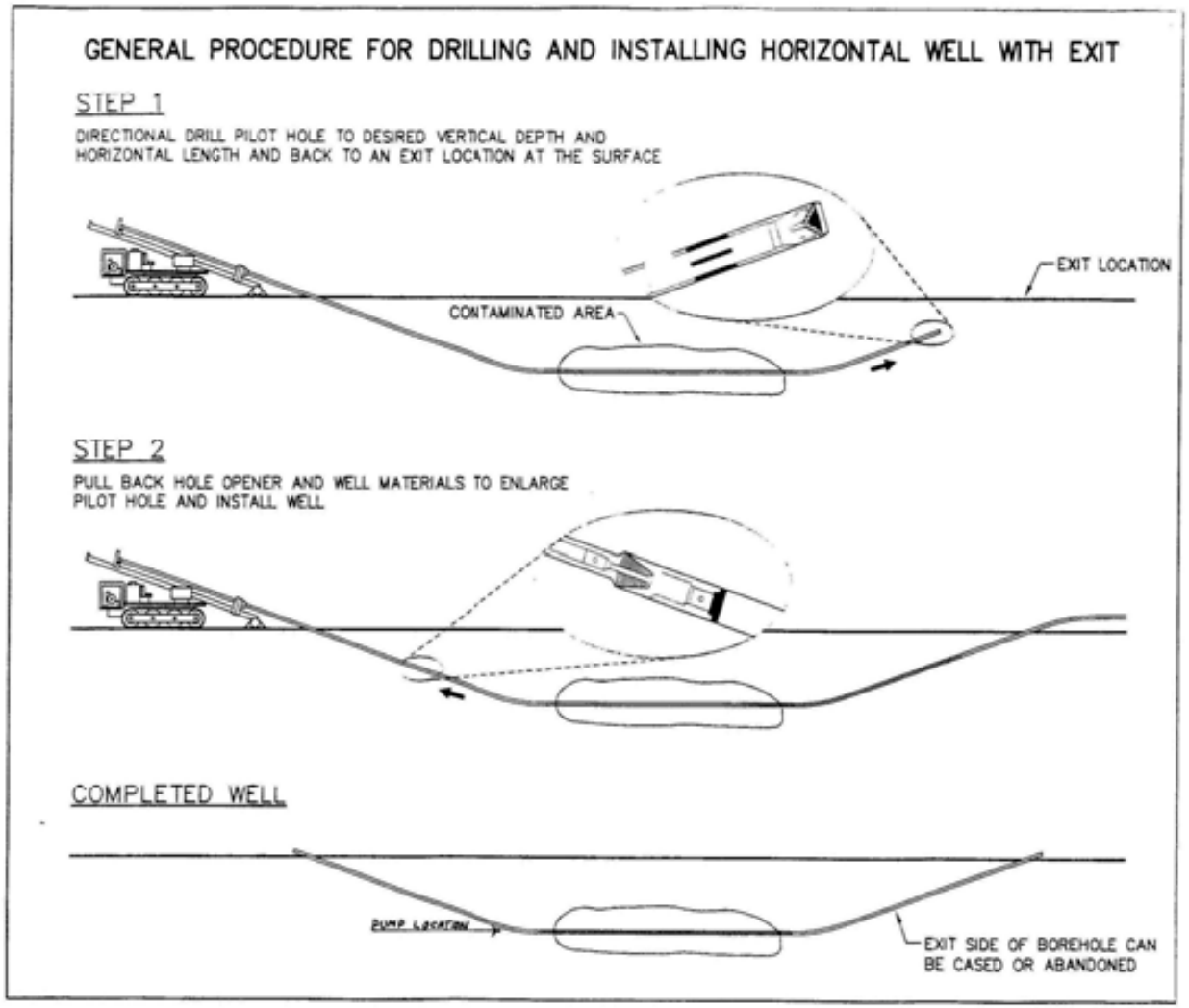

ZERT Zero Emissions Research and Technology

A Unique Test Facility at MSU

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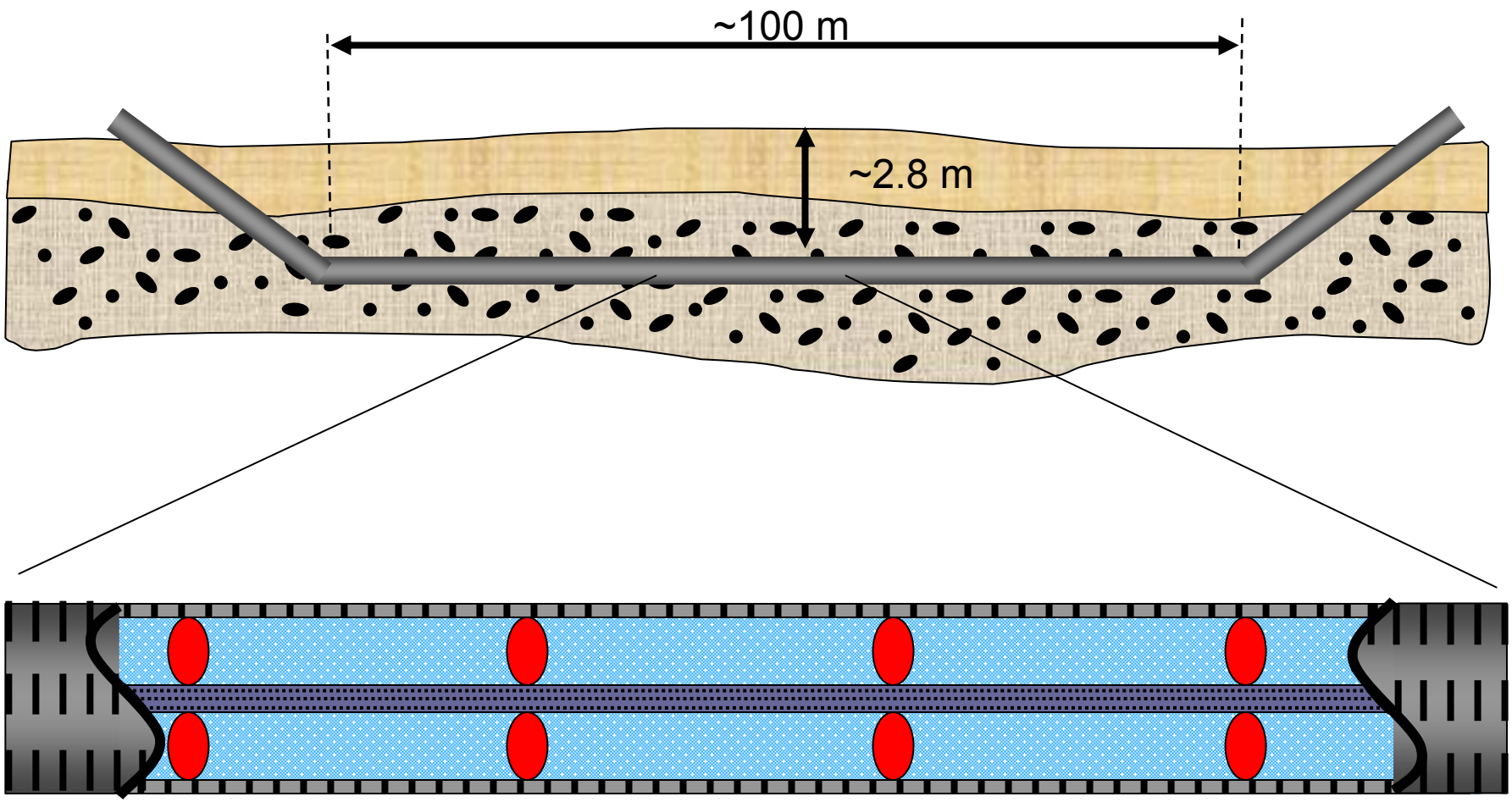

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A Unique Test Facility at MSU

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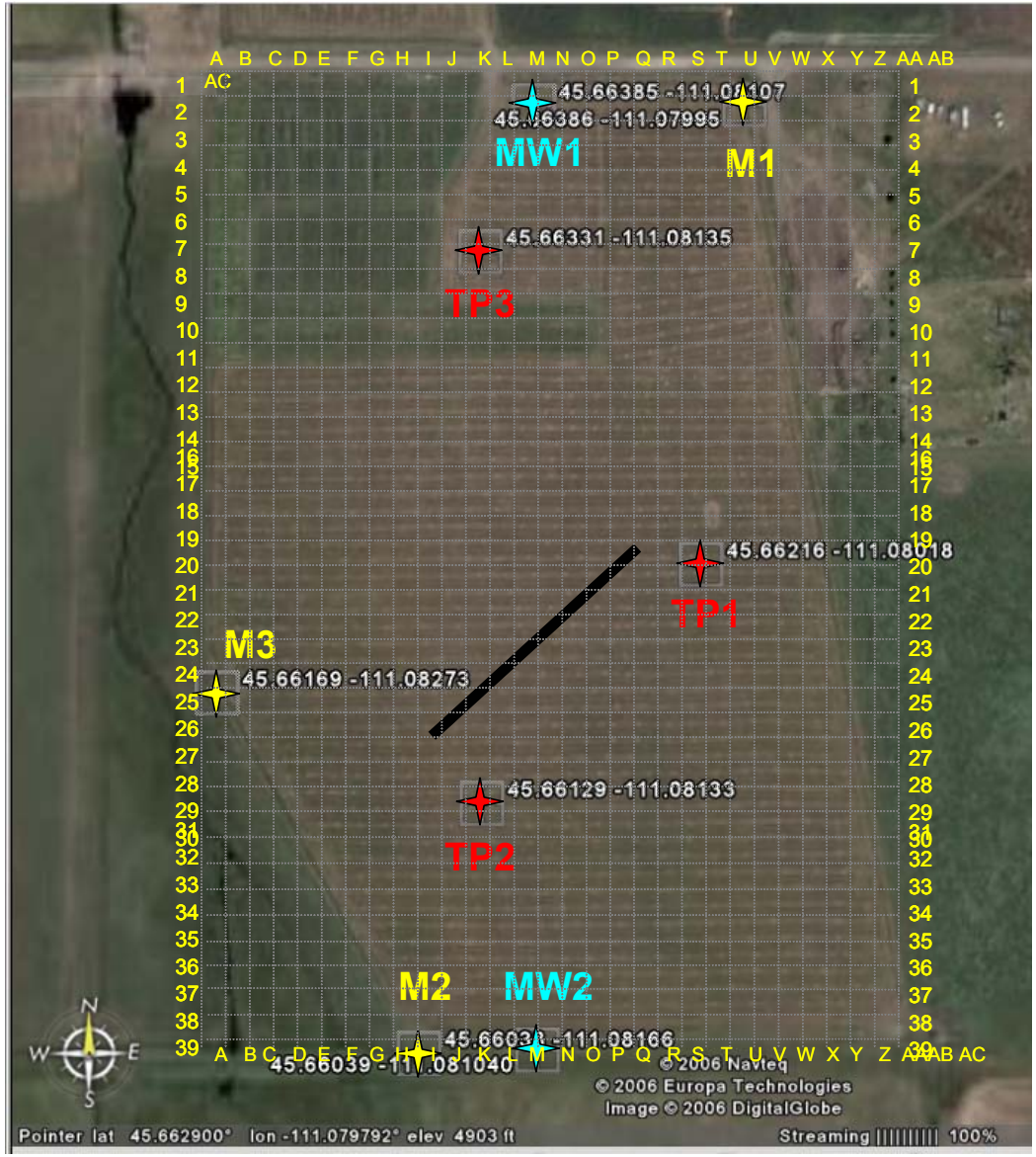

M=plugged bore hole

MW=monitoring well

TP=test pit

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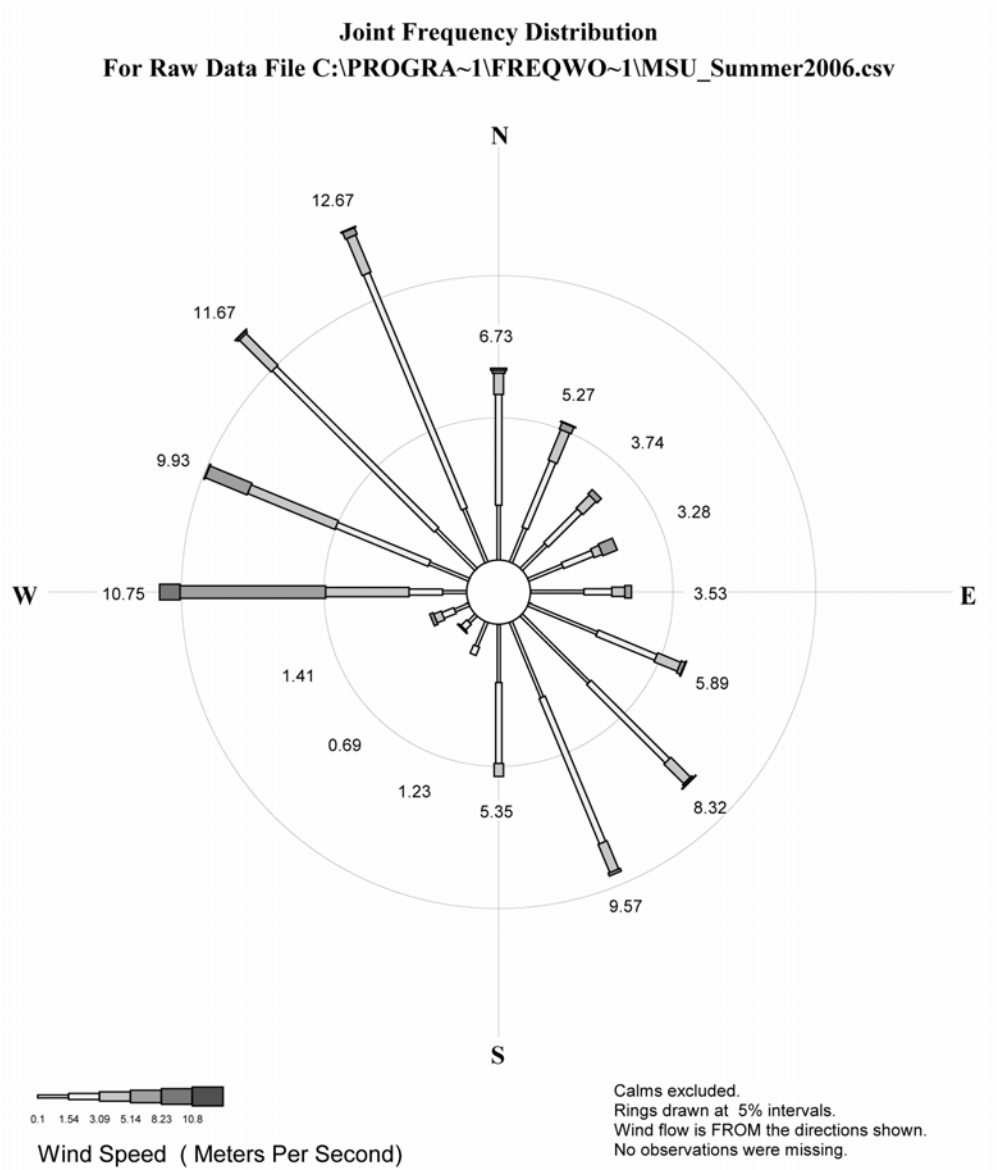
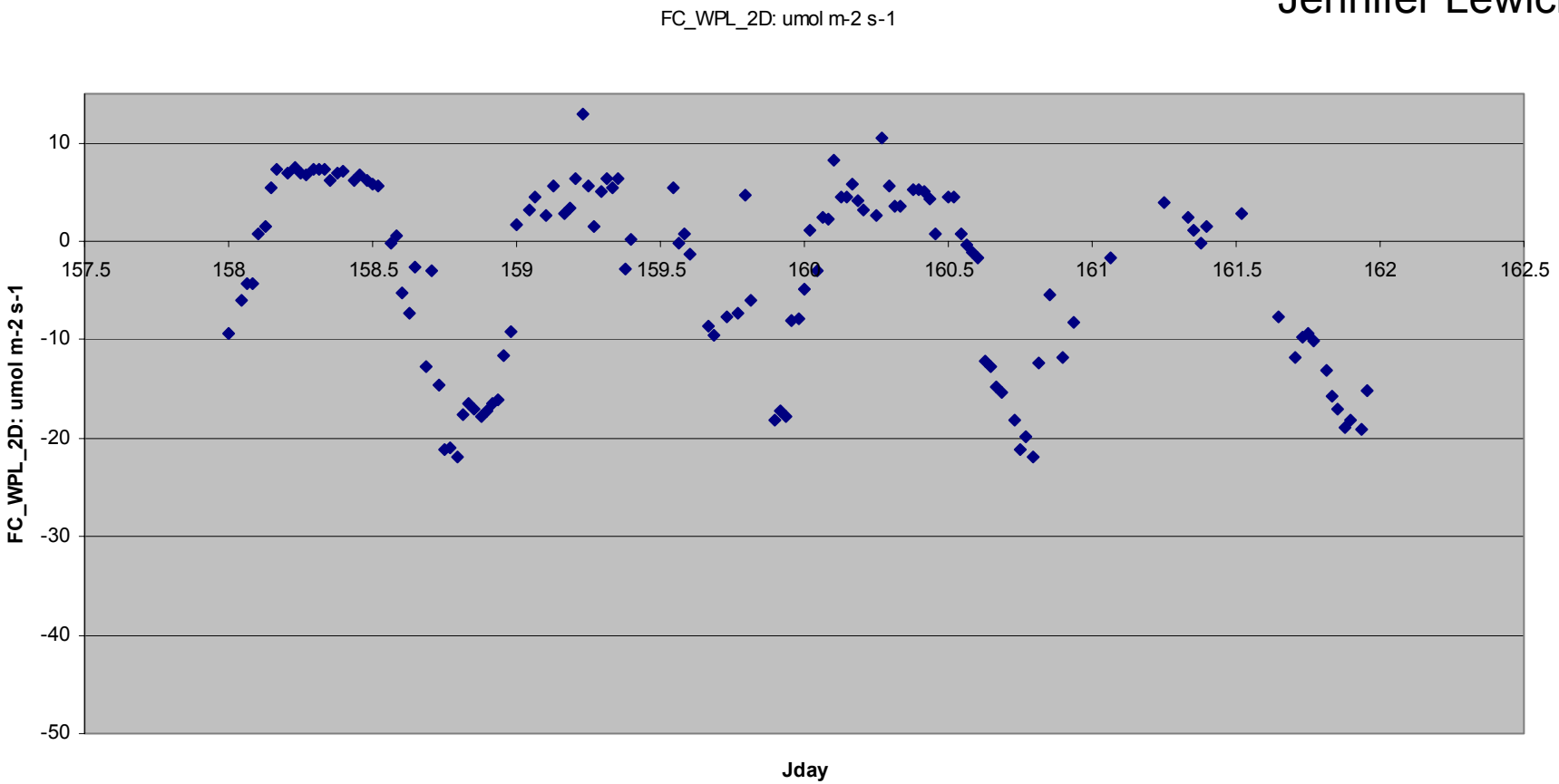
Wind Rose For Field Site Summer 2006

Jennifer Lewicki



CO_2 Fluxes from Eddy Covariance

Jennifer Lewicki



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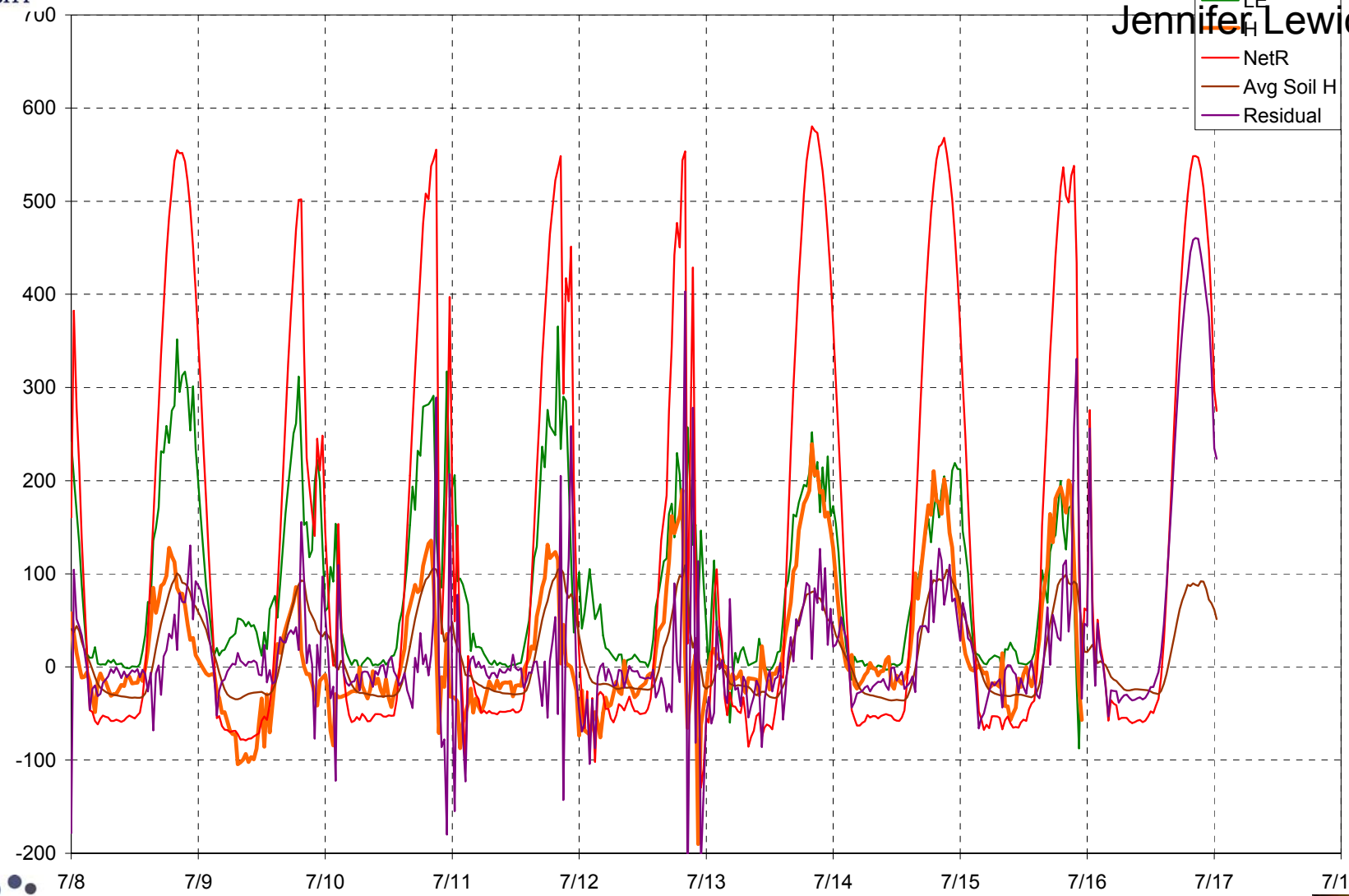
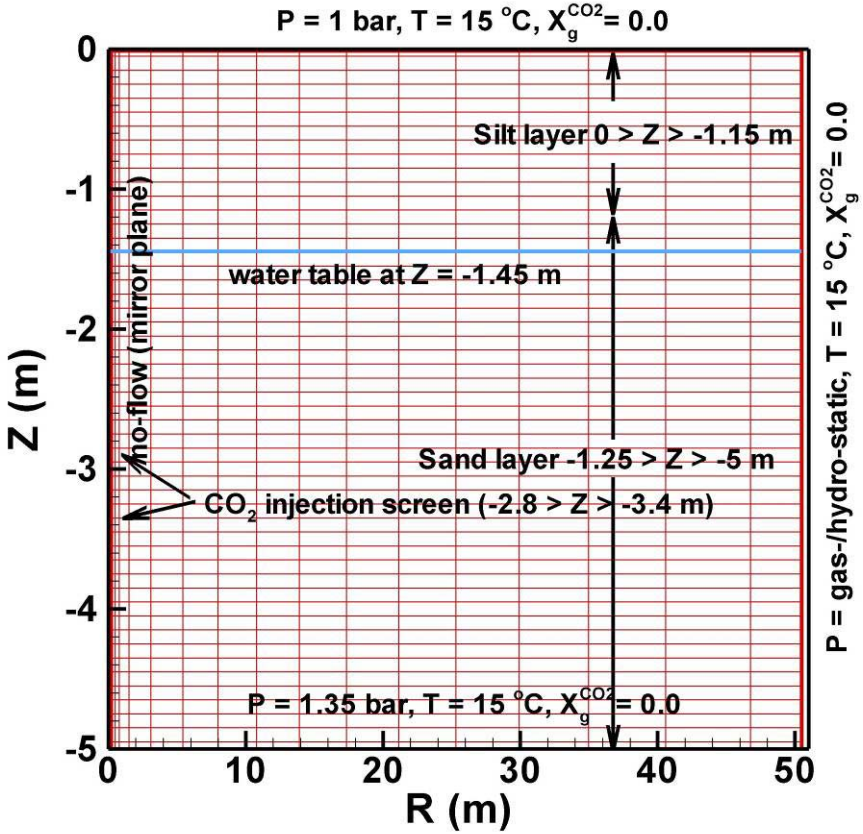
Energy Terms

Jennifer Lewicki

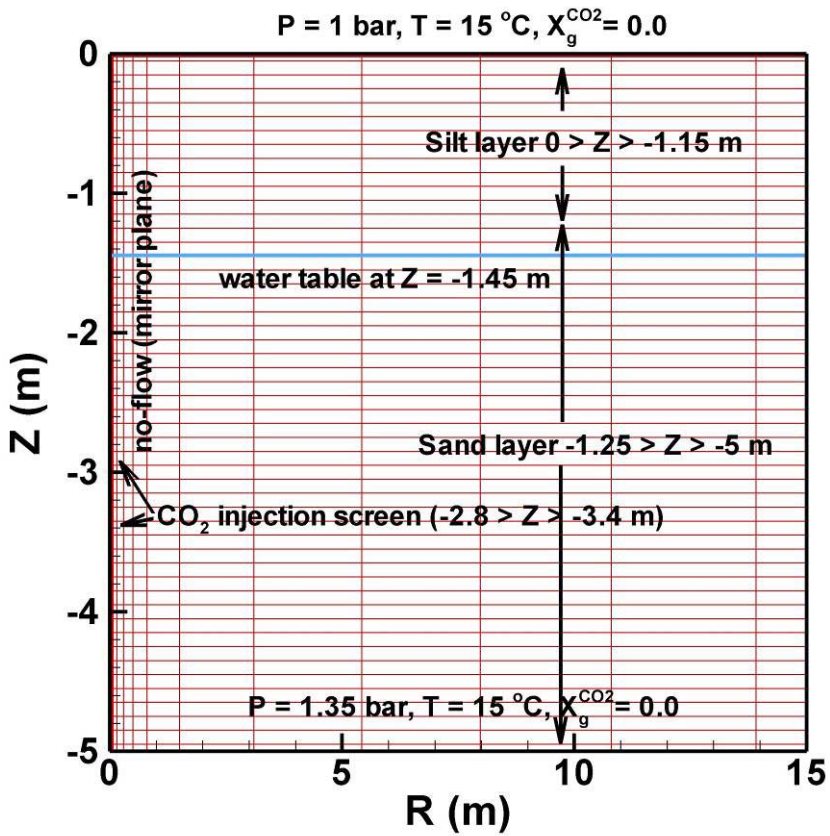


Grid and BCs of Radial Model

Curt Oldenburg



Full domain, vertical exaggeration ~ 10x.



Domain for plotting results.

Injection Rate Notes

Curt Oldenburg

For the horizontal well case, pore volume was used to derive a first-guess injection rate (this was discussed in earlier telecons).

$PV_g = LWH\ \phi\ S_g$

$L = 100$ m
$W = 3$ m
$H = 3$ m
$\phi = 0.3$
$S_g = 0.5$
$PV_g = 900\ m^3 \cdot 0.3 \cdot 0.5 = 135\ m^3$

At 1 bar, 20 °C,

$\rho_{air} = 1.2\ kg/m^3$

$\rho_{CO2} = 1.8\ kg/m^3$

$mass_{CO2} = 135\ m^3 \times 1.8\ kg/m^3 = 243\ kg\ CO_2$

If inject 10 pore volumes over 10 days,

$Q_{CO2} = 2430\ kg\ CO_2/10d * 1\ d/86400\ s$

$Q_{CO2} = 2.81 \times 10^{-3}\ kg\ CO_2/s$

In the conference call of 28 August, the suggested rate of injection for the vertical well was 1/300th that in the horizontal well.

$Q_{CO2} = 1/300\ (2430\ kg\ CO_2/10days)$

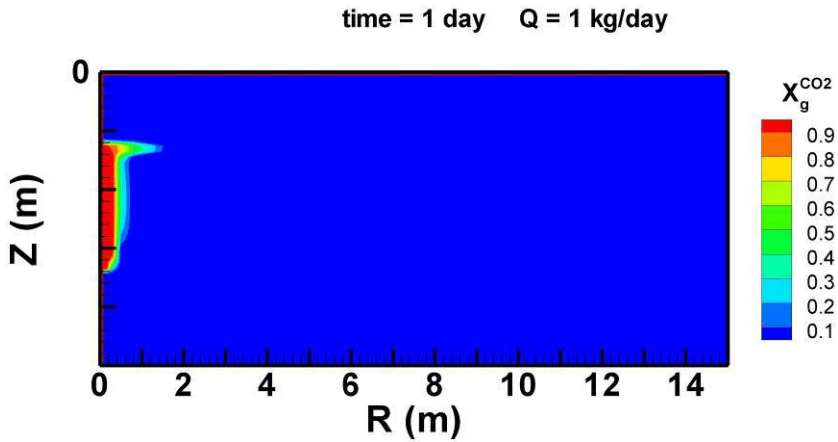
$Q_{CO2} = 0.81\ kg\ CO_2/day$

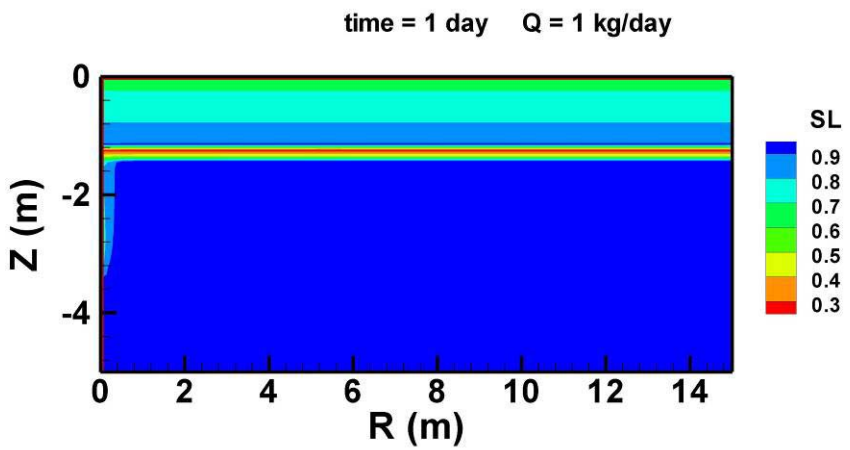
For the Cases 1 and 2 presented below, injection rates of 1 kg/day and 10 kg/day are used for comparison purposes.

