MONITORING WORKSHOP
INAUGURAL MEETING

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REPORT ON

MONITORING WORKSHOP

Organised by IEA Greenhouse Gas R&D Programme and BP
with the support of EPRI and the US DOE/NETL

Monday 8th to Tuesday 9th November 2004

Seymour Center, University of California Santa Cruz, California USA

MONITORING WORKSHOP

Executive Summary

A workshop has been held in California, U.S.A. to establish a new international research network covering the monitoring of injected CO_2 in geological storage formations. The inaugural meeting of the Monitoring Network was held at the Seymour Centre, University of California Santa Cruz, California, USA, on the 8th and 9th November 2004. The workshop was organised by IEA Greenhouse Gas R&D Programme and BP with the support of EPRI and the US DOE/NETL. The international workshop, which was attended by nearly 60 delegates, aimed to bring together the main research groups currently active in the field of monitoring CO_2 injected into geological formations and to discuss and critique the work that is currently underway.

The purpose of monitoring injected CO_2 is to address the three requirements for the safe and effective storage of CO_2 in geological formations. These requirements are:

- Worker and public safety
- Local environmental impacts to groundwater and ecosystems
- Greenhouse Gas mitigation effectiveness

The objective of the workshop was to get a common understanding of the current state of the art, to identify the techniques available, and to assess their limitations. This was achieved by using the results available from projects that are currently monitoring injected CO_2. The aim was then to develop a view of where the technology needs to go from here, in order to develop stakeholder confidence that injected CO_2 can be monitored and verified and any leakage quickly detected.

Some of the key messages from the workshop were:

- There is a substantial tool box of monitoring techniques already available for use. This tool box includes techniques for monitoring in situ CO_2 movement and monitoring for surface and well-bore leakage. Actual experience of their use provides additional confidence in their applicability and the particular limitations of the techniques available have been identified.
- Seismic surveying has proven itself capable of monitoring CO_2 movement in the subsurface at Sleipner and Weyburn. Seismic surveying of the overburden should also identify if leakage is occurring from a CO_2 storage formation.
- Monitoring of pilot projects can provide valuable information on the advantages and limitations of particular monitoring techniques and allows comparison to modelling results. Even monitoring experiences at small projects like the Frio and Nagaoka projects can provide enormous amounts of information.

- Monitoring costs will not add substantially to the operational costs of an injection project.
- For successful monitoring of an injection site it was essential to have detailed baseline conditions at the surface and in the subsurface prior to injection; to know as much about the reservoir as possible at the beginning. For oil fields, there will be information already available from exploration and production activities and this could result in lower overall costs of monitoring at these sites. However, for deep saline aquifers, characterization and monitoring will be most probably required from scratch. One of the benefits of a baseline study is the ability to identify naturally occurring fluxes of CO_2, distinguishing such CO_2 from what is injected and identifying other noise around the site that may mask a leakage or seepage signal.

The workshop identified a number of key research issues:

- Because there is such an extensive tool box of monitoring techniques, new injection projects need guidance on what to measure and where. Such information can be provided by a safety and risk assessment of the injection site if this were undertaken early in the project lifetime.
- As there are plenty of techniques available for monitoring injected CO_2, it became evident, through the discussions at the workshop, that some techniques would be more appropriate in certain locations due to their suitability to particular climate and local environmental conditions. The production of some form of "auditing" chart was suggested to enable the right combination of techniques to be selected for a particular project.

A number of actions were agreed which included:

- IEA GHG will add the Monitoring Network to the dedicated Networks site on www.co2captureandstorage.info. The presentations from the workshop will be in a delegates-only area of the site but a public domain summary report will be produced and placed in the public section of the site.
- The second meeting of the network will be in Autumn 2005.

MONITORING WORKSHOP

1. BACKGROUND

If deep reductions in anthropogenic greenhouse gas emissions are to be achieved, the introduction of CO_2 capture and storage in geological reservoirs is likely to be necessary. The technology would be deployed alongside other mitigation measures such as renewables, energy efficiency and fuel switching. There are a number of potential geological reservoirs that can be used to store captured CO_2. These geological reservoirs include depleted and disused oil and gas fields, deep saline aquifers and deep unminable coal seams. Geological storage of CO_2 is not a new technology. However, it is acknowledged that all the technical issues related to geological storage have not yet been fully resolved and that the outstanding issues must be addressed before the technology can be accepted by the policy makers and public for wide scale implementation.

One key issue that needs to be addressed is the integrity of the formation containing the injected CO_2 and the resultant safety of CO_2 storage and environmental impact issues should leakage occur. They are two ways of addressing the integrity of reservoir and the potential for leakage. First is to monitor the CO_2 injected at pilot scale and demonstration sites, like Frio, Sleipner, Weyburn, Rangely, West Pearl Queen and Nagaoka. The monitoring data can provide information on the fate of the CO_2 after injection coupled with physical evidence of migration out of the reservoir in the near term (next 50 years). Secondly, modelling coupled with risk assessment studies can predict the long term fate (1000's years) of the injected CO_2 and the long term migration potential. Of course monitoring studies also assist the modelling and risk assessment process by providing calibration points for predictions in the early years which can help to build confidence in the longer term predictions.

The monitoring of injected CO_2 therefore has a key role to play in the development of stakeholder confidence in CO_2 capture and storage as a mitigation option. There are many monitoring projects now underway in Norway, USA, Canada, Algeria and Japan and many more are planned. In the current and planned monitoring projects a wide variety of monitoring techniques are being used. It is important to bring together the results of these different monitoring projects as well as the practical experiences of the project operators to identify what has worked well and what has not and why. Such an activity can help to build confidence in monitoring technology as well as help to guide new projects in the selection of their monitoring techniques. To this end, the IEA Greenhouse Gas R&D Programme and BP have formed an international research network on monitoring to help facilitate the exchange of information between those organisations actively involved in monitoring injected CO_2 across the globe.

2. MONITORING WORKSHOP

2.1 Workshop aims and objectives

This international workshop aimed to bring together the main research groups currently active in the field of monitoring of CO_2 in geological formations, to discuss and critique the work that is currently underway.

The objective of the workshop was to get a common understanding of the current state of the art, what techniques are available now, and what their limitations are. From that understanding, the aim was then to develop a view of how the technology needs to develop in order to establish stakeholder confidence that injected CO_2 can be monitored and verified and any leakage quickly detected.

2.2 Workshop attendees

The workshop was attended by 57 delegates, from 38 different organisations and 7 different countries. The attendance list is given in Annex 1 for reference.

2.3 Workshop programme and structure

The two day workshop was designed to allow technical presentations and time for open discussion. The presentations were focused into five topics covering the different aspects of monitoring currently underway and future activities. The topics were:

1. Opening perspectives and overviews
2. Surface/leakage monitoring
3. Geophysical monitoring – aquifers
4. Monitoring CO_2 injection into oil fields
5. New monitoring projects/future activities

The discussion sessions aimed to answer the following questions:

1. Are there any limitations in the techniques currently used?
2. Are new techniques being developed?
3. Are there any barriers to the use of these techniques?
4. What further research is needed to improve confidence in the monitoring results?

The full programme for the two day workshop is shown in Table 1 for reference.

Table 1. Monitoring Workshop Programme

Day 1	**Monday 8th November 2004**
Opening Session	
08.30 to 08:45	Welcome, Safety Briefings Meeting objectives John Gale, IEA GHG
Session 1 – Opening Perspectives and Overviews	
08.45 to 09.15	Monitoring needs, a regulatory perspective - *Martha Krebs. West Coast Regional Carbon Sequestration Partnership*
09.15 to 09.45	Overview of status of monitoring technologies - *Sally Benson, LBNL*
09.45 to 10.15	Monitoring strategies and cost comparisons - *Larry Meyer, LBNL*
10.15 to 10.40	**Break**
Session 2 – Surface/leakage monitoring	
10.40 to 11.00	CO_2 Fluxes to the Atmosphere, and in Soil Gas: Detection of a Deep Source Masked by Near-surface Noise - *Ron Klusman, USDOE/NETL*
11.00 to 11.20	Surface monitoring techniques as applied at Weyburn and elsewhere – *Jonathan Pearce, BGS*
11.20 to 11.40	Monitoring and verification of CO_2 leakage from underground storage formations - *William Pickles, LLNL*
11.40 to 12.00	Preliminary Evaluation of the Ability of Airborne Reconnaissance Techniques to Find Abandoned Wells - *Rick Hammack, USDOE/NETL*
12.00 to 13.00	**Break**
Session 2 – Surface/leakage monitoring cont'd	
13.00 to 13.20	Leakage and seepage in the near surface environment: an integrated approach to monitoring and detection - *Curt Oldenburg, LBNL*
13.20 to 14.20	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? • What further research is needed to improve confidence in the monitoring results?
Session 3 – Geophysical monitoring - aquifers	
14.20 to 14.40	Review of geophysical monitoring results from the SACS project *Ola Eiken, Statoil*
14.40 to 15.00	Verifying the volumes of injected CO_2 – experience from the SACS project - *Gary Kirby, BGS*
15.00 to 15.20	**Break**
15.20 to 15.40	Geophysical Monitoring of CO2 Sequestration at An Onshore Saline Aquifer in Japan *Ziqiu Xue, RITE*
15.40 to 16.00	Initial results from the Frio Brine Injection project *Mark Holtz, Texas BEG*
16.00 to 17.00	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?
17.00	Close of Day 1

Table 1. Monitoring Workshop Programme, cont'd

Opening Session - Day 2	
08.30 to 09.00	Review of Day 1 and plan for Day 2 *John Gale IEA GHG and Charles Christopher, BP*
Session 4 – Monitoring CO_2 injection into Oil fields	
09.00 to 09.20	Tracer Results from the West Pearl Queen Field Pilot Sequestration Site *Arthur Wells, USDOE/NETL*
09.20 to 09.40	What worked and what didn't – experiences from the Weyburn Monitoring Project, *Malcolm Wilson, PTRC*
09.40 to 10.00	Review of seismic results from the Weyburn Monitoring project *Don White, GSC*
10.00 to 10.20	Geochemical monitoring at Weyburn *Kyle Durocher, ARC*
10.20 to 10.40	**Break**
10.40 to 11.30	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?
Session 5 – New monitoring projects/future activities	
11.30 to 11.50	The In-Salah project – monitoring plans *Iain Wright, BP*
11.50 to 12.10	Teapot Dome - baseline monitoring results and future monitoring programmes *Julio Friedmann, LLNL*
12.10 to 12.30	The EnergyINET project, *David Keith, University of Calgary*
12.30 to 13.30	**Break**
Session 6 - Workshop Review	
13.30 to 14.00	The Mountaineer project – monitoring plans *Neeraj Gupta, Battelle*
14.00 to 15.00	Facilitated discussion to cover the following points: What have we learnt? How confident are we in the results obtained to date? where are the gaps? What are the future research needs?
15.00 to 15.20	**Break**
Session 7 - Closing Session	
15.20 to 16.20	Way forward and Next steps Including discussion on establishment of an international research network
16.20 to 16.30	Closing Remarks

3. SUMMARY OF MONITORING NETWORK MEETING

3.1 Overview and perspectives of monitoring CO_2 injection

3.1.1 Public acceptance of CO_2 Capture and Storage

Introducing new energy technologies is hard; there are risks for both producers and consumers. Risks can be financial, environmental, health and safety related or due to more complex issues like the interdependencies among end use sectors. Risks can often be quantifiable unless there are uncontrollable externalities like wars.

There are several policy options available, for use by governments, to assist the introduction of CO_2 capture and storage. Research and development is probably the easiest to commit to although it can be controversial but demonstration and deployments can be difficult.

It is accepted that public outreach is critical to the introduction of any technology. Engagements in transparent exchanges with the "public" will assist in highlighting their concerns. In turn such exchanges provide targeted information about the possible role, benefits and risks of CO_2 storage and ensure that the right information that is being supplied.

It must be acknowledged that there are a range of public 'audiences', from the regulators and legislatures (decision makers), to the media, local government and business leaders (who can all influence opinion). Also, there are the national and international environmental groups although they may be less responsive than local environmental groups. Then finally the general public, the opinion of which has been scoped through general surveys undertaken in the UK and U.S.A. These surveys have helped to identify some of the (initial) concerns of the general public, but they have not necessarily been those of 'Backyard'. Despite the surveys and media coverage to date, it will be real projects that will bring the challenge of real people with real backyards (The NIMBY[1] Lobby). The one critical issue that the public will expect to be answered will be how long will the CO_2 remain stored? (1000, 2000 or 10 000 years?). As far as addressing the critical issue of the period required for storage integrity, the question is, who will decide that the answers are good enough? The time is now considered right to begin a transparent, but independent process that will allow the public to be satisfied with the answer to this question.

3.1.2 Sensitivity and resolution of monitoring

The most important aspect of monitoring for the public will be the sensitivity and resolution of methods for leakage detection. There are three requirements for safe and effective geological storage, firstly public and worker safety,

[1] NIMBY stands for Not In My Backyard

secondly local environmental impacts to groundwater and ecosystems and thirdly, greenhouse gas (GHG) mitigation effectiveness. The level of leakage will have different impacts on these three requirements; for example, a very small level of leakage over a long time period may only effect GHG mitigation.

There are many purposes for monitoring CO_2 following injection. Detecting plume location and leakage from a storage formation may not always be necessary from a regulatory perspective[2] but for many projects it will be useful information to communicate with the public. It will also give confidence if the results from monitoring match those obtained from modelling. Monitoring could also have a key role in providing assurance and accounting for monetary transactions and validation of emissions reductions. It could provide a form of accounting by monitoring injection rates versus potential leakage.

There are many techniques for monitoring, from wellhead and formation pressure monitoring, to well logs, to seismic geophysics, and this is good because it indicates how big the tool box is. The different techniques have different sensitivities and a selection can be made depending on what is required for a particular project. It is likely that it will be a combination of monitoring techniques that will be used at any one site. The decision on the technique will be dependant on what is it that the project will need to monitor or what the objectives of the regulators may be. The capabilities of the tests can be assessed by looking at scenarios of active projects. The key question for monitoring could be whether it is possible to obtain a cumulative amount of CO_2 that had leaked and could it be detected? Scenarios can show that even at low rates CO_2 rates can be detected within 50 years. More demonstrations are needed to improve monitoring techniques.

The ease of detecting leakage will depend on its nature. If leakage occurred across the whole footprint of the CO_2 plume, it might be difficult to identify CO_2 above the typical ecosystem flux. However, if leakage was concentrated through certain features (like an abandoned well bore or a fault) a flux higher than the "natural" ecosystem flux could be expected and the impact on vegetation etc. could be identifiable.

3.1.3 Monitoring costs

The cost of monitoring will not be a major factor in the total cost of a CO_2 storage project based upon a life time of 55-85 years approximately.

There are some components that will be required even for the most basic of monitoring packages with the option of additional measurements for an enhanced monitoring package. The monitoring of a site could be split into three phases: Pre-operational, Operational and Closure monitoring.

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[2] Injection programmes currently operating in the USA and Canada do not require in-situ monitoring of the injected gases or fluids. However it is currently uncertain whether this approach would be adopted in other regions of the world or whether even in North America in the future in-situ monitoring might become part of regulatory requirements.

For EOR some pre-operational monitoring will already have been completed and available for use by the operators of a storage project. As it is likely that there will have been no previous activity for a saline aquifer, the pre-operational monitoring will need to be more thorough and therefore comparatively more expensive; simply it will need to be done from scratch. It is estimated that the price for pre-operational monitoring could be $0.9million for EOR as opposed to $5.7million in the case of saline aquifers. This cost range is indicative and will depend highly on a number of site specific factors.

Once monitoring begins for the operational phase the price ratio changes. EOR has a fixed size survey with a cost estimated at $34million; whereas saline aquifers would be less at $23million because the size of the survey grows in time in relation to the growth of the plume. The costs for saline aquifers can be further split into two options: high residual gas saturation (HRG) and low residual gas saturation (LRG). In the case of HRG, CO_2 will be easily trapped in the pore spaces of the storage formation because the residual gas saturation is high (25%) and the plume will tend to be relatively compact and retained in the vicinity of the injection wells. This smaller plume will result in lower surveying costs. In fact, HRG saline aquifers could have a total cost for monitoring over the three phases that could be cheaper than that for EOR. LRG is likely to be the greatest expense in terms of monitoring because of the eventual size of the plume, with CO_2 migrating until it dissolves, along with the high cost of pre-operational monitoring. Again, these costs are indicative and will depend highly on a number of site specific factors.

The costs of a basic monitoring programme given a discount rate of 10% could be <$0.05 - 0.10 per tonne CO_2. Whereas an enhanced monitoring package which may be necessary for satisfying occupational health and safety concerns would be available at 40 – 60% over basic package. The most expensive technique is the seismic surveys but they are the best technology available.

Well measurements can provide many data sources (flow rate, temperature and pressure information) that seismic surveys cannot. However, how many wells do you want to drill in a saline formation? When the lack of wells can be seen as a benefit compared to the case in EOR.

At the moment the different monitoring techniques provide information in overlying maps but developing the technology to merge/integrate information together is the focus.

3.2 Leakage monitoring

3.2.1 Surface Monitoring Techniques

Surface flux measurements in the USA

Surface flux analyses have been undertaken at several CO_2-EOR fields in the USA (Rangely – Colorado, Teapot Dome - Wyoming and South Liberty - Texas). Surface fluxes have been measured using flux chambers that sit on the ground and using gas sampling tubes set into 10m deep hole. The results show that CO_2 in soil gas has two distinct origins, ancient CO_2 migrating up from the deep earth and biogenic CO_2 resulting from soil respiration and decomposition of roots. Generally, recently formed biogenic CO_2 is isotopically lighter than ancient CO_2 - i.e. biogenic CO_2 contains less ^{13}C than ancient CO_2. Thus, by carefully measuring the $^{12}C/^{13}C$ ratio in soil gas CO_2 one can determine its origin. If one is not careful, biogenic CO_2 can mask the results. In a large open system, this type of monitoring will be searching for a small, deep-sourced signal in the presence of substantial near-surface biological noise, but it can be done. The climate around the monitoring site is also important and due attention needs to be given to the different climatic conditions of a site when developing monitoring plans.

Even in a desert environment, photosynthesis can cause changes in the atmospheric CO_2 and there can be significant differences between the CO_2 flux of summer and winter. At the Rangely test site soil gas monitoring results have shown that the summer CO_2 flux can look random with no obvious pattern. In comparison, even though the biological CO_2 flux from photosynthesis does not reach 0 in the winter, the lower values show more detail in the NW part of the test site. Clearly, it will be important to understand any interference (natural or man-made[3]) that may effect or confuse the CO_2 measurements at each storage site.

At Rangely leakage of deep sourced methane has been identified, however, it cannot be confirmed that deep sourced CO_2 leakage is also occurring because the CO_2 has a similar $\delta^{13}C$ to the methane. It cannot be discounted that some of the deep sourced methane that is leaking has been converted to CO_2 by biological processes in the soil. It is, therefore, necessary in any monitoring exercise to measure a range of gaseous species not just CO_2.

After measuring the total CO_2 flux in soil gas samples at Rangely on a seasonal basis, and carefully correcting the measurements for contributions from biogenic sources, the total amount of CO_2 leakage from the petroleum reservoir is estimated to be less than 0.01% of the CO_2 stored over 15 years of operation.

[3] For example, natural interference can refer to the biological process of photosynthesis, vegetation and surface water cover or climatic variations. Man-made interference can refer to the development of the site, extra roads, buildings etc which may disturb the original monitoring locations.

Results from the Weyburn monitoring project

Surface flux measurements have been undertaken at the Weyburn CO_2 flood in Saskatchewan, Canada and the results compared with measurements taken in other countries as part of the NASCENT[4] project. The monitoring at the Weyburn site has been repeated and undertaken at the same time every year to get the best results. However, if monitoring occurs over an extended timeframe for example 50 years, the effects of climate change could have a big effect on the sampling results. Weyburn has used a continuous rather than batch gas sampling approach. This monitoring approach has worked well for the Weyburn project and the project emphasised the importance of obtaining the baseline conditions (initial dataset).

Results have indicated that monitoring for a range of gases (CO_2, HC, O_2, N_2, Rn, Tn, He) can give clues on whether there are conduits for gas migration, determining their presence can be indicative of a deep source, even identifying the source as a reservoir or whether the CO_2 is present from biogenic production. Other sources of information are essential to give a clear picture, soil gas monitoring alone is not enough. Other sources of information include: surface and sub surface geology, faults/fractures and linements to best target where to sample. Identification of potential release pathways helps to improve the risk assessment process and can help calibrate risk assessment results.

Surface flux analyses indicate that the CO_2 analysed at Weyburn is of biogenic origin. Overall, there is no evidence of CO_2 leakage from depth at Weyburn.

The study identified that it maybe necessary to have denser sampling, as one concern would be that a leak could be missed even if it occurs within a few meters of a sample site. Further work would be beneficial on the evaluation of potential gas migration pathways and on carbon isotope work.

Other improvements will be automatic continuous monitoring stations but the locating of these stations will be crucial and dependant on supporting information. The testing of such equipment can be done at sites of natural seepage, such as those investigated in the NASCENT project.

Further research required to improve confidence in monitoring results will include the integration with other techniques and the development of risk maps. However, the cost of using these techniques and the length of time it takes to get the results are potential barriers.

Geobotanical hydrospectral remote sampling

Geobotanical sensing can involve both airborne and satellite imagery. Airborne hyperspectral remote sensing methods allow early detection and spatial mapping of CO_2 leakage over whole regions. The technique has been tested at

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[4] Natural Analogues to the storage of CO_2 in the geological environment

Mammoth Mountain in California and at the Rangely CO_2-EOR field in Colorado. CO_2 can potentially leak from the subsurface by percolating up faults, cracks and joints and become concentrated in the soil. CO_2 concentrations of up to 50% have been observed at Mammoth Mountain to significantly affect local plant and animal ecologies.

Vegetation Stress Techniques or Geobotanical Remote Sensing can be used firstly, to create a baseline dataset, and then for mapping known or buried abandoned well heads, subtle or hidden faults cracks and joints and then signs of CO_2 leakage. It uses very high spatial resolution imagery with pixel size of 3x3m. This high resolution can be used to look for habitat changes due to CO_2 seepage as the shape of the habitat is likely to change. At Rangely the airborne sensing has indicated three distinct habitat regions which appear to have not changed (based on comparison with earlier aerial photographs) for 23 years. Whereas results at Mammoth Mountain where CO_2 leakage is known to have occurred, changes in habitat distributions are clearly seen. For reference, injection of CO_2 has been underway at the Rangely field for the last 15 years, which would infer that CO_2 seepage has not occurred and affected these habitats. However, results have shown that desert environments confuse plant analysis by this method. Sagebrush can look dead in some branches whilst remaining alive in others. Drought tolerant plants will cause problems and for this reason this method is not very well suited to such areas.

Airborne reconnaissance to identify abandoned wells

In the early days of oil and gas production, wells were not completed to any particular standard. Airborne reconnaissance can be used to identify potential leakage pathways from old wells before injection has started. Once identified these old wells could be remediated and sealed. Unmanned vehicles used for this type of survey can have up to 9hr flight times.

Three methods are used to identify abandoned wells:
1. Magnetics can identify steel cased wells.
2. Uncased and improperly plugged wells can be identified by the volatile components.
3. Electromagnetic surveys can locate saline incursions into freshwater aquifers.

When this technique was used to search for steel cased wells in the Powder River Basin, the well locations were compared to the locations recorded by the Wyoming Oil and Gas Commission. In this example, the wells indicated by old datasets are off-centre and slightly mislocated. Clearly, caution should be taken when using historical information. In some cases the wells listed did not exist at all.

Seeps of radon can be used to detect uncased wells. Wells with Radon and CH_4 anomalies should be re-plugged first; those that do not show an anomalously high Radon and CH_4 concentration will probably not leak CO_2 immediately.

Aerial reconnaissance to search for existing wells and faults allows uncharted or mis-located, improperly sealed wells to be mapped quickly, accurately, and inexpensively. Further, the airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching. This is important when one considers that the underground CO_2 plume from a sequestration site may extend over 10's of square miles.

Offshore shallow gas monitoring

A new application of marine acoustic and seismic surveying is being developed to monitor offshore shallow gas build up in sediments and the water column. This technique has been demonstrated to monitor shallow methane accumulations in the Black Sea. Monitoring of seeps of natural gas in offshore locations infers that CO_2 seeps could also be identified using the same techniques. The seeps of natural gas offshore leave pockmarks on the sea floor; these could become leakage pathways if they occur over CO_2 storage sites.

An integrated approach to monitoring and modelling

Even for small CO_2 fluxes, subsurface CO_2 concentration can be high. Diffuse seepage leads to passive dispersion in the surface layer. Surface atmospheric conditions are effective at dispersing CO_2 seepage although it can be less effective, for example, in areas of low-wind or if the CO_2 flux is particularly high.

There are some conventional monitoring techniques that are very well established, such as accumulation chambers linked to IRGA (infrared gas analyzers) or eddy correlation towers and truck mounted LIDAR (LIght Detection And Ranging), that can be used to measure surface fluxes. Accumulation cells are good for measuring fluxes at small features, whereas Eddy correlation and LIDAR techniques are better for measuring the average flux over larger areas. Some of the techniques would be used constantly and others at intervals. The length of time of monitoring, before/during/after injection, is currently highly speculative, although the goal should be to have a comprehensive understanding of the ecological system prior to injection.

The ability to conduct monitoring of the site will be determined by seasonal features and climate conditions. Sampling can also be limited in cases, such as at the Frio site because of vegetation cover or surface water, or original monitoring sites maybe covered by later additions to the site such as roads. Therefore, plenty of time should be given to study the variable climatic conditions throughout the year without the influence of other factors. Monitoring approaches may have to be developed to take into account a site's particular requirements and future infrastructure developments (such as roadways) around a monitoring site.

3.2.2 Discussion

Comments raised by the delegates in open discussion included:

Monitoring shows due diligence, a way of showing the public that project operators care. However, there are lots of noxious materials injected without monitoring, why does CO_2 storage require such efforts?

Some may argue that monitoring methods are too late and remediation methods could have been put in place before CO_2 reaches the surface. In the case of Rangely, methane flux has been detected but there is no evidence of CO_2 leakage from the injection site.

It is agreed that for monitoring to be successful a firm baseline of the conditions around the site will be required. It will be essential to determine the naturally occurring CO_2 versus that which has been injected. Then the surface monitoring technologies will need to be chosen depending on the location. Structured tests will be required to ensure that the monitoring results can be compared between sites.

As far as what to measure and where, answers maybe available from risk assessments completed for a site so they should be done hand in hand. Especially as the issues for a site will be very site specific.

It could be argued that monitoring is too expensive and modelling is enough with remediation work undertaken when required. Of course public reaction may change this decision but perhaps it should not be the case that this level of public response is pre-empted in the first instance. If there is to be any type of tax on CO_2 though, accounting will be necessary as it is more than likely that storage will be based upon the net storage rather than the gross storage and monitoring will help in this assessment.

There is plenty of experience within the USA for wastewater injection (includes storm water), is the amount of CO_2 to be injected unprecedented therefore making it necessary for monitoring? Use modelling where necessary to identify problems and remediate where necessary.

Monitoring is too expensive; it may miss the problem and should be used as a very last resort if public perception or specific regulation requires it.

3.3 Monitoring experience from saline aquifer projects

3.3.1 Monitoring in offshore Saline Aquifers

Results from the Sleipner project

Monitoring of the injected CO_2 at the Sleipner gas field in the North Sea has been underway since 1999. To date some 7 million tonnes have been injected into the Utsira formation, a deep saline aquifer above the gas field. Statoil have reviewed their monitoring options at Sleipner, an observation well was considered to be too expensive, whilst well seismic was considered to be too complicated and also too expensive. Repeat seismic surveys were therefore considered to be the most promising option. Four seismic surveys have now been completed at Sleipner. They have clearly defined the outer boundary of the CO_2 plume, and also no leakage has been identified. Results indicate that the leakage detectability threshold will be dependent on the CO_2 distribution and could range from a few tonnes to a few thousand tonnes.

Time lapse gravity surveying offers a lower cost complementary technique to seismic surveying. A baseline gravity survey was completed at Sleipner in 2002 and a repeat survey will be completed in 2005. Data on the suitability of this technique for monitoring injected CO_2 will therefore be available in late 2005/early 2006.

Verifying injected CO_2 volumes using seismic monitoring

The SACS project has also attempted to verify the volumes of injected CO_2 at Sleipner based on the seismic data. Initial attempts to calculate the CO_2 volumes within the aquifer, showed that some of the parameters used in the calculation had a huge impact on the ratio of calculated to known volume of CO_2 (range 63% - 231%). Therefore, uncertainty in the variables needs to be re-addressed, especially the in-situ temperature and nature of dispersal, whether it is fine scale homogeneous mixing or whether it is extreme and patchy mixing. This work is continuing.

3.3.2 Monitoring Onshore Saline Aquifers

Results from Japanese Onshore Saline Aquifer Study - Nagaoka project[5]

In comparison to the offshore location of the SACS project, the Nagaoka project undertaken by RITE[6] and ENAA[7] looks at the geophysical monitoring of CO_2 injection in an onshore saline aquifer in Japan. The CO_2 is being injected into a thin permeable zone of the reservoir at 20-40 tonnes per day. The CO_2 injection started on July 2003 and will end January 2005. The total amount of

[5] Since the Monitoring meeting in Santa Cruz (November 2004) the Japanese Onshore Saline Aquifer Study has been named the Nagaoka Project.
[6] Research Institute of Innovative Technology for the Earth
[7] Engineering Advancement Association of Japan

injected CO_2 will be about 10,000 tonnes. The pilot-scale demonstration allowed an improved understanding of the CO_2 movement in a porous sandstone reservoir. The results presented were based on experiences from cross well seismic tomography and comparison with well log data. Laboratory scale tests had indicated the potential for cross well seismic tomography as a tool for monitoring injected CO_2. The laboratory results were confirmed by the field experiment which demonstrated a p-wave reduction near the injection well as the CO_2 migrated past it. The presence of CO_2 was also identified by induction, sonic and neutron logging at the observation well. The seismic wave velocity showed a response to the injected CO_2 and has identified the mechanisms of how the CO_2 has displaced the formation water.

Results from Frio project

The Frio formation in Texas was chosen for an injection trial because there was extensive pre-injection characterisation data (3-D seismic, wireline logs from wells, core analyses and hydrological data was already available). Injection at the Frio site began on the 4th October 2004 and continued for 10 days, in which time 1,600 tonnes of CO_2 were injected. Post injection monitoring will continue until March 2005. Monitoring techniques being tested at Frio include: tracer injection, vertical seismic profiling (VSP) and cross well seismics, cross well electromagnetic, reservoir saturation tool (RST) logging as well as surface sampling for soil gas and groundwater contamination. The results from the monitoring will be combined and compared with an extensive programme of modelling that is running in parallel with the injection test. Modelling identifies the parameters that appear to control CO_2 injection and post injection migration. Physical measurements made can then confirm the correct values for these parameters.

There were some monitoring techniques that were not applied to the Frio project. They were not chosen because either it was estimated that they would be unlikely to collect useful measurements, they would interfere with the success of another experiment or they were simply cost prohibitive in the case of this project (although this may not be true of larger budget projects).

3.4 Monitoring experience from EOR projects

3.4.1 Results from monitoring at the West Pearl Queen site

Perfluorocarbon tracers (PFT's) were used to follow CO_2 migration and quantitatively estimate the CO_2 leak rate to the surface at a depleted petroleum well in the West Pearl Queen Field in New Mexico. Three tracers were co-injected with CO_2 including perfluoro-trimethylcyclohexane (PTCH), perfluoro-1,2-dimethylcyclohexane (PDCH) and perfluoro-dimethylcyclobutane (PDCB). The tracers were injected independently in 3, 12 hour slugs consisting of 500 ml each about a week apart along with the injected CO_2.

The concentration of each tracer detected in soil gas was small but relatively uniform over several months. The concentration of each of the three tracers in soil gas was approximately the same for each of the three tracers over the entire length of the experiment. The very small, but relatively constant concentration of tracer in soil gas indicates that the tracers were emanating from a very small leak from a large sink of tracer, ie. the petroleum reservoir. It appears that leakage occurred around the well bore. This is not surprising since the wells at the site are from the 1980's and had been previously over pressured, which could have caused small fractures in the annulus. The overall leak rate was estimated to be less than 0.1 % per year. A ground penetrating radar (GPR) survey of the caliche layer just below the sandy soil was conducted at the site. The GPR survey revealed areas of faulting to the north-west and thinning of the caliche to the south and south-west that coincide with leakage zones identified by the soil-gas monitors.

3.4.2 Results from monitoring at the Weyburn site

The Weyburn CO_2 Monitoring and Storage project consisted of 70 research projects and subdivisions which equated to 7 research areas. The project had CAN$20 million fund which will be difficult for other projects to duplicate. A key factor of the project was to fit in with the oil field operations and timing that would suit EnCana, the field operator. There were also difficulties with the local climate conditions where there is freeze/thaw and wet/dry cycles, subsequently, not all monitoring techniques were available. The monitoring has been undertaken over a four year period but how long is enough for some techniques?

As with other monitoring projects, the importance of the baseline survey stood out in its value to all subsequent work at Weyburn. There was also extensive information available for the field from 1000 wells, 600 cores, and all production injection history from 1955. Essentially all this information was available in the public domain. A good understanding of the long term storage capability of the cap rock was another significant result of the monitoring project at Weyburn. Tests showed that there was no communication through the cap rock and the preliminary risk assessment indicated that it was a good location for storage.

There can be plenty of improvement through the next phase of Weyburn (Weyburn II) with more quantification especially in seismics.

There were several kinds of monitoring techniques used at Weyburn including a 3D survey prior to CO_2 injection. The project discovered that initial modelling of the injection did not match seismic results. The modelling techniques were readdressed so that a second run matched what had been seen.

The geochemical monitoring and modelling of the Weyburn project enabled a model of the geochemical reactions in the reservoir over a 5000 year period to be developed for use in the risk assessment process. The CO_2 was tracked using carbon isotope signature which allowed the tracking of dissolution.

The injection of CO_2 into the Weyburn field resulted in a drop of 50-60% in resistivity and an increase in conductivity allowing fluids that had previously been inaccessible to be accessed. This improved production which was the purpose of the project.

Within the storage formation, flow units were identified with different flow properties. Each flow unit was modelled giving 5000 year reaction models. The models showed that the CO_2 will react given enough time assuming that the container is secure.

Geochemistry modelling was also used to look into the scenario that CO_2 had leaked from the reservoir. Each layer was assessed to see what minerals were available that would react with fluids. The layers included those below the Midale in case of down flow of injected CO_2. The modelling concluded that there was considerable excess storage capacity (solubility, ionic, and mineral) in the Weyburn Midale reservoir and that much of the geosphere above and below the reservoir had a high mineral trapping potential.

Some of the new modelling techniques are not suitable because of the expense and others need to be arranged so they fit in around the local climate conditions.

3.4.3 Discussion

Comments raised by the delegates in open discussion included:

For heterogeneous reservoirs, good modelling is increasingly important to better understand the reservoir.

There are positives and negatives for projects injecting CO_2 into an oil field with EOR. Monitoring of the injection site will benefit from access to reservoir models already available from oil recovery operations. It is also likely that the oil companies will have had better access to the high tech seismics than those involved with looking at CO_2 storage. Access to observation well data maybe available through the field operator and the produced fluid composition will have been recorded.

However, the experience gained from the pilot projects studying EOR can also provide some lessons for future projects. The schedule for an oil field will be driven by the operator and any project involved with that field will have to accept this priority and fit in accordingly. Similarly, the operations will be driven by the success of EOR rather than the amount of CO_2 that can be stored, although it is accepted that CO_2 could be more effectively used for EOR than it currently is. Other difficulties experienced when monitoring a CO2 injection site could be the noise interference of the other field operations. It will also need to be decided who had ownership or liability for the wells used during assessment and monitoring, research institutes and universities could have difficulty in accepting these liabilities.

The EOR resource for CO_2 storage is smaller than that for aquifers but there is plenty of information available. Where does this leave us in terms of monitoring aquifers? It has been suggested that monitoring should be undertaken along side risk assessments but at the end of the day it will be what data the modellers require and how that information can be provided? Again the question arises as to whether qualitative models can provide enough confidence or whether quantitative modelling is required. Progress may require a meeting with both the modellers and the monitors in the room at the same time.

It will be important to identify what can be done to bridge the gap which is something that the regional partnerships[8] in the U.S.A. are trying to approach. Monitoring needs to be done to satisfy the appropriate people but who these people are and how this would be achieved needs to be looked at in more detail.

The project results available for current CO_2 injection projects Weyburn and Sleipner have huge datasets that can be used to answer the questions. However, there could be some concern that seismics are being asked to perform tasks that were never required by the oil industry. Seismic monitoring can not do quantitative measurements alone but it is only one form of geophysics and there are other methods available. Perhaps geochemistry should be used to identify the actual site of the leakage first. The movement of CO_2 underground will be less of a concern if it does not involve seepage. Is it possible to identify how much of the CO_2 would be mineralised and therefore permanently stored?

In terms of the language used, it was suggested that climate modellers refer to % leakage. This value will drop over time and be different between projects therefore this is a useful piece of information that could be provided by the projects.

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[8] US DOE initative

3.5 New monitoring projects and future plans

3.5.1 Development of the In Salah CO_2 storage project

On an industrial scale, In Salah provides a project larger than Sleipner but smaller than Weyburn and it will provide another source of data for modelling and monitoring studies. The operation is part of a project to transport gas to Italy and Spain at a rate of 900 million scf/day. CO_2 will be injected at 1 million tonnes/year.

A range of models will be used at the site from regional to well scale. It is clear though that industry will not want to get involved in projects that leak. There is no recovery of costs at the moment for CO_2 injection and again industry will not be involved in these projects if there are not credits associated with storage of CO_2. Projects such as In Salah could be used to set precedents for the regulation and verification of the geological storage of CO_2, allowing eligibility for GHG credits.

3D seismics were used to identify the faults in the reservoir but it has held hydrocarbons for a significant period of geological time. The In Salah project could also have difficulties for certain monitoring techniques because of the local climate. Temperatures of $60^{O}C$ can be reached.

3.5.2 Development of the Teapot Dome CO_2 storage project

The Teapot Dome test centre is situated in Wyoming close to a major CO_2 pipeline (the Salt Creek pipeline). There are over 600 active wells and all the information is in the public domain. The structure is very well characterised which is certainly very important in planning new work. Whilst accepting that leakage studies are not something industry may want to be associated with, this new project would like to monitor engineered leakage to assess and model leakage profiles. Baseline Electro Resistance Tomography (ERT) and VSP surveys are now being taken in situ as well as geochemical and surface monitoring baseline data. Expansive outcrops of the reservoir rocks of Teapot Dome are allowing detailed studies of the reservoir properties including information about fracturing to be developed in advance of CO_2 injection. Large scale CO_2 injection is planned to commence in 2005.

3.5.3 Development of Mountaineer CO_2 storage project

On a regional basis the Mt Simon sandstone still has the best potential for storage but storage needs to be made feasible at the lowest cost. Site characterisation is the most important part.

The development of a monitoring project as part of the Mountaineer project showed that the regulatory monitoring requirements for injection wells and the scientific monitoring to understand the fate and transport of injected CO_2 will need to be addressed. It will be necessary to avoid setting costly precedents for future full scale sites. Monitoring does not want to be part of regulatory process unless absolutely necessary. The features of the site and the constraints related to the industrial setting need to be considered. Finally, the monitoring should have enough resolution in relation to the amounts of CO_2 injected.

3.5.4 New developments in Canada

Four new pilot CO_2-EOR projects are planned in Alberta, Canada. These projects will start operation in late 2004. One of these new pilot projects (details of which were still to be announced at the time of the workshop) will include a detailed monitoring programme of the injected CO_2. The monitoring project was expected to start operation in late 2004/early 2005.

4. SUMMARY OF MONITORING TECHNOLOGY AND LIMITATIONS

One of the aims of the meeting was to address the current status of monitoring techniques, assess their limitations and further development needs. The results of the workshop discussions on these issues are summarised in Table 2.

Table 2.	Current state of the art	Assess limitations	New Technology/further developments
Surface monitoring			
General	• Experience has shown that the development of baseline conditions at a site is an essential part of site characterisation for a CO_2 storage site. • Pathways can be identified near to the surface which could be potential leakage routes in the future. This can provide guidance for further monitoring. • Monitoring a range of gases can give clues as to whether potential pathways are conduits for gas migration. • Continuous monitoring has worked well at Weyburn and has been repeated and undertaken at the same time each year to provide consistent climatic conditions. It also provides real monetary value for surface monitoring. • From an existing operating site, extensive information is available for creating the baseline case. For Weyburn this information was available in the public domain and can significantly reduce the cost of monitoring.	Biological Interference: • Photosynthesis and soil respiration can cause changes in the levels of atmospheric CO_2 and can lead to significant differences between summer and winter. The lower biological interference during the winter can result in more detail being seen. • In a large open system, monitoring will be searching for small, deep-sourced signals in the presence of substantial near-surface noise. Local Climate Interference: • Sites where the local climate is both warm and wet can make surface monitoring very difficult, this was the experience at the Frio site. Weyburn experienced extreme conditions of freeze/thaw and wet/dry cycles, subsequently, not all monitoring techniques were available. Vegetation cover or surface water can unavoidably lead to biased sampling for some monitoring techniques. • Climate change could have a big effect on continuous monitoring. Over an extended timeframe (50 years of injection) the effects of climate change could impact on the monitoring results. Other factors: • Original monitoring sites can be lost with the development of the site. • Nitrogen fertilization from agricultural practices can modify the soil gas composition from that of unfertilized areas. • The Weyburn project was aware that any monitoring had to fit in with the commercial operations at the oil field.	Developments in methodology: • The baseline study will be essential to fully understand the noise at a site before CO_2 injection begins. • Surface monitoring technologies will need to be chosen depending on the location. Structured tests will be required to ensure that the monitoring results can be compared between sites. • Denser sampling should be a future development. Concern has arisen over leaks that could be missed even if they have occur within a few meters of a sample site. • Monitoring approaches may have to be developed to take into account a site's particular requirements. Technological developments: • Automatic continuous monitoring stations are a future technological development but the locating of these stations will be crucial and dependant on supporting information. Testing of this new technology can be done at sites of natural seepage, such as those investigated in the NASCENT project. • Further research to improve confidence will include integration with other techniques and development of risk maps.

	Current state of the art	Assess limitations	New Technology/further developments
Surface monitoring cont.			
Accumulation chambers/cells	• Surface leakage has been monitored at Rangely and Weyburn. Soil-gas flux measurements at Rangely indicate very low potential leakage rates (<0.01% per year), none at Weyburn. • Good for small features and delineating spatial trends. • Can be portable or fixed and automated	• The area covered by the chamber is small (~25cm diameter) so it will be essential to pin point the exact location of leakage sites to set up the monitoring station. This could be like looking for a needle in a hay stack. • Could miss a leak within a few meters of a sample site. • Diffuse leaks over a large area could be difficult to identify and quantify.	• Use in conjunction with other techniques. Can be used to fine tune after other techniques have located possible sites. • Link to RA to identify best sites to monitor • Need to monitor for other gases that can also indicate possible leakage pathways.
Eddy covariance	• Larger surface sampling area. The area of the footprint (m^2-km^2) is a function of the height of the tower and the meteorological conditions. Good for large areas with average flux measurement.	• As per accumulation chambers	• As for accumulation chambers
LIDAR	• Rapidly developing with good areal coverage	• Too early to define	• Too early to define
Electro magnetics	• This method of identifying abandoned wells has shown that historical data is not always accurate. The historical information of the location of wells does not always line up with the locations identified by this method. • Unmanned vehicles have been developed for this type of survey with up to 9hrs fly time. • Low cost technique • Seeps of radon can be used to detect uncased wells. Wells with radon and CH_4 anomalies should be re-plugged first.	• Current examples focus on large open areas that are not highly populated/urbanised. It may not be suitable for denser populated areas.	

<table>
<tr><th></th><th>Current state of the art</th><th>Assess limitations</th><th>New Technology/further developments</th></tr>
<tr><td colspan="4">Surface monitoring cont.</td></tr>
<tr><td>Aerial reconisance</td><td>• Airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching.
• Airborne hyperspectral remote sensing methods allow early detection and spatial mapping of CO_2 leakage from deep underground storage sites.
• Vegetation stress techniques or geobotanical remote sensing can be used to create a baseline dataset.
• Geobotanical sensing at Rangely showed no changes in vegetation patterns after 23 years of CO_2 injection.
• It can also be used for mapping known or buried abandoned well heads, subtle or hidden faults and joints and signs of leakage
• High spatial resolution can be achieved with a pixel size of 3x3m. This high resolution can identify habitat changes due to CO_2 leakage.</td><td>Biological Interference:
• Desert environments can cause problems for this method. Drought tolerant plants may cause confusion. It is therefore not necessarily suited to these conditions.
Local Climate Interference:
• Rainfall can significantly change the images making them look much brighter.
• Current examples focus on large open areas that are not highly populated/urbanised. It may not be suitable for denser populated areas, or areas with high air traffic density.</td><td>• Satellite could be next step</td></tr>
<tr><td>Tracers</td><td>• Perfluorocarbon tracers have been tested in a trial at West Pearl Queen.
• Initial results look promising that the technique could detect very low leakage rates (i.e. <0.01% per year)</td><td>• Further more extensive trials are needed</td><td>• Too early to define</td></tr>
</table>

	Current state of the art	Assess limitations	New Technology/further developments
Sub-surface monitoring			
Seismic General	• Seismic has been demonstrated at Sleipner and Weyburn capable of monitoring the movement of CO_2 in reservoirs. • Using time-lapse surface seismic 1.4 million m^3 (2500 tonnes) of CO_2 is the minimum detectable. • Seismic can also determine movement of CO_2 out of a storage reservoir but does not have the resolution to detect low level leakage	• Saline aquifers are a much larger resource for CO_2 storage that EOR but there is a lot less information available. Therefore, determining the baseline conditions for saline aquifers is essential and likely to make the pre-operation costs more expensive than those for EOR. • Can be expensive, especially offshore • Not suitable for use in very deep thin reservoirs • Not suitable where Karst systems present. • Seismic's are being asked to perform tasks that were never required by the oil industry. • Seismic monitoring should not be used alone but as part of a suite of monitoring techniques. • The more expensive techniques such as seismic will not be undertaken by industry unless there are regulatory requirement or financial credits for storage.	• Seismic is being used by industry and as a result the technology is rapidly developing
Sub surface gravimetry	• Baseline tests at Sleipner • Good areal coverage with lower cost but lower resolution	• Too early to define	• Potentially less expensive than Sleipner but not yet proven
3D Seismics	• Tested at Sleipner & Weyburn • Detected movement of CO_2 in sub surface • Allows profiling of up to 5000 meters below the sea bed. Can also show effects in the water column. • 3D seismics at Weyburn did not match the initial modelling. This allowed a second run of modelling which matched that which had been seen.	• Not applicable in all situations • Costly • There is difficulty with verifying results of seismic tests. Changing the temperature of the reservoir has had a huge impact on the percentage known volume of CO_2 that is calculated.	• 3D seismics can identify the faults

	Current state of the art	Assess limitations	New Technology/further developments
Sub-surface monitoring cont.			
Cross well seismics	• Japanese trial, Weyburn and Frio • Observed CO_2 at observation well • Covers a relatively large cross section (Japan – 160m). • Following tests in Japan, researches were confident that the seismic wave velocity showed a response to the injected CO_2 and has identified the mechanisms of how the CO_2 has displaced the formation water.	• To early to define	• Not applicable in larger offshore fields
Observation wells	• Japanese test and Frio • Onshore existing wells can be utilised.	• Expensive, especially offshore too much for a research project. • Limited spatial information • Possible increased risk of leakage if new wells drilled through cap rock	• None
Produced Fluid and Gas	• Relatively inexpensive method to sample and analyze in-situ fluids, gas, and oil (if present). • Using in-situ P and T, can calculate reservoir fluid and gas compositions from surface samples (e.g. Weyburn). • U-tube technology allows sampling at in-situ P-T (e.g. Frio). • Can determine qualitative and quantitative effects of CO_2 injection on dissolution and/or precipitation processes with existing fluid, gas, oil, and minerals (e.g. Weyburn).	• Not all injection sites have good spatial coverage of monitoring or producing wells. • Drilling new monitoring wells for produced fluids and gases can be prohibitively expensive. • Field-wide P and T surveys are difficult, dataset can be incomplete. • Mass balance calculations can be complex, quantitative calculations associated with dissolution and precipitation of CO_2 contain some assumptions. • Can be difficult to overlay geochemical results with high-resolution seismic.	• In-line continuous gas measurements (e.g. Frio). • In-line gas detectors and downhole P, T instrumentation. • Need for "basic toolset" of geochemical parameters that can be measured quickly to assess subterranean CO_2 movement.

5. CONCLUSIONS

Major conclusions from the workshop:

- It is accepted that public outreach is critical. It allows the benefit of transparency whilst highlighting the concerns of the public. It provides targeted information about the possible role, benefits and risks of CO_2 storage and ensures that it is the right information that is being supplied.

- There are many techniques for monitoring and this is good because it indicates how big the tool box is.

- It is likely that a good monitoring strategy will include a combination of monitoring techniques that will be used at any one site. The decision on the techniques to be used will be dependant on what it is that the project will need to monitor or what the objectives of the regulators may be. The capabilities of the tests can be assessed by looking at scenarios of active projects.

- The cost of monitoring will not be a major factor in the total cost of a CO_2 storage project based upon a life time of 55-85 years approximately. The costs of basic monitoring given a discount rate of 10% could be <$0.05 - 0.10 per tonne CO_2. The enhanced monitoring package which would be necessary for occupational health and safety would be available at 40 – 60% over basic package. The most expensive technique is the seismic surveys.

- The monitoring of a site could be split into three phases: Pre-operational, Operational and Closure monitoring. For EOR monitoring some pre-operational will already have been completed and available for use by the operators of a storage project. As it is likely that there will have been no previous activity for a saline aquifer, the pre-operational monitoring will be more thorough and therefore more expensive; simply it will need to be done from scratch. However, the price ratio could change during the operation and closure phases. The cost will depend highly on a number of site specific factors.

- Soil gas flux measurements the Rangely EOR field and have indicated very low potential leakage rates (>0.01 % per year). However, near surface biological noise can mask the results of CO_2 flux measurements to the atmosphere. Thus, one must carefully measure the ^{12}C /^{13}C ratio in the CO_2 from soil-gas to distinguish between ancient CO_2 and biogenic CO_2. It is essential that baseline surveys are completed before injection to fully understand any interference to monitoring. It is both timely and expensive to return to a baseline conditions once injection has taken place.

- The local climate can have significant impact on the results of monitoring. In fact there will be some techniques that will not be suited to certain environments. An auditing tool to identify a suitable selection of techniques could be a good idea.

- Sampling can be biased through vegetation cover, seasonal climate conditions or surface water and original monitoring sites can be covered over during the development of the site (i.e. new roads). Therefore, in order to obtain a good baseline of the site, plenty of time should be allowed for monitoring before development begins to take place. The monitoring of a site will have to be developed to take in to account the sites requirements.

- Monitoring for other gases can be a way of identifying conduits for gas migration and determining their source through isotopic analysis.

- A continuous monitoring approach at the same time each year has been a successful approach at the Weyburn project. Denser sampling could help to find all leakage as it was identified that it could be possible to miss leakage even if a sample site was close by. Automated continuous monitoring stations will be a technological development.

- Aerial reconnaissance to search for existing wells and faults allows uncharted or mis-located, improperly sealed wells to be mapped quickly, accurately, and inexpensively. Further, the airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching. This is important when one considers that the underground CO_2 plume from a sequestration site may extend over 10's of kilometres.

- Monitoring of existing injection projects such as Weyburn and Sleipner provide access to actual results whilst providing an opportunity to identify areas of further work and highlighting limitations and uncertainties. Injection projects like Frio show the process of a project from site selection through to post-injection monitoring providing enormous amounts of information.

- Monitoring of a CO_2 injection site at an active oil field for EOR purposes will have positives and negatives. There should be vast amounts of information from cores and wells as well as a documented production history and the oil recovery operations will have access to high tech seismics. However, the schedule of the oil field will be driven by the operator and the operation will be driven by enhanced production rather than the storage of CO_2.

- There is still more that needs to be known about the conditions within the reservoir in the case of saline aquifers.

- Projects such as In Salah provide industrial scale examples of monitoring and modelling of CO_2 injection. However, at the moment there is no recovery of costs for CO_2 injection and industry will not be involved if there are not credits for storage. Neither will industry want to get involved with projects that will leak.

- Precedents for monitoring requirements of new CO_2 injection projects should not be set where they become cost prohibited.

6. FUTURE RESEARCH NEEDS

The workshop identified a number of future key research needs:

- Because there is such an extensive tool box of monitoring techniques, new injection projects need guidance on to what to measure and where. Such information can be provided by a safety and risk assessment of the injection site if this were undertaken early in the project lifetime.
- Once again because there are plenty of techniques available for monitoring injected CO_2 and it became evident, through the discussions at the workshop, that some techniques would be more appropriate to certain locations due to their suitability to particular climate conditions. The production of some form of "auditing" chart was suggested to enable the right combination of techniques to be selected for a particular project.

7. NEXT STEPS

A number of actions were agreed which included:

- IEA GHG will add the Monitoring Network to the dedicated Networks site on www.co2captureandstorage.info. The presentations and report of the workshop will be in a delegate's only area of the site but a public domain summary report will be produced and placed in the public section of the site.

- The second meeting of the network will be in autumn 2005, details will be sent out by the organising committee.

Appendix 1

Delegate List

Sally Benson Deputy Director for Operations Lawrence Berkeley National Lab. 1 Cyclotron Road, MS 5DA - 4112 Berkeley CA USA 94720 smbenson@lbl.gov	Jay Braitsch Strategic Planning/Carbon Sequestration U.S. Dept. of Energy Office of Fossil Energy 4G067 1000 Independence Avenue Washington, DC USA 20585 jay.braitsch@hq.doe.gov
Grant Bromhal Research Engineer USDOE - NETL Morgantown WV USA 26507 0880 bromhal@netl.doe.gov	Charles Christopher Project Manager BP America, Inc. 501 WestLake Park Blvd., Houston, TX USA 77079 christca@bp.com
William Daily Physicist Lawrence Livermore National Lab. L-130 PO Box 808 Lawrence Livermore National Laboratory CA 94551-0808 Livermore USA 94551-0808 Daily1@llnl.gov	Eric Davis Manager of Technical Development Pinnacle Technologies 600, Townsend St. Suite 160 W San Francisco CA USA 94103 eric.davis@pinntech.com
Kevin Dodds CO2CRC CSIRO 26 Dick Perry Avenue Bentley Perth Australia kdodds@co2crc.com.au	Kyle Durocher Research Geologist Alberta Research Council 3608 - 33rd Street NW Calgary Alberta Canada T2L 2A6 durocher@arc.ab.ca
Dan Ebrom Senior Geophysical Associate BP America, Inc. 501 WestLake Park Blvd., Houston, TX USA 77079 ebromda@bp.com	Ola Eiken Dr. / geophysicist Statoil Arkitekt Ebbells vei 10 Trondheim Norway N-7005 oei@statoil.com
Tony Espie CO2 Storage Programme Manager BP Sunbury Business Park Chertsey Road Sunbury-Upon-Thames UK TW16 7LN espiet@bp.com	Julianna Fessenden Technical Staff Member Los Alamos National Lab. EES-6 MS USA D462 julianna@lanl.gov

S. Julio Friedmann Initiave Leader, Carbon Sequestration Lawrence Livermore National Lab. 7000 East St, Livermore, CA USA 94550-9234 Friedmann2@llnl.gov	John Gale Project Manager IEA GHG Programme Orchard Business Centre Stoke Orchard Cheltenham Gloucestershire UK GL52 7RZ JohnG@ieagreen.demon.co.uk
Neeraj Gupta Research Leader Battelle 505 King ave Columbus Ohio USA 43201 gupta@battelle.org	Richard Hammack Physical Scientist USDOE - NETL PO Box 10940 MS USA 84/108 richard.hammack@netl.doe.gov
Mark Holtz Research Associate University of Texas, Austin University Station Box X Austin TX USA 78713 8924 mark.holtz@beg.utexas.edu	Michael Hoversten Energy Resources Program Head/Staff Scientist Lawrence Berkeley National Lab. One Cyclotron Rd Berkeley CA USA 94720 gmhoversten@lbl.gov
Scott Imbus Sr. Research Scientist Chevron Texaco Energy Technology 4800 Fournace Place Bellaire TX USA 77401 scott.imbus@chevrontexaco.com	Anhar Karimjee Hyrdogeologist U.S. Environmental Protection Agency 1200 Pennsylvania Ave NW USA 6207J Karimjee.anhar@epa.gov
David Keith Canada Research Chair in Energy and the Enviro University of Calgary Chemical and Petroleum Engineering University of Calgary 2500 University Drive NW, Calgary AB Canada T2N 1N4	Gary Kirby British Geological Survey Keyworth, Nottingham, Nottinghamshire UK NG12 5GG gak@bgs.ac.uk
Ronald Klusman Colorado School of Mines Department of Chemistry & Geochemistry Golden CO USA 80401 rklusman@mines.edu	Martha Krebs President Science Strategies 2139 Kew Drive Los Angeles CA USA makpec@att.net

Don Lawton Chair in Exploration Geophysics University of Calgary Dept of Geology and Geophysics 2500 University Drive N.W. Calgary Alberta Canada lawton@ucalgary.ca	Angela Manancourt Research Officer IEA GHG Programme The Orchard Business Centre Stoke Orchard, Cheltenham Gloucestershire UK GL52 7RZ angela@ieagreen.demon.co.uk
Brian McPherson Professor New Mexico Institute of Mining and Technology 801, Leroy Place Socorro New Mexico 87801 brian@nmt.edu	Mark Meadows VP, Research & Development 4th Wave Imaging 16 A Journey Suite 200 Aliso Viejo CA USA 92656 mark.meadows@4thwaveimaging.com
Larry Myer Staff Scientist Lawrence Berkeley National Lab. Mailstop 90-1116 Berkeley CA USA 94720 lrmyer@lbl.gov	Dai Nobuoka Geophysicist OYO Corporation Geophysical Dept.,Energy Business Division 2-2-19,Daitakubo Minami, Saitama Saitama Japan Nobuoka-dai@oyonet.oyo.co.jp
Susann Nordrum Senior Engineer Chevron Texaco 100 Chevron Wayy PO Box 1627 Richmond CA USA 94802 sbnordrum@chevrontexaco.com	Dag Nummedal Director Colorado Energy Research Institute Colorado School of Mines 1500 Illinois St USA nummedal@mines.edu
Curt Oldenburg Staff Scientist Lawrence Berkeley National Lab. Earth Sciences Division 90-1116 1 Cyclotron Rd. Berkeley CA USA 94720 cmoldenburg@lbl.gov	Jonathan Pearce British Geological Survey Keyworth, Nottingham Nottinghamshire UK NG12 5GG jmpe@bgs.ac.uk
Bill Pickles Senior Scientist Lawrence Livermore National Lab. 7000 East Ave, l-644 Livermore CA USA 94551 pickles1@llnl.gov	Donald Potts Professor of Biology University of California Department of Ecology & Evolutionary Biology Earth & Marine Sciences Building Santa Cruz California USA 95064 potts@biology.ucsc.edu

Abe Ramirez Geophysicist Lawrence Livermore National Lab. PO Box 808, L-208 Livermore CA USA Ramirez3@llnl.gov	Veronica Brieno Rankin PHD Candidate Michigan Technolgical University DOW 422 1400 Townsend Drive Houghton MI USA 49931-1295 vjbrieno@mtu.edu
Alan Rezigh Manager – Reservoir Dynamics & Performance ConocoPhillips 600 North Dairy Ashford (OF 2008) Houston TX USA 77079 Alan.A.Rezigh@conocophillips.com	Richard Rhudy Manager, Enviromental Control Projects EPRI 3412 Hillview Ave. Palo Alto, California USA rrhudy@epri.com
Livio Ruvo Senior Reservoir Geologist Eni E&P Via Emilia 1 - 20097 San Donato Milanese Italy livio.ruvo@agip.it	Hideki Saito Deputy General Manager, OYO Corporation Engineering Geophysics R&D Dept. 4-2-6 Kudan-Kita, Chiyoda, Tokyo Japan 102-0073 Saito-hideki@oyonet.oyo.co.jp
Renato Savino Senior Reservoir Geologist Eni E&P Via Emilia 1 - 20097 San Donato Milanese Italy renato.savino@agip.it	Don Seeburger Team Leader Formation Evaluation Development Chevron Texaco ETC 6001 Bollinger Canyon Rd D2324 San Ramon, CA USA 94583-2324 dase@chevrontexaco.com
Don Sherlock CO2CRC CSIRO 26 Dick Perry Ave Kensington Perth Australia 6102 Don.sherlock@csiro.au	Duane Smith Research Group Leader U.S. Dept. of Energy NETL Morgantown WV USA 26507-0880 Duane.smith@netl.doe.gov
Vicky Stamp CO2 Program Manager RMOTC / DOE Casper WY USA vicki.stamp@rmotc.doe.gov	Toru Takahashi VP Engineering OYO Corporation 2190 Fortune Drive, San Jose, USA CA95131 toru-oyousa@att.net

Daiji Tanase SEC Engineering Advancement Association of Japan (ENAA) 1-4-6, Nishi-shinbashi, Minato-ku, Tokyo Japan Sec549@enaa.or.jp	Roger Turpening Research Professor Geological & Mining Engrg. & Sciences 630 Dow ESE Building 1400 Townsend Drive Houghton MI USA 49931-1295 roger@mtu.edu
Arthur Wells Research Chemist USDOE - NETL PO Box 10940 MS USA 94/412 arthur.wells@netl.doe.gov	Don White Geophysicist Geological Survey of Canada 615 Booth Street, Ottawa, ON Canada don.white@nrcan.gc.ca
Malcolm Wilson Director, Engineering University of Regina 301-6 Research Drive PTRC Building Regina Saskatchewan Canada S4S 7J7 malcolm.wilson@uregina.ca	Iain Wright CO2 Project Manager BP BP Group Technology Chertsey Road Sunbury Middlesex UK TW16 7LN wrightiw@bp.com
Ziqiu Xue RITE 9-2 Kizugawadai, Kizu-cho, Soraku-gun Kyoto Japan 619-0292 xue@rite.or.jp	

Appendix 2
Monitoring Workshop Programme

Day 1 Monday 8th November 2004	
Opening Session	
Welcome, Safety Briefings Meeting objectives John Gale, IEA GHG	
Session 1 – Opening Perspectives and Overviews	
Monitoring needs, a regulatory perspective	*Martha Krebs. West Coast Regional Carbon Sequestration Partnership*
Overview of status of monitoring technologies	*Sally Benson, LBNL*
Monitoring strategies and cost comparisons	*Larry Meyer, LBNL*
Session 2 – Surface/leakage monitoring	
CO_2 Fluxes to the Atmosphere, and in Soil Gas: Detection of a Deep Source Masked by Near-surface Noise	*Ron Klusman, USDOE/NETL*
Surface monitoring techniques as applied at Weyburn and elsewhere	*Jonathan Pearce, BGS*
Monitoring and verification of CO_2 leakage from underground storage formations	*William Pickles, LLNL*
Preliminary Evaluation of the Ability of Airborne Reconnaissance Techniques to Find Abandoned Wells	*Rick Hammack, USDOE/NETL*
Leakage and seepage in the near surface environment: an integrated approach to monitoring and detection	*Curt Oldenburg, LBNL*
Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? • What further research is needed to improve confidence in the monitoring results?	
Session 3 – Geophysical monitoring - aquifers	
Review of geophysical monitoring results from the SACS project	*Ola Eiken, Statoil*
Verifying the volumes of injected CO_2 – experience from the SACS project	*Gary Kirby, BGS*
Geophysical Monitoring of CO2 Sequestration at An Onshore Saline Aquifer in Japan	*Ziqiu Xue, RITE*
Initial results from the Frio Brine Injection project	*Mark Holtz, Texas BEG*
Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?	

Monitoring Workshop Programme

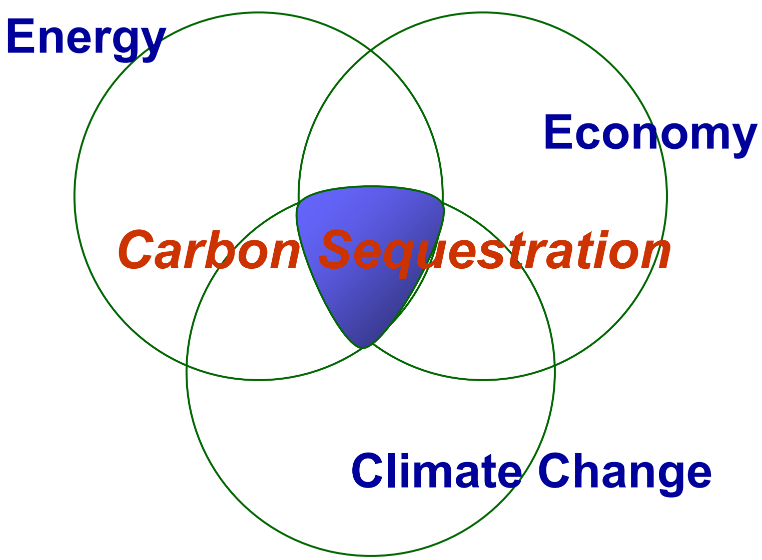
Opening Session - Day 2	
Review of Day 1 and plan for Day 2	*John Gale IEA GHG and Charles Christopher, BP*
Session 4 – Monitoring CO_2 injection into Oil fields	
Tracer Results from the West Pearl Queen Field Pilot Sequestration Site	*Arthur Wells, USDOE/NETL*
What worked and what didn't – experiences from the Weyburn Monitoring Project	*Malcolm Wilson, PTRC*
Review of seismic results from the Weyburn Monitoring project	*Don White, GSC*
Geochemical monitoring at Weyburn	*Kyle Durocher, ARC*
Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?	
Session 5 – New monitoring projects/future activities	
The In-Salah project – monitoring plans	*Iain Wright, BP*
Teapot Dome - baseline monitoring results and future monitoring programmes	*Julio Friedmann, LLNL*
The EnergyINET project	*David Keith, University of Calgary*
Session 6 - Workshop Review	
The Mountaineer project – monitoring plans	*Neeraj Gupta, Battelle*
Facilitated discussion to cover the following points: What have we learnt? How confident are we in the results obtained to date? where are the gaps? What are the future research needs?	
Session 7 - Closing Session	
Way forward and Next steps Including discussion on establishment of an international research network	
Closing Remarks	

Monitoring Network

Key issues

- Any limitations in techniques?
- Are new techniques being developed?
- Any barriers to use?
- What further research is needed?

Monitoring Carbon Sequestration:
The Very End of the Carbon Fuel Cycle



Martha Krebs
Science Strategies
November 8, 2004

Outline

- The risks of technology introduction
- Policy options and the role of public outreach
- Who are the Public
- What do they know
- Where does Monitoring fit in

Introducing New Energy Technologies Is Hard

There are risks for both producers and consumers

- Financial
- EH&S
- Shortages
- Complexity
  - Interdependencies among the end-use sectors
  - Competing technologies
  - Difficulty in Forecasting the Future
  - Uncontrollable externalities – War in Iraq; Saudi Arabia as the flywheel of oil production

What Are The Policy Options

- R&D
- Federal and State Standards
- Tax incentives
- Demonstration and deployment of low/no carbon technologies
- Establishment of carbon markets

Public Outreach is Critical

Programs must be designed at the national and local levels to:

- Engage in transparent exchanges with the many affected publics that are not always knowledgeable about climate change and the full range of reasonable technology and policy responses;
- Identify the concerns of the public with respect to both carbon sequestration and the larger context in which it will be pursued
- Provide properly targeted information about the possible role, benefits and risks of sequestration;
- Assist in satisfying the applicable regulatory procedures.

The Public and Their Surrogates

- Decisionmakers
  - Executive Agencies
  - Regulators
  - Legislatures
- Opinion Leaders
  - Media
  - Local Government
  - Business Leaders
  - Insurance Industry
  - Think Tanks
- National Environmental Organizations
- Local Environmental and Community Organizations
- The Public

BBC NEWS WORLD EDITION

Climate gas cuts 'are affordable'

“His list of 15 possible ways of reducing emissions of carbon dioxide, the main greenhouse gas produced by human activities, is exhaustive. It includes more efficient vehicles an buildings, reduced vehicle use, ***capturing CO2 at the point of emission***, and where possible replacing coal, oil and gas with other fuels.”

November 3, 2004

Climate Change Think Tanks Are Getting the Message

We need a far more vigorous effort to promote energy efficient technologies; to prepare for the hydrogen economy; to ***develop affordable carbon capture and sequestration technologies***; and to spur the growth of renewable energy, biofuels, and coal-bed methane capture.

Eileen Claussen, Science, October 29, 2004,p.816.

PEW CENTER ON Global CLIMATE CHANGE

National Environmental Organizations are **FOR** Renewables and Efficiency

- They are often silent on Fossil Fuels

- Greenpeace is explicitly against the use of Fossil Fuels

- Regional offices are often more responsive to local issues than national leadership and may be more ideological than the headquarters

But Some Have Taken Notice

The "toolbox" of current lower carbon technologies is well known: substantial reductions in energy consumption by vehicles, appliances, buildings and the megalopolises they form are achievable without any loss in services; renewable resources like wind, solar and biomass are already cost-competitive in certain applications even though their lower CO_2 emissions attributes is currently valued at zero in most markets -- and further cost reductions are likely; preferential use of lower carbon fossil fuels like natural gas is expanding; ***all of the elements of CO_2 capture and geologic disposal techniques have been demonstrated at commercial scale in a number of countries***.

David Hawkins, Vancouver Conference, September 6, 2004

The Public and Their Surrogates

- Decisionmakers
  - Executive Agencies
  - Regulators
  - Legislatures
- Opinion Leaders
  - Media
  - Local Government
  - Business Leaders
  - Insurance Industry
  - Think Tanks
- National Environmental Organizations
- Local Environmental and Community Organizations
- The Public

Real Projects Will Bring the Challenge of Real People with Real Backyards

MIT Survey

- Environment is not at the top of their list of important concerns
- Climate change is not the most important environmental issue
- The connection between carbon emissions and specific energy production or end use activities is not always clear.
- Carbon sequestration is virtually unknown
- Information about energy costs makes a difference
- People were not willing to pay more $6.50/month on the electricity bill to solve global warming.
- Long term issues of carbon sequestration were not addressed

Tyndall Citizen Panels and Survey

- Initial awareness and favorability of carbon sequestration was low
- Information increased both favorability and non-acceptance
- Concerns about leakage and long term security of geological formations were expressed
- Affirmed interest of citizens in participatory, open process

Curry et al., MIT, September 2004

Shackley et al. Tyndall Center, January 2004

Long Term Monitoring: Status

- Long term generic concerns are known: CO_2 Accounting, Health and Safety, Environmental, Ecosystems
- Monitoring technologies have been identified
- Monitoring protocols tailored to technical risk have been costed for first 100 -150 years. *Benson et al.*
- Initial consideration of policy and legal issues surrounding long term liability. *Herzog et al***.**

Expected Period for Storage Integrity: **A Critical Issue**

- 1000 years, 2000 years, 10,000 years?
- How does one decide?
- A process is needed now before large demonstrations are identified
  - The technical community needs to lead but in an open, independent fashion; the National Academies could be one approach
  - More systematic work needs to be done with the public in relevant communities along the Tyndall model but independent of specific projects
  - Specific projects must also address the issue
  - Specific funding must be provided but independence must be assured; government funding is critical

Overview of the Status of Monitoring Technologies

Sally M. Benson
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

IEA / BP Monitoring Workshop

Santa Cruz, CA

November 8-9, 2004

IEA GREENHOUSE GAS R&D PROGRAMME

Topics

- Performance requirements
- Purposes for monitoring
- Monitoring techniques
- Sensitivity and resolution of methods for leak detection
- Conclusions

Requirements for Safe and Effective Geologic Storage of CO_2

Requirements for Geologic Storage

Worker and Public Safety

Local Environmental Impacts to Groundwater and Ecosystems

GHG Mitigation Effectiveness

Leakage and Seepage of CO_2

- **Injection well leakage**
- **Leakage from the primary storage reservoir**
- **Surface seepage from the ground and abandoned wells**

Injection Well Controls

- **Wellhead and formation pressure**
- **Injection rates**

Purposes for Monitoring

- Establish baseline conditions to assess CO_2 storage impacts
- Ensure effective injection controls
- Detect plume location and leakage from storage formation
- Assess the integrity of shut-in, plugged or abandoned wells
- Identify and confirm storage efficiency and processes
- Model calibration and performance confirmation
- Detect and quantify surface seepage
- Assess environmental, health and safety impacts of leakage

Purposes for Monitoring (cont.)

- Micro-seismicity associated with CO_2 injection
- Design and evaluate remediation efforts
- Provide assurance and accounting for monetary transactions and validation of emission reductions
- Evaluate impacts on other geological resources
- Settle legal disputes due to leaks, seismic events, or ground movement
- Assure the public where visibility and transparency is of prime importance
- Perform scientific experiments to improve understanding of CO_2 storage

Monitoring Techniques

- Wellhead and formation pressure
- Injection and production rate
- Casing and annulus pressure testing
- Temperature
- Well logs
- Fluid and gas composition
- Seismic geophysics
- Electrical and electromagnetic geophysics

Monitoring Techniques

- Gravity
- Land surface deformation
- Tilt measurements
- Airborne or satellite imaging
- Soil gas and vadose zone monitoring
- Fluid and gas phase tracers
- Surface flux monitoring
- Atmospheric CO_2 concentration
- Micro seismicity

Monitoring Approaches

Likely to be used

Possible to use

	Wellhead and Formation pressure	Injection and Production Rate	Casing and Annulus Pressure Testing	Casing Integrity Logs	Temperature	Well Logs	Fluid and Gas Composition	Seismic Geophysics	Electrical and Electromagnetic Geophysics	Gravity	Land Surface Deformation	Tilt Measurements	Airborne or Satellite Imaging	Soil Gas and Vadose Zone Monitoring	Surface Flux Monitoring	Atmospheric CO_2 Concentration	Micro Seismicity
Baseline	Likely				Likely	Likely	Likely	Likely	Possible	Possible	Possible		Possible	Possible	Possible		Likely
Injection controls	Likely	Likely	Likely	Likely	Likely	Likely											Possible
Location of plume	Possible	Likely				Possible	Possible	Likely	Possible	Possible		Possible					Possible
Integrity of wells	Possible					Likely	Possible	Possible					Possible	Possible	Possible	Possible	
Efficiency and processes	Likely	Likely				Likely	Possible	Likely	Possible								
Calibration and performance	Likely	Likely			Possible	Likely	Possible	Likely	Possible	Possible							
Surface seepage													Possible	Likely	Likely	Likely	
Environmental health & safety							Likely	Likely	Possible	Possible	Possible	Possible	Possible	Likely			
Micro-seismicity											Possible	Possible					Likely
Remediation efforts	Possible					Possible	Possible	Likely	Possible				Possible	Possible	Possible	Possible	
Monetary transactions	Likely	Likely						Possible									
Impacts to other resources	Possible	Possible					Likely	Likely	Possible								
Legal disputes	Possible					Possible	Possible	Likely	Possible		Possible	Possible	Possible	Possible	Possible	Possible	Possible
Visibility and transparency	Likely	Likely				Possible	Likely	Likely	Possible		Possible	Possible	Possible	Possible	Possible	Possible	Possible

A Tailored Approach to Monitoring is Needed

- Site specific regulatory requirements
- Different storage strategies will require different parameters to assure performance
- Site specific geological conditions
  – Measurement quality and performance
- Site specific risks require different monitoring strategies

Potential for Detection Using Seismic Imaging

Two scenarios are examined to estimate amount of CO2 that may be released from leaking storage projects

Scenario	1 Mt CO_2/year			500 MW Power Plant 3.6 Mt CO_2/year		
Leakage Rate (% stored / year)	0.01	0.1	1	0.01	0.1	1
Leakage in 1 year (Mt)	0.0001	0.001	0.01	0.00036	0.0036	0.036
Leakage in 10 years (Mt)	0.0055	0.055	0.55	0.02	0.2	2.0
Leakage in 50 years (Mt)	0.128	1.2	12.8	.46	4.6	46

Myer et al., 2002: 10,000 tonnes (0.01 Mt)

Arts et al., 2004: Sleipner, 4000 tonnes (0.004 Mt)

White el al., 2004: Weyburn, 2500 tonnes (0.0025Mt)

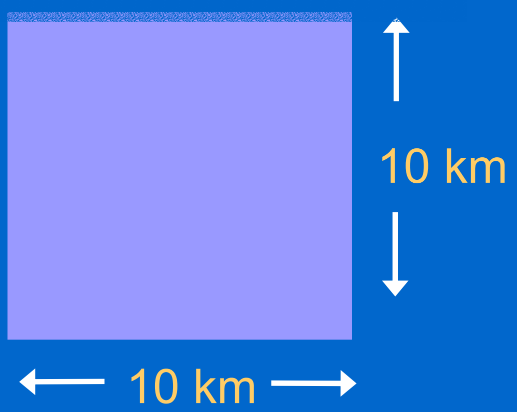
Probable

Possible

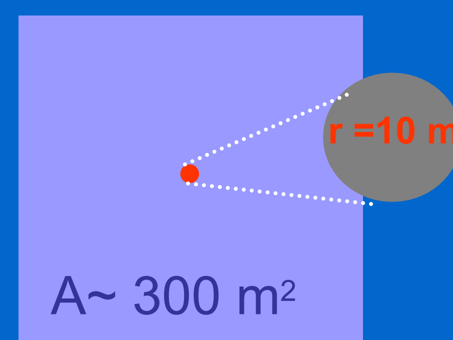
Uncertain

Example Seepage Scenarios

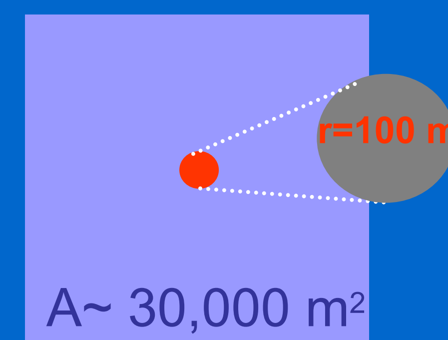
Footprint of CO_2 plume

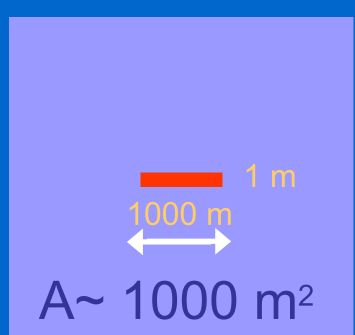


Seepage around a well

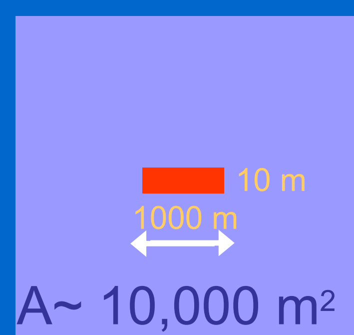


Seepage around a well





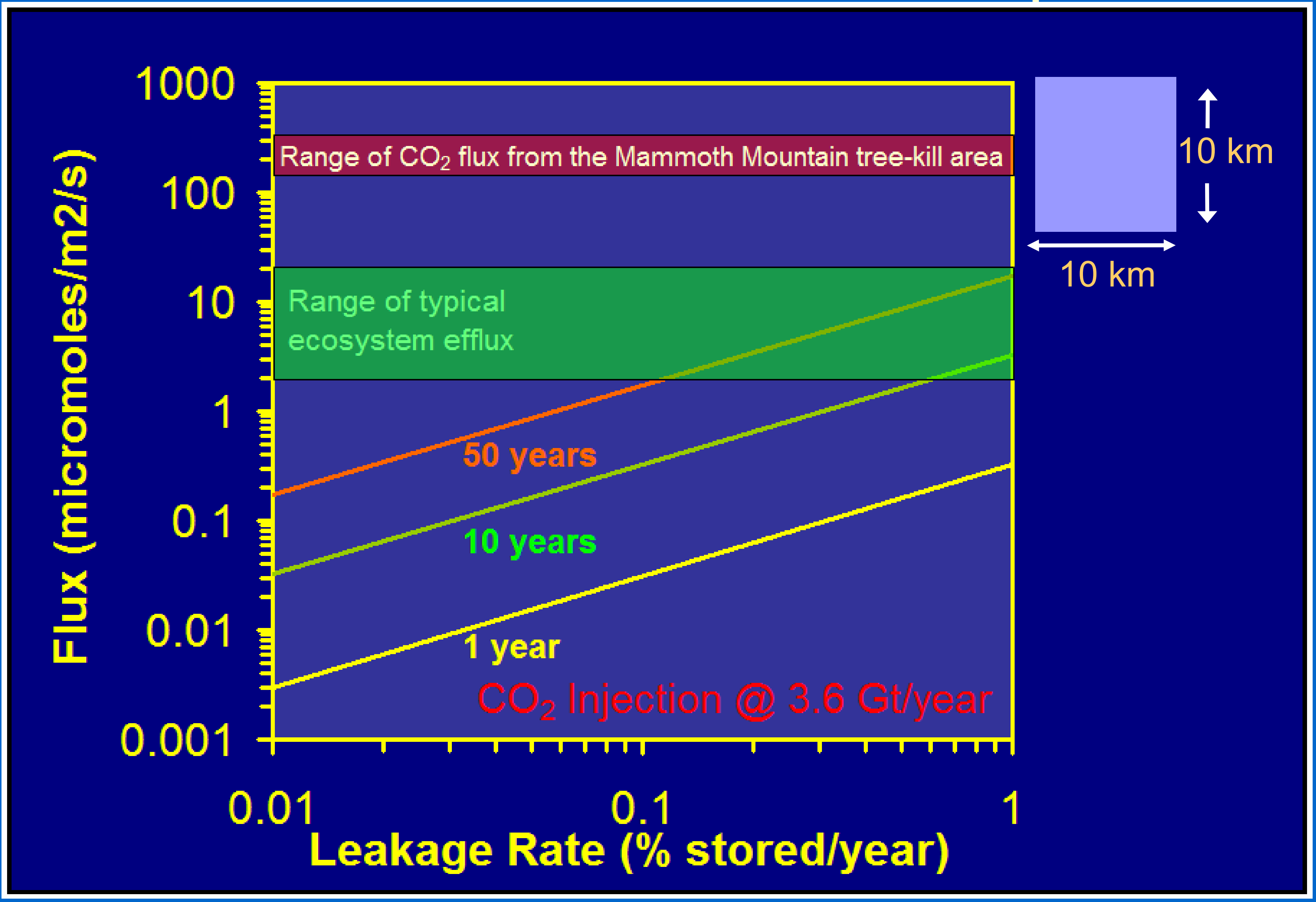
Seepage along a narrow fracture zone



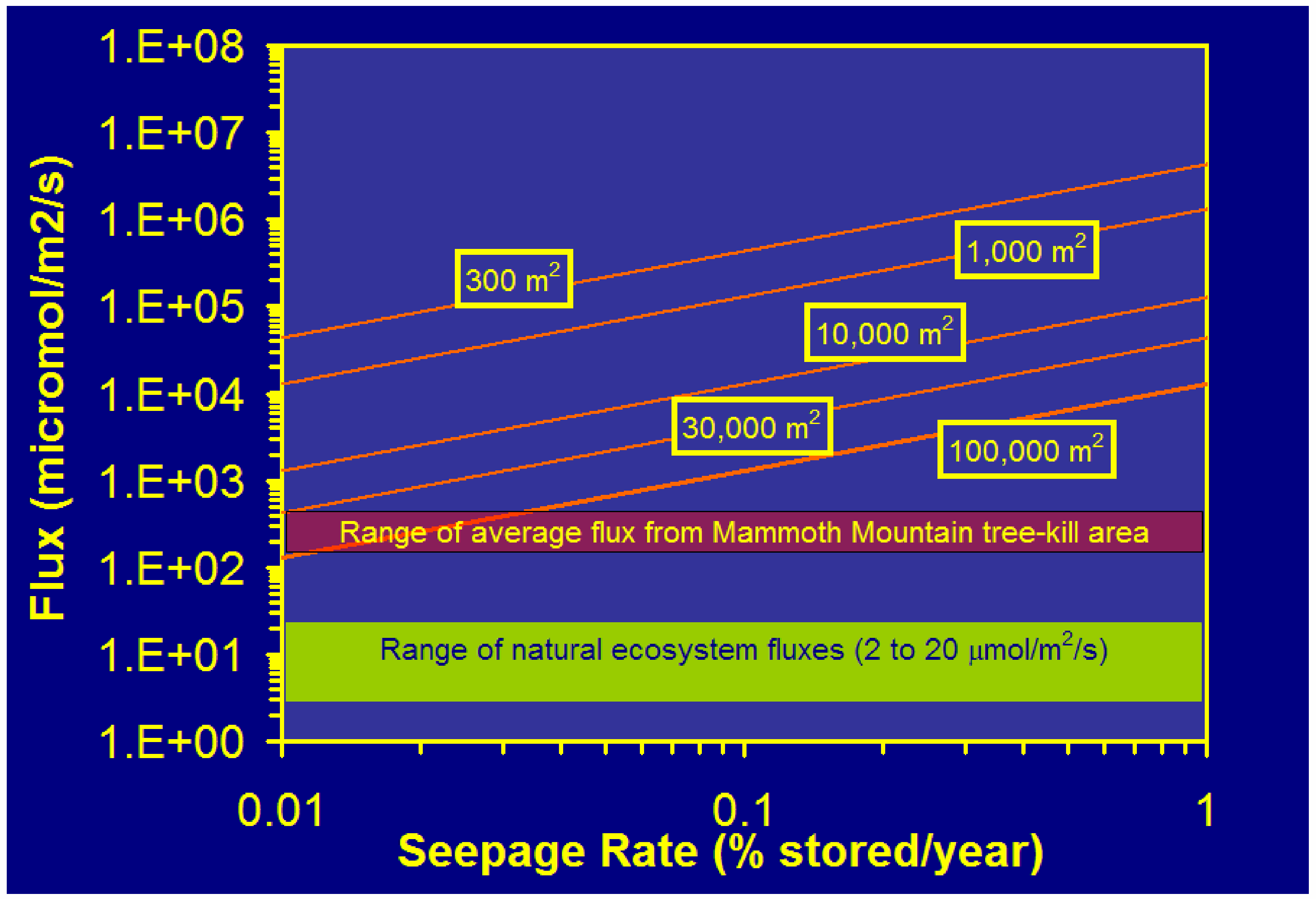
Seepage along a fault zone

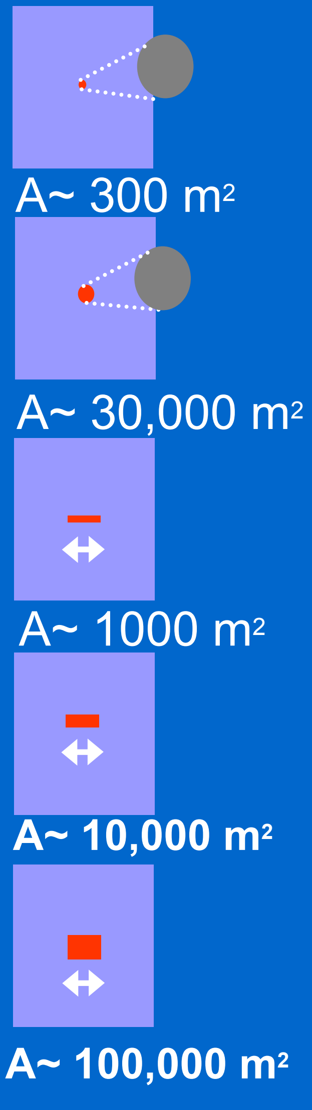
Seepage along a fault zone

Flux Distributed Over Footprint



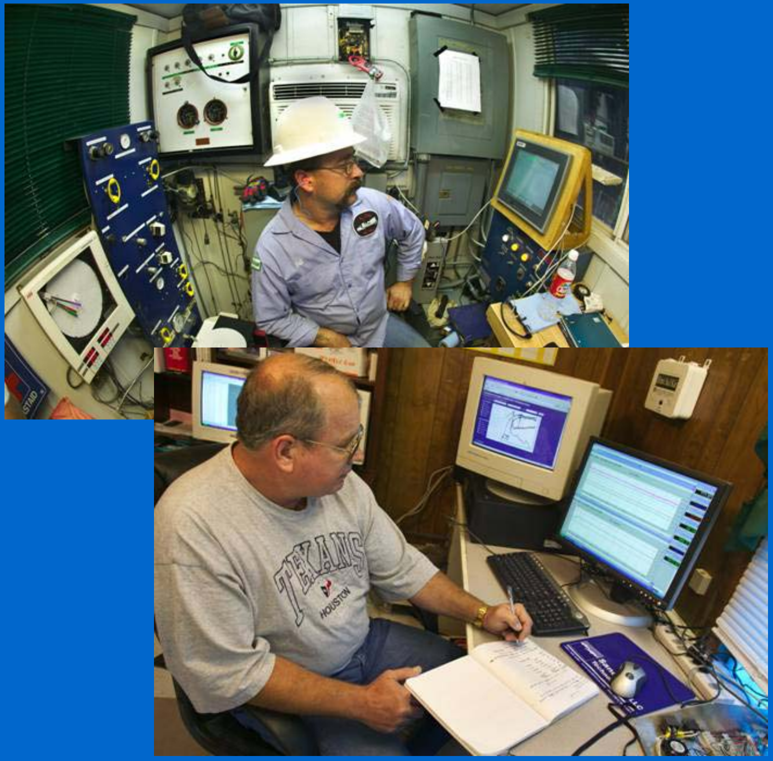
Seepage Fluxes Far Exceed Background





Conclusions

- Many monitoring options available
- Combinations of techniques will be needed
- Leaks are likely to fluxes far greater than background fluxes
- Detection of significant leaks (>0.01%/year) may be possible under many circumstances
- More demonstrations are needed



Monitoring Strategies and Cost Comparisons

Larry Myer
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

IEA / BP Monitoring Workshop

Santa Cruz, CA

November 8-9, 2004

Topics

- Hypothetical monitoring scenarios
- Suggested monitoring packages
- Unit costs
- Comparison of costs
- Implications of longer-term monitoring
- Conclusions

Life Cycle of a Storage Project and Monitoring Requirements

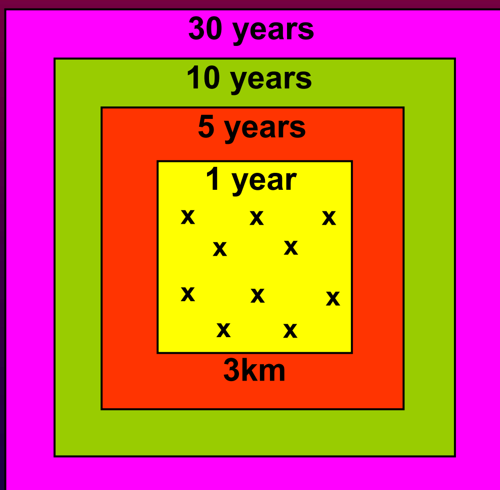
Pre-operation Phase	Operation Phase	Closure Phase	Post-closure Phase
• Site character-ization • Risk assessment • Establish monitoring baseline	• CO_2 injection • Surface facilities and injection rates monitored • Track location of plume • Ensure safe operations • Detect and prevent environmental impacts	• CO_2 injection stops • Surface facilities removed; wells abandoned • Confirm long-term security of storage project	• Completed records given to regulatory authorities • Monitoring needed only if long term storage security not established

0 5 35 55 - 85

Approximate Time-Line (Years)

Monitoring Scenarios

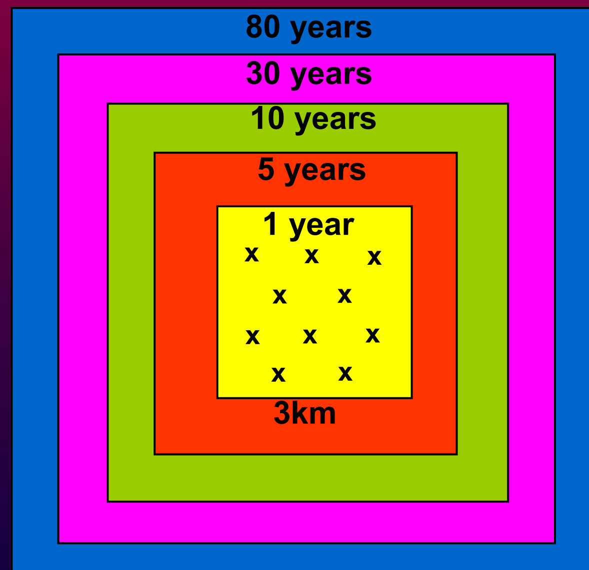
Saline Formation HRG[1]



← 14 km →

50 years
closure monitoring

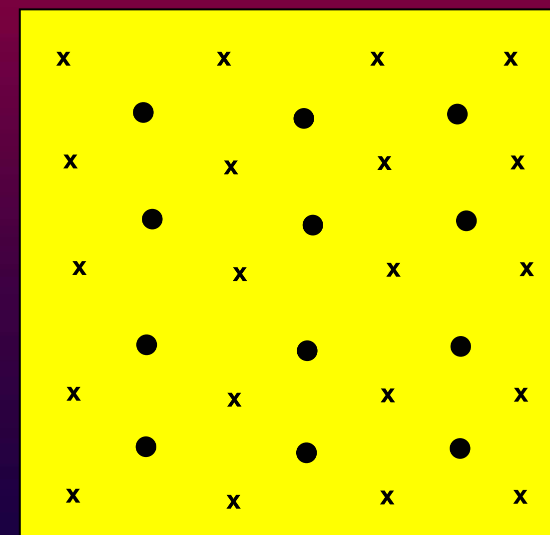
Saline Formation LRG[2]



← 19 km →

50 years
closure monitoring

EOR



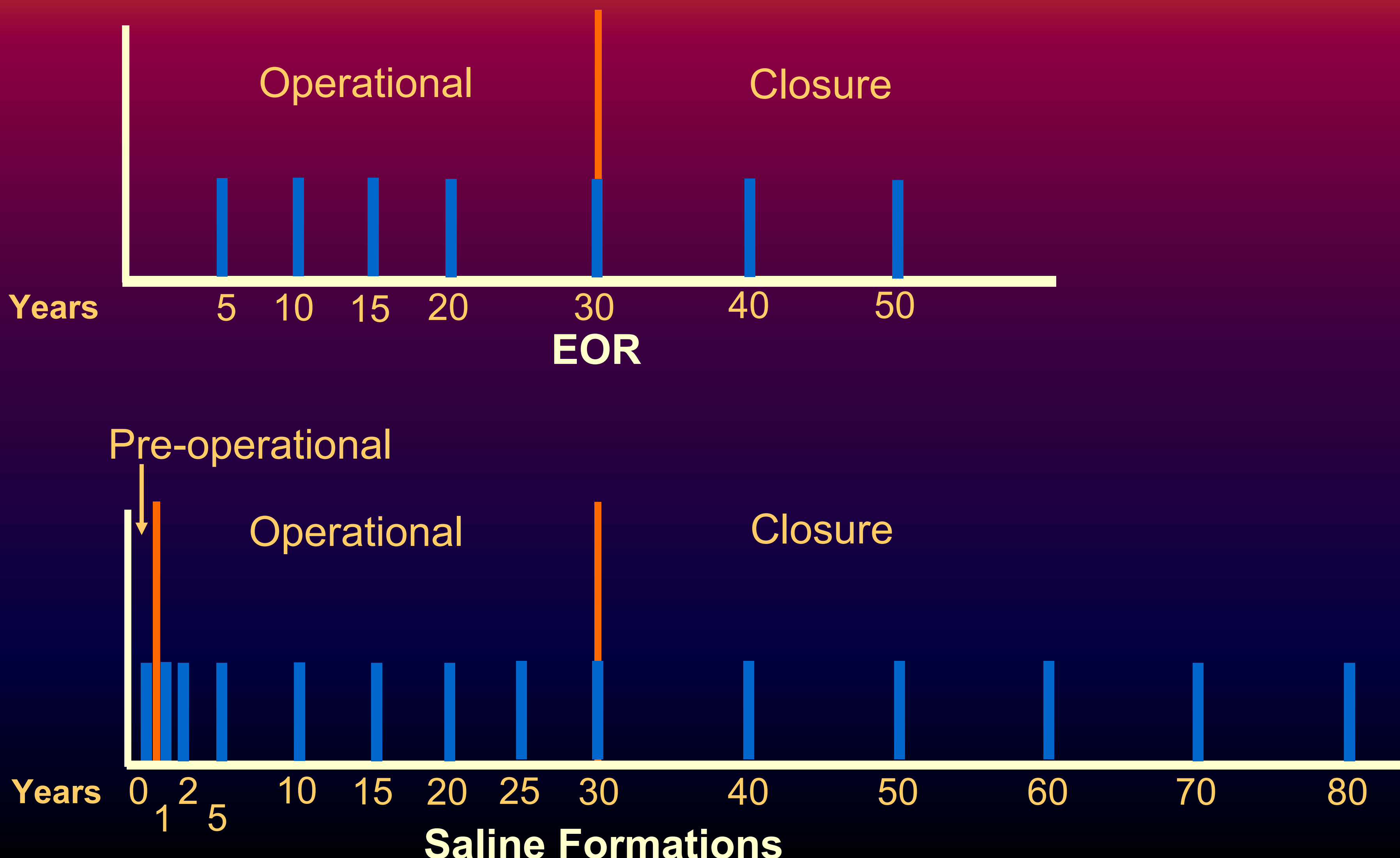
← 18 km →

20 years
Closure monitoring

[1] High residual gas saturation
[2] Low residual gas saturation

Operational period: 30 years injection @ 8.6 Mt/year totaling 258Mt CO_2

Monitoring Scenarios: Frequency of Geophysical Measurement



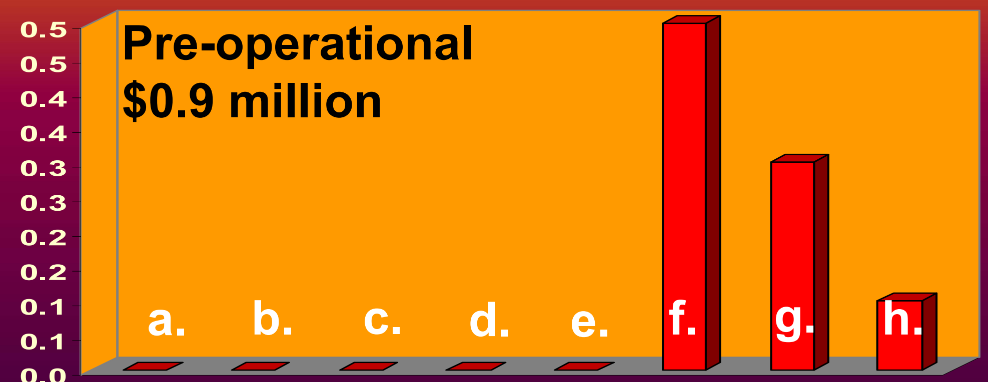
Components of the Basic and Enhanced Monitoring Packages

	Basic Monitoring Package	Additional Measurements for Enhanced Monitoring Package
Pre-operational Monitoring	• Well logs • Wellhead pressure • Formation pressure • Injection and production rate testing • Seismic survey • Atmospheric CO_2 monitoring	• Gravity survey • Electromagnetic survey • CO_2 flux monitoring • Pressure and water quality above the storage formation
Operational Monitoring	• Wellhead pressure • Injection and production rates • Wellhead atmospheric CO_2 monitoring • Microseismicity • Seismic surveys	• Well logs • Gravity survey • Electromagnetic survey • Continuous CO_2 flux monitoring at 10 stations • Pressure and water quality above the storage formation
Closure Monitoring	• Seismic survey	• Gravity survey • Electromagnetic survey • Continuous CO_2 flux monitoring at 10 stations • Pressure and water quality above the storage formation • Wellhead pressure monitoring for 5 yeas, after which time the wells will be abandoned

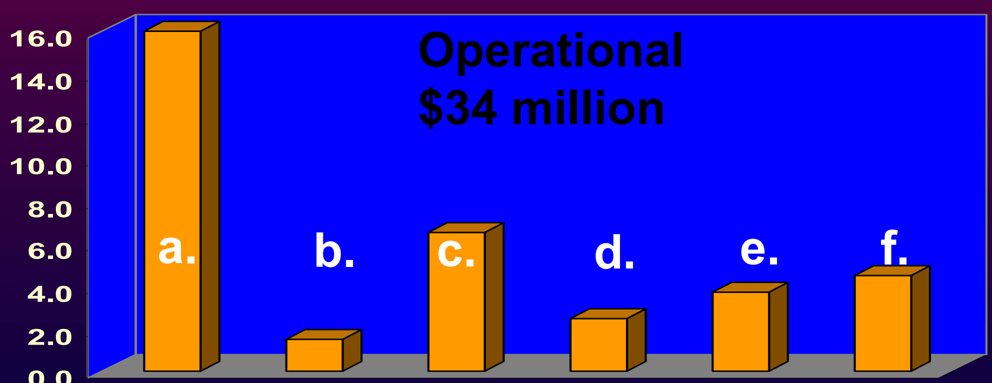
Unit Costs

- Seismic
  - $10,000/km^2 & $1000/km^2 for interpretation
- Gravity and EM (1 station per km^2)
  - $1000 per station
- Surface flux (10 stations)
  - $70,000 set-up per station
  - $10,000 per station for interpretation
- Casing integrity logs
  - $20,000 per injection well per year
- CO_2 concentrations at wellhead
  - $10,000 per well installation
- Microseismicity
  - $40,000 per station & $75,000 per year
- Pressure and groundwater samples above the storage formation
  - $950,000 for well
  - $45,000 for baseline chemistry
  - $5000 for pressure transducer
  - $1,500/sample, taken monthly

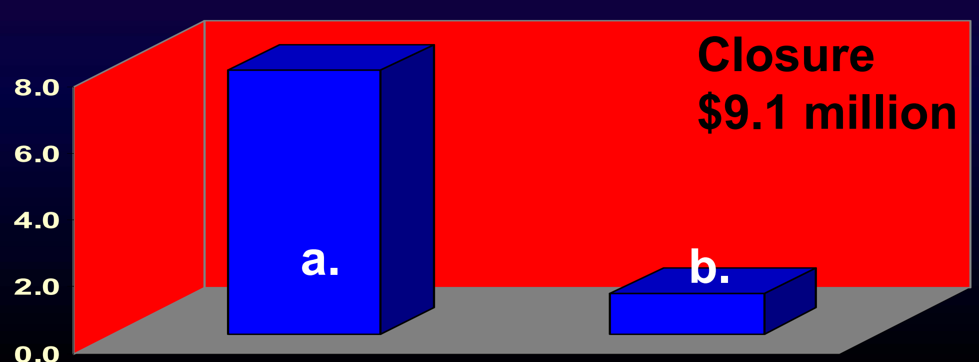
Monitoring Cost for EOR Scenario



a. Well logs
b. Wellhead pressure
c. Formation pressure
d. Injection and production rate testing
e. Seismic survey
f. Microseismicity baseline
g. Baseline atmospheric CO_2 monitoring
h. Management (15%)

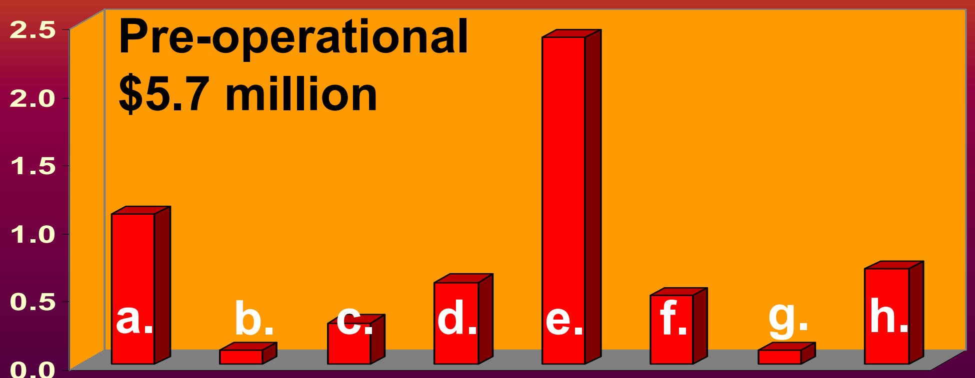


a. Seismic survey
b. Wellhead pressure
c. Injection and production rates
d. Wellhead atmospheric CO_2 concentration
e. Microseismicity
f. Management (15%)

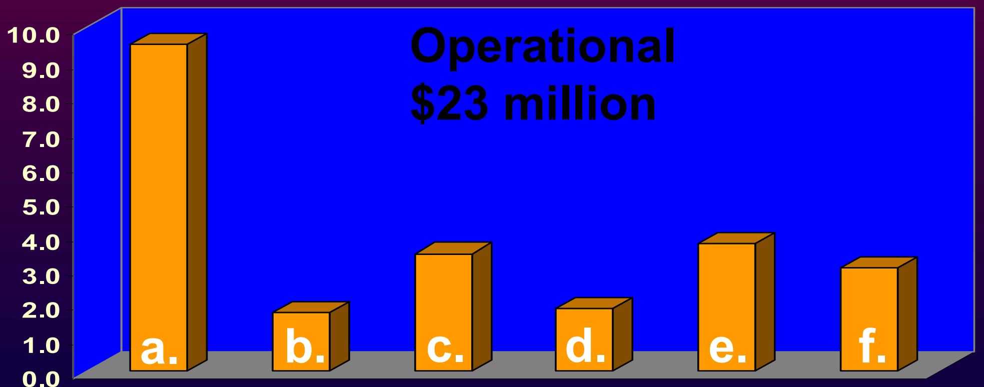


a. Seismic survey
b. Management (15%)

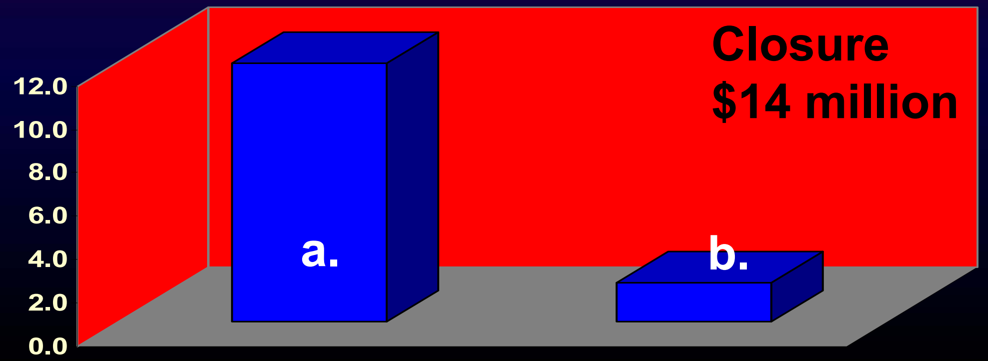
Monitoring Cost for Saline Formation (HRG)



a. Well logs
b. Wellhead pressure
c. Formation pressure
d. Injection and production rate testing
e. Seismic survey
f. Microseismicity baseline
g. Baseline atmospheric CO_2 monitoring
h. Management (15%)

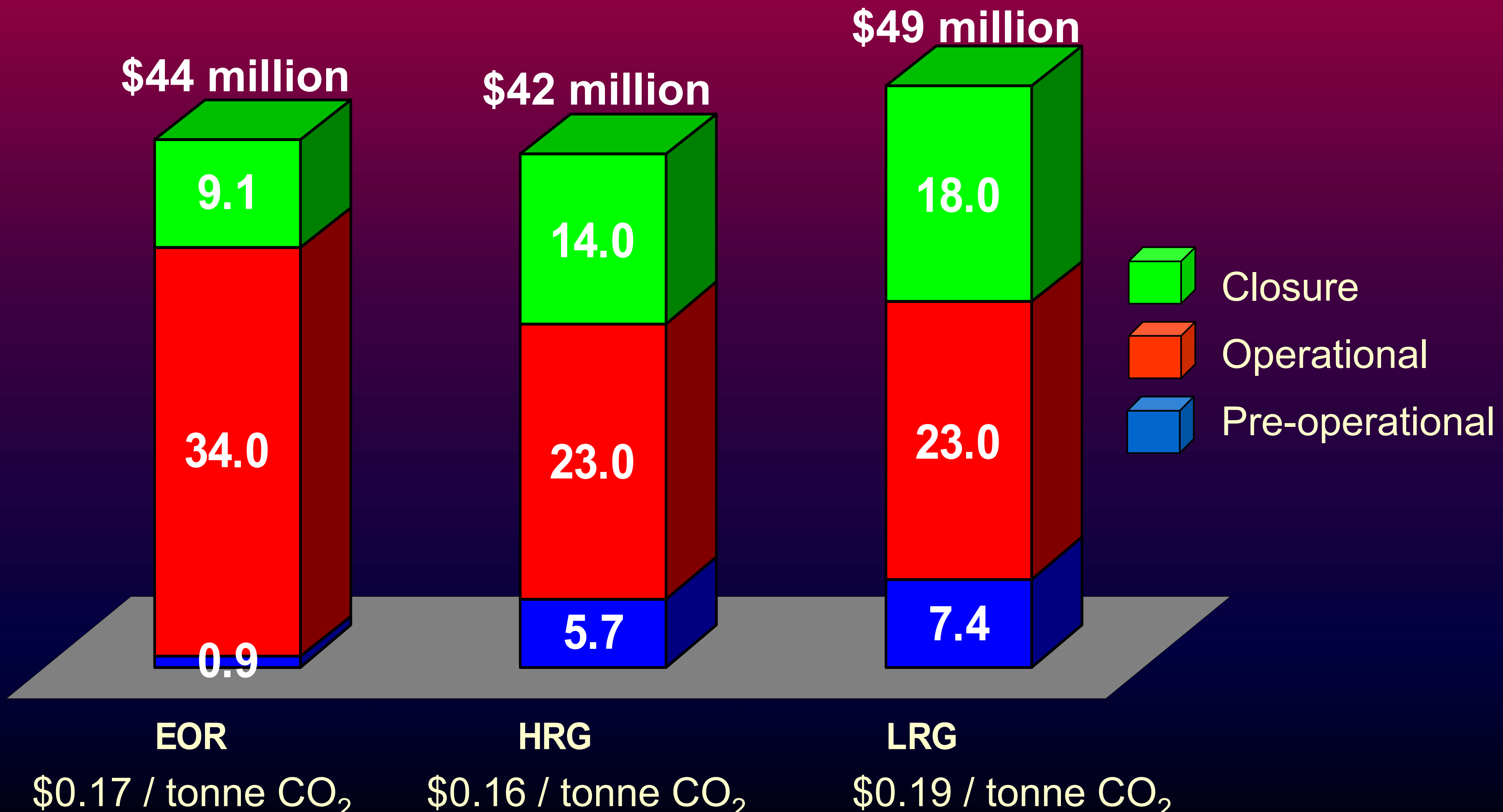


a. Seismic survey
b. Wellhead pressure
c. Injection and production rates
d. Wellhead atmospheric CO_2 concentration
e. Microseismicity
f. Management (15%)

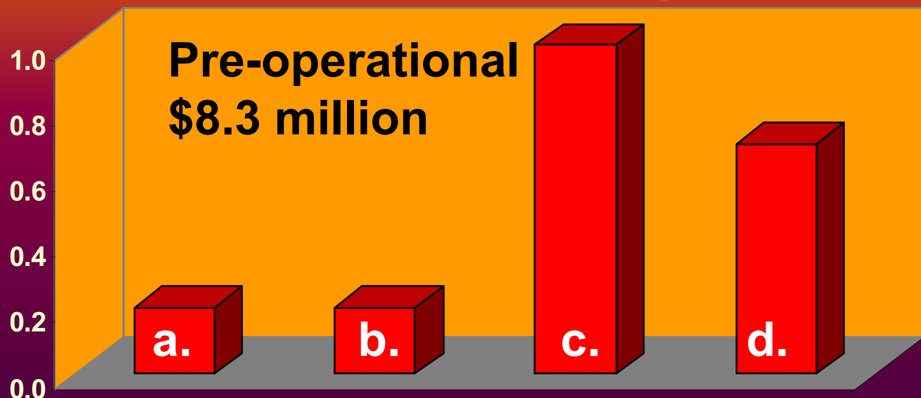


a. Seismic survey
b. Management (15%)

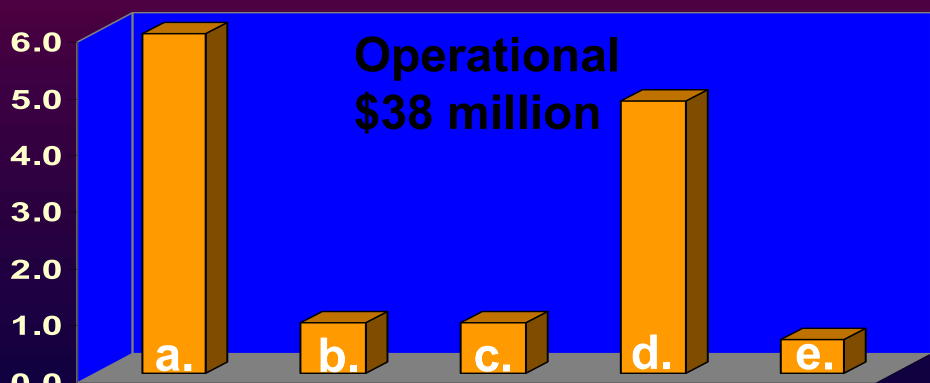
Comparison of Monitoring Costs



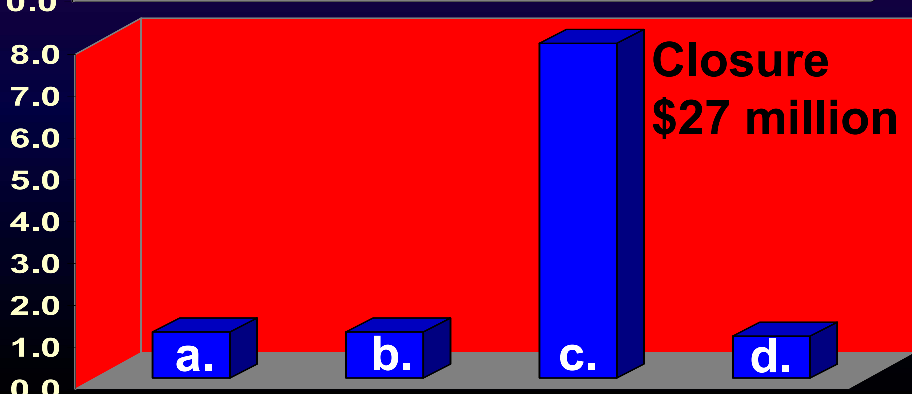
Cost for Enhanced Monitoring Program (Saline HRG)



a. Baseline EM survey
b. Baseline gravity survey
c. Pressure and water quality above the storage formation
d. Baseline CO_2 flux

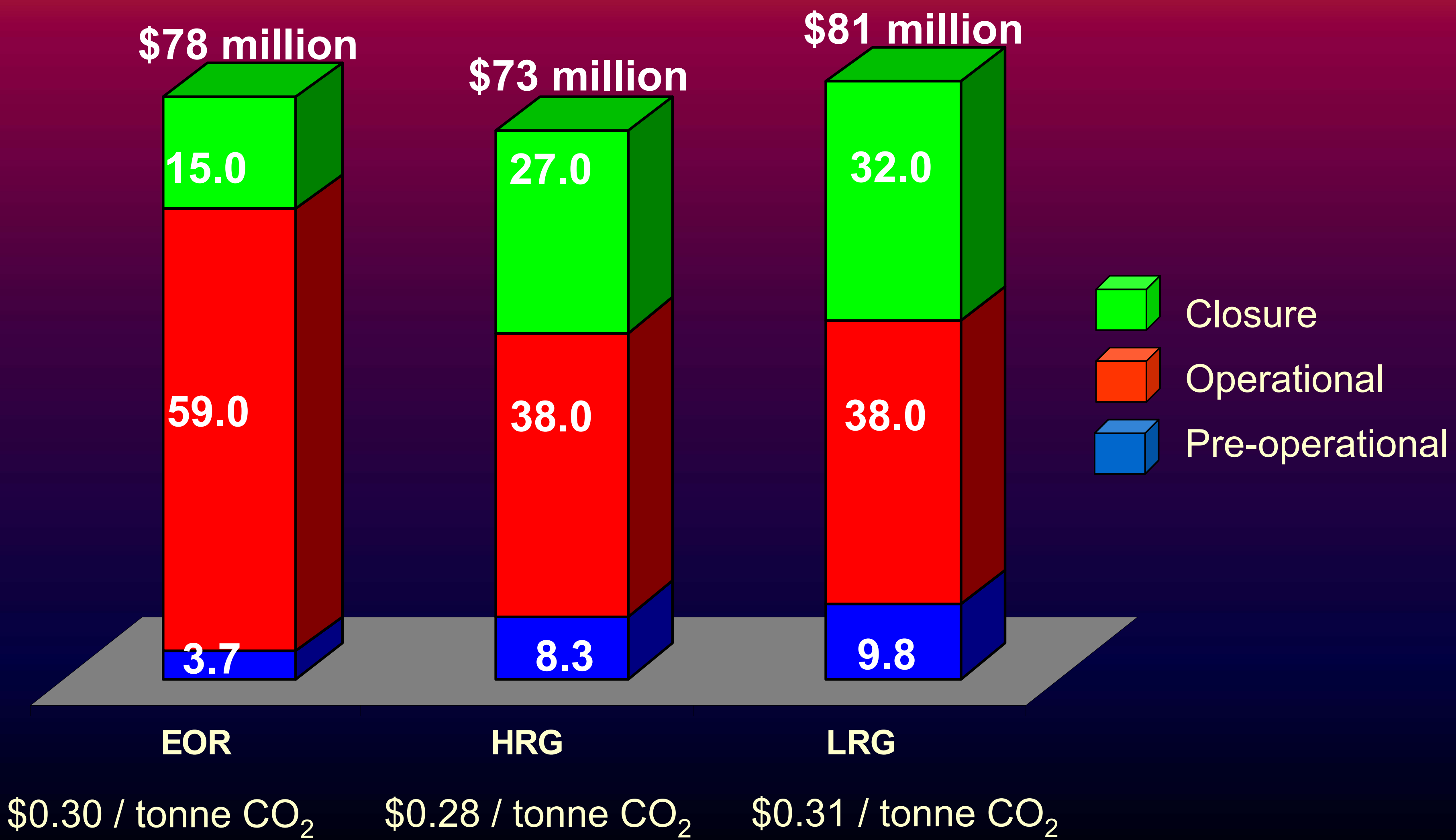


a. Casing integrity logs
b. EM surveys
c. Gravity surveys
d. CO_2 flux monitoring
e. Pressure and water quality above the storage formation

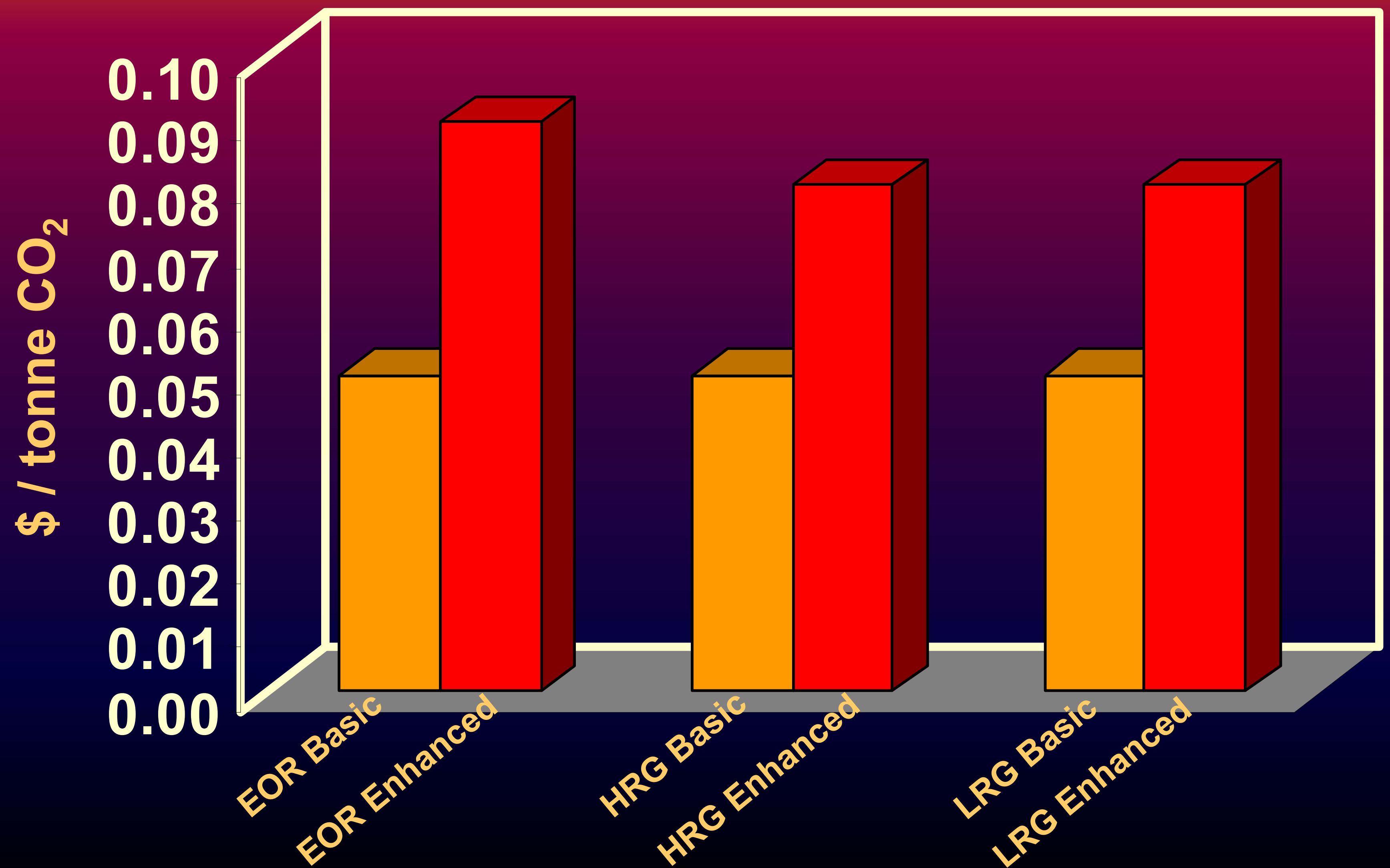


a. EM surveys
b. Gravity surveys
c. CO_2 flux monitoring
d. Pressure and water quality above the storage formation

Comparison of Enhanced Monitoring Costs



Discounted Costs (@10%)



Implications of Longer-term Monitoring

- 1000 year period
- Repeat seismic surveys every 10 years
- Basic monitoring package
  - Intergenerational discount rate of 1% after 30 years
  - $0.053/tonne increases to $0.059/tonne
- 10% increase in cost
- Non-financial issues
  - Responsibility for monitoring
  - Oversight and record keeping
  - Responsibility for remediation

Conclusions

- Discounted costs for monitoring range from $0.05 to $0.10 per tonne CO_2
- Enhanced monitoring package available at additional cost of 40-60% over basic package
- Seismic surveys are major cost driver
  - No obvious substitute at this time
  - Sleipner and Weyburn demonstrate effectiveness
- Monitoring is a small part of overall CCS costs ($30-$70 per tonne) and storage costs ($2-$12 per tonne)

CO_2 Fluxes to the Atmosphere, and in Soil Gas: Detection of a Deep Source Masked by Near-surface Noise

Ronald W. Klusman

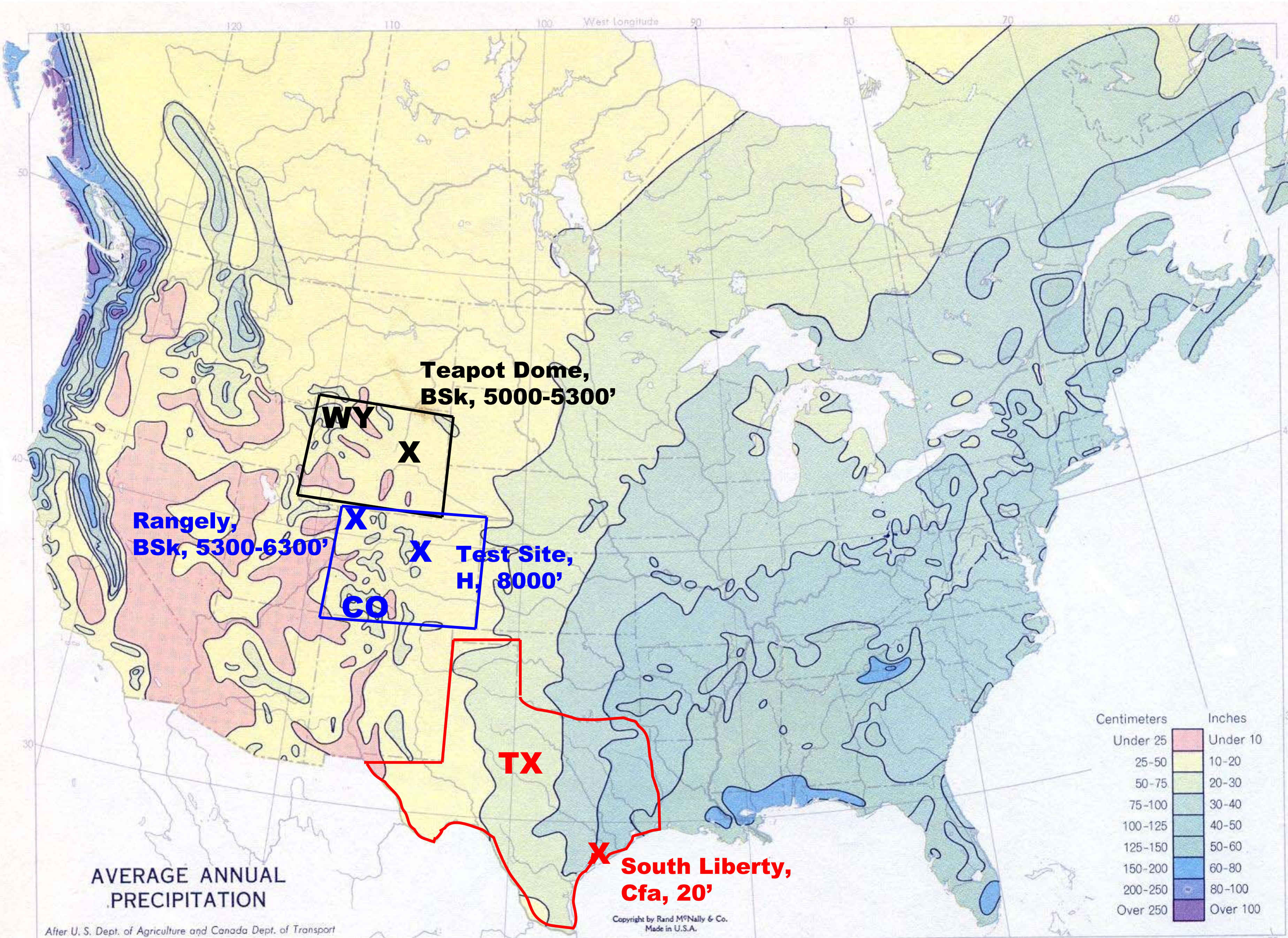
Colorado School of Mines and

Research Associate at National Energy Technology Laboratory

and

Brian R. Strazisar

National Energy Technology Laboratory


West Longitude
130
120
110
100
90
80
70
60
50
40
30
Teapot Dome,
BSk, 5000-5300’
WY
X
Rangely,
BSk, 5300-6300’
X
X
Test Site,
H, 8000’
CO
TX
X
South Liberty,
Cfa, 20’
Centimeters
Inches
Under 25
Under 10
25-50
10-20
50-75
20-30
75-100
30-40
100-125
40-50
125-150
50-60
150-200
60-80
200-250
80-100
Over 250
Over 100
AVERAGE ANNUAL
PRECIPITATION
After U. S. Dept. of Agriculture and Canada Dept. of Transport
Copyright by Rand McNally & Co.
Made in U.S.A.

IMPORTANCE OF CO_2 AND CH_4

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

PROBLEMS IN MONITORING RESEARCH

- **Large, open system,**
- **Dynamic, where “equilibrium” is only occasionally approximated,**
- **Systematic variation on at least two time scales and possibly two spatial scales,**
- **Searching for a small, deep-sourced signal in the presence of substantial near-surface noise,**
- **An understanding of the noise is essential.**

VARIOUS SAMPLE TYPES AND MEASUREMENTS

- CO_2 and CH_4 fluxes from soil to atmosphere with triplicate chambers 10 m apart, + flux is upward, - flux is downward,
- $\delta^{13}C$ for CO_2 in final chamber sample,
- CO_2 and CH_4 in soil gas at depths of 30 cm, 60 cm, and 100 cm,
- $\delta^{13}C$ for CO_2 in soil gas at all three depths,
- $\delta^{13}C$ for CO_2 in an atmosphere sample.

ANALYTICAL METHODS

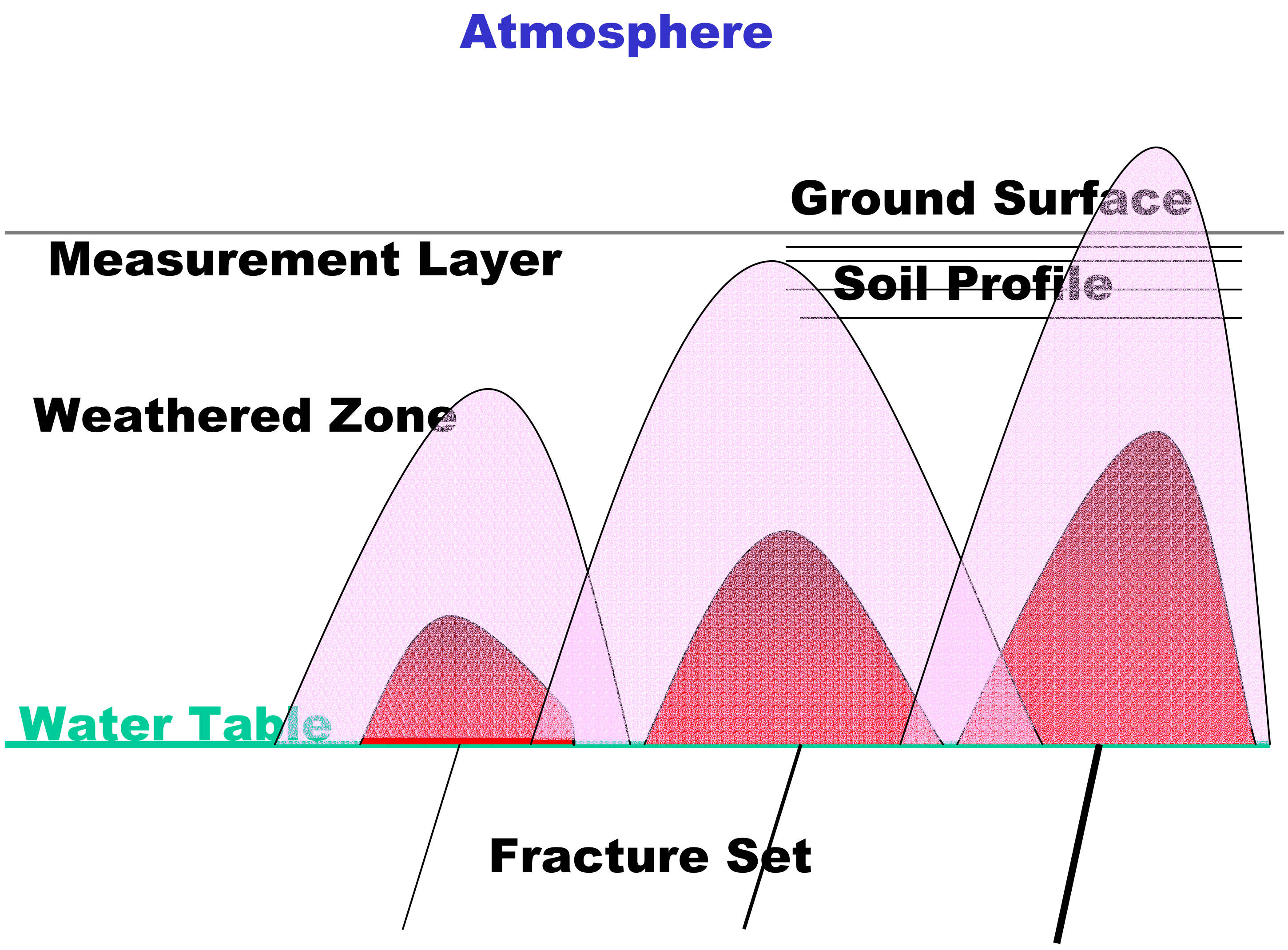
- **CO_2 under flux chambers – Field portable infrared spectrometry,**
- **CO_2 in soil gas – Laboratory GC with TCD or methanation of CO_2,**
- **CH_4 from flux chambers and in soil gas – Laboratory GC with FID,**
- **Stable carbon isotopes – Isotope ratio mass spectrometry (IRMS),**
- **Carbon-14 – Accelerator mass spectrometry (AMS).**

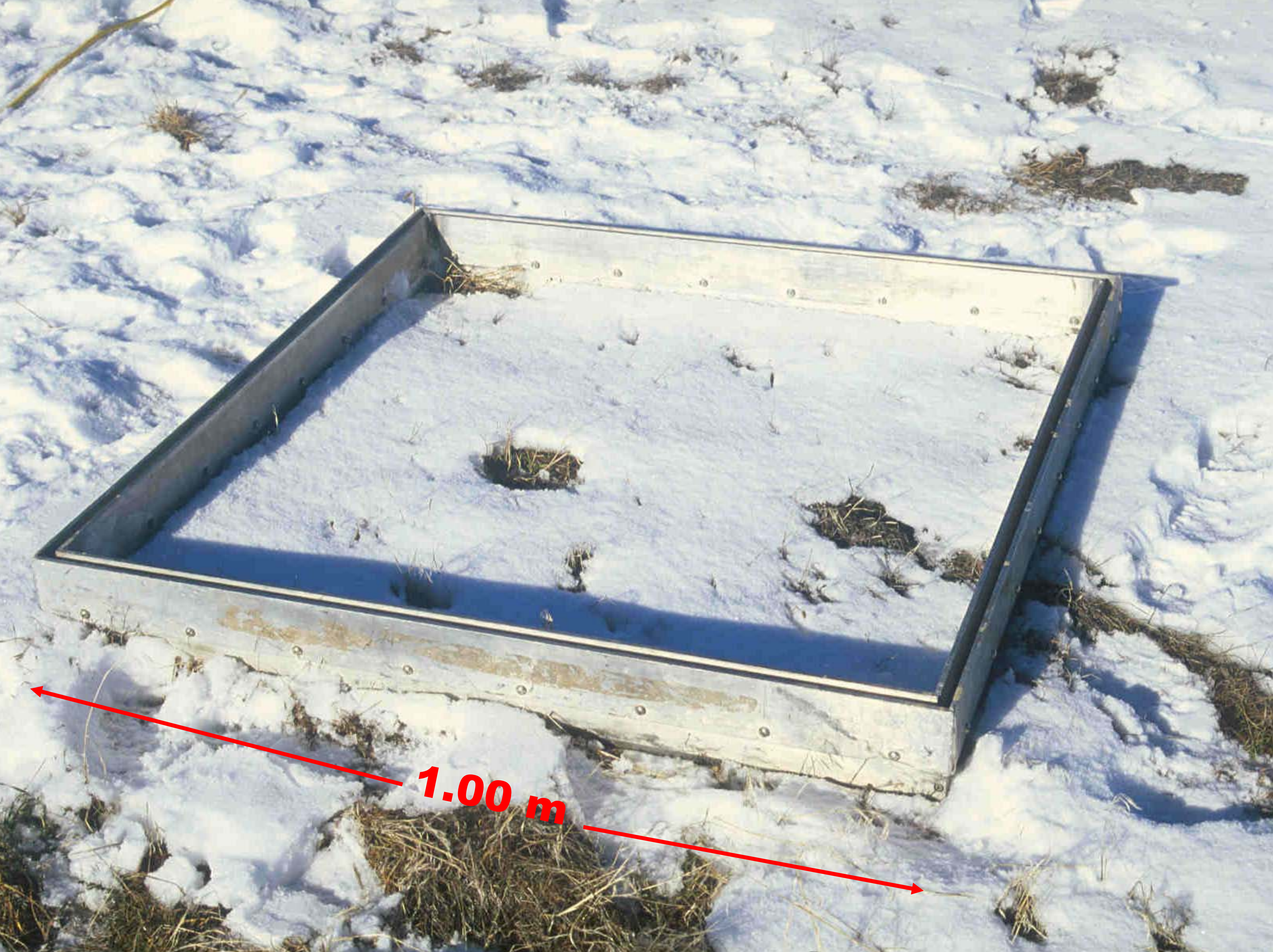
$$\delta_X = \frac{R_X - R_{std}}{R_{std}}$$

$R_X = {}^{13}C/{}^{12}C$ or ${}^{18}O/{}^{16}O$ or ${}^{2}H/{}^{1}H$

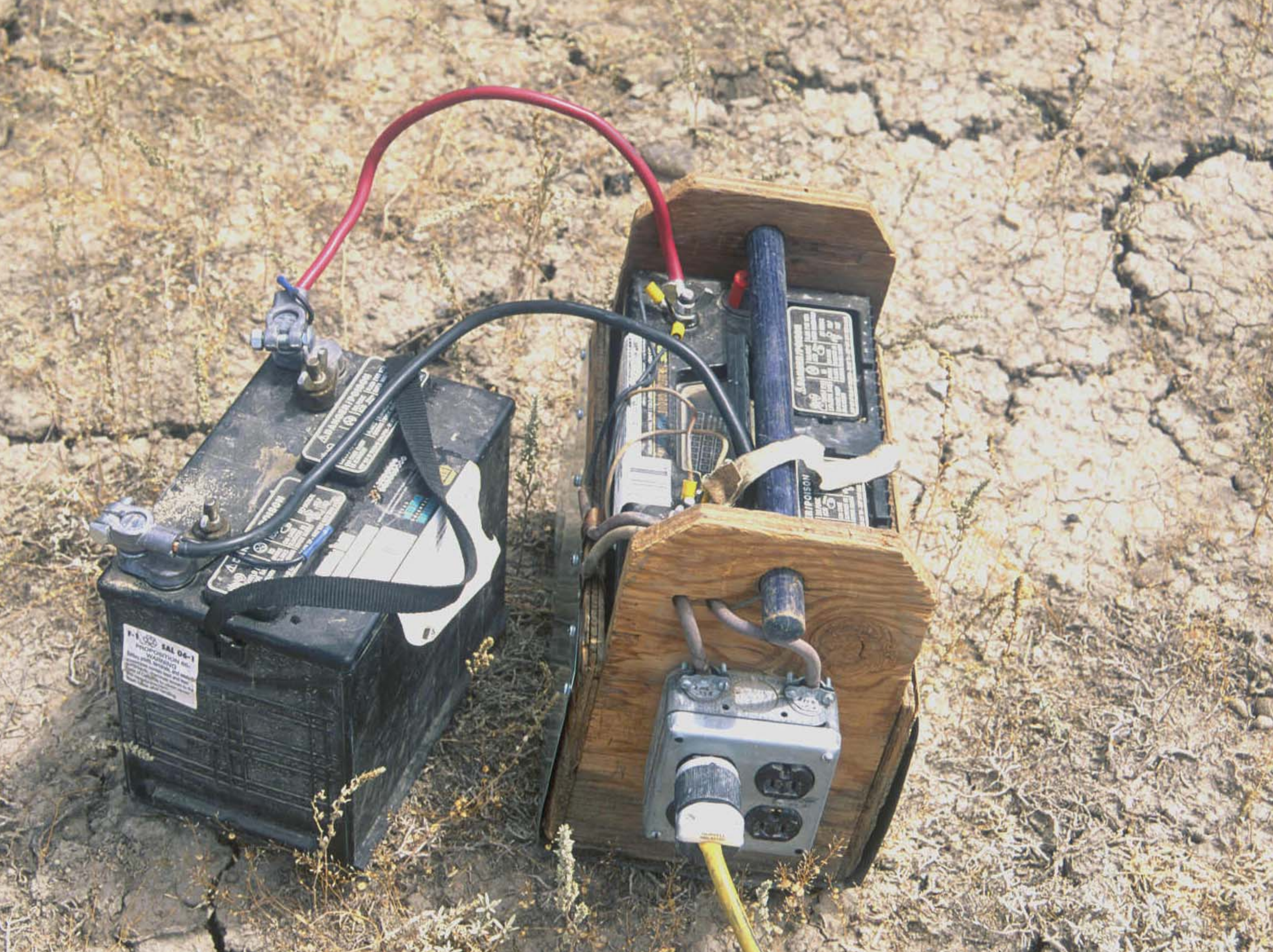
$$\delta_{samp} = \left[\frac{R_{samp}}{R_{std}} - 1\right] \cdot 1000$$

where "del" is parts per thousand, permil, ‰


Atmosphere
Ground Surface
Measurement Layer
Soil Profile
Weathered Zone
Water Table
Fracture Set

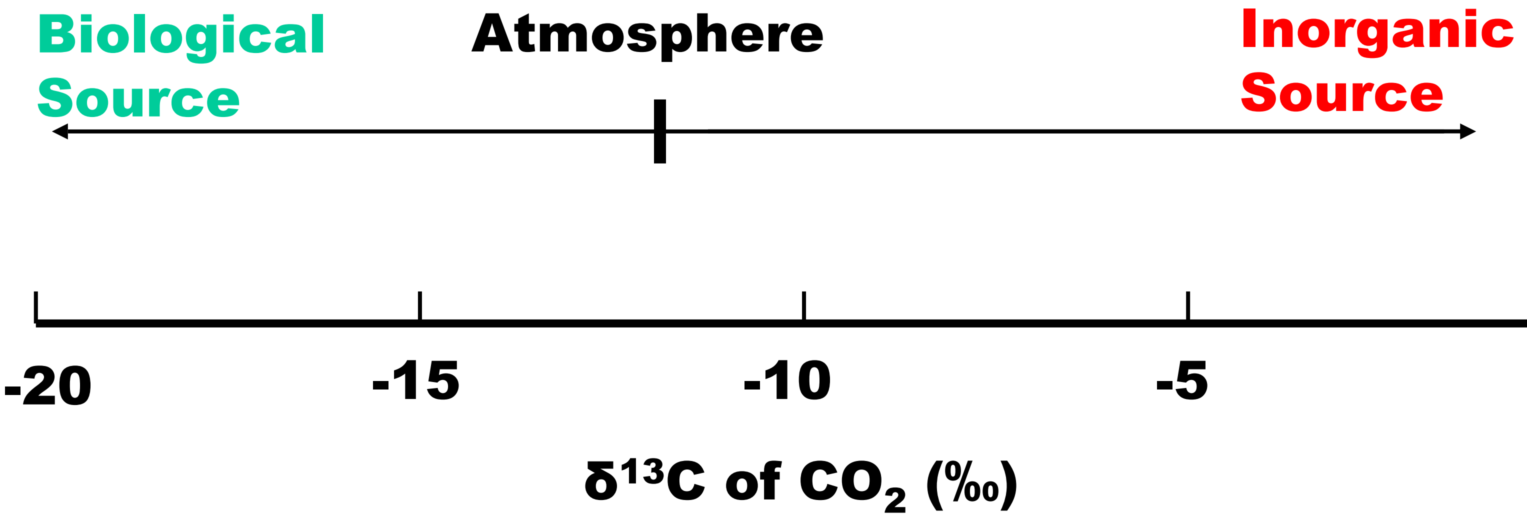

1.00 m


LI-7000 CO_2/H_2O Analyzer

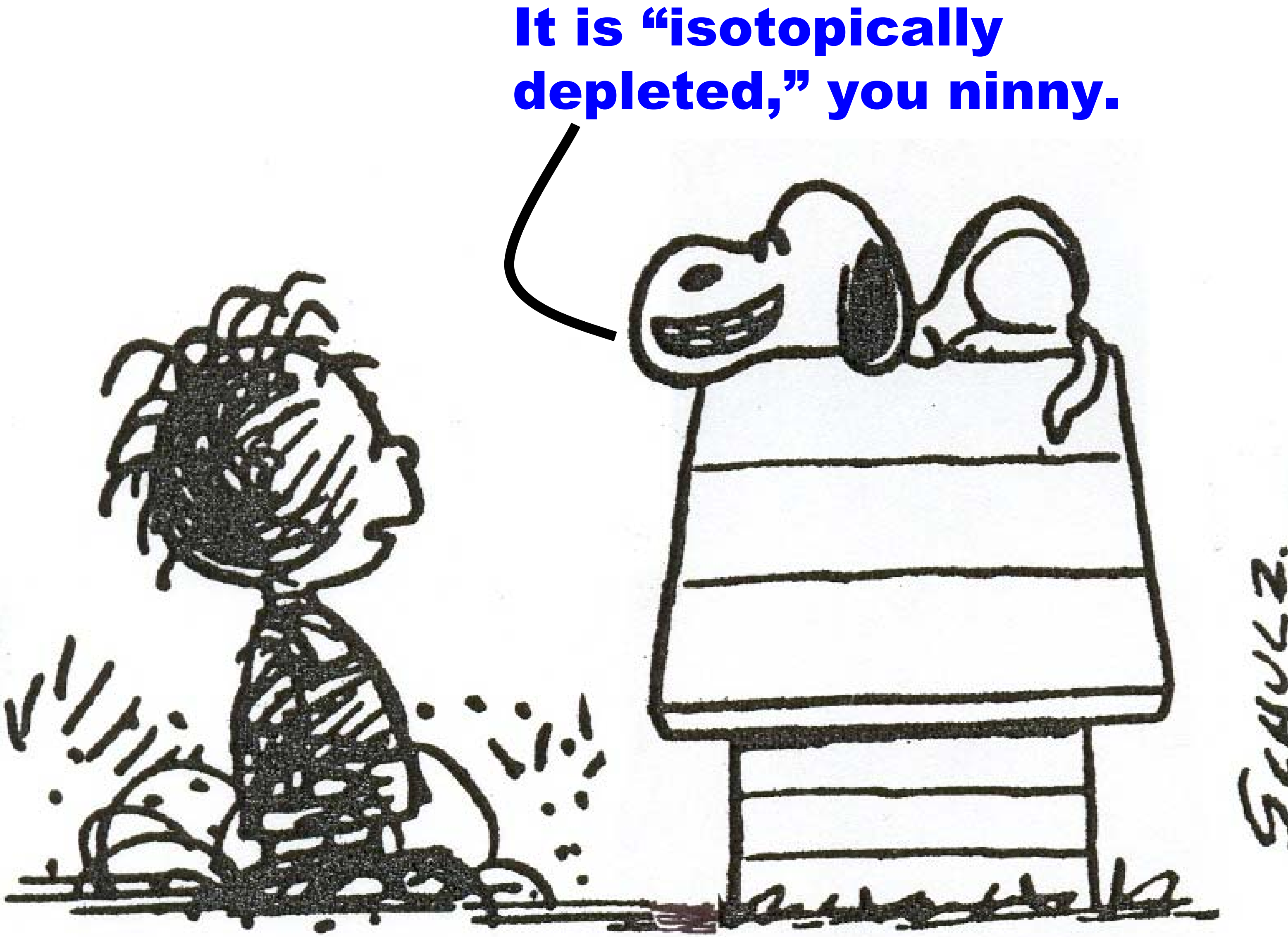

SAL 06-1
WARNING


72X 30mL
2
8
Alltech

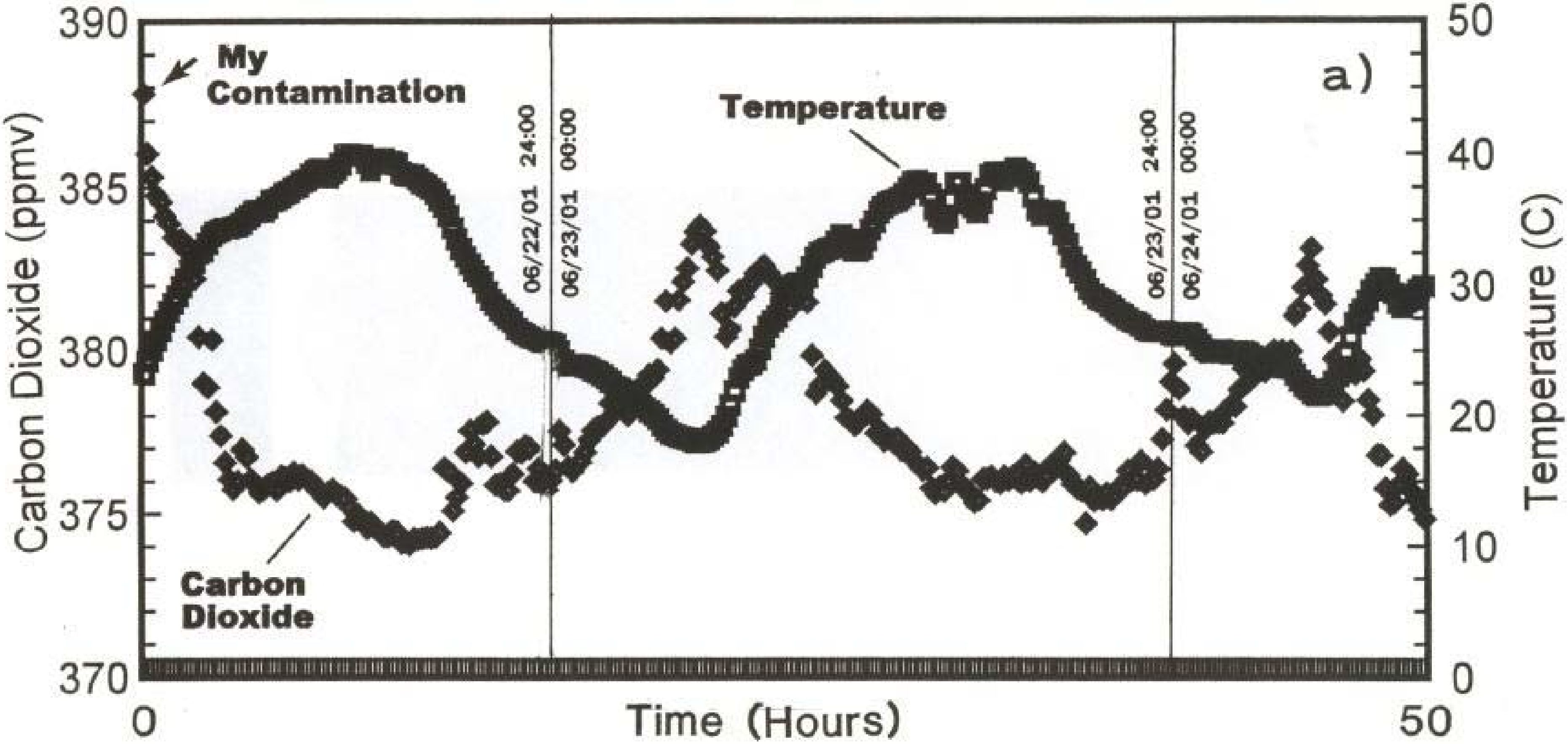
SIMPLIFIED ISOTOPIC SHIFT MODEL



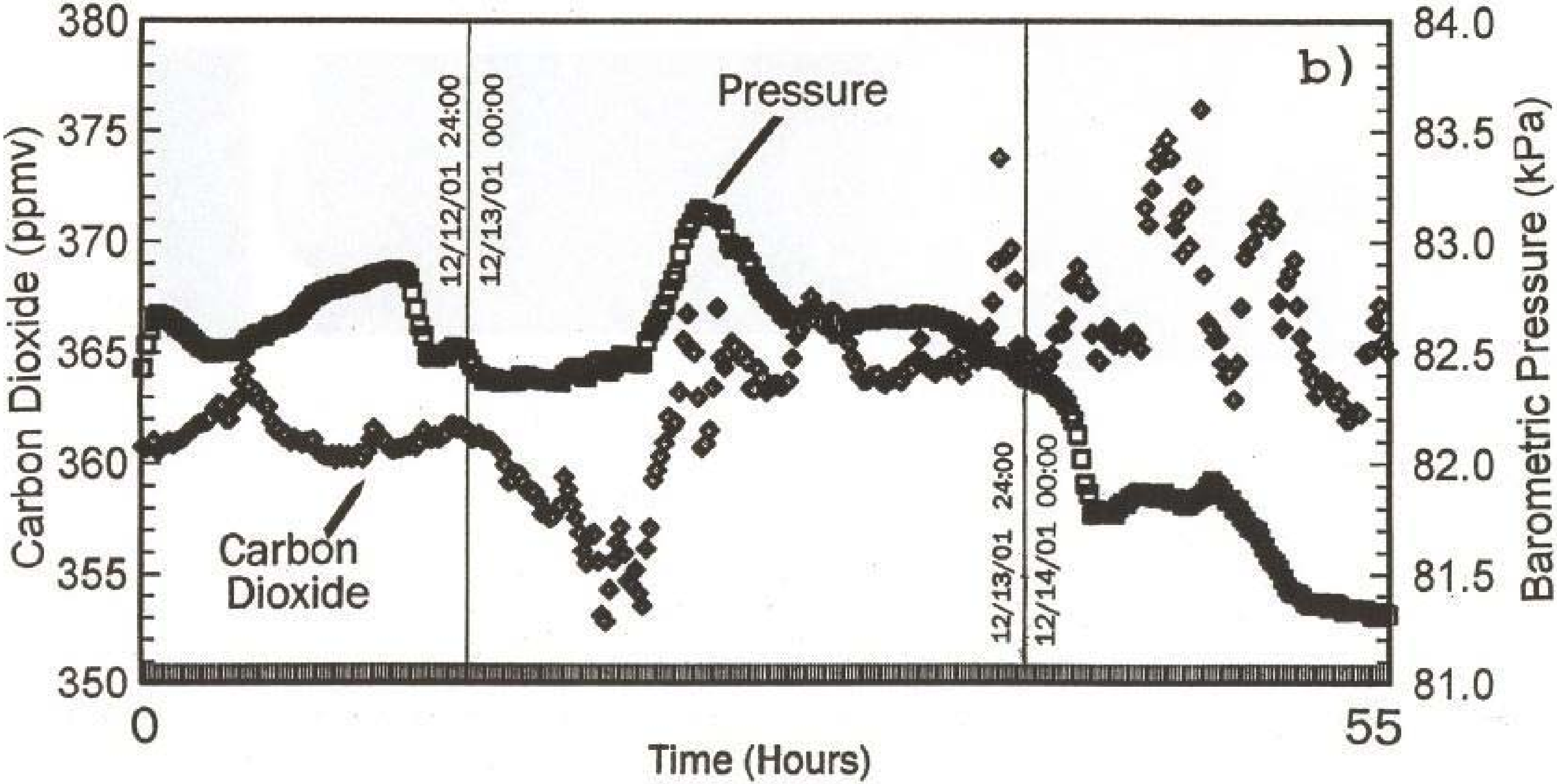
I try to do good research, but it is necessary to work in the dirt, and live in this cloud of isotopically light CO_2.


It is “isotopically depleted,” you ninny.
SCHULZ.

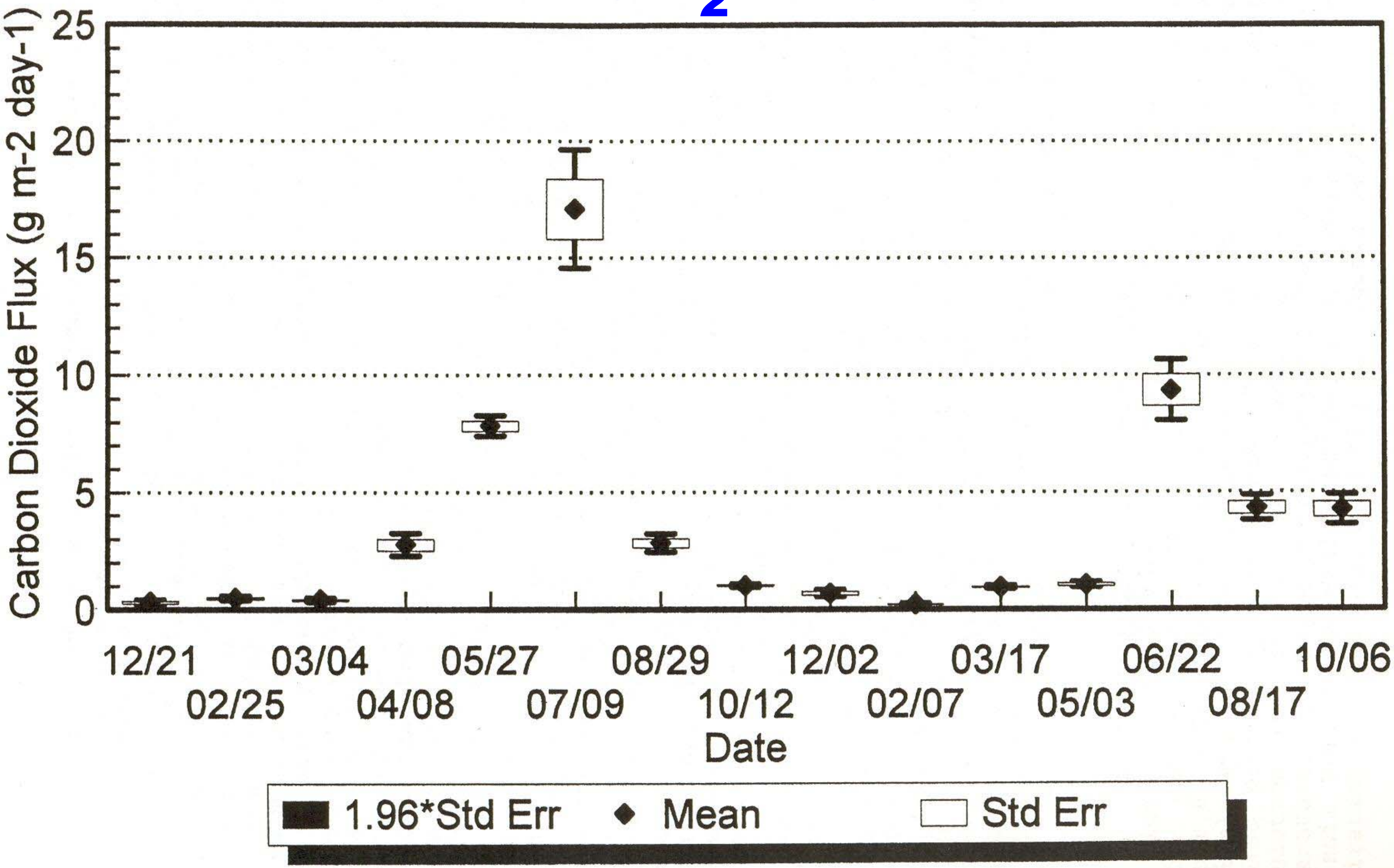
RANGELY ATMOSPHERIC CO_2
06/22/2001 TO 06/24/2001



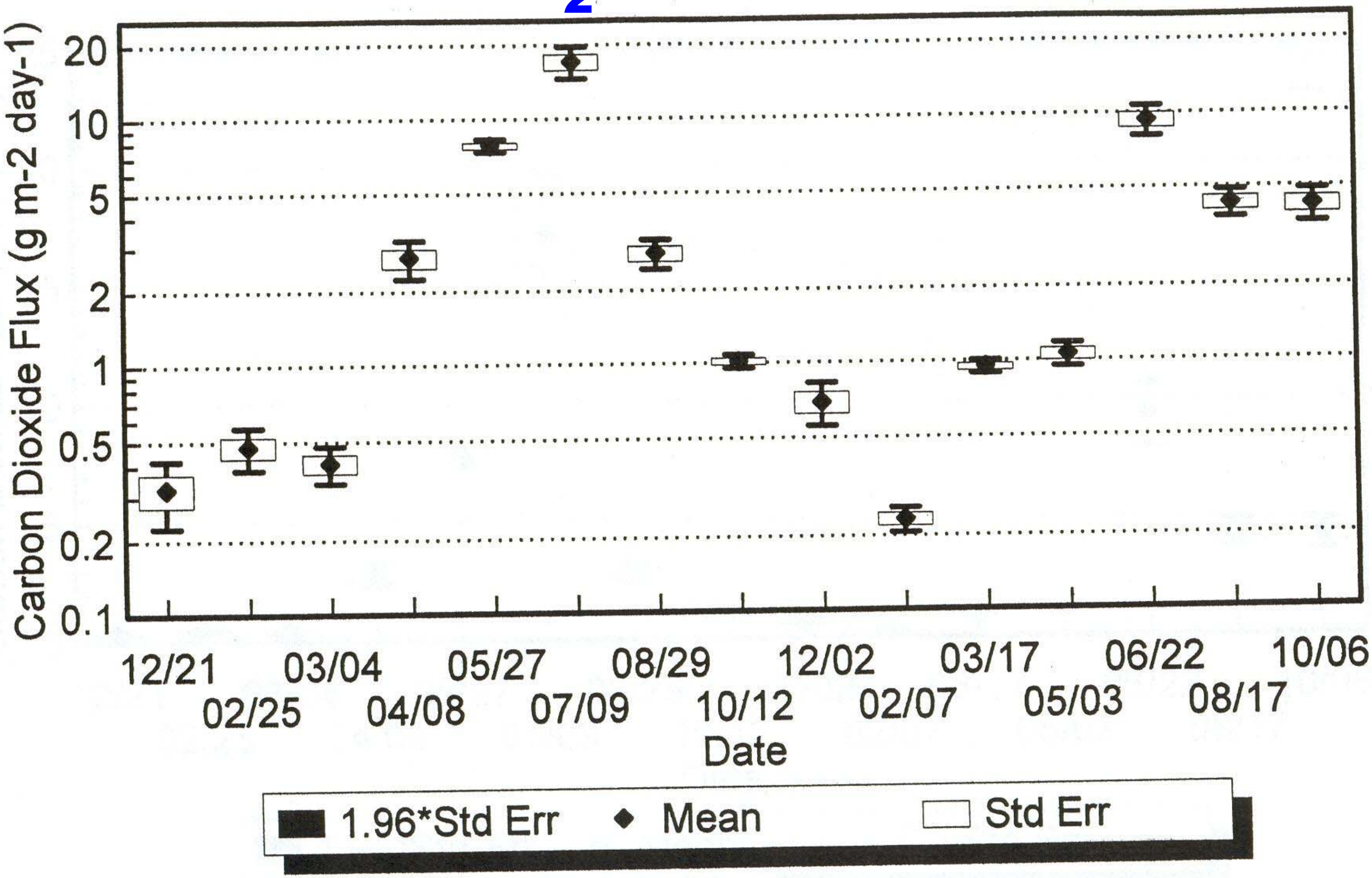
RANGELY ATMOSPHERIC CO_2
12/12/2001 TO 12/14/2002



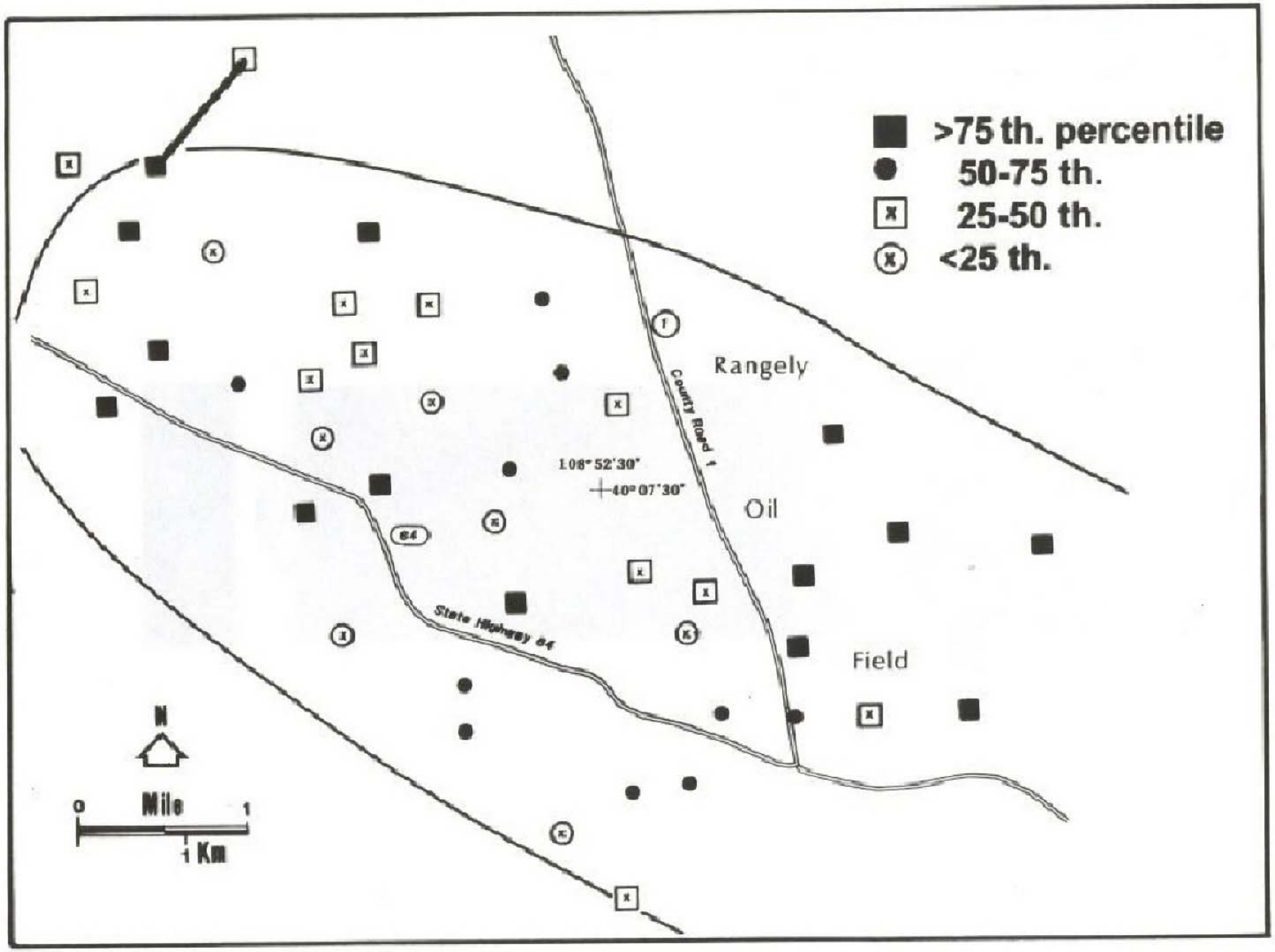
TEST SITE – SEASONAL CO_2 FLUX



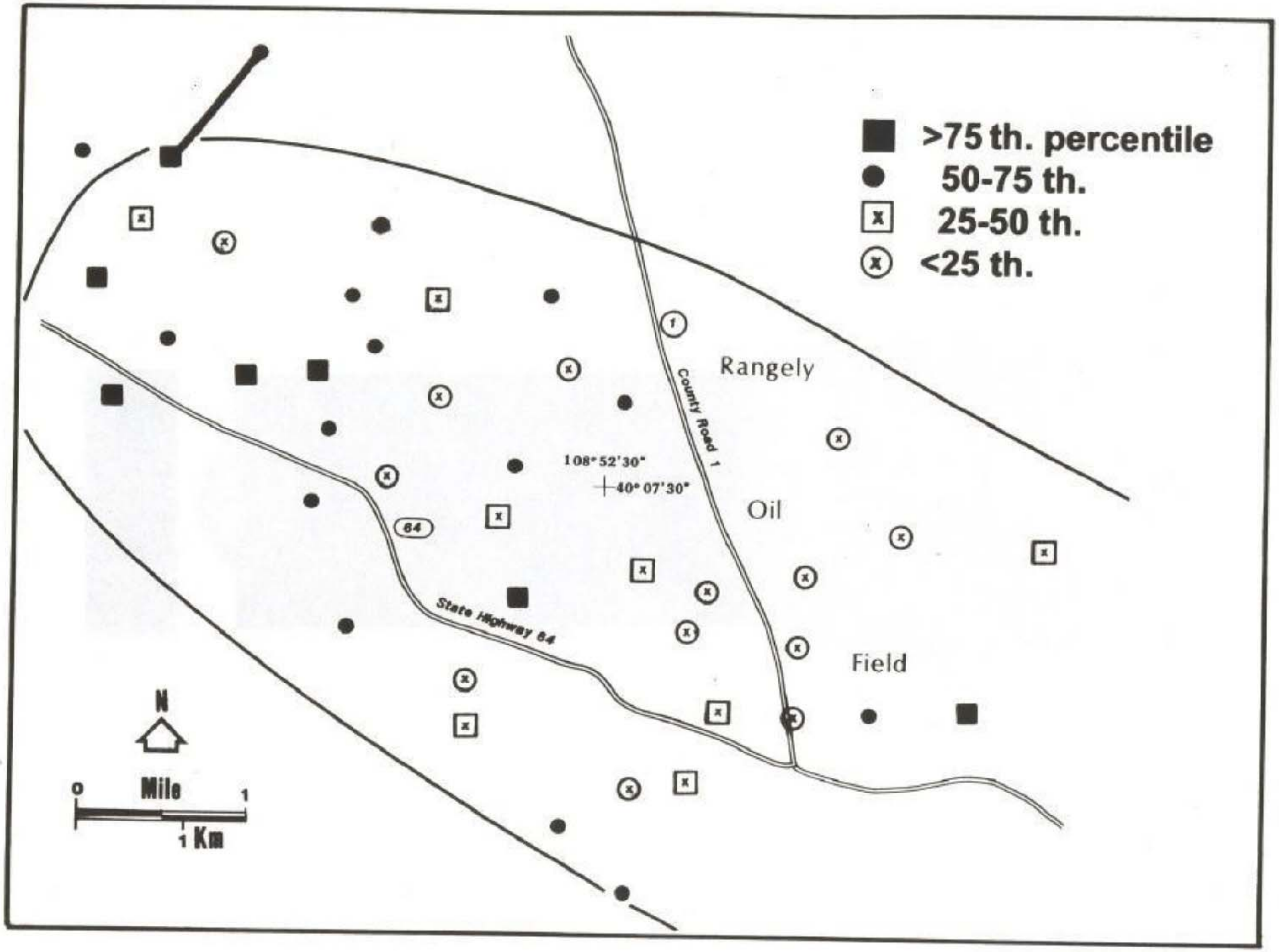
TEST SITE – SEASONAL CO_2 FLUX



RANGELY CO_2 FLUX – SUMMER, 2001



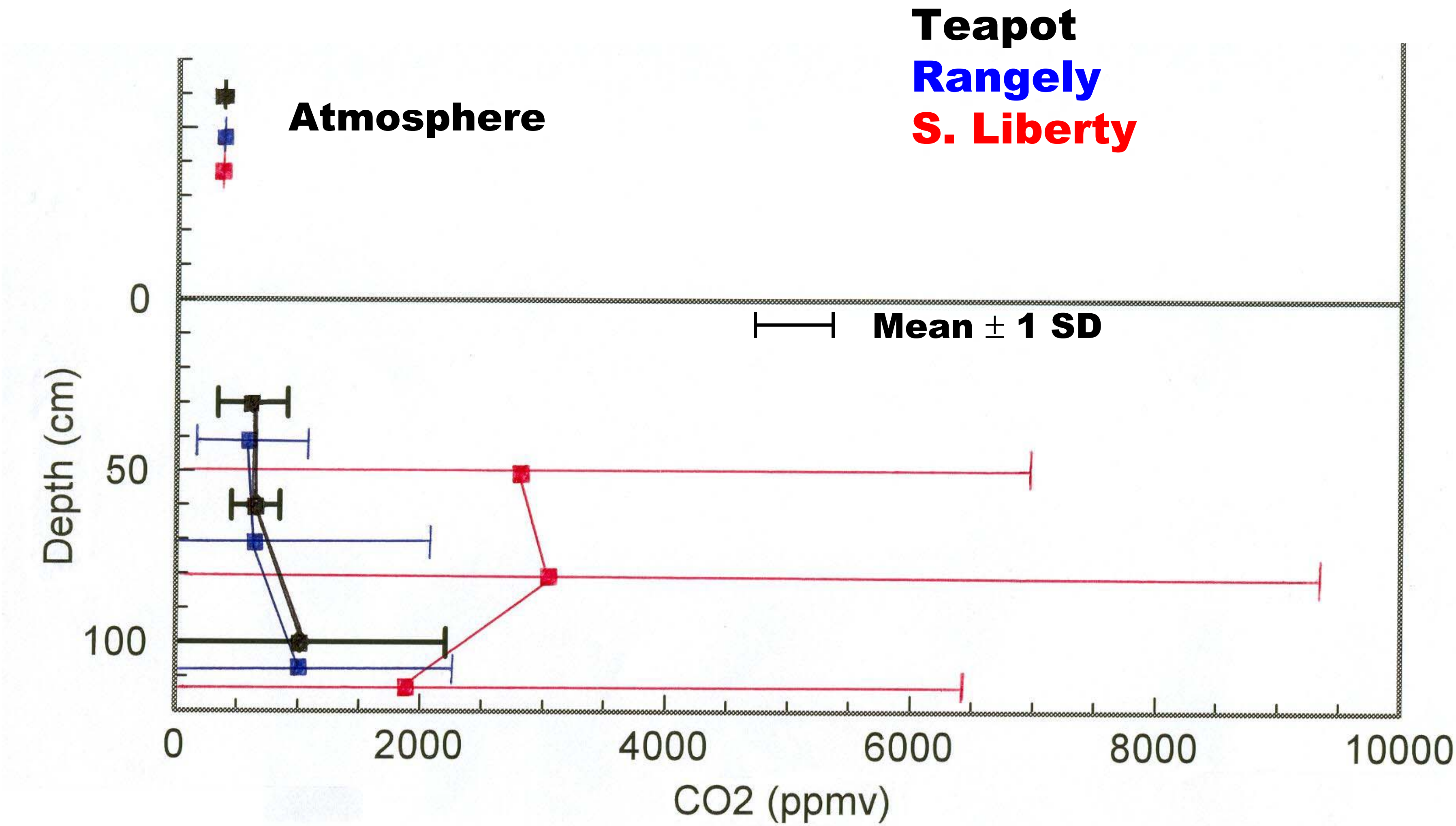
RANGELY CO_2 FLUX - WINTER, 2001/2002



CARBON DIOXIDE FLUXES
(mg $CO_2 m^{-2} day^{-1}$)

	Mean	Median	Std. Dev.
Rangely W01/02	302.	67.9	1134.
Teapot Dome W04	228.	187.	214.
S. Liberty w04	5019.	4526.	3997.

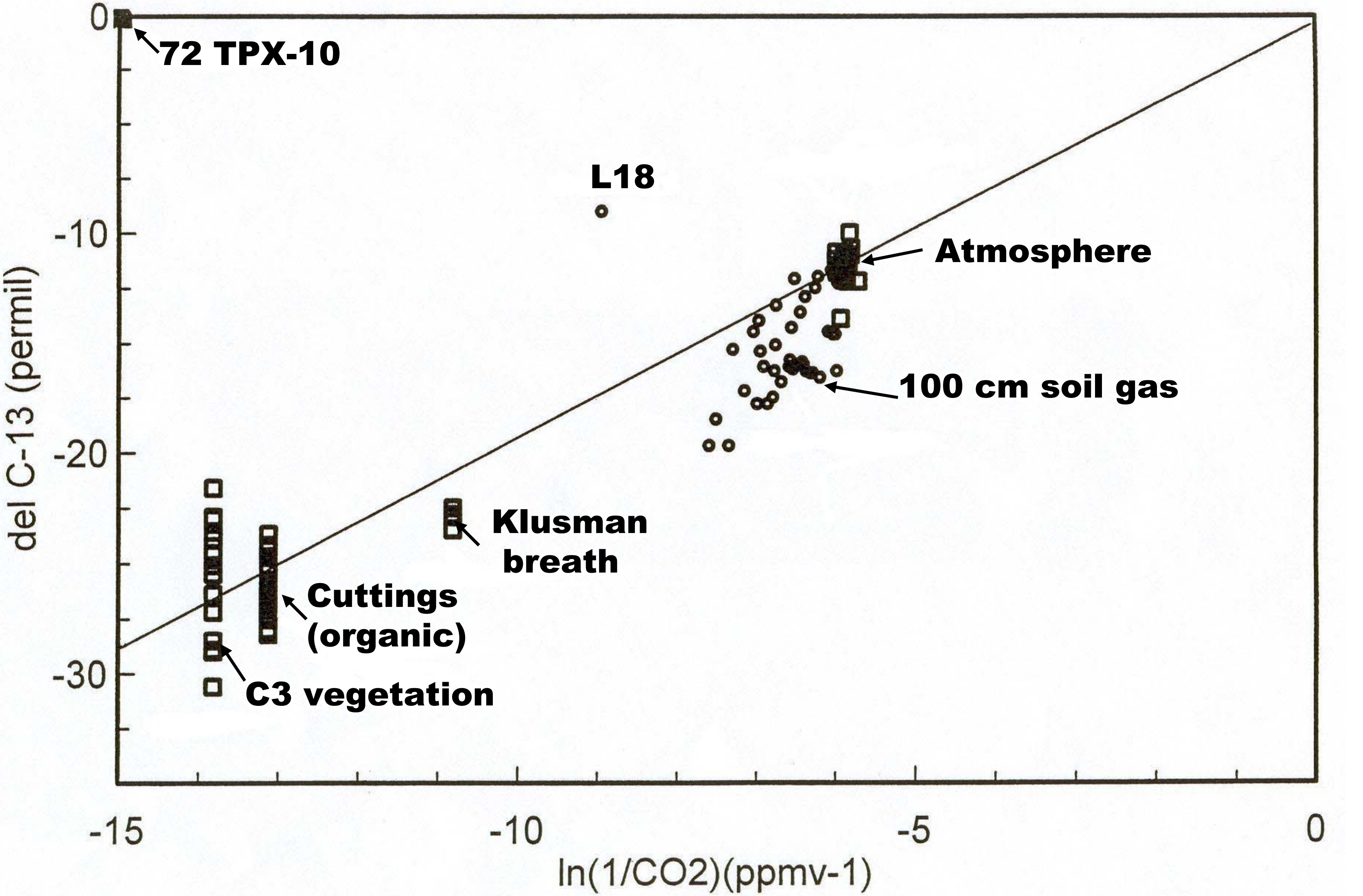
CO_2 IN SOIL GAS



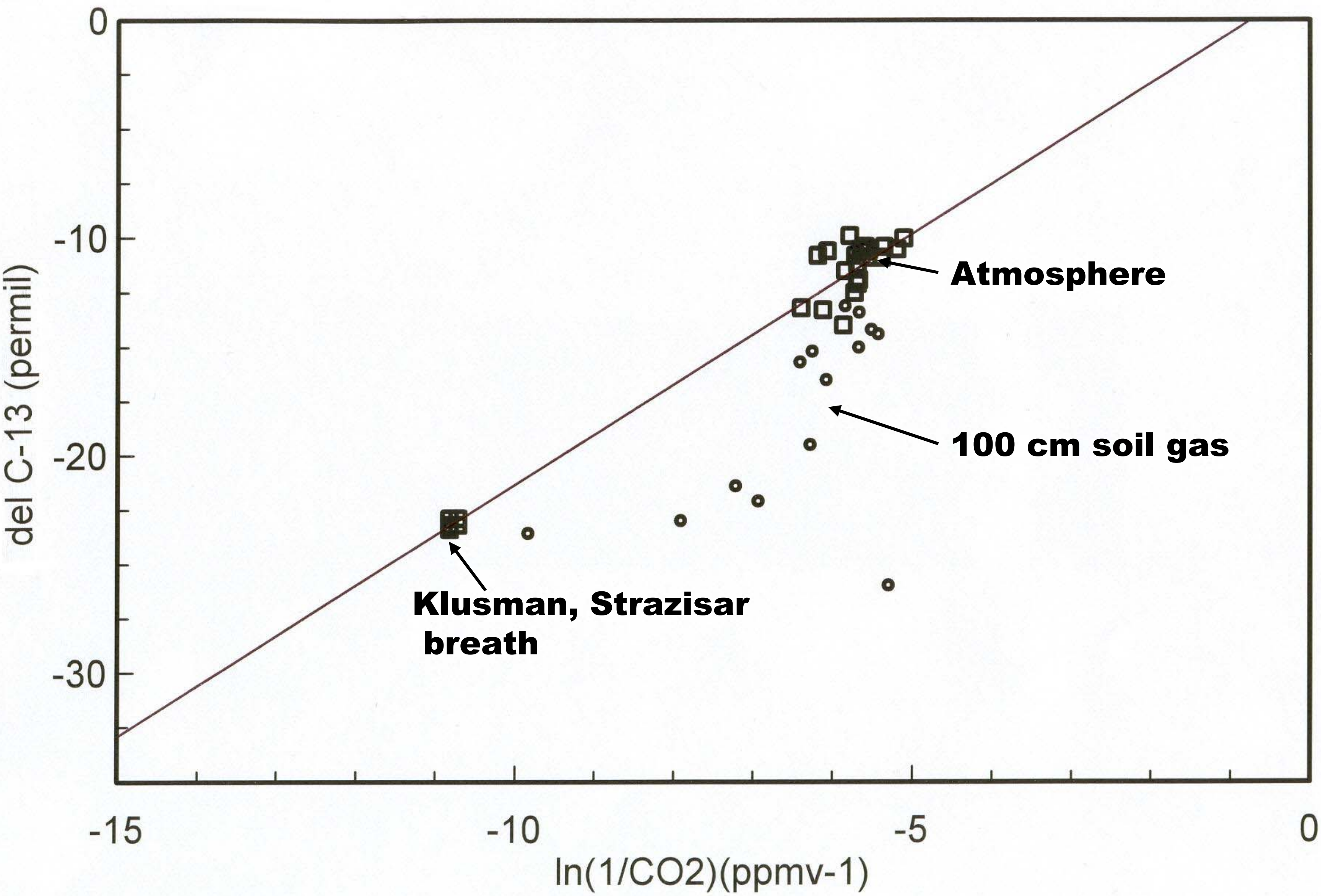
SELECTION OF "INTERESTING" LOCATIONS FOR 10-m HOLES

- **Magnitude and direction of both CO_2 and CH_4 fluxes,**
- **Magnitude and gradient of both CO_2 and CH_4 in soil gas profiles,**
- **Isotopic shift in 60-, and 100 cm soil gas CO_2.**

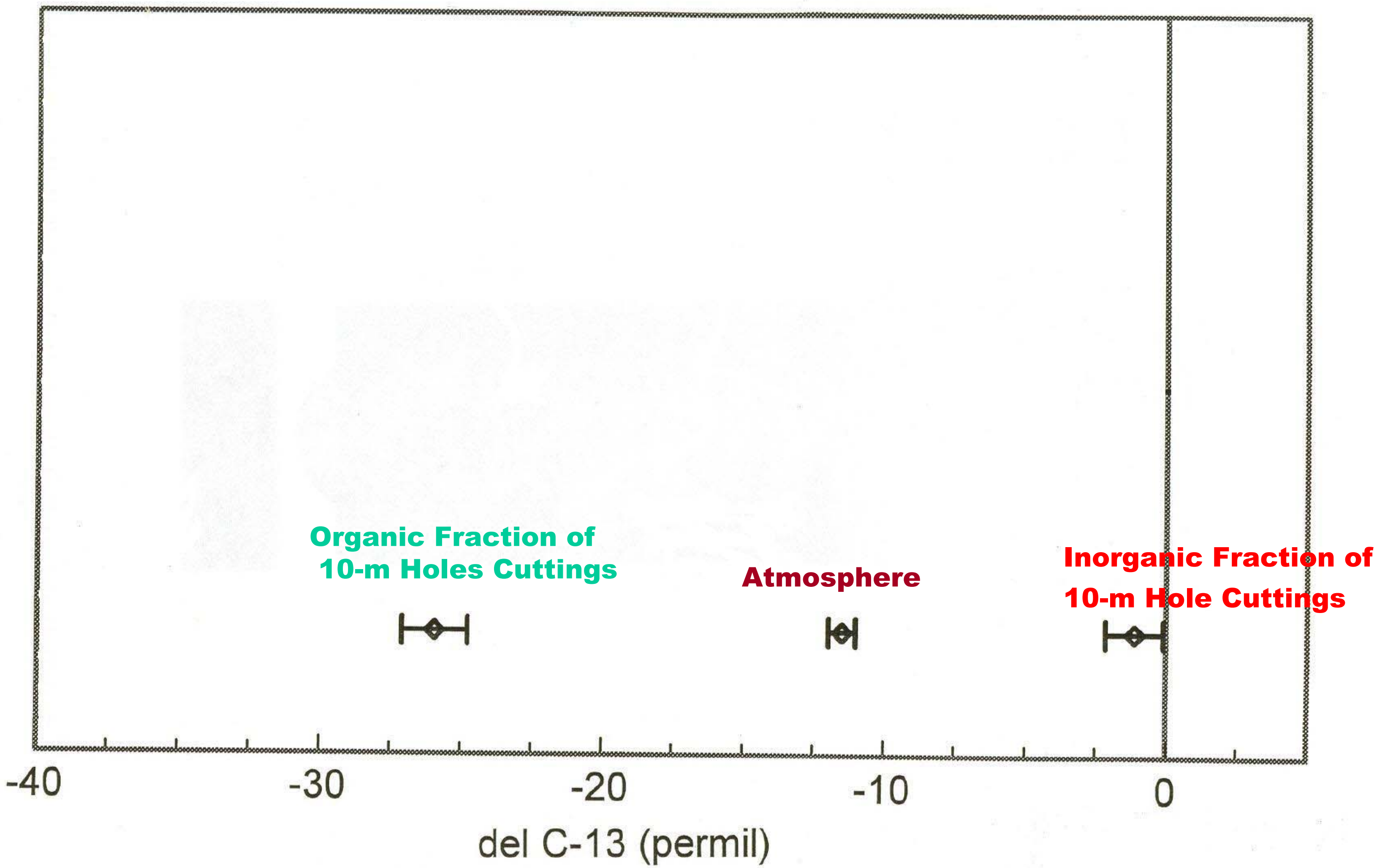
TEAPOT, WINTER, 2004



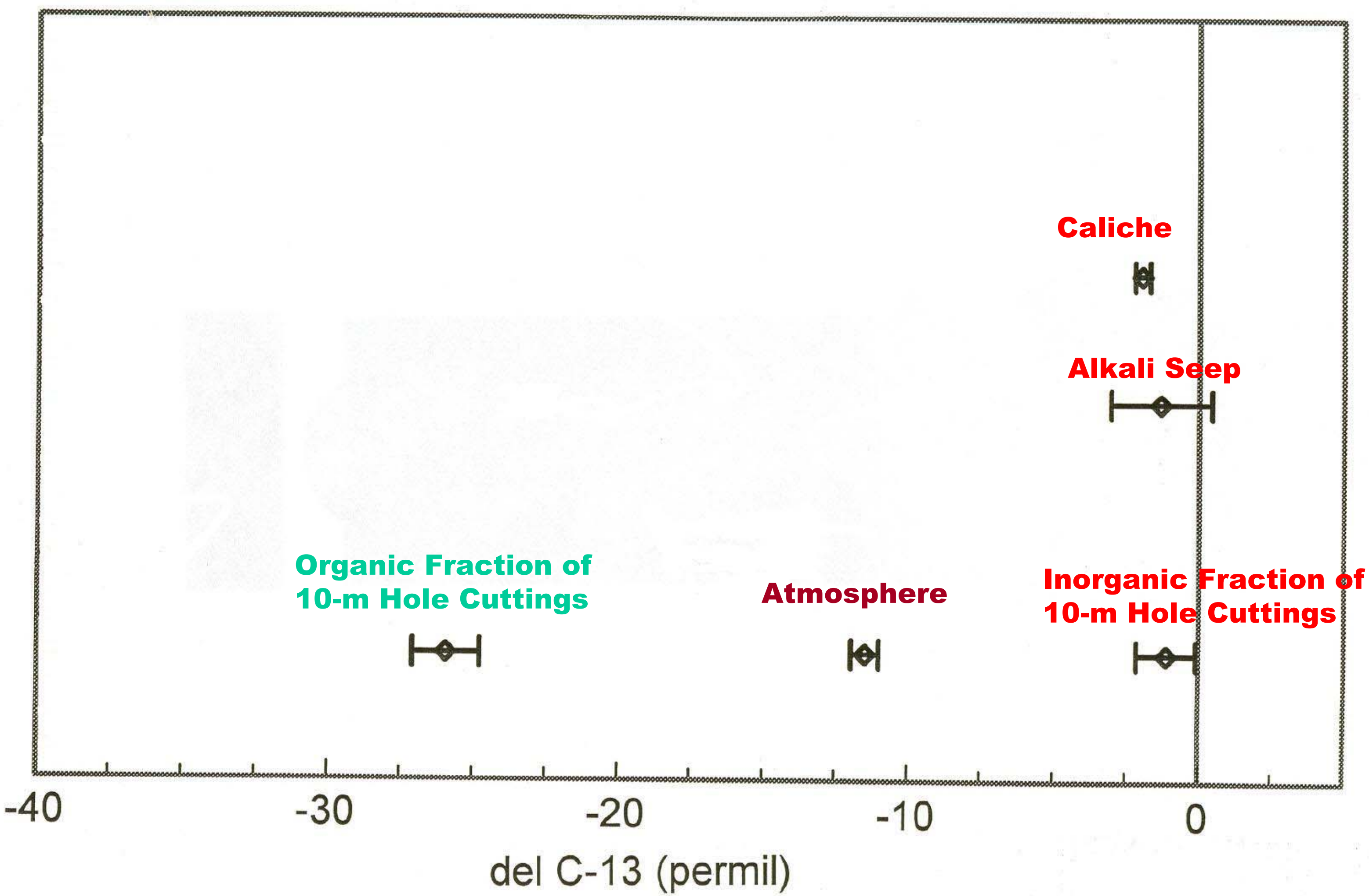
SOUTH LIBERTY, WINTER, 2004



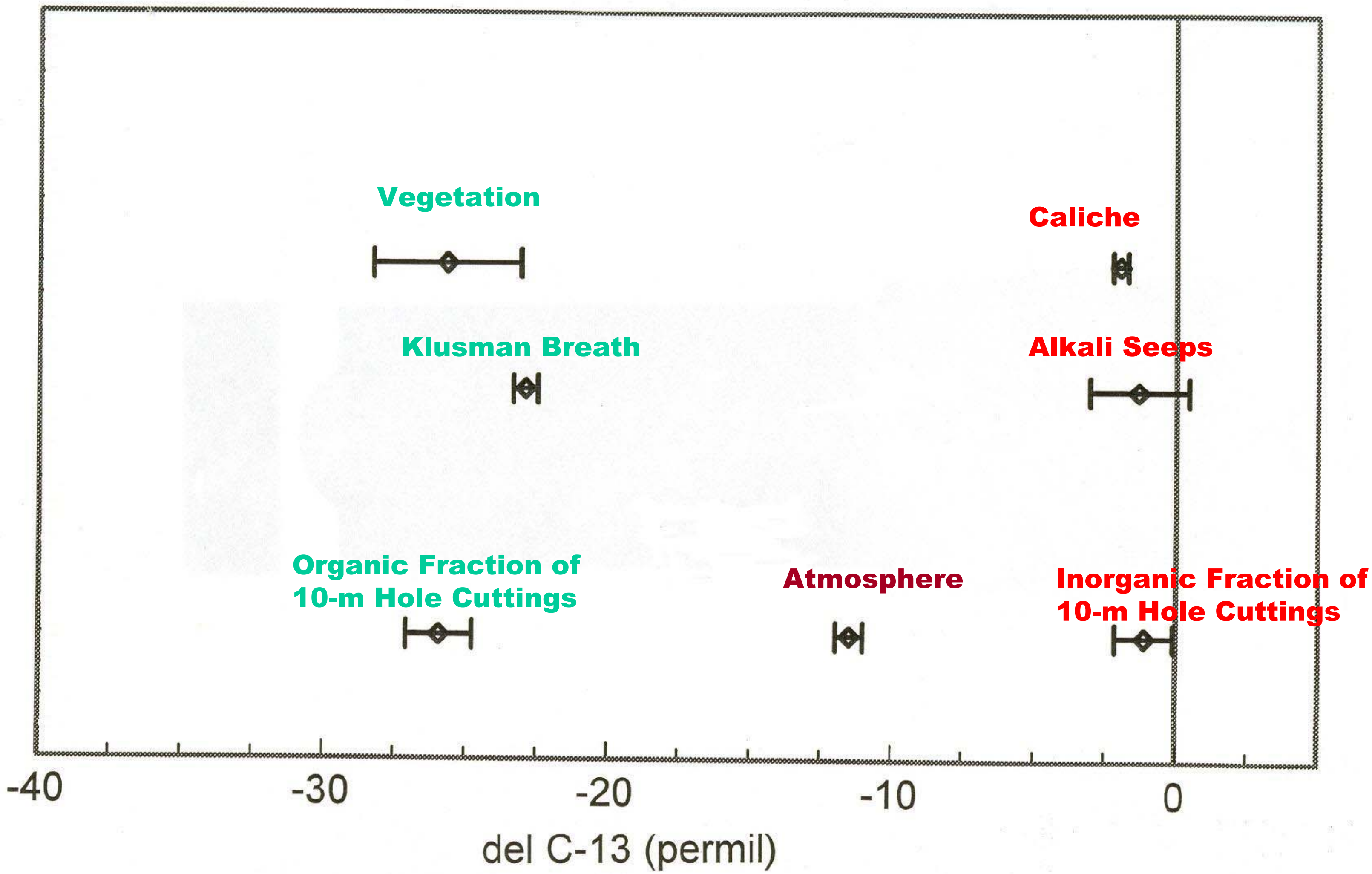
TEAPOT, WINTER, 2004



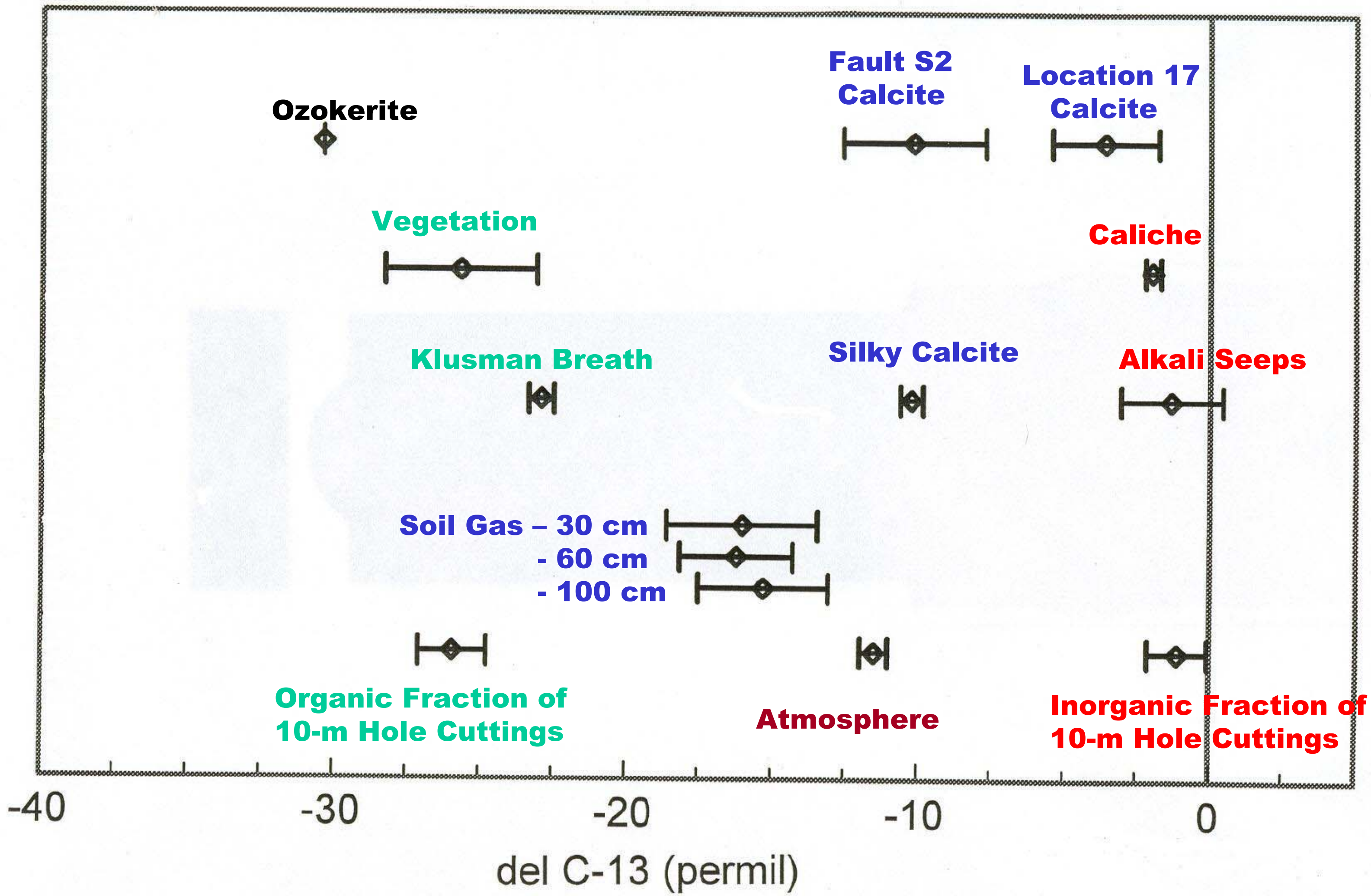
TEAPOT, WINTER, 2004

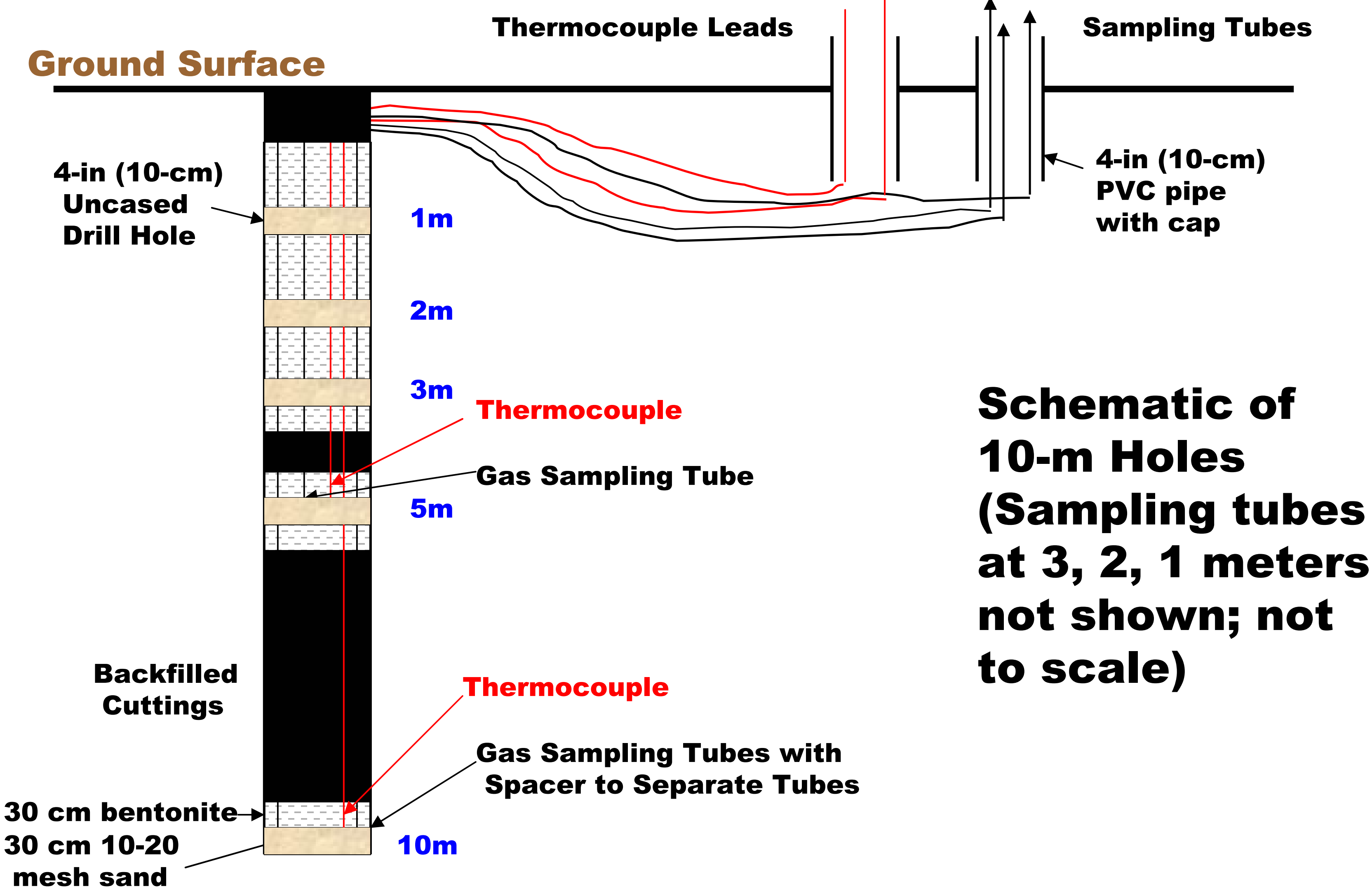


TEAPOT, WINTER, 2004

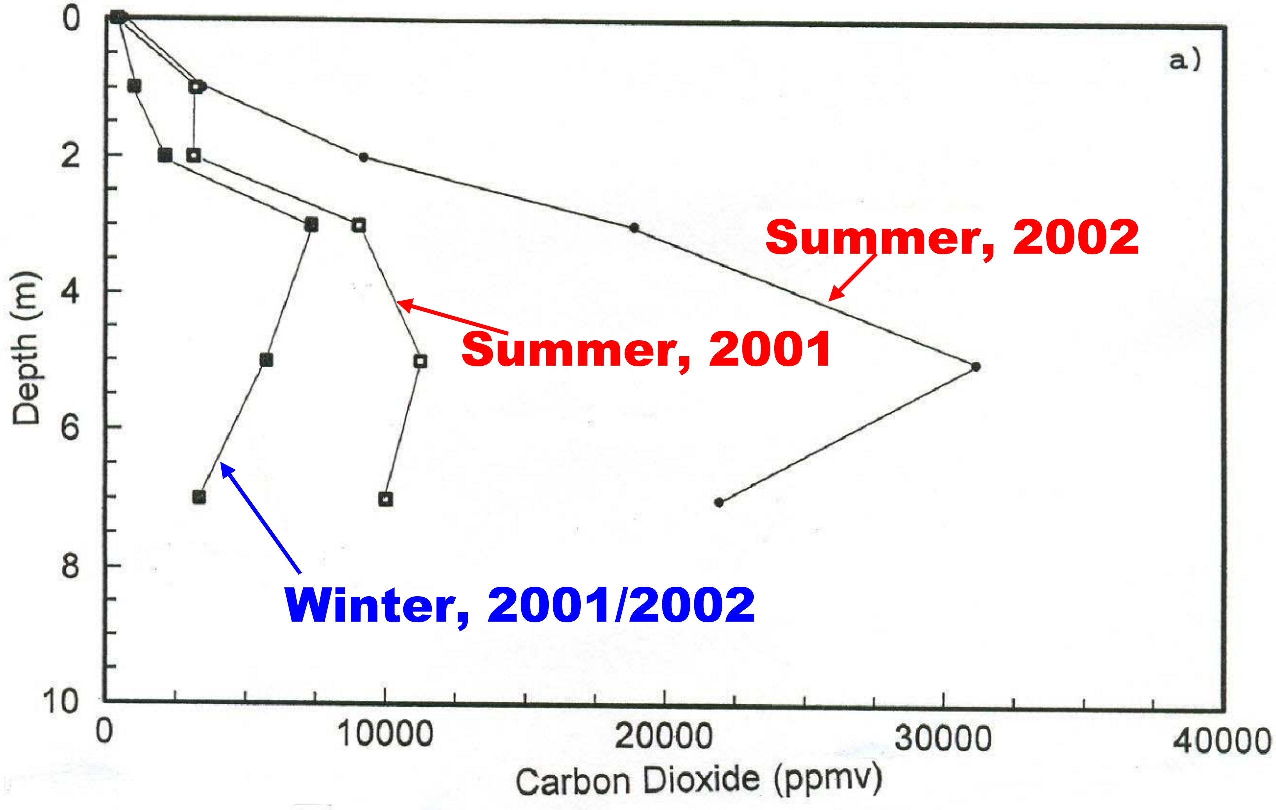


TEAPOT, WINTER, 2004

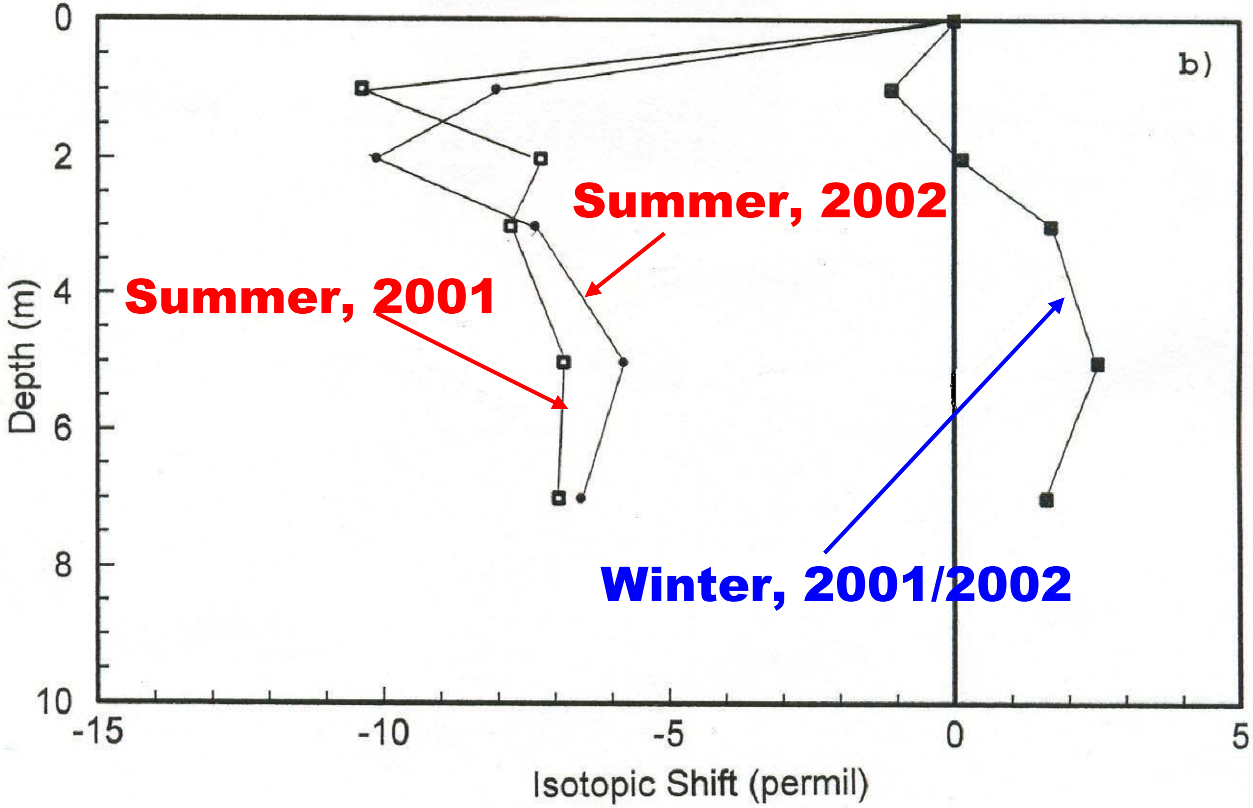



Ground Surface
Thermocouple Leads
Sampling Tubes
4-in (10-cm) Uncased Drill Hole
4-in (10-cm) PVC pipe with cap
1m
2m
3m
Thermocouple
Gas Sampling Tube
5m
Backfilled Cuttings
Thermocouple
Gas Sampling Tubes with Spacer to Separate Tubes
30 cm bentonite
30 cm 10-20 mesh sand
10m
Schematic of 10-m Holes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

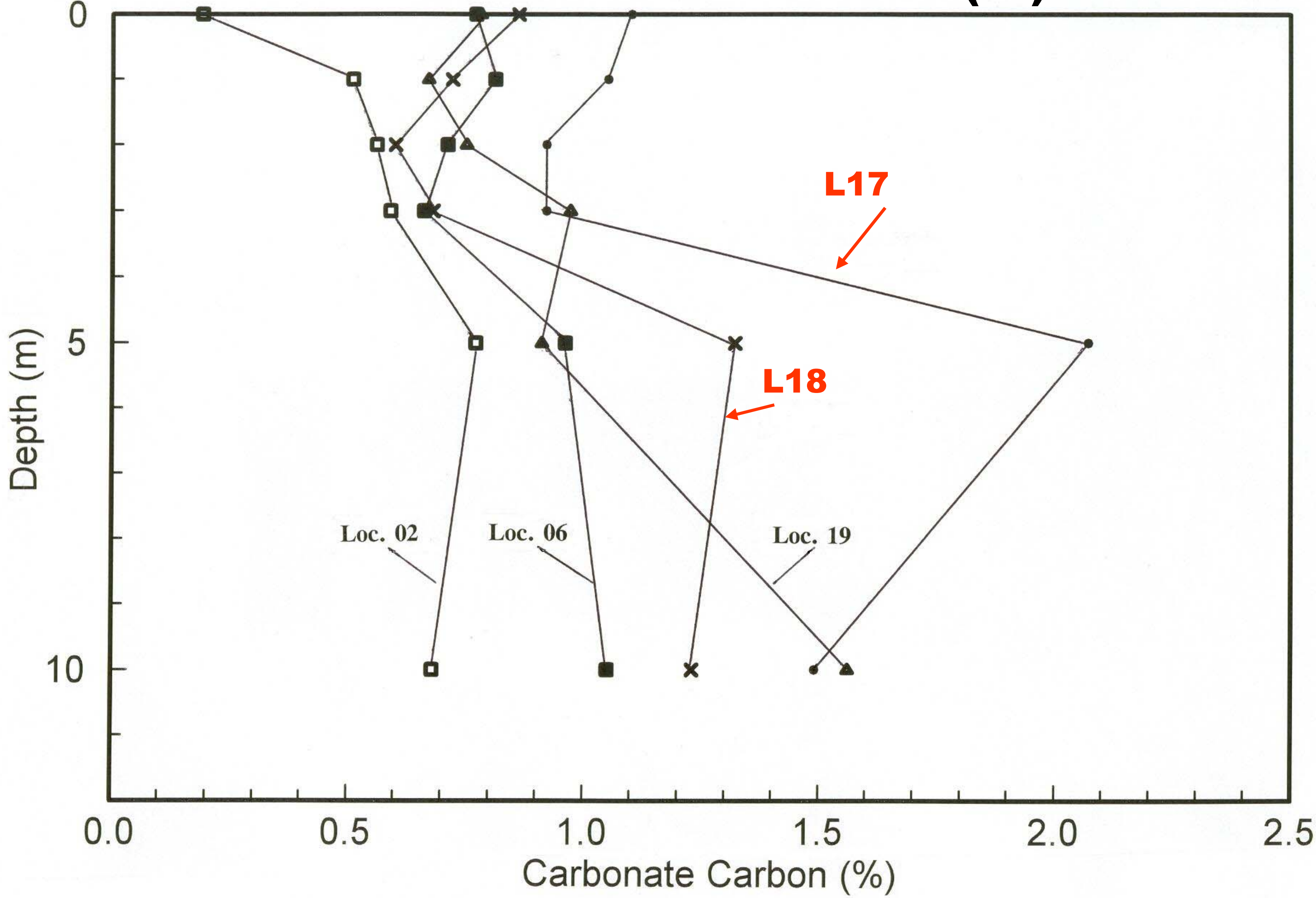
RANGELY – CO_2 IN 10m HOLE L01



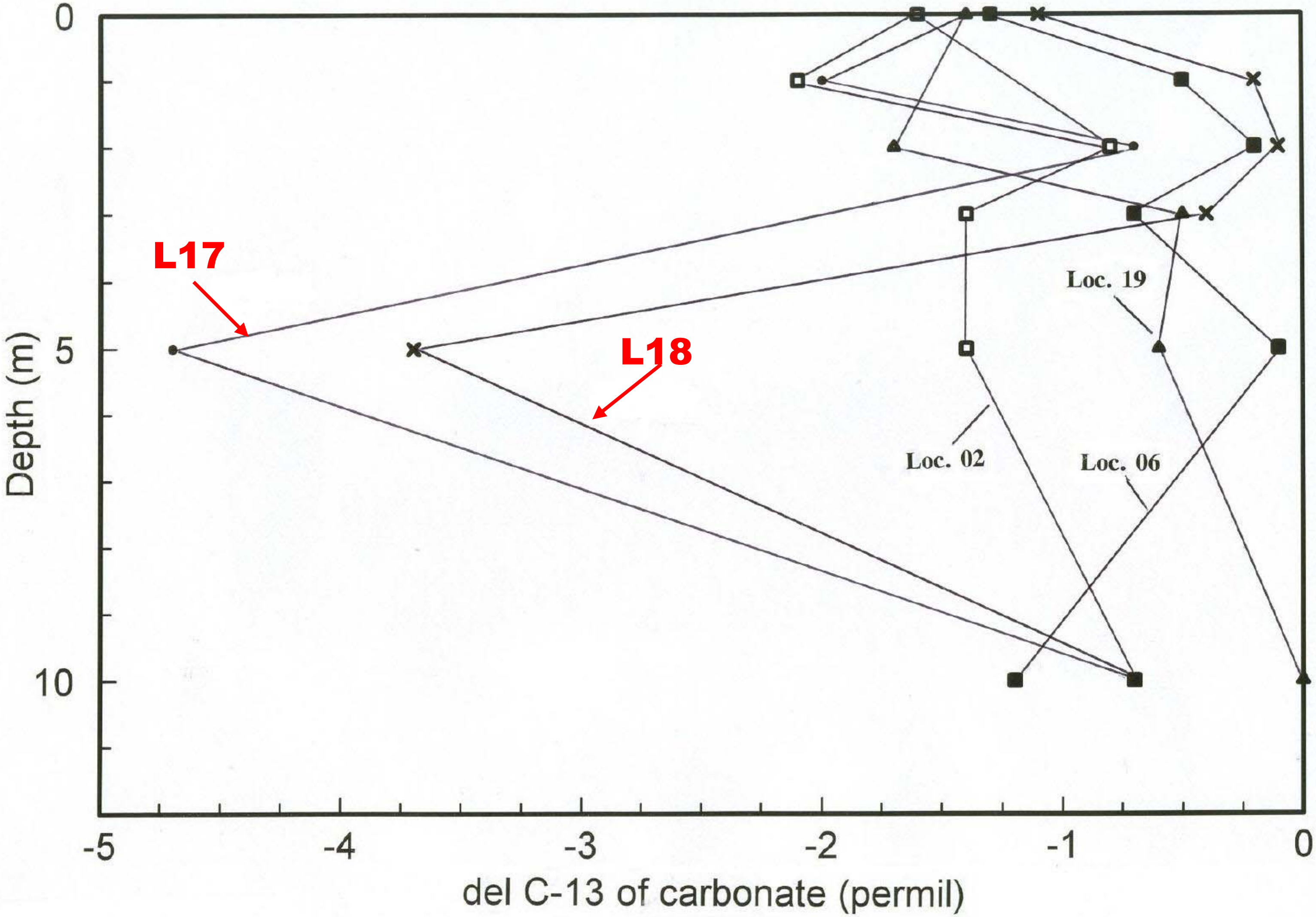
ISOTOPIC SHIFT OF $\delta^{13}C$ OF CO_2 IN 10m HOLE L01 FROM THE AVERAGE SEASONAL ATMOSPHERIC $\delta^{13}C$ OF CO_2



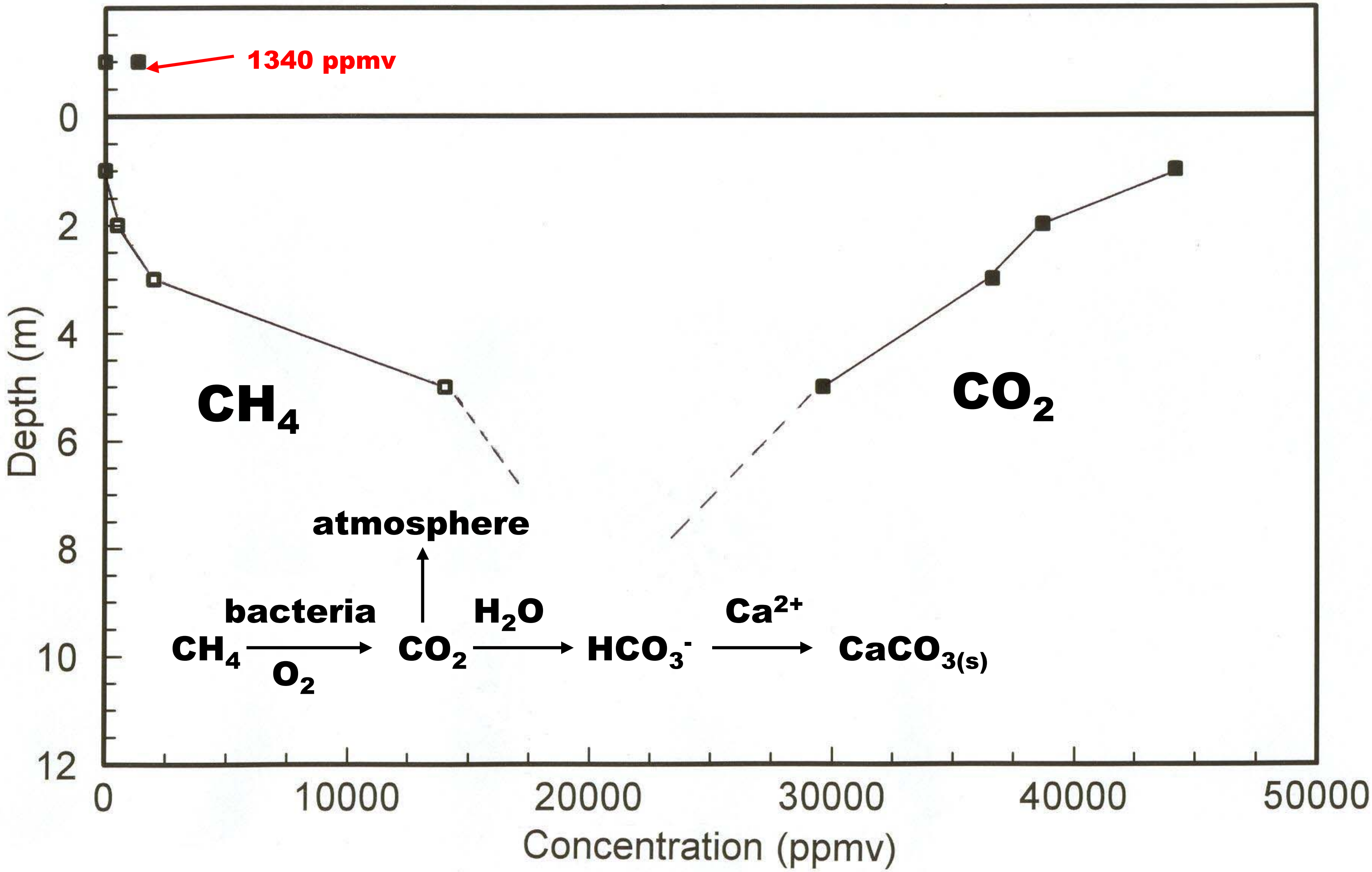
TEAPOT, SUMMER, 2004, INORGANIC CARBON IN CUTTINGS (%)



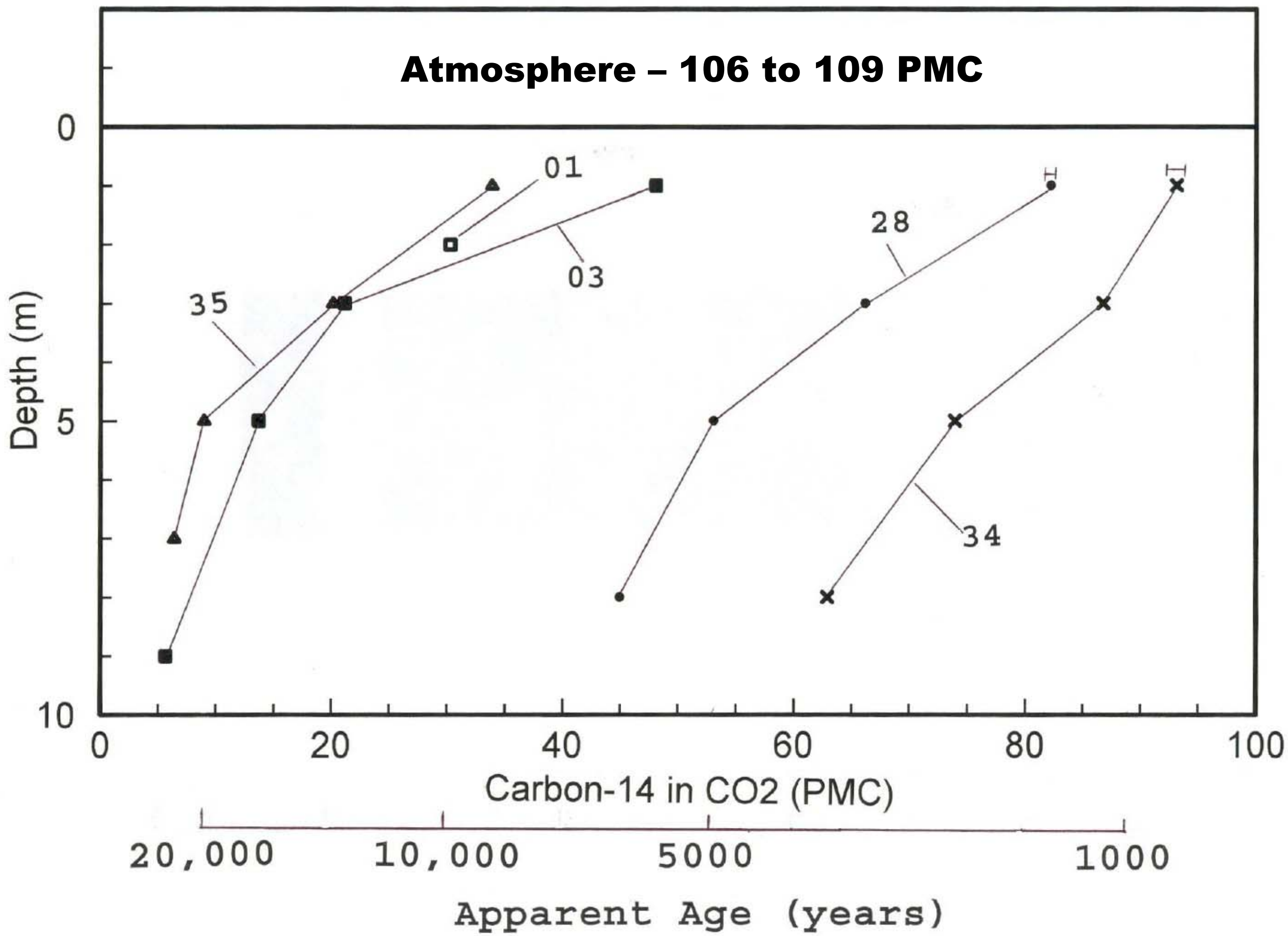
TEAPOT, SUMMER, 2004
$\delta^{13}C$ OF INORGANIC CARBON (‰)



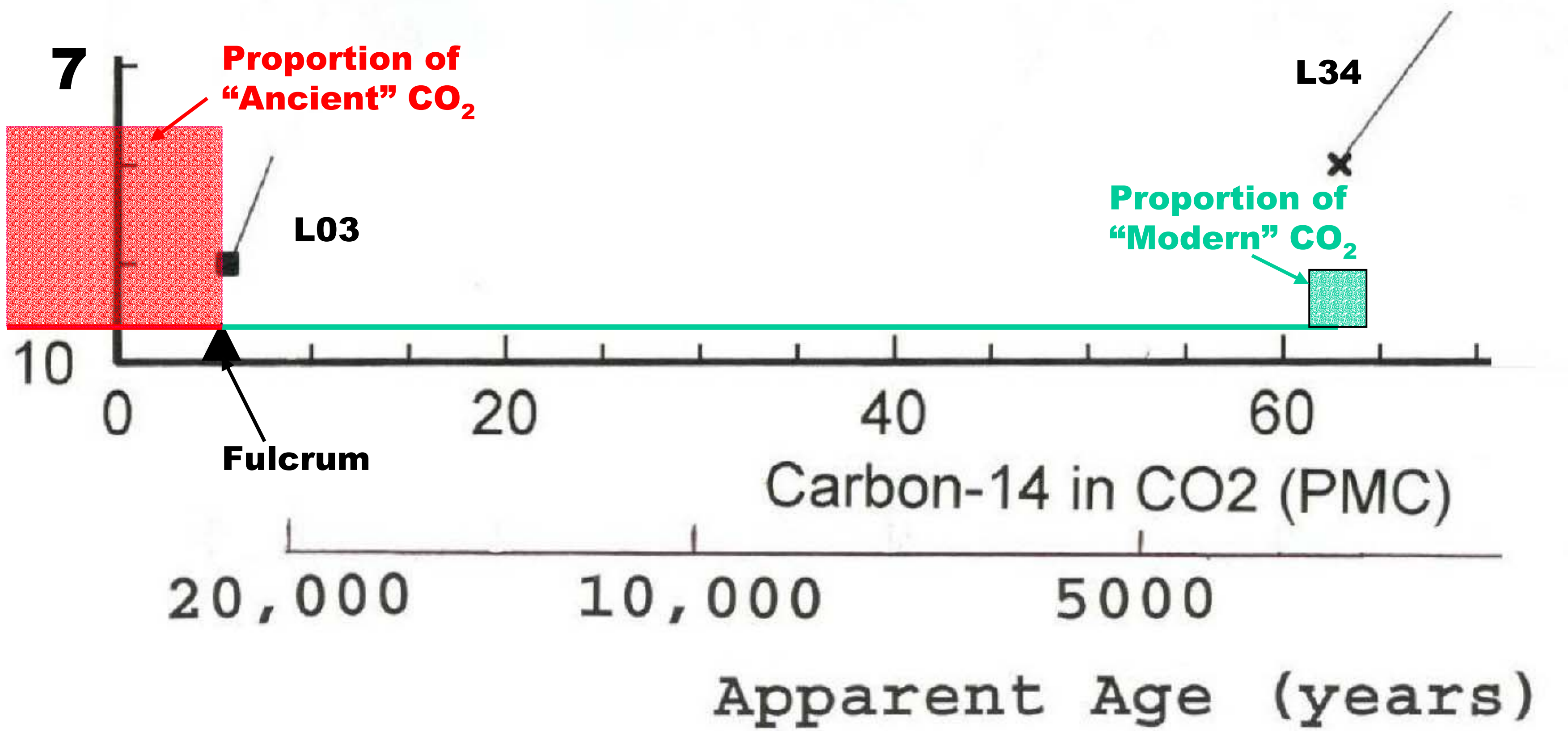
TEAPOT, SUMMER, 2004
10-m HOLE AT L18



CARBON-14 CONTENT OF CO_2 FROM FIVE 10m HOLES, WINTER, 2001/2002



APPLICATION OF THE LEVER RULE TO THE MIXING OF "ANCIENT" AND "MODERN" CO_2



ESTIMATION OF CO_2 MICROSEEPAGE INTO THE ATMOSPHERE AT RANGELY

- **Using the $\delta^{13}C$ data for CO_2 in soil gas and flux data, the microseepage to the atmosphere was estimated at <3800 metric tonnes $year^{-1}$,**
- **Using the lever rule on L03, which is typical for an area of microseepage, and L34 where there appears to be no microseepage, ≈ 90% of the CO_2 at the bottom of 10 m hole L03 is ancient,**
- **The average winter CO_2 flux over the field is 0.302 g $m^{-2}day^{-1}$, 4/41 locations on the field are "anomalous," yielding 170 metric tonnes $year^{-1}$ as a specific estimate.**

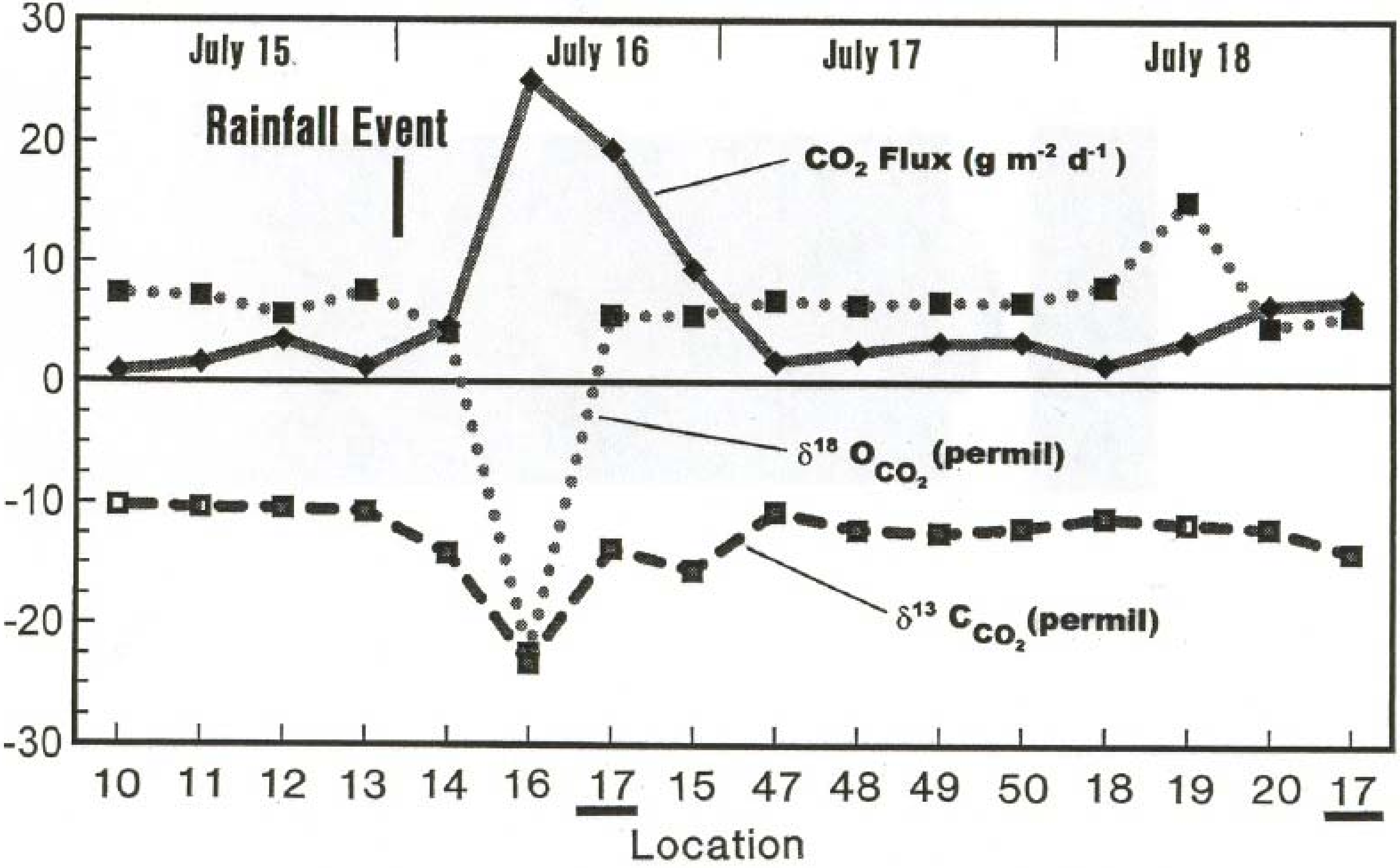
ESTIMATION OF CO_2 MICROSEEPAGE INTO THE ATMOSPHERE AT RANGELY

- **BUT**, the computer modeling of the methanotrophic oxidation of CH_4 , indicates very high rates in the anomalous 10 m holes,
- It is probable that most of the radiocarbon “dead” CO_2 is produced from oxidation of microseeping radiocarbon “dead” CH_4, being a 4^{th} specific source of CO_2 ,
- The CO_2 seepage into the atmosphere must be revised to <170 metric tonnes year^{-1}.

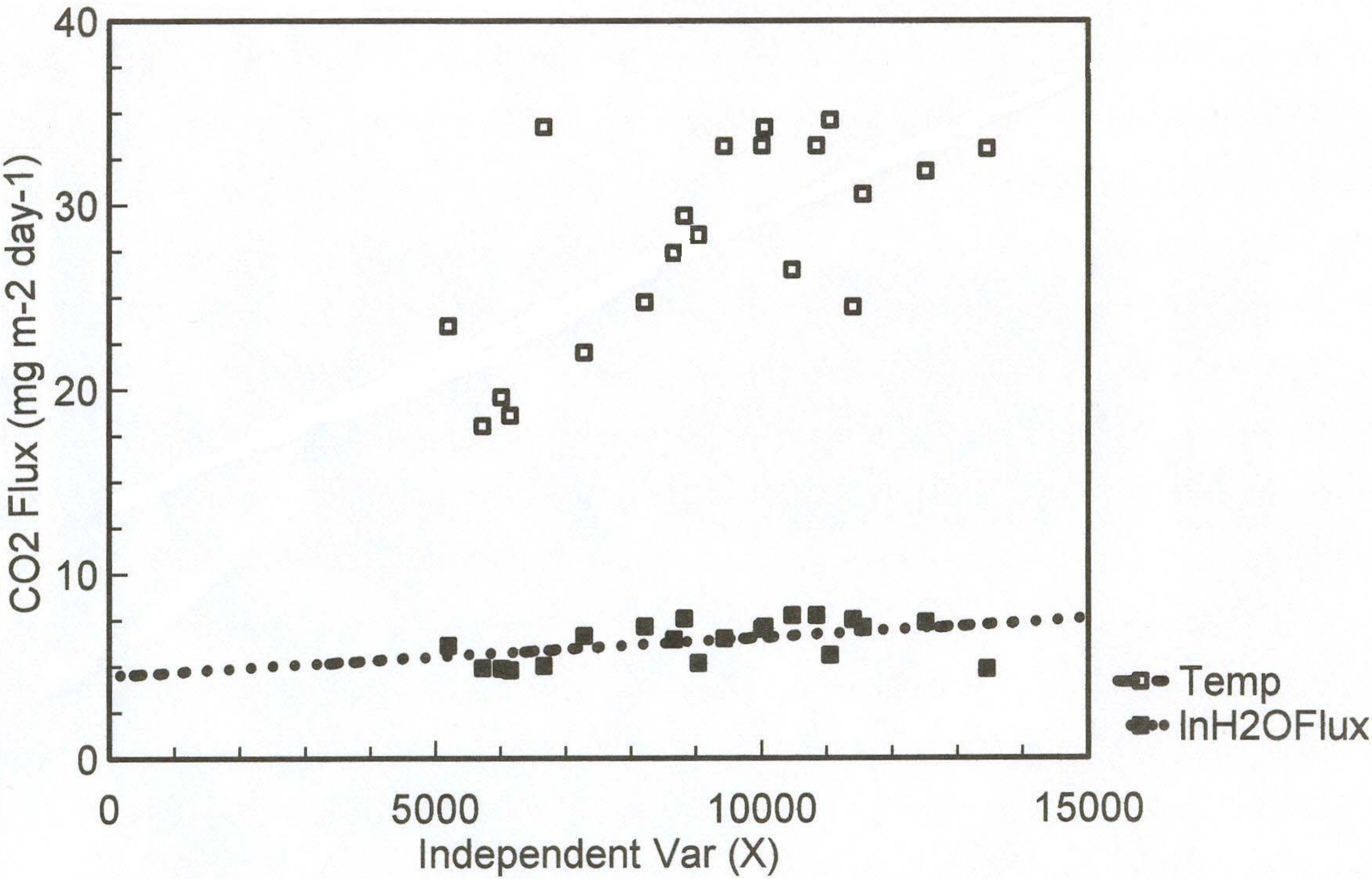
ESTIMATION OF CO_2 MICROSEEPAGE INTO THE ATMOSPHERE AT RANGELY

- **Taking the maximum of 170 metric tonnes year^{-1}, multiplied by the 15 years between 1986 and 2001, yields 2550 tonnes,**
- **2.550×10^3 tonnes/2.3×10^7 tonnes stored = 0.00011, which is ≈ 0.01% in <u>15 years</u>,**
- **The actual direct CO_2 microseepage is likely substantially less,**
- **CO_2 <u>and</u> CH_4 flux measured and verified.**

RANGELY – EFFECT OF A RAINFALL EVENT, JULY 15, 2001



TEST SITE, JULY 7, 2004



RECOMMENDATIONS FOR ADDITIONAL FLUX RESEARCH

- **Tower Methods**
- Eddy Covariance (Eddy Correlation)
- Bowen Ratio
- **Long-, Open-Path Methods**
- Tunable Infrared Laser Differential Absorption
- Spectroscopy (TILDAS)
- Differential Optical Absorption Spectroscopy
- (DOAS)
- Fourier Transform Infrared Spectroscopy (FTIR)

CRITICAL NEEDS FOR SUCCESSFUL APPLICATION OF MMV

- **Must develop an understanding of noise at each sequestration site,**
- **Warm, wet climates will be much more <u>difficult</u> for MMV,**
- **Methane will be a <u>trouble-maker</u> and must be a component of MMV program,**
- **Methods of Klusman adequate for reconnaissance or baseline assessment, AND finding "interesting" locations,**
- **Stable carbon isotopic ratio determination essential in sorting out carbon gas source strengths,**
- **Tower- and open-path methods need to be evaluated in the study of "interesting" locations.**

ACKNOWLEDGEMENTS

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


Sunset over Raven Ridge at Rangely

LIMITATIONS AND BARRIERS

- Ability for direct detection of a deep-sourced signal in the presence of near-surface biological noise, particularly in warm, wet climates,
- Above-ground techniques like tower- and open-path methods should be focused in pre-determined areas of interest,
- Reduction of uncertainty in atmospheric exchange estimates above sequestration reservoirs,
- CH_4 microseepage off-setting gains from CO_2 sequestration?
- Loss of injectivity due to mineral precipitation shortening the life of a sequestration reservoir?
- Under-sea injection; side-scan sonar to determine bubble column density, followed by compositional and isotopic analysis of selected seeps?

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Surface Monitoring Techniques - Using Weyburn as a Case Study

J. M. Pearce,

M.H. Strutt and D.G. Jones

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

NATURAL ENVIRONMENT RESEARCH COUNCIL

Acknowledgements

- EC Energy, Environment and Sustainable Development Programme co-funding for the Weyburn and Nascent projects
- Encana for access to Weyburn site
- Weyburn shallow gas team:
  - URS: Stan Beaubien and Salvatore Lombardi
  - BRGM: Jean-Claude Baubron
  - INGV: Fedora Quattrocchi
  - Mollard: Lynden Penner
- Barthold Schroot, TNO

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

Why monitor at the surface?

1. **Site characterisation**
   - **To identify background or baseline conditions**
     - Evaluate natural variations in shallow gas including seasonal effects
   - **To identify pathways in the near surface for potential future leaks, which improve risk assessments**
     - Identify sites that may be indicative of deep gas escape or potential gas escape
       - Abandoned wells/infrastructure
       - Lineaments/fractures
       - Anomalies in soil gas

Why monitor at the surface?

2. Operational phase during injection
   - To assess site performance
   - To demonstrate injection and storage meets operational HSE requirements
   - To verify injected mass to earn credits/ allowances…?

Why monitor at the surface?

3. During and after abandonment

- **To demonstrate storage and abandonment practices are successful,**
  - enabling transfer of liability from operator to the state…?
- **To validate risk assessments**
  - Diffuse leaks over a large area could be difficult to identify and quantify

Monitoring Program at Weyburn

Which gases?

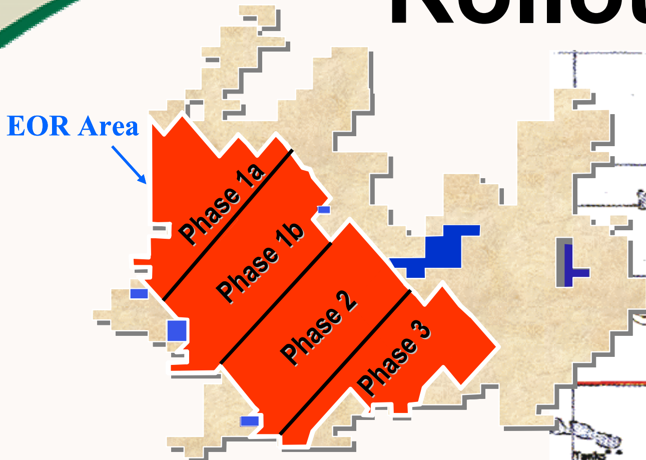
- C1 to C4 hydrocarbons (HC),
- sulphur species (COS, SO_2),
- major gases (CO_2, O_2, N_2)
- radon/thoron
- trace gases - helium

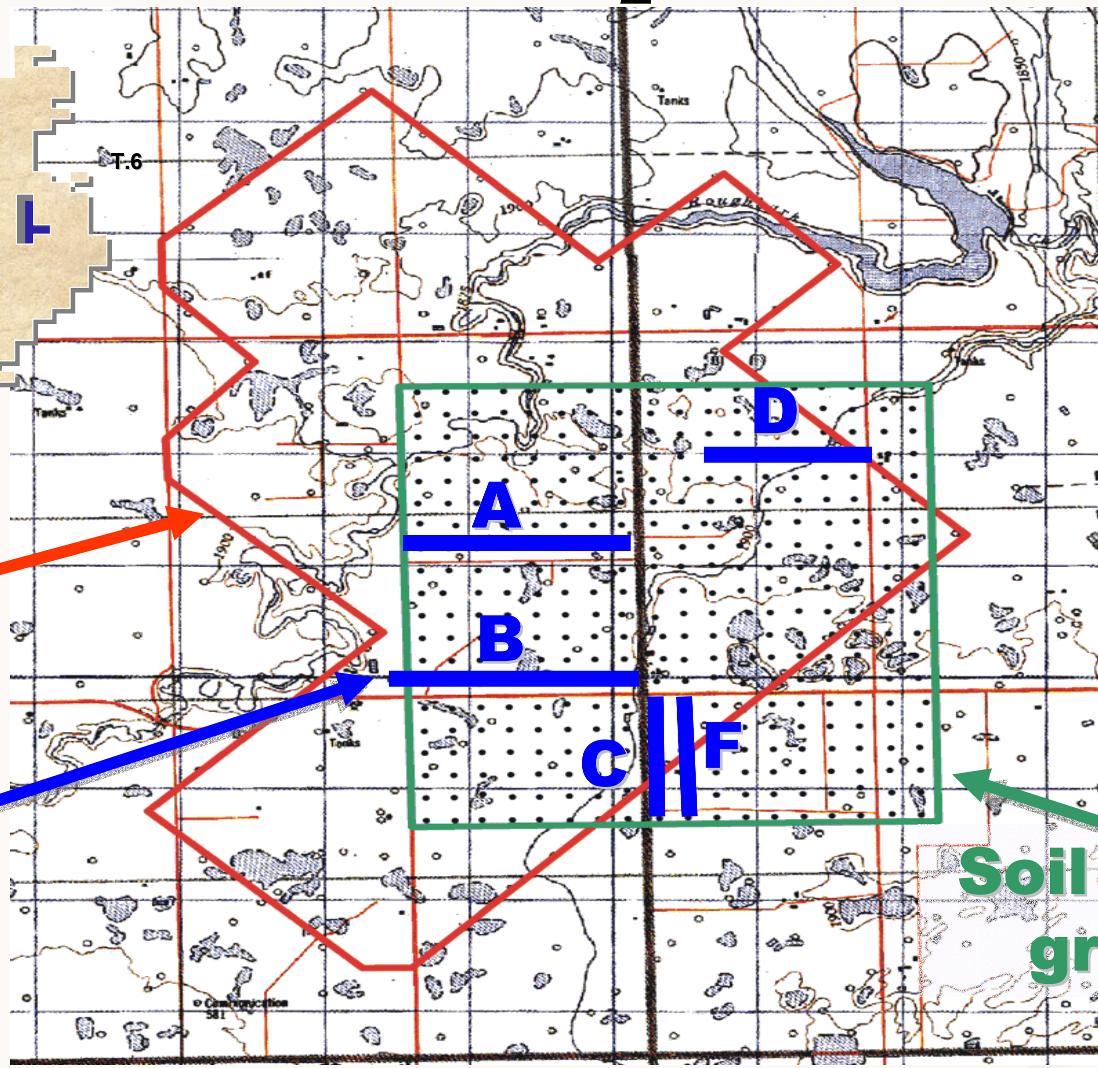
Why these?

- CO_2 – obvious (but biogenic production)
- HC and sulphur species - reservoir
- O_2, N_2 – quality control and microbial reactions
- Rn/Tn/He – can indicate conduits for gas migration (deep source/CO_2 carrier)

- Gamma spectrometry – link to Rn/Tn, continuous profiles, compositional comparison to background

Rollout of the CO_2 flood



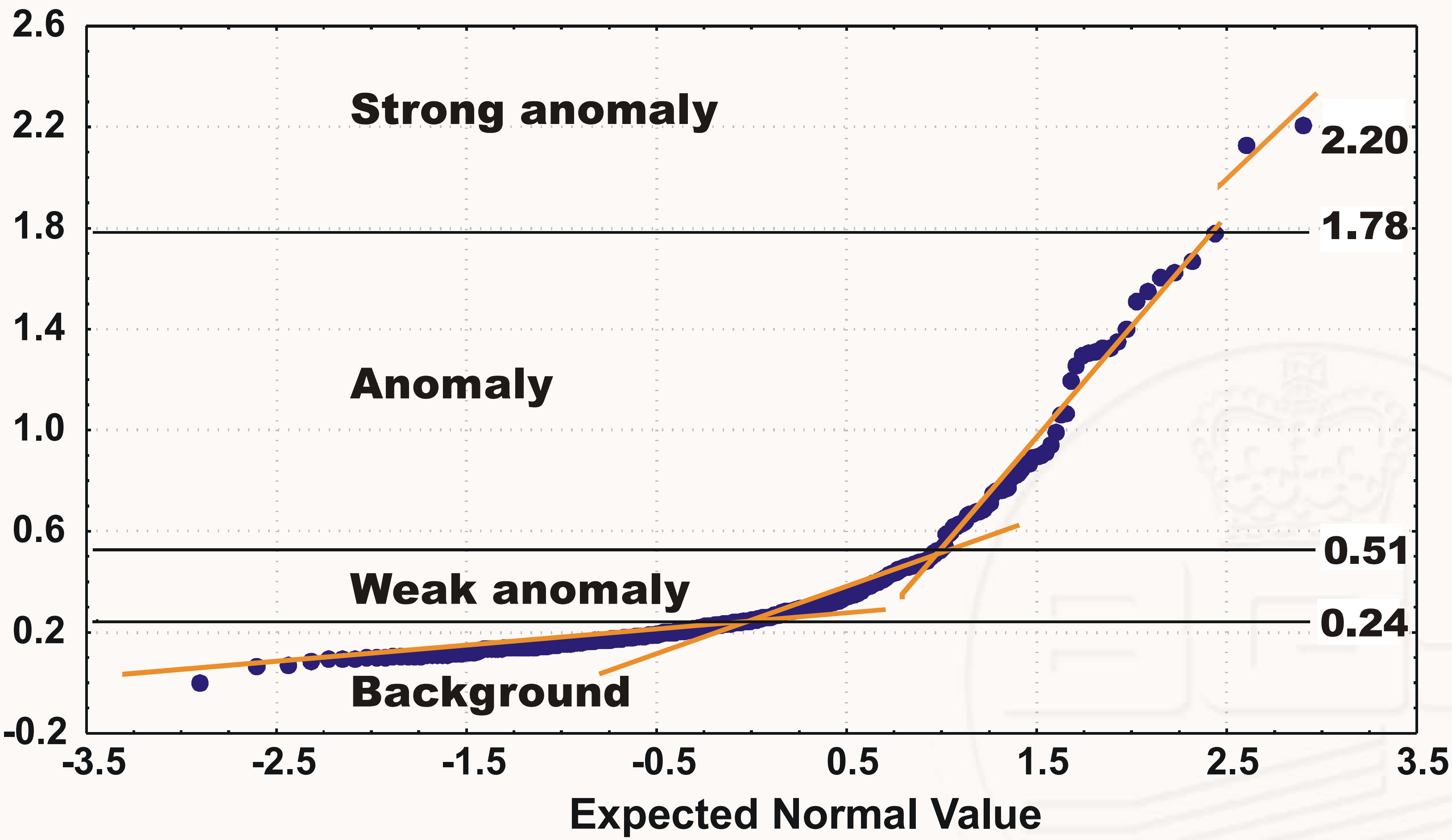


1A Injection panel

Profiles

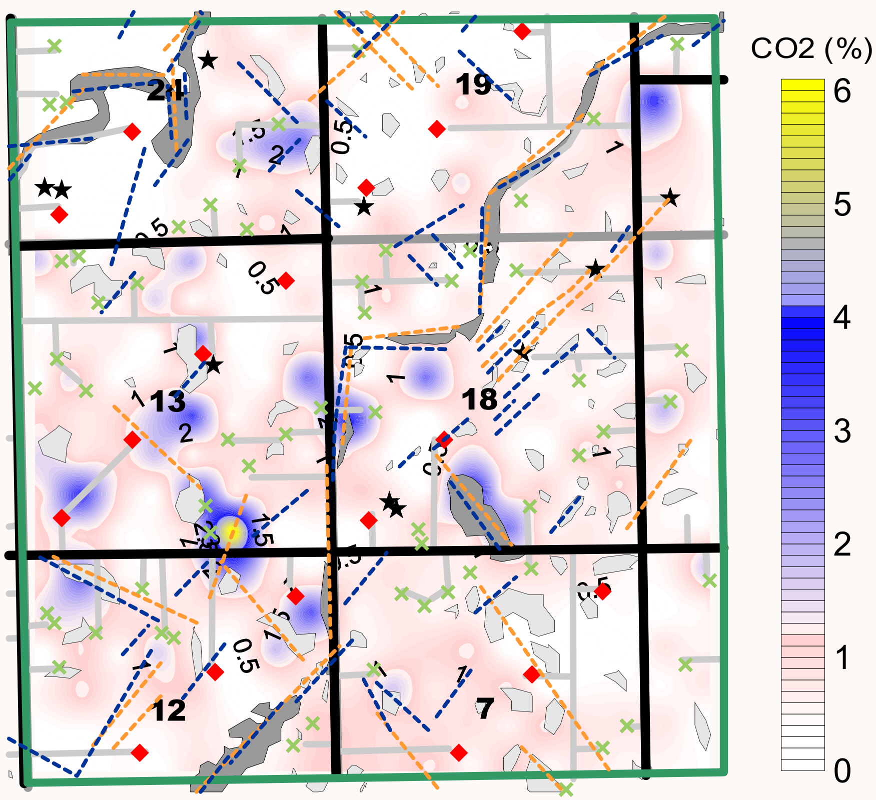
Soil gas grid

Normal probability plot for CO_2

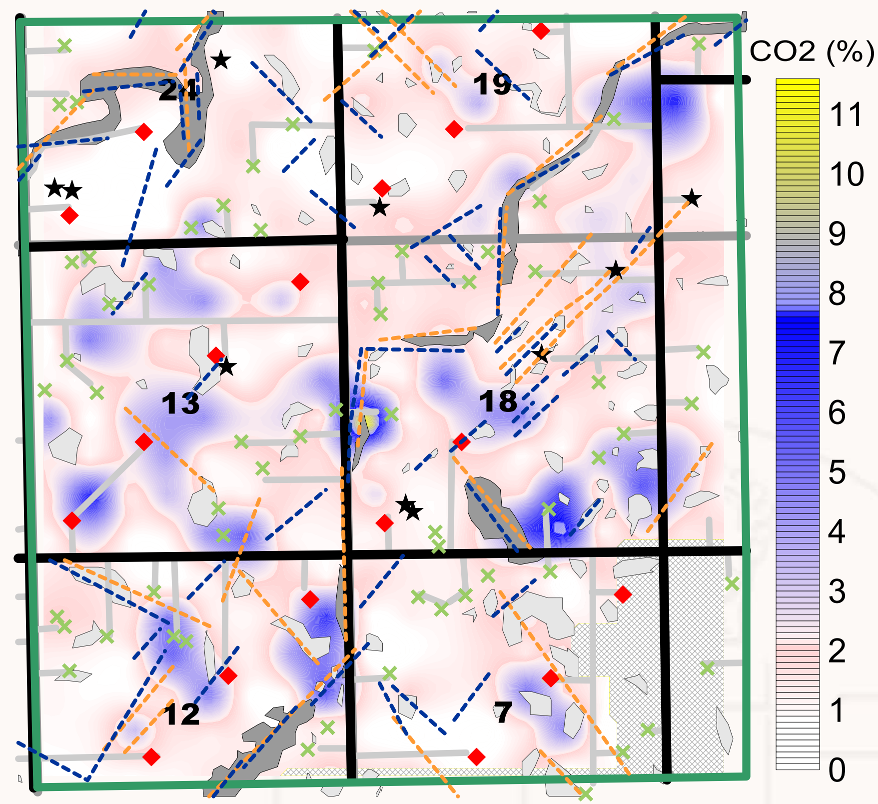


CO_2 distribution - 2002 v 2001 data

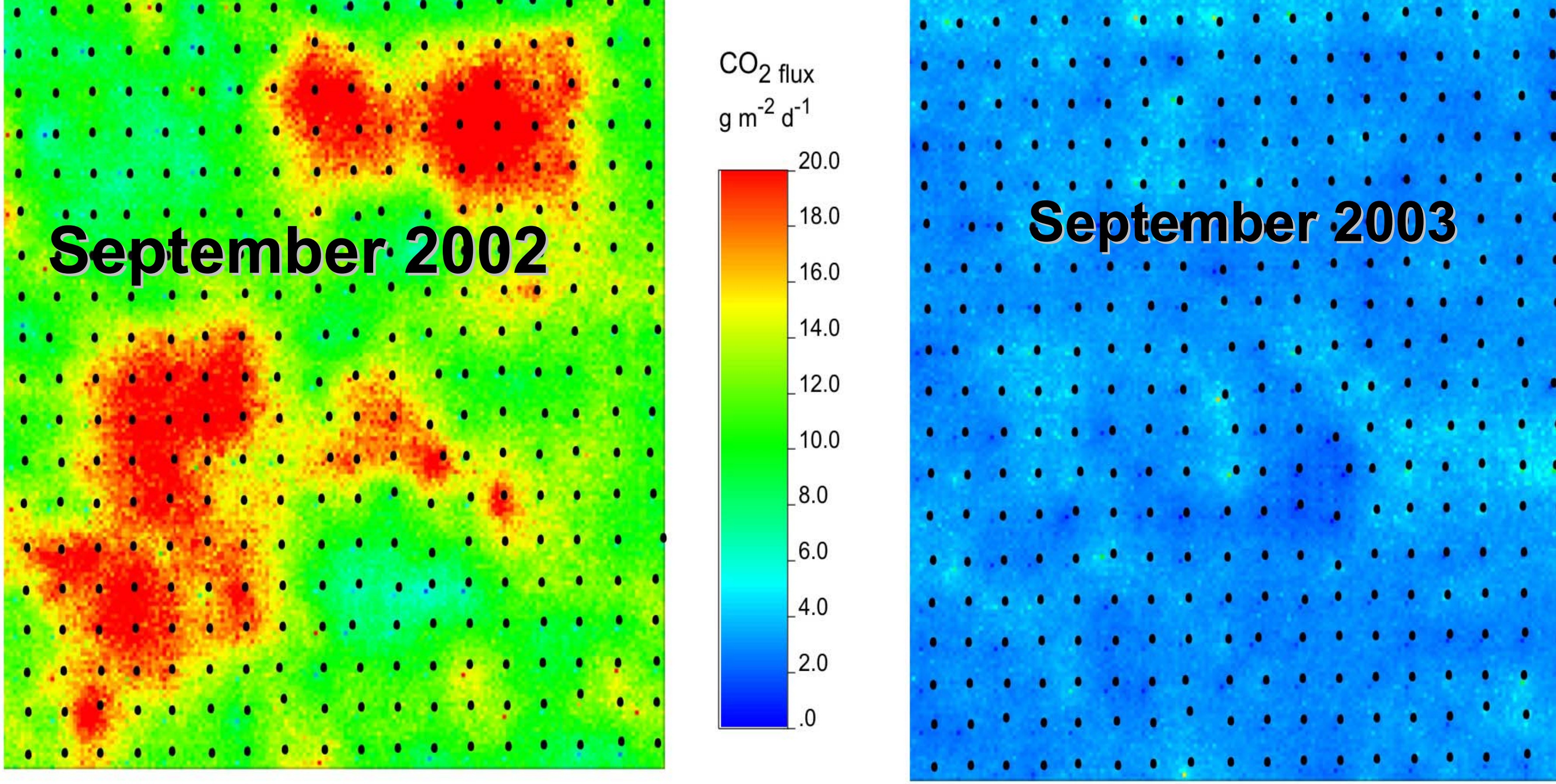
URS lab data - 2002



URS lab data - 2001



- very similar distribution, much lower values in fall 2002



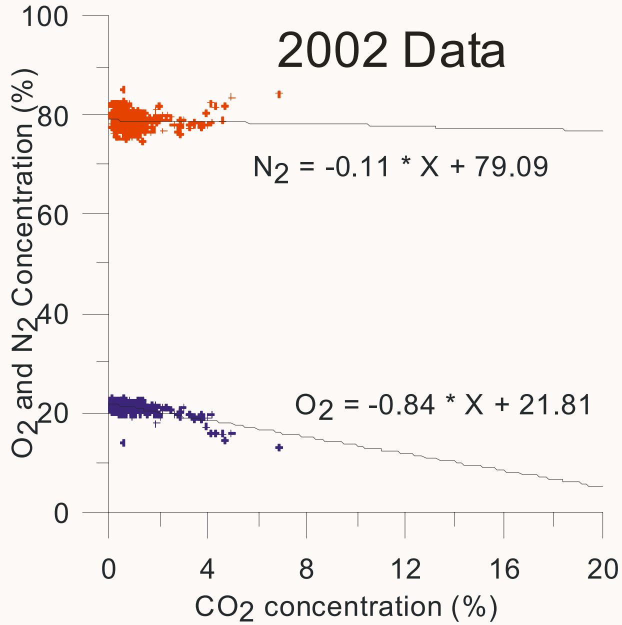
mean	12.73 g m^{-2} d^{-1}	mean	3.03 g m^{-2} d^{-1}
max	56.4 g m^{-2} d^{-1}	max	16.2 g m^{-2} d^{-1}
min	0.84 g m^{-2} d^{-1}	min	0.11 g m^{-2} d^{-1}
std	9.24 g m^{-2} d^{-1}	std	2.38 g m^{-2} d^{-1}

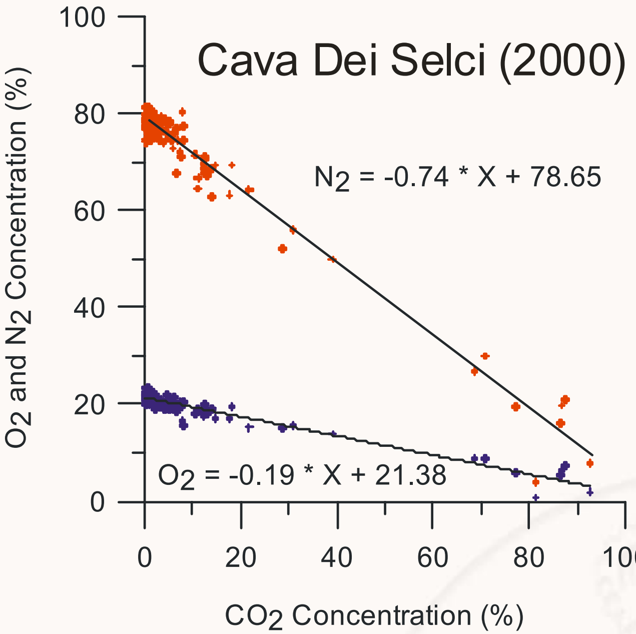
Total CO_2 output =
181.1 ± 4.4 t/d
(14 km^2 A1 Injection area)

CO_2 flux

Total CO_2 output =
42.54 ± 0.6 t/d
(14 km^2 A1 Injection area)

O_2 and N_2 versus CO_2

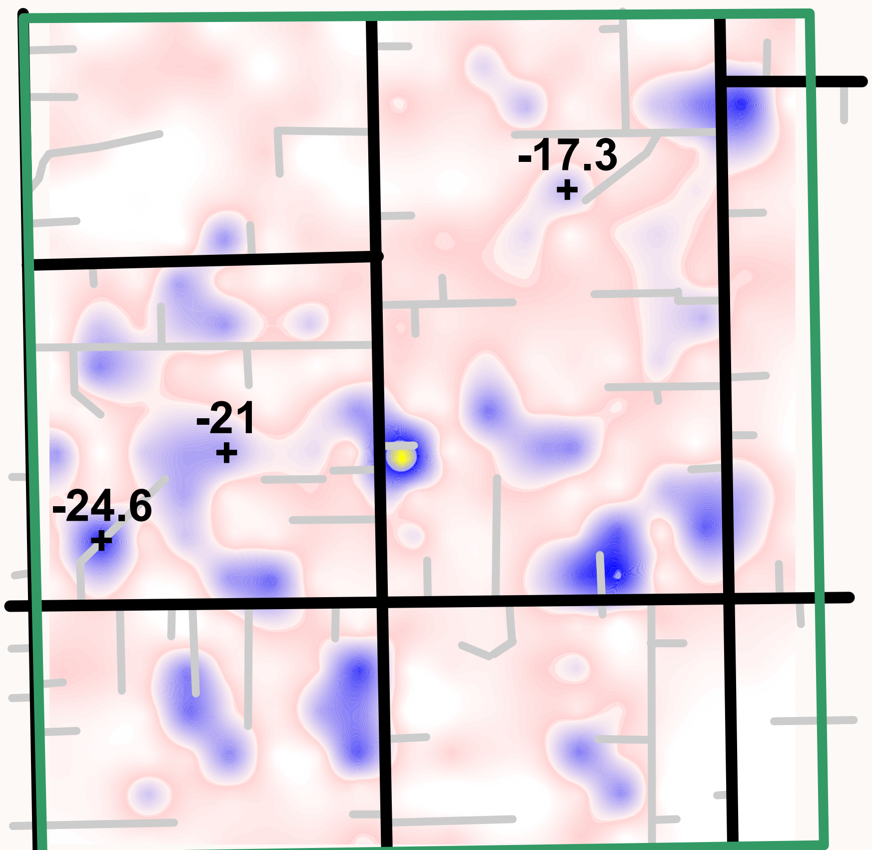




- N_2 values essentially constant
- O_2 decreases at a rate almost equal to 1:1 towards 20% CO_2
- implies microbial origin of CO_2 via aerobic chemoheterotrophs

organic matter + O_2 ------> energy + CO_2 + H_2O

$\delta^{13}C$ Isotopic analysis of soil gas CO_2

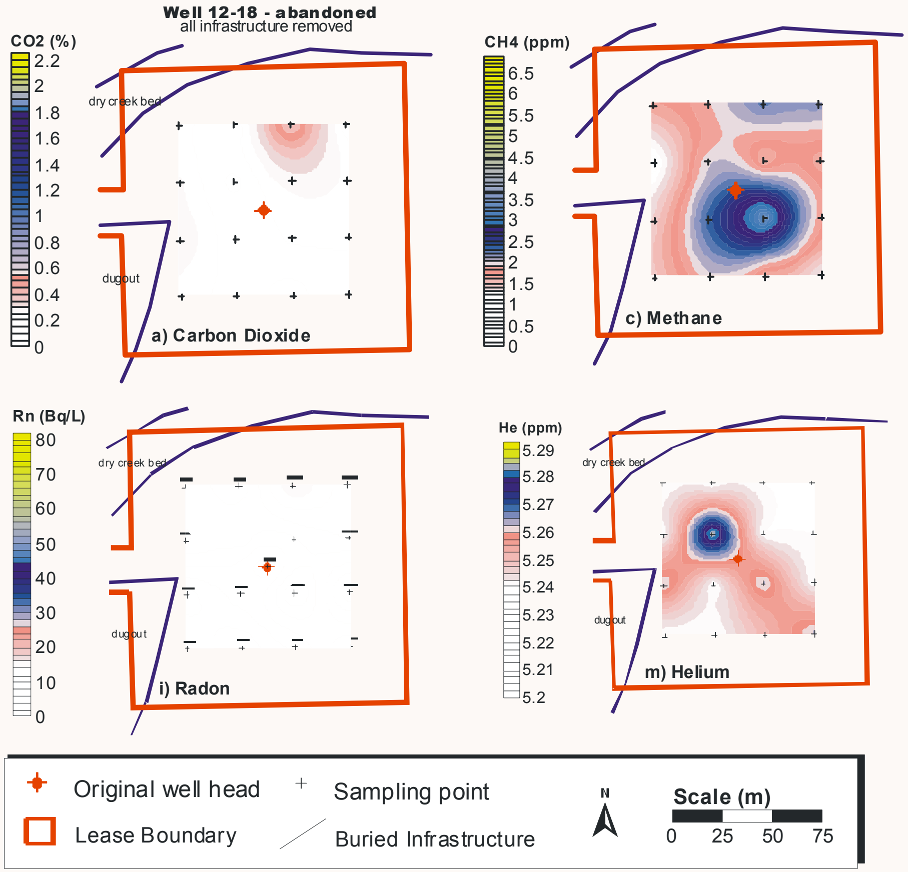


- Samples originally collected in summer of 2001
- Analysed by the University of Calgary
- Plotted here on the soil gas CO_2 data from 2001
- Values range from –17.3‰ to –24.6‰

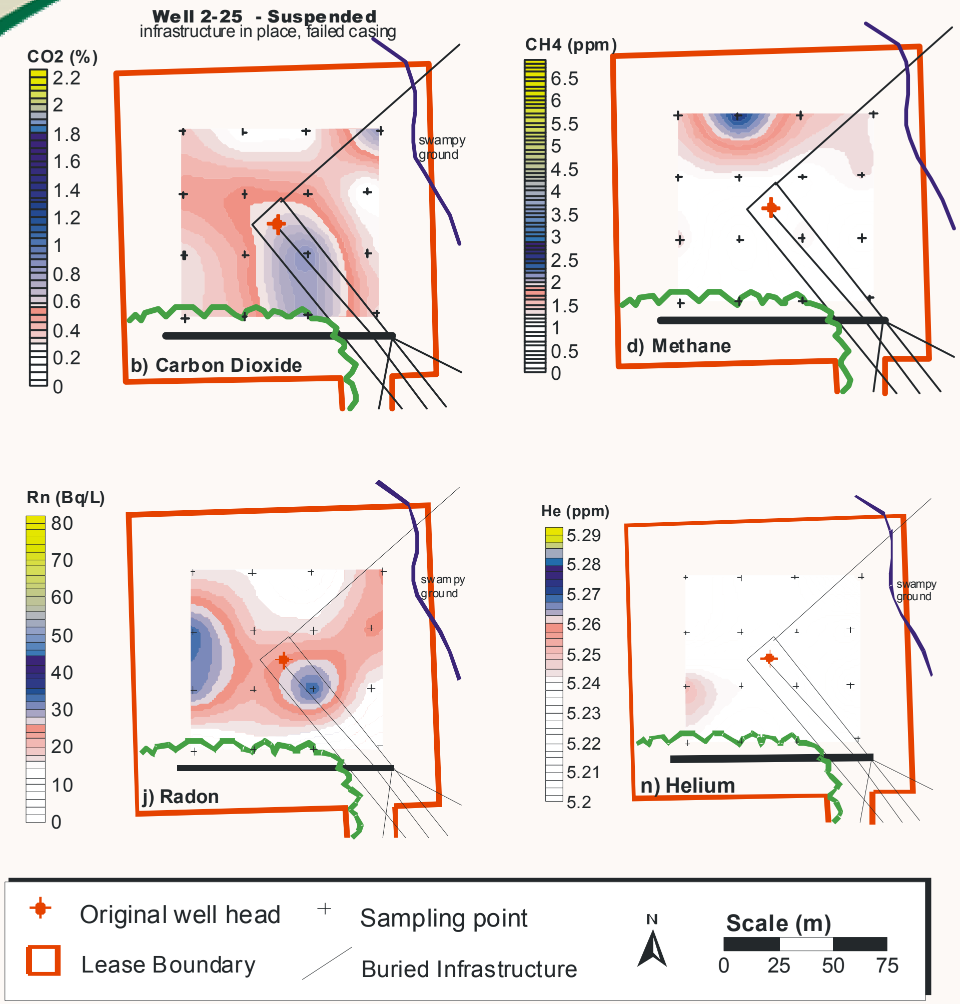
$\delta^{13}C$ Isotopic analysis of soil gas CO_2

	δ13C value
C3 plants (eg. wheat)	-35 to -21 ‰
C4 plants (eg. corn)	-21 to -9 ‰
Injected CO_2	-35‰
Atmospheric CO_2	-11‰
Weyburn 19SE-5	-17.3‰
Weyburn 13SE-13	-21‰
Weyburn 13SW-6	-24.6‰

- Values are within range of soil gas CO_2 produced by microbial or root metabolism of organic matter from local plants
- Values are substantially higher than that of the injected CO_2
- Range of values may be due to different plant types or variable dilution with atmospheric air


Well 12-18 - abandoned
all infrastructure removed
CO2 (%)
dry creek bed
dugout
a) Carbon Dioxide
CH4 (ppm)
c) Methane
Rn (Bq/L)
i) Radon
He (ppm)
m) Helium
Original well head
Sampling point
Lease Boundary
Buried Infrastructure
N
Scale (m)
0 25 50 75


Abandoned well 12:18


Well 2-25 - Suspended
infrastructure in place, failed casing
CO2 (%)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
swampy ground
b) Carbon Dioxide
CH4 (ppm)
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
d) Methane
Rn (Bq/L)
80
70
60
50
40
30
20
10
0
swampy ground
j) Radon
He (ppm)
5.29
5.28
5.27
5.26
5.25
5.24
5.23
5.22
5.21
5.2
swampy ground
n) Helium
Original well head
Sampling point
Lease Boundary
Buried Infrastructure
N
Scale (m)
0 25 50 75


Suspended well 2:25

Conclusions

- Approach:
  - repeat general monitoring
  - focus on sites where escape from depth is more likely (lineaments, abandoned wells)
  - both for repeat measurements and continuous monitoring.
- Data from 2001-03 are all consistent with a biogenic CO_2 origin
- The background site gave similar data to main grid area (soil composition and gas concentrations/flux)
- No indications of significant gas escape at new sites
- Barasols give derived CO_2 flux at 2m depth 10-20 times lower than at surface
- So far no evidence for escape of injected CO_2

Lessons from Weyburn

- Grid → profile → continuous monitoring approach seems to work well
- Baseline important (need a good initial dataset) but annual/continuous monitoring needed to establish and understand baseline variability
- Other sources of information important (surface and subsurface geology, faults/fractures, lineaments)
- May need denser sampling (rapid field techniques), continuous monitoring of more gases/parameters and research into microbial processes
- Further evaluation of potential gas migration pathways (wells, lineaments etc)
- More C isotope work (inc. vertical profiles)

Summary: Are there any limitations in the techniques currently used?

- Need supporting data from other studies including
  - microbiology
  - soil/surficial sediment characterisation
  - shallow geophysics
  - lineament characterisation
- Seasonal, meteorological and diurnal variations could mask episodic gas release at low concentrations
- Point-specific measurements
- Defining source of a CO_2 anomaly
  - Inert tracers co-injected with the CO_2…?
  - Isotopes
  - Relations between different gases (e.g. Rn, He, C_n…)

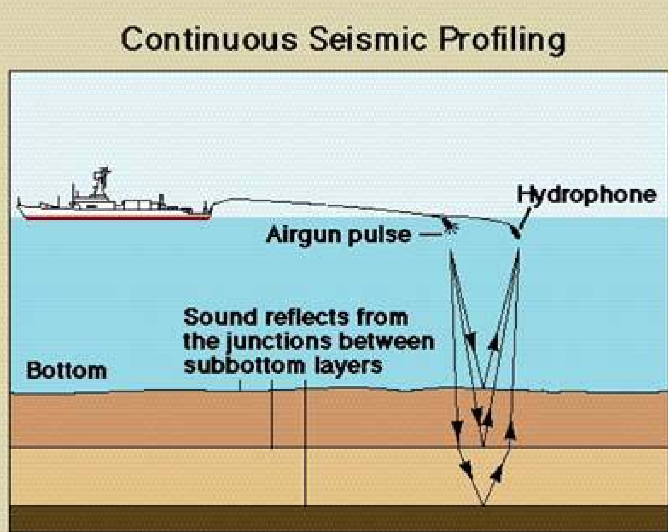
Summary:
Are new techniques being developed?

- Offshore shallow gas monitoring
  - High frequency sub-bottom profiler records gas occurrences in sediments & water column (TNO Nascent project)
  - Already demonstrated by URS for CH_4 in Black Sea
  - Being developed for atmospheric-marine CO_2 exchange by PML in UK

Marine acoustic and seismic surveys

Hull mounted or floating single channel 3.5 kHz system (sub-bottom profiler)

Marine seismic data acquisition

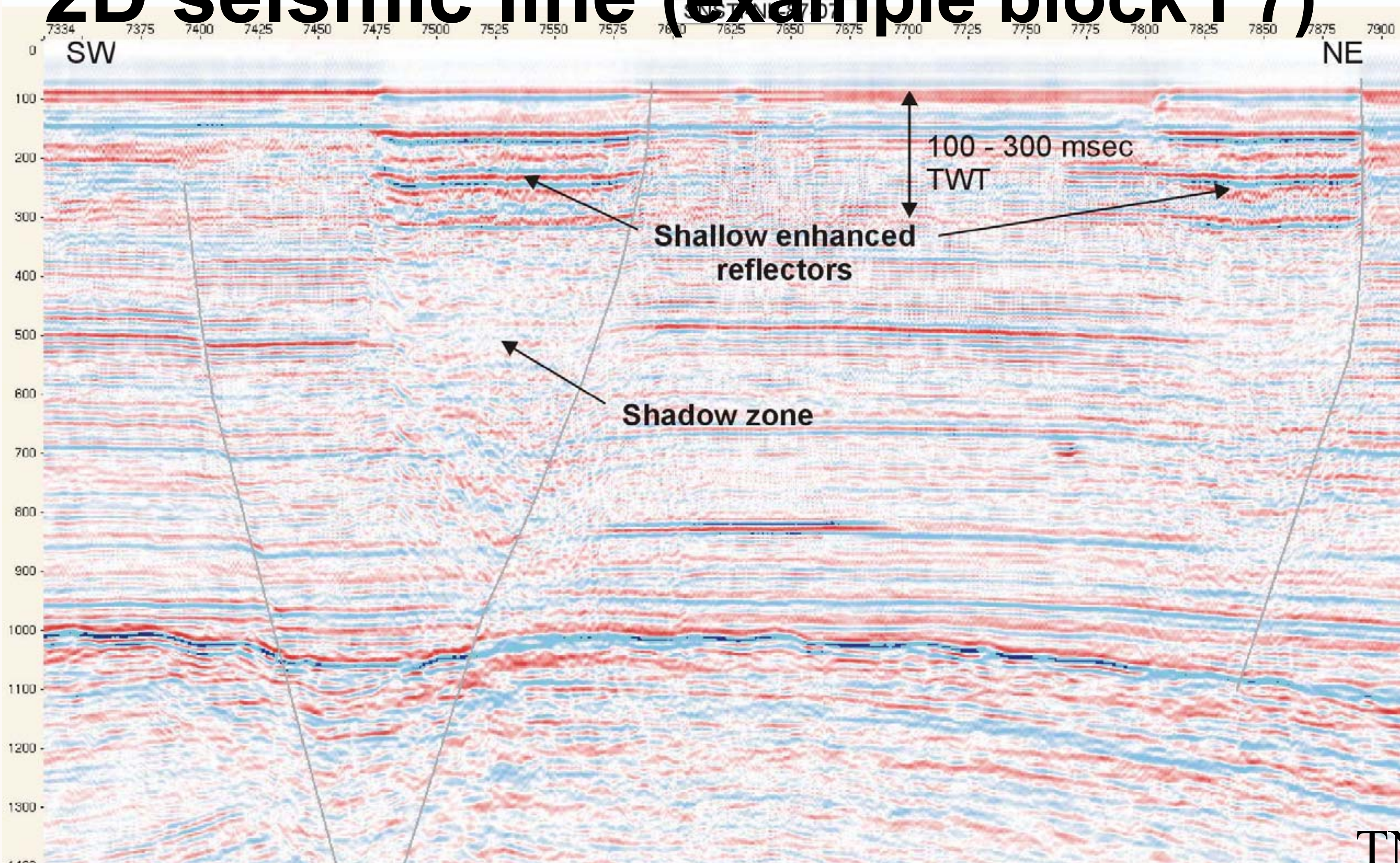


Images up the 5000 meters below sea bed

Images the shallowest tens of meters below sea bed, but also effects in the water column

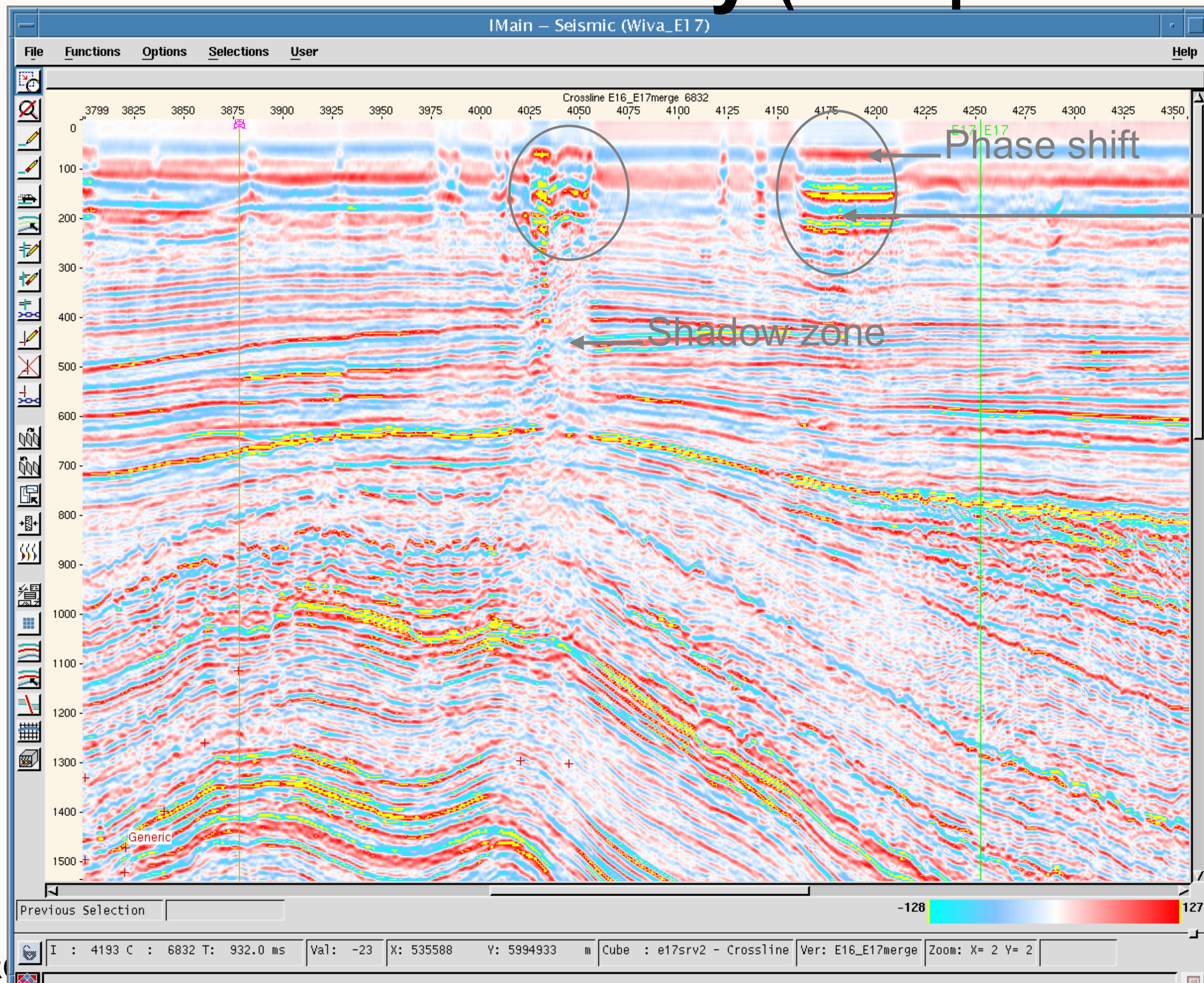
TNO

Shallow enhanced reflectors on 2D seismic line (example block F7)



TNO

Shallow enhanced reflectors on 3D seismic survey (example block E17)



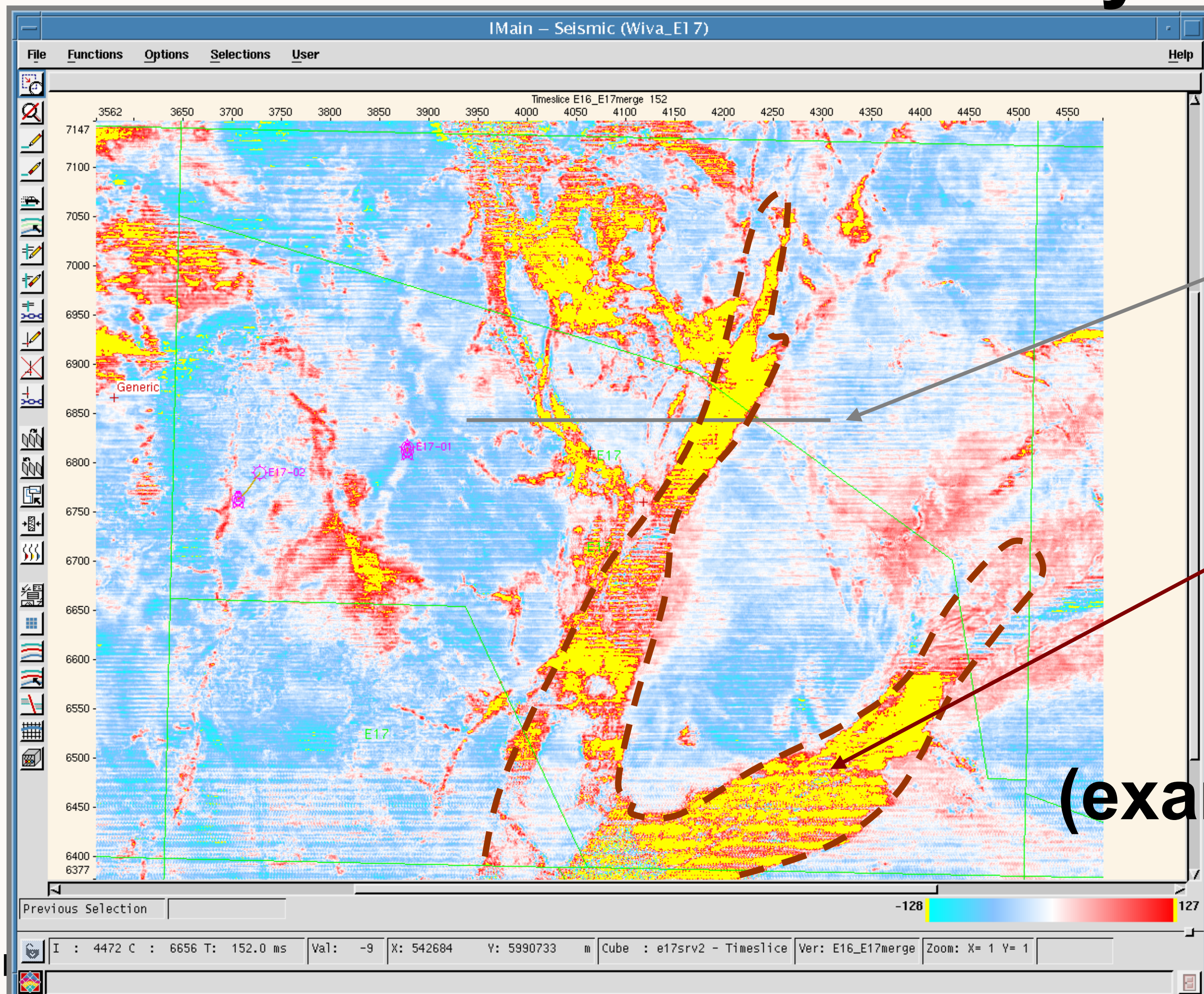
Multiple of the first gas-sand ??

These are seismic anomalies corresponding to gas saturation of shallowest layers.

TNO

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

Shallow enhanced reflectors on 3D seismic survey



Time-slice at 152 msec

Profile from previous slide

Glacial Channels?

(example block E17)

TNO

Area 1: A seabed pockmark in block A11

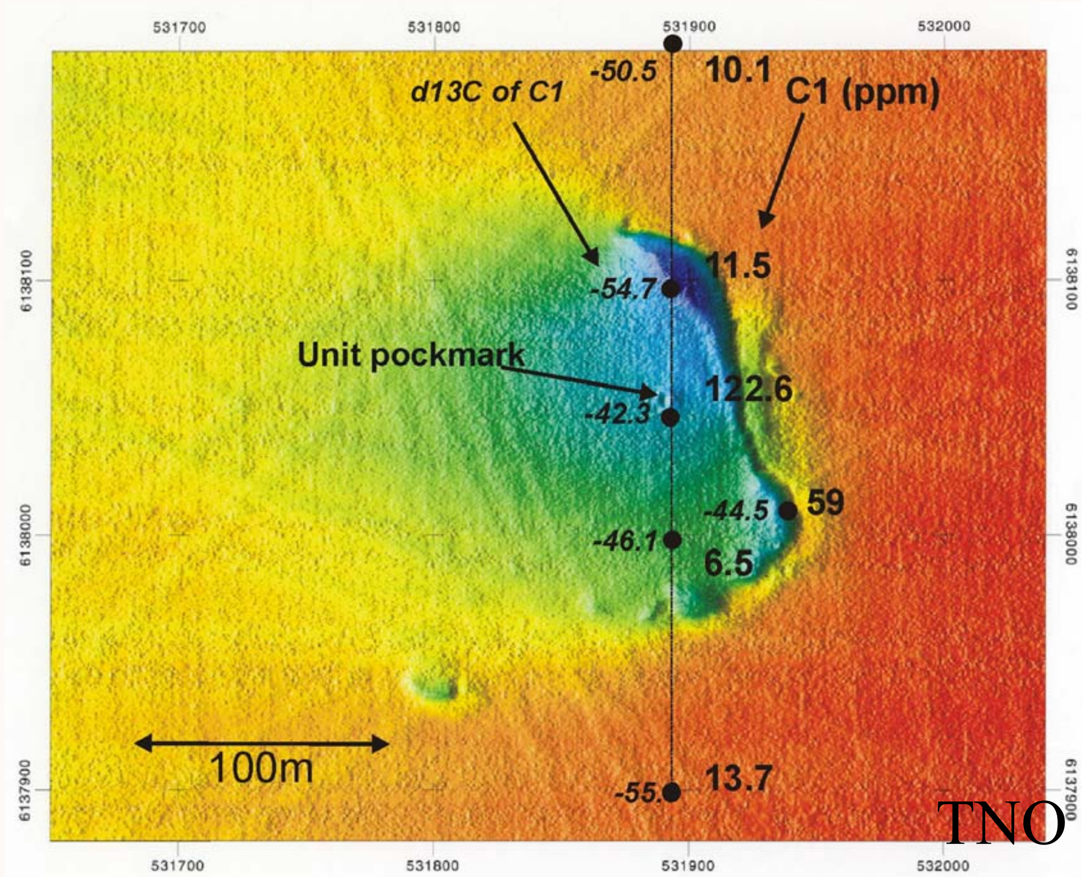
multi-beam image & headspace gas analysis

1. Multi-beam image shows seabottom morphology:

   depression = seabed pockmark

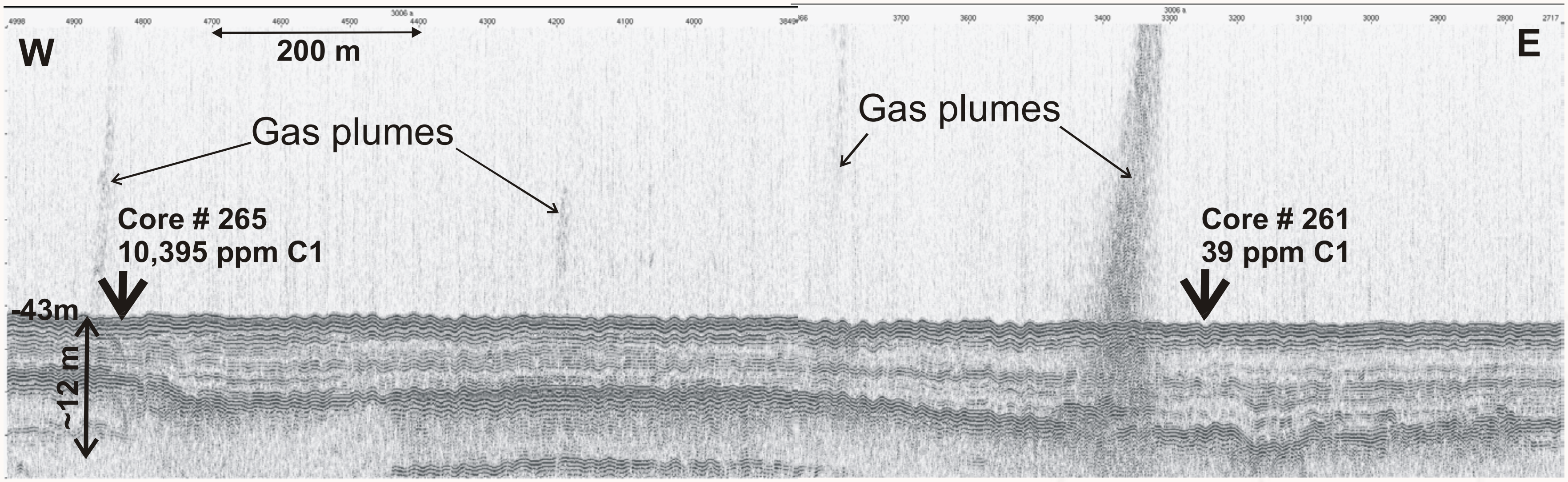
2. Geochemical analysis:

   122.6 ppm CH4 represents a geochemical anomaly



Gas plumes in the water column

example from block B13 (area # 2)



High frequency sub-bottom profiler record (TNO, 2002):
Active venting observed in block B13 over a Plio-Pleistocene shallow gas field

Associated : geochemical anomalies (up to 10,395 ppm methane)

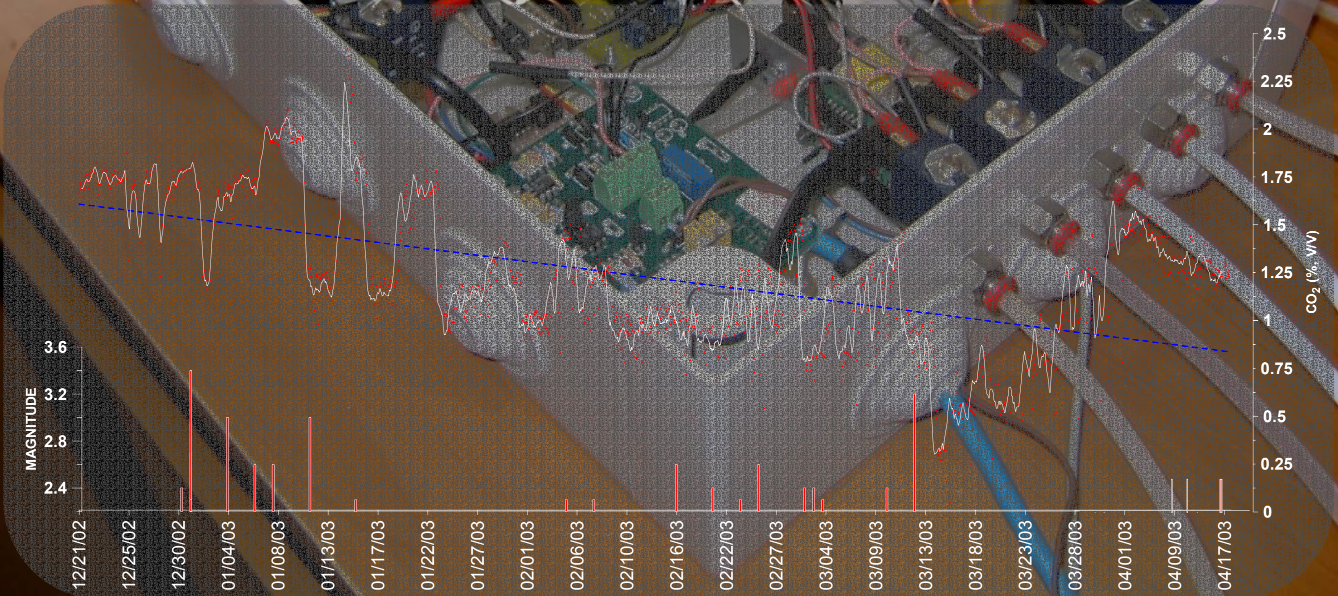
TNO

Summary:
Are new techniques being developed?

- Automatic “continuous” monitoring stations
  - Location of station is crucial – needs supporting data
  - Tested at sites of natural seeps (Nascent) which demonstrated technology

Continuous automatic monitoring

- Developed at URS and tested at San Vittorino, Italy to monitor sinkhole development
  - Rapid limestone dissolution in CO_2-rich groundwaters
- Dissolved CO_2 measured continuously
- Linked to seismic events during same period



Summary

- **Closer integration with other techniques**
  - **Remote sensing:**
    - Airborne – hyperspectral, thermal infrared, EM
    - Satellite – radar interferometry
  - **Open path laser methods for rapid surveying**
    - Involves firing an eye safe IR laser above the ground for distances up to 1-2km.
    - Small increases in atmospheric concentrations (e.g. CO_2 or CH_4 from any leaks) can be detected.
    - Suited to sites that are onshore, relatively flat and generally free of obstructions.
  - **Eddy covariance**
  - **Water chemistry (pH, dissolved gas) in shallow wells, springs, monitoring wells – used at natural analogues in Nascent project**

Summary

- **Are there any barriers to the use of these techniques?**
  - **Cost**
  - **Speed**
- **What further research is needed to improve confidence in the monitoring results?**
  - **Integrate with other techniques and develop 'risk' maps**
  - **Improve calibration protocols**

Geobotanical Hyperspectral Remote Sensing

Monitoring and Verification of Possible CO2 Leakage from Underground Storage Formations

We Use Airborne High Resolution Hyperspectral Imagery, and Satellite Imagery

The Test sites are the Rangely CO, EOR Field and
The Casper RMOTC NPR-3 Tea Pot Dome Oil field

William L. Pickles, LLNL and UC Santa Cruz
Wendy A. Cover, UC Santa Cruz
Donald C. Potts, UC Santa Cruz
Brigette A. Martini, HyVista Corp, Sydney, Australia
Donald G. Price, PG&E Corp, San Ramon CA, USA
CCP2 Monitoring Nov 8, 2004

Monitoring and Verification of CO_2 Leakage from Underground Storage Formations

- We have developed airborne hyperspectral remote sensing methods for early detection and spatial mapping, over whole regions simultaneously, of any significant CO_2 leaks from deep underground storage formations.
- If CO_2 gas percolates up along faults, cracks, or joints, from a storage formation below to within plant root depth near the surface, it will spread out and “hang-up” in the soil
- The CO_2 soil concentrations near the surface will become highly elevated and will affect individual plants and their local plant ecologies or habitats.
- 50 % CO_2 soil concentrations are observed to significantly affect local plant and animal ecologies at Mammoth Mountain CA USA.

Natural CO2 leaks from underground magmatic formations occur at Mammoth Mountain California USA

- Horseshoe Lake southeast of Mammoth Mountain
- Lethal CO2 concentrations for animals and humans exist near the ground and in holes, buildings, etc.