Injection Calculations for Low Perm Silt

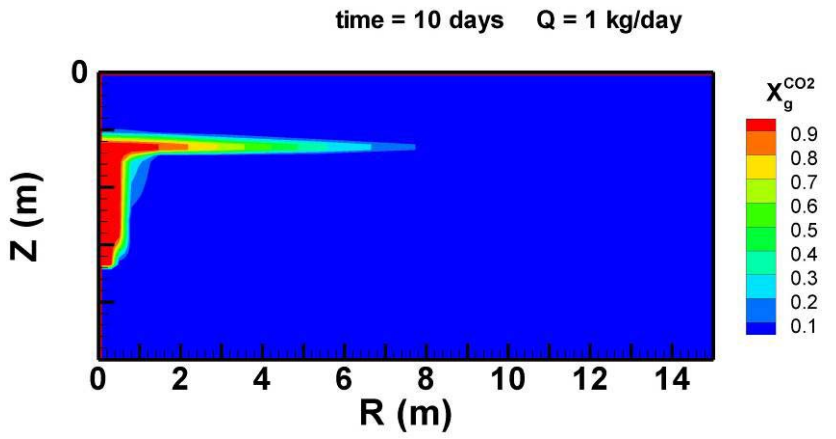
Curt Oldenburg

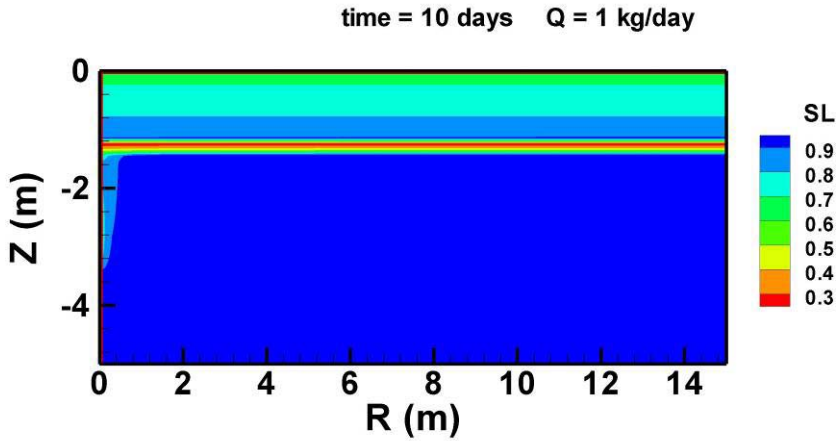
Results for 1 kg/day at 1 day



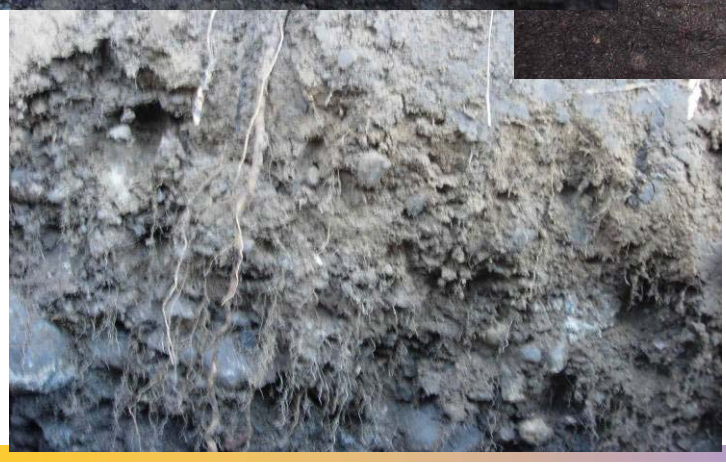


Results for 1 kg/day at 10 days





Site Soil Characteristics



Site Soil Characteristics

Site Heterogeneity

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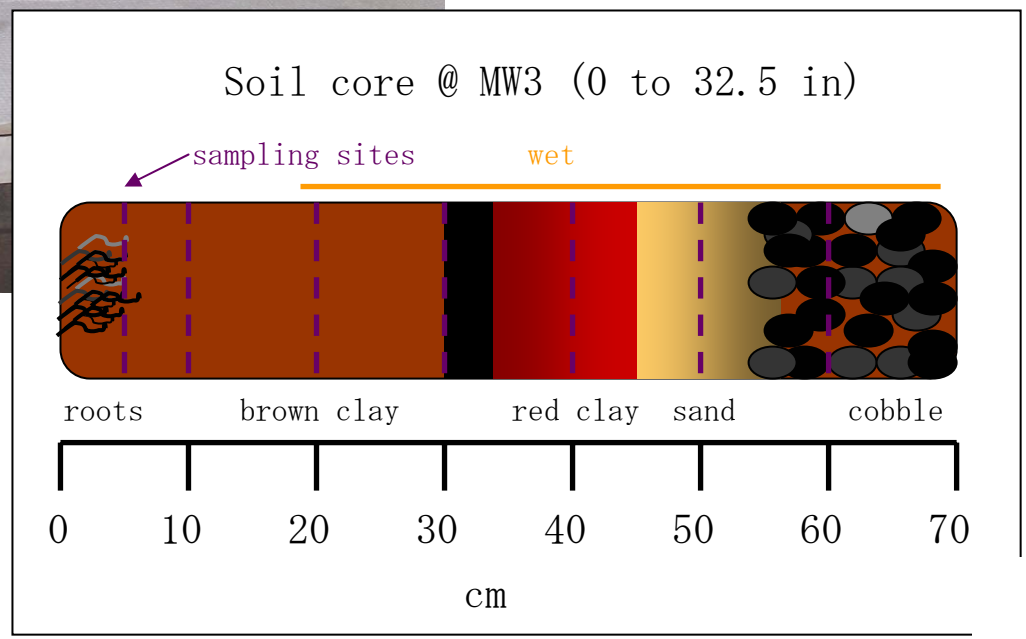
Soil Core taken from MW3 (upper 32 “)

Julianna Fessenden

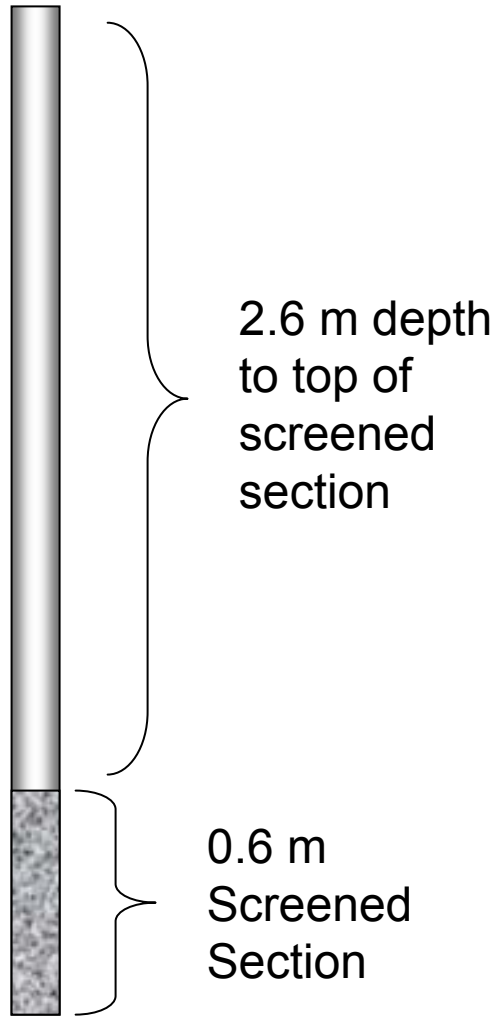


Vertical Test Injection Rate

Vertical Injection Rate = 0.8 l/min = 2.26 kg / day

Scaled up a factor of 400 (to ~ 100m)

Equivalent of 0.9 tonne / day



Vertical Injection Site

Shallow Vertical Well Installation

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Mokwa Group, MSU

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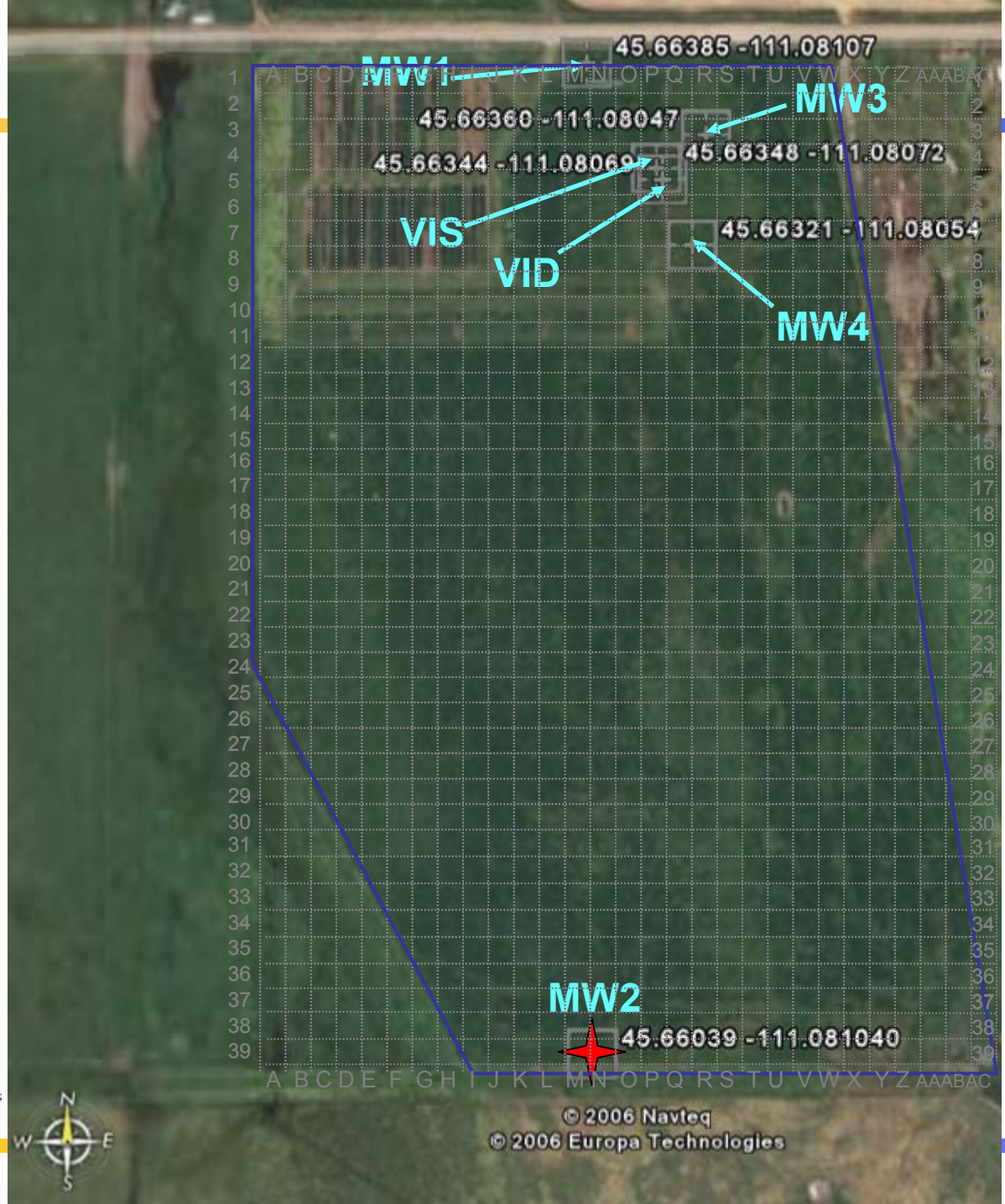

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Well Locations

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"Deep" (8 ft) Vertical Injection Well

VID	45.66344˚ -111.08069˚	12T 0493715 5056656

Shallow (2 ft) Vertical Injection Well

VIS	45.66348˚ -111.08072˚	12T 0493713 5056662

Monitoring Wells

	lat long	UTM
MW1	45.66385˚ -111.08107˚	12T 0493683 5056703
MW2	45.66039˚ -111.081040˚	12T 0493687 5056317
MW3	45.66360˚ -111.08047˚	12T 0493731 5056677
MW4	45.66321˚ -111.08054˚	12T 0493725 5056631

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Map Datum=NAD83
Typical resolution of hand held GPS = +/- 4 m

Large Number of Participants / Methods

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MSU – Geotechnical, O2, CO2 (isotope) Lidar, soil microbes.

LBNL – Eddy Covariance, Soil Gas Chamber, Modeling

LANL – EC, Stable Isotopes Gas & Water

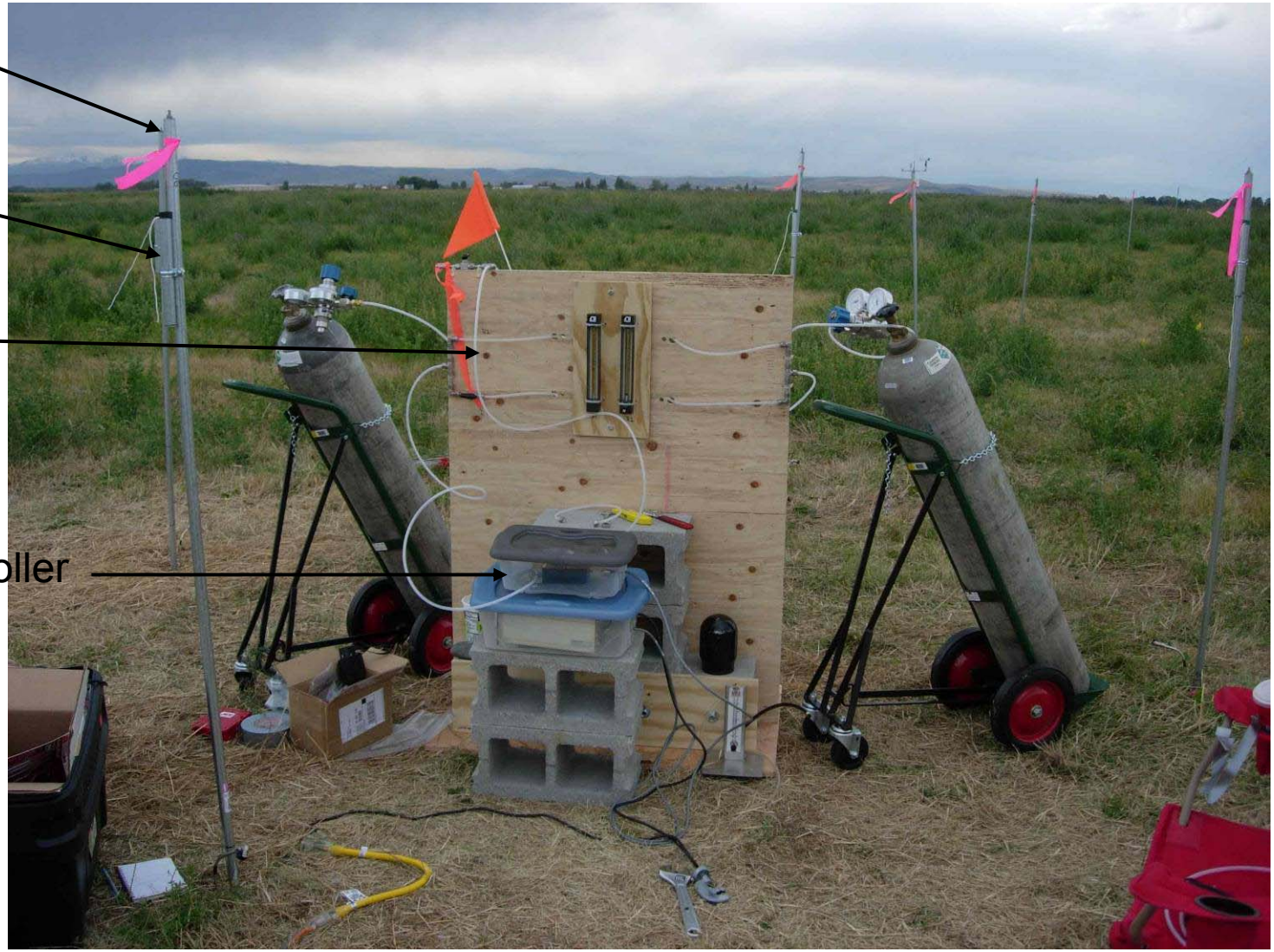
PNNL – Soil & Hydrology, Tracers

LLNL – Gas Stable Isotope, Soil Microbes, Hyperspectral,

NETL – Background Charaterization, Tracers (sorption tubes)

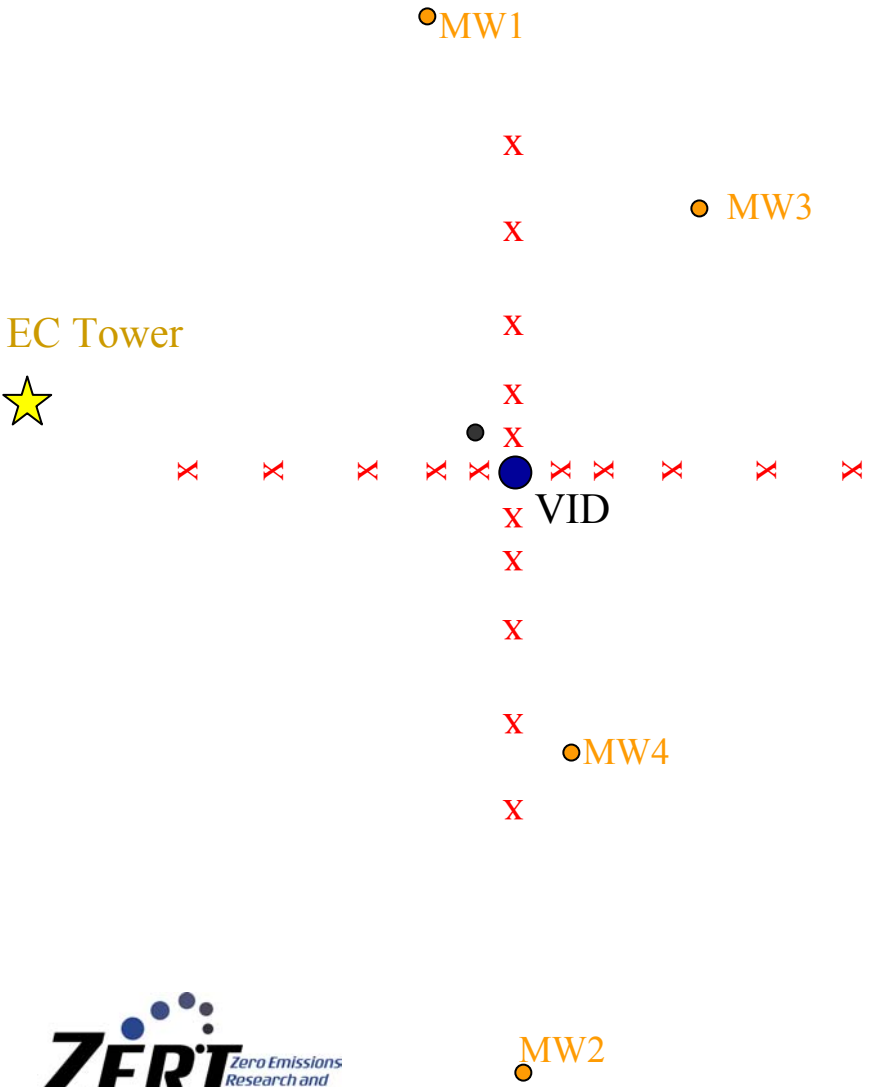
WVU – Water Chemistry

Injection System



Tracer Studies

Art Wells
David Wildman



Sorption tubes placed at 2, 3.5, 5, 10, 25, and 50 m from injector

Tracer introduced for first 12 hrs of flow

Data not available yet

CO_2 Soil Gas Measurement

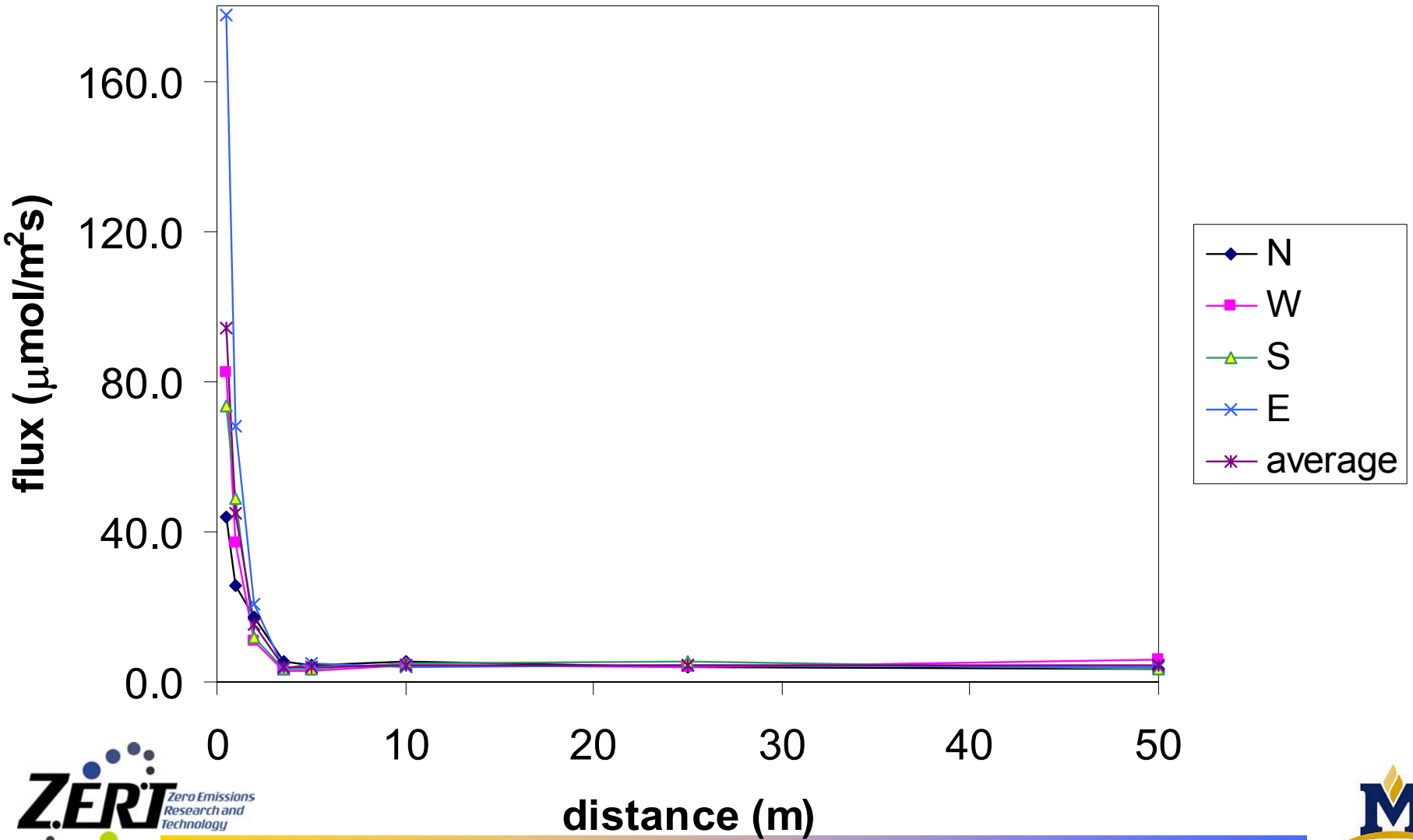
Brian Strazisar

distance (m)	fluxes (μmol/m^{2}s) N	W	S	E	average
0.5	44.0	82.3	73.4	177.7	94.4
1	25.8	36.9	48.7	68.0	44.8
2	17.2	10.7	12.1	20.9	15.2
3.5	5.4	3.0	3.5	3.6	3.8
5	4.4	3.1	3.5	5.1	4.0
10	5.4	4.6	4.8	3.8	4.7
25	4.1	4.1	5.4	4.3	4.5
50	3.5	6.0	3.7	4.0	4.3

CO_2 Soil Gas Measurement

ZERT vertical injection average CO_2 fluxes

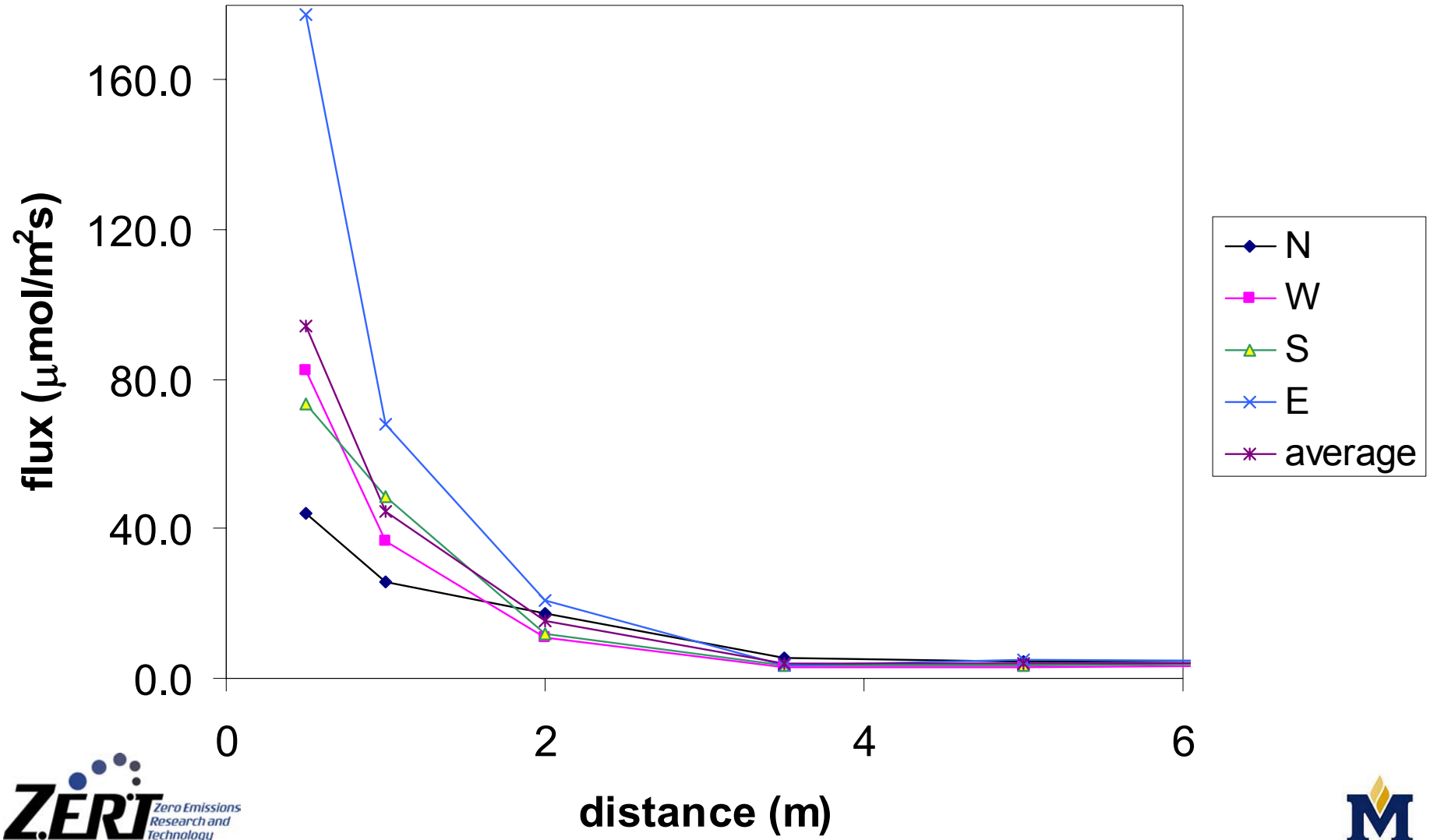
Brian Strazisar



CO_2 Soil Flux Measurement

ZERT vertical injection average CO_2 fluxes

Brian Strazisar



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CO_2 Soil Gas Measurement

Brian Strazisar

60 cm soil gas samples

	North		East		South		West		average	
distance	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$
m	%	‰	%	‰	%	‰	%	‰	%	‰
0	80.53	-56.1	80.53	-56.1	80.53	-56.1	80.53	-56.1	80.53	-56.09
3.5	0.84	-22.1	0.61	-21.1	0.57	-22.0	1.32	-22.9	0.835	-22.0225
10	1.26	-21.7	1.05	-23.9	0.46	-21.7	0.83	-22.1	0.9	-22.35
25	0.83	-24.4	1.17	-22.5	0.69	-21.9	1.07	-22.6	0.94	-22.845
50	0.65	-21.9	1.17	-21.9	0.45	-20.5	0.76	-21.2	0.7575	-21.3875

Zero Emissions Research and Technology

CO_2 Soil Gas Measurement

Brian Strazisar

30 cm soil gas samples

	North		East		South		West		average	
distance	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$	CO_2	$\delta^{13}CO_2$
m	%	‰	%	‰	%	‰	%	‰	%	‰
0	30.99	-55.0	30.99	-55.0	30.99	-55.0	30.99	-55.0	30.99	-55.03
3.5	0.57	-22.6	0.32	-22.3	0.28	-22.9	0.7	-22.6	0.4675	-22.5825
10	0.46	-22.8	1	-22.4	0.21	-20.2	0.41	-22.2	0.52	-21.91
25	0.46	-23.4	0.66	-23.5	0.32	-22.9	0.71	-23.0	0.5375	-23.2075
50	0.37	-22.6	0.31	-21.2	0.24	-21.9	0.33	-21.6	0.3125	-21.8175

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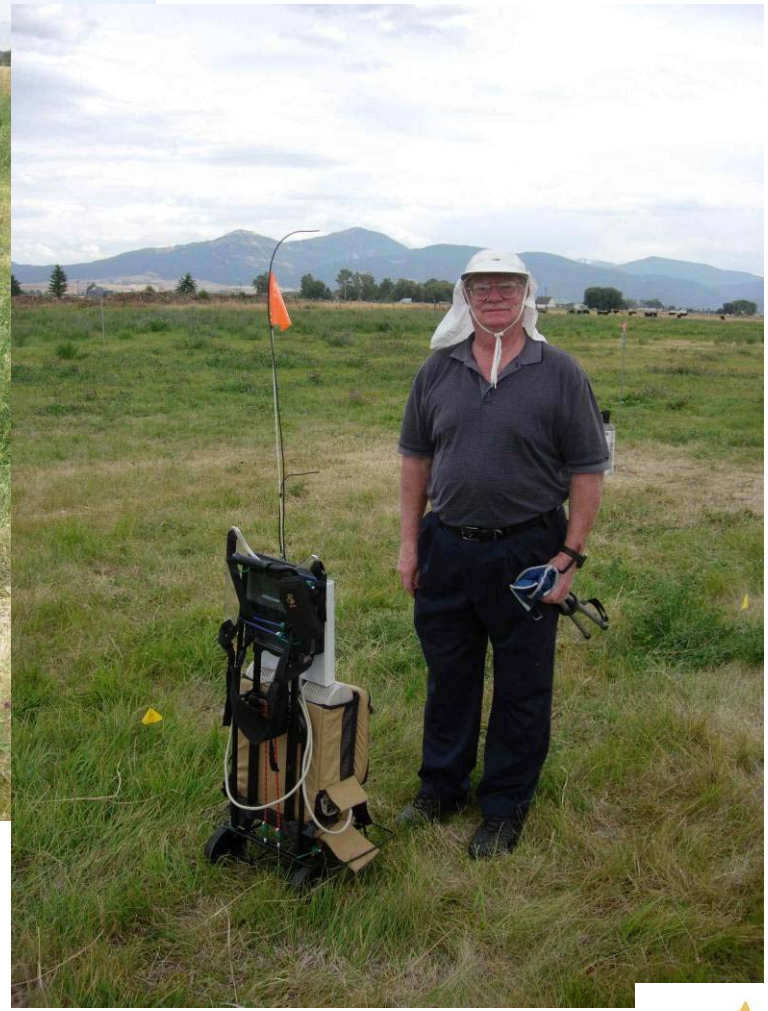
Hyperspectral Imaging (Ground-based)