- Areas of tree kills are found at many places on Mammoth Mountain
- They are caused by highly elevated CO2 soil concentrations (>50%) that suffocate the root systems,
- Roots require Oxygen to function properly

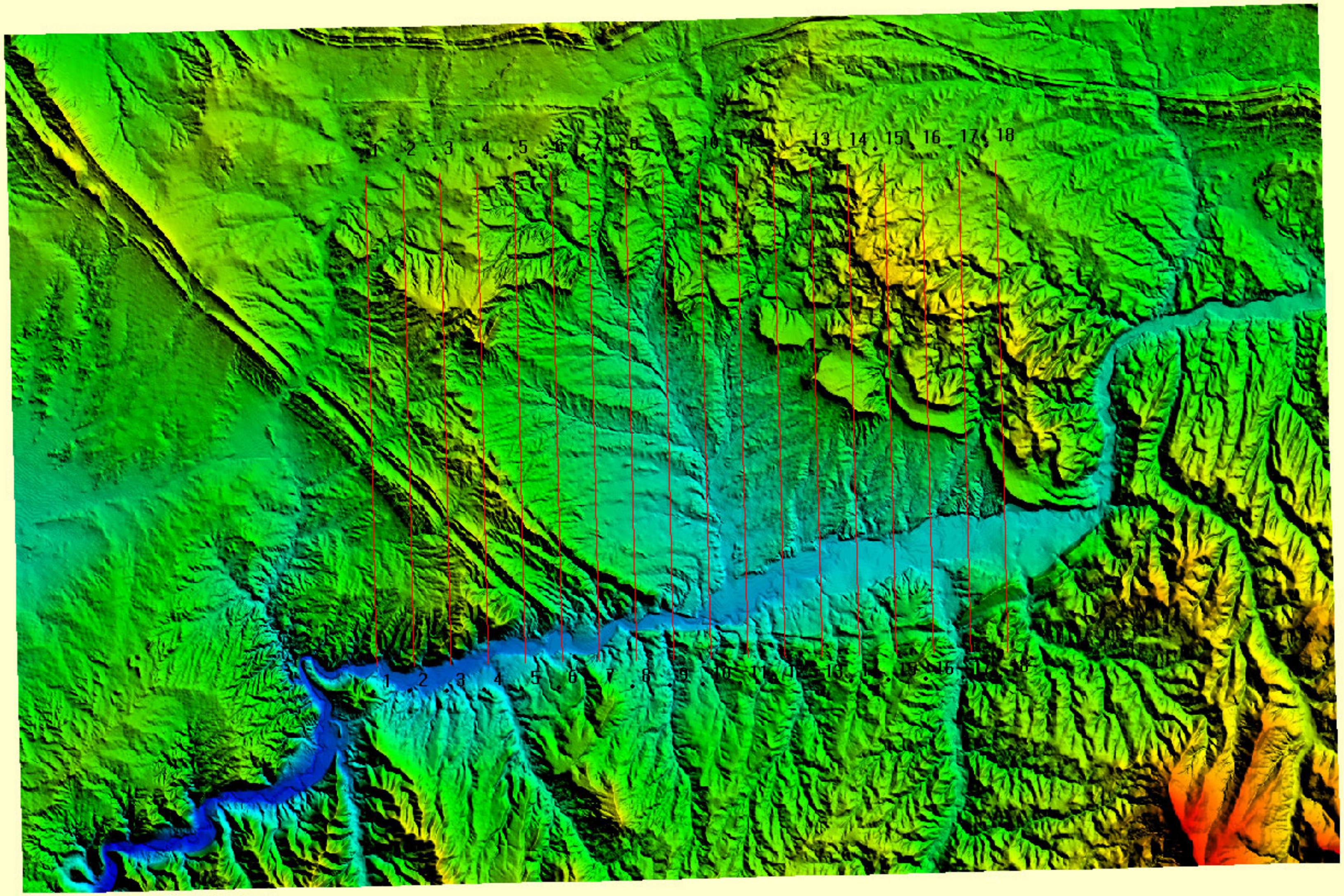
LLNL/UCSC Geobotanical Remote Sensing CO2 Monitoring Program for CCP SMV

- We are applying our Geobotanical remote sensing techniques
  - For mapping "habitats *" for baselining and subsequent change detection to find any effects of leaking CO_2/CH_4
  - For mapping subtle or hidden faults, cracks, and joints
  - For mapping known, or buried abandoned well heads
  - For possible direct detection of large CO_2/CH_4 leaks into the air using an absorption feature in the hyperspectral imagery
- We use very high spatial resolution imagery including
  - Manned Airborne
    - Hyperspectral by HyVista 3m or less spatial resolution
  - Unmanned Aerial Vehicles UAV
    - Hyperspectral 1 m and possible CO2/Ch4 gas sniffers, small NASA AMES UAVs, low altitude
  - Satellite High resolution
    - Digital Globe- Quickbird 0.6 meter resolution PAN & 2.4 M MS
- Rangely Colorado EOR field demonstration site
    - 3 meter spatial resolution hyperspectral imagery -acquired Aug 2002
    - Detailed analysis of the Hyperspectral imagery using ENVI done by Wendy Cover during spring/summer 2003
    - Extensive in the field analysis interpretation has been done by Wendy Cover and Bill Pickles, August 2003 Field work at Rangely CO
- Complete report published in the Two Volume CCP book

The Twin Otter is our most used aircraft

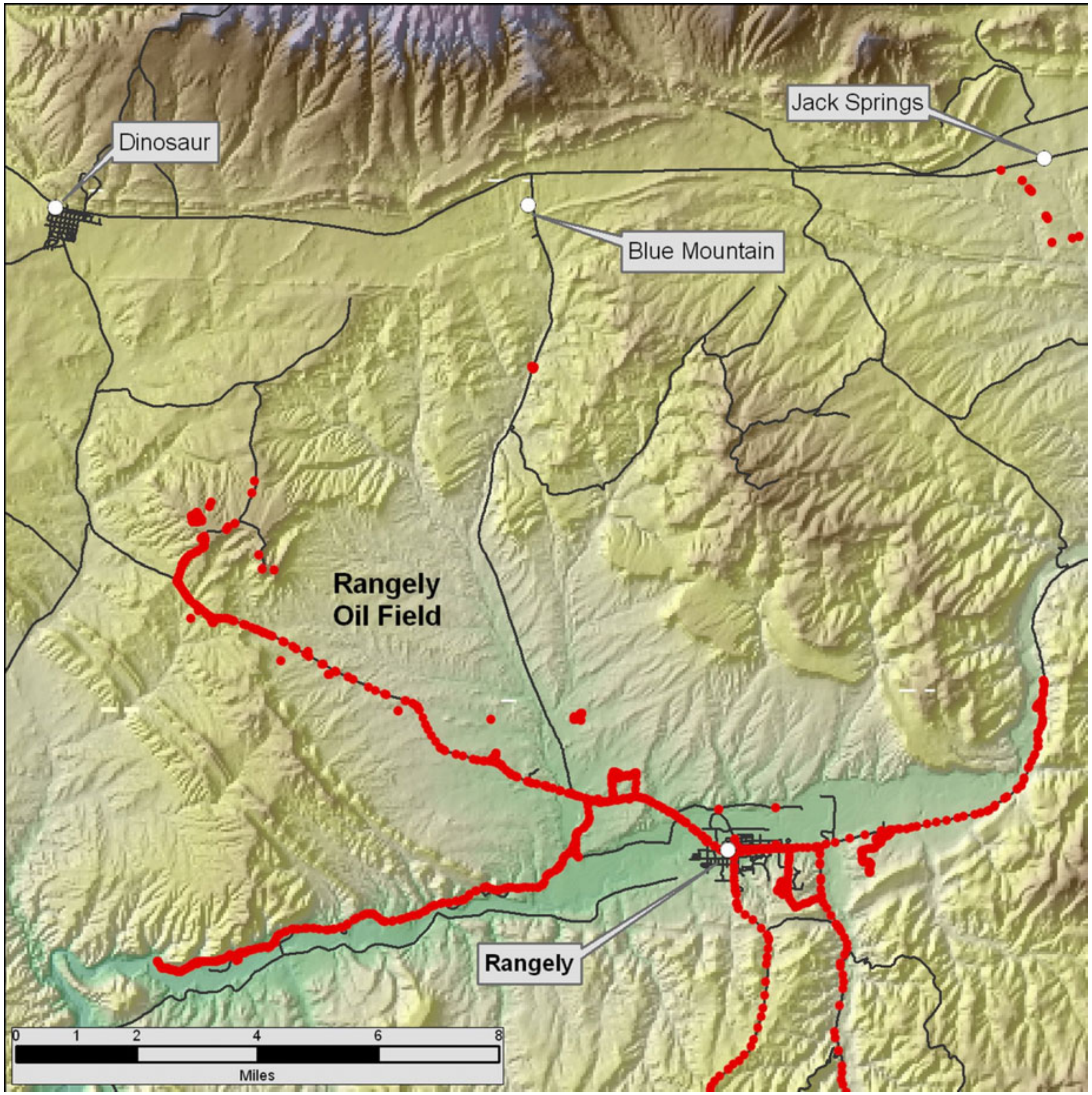
The hyperspectral imager (white) is mounted on an Inertial motion unit (yellow) in the aircraft over a hole in the floor

The spectrum and geolocation of each image pixel is stored by the on-board computer, in flight



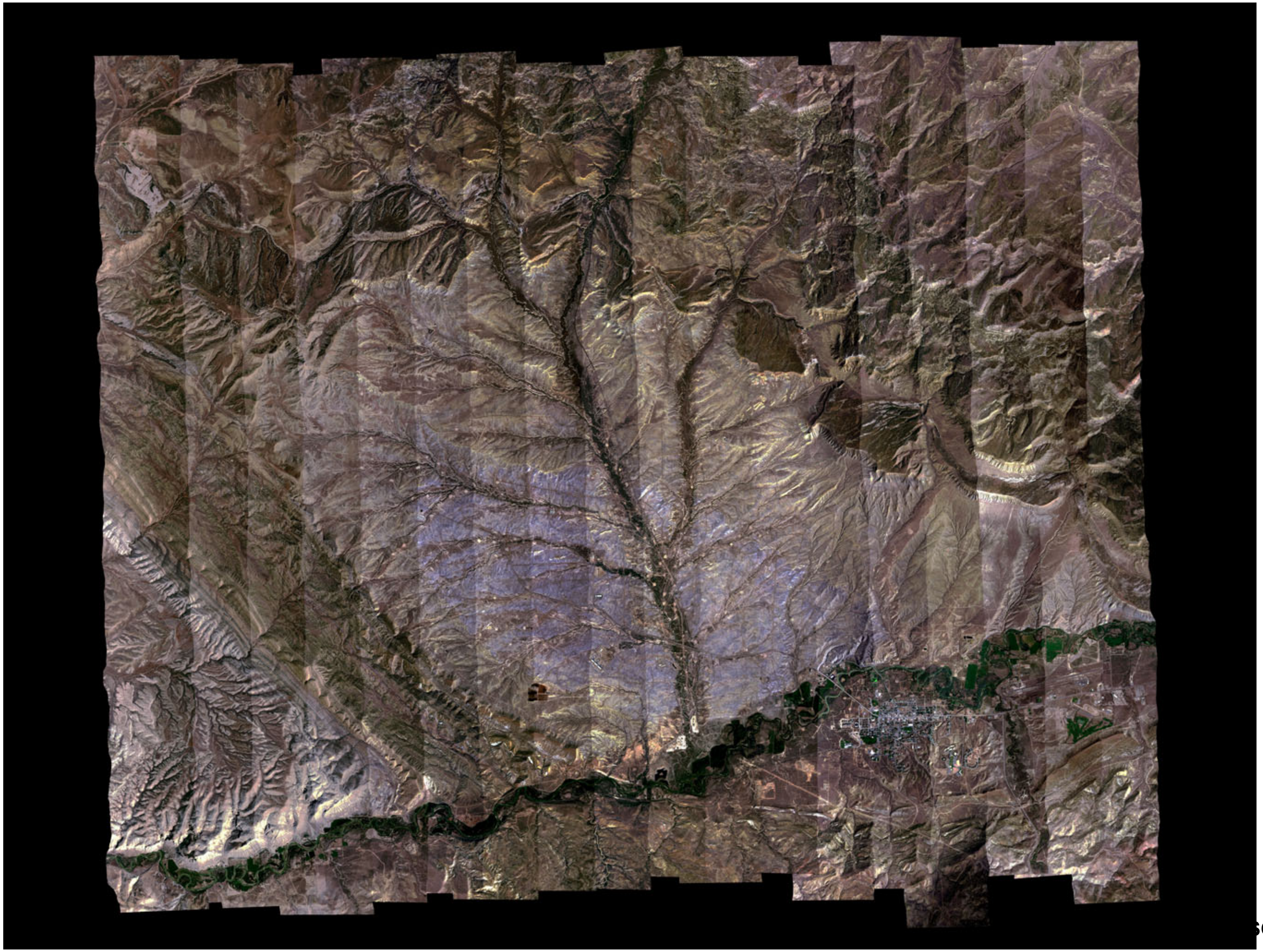
This is a digital elevation model of the Rangely Oil Field basin and surrounding formations. The White river basin is shown running from the center right to the lower left corner. The Rangely Oil field basin is in the center of the figure. The 18 flightlines that were flown to acquire the 18 strip images are shown in red. They are exactly due north and south by design. They are labeled 1 through 18. The town of Rangely CO is located in the White River Basin close to line 14. The folded formations whose motion created the oil field are easily seen running from southeast to northwest on either side of the basin and east west across the top. Mellen Hill and the Mellen Hill fault can be easily seen at the north west end of the oil field basin. (Done by Brigette Martini)

Relief map of the Rangely Oil Field and surrounding area with our study locations recorded by DGPS



Rangely Oil Field picture taken along northern study route

Mosaic of RGBs made from all 18 Flightlines of Hyperspectral Imagery of Rangely EOR field White River and the town of Rangely

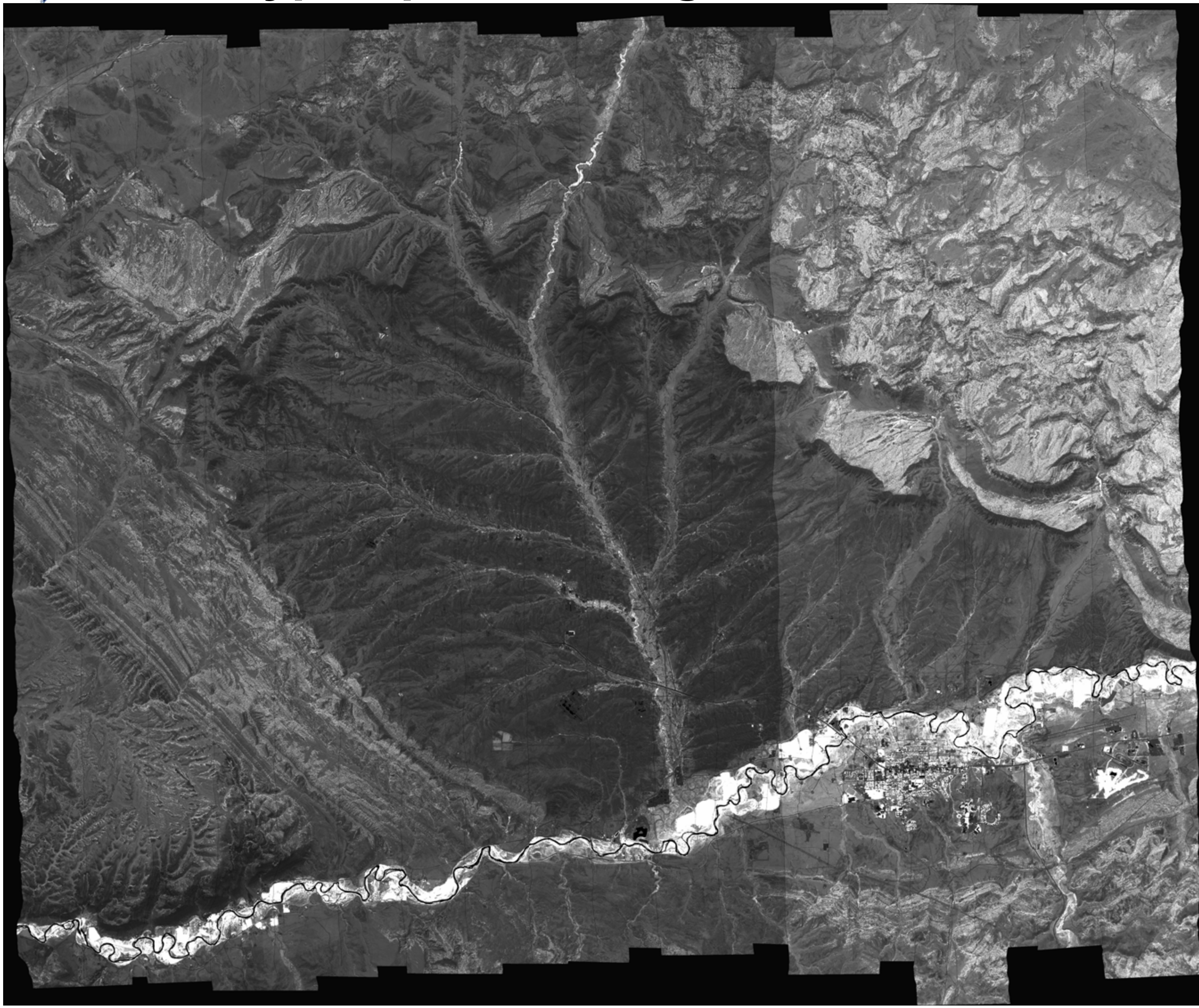


- Oil Field is approximately the bluish area
- Folded formations box the basin
- The White River runs across the bottom
- The town of Rangely is in the lower right quadrant south of the White River

UCSC Martini-9-21-03

HyVista Cocks-9-21-03

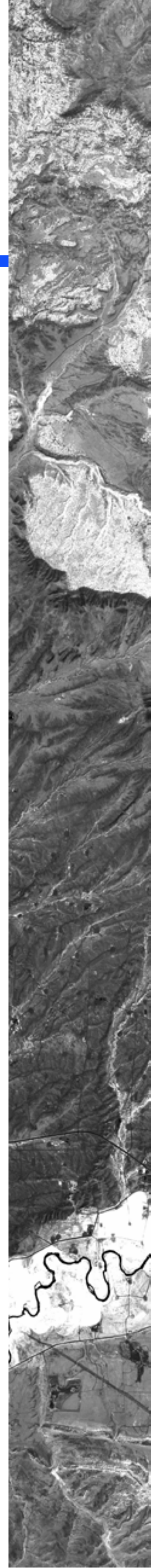
NDVI Vegetation Index applied to the Mosaic of all hyperspectral images



- NDVI Greyscale
- Whiter is higher probability of vegetation and/or healthier vegetation
- Right 1/3 of mosaic is from line 12 to 18 and was acquired after heavy thunder storms
- Provides highly accurate and detailed location of all vegetation at Rangely

Before and after rain line 12 shows increased plant greenness

- Line 12a on left was acquired on Tuesday in perfectly clear skies
- Wednesday and Thursday it rained heavily
- Friday 12 b on right was acquired in perfectly clear skies

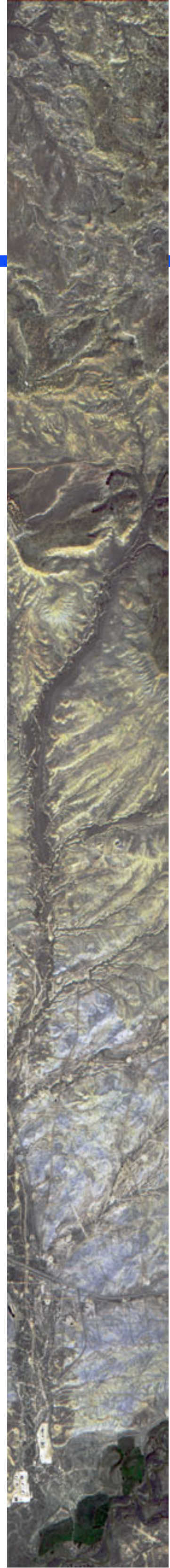


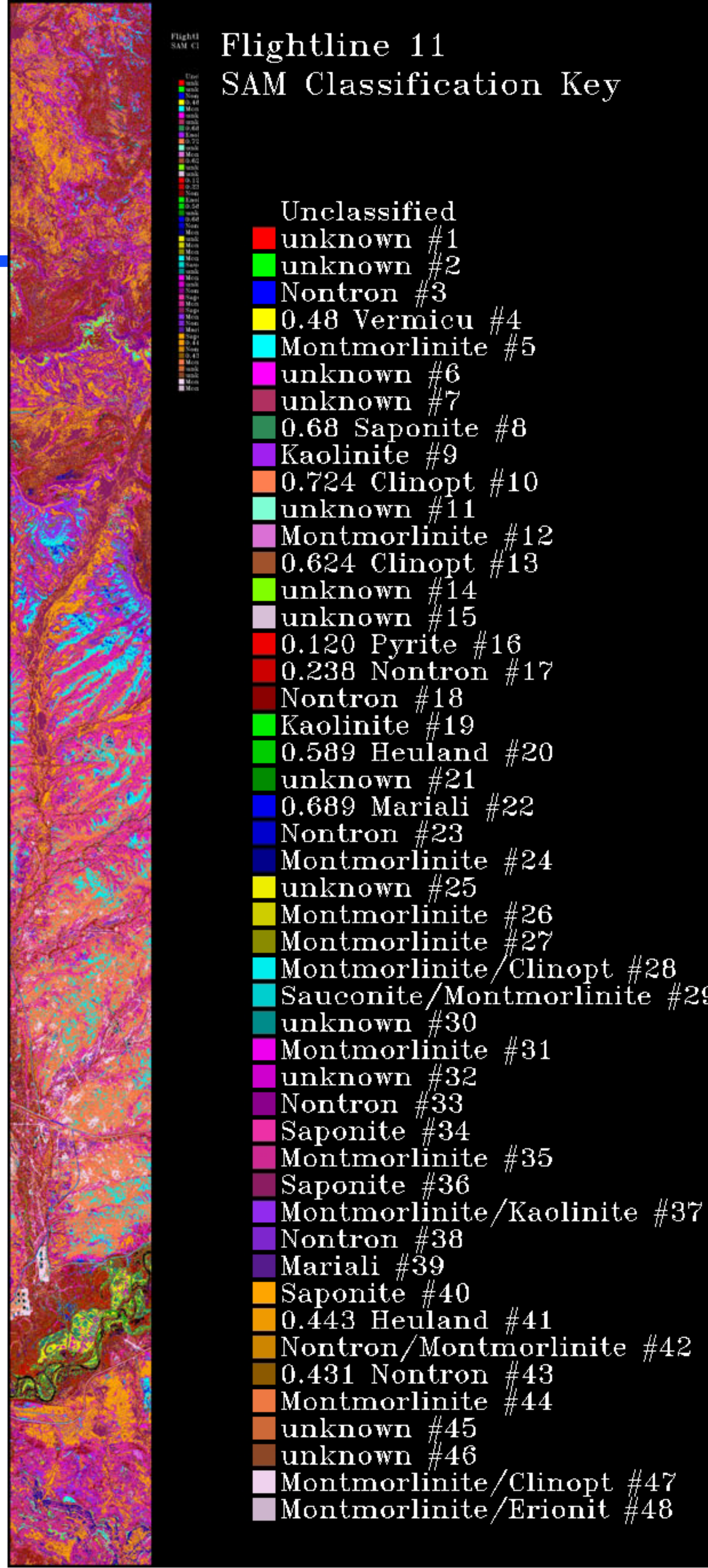
- 12A and 12 B showing plant pattern distribution does not change with rain
- the plants just get somewhat greener so
- environmental factors do not alter habitats rapidly
- Habitat shape changes could be caused by external factors such as CO_2 soil concentrations rising above normal ranges
- Changes would be recorded by reimaging the area on a time scale long enough for habitat change but short enough to ensure reservoir integrity

CCP SMV Geobotanical Hyperspectral imaging Program

- analyzed the Aug 2002 Rangely hyperspectral imagery, for the whole area, producing highly detailed and accurate "baseline"mapping of
  - "Habitats" * a new result explained later in this presentation
  - Soil /rock/mineral types
  - Plant distribution and relative apparent "greenness"
  - Water conditions in the White River
  - Rangely Town signatures
- used the analyzed imagery along with DGPS, "live" in our SUV, to direct our detailed on the ground studies at Rangely
- We have found absolutely no evidence of formation CO2 leakage in any of the imagery analysis or in our observations on the ground
- We have discovered that the hyperspectral imagery analysis naturally separates out mixed plant species "habitats" or intermediate scale ecologies.
- Slow gradual seepage of of moderate levels of CO2 will probably be seen as Habitat shape distributions
- "Plant stress" will be very difficult to detect in the high desert environment like Rangely because the plants species and soils are highly mixed in most pixels
- The plants like sage brush have many desiccated looking branches while they are very much alive and well. They are drought adapted species as are many at Rangely

SAM Analysis flight line 11



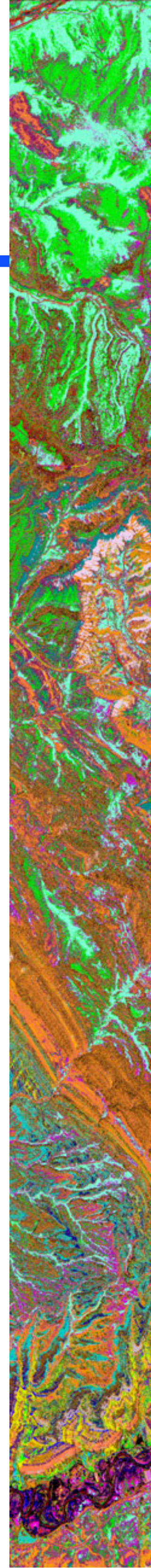


- "true" color image made from flight line 11 Bands 15,9,2 as RGB is on the left >
- Note the difference between a "true color" "picture" and the SAM analysis for mixed vegetation "habitats" , soils, and water on the right
- All flightlines are mosaiced so we can map regional habitats

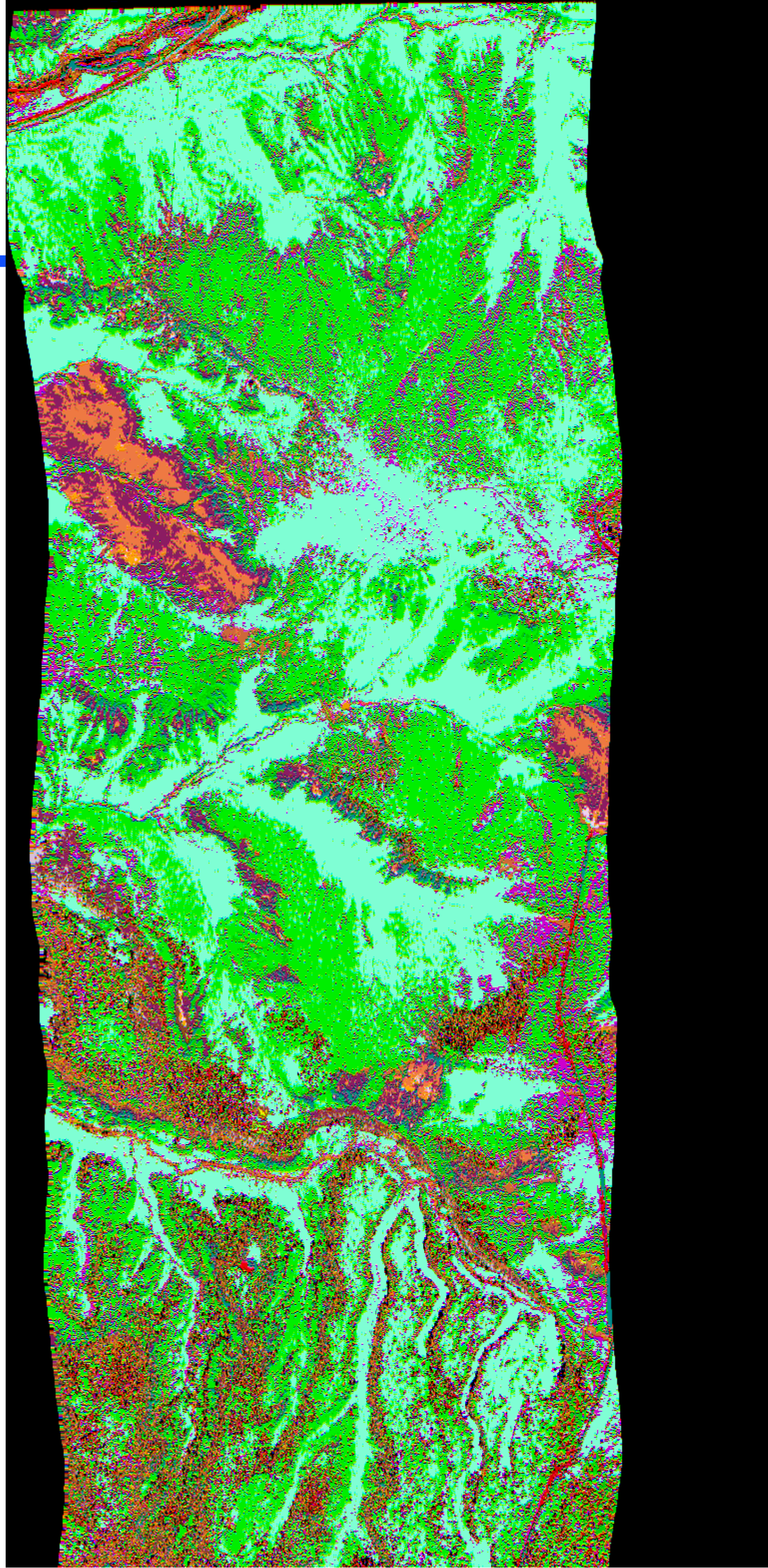
- 58 categories were found
- Many were identified using the USGS mineral spectral library
- The unknown categories were found to be mixed vegetation "habitats" when we went back into the field at Rangely with these analysis products
- During the field work we used georectified analysis maps such as this one in our laptops and DGPS live in our SUV to accurately locate and the identify these categories at many places in the oilfield, town, and surrounding areas

SAM Habitat map flight line 3

- “True color” image of flight line 3 made with Bands 15, 2, 9 as RGB is on left >
- Next to the right is the analysis for Montmorillonite and Kaolinite soil mixtures > and lush green vegetation which is found primarily near the White River > shown over the RGB



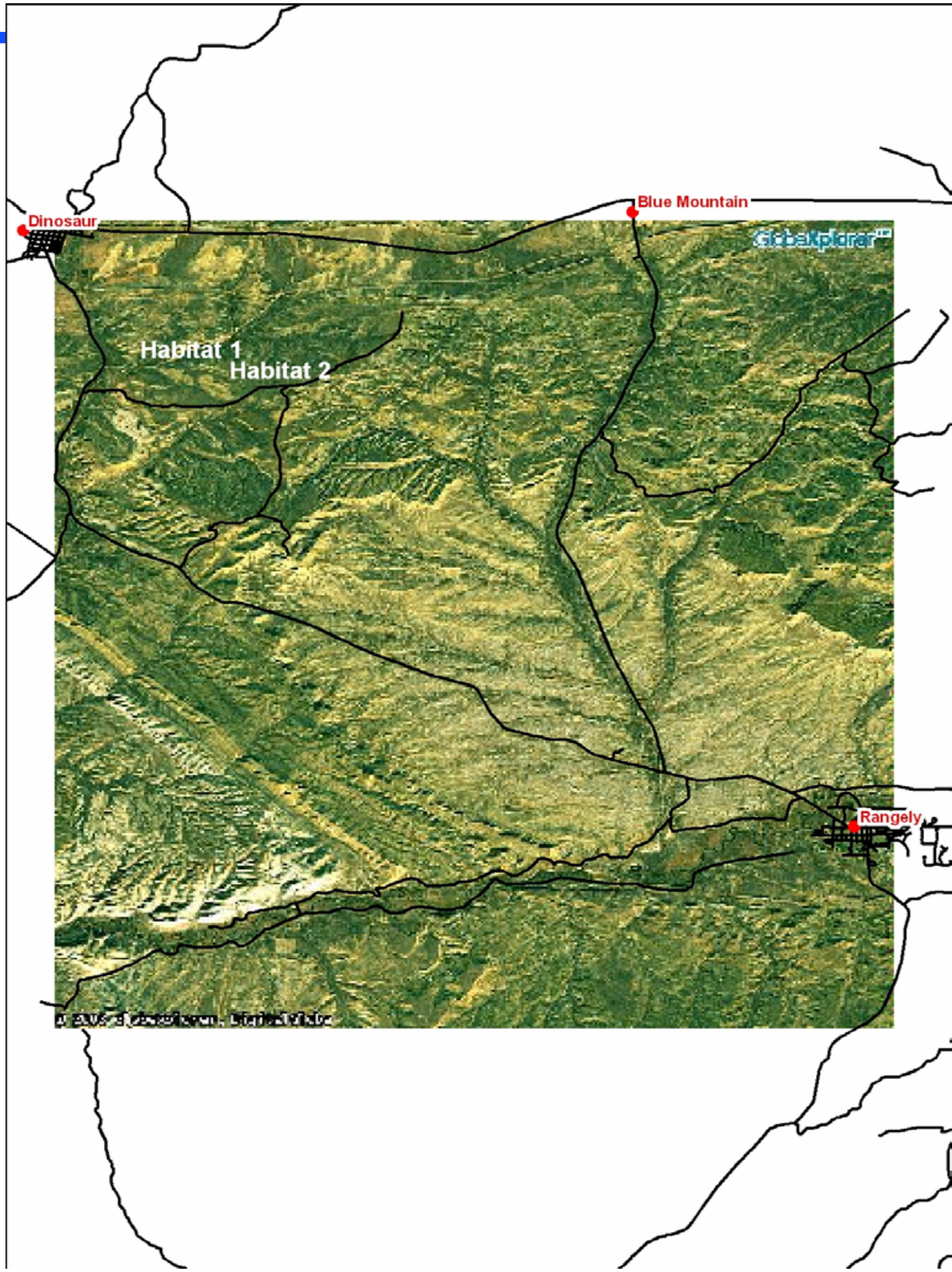
- In flight line 3 the SAM analysis categories shown in light blue and in green were found to be two distinct mixed vegetation “habitats” when we went back into the field at Rangely with these analysis products
- The habitats consist of healthy sage brush, mixed with golden dry cheek grass, and a percentage of dry soils
- We found these two habitats were all over the Rangely region once we learn to recognize them from the SAM analysis
- This result was unexpected and is a powerful means of mapping subtle meso-ecologies or “Habitats” with Mixed vegetation and soils



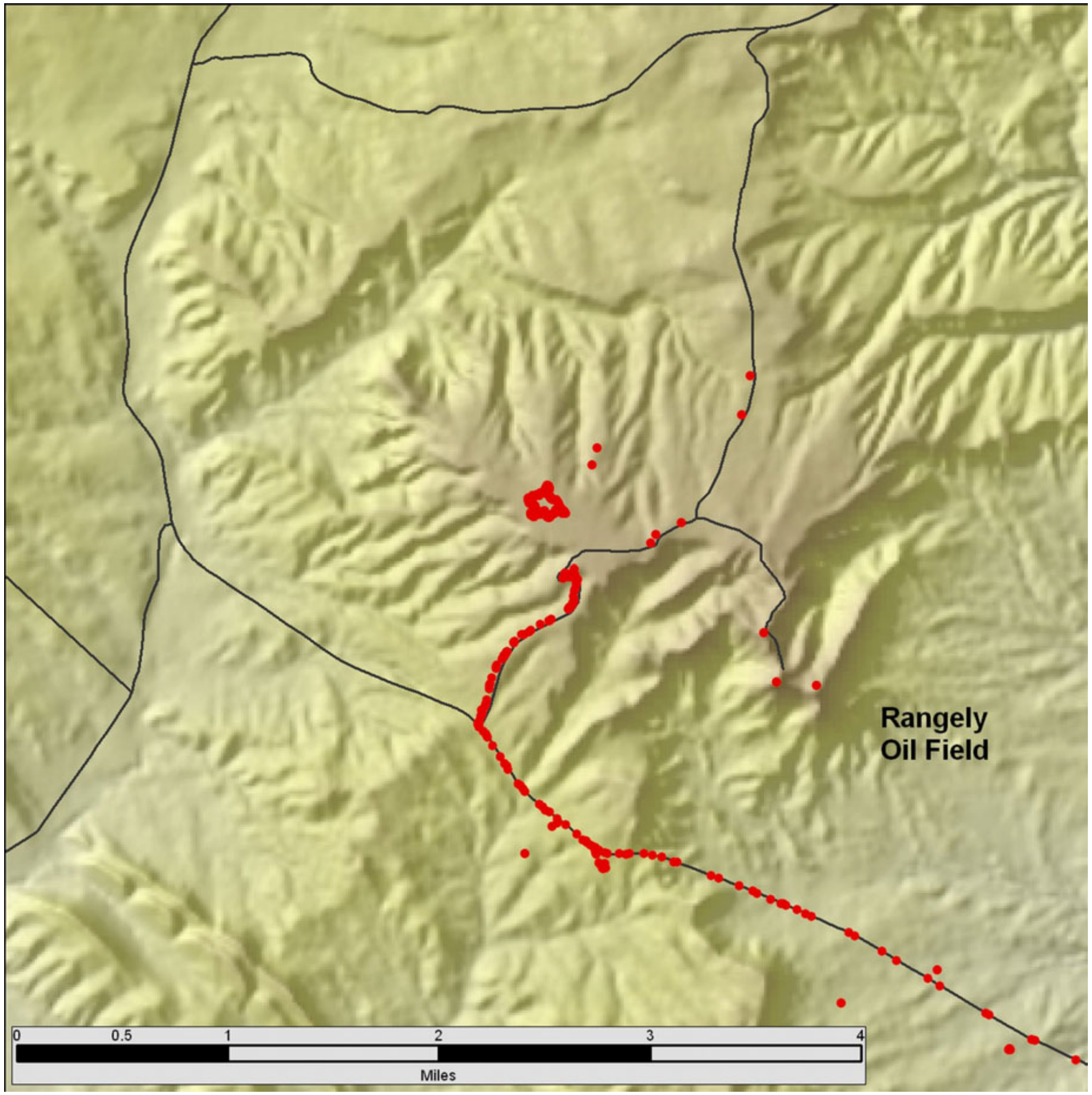
Subtle Habitats discovered by the imagery SAM analysis

- Enlarged view of the SAM analysis for the top of flight line 3 showing two of the habitats discovered by using the imagery analysis to guide us in the field
- Light blue was found to be healthy sage brush, mixed with golden dry cheek grass, and almost zero percentage of dry soils
- Dark green was found to be smaller sage brush plants mixed with cheek grass but with dry soil showing over about 50% of the area between the sage brush plants
- The delineation was remarkable
- We walked the edges of some of these areas with DGPS and found the mapping to accurate to 1 or 2 pixels!
- We feel any CO2 leakage would begin to effect the shape of these habitats and hence be easily seen in subsequent reimaging

Habitat "discovery" area shown on satellite image and a "roads" GIS layer



The "green" habitat is shown as the red polygon of DGPS waypoints (center) recorded by walking the perimeter



Boundary between the two habitats. Collecting reflectance spectra of individual plants and soils

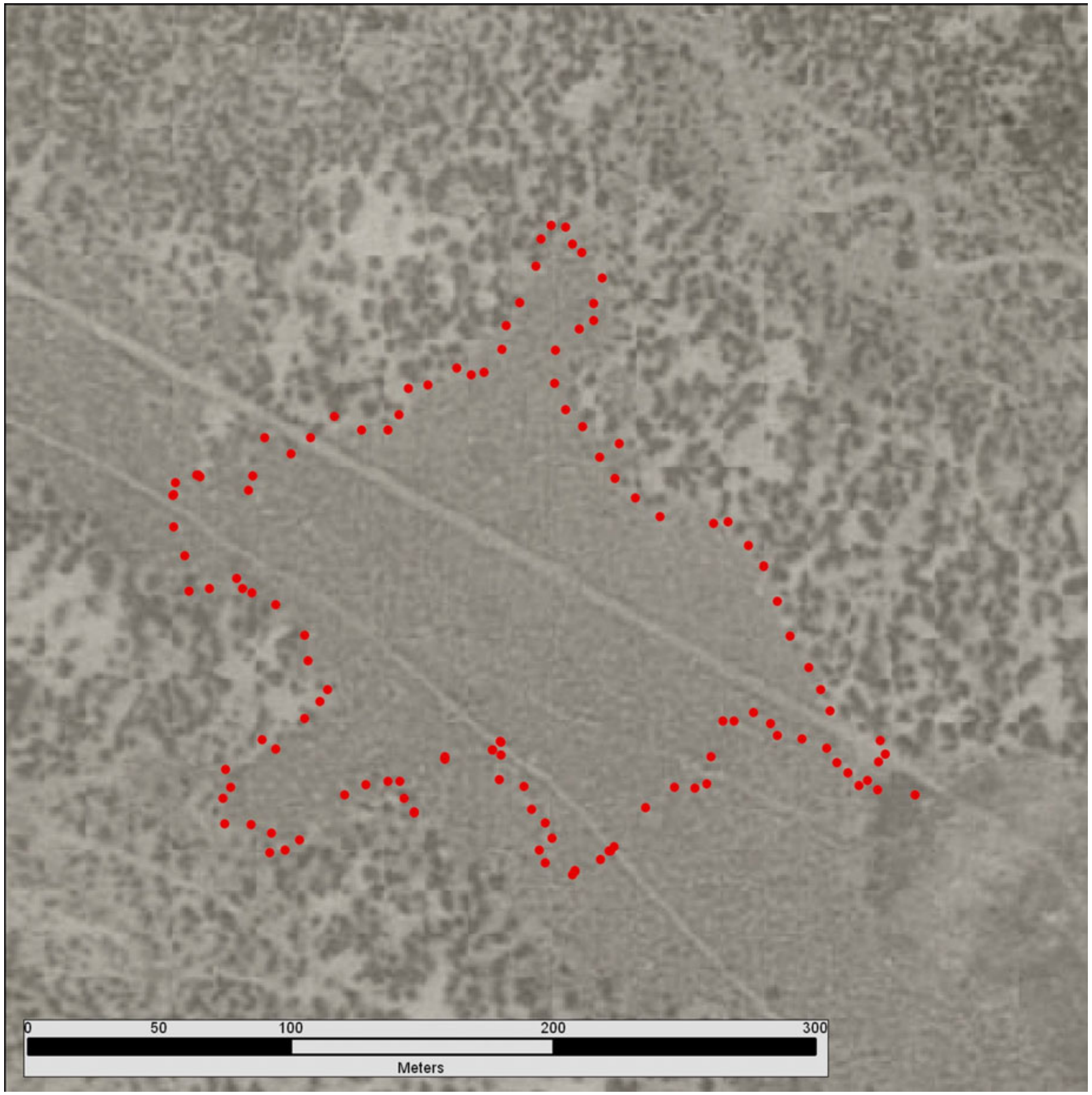
Adjacent habitat visual differences

- **Above is the "light blue" Habitat north of SUV**
- **Below is "green" habitat south of SUV**

Northern habitat is surrounded by a third habitat of Junipers and grasses

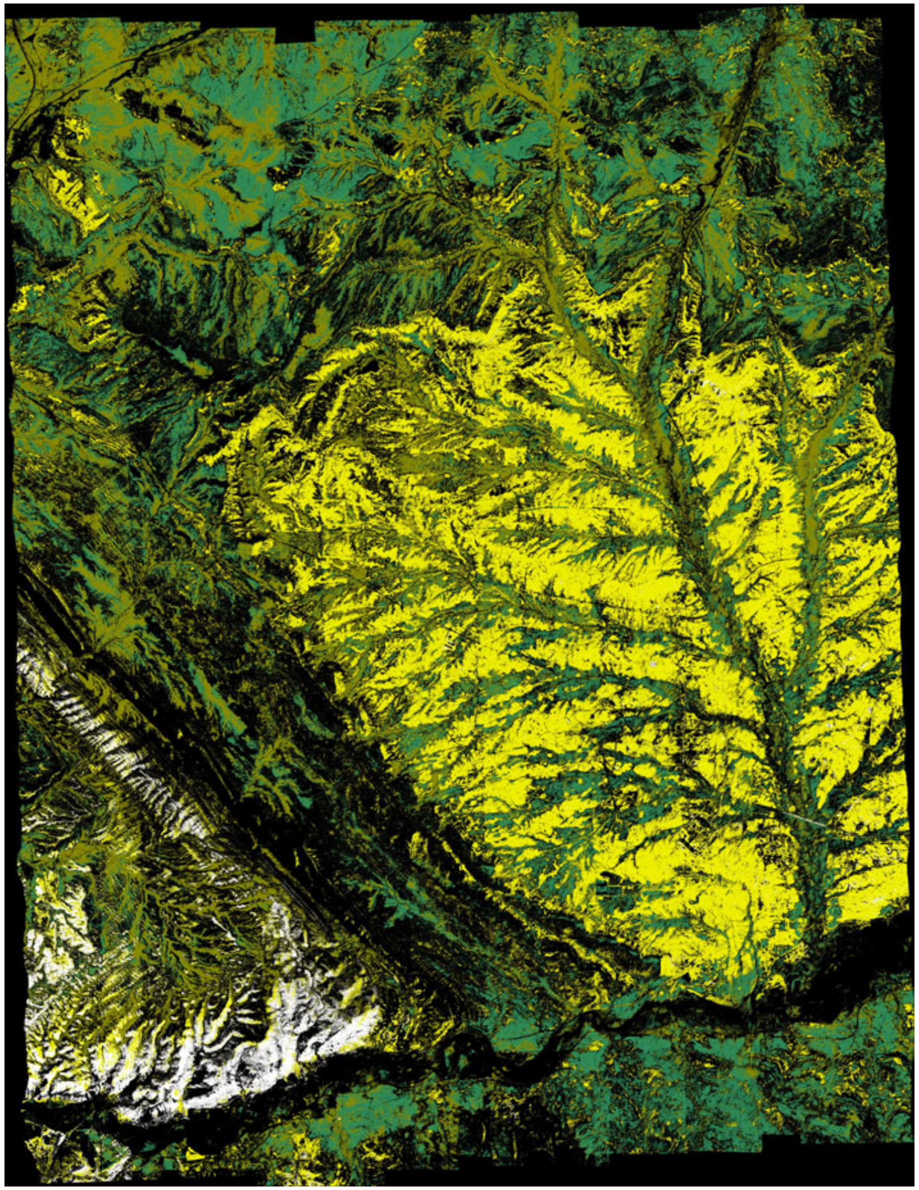
This is the boundary of the "green" habitat that was walked measuring DGPS waypoints.

DGPS Way point perimeter of "green" habitat established by the hyperspectral imagery analysis measured by walking, overlaid on a 1990 airphoto, shows little or no change of this habitat over 23 years,



- The detailed shape of this habitat has persisted for over a quarter of a century, inspite of 15 years of CO_2 injection in the EOR field
- Using remote sensing to map these vegetation habitats will provide century long monitoring for a pattern of small CO_2 and or CH_4 leaks
- Based on our geothermal research program at Mammoth Mountain CA, we know any small CO_2 leaks will "hang-up" in the soil and over time will change these habitat distributions
- We are seeing a very subtle "equilibrium" of all climatic and soil condition averages and variations

Three distinct habitats (yellow, green, and brown) and a soil type (White) mapped across the entire Rangely Oilfield

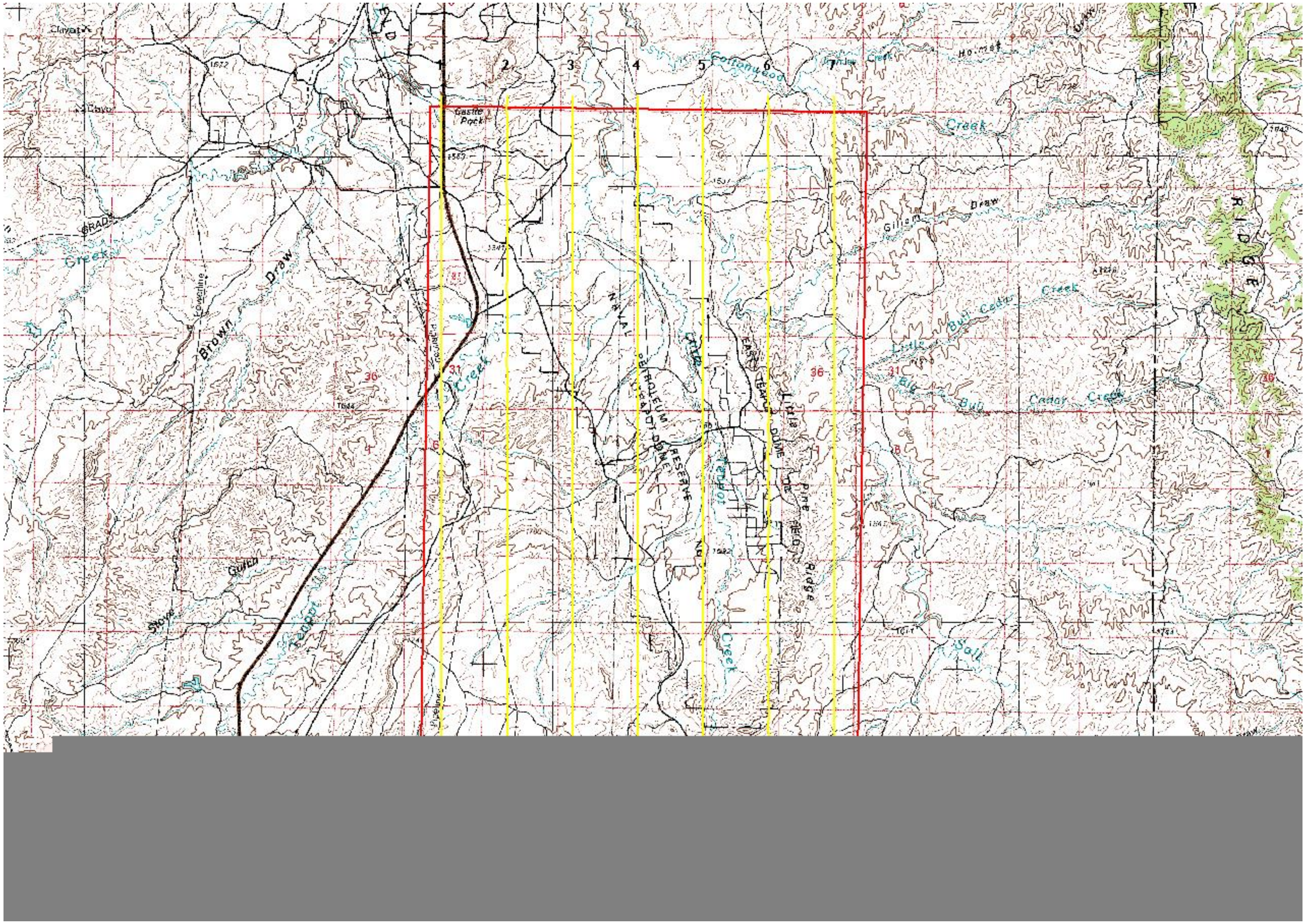


- By carefully selecting ENVI SAM "endmembers", four of the most obvious "habitats" or ecologies, were mapped in all the flight lines imaged at Rangely.
- These ecologies are discernable and mapable even though the eastern 1/3 of the flight lines that were acquired on Friday after the heavy rains on Wednesday and Thursday.
- This leads us to believe that we are indeed mapping ecologies that are independent of detailed weather conditions by using this SAM analysis.

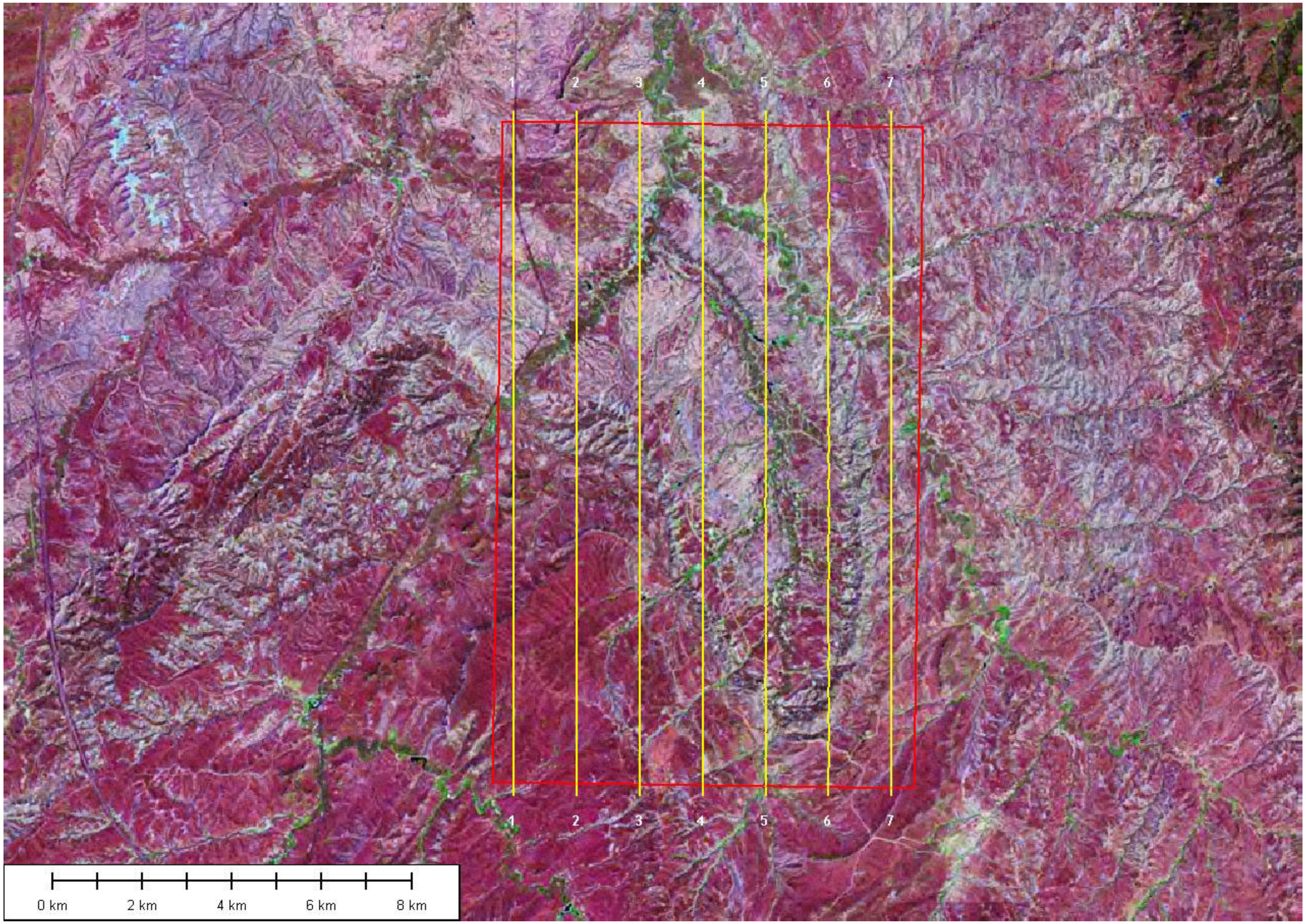
Recent Related Research Results

- DOE NETL gas pipeline underground CH4 leak detection Program
- DEMO done at RMOTC NPR-3 near Casper WY USA Sept 9 – 17 2004
- 5 underground CH4 leaks created under local “vegetation”
- Leaks started August 30
- Hyperspectral imaging by HyVista Sept 9 and Sep 15
- Preliminary analysis is currently underweigh

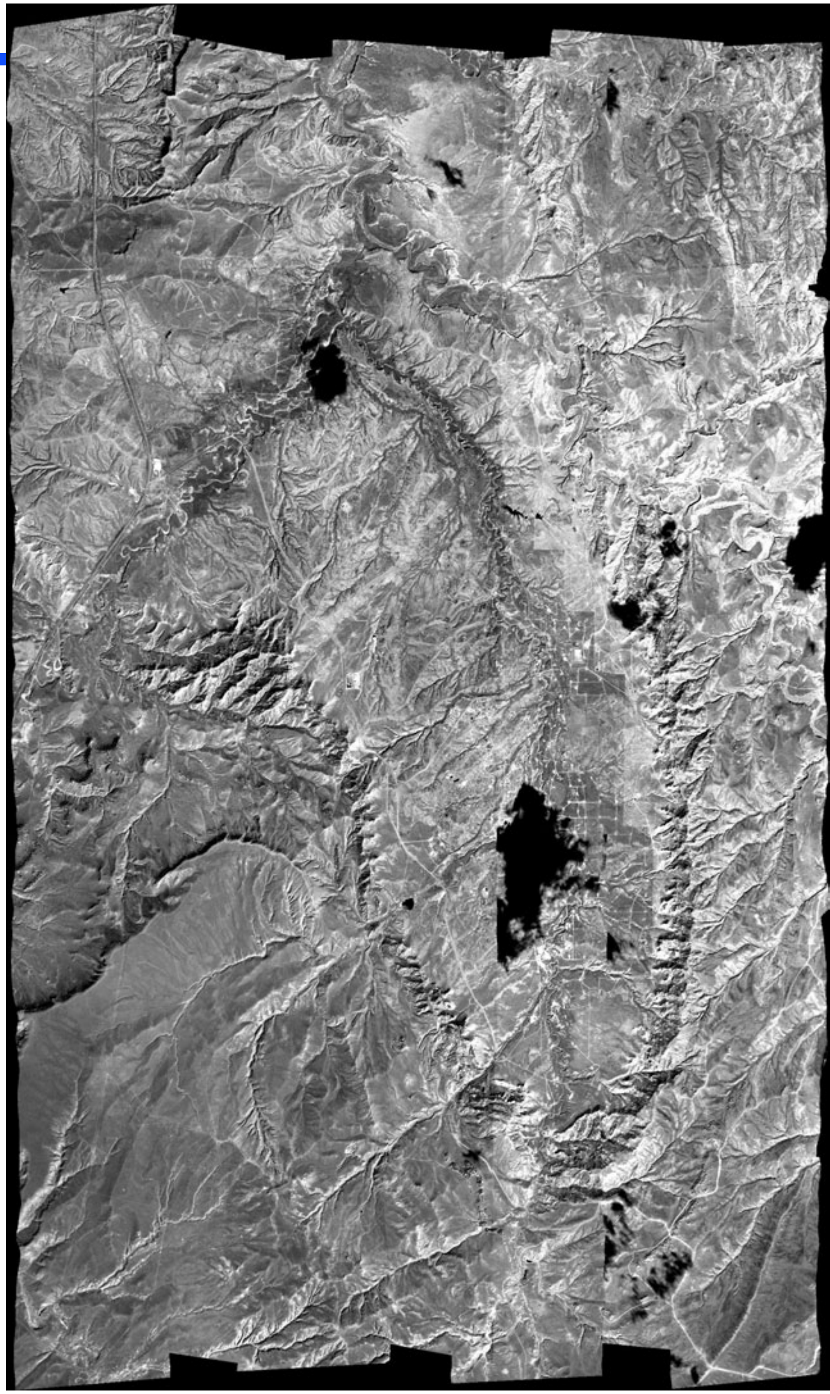
CH4 underground leak detection DOE NGIR DEMO at the RMOTC NPR-3 test site - Hyperspectral flight lines



HyVista flight lines for imaging all of NPR-3

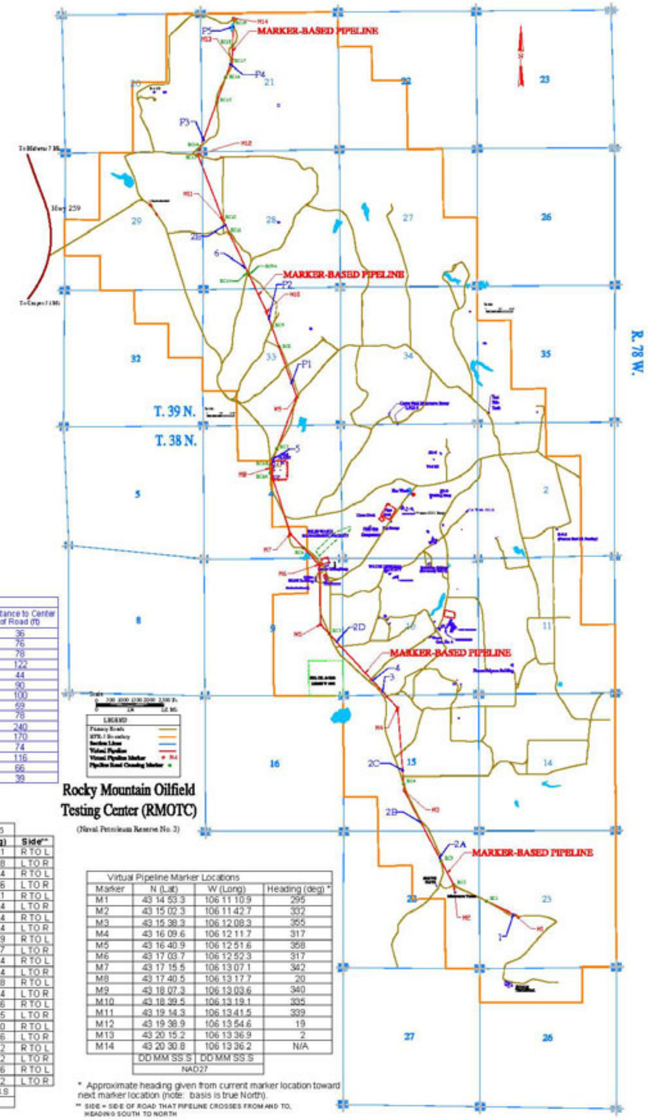


Mosaic of all seven HyVista flight line images of NPR-3



- Hyperspectral imagery was available georectified the same day the imagery was acquired!
- Mosaic was done in Australia over night
- Spatial resolution was 3 meters

Virtual Pipeline leak locations created at NPR-3



Leak Locations			
LEAK SITE	N (Lat)	W (Long)	Distance to Center of Road (ft)
1	43 14 53.6	106 11 12.1	36
2A	43 15 12.9	106 11 50.1	76
2B	43 15 26.3	106 11 59.9	78
2C	43 15 46.0	106 12 09.1	122
3	43 16 15.7	106 12 19.5	44
4	43 16 20.1	106 12 24.6	90
2D	43 16 34.4	106 12 43.2	100
5	43 17 44.1	106 13 15.8	59
P1	43 18 12.7	106 13 06.3	78
P2	43 18 37.0	106 13 17.9	240
6	43 18 56.4	106 13 30.4	170
2E	43 19 12.4	106 13 40.3	74
P3	43 19 44.5	106 13 51.5	116
P4	43 20 13.2	106 13 37.8	66
P5	43 20 27.7	106 13 36.3	39
	DD MM SS.S	DD MM SS.S	
	NAD27		

Road Crossing Marker Locations			
Marker	N (Lat)	W (Long)	Side**
RC1	43 14 57.4	106 11 26.1	R TO L
RC2	43 15 02.5	106 11 42.8	L TO R
RC3	43 15 11.7	106 11 49.4	R TO L
RC4	43 15 40.8	106 12 08.6	L TO R
RC5	43 16 37.3	106 12 47.1	R TO L
RC6	43 17 10.1	106 13 00.4	L TO R
RC6A	43 17 38.5	106 13 17.4	R TO L
RC6B	43 17 41.7	106 13 17.4	L TO R
RC7	43 17 47.8	106 13 13.9	R TO L
RC8	43 18 26.5	106 13 12.7	L TO R
RC9	43 18 33.9	106 13 16.4	R TO L
RC9A	43 18 53.6	106 13 28.4	L TO R
RC10	43 18 54.6	106 13 28.8	R TO L
RC11	43 19 09.4	106 13 38.4	L TO R
RC12	43 19 14.4	106 13 41.6	R TO L
RC13	43 19 39.0	106 13 54.5	L TO R
RC14	43 19 42.1	106 13 53.0	R TO L
RC15	43 19 59.1	106 13 44.6	L TO R
RC16	43 20 08.3	106 13 40.2	R TO L
RC17	43 20 14.6	106 13 37.2	L TO R
RC18	43 20 20.5	106 13 36.6	R TO L
RC19	43 20 30.2	106 13 36.2	L TO R
	DD MM SS.S	DD MM SS.S	
	NAD27		

Virtual Pipeline Marker Locations			
Marker	N (Lat)	W (Long)	Heading (deg) *
M1	43 14 53.3	106 11 10.9	295
M2	43 15 02.3	106 11 42.7	332
M3	43 15 38.3	106 12 08.3	355
M4	43 16 09.6	106 12 11.7	317
M5	43 16 40.9	106 12 51.6	358
M6	43 17 03.7	106 12 52.3	317
M7	43 17 15.5	106 13 07.1	342
M8	43 17 40.5	106 13 17.7	20
M9	43 18 07.3	106 13 03.6	340
M10	43 18 39.5	106 13 19.1	335
M11	43 19 14.3	106 13 41.5	339
M12	43 19 38.9	106 13 54.6	19
M13	43 20 15.2	106 13 36.9	2
M14	43 20 30.8	106 13 36.2	N/A
	DD MM SS.S	DD MM SS.S	
	NAD27		

* Approximate heading given from current marker location toward next marker location (note: basis is true North).

** SIDE = SIDE OF ROAD THAT PIPELINE CROSSES FROM AND TO, HEADING SOUTH TO NORTH

Leak Creation

Site P4– View of leak site and vegetation. The gas leak emits near the middle of the greasewood bushes in the center of the picture.

Site P4 – View from the road.

Lone Plant!

Site 6 – View at top of the hill. Underground leak at gravel located approximately 10 feet from rotometer.

Site P1 – Underground leak. Directionally drilled such that leak emits under greasewood bush located approximately 20 feet from rotometer.

Summary and new remote sensing directions

- Vegetation stress techniques studied so far are not well suited to arid environments
- Vegetation habitat shapes are well suited to verify a lack of significant CO_2 leakage over century time scales
- Habitat pattern mapping techniques using satellites with 0.6 meter and better resolution are being developed
- Direct detection of CO_2 and CH_4 using hyperspectral thermal imagers is started
- Creating a program using the new OCO satellite to monitor local CO_2 and CH_4 background levels very locally is started and should be supported by our community
- We need test sites to begin to quantify CO_2 and CH_4 underground leak effects on plant and soil microbial habitats
- Soil CO_2 and CH_4 normal variations studies should continue (Ron Klusman's work) at the plant effects test sites
- Develop smart networkable nano sensors for CO_2 and CH_4 on the ground deployment

Web Sites and Resources

- The Center for Remote Sensing at University of California Santa Cruz
  http://emerald.ucsc.edu/~hyperwww/
- Energy and Environment, at LLNL

  http://en-env.llnl.gov/
- Additional reading of interest
  - Response of Soil Mineral Weathering to Elevated CO2, Jennie C. Stephens, Ph. D. Thesis, California Institute of Technology, 2002
  - Carbon Dioxide and Environmental Stress, Yigi Luo, DRI Reno NV USA, and Harold A. Mooney, Stanford University, CA USA Academic Press, 1999, Library of Congress 99-600087
  - The Carbon Dioxide Dilemma: Promising Technologies and Policies http://www.nap.edu/catalog/10798.html?do_se92
  - Living on an Active Earth: Perspectives on Earthquake Science http://www.nap.edu/catalog/10493.html?do_se92

END

- END

We want to study actual lower limits of CO_2 leak detectability using plant habitat responses

- We propose that the CCP establish a CO_2 effluent, plant effects study station, using emission areas at Mammoth Mountain California, USA and at the RMOTC DOE site in Casper Wyoming, USA
- Using areas of known CO_2 effluent, establish real time continuous soil and near surface CO_2 concentration recordings
- Make periodic direct metabolic measurements of individual plant health
- Would involve collaboration with the USGS, the DOE, and other Universities
- Could be a test-bed for several parts of the larger CCP program needs
- Mammoth would provide credibility for the CCP by having an operating facility in a public use area with known potential life threatening CO_2 effluents
- Would allow studying both dose effects and dose rate effects on different species through all seasons

IN CCP2 we are reopening study of direct CO2 gas detection for very dry sites by several means

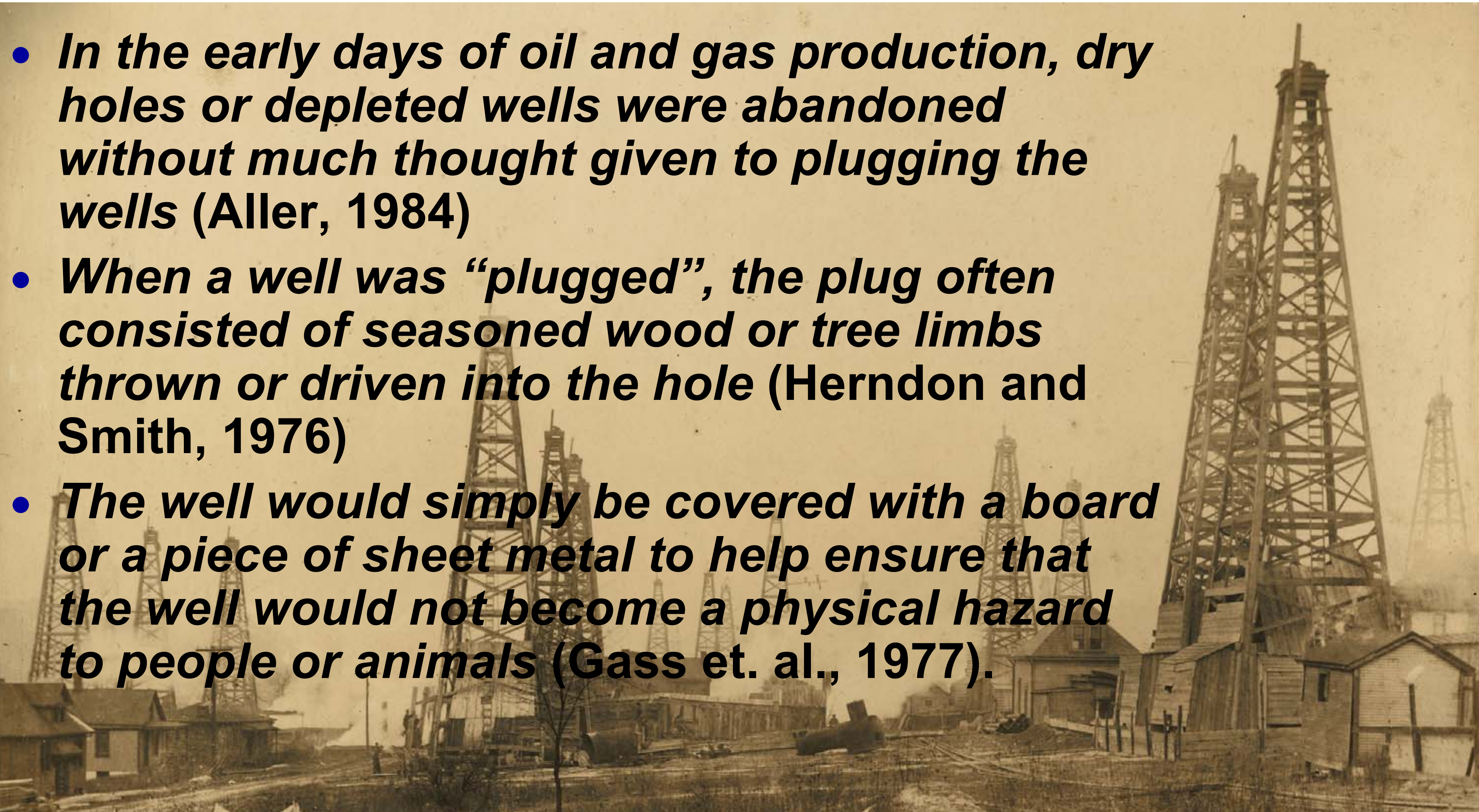
- Dr Brigette A. Martini thesis
  - http://cmg-en-env-rr.llnl.gov/other/brigette/
- Sites with no apparent vegetation of any kind may be perfect for direct detection of CO2 gas escaping using one of the 2 micron absorption features
- Hyperspectral thermal infra-red sensors may be useful

Using Airborne Reconnaissance to Find Abandoned Wells

Identification of potential leakage zones before CO_2 injection

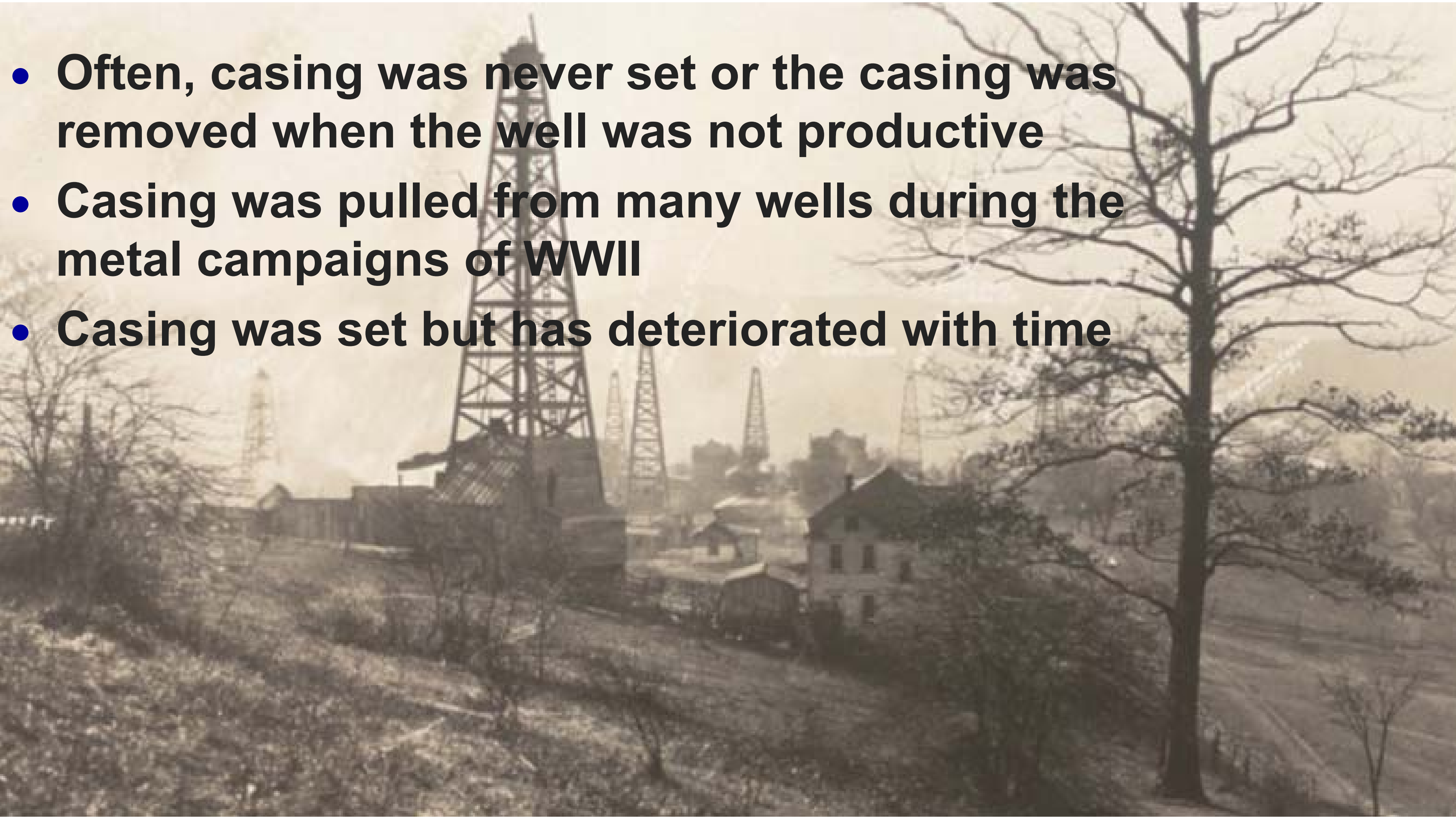
Unplugged or Improperly Plugged Wells

- *In the early days of oil and gas production, dry holes or depleted wells were abandoned without much thought given to plugging the wells* (Aller, 1984)
- *When a well was "plugged", the plug often consisted of seasoned wood or tree limbs thrown or driven into the hole* (Herndon and Smith, 1976)
- *The well would simply be covered with a board or a piece of sheet metal to help ensure that the well would not become a physical hazard to people or animals* (Gass et. al., 1977).



Well Casing

- Often, casing was never set or the casing was removed when the well was not productive
- Casing was pulled from many wells during the metal campaigns of WWII
- Casing was set but has deteriorated with time



Hutchinson, Kansas-January 17, 2001

Explosion of natural gas from improperly plugged brine wells destroys two downtown businesses

Hutchinson, Kansas-January 17, 2001

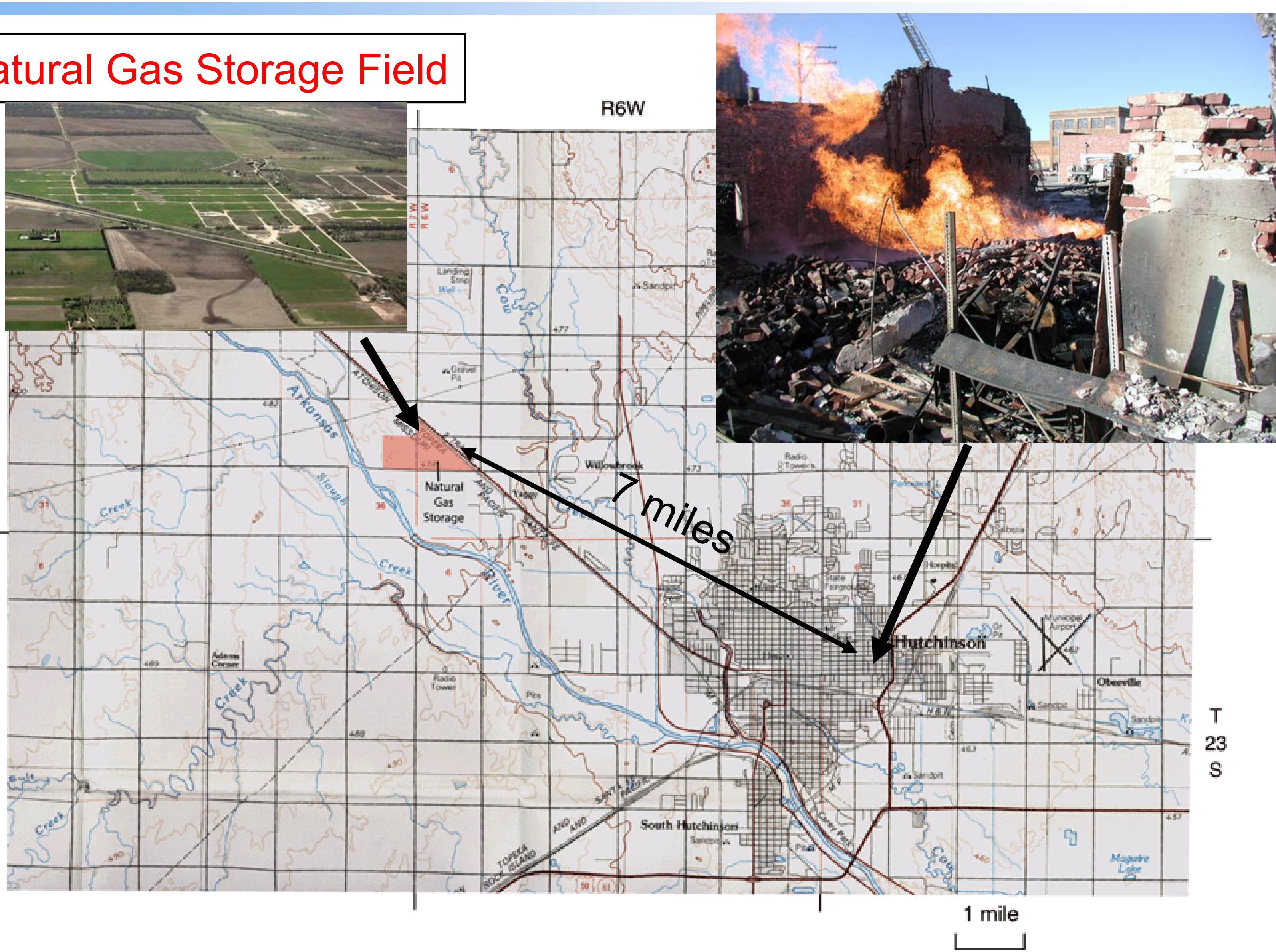
Explosion of natural gas from improperly plugged brine wells destroys two downtown businesses

THE NEXT DAY

Explosion of natural gas three miles away kills two residents and forces the evacuation of hundreds

http://www.geotimes.org/oct01/feature_kansas.html

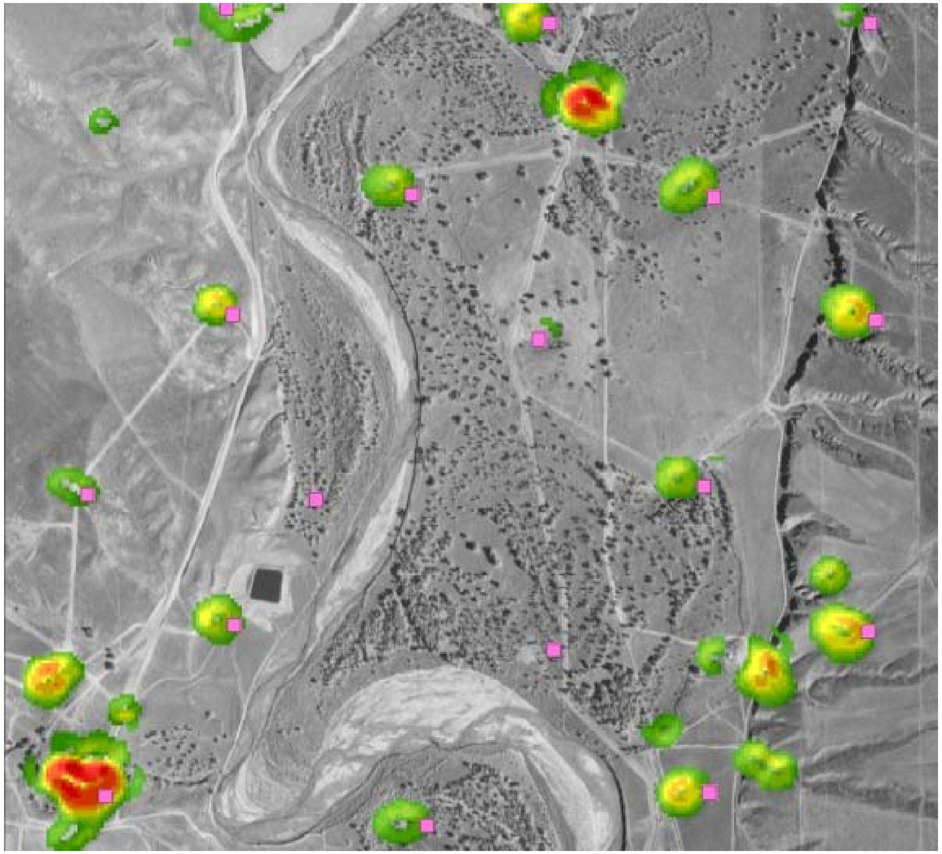
Natural Gas Storage Field



Technical Approach

- to use magnetics to locate steel-cased wells
- to locate uncased and improperly plugged wells by detecting volatile components from sedimentary formations
  - radon
  - methane and ethane
  - hydrogen sulfide
- to locate saline incursions into freshwater aquifers using airborne electromagnetic surveys

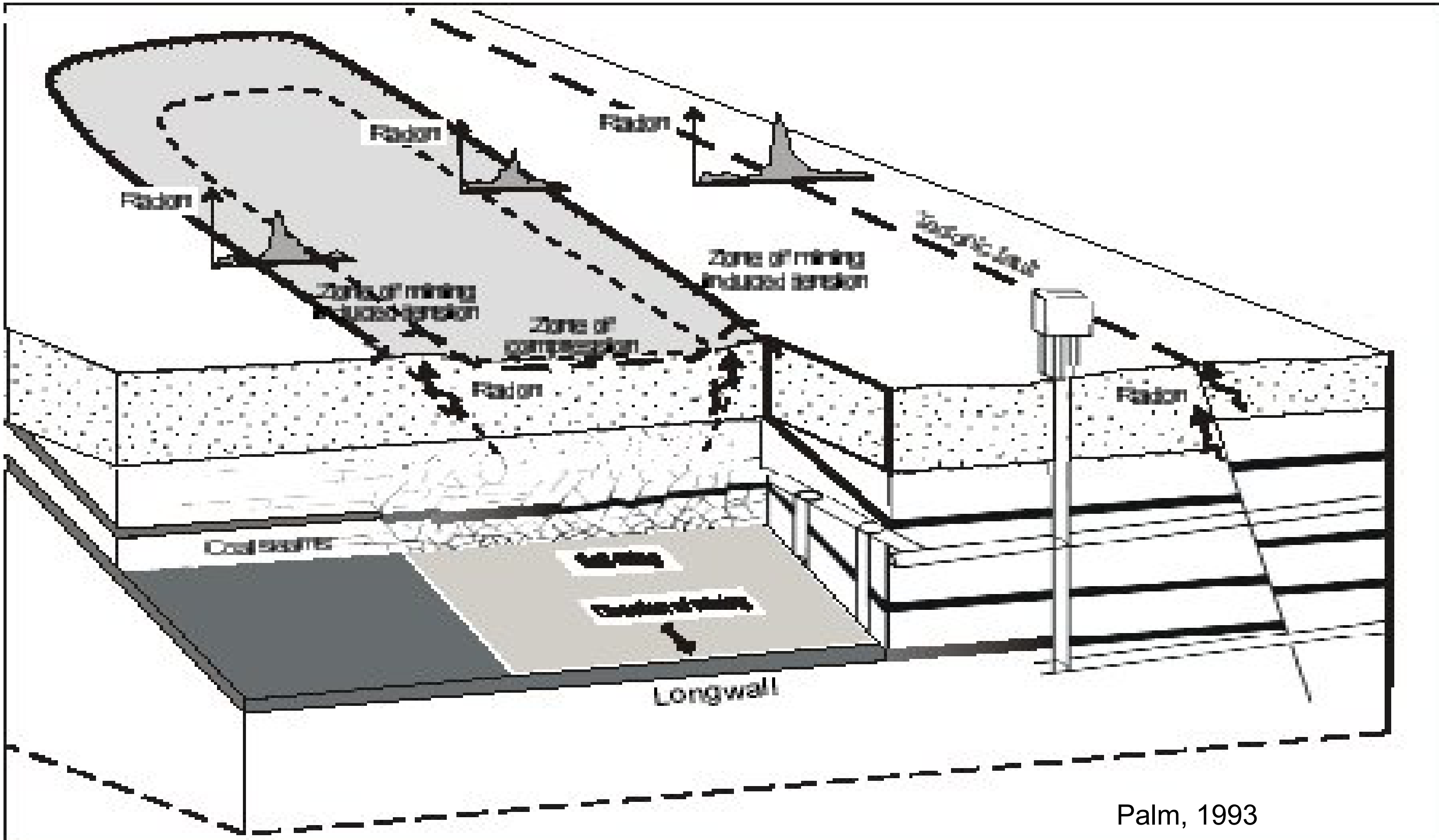
Aeromagnetics for Locating Steel-Cased Wells



Helicopter Magnetic Surveys

Unmanned Airborne Vehicle (UAV)

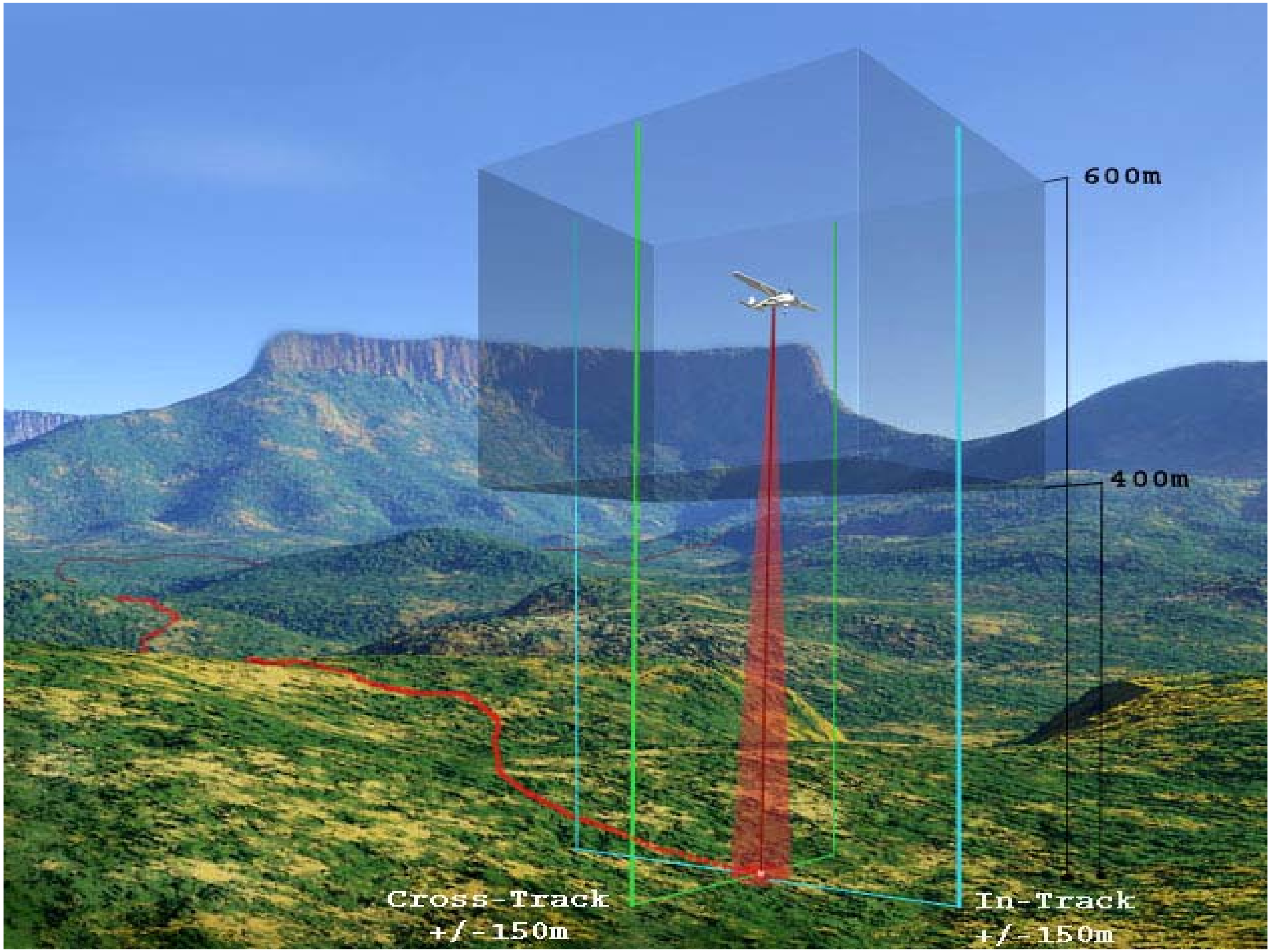
Radon Seeps – Has the potential to detect uncased wells



Radiometric Surveys

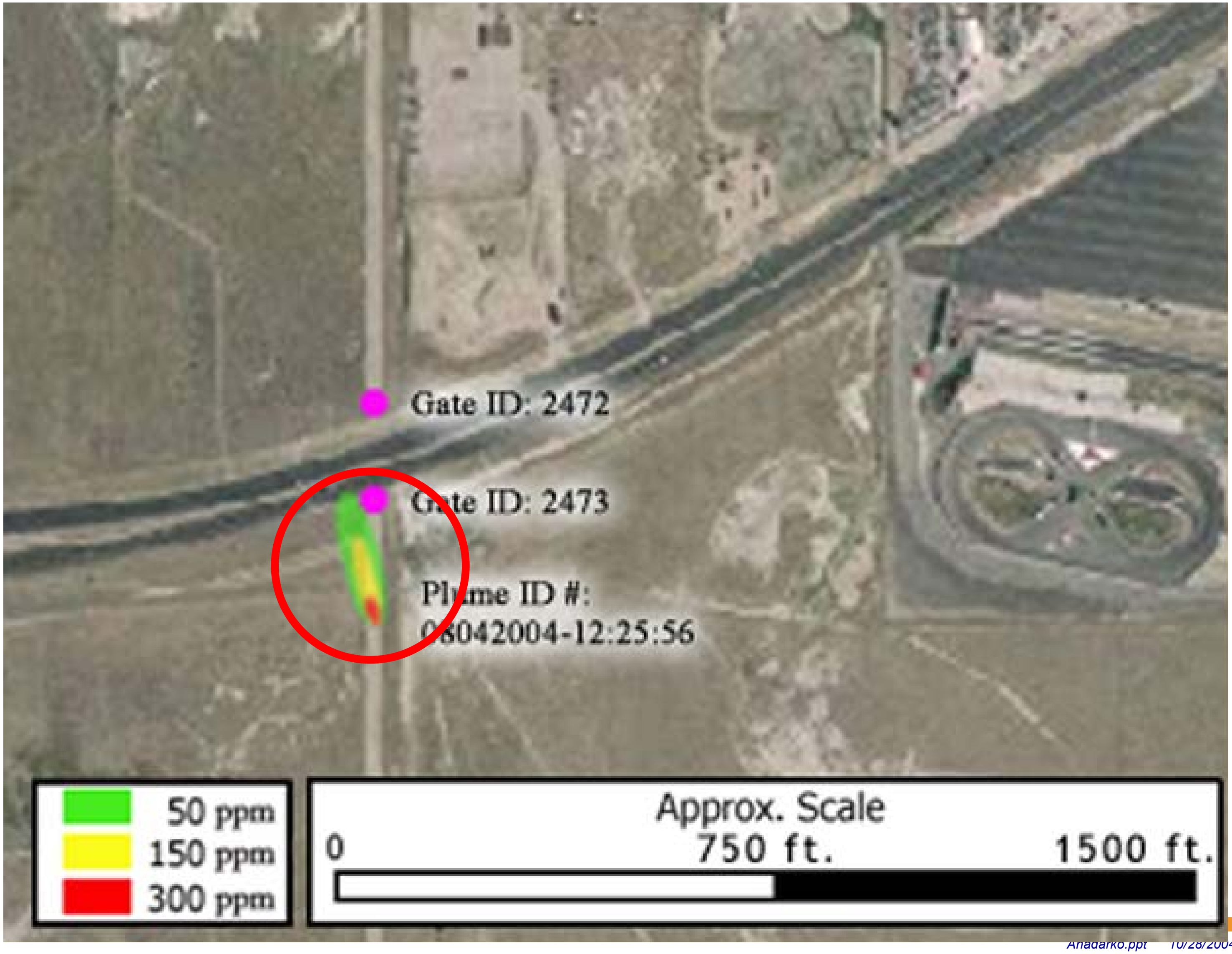
Airborne Detection of Methane/Ethane Leaks-

Has the potential to detect uncased wells



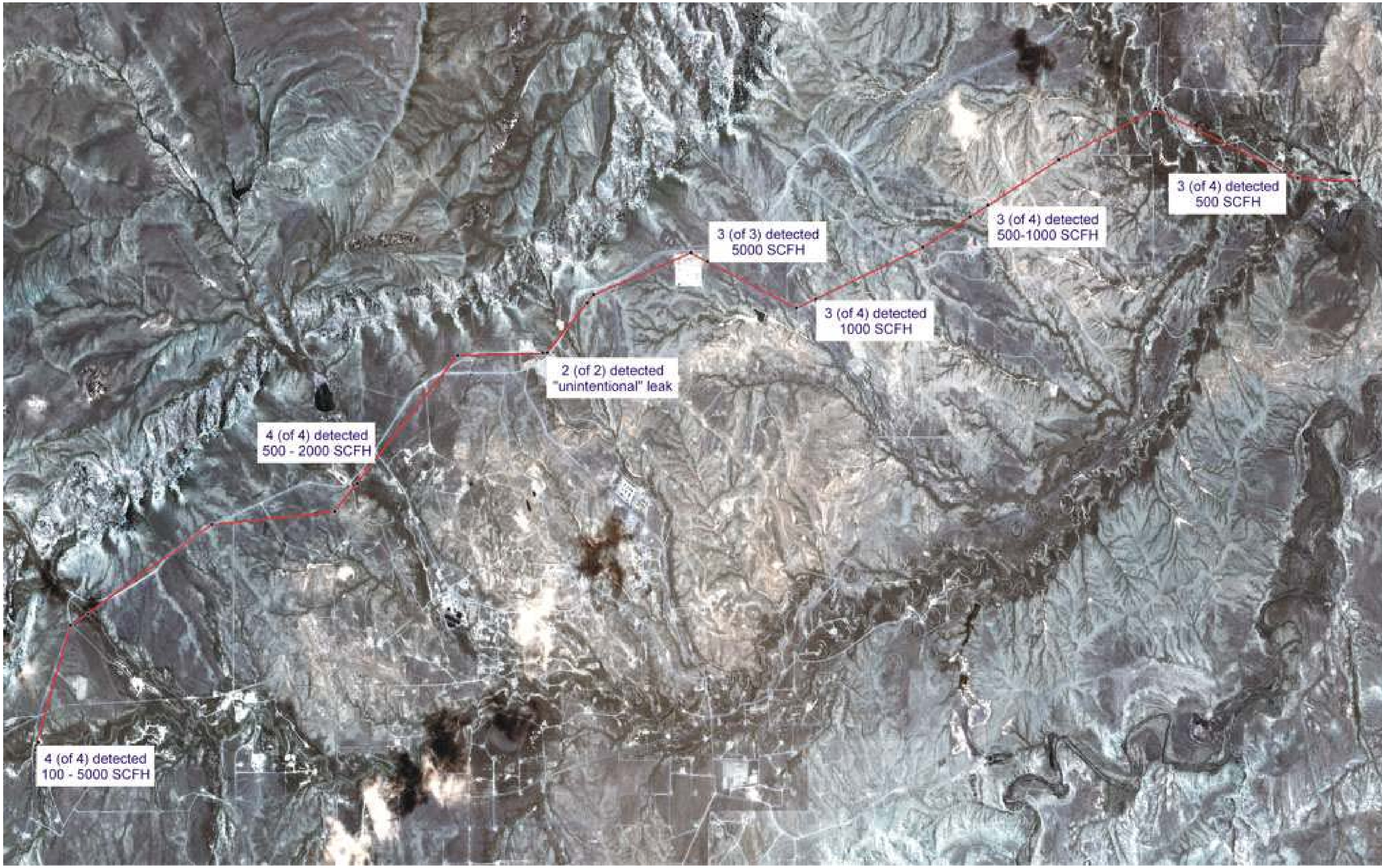
Airborne Detection of Methane/Ethane Leaks-

Has the potential to detect uncased wells



ALPIS performing inspection of a “virtual” pipeline
at the Rocky Mountain Oilfield Testing Center (RMOTC)

ALPIS performing inspection of a "virtual" pipeline
at the Rocky Mountain Oilfield Testing Center (RMOTC)



3 (of 4) detected
500 SCFH
3 (of 4) detected
500-1000 SCFH
3 (of 3) detected
5000 SCFH
3 (of 4) detected
1000 SCFH
2 (of 2) detected
"unintentional" leak
4 (of 4) detected
500 - 2000 SCFH
4 (of 4) detected
100 - 5000 SCFH


LASEN

ANGEL Transceiver in Test Aircraft

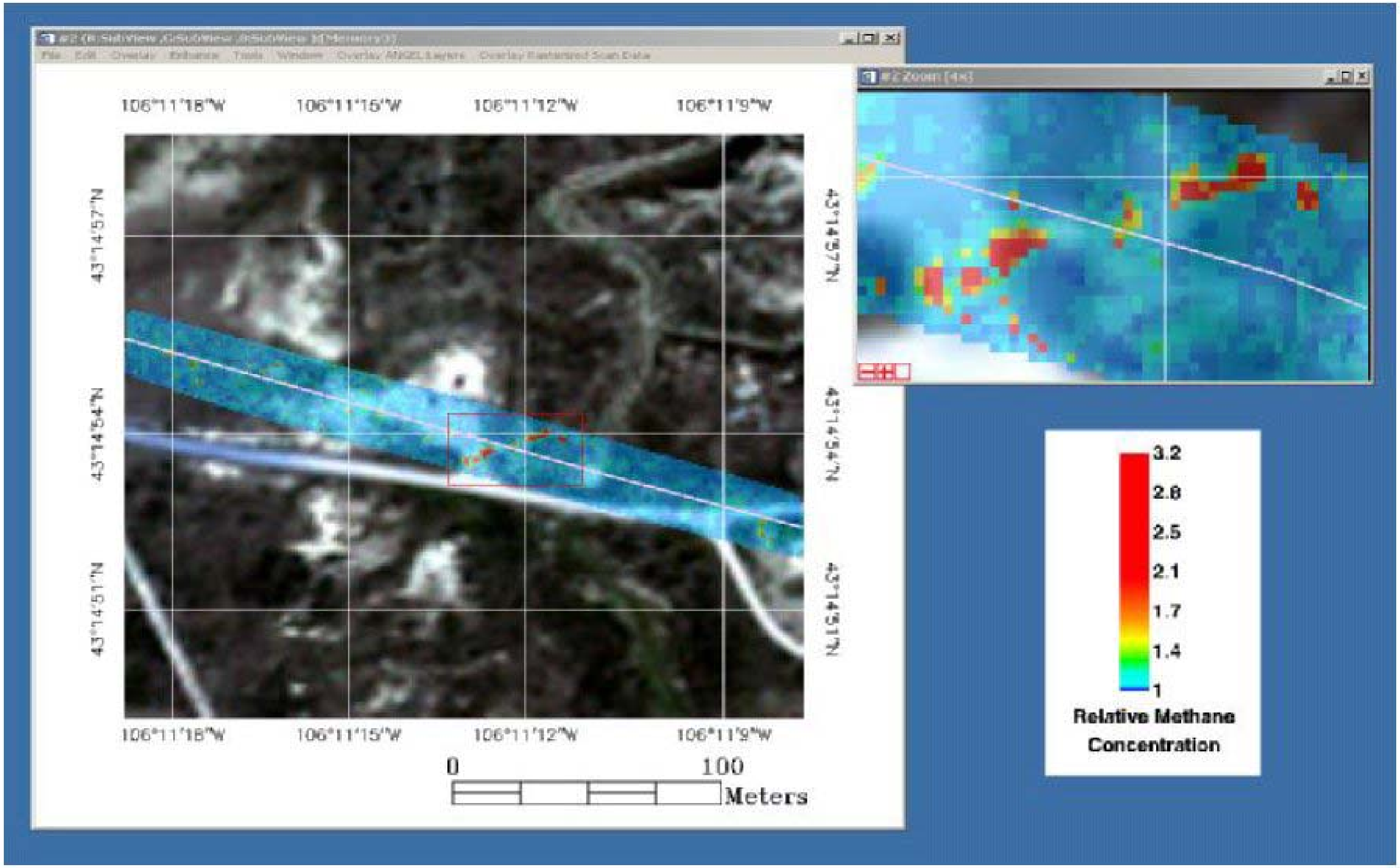
ITT Industries Airborne Natural Gas Emission Lidar (ANGEL)

ANGEL Transceiver in Test Aircraft

ITT Industries Airborne Natural Gas Emission Lidar (ANGEL)

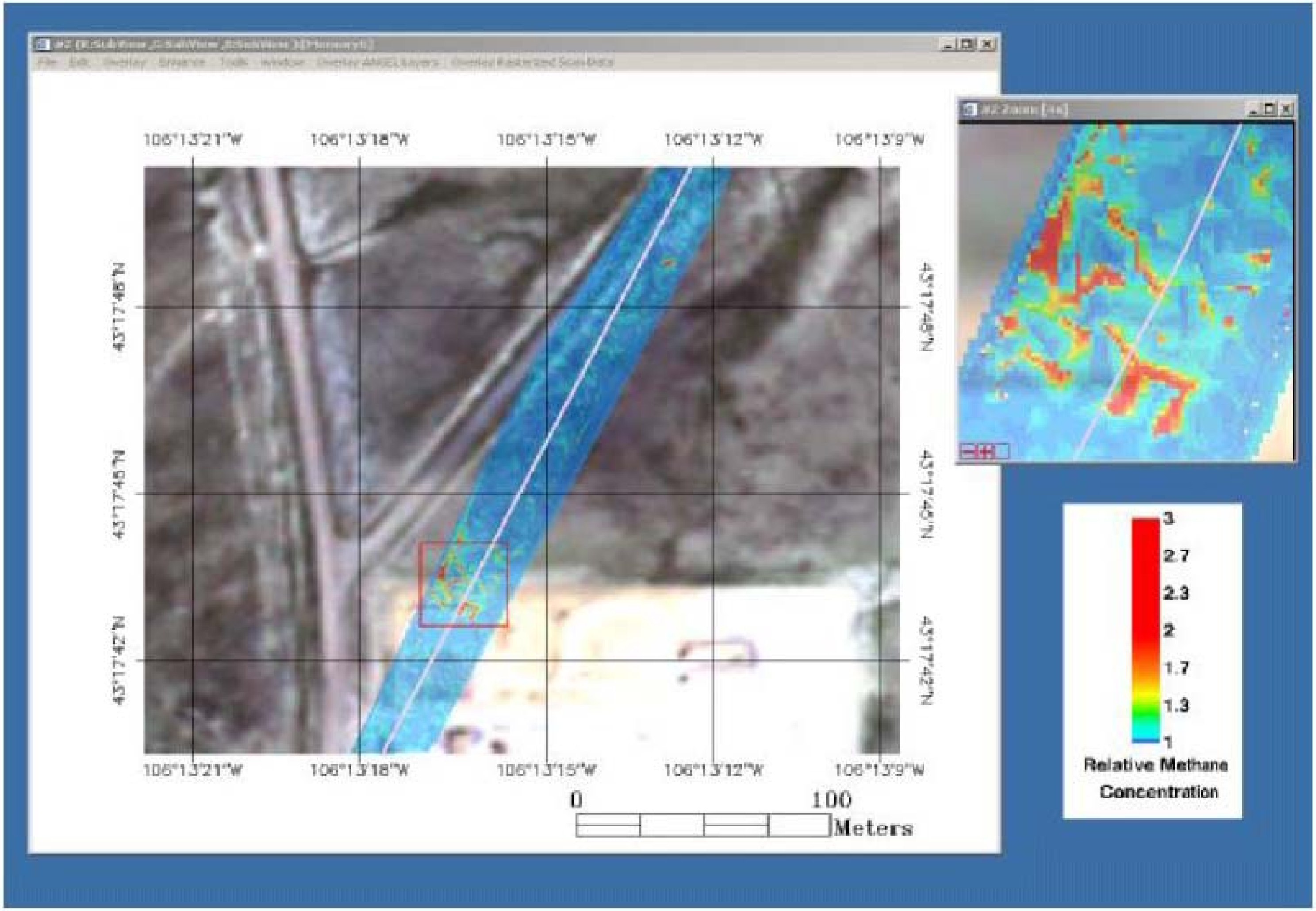
ANGEL Transceiver in Test Aircraft

Calibration Leak at RMOTC on Friday, September 17, 2005
5000 scfh

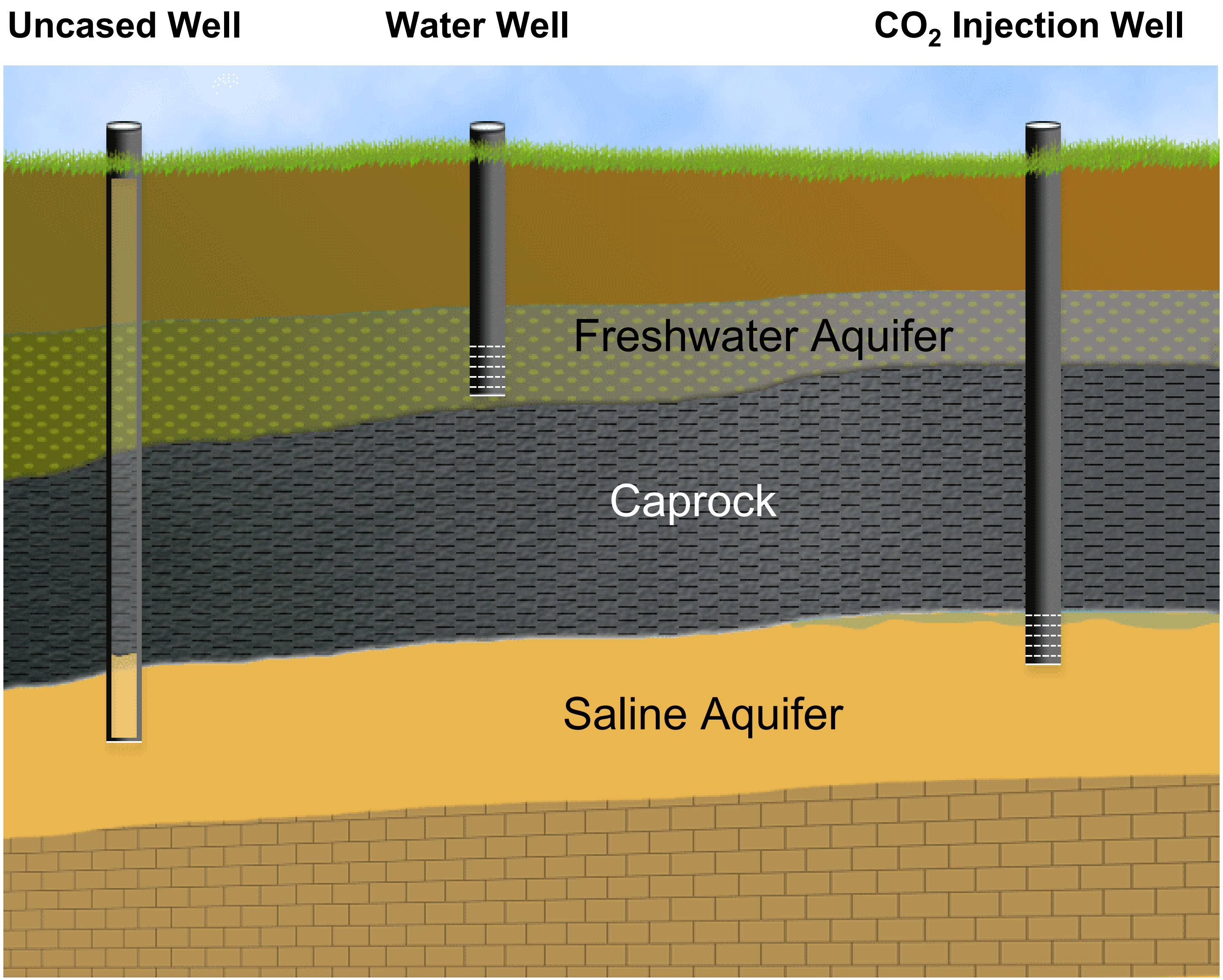


Swath width is shown in blue, elevated methane concentrations are in yellow and red

Leak at RMOTC Gas Plant – Friday 17 September

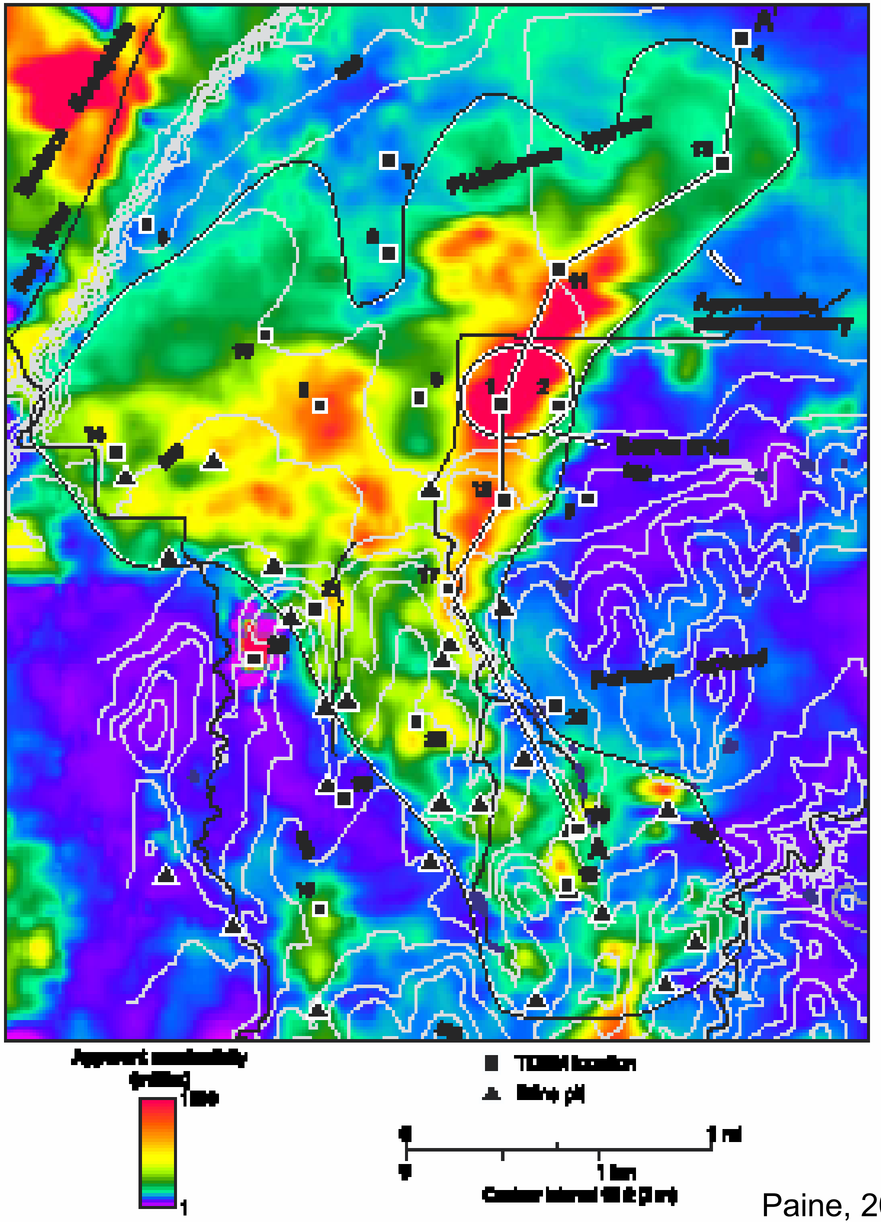


NASA Methane Detector


Uncased Well
Water Well
CO_2 Injection Well
Freshwater Aquifer
Caprock
Saline Aquifer

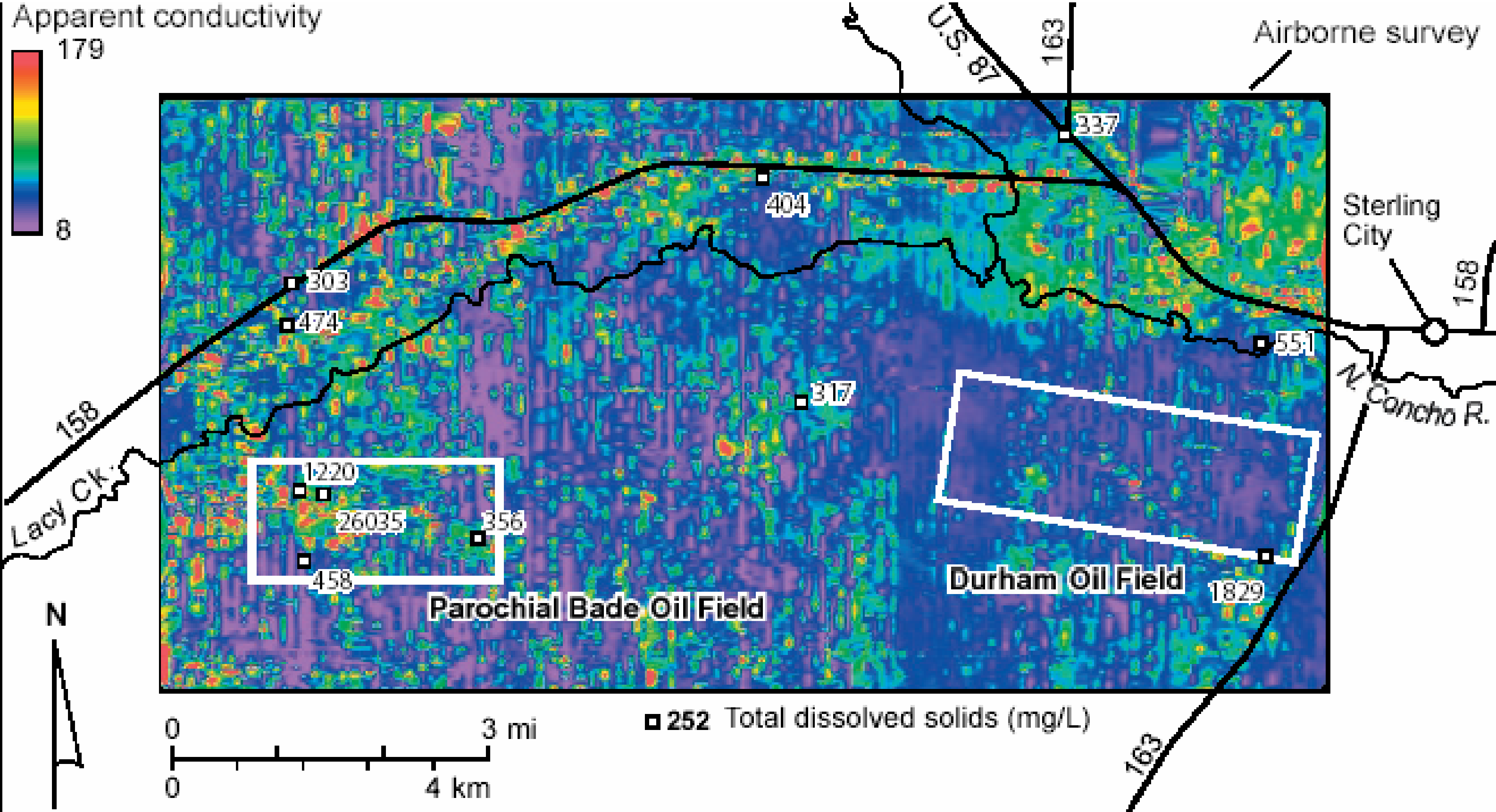
Electromagnetic Survey

Airborne EM Conductivity map of Saline Plume in Oil Fields of the Red River Basin, Texas and Oklahoma



Paine, 2003

Electromagnetic Conductivity of Saline Plumes Related to Oil and Gas Production, Sterling County, Texas



Paine and Collins, 2003

Approach

- **Ground Survey**
  - Evaluate magnetometry for locating steel-cased wells in areas of high cultural interference
  - Measure size, shape, and concentration of methane, ethane, radon, and hydrogen sulfide anomalies
- **Airborne Survey**
  - Magnetic survey for steel-cased wells
  - Radiometric survey for radon daughters
  - Differential absorption LIDAR (DIAL) survey for methane and ethane

Airborne Well Detection

AIRBORNE RECONNAISSANCE CAN SURVEY LARGE AREAS QUICKLY AND INEXPENSIVELY

- Airborne magnetometry combined with radon or methane sensing may detect cased and leaking, uncased wells (and seeps).
- Magnetometry in conjunction with radon or methane sensing can potentially determine which steel-cased wells are leaking.
  - Wells with Rn and CH_4 anomalies should be re-plugged first.
  - Wells that do not show an anomalously high Rn and CH_4 concentrations probably will not leak CO_2 immediately.

Leakage and Seepage in the Near-Surface Environment: An Integrated Approach to Monitoring and Detection

Curtis M. Oldenburg

Jennifer L. Lewicki

Earth Sciences Division

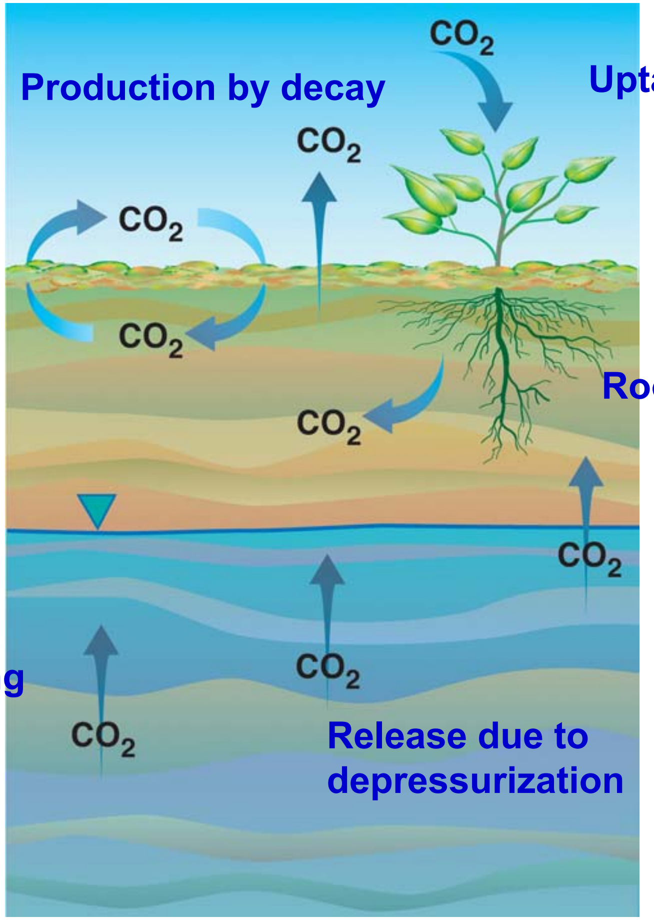
Santa Cruz, CA

November 8-9, 2004

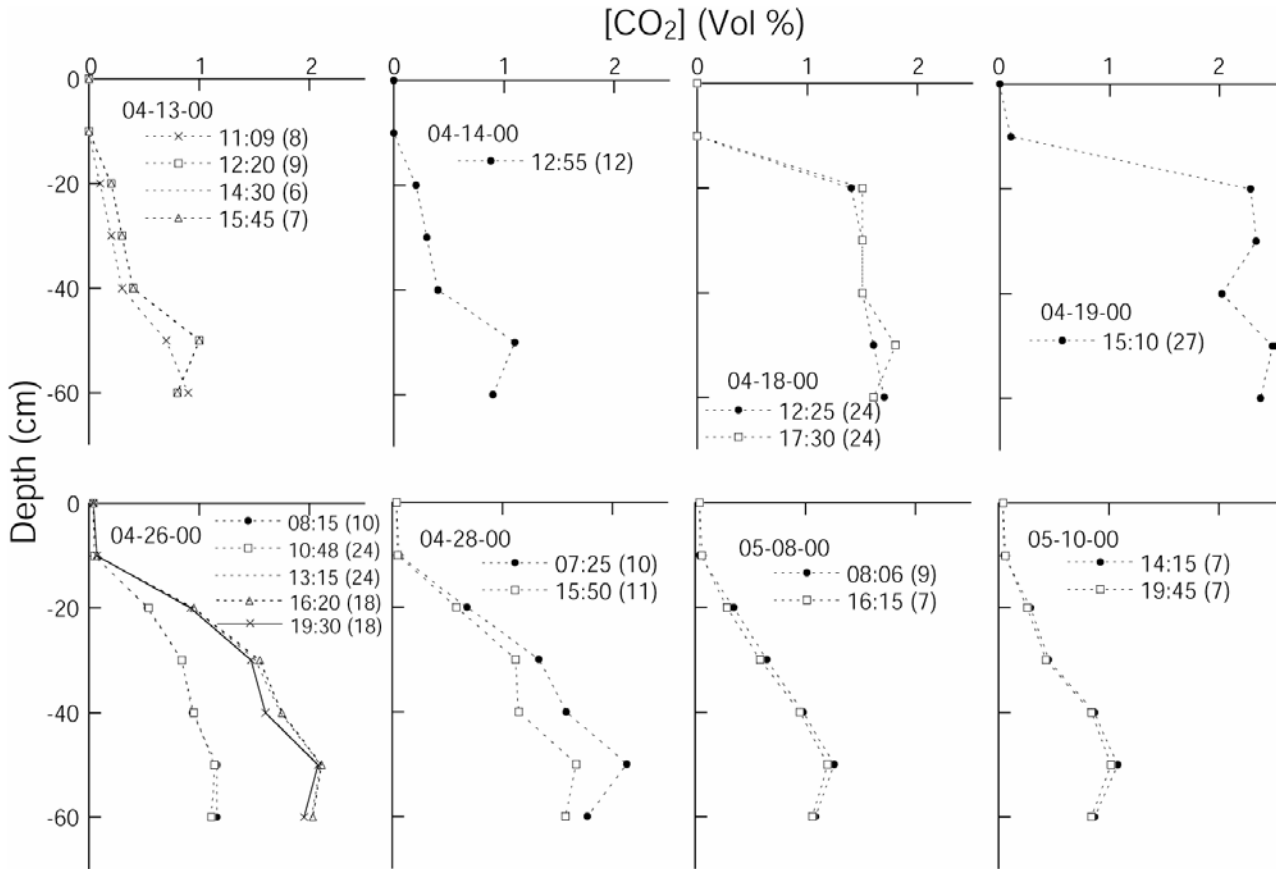
Introduction

- Injection of CO_2 into deep geologic formations involves risk that CO_2 will migrate away from primary target.
- Verification of CO_2 sequestration integrity is needed to satisfy concerns about:
  - Health, Safety, and Environmental (HSE) risk
  - Costs of sequestration (energy, emissions, land use)
- Verification involves field monitoring and measurements.
- Technology to measure CO_2 concentrations and fluxes is well established.
- However, the challenge is that CO_2 is naturally ubiquitous, and conditions in the field can be difficult.

Natural CO_2 Sources and Sinks



Trend and Variability in CO_2 Profile



(modified from Lewicki et al., *J. Geophys. Res.*, *108*, 2003)

What would a CO_2 leakage and seepage profile look like, and how would one go about detecting leakage and seepage?

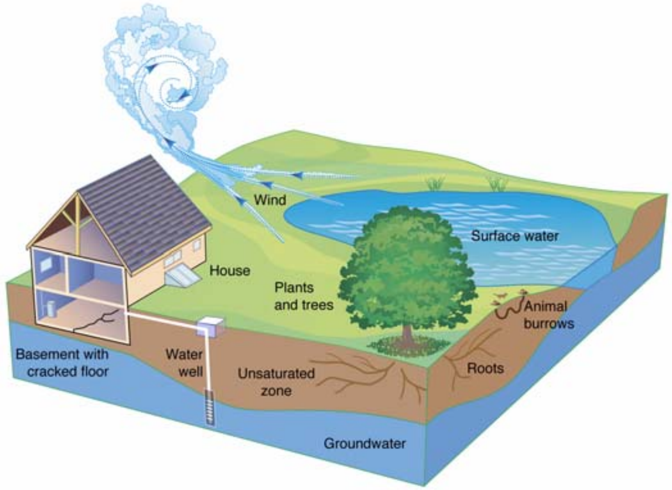
Background and Outline

- We have done modeling studies of leakage and seepage.
- We have developed an integrated near-surface monitoring and modeling approach.
- We are carrying out surface monitoring at the Frio pilot site.

- In this talk,
  - Briefly review modeling results.
  - Discuss monitoring challenges and approaches.
  - Report on Frio monitoring and lessons learned.

Terminology

- **Leakage = CO_2 migration away from primary sequestration target.**
- **Seepage = CO_2 transport out of the ground into the atmosphere or into surface water.**
- **Ebullition = bubble formation from seepage into surface water.**
- **Surface layer = bottom 1/10 of the atmospheric boundary layer**
- **Near-surface environment = ~ 10 m depth – ~ 10 m height.**
- **LOSS = Leakage Or Seepage Signal**



Modeling Summary

- Even for small leakage fluxes, subsurface CO_2 concentrations can be high.
- Diffuse seepage leads to passive dispersion in the surface layer.
- Atmospheric dispersion is effective at dispersing seeping gases, subject to caveats, among which are:
  - CO_2 concentrations will be higher in stagnant (low-wind) areas.
  - CO_2 concentrations will be larger for higher fluxes.
  - CO_2 concentrations may be higher periodically.

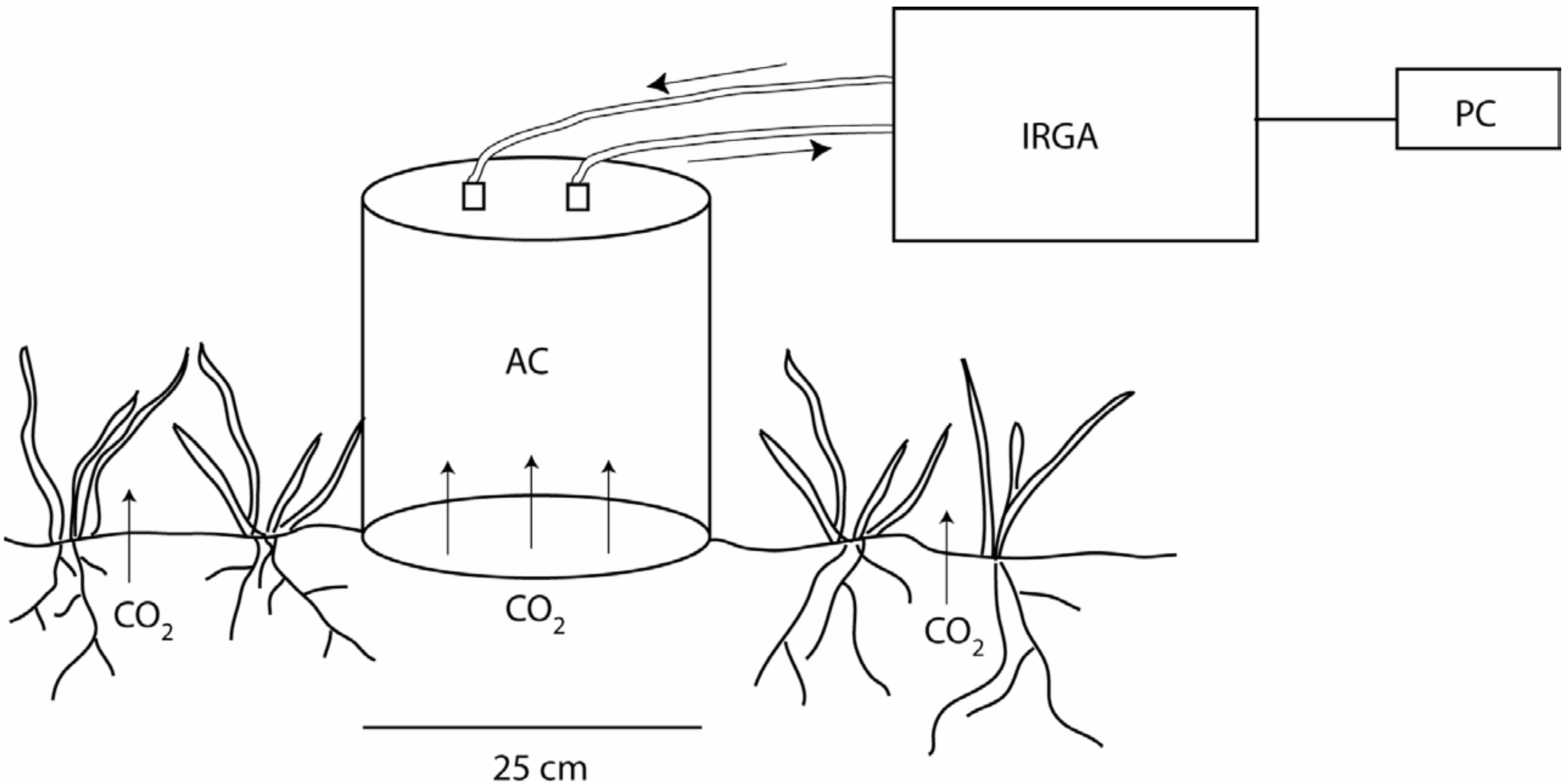
(Oldenburg and Unger, *Vadose Zone Journal*, *2*, 287–296, 2003)
(Oldenburg and Unger, *Vadose Zone Journal*, *3*, 848–857, 2004)

- Result is small LOSS in atmospheric surface layer.
- Larger LOSS in the subsurface.
- Therefore, subsurface and near-surface monitoring is preferred.

Approaches for Monitoring

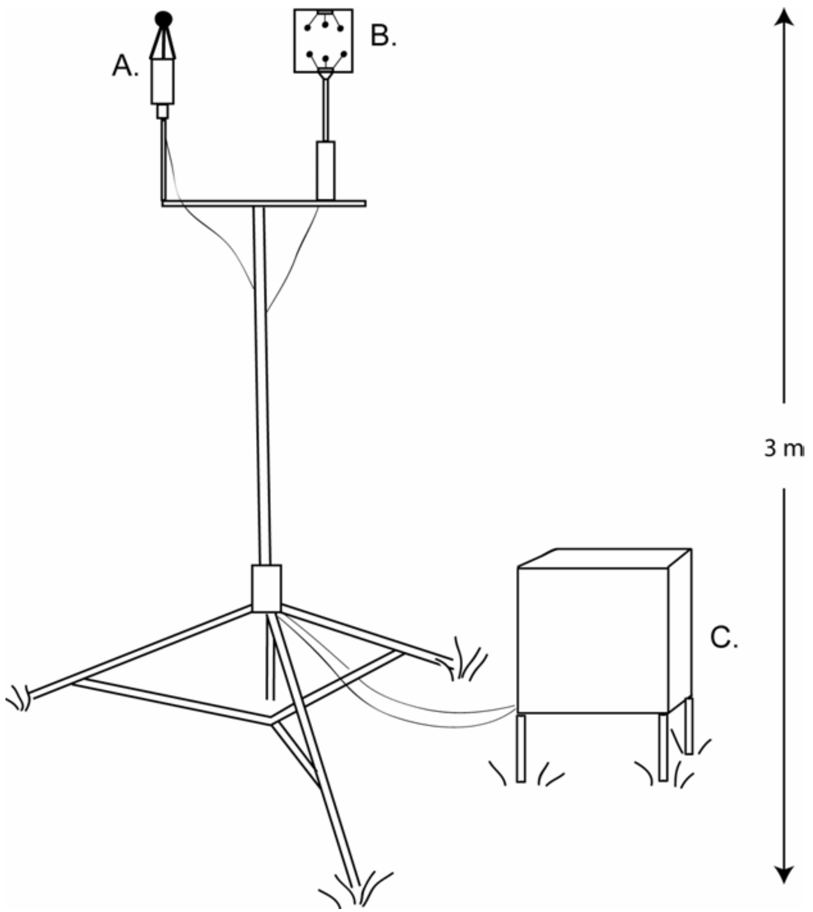
- Conventional CO_2 Monitoring Technologies:
  - IRGA (infrared gas analyzer) for point measurements of CO_2 in gas.
    - Absorption at 4.26 μm.
    - Frequency 1-10 Hz.
    - Typically 0–3000 ppmv detection range, also up to 100% CO_2.
    - Precision +/- 0.2 ppmv at 350 ppmv.
    - $5–30k.
    - Transportable.
    - Although point measurement, can be combined with other instrumentation to measure fluxes over small (accumulation chamber) and large (eddy correlation) areas.

Schematic of Accumulation Chamber (AC)



Soil gas is circulated and CO_2 concentration recorded every 1 sec.
Rate of accumulation of CO_2 in AC is measured.
Flux is calculated from rate of accumulation of CO_2.

Schematic of Eddy Correlation (EC) Tower



Time averaging of fluctuating CO_2 and vertical wind results in mean flux.
Mean flux is over an upwind footprint typically m^2 – km^2 in area.
Area of footprint is function of tower height and meteorological conditions.

Schematic of Truck-Mounted LIDAR

LIDAR = LIght Detection And Ranging.
Raman LIDAR = detecting wavelength shifts due to Raman scattering.
DIAL = DIfferential Absorption LIDAR = tunable laser to create backscatter ratios.
Rapidly developing, good areal coverage.
Concentration integrated over path length.

Chemical and Isotopic Signatures

CO_2 source	$\delta^{13}C_{CO2}$ ‰	$\Delta^{14}C_{CO2}$ ‰	Near-surface CO_2 conc.	CO_2 conc. profile with depth	O_2 conc. profile with depth
Atmosphere	-7	-70	Low	–	–
Plant root respiration and oxidative decay of young soil organic matter	C_3: -24 to -38 C_4: -6 to –19	≥ -70	Low to moderate	Increasing through soil zone	Decreasing through soil zone
Oxidative decay of ancient organic matter	C_3: -24 to -38 Aquatic/C_4: -6 to –19 Also age dependent	Highly depleted to absent, depending on age	Low	Increasing potentially through vadose zone	Decreasing potentially through vadose zone
Marine carbonate rocks	0 ± 4	absent	Low	Increasing through vadose zone	No effect
Fossil fuel	Average: -27	absent	Moderate to high	Increasing through vadose zone	No effect

Conc., C_3, and C_4, refer to concentration, C_3 plants, and C_4 plants. All near-surface concentrations given are general estimates; these concentrations will be strongly dependent on the magnitude of the CO_2 flux.

Overall Strategies for Storage Verification

- Subsurface gas geochemistry.
  - Carbon isotopes (^{13}C, ^{14}C).
  - Bulk soil gas composition.
    - Trends with depth. Spatial trends.
- Surface CO_2 concentration and flux monitoring.
  - EC good for large areas and average flux measurements.
  - AC good for small features and delineating spatial trends.
- Water chemistry.
  - pH. Ebullition. Dissolved Inorganic Carbon.

Integrated Sampling Strategy

- Baseline monitoring and modeling.
  - — Characterize spatial and temporal variability
    - Soil, parent material, vegetation, hydrology, topography, surface water, ...
  - — Flow modeling (TOUGH2) and ecological modeling (LSM).

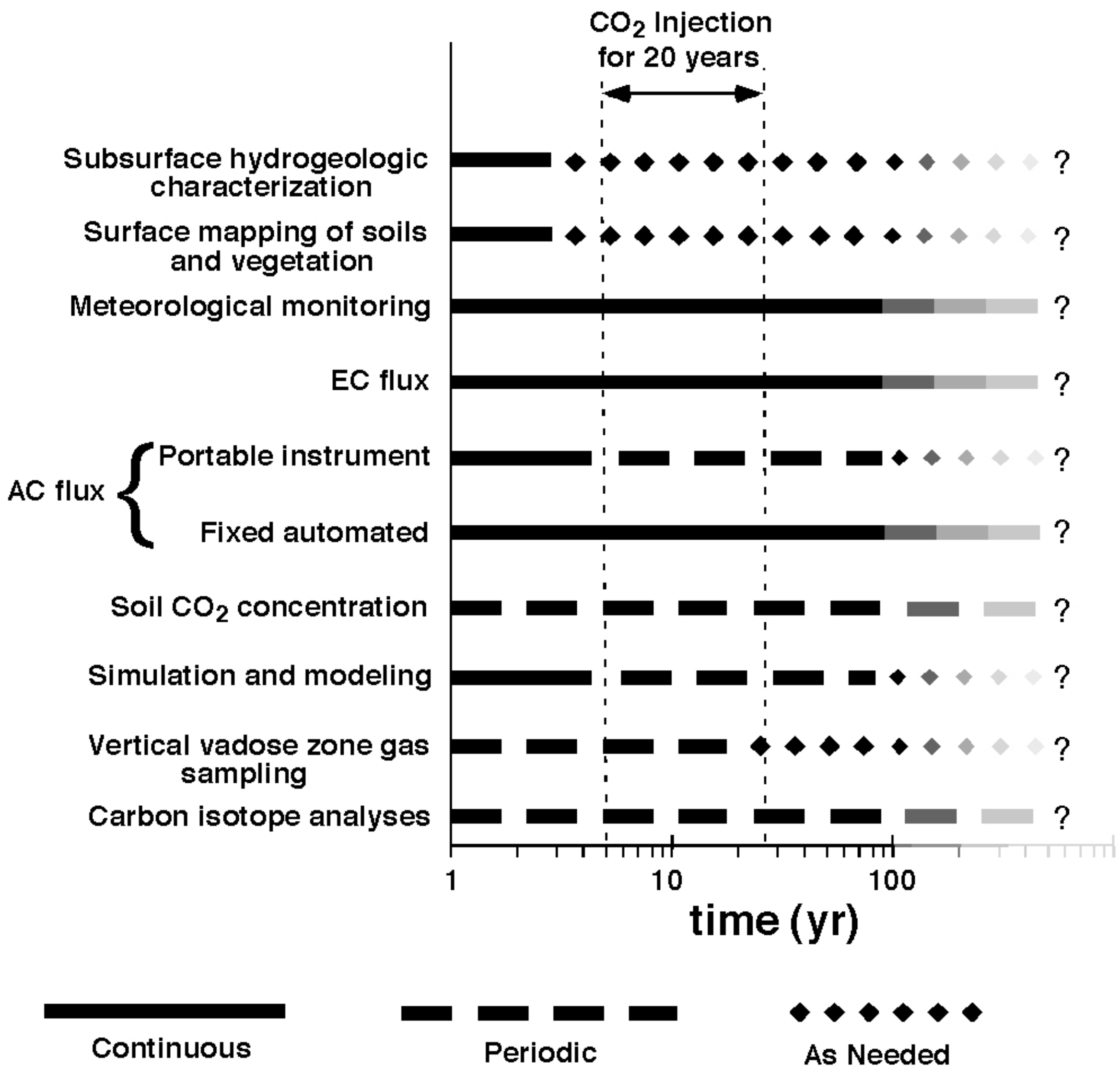
- Surface CO_2 concentration and flux monitoring (AC and EC).

- Soil gas sampling and analysis. Fixed sites over time.

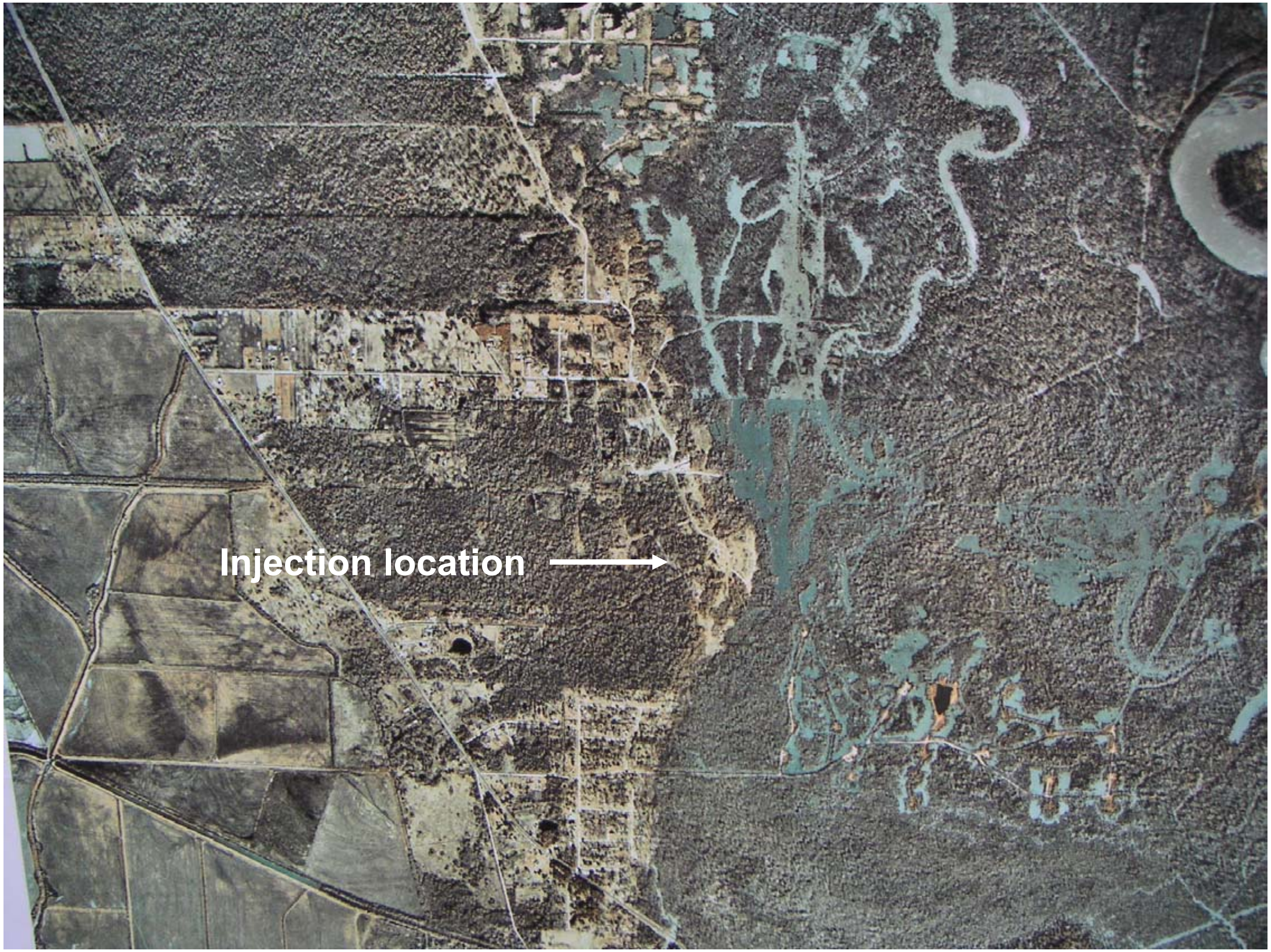
- Soil moisture and temperature.

- Goal is to understand the natural ecological system prior to injection so that LOSS can be discerned.

Potential Activities and Schedule



Overhead Photo of Frio Pilot Site

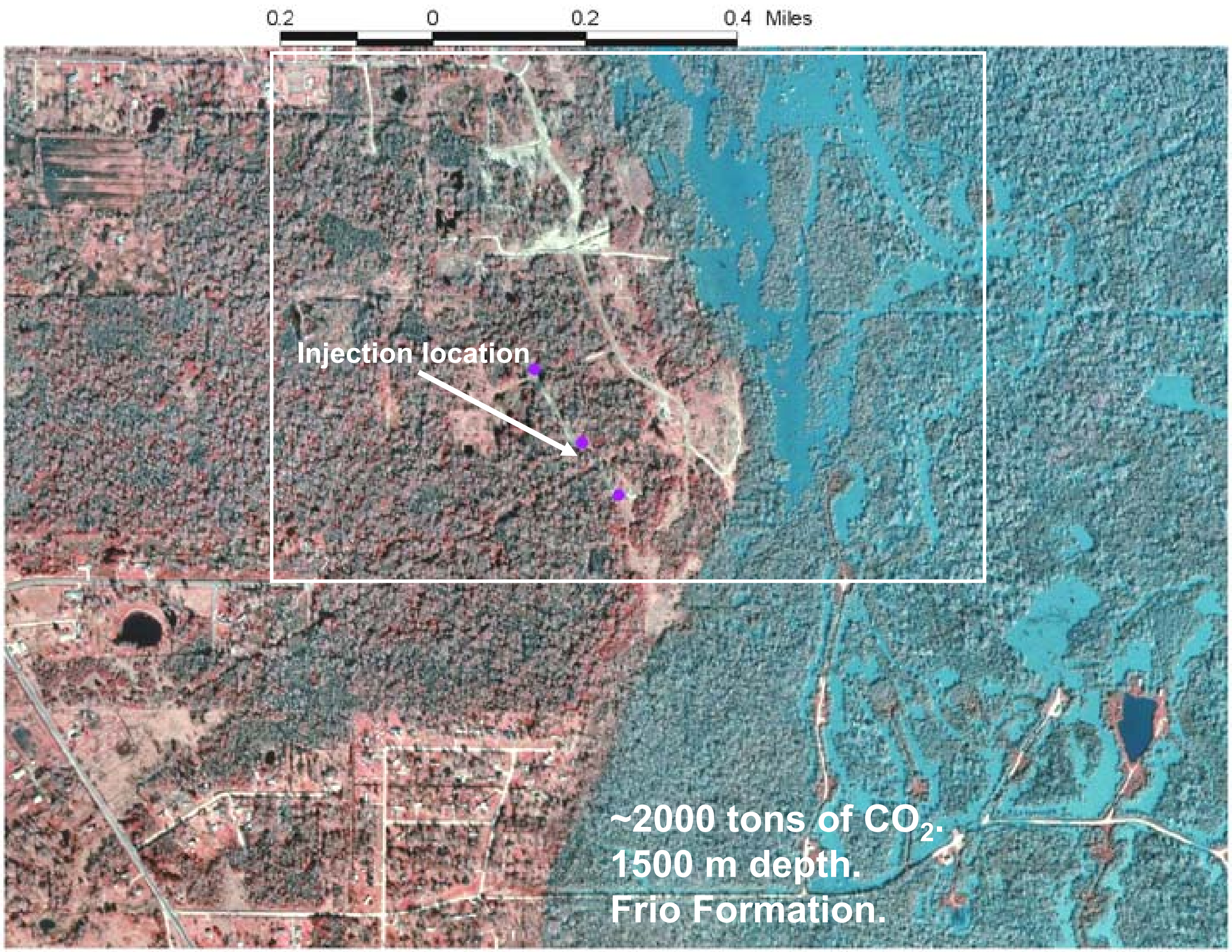


Injection Well and Fog at 85 °F

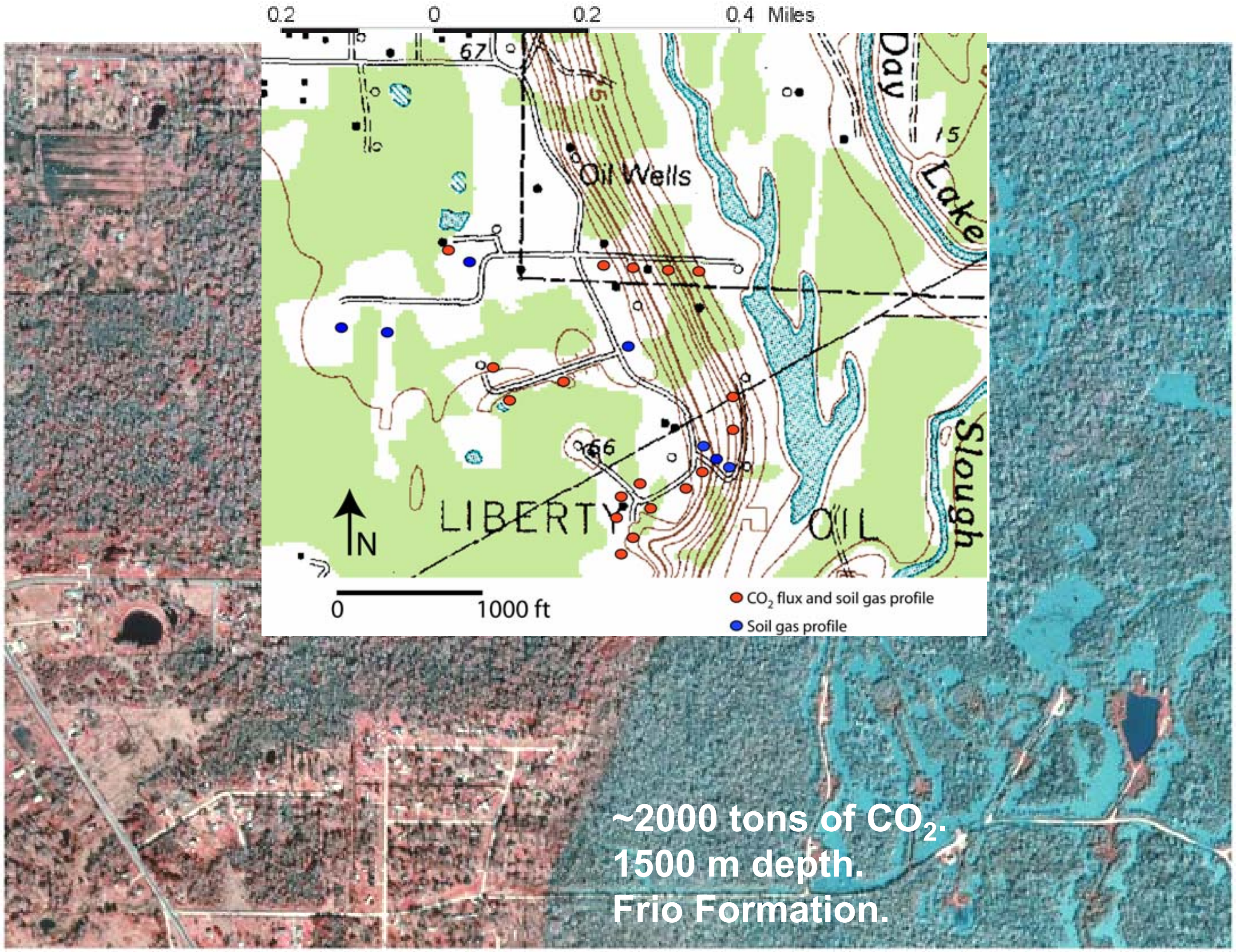
Observation Well and Dense Vegetation

Shallow Monitoring Well

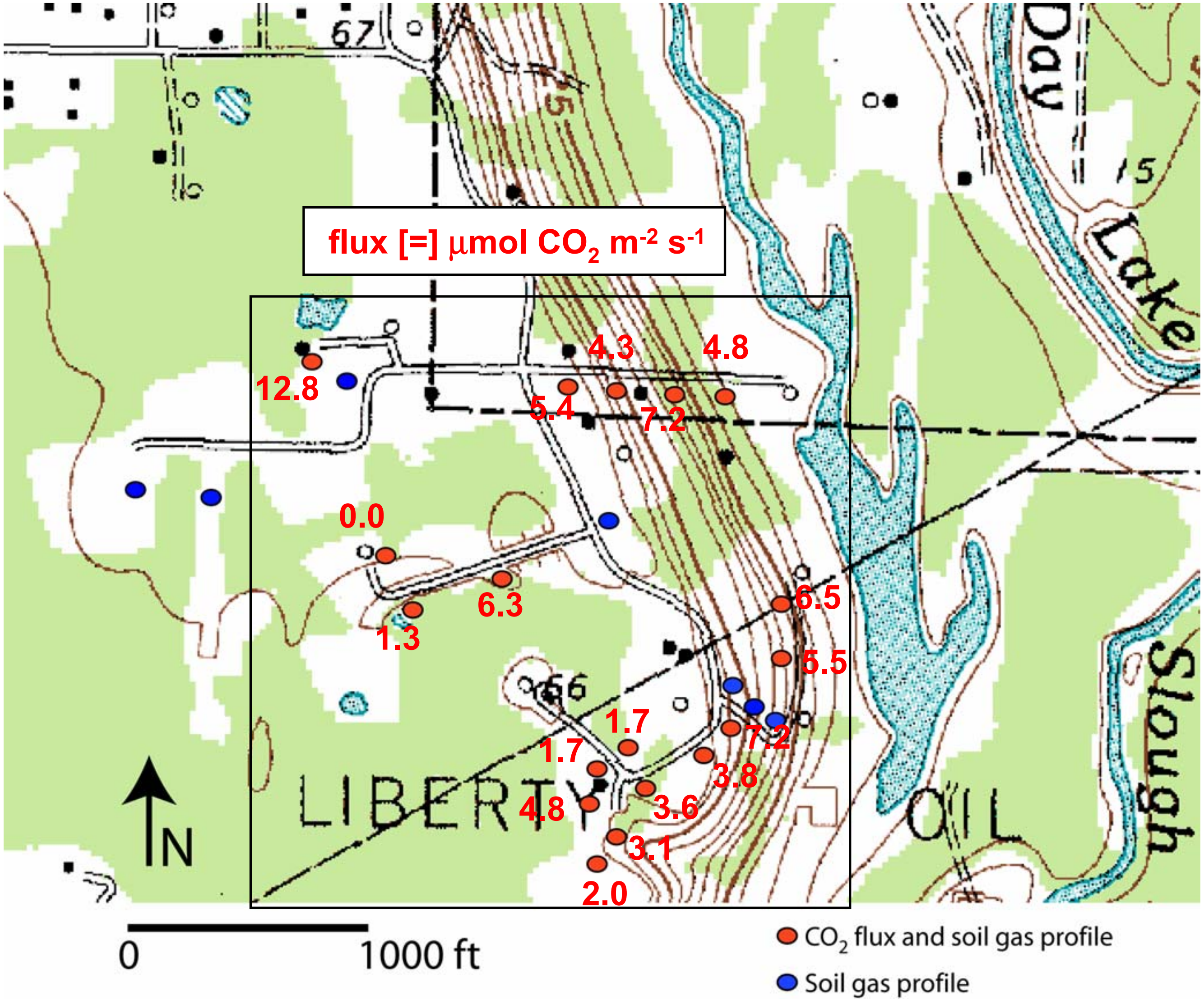
South Liberty Site (Frio Pilot Study)



South Liberty Site (Frio Pilot Study)

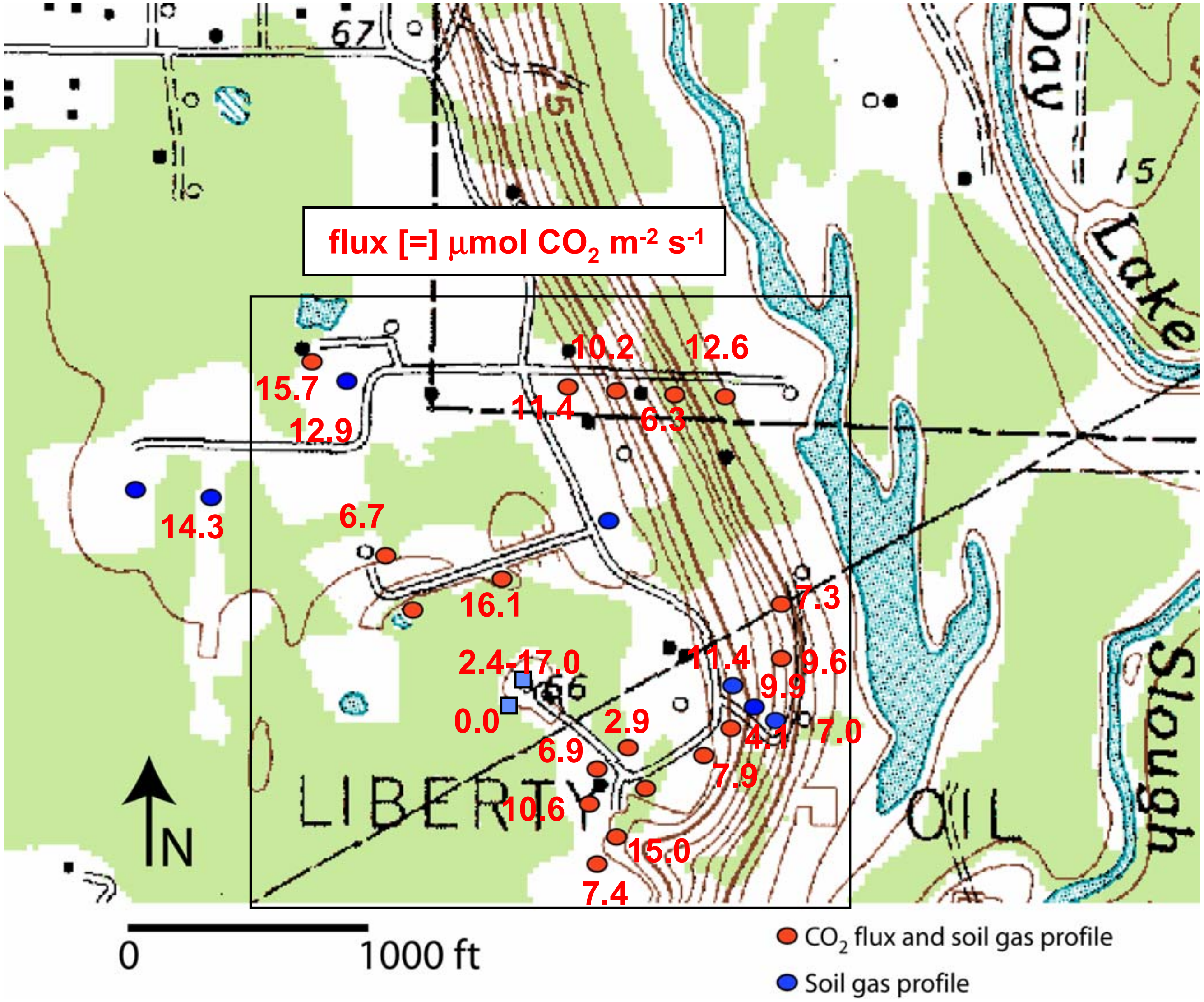


CO_2 Flux Baseline Survey (Jan. 2004)



1 μmol CO_2 m^{-2} s^{-1} = 4.4 x 10^{-8} kg CO_2 m^{-2} s^{-1}

CO_2 Flux Baseline Survey (Sept. 2004)



1 μmol CO_2 m^{-2} s^{-1} = 4.4 x 10^{-8} kg CO_2 m^{-2} s^{-1}

Lessons Learned from the Frio

- Background pre-injection surface and near-surface monitoring is limited by
  - Seasonal features, e.g., open water on the flood plain.
  - Seasonal conditions, e.g., saturated soils.
  - Rainfall and high humidity that affect portable instruments (e.g., LICOR 6400).
- Dense vegetation limits access. Sampling tends to be near roads.
- Avoidance of surface water can lead to biased sampling.
- Pre-injection monitoring points may be obliterated by project roads/pads.
- Operational realities such as gas venting can release tracers.
- Shallow monitoring wells may not be constructed until injection wells and pads are located.

Recommendations

- Allow plenty of time to study local conditions over all seasons.
- Develop monitoring approaches appropriate for these conditions.
- Define areas of likely future road/pad development and avoid these as monitoring points.
- Establish some level of security in the region to avoid vandalism of equipment.
- Set aside sufficient time and money to carry out thorough job for the given site, taking into account its particular requirements.

Summary

- Despite extensive general knowledge about natural CO_2 occurrence, and model-derived expectations of seepage behavior, discerning small CO_2 LOSS from natural background variation is challenging.
- Strategy we propose involves comprehensive baseline monitoring and modeling to develop understanding of natural system.
- Program of multiple and integrated measurement and monitoring can be applied during and after injection.
- Measurements in conflict with expectations of the natural system would be investigated thoroughly by more detailed studies.
- Field and operational realities present challenges that will be unique to each project.

Acknowledgments

This work was supported in part by the Office of Science, U.S. Department of Energy, and by the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC03-76SF00098 .

Review of geophysical monitoring results from the SACS project

Ola Eiken, Statoil

with input from Andy Chadwick, Rob Arts

and the CO2STORE/SACS team

Monitoring workshop

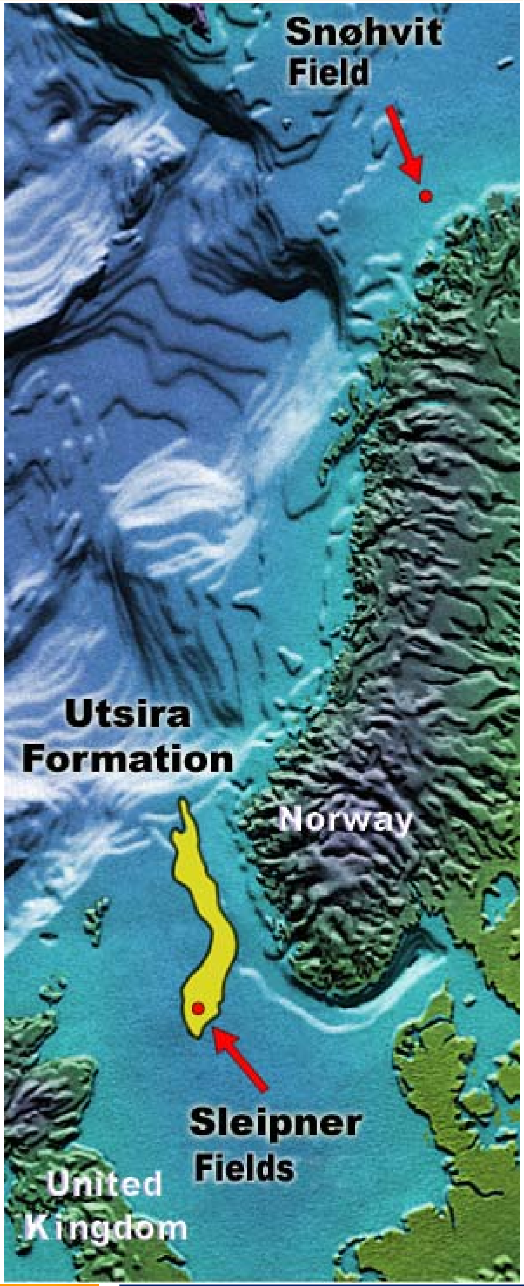
University of California Santa Cruz

8th to 9th November 2004

STATOIL

Outline

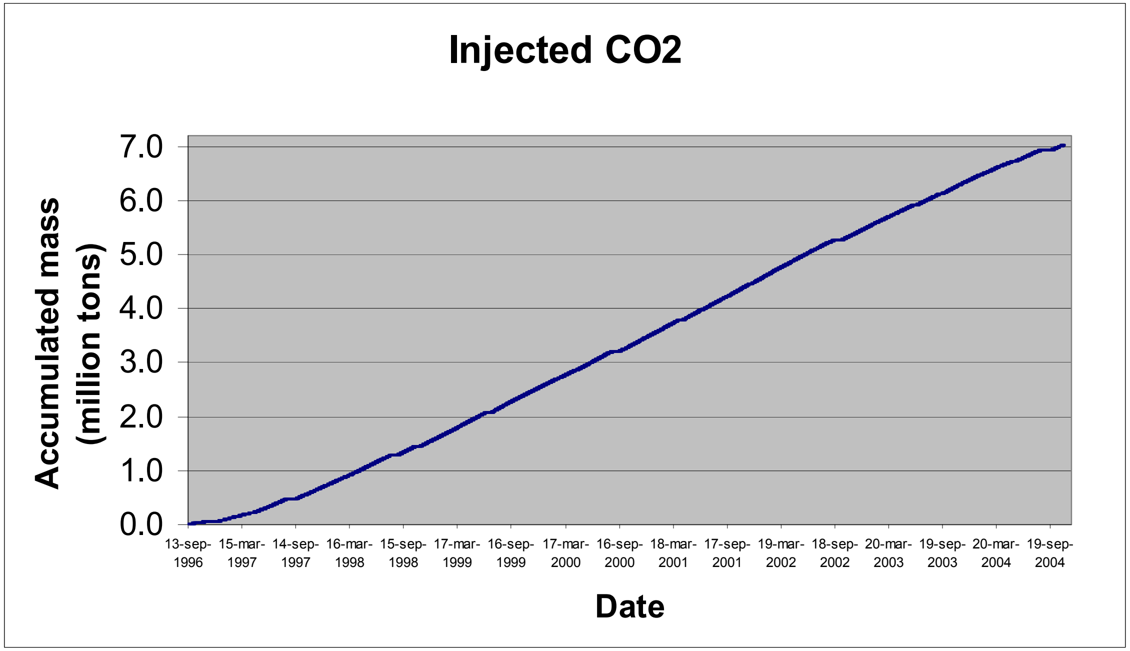
- Sleipner site
- Injection data
- Monitoring strategy
- Seismic surveys
- First order observations:
  - Extent of CO_2 plume
  - Non-leakage
  - Internal structure; layers, chimney
- Gravity survey
- Further plans
- Uncertainties and limitations

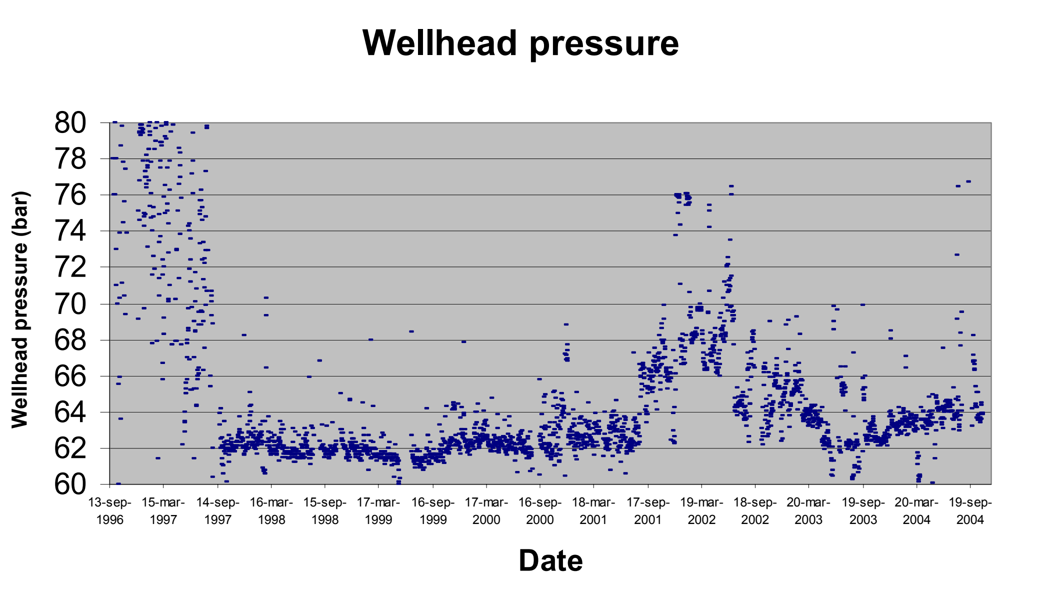


- CO_2 is injected into a thick sandstone layer (Utsira Fm.) at 800-1100 m depth below sealevel
- The sandstones have porosities of 35-40 % and permeabilities of >1 D

Injection data

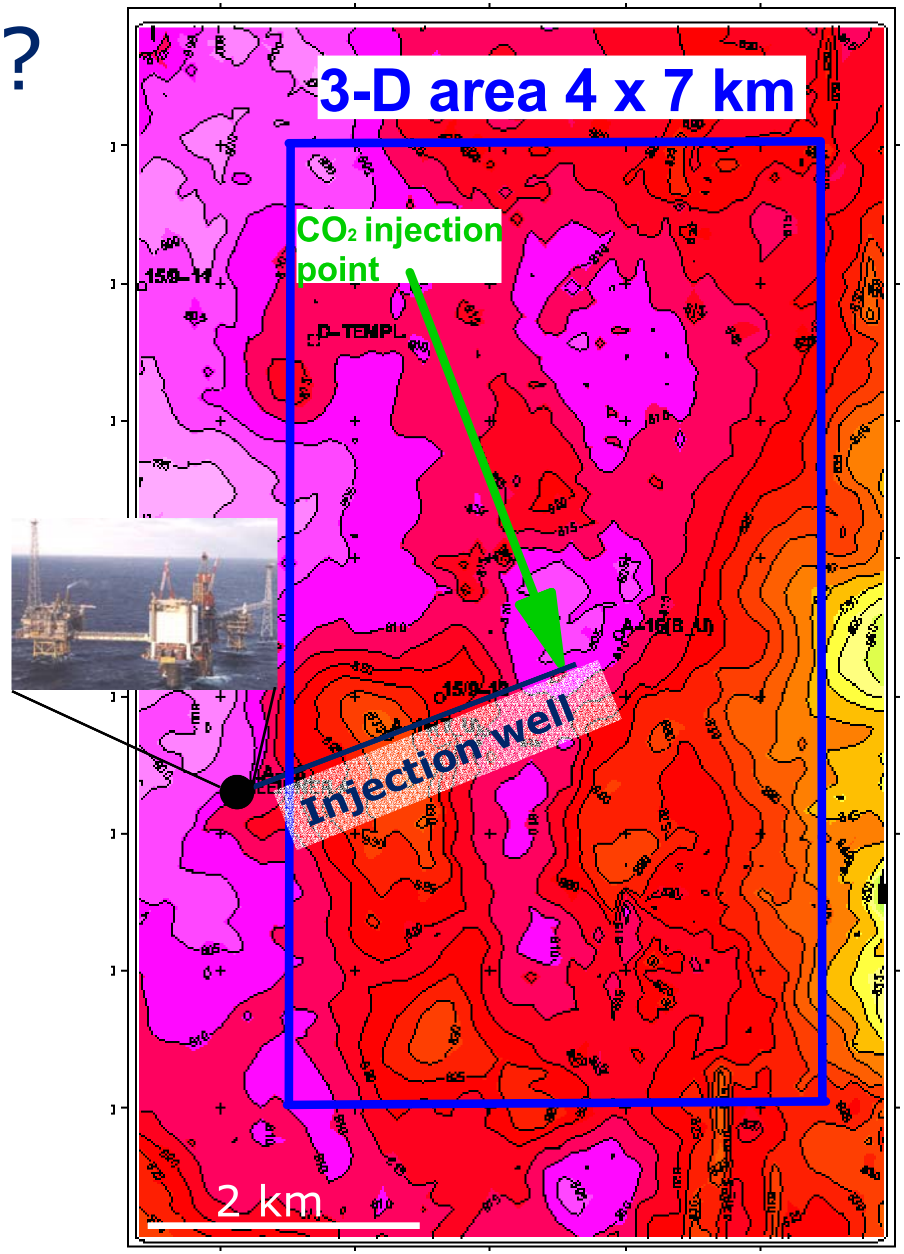
- 7 mill. tons have been injected over 8 years
- Minimal increase in wellhead pressure





Monitoring strategy ?

- Observation well
  - cost of ~ $ 5-8 million, too much for a research project
  - limited spatial information
  - increased risk of leakage ?
- Well seismic (injection well)
  - technically complicated and costly
  - limited volumetric information
- 3-D / 2-D time-lapse seismic
  - good /reasonable areal coverage
  - medium/low cost
  - high resolution
- Time-lapse gravity
  - good areal coverage
  - lower cost
  - lower resolution



STATOIL

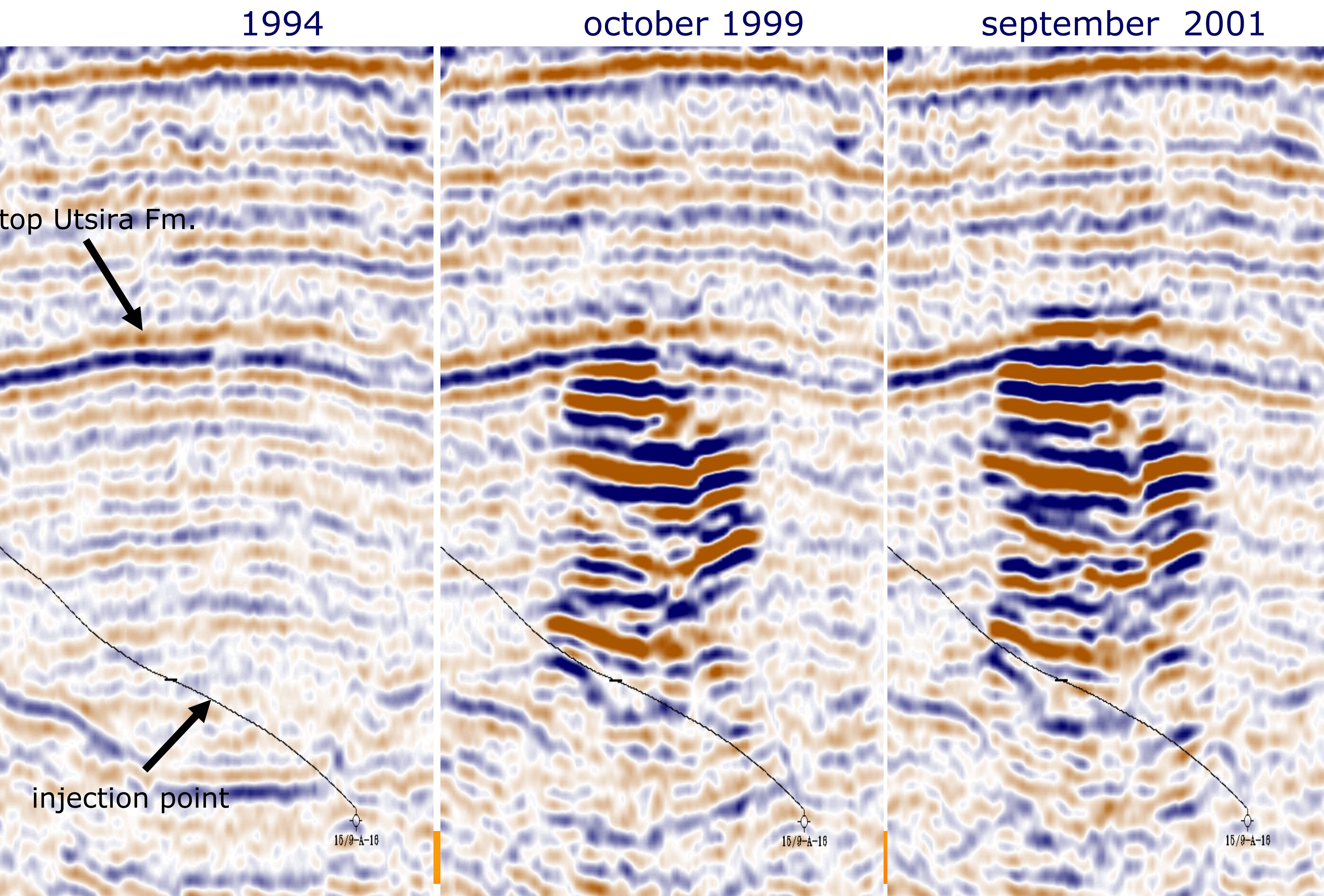
Seismic data acquisition

	1994	Oct-1999	Sep-2001	May-2002
Amount of CO_2 injected [million tons]	0	2.3	4.2	5.0
Cost (acq. + proc)	n.a.	$380 000	$450 000	($60 000)
Shooting direction	N-S	N-S	N-S	N-S
Tow depth (s,r)	6m, 8m	6m, 8m	6m, 8m	6m, 8m
Cable length	3000m	3600m	3000m	3000m
CMP line separation	25m	25m	25m	25m
Nominal fold	20	30	30	20
Contractor	Geco-Prakla	Geco-Prakla	WesternGeco	WesternGeco

Seismic data processing

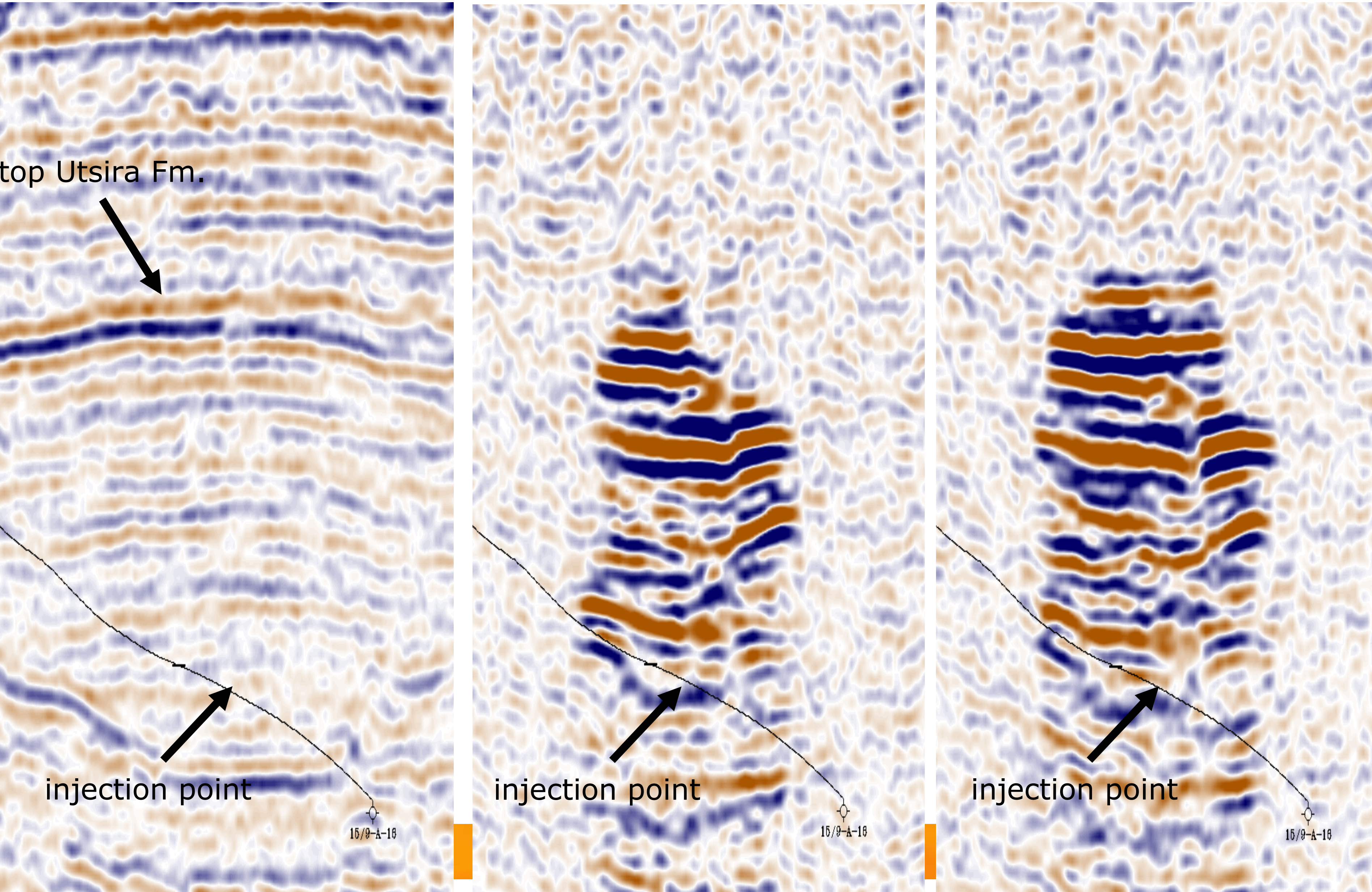
- Simultaneous 4D processing of surveys, starting from raw data – at Geco-Prakla / WesternGeco
- Comprehensive processing sequence with aim of maximum repeatability
- Global wavelet matching (deterministic + residual)
- Line-dependent residual timeshifts
- New velocity analyses in CO_2 injection area

East-west line through injection point

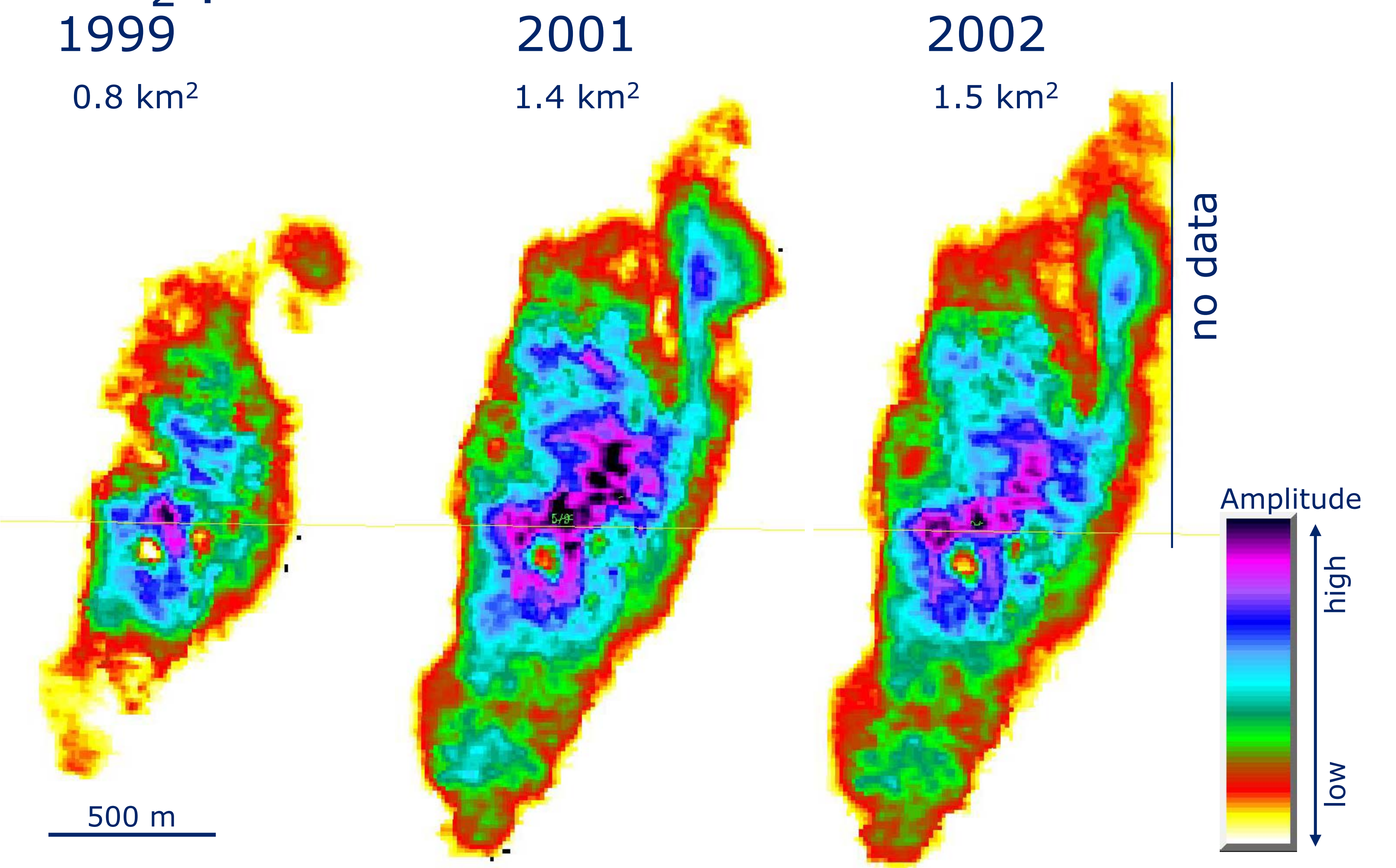


East-west line through injection point

1994 | 1999-1994 | 2001-1994



CO_2 plume – summed amplitudes of upper part



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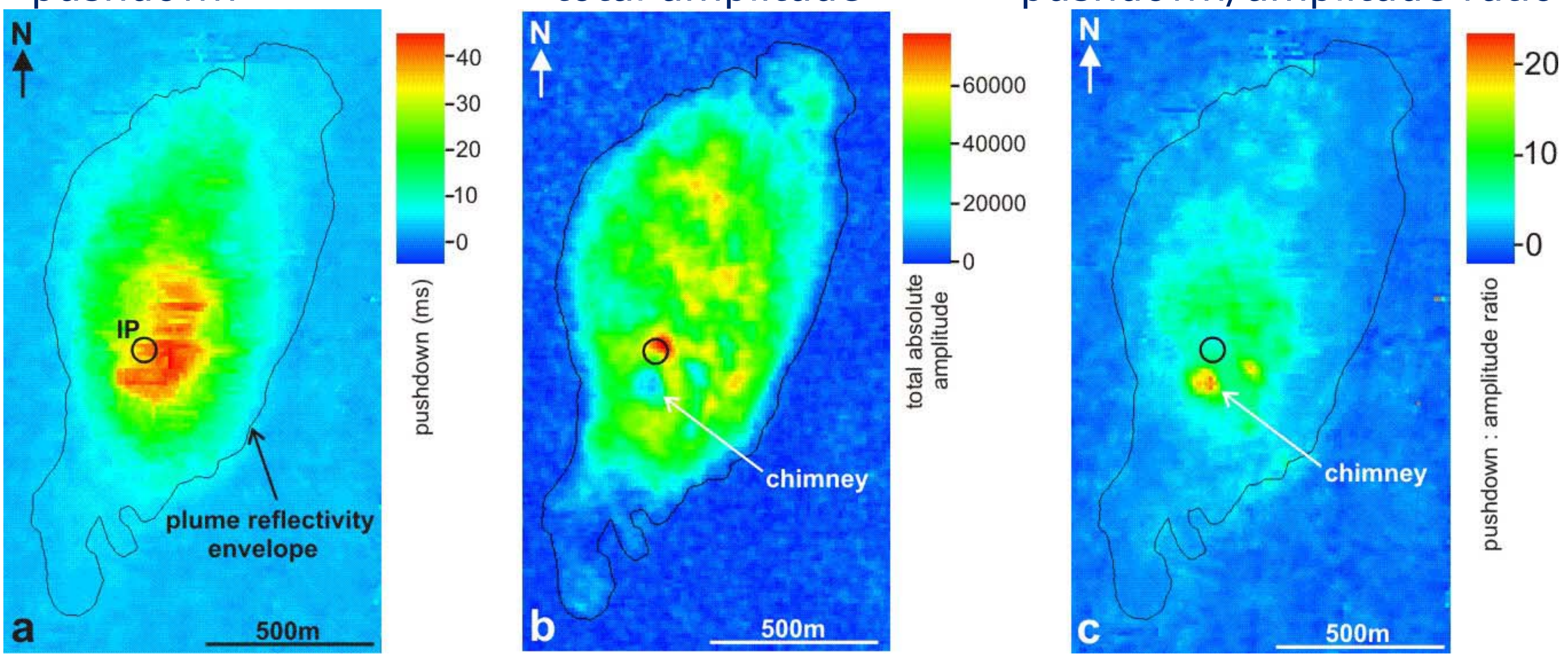
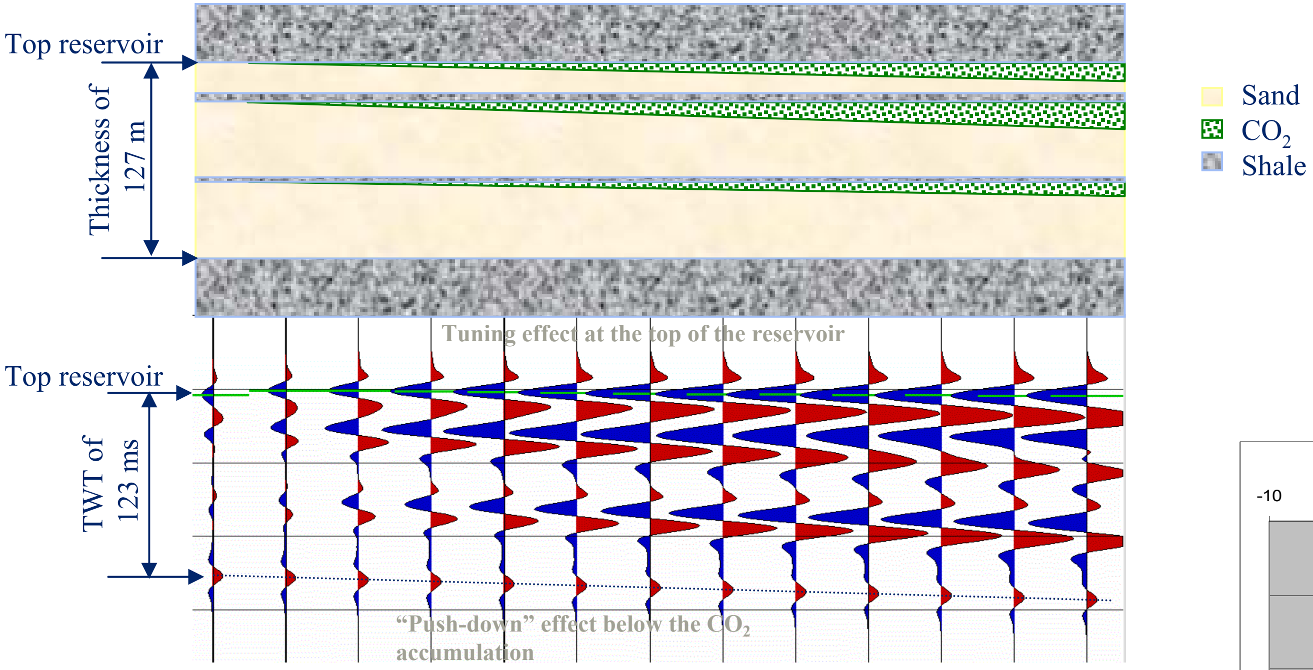
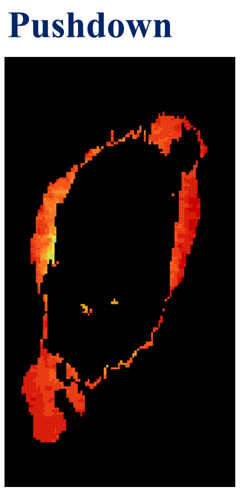
1999 CO_2 plume
reflectivity and pushdown

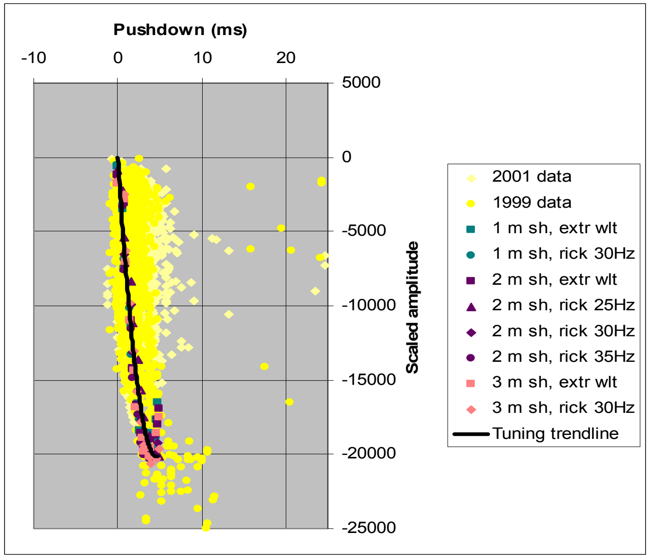
pushdown | total amplitude | pushdown/amplitude ratio



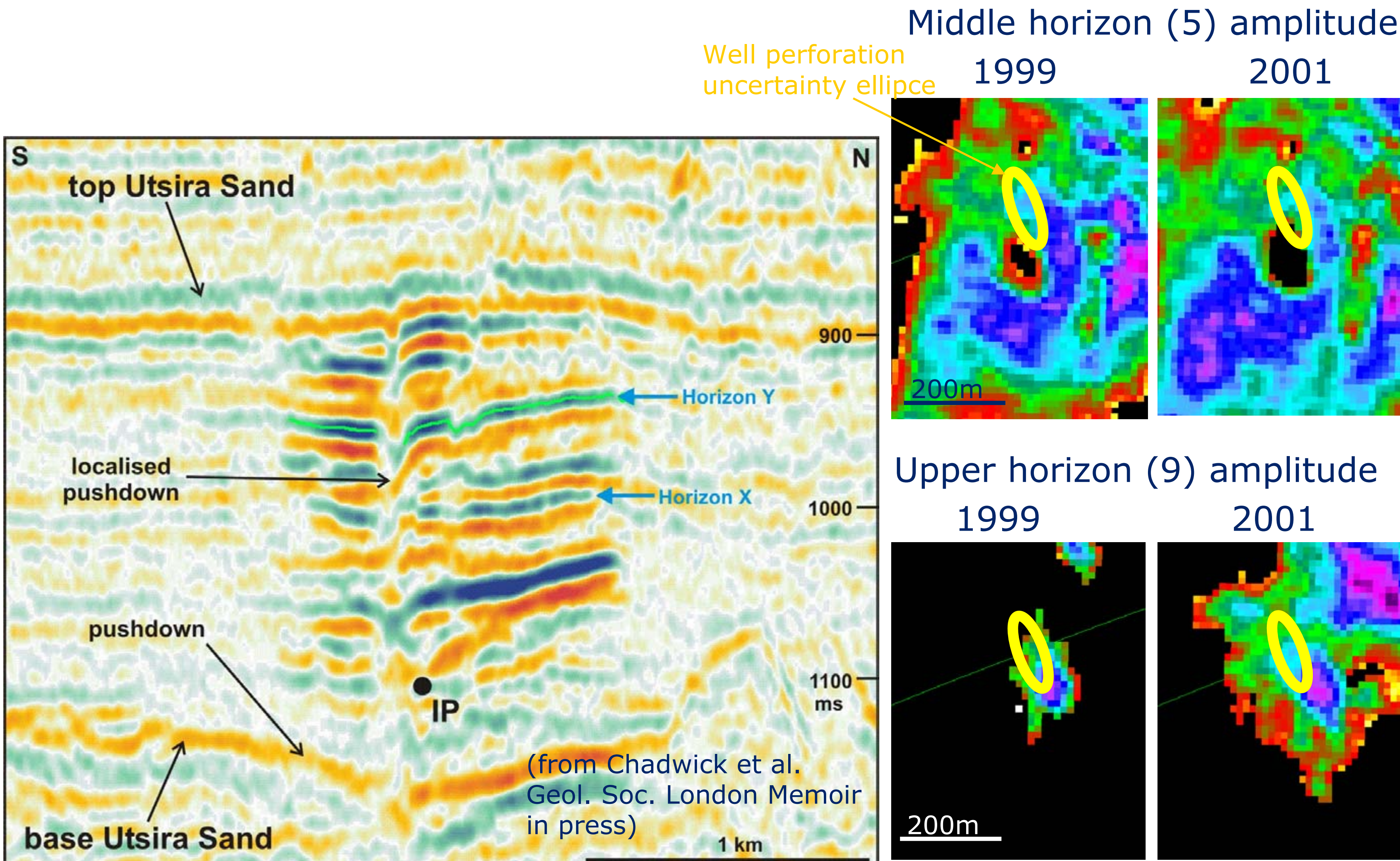
Thin layer response







Seismic chimney



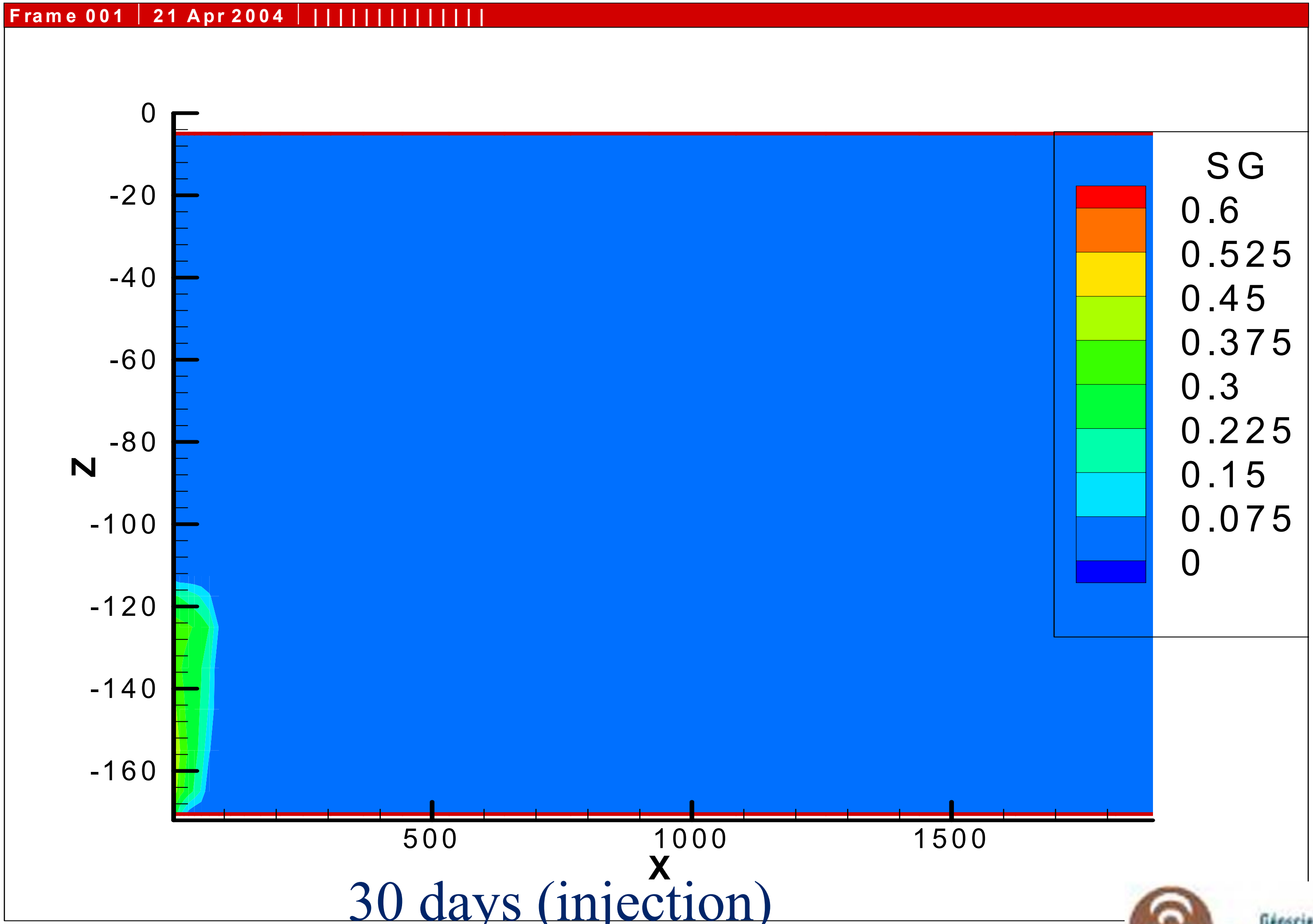
(from Chadwick et al.
Geol. Soc. London Memoir
in press)

Important monitoring results

- Reflectivity and time-delays are spectacular
- The outer boundary of the CO_2 plume is well defined
- No leakage is observed
- Leakage detectability threshold depends on the CO_2 distribution
  - May range from a few tons to a few 10^3 tons

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



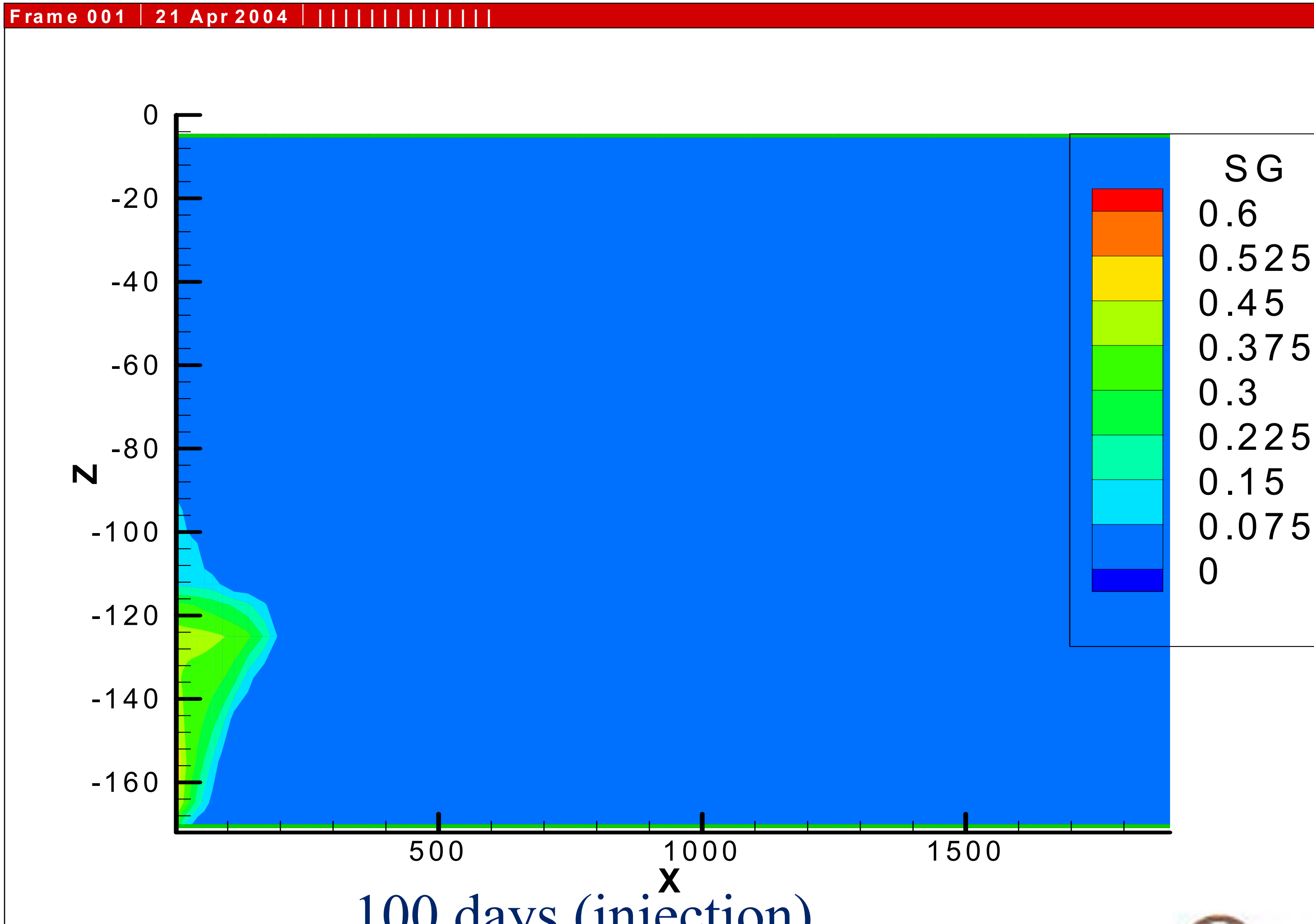
30 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Géosciences pour une Terre durable brgm

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



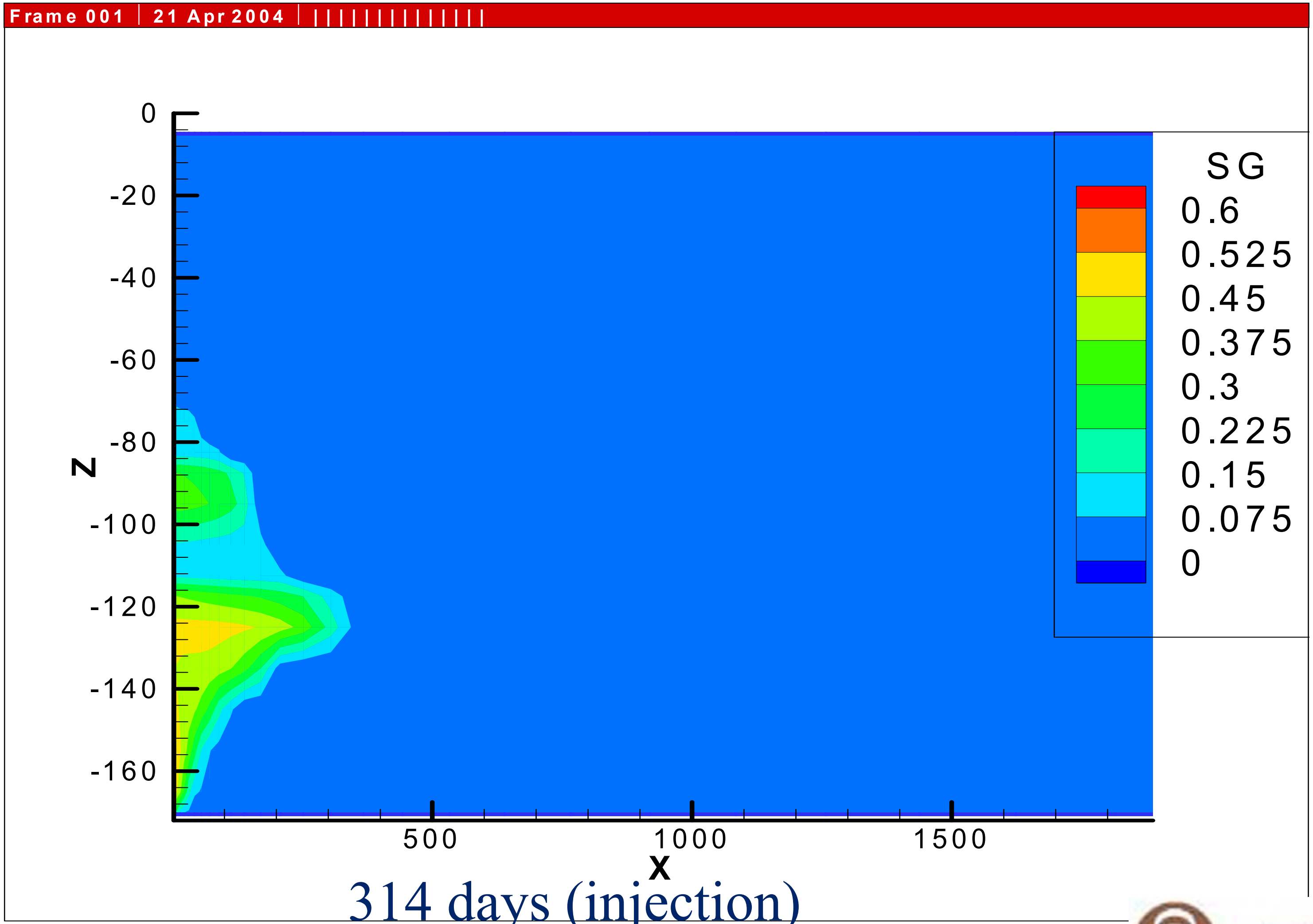
100 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Géosciences pour une Terre durable
brgm

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



314 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

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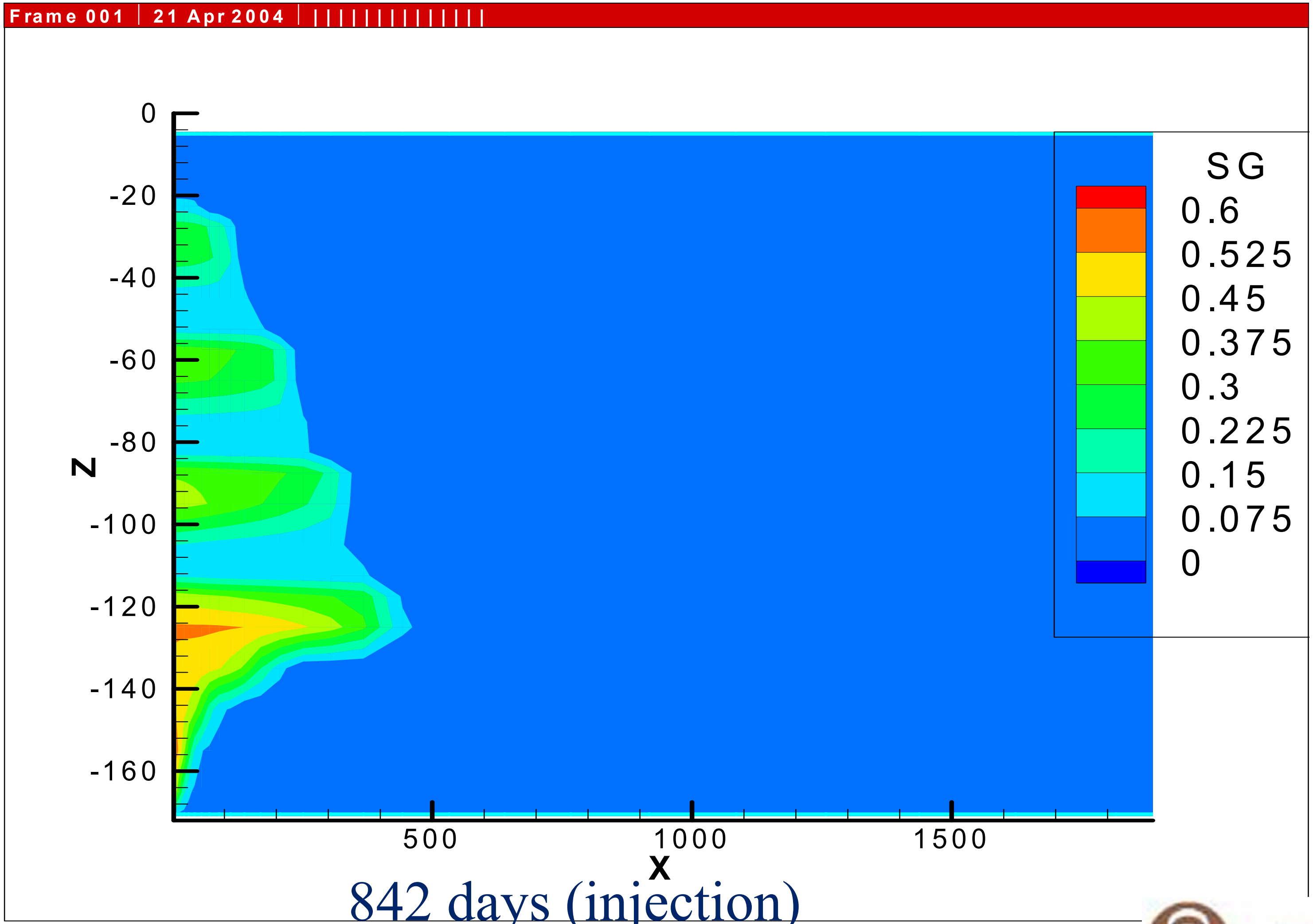
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front

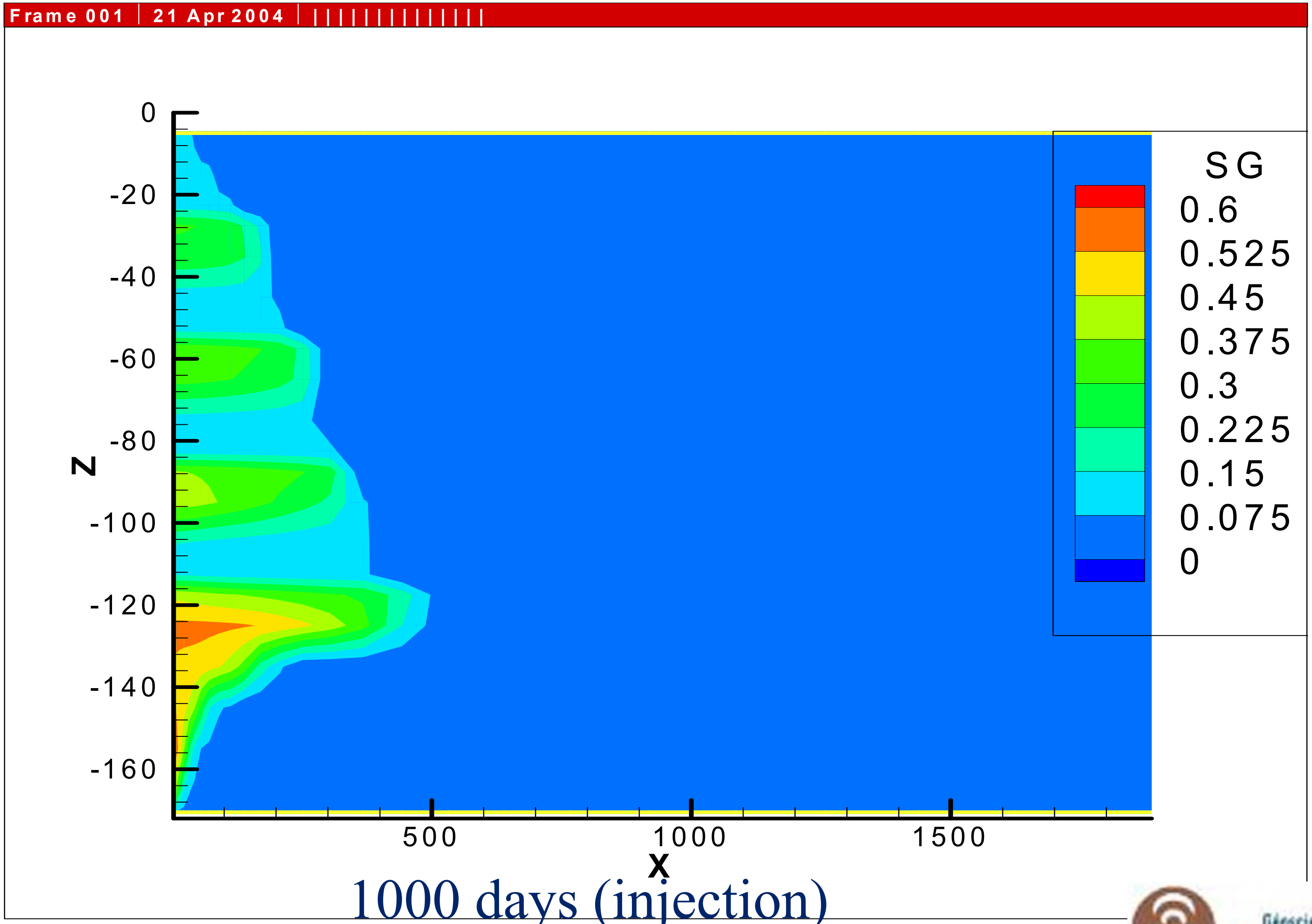


842 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



1000 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

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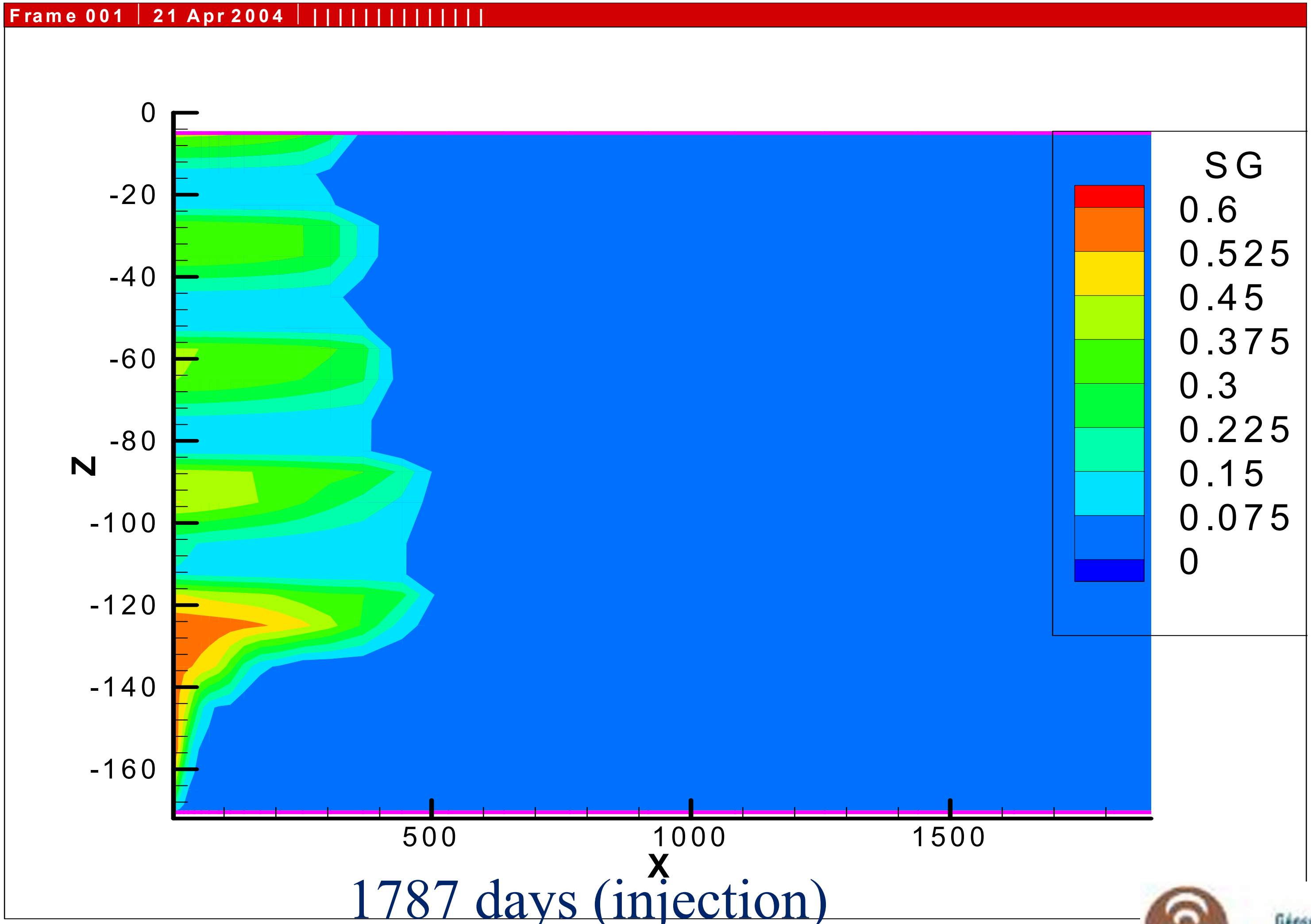
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



from Pascal Audigane, Bureau de Recherches Géologique et Minières

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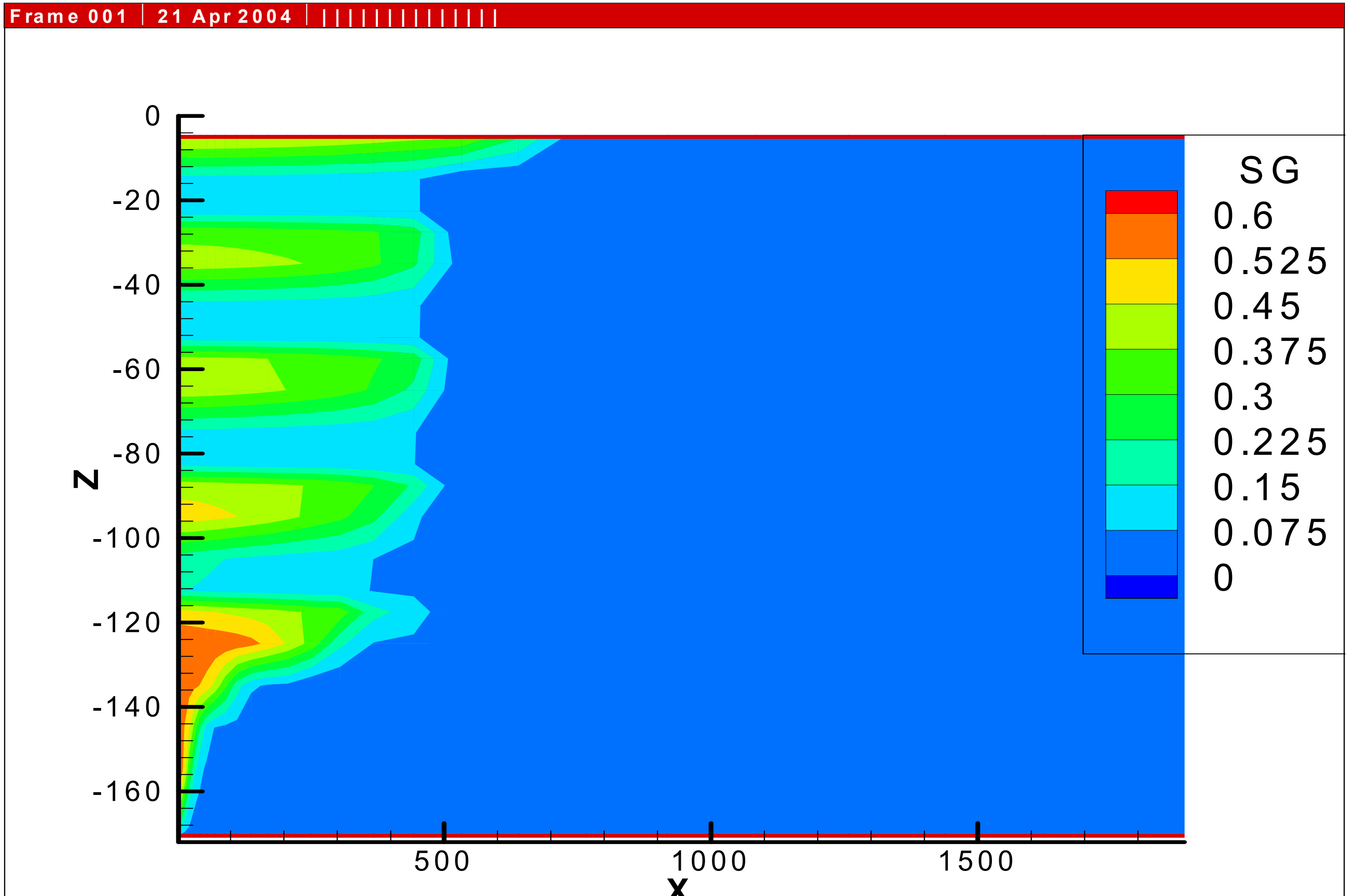
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



2710 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

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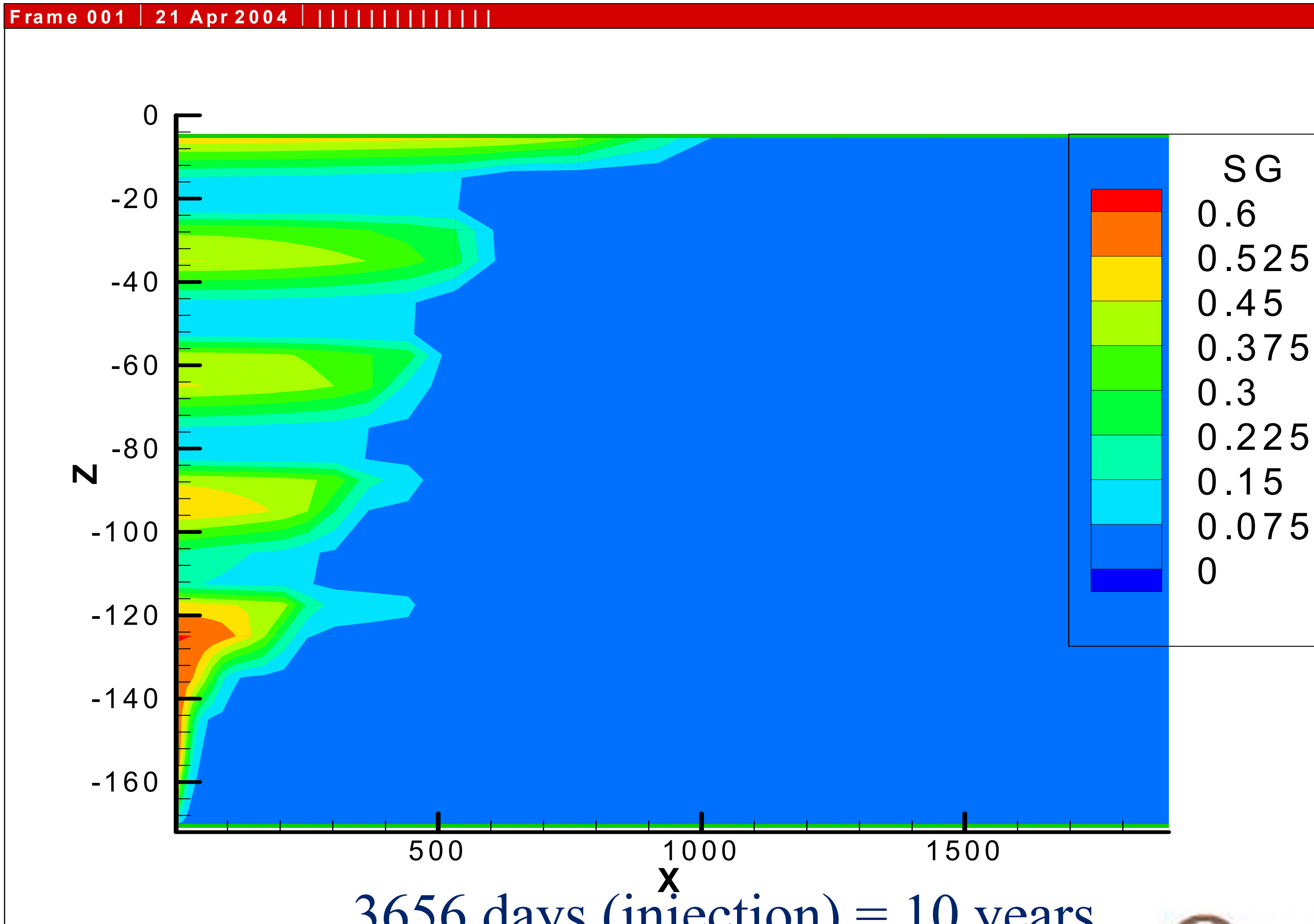
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front

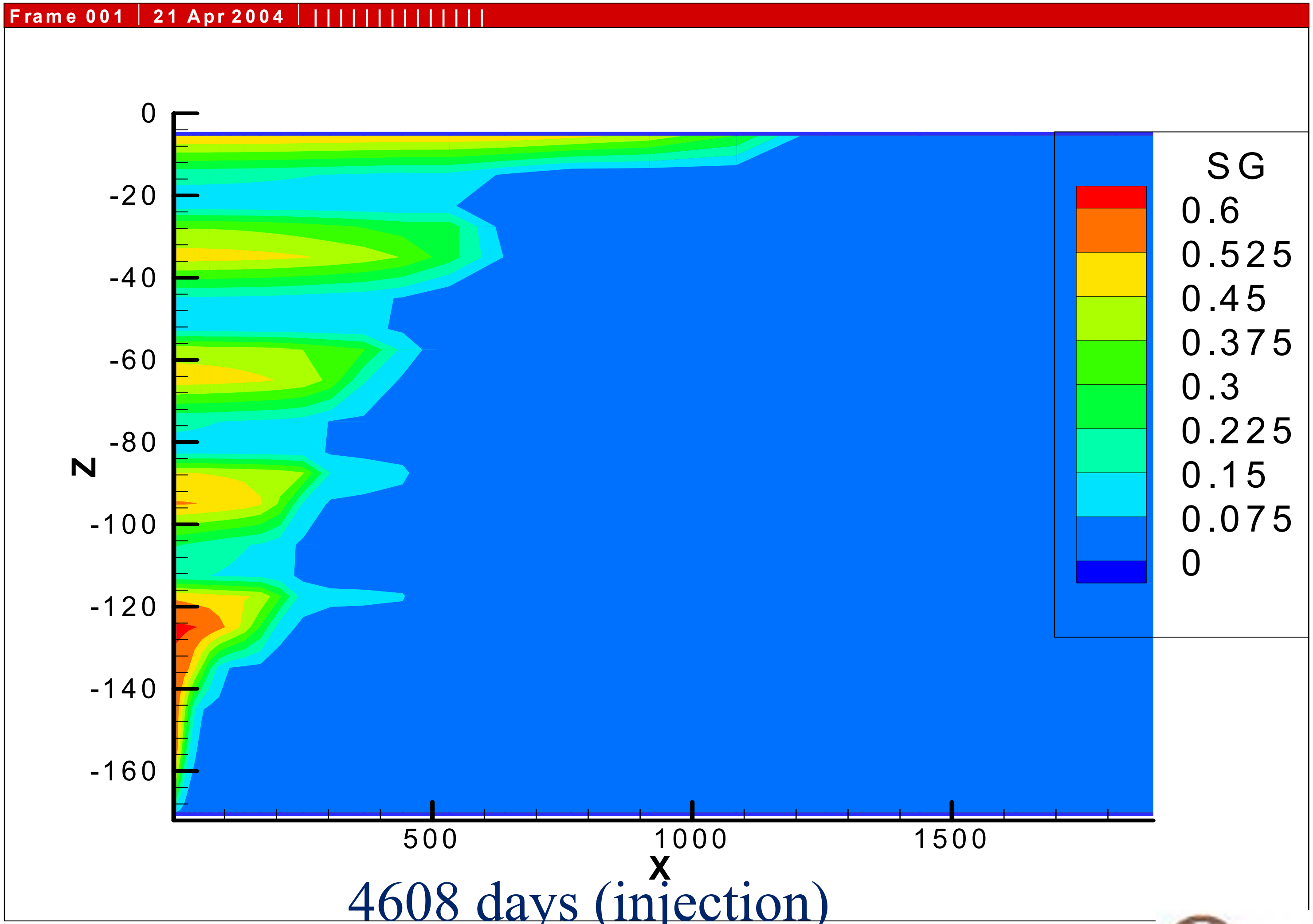


3656 days (injection) = 10 years

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



4608 days (injection)

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Géosciences pour une Terre durable

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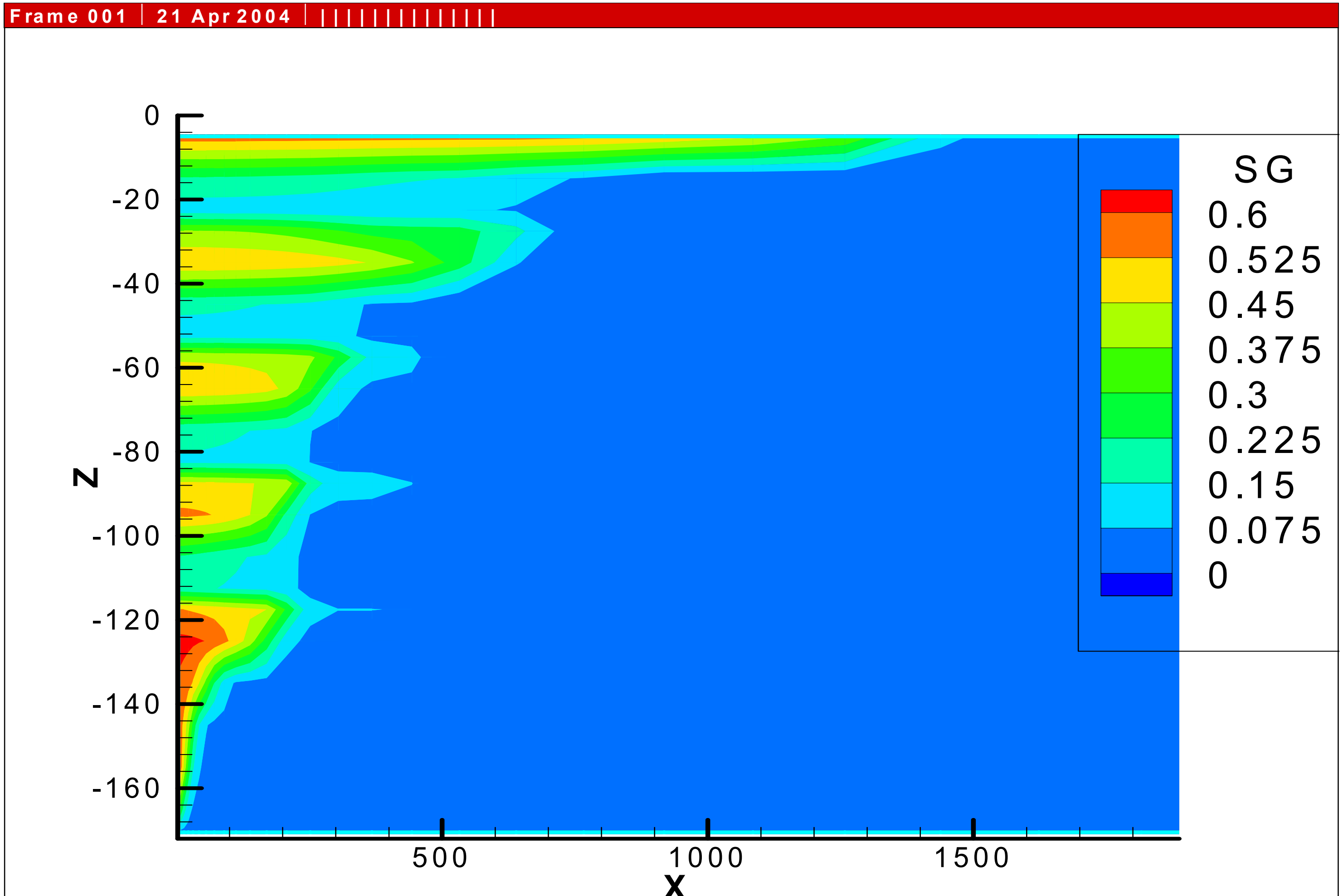
Dynamic modelling: link to long-term predictions

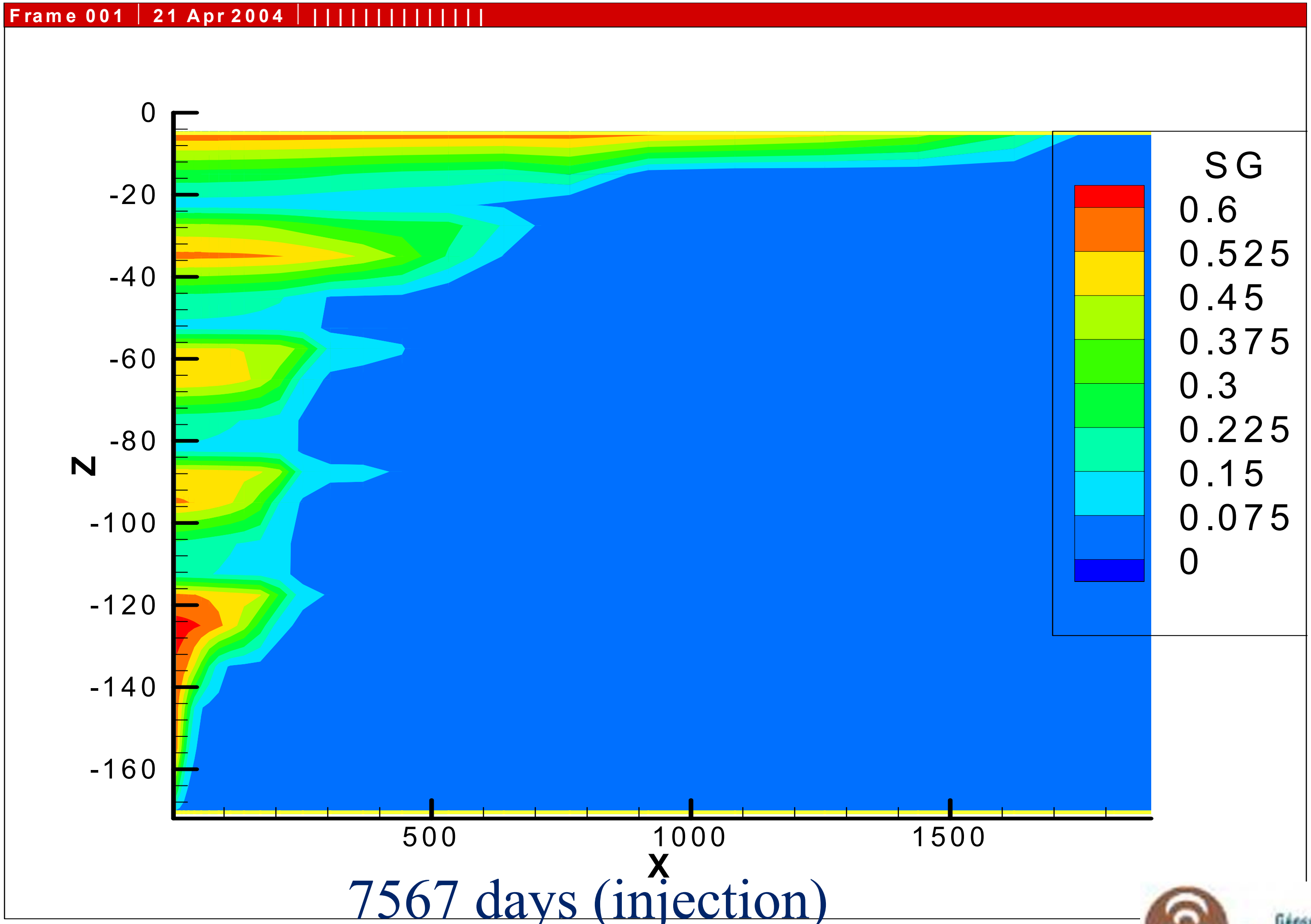
Example of 2D cylindrical model of gas saturation front



5895 days (injection)

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



from Pascal Audigane, Bureau de Recherches Géologique et Minières

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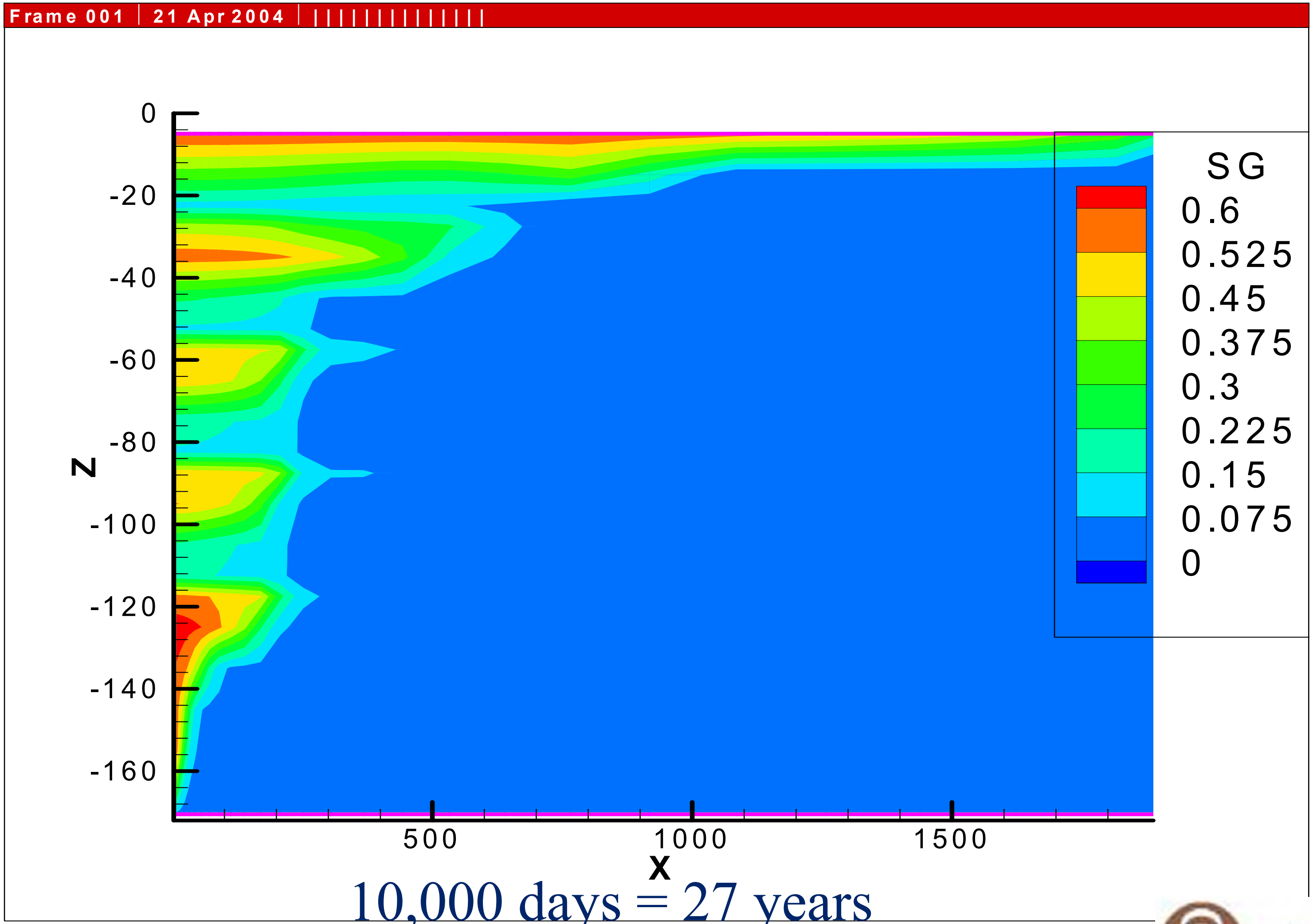
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front

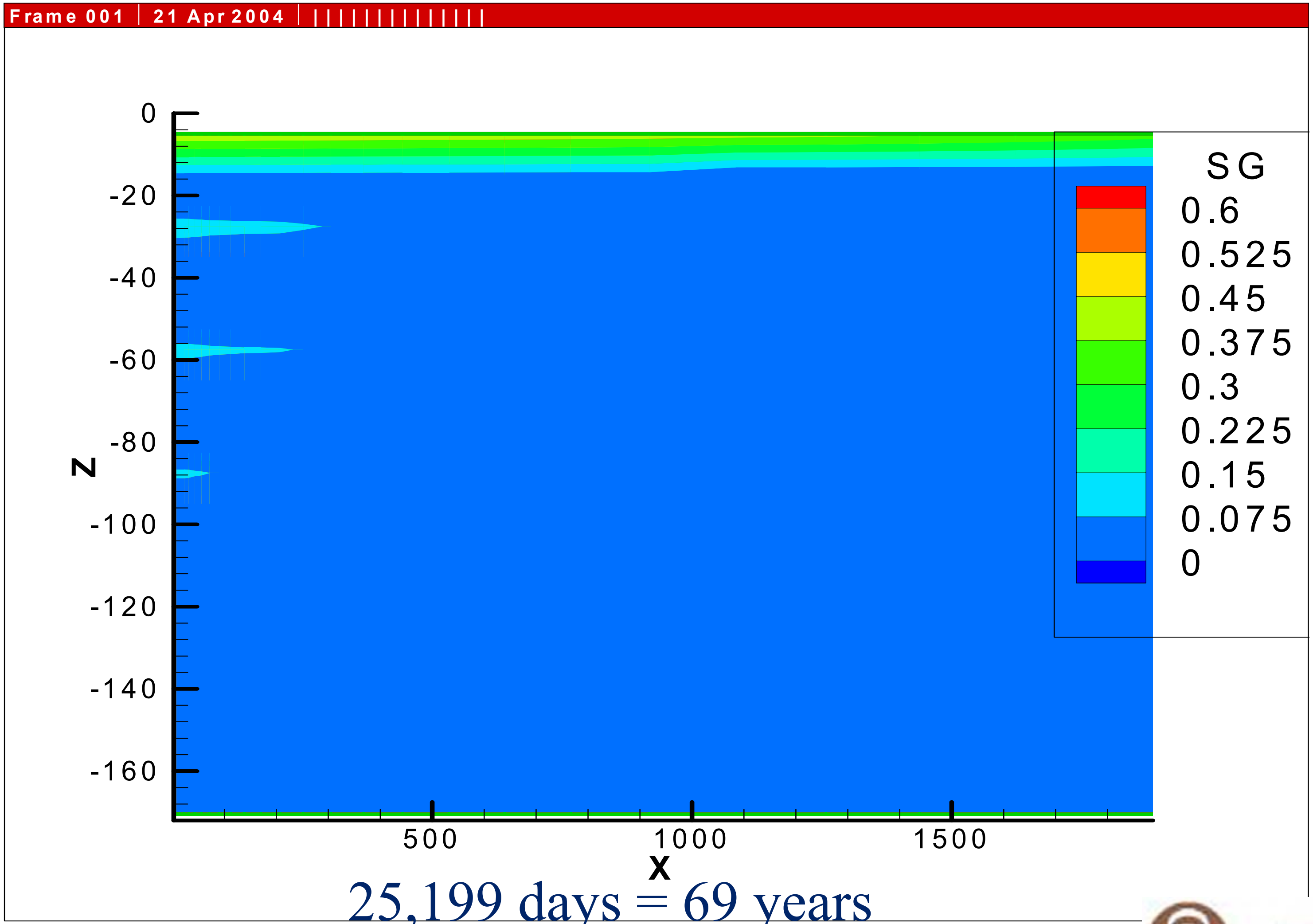


10,000 days = 27 years

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



25,199 days = 69 years

from Pascal Audigane, Bureau de Recherches Géologique et Minières

Géosciences pour une Terre durable
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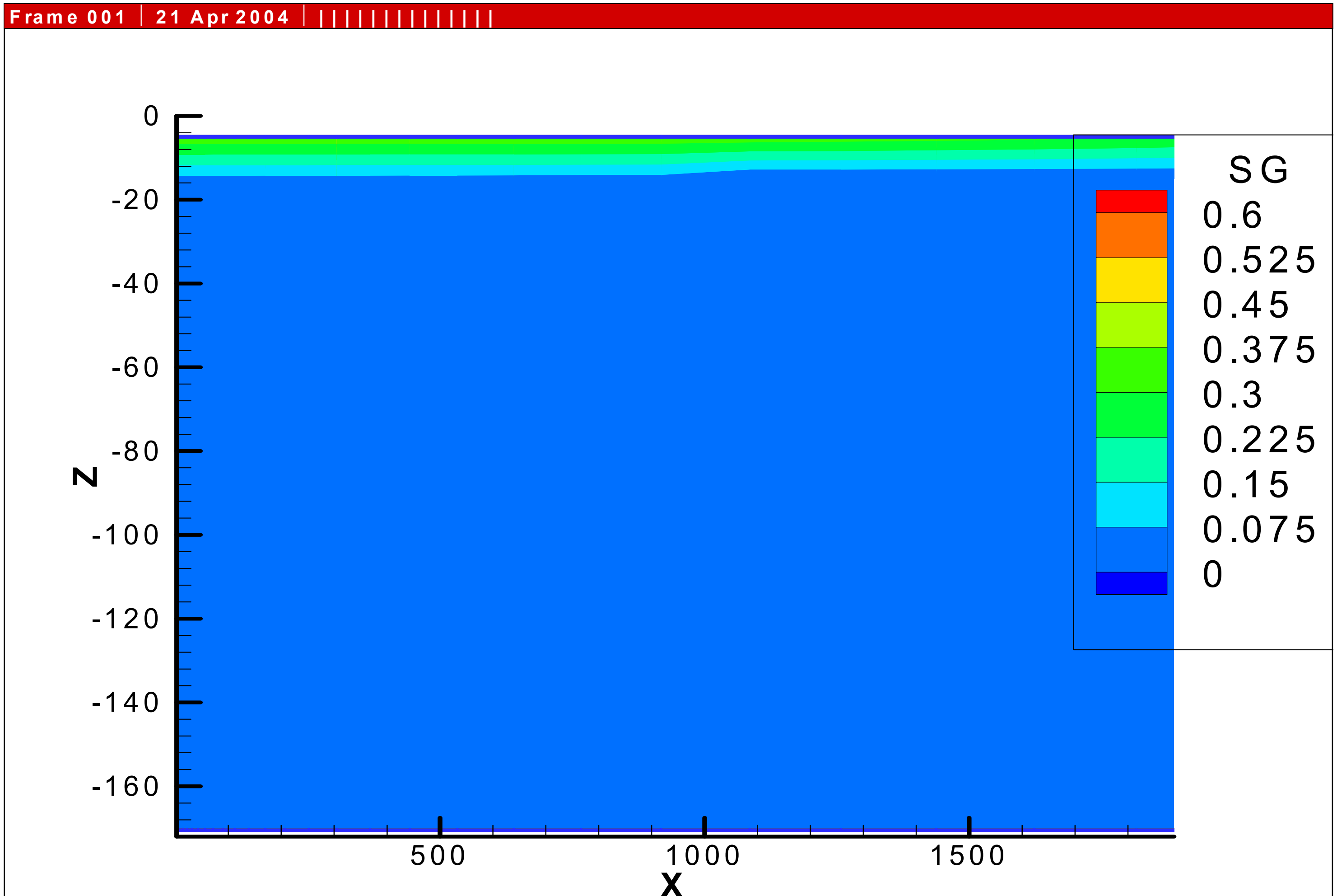
Dynamic modelling: link to long-term predictions

Example of 2D cylindrical model of gas saturation front



48,071 days = 131 years

from Pascal Audigane, Bureau de Recherches Géologique et Minières

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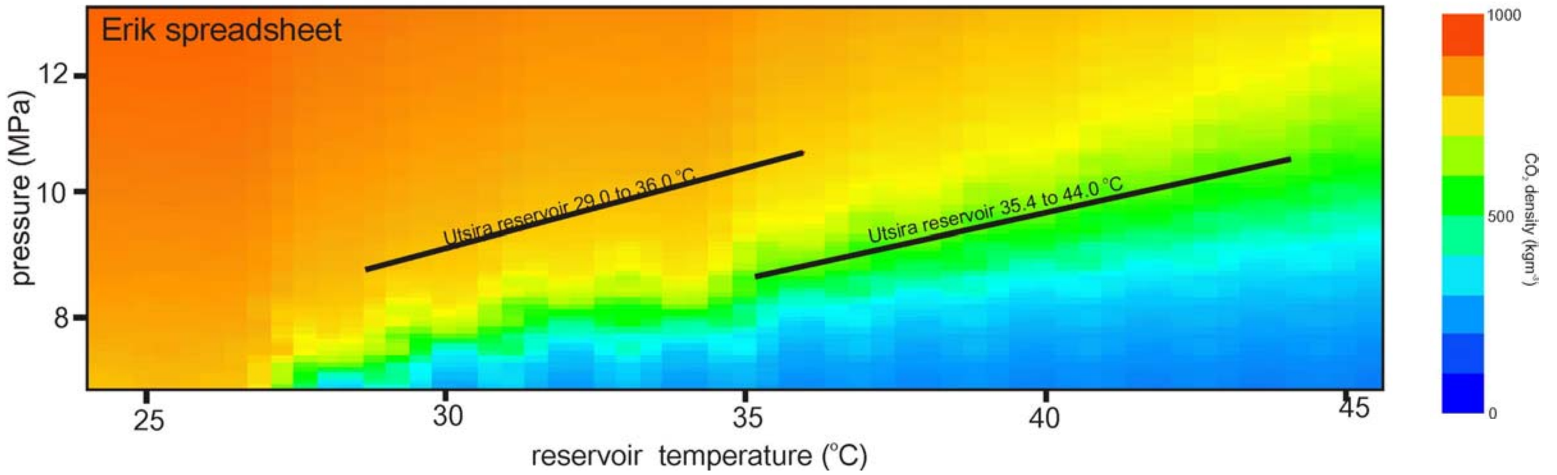
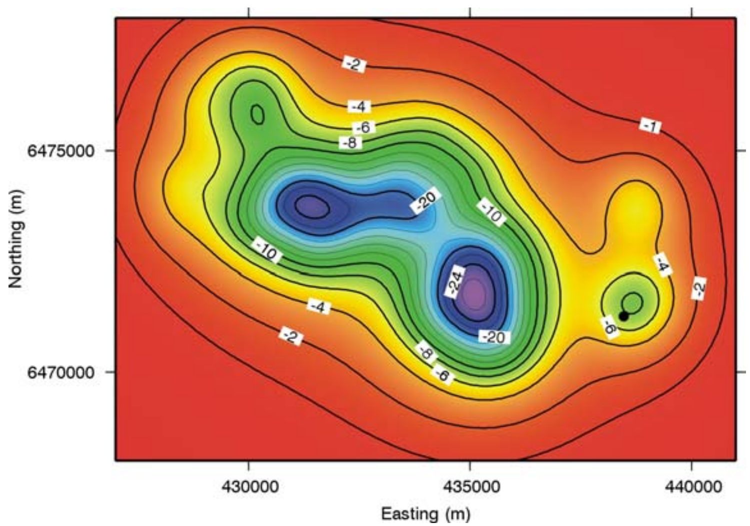
Temperature uncertainty = density ambiguity

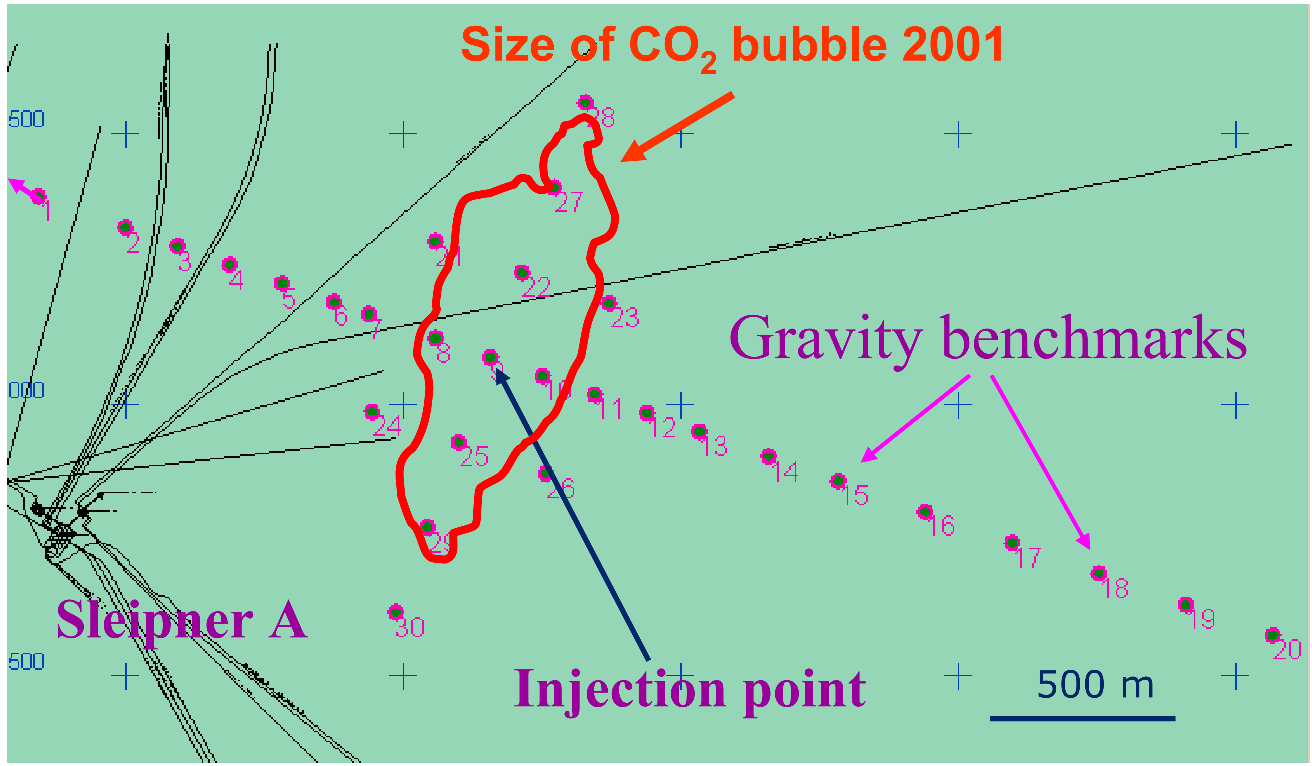




Gravity change caused by injection of 10.5 million tonnes of CO_2 with 350 kg/m^3 in-situ density [in μGal].

STATOIL

Gravimetric monitoring

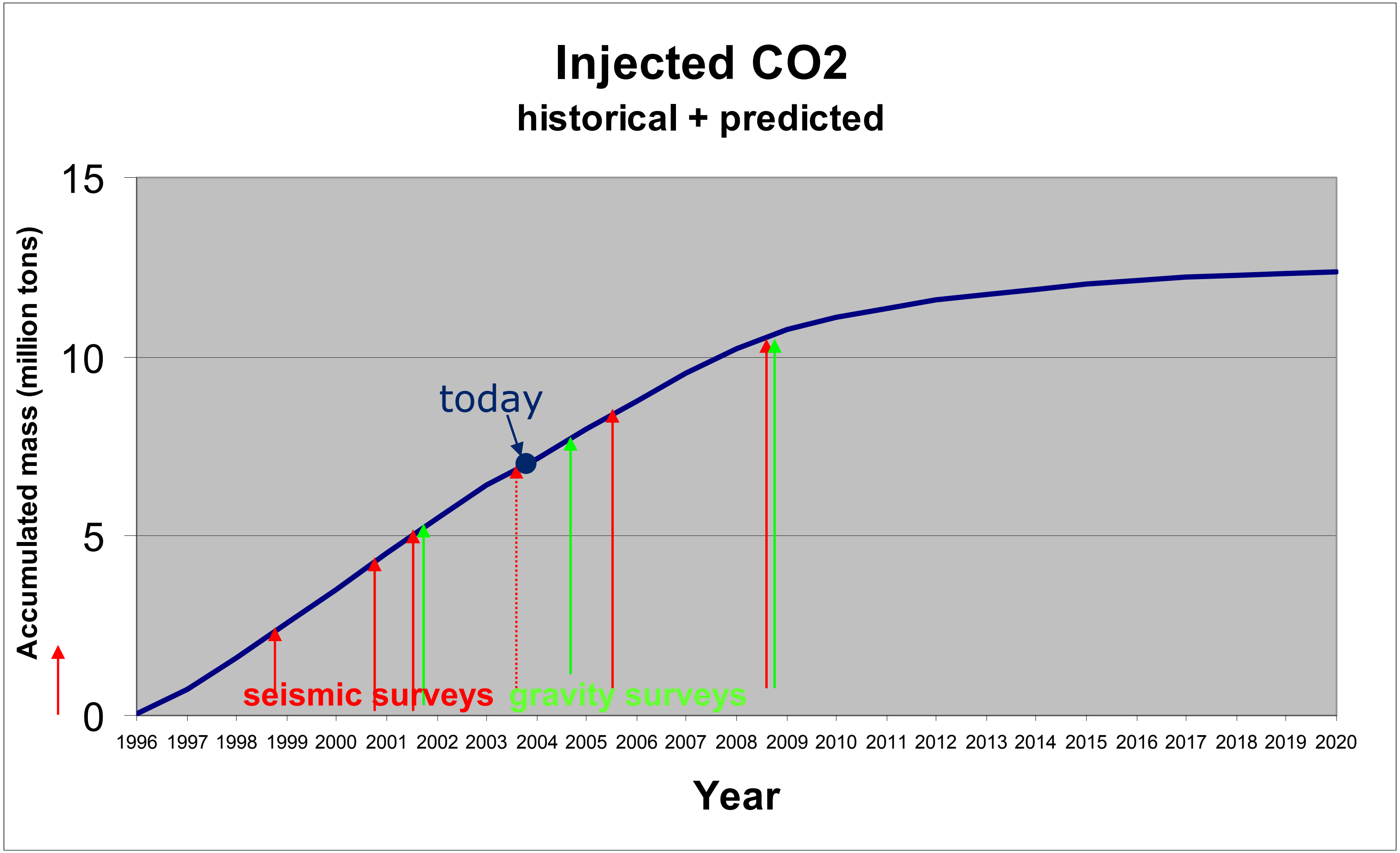


2002 base survey achievements:

- 3 μGal gravity repeatability (s.d.)
- 5 mm seafloor depth repeatability (s.d.)


5t SWL

Accumulated CO_2 storage



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Further work

- *More detailed seismic analysis*
  - *Time-shifts*
  - *Velocities*
  - *Imaging of chimney*
  - *Imaging of lower plume*
  - *Time-lapse aspects*
- *Better understand flow mechanisms*
  - *Penetration through shales*
  - *Flow at low saturations*
  - *Importance of chimney*
  - *Dissolution of CO_2 in formation water*
- *Monitoring*
  - *Injection rates and wellhead pressure*
  - *Seismic*
  - *Gravity*
  - *Seafloor (elevation changes, soil sampling, visual inspection)*

Limitations and uncertainties… are of basic nature

- Rock physics
- Seismic quantification
- Scale of seismic information
- Physics of CO_2 flow

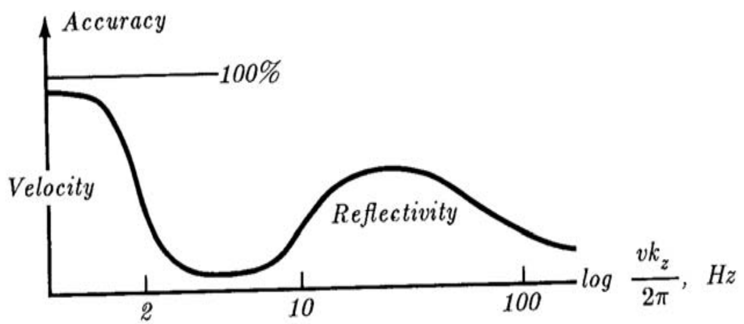
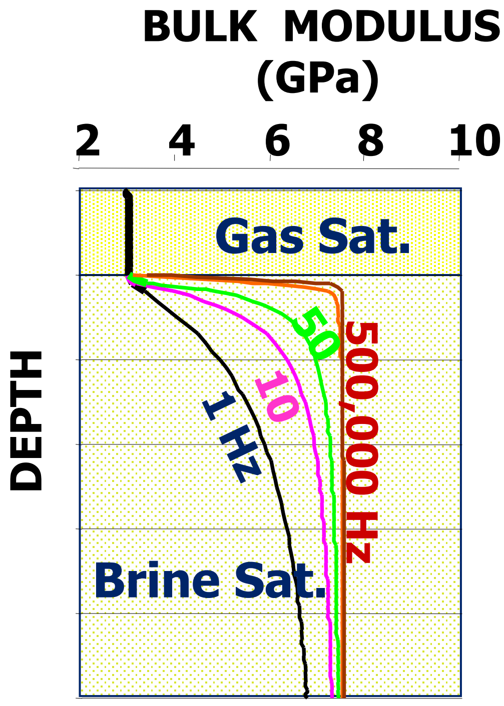


FIG. 1.4-3. Reliability of information obtained from surface seismic measurements.

From Claerbout (1985)



from Hofmann & Batzle

Acknowledgement

Rob Arts , Andy Chadwick, Erik Lindeberg, Bert van der Meer and the multi-diciplinary SACS/CO2STORE team.

Statoil and the Sleipner field partners Exxon, Norsk Hydro and Total.

Statoils SACS & CO2STORE partners BP, Norsk Hydro, Exxon, Total, Vattenfall, UK DTI, British Geological Survey, Bureau de Recherches Gèologiques et Minières, Bundesanstalt für Geowissenschaften und Rohstoffe Geological Survey of Denmark and Greenland, Institut Francais du Pètrole, Netherlands Institute of Applied Geoscience, Sintef Petroleum Research, Schlumberger.

WesternGeco, Nansen Research Centre.

Scripps Institution of Oceanography & US Department of Energy.

IEA Greenhouse Gas R&D Programme.

The European Union R&D programme Thermie.

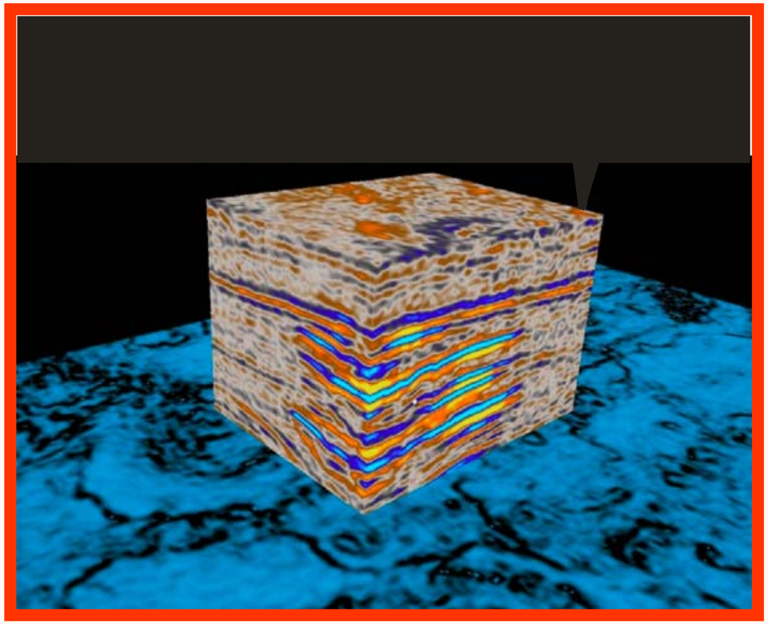
SACS CO_2

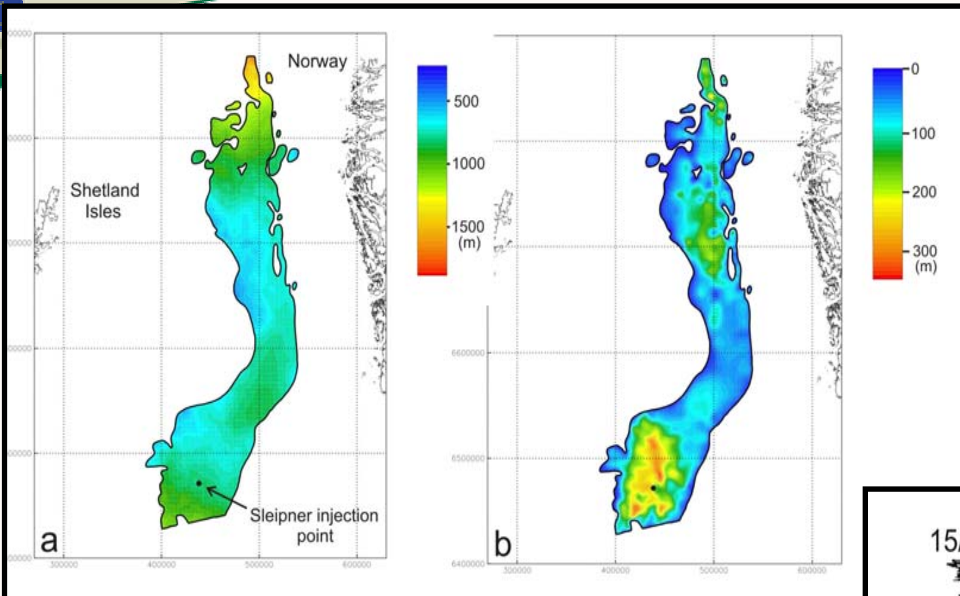
STATOIL

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

Verifying volumes of injected CO2 – Experiences from the SACS project

Andy Chadwick
Gary Kirby
(British Geological Survey, UK)
Rob Arts (TNO)
Ola Eiken (Statoil)

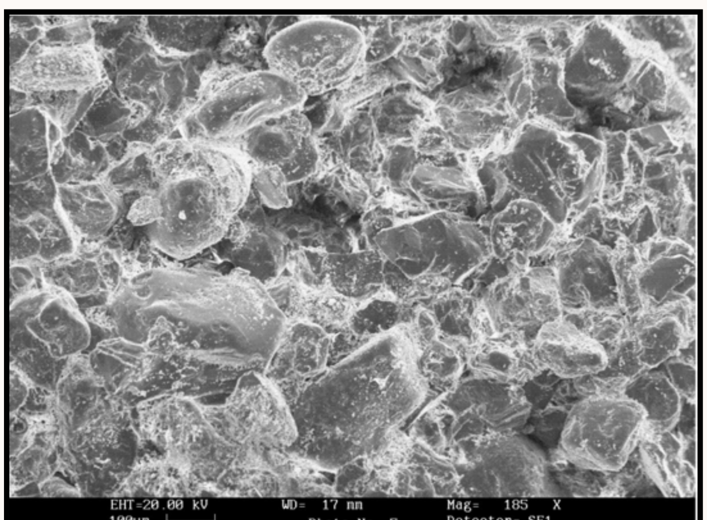


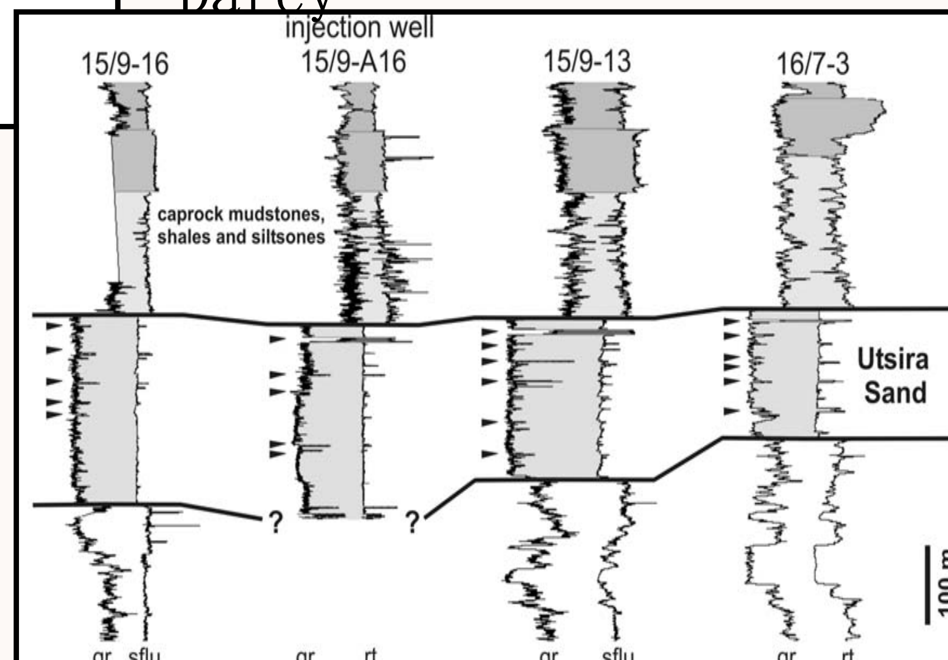


Utsira Sand:

Porosity ~37%

Permeability 1 - 3 Darcy





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Seismic Monitoring

- **<u>Aims</u>**
  - **Detection & Distribution**
    - Where is the CO_2 and how is it distributed within the reservoir?
  - **Movement**
    - Where will it move to?
    - Is it leaking from the reservoir?
  - **Quantification**
    - How much is there?
- **<u>Time lapse surveys</u>**
  - **1994 prior to injection**
  - **1999 2.35 MT CO_2 *in situ***
  - **2001 4.26 MT CO_2 *in situ***
  - **2002 4.97 MT CO_2 *in situ***

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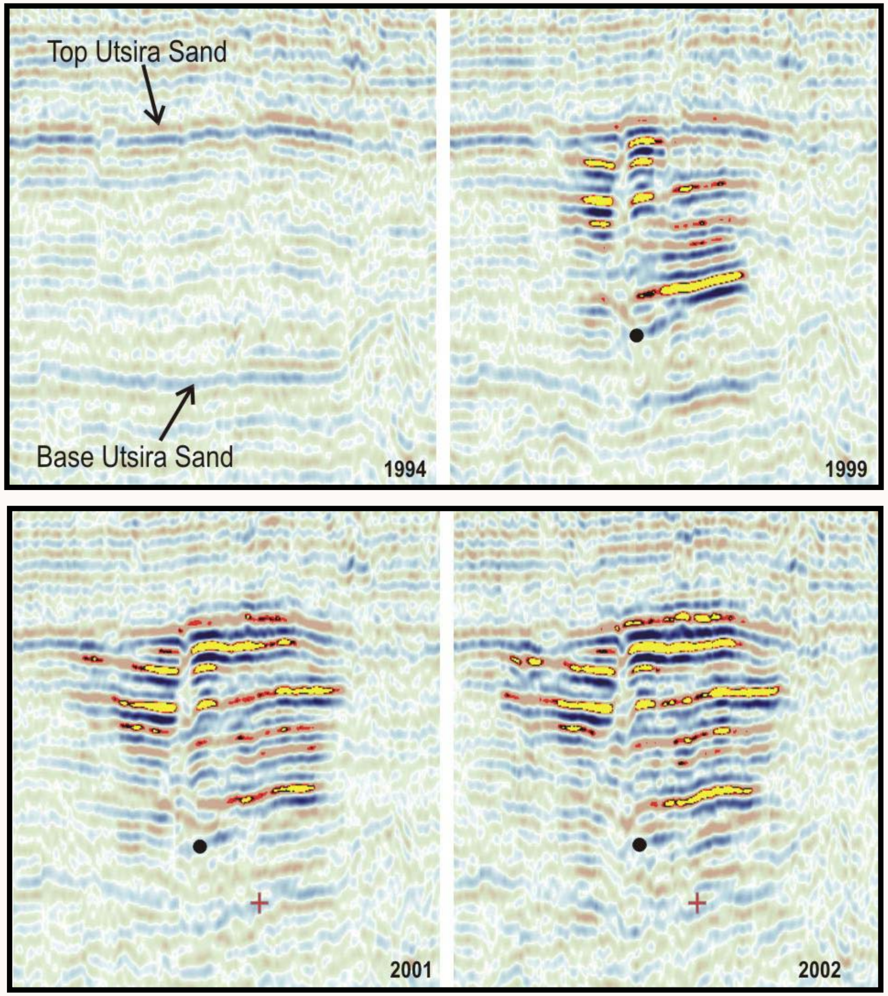
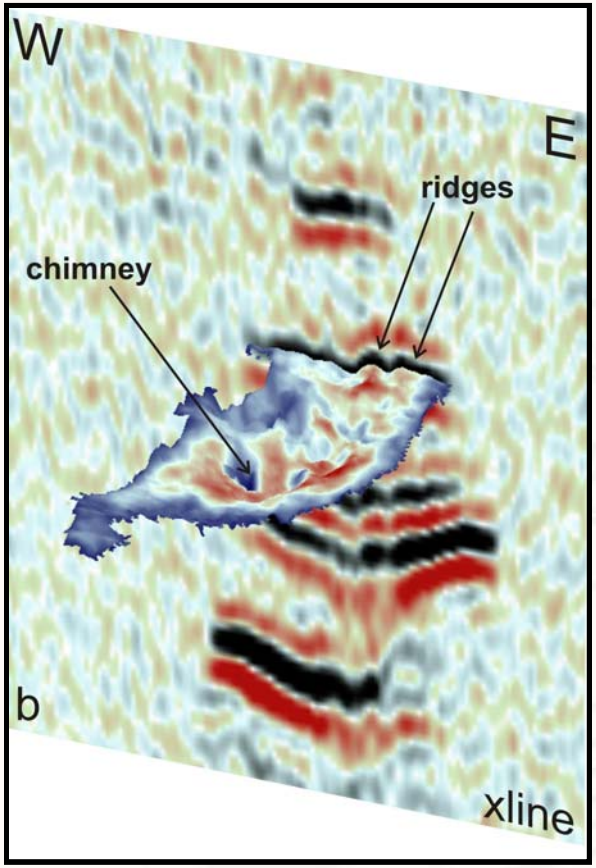
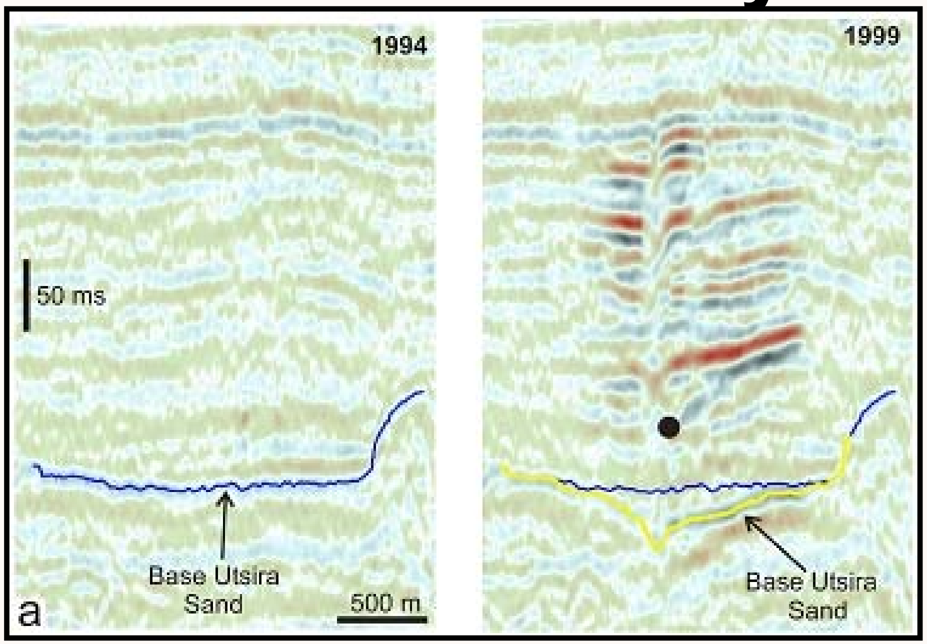
Detection & Distribution

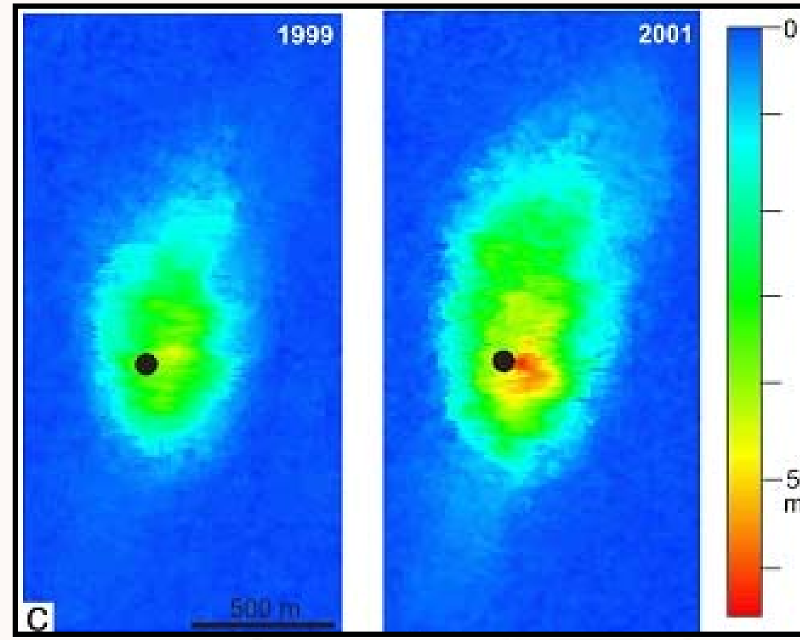


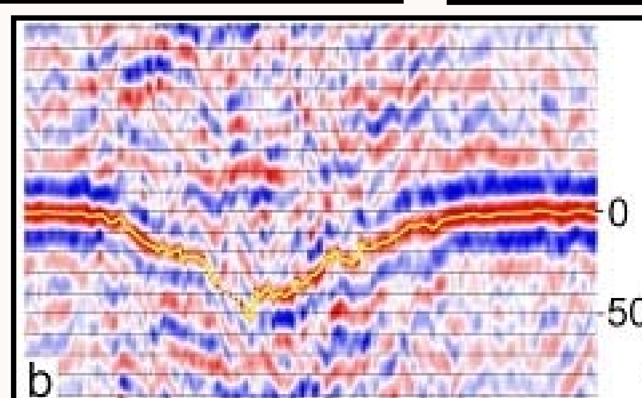
High reflectivity horizons



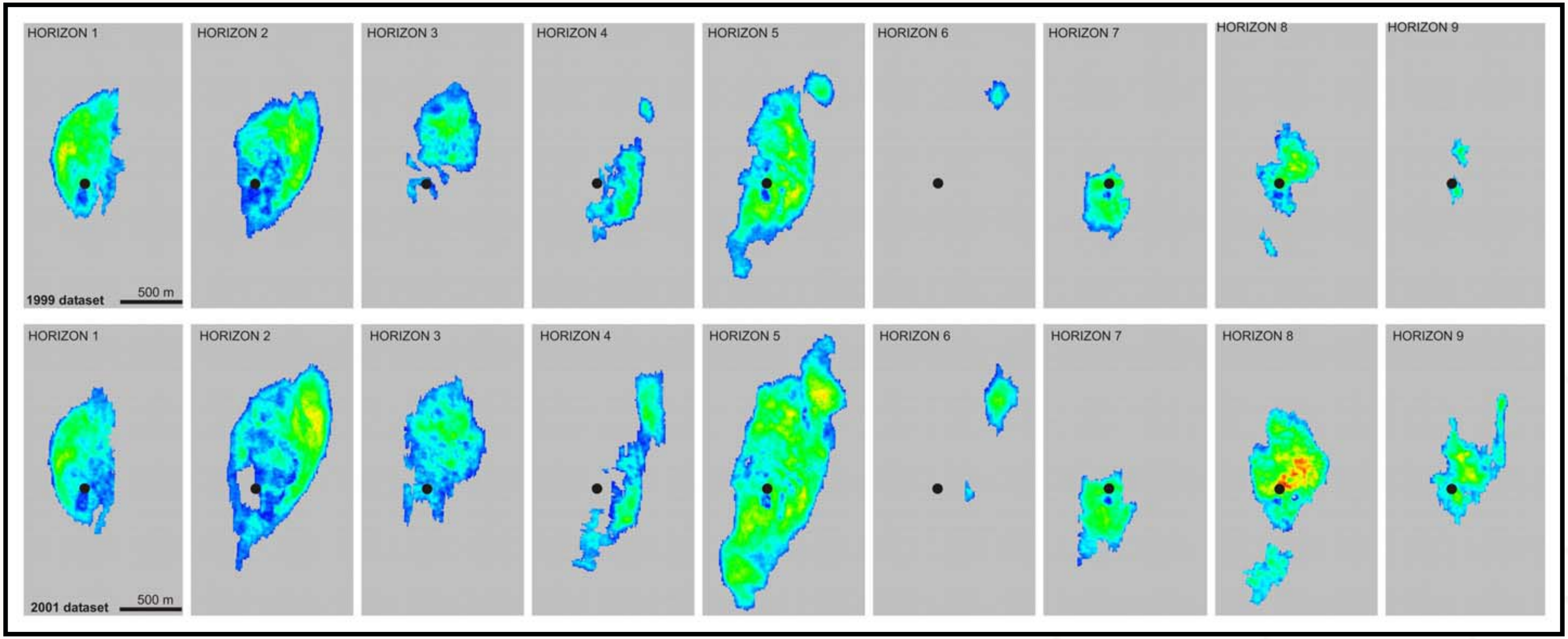
Detection & Distribution: Velocity Pushdown





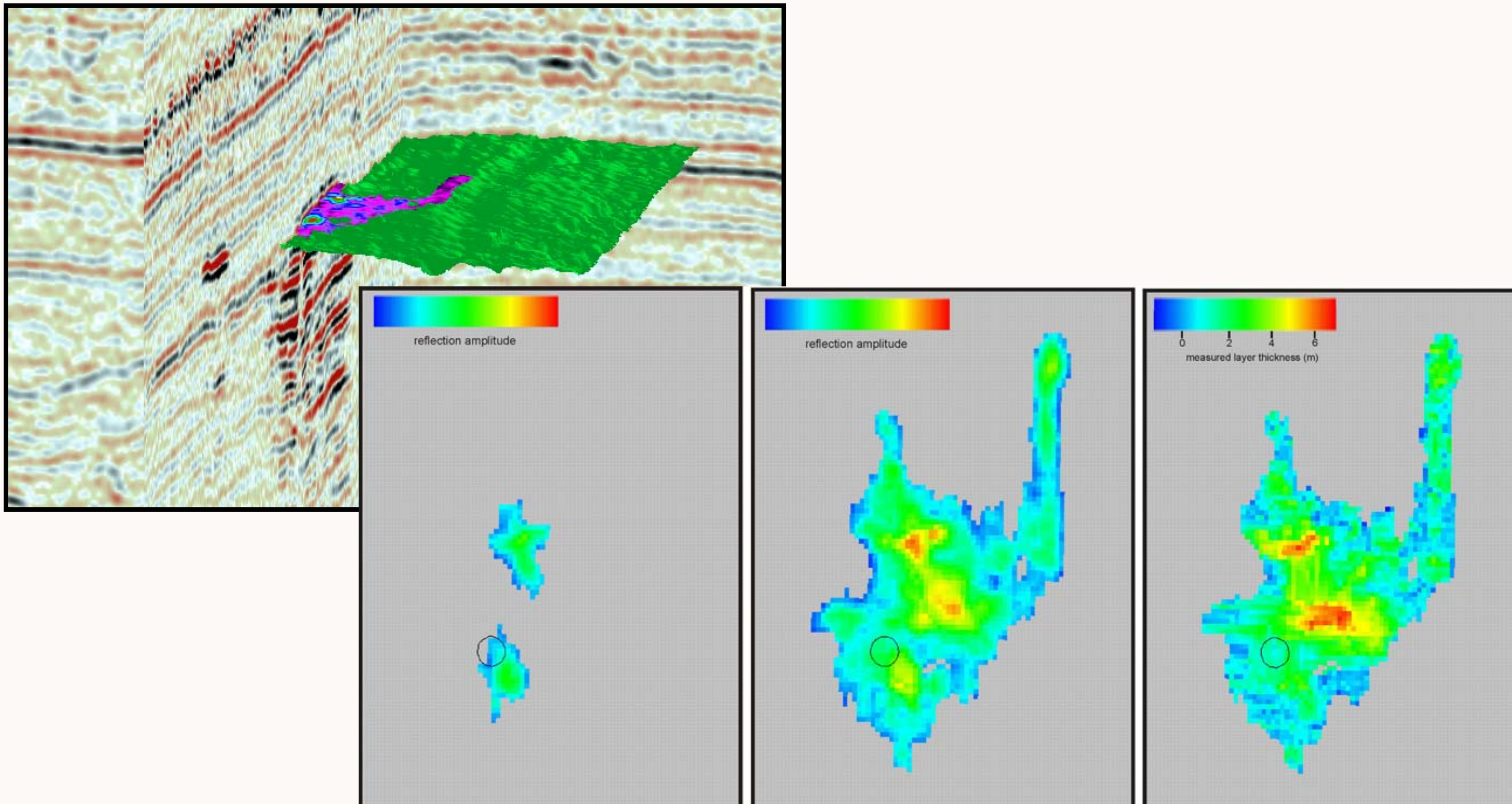


Distribution & Movement



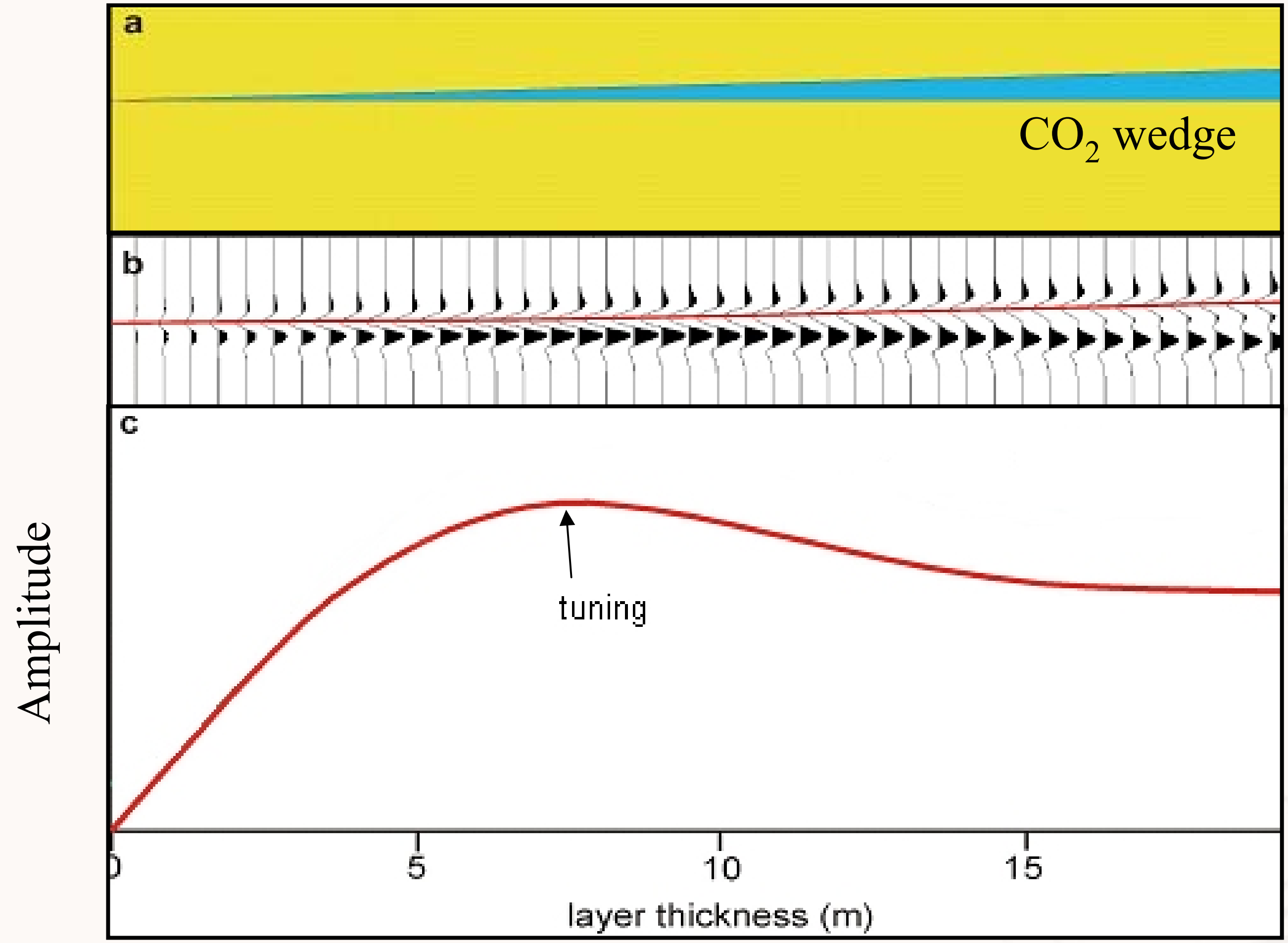
Plume growth 1999 - 2001

Distribution: Top Reservoir Trapping



1999 - reflection amplitude | 2001 reflection amplitude | 2001 measured thickness

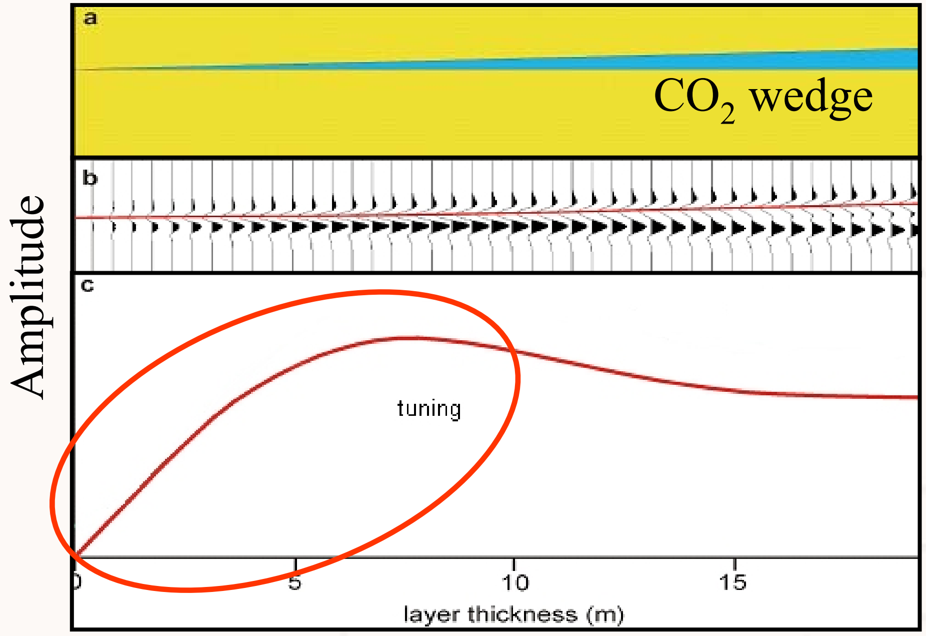
High reflectivity layers: Thin Bed Tuning



Quantification: thin layers & reflectivity

- Amplitude α thickness
- Thickness α saturation
- Calculate average saturation for each layer
- Net CO_2 thickness =

  av saturation . thickness . ϕ
- volume CO_2 *in each layer* = Area x thickness
- total volume CO_2 = Sum all layer volumes
- Accounts for 2.43 Mm^3 (72% known injected volume) *assuming IP temperature of 36°c*



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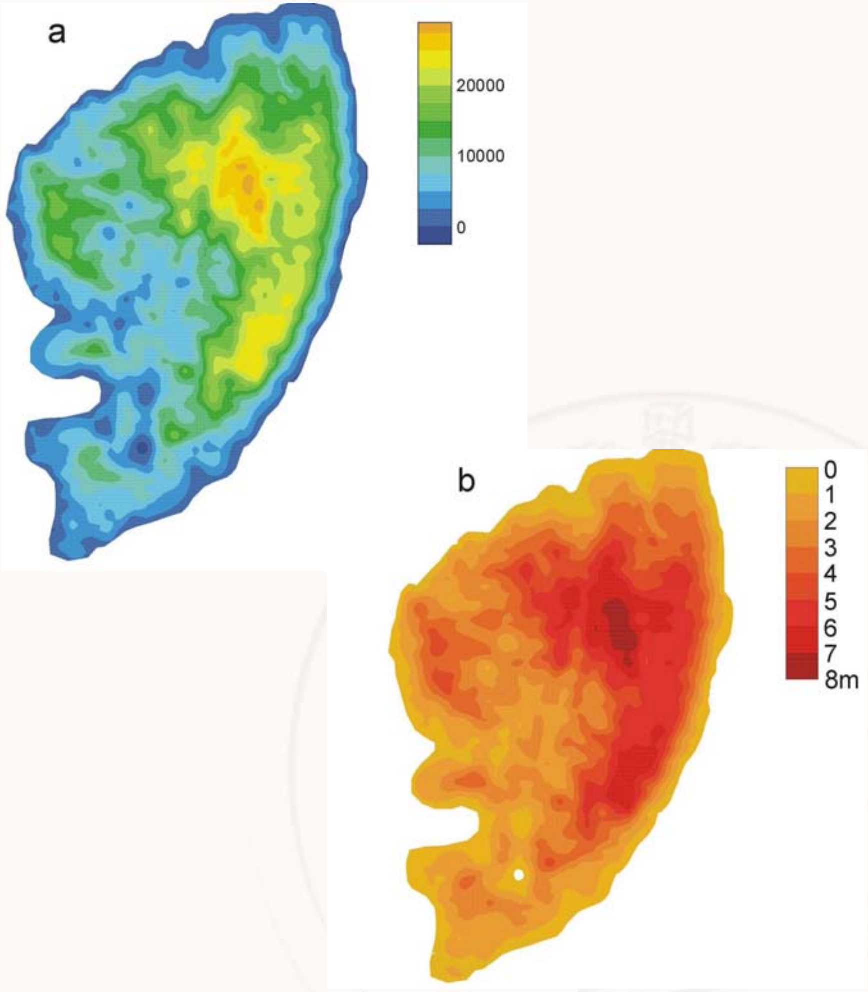

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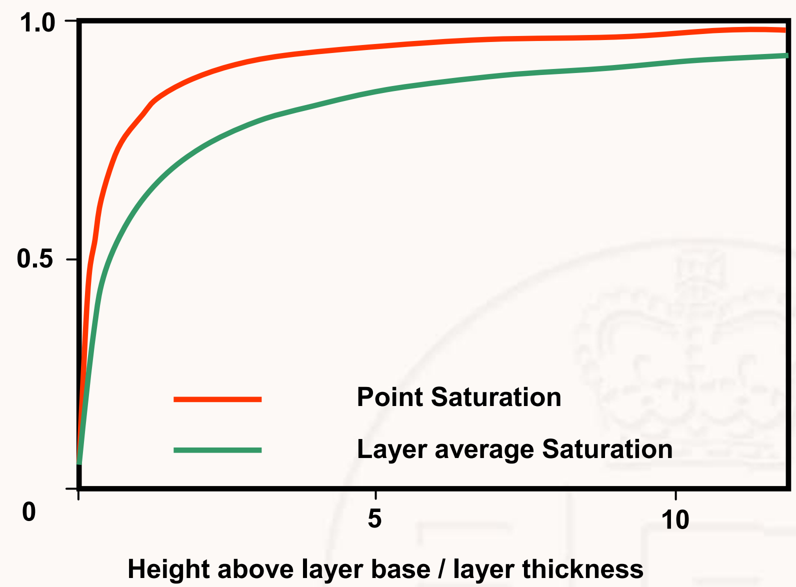

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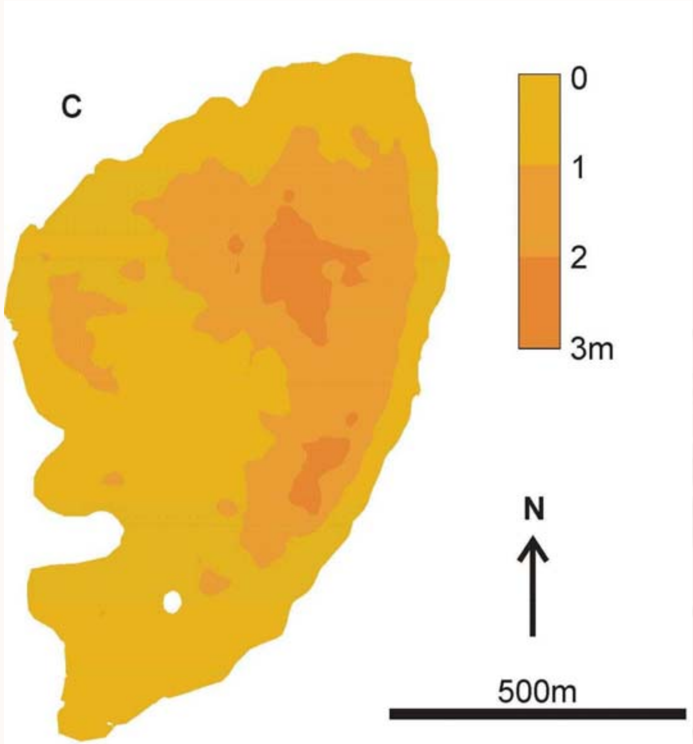
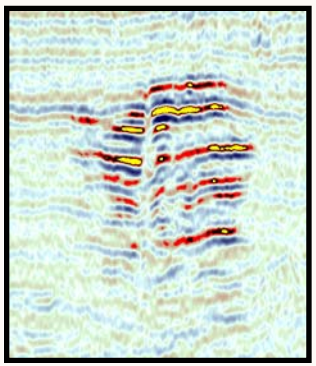
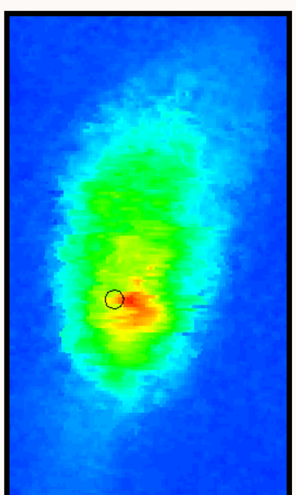
- **volume CO_2 *in each layer* = Area x thickness**
- **total volume CO_2 = Sum all layer volumes**
- **Accounts for 2.43 Mm^3 (72% known injected volume)** *assuming IP temperature of 36°c*