Bill Pickles



Jim Ammonette

Ambient after rain ~400 ppm

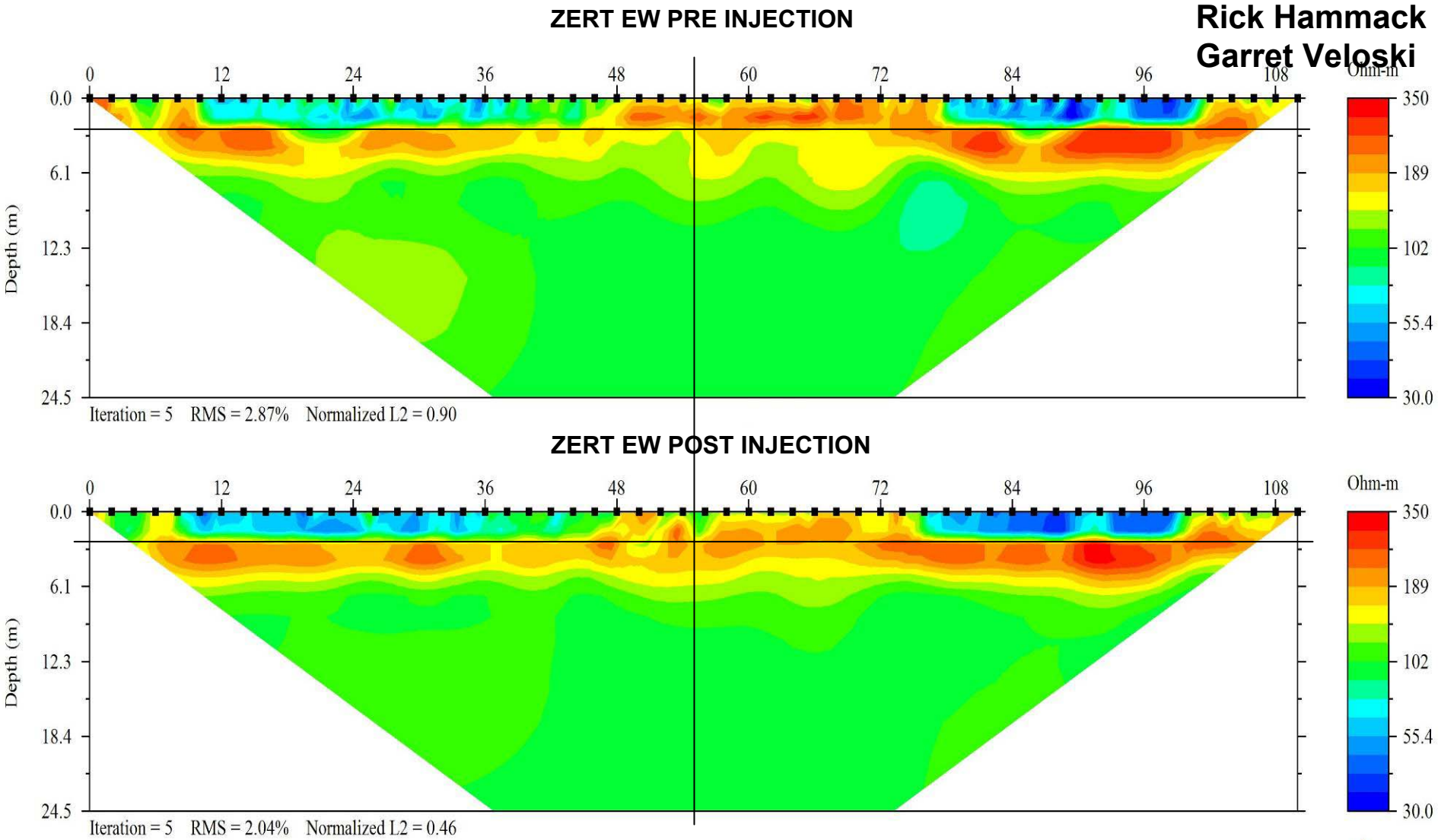
Within 2 m of injection after 1 week ~800 ppm

Resistivity Measurements

Rick Hammack
Garret Veloski

Resistivity Measurements

Rick Hammack
Garret Veloski



Injection well at 55 m on both profiles

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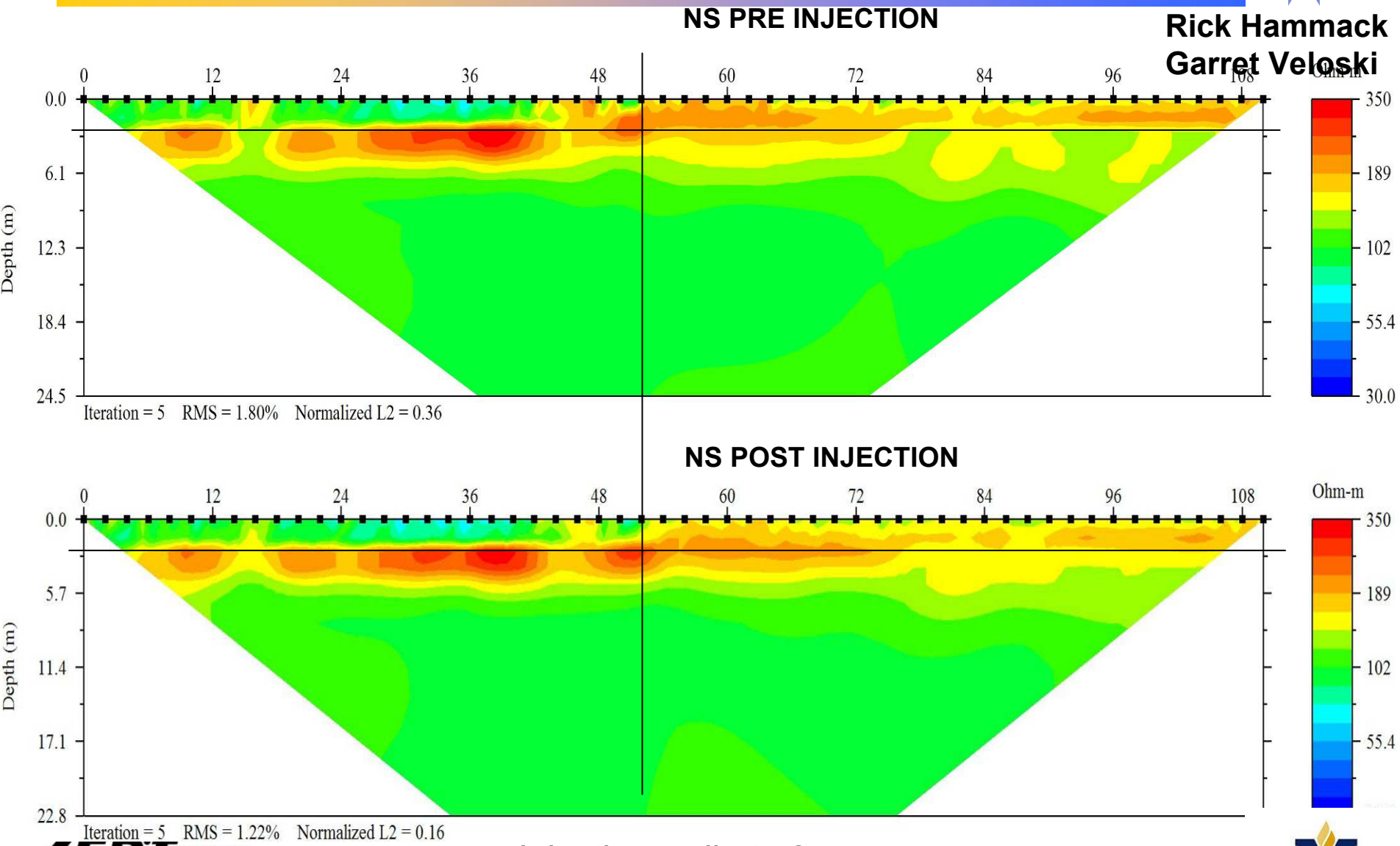
Resistivity Measurements

Rick Hammack
Garret Veloski



Injection well at 52 m

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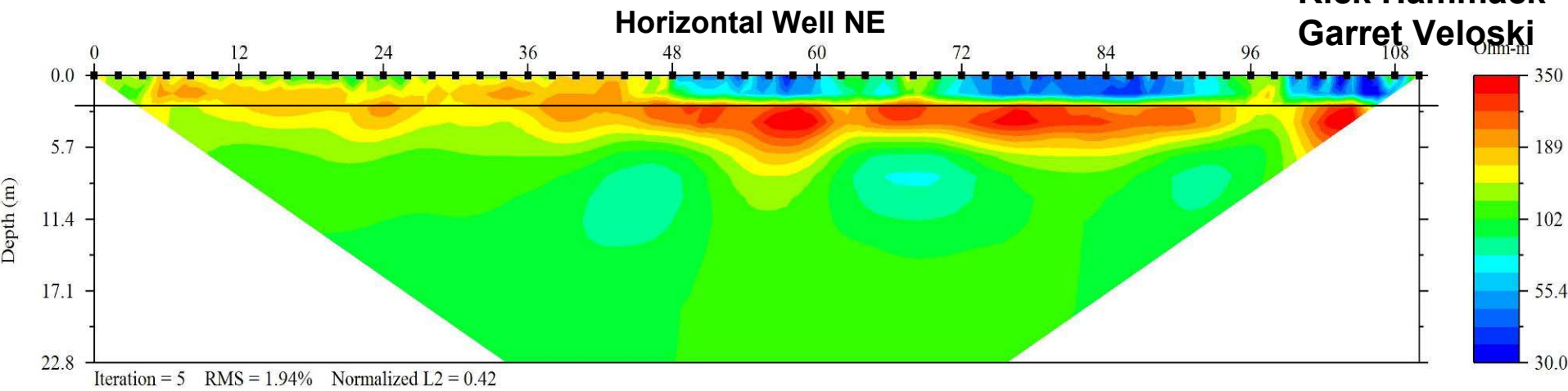
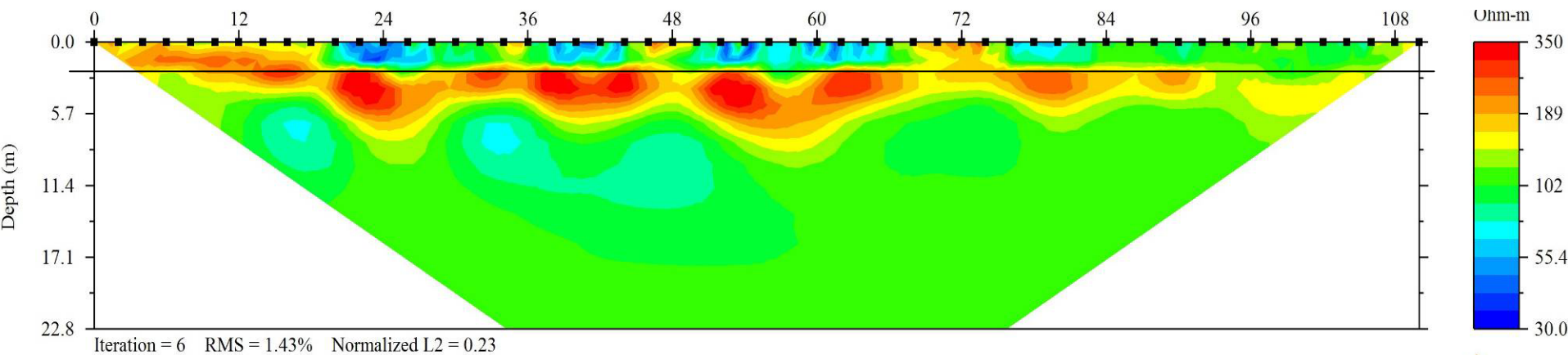
Planned orientation for horizontal well

Rick Hammack
Garret Veloski



Normal to planned orientation; intersecting at midpoint (55 m)



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Controlled Release – Experimental Design

9/17/06 to 9/21/06

Julianna Fessenden

MW1

MW3

EC Tower

CH 2

Tower

CH 3

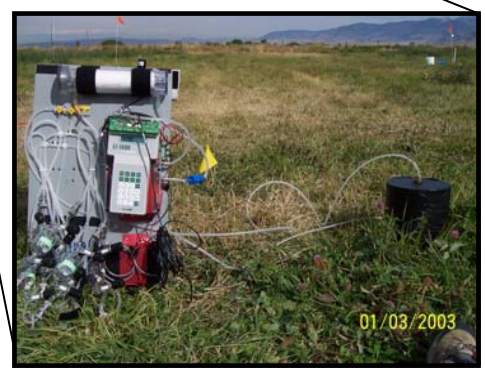
CH 1

VID

MW4

MW2

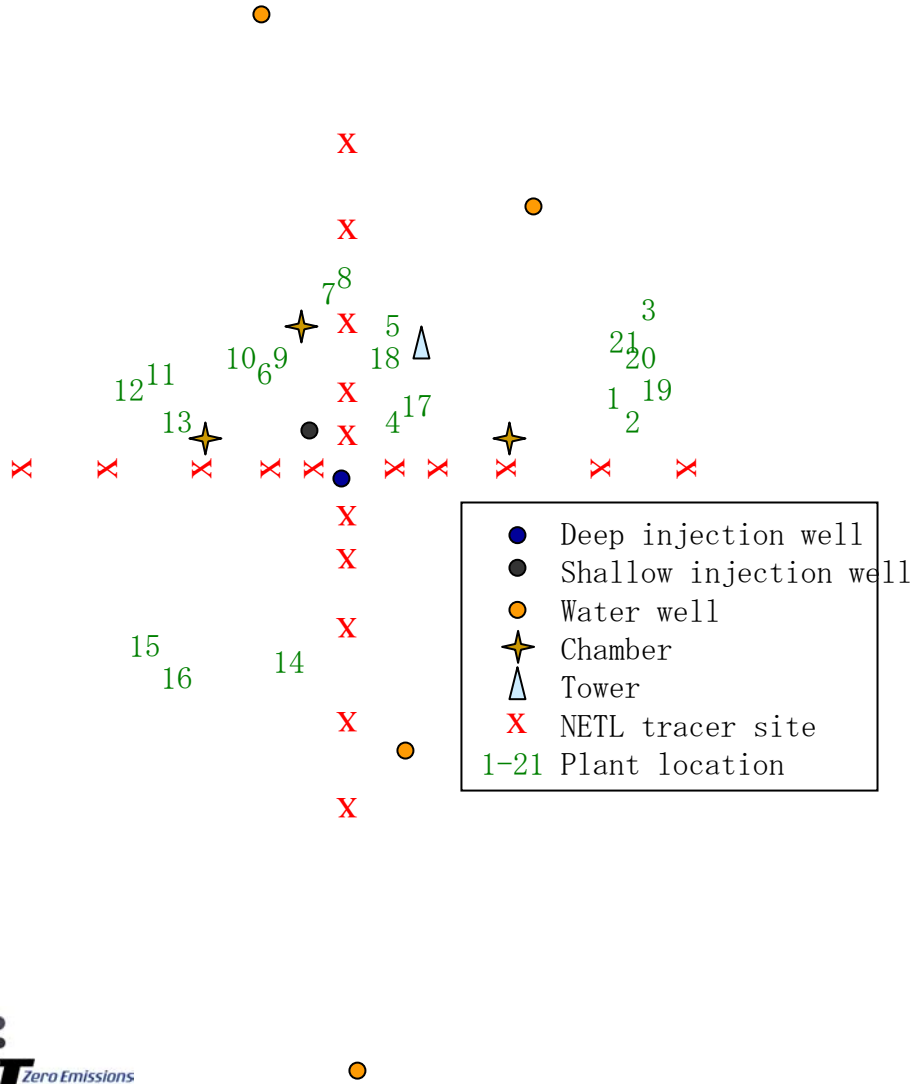
- Deep injection well
- Shallow injection well
- Water well
- Chamber
- Tower
- x NETL tracer site
- 1-21 Plant location



Controlled Release – Plant Stations

Julianna Fessenden

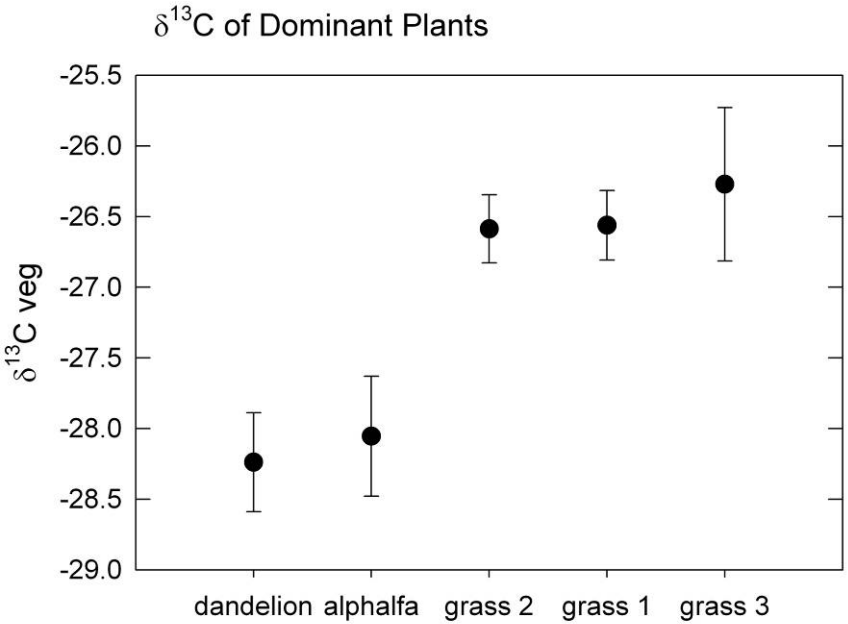
9/17/06 to 9/21/06

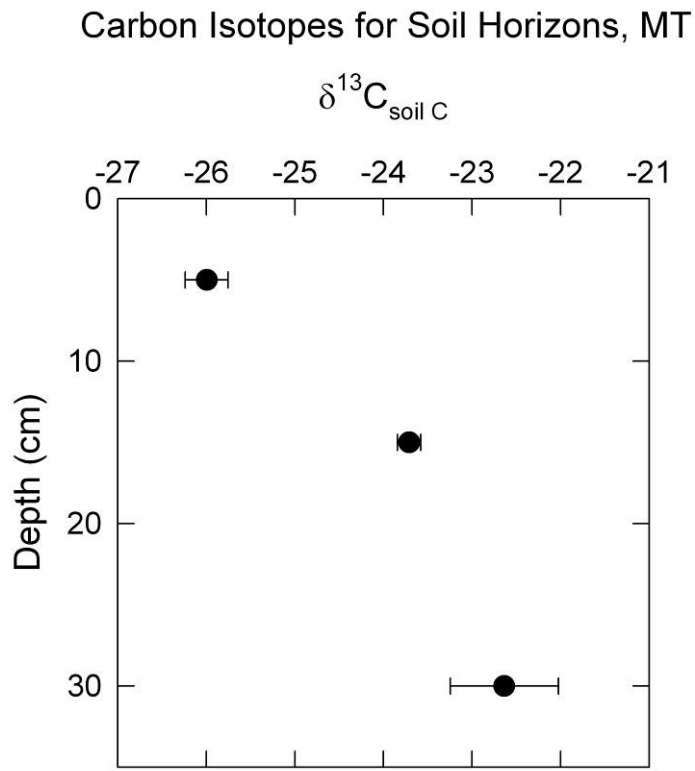


$\delta^{13}C$ of the Dominant Carbon Pools (Plants and Soils)

From 6/12/06

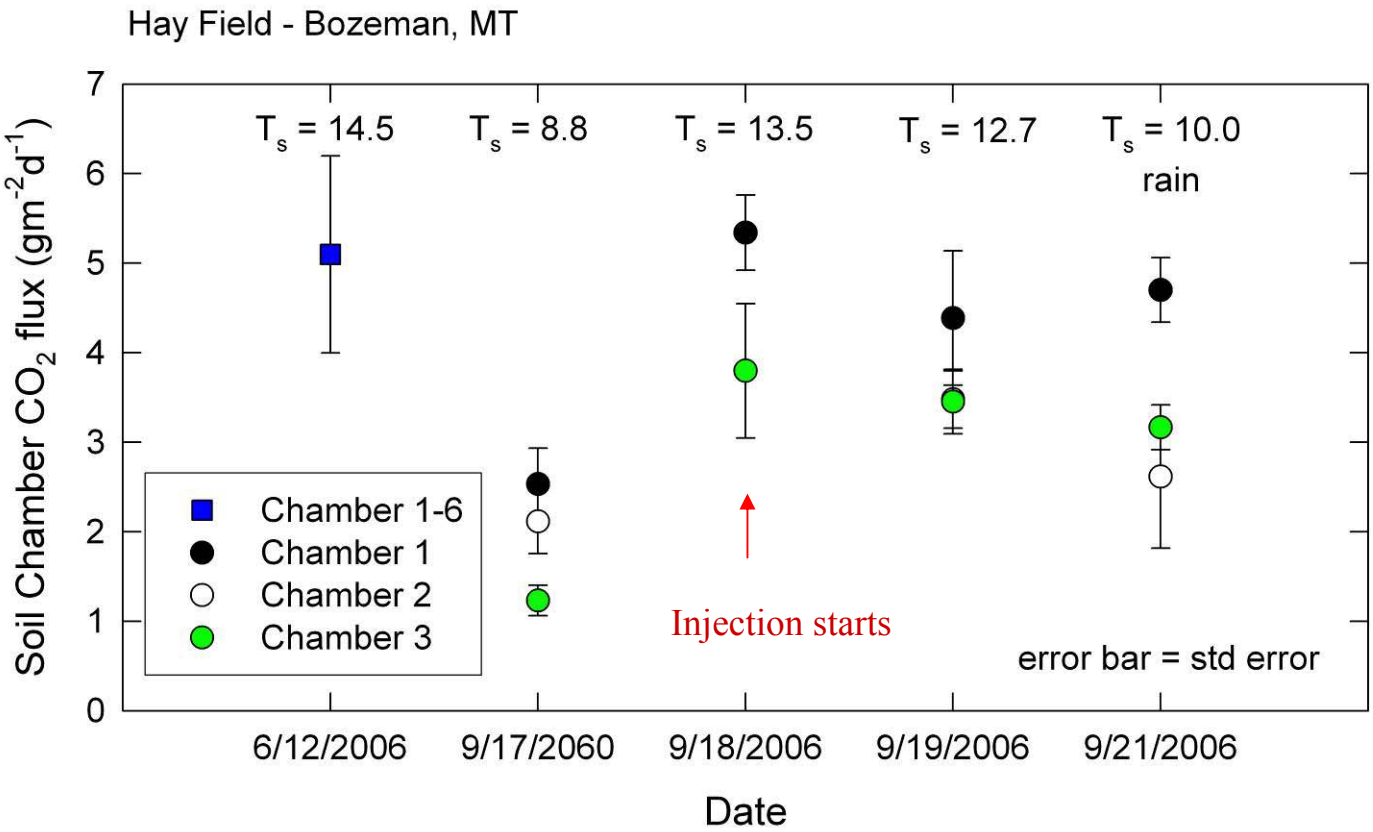
Julianna Fessenden

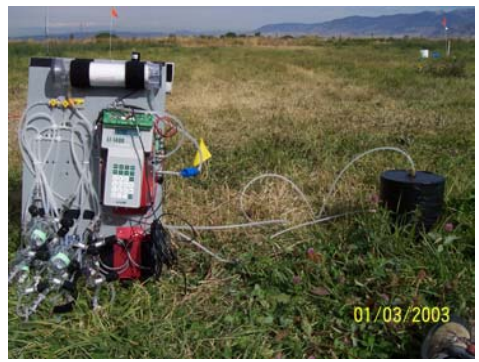




Soil CO_2 flux (Chamber Measurements)

Julianna Fessenden



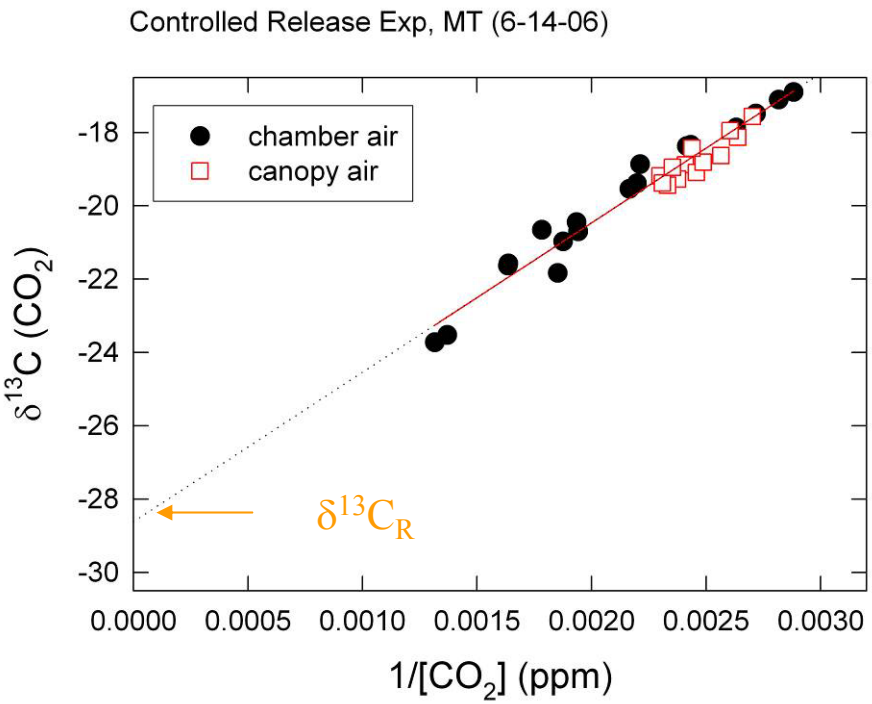


$\delta^{13}C$ of Regional CO_2 and Soil Respired CO_2

(Example from 6/12/06)

Julianna Fessenden

Mixing Model – Keeling Plot (Linear Regression): calculates $\delta^{13}C$ of CO_2 Source

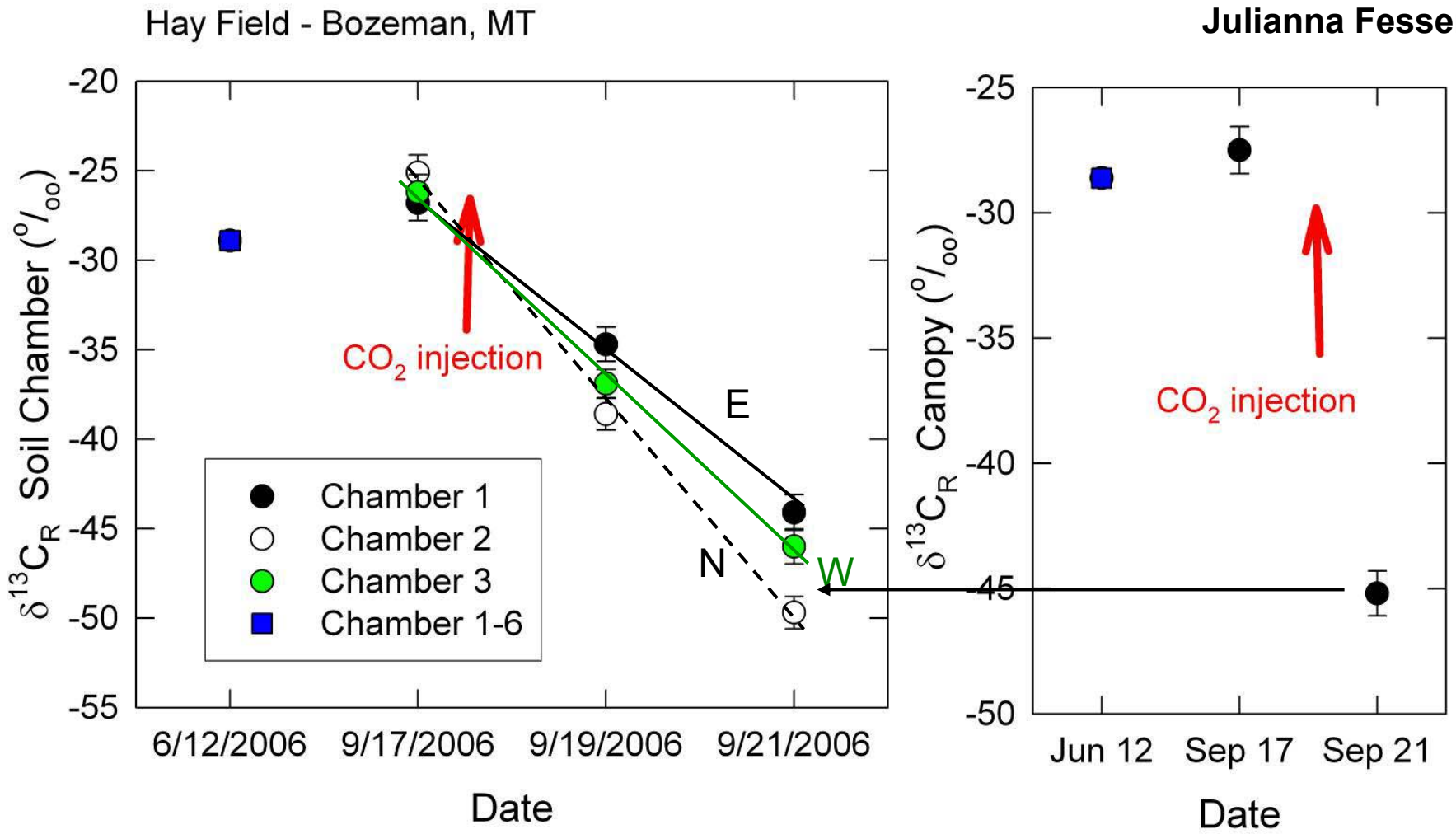


Intercept value ($\delta^{13}C_R$) =

1. $\delta^{13}C$ of source of CO_2
2. Integrates multiple sources
3. Integrates over varying scales

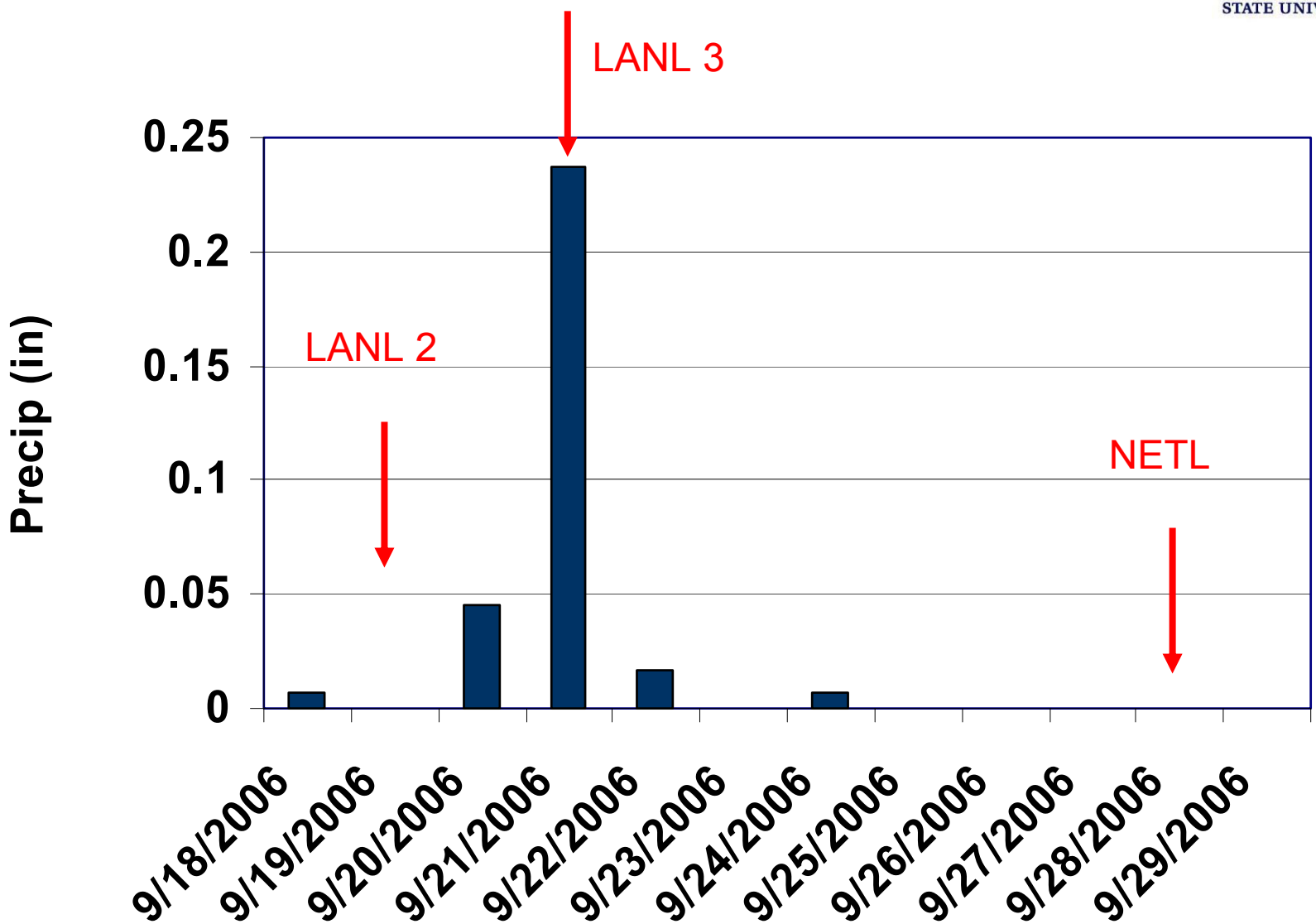
$\delta^{13}C$ Values of CO_2 (chamber and canopy air)