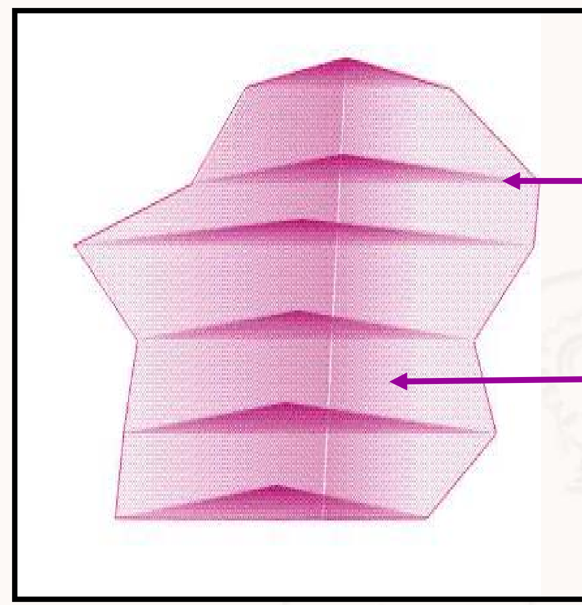


Distribution & Quantification

Inverse modelling





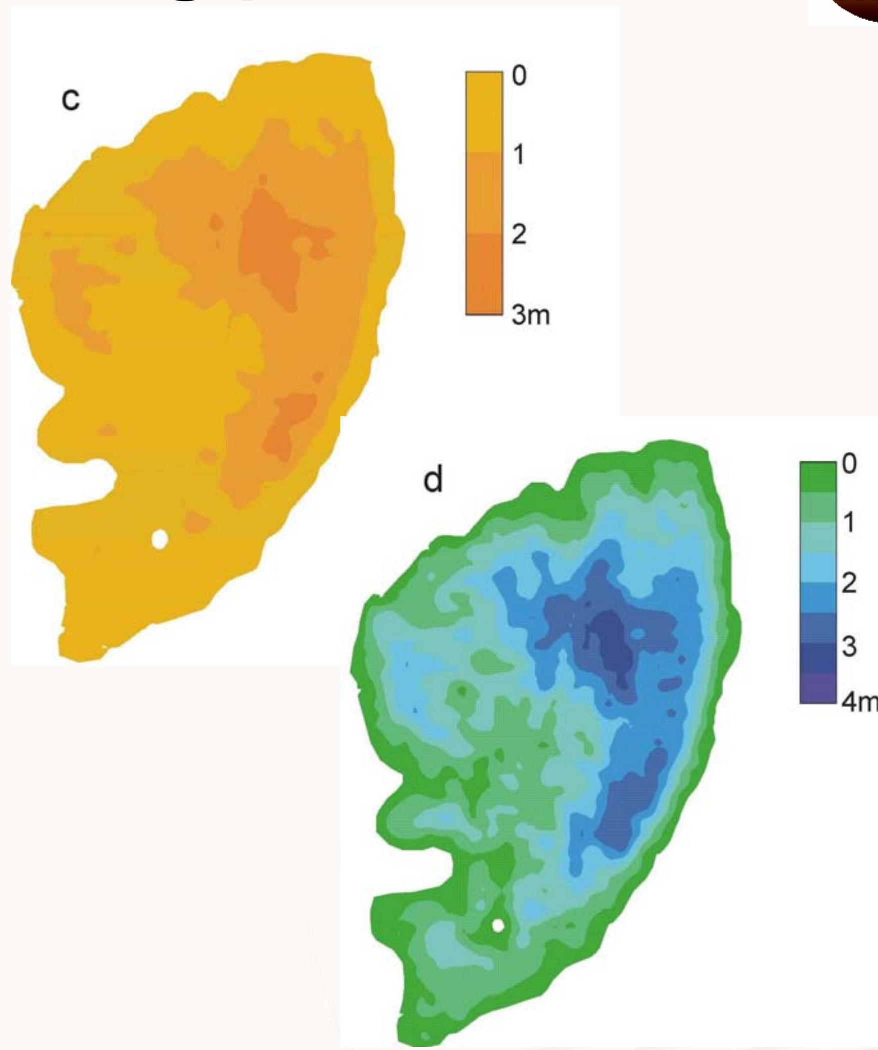


2-component plume saturation model

- High saturation layers
- Diffuse intra-layer CO_2 in the residual plume

Quantification: using pushdown

- Plume reflectivity can be related to thickness of high saturation CO_2 layers
- Calculate Pushdown due to each layer
- Calculate cumulative Pushdown for all thin layers
  - Much less than total pushdown (which is locally >40ms)
- Calculate residual pushdown
  - This can be related to the net thickness of intra layer CO_2



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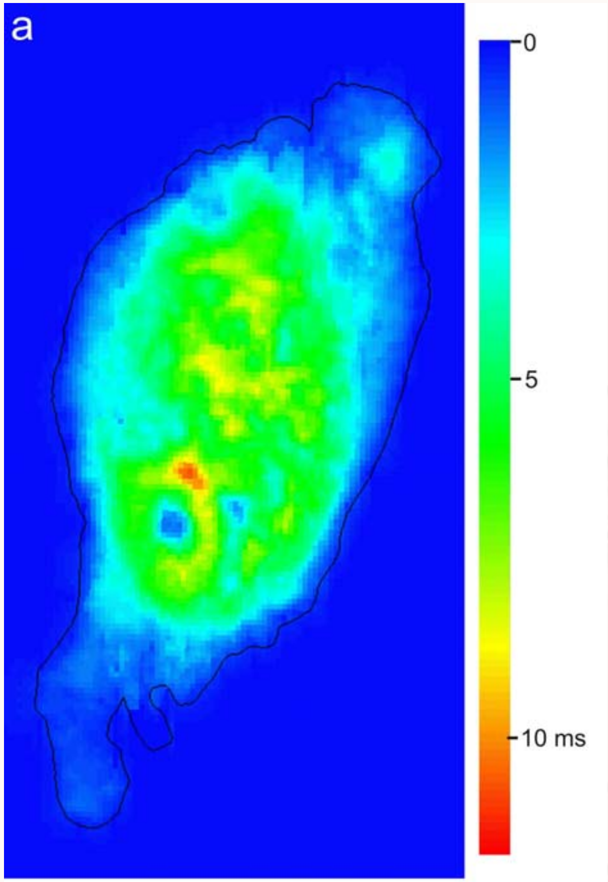

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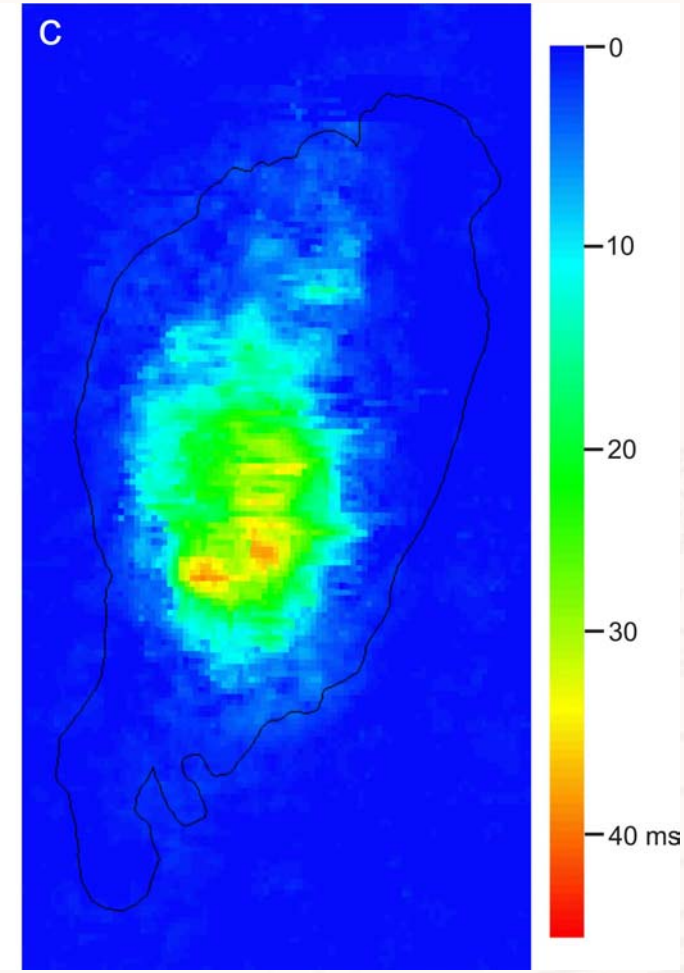

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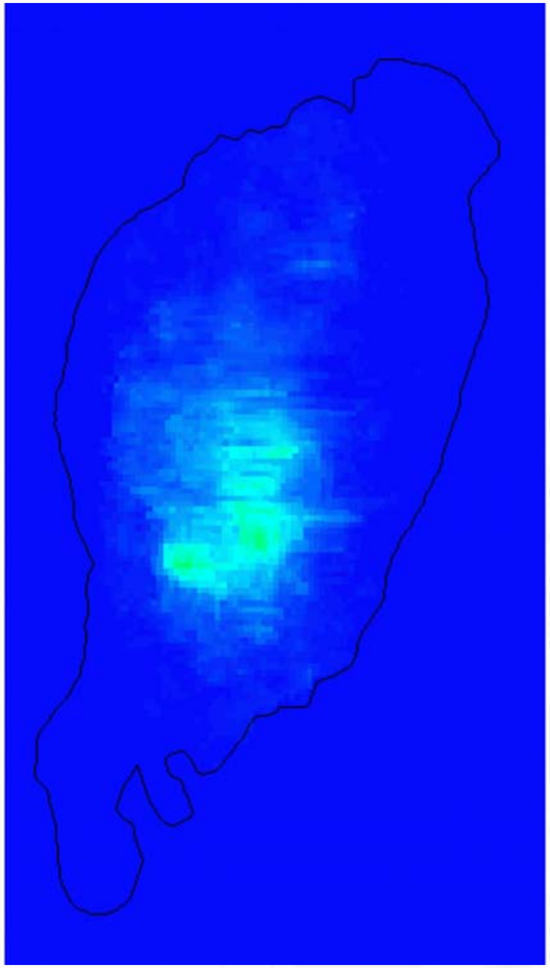
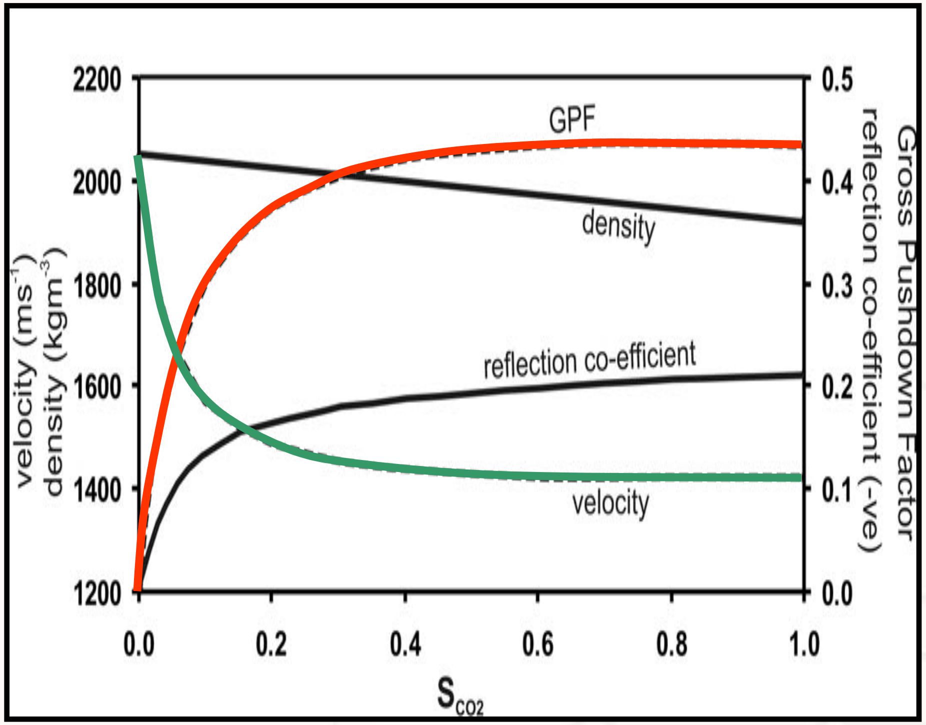


Pushdown and CO_2 saturations

For zero offset seismic data, velocity pushdown at any point can be related to an overlying column of CO_2 by:

$$\Delta T = \frac{2(V_{SW} - V_{SCO2})Z}{V_{SW}V_{SCO2}}$$

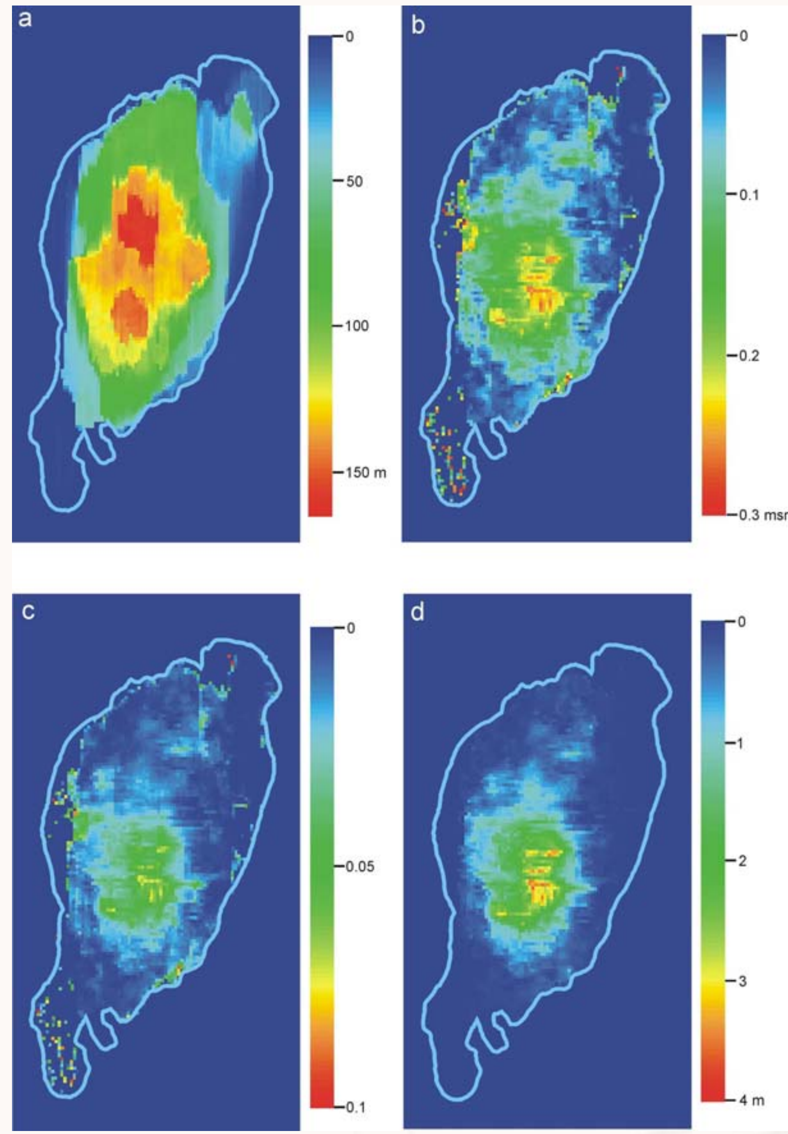
$= $ **'Gross Pushdown Factor'**$.Z$



Gassmann (fine scale mixing)

Residual plume

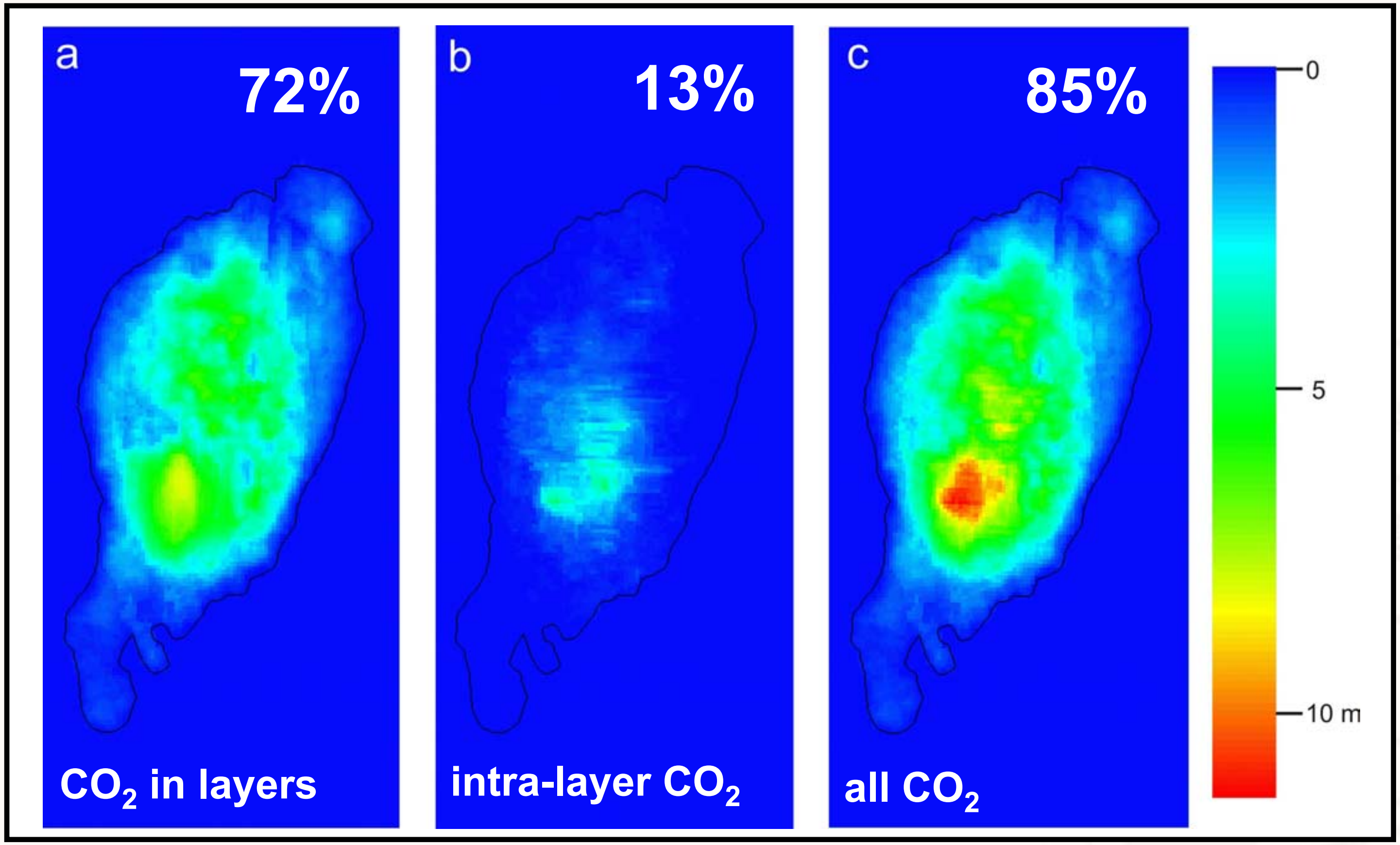
- **Calculate isopach of residual plume**
- **Determine residual pushdown**
- **Gross pushdown Factor = residual pushdown / residual isopach**
- **Gross pushdown factor gives saturation**
- **Volume = Saturation x isopach**
- **= 13% known injected volume** *assuming IP temperature of 36°c*



Final 3D saturation model

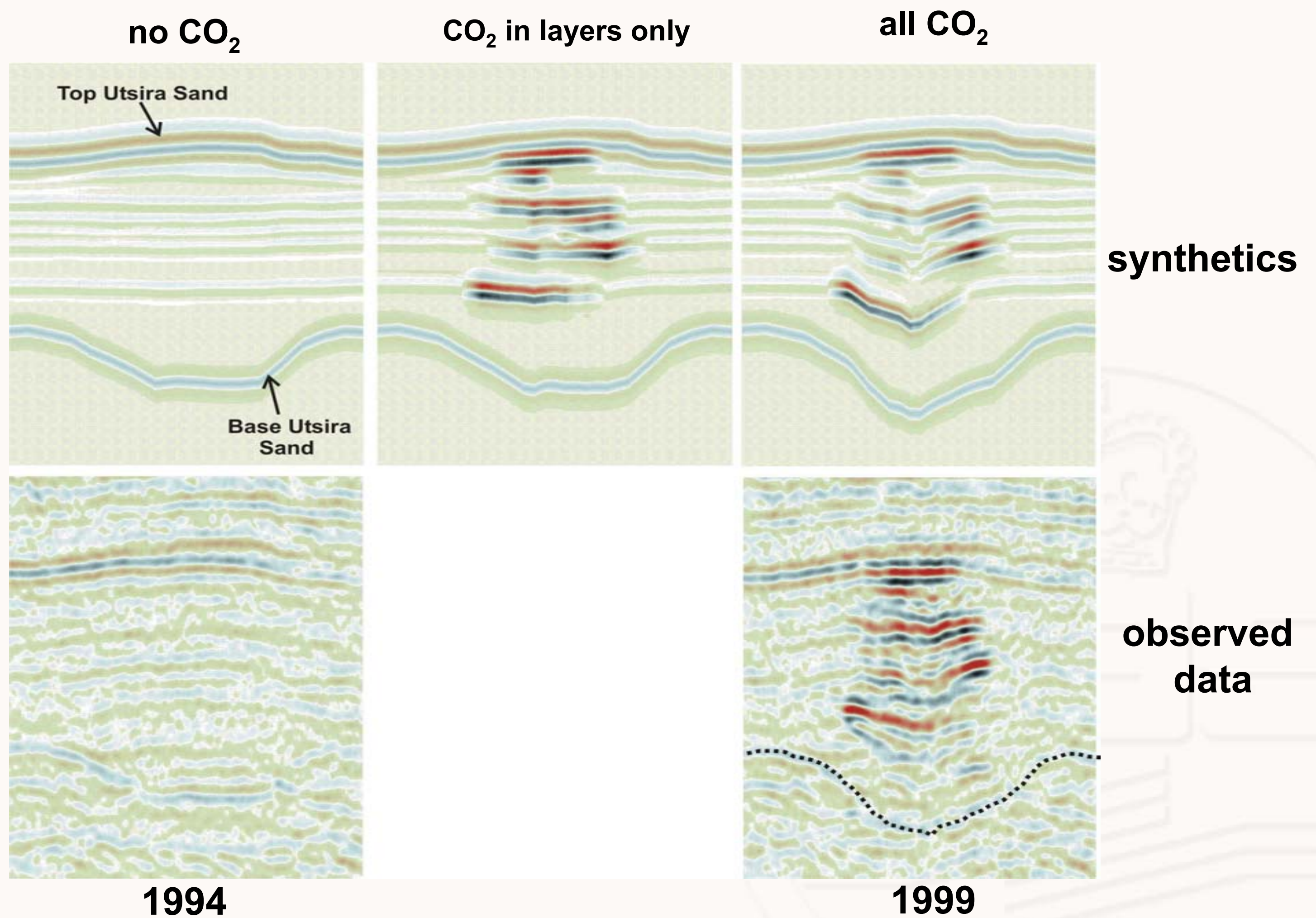
Net thicknesses of CO_2 - 85% total injected volume

(assuming IP temperature of 36°c)



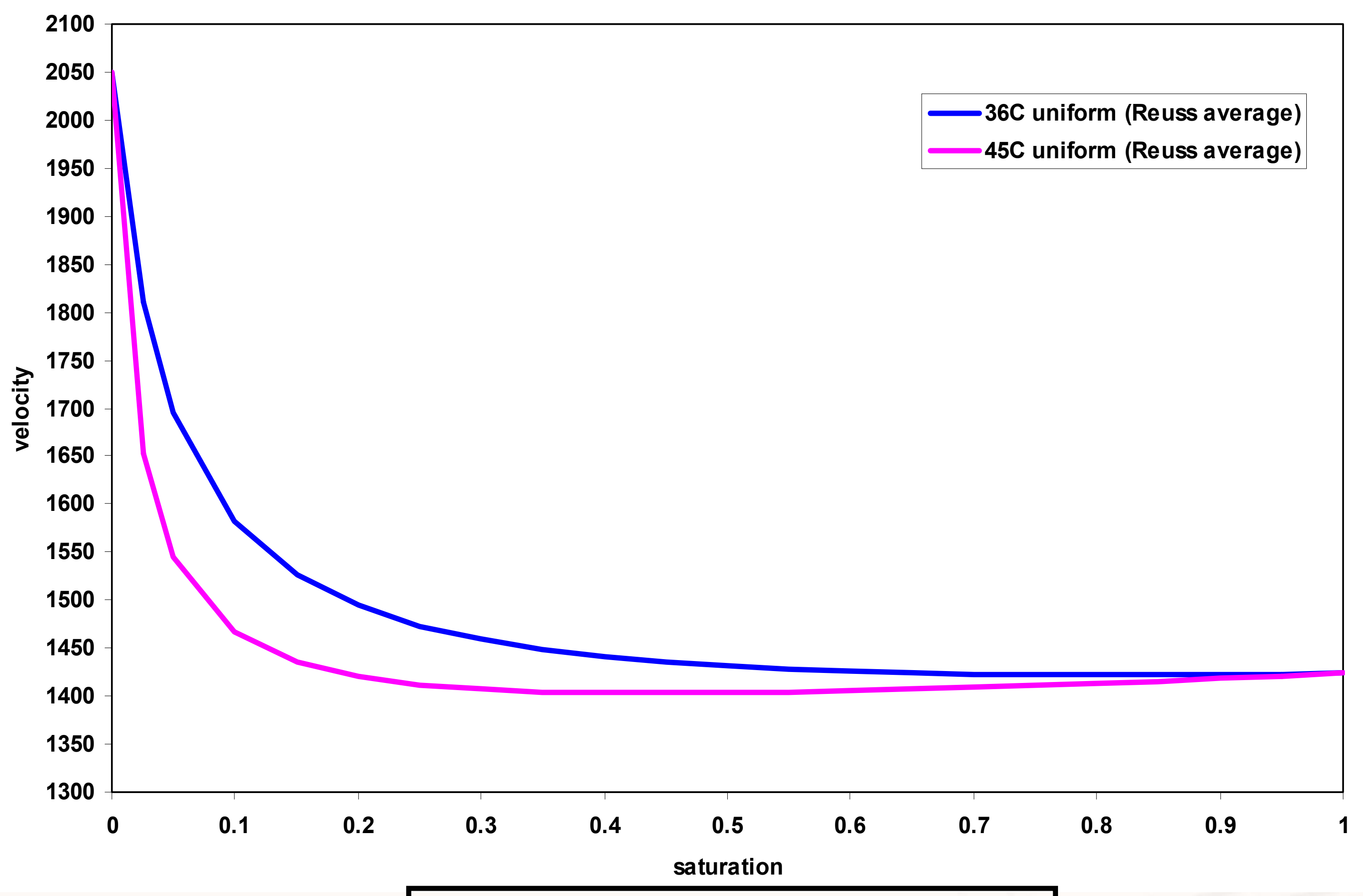
Synthetic seismic model

- 36ºc at injection point in reservoir
- Thin layers *and*
- Uniform mixing in dispersed distribution
- Can account for 85% known injected CO_2



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

Temperature uncertainties: Calculated dispersed CO_2 volumes



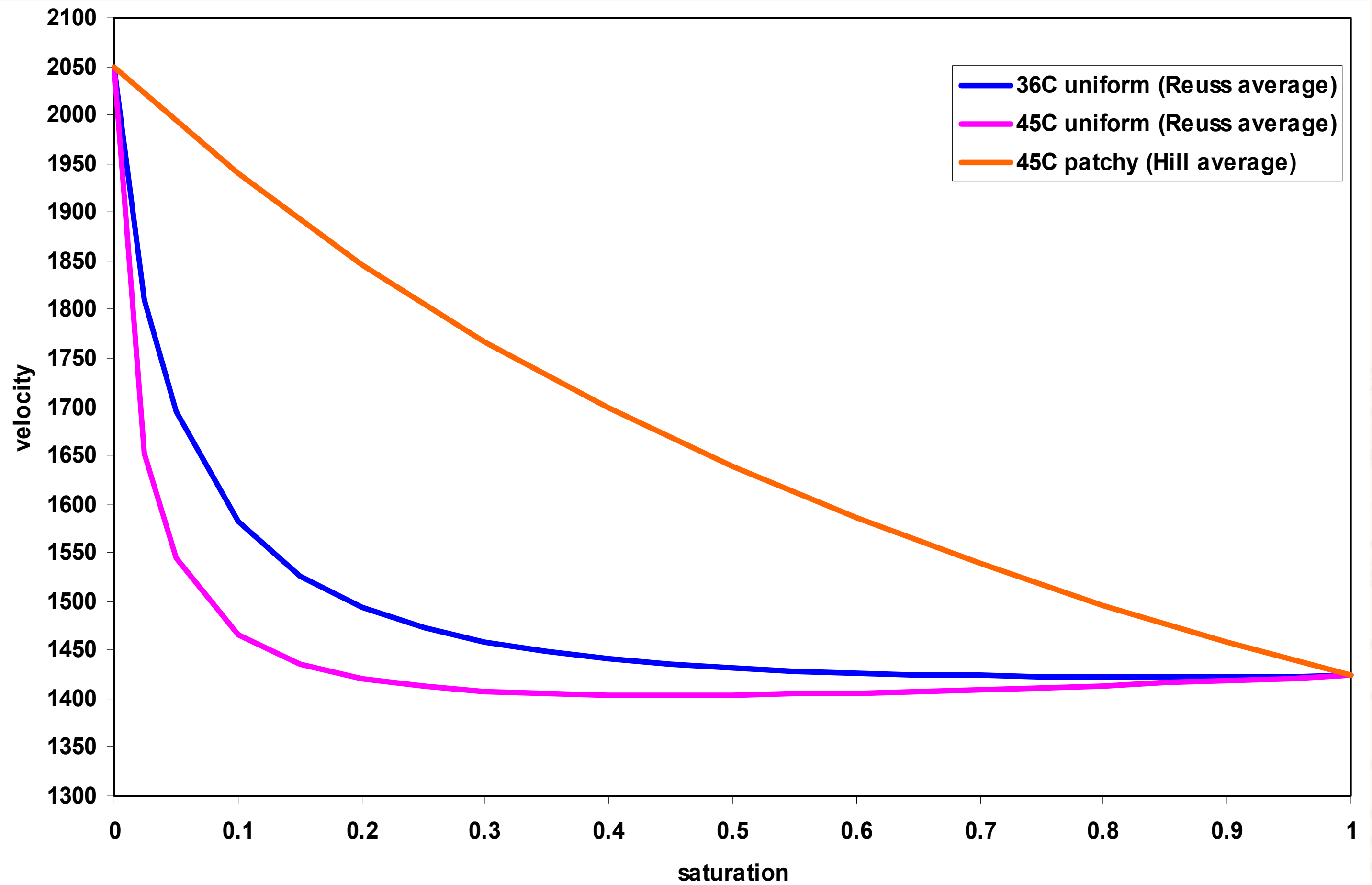
Gassmann (fine scale

Temperature uncertainties: Calculated dispersed CO_2 volumes

	36°c	45°c
Thin layer volume	2.43	2.53Mm^3
Dispersed volume	0.44 (homogeneous)	0.17Mm^3 (homogeneous)
Total	2.87	2.7Mm^3
% known volume	85%	63%

Gassmann (fine scale

Velocity v Saturation
Different temperatures & Fluid mixing

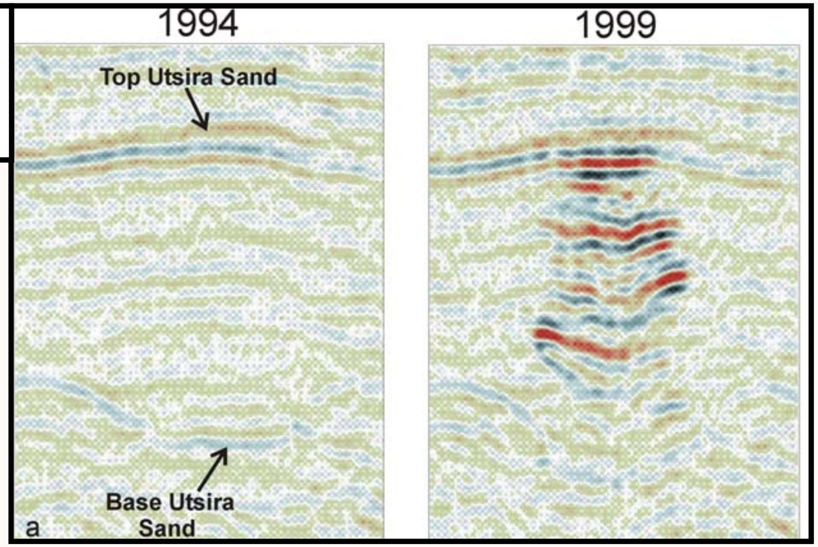


Calculated CO_2 volumes

	36°c	45°c	45°c
Thin layer volume	2.43	2.53Mm^3	2.53Mm^3
Dispersed volume	0.44 (fine scale mixing)	0.17Mm^3 (fine scale mixing)	6.73Mm^3 (Extreme patchy)
Total	2.87	2.7Mm^3	9.26
% known volume	85%	63%	231%

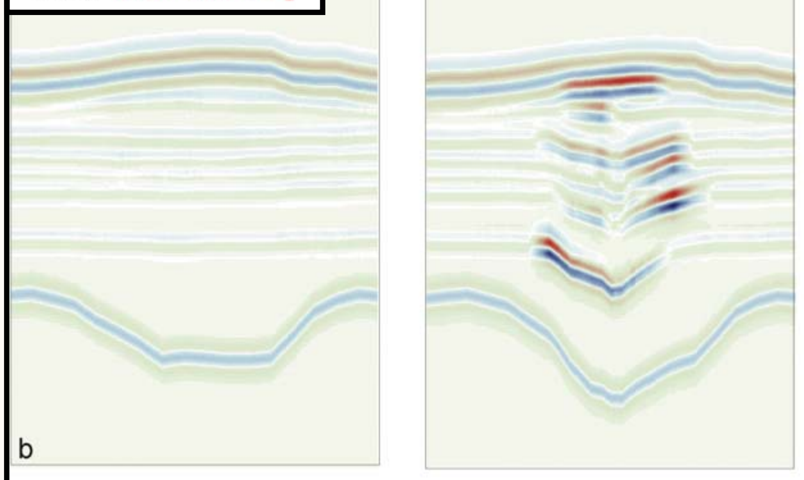
Observed

2.35 MT CO_2



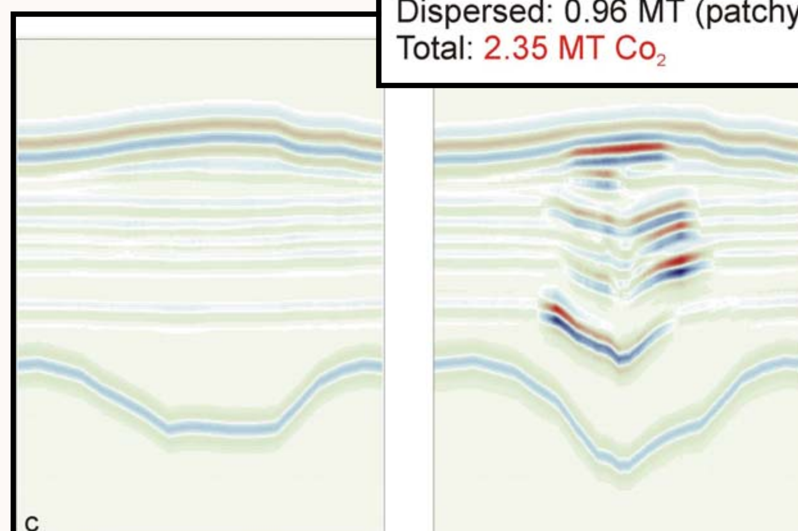
Synthetics

T_{inj} = 36 °C
ρ_{CO2} = 700 kgm^{-3}
K_{CO2} = 0.080 Mpa
Layers: 1.70 MT
Dispersed: 0.31 MT
Total: 2.01 MT Co_2



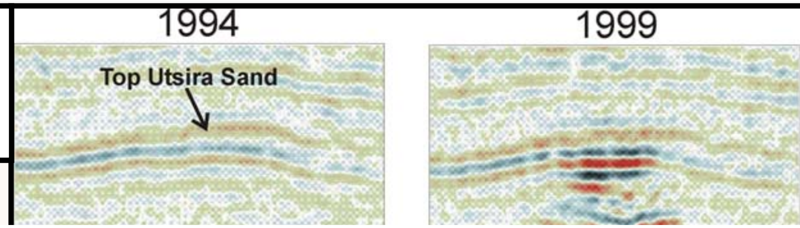
Synthetics

T_{inj} = 45 °C
ρ_{CO2} = 550 kgm^{-3}
K_{CO2} = 0.032 Mpa
Layers: 1.39 MT
Dispersed: 0.96 MT (patchy)
Total: 2.35 MT Co_2



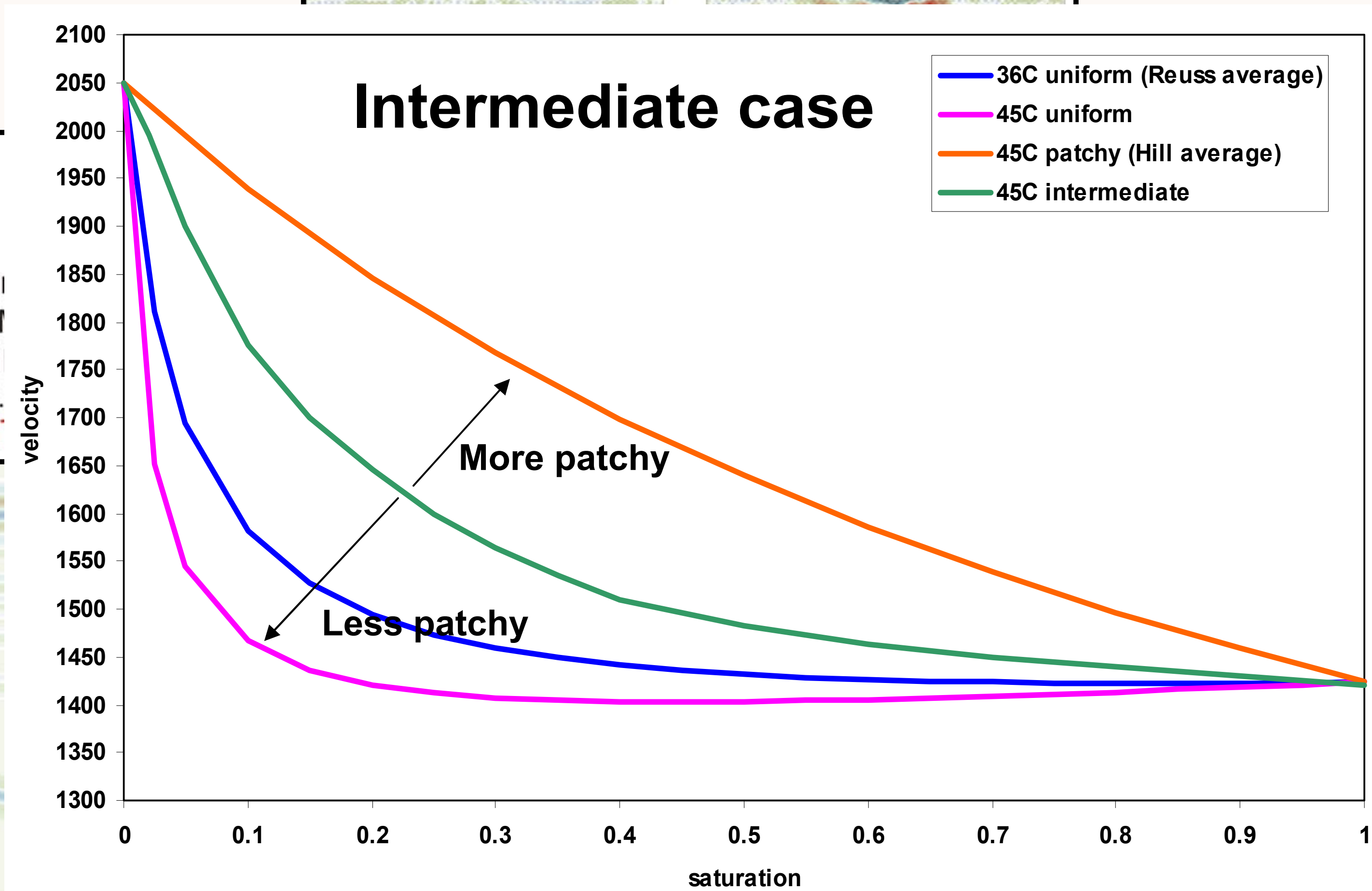
Observed

2.35 MT CO_2

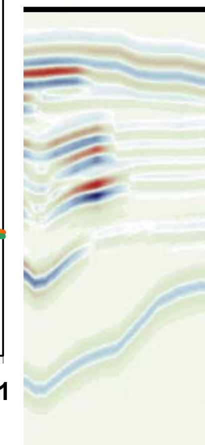


Synthetics

T_{inj} = 36 °C
ρ_{CO2} = 700 kg
K_{CO2} = 0.080
Layers: 1.70
Dispersed: 0.
Total: 2.01 M



-3
pa
T
6 MT (patchy)
Co_2



Issues

- **Are there any limitations in the techniques currently used?**
  - Seismic wavelengths
  - Detection limits
  - Distribution of dispersed CO2 vertically
  - Tuning thickness – observed amplitude relationship, interference
- **Are new techniques being developed?**
  - Synthetic modelling using advanced wave propagation through complex media
- **What further research is needed to improve confidence in the monitoring results?**
  - Basic information on reservoir

Sleipner Summary

1. Time - lapse data images CO_2 clearly

2. Quantitative modeling is consistent with observations

    - If reservoir temperature is higher than the one observed measurement, a degree of patchy mixing is required

3. Shows no evidence of leakage (to 2002)

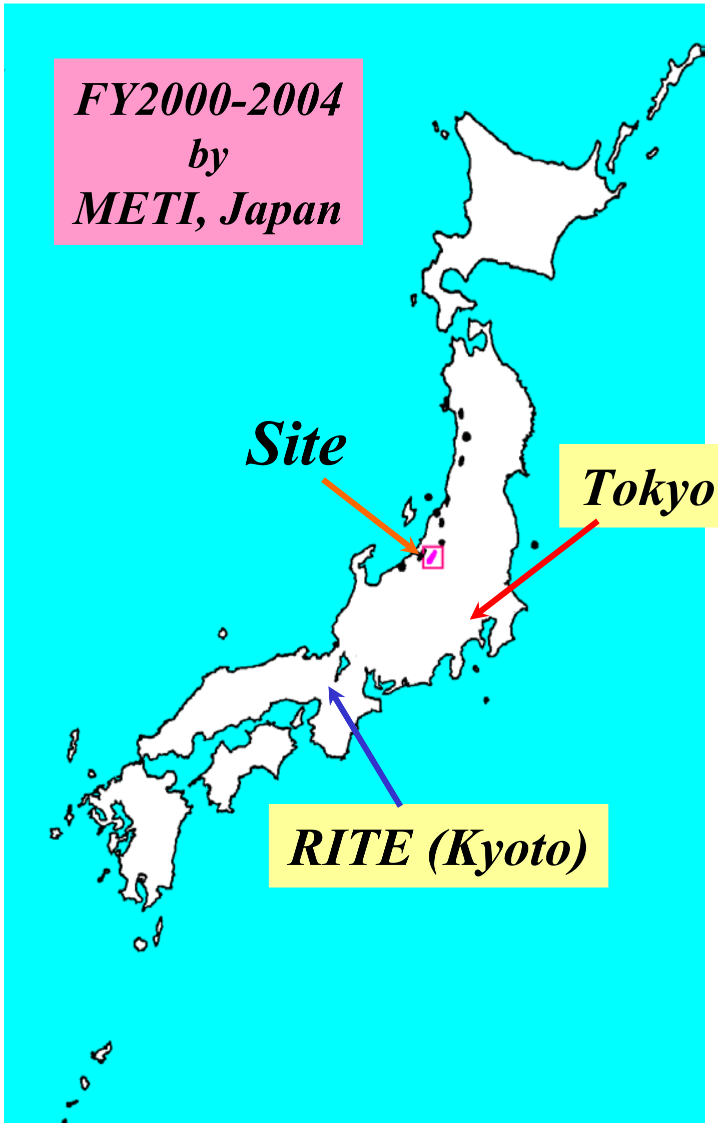
Geophysical Monitoring of CO_2 Sequestration at An Onshore Saline Aquifer in Japan

Ziqiu Xue [1) & Daiji Tanase [2)

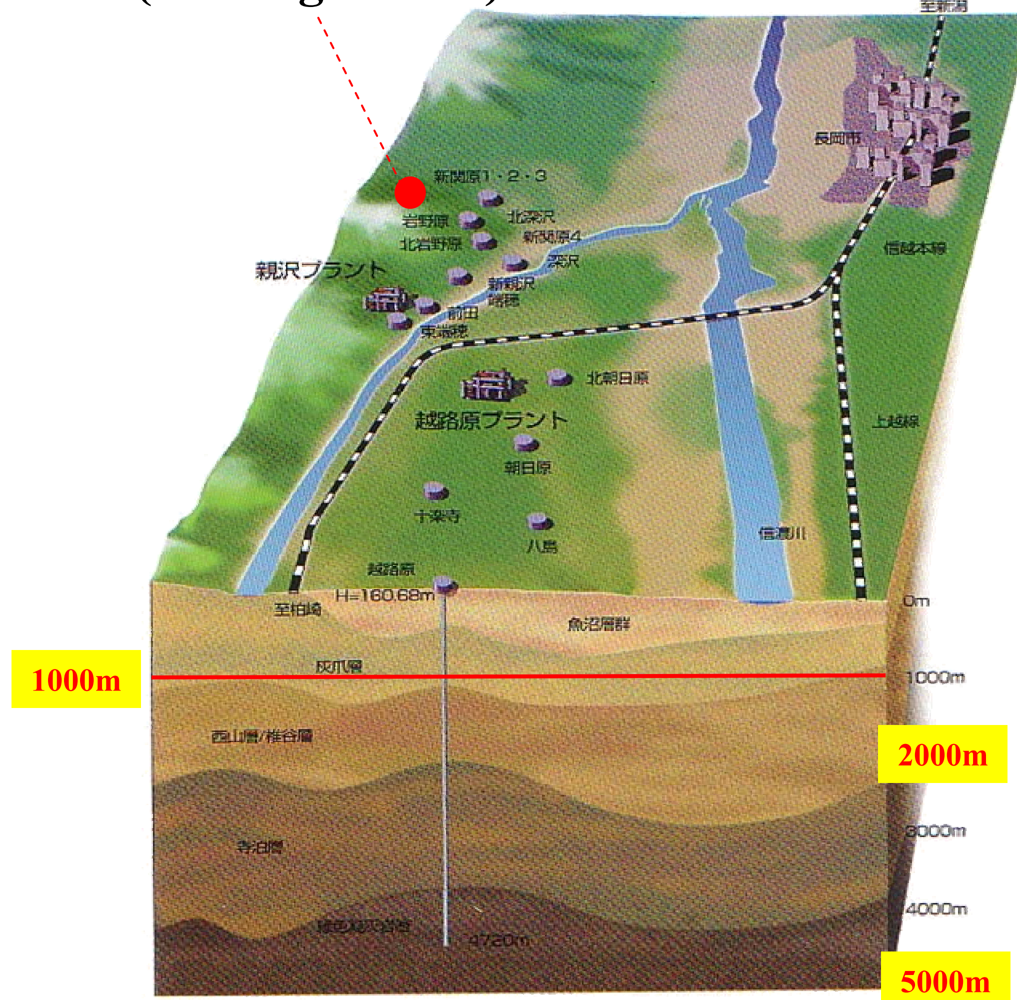
1: Research Institute of Innovative Technology for the Earth (RITE)

2: Engineering Advancement Association of Japan (ENAA)

Location of the Field Test Site for CO_2 Injection



Teikoku Oil, Niigata Prefecture
(active gas field)



Overview and Objectives of the Project
- A Pilot-scale Demonstration -

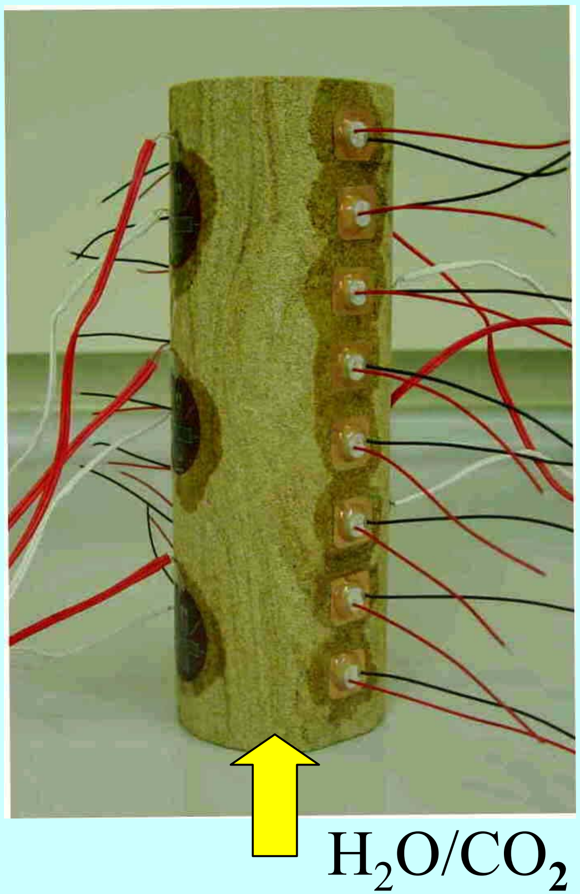
- ♦ **Improved Understanding of the CO_2 Movement in the Porous Sandstone Reservoir**

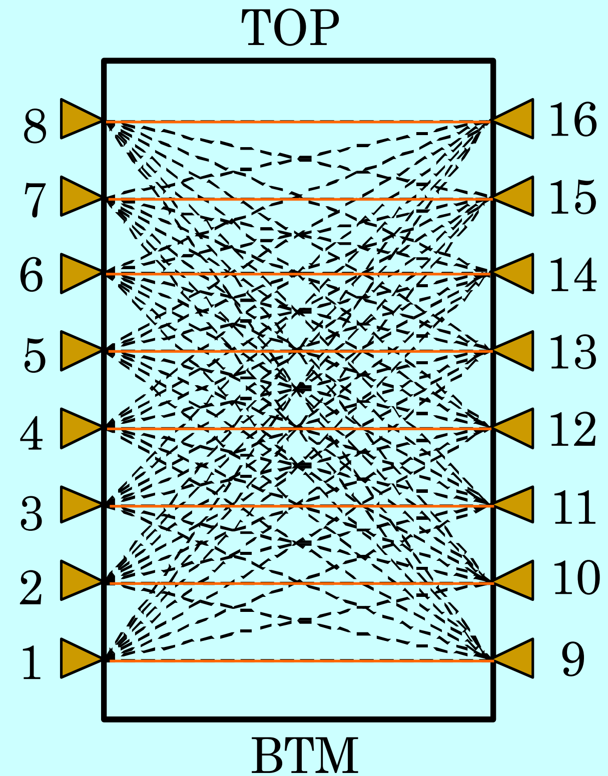
  - ▸ **Seismic Wave Velocity Response to CO_2 Injection**
  - ▸ **Mechanism for the Injected CO_2 Displacing the Formation Water**

  - ▸ **Crosswell Seismic Tomography and Well Logging**
  - ▸ **Measurements of the Formation Pressure Buildup**
  - ▸ **3D Surface Seismic Survey (GHGT7, Vancouver)**

  - ▸ **a simulator for the long-term behavior predication**
  - ▸ **system studies on modeling and public outreach**

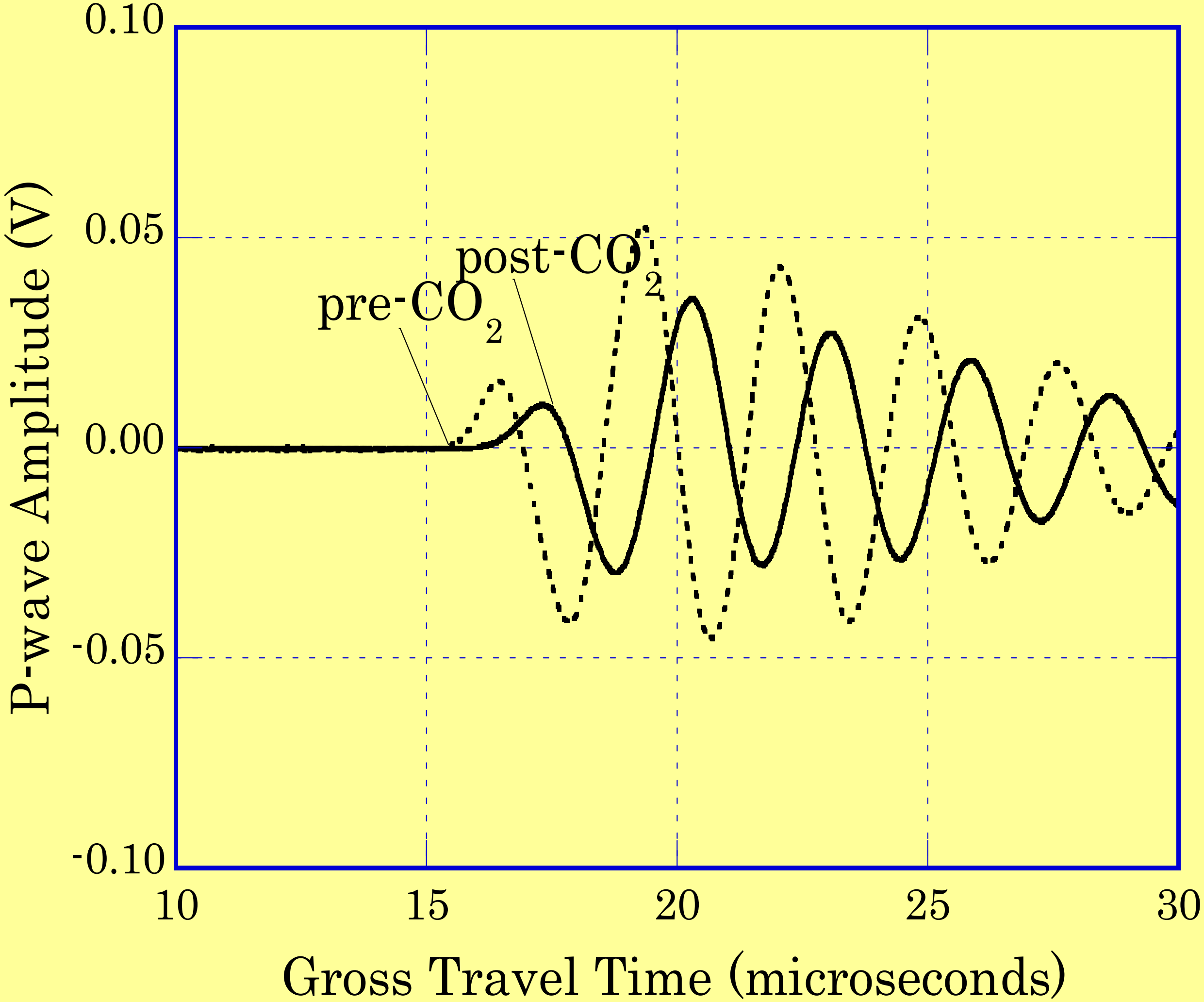
Expt. Study of Crosswell Seismic Tomography



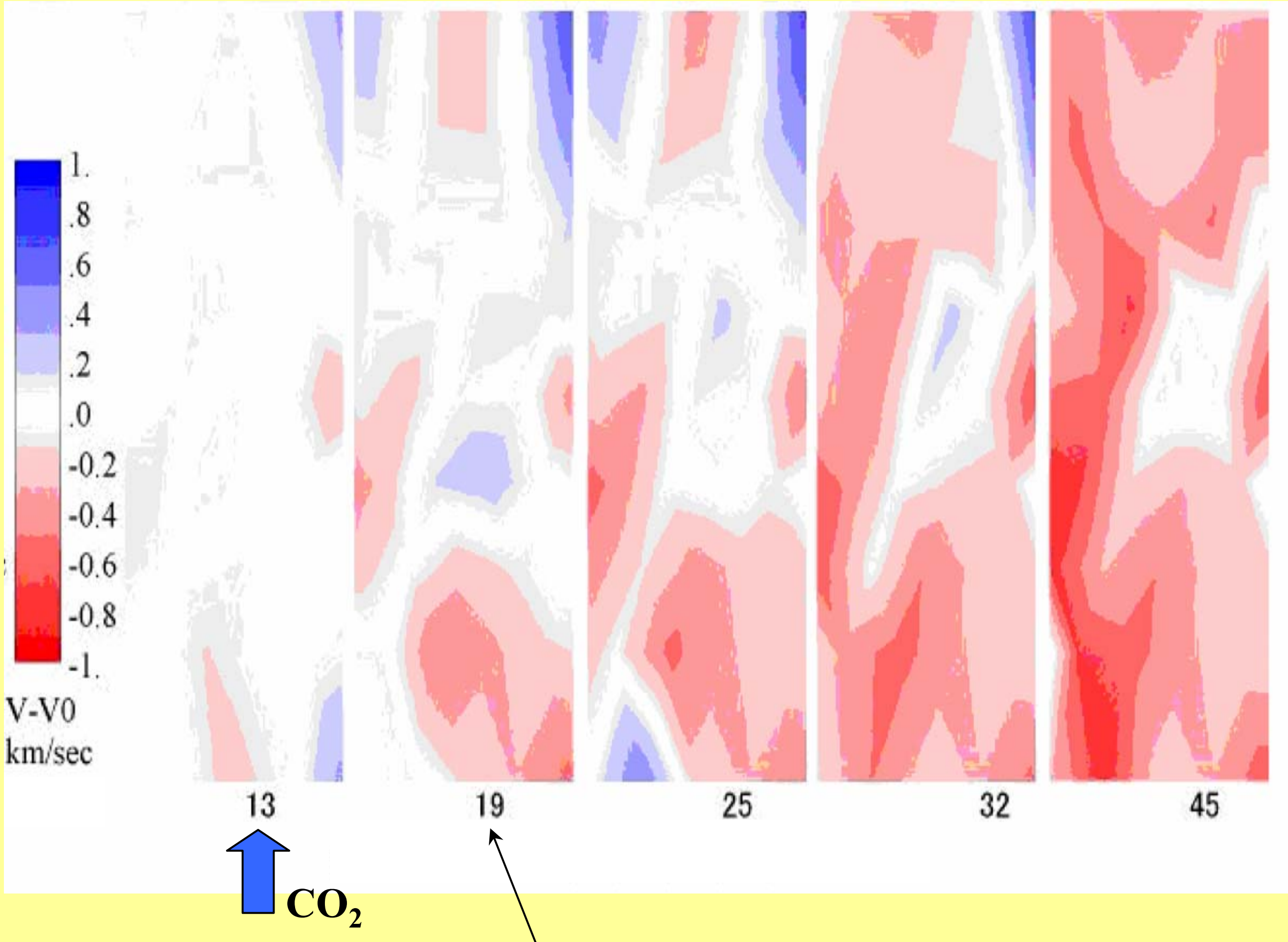


Porosity: 23%; Permeability: 5md
(porous sandstone)

P-wave forms changes for pre- and post-CO_2 flooding in a porous sandstones.

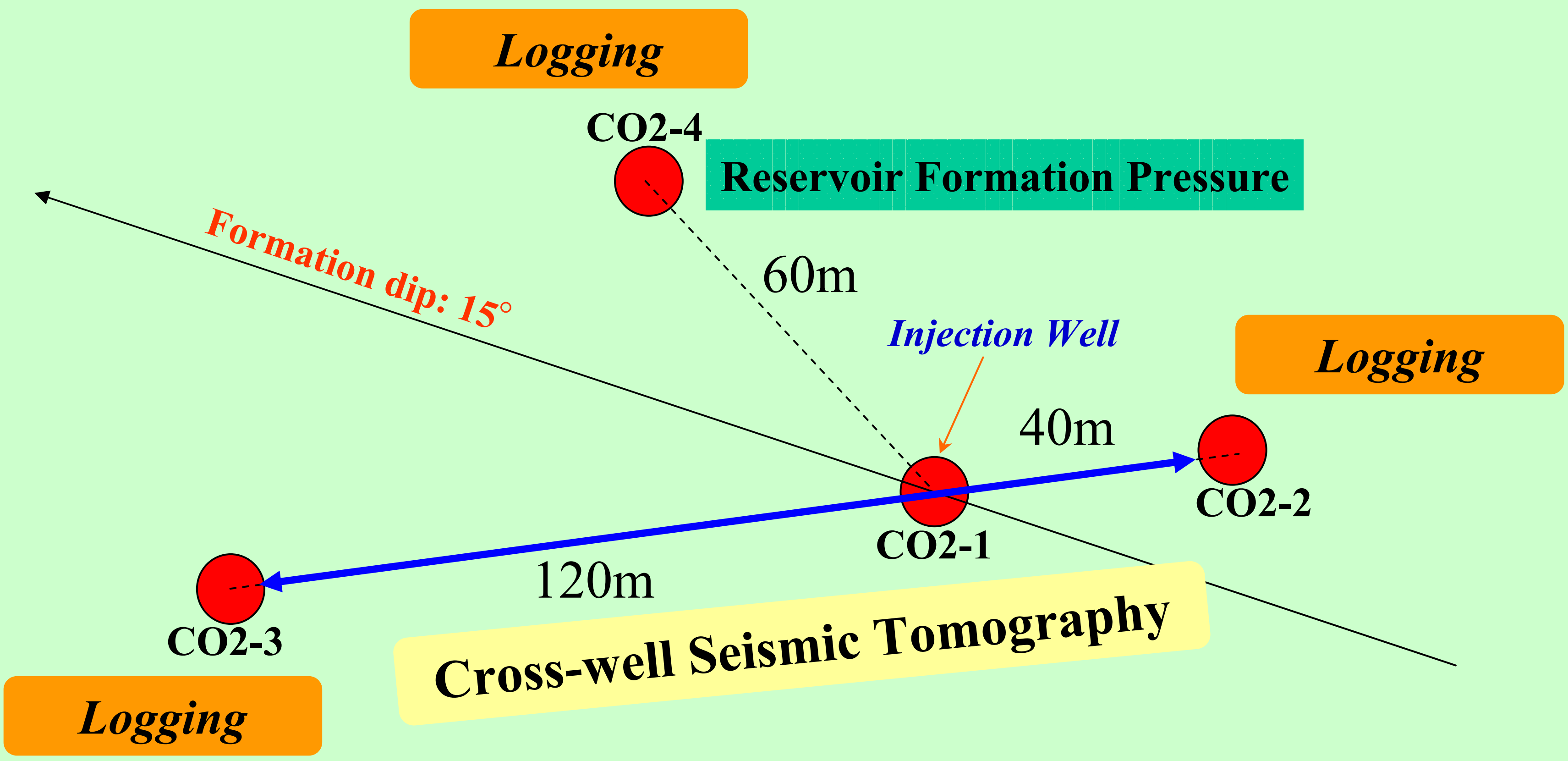


Movements of the injected supercritical CO_2



Elapsed time from starting CO_2 injection: minute

Geophysical Monitoring of CO_2 Sequestration



Term of the surveys :

Feb. 8th 2003 -Feb. 19th 2003 (BLS)

Jan. 26th 2004 -Feb 9th 2004 (MS-1)

(3,200 ton-CO2 injected)

July.21st 2004 -July.30th 2004 (MS-2)

(6,200 ton-CO2 injected)

Area of the surveys :

900 m ～ 1284 m : Source Well (CO2-2)
(Shot every 4 m)

900 m ～ 1248 m : Receiver Well (CO2-3)
(Receive every 4 m)

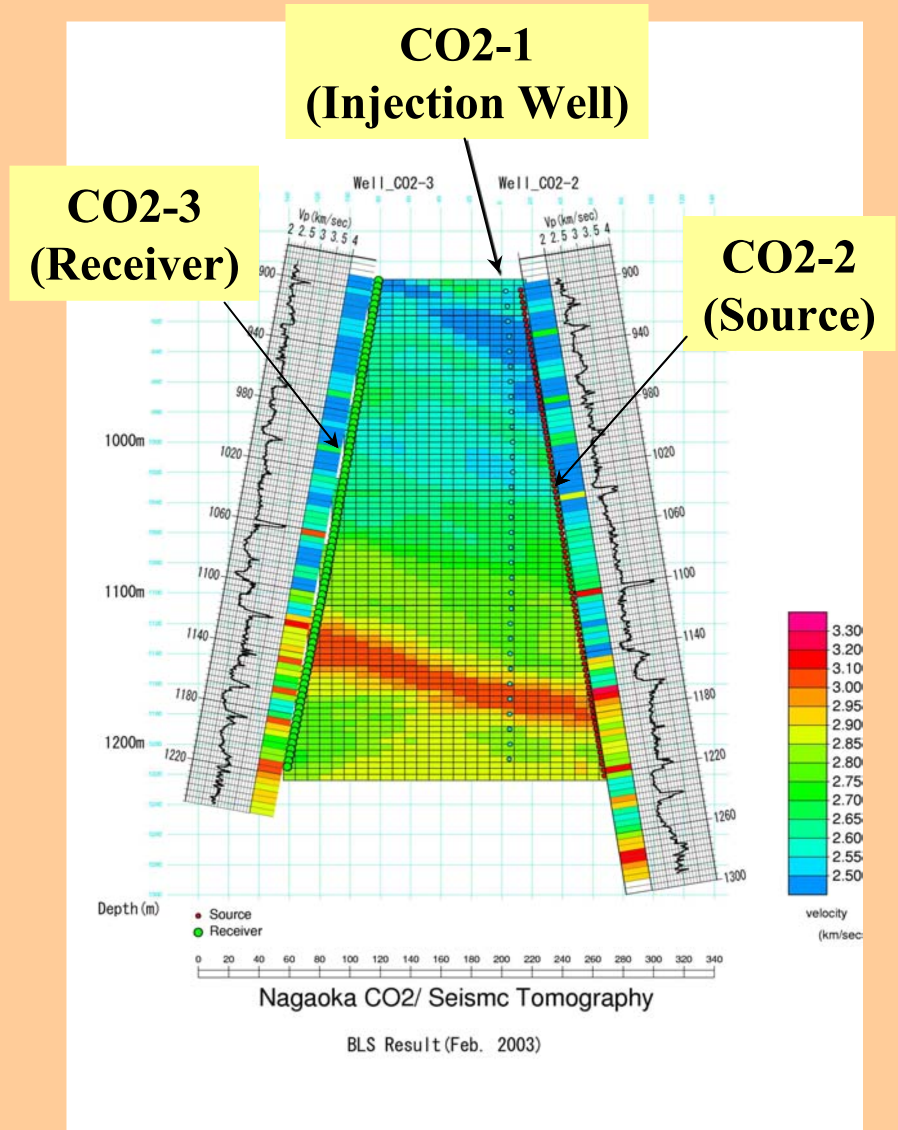
Survey systems :

Source : OWS

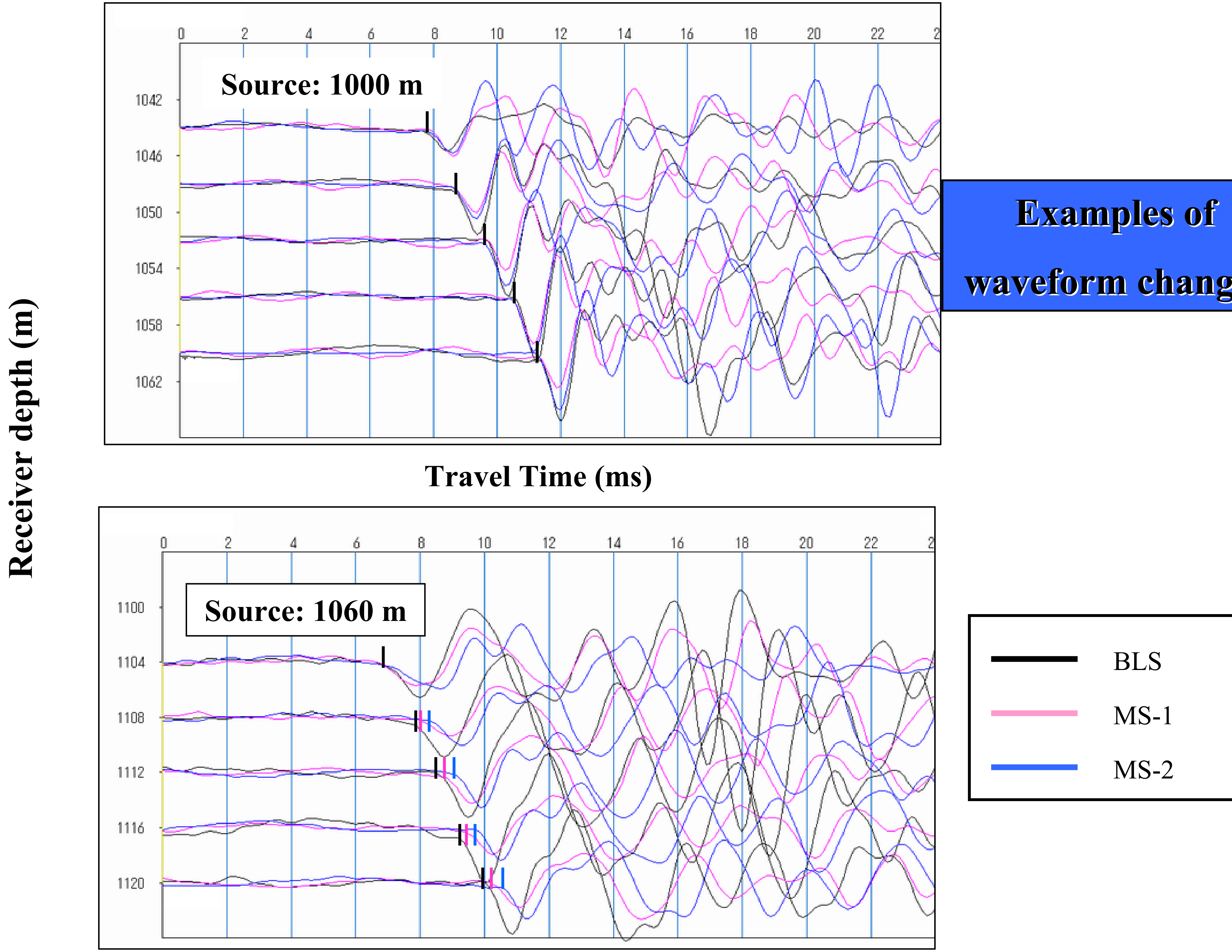
Receiver : Hydrophone (24ch)

Acquisition system : DAS-1(24bit A/D)

Result of the BLS

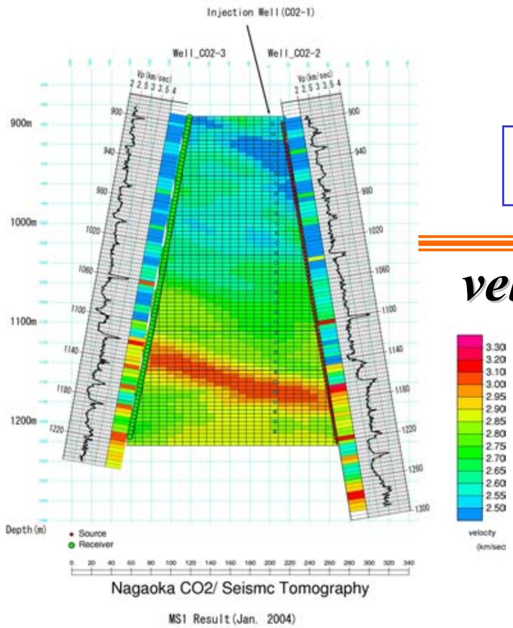


Examples of waveform changes



Result of the MS-1 (1^{st} Monitoring Survey)

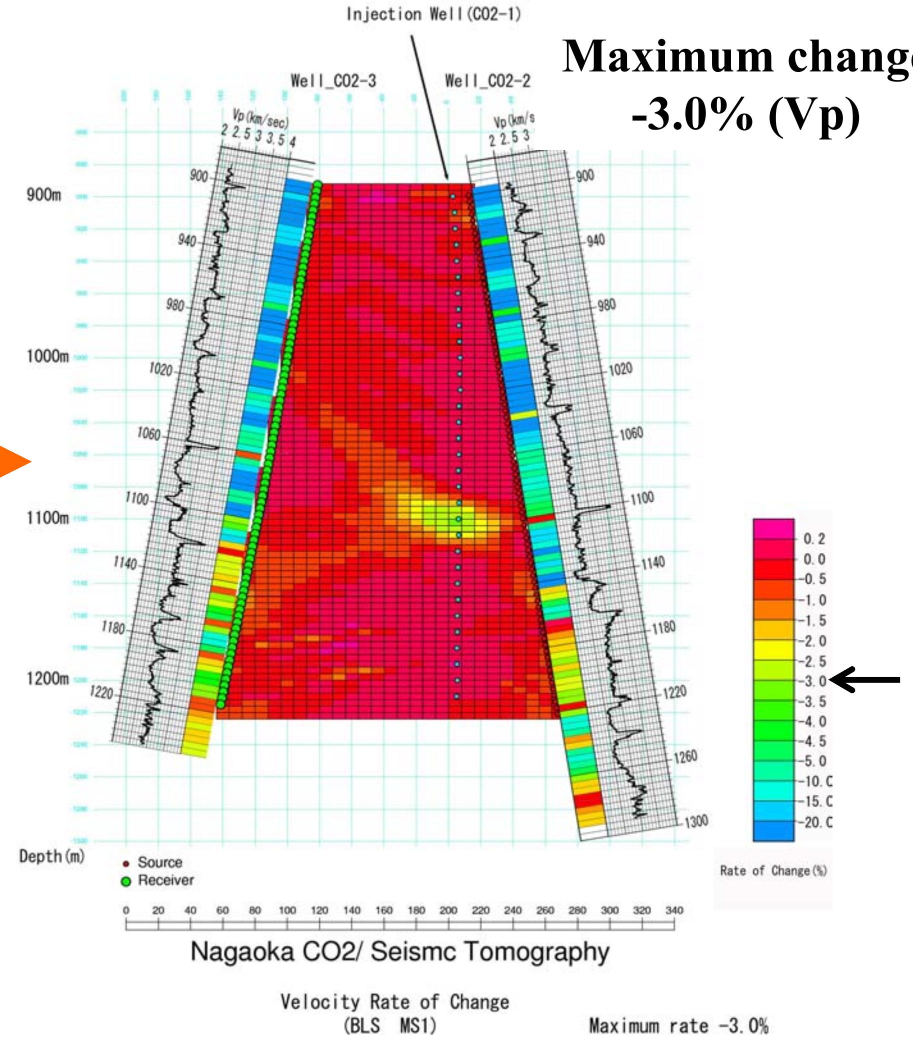
Result of the MS-1



ΔV/Vo (%)

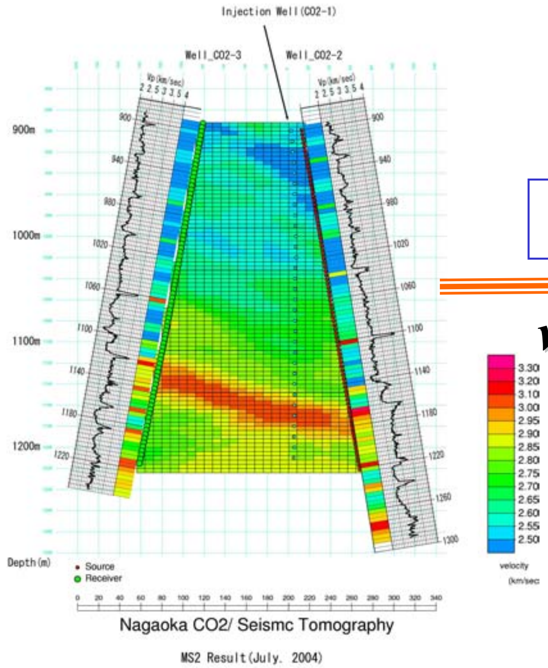
velocity change

Maximum change -3.0% (Vp)



Result of the MS-2 (2nd Monitoring Survey)

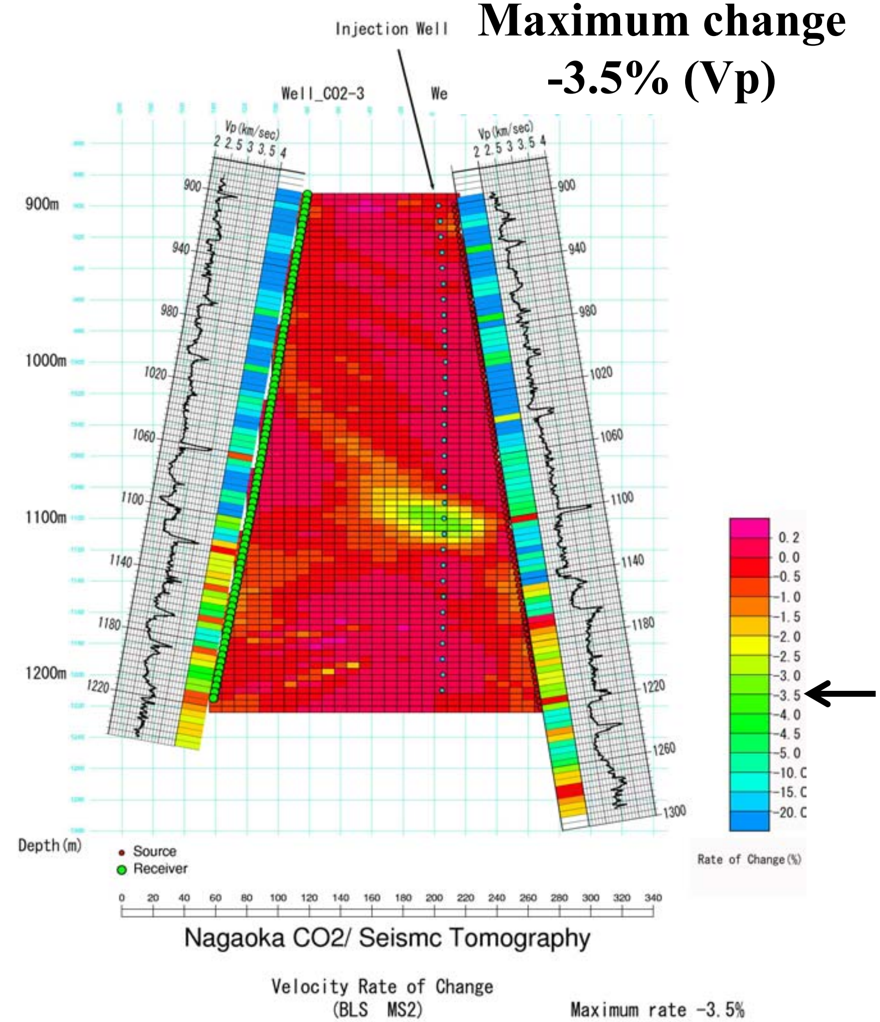
Result of the MS-2



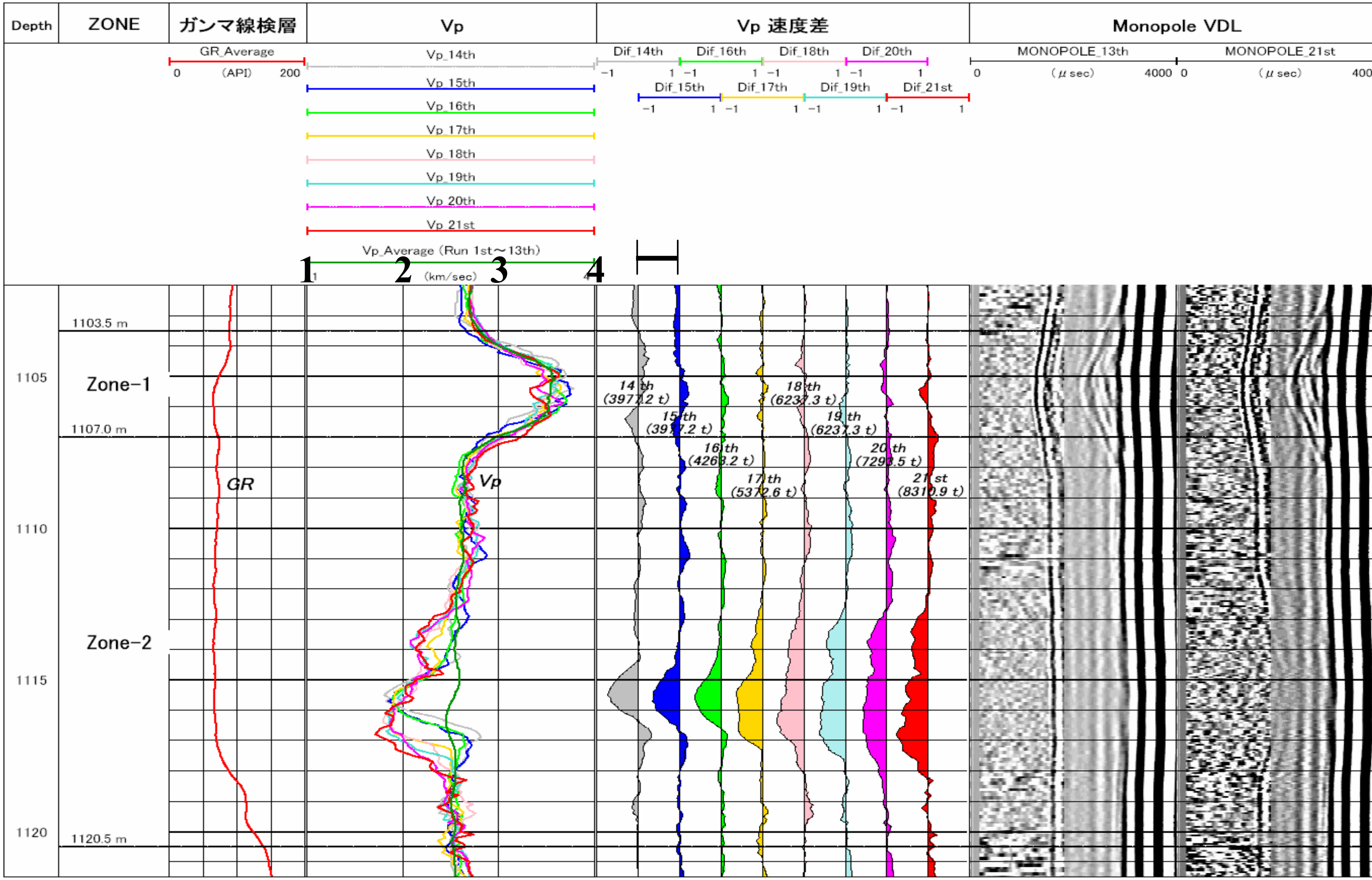
ΔV/Vo (%)

velocity change

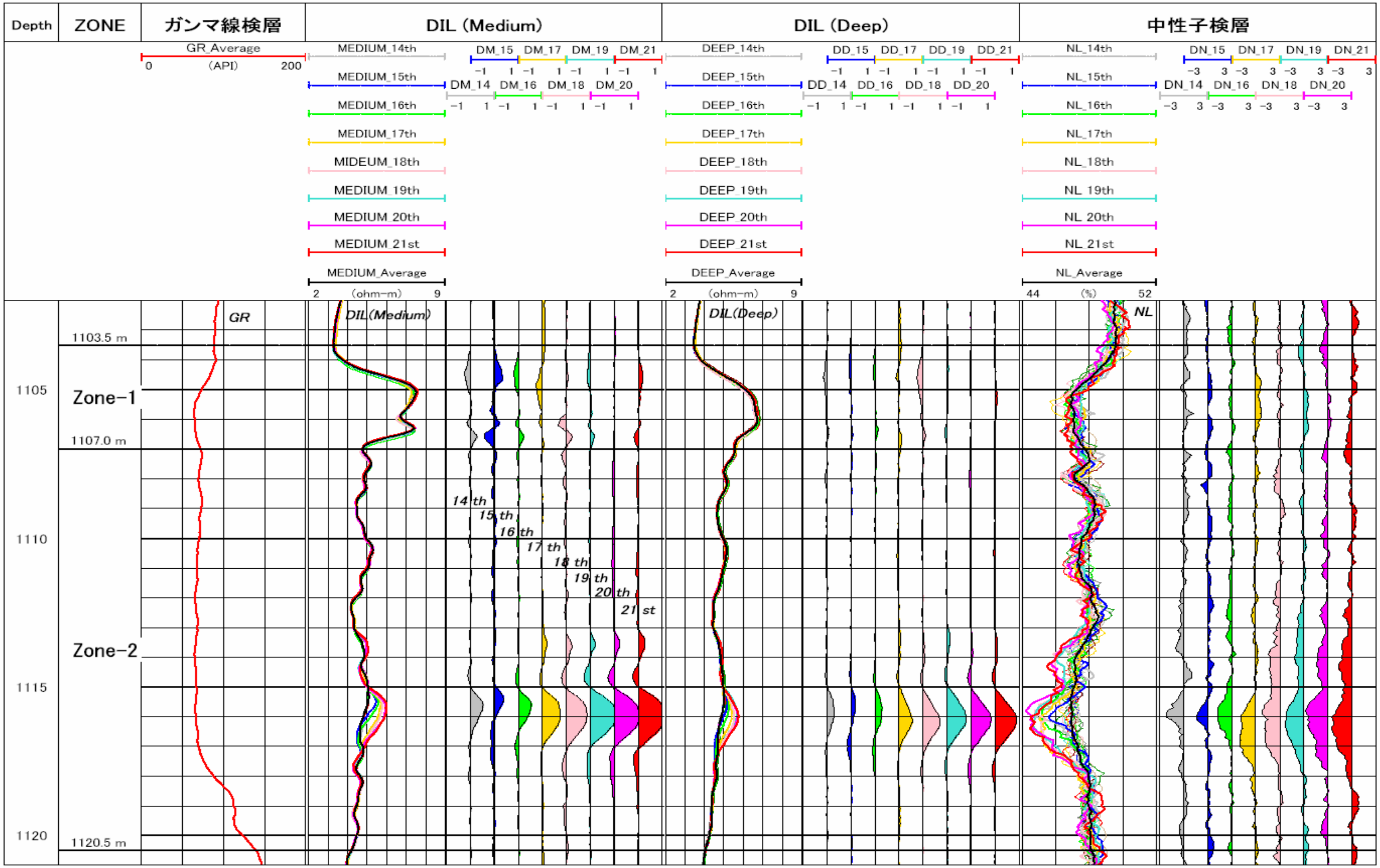
Maximum change -3.5% (Vp)



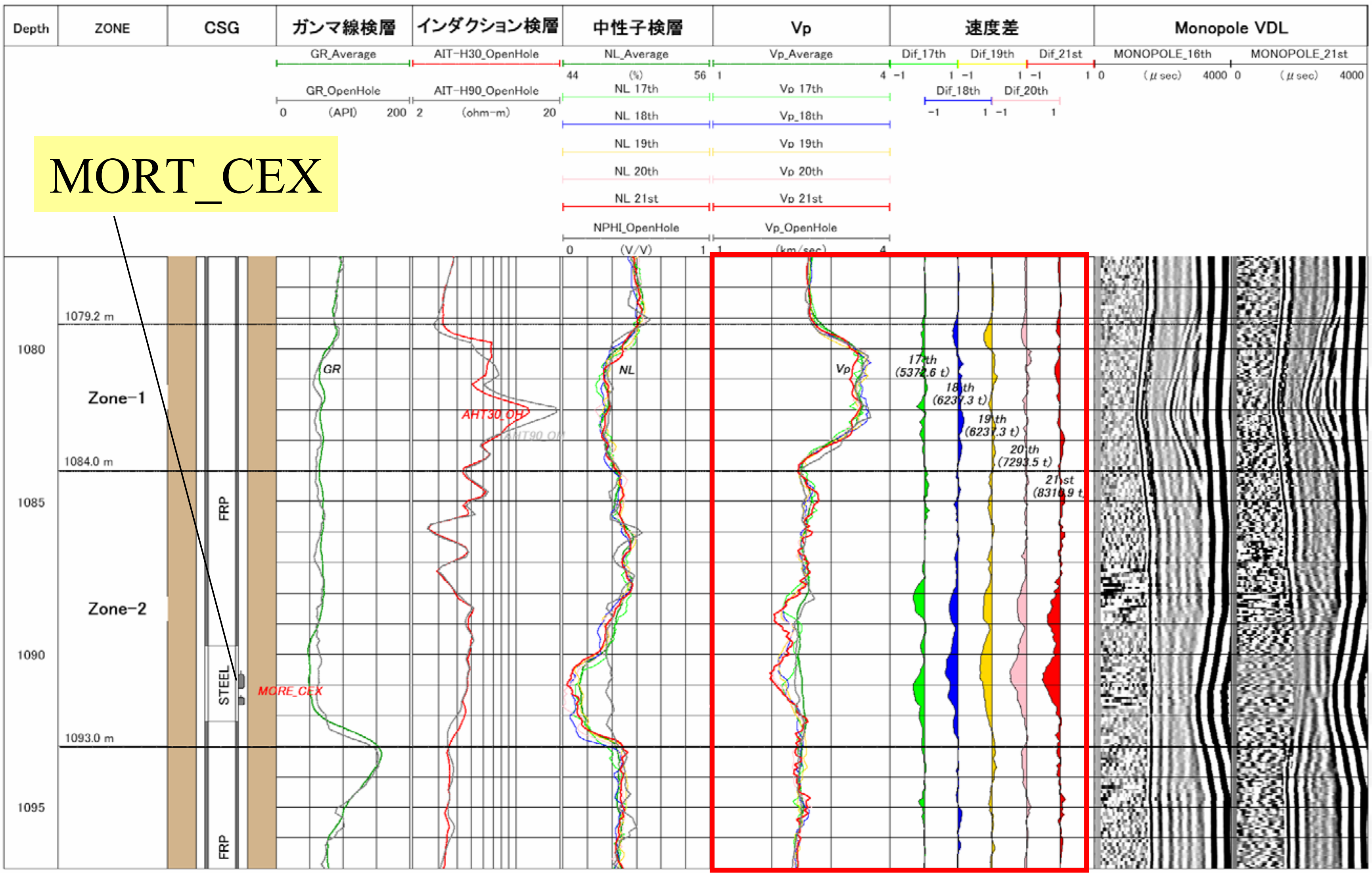
CO2-2　Vp (Sonic)



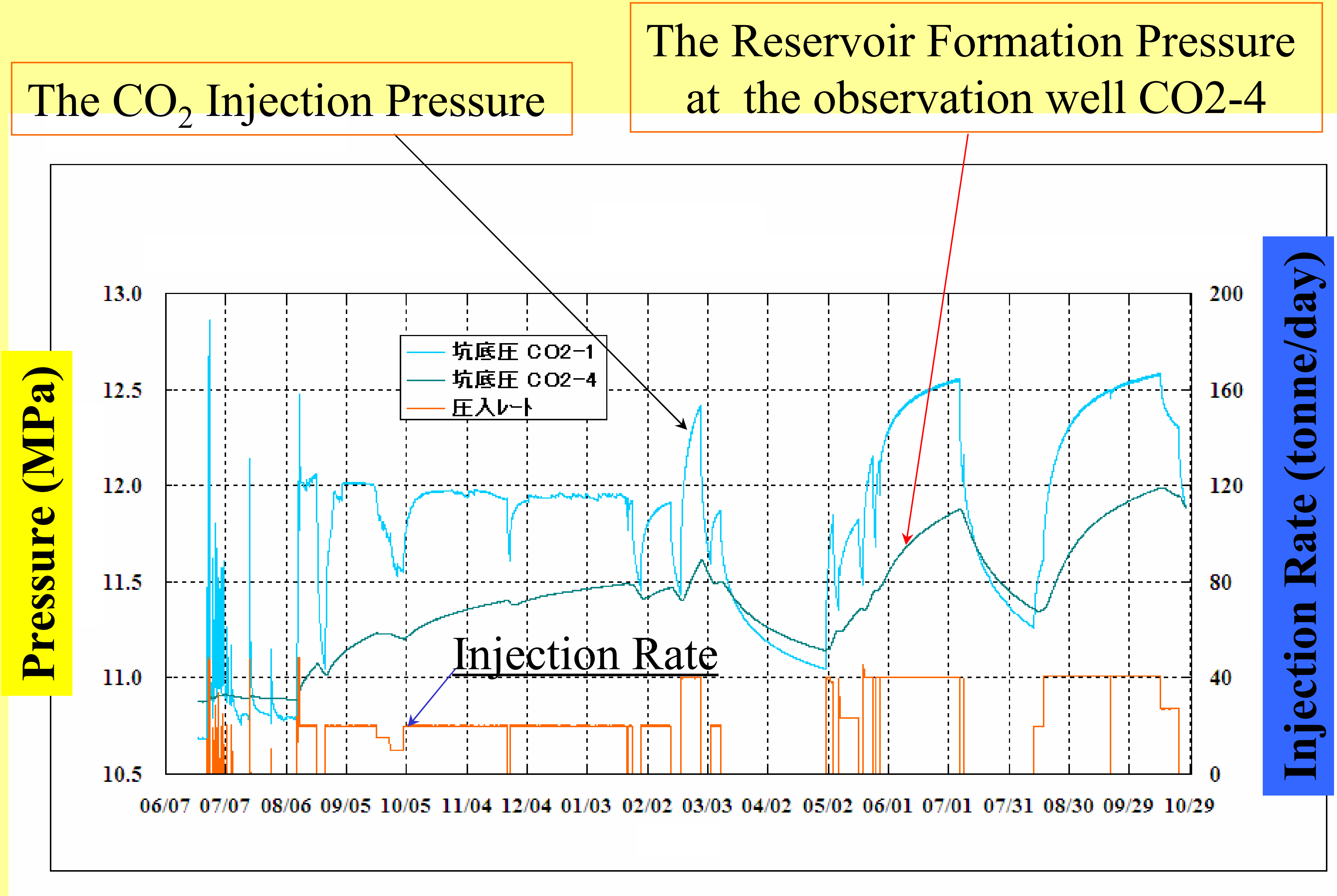
CO2-2 (Induction & Neutron)



CO2-4 Vp (Sonic)



Vp



The CO_2 Injection Pressure
The Reservoir Formation Pressure at the observation well CO2-4
Pressure (MPa)
Injection Rate (tonne/day)
Injection Rate
坑底圧 CO2−1
坑底圧 CO2−4
圧入レート
13.0
12.5
12.0
11.5
11.0
10.5
200
160
120
80
40
0
06/07 07/07 08/06 09/05 10/05 11/04 12/04 01/03 02/02 03/03 04/02 05/02 06/01 07/01 07/31 08/30 09/29 10/29

Conclusion Remarks

♦ *Lab-scale:*

- P-wave velocity reduction due to CO_2: 6% - 16%.
- Confirmed the usefulness of crosswell seismic tomo.
- CO_2 migration depends strongly on heterogeneous pore structure and bedding plane.

♦ *Field-scale:*

- An area of P-wave velocity decrease appeared near the injection well and the injected CO_2 is migrating along the formation direction.
- Significant changes observed in *Induction*, *Sonic* and *Neutron* loggings at the observation well CO2-2.
- At the well CO2-4, changes were observed in *Sonic* and *Neutron* loggings.

Conclusion Remarks (cont.)

- **Effects of well geometry and the thin high-velocity layer appeared in tomograms. → Ghost & vertical velocity anomaly distribution.**

- **Sonic logging detected more wider CO_2-zone than Neutron and (*Induction*) loggings at both CO2-2 and CO2-4. → Need a clear explanation.**

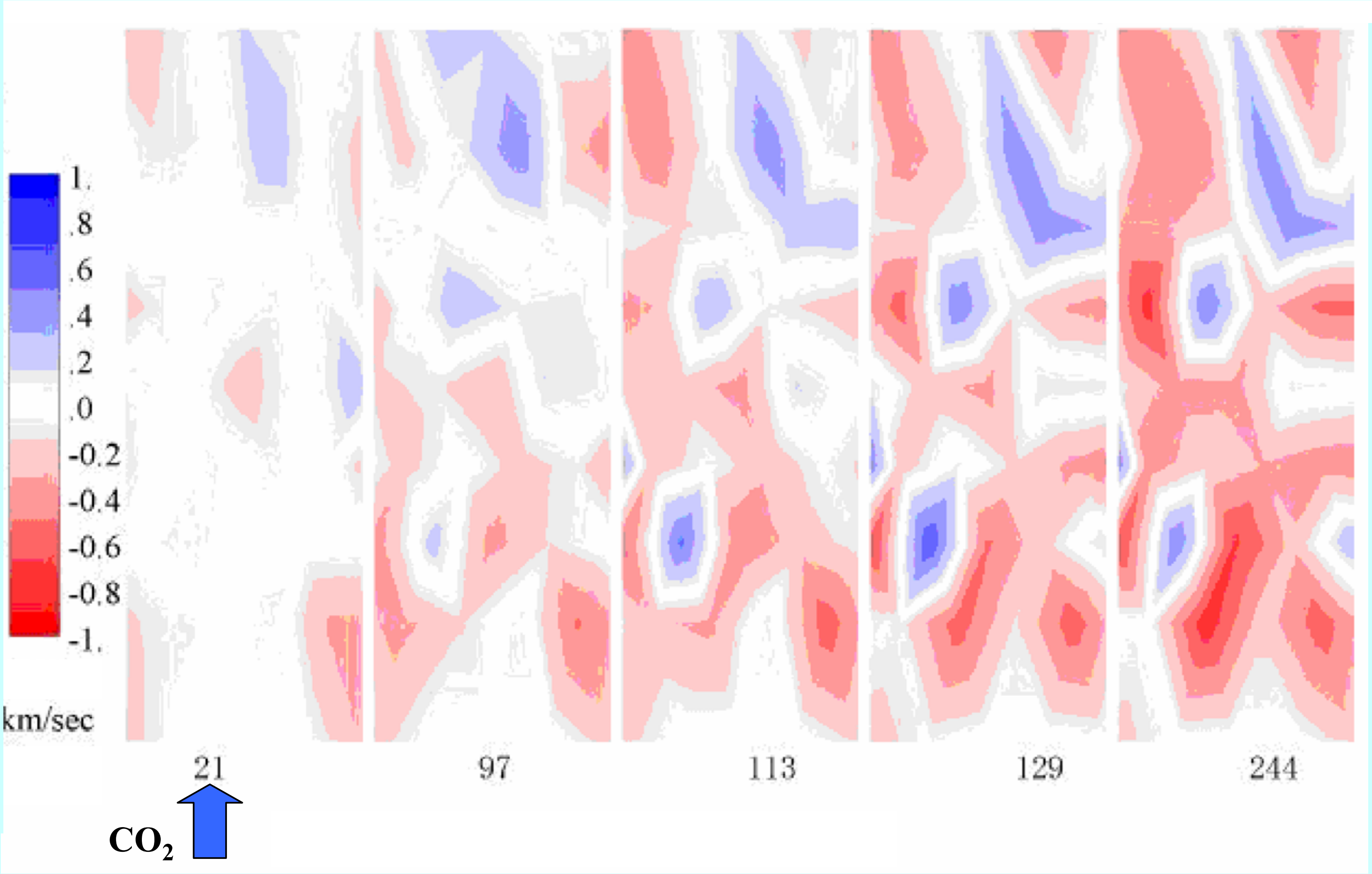
ACKNOWLEDGMENTS

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

- We thank OYO Co. Ltd. for conducting the crosswell seismic tomography surveys and Geophysical Surveying Co. Ltd. for conducting the well logging surveys at the CO_2 injection site.

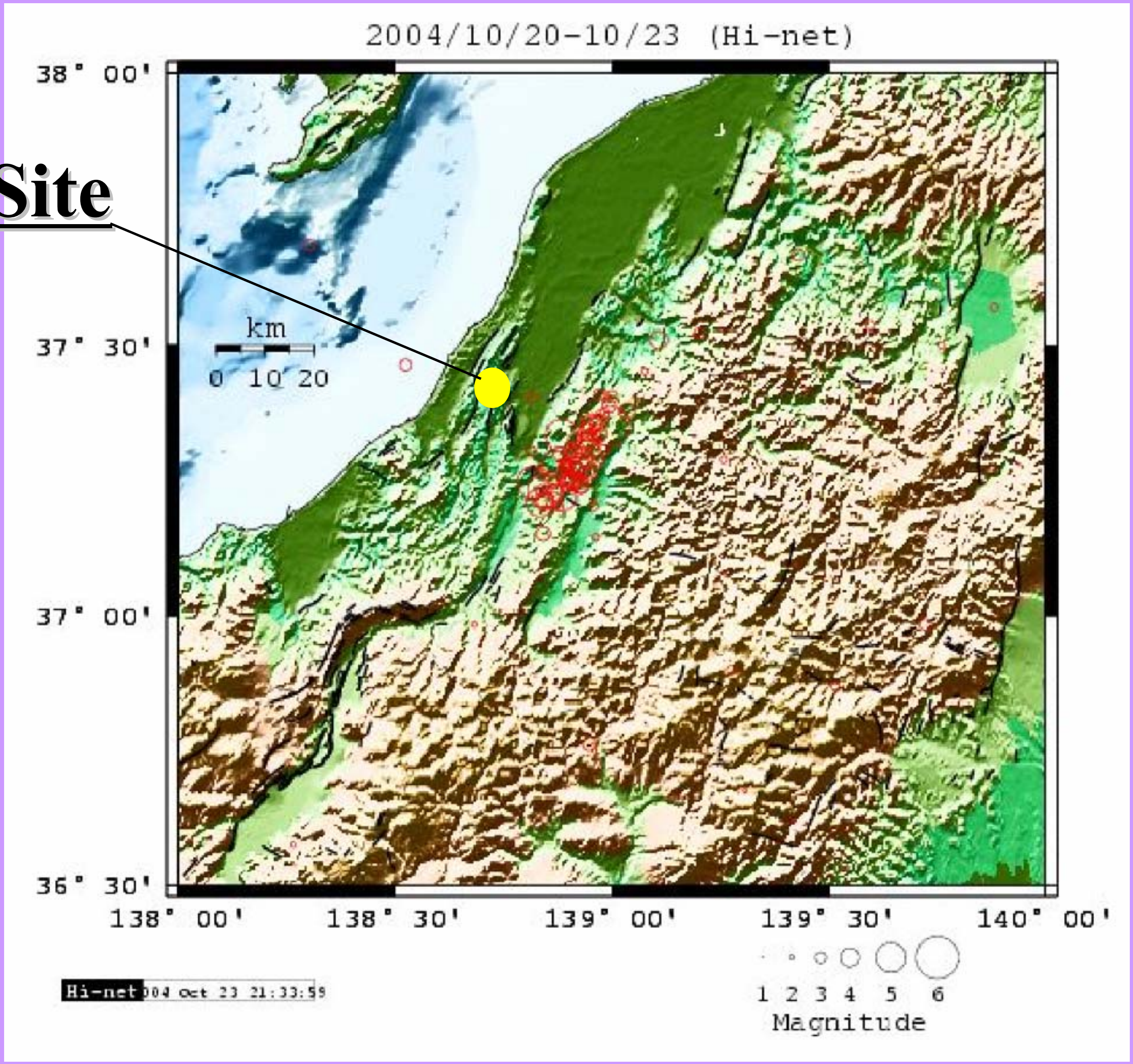
Supercritical CO_2 movement by monitoring P-velocity changes

(sample axial __perpendicular__ to the bedding plane) ⊥



Chuetsu Earthquake Information

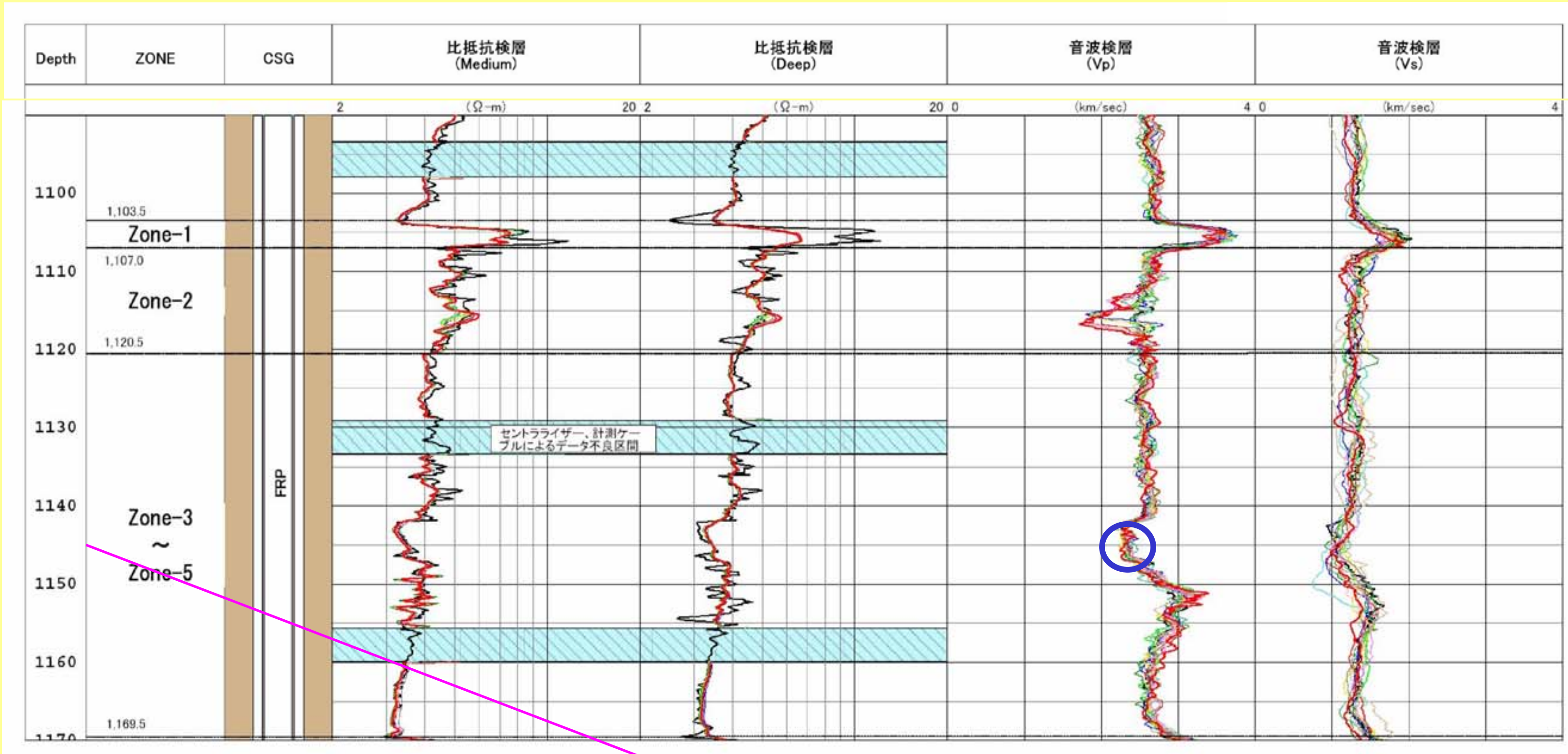
CO_2 Injection Site



Date : 23 Oct. 2004
Time: 17:56

Magnitude: 6.8
Depth : 10 km

Observation Well CO2-2



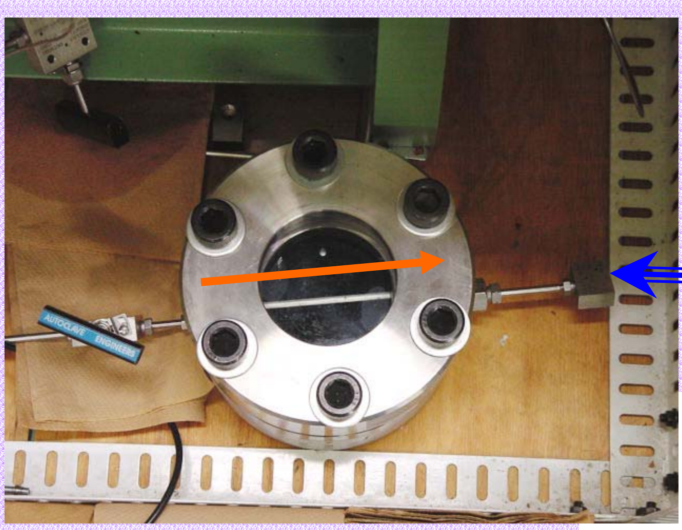
fine-grain sandstone

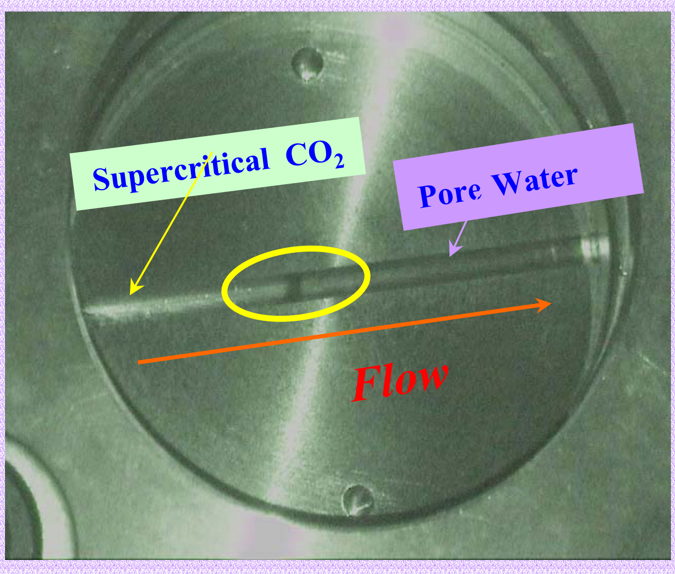
diameter: 5cm, length: 7cm

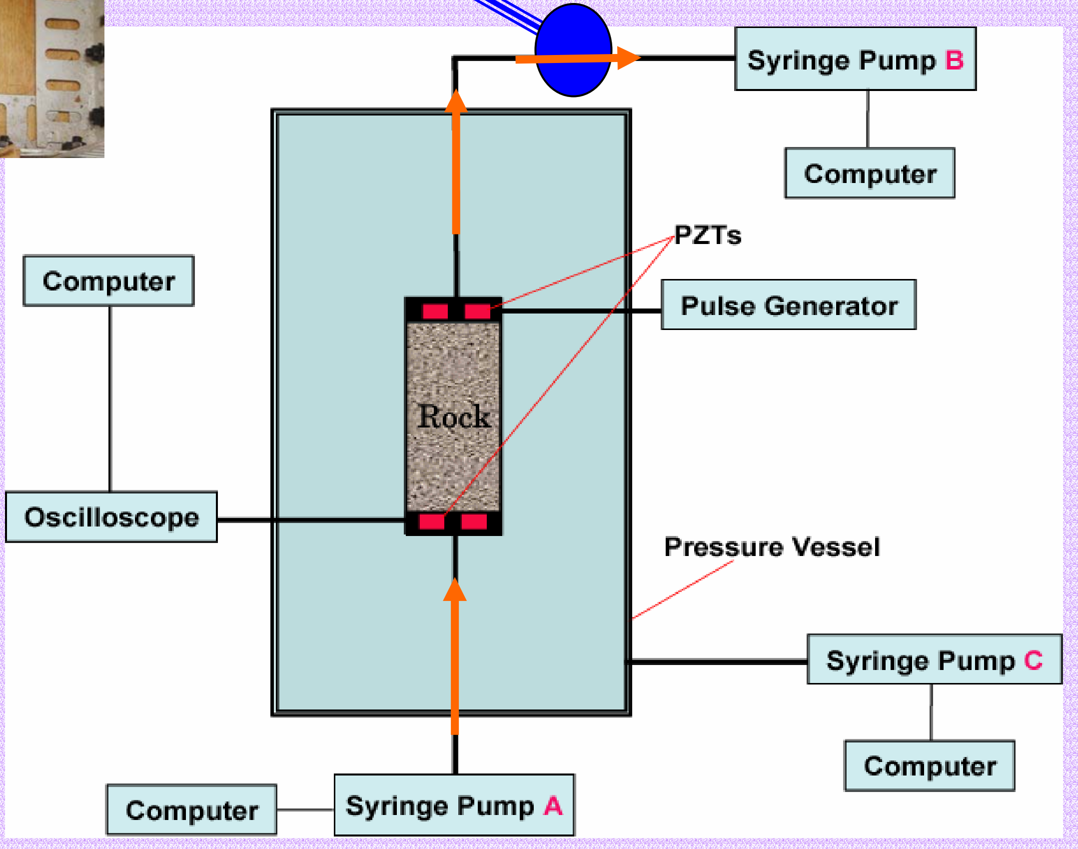
1145.49m - 1145.58m

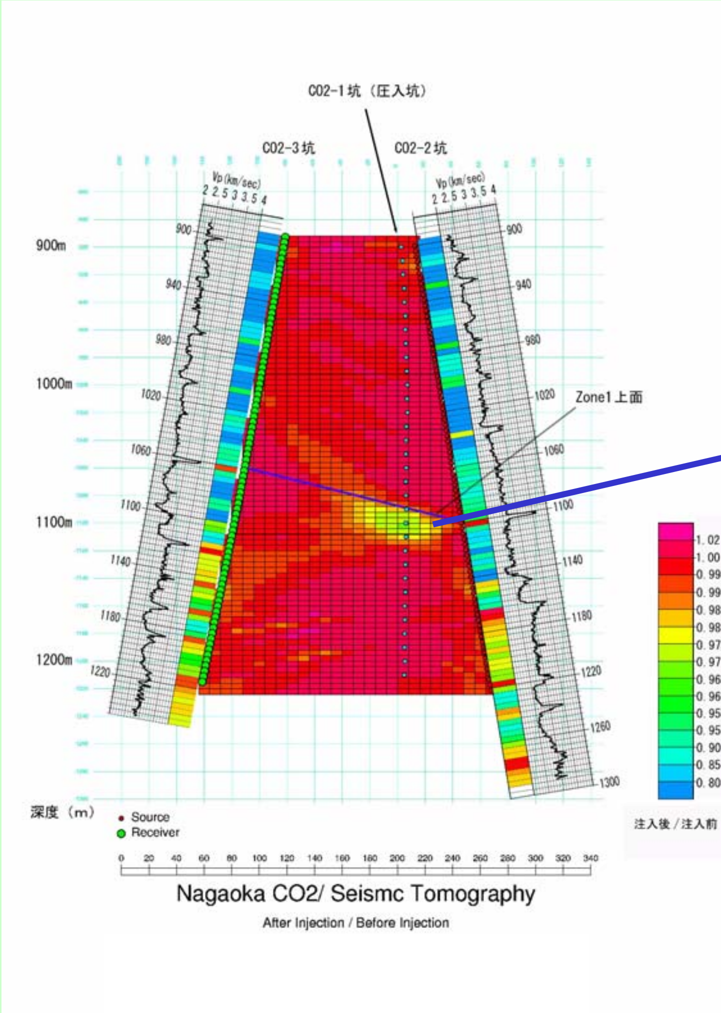
Experimental System Diagram

Measurements of Vp and permeability during injection of CO_2.

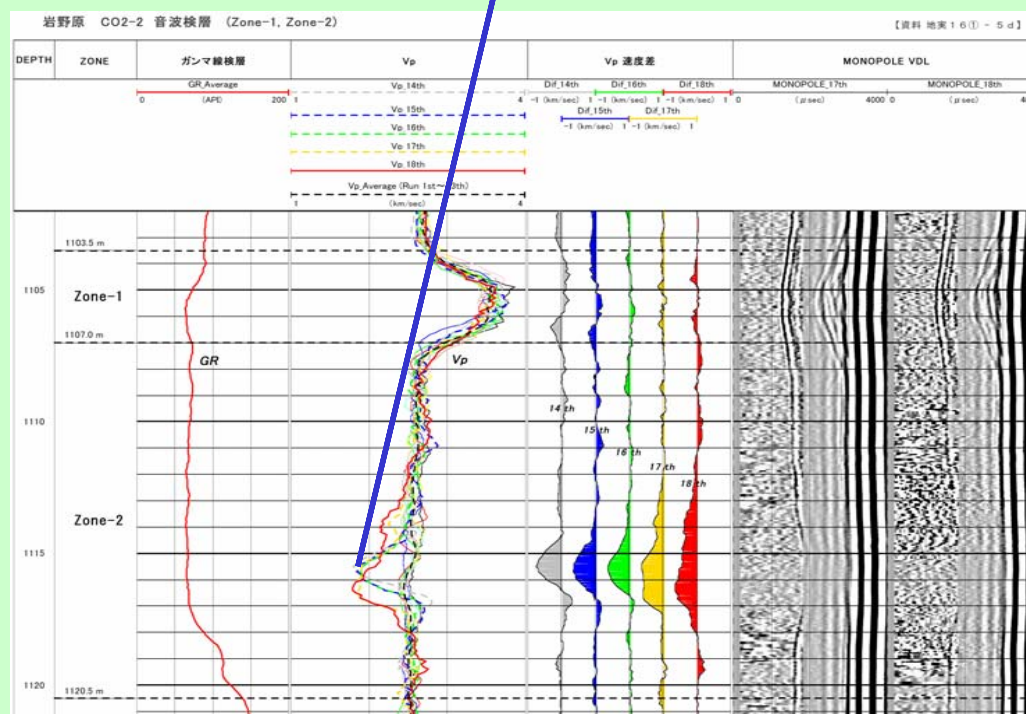




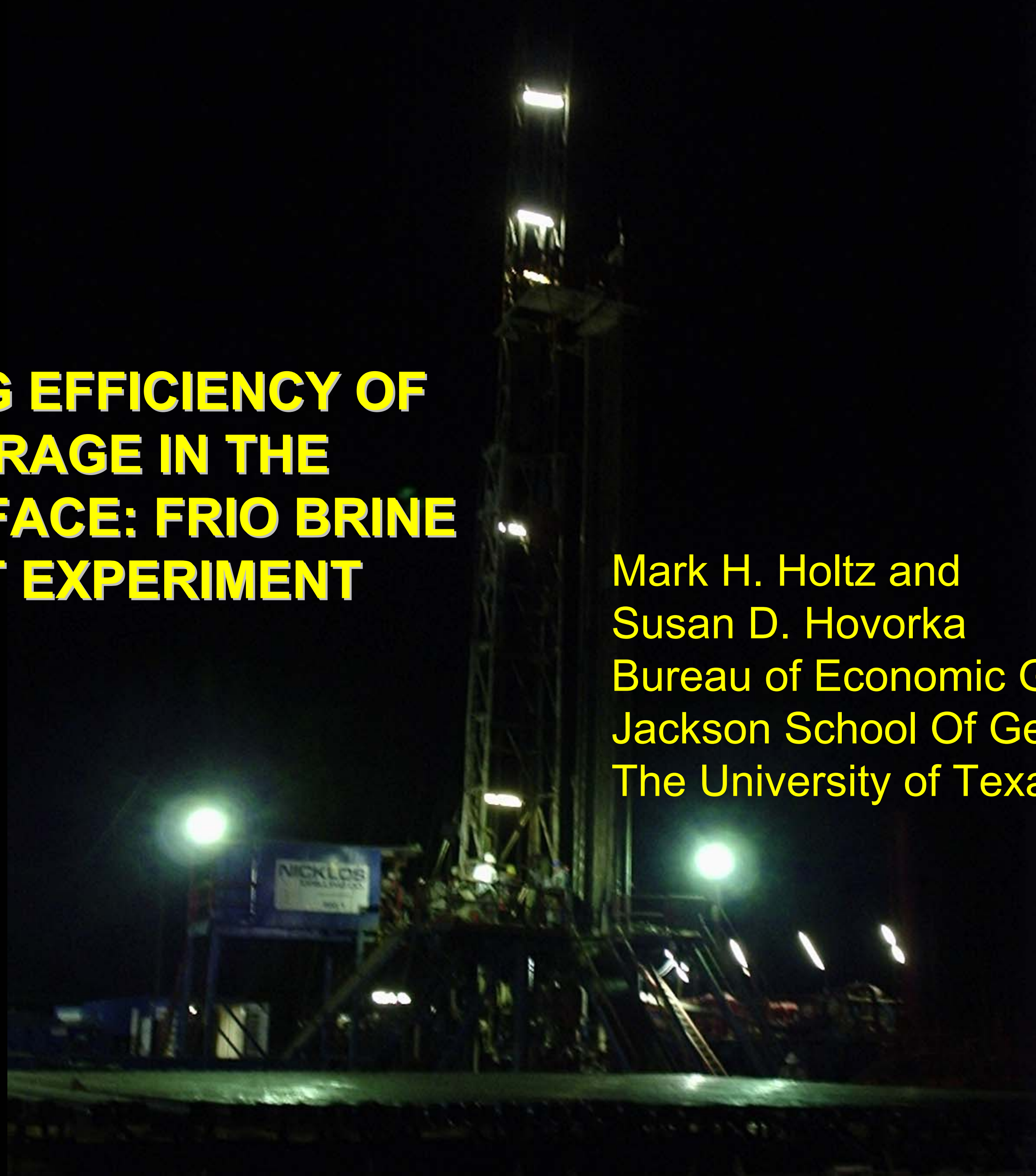




CO_2 saturation
?



TESTING EFFICIENCY OF STORAGE IN THE SUBSURFACE: FRIO BRINE PILOT EXPERIMENT



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

Frio Brine Pilot Research Team

- Funded by US DOE National Energy Technology Lab: Karen Cohen/Charles Byrer
- Bureau of Economic Geology, Jackson School, The University of Texas at Austin: Susan Hovorka, Mark Holtz, Shinichi Sakurai, Seay Nance, Joseph Yeh, Paul Knox, Khaled Faoud, Jeff Paine
- Lawrence Berkeley National Lab, (Geo-Seq): Larry Myer, Tom Daley, Barry Freifeld, Rob Trautz, Christine Doughty, Sally Benson, Karsten Pruess, Curt Oldenburg, Jennifer Lewicki, Ernie Major, Mike Hoversten, Mac Kennedy; Don Lippert
- Oak Ridge National Lab: Dave Cole, Tommy Phelps, David Riestberg
- Lawrence Livermore National Lab: Kevin Knauss, Jim Johnson
- Alberta Research Council: Bill Gunter, John Robinson
- Texas American Resources: Don Charbula, David Hargiss
- Sandia Technologies: Dan Collins, “Spud” Miller, David Freeman; Phil Papadeas
- BP: Charles Christopher, Mike Chambers
- Schlumberger: T. S. Ramakrishna and others, Mike Wilt
- SEQUIRE – National Energy Technology Lab: Curt White, Rod Diehl, Grant Bromhall, Brian Stratizar, Art Wells
- University of West Virginia: Henry Rausch
- USGS: Yousif Kharaka, Bill Evans, Evangelos Kakauros, Jim Thorsen
- Praxair: Joe Shine, Dan Dalton
- Australian CO2CRC (CSRIO): Kevin Dodds
- Core Labs: Paul Martin and others

Gulf Coast Carbon Center

Frio Brine Pilot
Tapping the Potential for Large Volume Sequestration: MMV Demonstration

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

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

Gulf
Coast
Carbon
Center

Scientific Monitoring vs. Monitoring During Implementation

- Frio project is an experiment
  - Intense monitoring for tool testing and model validation
  - Deliberate redundancy of tools
  - Monitoring in excess of any reasonable environmental protection and heath and safety needs
- During implementation monitoring will be designed to meet needs and be cost-effective.
  - Credits and emissions trading
  - Regulatory Compliance
  - Public Acceptance

MMV for CO_2 Injection Implementation Already Exists

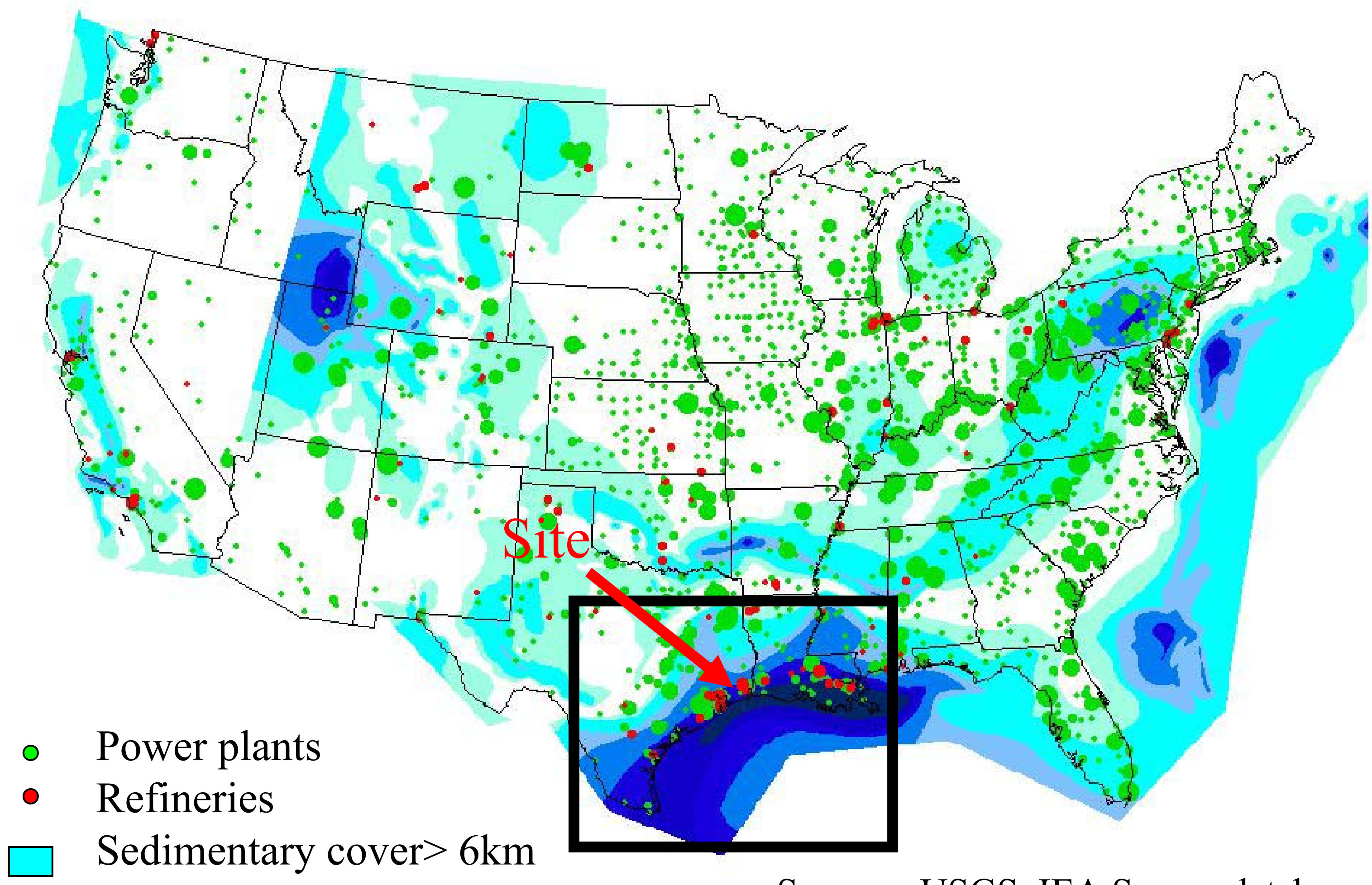
- Health and safety procedures for pipelines, shipping, handling, and storing
- Pre-injection characterization and modeling
- Isolation of injectate from Underground Sources of Drinking Water
- Maximum allowable surface injection pressure
- Mechanical integrity testing
- Standards for well completion and plug and abandonment in cone of influence and area of review around injection wells.
- See details in our report to accompany class 5 permit: www.gulfcoastcarbon.org

Potential Shortfalls in Existing MMV

Do current processes adequately consider:

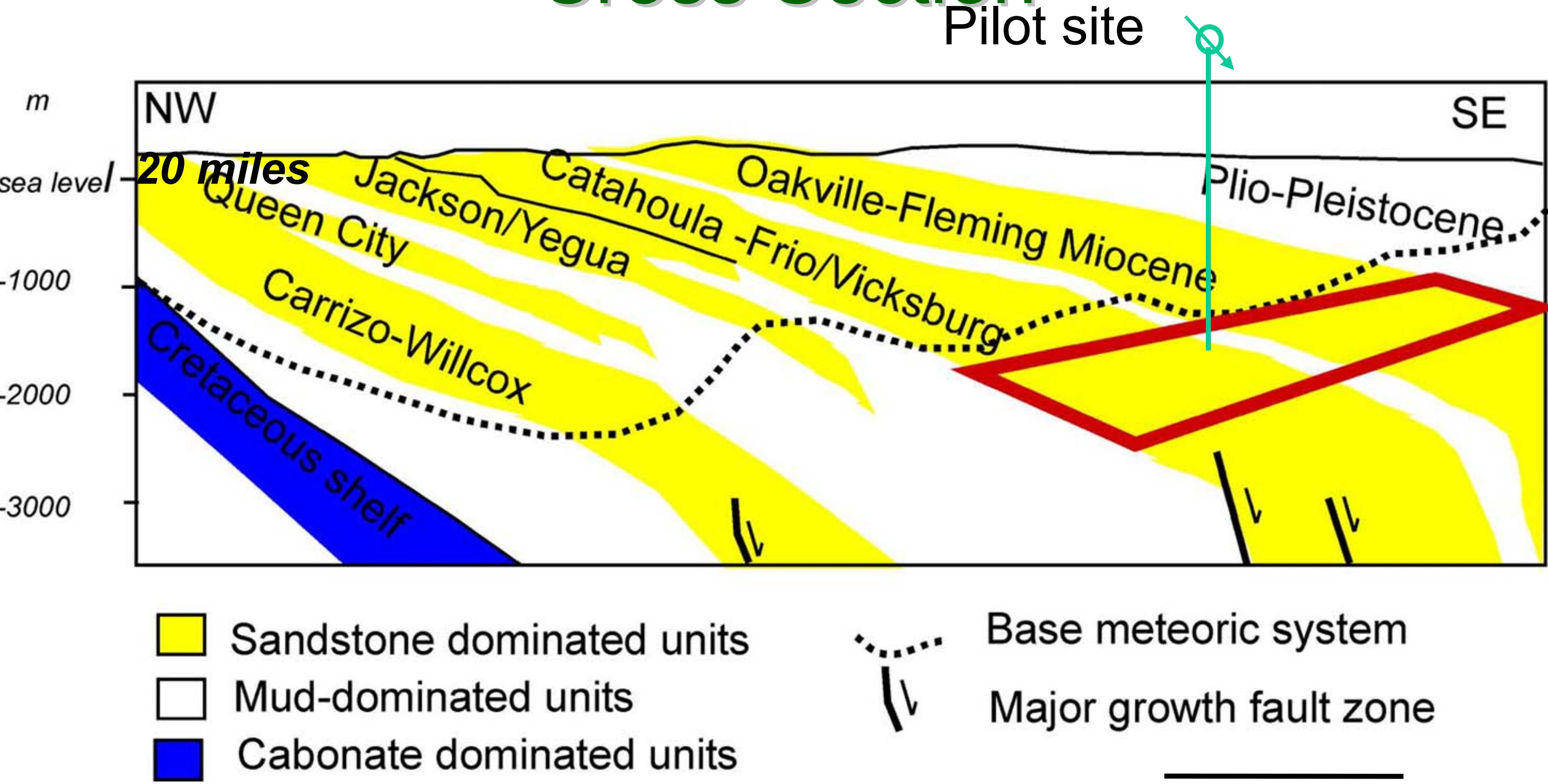
- Unique properties of CO_2
- Impacts away from injection well
- Slow, long term leakage back to atmosphere

Site Search



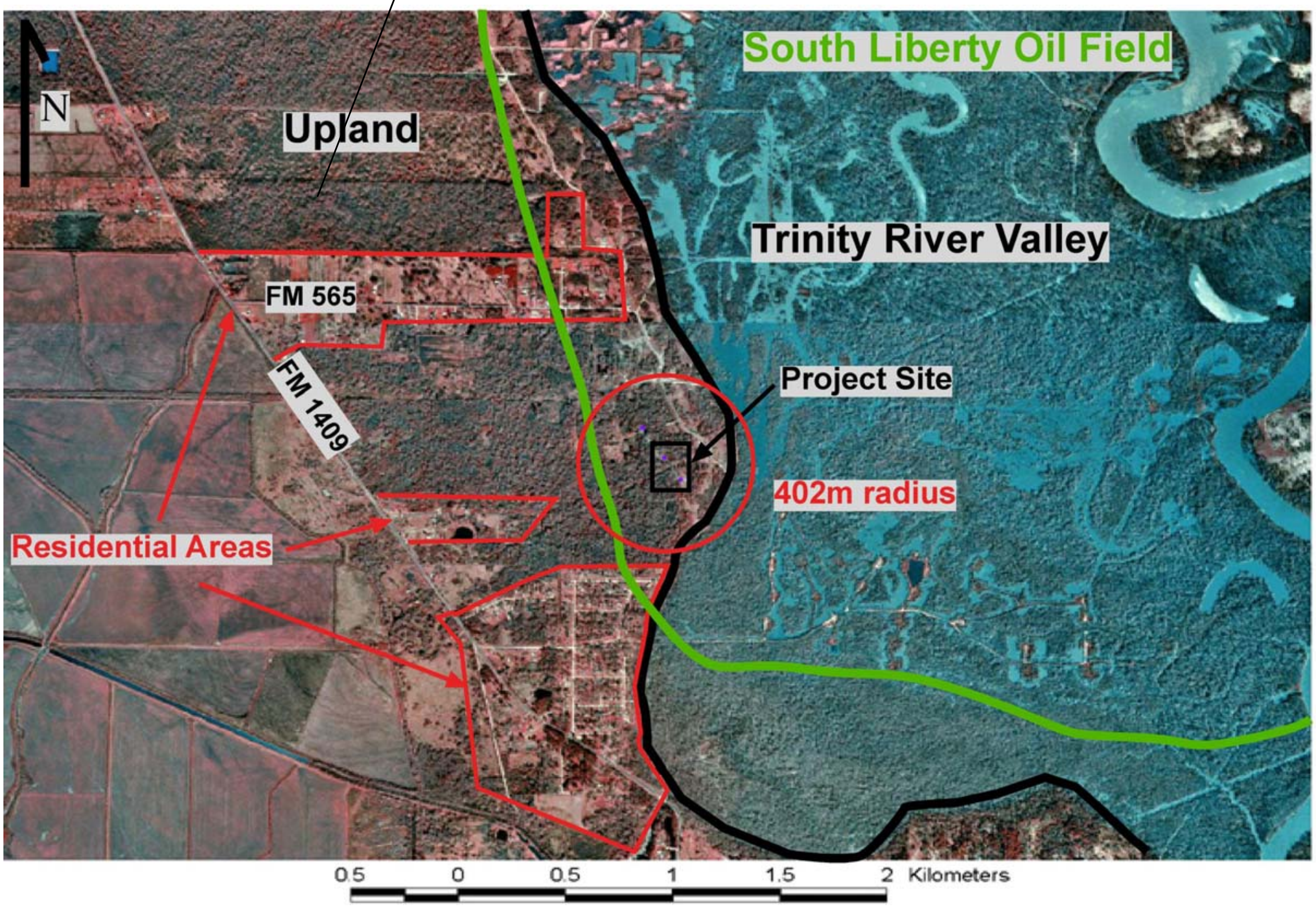
Sources: USGS, IEA Source database

Regional Geologic Setting – Cross Section

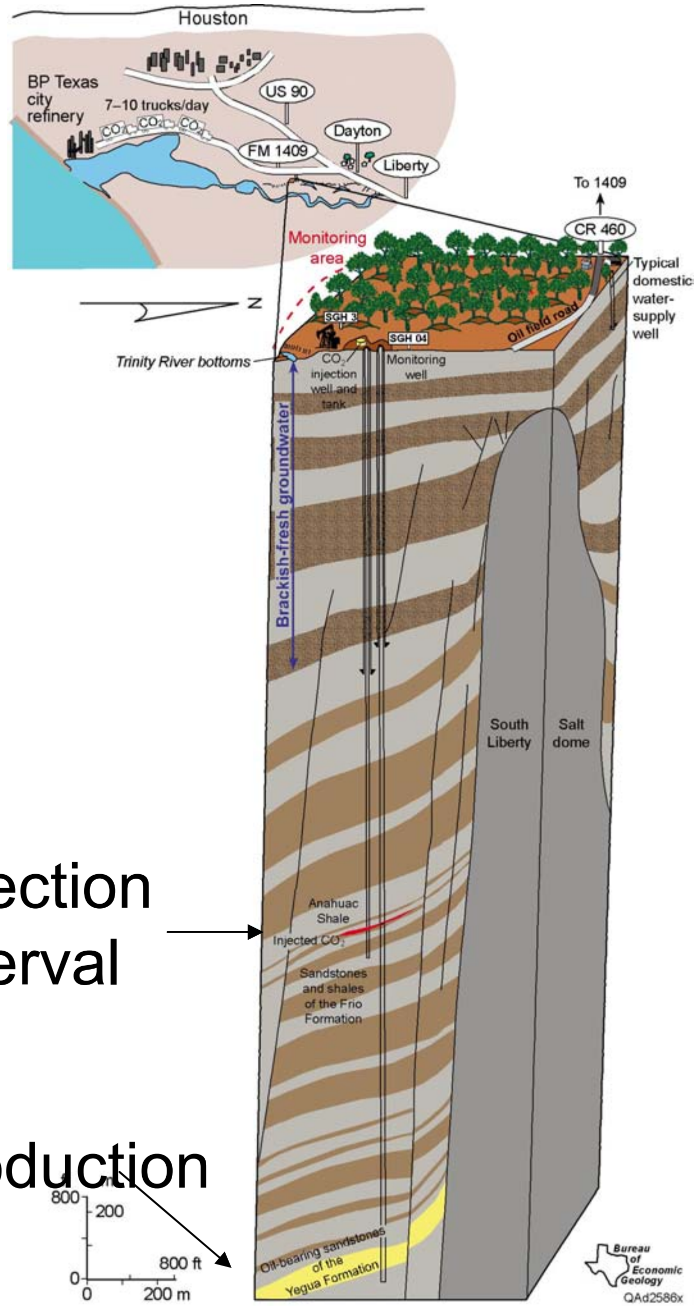


Modified from Galloway and others, 1982

Site Setting



Frio Brine Pilot



Injection interval

Oil production

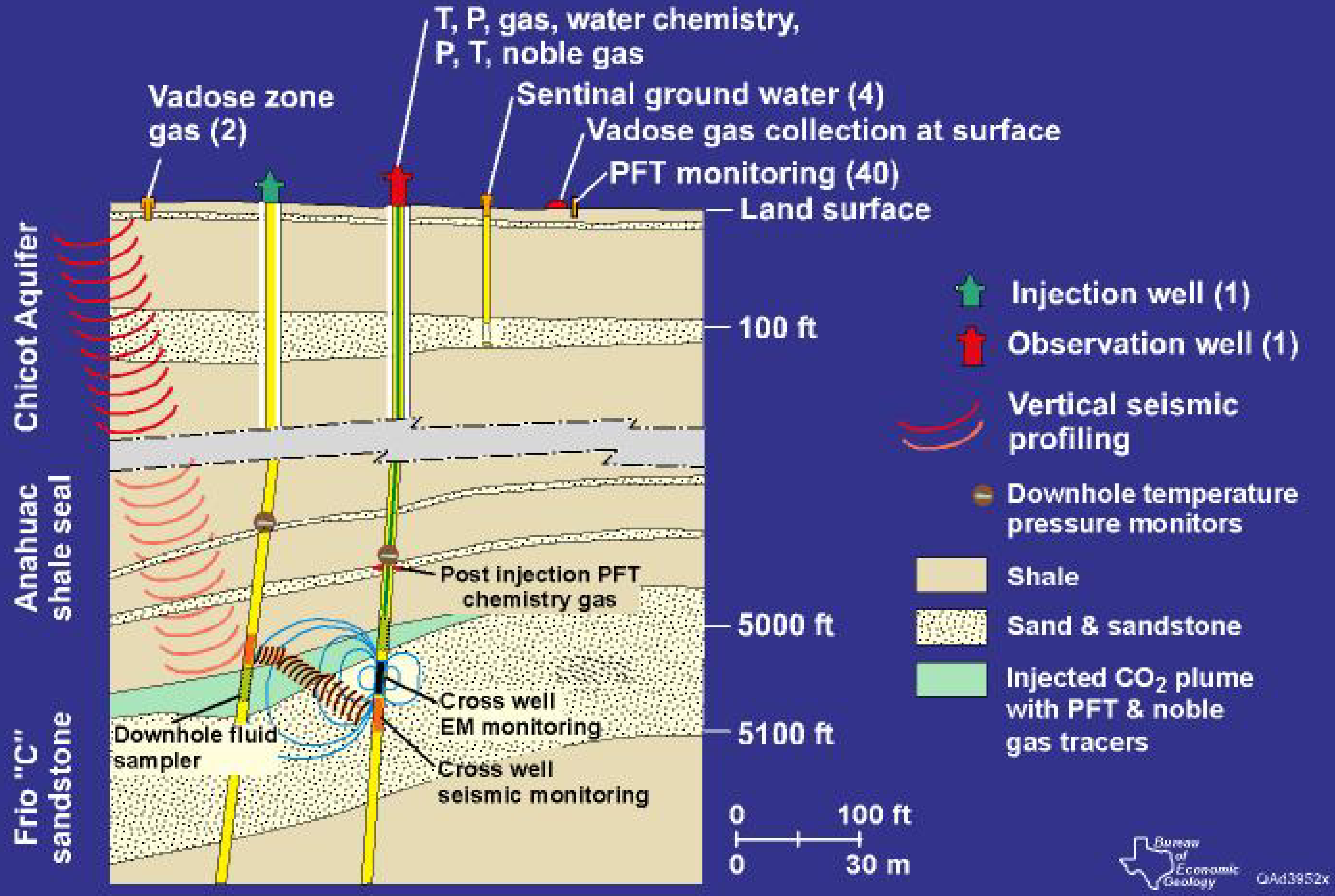
- Injection interval: 24-m-thick, mineralogically complex Oligocene reworked fluvial sandstone, porosity 30%, Permeability 1.5 Darcys
- 7m perforated zone
- Seals – numerous thick shales, small fault block
- Depth 1,500 m
- Brine-rock system, no hydrocarbons
- 150 bar, 53 degrees C, supercritical CO_2

Review of the Status of Frio Brine Pilot

1) site selection, with general characterization and scoping modeling;
(2) geologic characterization;
(3) modeling and experimental-design refinement;
(4) permitting;
(5) site preparation;
(6) detailed site characterization;
(7) baseline monitoring;
(8) injection and syninjection monitoring; 10/4-10/13
(9) postinjection monitoring: 10/14 to 3/05

Gulf Coast Carbon Center

MONITORING AND VERIFICATION TECHNOLOGIES AT FRIO BRINE PILOT SITE

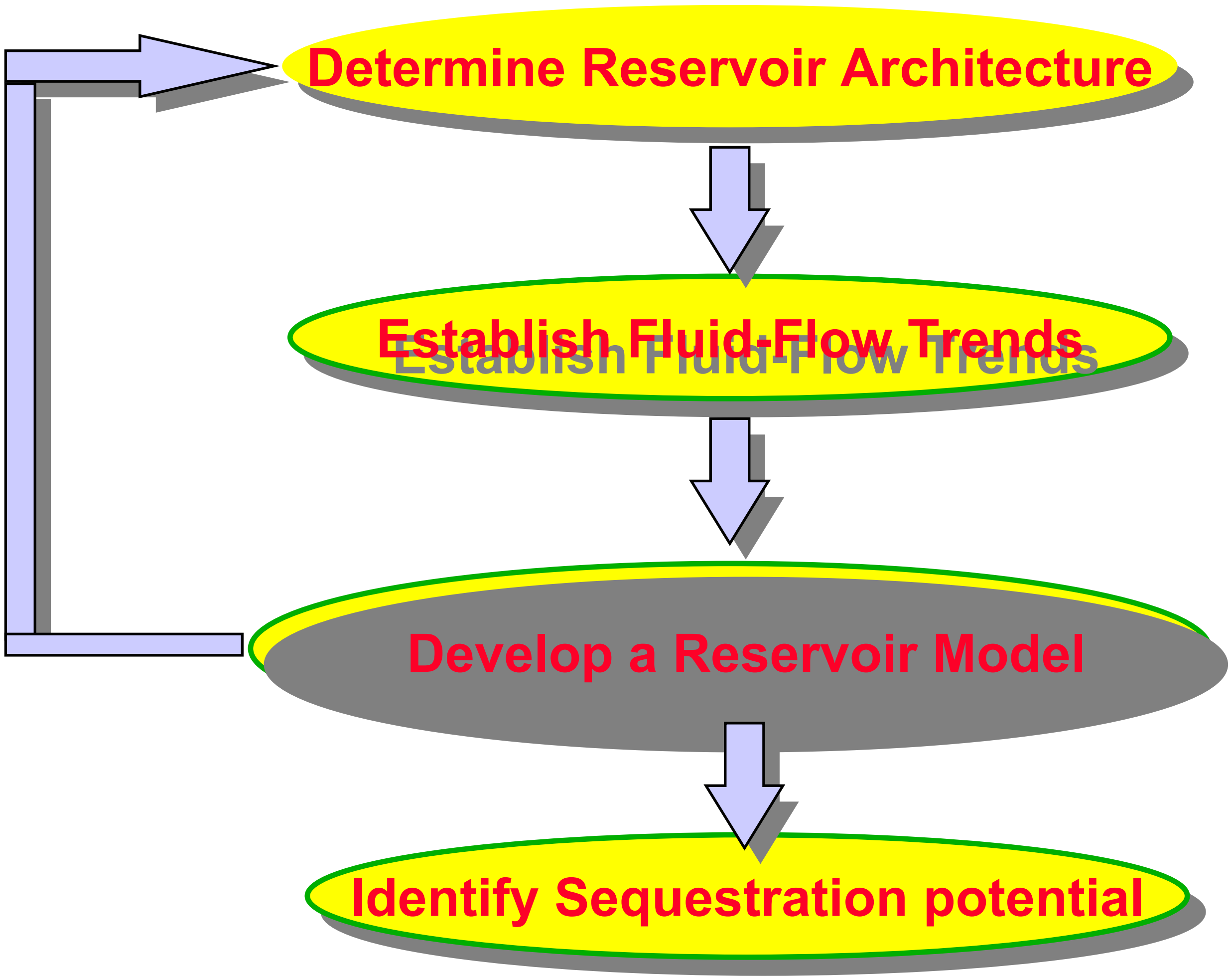


MMV Techniques used at Frio Brine Pilot

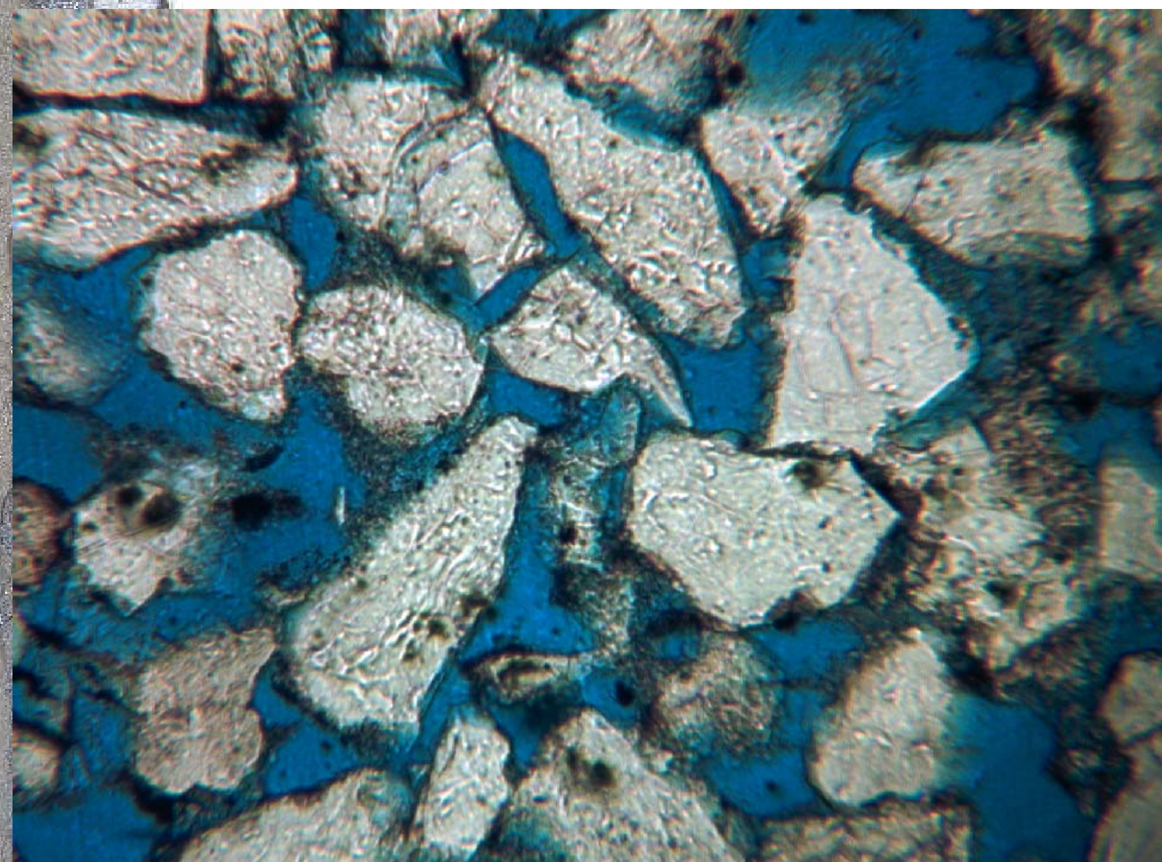
- Extensive preinjection characterization
  - 3-D seismic
  - Wireline logs of historic wells and new injection well
  - Core analysis
  - Hydrologic testing
- Extensive pre-injection modeling
- Down hole and surface P and T real-time readouts
- Brine and gas sampling for ph conductivity, alkalinity, major and minor ion chemistry, stable isotope chemistry
- RST logging for saturation
- Tracer injection and recovery – 6 PFTs noble gasses, SF_6
- Geophysics: cross-well seismic, cross-well, cased hole EM, and VSP
- Surface monitoring - PFTs, CO_2, methane
  - Groundwater
  - Vadose zone
  - Soil
  - Surface

Subsurface monitoring begins with proper characterization of the subsurface

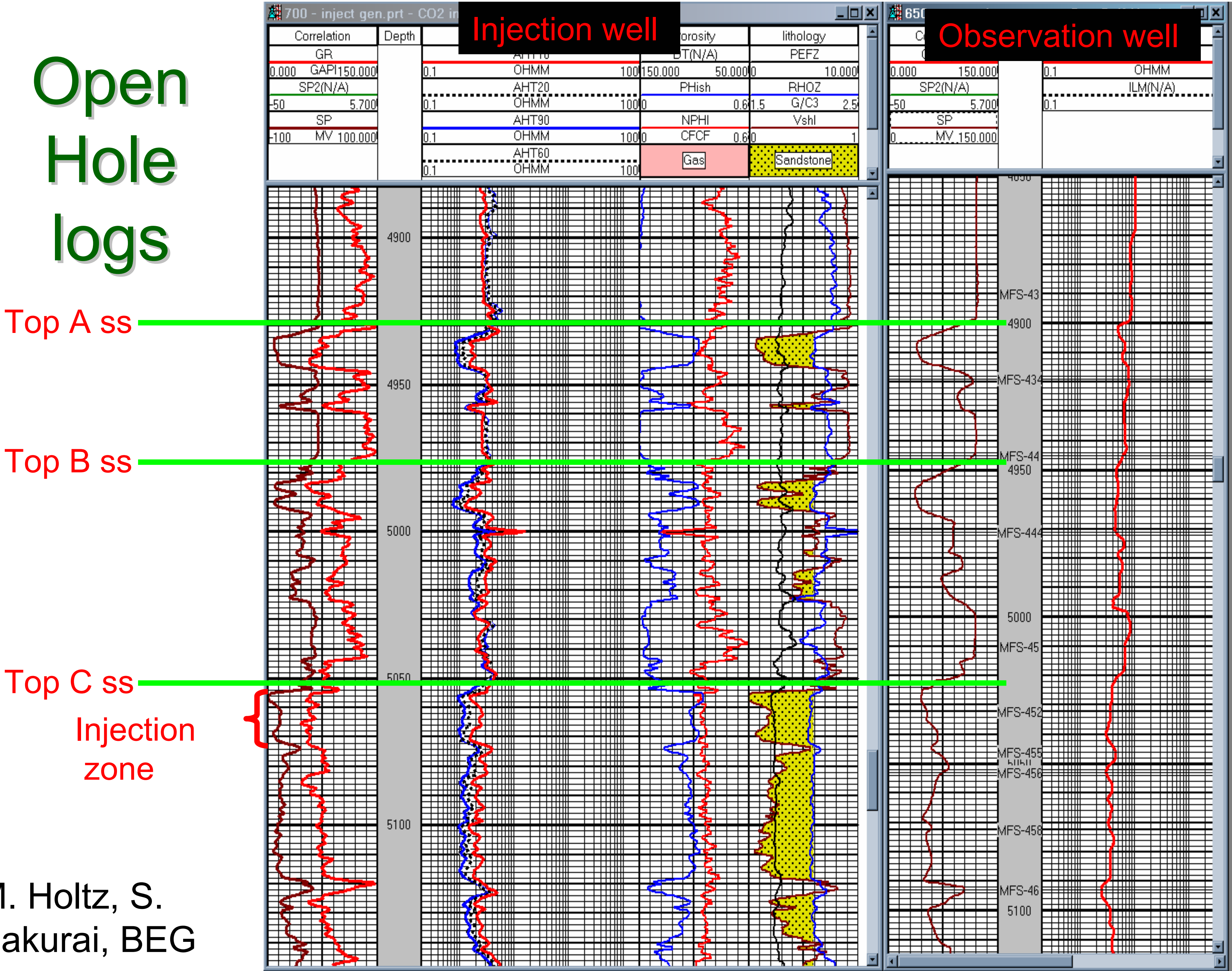
Reservoir Characterization Work Flow



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

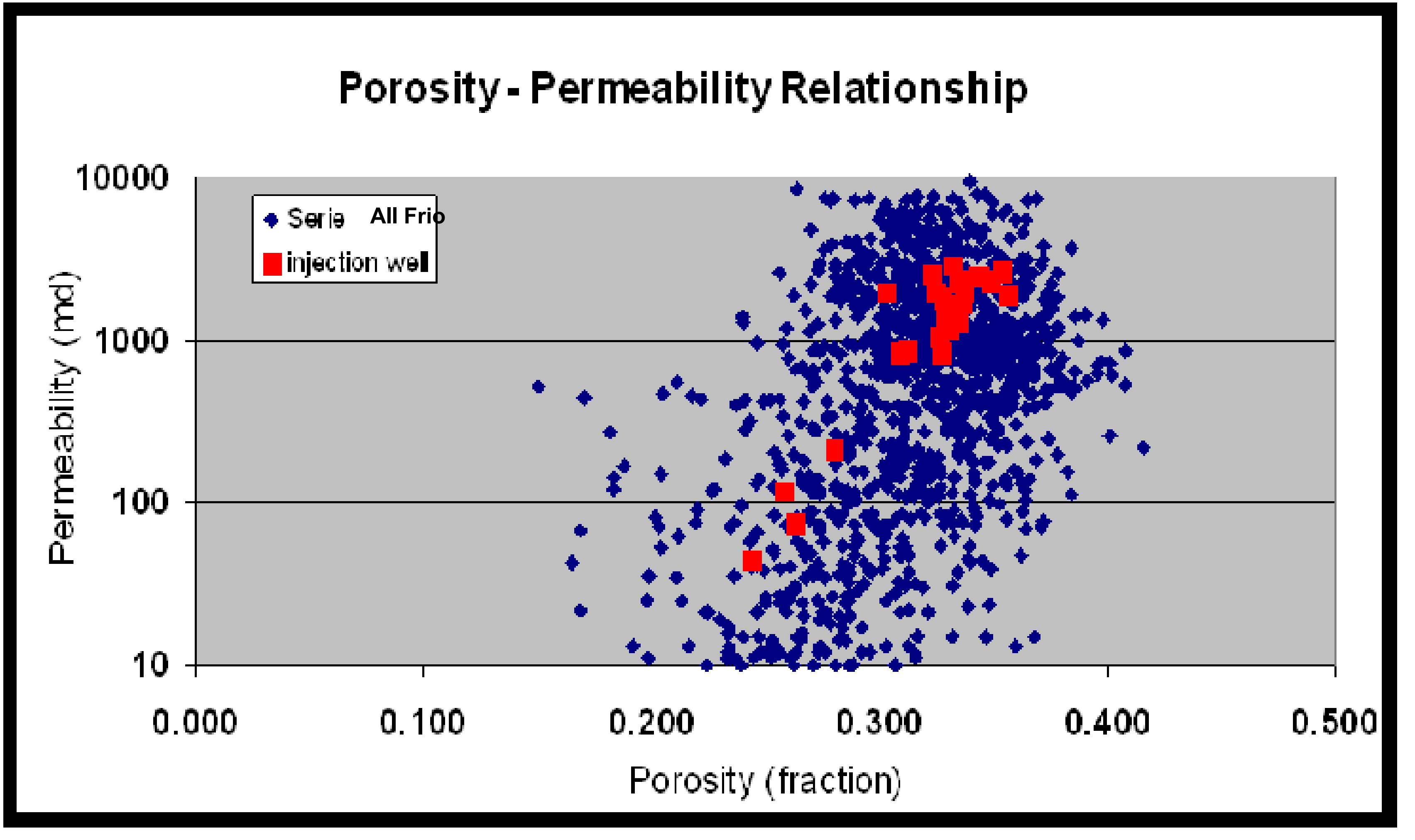


Open Hole logs



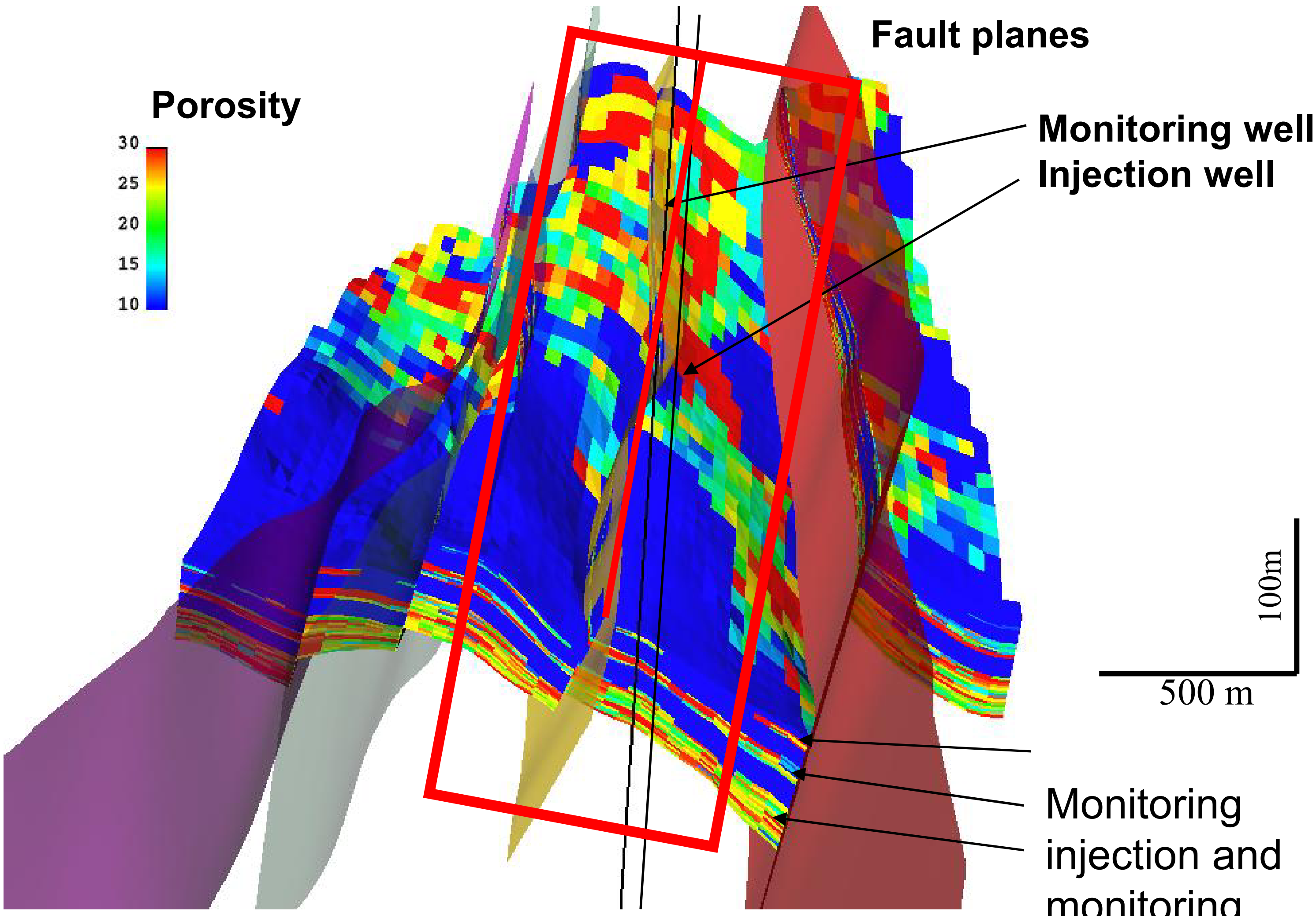
M. Holtz, S. Sakurai, BEG

Porosity vs. Permeability cross plot



M. Holtz, BEG

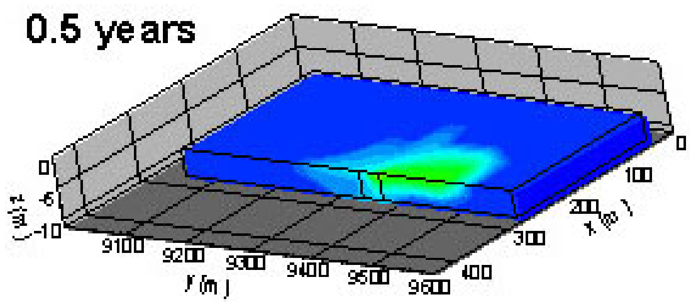
Reservoir Model



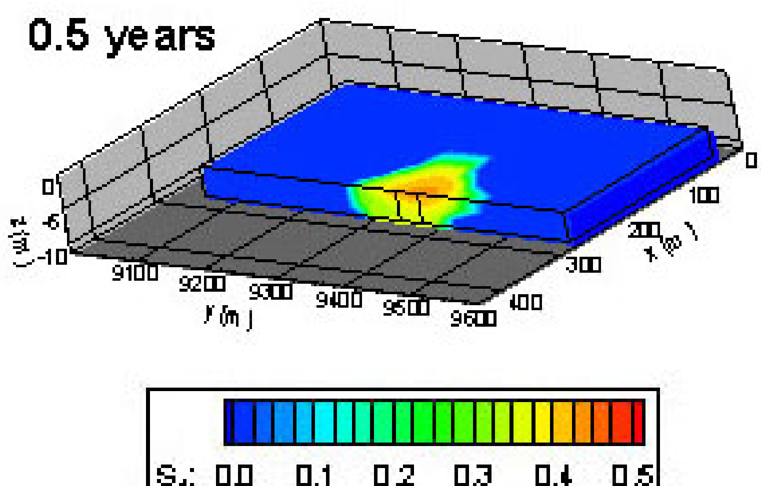
M. H. Holtz, P. K. Knox. J. S. Yeh, K. Faoud, BEG

How Modeling and Monitoring will Assess CO_2 Performance

Residual gas saturation of 5%



Residual gas saturation of 30%

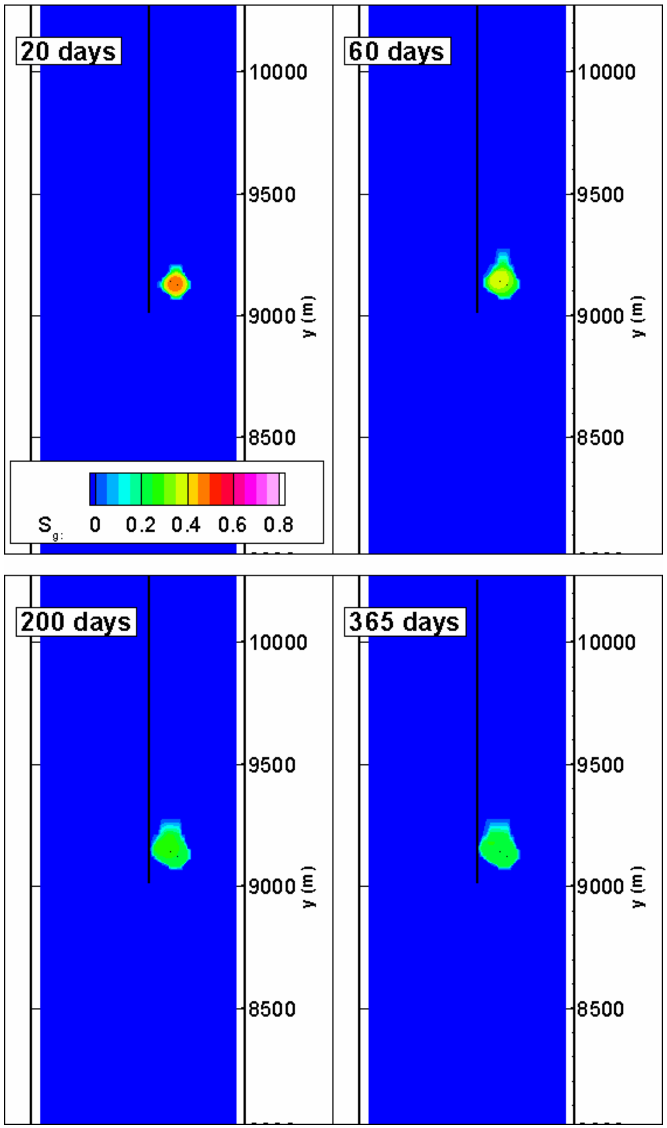


- Modeling has identified variables which appear to control CO_2 injection and post injection migration.
- Measurements made over a short time frame and small distance will confirm the correct value for these variables
- Better conceptualized and calibrated models will be used to develop larger scale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

TOUGH2 simulations

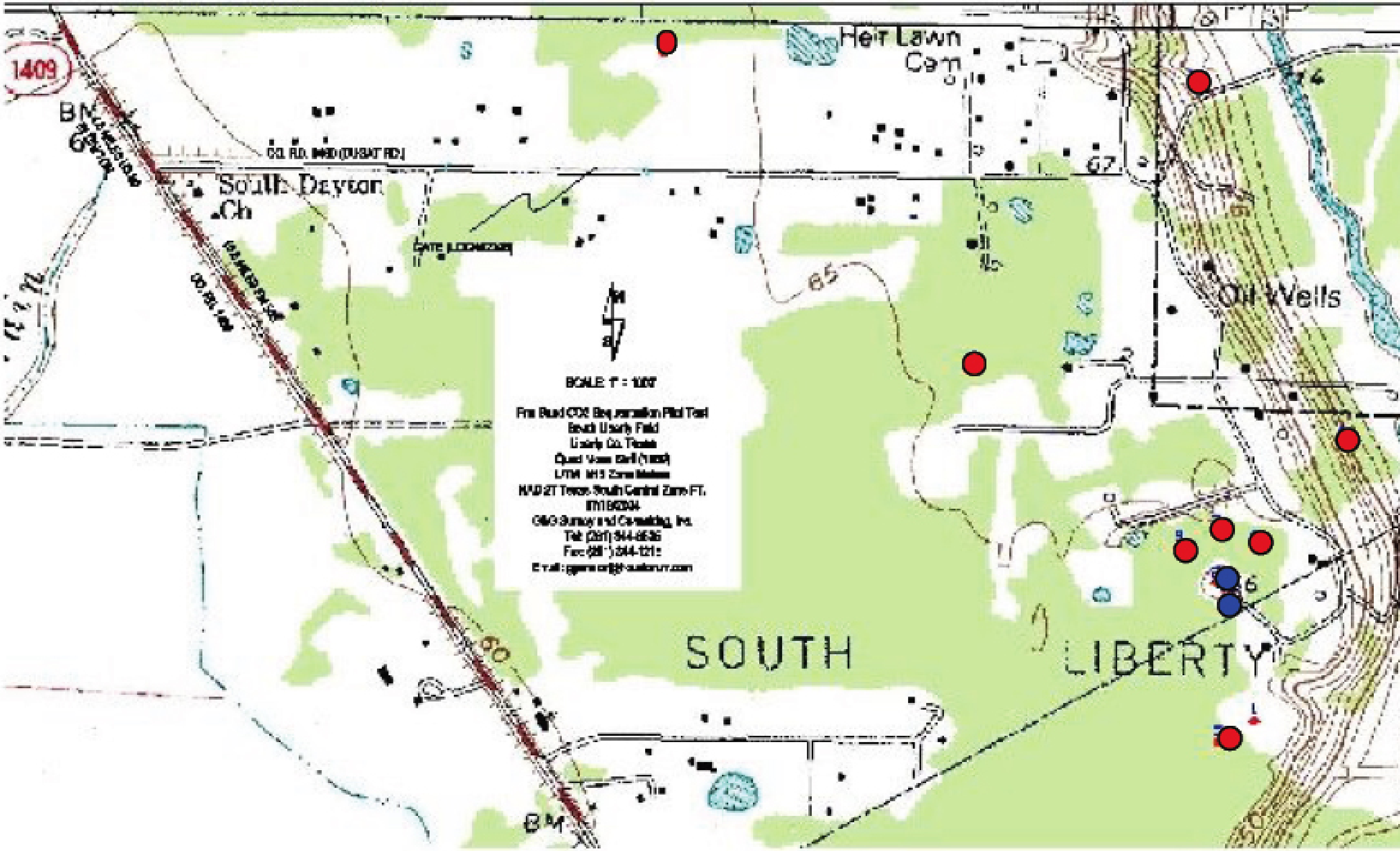
C. Doughty LBNL

Pre-injection Modeling using TOUGH2 for Experiment Design



Model assumptions: 250 tons over 12 days residual saturation 30%

C. Doughty, LBNL

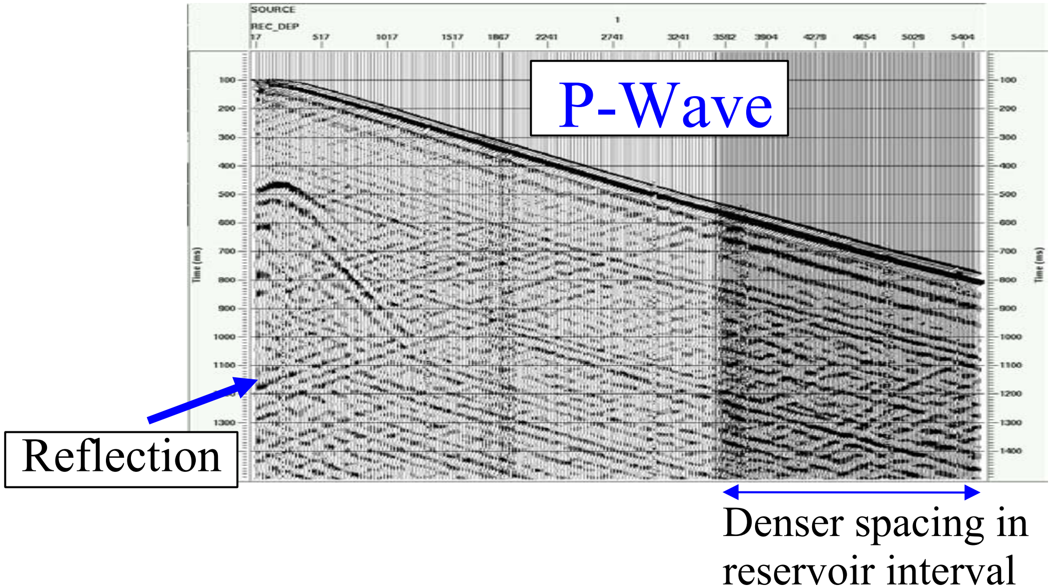


● Shot Point
● CO_2 Test Wells

Frio Pre-Injection Geophysics

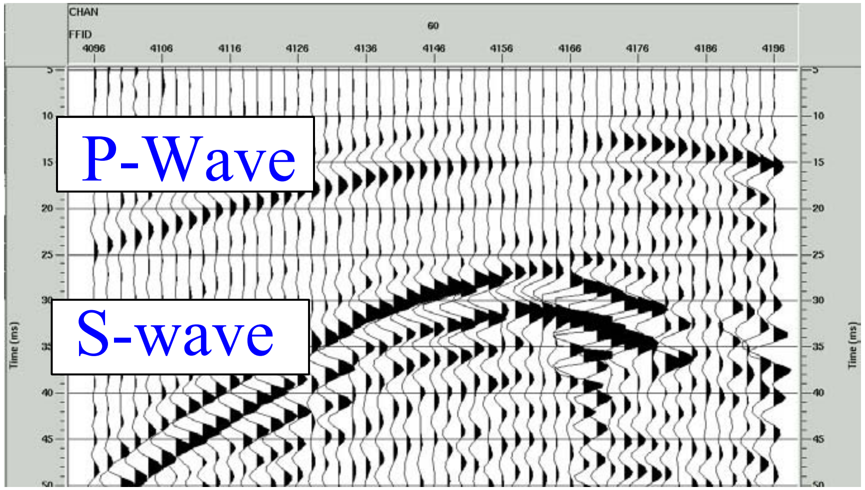
VSP

- Designed for monitoring and imaging
- 8 Explosive Shot Points (100 – 1500 m offsets)
- 80 – 240 3C Sensors (1.5 – 7.5 m spacing)



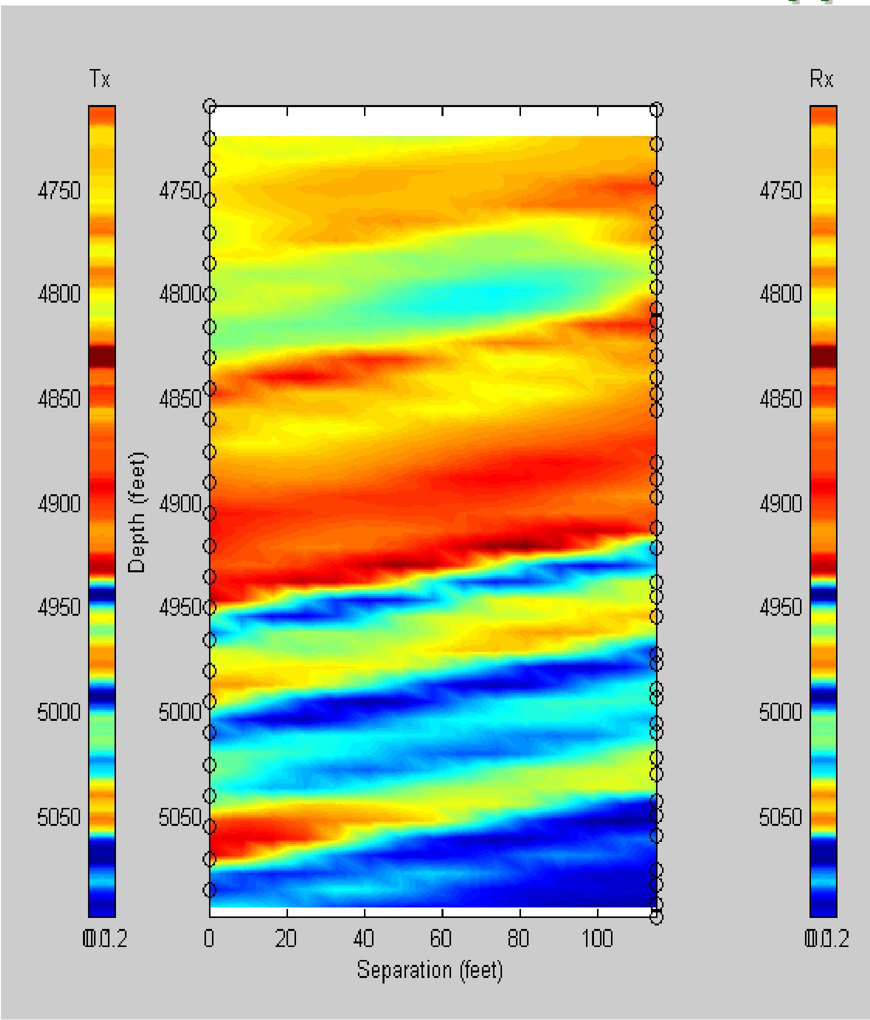
Cross Well

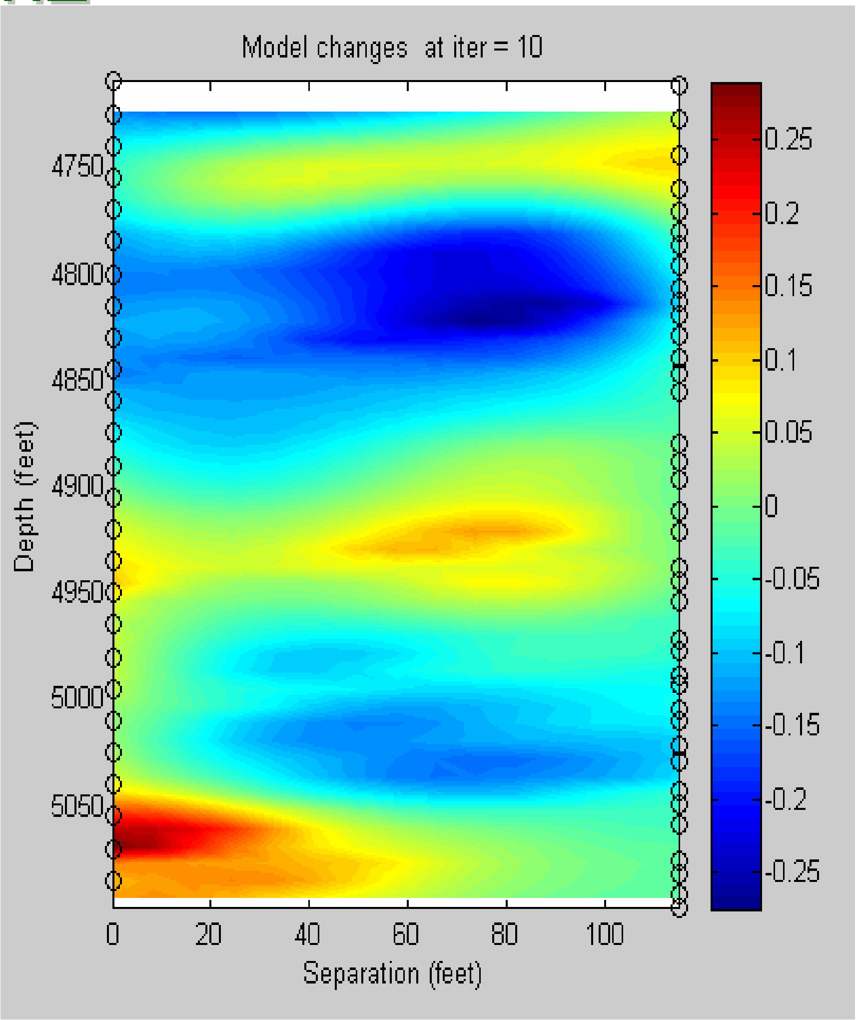
- Designed for monitoring and CO_2 saturation estimation
- P and S Seismic and EM
- > 75 m coverage @ 1.5 m Spacing (orbital-vibrator seismic source, 3C geophone sensor)
- Dual Frequency E.M.



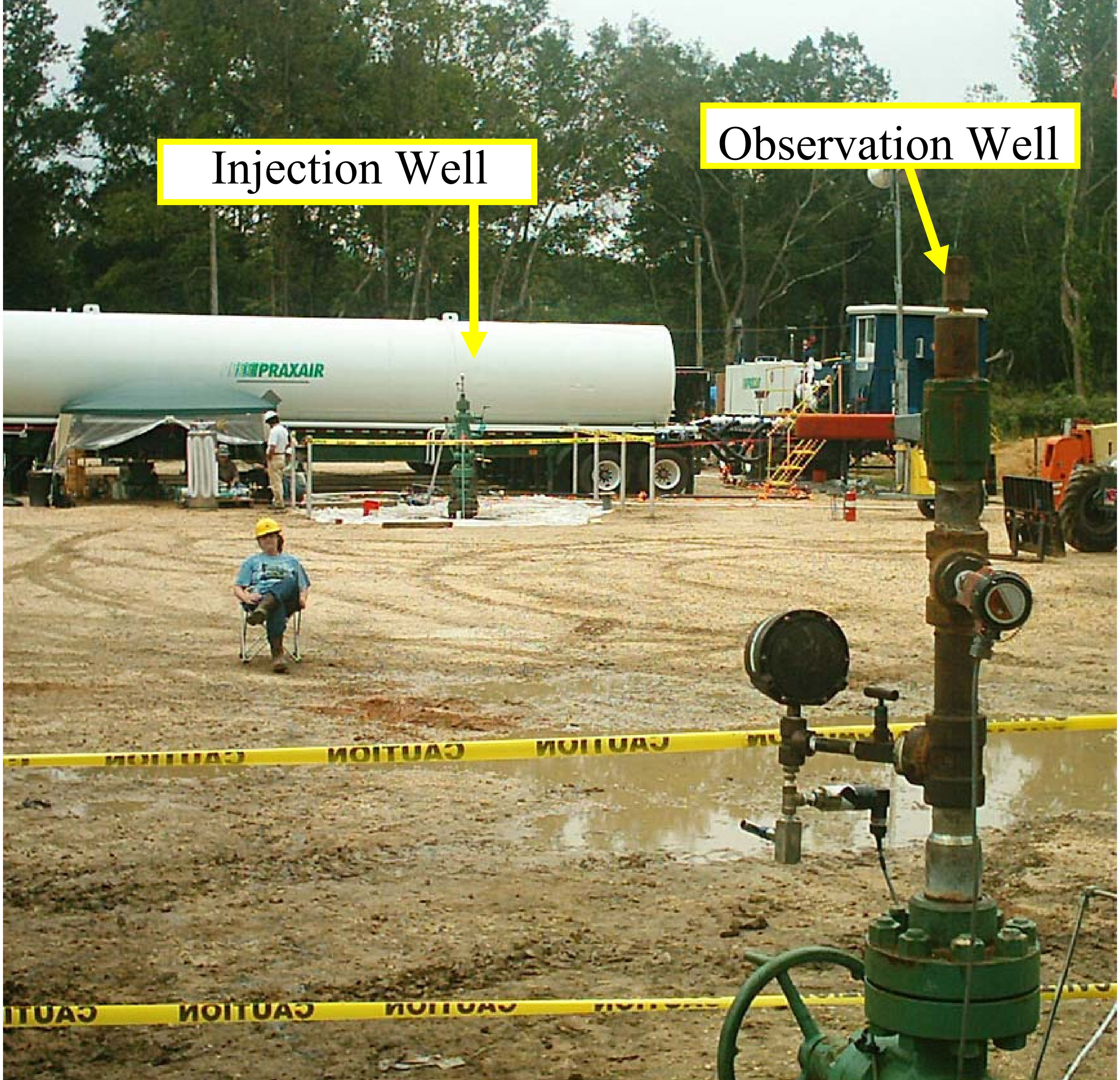
Tom Daley, LBNL: Paulsson Geophysical

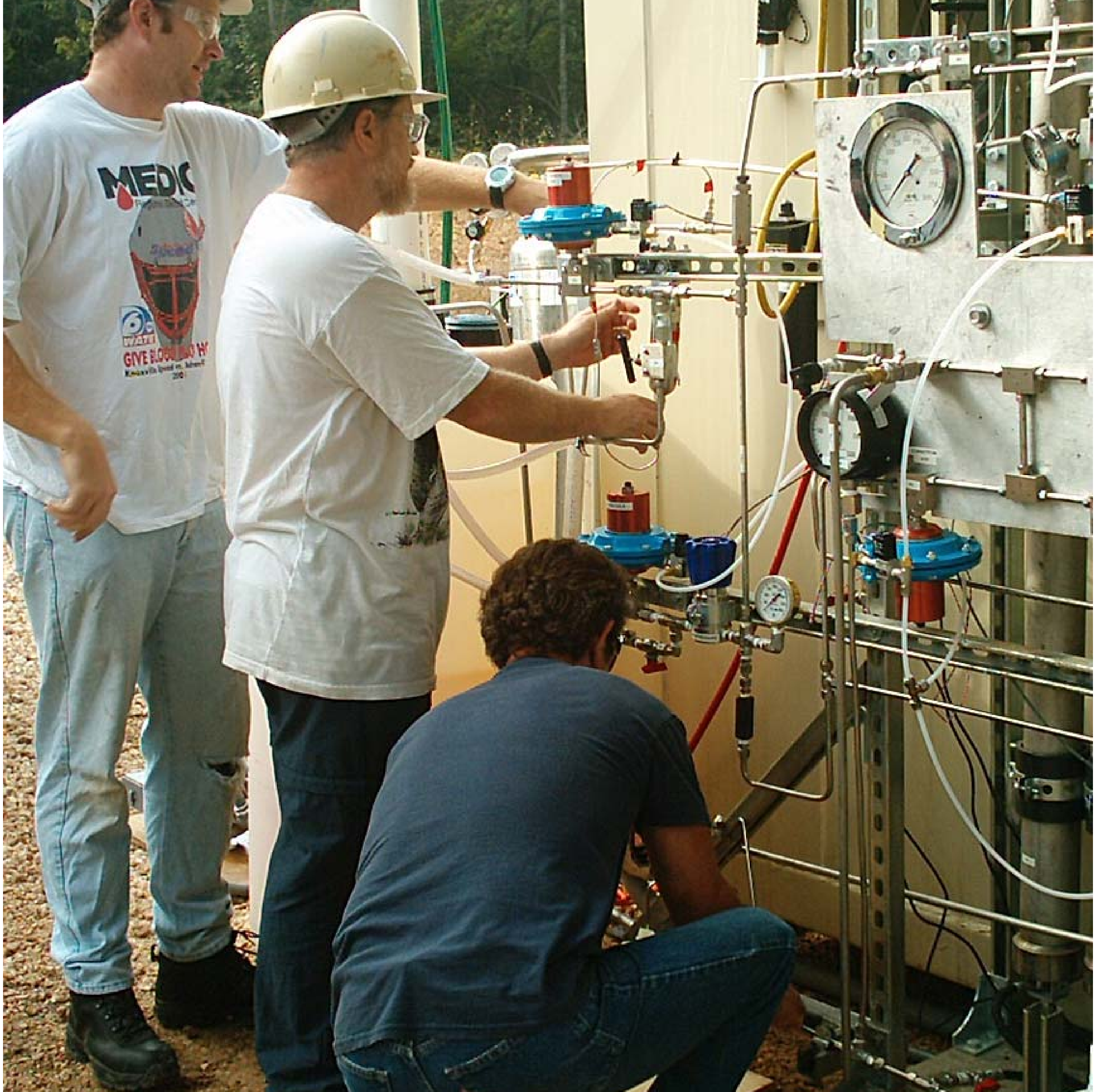
Pre-injection Cross-Well EM Inversion 47 hz



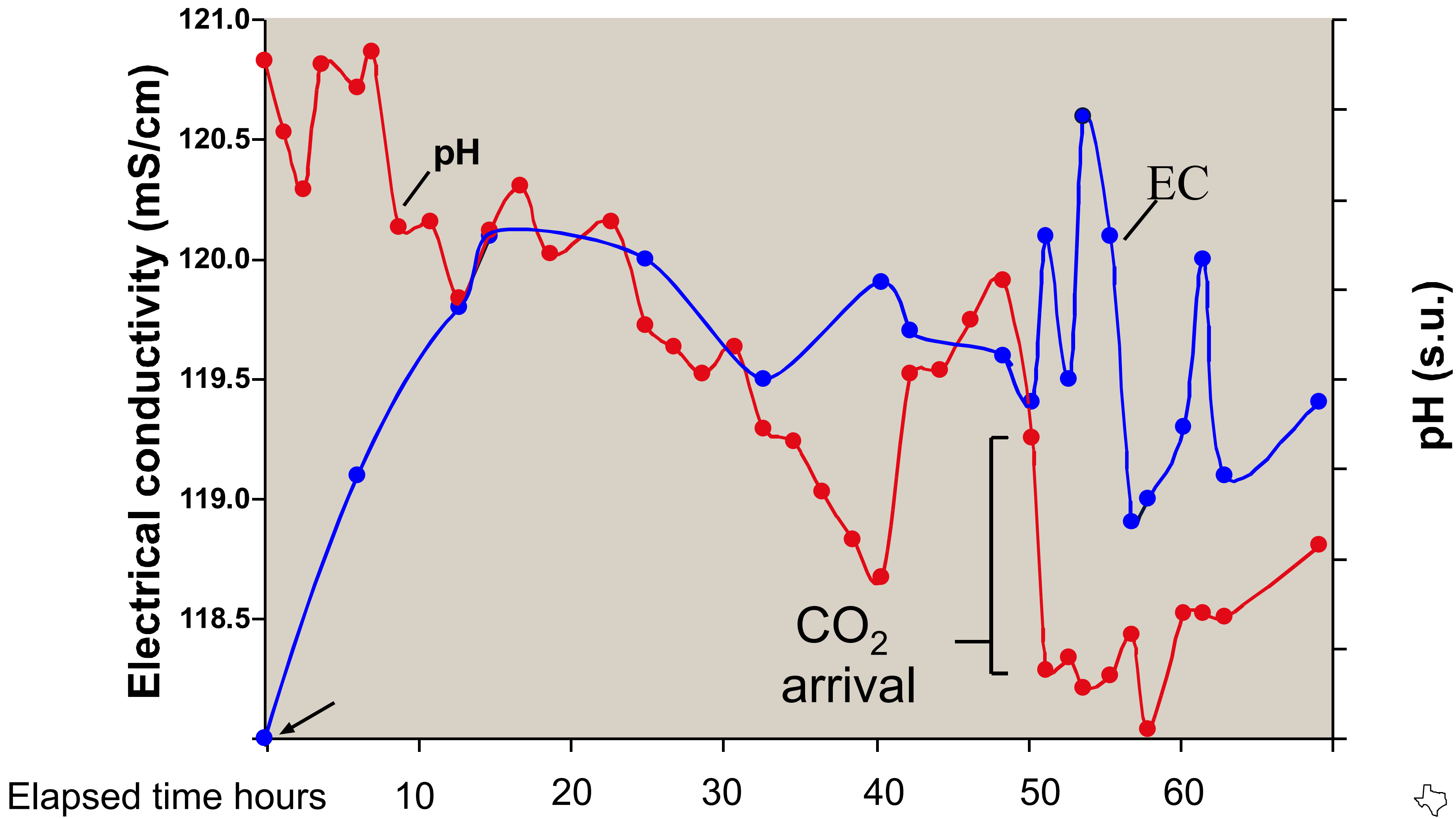


Mike Wilt, Schlumberger/EMI


Injection Well
Observation Well
PRAXAIR
CAUTION


MEDIC

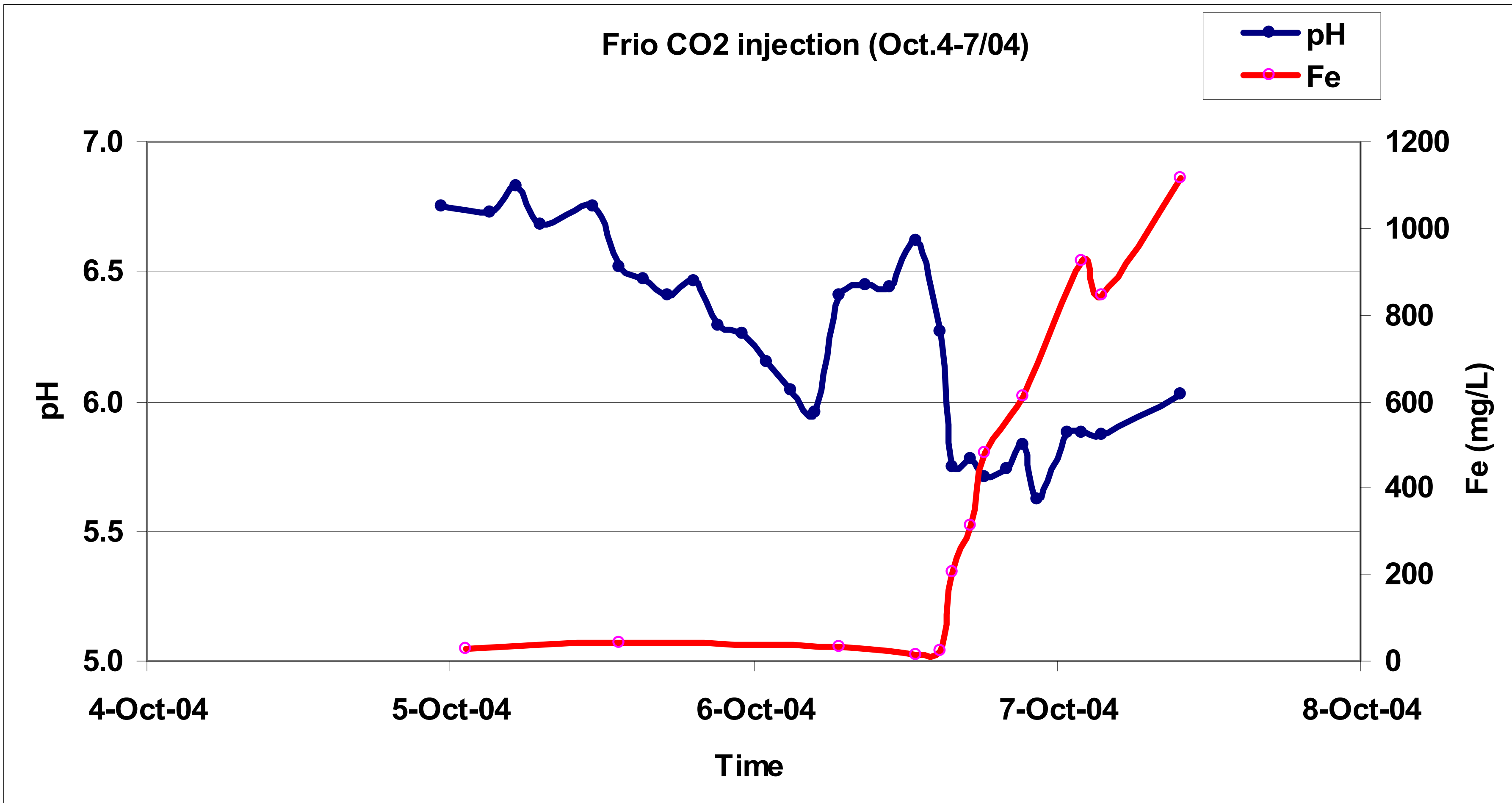
Electrical Conductivity and pH of Brine from Observation Well During CO_2 Injection



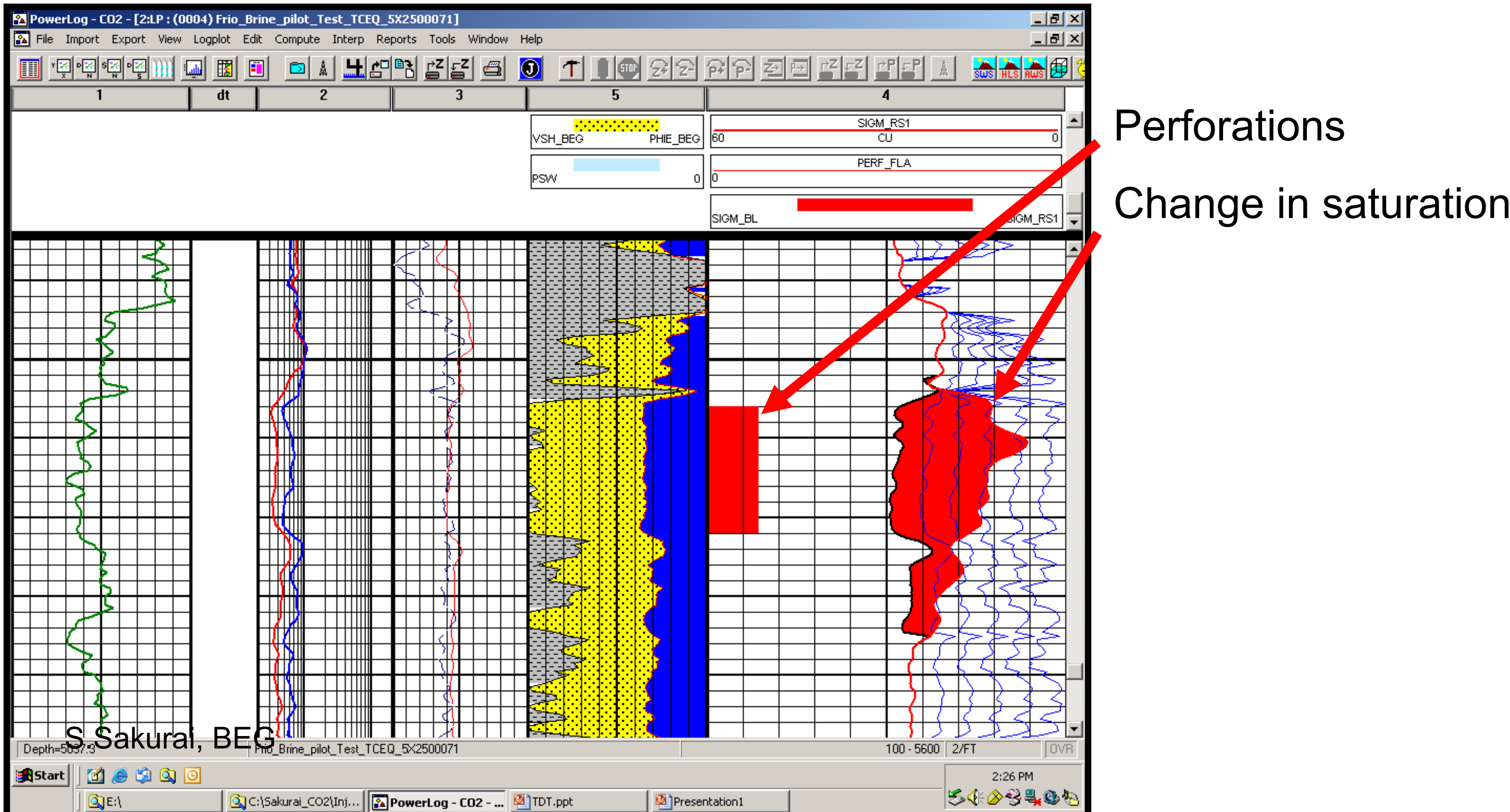
H. S. Nance, BEG


LCRA

Time-Series of Down-hole Sampling

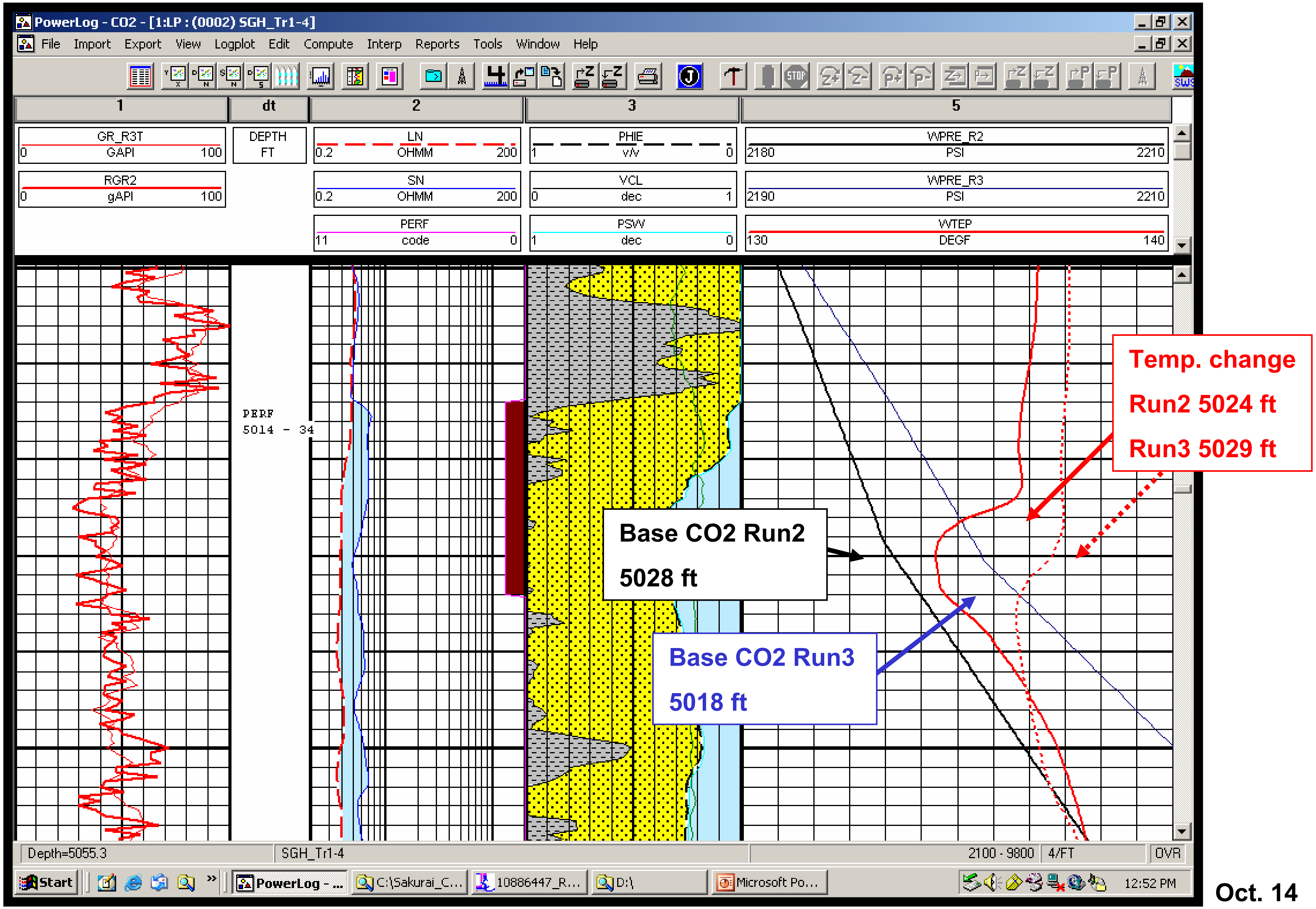


Injection Well
CO_2 Saturation Change Day 11
RST Run – Baseline from Density



S.Sakurai, BEG

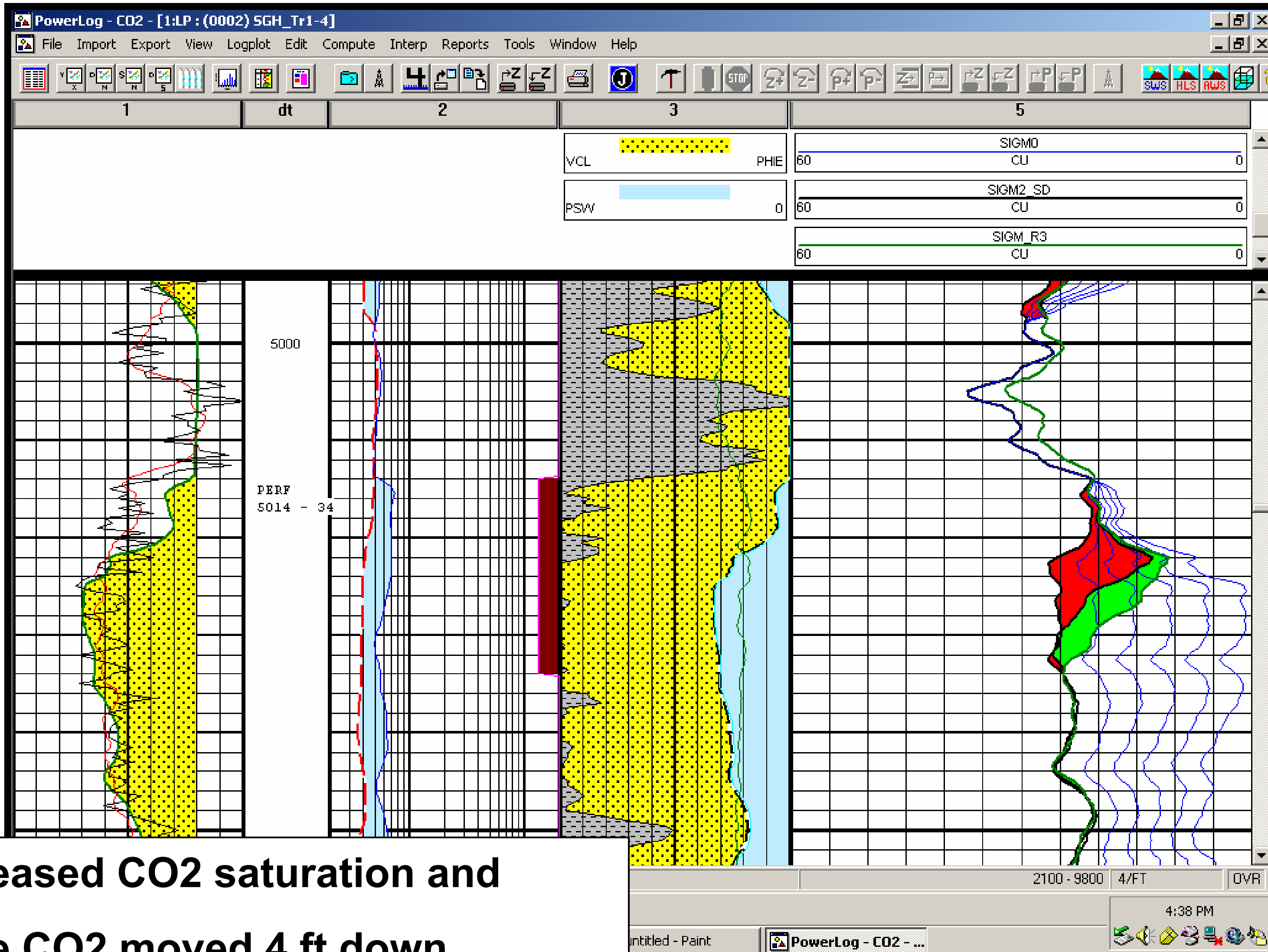
Pressure and Temperature Change During Injection, Observation Well



Oct. 14

CO2 Saturation Change

RST Runs – Baseline, Day 4 & Day 10



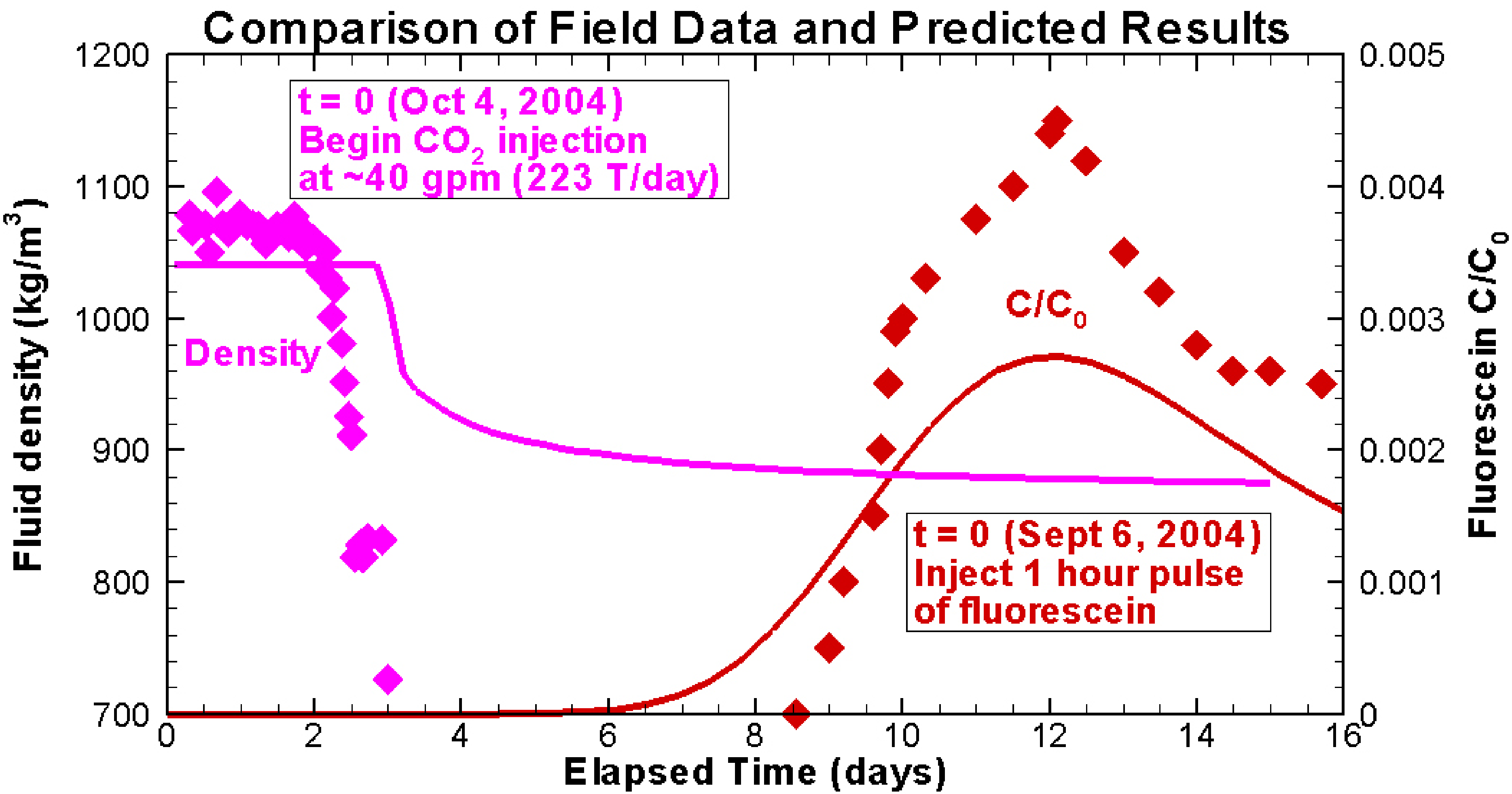
Increased CO2 saturation and

Base CO2 moved 4 ft down

S. Sakurai, BEG

Oct. 14

Single Phase and Two Phase Tracers



B. Freifeld and R. Trautz, LBNL

Experiments not done at Frio

Experiment	why not done?
Large volume of CO_2	Risk, $
Interaction with faults	Risk, complex, premature
4-D survey	Problematic, $
Observation well array in zone	$
Tilt	Problematic, $
Microseismic array	Problematic,$
WAG	Interference
EOR	interference
EGR	interference
Streaming potential	$
Ecosystem impact survey	Problematic, $
Massive pre-project PR	Problematic
Legal system test case	Problematic
During experiment pressure monitoring in overlying brine aquifers, fresh aquifers	Interference
Ecosystem CO_2 flux towers	Problematic, $
Surface CO_2 monitoring with lasers	Problematic, $
Airborne/ satellite monitoring	Problematic
Dealing with dissolved methane	no plan
Exhaustive logging	Problematic, $
Other edgy down hole monitoring (e.g. non-conductive wells)	$
Long-term monitoring	problematic, $
Pipeline issues	premature
Complex gas injection	interference
Inject low, recover high	$
Well integrity, special cement	premature
Long-term geochemistry	$

Problematic = estimated to be unlikely to collect useful measurements at scale, duration, site specific conditions

Interference = interferes with success of another experiment

$ = cost prohibitive in total project context. Might be used in a larger budget project

Conclusions

- Success!
- CO_2 introduced into well-characterized relatively homogenous high permeability sandstone system
- Saturation and transport properties measured horizontally, vertically, and through time
- Geophysical analysis to come this month
- Surface monitoring underway
- Improved model conceptual and numerical inputs
- Vigorous public/industry outreach
- Results posted: www.gulfcoastcarbon.org

Monitoring Network

Presentations

- Hosted on IEA GHG web site
  - www.co2captureandstorage.info
  - Listed under Technical Workshops
  - Notify you when available
- Key points from meeting
- Detailed report later
- If not pre-registered please leave business card to ensure you get details

Monitoring Network

Next technical meeting

- October 2005
- Venue Europe?
- Contact delegates in June to identify new developments
- Announcement in August

MONITORING WORK SHOP
November 9, 2004

TRACER RESULTS FROM THE WEST PEARL QUEEN FIELD PILOT SEQUESTRATION SITE

NETL: Arthur Wells, J. Rodney Diehl, Thomas H. Wilson
Grant Bromhal, Curt White

TECHNICAL APPROACH

GEOPHYSICAL SURVEY: (Professor Thomas Wilson, WVU)

- **Provide Evaluation of Monitoring Sites**
- **Remote Sensing for Lineaments and Geologic Features: Satellite Radar and Imaging, and Optical Aerial Photography**
- **Ground Based Measurements: Ground Conductivity Measurements, and Ground Penetrating Radar**

CARBON DIOXIDE TRACERS

Added 3 Different Tracers at the Well Head as 3 12-Hour Slugs, about a Week Apart

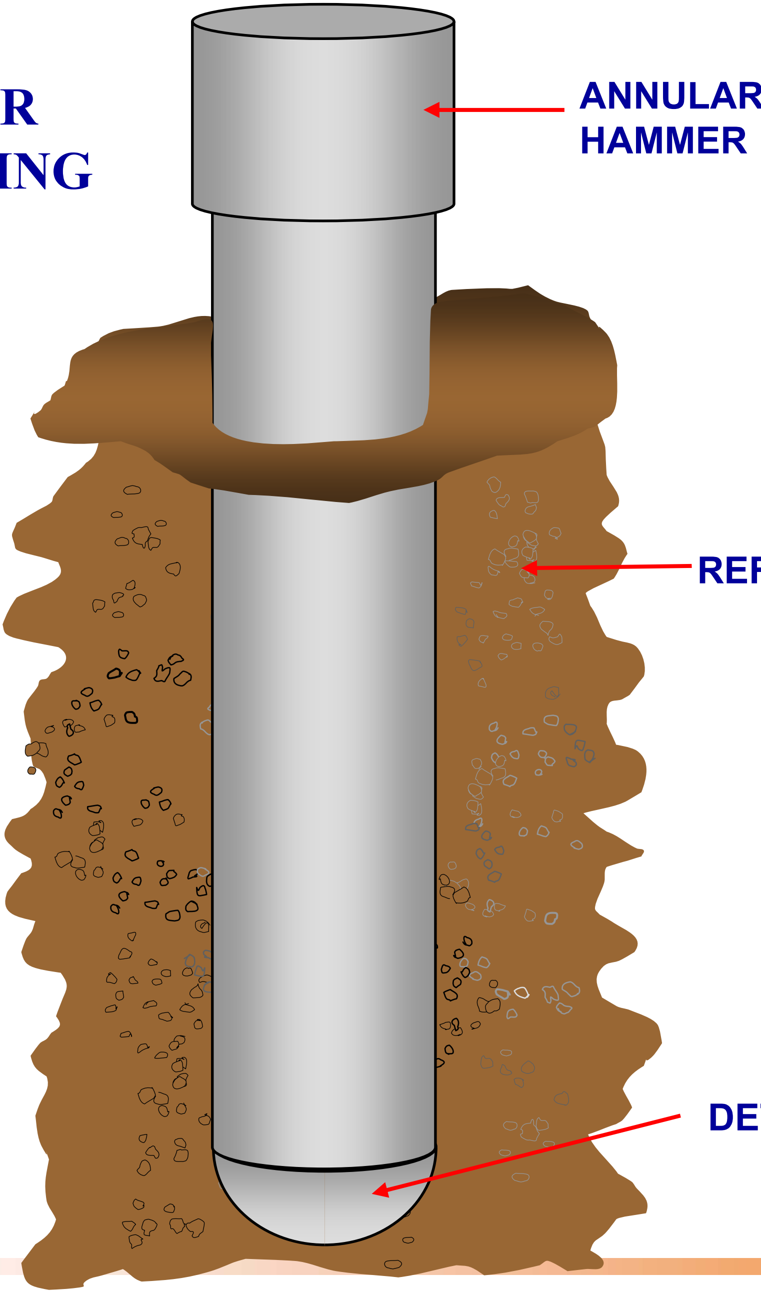
- **Soil Monitoring with Adsorbent Packets (CATS) Placed in Monitoring Pipes in a Matrix around the Injection Well**

TRACERS USED AT WPQ

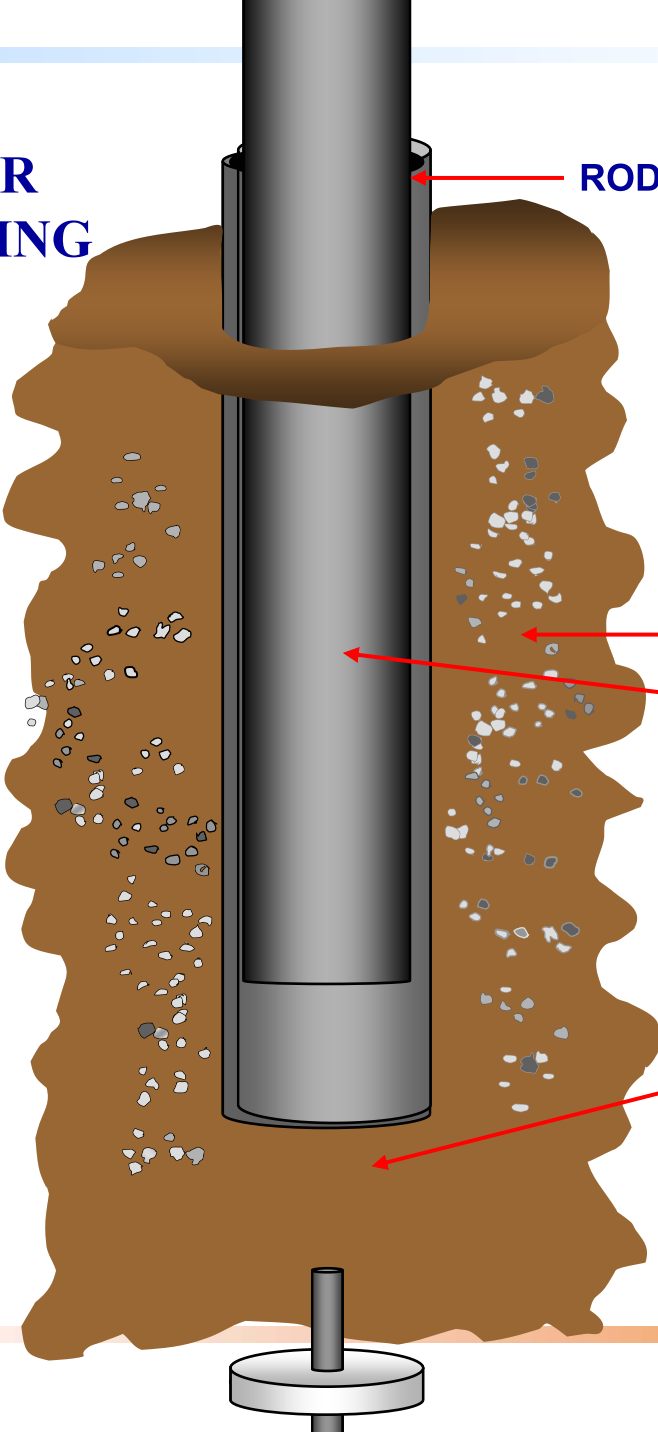
PFTs	Mol. Wt.	Abbreviations
Perfluoro-Trimethylcyclohexane	450	PTCH
Perfluoro-1,2-Dimethylcyclohexane	400	PDCH
Perfluoro-Dimethylcyclobutane	300	PDCB

- Completely Miscible with Carbon Dioxide
- Non-Toxic
- Non-Flammable
- Non-Explosive
- Non-Radioactive
- Non-Corrosive
- Detection Limits of 10 Parts per Quadrillion in Soil-Gas or Air

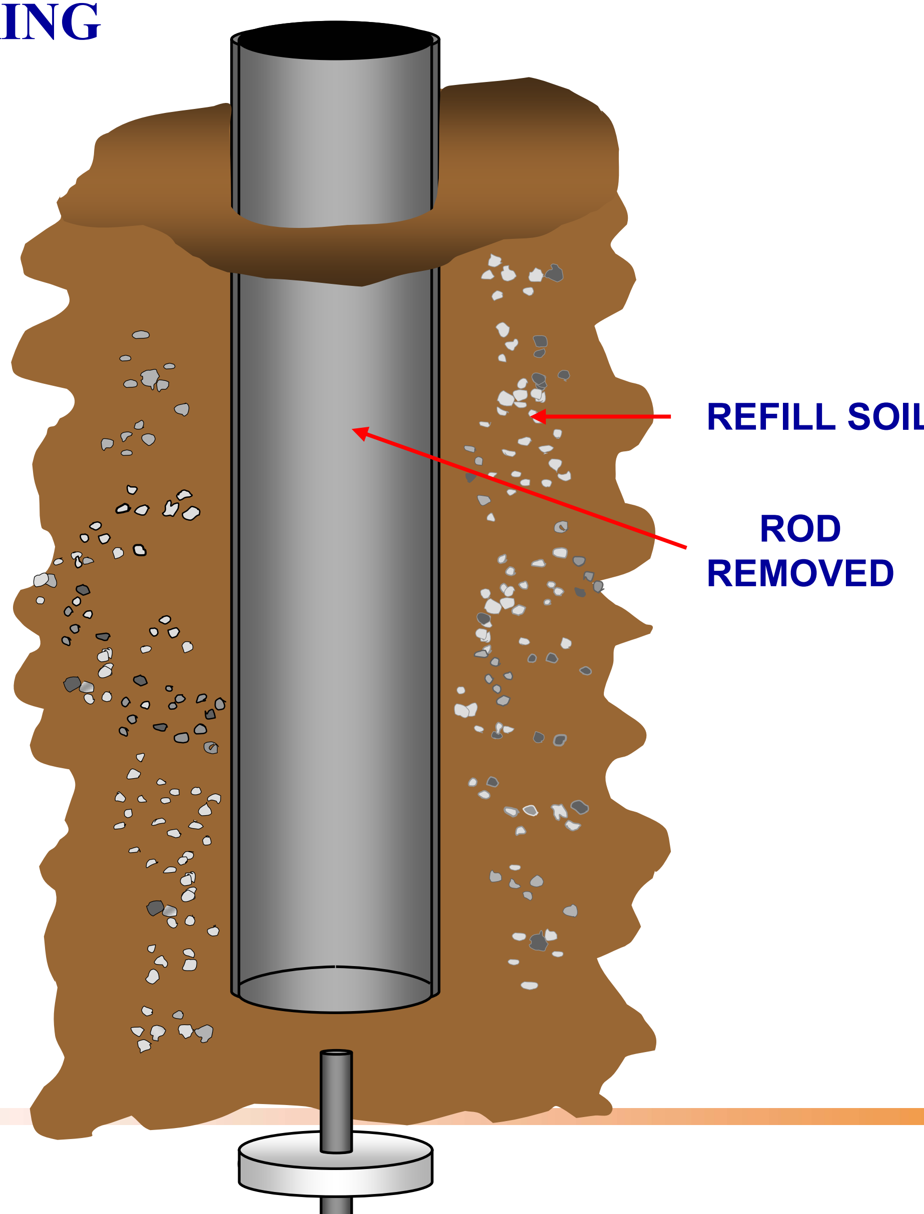
DETACHABLE HEAD PENETROMETER FOR SOIL-GAS MONITORING



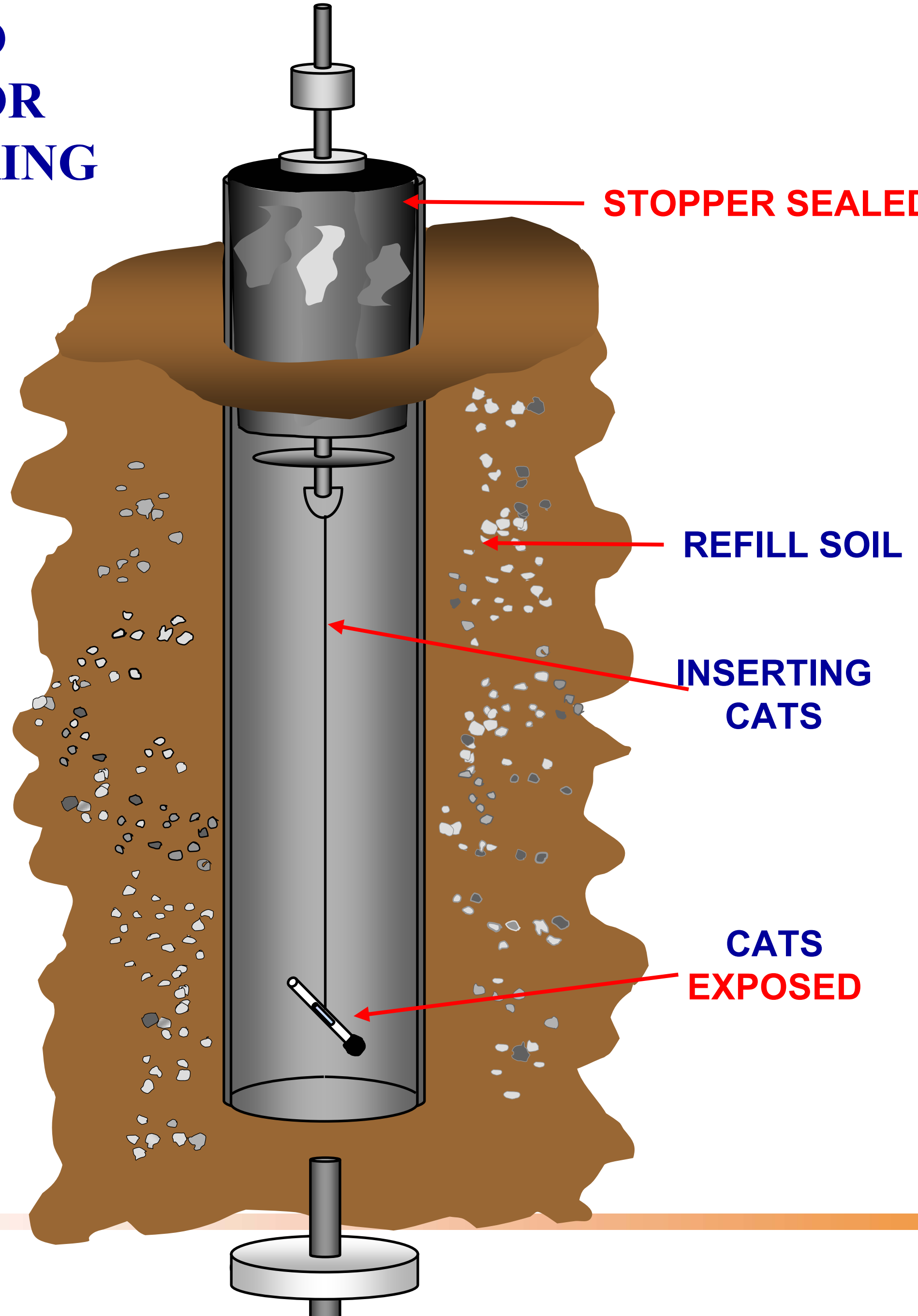
DETACHABLE HEAD PENETROMETER FOR SOIL-GAS MONITORING



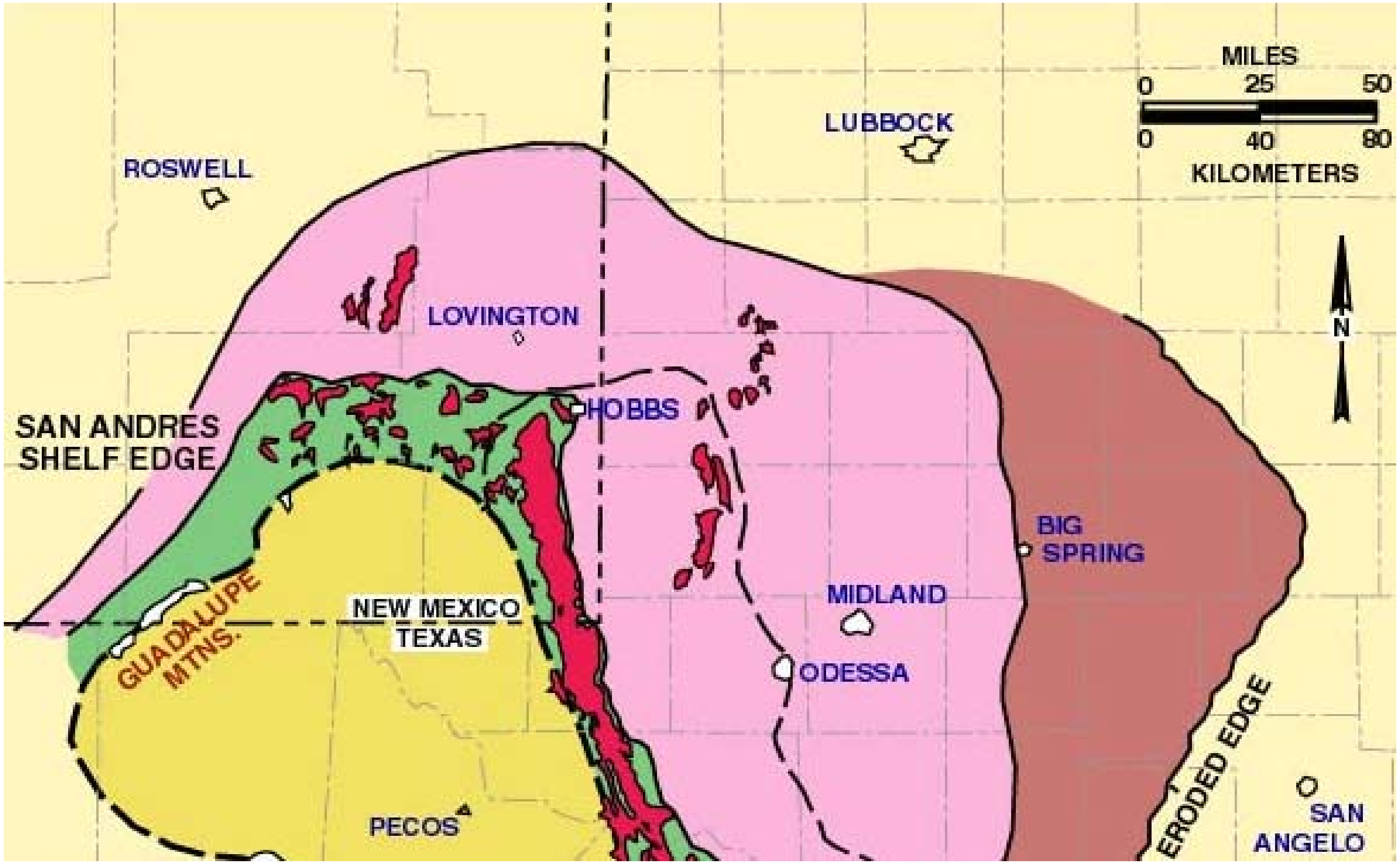
DETACHABLE HEAD PENETROMETER FOR SOIL-GAS MONITORING



DETACHABLE HEAD PENETROMETER FOR SOIL-GAS MONITORING

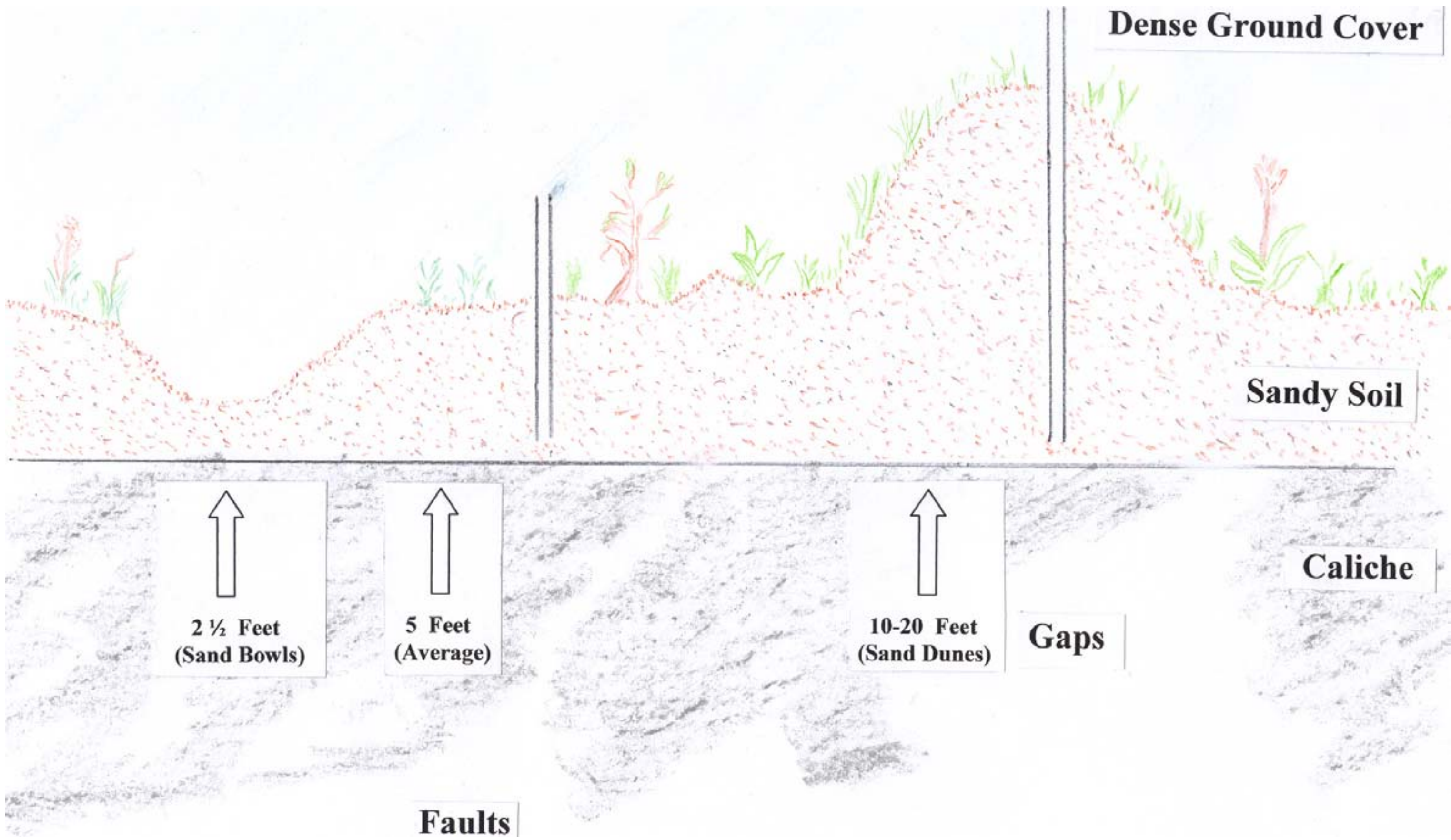


The pilot site is located approximately 25 miles southwest of Hobbs, NM Oil and gas fields in the area are highlighted in red. Map taken from Ward (1986)



(http://geoinfo.nmt.edu/staff/scholle/guadalupe.html An introduction and virtual geologic field trip to the Permian reef complex, Guadalupe and Delaware mountains, New Mexico-West Texas).

WEST PEARL QUEEN SITE
NEW MEXICO



TIME LINE AT WEST PEARL QUEEN

CARBON DIOXIDE

Injection	1 ½ Months	Dec. -- Feb. 2002/2003
"Soak" Period	6 ½ Months	Feb. – Aug. 2003
Pumping/Venting	3 ½ Months	Sept. – Dec. 2003

- Additional Vent-Soak Periods not Associated with the Study

TIME LINE AT WPQ (CONTINUED)

TRACER INJECTIONS / MONITORING

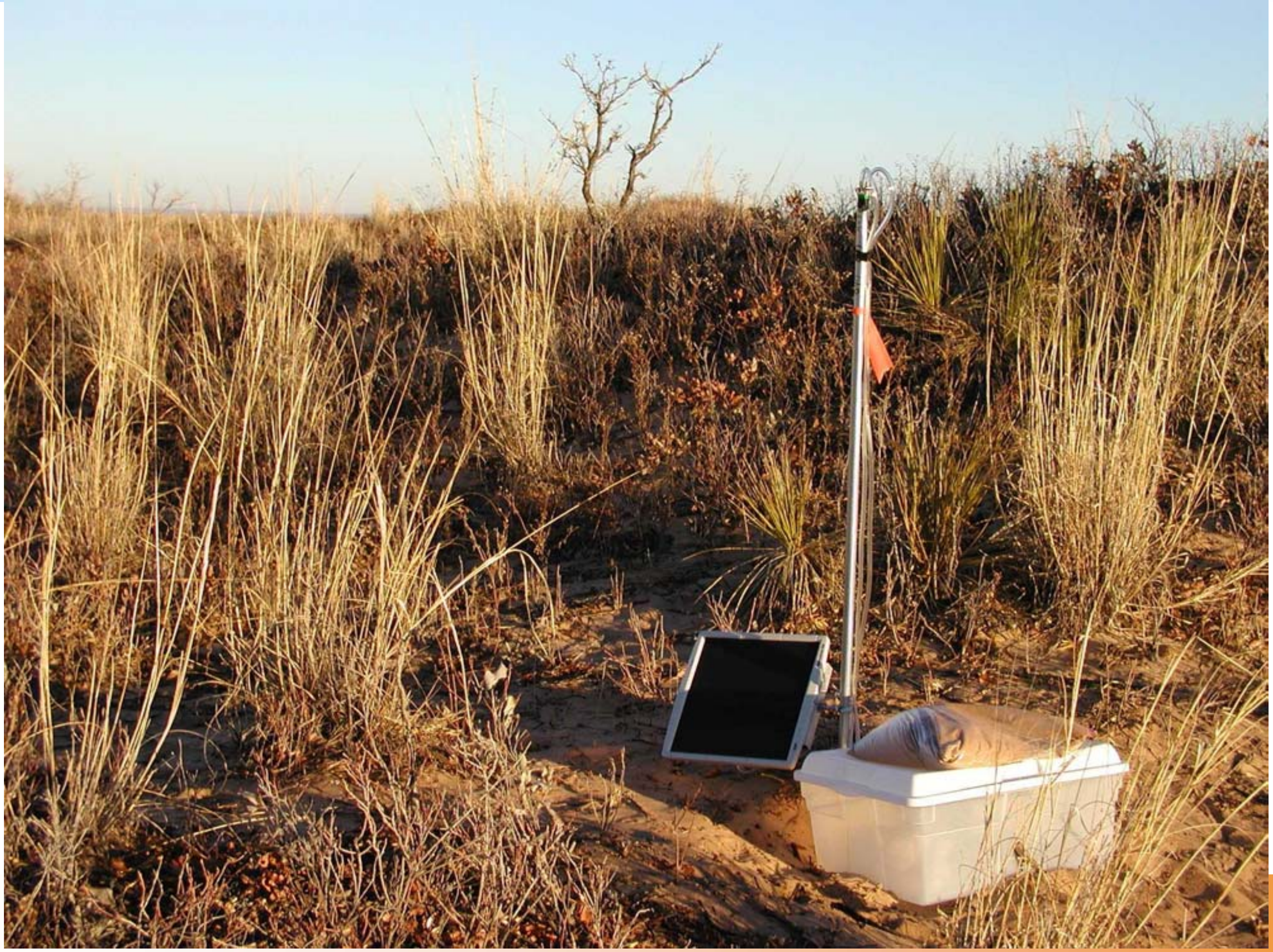
- PDCH Injection — 12 Hour Injection the 2nd Day After CO_2 Injection Started
- CAT Set No. 1 — In the Ground for 6 Days
- PTCH Injection — 12 Hour Injection
- CAT Set No. 2 — In the Ground for 10 Days
- PDCB Injection — 12 Hour Injection
- CAT Sets No. 3 & 4 — Each in the Ground for 54 Days
- Additional CAT Sets — During and Following the Venting of CO_2

VAN WITH TRACER SYRINGE PUMP DURING INJECTION: WEST PEARL QUEEN SITE, NEW MEXICO

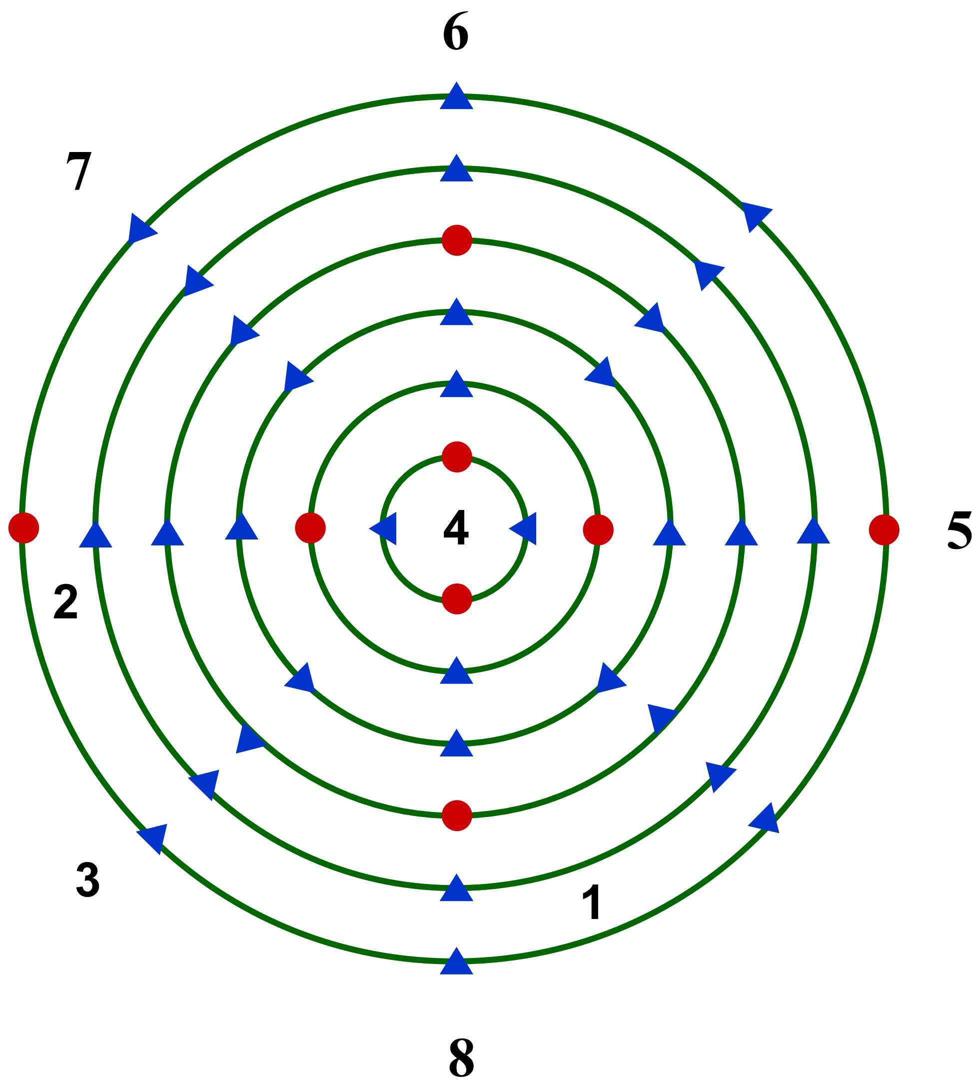
TRACER ADDITION AT WELL HEAD

MONITORING HOLE ON A SAND DUNE
WEST PEARL QUEEN, NEW MEXICO

MONITORING SITE WITH AIR PUMP, WEST PEARL QUEEN, N. M.



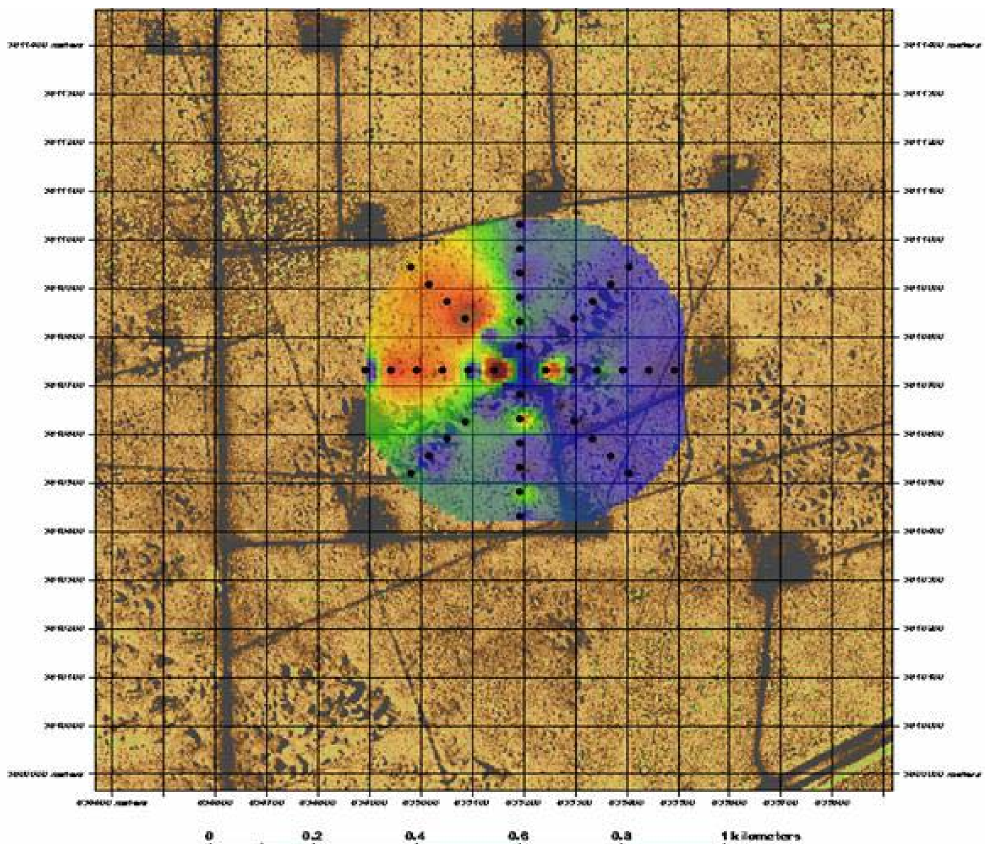
MONITORING GRID IN WPQ NEW MEXICO



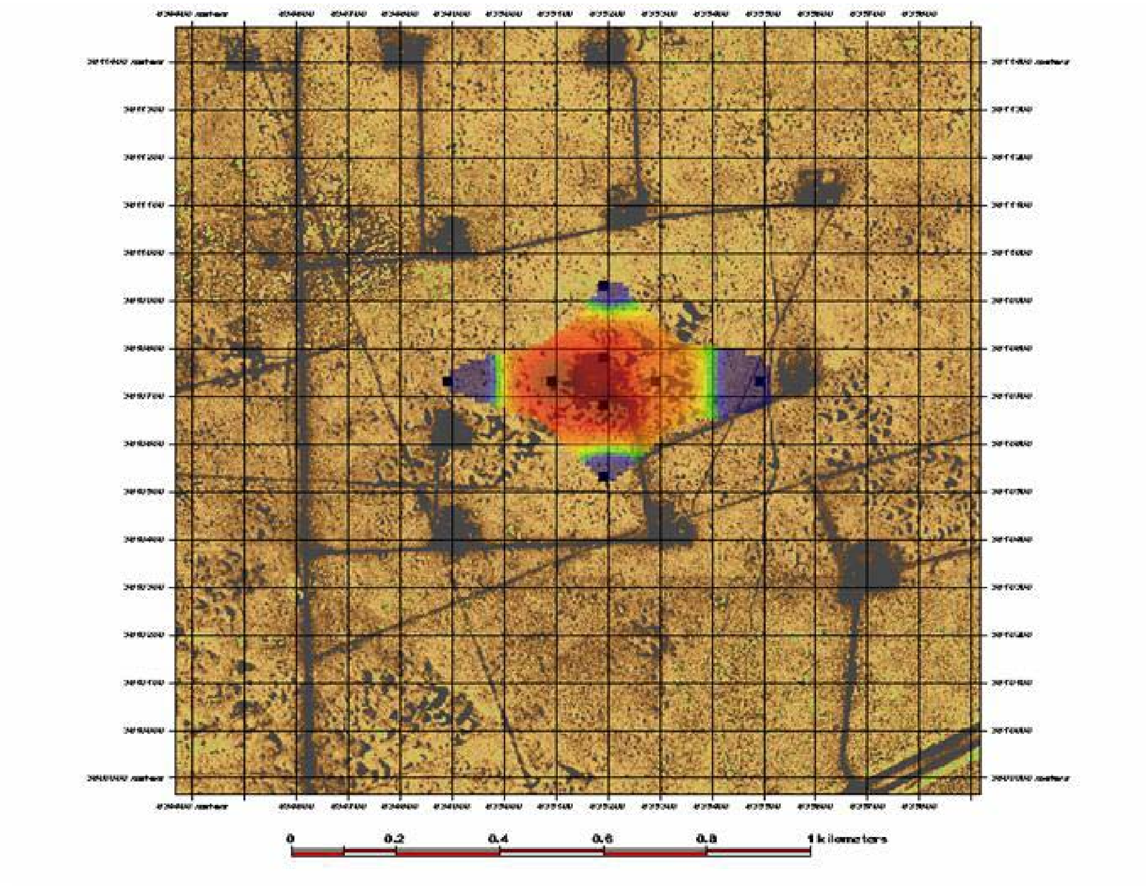
▲	Passive Monitors
●	Pumped Monitors
4	CO_2 Injection Well
5	Monitoring Well
1&3	Small Bore Wells
2	Plugged Well

6, 7 & 8 Active Wells

West Pearl Queen Results: PDCH & PTCH CAT Sets 1 & 2: Sites Without Pumps

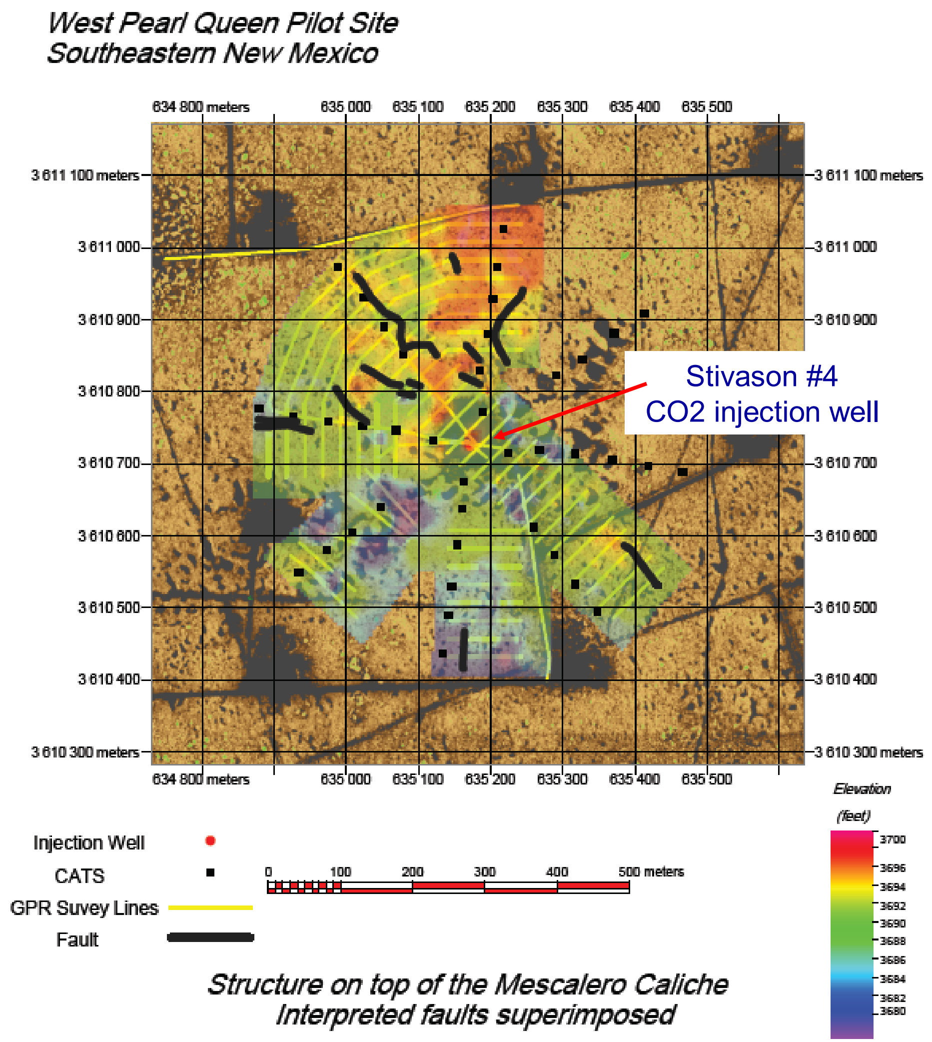


West Pearl Queen Results: PDCH & PTCH CAT Sets 1 & 2: Sites With Pumps



NETL

Structure of the Mescalero caliche is superimposed on an orthophoto of the injection site. GPR survey lines are shown in yellow. Locations of the injection well, CATS, and interpreted faults are also shown.



Structure on top of the Mescalero Caliche
Interpreted faults superimposed

TRACER IN SOIL-GAS BACKGROUND LEVELS ON A PER-DAY BASES (10^{-13}L/L SOIL-GAS)

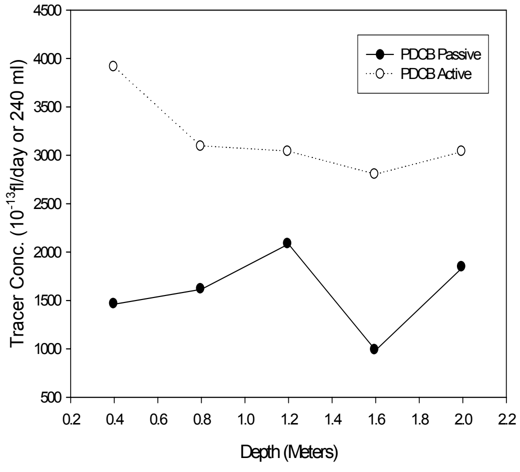
CAT SET NUMBER	SET No. 1	SET No. 2	SET No. 3	SET No. 4	AVERAGE OF SETS 1-4
DAYS EXPOSURE	6 DAYS	10 DAYS	54 DAYS	54 DAYS	
PDCH	0.32	0.23	0.28	0.48	0.33 $\pm$.11
PTCH	0.30*	0.23	0.13	0.41	0.27$\pm$.11
PDCB	1.5*	1.6*	1.0	1.3	1.3$\pm$.3

* Full background sets

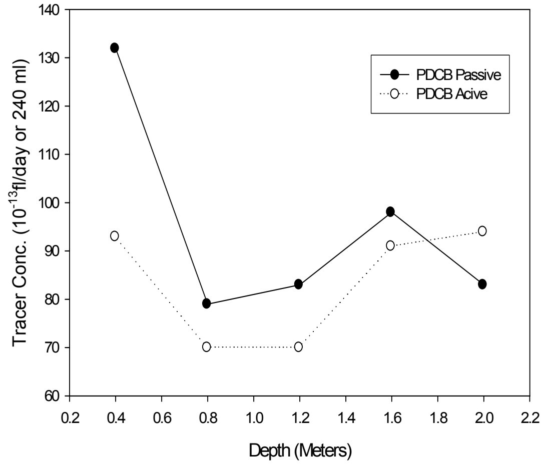
PERCENTAGE OF THE TOTAL CO_2 LOST ON A YEARLY BASES

CAT SET No.	PDCH	PTCH	PDCB
1	0.046%		
2	0.088%	0.056%	
3	0.028%	0.017%	0.053%
4	0.034%	0.017%	0.034%
Ave.	0.049%	0.030%	0.043%

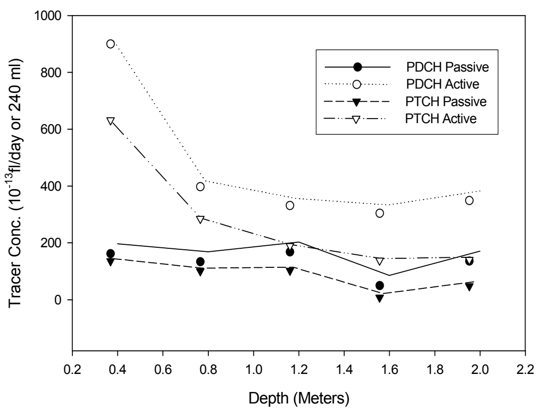
Depth Profile of Tracers in Soil-Gas During Venting (9 Days Passive and 240ml Syringed Samples)



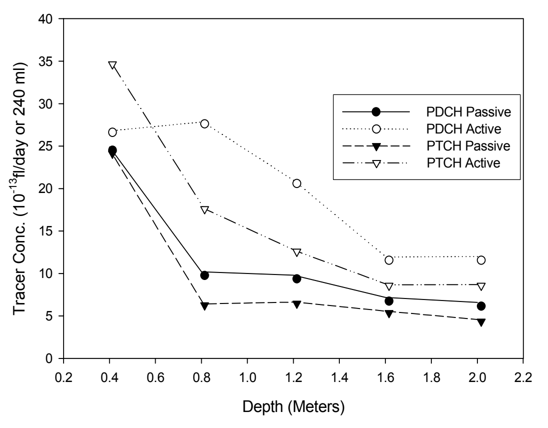
WEST



SOUTH

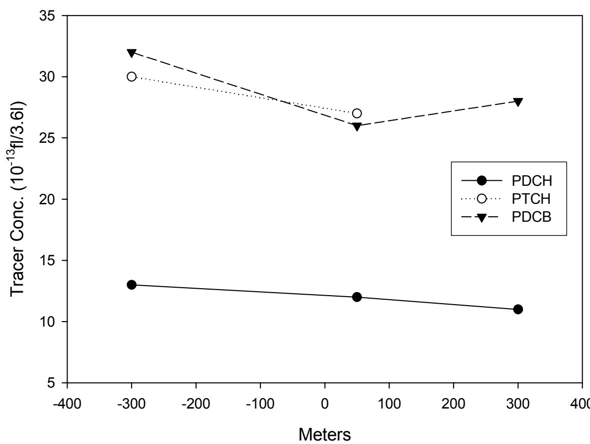


WEST

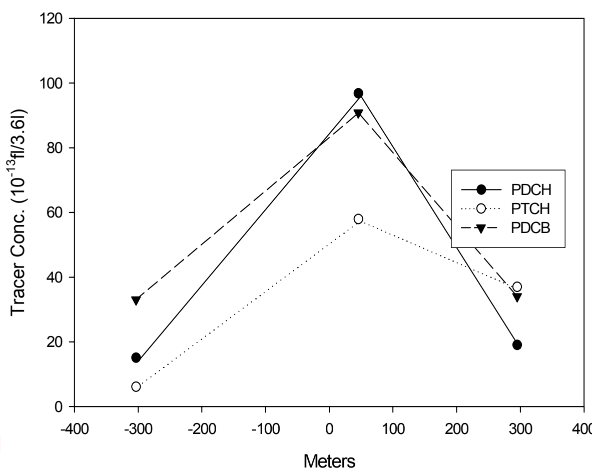


SOUTH

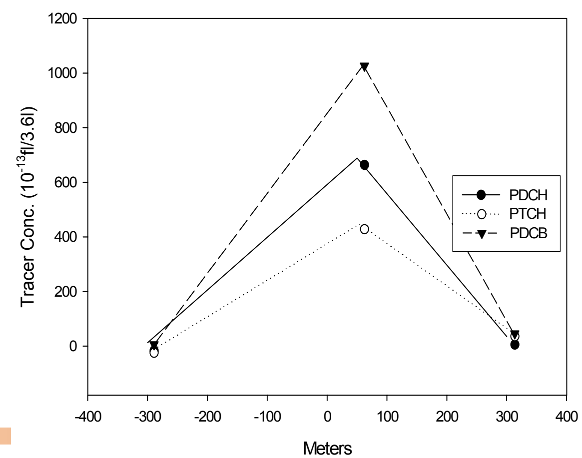
ATMOSPHERIC SAMPLES



First Soak Period

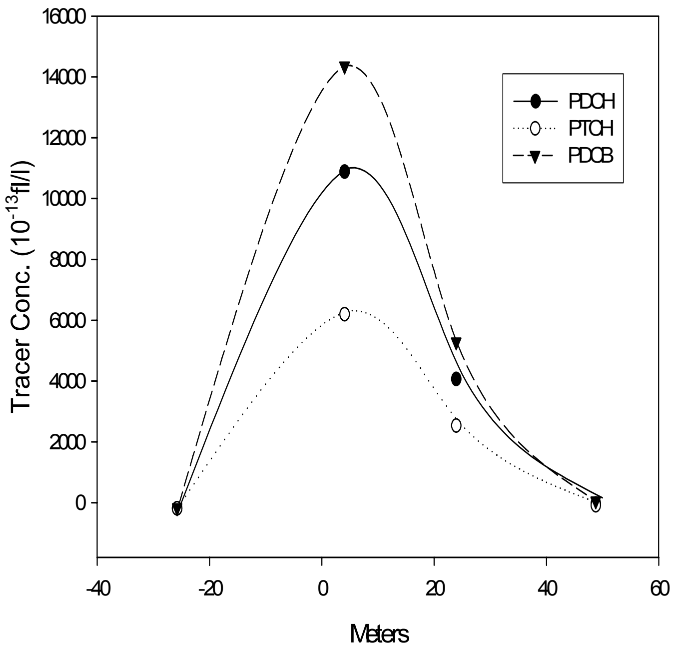


Second Soak Period

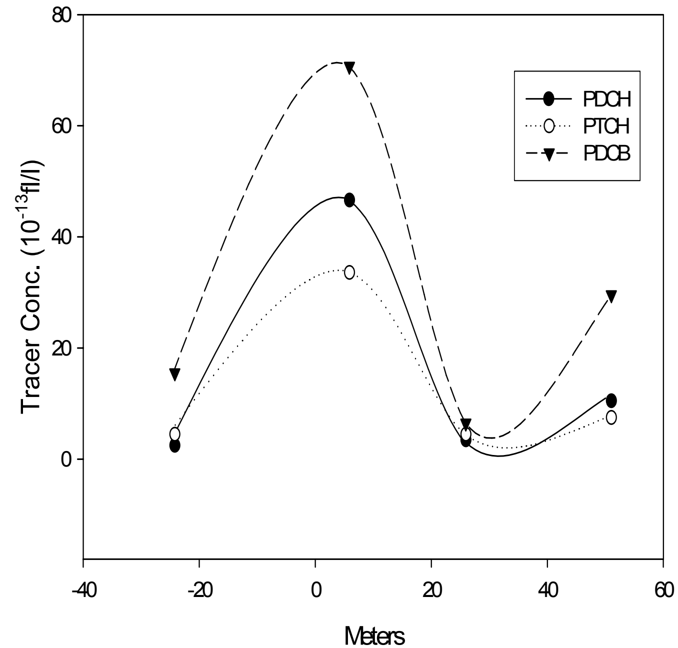


Second Venting Period

ATMOSPHERIC TRACER PLUMES DURING VENTING



Plume From Vent



Plume From Well Head

CONCLUSIONS

- PFTs were Successfully Employed at the West Pearl Queen Site to Monitor for Low Level Leakage of Carbon Dioxide
- Leakage was Detected from the First Week After Injection and Over a Period of Several Months Prior to Venting.
- Leakage Rate Estimates were Fairly Uniform Over 4 Consecutive CAT Sets, and between the 3 Different Tracers at less than 0.1% of the total CO_2 Lost per Year.
- Leakage was Associated with the Injection Well Bore. There was no Evidence for Leakage Associated with any other Wells in the Vicinity.
- Leakage Patterns Consisted of a Diffusive Pattern Within 100 Meters of the Injection Well, and Directional Patterns Beyond 100 Meters to the North-West, West, South-West and South.
- Leakage Appears to be Associated with Surface Faults and Areas of Discontinuity and Gaps in the Mescalero Caliche Layer.

COMPREHENSIVE MONITORING "SEQURE" TECHNOLOGIES

SUITE OF MONITORING TECHNOLOGIES

- TRACERS
- DIRECT CO_2 / METHANE / RADON FLUX AND SOIL-GAS MONITORING
- AIRBORNE RADIOMETRY / METHANOMETRY / ETHANOMETRY (TO FIND EXISTING WELLS)
- SHALLOW WATER AQUIFER CHEMISTRY MONITORING

SUPERCRITIAL FLUID STUDIES OF CO_2 / TRACER INTERACTIONS WITH RESERVOIR AND OVERLYING STRATA

IEA GHG Weyburn CO_2 Monitoring and Storage Project

What worked and what didn't

Malcolm Wilson

ptrc
Petroleum Technology Research Centre

UNIVERSITY OF REGINA

ptrc
Petroleum Technology Research Centre

The Partners

IEA Greenhouse Gas R&D Programme

Natural Resources Canada

Saskatchewan Industry and Resources

United States Department of Energy

European Commission

Petroleum Technology Research Centre

EnCana Corporation

Saskatchewan Industry and Resources

Natural Resources Canada — Ressources naturelles Canada

ptrc Petroleum Technology Research Centre

ENCANA

PROJECT LOCATION

Petroleum Technology Research Centre

4 Research Themes

THEME 1
GEOLOGICAL CHARACTERIZATION OF THE GEOSPHERE AND BIOSPHERE

THEME 2
PREDICTION, MONITORING AND VERIFICATION OF CO_2 MOVEMENTS

THEME 3
CO_2 STORAGE CAPACITY AND DISTRIBUTION PREDICTIONS AND THE APPLICATION OF ECONOMIC LIMITS

THEME 4
LONG-TERM RISK ASSESSMENT OF THE STORAGE SITE

Overall the project was a success

- Dedicated management was essential to the project achieving most of its goals.
- PCSMs were good avenues for the sponsors to learn of progress.
- The project had a degree of flexibility within the vision and goals.
- Generally fairly well resourced, other projects will have trouble matching these resources.

Limitations and Barriers

- All activities must fit into oilfield operations and timing
- Sampling generally at surface not at reservoir pressures and temperatures
- Nature of the surface – climatic conditions
- Differences of opinion on value of research
- Research integration
- Four years of monitoring, how long is enough for some techniques?
- Public and regulator understanding limited.

Technically what stands out?

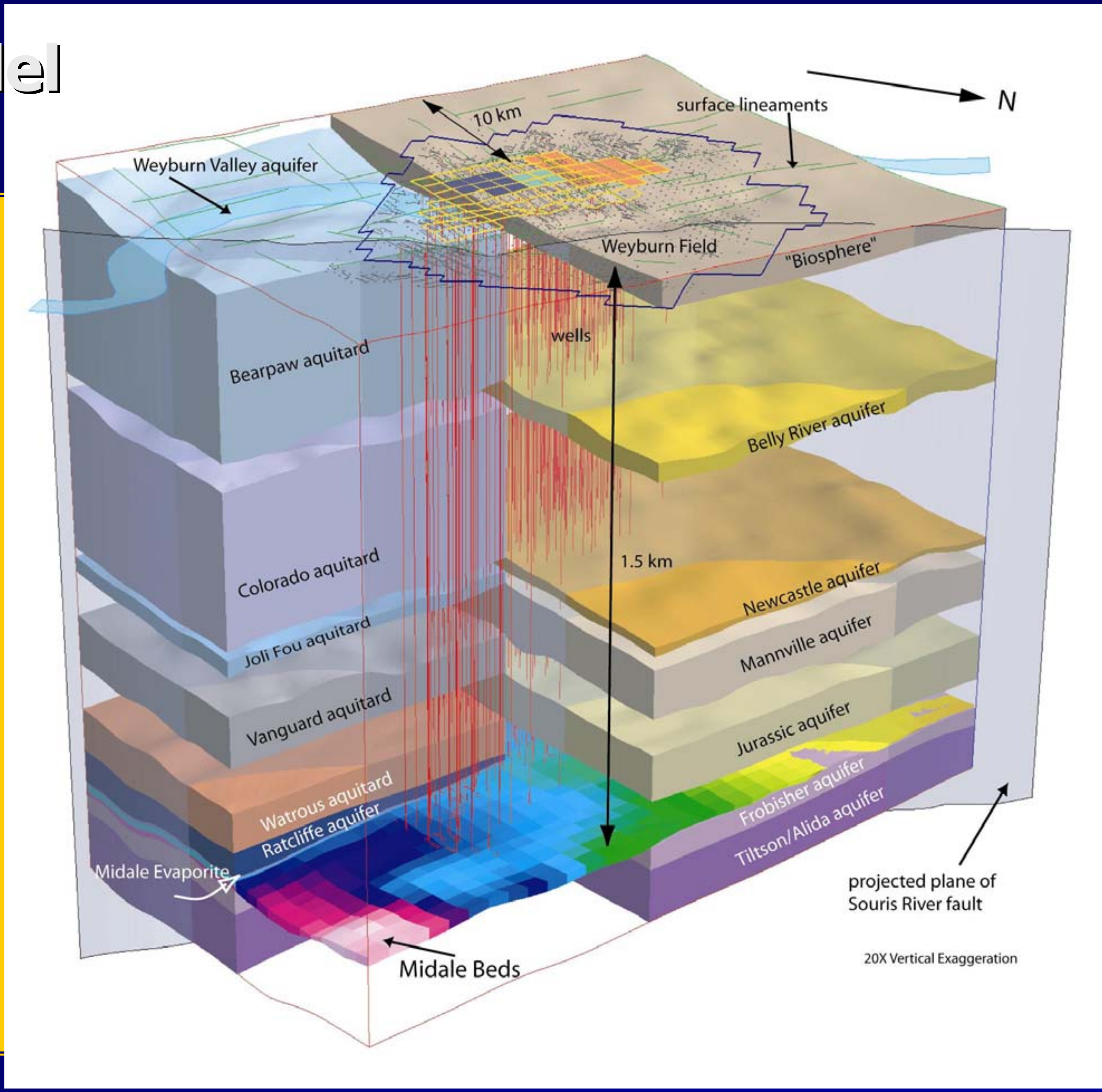
- The value of the baseline survey to all subsequent work.
- The value of existing information, core samples etc.
- Understanding the long term storage capability of the caprock
- The level of detail from the time-lapse seismic surveys.
- Partial discrimination of the Marly from the Vuggy.
- Seismic expression of CO_2 channels suggested.
- The geological interpretation, particularly the upper geosphere and reservoir work. This includes understanding the aquifer-aquitard packages, fluid flows etc.
- Geochemical interpretation, including the use of carbon as a tracer.

Technically where can we improve?

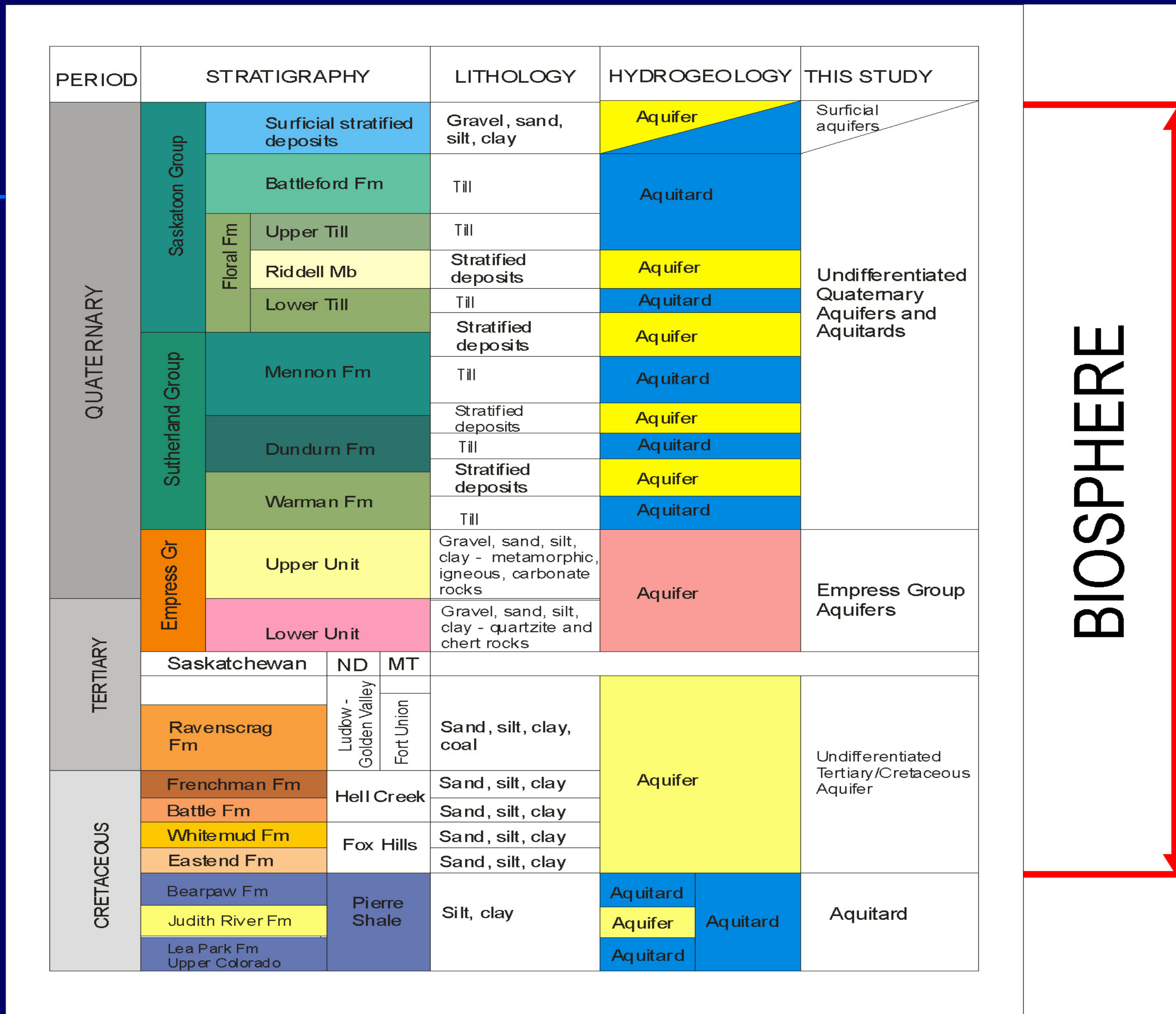
- There is much room to improve simulation.
- There is room to improve in the area of risk assessment.
- Improved understanding of fracture systems.
- Improved understanding of cement and wellbore integrity over time.
- Improved understanding of the biosphere and longer term issues with lower geosphere.
- Increased quantification of seismic results.
- Undertake risk assessment as a parallel not sequential activity.
- Improved integration of geological interpretation and monitoring.

Geological Model

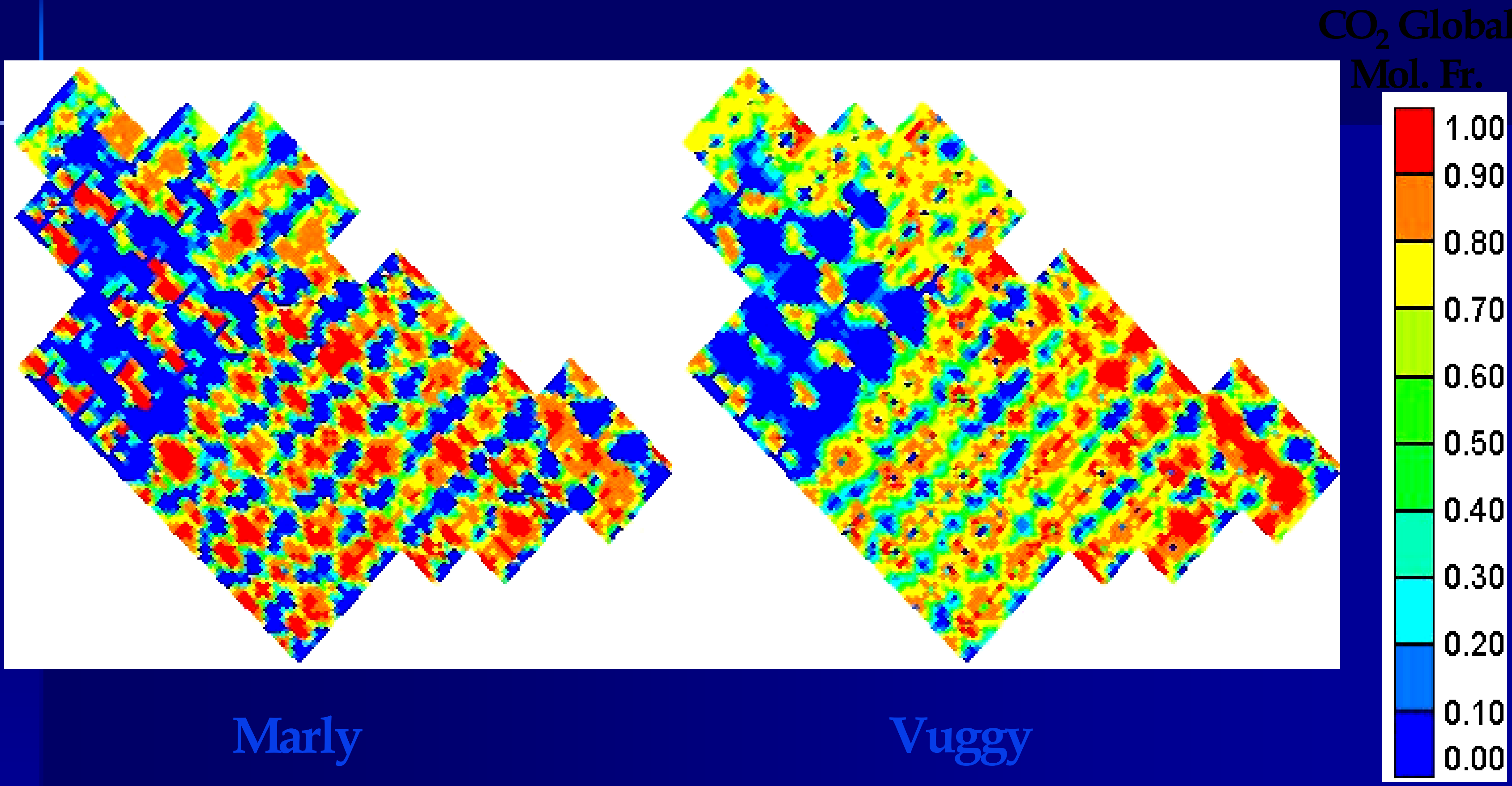
- Areal extent 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system
  - lithology
  - hydrogeological characteristics
  - faults
- Can be tailored for different RA methods and scenario analyses



BIOSPHERE CHARACTERISTICS

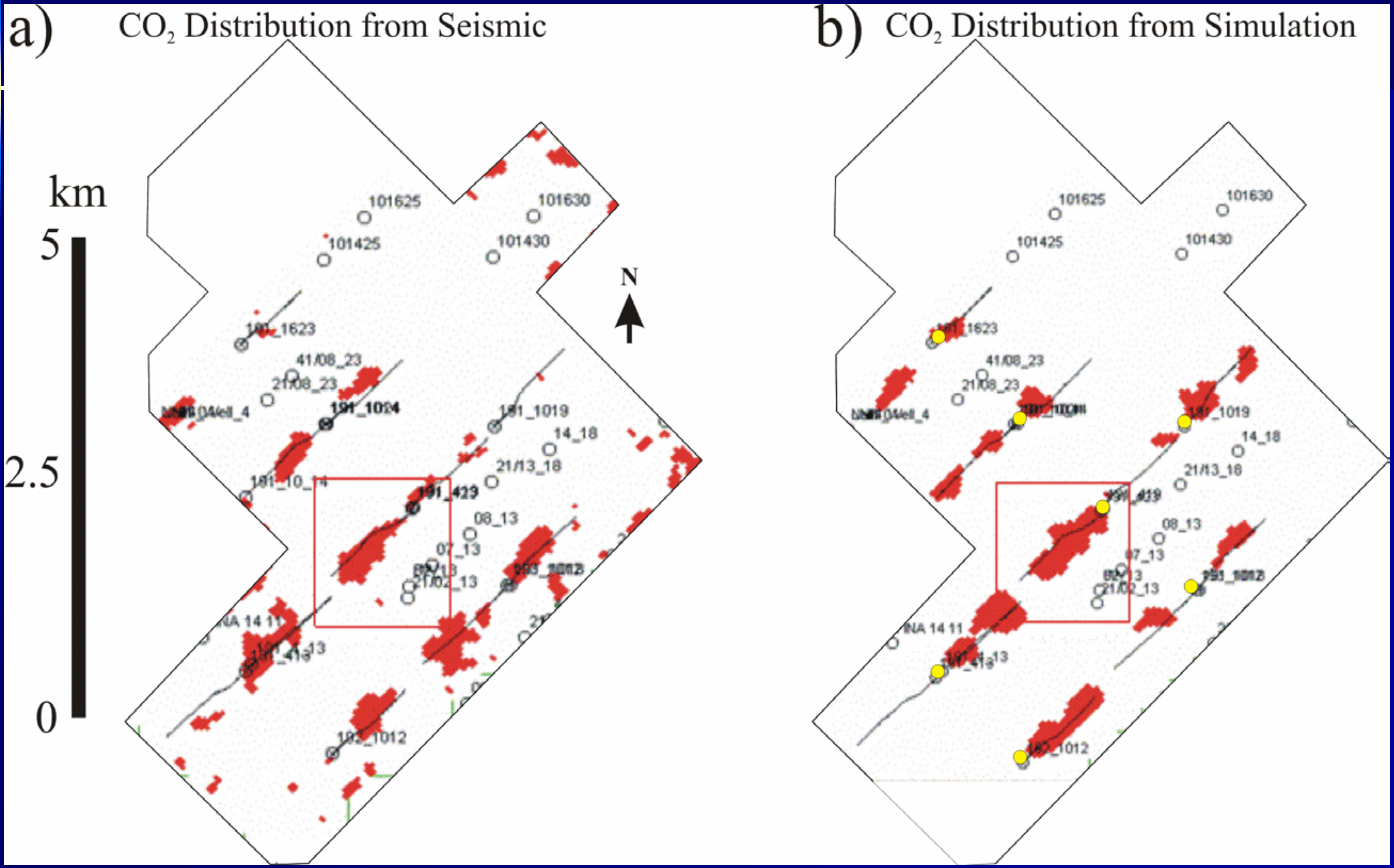


CO_2 Distribution at end of EOR

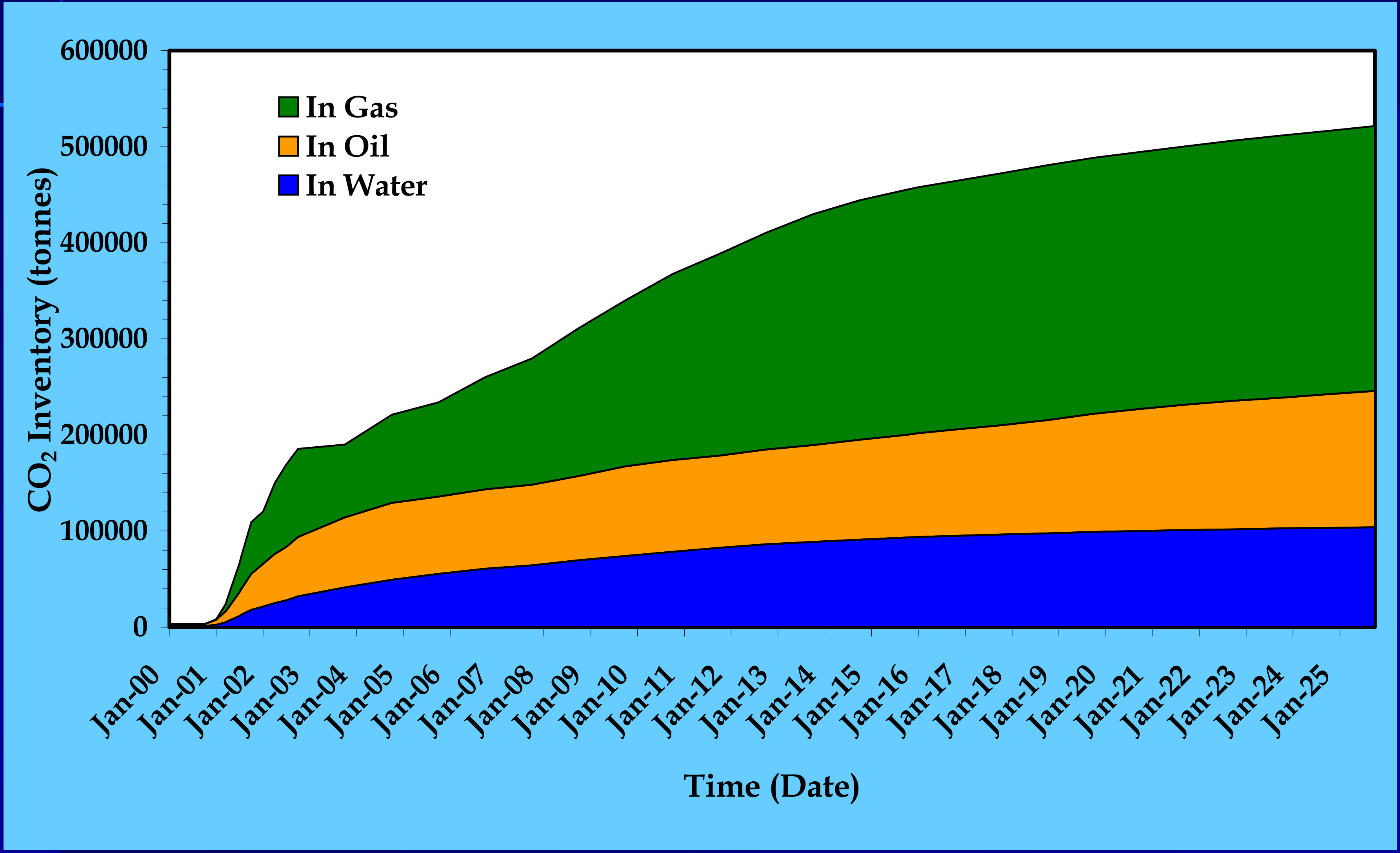


@ 01 / 01 / 2034 (End of EOR)

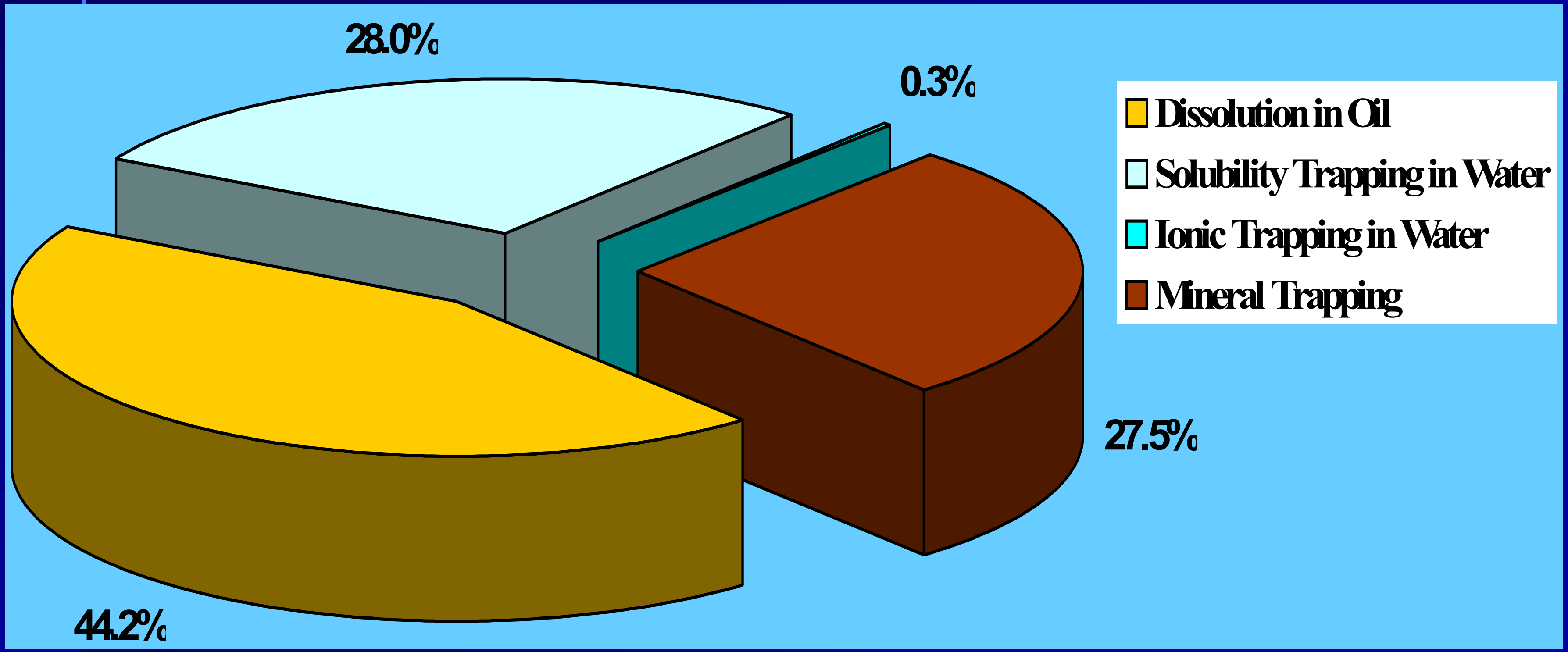
Comparison of CO_2 distribution from prediction and remote sensing



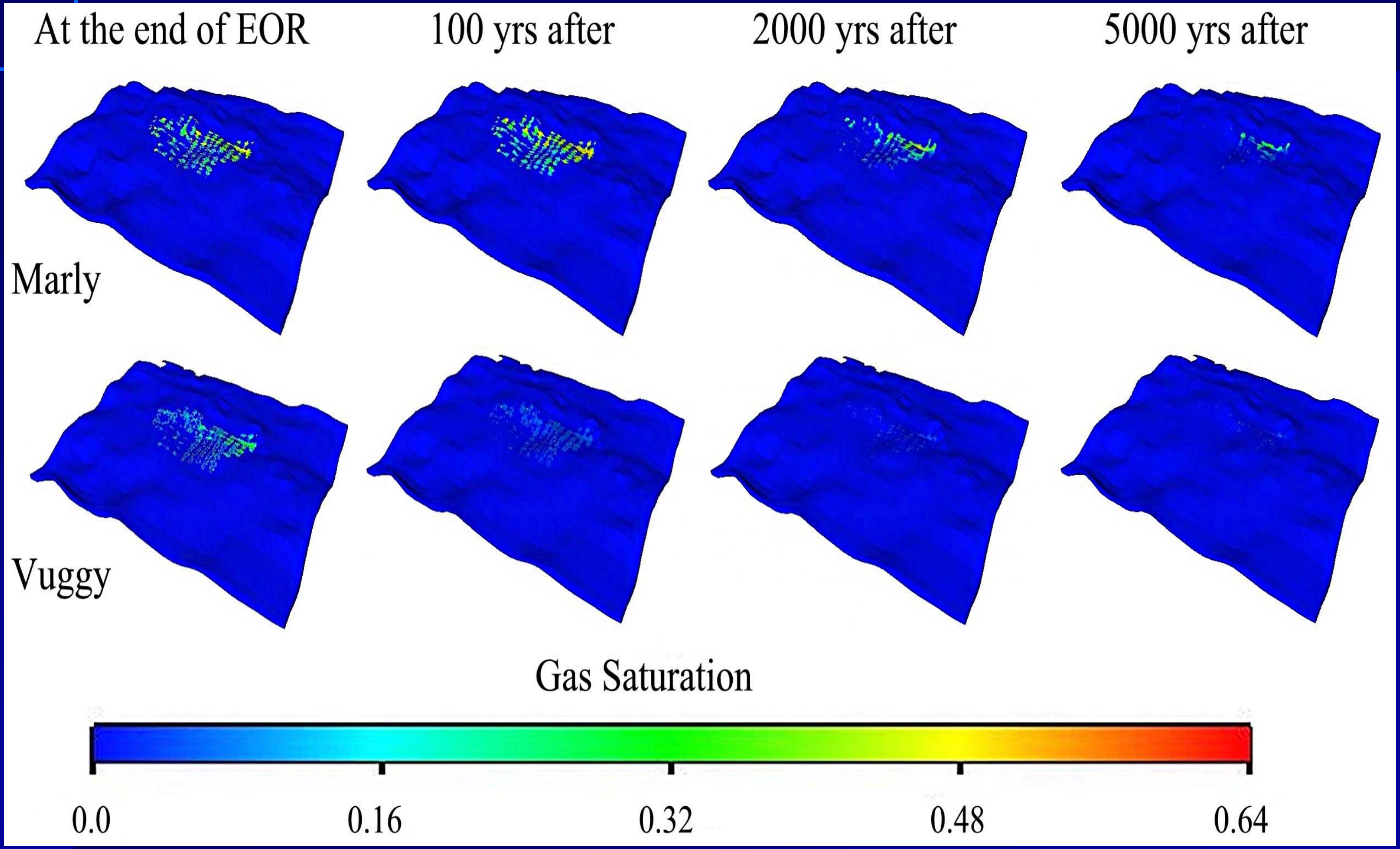
CO_2 Inventory



Trapping Mechanisms

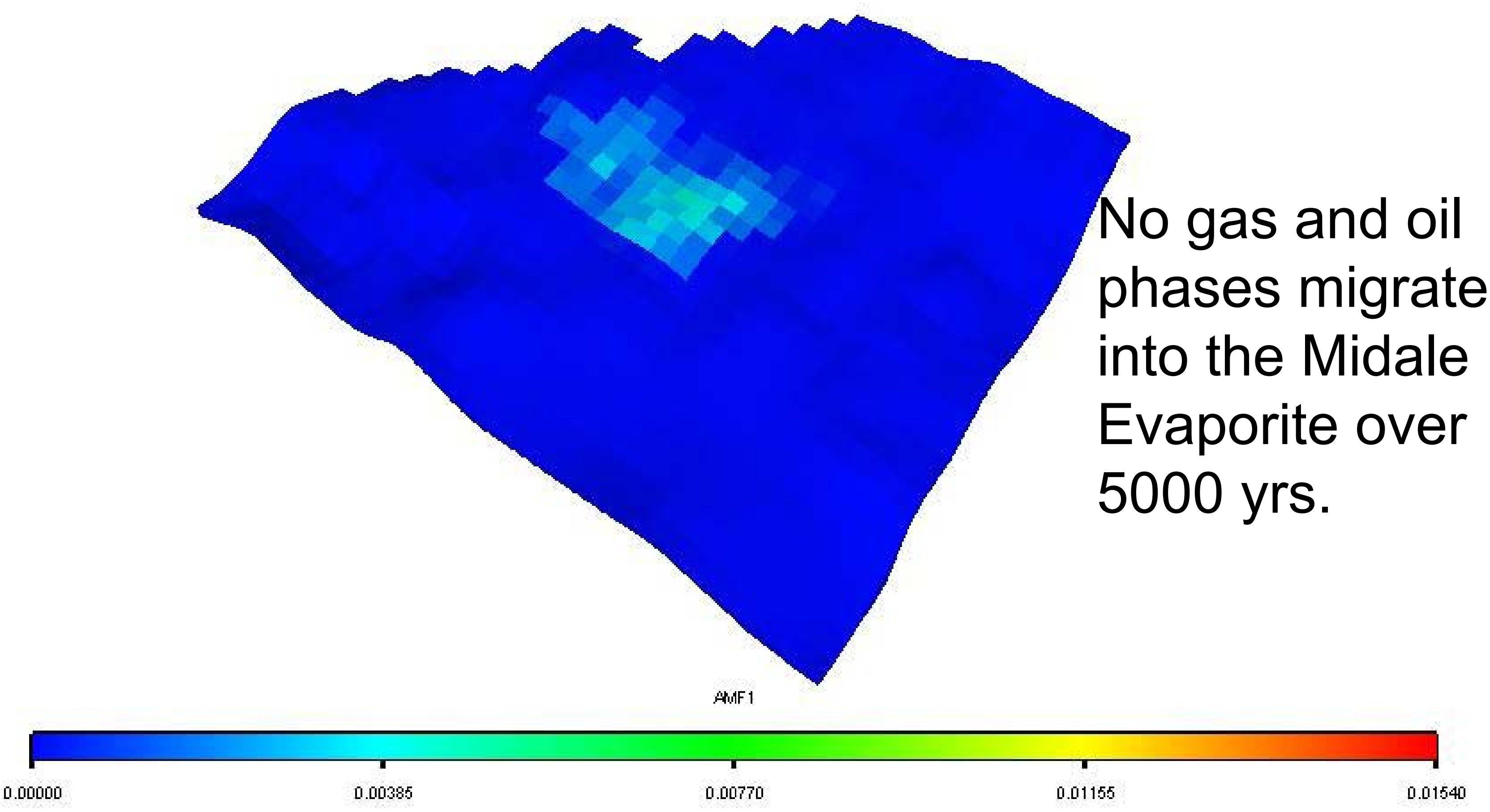


Gas Saturation with Time

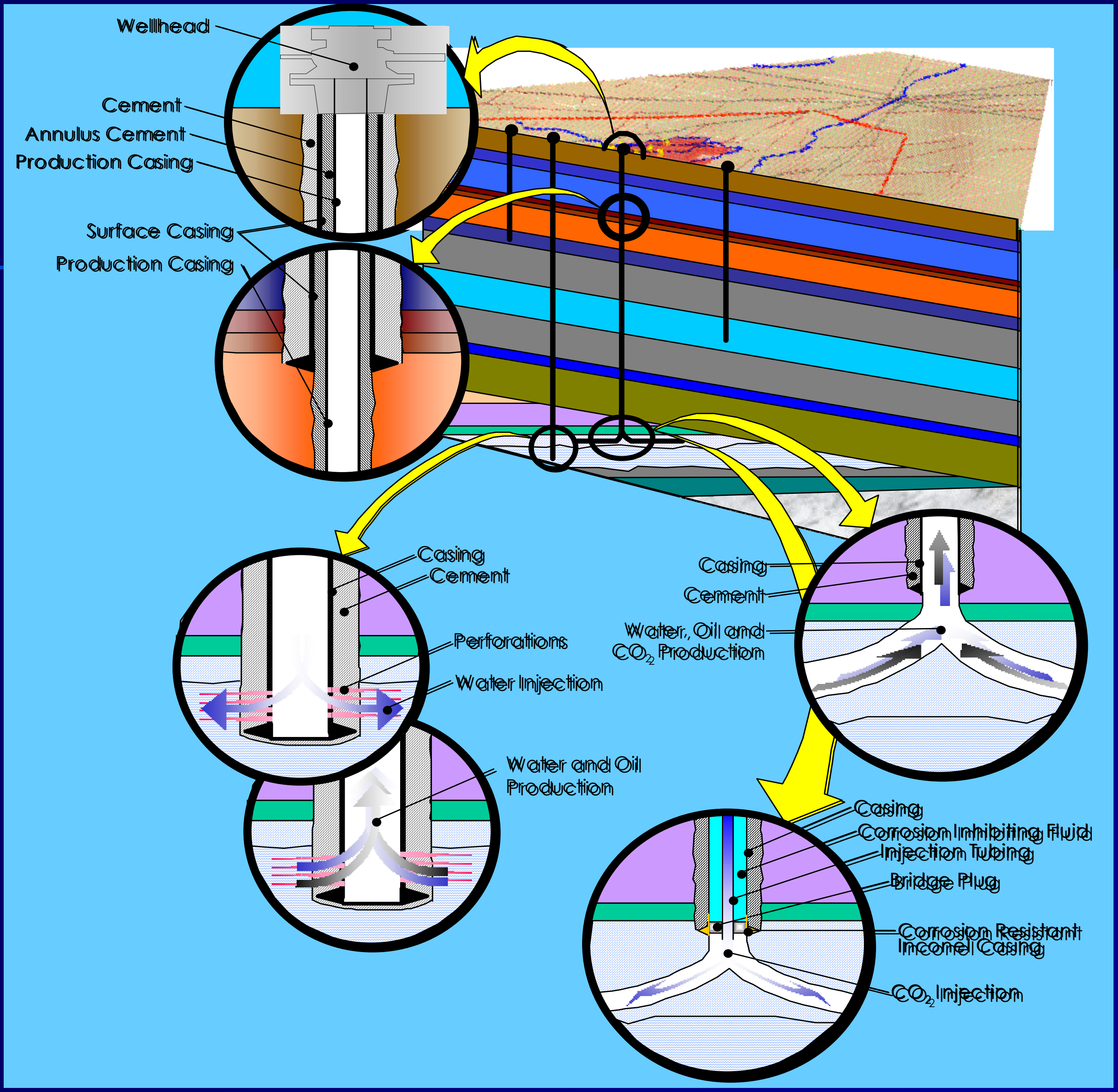


Element of Risk: CO_2 Aqueous Concentration in Midale Evaporite

5000 yrs

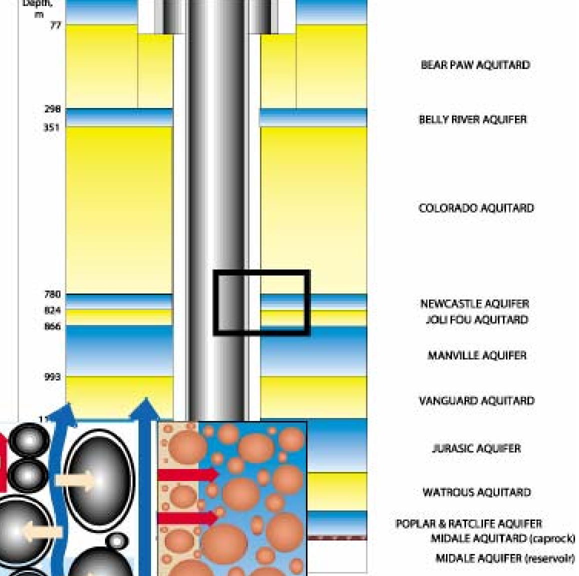


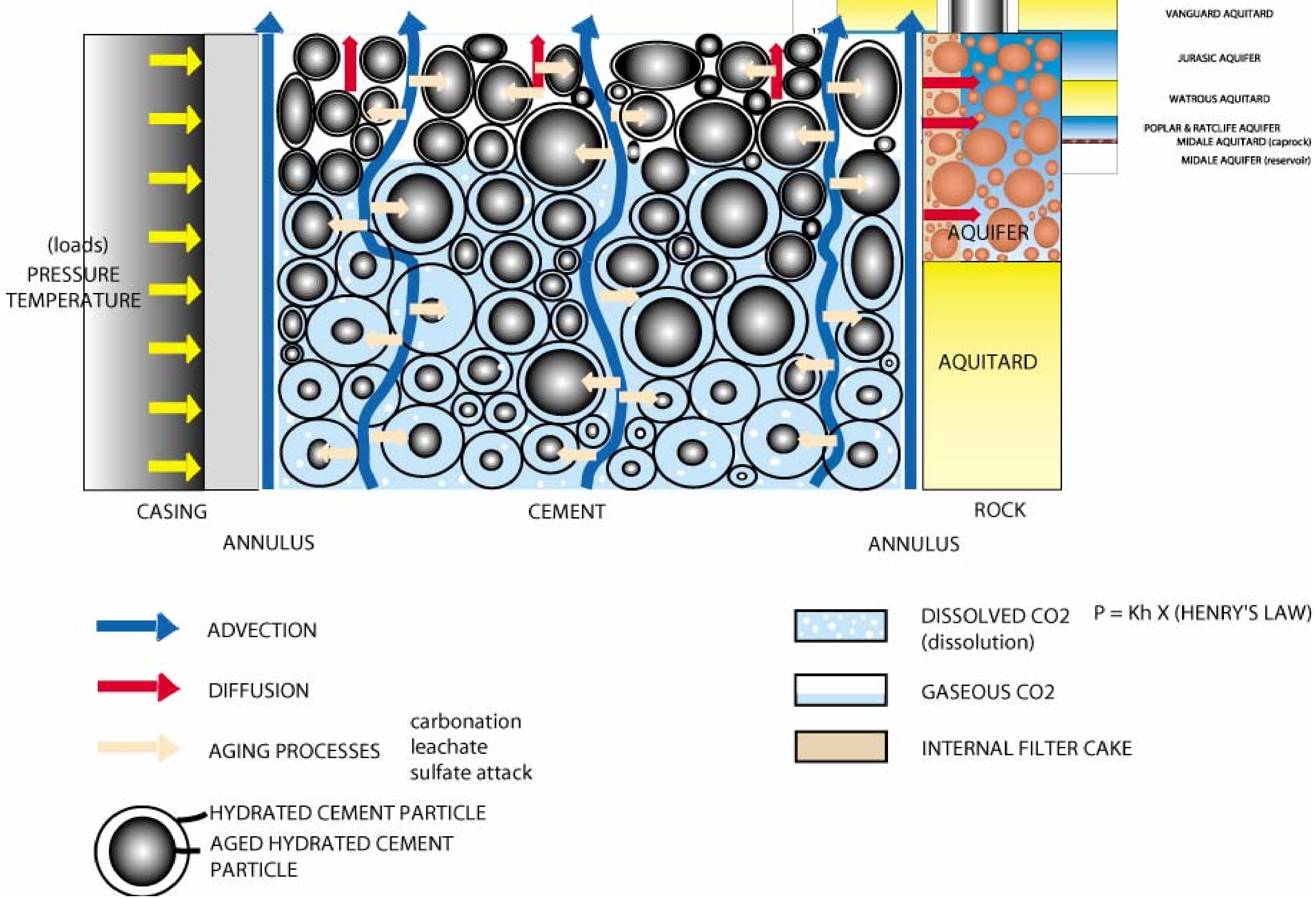
No gas and oil phases migrate into the Midale Evaporite over 5000 yrs.