Julianna Fessenden



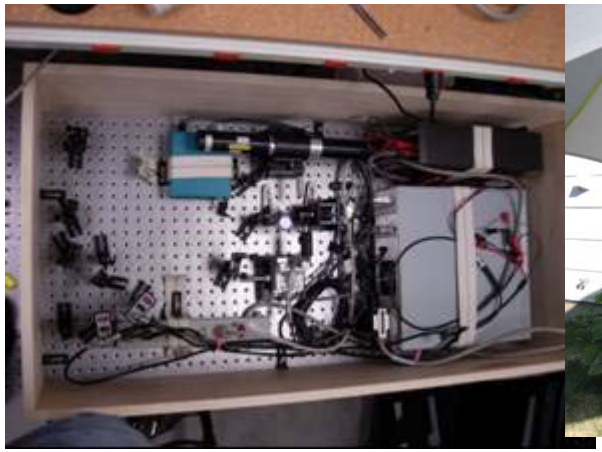
A clear isotopic shift is seen in the source of CO_2 after injection, both in the chambers and in the canopy air

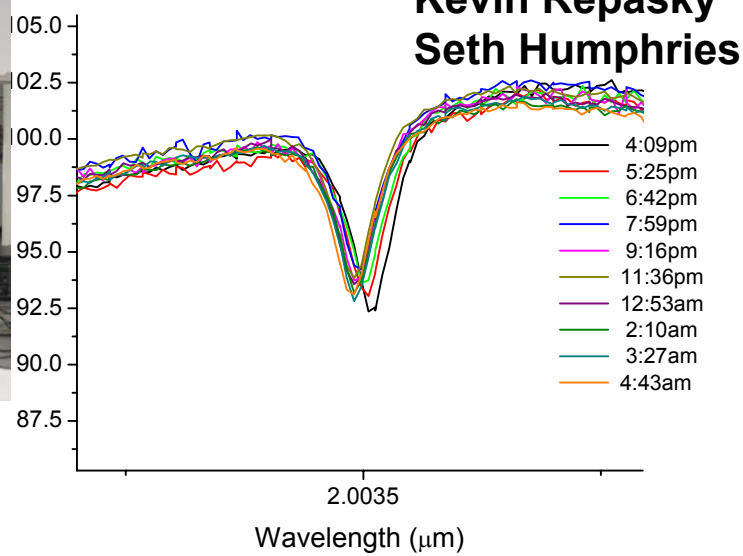
Precipitation

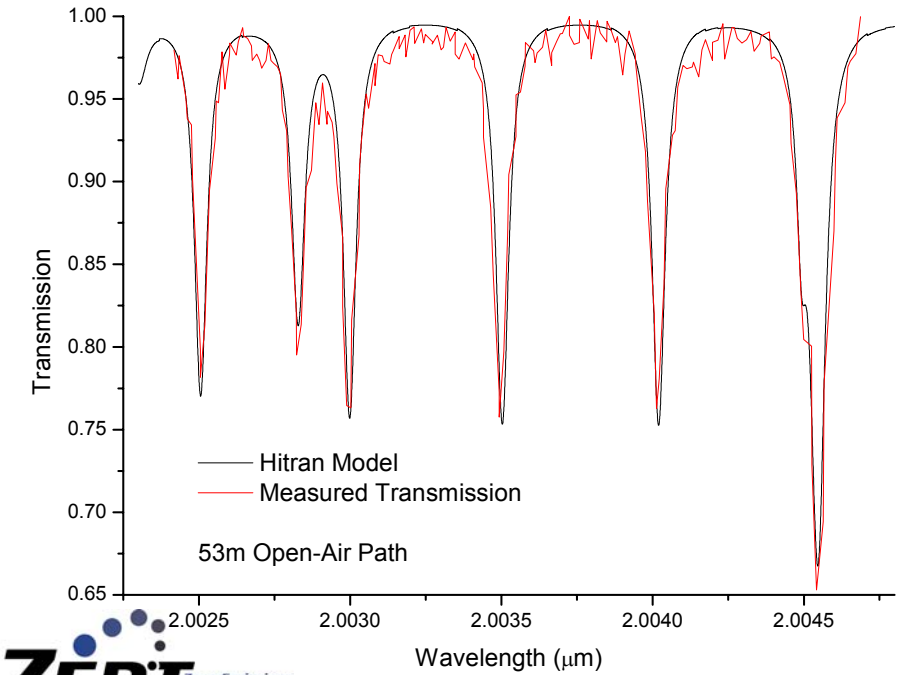


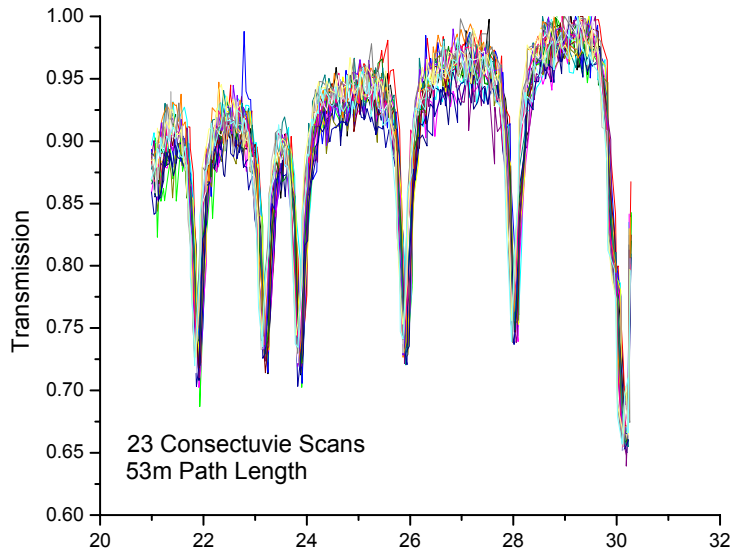
LIDAR System, Performance

MONTANA STATE UNIVERSITY
Kevin Repasky
Seth Humphries









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LIDAR Data at Injection Well

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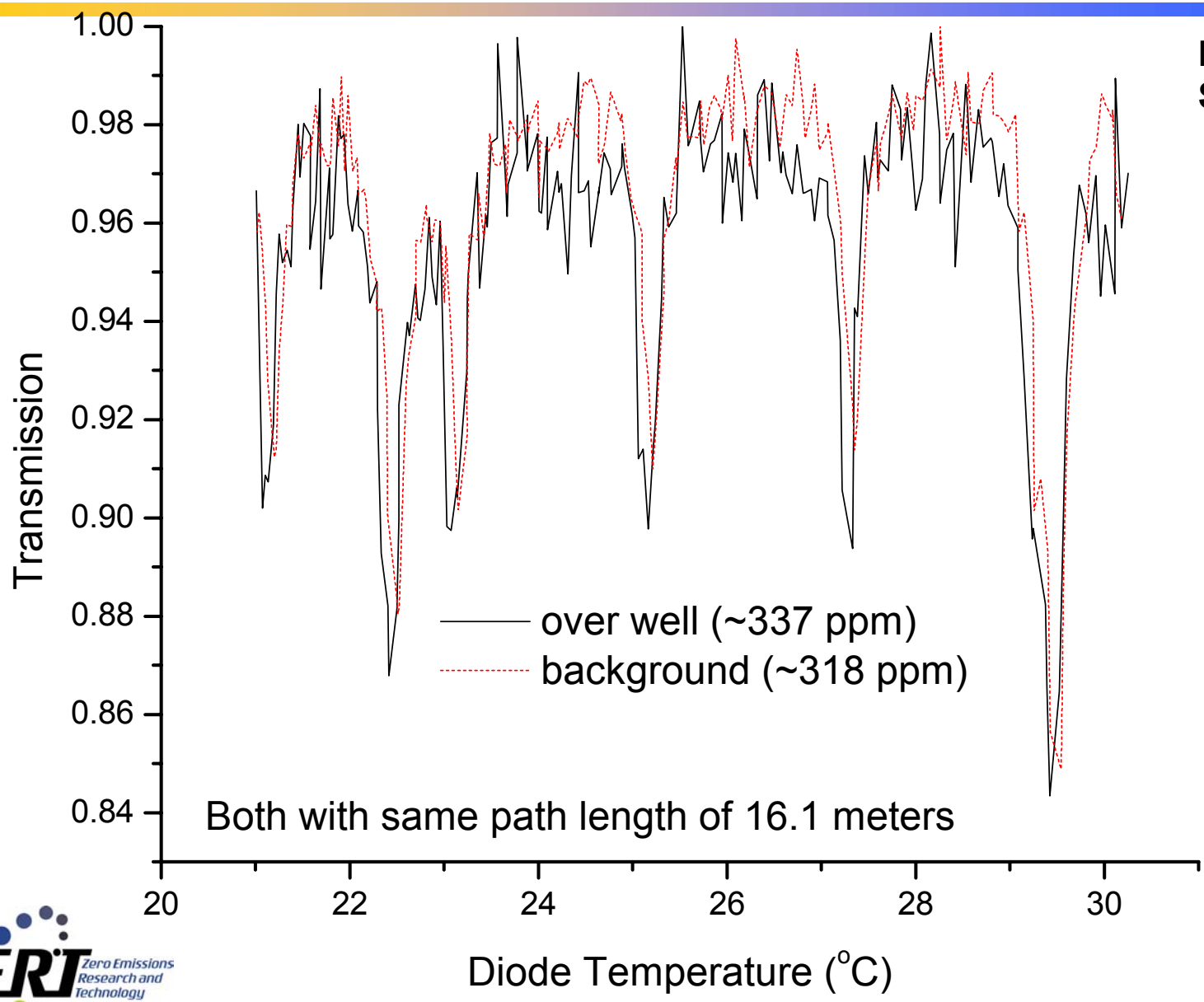
Kevin Repasky
Seth Humphries



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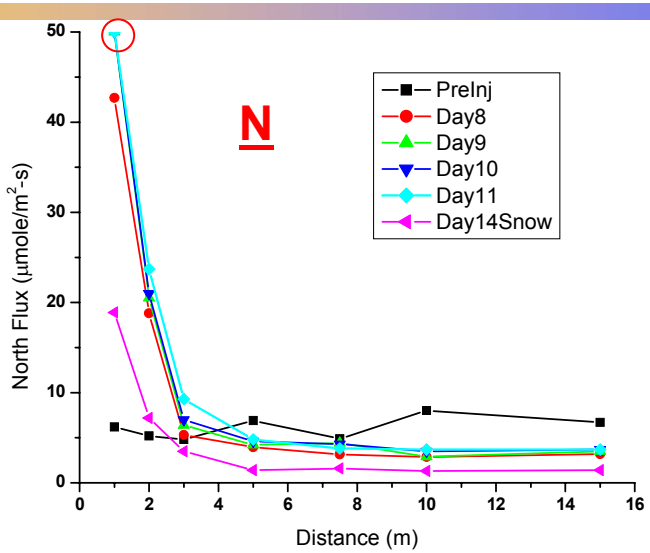
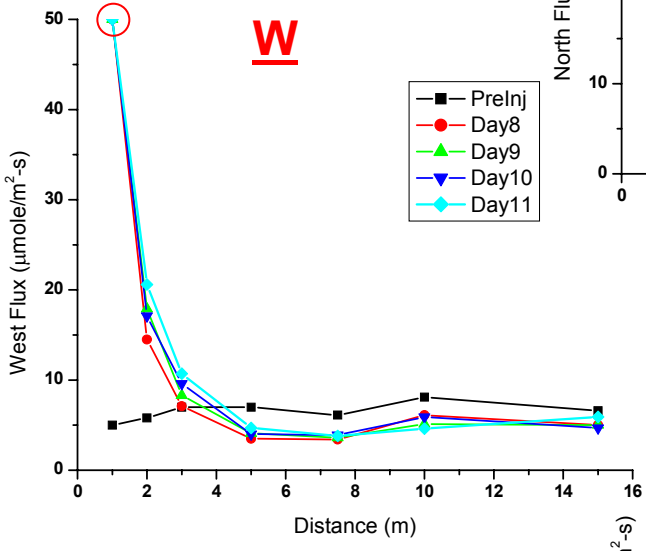
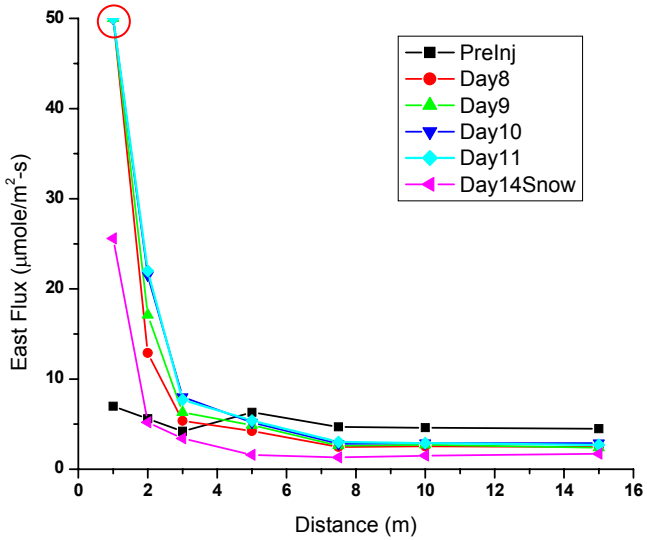
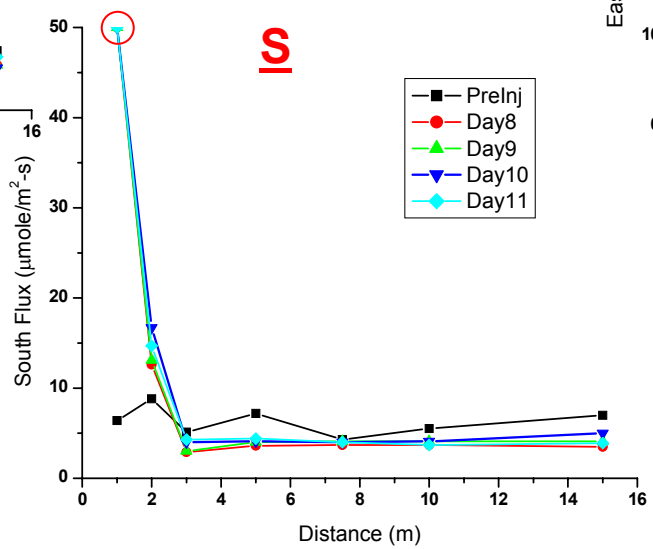
Soil Flux Radial Distribution, New Injector

MONTANA STATE UNIVERSITY
Laura Dobeck
Lee Spangler









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Soil Flux Radial Distribution, New Injector

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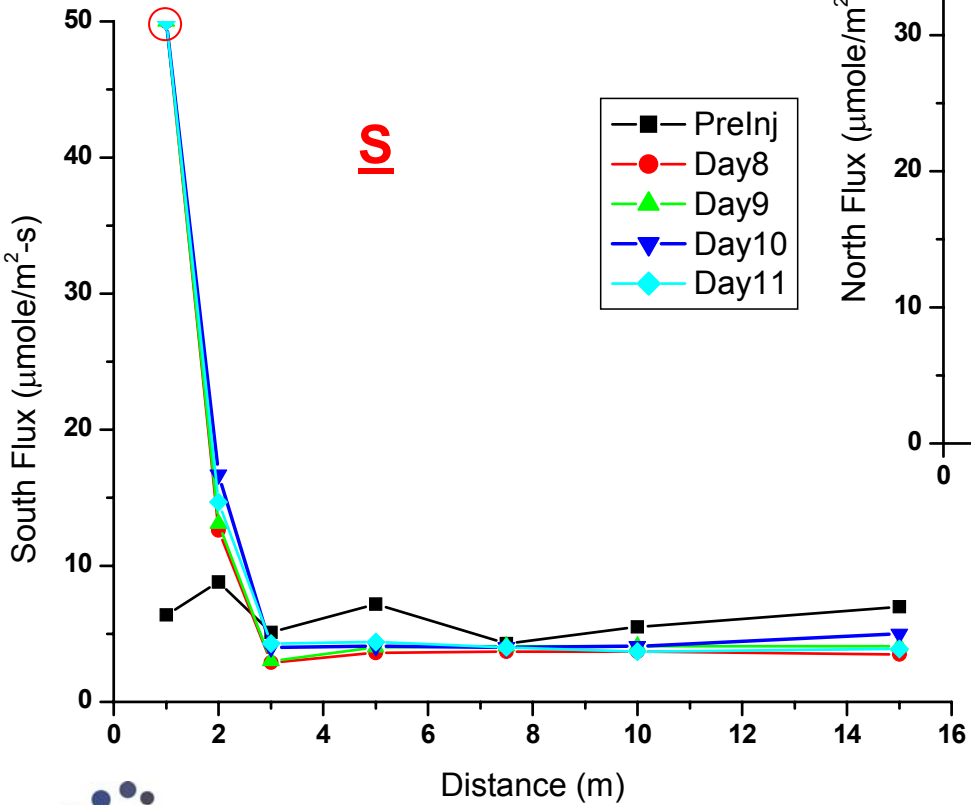
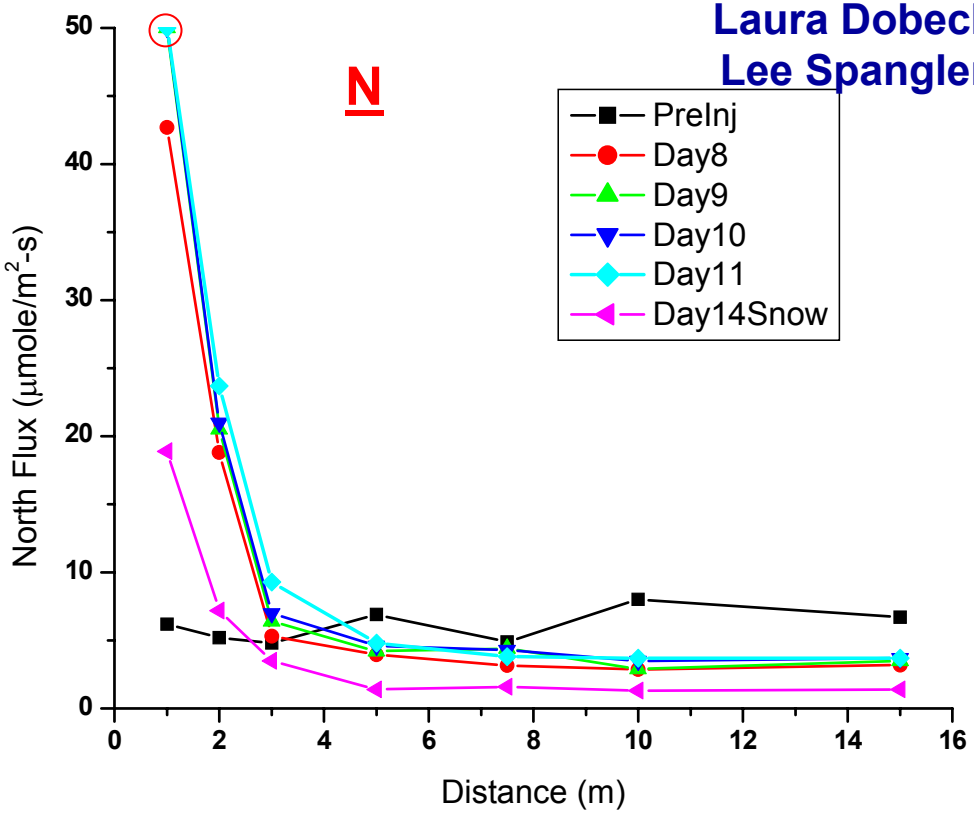
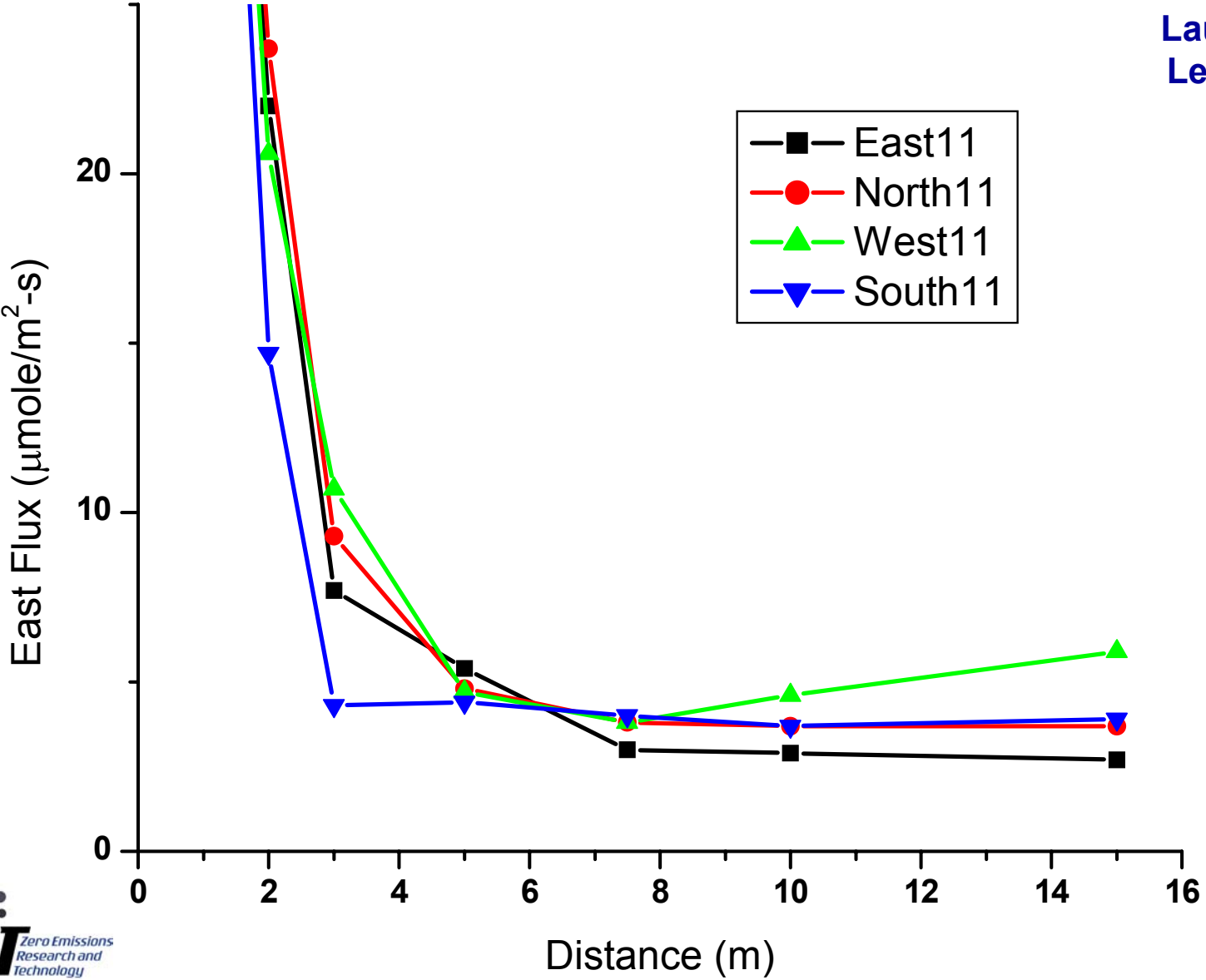




Soil Flux Radial Distribution, New Injector

MONTANA STATE UNIVERSITY
Laura Dobeck
Lee Spangler



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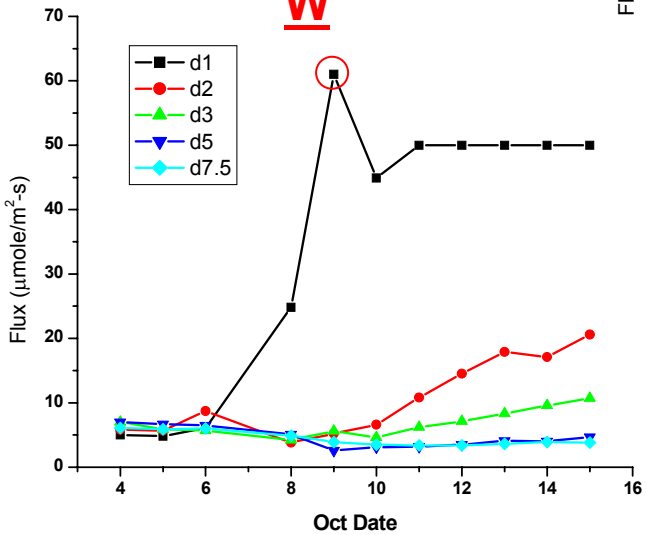
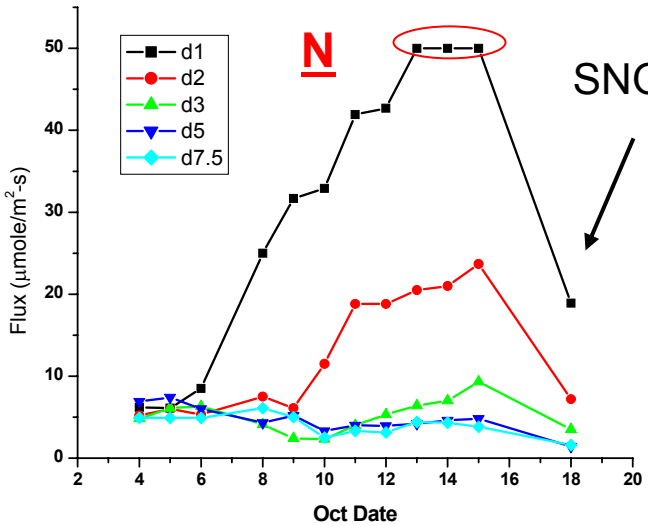
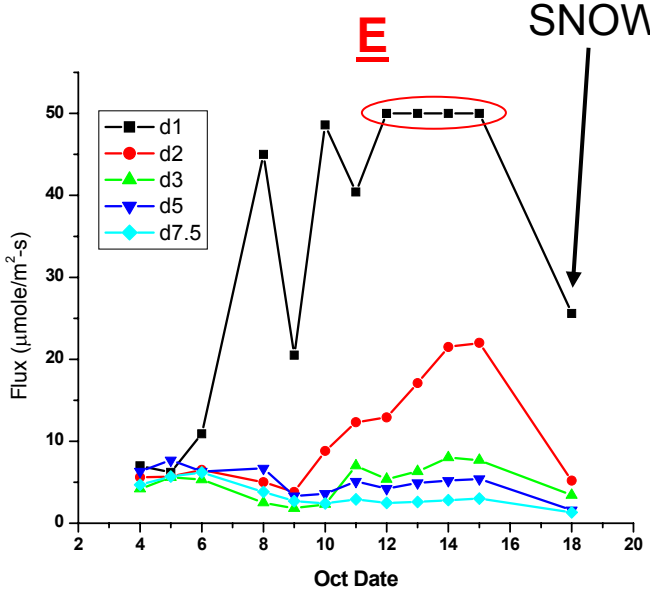
Soil Flux Time Series, New Injector

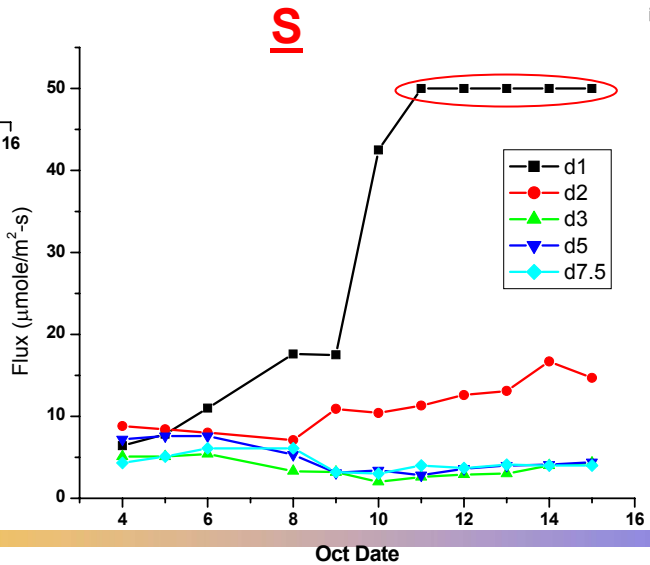
MONTANA STATE UNIVERSITY
Laura Dobeck
Lee Spangler

Note: No flux increase at 0 m in first 6 hours









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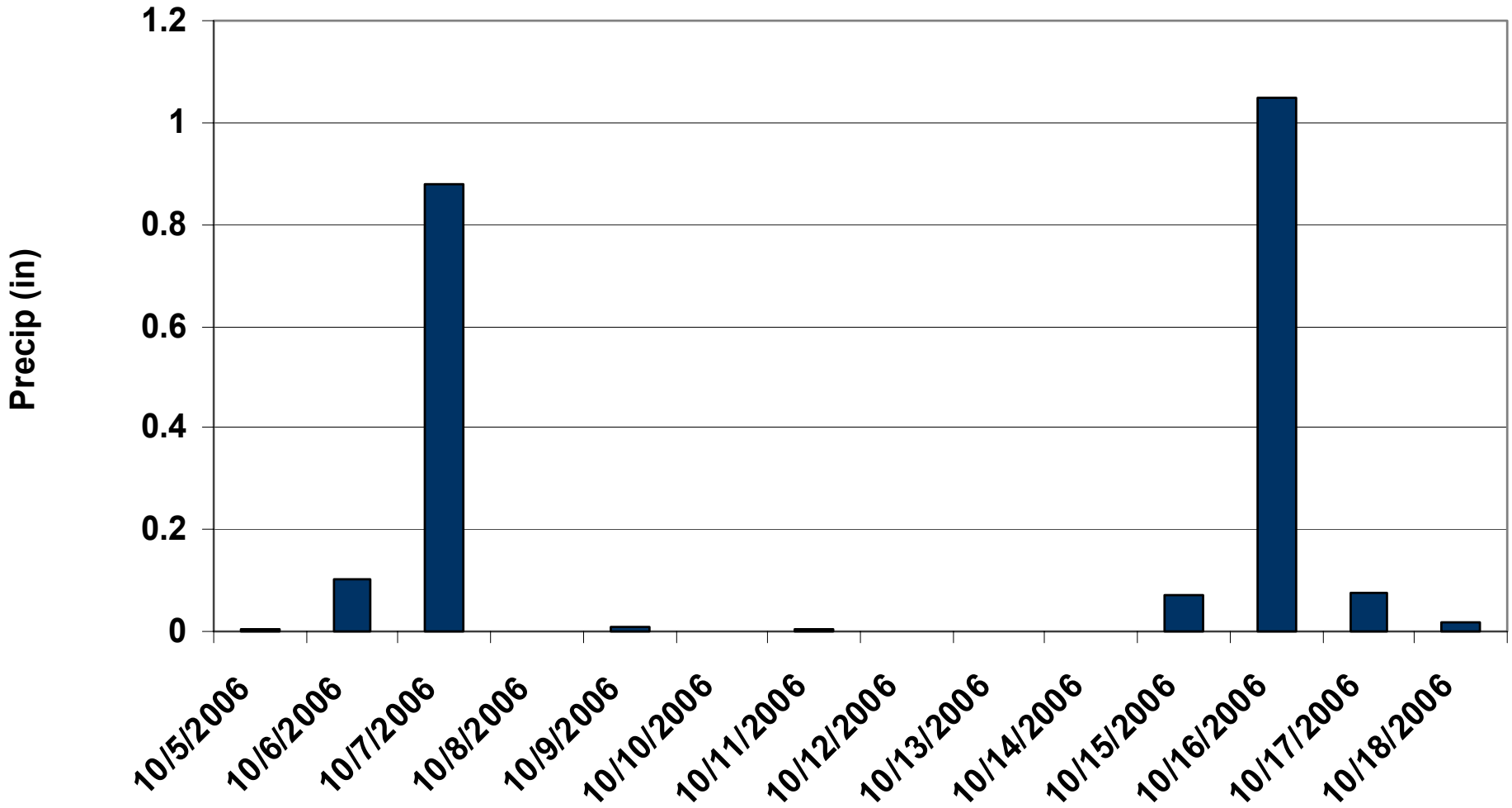
Precipitation for 2nd Vertical Injection