Wellhead
Cement
Annulus Cement
Production Casing
Surface Casing
Production Casing
Casing
Cement
Perforations
Water Injection
Water and Oil
Production
Casing
Cement
Water, Oil and
CO_2 Production
Casing
Corrosion Inhibiting Fluid
Injection Tubing
Bridge Plug
Corrosion Resistant
Inconel Casing
CO_2 Injection

Bounding Seal Performance Integrity Methodology





Goals for Phase 2

- Better integration between work groups.
- Improved integration with EnCana, there needs to be more thinking about opportunities for the monitoring.
- Filling of gaps.
- Use of modeling and risk assessment to help define monitoring packages for prediction. (ie monitoring for oil production versus integrity)
- Improved geochemical modeling for trapping predictions.

QUESTIONS?

QUESTIONS?

IEA GHG Weyburn CO_2 Monitoring and Storage Project

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

Seismic Results from the Weyburn Monitoring Project

PRESENTED BY: Don White, Geological Survey of Canada

Monitoring Workshop
8-9 November, 2004, Santa Cruz, California

Acknowledgement of Sponsors

Natural Resources Canada | Ressources naturelles Canada

ptrc
Petroleum Technology Research Centre

IEA GREENHOUSE GAS R&D PROGRAMME

ENCANA

Acknowledgements

- Tom Davis, Colorado School of Mines
- Keith Hirsche, Hampson-Russell Software
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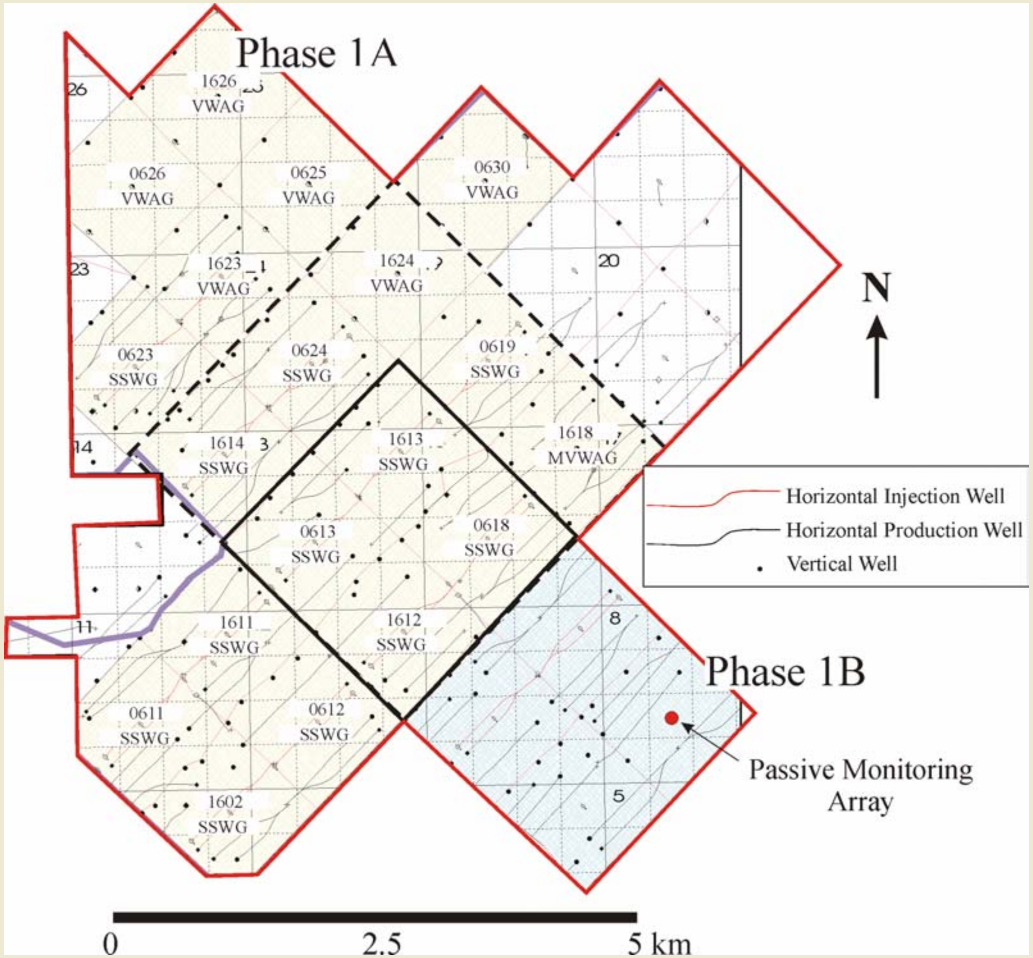
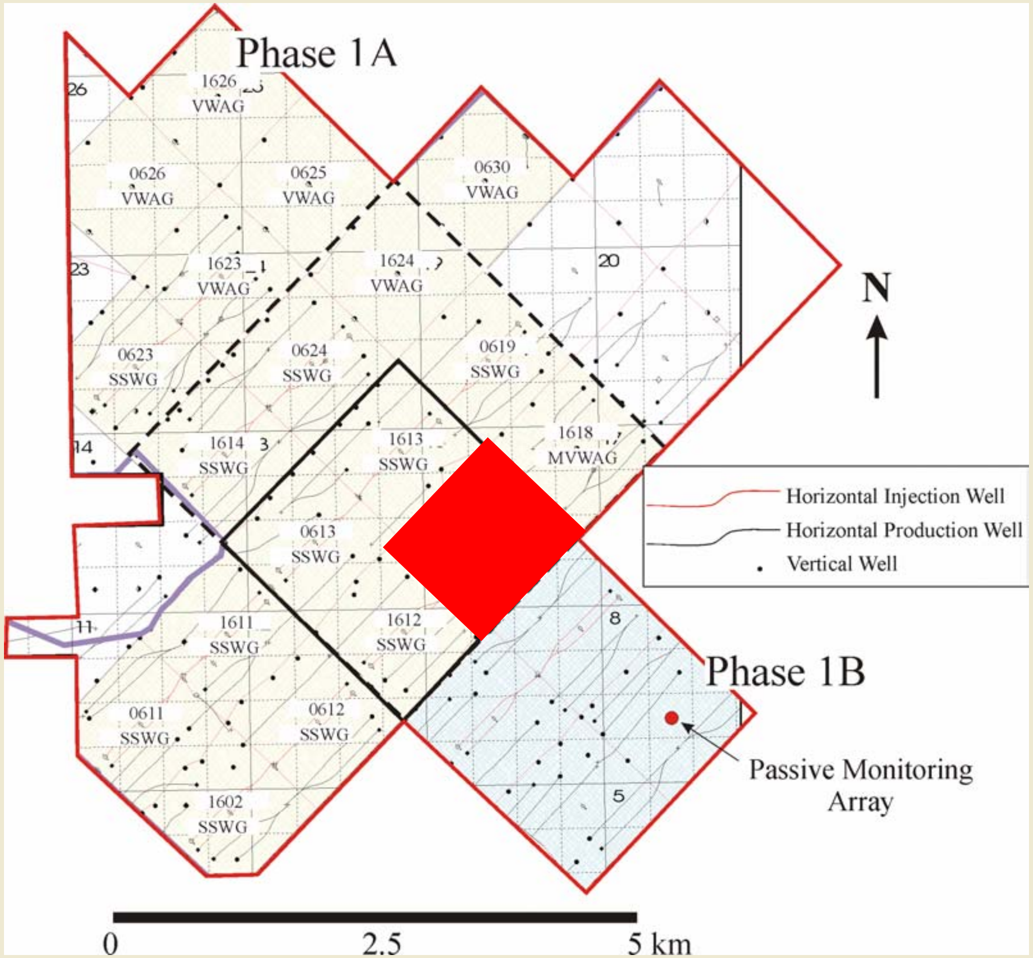
- Shawn Maxwell, Engineering Seismic Group
- Hubert Fabriol, BRGM
- Geoff Burrowes, Sandy Graham, Ryan Adair, David Cooper, David Hassan, Guoping Li, EnCana

1. The IEA Weyburn Project

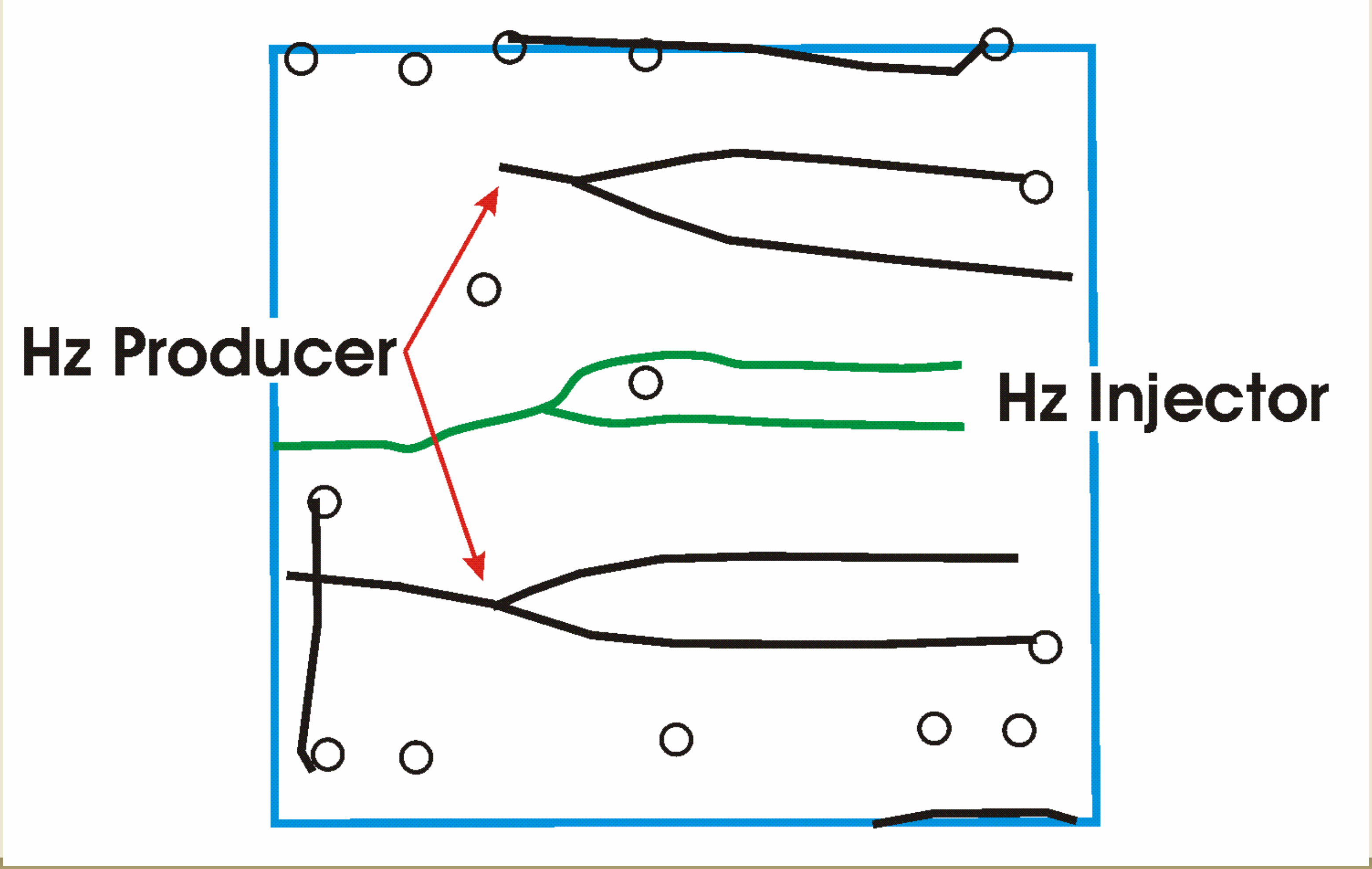
Weyburn Field: Phase 1A EOR Area



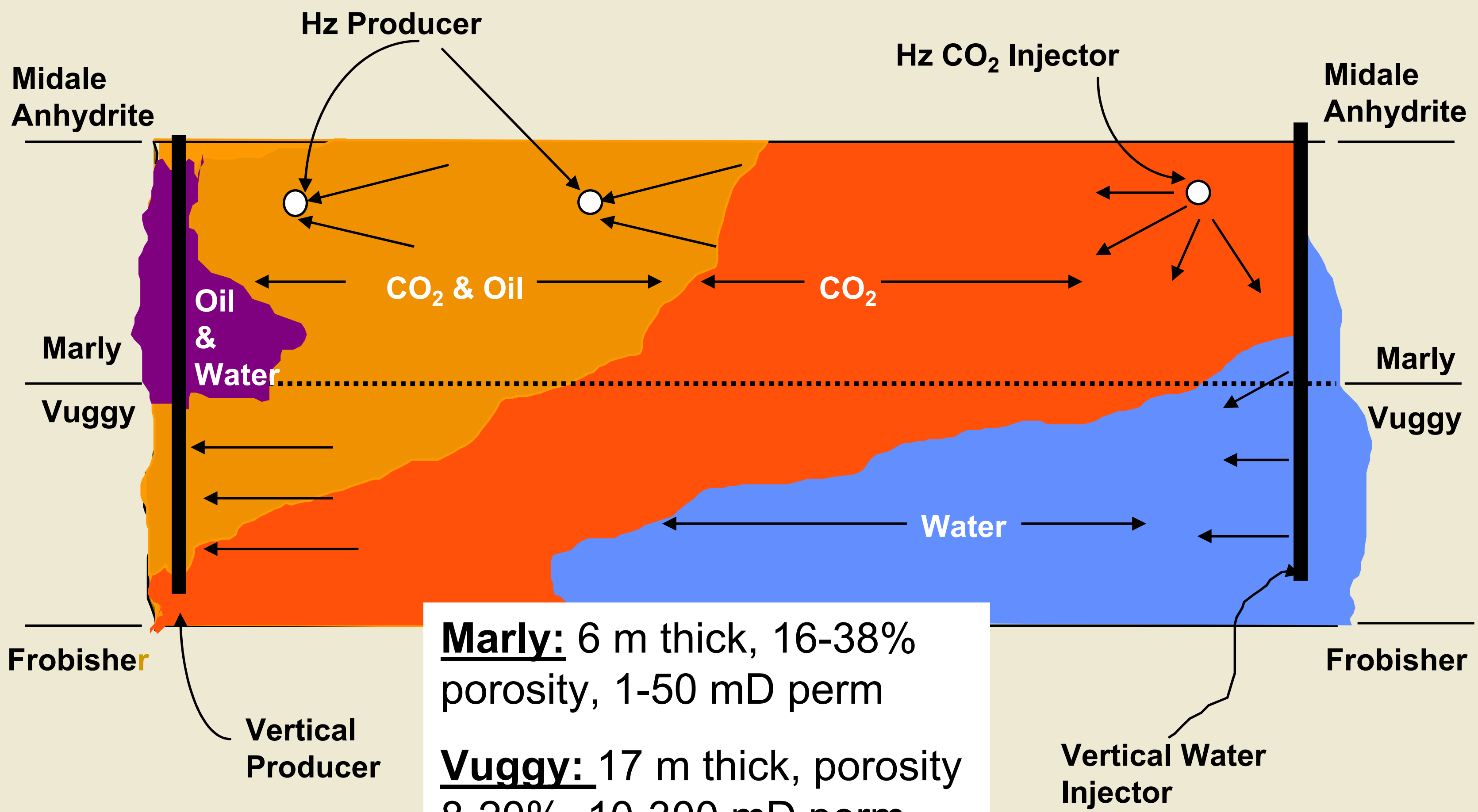
Weyburn Field: Phase 1A EOR Area



Weyburn Field: Phase 1A EOR Area



The CO2 Flood

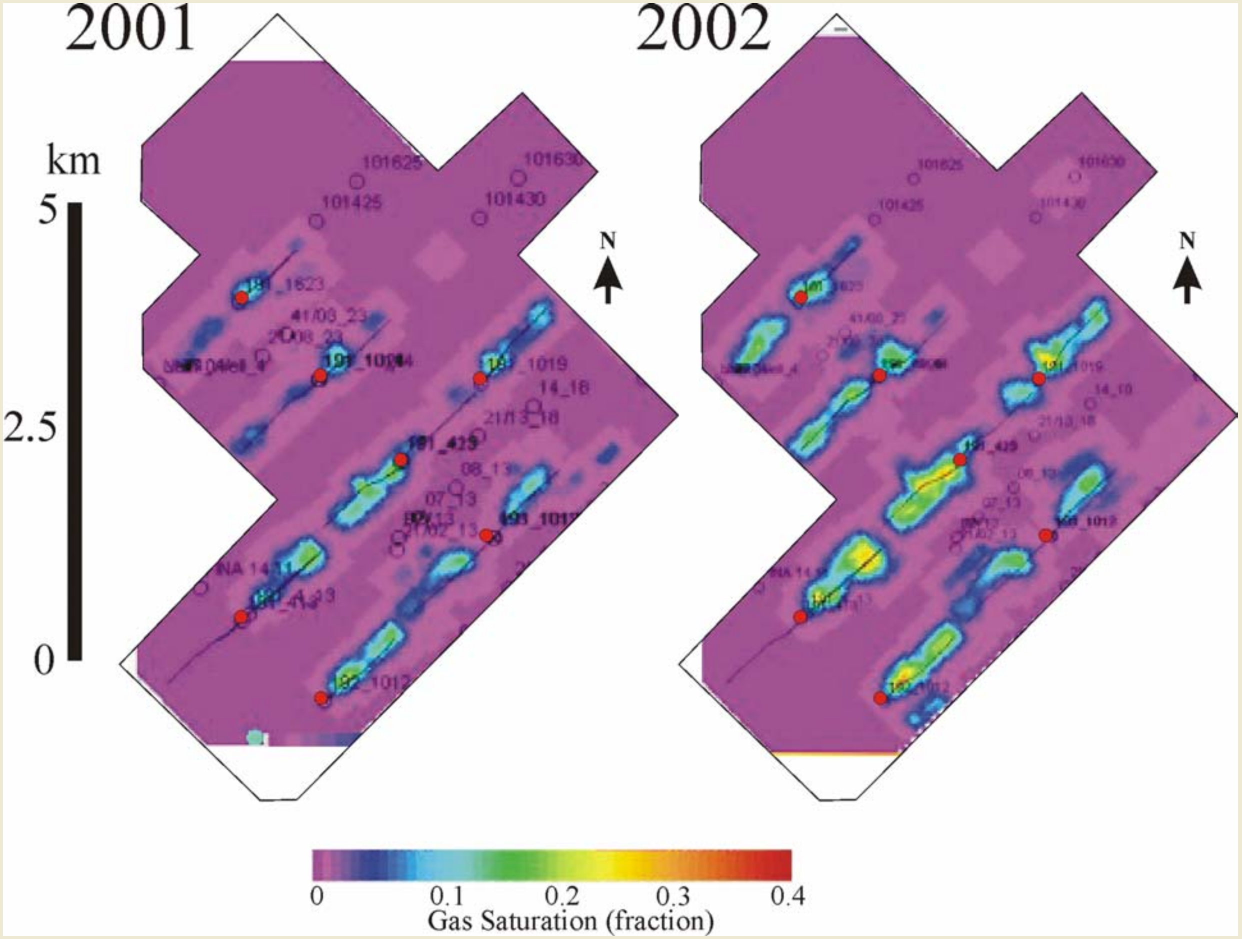


Marly: 6 m thick, 16-38% porosity, 1-50 mD perm

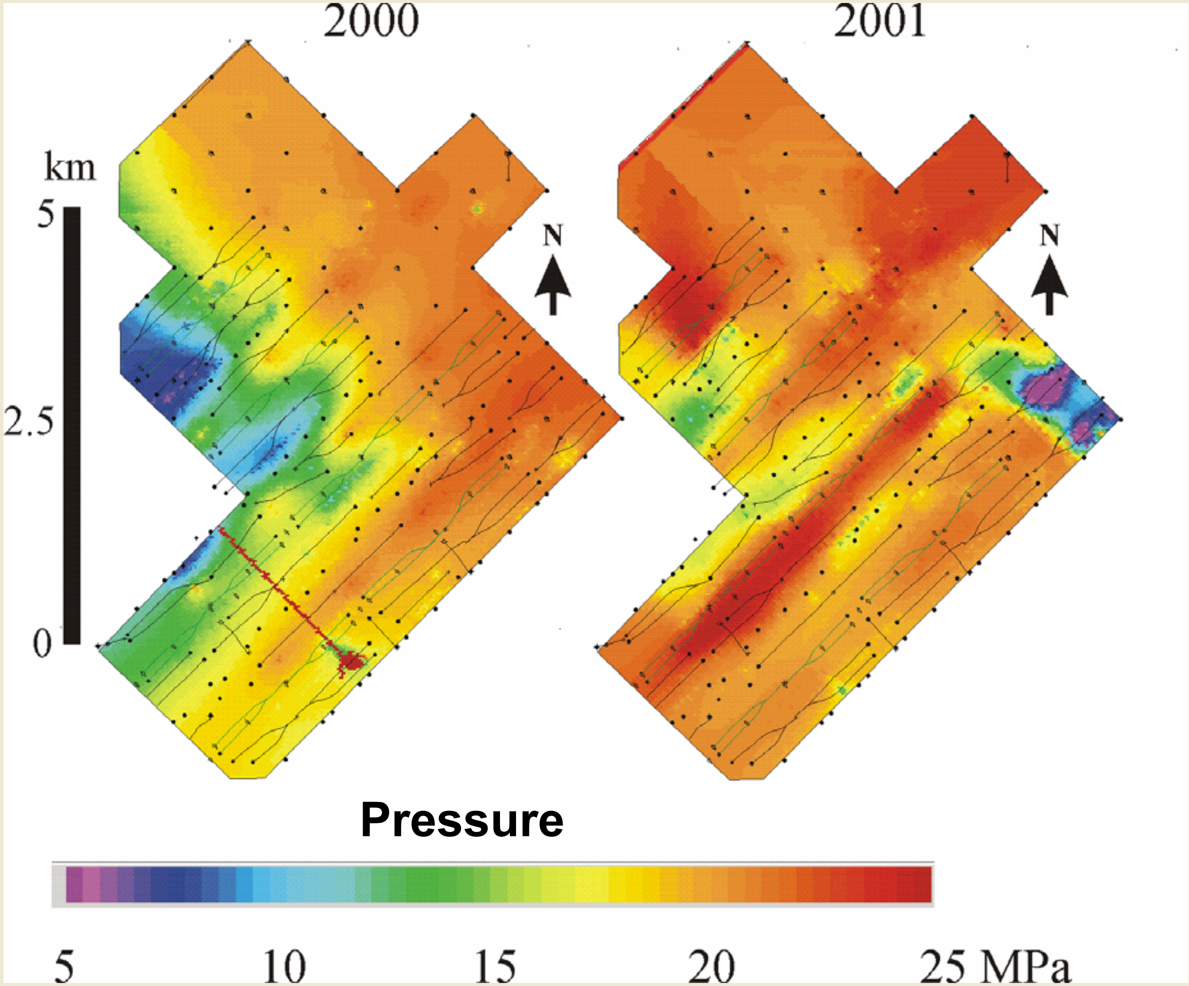
Vuggy: 17 m thick, porosity 8-20%, 10-300 mD perm


2. Pre-Injection Prediction

Pre-injection Prediction



Pre-injection Prediction

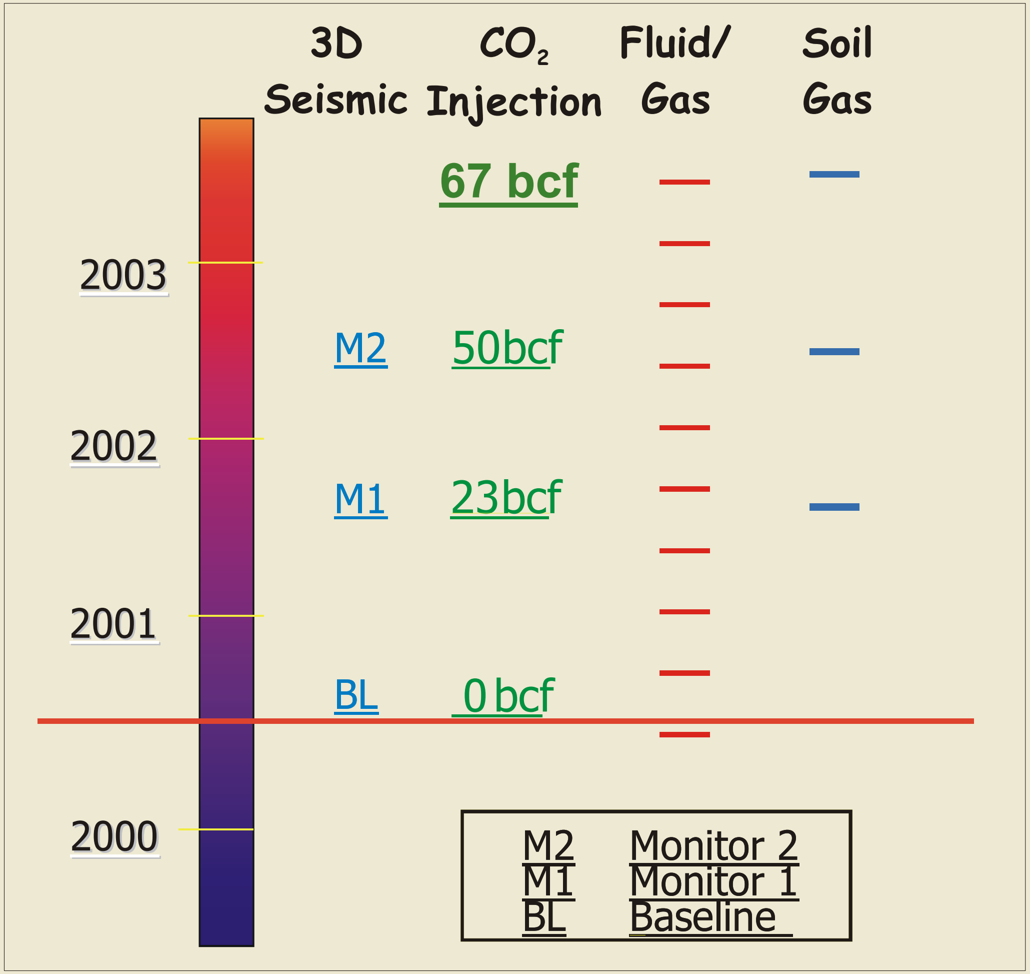


3. Monitoring of CO_2 Movement and Effects at the Reservoir

Monitoring Techniques

- **3D Multi-component Time-Lapse Surface Seismic (P, S,** and PS, SP**)**
- **Horizontal &** Vertical X-Well Tomography
- **Passive Microseismic Monitoring**
- 3D Multi-component Time-Lapse VSP
- Production Data
- Geochemistry of Production Fluids/Gases
- Soil Gas Sampling

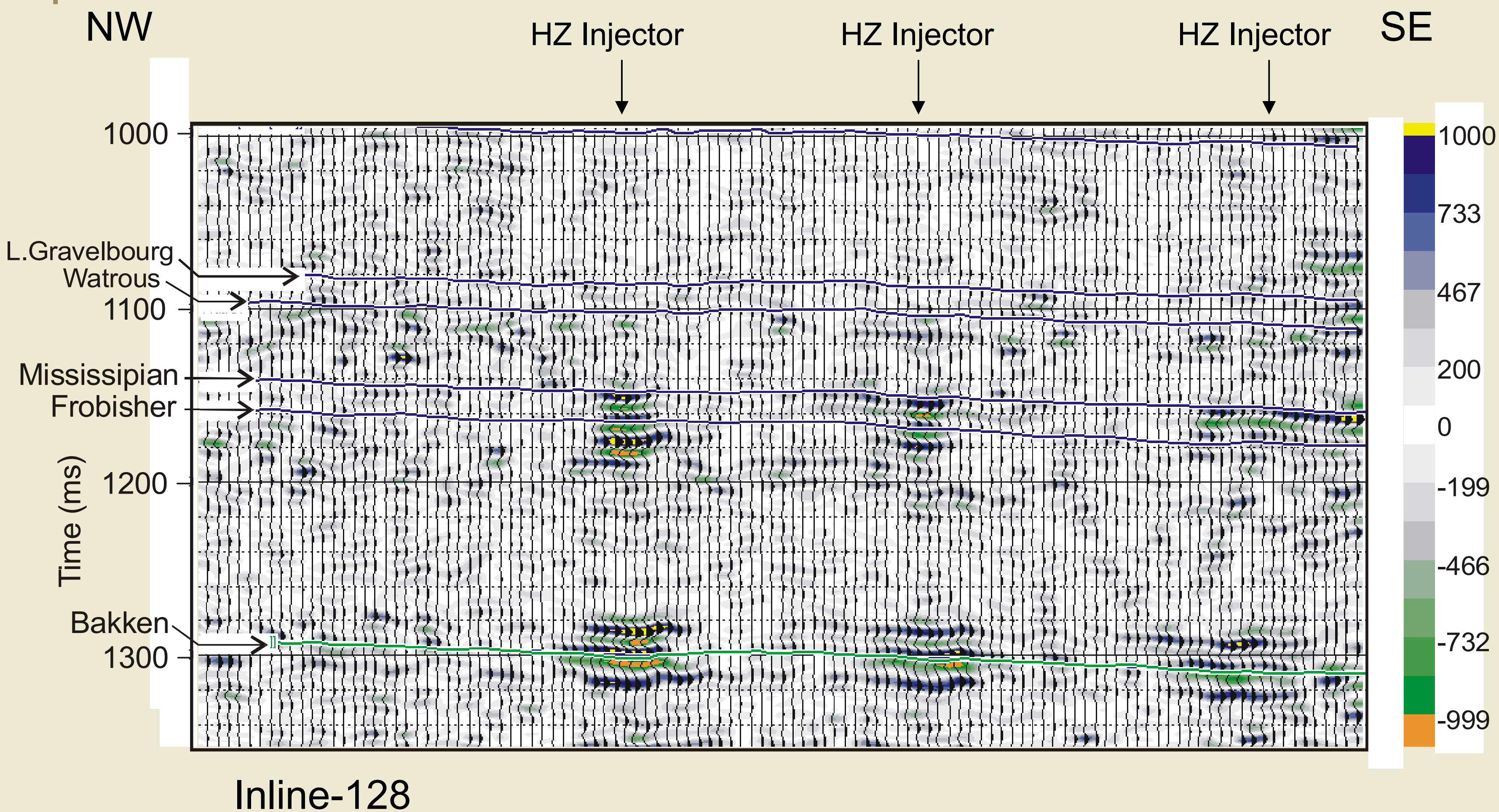
Monitoring Schedule



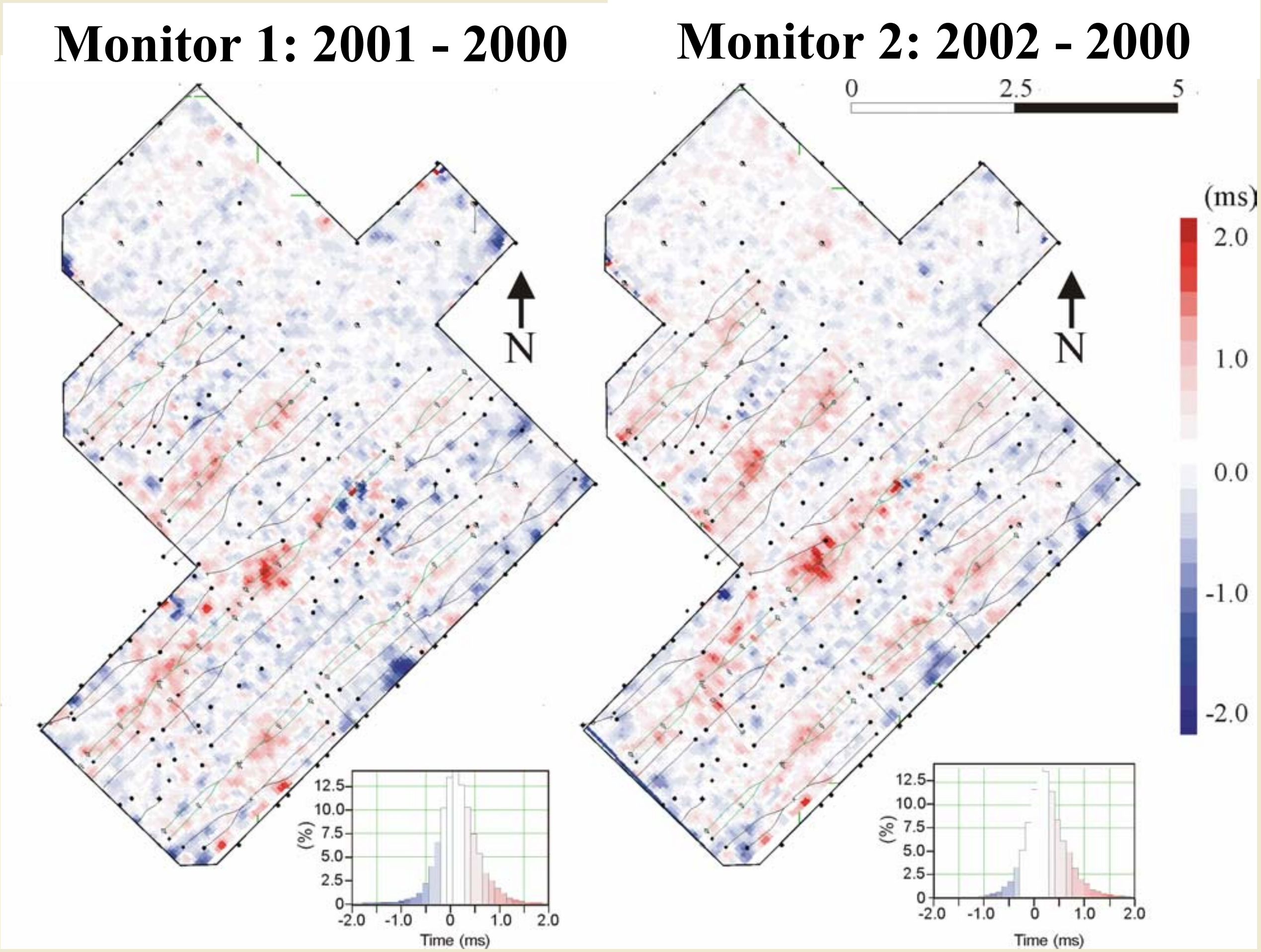
Time-Lapse Seismic

- P- and S-Wave
- Time delays
- Amplitude differences

Monitor 2 Time-Lapse Image

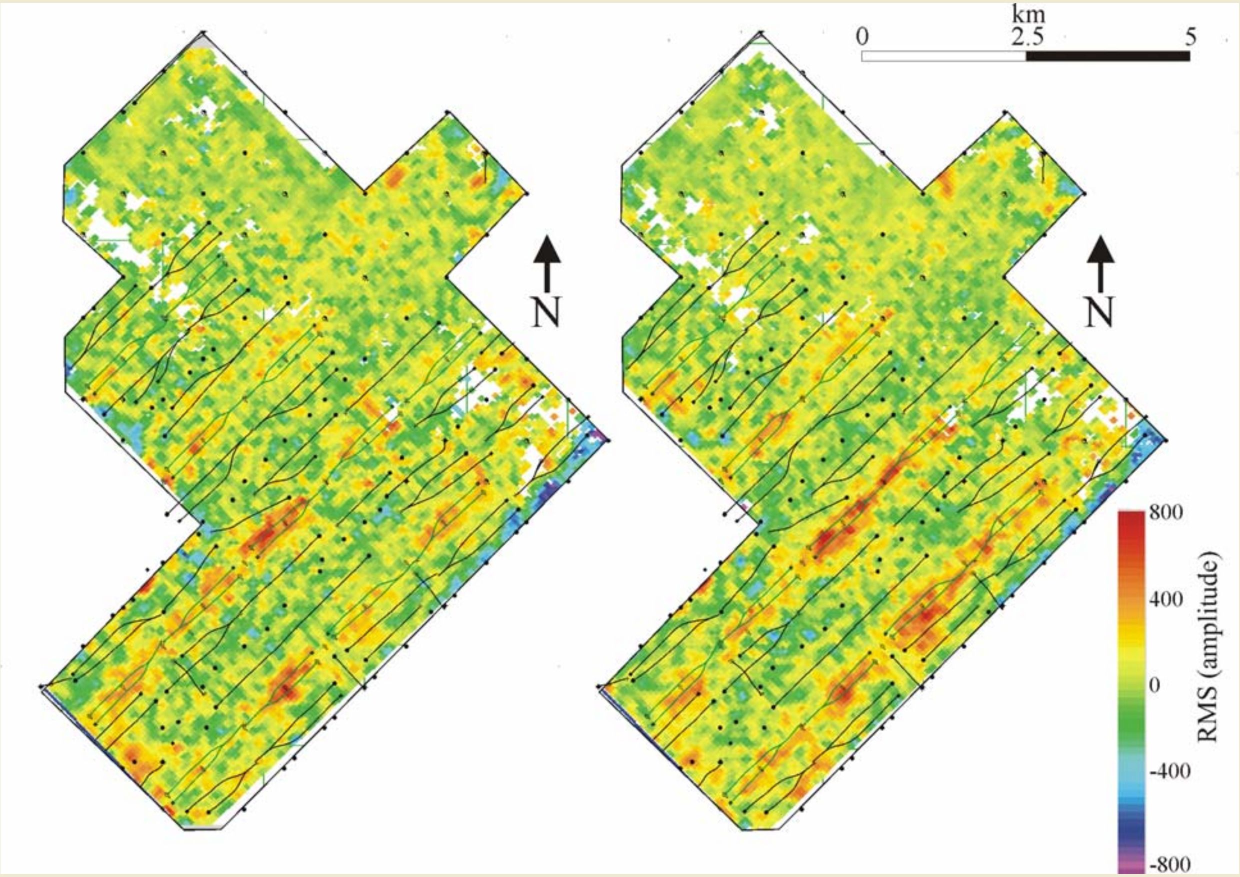


Monitor 1 and 2 Time delay map

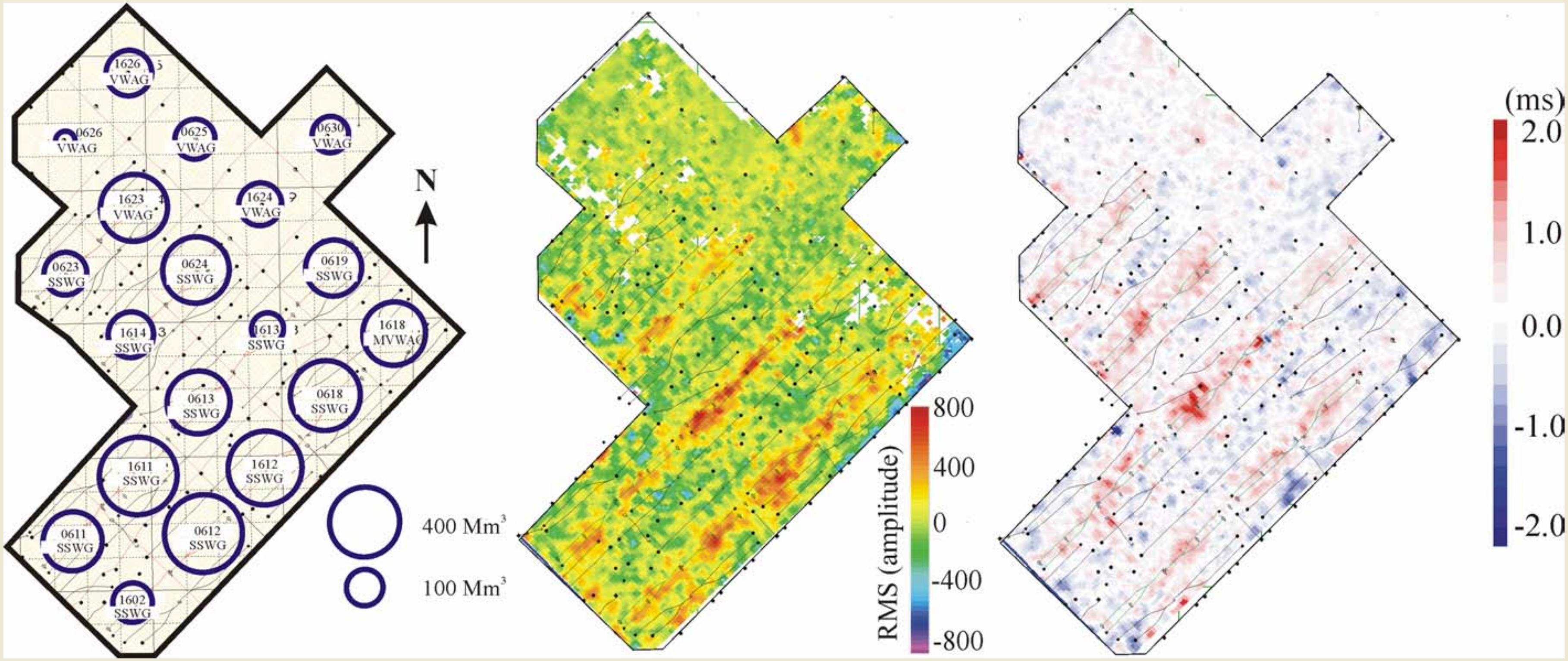


Monitor 1 and 2 Amplitude difference

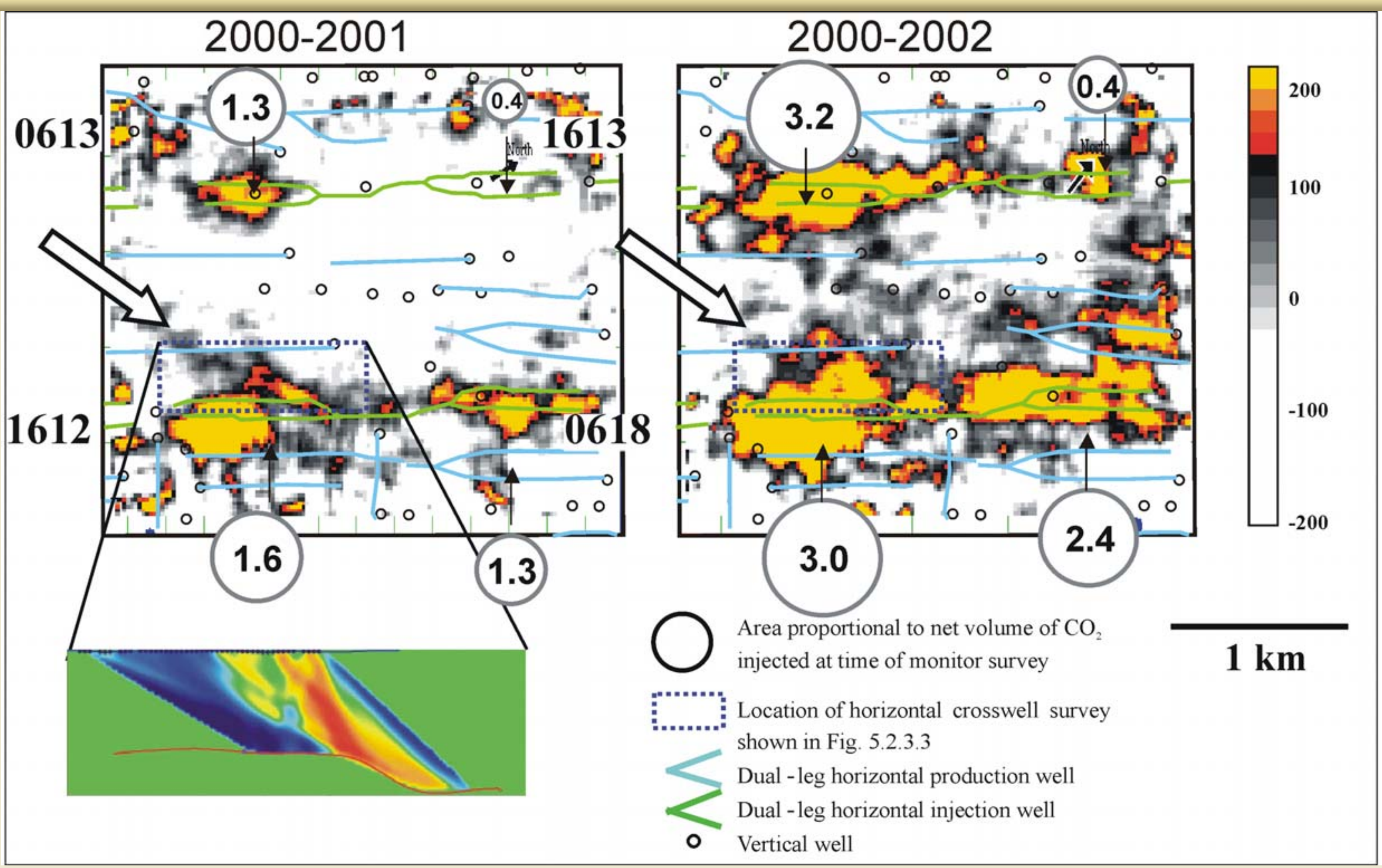
Monitor 1: 2001 - 2000 Monitor 2: 2002 - 2000



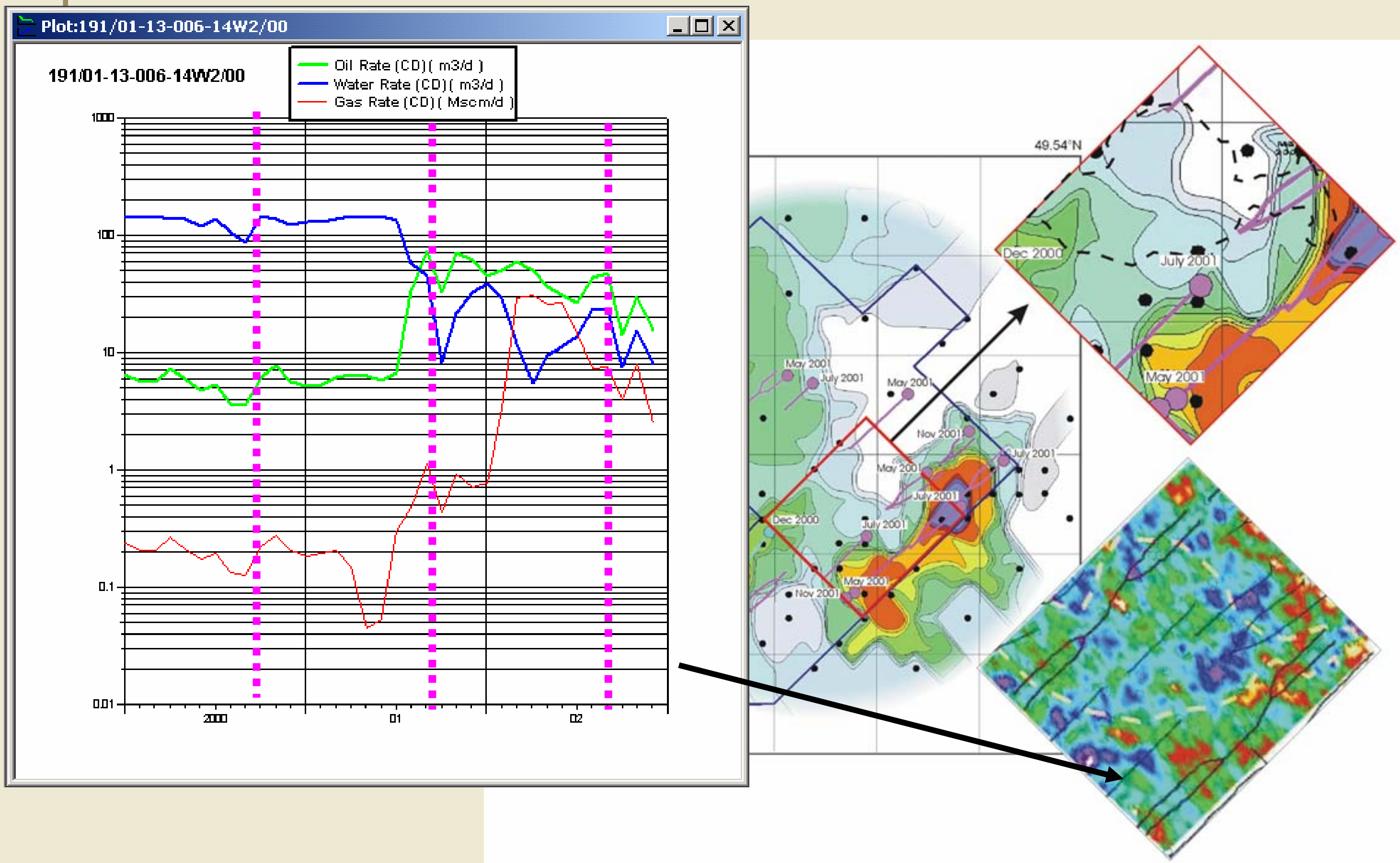
Monitor 2 Production-Seismic Comparison



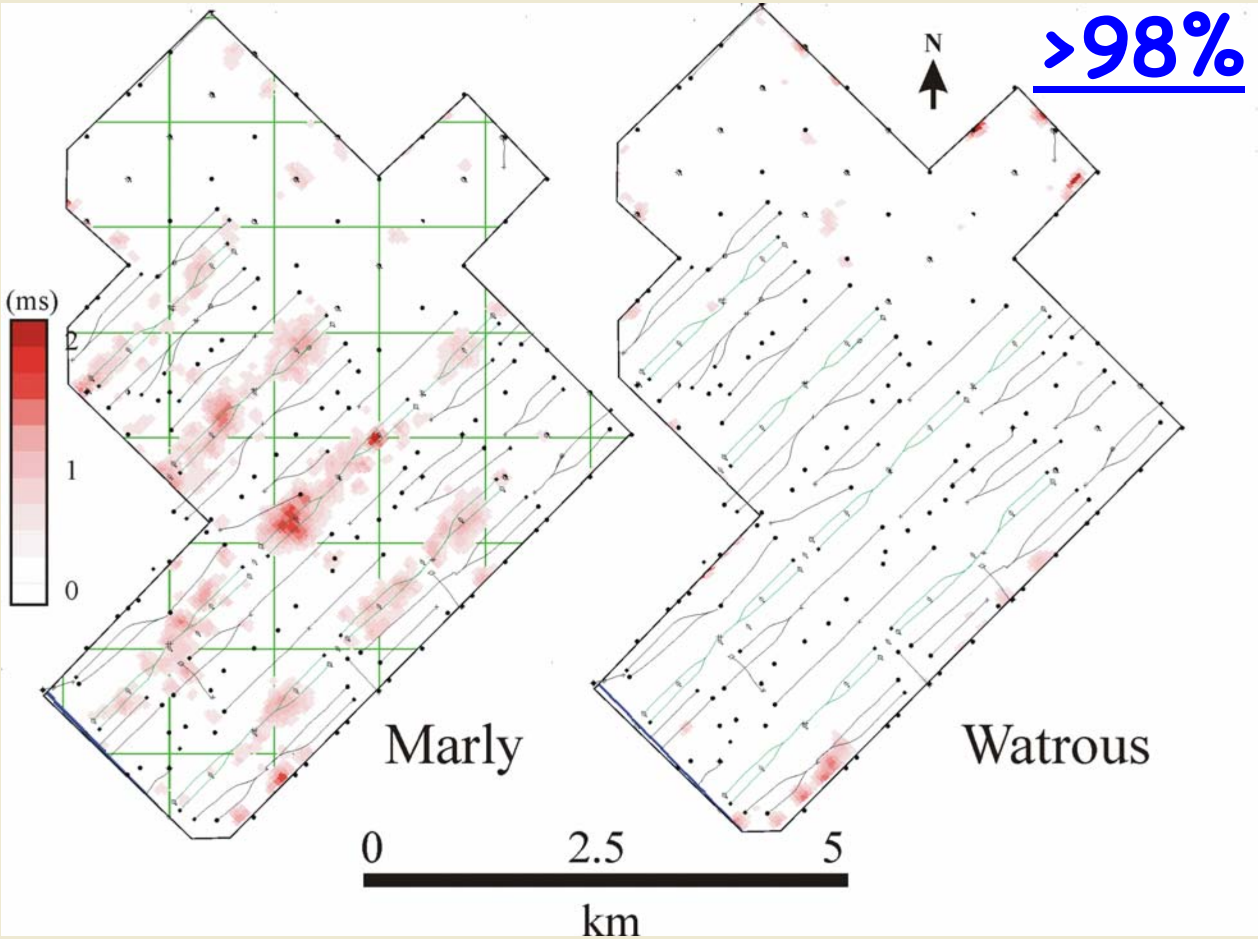
Amplitude Anomalies at the Reservoir



S-wave and Geochemical Anomalies

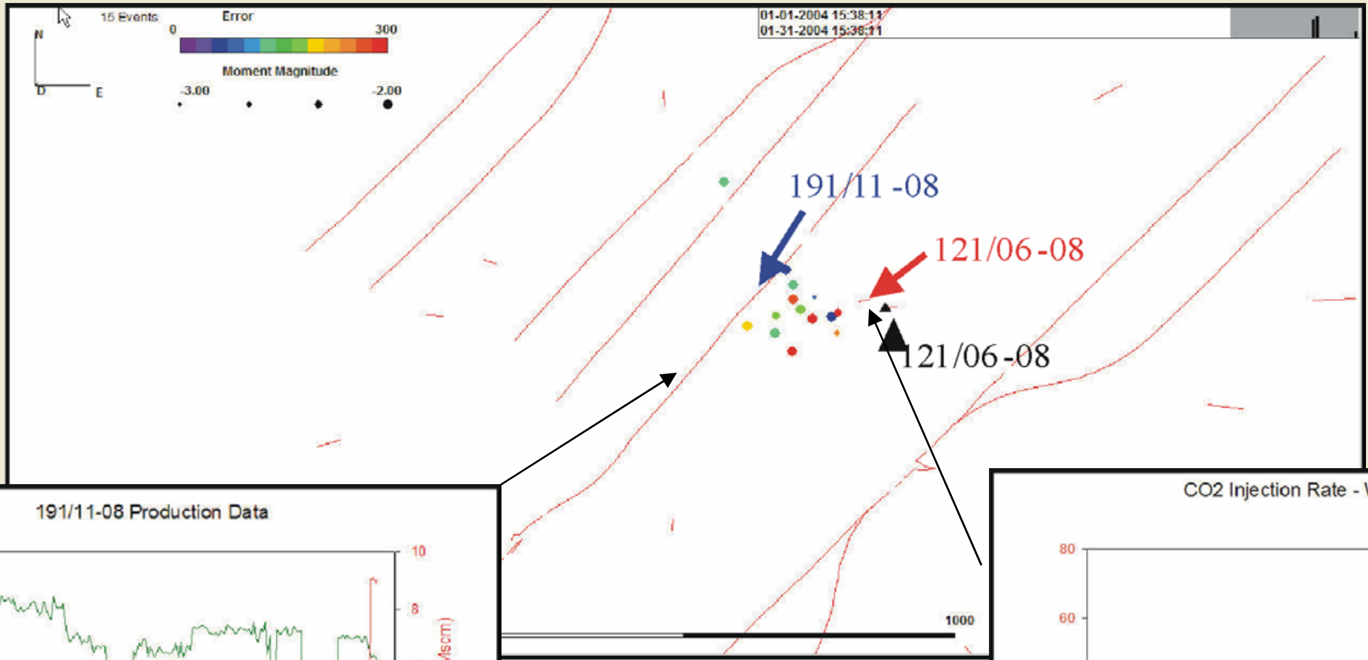


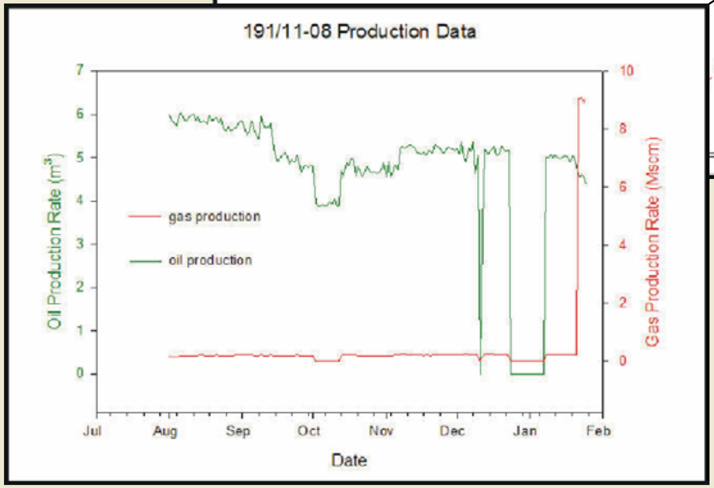
Containment Estimate from Seismic

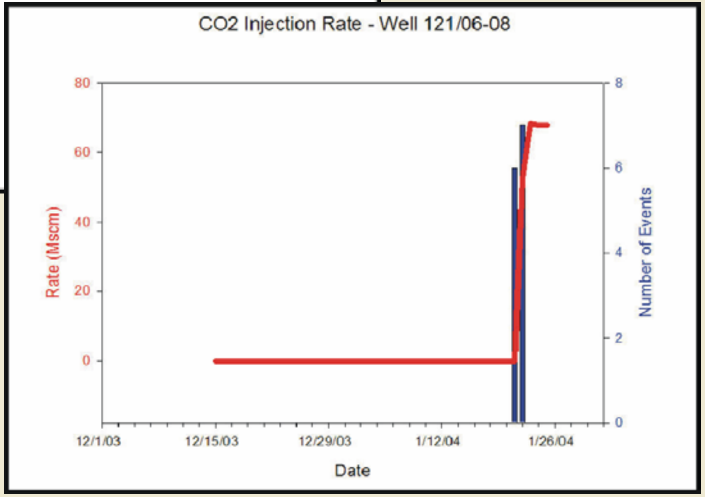


No Evidence for leakage!

Microseismicity: Plan View

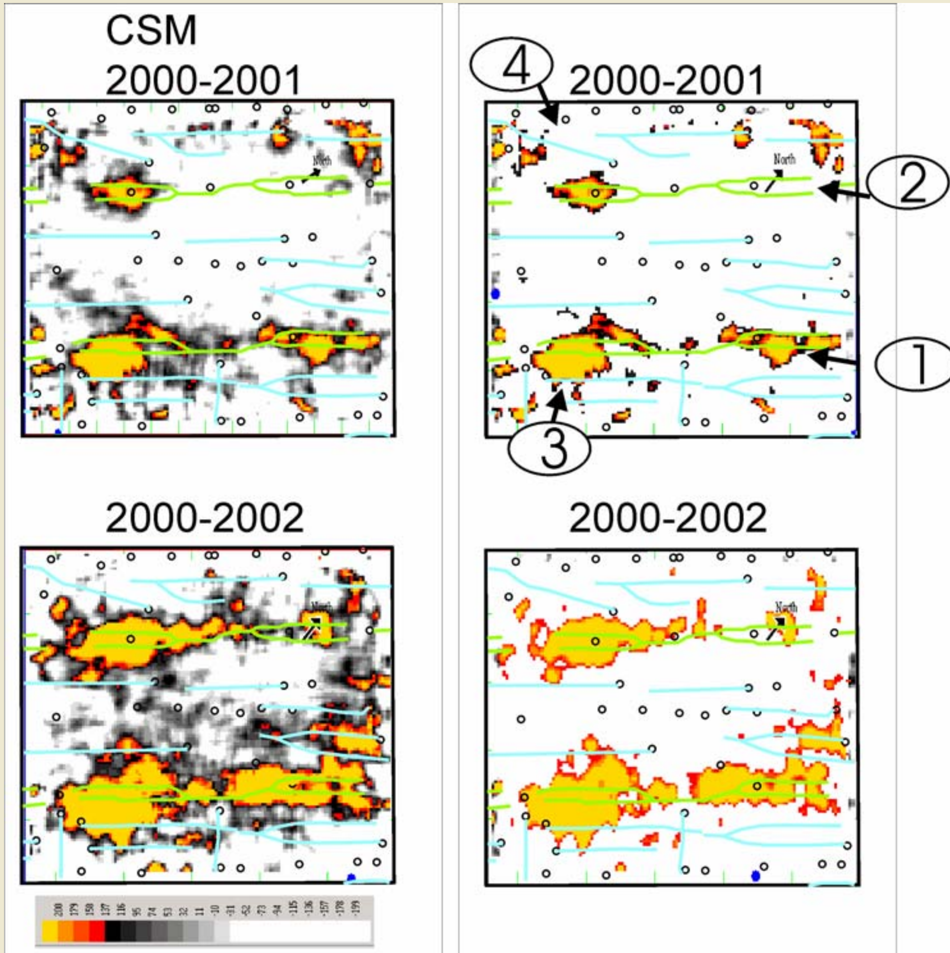






4. Verification & Improved Prediction

First-Order Volumetrics



<u>Reservoir Properties:</u>

T=63 deg C

P= 15 MPa

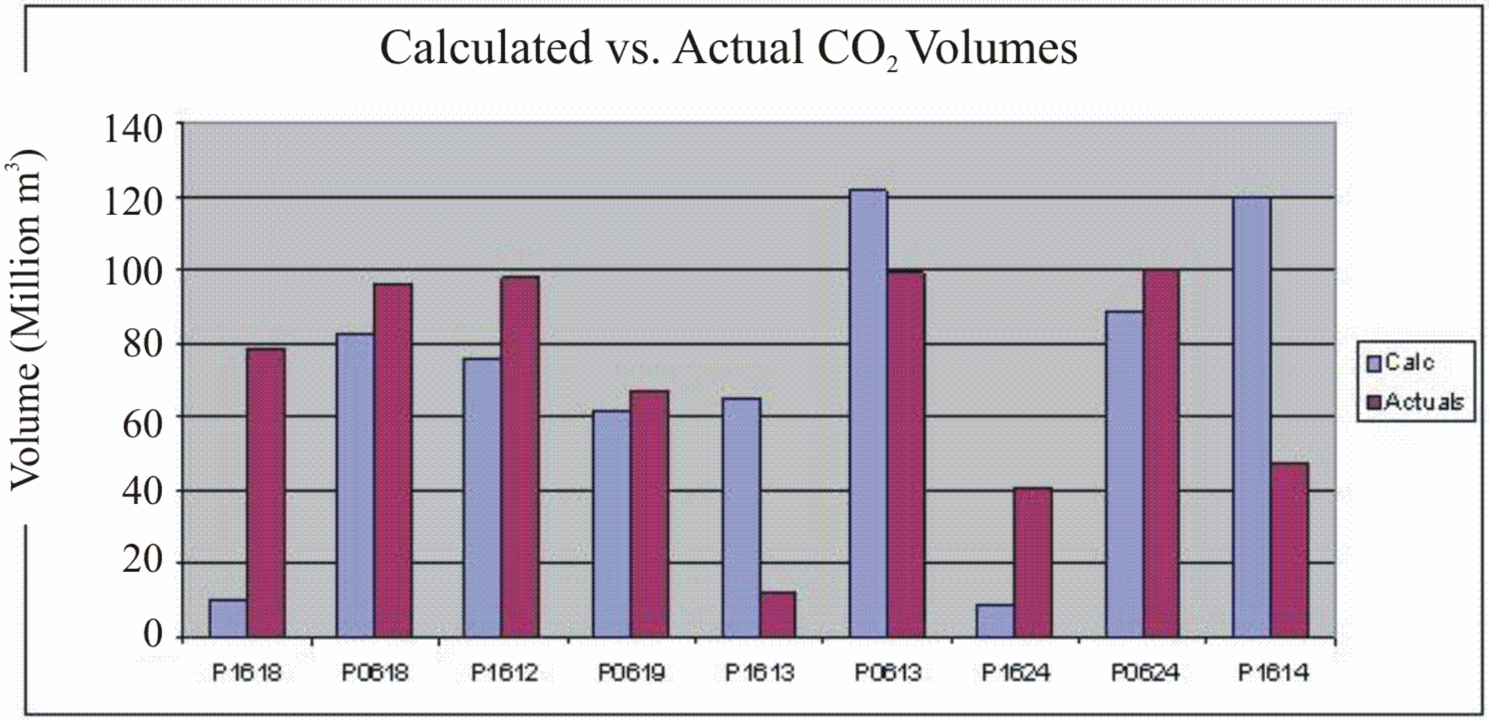
Porosity=0.13

Thickness=23 m

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

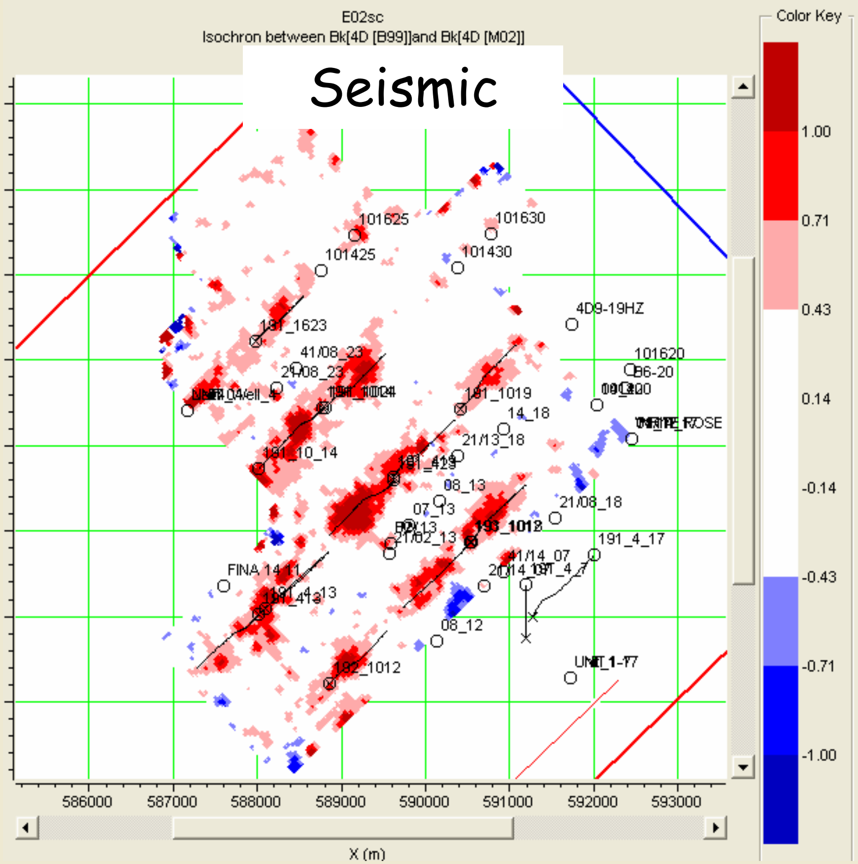
Mean Saturation=0.19-0.23

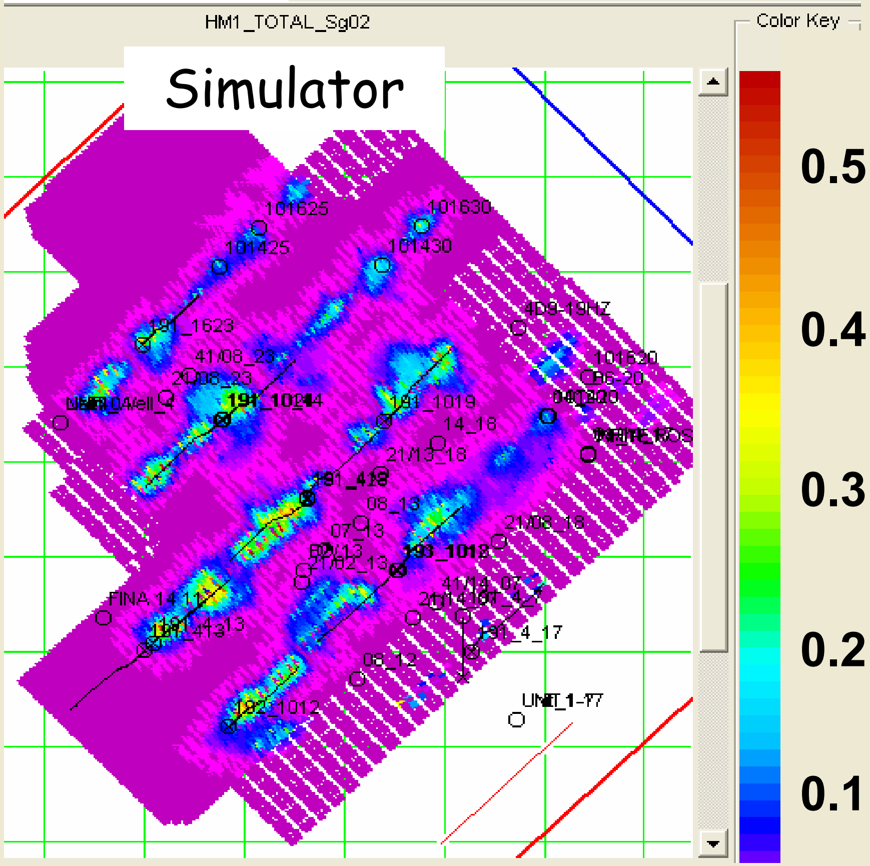
Net CO_2 injected vs seismic estimate



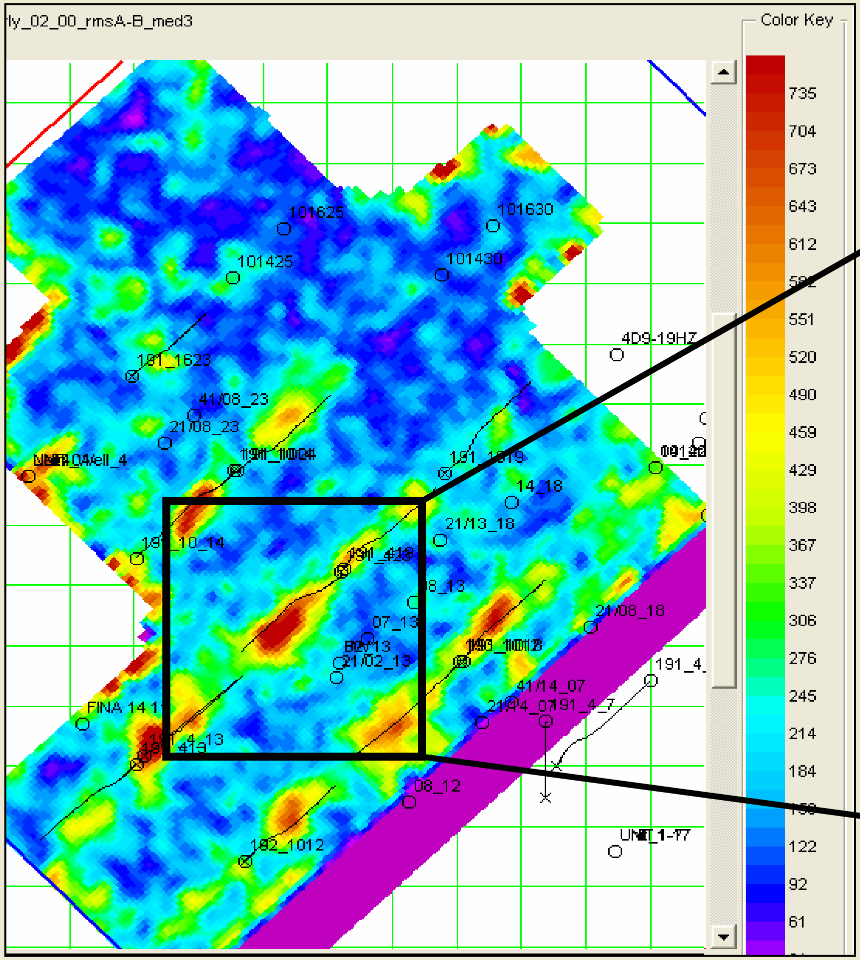
Assumes average Sg of 0.20

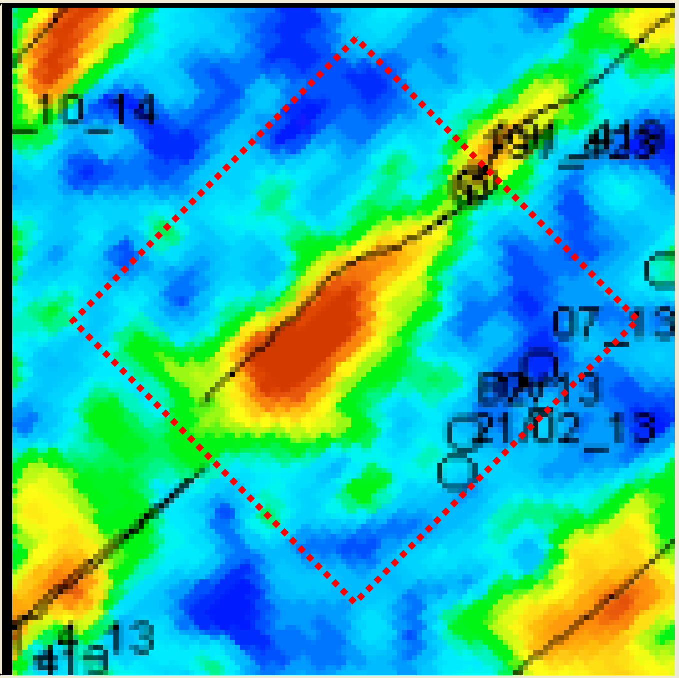
CO2 distributions from Seismic and Simulator, 1st iteration (Monitor 2 Survey)



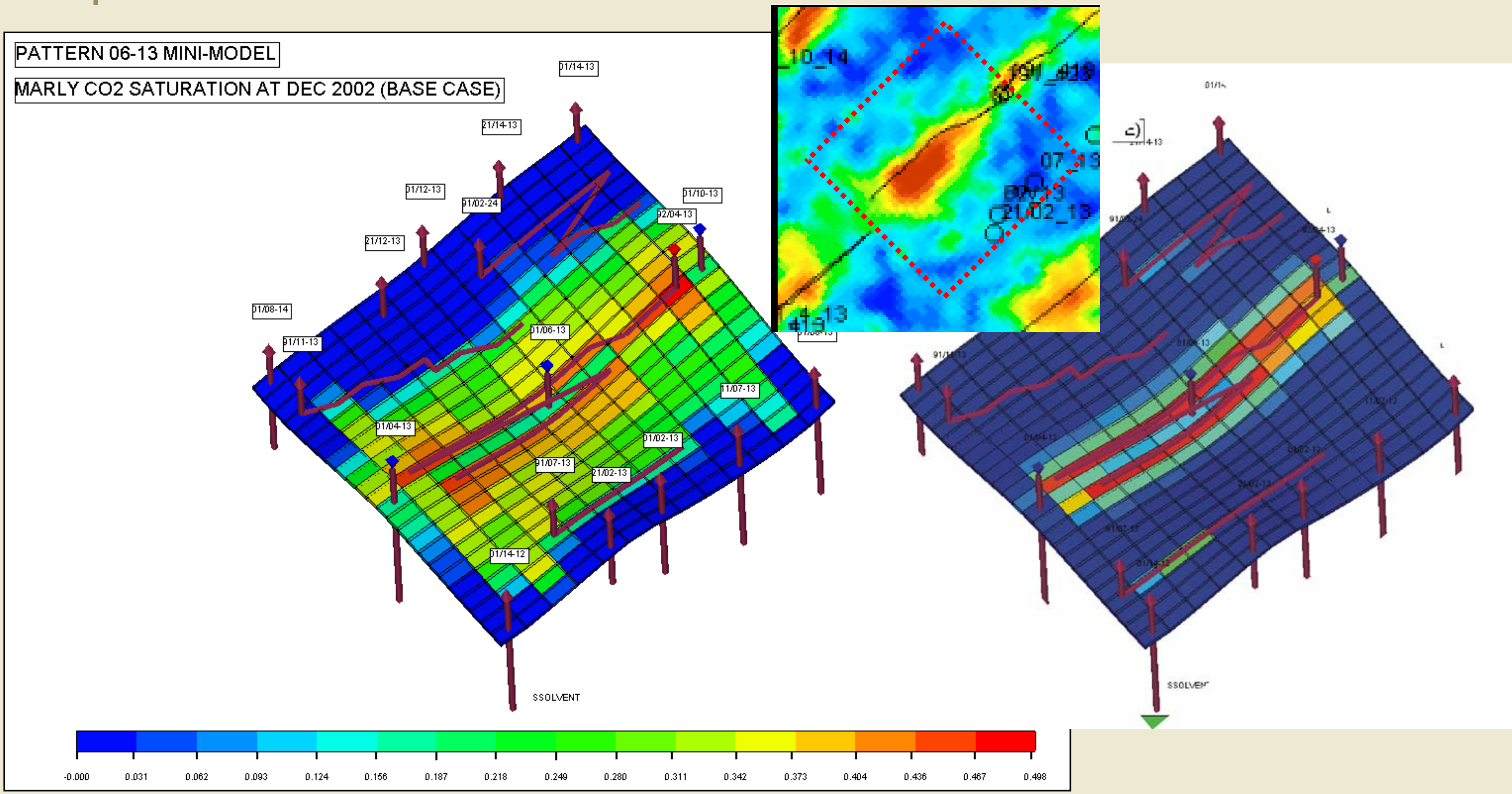


Pattern 06-13-006-14W2 Monitor Amplitude Difference for Marly Unit Only

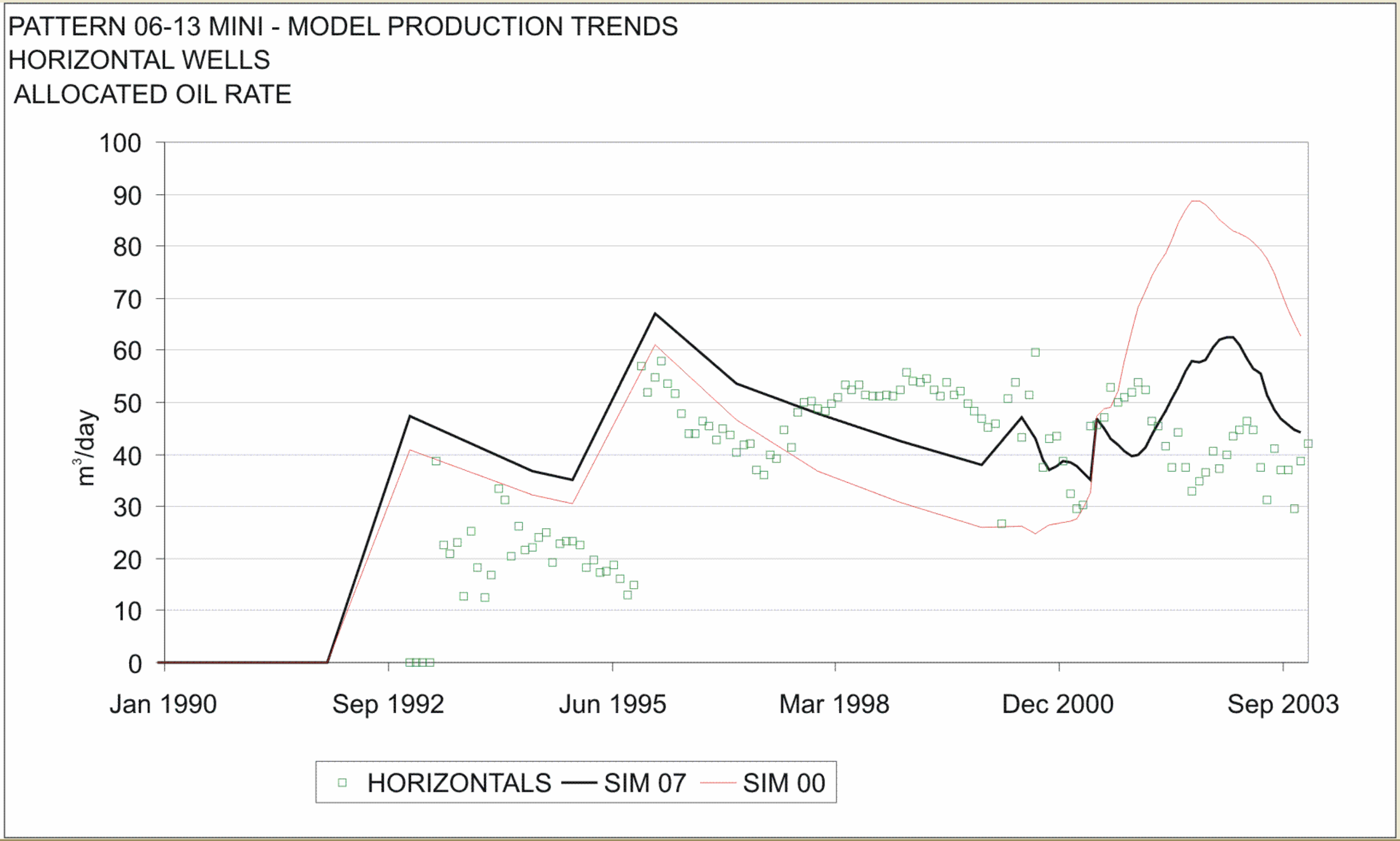




Marly CO2 Saturation for Rev 0 Model



Improved history match



Summary & Conclusions

- **Monitoring methods** clearly show physical and chemical effects associated with CO_2 injection.
- **Seismic** methods show **robust time and amplitude anomalies**.
  - P-wave amplitudes are highly sensitive to CO_2-rich gas phase at low levels of **saturation (5-10%); good for detection**, but makes volume estimation difficult.
  - Volumetric analysis of seismic anomalies: **mean CO_2 saturation of ~20%,** similar to reservoir simulator results.
  - Vp changes of up to 12%: **mainly Sg** with **secondary P effects (2-3%)**.
  - Off-trend anomalies identify areas of **CO_2 channelling.**
  - Sensitivity of amplitude response to upper reservoir changes (Marly unit) allows **partial discrimination of vertical CO_2 distribution.**

Summary & Conclusions

- **1.4 million m^3 (2500 tonnes)** of CO_2 is the **minimum detectable amount** using time-lapse surface seismic. This estimate may be overly conservative by an order of magnitude.
- **No evidence for CO_2 escaping** from the reservoir. Based solely on the seismic results, the maximum amount of CO_2 that may have migrated above the reservoir is **<2% of the total injected volume**.
- Contribute to more **accurate reservoir flow simulations.**

- **Microseismicity** is **low** level.
  - 60 microseismic events with M=–3 to –1 during 6-months.
  - Events associated with production/injection changes (*e.g.*, water-to-gas) where **pressure transients** might be expected.
  - Induced microseismicity is **less than for water flooding** that has occurred for more than 30 years.

Further Research: Refinement of Techniques

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

IEA Weyburn CO_2 Monitoring and Storage Project

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Program Led by the PTRC Based
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QUESTIONS ?

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As well as 8 Industry Sponsors:

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

IEA GHG Weyburn CO_2 Monitoring and Storage Project

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

Petroleum Technology Research Centre

IEA Greenhouse Gas R&D Programme

EnCana

Geochemical Monitoring and Modeling Of The Weyburn CO_2-Injection EOR site, Saskatchewan, Canada

Kyle Durocher, Bill Gunter & Ernie Perkins
Alberta Research Council

Alberta Research Council

International Energy Agency - BP
CO_2 Monitoring Workshop
8-9 November, 2004, UC-Santa Cruz, California

Outline

Monitoring & Experiments

• Detailed field fluid sampling program, for approximately 50 wells, started before CO_2 injection and ***still continuing.***
• Detailed mineralogical analysis of the Weyburn Midale reservoir and the adjacent geosphere.

Prediction

• Modeling of the *potential* reactions in the reservoir over a 5,000 year period.
• Modeling of *potential* reactions in the adjacent geosphere.

Geochemical Monitoring

- Twelve sampling surveys: 1 Baseline (pre-injection) and 11 Monitor (syn-injection).
- Produced brine, gas, and oil are collected from 50-60 wellheads, 40 geochemical & isotopic parameters measured for each sample.

- Net result is a database with approximately 25,000 analytical entries. **These are the only *direct* measurements of CO_2 interaction with reservoir brine, gas, oil, and minerals.**

CO_2-Water-Rock Reactions

Within a dominantly carbonate reservoir, two primary reactions are observed as a result of CO_2 injection:

- **CO_2 Dissolution**

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

- **Carbonate (calcite) Dissolution**

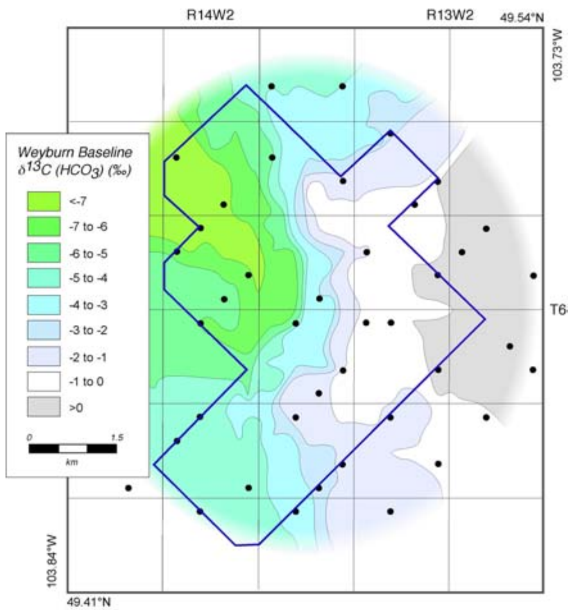
$$CO_2 + H_2O + CaCO_3 \leftrightarrow Ca^{2+} + 2HCO_3^-$$

Certain measured geochemical parameters best illustrate these processes…

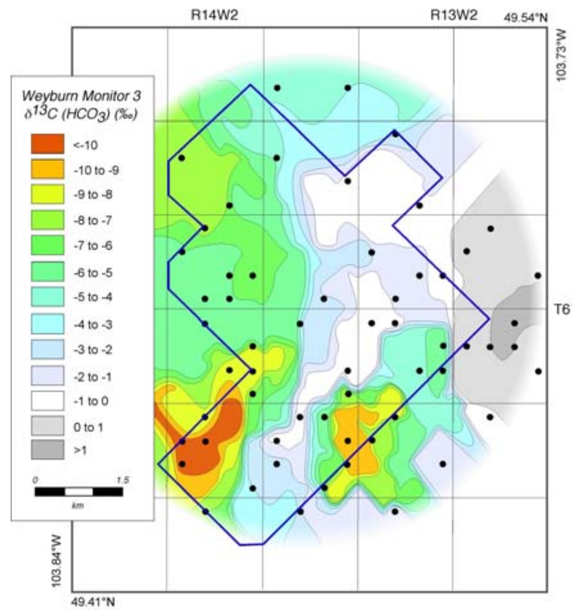
Injected CO_2 Dissolution

$\delta^{13}C_{HCO3}$ in produced fluids

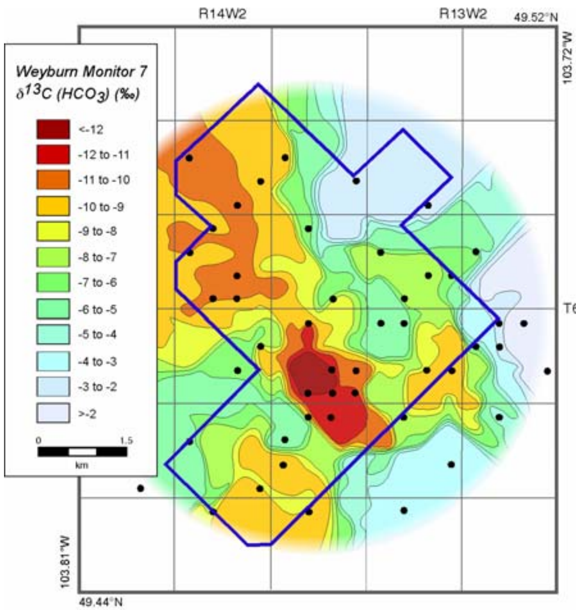
Pre-injection



12 months



31 months



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

Injected CO_2: $\delta^{13}C$=-20‰

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

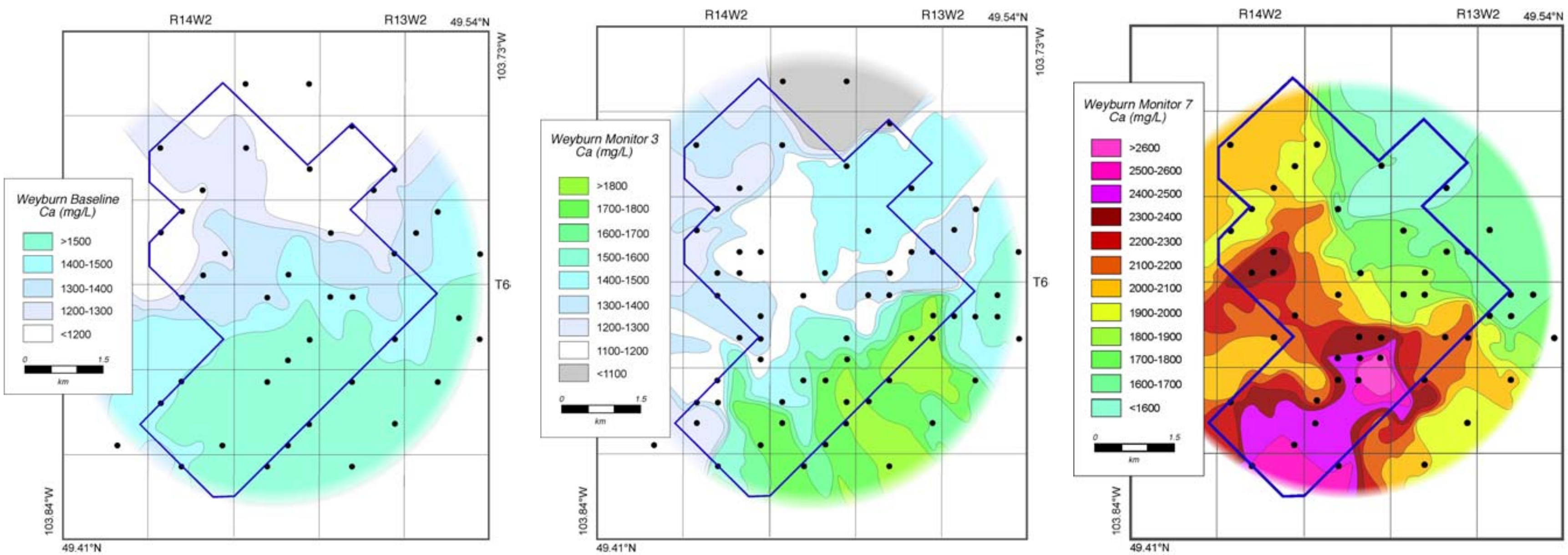
Reservoir Mineral Dissolution

Ca^{2+} in produced fluids

Pre-injection

12 months

31 months



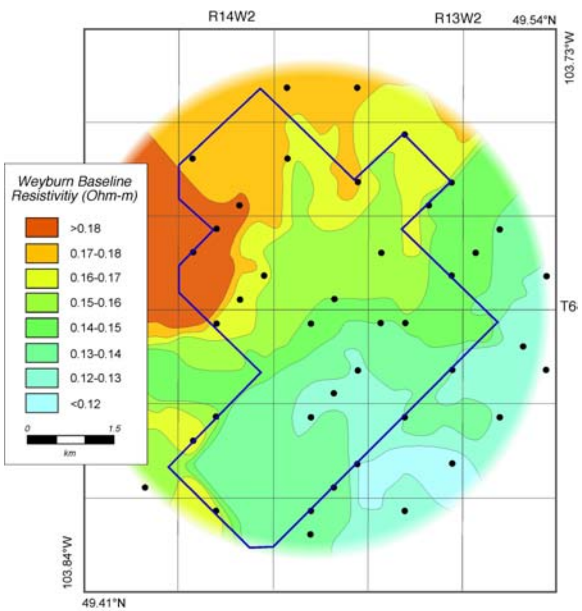
Calcite and dolomite dissolution increases the Ca^{2+} and Mg^{2+} concentrations in produced fluids.

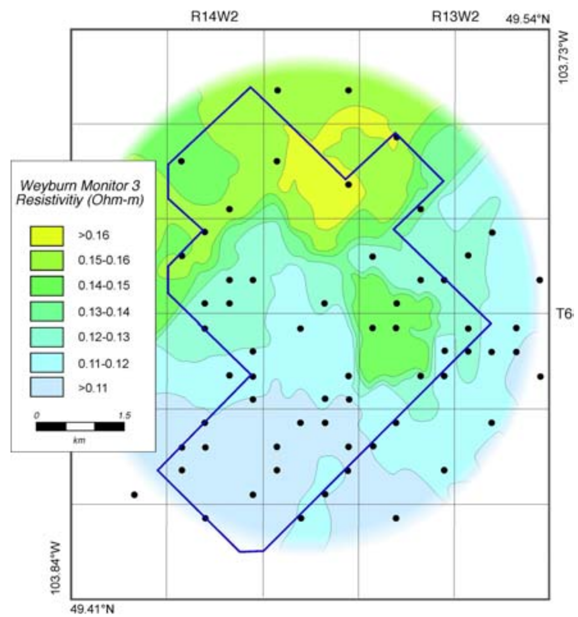
$$CaCO_3 + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2HCO_3^-$$

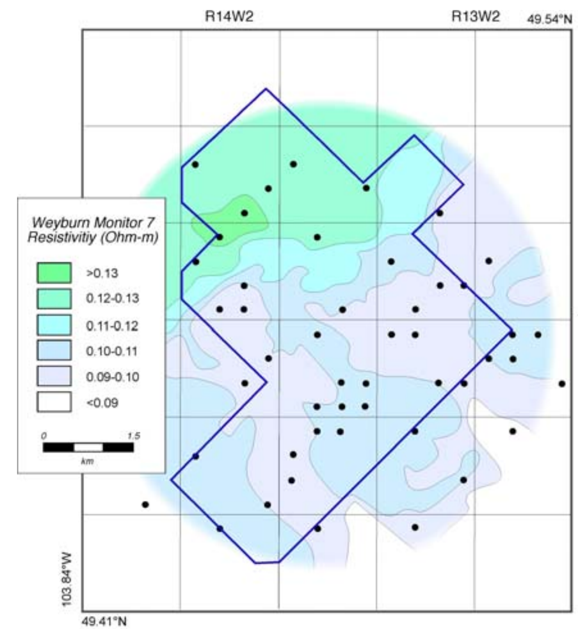
Enhanced Sweeping of Reservoir

Resistivity of produced fluids

Pre-injection	12 months	31 months





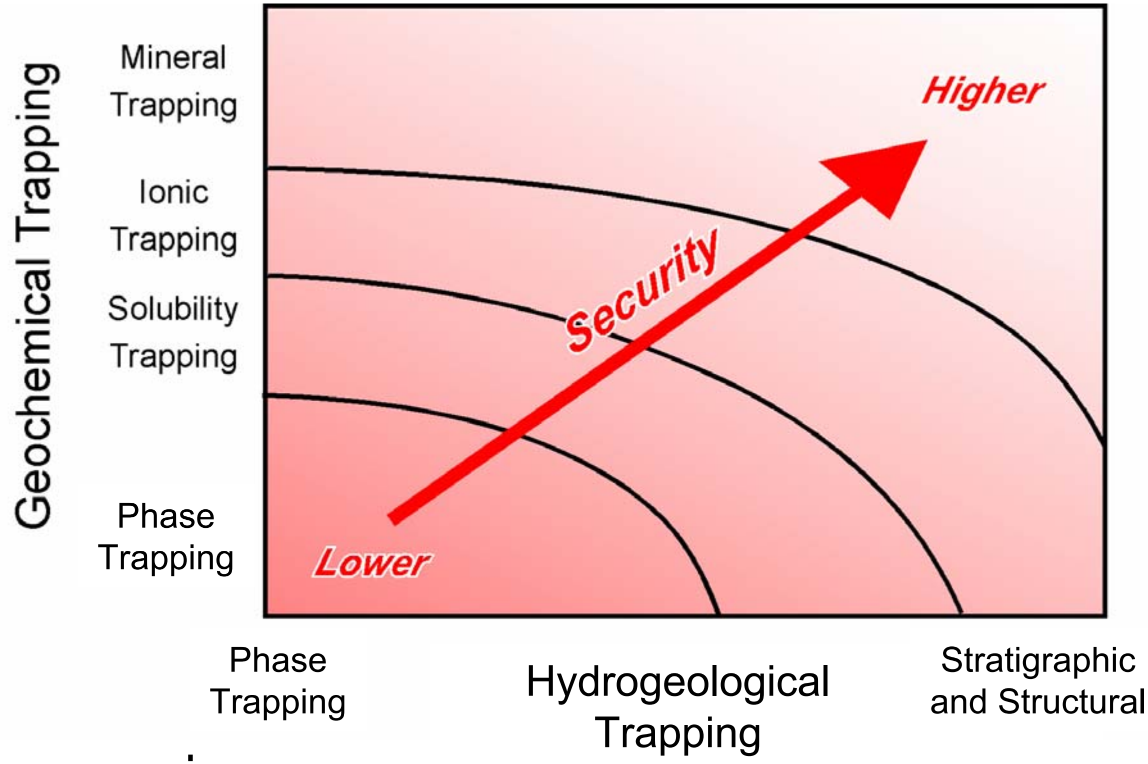


- Resistivity decreasing with time (i.e. conductivity increasing).
- TDS dominantly a function of dissolved Na^+ and Cl^-.
- The CO_2 sweep may be producing previously inaccessible saline fluids from the Midale beds.

Prediction of Geochemical Storage

How much CO_2 is stored via:

- Solubility trapping
- Ionic trapping
- Mineral Trapping

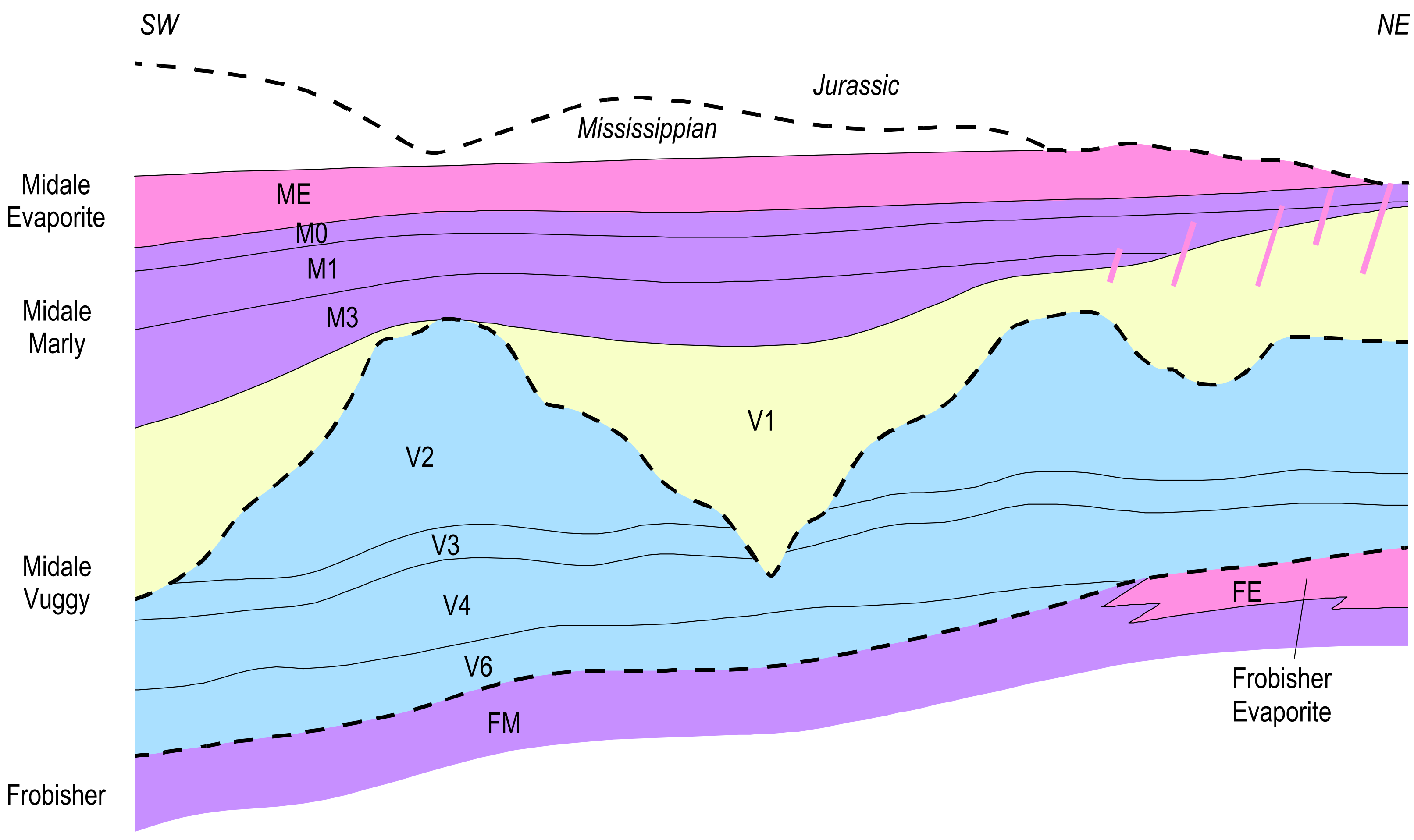


Details:

- Model the Weyburn Midale reservoir
- Model the adjacent geosphere.
- Kinetic based reactions over a 5,000 year period.
- Data based on the field monitoring study

CO_2 Storage in the Weyburn Reservoir

- 15 drill cores sampled, 93 total samples, sampled by “flow unit”.
- Semi-quantitative mineral norms.



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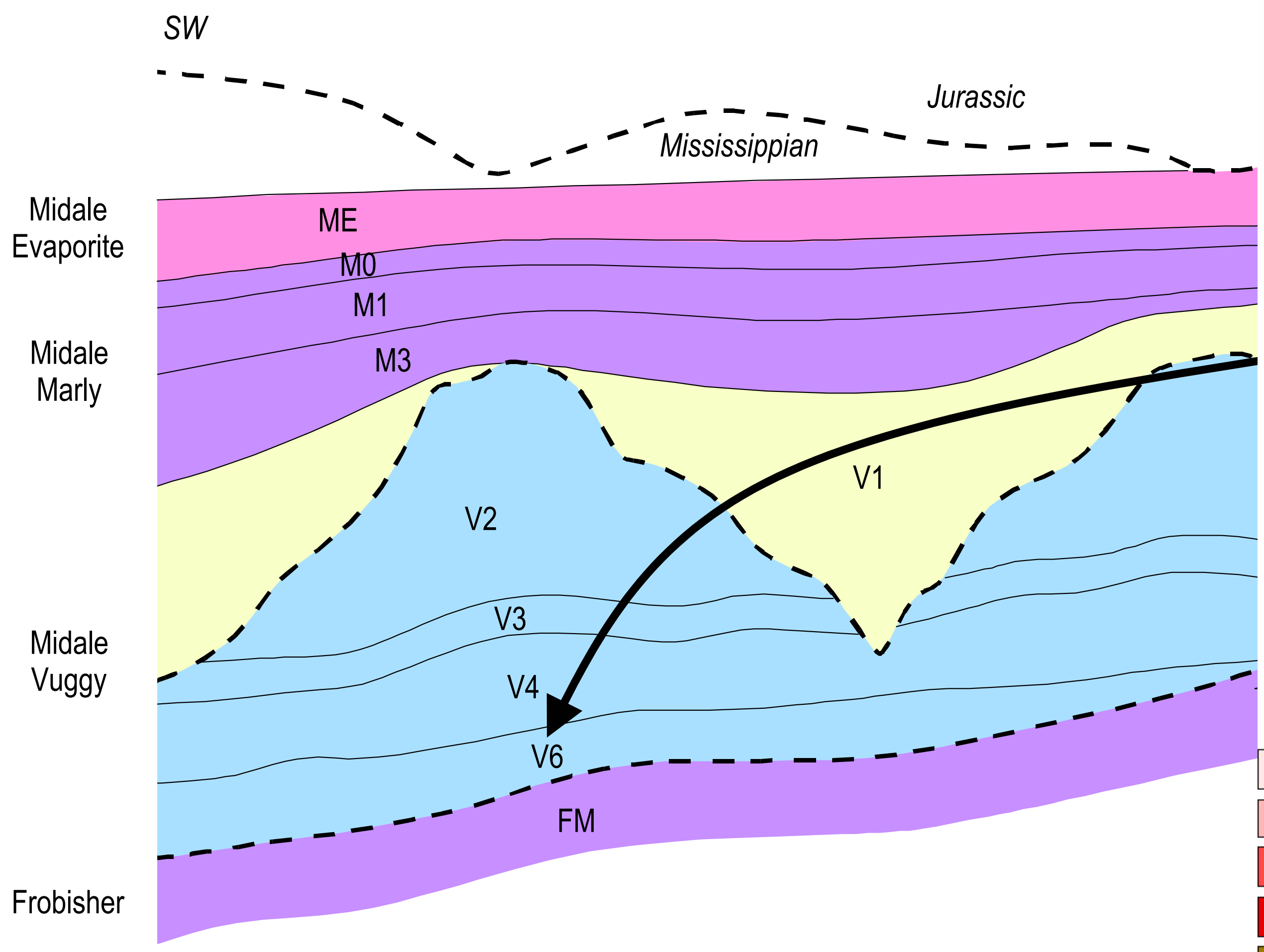
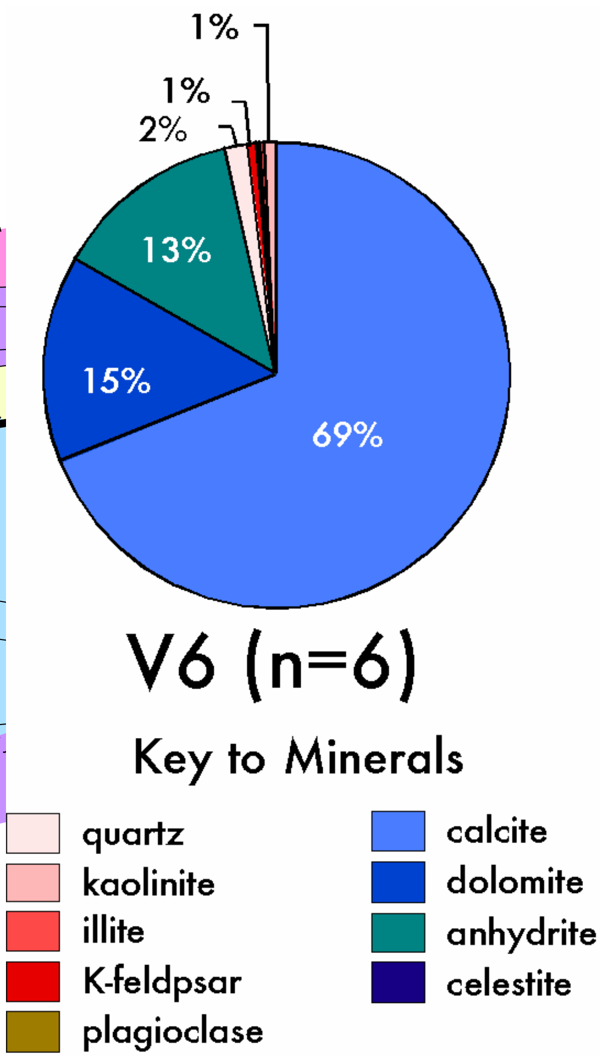
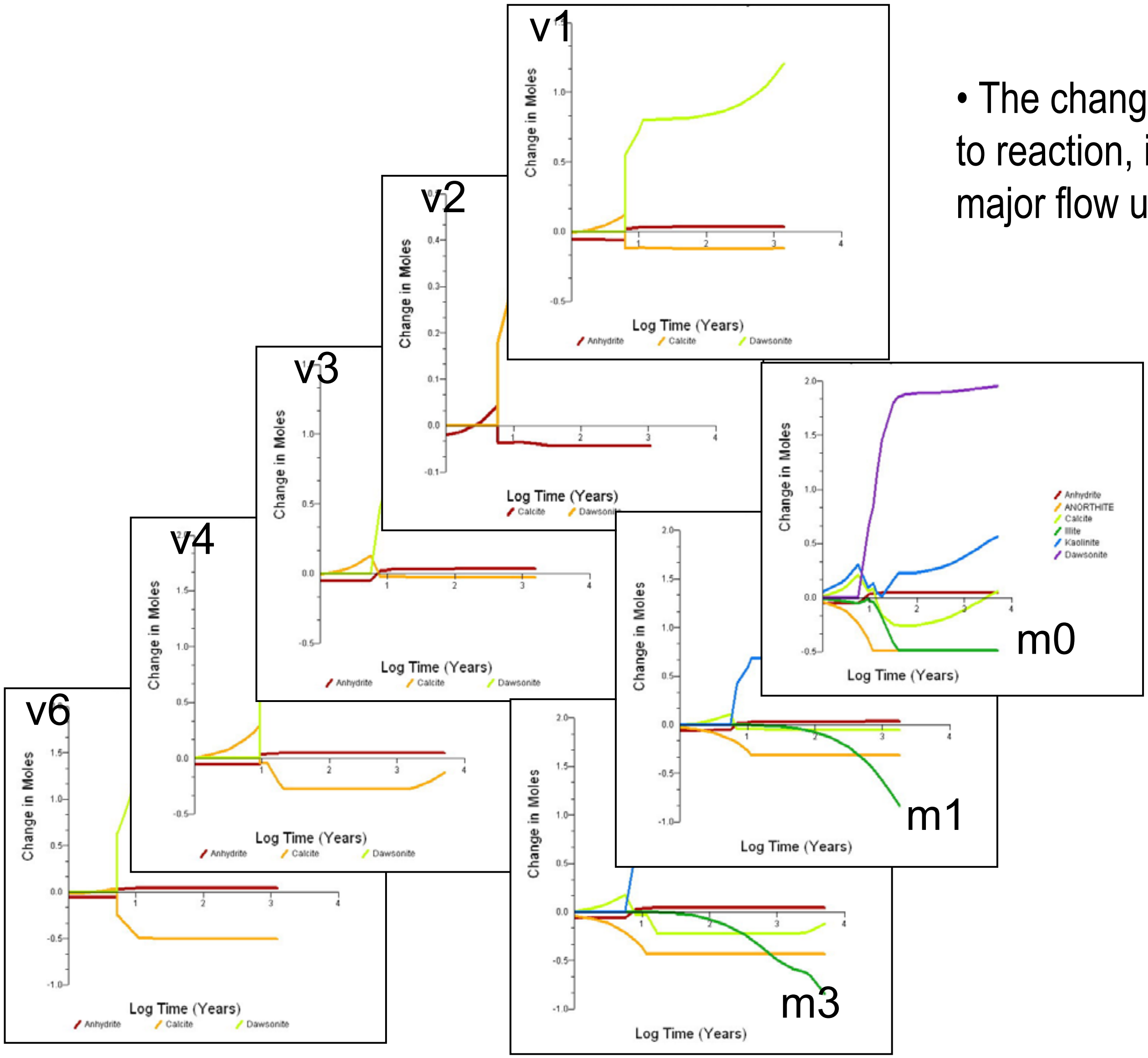




Geochemical Modeling Results – Weyburn Midale Reservoir



- The change in the amount of solids, due to reaction, is shown for in each of the major flow units as a function of time.

- Short term effects are dominated by carbonate dissolution.

- Long Term effects are controlled by silicate reactions driving carbonate precipitation.

Maximum Potential CO_2 Trapping in the Weyburn Midale Reservoir

~ 45 Million tons of CO_2 potential geochemical trapping

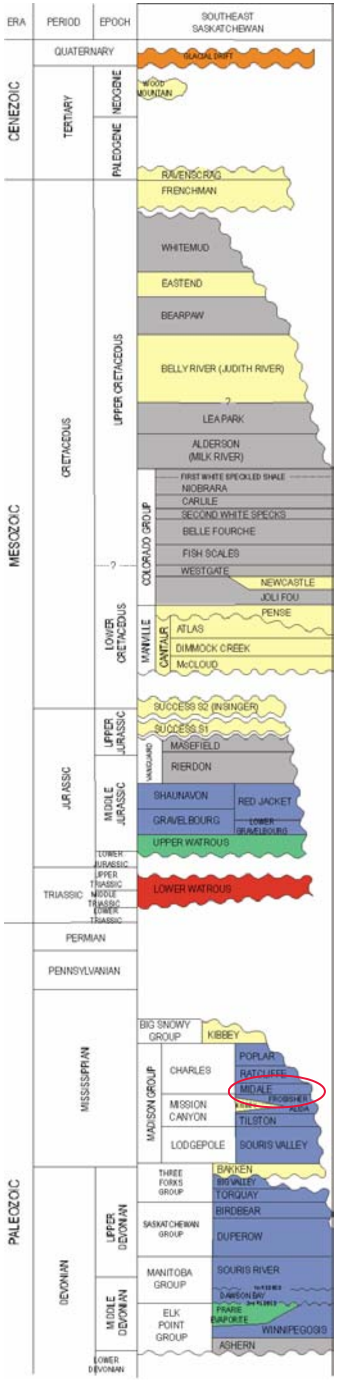
- 22.5 Million tons Solubility trapping of CO_2
- 0.257 Million tons Ionic trapping of CO_2
- 22.3 Million tons Mineral trapping of CO_2

~ 20 Million tons CO_2 planned injection.

Thus, the Weyburn Midale reservoir has **excess** greenhouse gas storage potential.

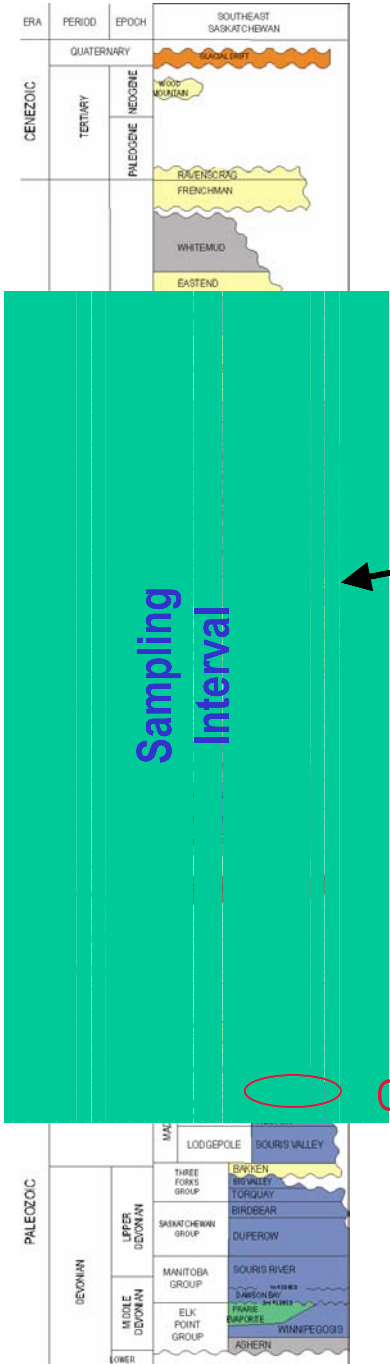
These are the maximum potential storage values for a 5,000 year period. All silicates assumed to be available for reaction. Sufficient CO_2 must be present in each flow unit – not necessarily the case.

Should CO_2 Escape the Reservoir

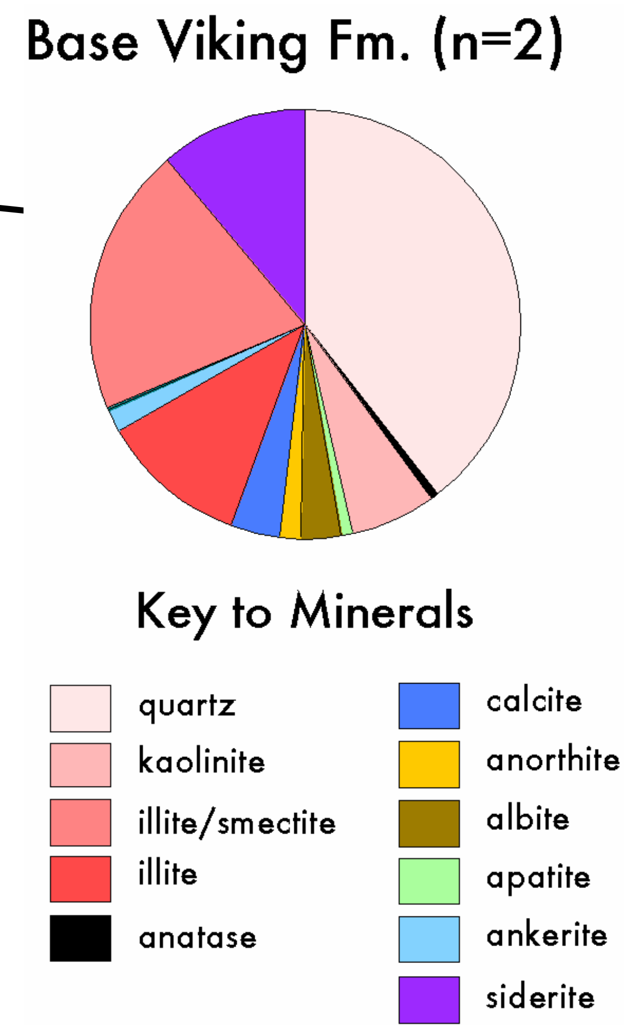


CO_2 into Midale beds

Should CO_2 Escape the Reservoir



CO_2 into Midale beds



Potential for CO_2 Mineral Trapping in the Adjacent Geosphere

• Abundant silicate mineralization, CO_2 storage potential “infinite”.

Formation	Tons CO_2 *
Bearpaw	15100
Belly River	15000
Lea Park	15000
Lower Colorado	15000
Top Viking	15500
Base Viking	14500
Mannville	4480
Vanguard	14900
Upper Shaunavon	23800

Formation	Tons CO_2 *
Upper Gravelbourg	77
Lower Gravelbourg	-600
Upper Watrous	19400
Lower Watrous	8060
Poplar	14200
Ratcliffe	-709
Frobisher	2700
Kisbey	4890

** Tons CO_2 per square kilometer per meter thickness of formation*

• Negative values reflect carbonate mineral dissolution, resulting in increased alkalinity & lowering of P_{CO2} in the fluid.

• These are the maximum potential storage values for a 5,000 year period. All silicates assumed to be available for reaction. Sufficient CO_2 must be present in each flow unit – not necessarily the case.

Conclusions - 1

- Geochemical monitoring program has resulted in a unique analytical data set over 3+ years, encompassing over 50 wells, showing the changes in reservoir chemistry as a function of CO_2 injection.

- Three primary processes take place as a result of CO_2 injection:

1) CO_2 dissolution - decrease in $\delta^{13}C_{HCO3}$, increased TDC
2) Enhanced sweep of reservoir fluids - high TDS, lower resistivity
3) Carbonate dissolution - increase in $\delta^{13}C_{HCO3}$, increased total alkalinity, and $[Ca^{2+}]$

Conclusions - 2

- Geochemical modeling has established that:

  1) There is excess storage capacity (solubility, ionic and mineral) in the Weyburn Midale reservoir.

  2) Much of the geosphere above and below the reservoir has a high mineral trapping potential.

Techniques and Limitations

Limitations

• are fluid, gas, and mineralogical samples representative (e.g. phase separation at wellhead)?

• mass transfer models – what is the reactive surface area? % mineral surface exposed to pore space? kinetic database issues

• mass transport models – can permeability changes coupled with mineral reactions be accurately modeled?

New Techniques

• wellhead versus downhole (e.g. U-tube) sampling

• in-line “continuous” measurements of gas compositions

Barriers to Use

• weather (cold weather freezes wellhead)

• water producer shut-ins and variable gas/water injection rates must be factored into models

Further Research to Improve Confidence

• Calibrate forward models by improving geological & hydrogeological models & improving kinetic mineral data

Sponsors

Natural Resources Canada | Ressources Naturelles Canada

Saskatchewan Industry and Resources

European Commission

As well as 8 Industry Sponsors:

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

In Salah Gas

Carbon Dioxide Storage

The In Salah Gas Project
Central Algeria

Iain W. Wright

sonatrach bp STATOIL

Local Scenery

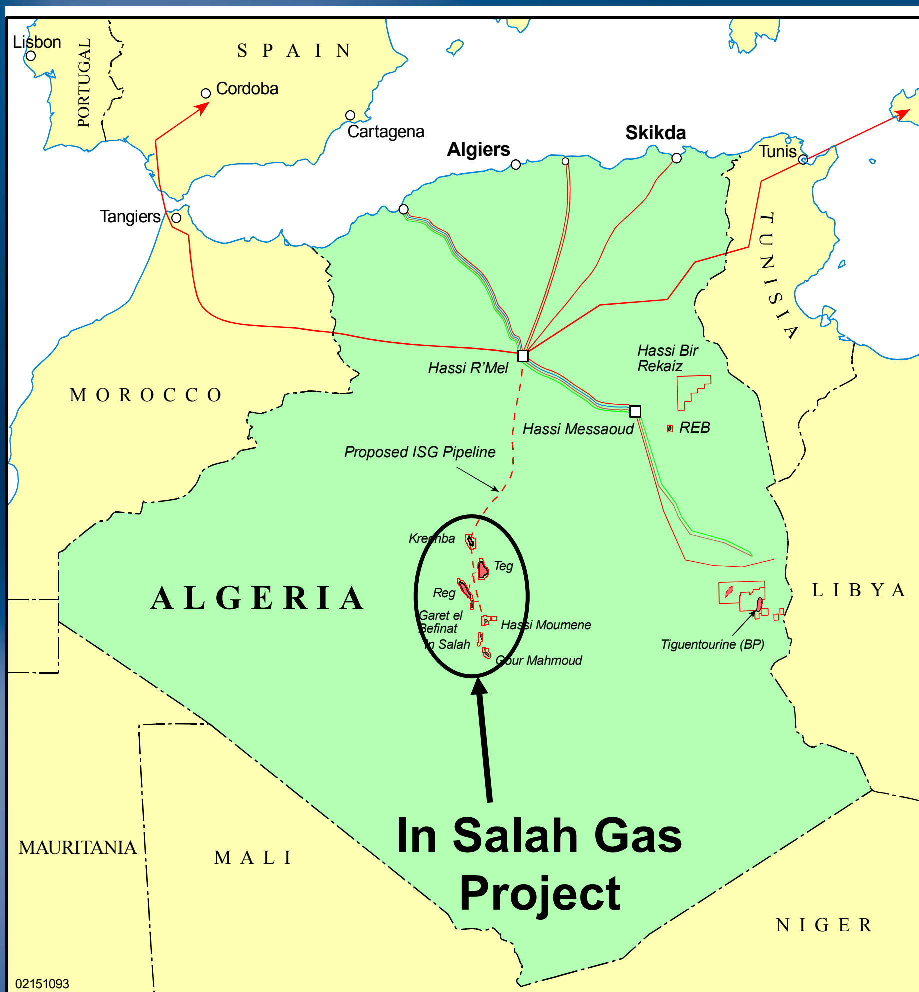
Foreign Legion Fort

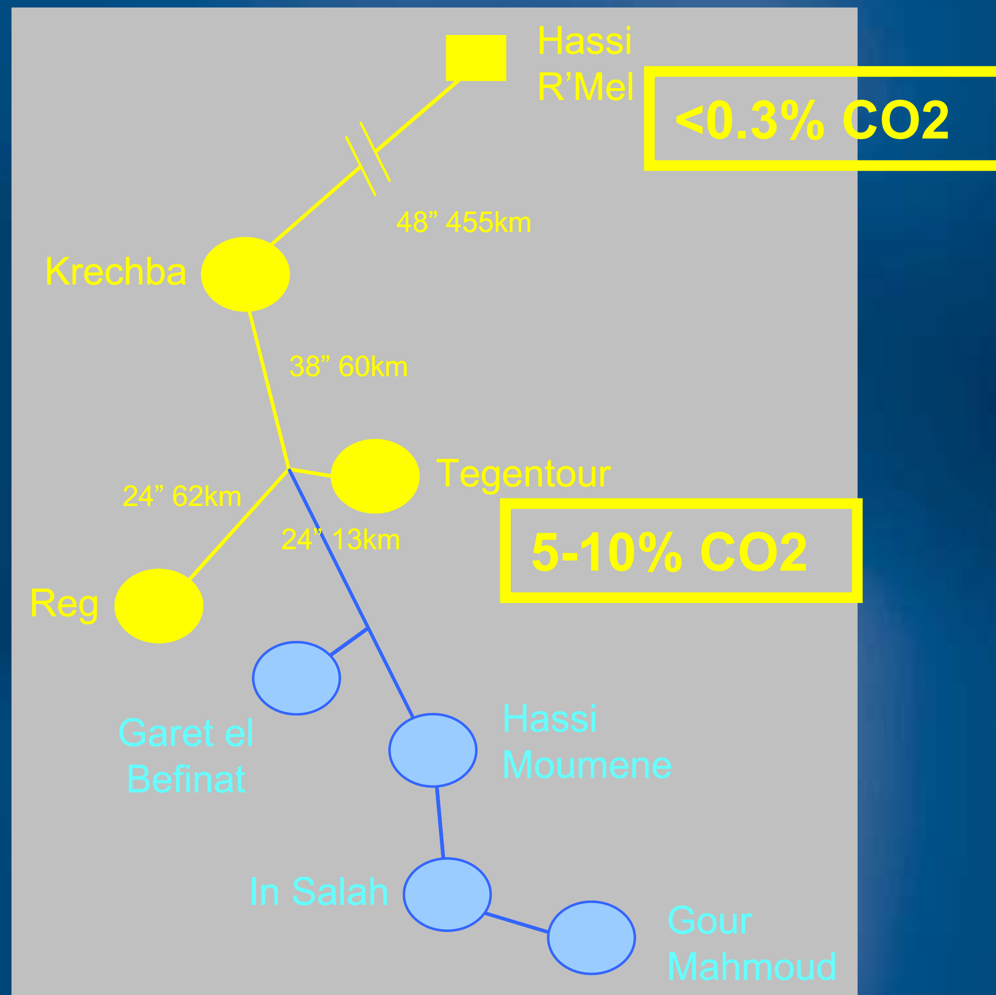
Kb-501 CO2 injection Well

Agenda

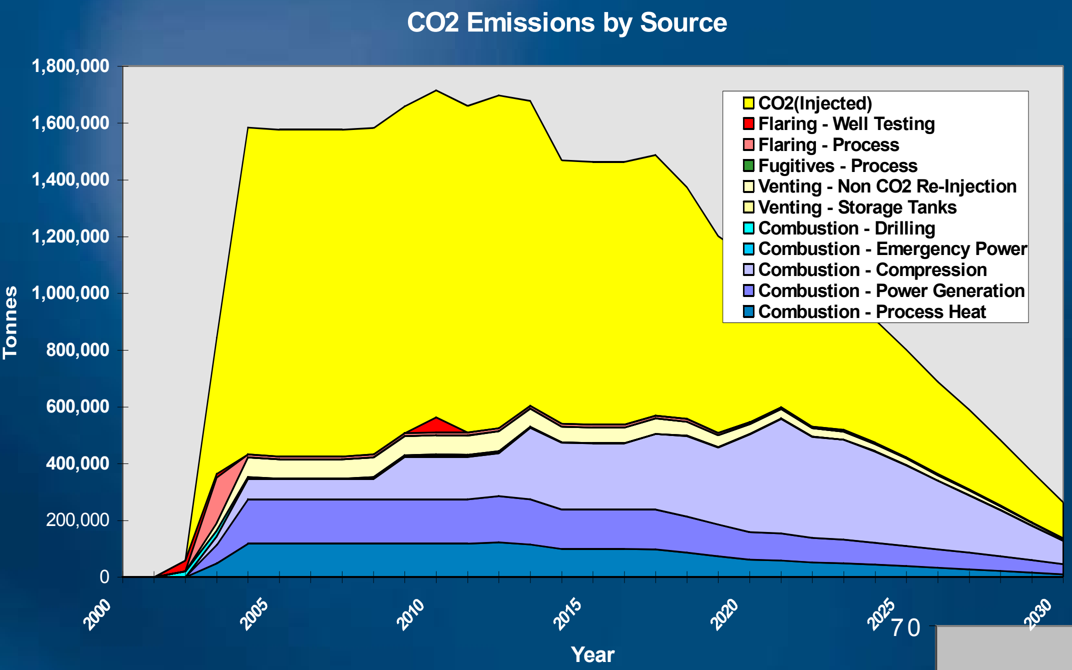
- **Outline of In Salah Gas Project**
  - Sonatrach / BP / Statoil Joint Venture
  - Multi-field Gas Development
- **Outline of CO_2 Storage Concept**
  - Project Emissions
  - CO_2 Storage in the Carboniferous Reservoir
- **Project Status**
  - Operations Strategy
  - Reservoir Performance
- **Joint Industry Project: Storage Assurance**
  - Technical Program
  - Budget

In Salah Gas Project, Algeria

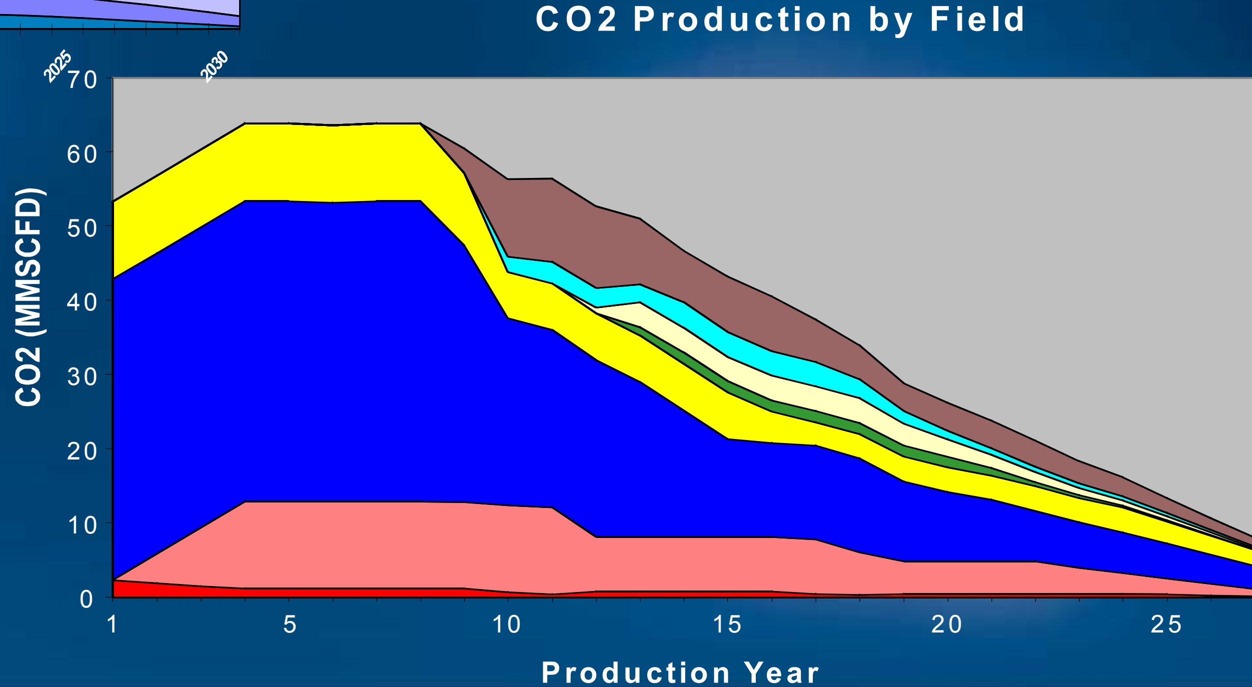




Carbon Dioxide Production Profile



- Only the separated (yellow) CO_2 will be re-injected ~60 mmscf/d (1mmtpa)
- CO_2 from combustion sources will be vented



- The geologically stored CO_2 will come from several sources

Project Status: November 2004

- Krechba facilities now onstream
- Producing gas (900 mmscf/d)
- Injecting CO2 (1mmtpa)
- Three CO_2 injection wells complete
- Storage assurance program commencing
- Storage assurance JIP being formed
    - Application for part-funding within EU FP-6 (CO2 ReMoVe)

Operations Strategy

Establish a performance target & management process that maximises the business value of In Salah's investment in CO_2 storage

Optimise commercial value

Drive environmental performance within operations

Target

Maximize the total volume of CO_2 stored per annum

Set annually based on historic performance (+ stretch)

Through

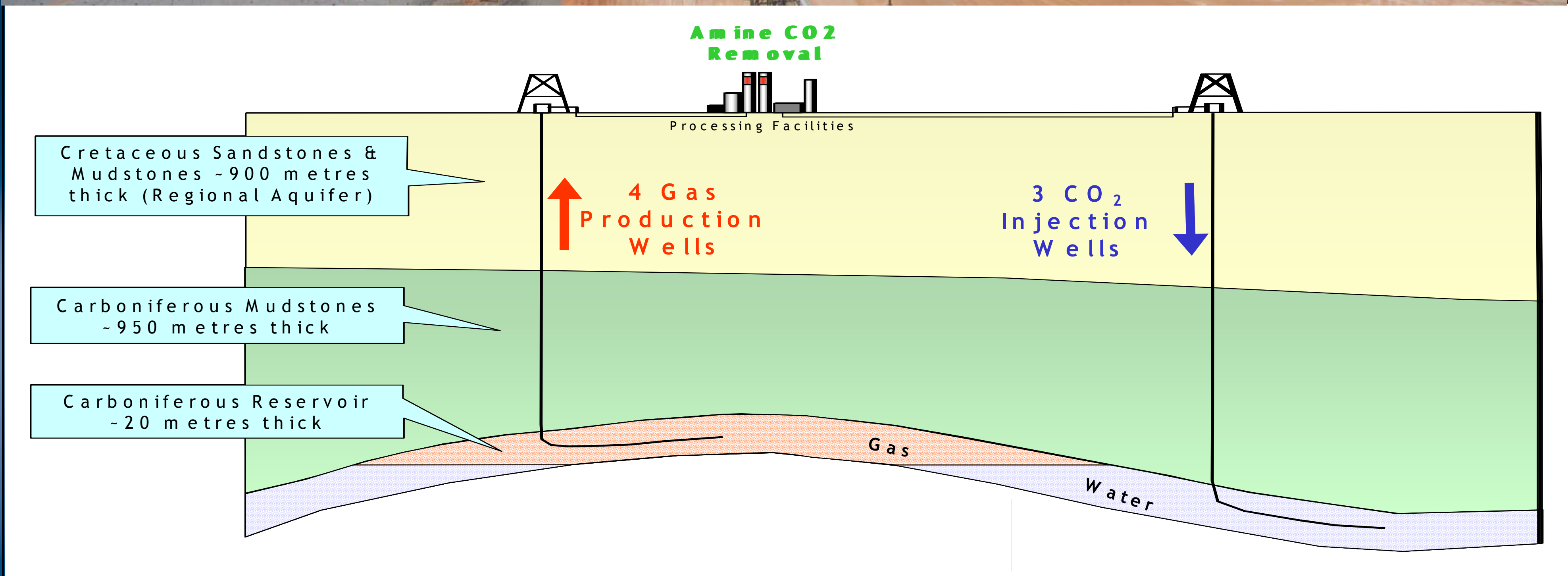
Managing well allocation

Operational efficiency of Power

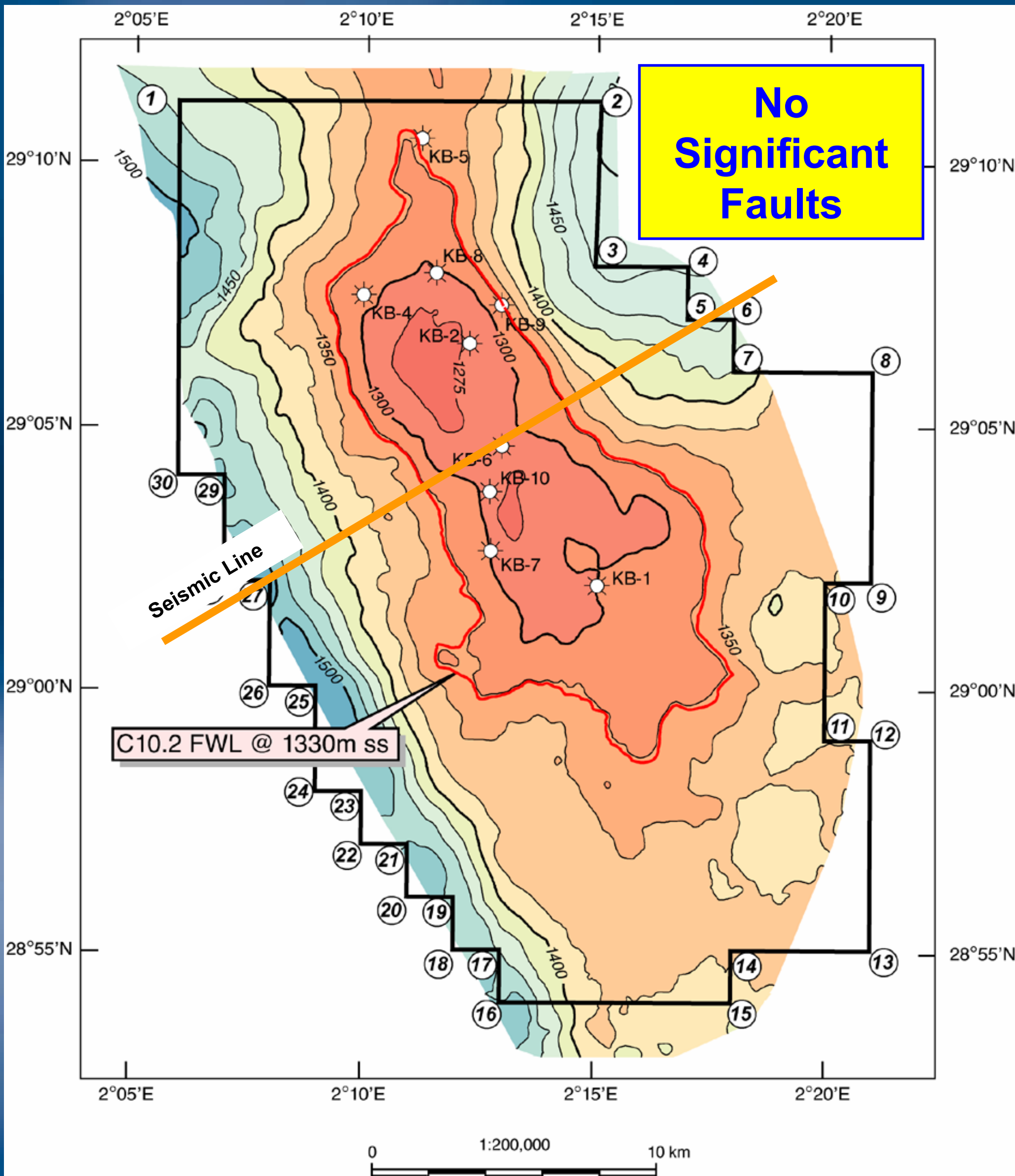
Operational efficiency of CO_2 compressors

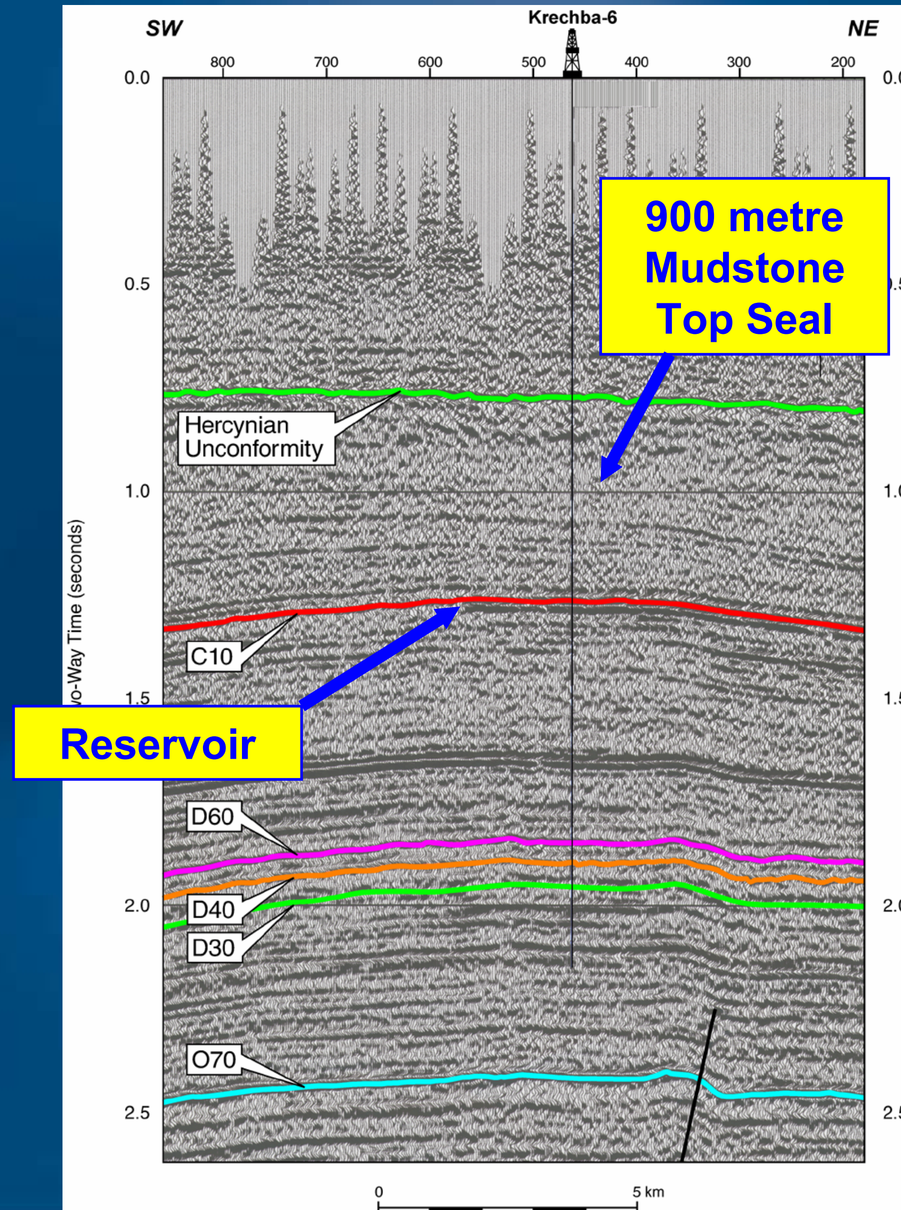
Operational efficiency of CO_2 re-injection wells

CO_2 Storage at Krechba

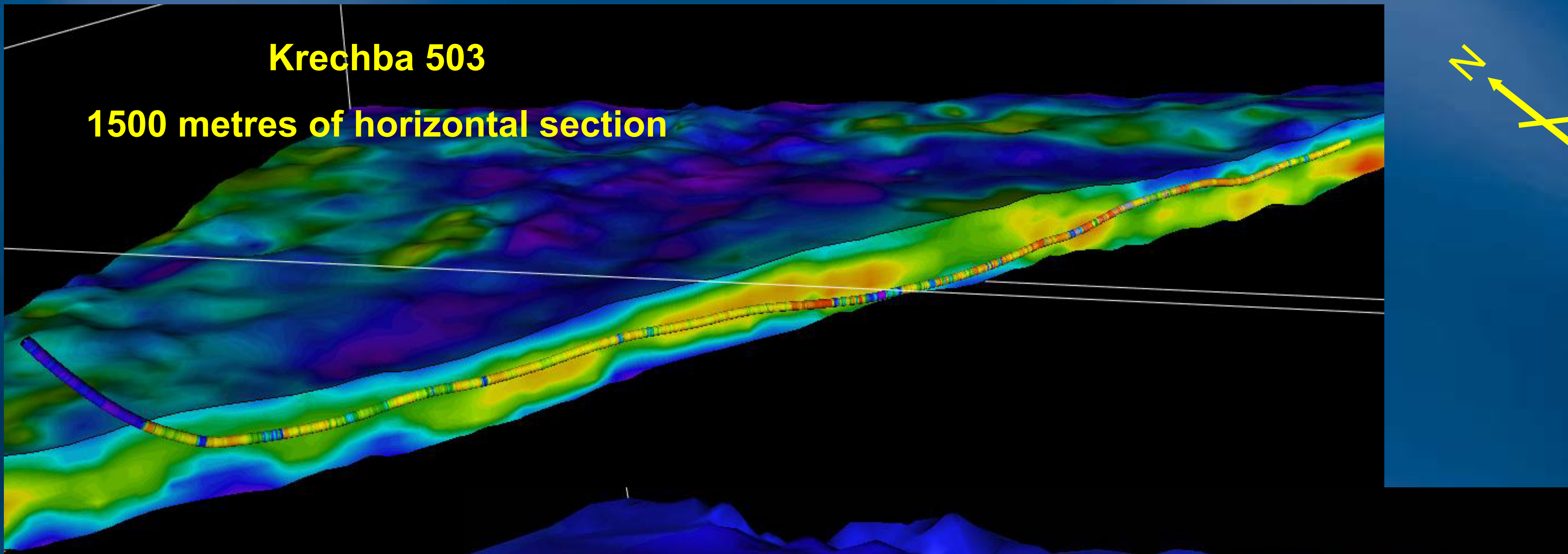


Krechba Geology

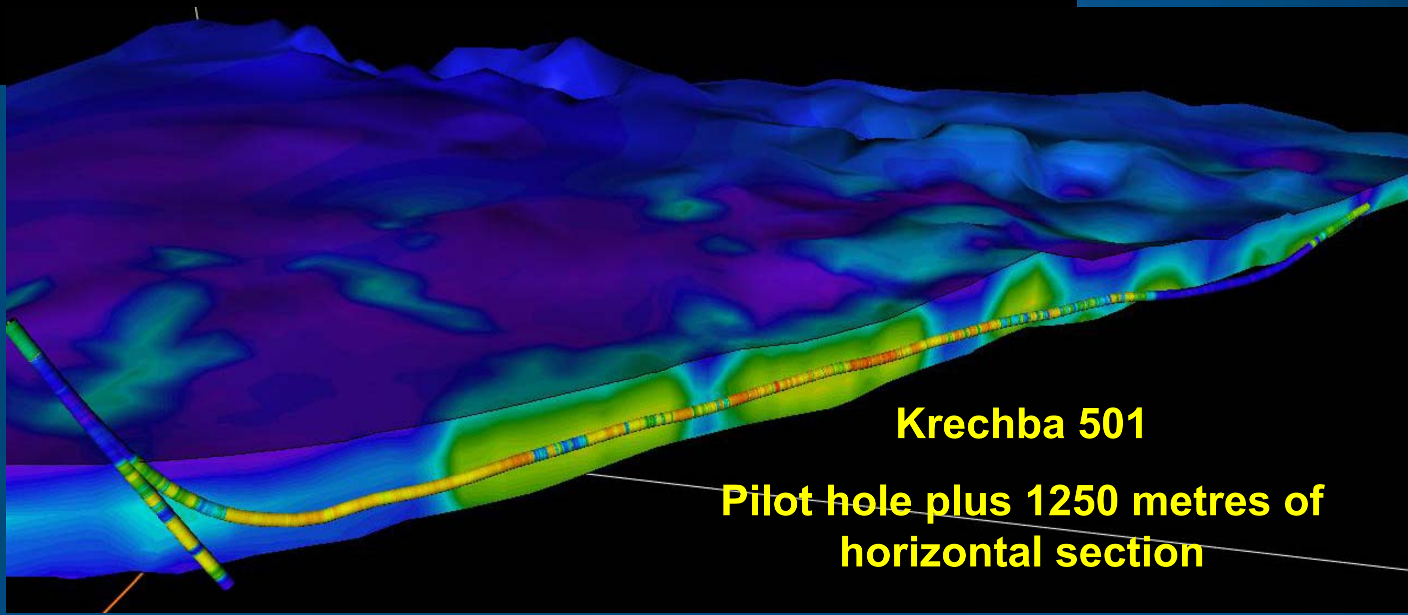




Horizontal CO_2 Injection Wells

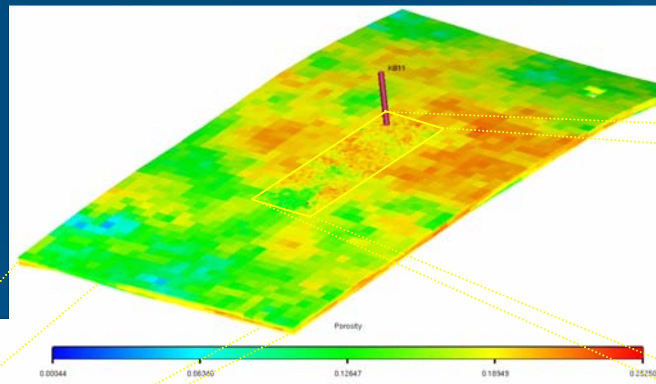


Wells geo-steered through 20m thick reservoir unit to maximise the penetration of high porosity sandstones