Soil Flux Time Series, New Injector

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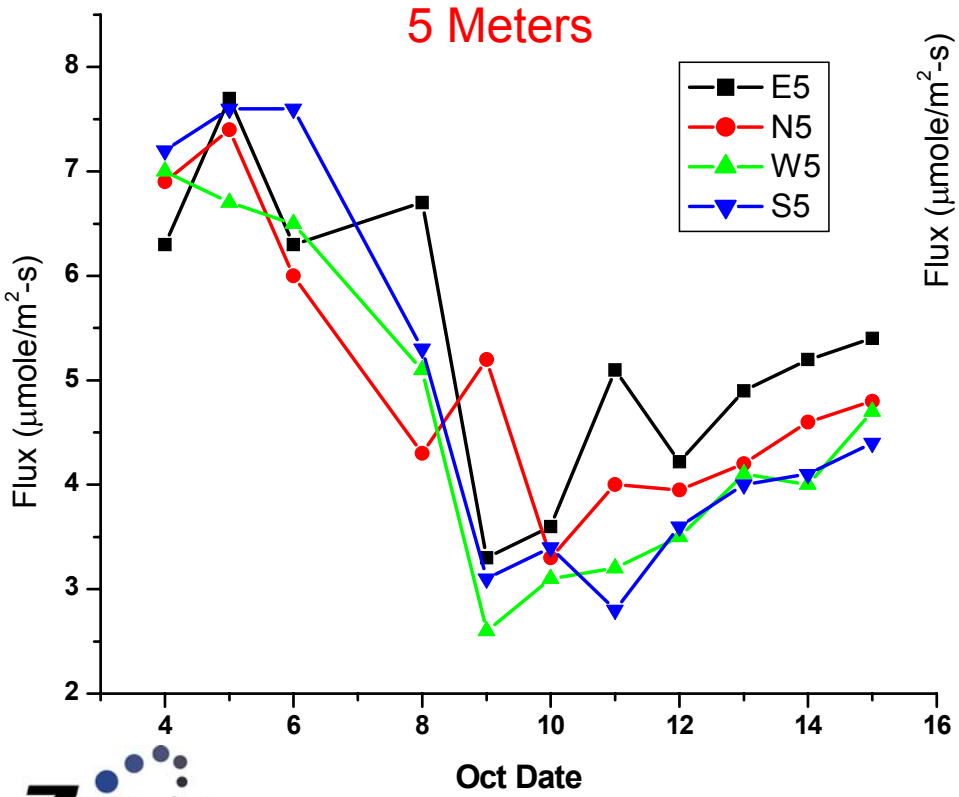
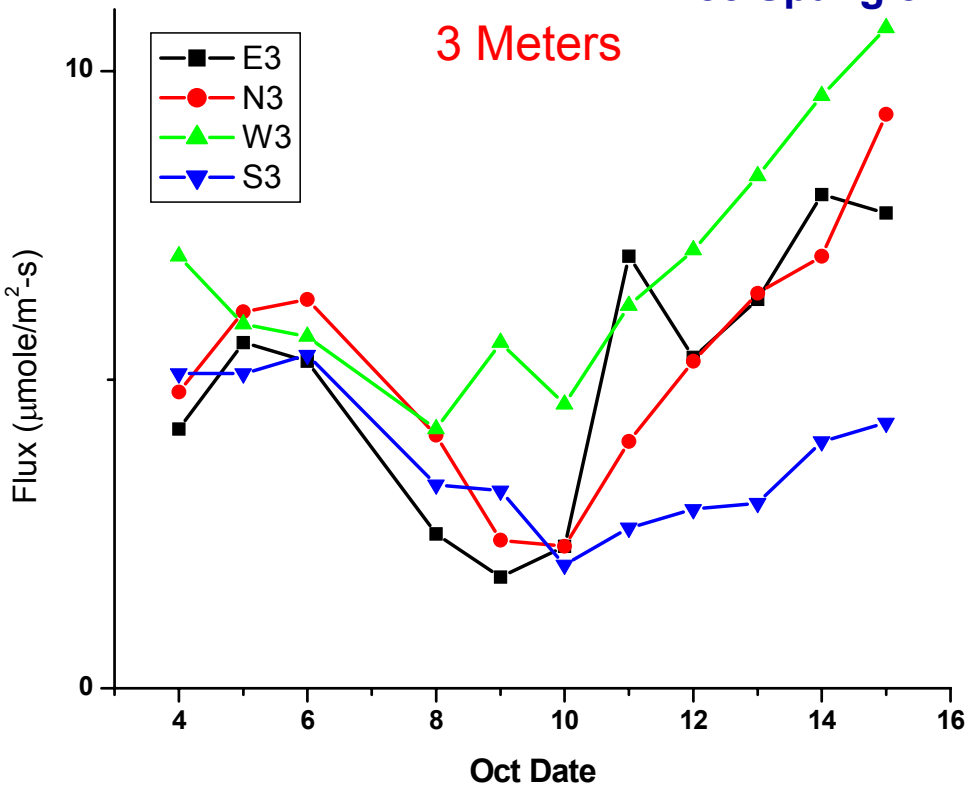
Laura Dobeck
Lee Spangler





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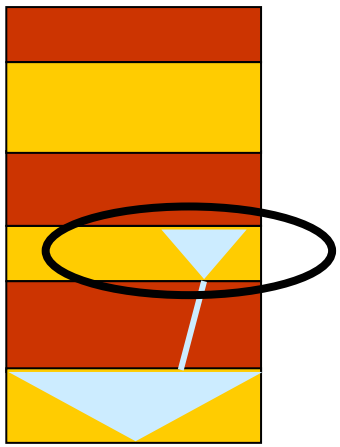
~~Conclusions~~ Preliminary Thoughts

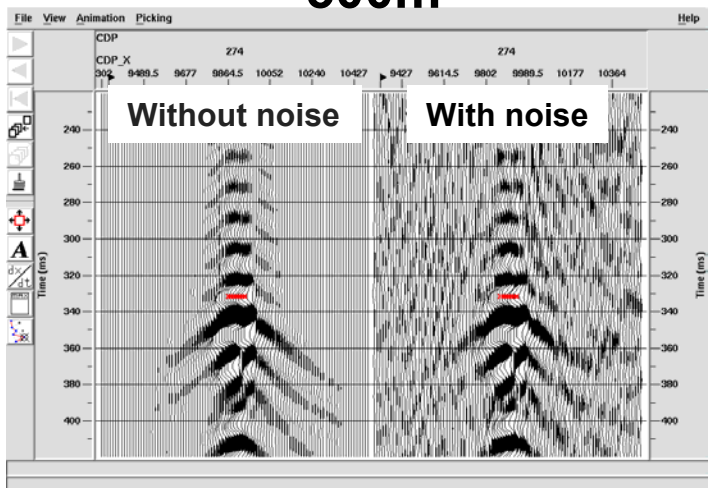
- Concentration and flux measurements are probably less sensitive than ^{13}C
- Soil moisture content and temperature can have a large impact on soil flux measurements
- CO_2 flow may desiccate soil, increase gas permeability, and generate a faster flow pathway. I.e. flow may effect plume diameter over time.
- Depending on geometry of underground source, relevant surface fluxes may be measurable

Detection Limits for Seismic Imaging

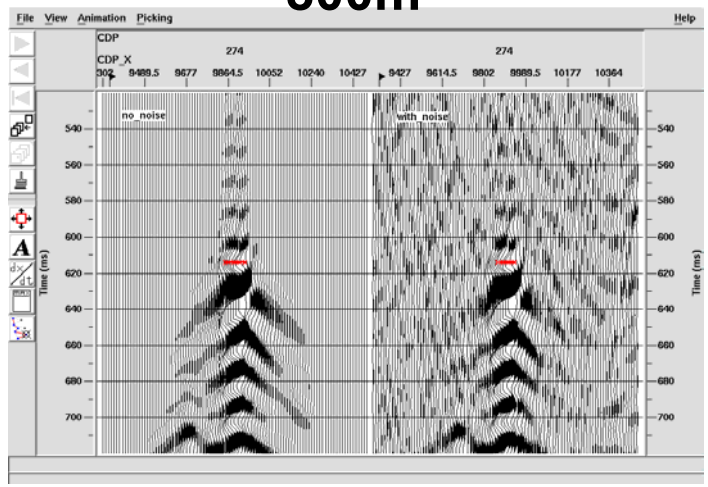
Conceptual Model



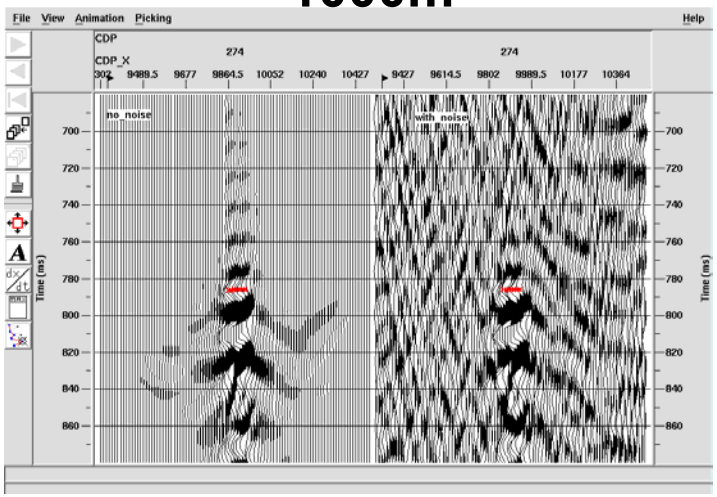
500m



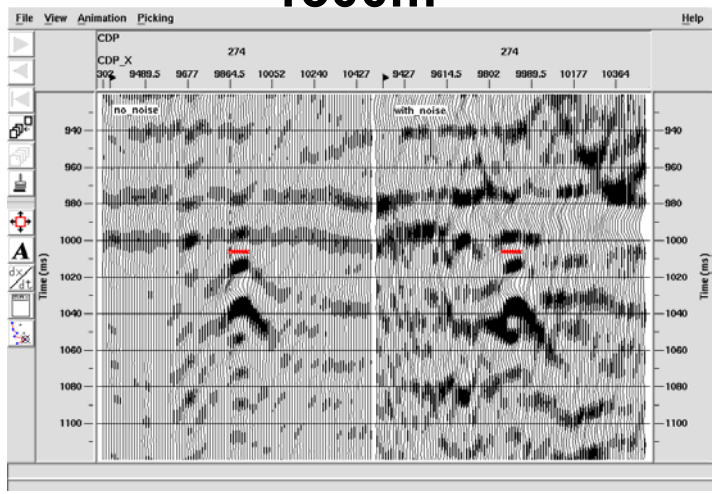
800m



1000m



1300m



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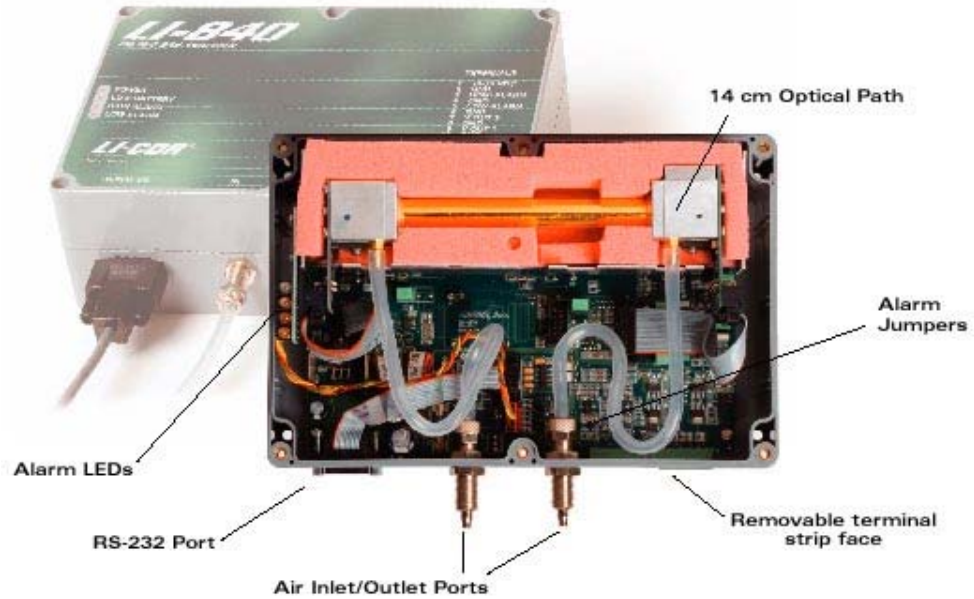
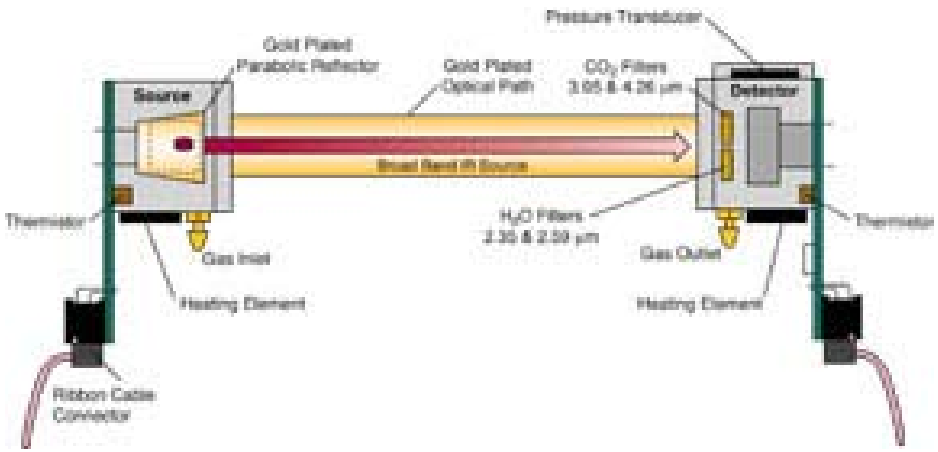
1000 tonne accumulation at various depths are all visible

CO_2 Soil Gas Measurement





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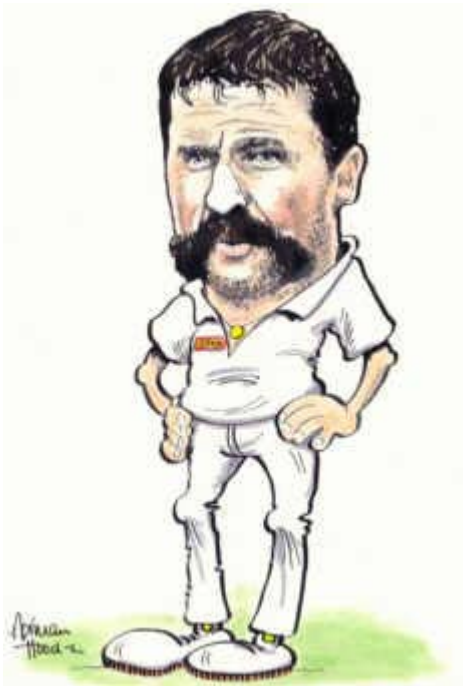
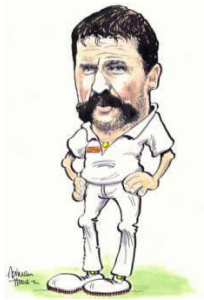
IEA GHG R&D Programme
CCS Monitoring Network
30 October 2006

Regulatory outcomes – a discussion on MERV



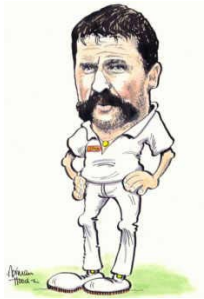
Mark Bonner
Director, Technology Futures

Australian Greenhouse Office
Dept of the Environment and Heritage



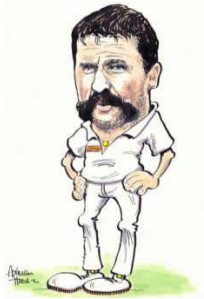
start of therapy session

- “the role of regulator is in its infancy …
- “no natural technical expertise within regulators …
- “how to skill up in a timely way is key challenge
- “there are a lot of analogues to inform – but which are relevant?
- “we need to leverage existing legislative processes as far as is appropriate
- “sceptical – so many environmental incidents in industrial applications from operators who gave assurances of safety …



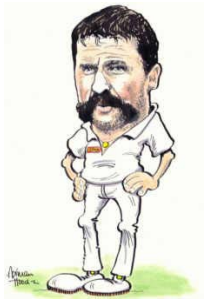
quest for basic meaning - therapy session #2

- “what are the key risks…
- “what are the key values to be protected (minimise or prevent continued damage to climate; groundwater etc)
- “how can risks be managed and/or mitigated
- “what is the role of MERV in management
- “what is the role of standards based systems MERV systems
  “at the end of the day, what is the most chronic risk of incident and what options are there for mitigation, remediation and/or rehabilitation



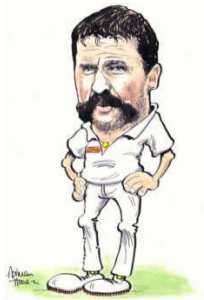
'intuitive' - principles

- equity "who bares the intergeneration risk
- efficient "is this commercially attractive
- dependable "is there permanent CO_2 isolation from atmosphere
- independence "of assessment - public demands this
- transparency "science based, inventory reporting
- flexibility "continuous improvement; objective site by site requirements
- consultative – stakeholders, general public
- Others



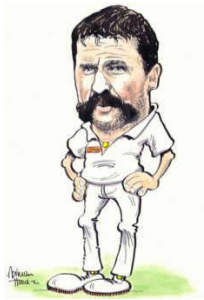
political realities

- "it is political judgement that ultimately defines the term dangerous climate change – *can't afford lose sight of this*
- "scientists provide evidence for political judgements to be made – *this also likely applies to MERV applications*
- there are many uncertain tipping points: (time) 5-10 years? (metrics) < 2 degrees C; 450-500ppmv; (economics) xtCO_2$
- "we need to deliver CCS to a public (inc. business) that is still wondering how it all works [*suggests social preferences prevail – performance standards, costs, ethics*]



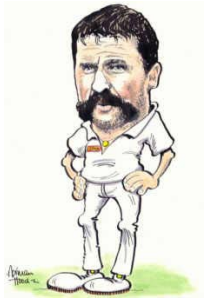
...

- “politicians want numbers – even if not understood
- “key to success is the maintenance of integrity of public confidence
- “if CO_2 is not stored for a minimum of 1,000 years – the site is not sufficiently robust
- “NIMBY: out of (OO) sight does not equal OO mind
- “NOMW – short term election cycles
- “whipped up controversy on CCS is not helpful



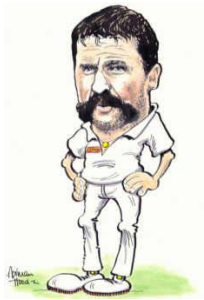
...

- “we need a multi tracked approach but CCS is a technology we can’t do without
- “… and in some ways we've left it too late
- “there seems to be much angst over who accepts long term liability
- “important to understand private sector risks of CCS
- “CCS intuitively offers greater benefits than disbenefits



possible values to be protected, avoided, understood

- "LDCs need to slow the rate of increase in emissions – not deliver absolute reductions
- "our generation [not sure who 'our' is] is focused on stabilisation – next generation will be absolute reduction
- "low or high rates of CCS deployment will have profound implications for other mitigation option contributions – *CCS has to work if deployed at scale*
- "CCS is between 15%-20% of the challenge in the near term
- "if it's going to fail at scale, we need to know sooner rather than later



...

- "proponents of one solution tend to disparage other options (wind Vs solar; renewables Vs FF – *geomechanics Vs geophysics?*) – this is not helpful
- "there is not enough time for sequential introduction of low emissions technologies … or "for markets to deliver the solutions
- "how do we get to better understand this new industry of CCS – *this is how regulators see the challenge*

'An' end state

What is needed is a shared vision among regulators as to what the 'end state' for MERV is - it will likely be some function of the following considerations (among others) …

Government(s) appetite to underwrite risks associated with CCS investments

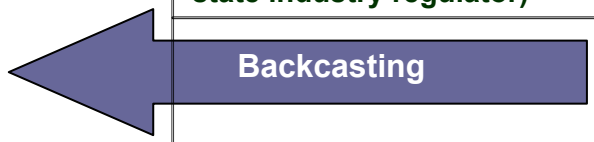
Economic cost of deployment

Technical scope of MERV options

Delivery of environmental services being relied upon

Social willingness to pay - public acceptability

Protecting the national interest (note Australia's recent interest in security implications of climate change)



IEA Monitoring Network Regulators Day 30 Oct 06

"discussion is revolving around what is technically feasible - not what is environmentally or economically sensible …

45-50 Monitoring tool options: Seismic; Sonar; Gravitmetry; Electric/Electro magnetic; Geomechanical; Remote Sensing; Ecosystems; Others

"Not any one monitoring tool can provide the answer to all questions …

"It is what the atmospheric readings of CO2 are that's acceptable or not (source: Australian state industry regulator)

"Geomechanical will be most critical in giving early signals of failure

"perfect storage sites and CO2 streams don't exist

Geologists prefer the term "microseismic activity", the public and media will adopt "earthquakes" …

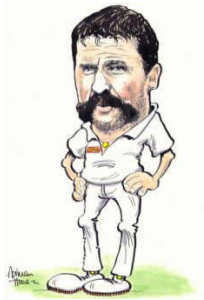
"How can regulators make practical sense of pilots and demos when "MERV should be designed as 'fit for purpose'

"There is no ability for pilot/demos to deliver the evidence of what the public demands …

Monitoring aims: Plume Imaging; Top Seal Integrity; Well Integrity; Induced Seismicity; Migration of Overburden; Quantification in Situ; Storage Efficiency; Public Acceptance; Calibration

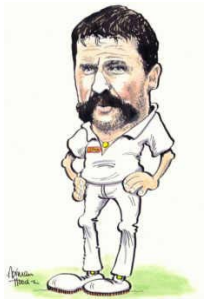
"Without knowing how CCS is to be rolled out (carbon tax, trading) it is impossible to answer all these questions …

"Environmental regulators look to provide assurances to the community rather than just toxic impacts of the stream



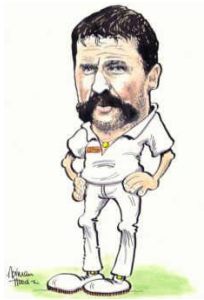
economics

- "cost of getting CCS wrong will be huge … we are still paying to clean up legacy standards
- 1% leakage accumulated from $GtCO_2$ storage could translates to $bn – who bares this long term risk?
- "need to protect the integrity of emission caps for both market and environmental reasons
- "CCS still needs to confirm its legitimacy as a mitigation option when compared to other options – *but how given the scale of what's being asked of it – both time and abatement?*
- "cost of action under imperfect information Vs. cost of inaction – when to act?



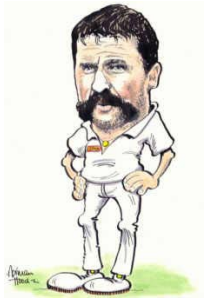
regulatory tool box

- “many analogous activities to draw guidance from … national gas storage; nuclear; waste management; mining site closures etc
- USEPA UIC programme – regulates all fluid underground injection
- strategic Environmental Impact Assessments
- compliance with mandated performance standards (and/or)
- consistency with established guidelines
- agreed protocols for users to provide sufficient evidence of compliance (burden of proof is on users)

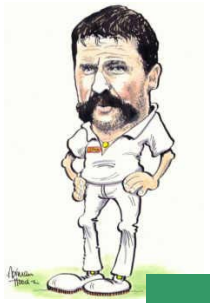


still much confusion and uncertainty among policy and regulators

- "do we fully understand the storage mechanisms – *and how much knowledge is enough* …
- "can we monitor and verify the sub surface – *to an agreed and accepted standard* …
- "can we permit long term storage and closure arrangements – *on existing knowledge*…
- "how do we handle failure … and can we fully describe the most chronic situation regulators will have to manage
- is the current risk level and uncertainty undermining governments preparedness to encourage a pragmatic approach to CCS deployment …



- “we can’t monitor forever – *how long is long enough*
- “can we live with leakage – *how much is acceptable*
- “emission reductions with EOR without monitoring will be counted as 100% emitted – *what rules should apply to CCS*



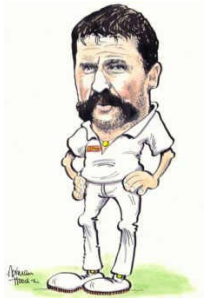
standards – politicians need #s

	User	Regulator
M	Monitoring (tools)	Performance standards and protocols (fluid pressure; volume; temperature; leakage; seepage)
E	Evaluation	Approvals and permitting (state, federal)
R	Reporting	Guidelines
V	Verification	Certification and compliance
	Long term liability	Post site closure arrangements

Requirements

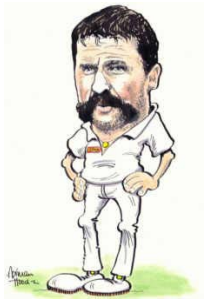
Compliance

- do we design for zero leakage (knowing there is no perfect site or CO_2 stream or design for acceptable leakage and seepage rates (what are these rates – and how do we determine what's acceptable)?



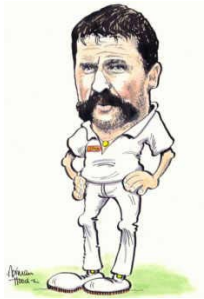
standards – business and public acceptance?

- "liability insurance is the focus as is … occupational health (H) and safety (S) - less so the environment (E) – *does H and S MERV systems go a long way to delivering on E?*
- perceptions are already forming – and not many insurers are in the CCS game possibly due to: reputational risk; lack of solidarity of exposures; nature of risk (can only insure for sudden and accidental off – not slow and continuous); high pressure systems notorious for finding and creating leaks; more Qs than As!



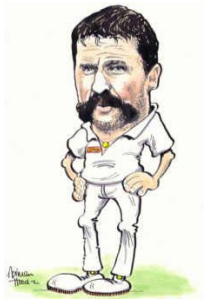
standards – what, why and how?

- should we be striving for metric driven standards or technically based standards (ie. best of breed) – *ultimately ranked by a metric based assessment?*
- "demonstrate site is currently performing as expected (need to identify non-conformance) – *how are credible expectations established*
- CCS permitting processes are likely to be data hungry upfront (risk assessments etc) Vs less so when site is behaving predictably at the end – *does this suggest enhanced monitoring package upfront and a basic package towards the end (if site is conforming)?*



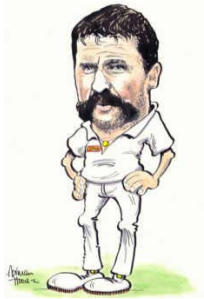
timing urgency

- “the permitting approvals are required today – not in the future
- 31 Dec 06 = EU CCS report on robust M&V framework
- Dec 07 = EU Communiqué on permitting CCS (includes MERV)
- Now to 2010: FIDs for projects that will commence …
- post 2010 = most commercial scale activity (x6 UK, likely >6 Australia, etc)



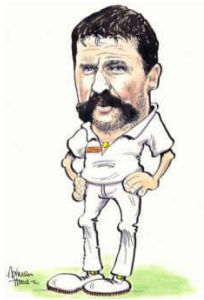
5 conclusions

- “not all about technical aspects – equally about making contacts and connections
- “dialogue is all important (federal/state; env/industry; researchers)
- “design basis is crucial – what are we designing for and the policy and research community has a responsibility to rise to this challenge
- “parallels with other processes (regulatory/risks etc)
- “need to be flexible (community standards change over time and continuous improvement



another 5 conclusions

- “need for transparency and openness to bring along the community
- “learning by doing is the way forward – but decisions can’t wait for perfect information
- “timeframes of ’00s and ’000s of years mean nothing to politicians
- “politicians demand ‘numbers’ – there needs to be a quantifiable end state
- “issue of MERV regime – are we monitoring for a market or environment – or both, in which case compromises will be inevitable



final messages …

- “the logic of this Network is very clear from this broader picture – we need this Network to deliver CCS MERV to a public that is still wondering how it all works
- “all regulatory agencies have an important role to play in building public confidence and outreach
- “it is government policy that makes sense of all of this discussion on regulation and CCS deployment – and we shouldn’t lose sight of what the policy objectives are (... this is my only original quote, thks

CO2 CRC COOPERATIVE RESEARCH CENTRE FOR GREENHOUSE GAS TECHNOLOGIES

Reducing greenhouse gas emissions to the atmosphere

The Latrobe Valley CO_2 Storage Assessment

Catherine M. Gibson-Poole[1,2], L. Svendsen[1,2], J. Underschultz[1,3], M. Watson[1,2], J. Ennis-King[1,3], P. van Ruth[1,2], E. Nelson[2], R. Daniel[1,2], Y. Cinar[1,4] and A. Rigg[1]

[1]CRC for Greenhouse Gas Technologies
[2]Australian School of Petroleum, The University of Adelaide
[3]CSIRO Petroleum
[4]The University of New South Wales

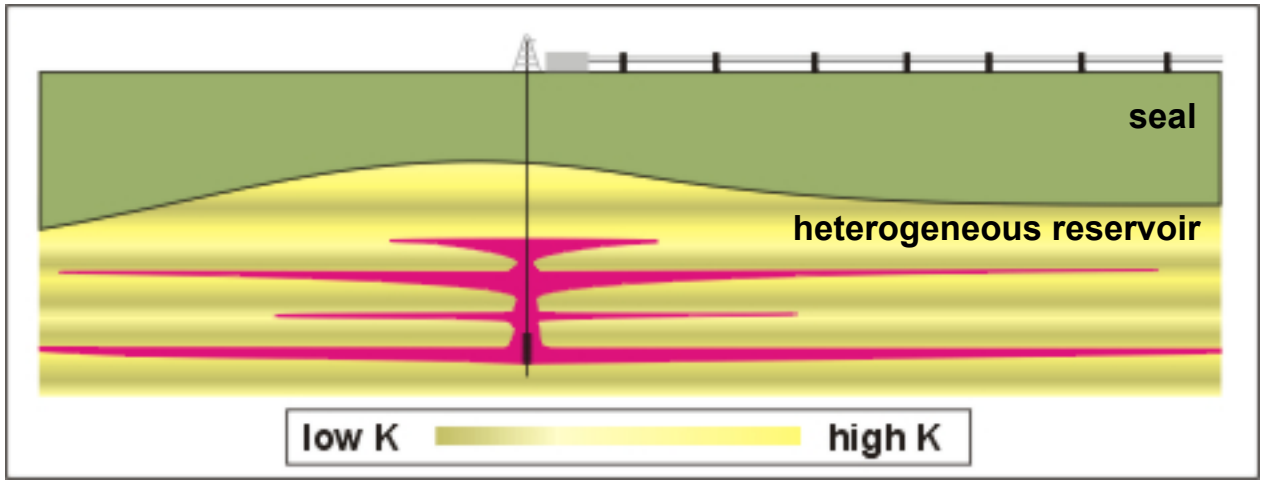
IEA Workshop – Melbourne, VIC – 1st November 2006

UNSW CSIRO ASP Australian School of Petroleum THE UNIVERSITY OF ADELAIDE AUSTRALIA CRC

Presentation Outline

- Introduction
- Workflow for detailed site characterisation
- Gippsland Basin, southeast Australia
  - Base regional seal migration pathways
  - Kingfish Field: sequence stratigraphy and depositional model
  - Injectivity: reservoir quality, geometry & connectivity
  - Containment: seal capacity, migration pathways, trap mechanism, geomechanical assessment, hydrodynamic analysis
  - Capacity: 3D geological model & pore volume
  - Numerical flow simulation
- Conclusions

Introduction



Amount of CO_2 geologically stored influenced by:

- Rate of CO_2 migration
- Style of multiphase flow
- Rate of CO_2 dissolution
- Rate of chemical reaction with minerals

Controlled by many variables, including:

- Reservoir and seal structure
- Stratigraphic architecture
- Reservoir heterogeneity
- Faults/fractures
- Pressure/temperature conditions
- Hydrodynamics and chemistry of *in situ* formation fluids

(CO_2 concept model courtesy of Robert Root)

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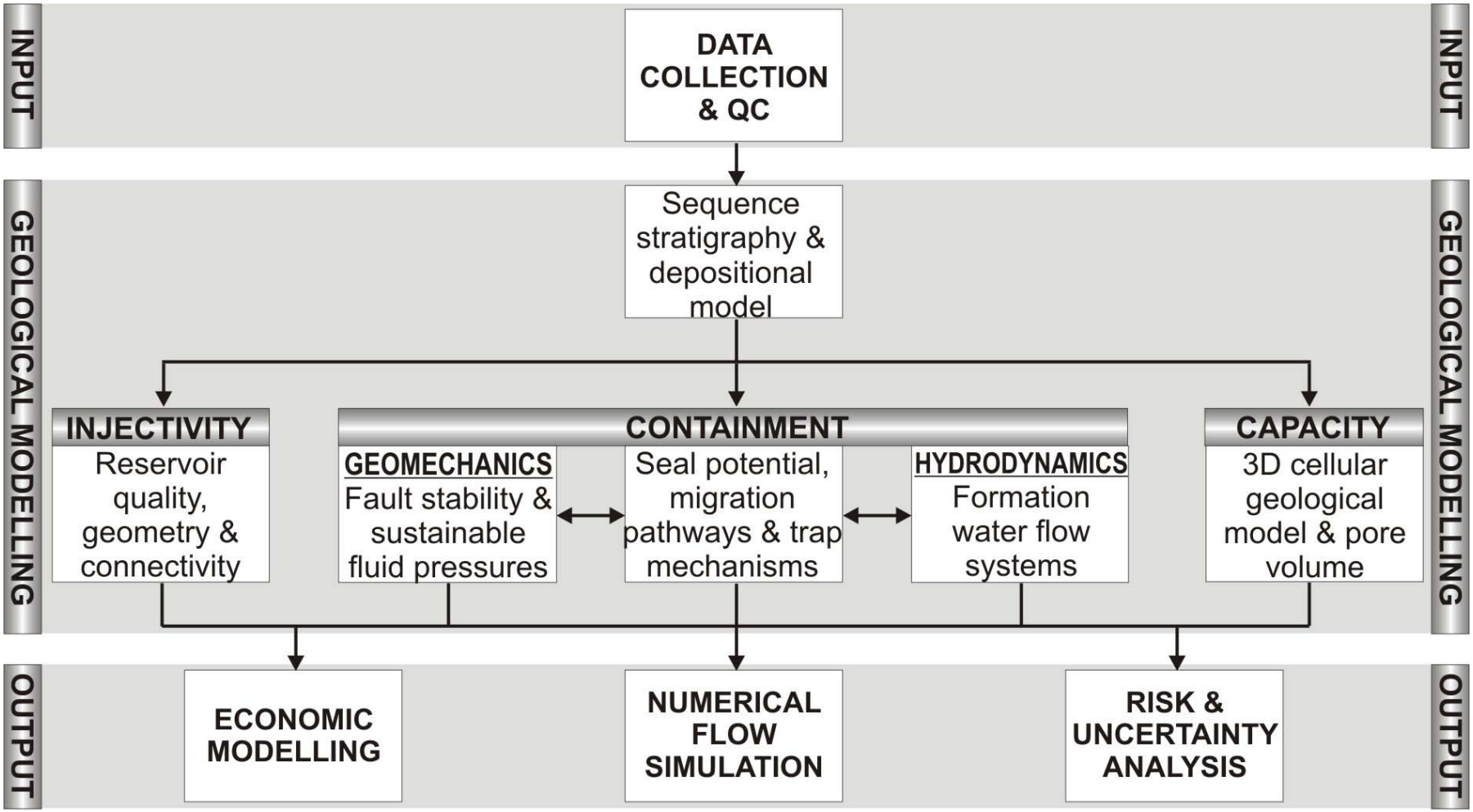
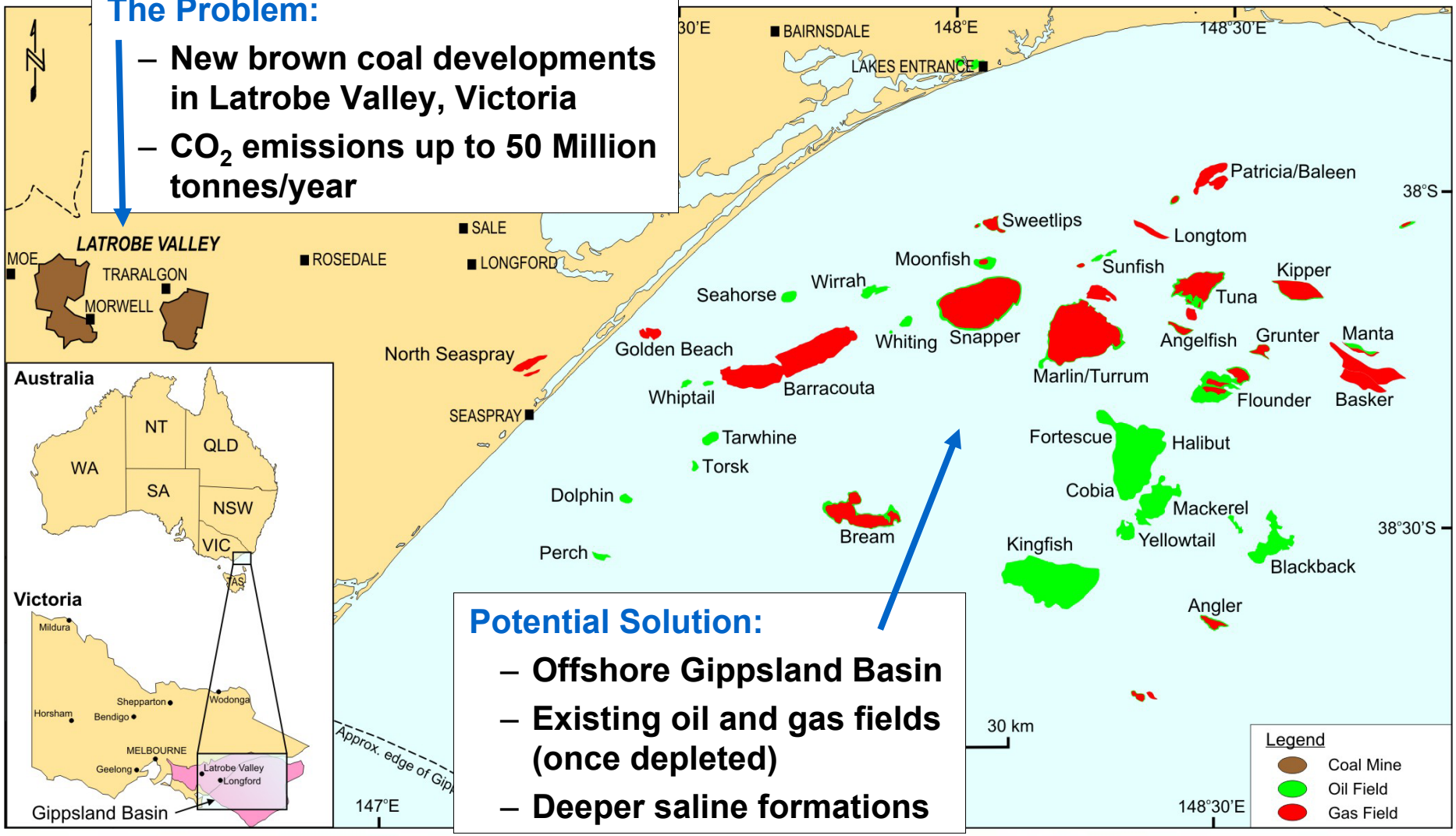
Site Characterisation Workflow



Gippsland Basin, Southeast Australia



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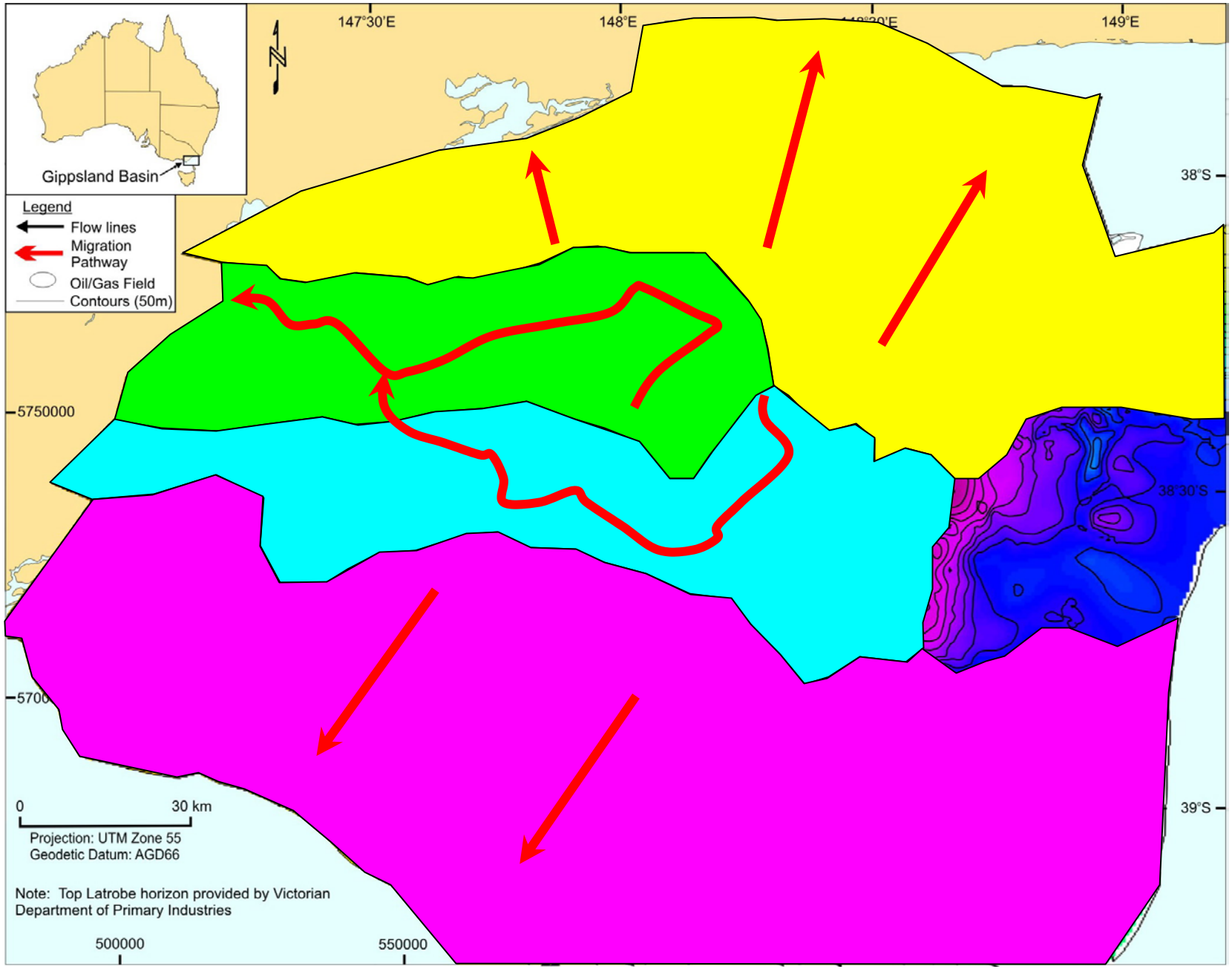
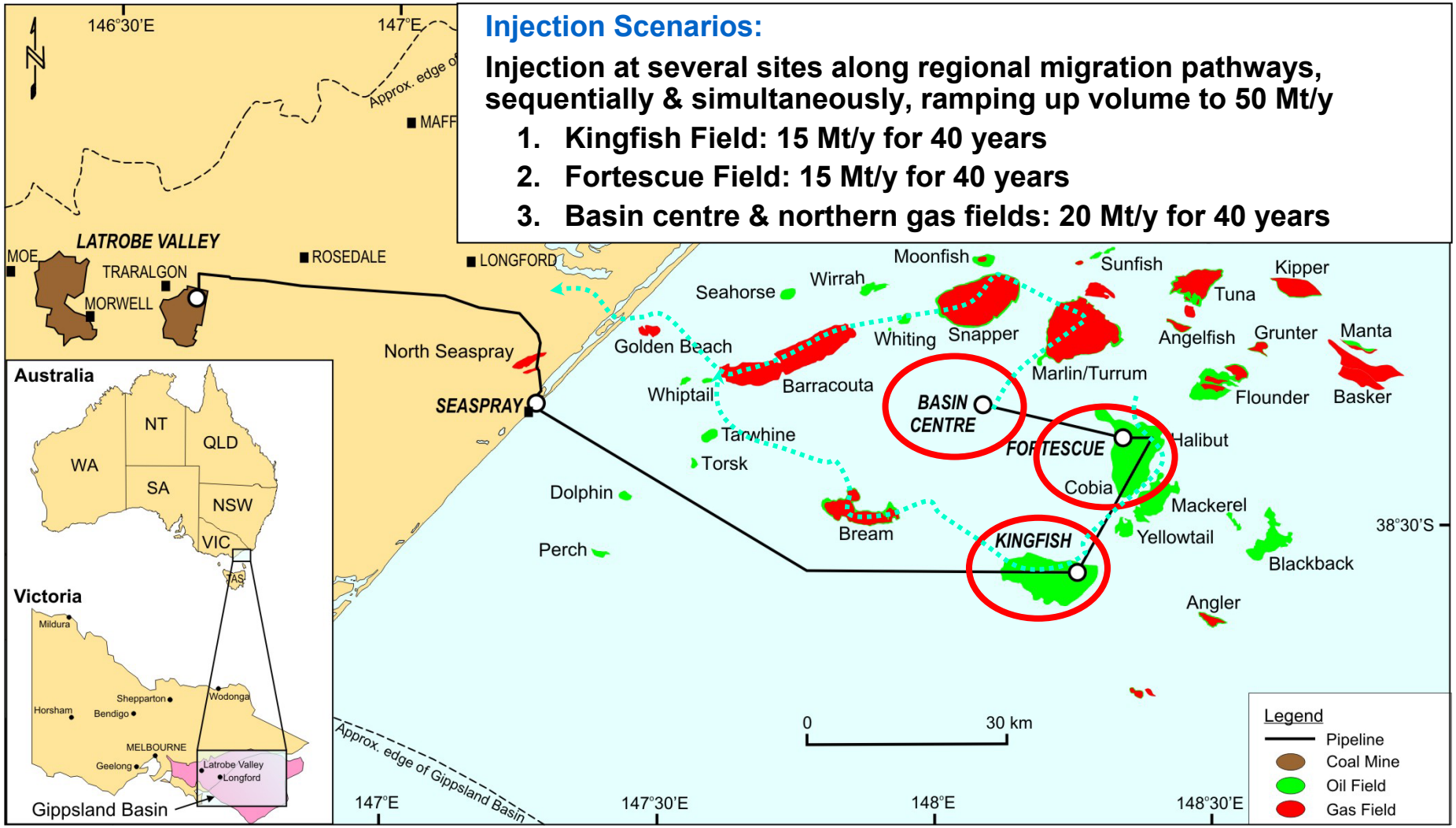
Buoyancy migration pathways at base regional seal



Selected Site Scenarios



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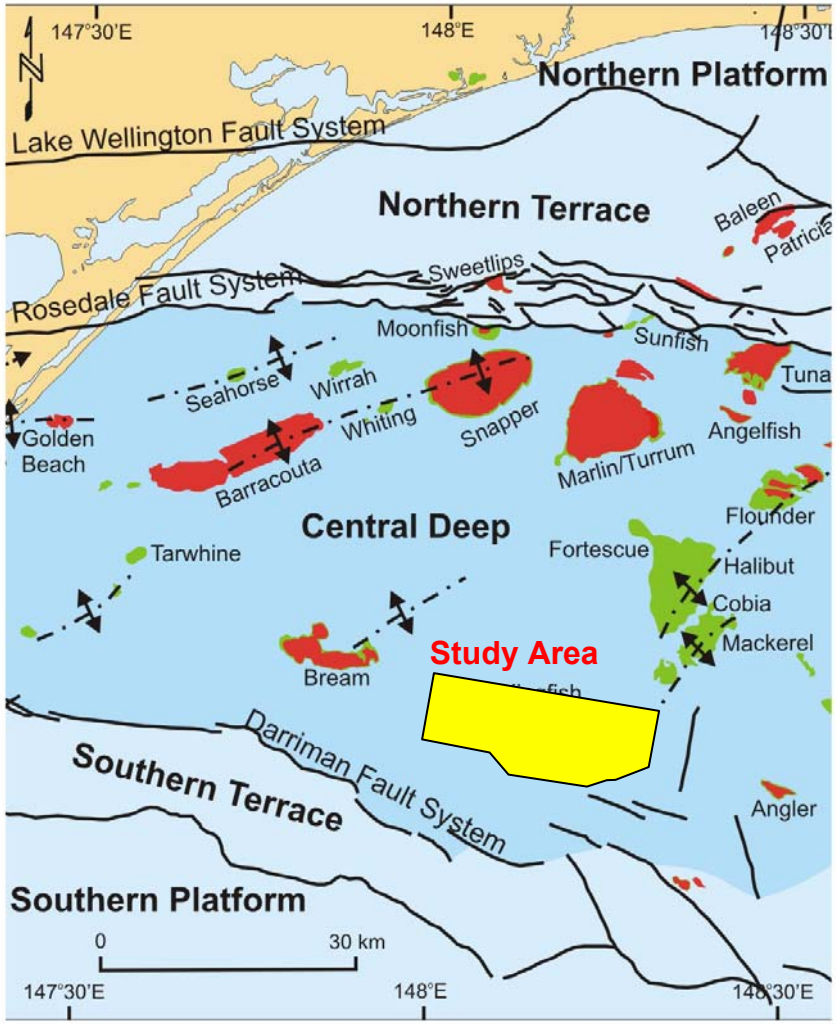
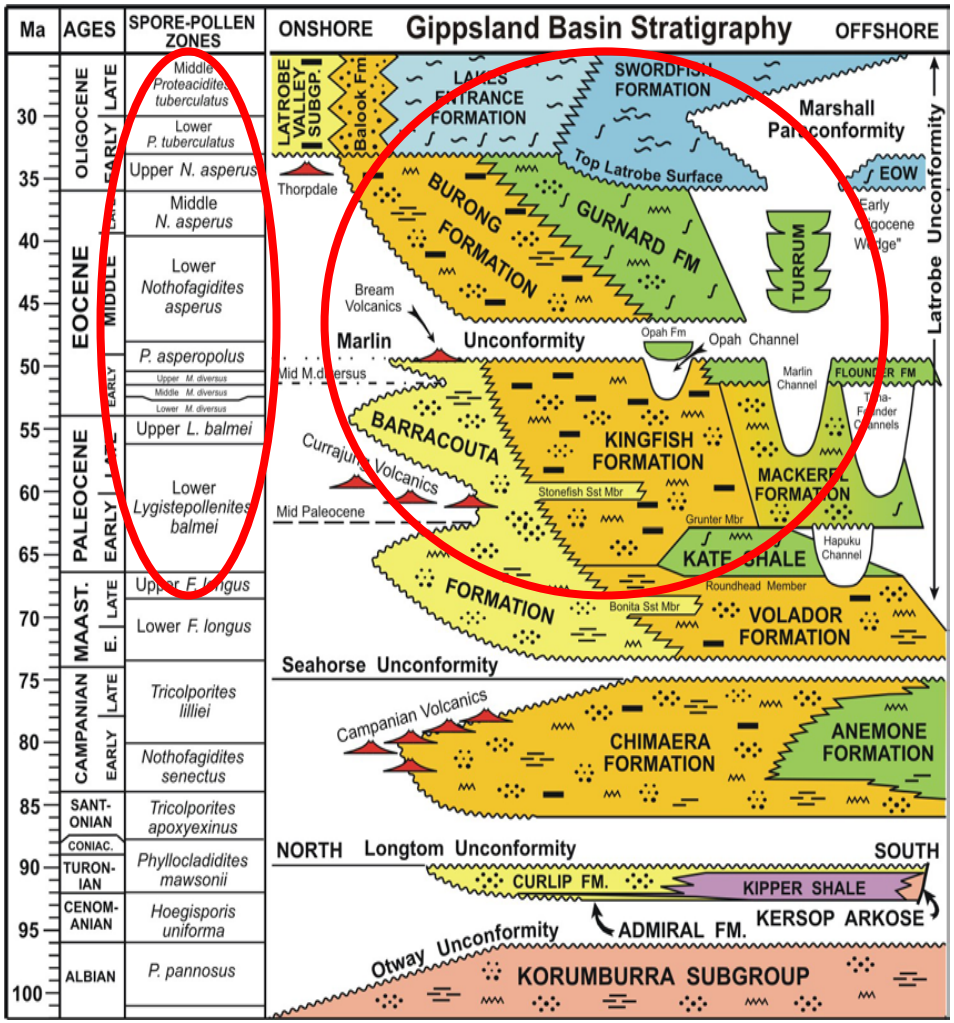
Detailed Characterisation: Kingfish Field

Location map of Gippsland Basin



(modified after Power et al., 2001)

Stratigraphic column



(after Bernecker & Partridge, 2001)

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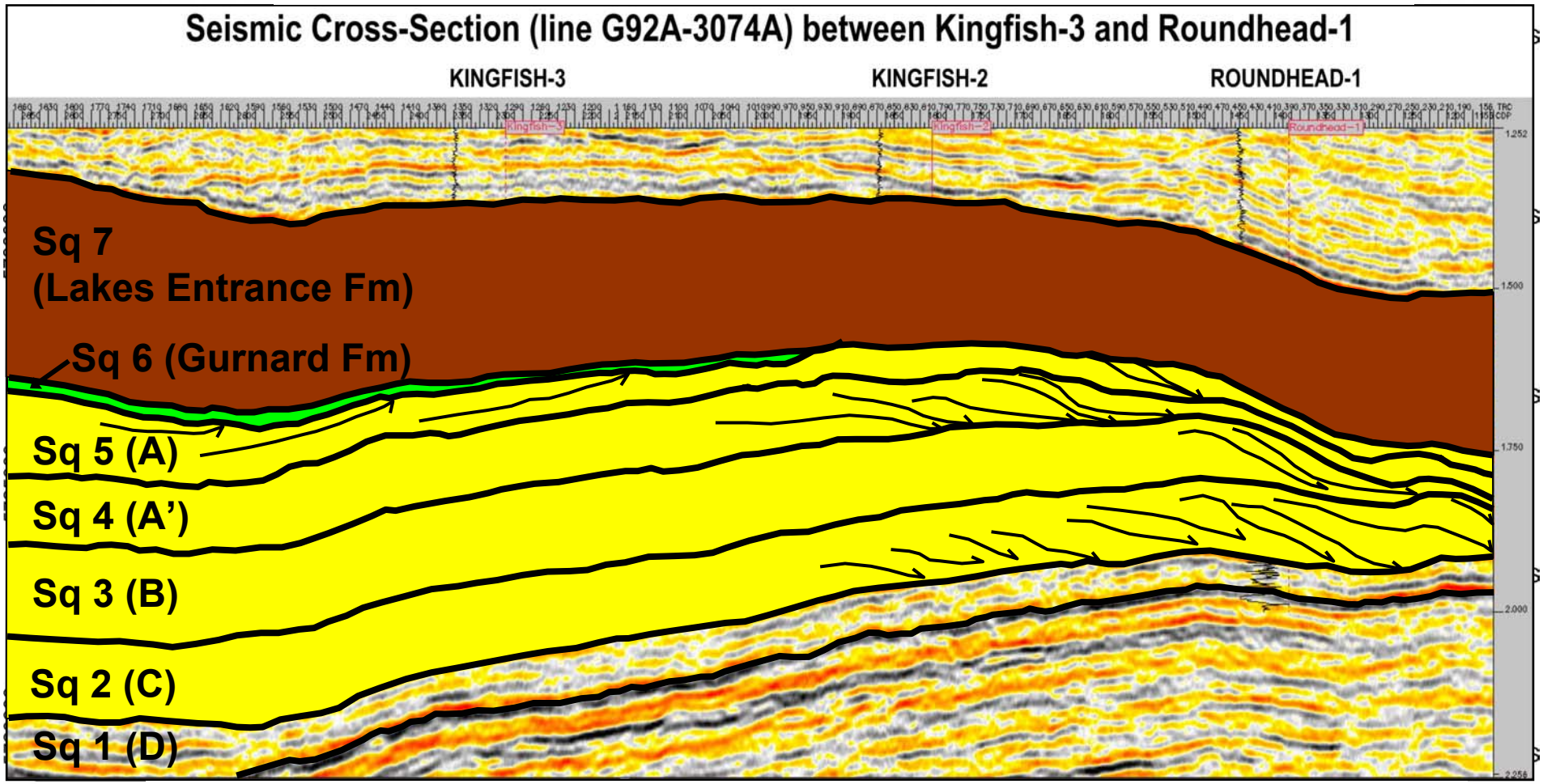
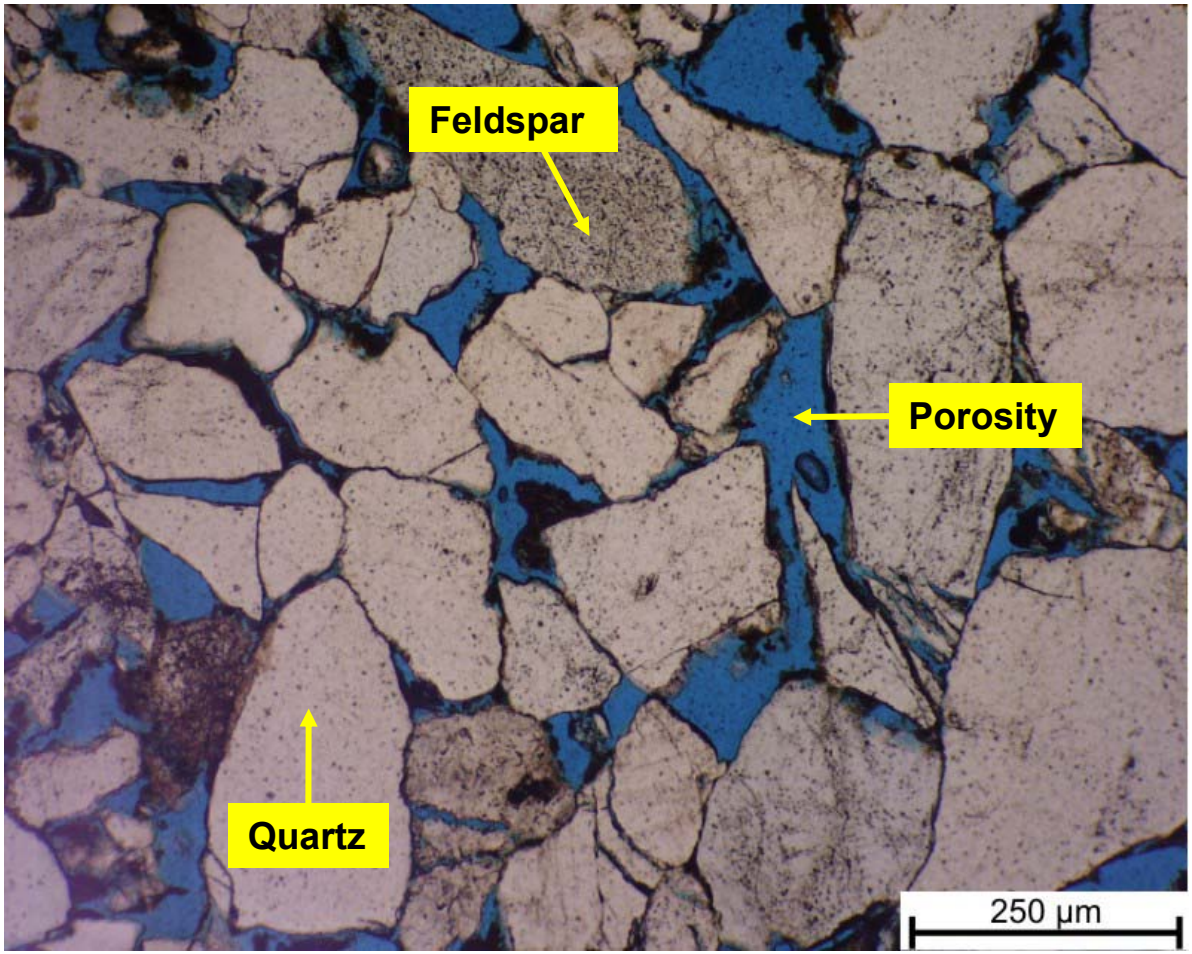
Sequence Stratigraphy



Injectivity: Reservoir Quality



Thin section micrograph: Kingfish Fm, nearshore facies

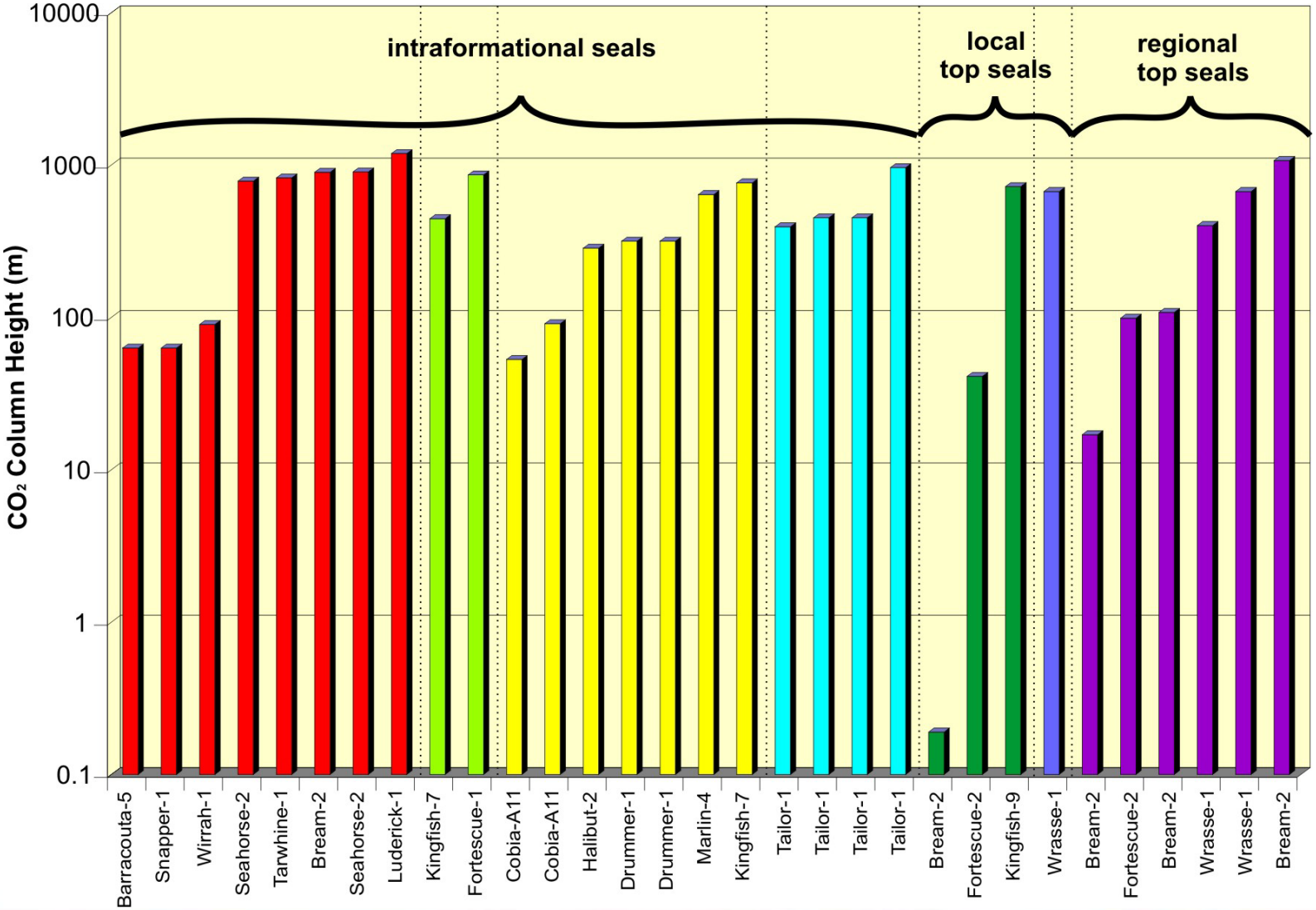
Kingfish Fm

- 15-30 % porosity
- 10-10,000 mD perm
- Good to excellent reservoir quality

Geochemical reactions

- Reservoir units lack minerals reactive to CO_2
- Injectivity unlikely to be compromised

Containment: Seal Capacity (MICP analysis)



Intra-formational seals

- 53–1191 m
- Avg 517 m

Local top seals

- 0.2 –723 m
- Avg 360 m

Regional top seal

- 17–1071 m
- Avg 395 m

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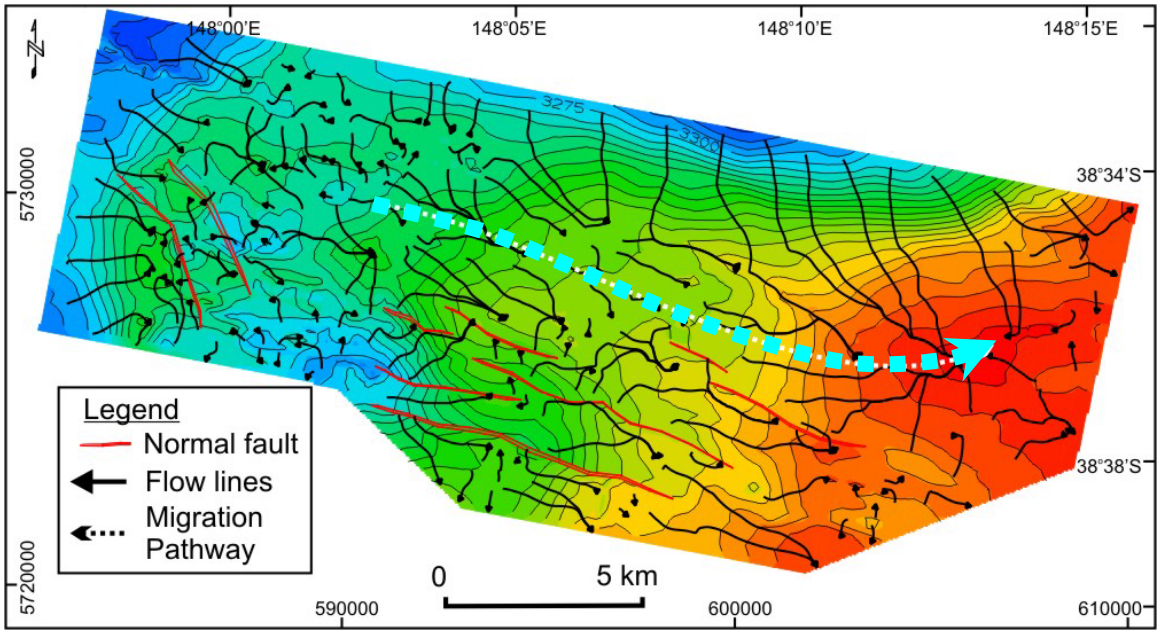
Containment: Migration Pathways

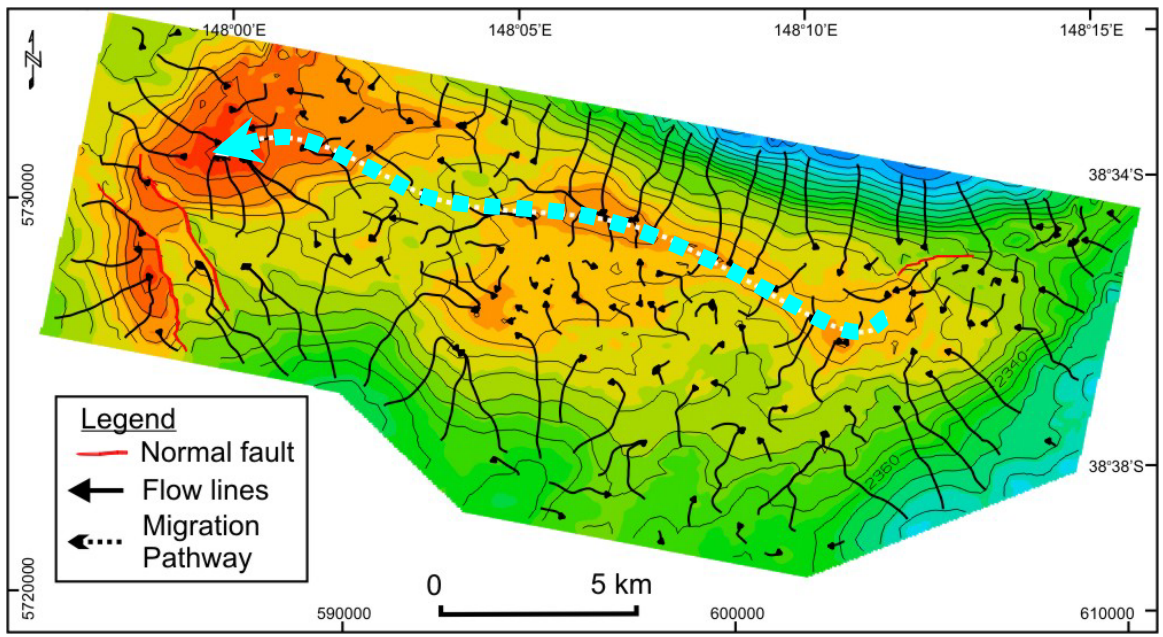


Intra-Latrobe Gp

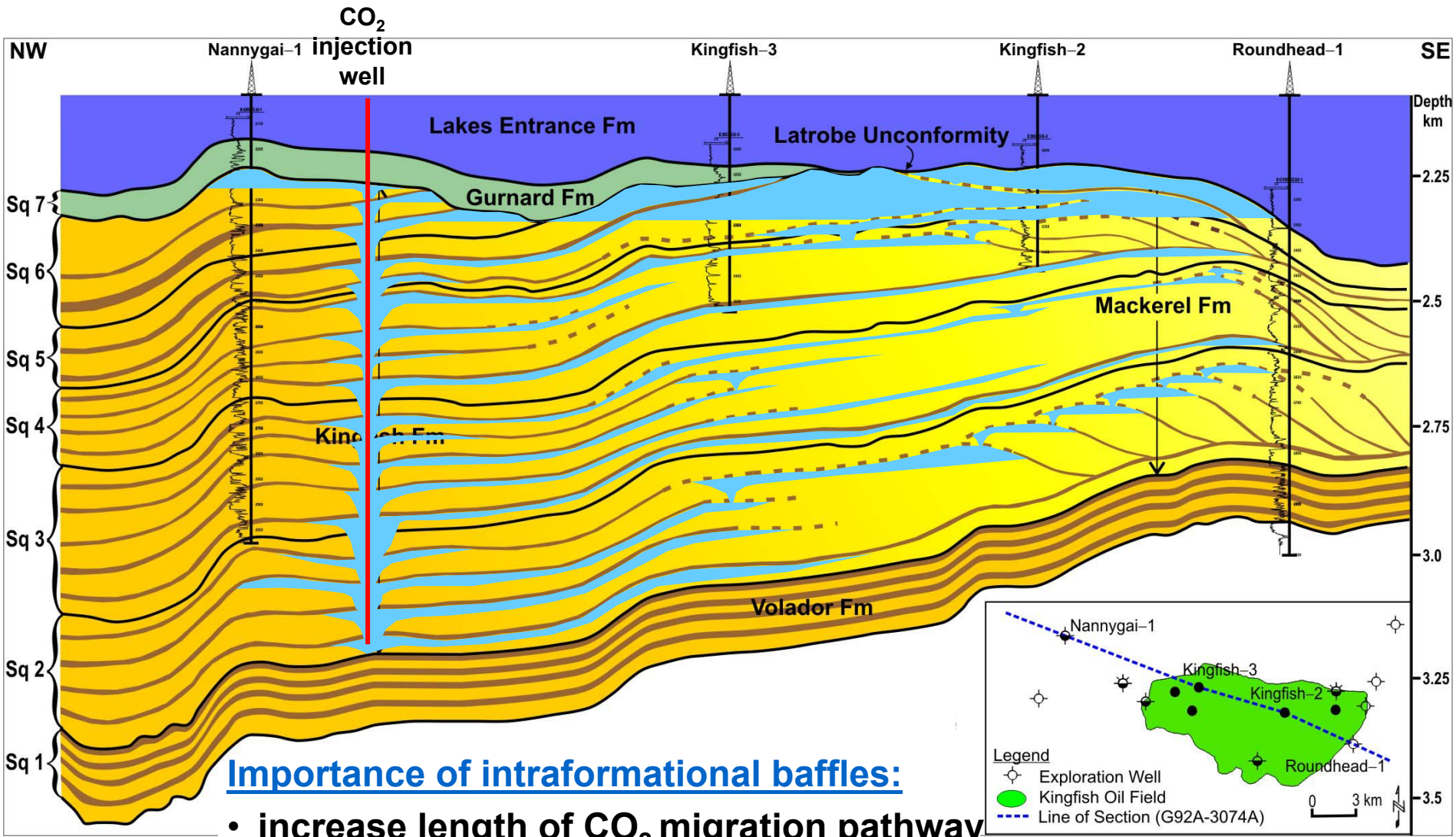
- Stratigraphy dips down to west
- CO_2 will migrate updip to east

Top Latrobe Gp

- Base regional seal dips down to east
- CO_2 will migrate updip to west (towards Bream)



Containment: Migration Pathways Concept



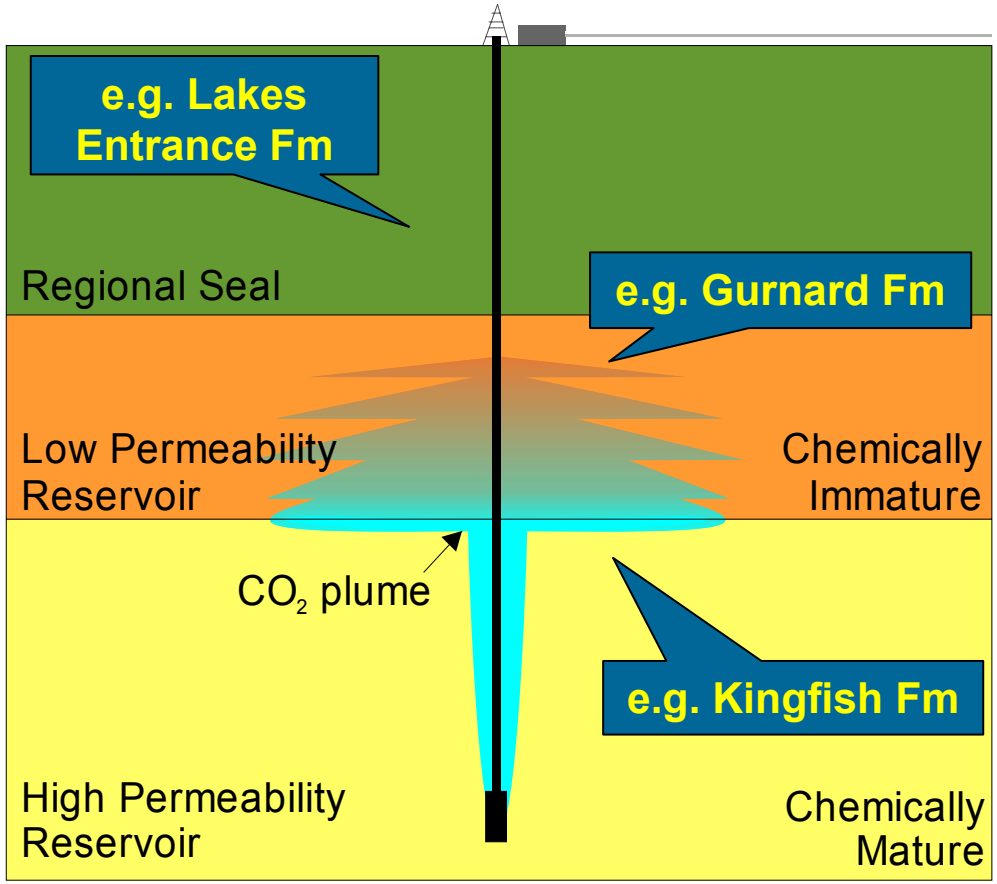
Importance of intraformational baffles:

- increase length of CO_2 migration pathway
- increase volume of pore space moved through

= greater residual gas trapping & dissolution

Containment: Geochemical Trapping

Ideal Reservoir System



Lakes Entrance Fm

- High seal capacity
- Quartz & illitic-smectite

= limited mineral reactions

Gurnard Fm

- Low permeability
- Calcium, iron & magnesium-bearing minerals

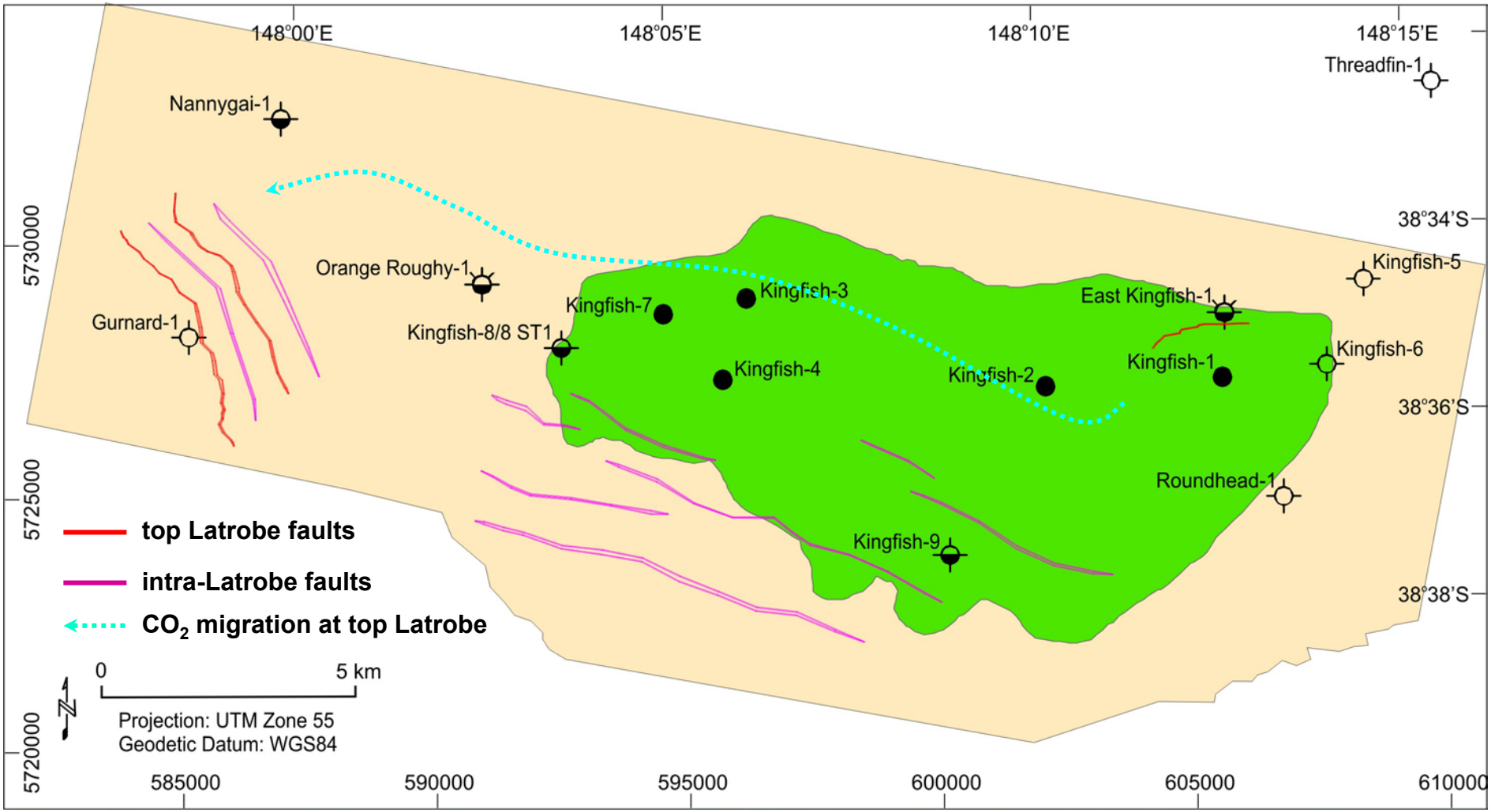
= **significant potential for mineral trapping of CO_2**

Kingfish Fm

- Moderate to high permeability
- Non-reactive minerals

= limited mineral reactions

Containment: Geomechanics



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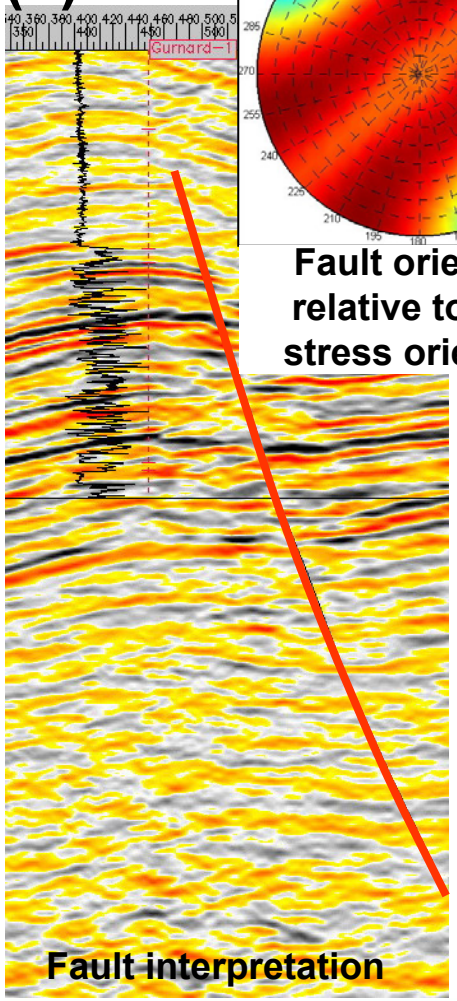
Containment: Geomechanics

(1)



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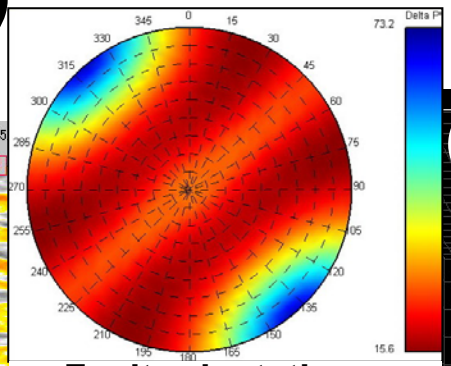
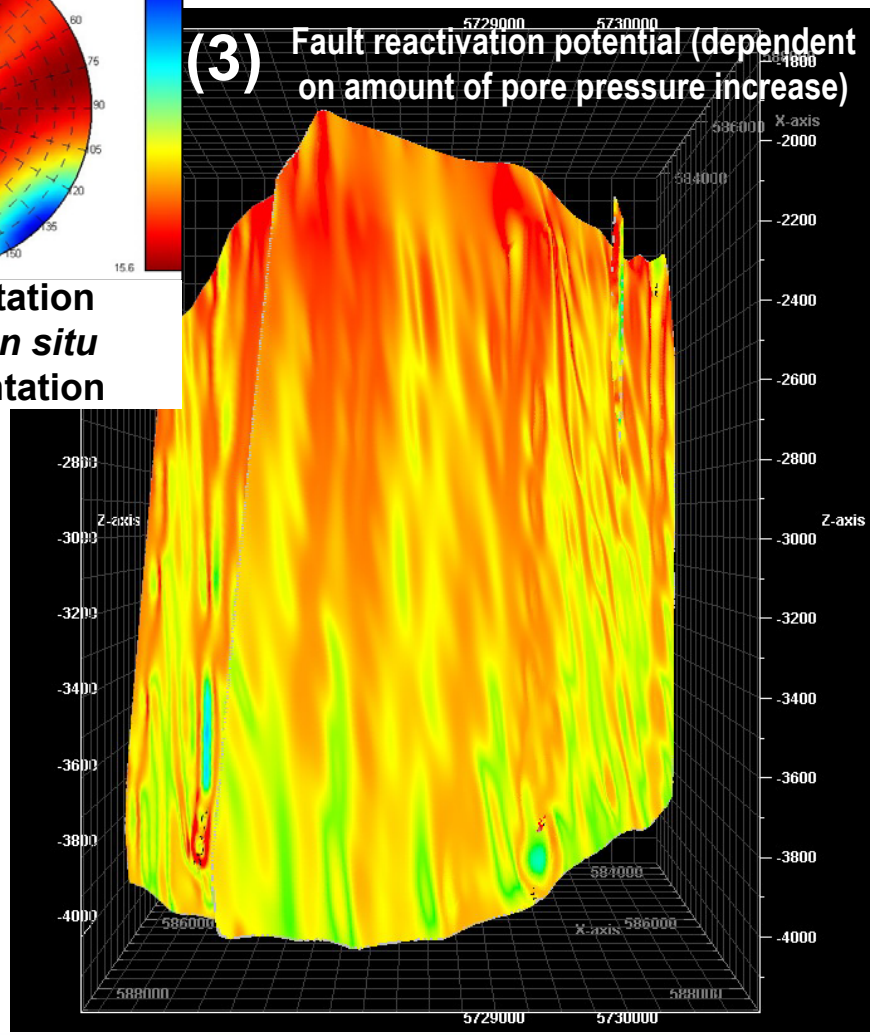


Fault orientation relative to *in situ* stress orientation

(3) Fault reactivation potential (dependent on amount of pore pressure increase)



Seismically-resolvable faults

- 3 cut the top Latrobe unconf.
- 7 terminate within Latrobe Gp
- Most have moderate to high fault reactivation potential
- However, most not in immediate migration pathway

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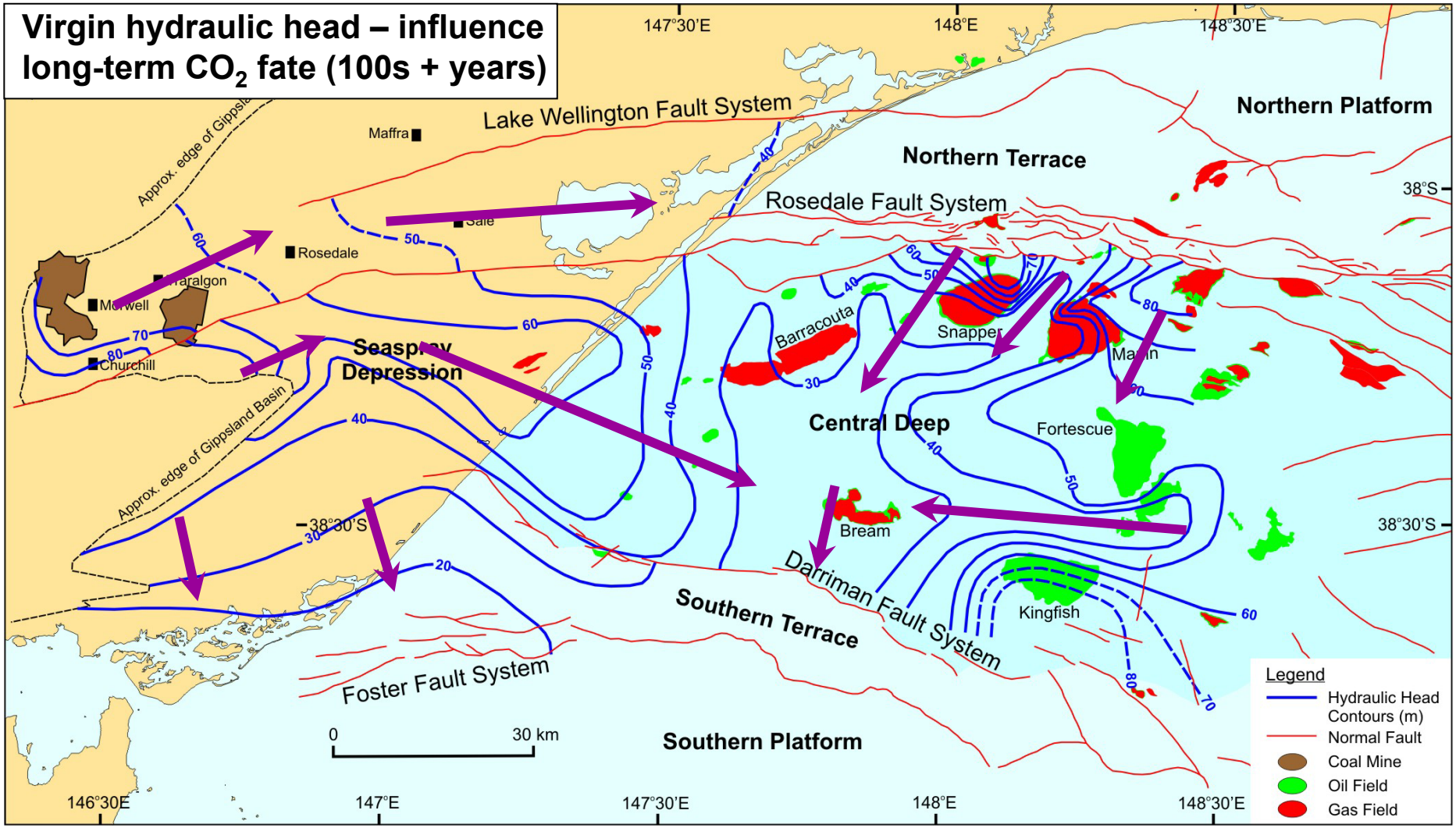
Containment: Hydrodynamics



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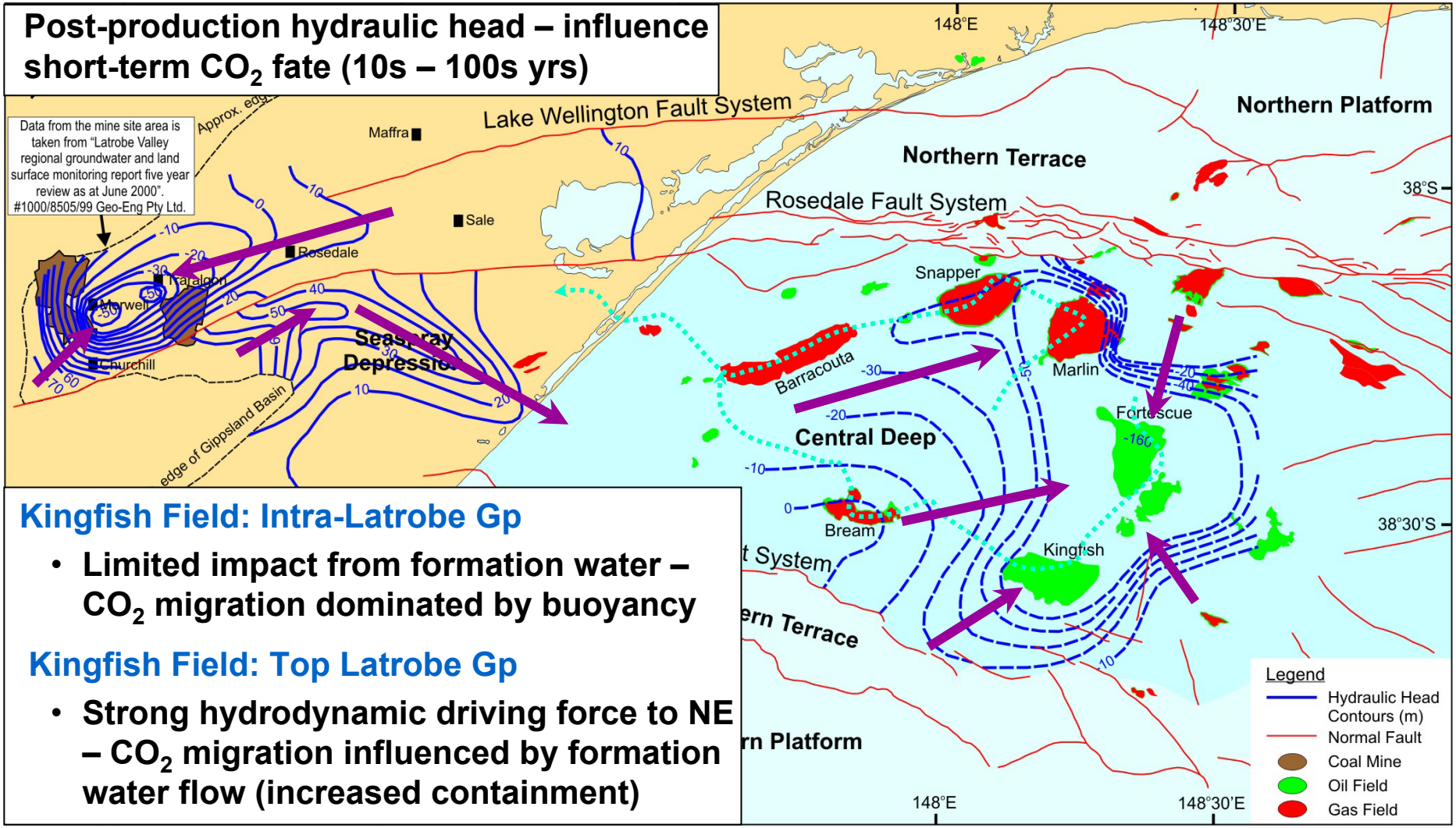
Containment: Hydrodynamics

Post-production hydraulic head – influence short-term CO_2 fate (10s – 100s yrs)



Kingfish Field: Intra-Latrobe Gp

- **Limited impact from formation water – CO_2 migration dominated by buoyancy**

Kingfish Field: Top Latrobe Gp

- **Strong hydrodynamic driving force to NE – CO_2 migration influenced by formation water flow (increased containment)**

CO_2 buoyancy migration at top Latrobe

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Capacity

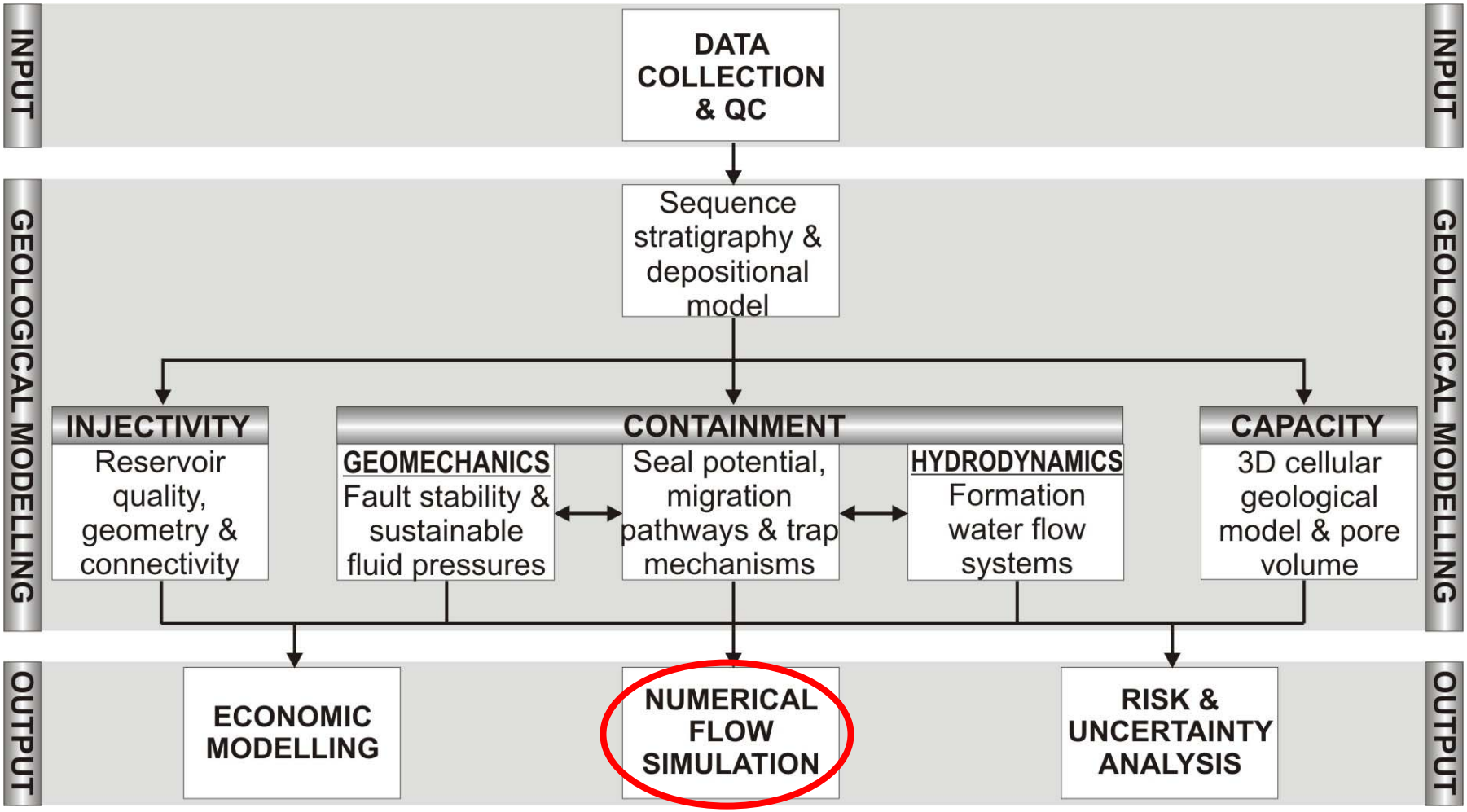
CO_2 Storage Capacity

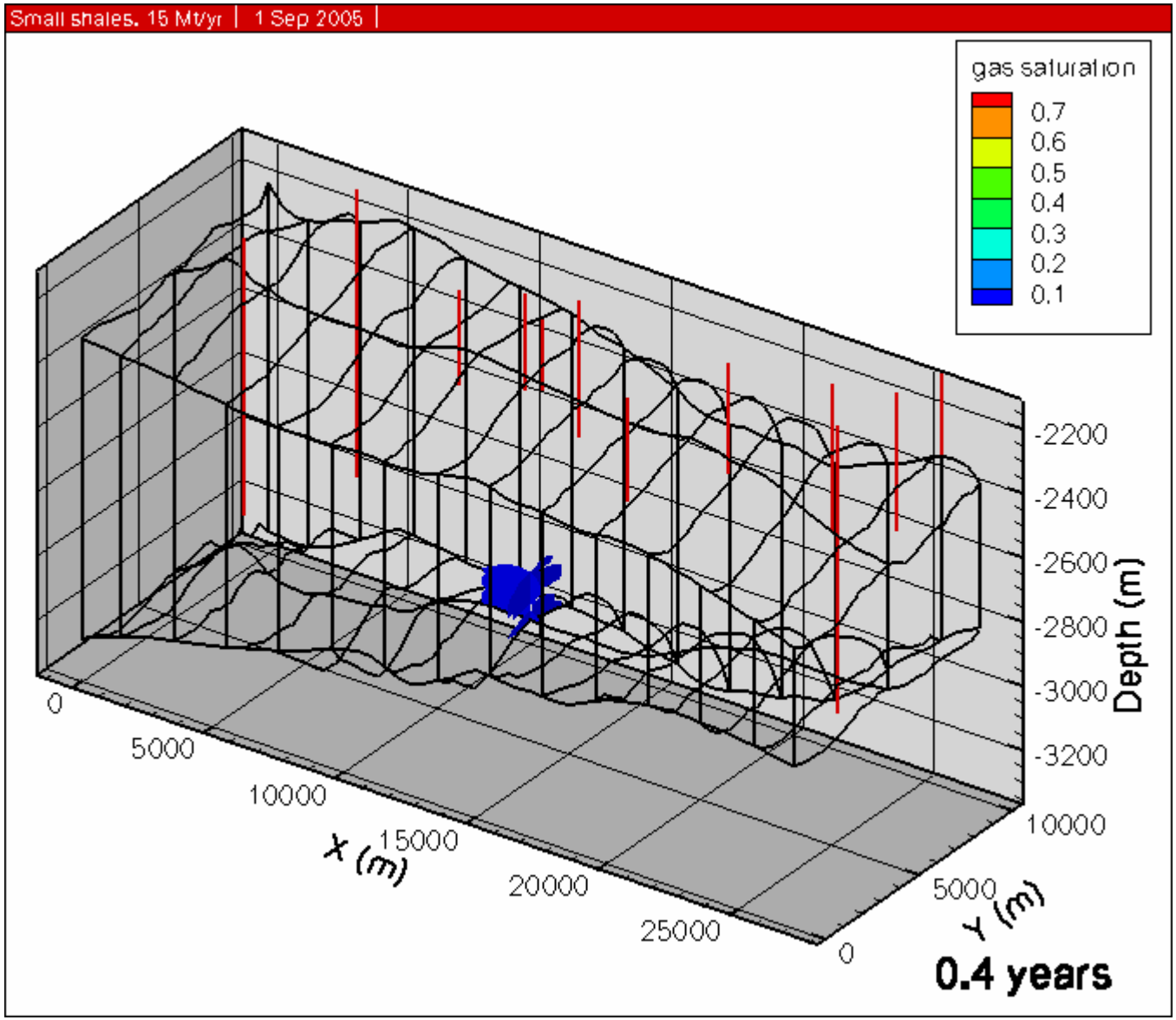
- Available pore volume calculated geologically
- Numerical simulation required to verify pore volume used (sweep efficiency)
- Sweep efficiency dependent on: rate of CO_2 migration, dissolution into formation water, precipitation of new minerals, fill-to-spill structural closures along migration path

Kingfish Field

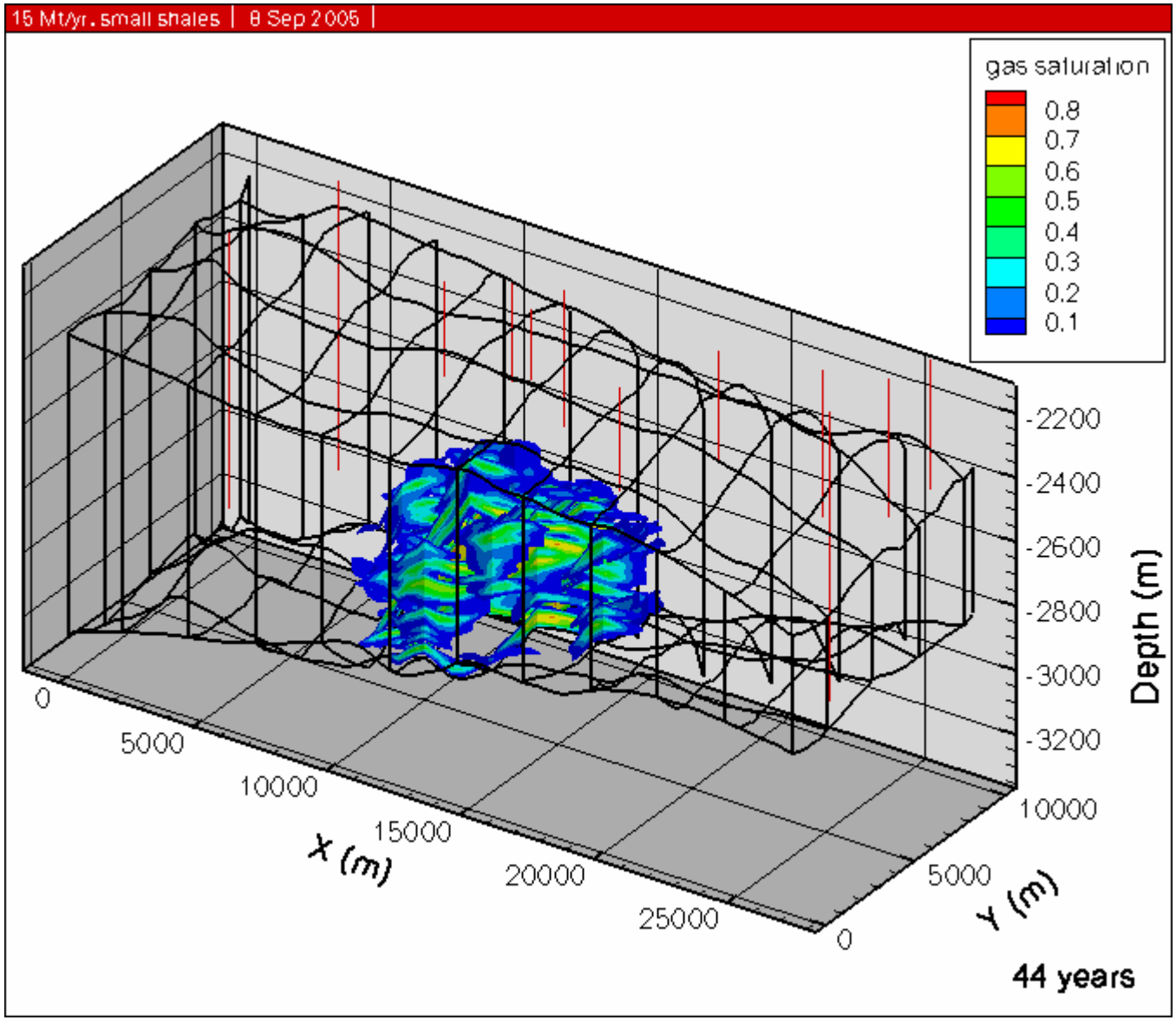
- Calculated structural closure capacity (existing oil zone) and deeper intra-Latrobe stratigraphy
- Combined capacity > 600 Mt (sufficient for 15 Mt/y for 40 years)
- Intra-Latrobe stratigraphy 3 times the capacity of the structural closure – demonstrates how a deeper injection strategy may provide significantly more CO_2 storage capacity

Numerical Flow Simulation

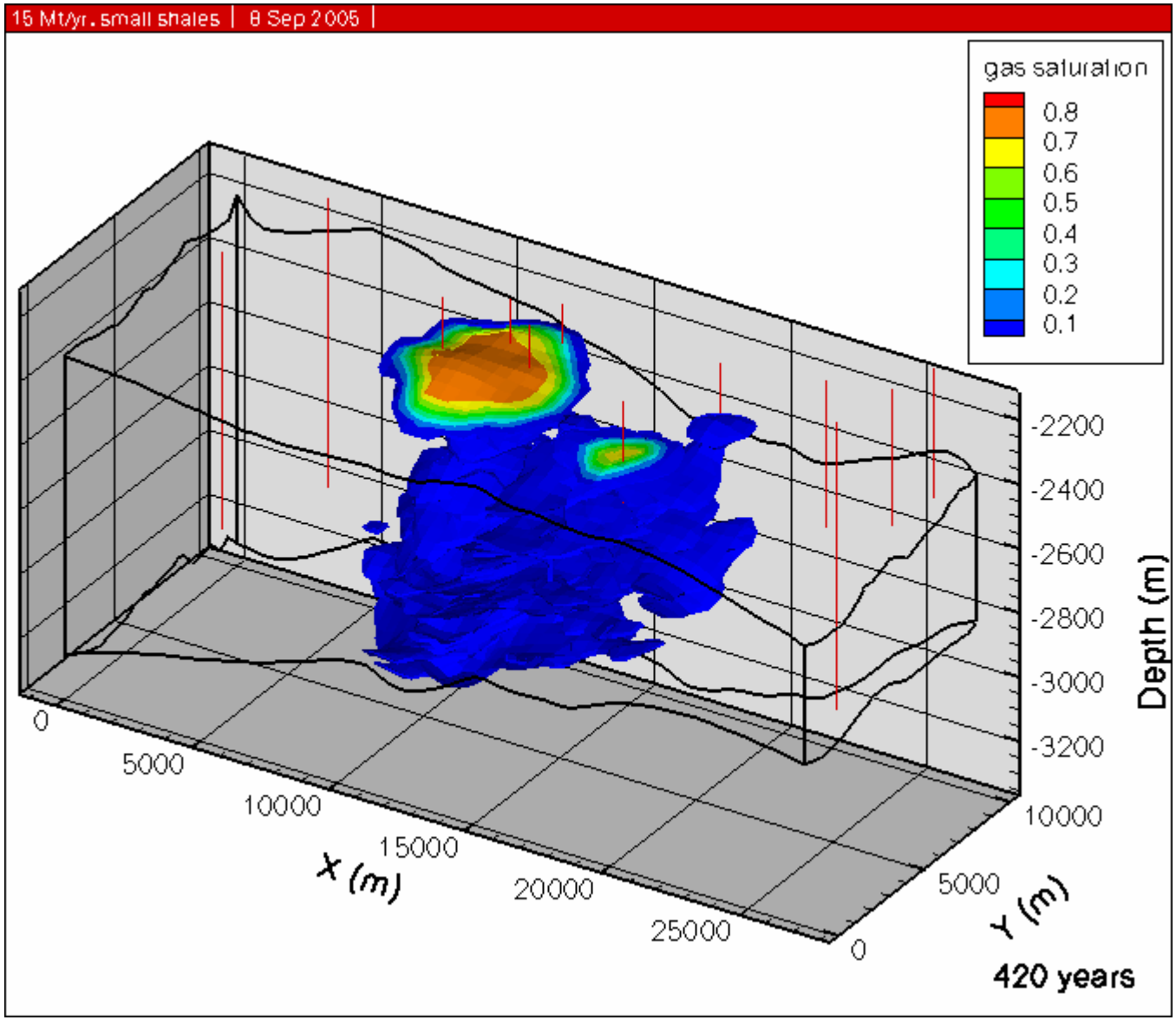




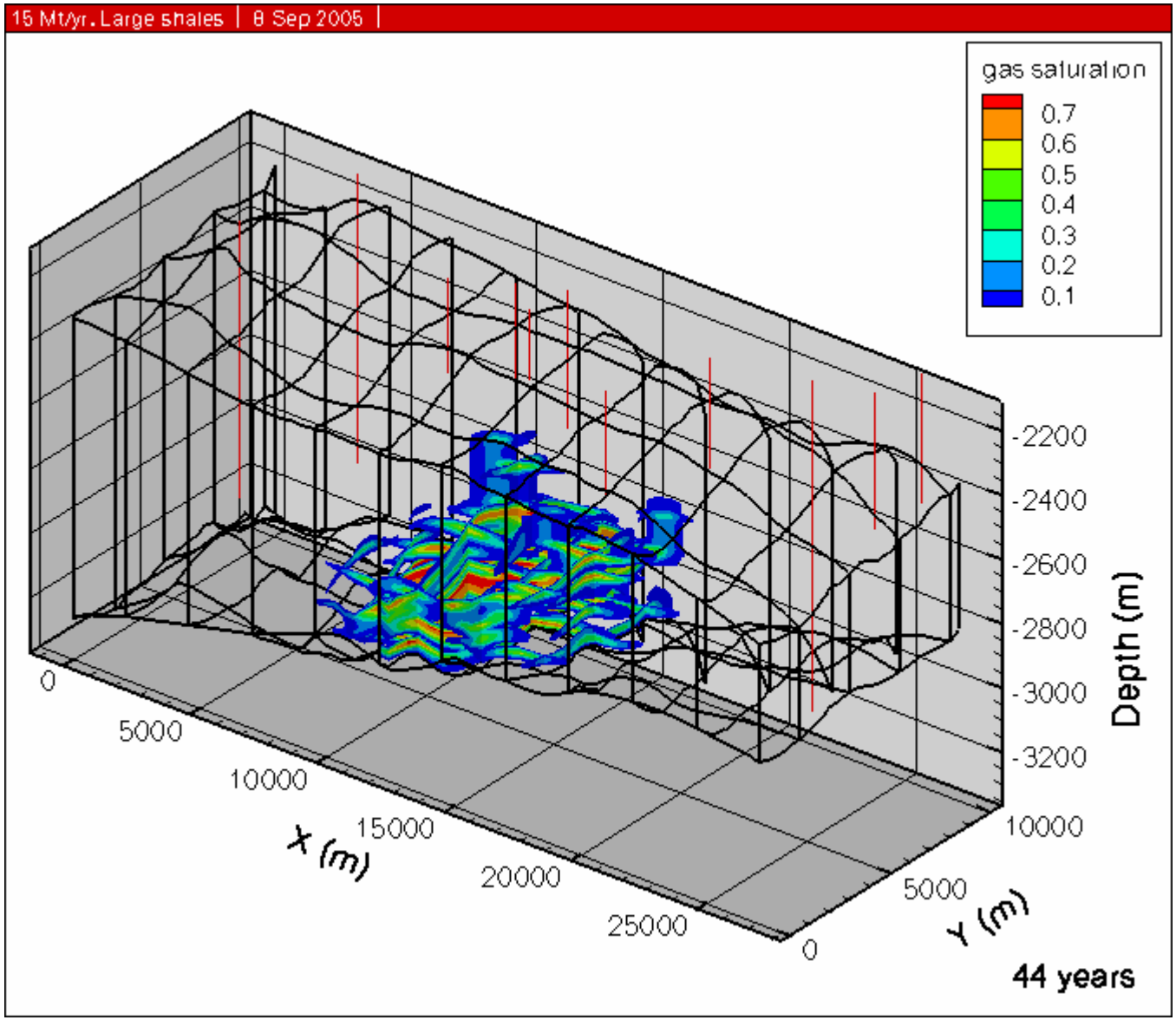
- **15 Mt/y for 40 years**
- **Post-injection small shales 0–40 yrs**



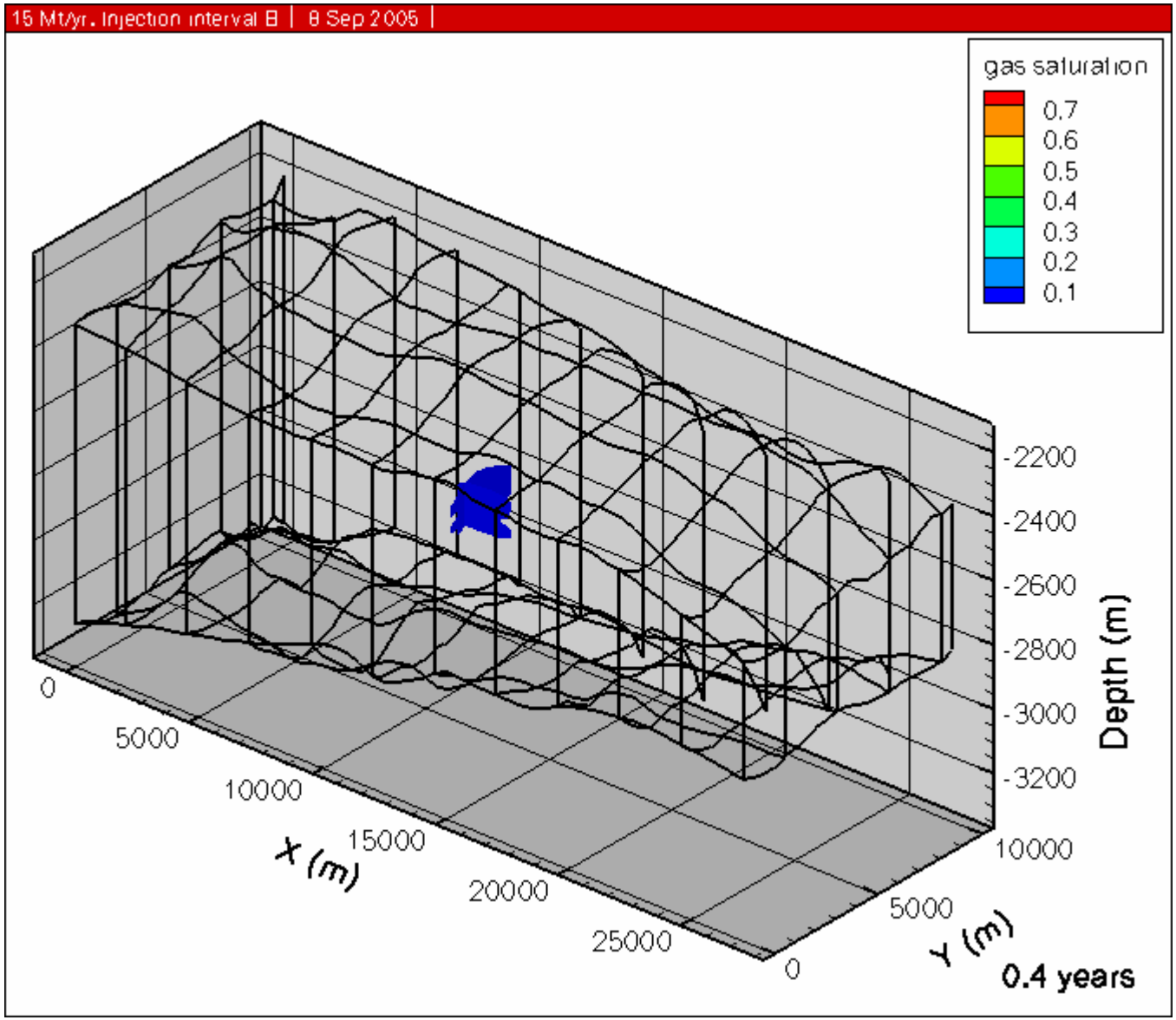
- **15 Mt/y for 40 years**
- **Post-injection small shales 40–400 yrs**



- **15 Mt/y for 40 years**
- **Post-injection small shales 400–1140 yrs**



- **15 Mt/y for 40 years**
- **Post-injection large shales 40–400 yrs**

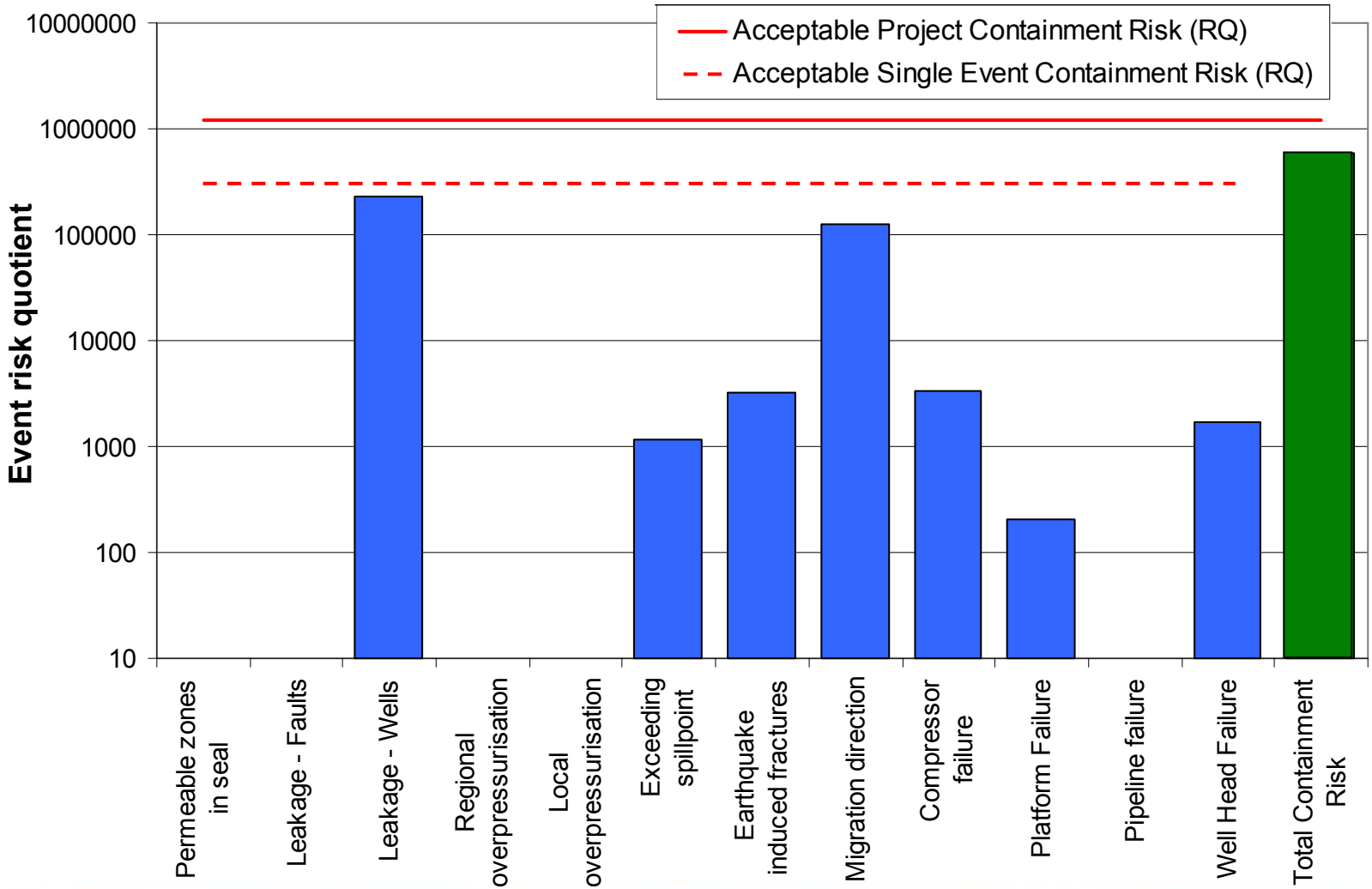


Simulation results:

- **Injection rate achievable – lower permeability or extensive shale barriers require more wells**
- **Migration time to the oil-bearing zone is 40–200 years for deep injection – less for shallow injection, more for wider shale barriers**
- **Storage capacity sufficient with deep injection – more CO_2 trapped as residual gas**

- **15 Mt/y for 40 years**
- **Shallower injection – B interval (Sq 3)**

Risk Assessment

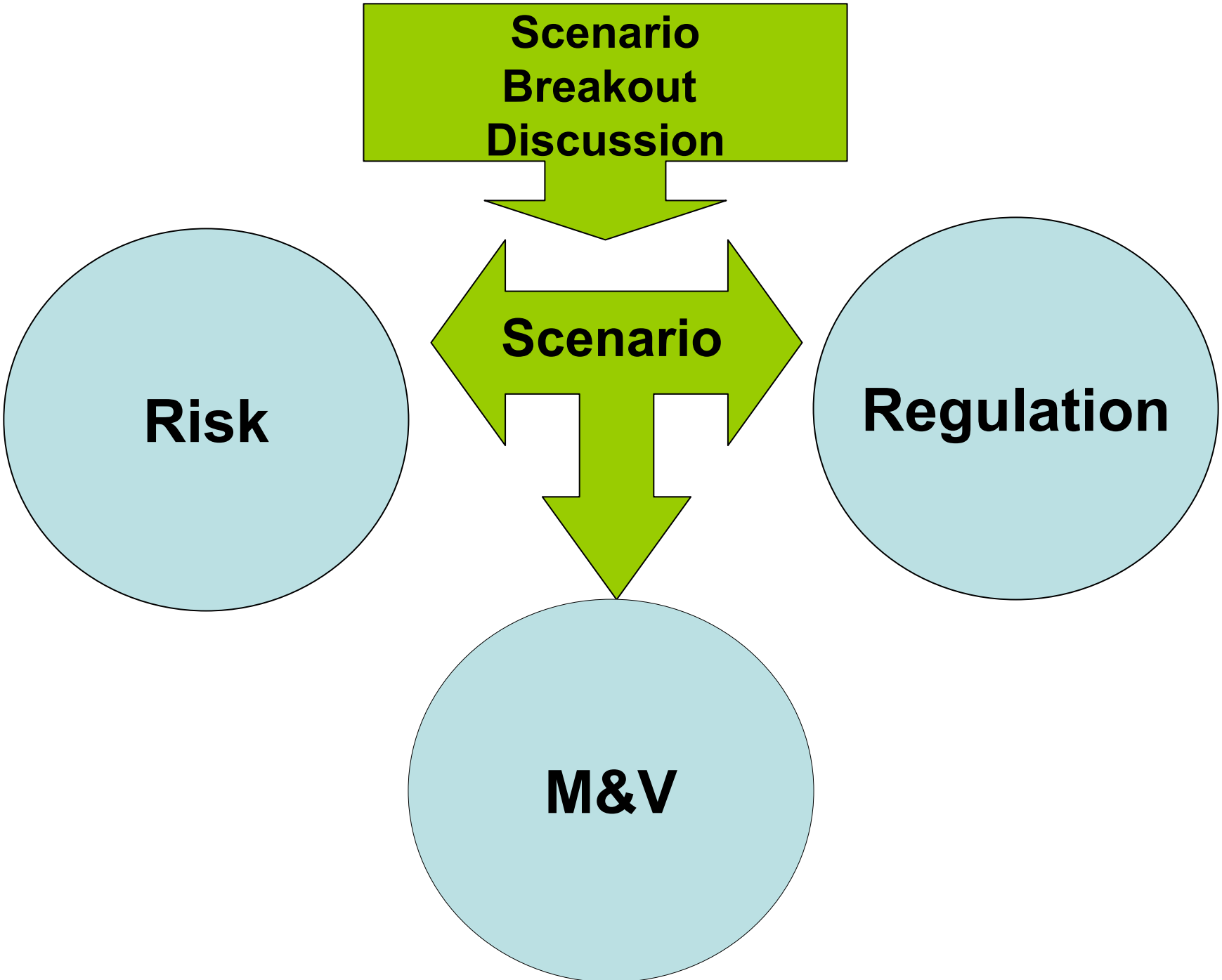


Conclusions

Suitability of Kingfish Field/Gippsland Basin as CO_2 storage site:

- **Complex stratigraphic architecture which slows vertical migration and increases residual gas trapping**
- **Non-reactive reservoir units with high injectivity**
- **Geochemically-reactive, low permeability reservoir just below regional seal to provide additional mineral trapping**
- **Several depleted oil fields to provide storage capacity coupled with transient flow regime that enhances containment**
- **Long migration pathways beneath competent regional seal**
- **Kingfish Field, in conjunction with other sites (e.g. Fortescue, northern gas fields), indicate that Gippsland Basin has sufficient capacity to store very large volumes of CO_2.**

Acknowledgements: LVCSA Team


Scenario
Breakout
Discussion
Scenario
Risk
Regulation
M&V

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 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 ?

Risk Register

- Leakage through Wells
  - Through Plugged and Abandoned Exploration Wells (can't re-enter)
  - Cement Quality
  - Corrosion of Casings/Tubing etc.
  - Mitigation: Re-completions
- Fault Reactivations/local over-pressurisation
  - Un-characterised faults (sub-seismic?)
- Seals
  - Quality – lots of baffles and primary one is excellent
  - Multiple Seals - good
- Migration Direction
  - Aquifer re-pressurisation (Hydrodynamic effects)
  - Spill Point
- Impact on other resources: Oil and Gas, Fresh Water

Regulators

- Need to satisfy regulator that existing oil/gas operators will not loose hydrocarbon recovery
- Monitoring required to confirm migration path matches model that CO2 won't reach oil/gas fields before oil/gas field abandonment.
- Liability issues need to be resolved – proponent will need to take on liability for life of project and then post-project monitoring will be required until hand-over to the government.
-

Monitoring Tools

	Pre-injection	Injection	Post-Injection	Post Cl
Well Leakage	Well Integrity study; re-enter as needed Seafloor study (sparker, bubbles, biologic) CBL/MIT on injectors	Annulus pressures, Mechanical integrity Seafloor study (sparker, bubbles, biologic)	Seafloor study (sparker, bubbles, biologic) – tied to modelling	
Faults	Seismic	Downhole Pressures and Fall-offs, Microseismicity	Simple Model Match	
Seals		Temperature..		
Migration Direction				

Conclusions - Monitoring

-

MERV

- Pressure/Flow/Temp
- Baseline benthic survey
- 3-D surface seismic (for baseline)
- Multi-beam echo/geophysical logs/fluid chemistry
- Follow on seismic work 2-D seismic