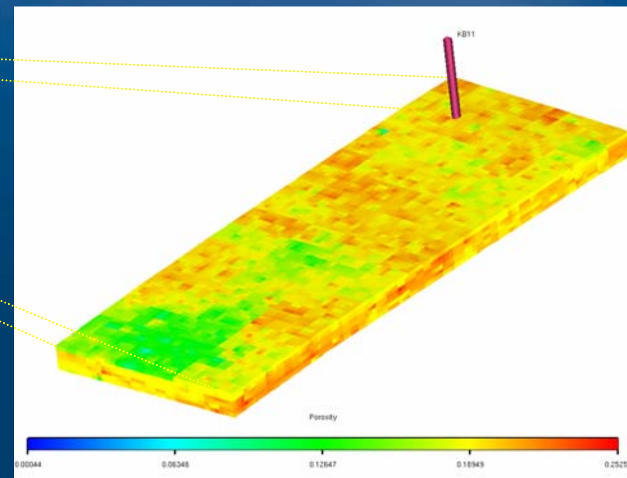


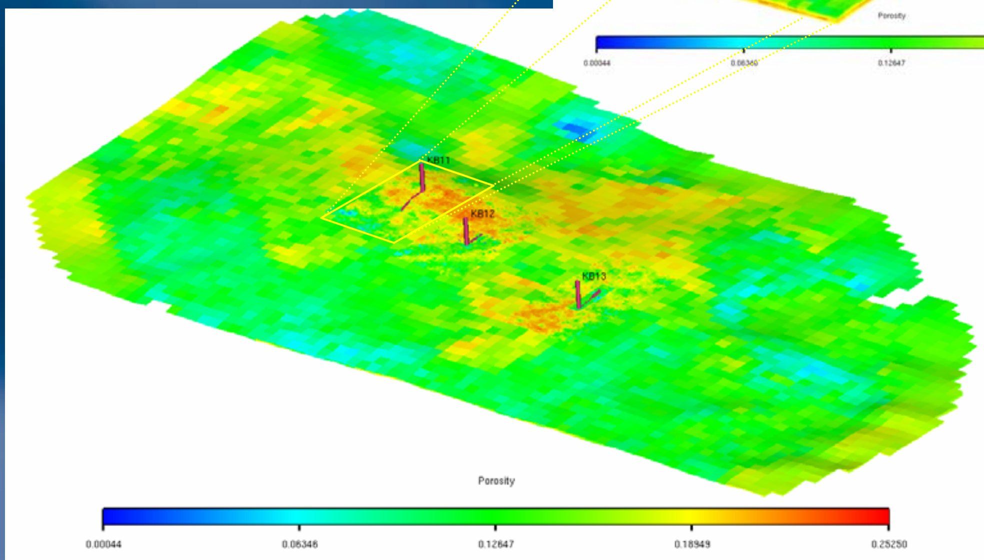
Simulation Models

Sector model



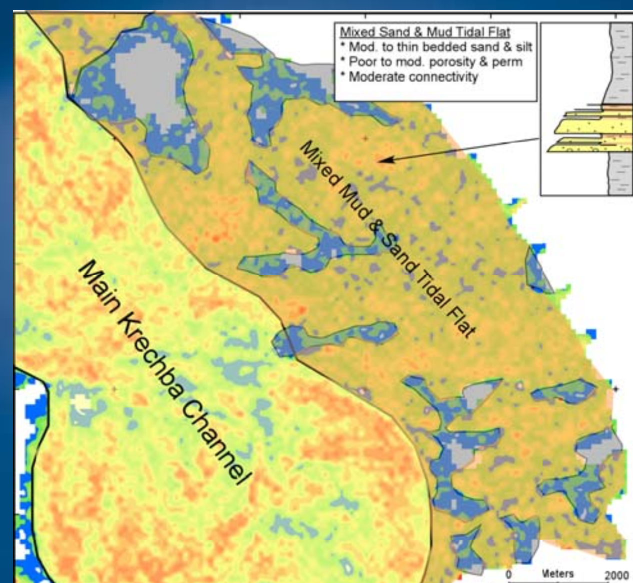
Well model



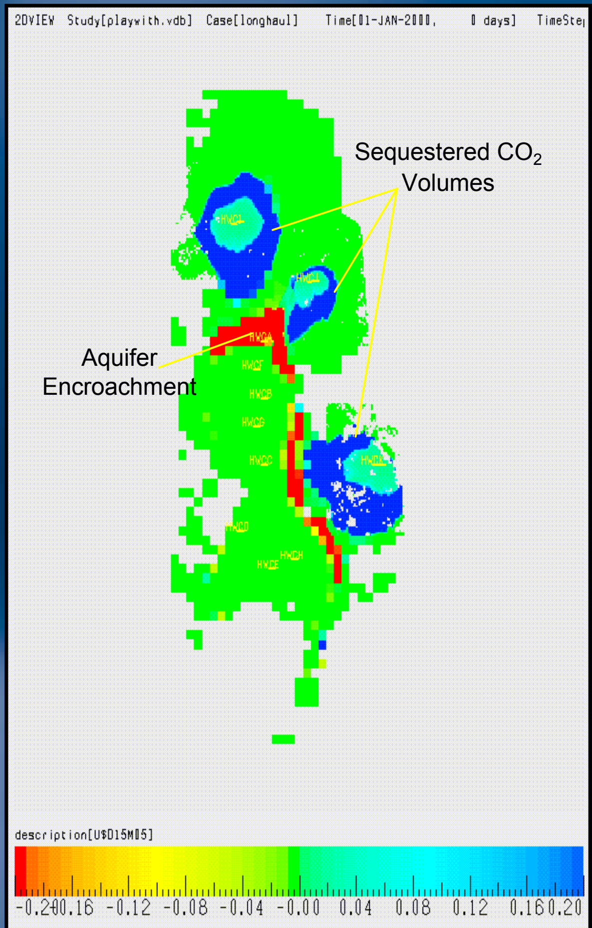


Full field model

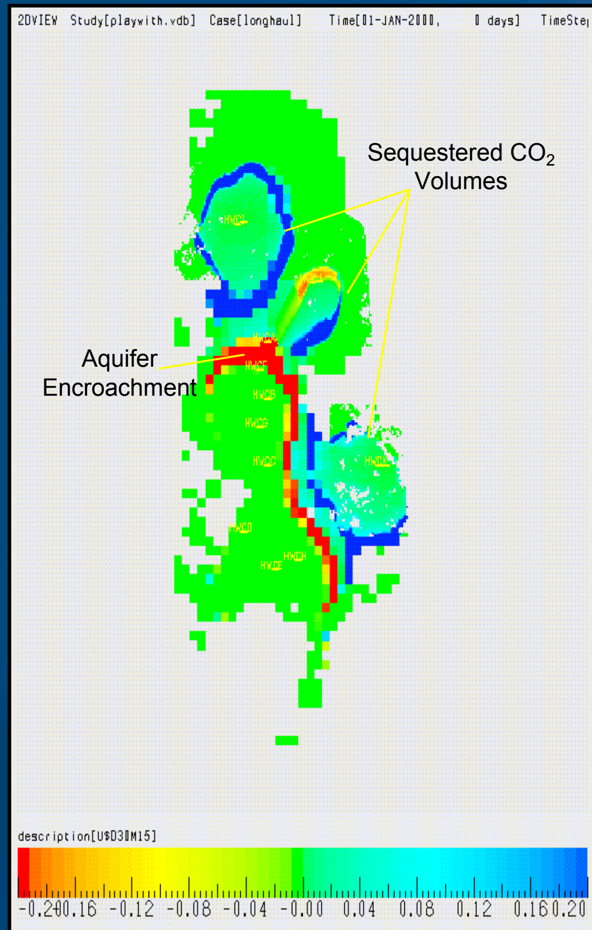
Geological model



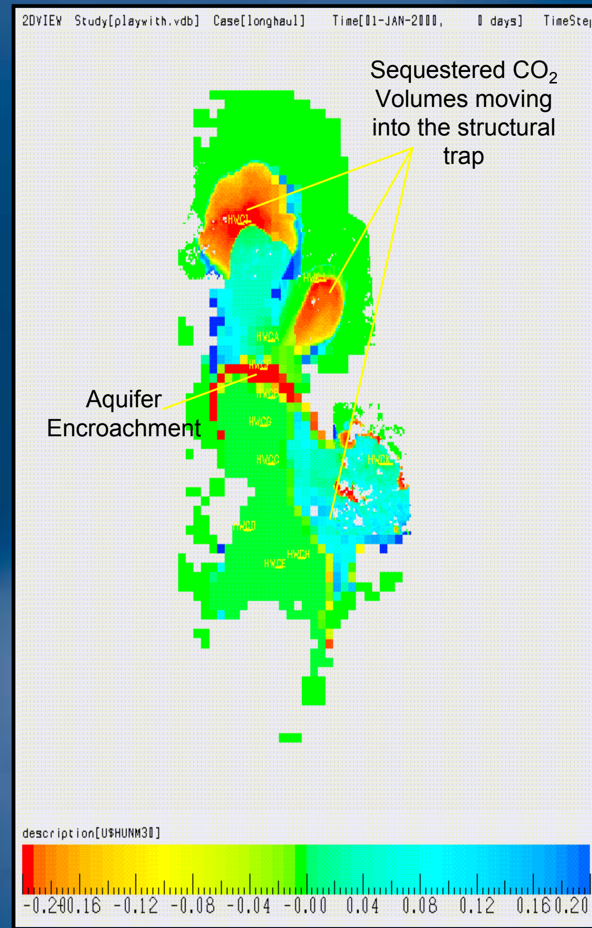
Simulation Prediction



Sg diff years 15-5



Sg diff years 30-15



Sg diff years 100-30

CO2 Capture & Storage Challenges

1. The cost of capture is too high

2. Public, government and stakeholder acceptance that CO_2 storage can be safely and effectively managed for the long term

3. No commercial incentives for GHG mitigation using CCS (regulation, cap & trade etc)

In Salah Joint Industry Project

Joint Industry R&D Project

Objectives (2004-09)

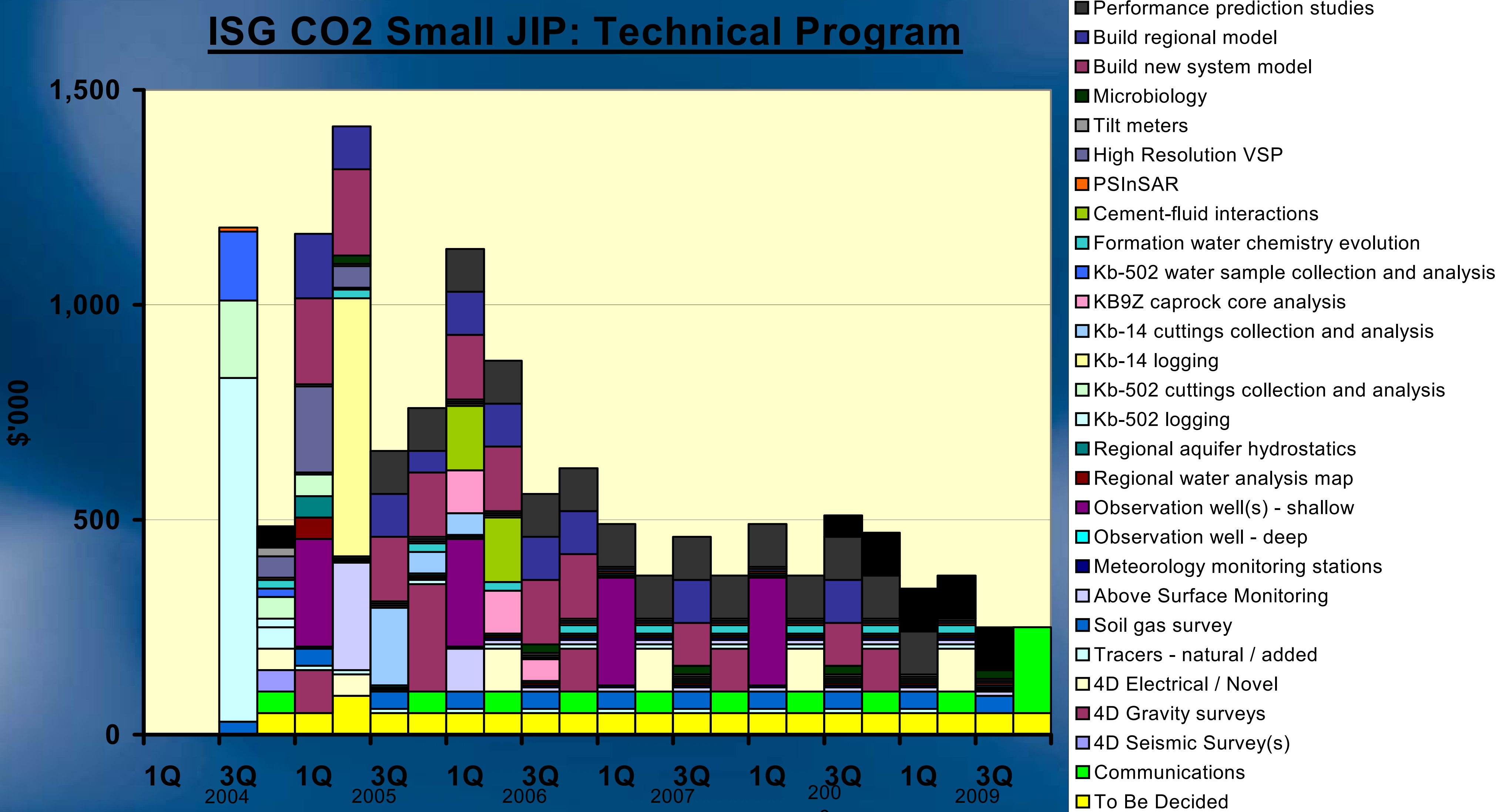
1. Provide assurance that secure geological storage of CO_2 can be cost-effectively verified and that long-term assurance can be provided by short-term monitoring.
2. Demonstrate to stakeholders that industrial-scale geological storage of CO_2 is a viable GHG mitigation option.
3. Set precedents for the regulation and verification of the geological storage of CO_2, allowing eligibility for GHG credits

JIP Technical Program

- Sample analysis of water, gas and solids.
- Noble gas tracers will be injected with the CO_2
- Pressure surveys, surface and down-hole (static and interference)
- Electric logs (production, SP and tomography)
- Gravity baseline, soil-gas survey, micro-seismic and tilt-meters
- Meteorology and microbiology
- 4D Seismic
- Aquifer monitoring well with oriented cap-rock core and cuttings analysis
- Down-hole gravity and geo-mechanical monitoring
- Surface eddy flux co-variance data

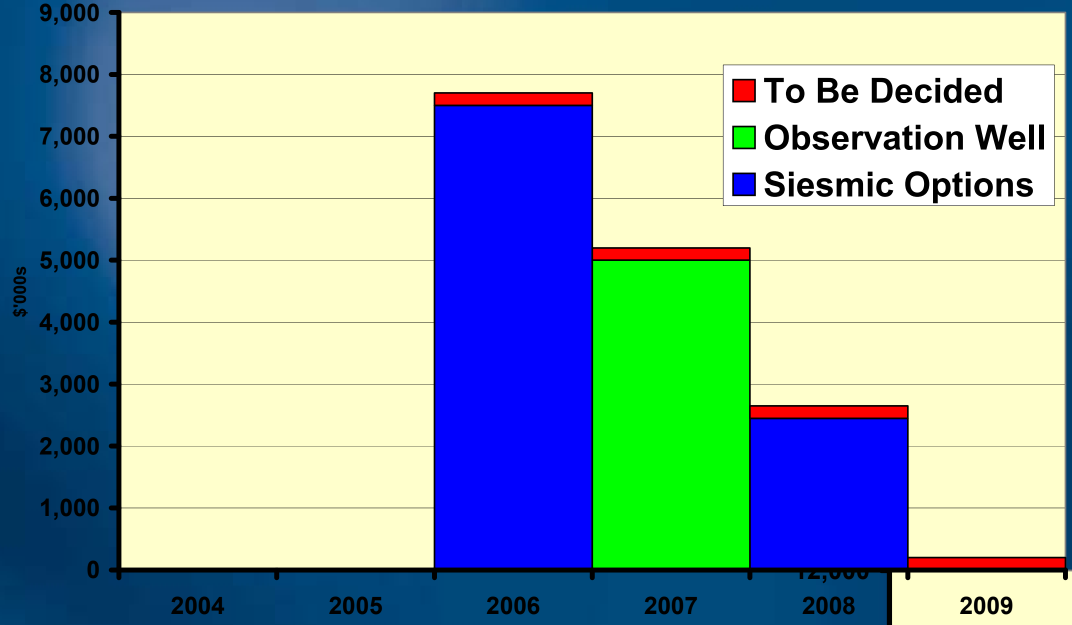
JIP Budget (Base Case)

2004

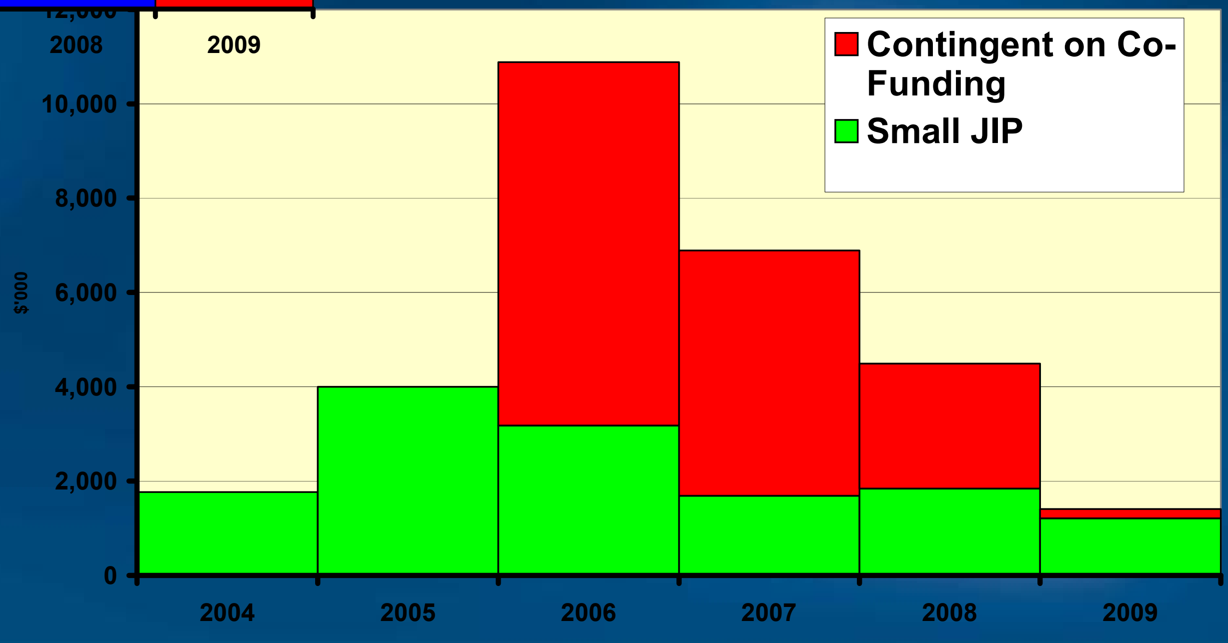


JIP Budget (with Co-funding)

Large JIP: Contingent on Co-Funding



Small JIP vs Large JIP



Conclusions

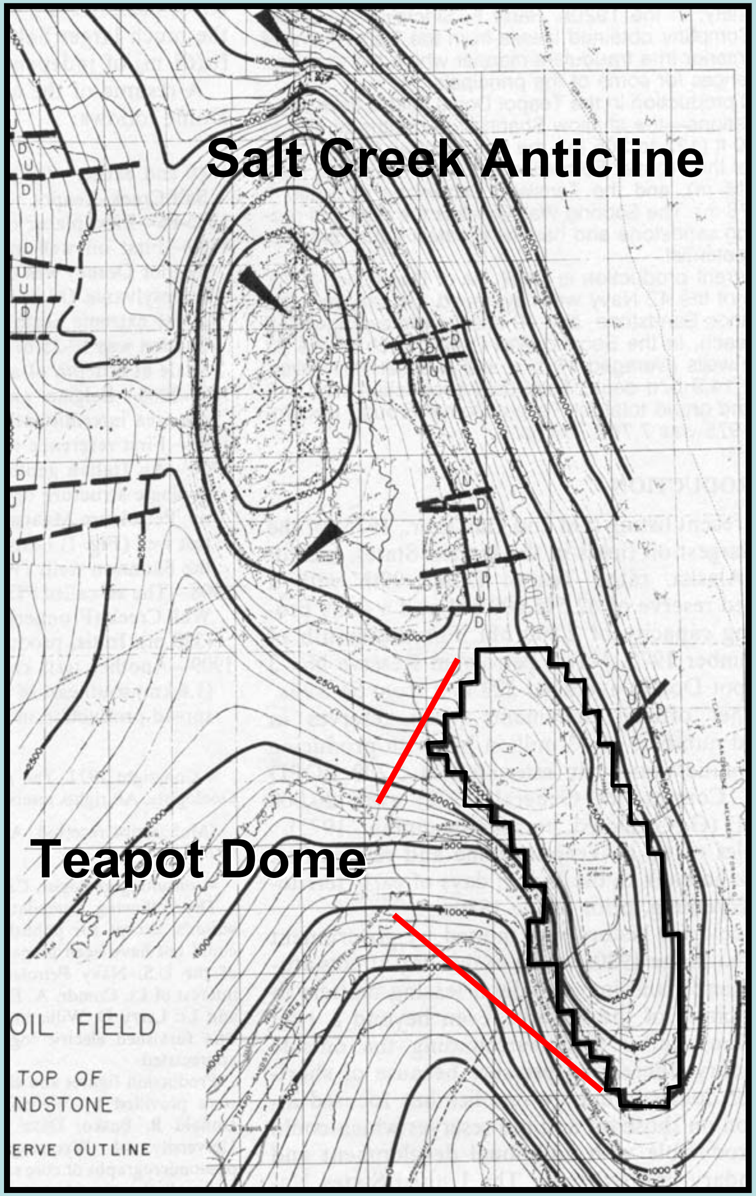
- In Salah is now a world-class CO_2 Geological Storage project
- Storing 1mmtpa CO_2 in the water leg of a producing gas field
- The In Salah Partners are willing to make the project available as a research field trial to advance geological storage of CO_2
- A Joint-Industry Project is being set up
- For details: see Iain Wright (wrightiw@bp.com)

Teapot Dome (NPR-3)

Baseline monitoring results and future monitoring programmes

S. Julio Friedmann
Energy & Environment Directorate
Lawrence Livermore National Lab

Be the change you want to see in the world
--- M. Gandhi



http://eed.llnl.gov/co2

Conclusions

Earth science and technology developments are needed to demonstrate feasibility of carbon storage at a grand scale, which ultimately require large-scale field experimental tests

Teapot Dome is an outstanding site for collaborative research to resolve key geoscience questions of monitoring and storage.

Current activity show the strengths of Teapot Dome for MMV technology demonstration and collaborative research.

Acknowledgements

Vicki Stamp, Mark Milliken, Doug Tunison
Rocky Mt. Oilfield Testing Center (RMOTC)

Dag Nummedal, Ron Klusman, Neil Hurley
Colorado School of Mines (CSM)

Bill Pickles, Bill Daily, Abe Ramirez – LLNL
Bob Burruss, Sean Brennan – USGS
Ernie Majer, Mike Hoversten – LBNL
Roy Long – NETL/DOE Tulsa

Anadarko Petroleum Company

Critical Geoscience Uncertainties

Better Capacity Estimation (> order of magnitude)!

Affect siting of future plants (e.g., FutureGen)
Affect economics of fossil fuel consumption
Underlie any cap & trade system

Leakage and Risk Characterization

Health & safety concerns
Efficacy of approach for carbon management
Environmental and groundwater concerns
Affect litigation exposure & insurance costs

Measurement, Monitoring, and Verification (MMV)

Underlies both capacity and leakage ability
Affect regulatory approach
Key to answering scientific questions

A Carbon Storage Test Site

Teapot Dome (NPR-3) for science & technology advancement and transfer

Rocky Mountain Oilfield Testing Center

Anadarko Petroleum Corporation

McCutcheon Energy Company Applied Earth Sciences

iReservoir.com e-solution for global energy

PEI Princeton Environmental Institute

School of Mines Colorado 1874

INEEL Home of Science and Engineering Solutions

Sandia National Laboratories

University of Wyoming

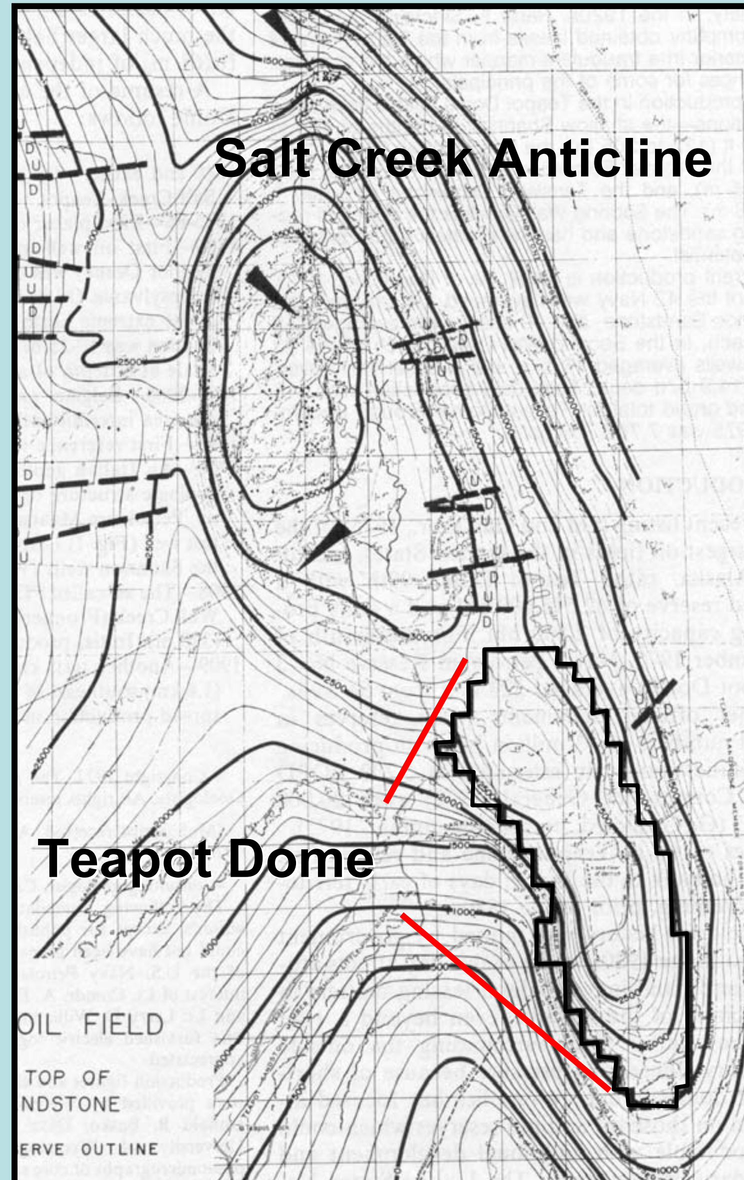
Los Alamos National Laboratory

Carbon Mitigation Initiative

Texas A&M Petroleum Engineering

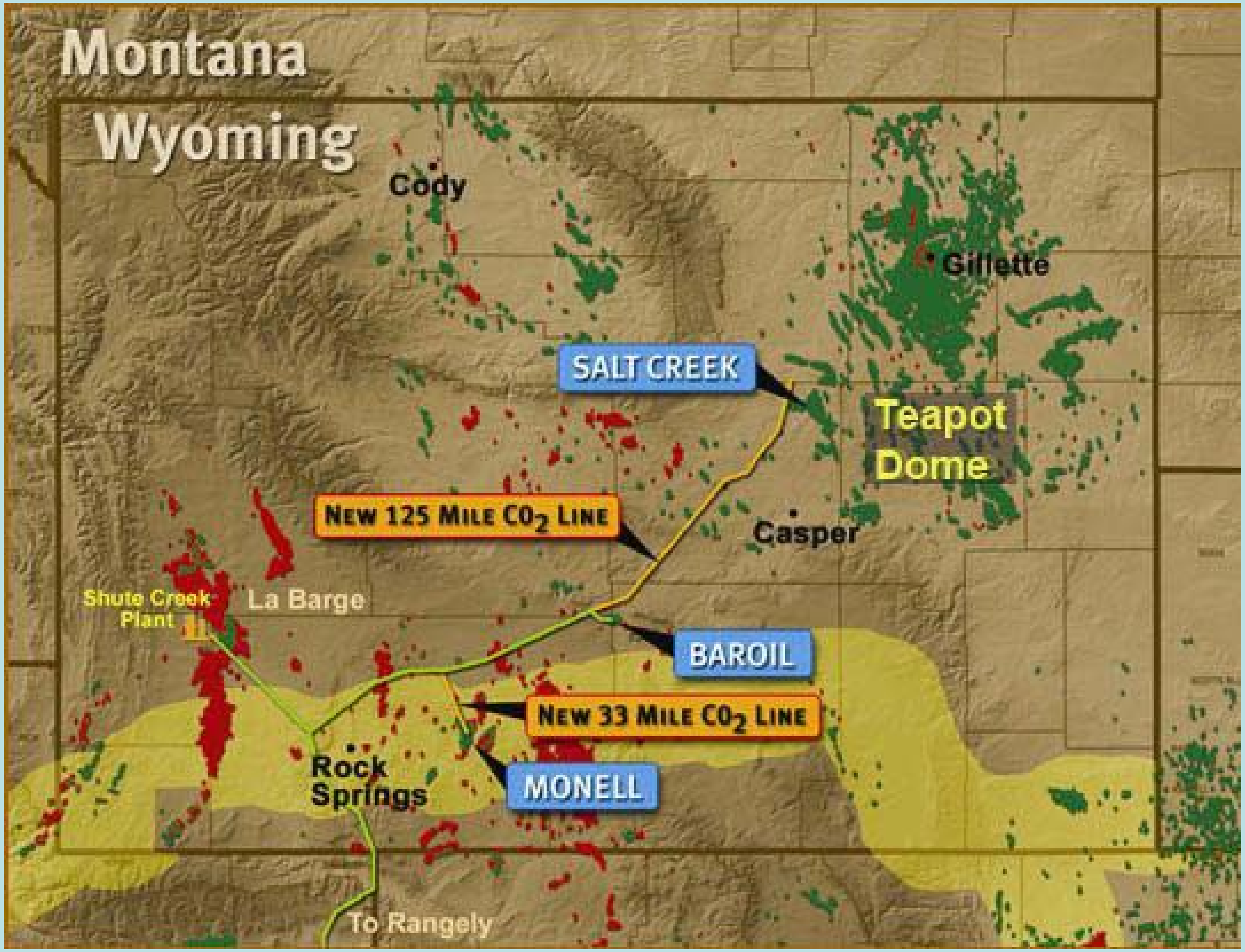
USGS science for a changing world

Berkeley Lab



Wyoming EOR: Growth & Opportunity

The state has 8-12 billion barrels OOIP, a low severance tax, and many anthropogenic sources



- 125 Mile CO_2 Pipeline to Powder River Basin (Jan. 2004 completion)
- Salt Creek to Become One of the Largest Carbon Sequestration Projects in the World.
- Teapot Dome will receive large volumes of CO2 from Salt Creek pipeline

Courtesy Anadarko Petroleum Co.

Existing infrastructure and data

Over 600 active wells, 1300 wells total, vast data archive
CO_2 initially trucked; pipeline for 2007 (NEPA); Anadarko

NPR-3 Reservoir Summary

9 Producing (oil bearing) intervals

- Depths 500'-5500' (Shannon to Tensleep)
- Miscible & immiscible floods
- Good range of oil and rock chemistry
- Range of rock composition & petrophysics

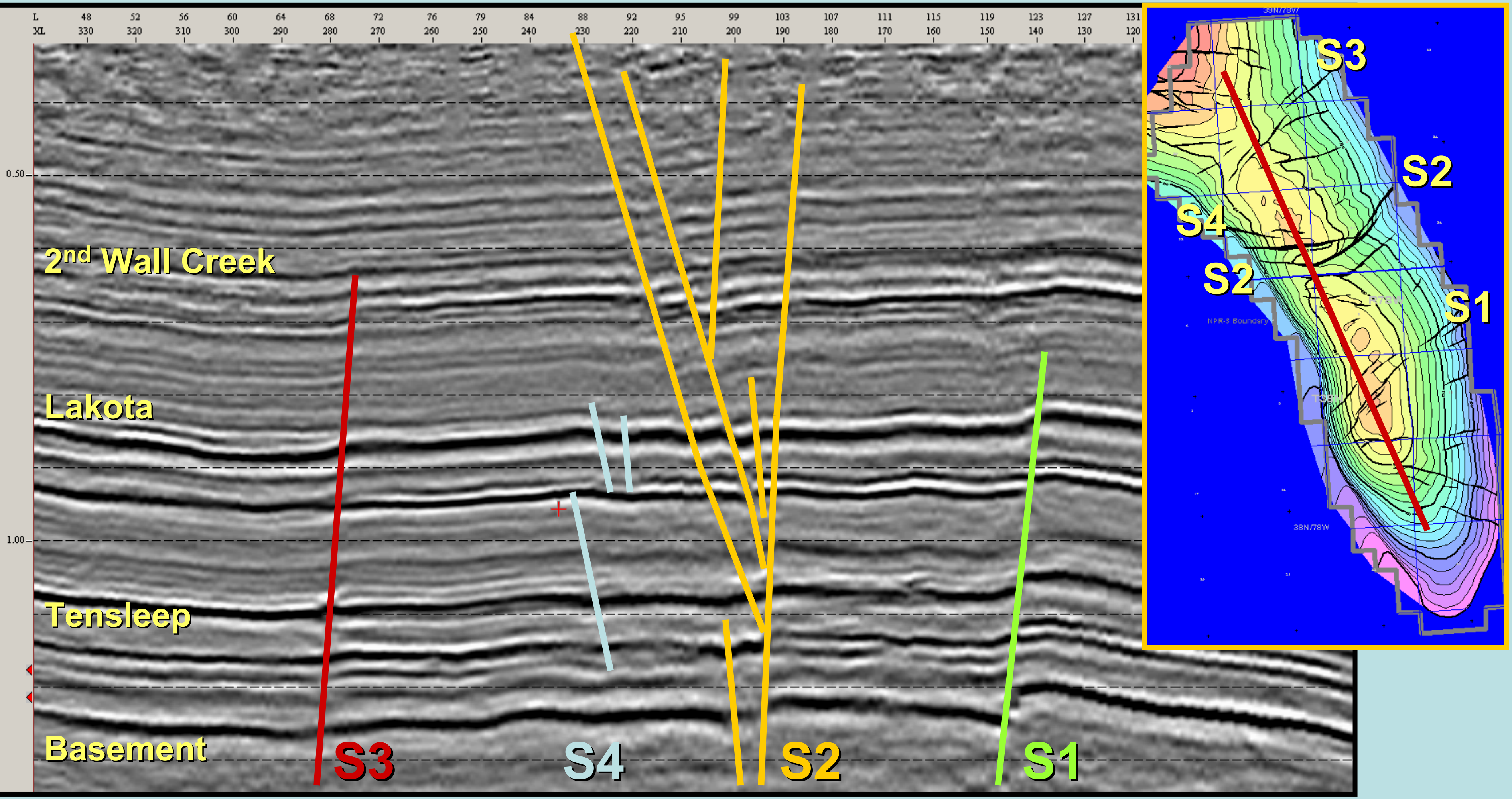
Additional (6 or more) water bearing units

- Fresh and saline, 3000-8000' depth
- Range of dep. environments, clastic & carbonate

Well-understood geological and geochemical setting

- 100 years of production, industry data
- Detailed state and regional studies
- Field-targeted studies (e.g. fractures, water flood)

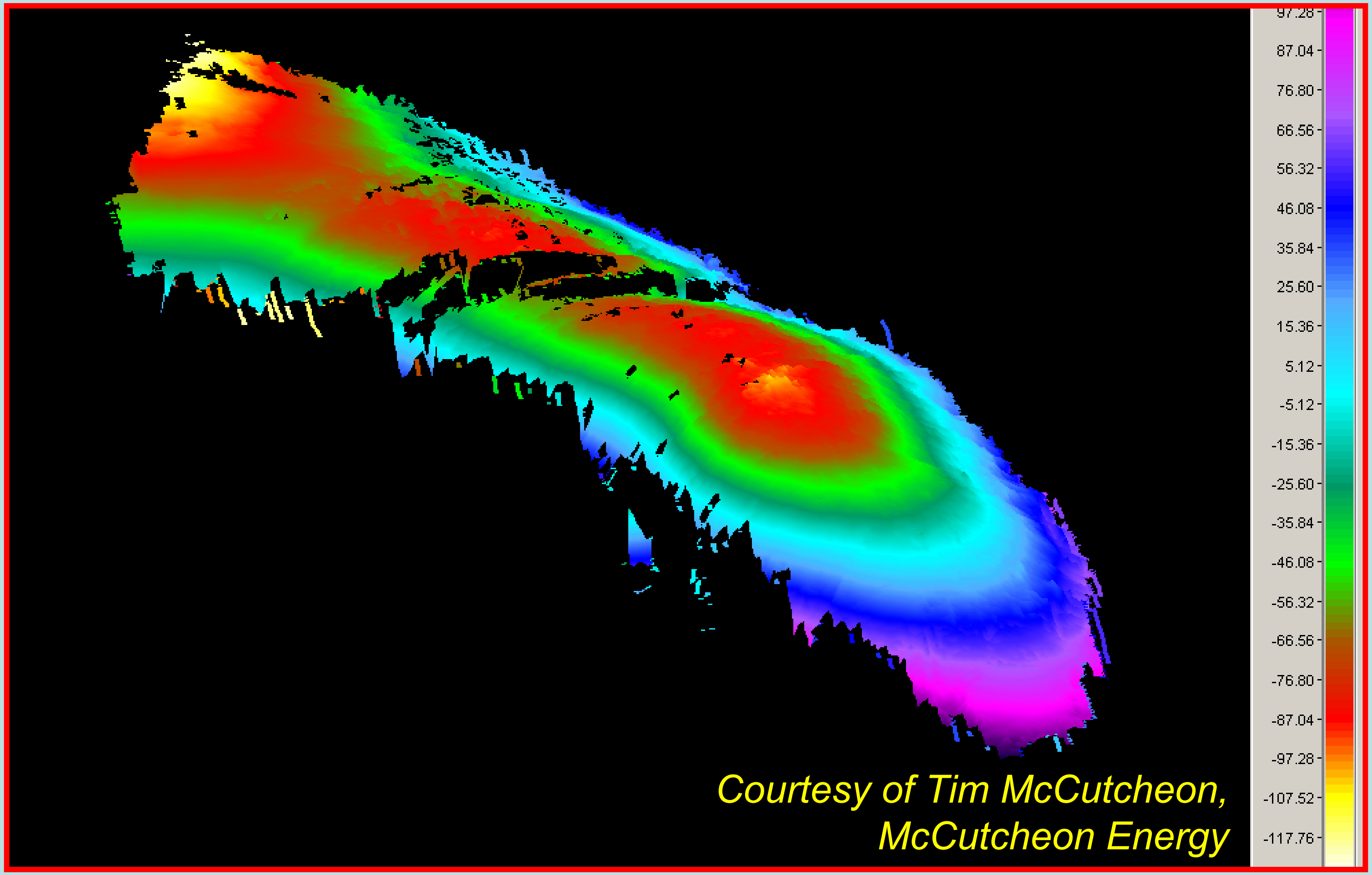
3D Seismic Volume



Outstanding control on subsurface strata & structure

Courtesy of McCutcheon Energy

3D Seismic Volume



The en echelon relays along these near surface tear faults also make it possible to look for cross-stratal and cross-fault fluid migration

Two Experiments, Three Targets

Maximizing Storage: Tensleep

- 5500' depth, 27 wells; 2/3 of Wyoming's production
- Mixed aeolian sandstone + sabkha carbonates
- Heterogeneous, dual porosity (fractures + matrix)
- Depleted oil-bearing unit

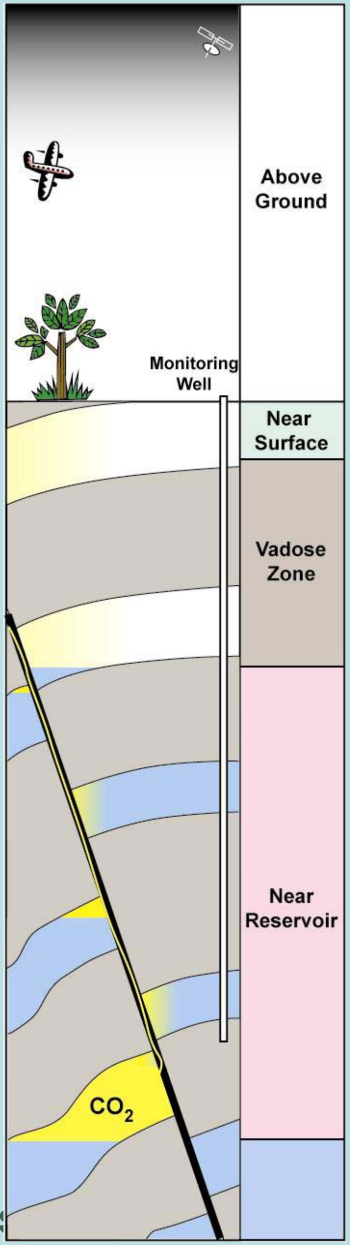
Engineered Leakage (CO_2 crustal transect):

- Shallow target near leaks & wells
- 2^{nd} Wall Creek, fault zone S2 likeliest
- Will include prediction & mitigation potential

MMV in both experiments

- Automated, non-invasive, cheap technologies
- Multiple suites, cross-comparison
- Data management & dissemination component

Effective Monitoring and Verification



Successful monitoring should occur in four domains
Focus on resolution, detection threshold, cost, ease
Multiple approaches (suites) with cross comparison

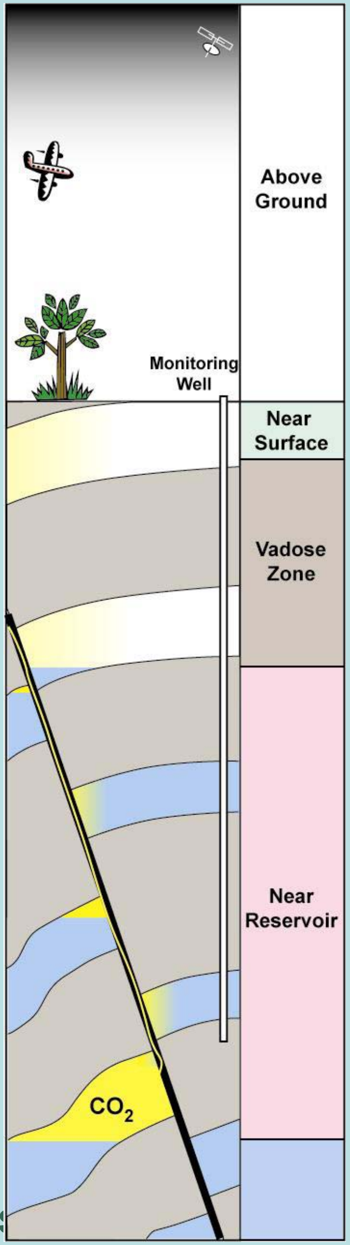
Geophysical Approaches

- 3D and 4D refl. seismic
- Other refl. seismic (VSP, cross-well)
- Electrical techniques (ERT and EMIT)
- Surface and/or downhole microseismic
- Surface and/or downhole tilt-meters
- Fiberoptic Bragg grating
- Pressure data

Geochemical Approaches

- Space-based
- Airborne
- Atm. eddy towers
- Soil surveys
- Well-head chromatography
- Brine sampling
- Isotopic tracing (noble gas, stable, U-series
- Organic geochem
- New gas tracing (PFC, SF_6)

Effective Monitoring and Verification



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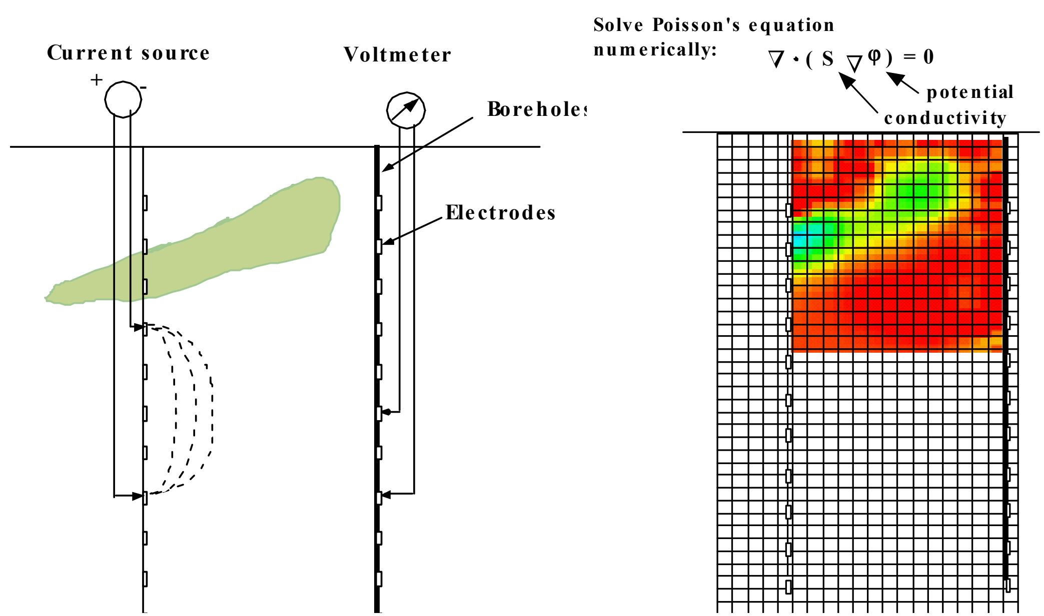
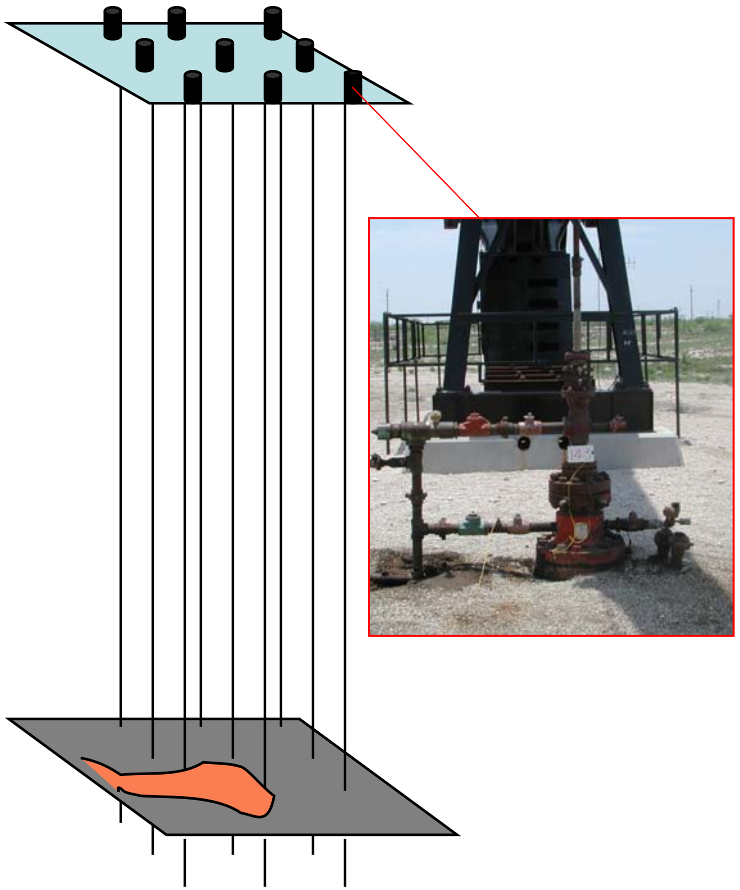
Electrical Resistance Tomography: ERT



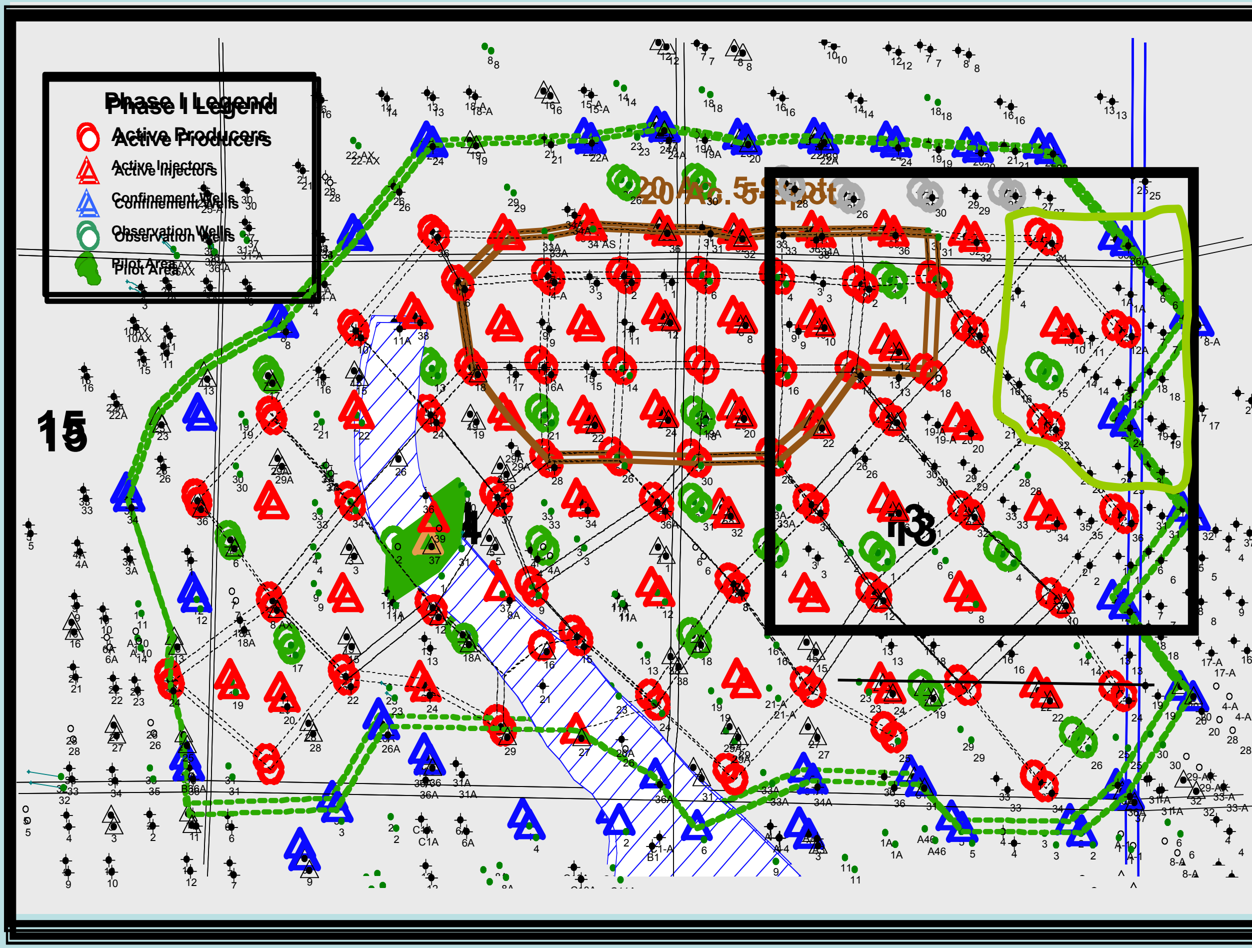


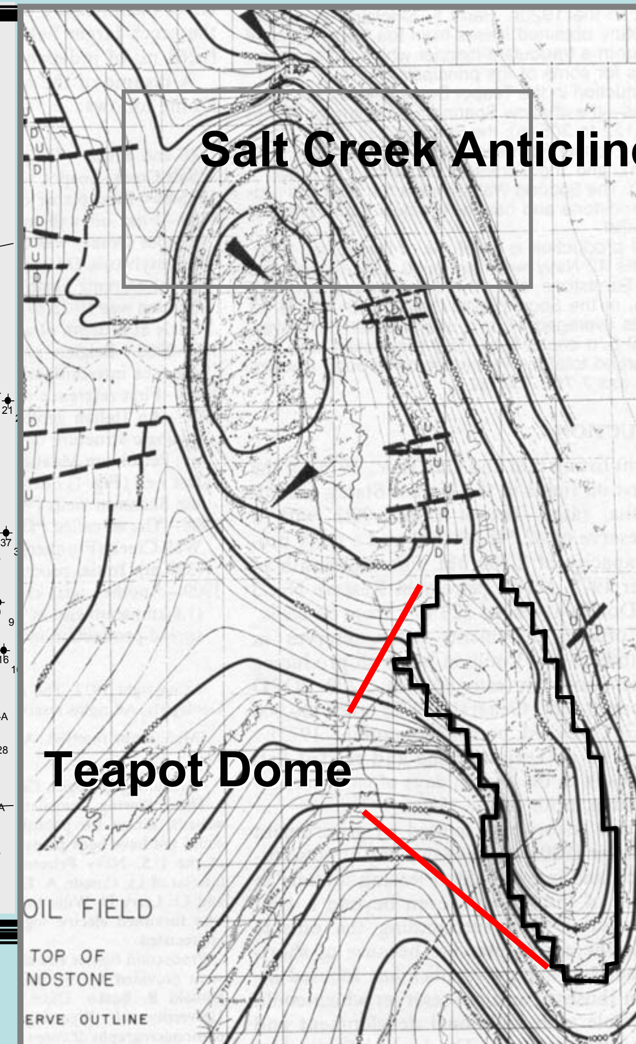
- Measures resistance between electrodes (passive)
- Vertical spaced or long electrodes
- Fast, cheap, easy

Good specifically for understanding pore-fluid changes

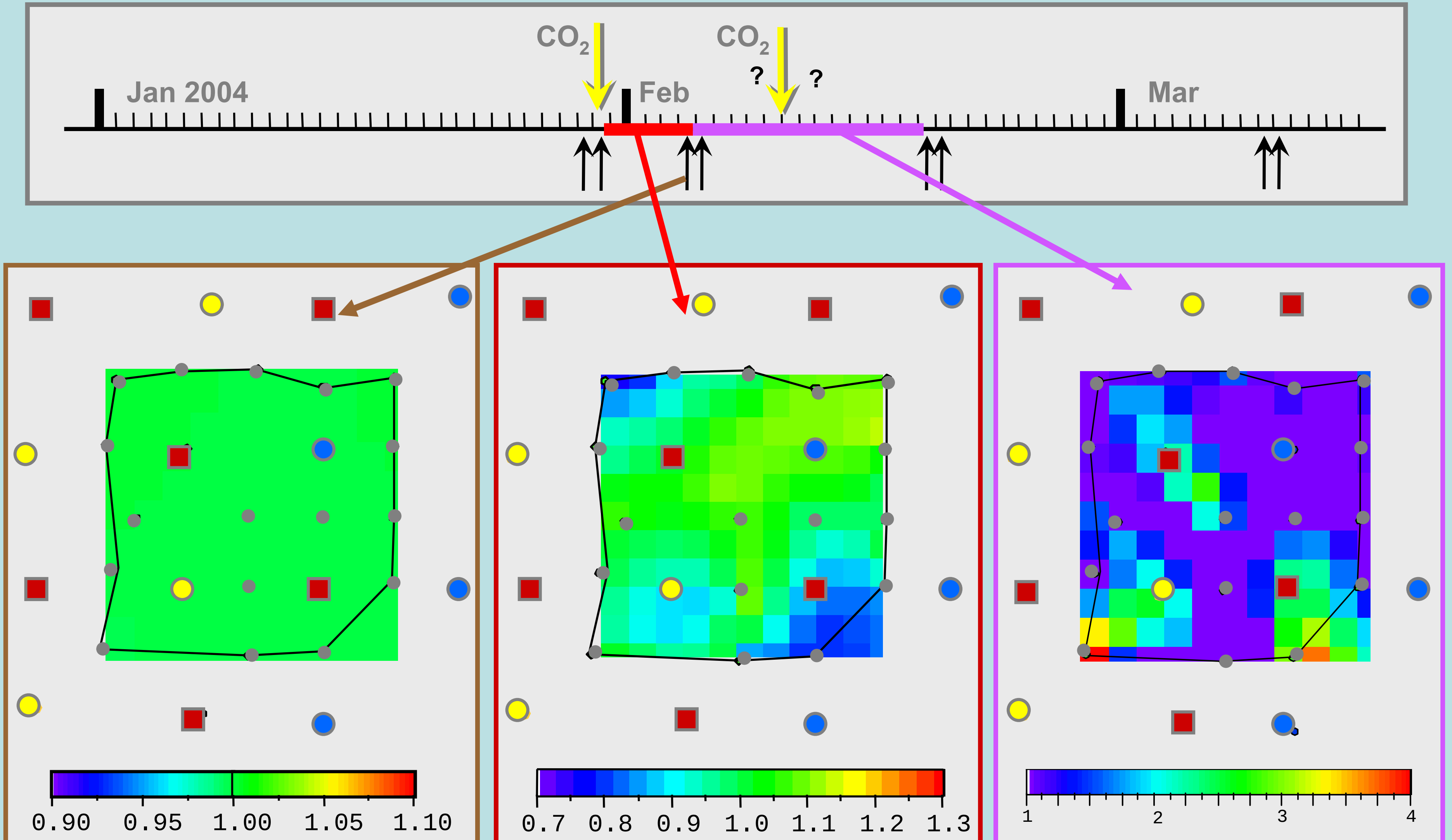
Salt Creek ERT

ERT Monitoring Area



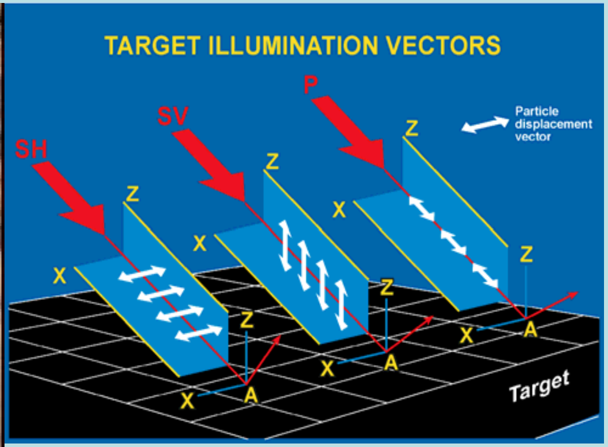


ERT Baseline & difference maps



NETL Microdrilling at RMOTC

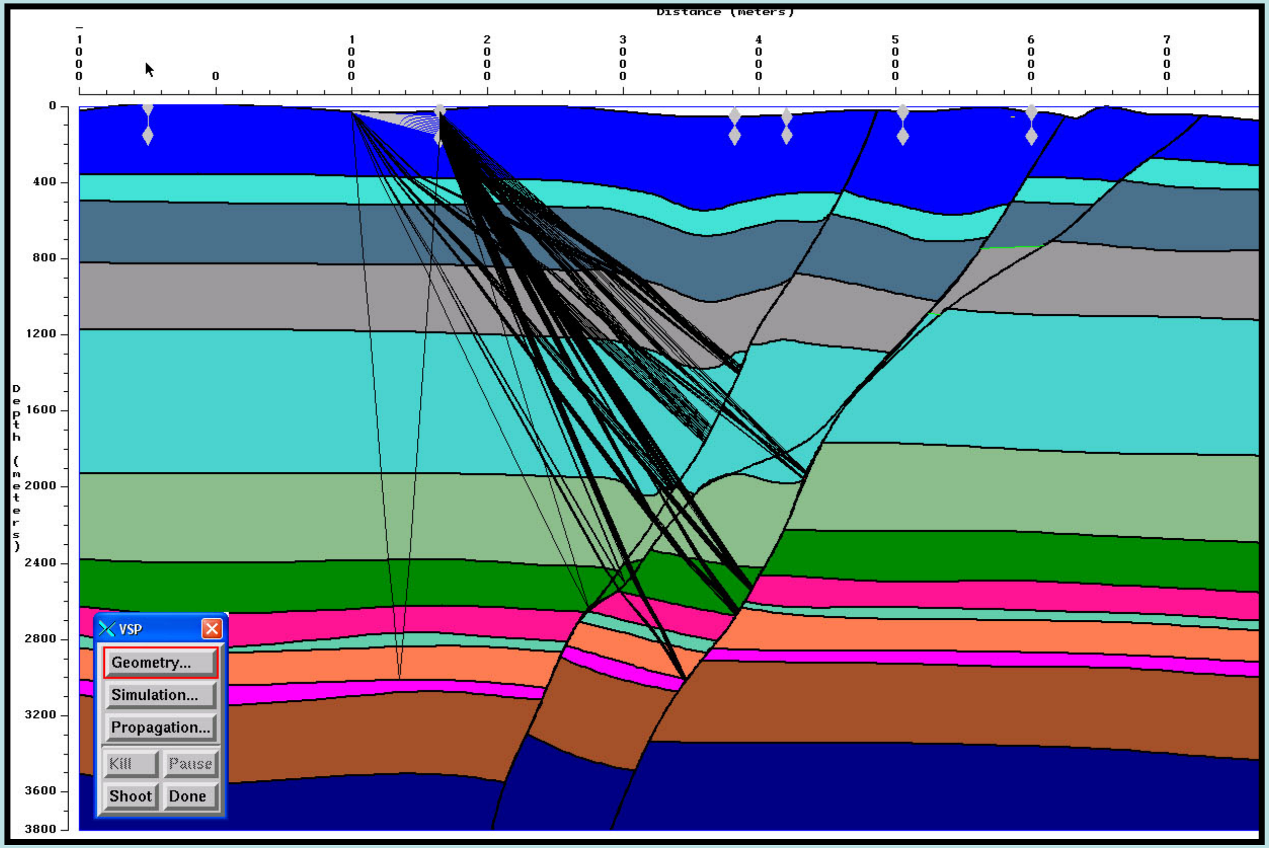
Technology Solutions for IOR and E&P



- First Implementation of "designer seismic" for VSP
  - Geophysics Team (LBNL & U. of Wyoming) Specifies Locations
  - LANL Drills "Ultra-quiet" VSP Micro-boreholes (Cemented PVC Pipe)
  - State-of-Art MEMS Geophones Used to Achieve Better Resolution
  - Provides Key Technology for RMOTC CO_2 Program
    - Maximizes Potential for successful CO_2 Flood Monitoring
- Low Cost VSP Instrumentation Boreholes
  - For Improved Resolution over Weyburn Project for CO_2 Monitoring
  - Attempt to Image to 6,000' with 600' VSP Boreholes for E&P

Vertical Seismic Profiling

- Good at detection of small gas concentrations
- New technique brings data from much deeper than well
- Dynamite source; high-end geophones
- Data collection *IN PROGRESS!*

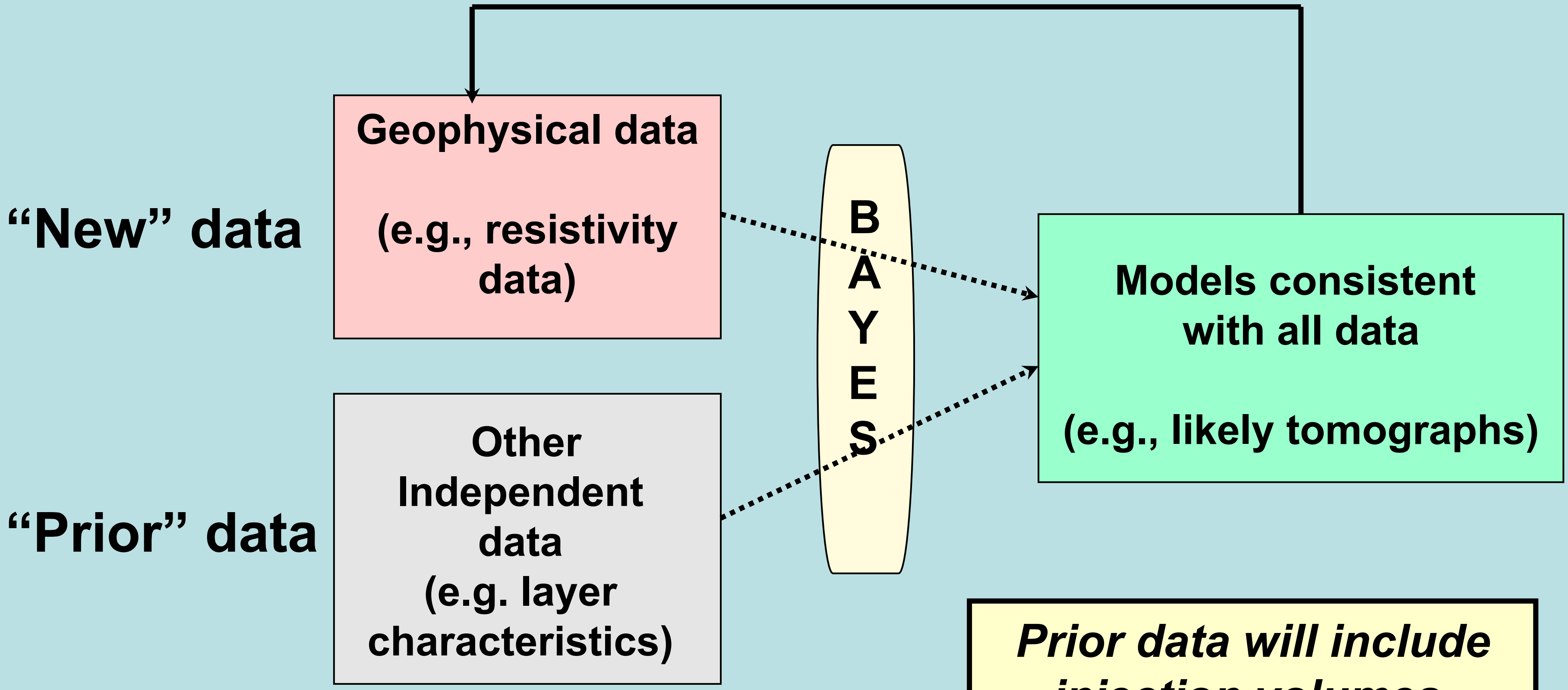


Excellent resolution of geological strata & structures
Potential for new fluid detection aspects

Stochastic Engine

LLNL proprietary platform to analyze orthogonal subsurface data sets

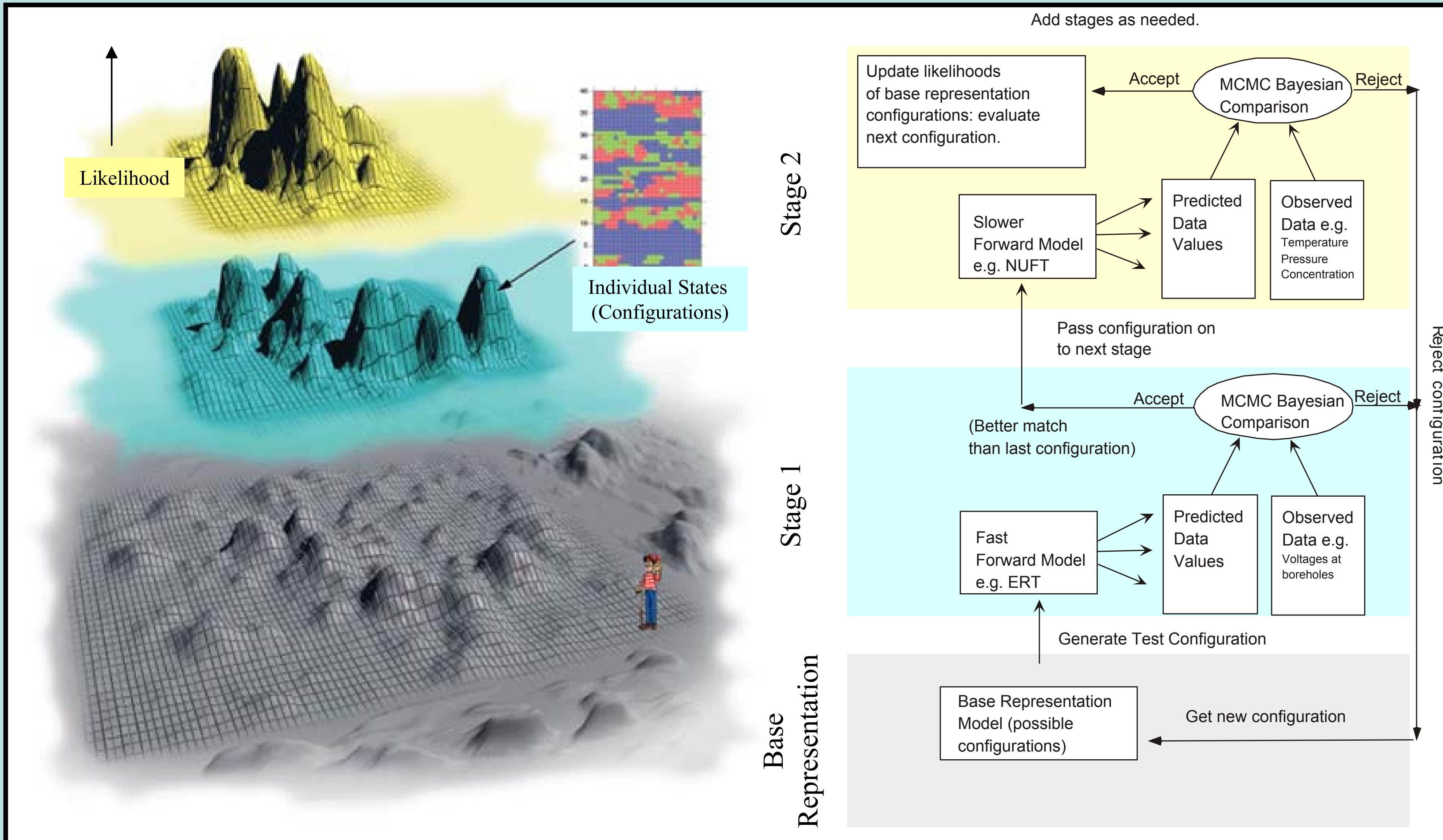
- **Probabilistic method to find models consistent w/ all available data**
- **Uses Bayes Theorem to combine “prior” and “new” information**



Prior data will include injection volumes, locations, units, etc.

Stochastic Engine

Monte Carlo, Markov Chain approach to find models consistent with all available data

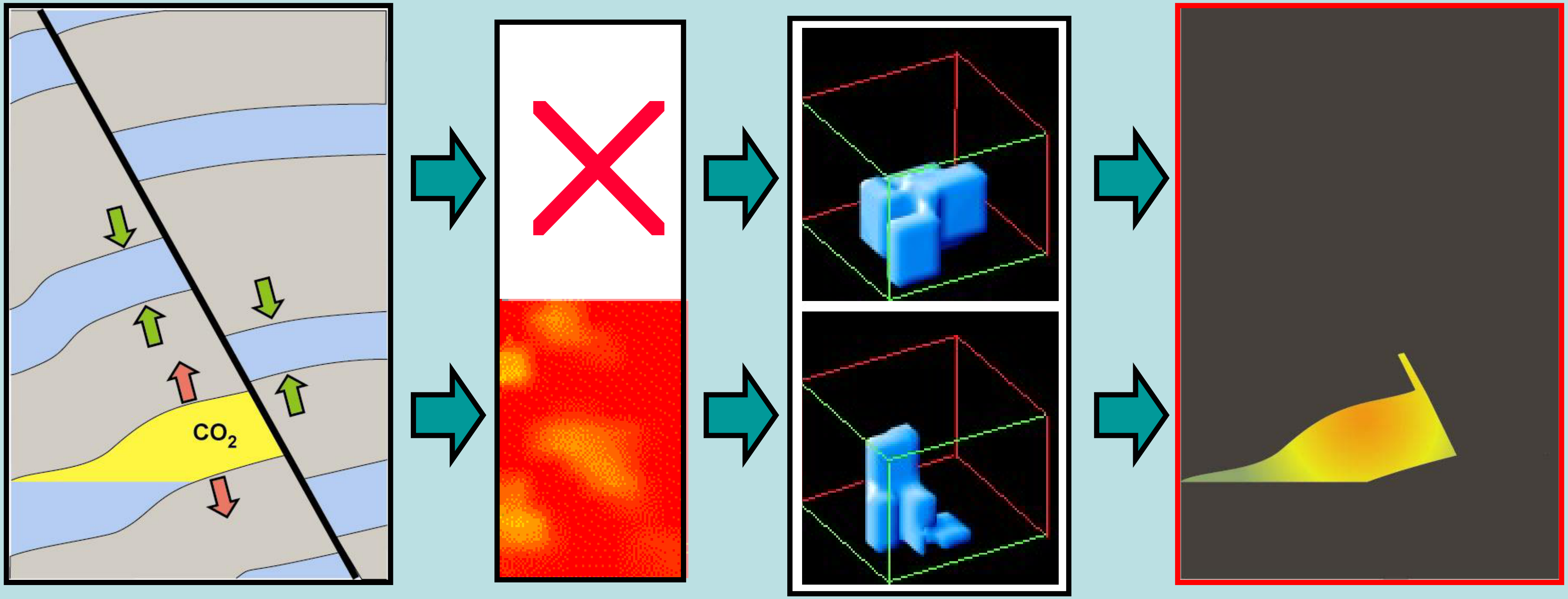


Stochastic Engine Benefits

- **Good for non-linear, ill-posed problems (e.g. earth heterogeneity):**
  - Improvement on methods that badly magnify small changes in data (e.g. measurement, round-off errors)
  - Constrains non-unique inverse
  - Handles contradictory data, sparse data
  - No linearization required
  - Explicit estimates of solution uncertainty
- **Can use complicated & varied prior information, measurements**
  - Cross-borehole surveys, electrical resistivity logs, lithology, and hydrologic data, production data, a geological model

Forward & Inverse Model Linkage

Ties and iteration between the various modeling and data collection phases are crucial to successful comparison and ranking. The ties between field data, stochastic engine realizations, and various forward models are the pore volume changes.



Detection and mapping of the produced physical and chemical responses is the goal

New Tensleep well

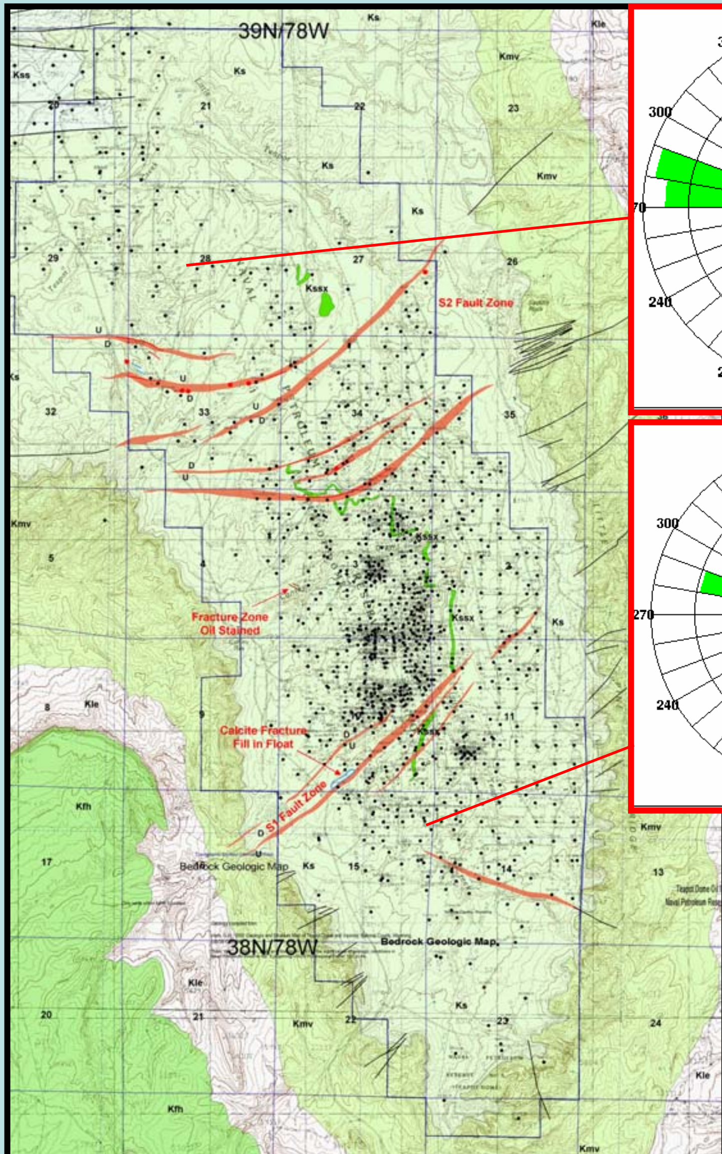
In May 2004, RMOTC drilled a well into the Tensleep to serve several goals:

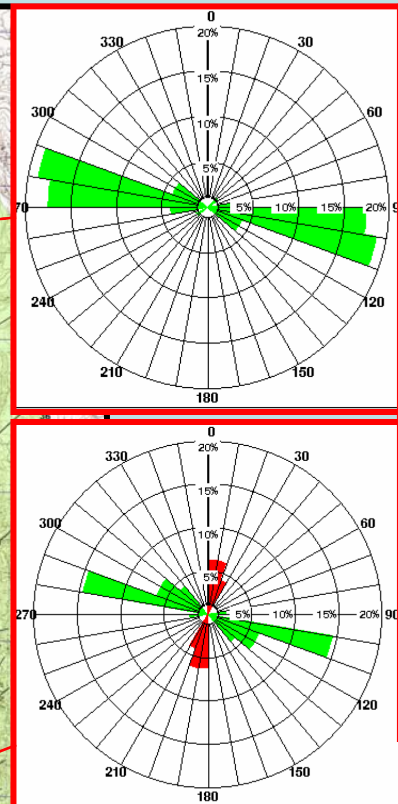
- Test seismic interpretation
- Look for variations in oil comp.
- Penetrate oil/water contact
- Extensively sample cap rock

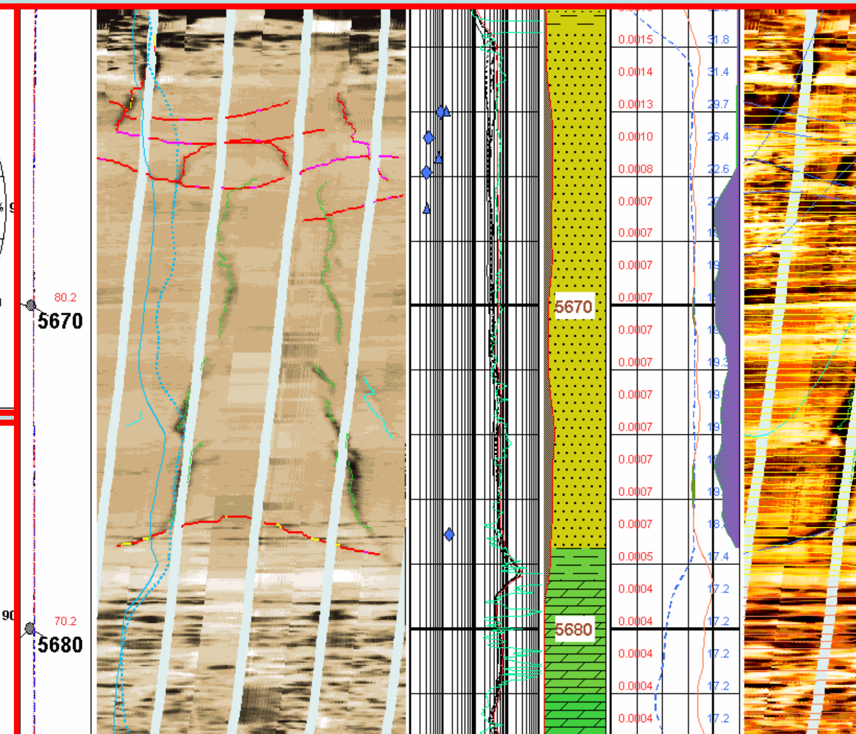
The well was a great success. Over 500 ft. of continuous core was recovered (>90% recovery) including >150 ft. of shale, siltstone, and anyhydrite cap rock.

This well also collected information on in-situ stress magnitude and azimuth, which can be used to predict fault-fluid behavior.

In-situ stress information







New wells at NPR-3 provide data on stress orientation & magnitude. This information is vital to the prediction of fault reactivation and buoyant fluid migration.

Stanford, Lawrence Livermore National Laboratory

Organic Geochemistry: Baseline

Along fractures & faults within the field, hydrocarbon residues & carbonate minerals provide evidence of fluid flow to the surface. B. Burruss and his staff collected surface and subsurface samples.

- **All reservoirs sampled at Teapot**
- **Tensleep sampled at Salt Creek**
- **Surface bitumen deposits and veins**
- **New trenches to access faults & fractures**

Evidence of the

- **Evidence of biodegradation compartments**
- **Possible to uniquely fingerprint HC sources**

Soil Carbon Survey: Baseline

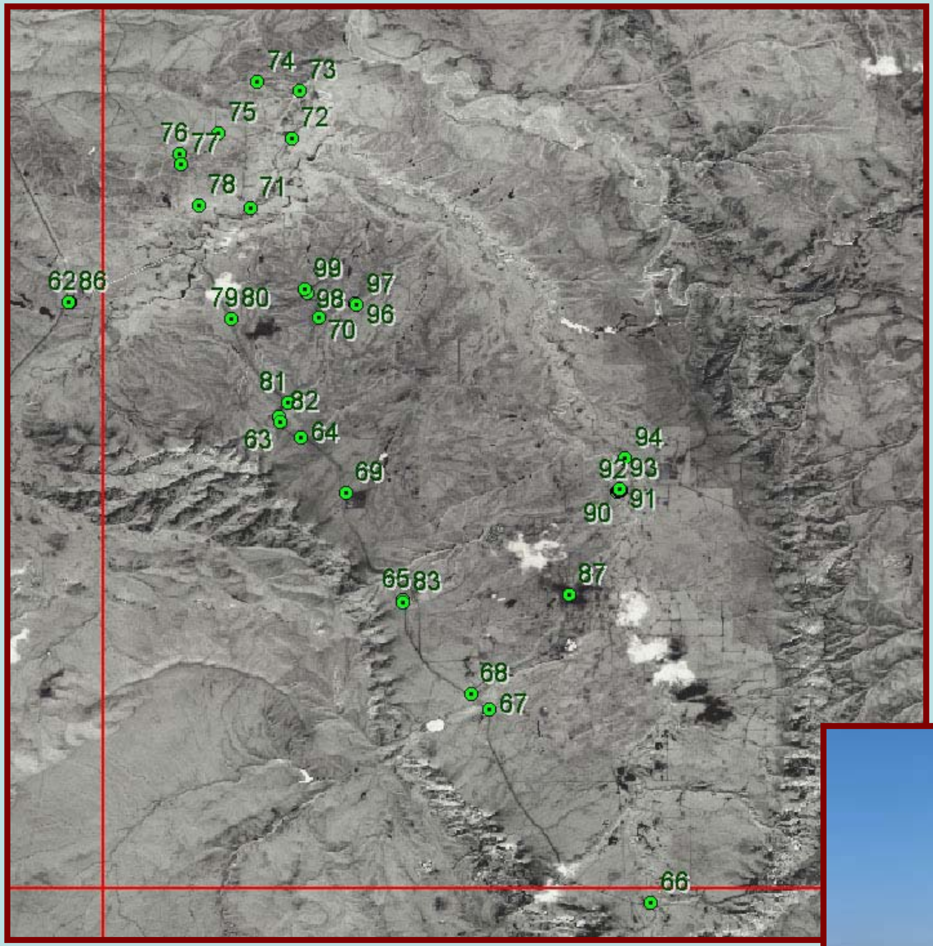
R. Klusman has collected & analyzed the first year of soil carbon baseline data using two approaches:

- Surface chambers (40 stations)
- 10 m deep borehole arrays (5 stations)

Report data include CO_2 & CH_4 concentration, flux, & stable isotope.

Colorado School of Mines

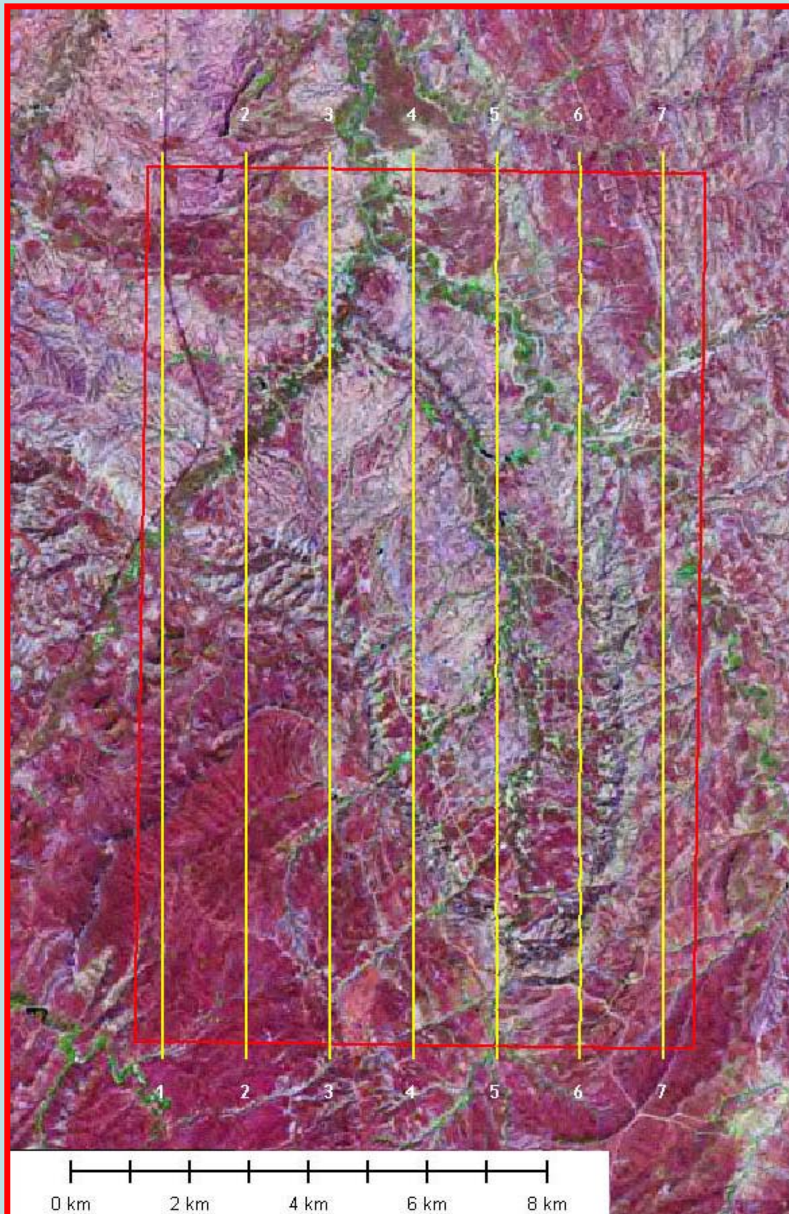
Airborne Hyperspectral



W. Pickles has collected baseline HyVISTA data from an airborne platform, like that used at Rangely. Can currently resolve many different plant “habitats”.

This approach was used for a natural gas detection methods test run in Sept. 04. A similar CO_2 detection test is in the planning stages.

Airborne Hyperspectral



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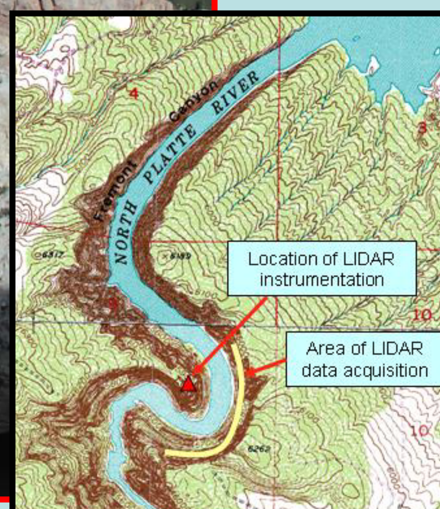
Reservoir Heterogeneity: LIDAR mapping

A new laser-based surveying technique collects many millions of amplitude and XYZ data, which can render the outcrop in high detail.

This data is being used to characterize the heterogeneity of the Tensleep SS, including fracture distribution & character.



Colorado School of Mines

Organization and funding

Currently, the project is funded from RMOTC's budget.

- **FY2003 + 2004 is roughly $1.4 MM**
- **New staff, including geologist & data manager**
- **There is a comparable amount from other funding or in-kind contributions**
- **FY2005 is in progress; aimed at data collection, digitization, & reservoir simulation**

Project organization will evolve over the coming year, but will emphasize research goals.

- **Consortium of labs & universities will drive research**
- **Research participation from all partners**
- **Steering committee from key stakeholders will provide recommendations to project**
- **RMOTC will control field operations and data**

Parallel, non-science roles

Teapot Dome can serve as a a platform for technology transfer, training, and outreach

- **Public access, operational oil field in public domain**
- **Synergies with other DOE programs**
- **Provide information directly to stakeholders**

Teapot Dome is a natural site for national and international collaboration and interest

- **Similarities to aspects of national geology, esp. Rockies, California, Appalachia**
- **Similarities with aspects of foreign geology, especially China, India, N. Sea, Australia, N. Africa**

Conclusions

Earth science and technology developments are needed to demonstrate feasibility of carbon storage at a grand scale, which ultimately require large-scale field experimental tests

Teapot Dome is an outstanding site for collaborative research to resolve key geoscience questions of monitoring and storage.

Current activity show the strengths of Teapot Dome for MMV technology demonstration and collaborative research.

Demo Projects v. Field Experiments

These two kinds of field project have different goals and means.

Demo projects

Chief goal: Tons C underground

Chief driver: commercial

Chief limit: business

Examples: Sleipner, Weyburn, Mountaineer, Allison

Field experiments

Chief goal: new knowledge

Chief driver: scientific

Chief limit: financial (scale)

Examples: Frio Brine Pilot, Hobbs

Although both are needed to test the true viability of wide-scale geological carbon storage, large scale field experiments are the *sine qua non* for success

Large Scale Projects: Primary Effort

There are many large projects, planned or pending, which could serve as very good natural laboratories. There may be moneys available from the State Dept., foreign countries, industry, and the DOE.

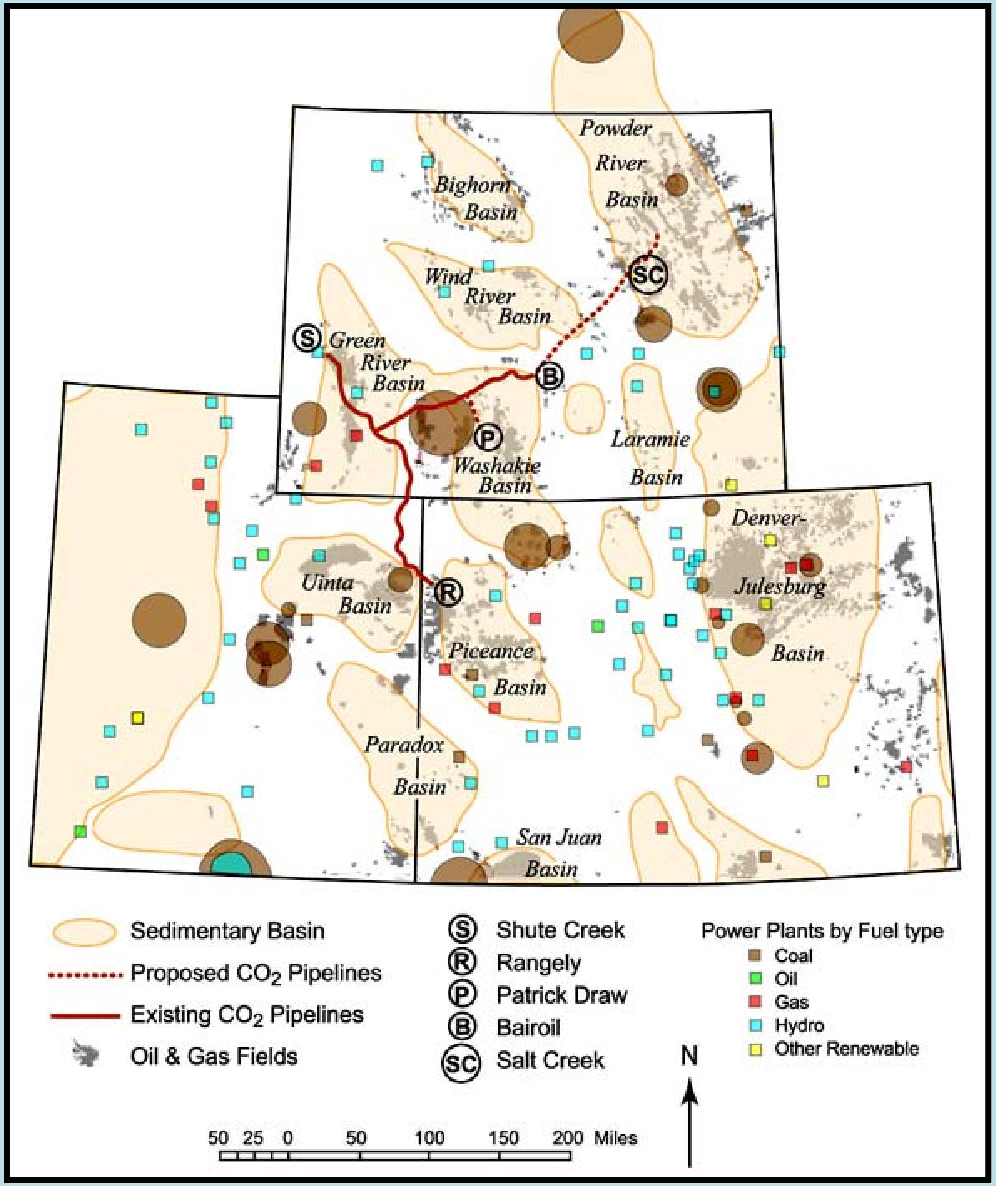
Pending

- **Snøhvit (saline aquifer, Statoil)**
- **Low—BTU gas, CO_2 injected into water leg (In Salah & Tangguh, BP; Snøhvit, Statoil; Natuna, ExxonMobil)**
- **Gull Fachs (EOR, Norsk Hydro)**
- **Mountaineer (saline aquifer, Batelle/AEP)**

Planned

- **Ormen Lange (saline aquifer + depleted gas field, Statoil)**
- **Betzin (saline aquifer, BRD)**
- **FutureGen (unknown, DOE)**
- **Alberta Basin (EOR + saline aquifer, ARC, AGS, & industry)**
- **Wyoming EOR (local comp.)**
- **Regional Partnership efforts**

Rocky Mountains as a Test Center



- Teapot Dome geology VERY similar to many Rocky Mountain producing fields
- Teapot & other sites are near both pipelines and very large point sources
- Enormous regional EOR potential (~15-20 Billion OOIP)

Geology similar in many ways to Appalachian & Illinois basins, N. Sea, Germany, China, & India

EnergyINet: An Overview of Monitoring and Risk Assessment Activities in Western Canada

IEA Monitoring and Verification Workshop, Santa Cruz,
9 November 2004

David Keith
On behalf of EnergyINet and associated researchers in Western Canada

(keith@ucalgary.ca)
Department of Chemical and Petroleum Engineering
Department of Economics
University of Calgary


Canada's Sedimentary Basins Most Suitable for CO_2 Storage
North Pole
Alpha Ridge
Canada Basin
Greenland
Beaufort Basin
Arctic Basins
Baffin West Basin
Foxe Basin
CORDILLERAN OROGEN
Mackenzie Basins
Intramontane Basins
PRECAMBRIAN SHIELD
Pacific Basins
Rocky Mountain
Alberta Basin
Athabasca Basin
Severn Arch
Hudson Bay
Labrador Basins
PRECAMBRIAN SHIELD
Bow Island Arch
Williston Basin
Transcontinental Arch
Moose River Basin
St. Lawrence Basins
Saguenay Arch
Nova Scotia
Atlantic Basins
U.S.A.
Frontenac Arch
Algonquin Arch
APPALACHIAN OROGEN
ALBERTA RESEARCH COUNCIL
EUB
AGS

EnergyINet

Today's Reality

Declining energy research investments and capability

Fragmentation among governments, industry and research providers

Competition for scarce resources

Project-driven research

Generally short-term industry thinking

Uncoordinated funding pots

No overarching vision

The EnergyINet Promise

Transformative vision

- "Integrated Energy Economy"
- Strategic research and innovation leading to commercialization

Transcending alliance which aligns:

- Multiple funders
- Research providers
- Industry and governments for achieving a common vision

Program Implementation

Advisory Board

- Management Committee
- Technical Committee

Program Director

Approved Business Plan

- Integrated across research providers

Several Funders

Programs

Oil Sands Upgrading

Clean Carbon

Improved Recovery

Alternative and Renewable Energy

Water Management

CO_2 Management

Canadian Carbon Management Projects

- Acid Gas Injection (an industrial analogue for CO_2 Storage) in Western Canada
- Cassier Tailing Mineralogy, Toxicity and Suitability for CO_2 Sequestration
- CO_2 Sequestration in British Columbia
- The Potential for CO_2 Sequestration in British Columbia Coal Seams
- CO_2 storage capacity of deep coal seams in the vicinity of large CO_2 point sources in central Alberta and Nova Scotia, (assessment of)
- CO_2 Storage by Mineral Carbonation Reactions: Kinetic and Mechanical Insight from Natural Analogs
- Enhanced Coalbed Methane Recovery for Zero Greenhouse Gas Emissions
- Fixation of Greenhouse Gases in Mine Residues
- Geologic sequestration of CO_2 and simultaneous CO_2 sequestration / CH_4 production from natural gas hydrate reservoirs
- IEA GHG Weyburn CO_2 Monitoring and Storage Project

Over $70 Million Invested

- Mineral carbonation in chrysotile mining waste: biological and chemical processes
- PTRC Studies on CO_2 Utilization and Extraction
- Sequestration of Carbon Dioxide in Oil and Gas Reservoirs in Western Canada
- Sequestration of Carbon Dioxide in Oil Sands Tailings Streams
- Suitability of Canada's Sedimentary Basins for CO_2 Sequestration
- Integrated Economic Model for CO_2 Capture and Storage
- Development of a multi-level online auction website designed to foster the development of a sustainable carbon dioxide (CO_2) market
- Enhanced Coalbed Methane and CO_2 Storage Piloting in Qinshui Basin, Shanxi Province, China
- Carbon Sequestration and Enhanced Methane Production Pilot (CSEMP)
- Monitoring of Alberta’s 4 Experimental EOR Pilots
- CBM Through ECBM Followed by Bacterial Regeneration of the CBM Reservoir: An Approach to Sustainability

CO_2-Enhanced Coalbed Methane/CSEMP

PHASES	YEAR	
I	1997	Proof of Concept for Alberta
II	1998	Single Well CO_2 Micro-Pilot
IIIA	1999 - 2001	Single Well Flue Gas Micro-Pilots
IV	2002 - 2005	Matching CBM Resources with CO_2 Sources
IIIB	2002 - 2005	Three-Well CO_2 Pilot
V	2002 - 2010	Methanogenesis of Coals

In Deep Coals > 1000 meters

CO_2 Sources:
- Ethanol Plant

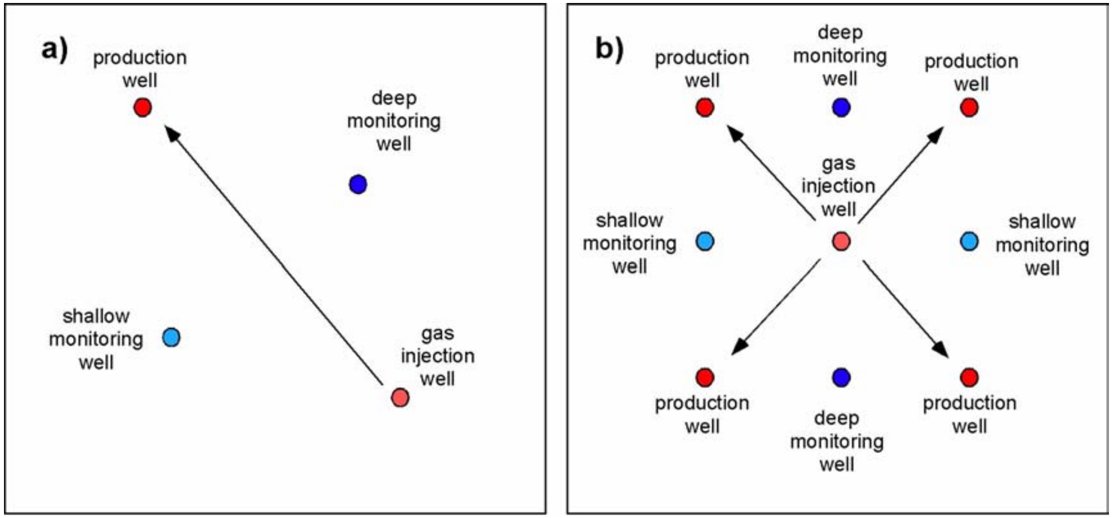
CO_2 Sources:
- Land Fill
- Fertilizer
- Gas Plant
- Coal Fired Utility
- Portable Novel
- Hydrogen Plant

Ardley Coal < 500 meters

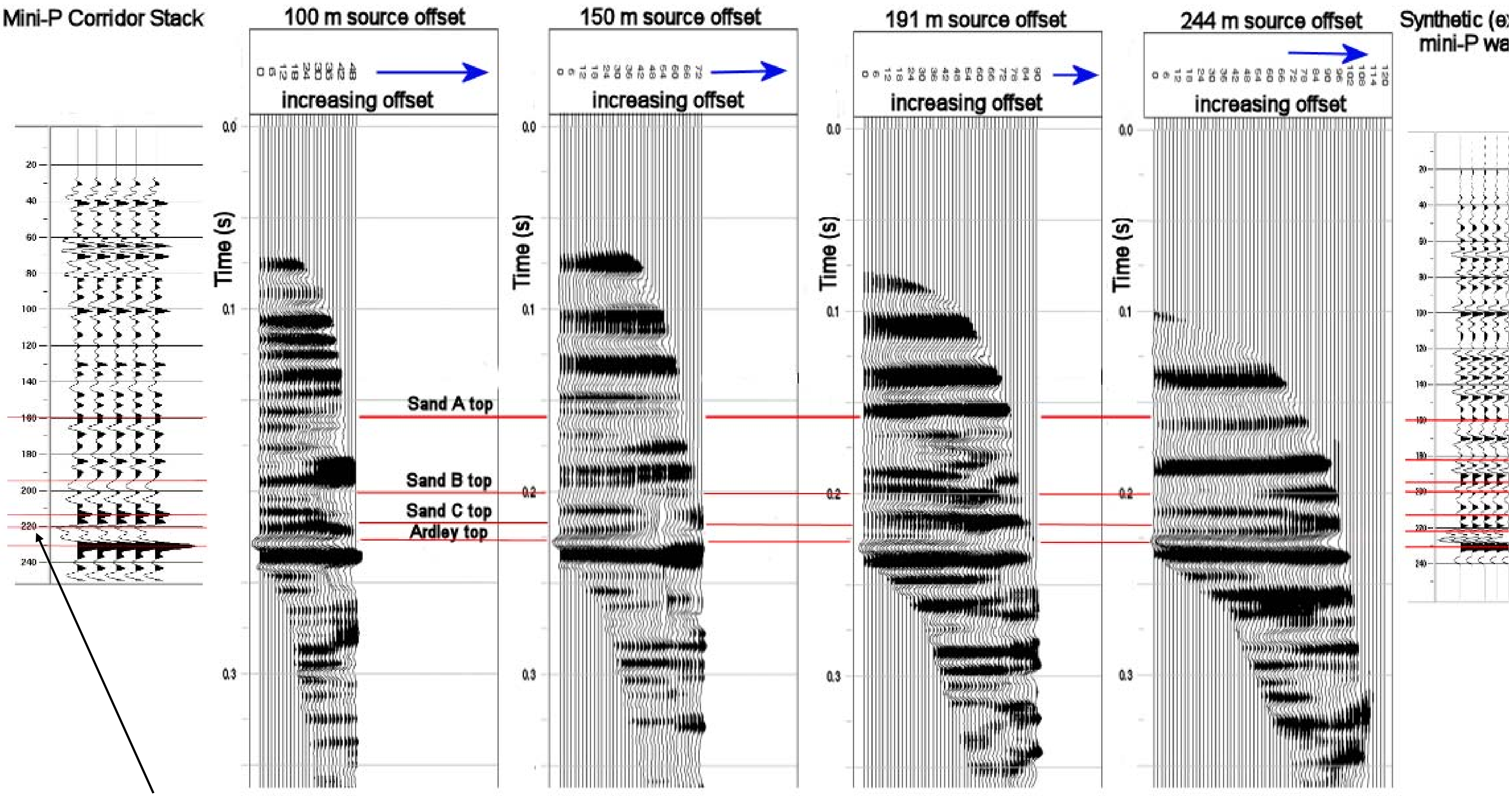
CO_2-ECBM Monitoring

Monitoring plans

- About 400m, several zones about 6 m thick max. Production now ongoing via dewatering. CO_2-ECBM starting in next few months using trucked in CO_2 at injection rates similar to EOR pilot which will run at about 70 t-CO_2 /day.
- Geochemical monitoring of fluids from shallow and deep monitoring wells, and drinking water wells.
- Vertical seismic profiling using a 40-geophone array with simultaneous PP and PS wavefields simultaneously with multi-component surface seismic.
- Passive seismic from monitoring well with permanent geophones.
- Soil gas survey.



Offset VSP P-wave imaging of coal zone at proposed CO_2 injection & CBM site, Alberta

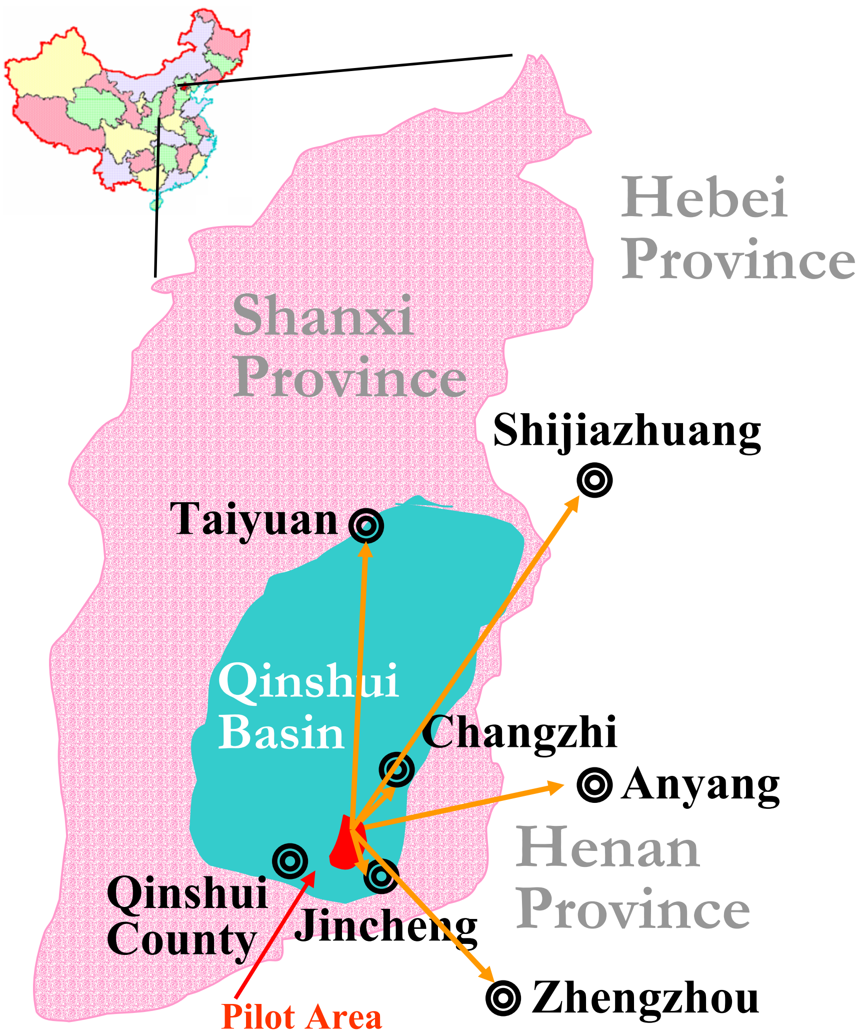


Coal seam ~10 m thick at 220 m depth

VSP used ~16 element geophone array.

Courtesy of Don Lawton

Canadian International Development Agency: CO_2-ECBM



- Joint Canadian Consortium for ECBM and China United Coalbed Methane Corp. (CUCBM)
- Potential pilot site selection
- Geological/engineering/environmental characterization and ranking of selected 3 pilot sites
- Design of micro-pilot field test procedures to evaluate CBM reservoir properties
- Carry out a single well micro-pilot field test at the best suitable site
- Selection of existing wells or drilling new wells
  - Up to three micro-pilot tests will be performed if first two tests do not show commercial potential

Weyburn: Accomplishments & Plans for Phase Two

Accomplishments

- Successful demonstration of technology
- Preliminary indication of integrity
- Well structured research program
- International nature of venture

Plans for Phase Two

- Improved risk assessment and modeling
- Continued cooperative research
- Improved integration
- Continued monitoring

New CO_2-EOR Pilots in Alberta

Five-year, $15-million program announced April 30, 2004

- Four pilot projects expected to generate at least $30 million in incremental royalties over 20 years.
- Could result in CO_2 storage of a minimum of 22 million tonnes, equivalent to an average of 1.1 million tonnes per year.

Company	Project	Process
Anadarko Canada Corp.	Enchant Arcs A&B CO_2 Injection Pilot	CO_2-EOR (WAG)
Apache Canada	Zama Area CO_2 Enhanced Oil Recovery	CO_2-EOR
Devon Canada Corp.	Swan Hills Unit #1 CO_2 Injection Pilot	CO_2-EOR (WAG)
Penn West Petroleum Ltd.	Pembina Cardium 'A' Lease CO_2 Pilot	CO_2-EOR

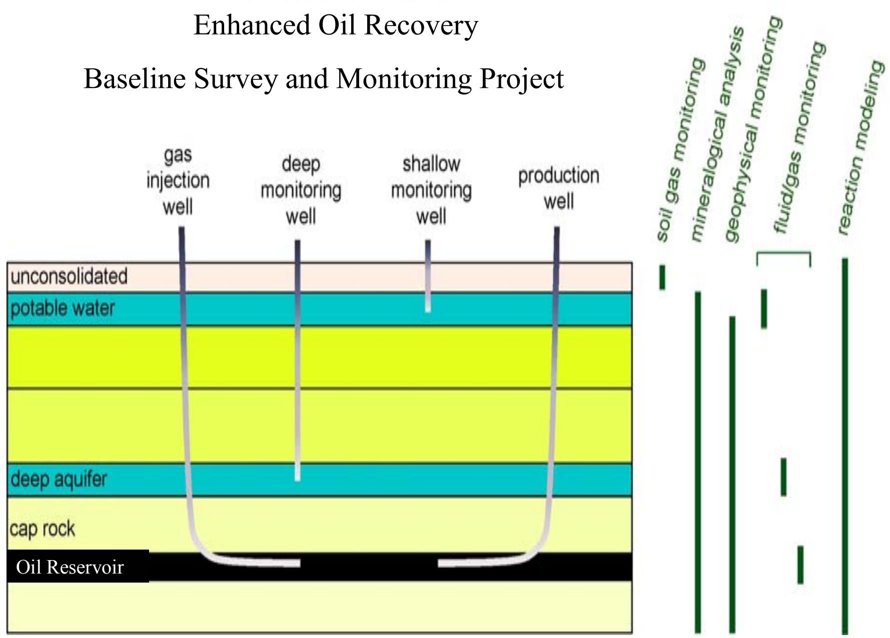
Monitoring at one of the EOR pilots

Reservoir Characteristics

- Marine sandstone interbeded with shales. Roughly 20 md max permeability.
- Cumulative thickness ~20m in four units at about 1600 m depth.
- Now under waterflood. All production & injection wells to be fractured.
- EOR pilot using two injectors and 6 producers, 75 t-CO_2/day for two years.

Monitoring Plans

- Monitoring well with P, T, fluids, and eight geophones.
- Monitoring wells above reservoir.
- Vertical seismic profiling with simultaneous S & P wave retrievals.
- Expected start in late 2004 early 2005.
- Sealed high quality cores recovered.
- Pressure interference test between producers and injectors.
- Recovery of cement samples.



Integrated Risk Management

Development of integrated geologic storage simulator

- Reservoir models driven by geo-statistical tools to produce probabilistic leakage scenarios.
- Simulation of monitoring methods (seismic, pressure monitoring, fluid sampling, EM, …).
- Integrated well bore model (geomechanics, geochem and transport) .

Objectives

- Development and testing of integrated monitoring strategies.
- Reservoir engineering methods to reduce risk or improve sweep efficiency.

Status

- Collaborators: University of Calgary, University of Alberta, Alberta Research Council, and Lawrence Livermore (reservoir engineering).
- Initial start-up funding at UofC.
- Promising early results on reservoir engineering to accelerate dissolution.

Opportunities for Capture and Storage in Western Canada

Natural gas associated CO_2

- Acid gas injection provides technological and regulatory analog.
- Mean CO_2 concentration now ~2.5%. May be growing as production moves deeper and northward.
- In Canada NG-CO_2 is now >9 Mt CO_2/yr, about 1.5% CND of emissions.

Hydrogen associated CO_2

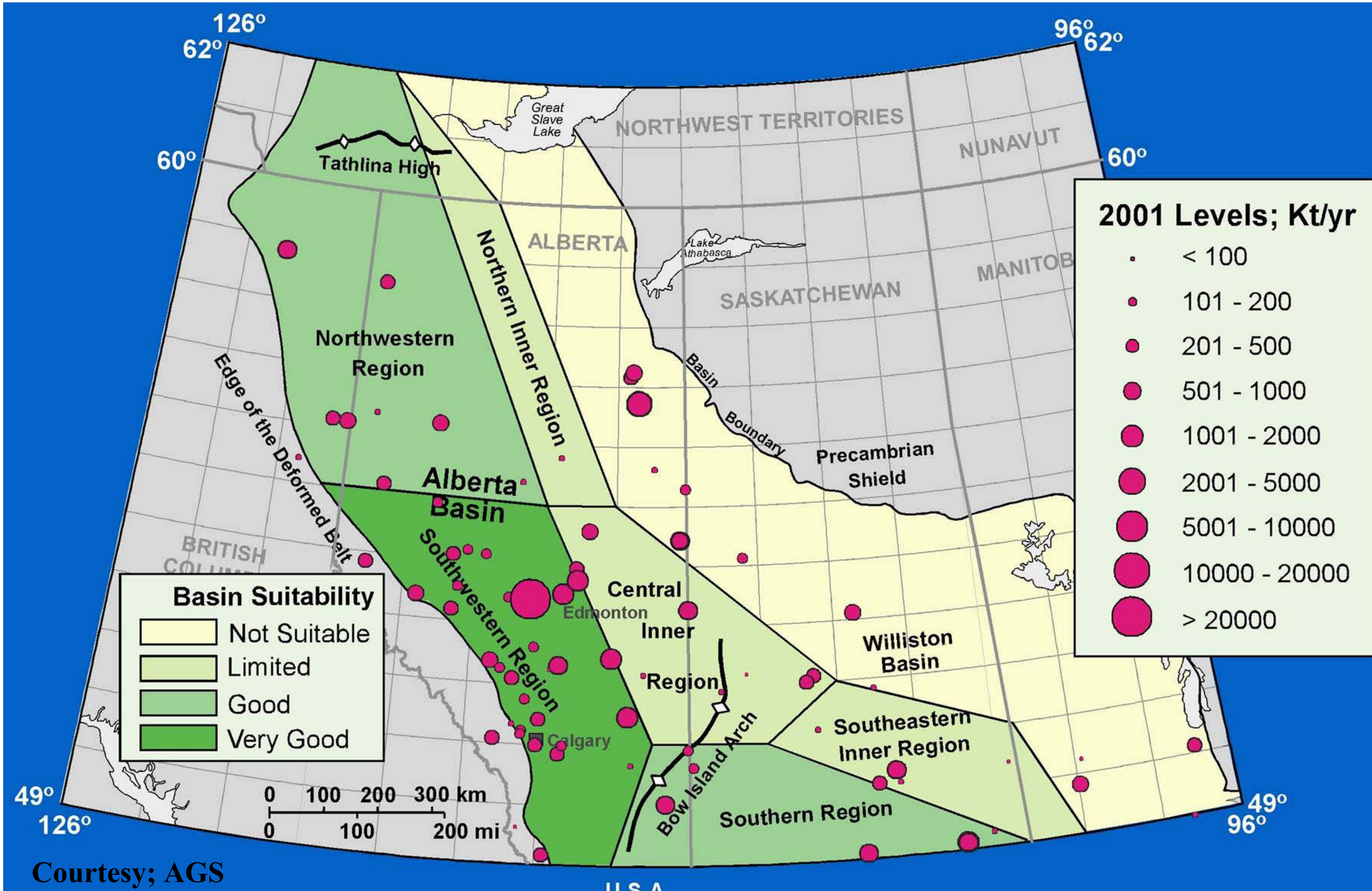
- About 5 MtCO_2/year for each million bbl/day of synthetic crude
  - Potential to substantial increase the amount CO_2 capture—and the cost—by integrating coal gasification into plant fuel gas and hydrogen.
- Comparatively low capture cost because (i) it new capacity and (ii) syngas.

Low cost capture from **new** non-combustion sources

+ well developed basin with opportunities for EOR and ECBM
+ commitment to emissions reductions (Kyoto ratified)

➔ Canada has an unusual good opportunity for early large-scale action

Sources and Sinks



Courtesy; AGS

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CBM Through ECBM Followed by Bacterial Regeneration of the CBM Reservoir: An Approach to Sustainability

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Development of Monitoring Plans for Potential CO_2 Injection Tests in the Ohio River Valley Region

Neeraj Gupta[1], Phil Jagucki[1], Joel Sminchak[1], Jim Dooley[2], Ken Humphreys[2], Mark White[2], Frank Spane[2]

1. Battelle, Columbus, Ohio, 2. Battelle/Pacific Northwest National Laboratory

November 9, 2004, IEA Monitoring Workshop, Santa Cruz, CA

NETL AEP® bp BURN OHIO COAL Ohio Coal Development Office Pacific Northwest National Laboratory Operated by Battelle for the U.S. Department of Energy Schlumberger

Mountaineer Site – Current Status

- Based on current data, we continue to believe that large/commercial scale injection is possible and economically feasible at the Mountaineer Plant
- Potential reservoir candidates include:
  - The Rose Run Sandstone – testing and modeling shows injection potential exceeding 100,000 t/yr in a single vertical well
  - Presence of high permeability zones in the dolomite layers provides a potential new regional storage zone
  - Basal Sandstone (Mt. Simon Sandstone) – potentially high cementation/low permeability in deeper parts of Appalachian and Illinois basins but very high storage potential elsewhere in the region
- There is excellent containment at the site and in the region
- Next steps are focused on design feasibility including CO_2 source, permitting, stakeholder outreach, and development of the regional geologic framework

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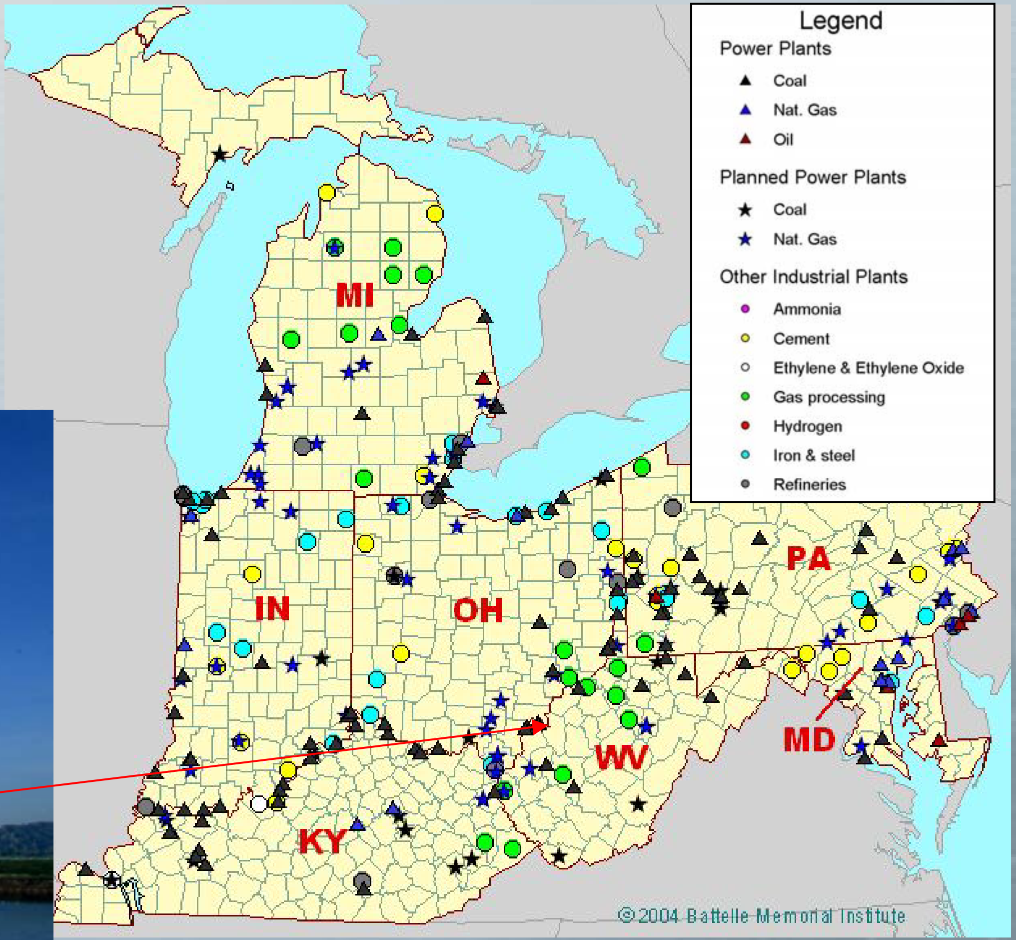
Ohio River Valley CO_2 Storage Project – Key Motivations

- A large number of CO_2 sources lie in the Ohio River Valley region. Therefore it is important to determine the CO_2 storage opportunities in this region
- Systematic field studies are essential for understanding the storage potential and building stakeholder confidence
- The objective of this project are to characterize the CO_2 storage potential in geologic reservoirs in the region on a site-specific and regional basis
- The objective is not to simply go to the best known sandstone and demonstrate injection of CO_2.
- During the last 18 months the first steps in this process have been completed through site characterization in a deep test well and seismic surveys

Project Motivation – Why the Ohio River Valley Region?

- Mountaineer Plant - 1,300-MW, flagship, coal-fired plant with installed SCR for NOx control and FGD for SOx under construction
- Numerous other sources in the region and high potential for additional sources



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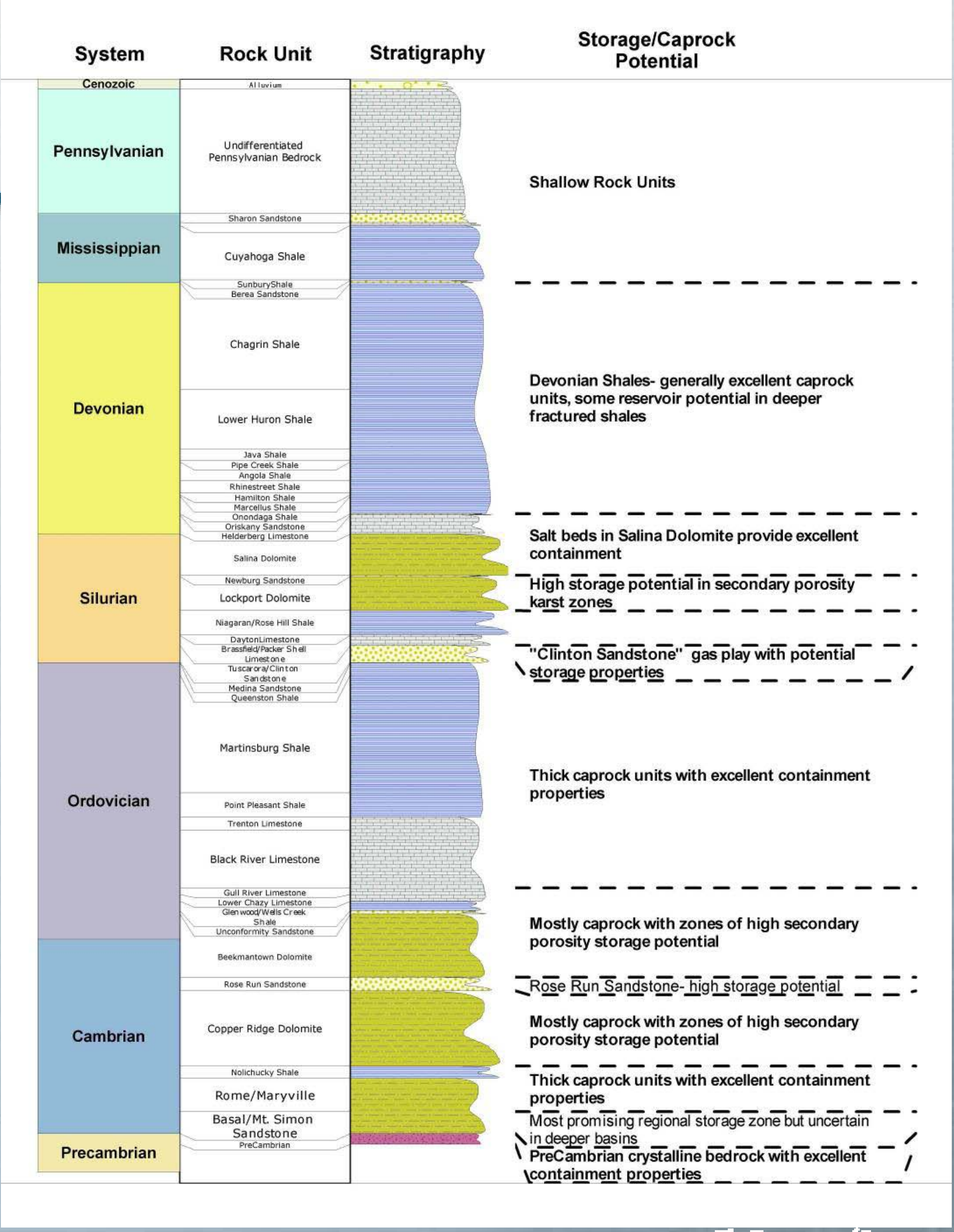
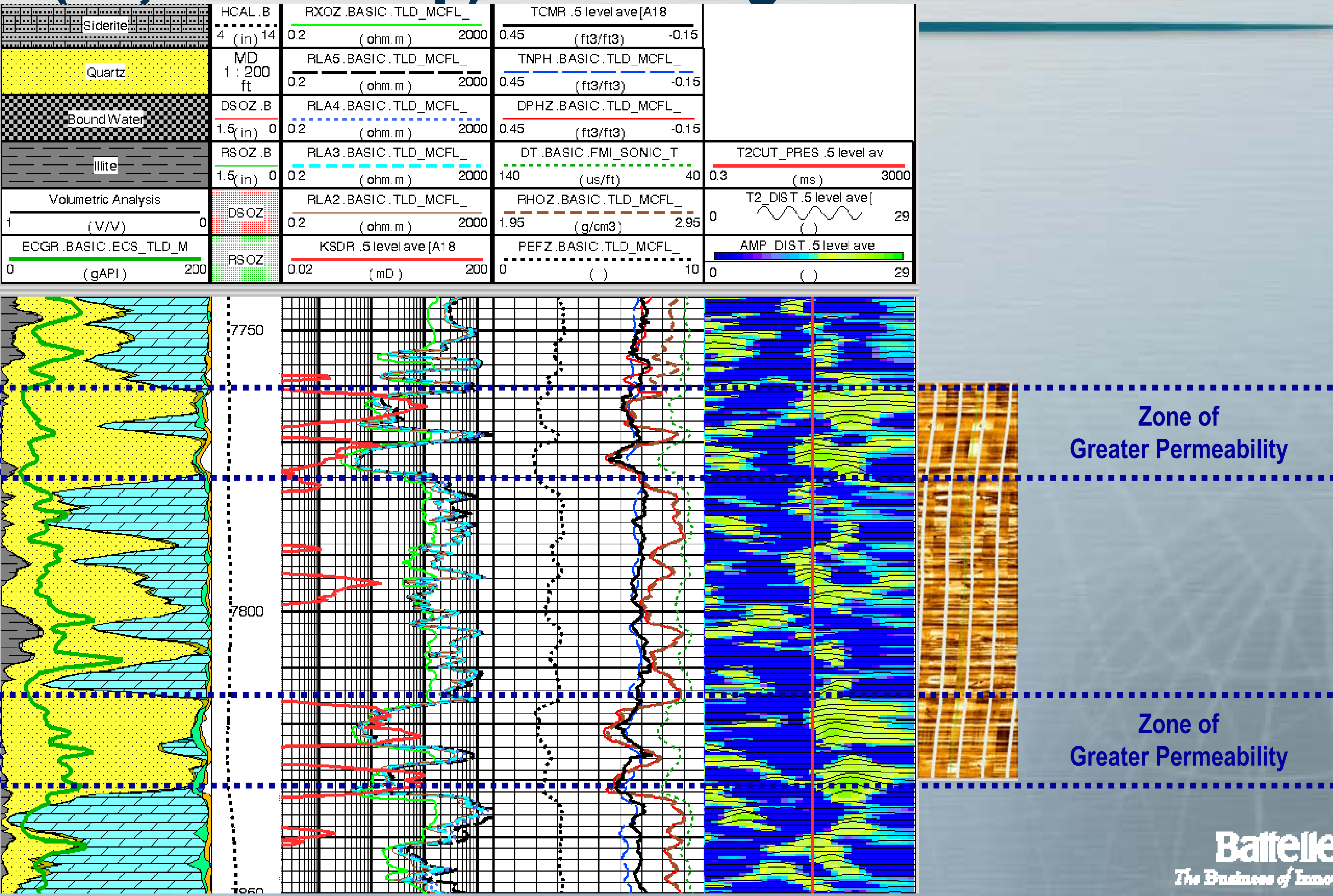
General Geology

- Multiple potential injection zones are present at the site and in the region
- Up to 15,000 ft of sedimentary column
- Deeper formations require continued exploration



Borehole Logging – Rose Run Sandstone (~7,800 ft deep) shows high k zones



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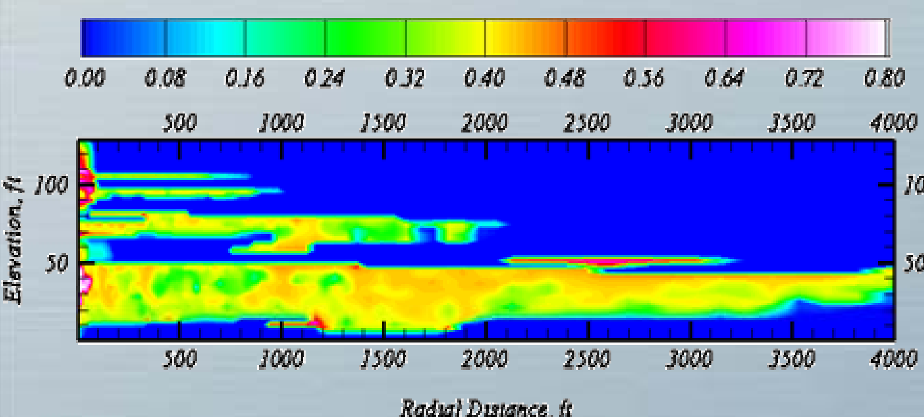
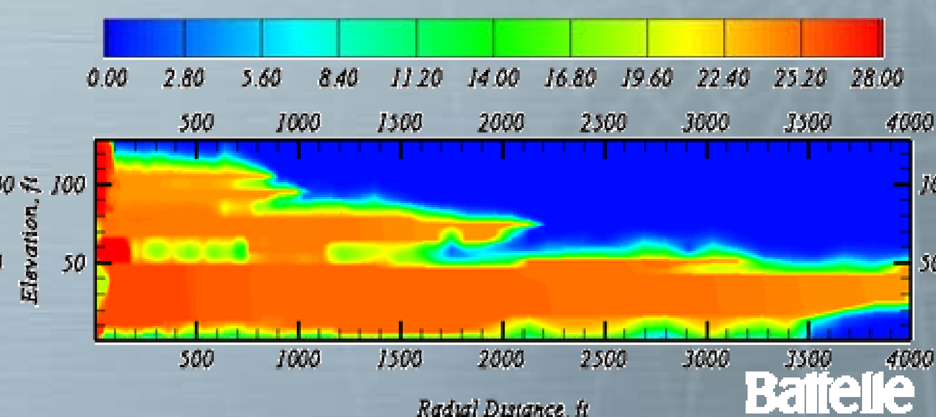
Rose Run Sandstone – Single Vertical Well Simulations Using STOMP-CO_2

- 2-D, single vertical well simulations with log and core data show injection rates can exceed range from 36 to 300 ktons/yr over 20 years
- Significant increase in injection possible with lateral wells
- Site amenable to hydro-fracturing because Rose Run fracture pressure < caprock fracture pressure
- Dissolution rates 11-70% after 100 years (needs verification)





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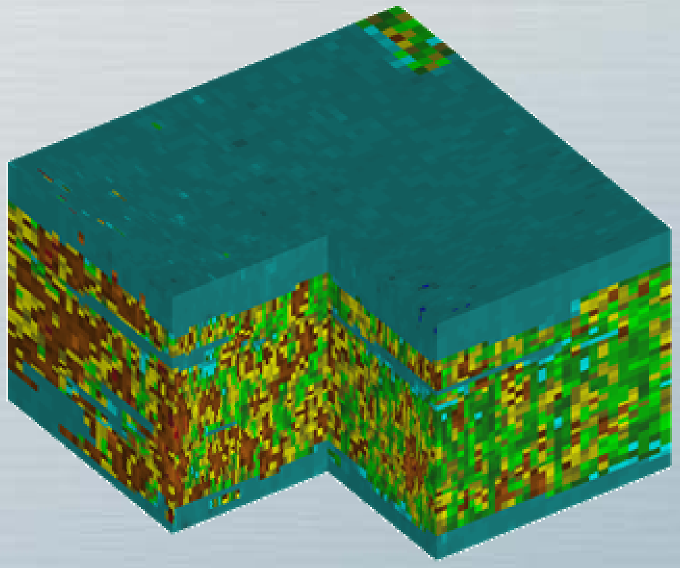
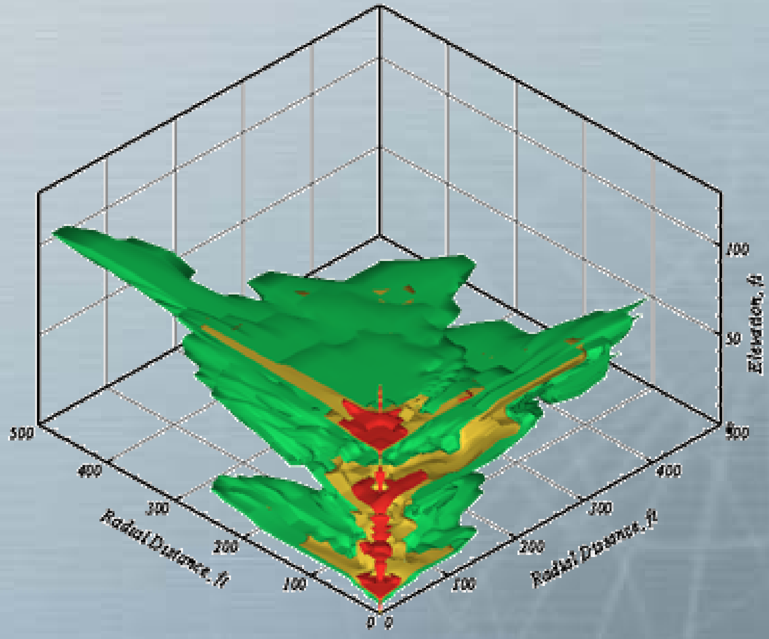
3-D Simulations using STOMP-CO_2 Code

- Future simulations include lateral wells and effects of reservoir stimulation

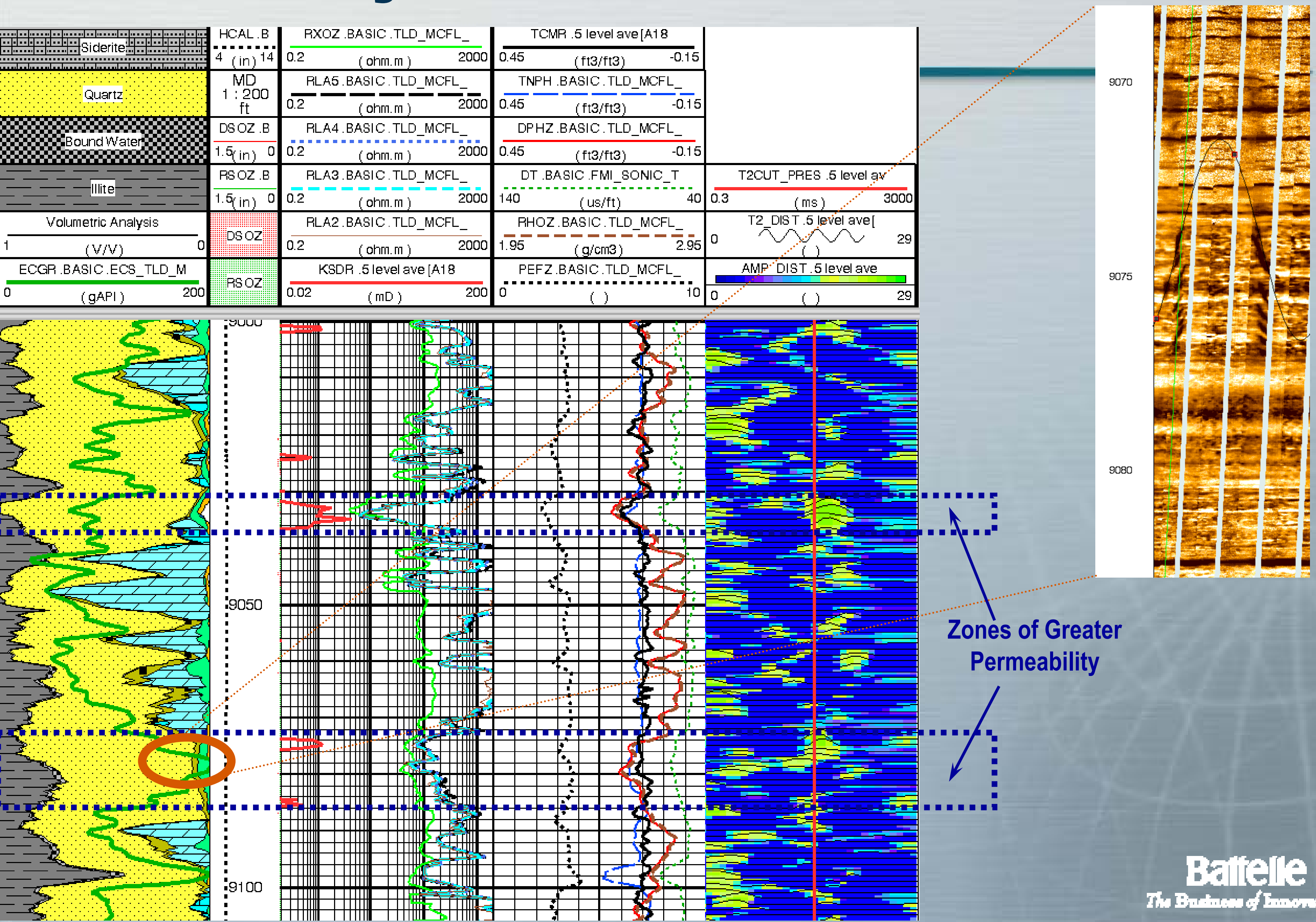


3-Dimension Random Field- Realization of Intrinsic Permeability, ln(mD)

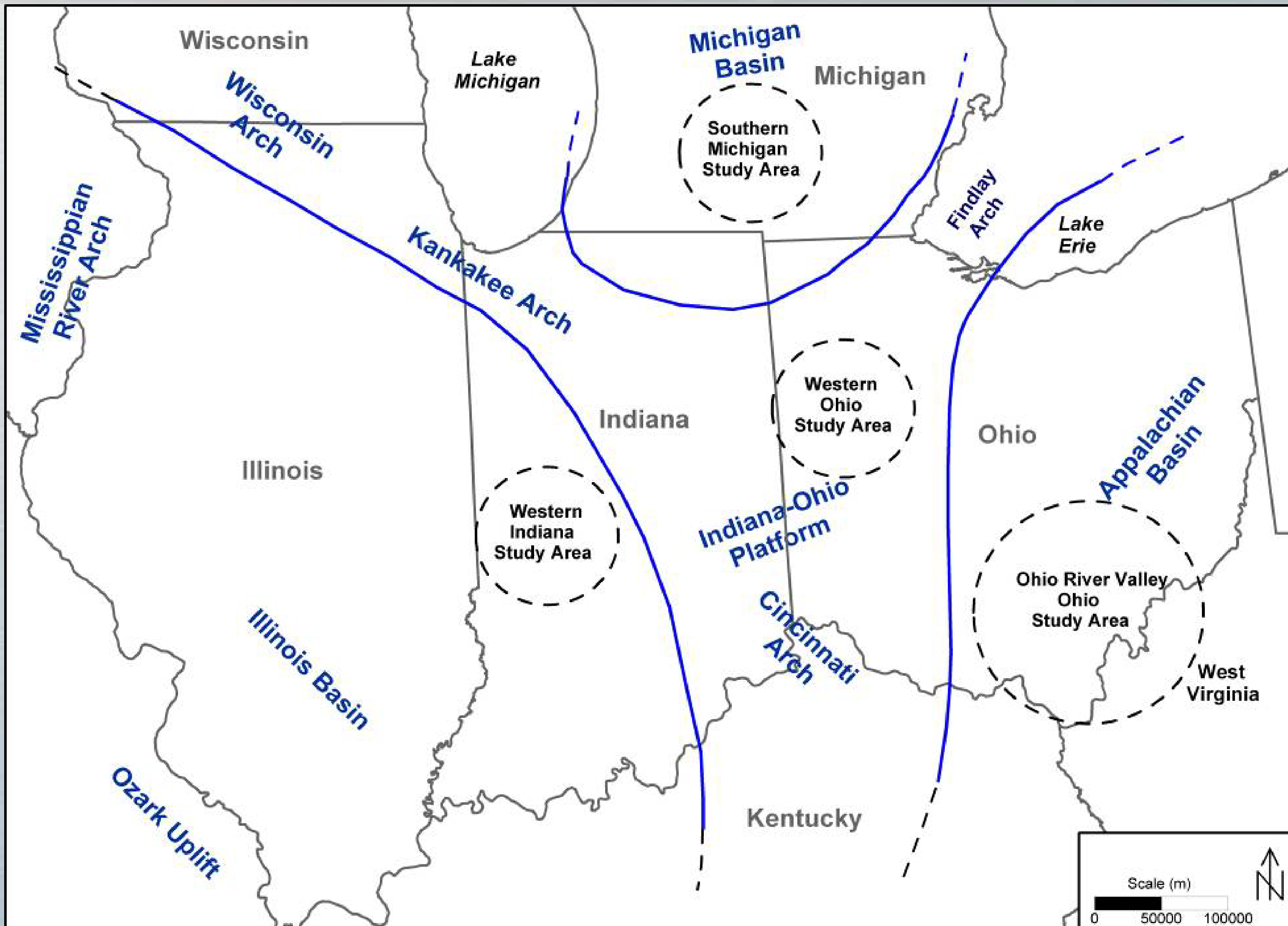


CO_2 Saturation Isosurfaces (0.01, 0.2, 0.3) @ 44 days (Saturation Range 0.0 - 0.81)

Lower Marysville/Basal Sandstone Data

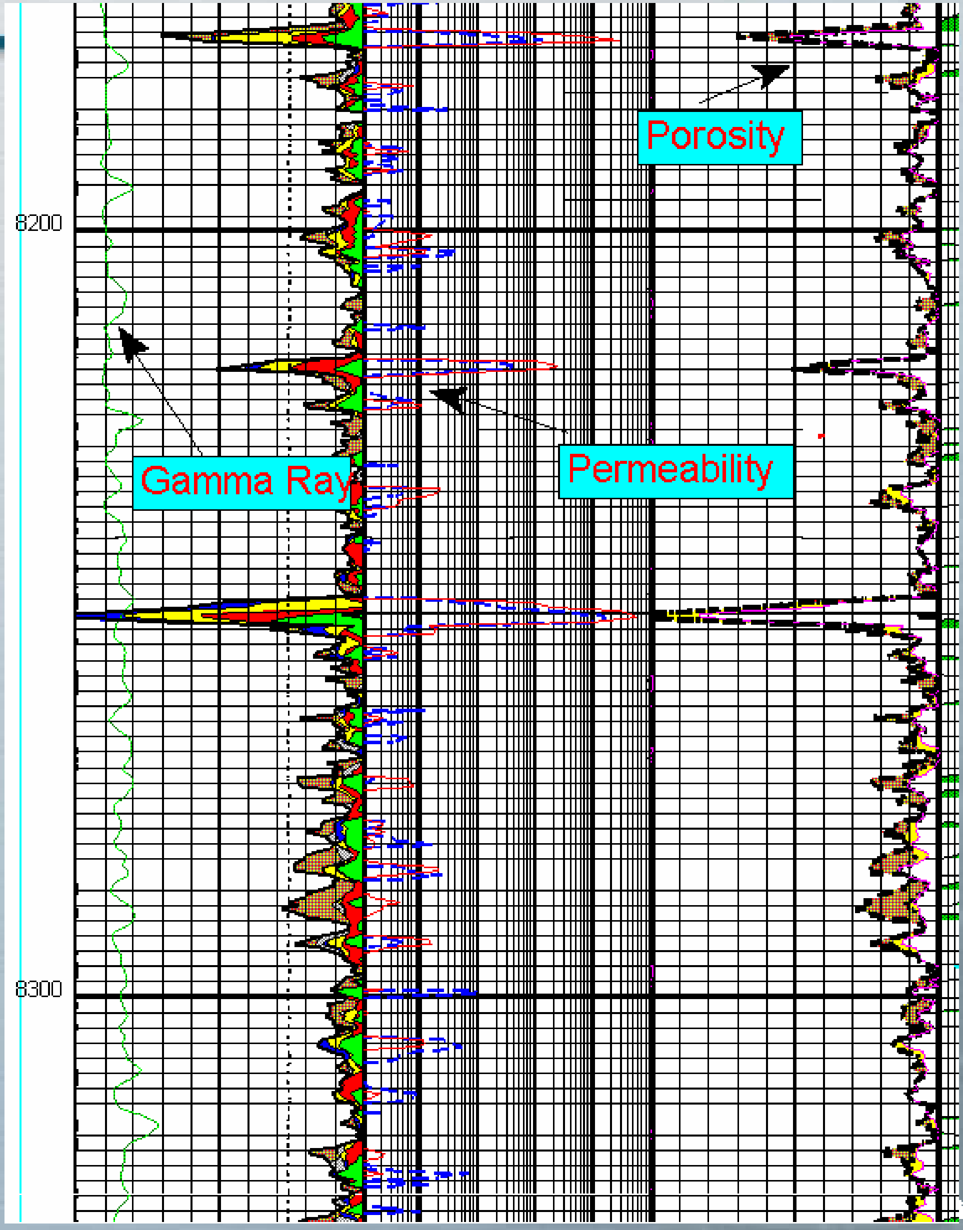


On a Regional Basis, Mt. Simon is the Best Storage Candidates

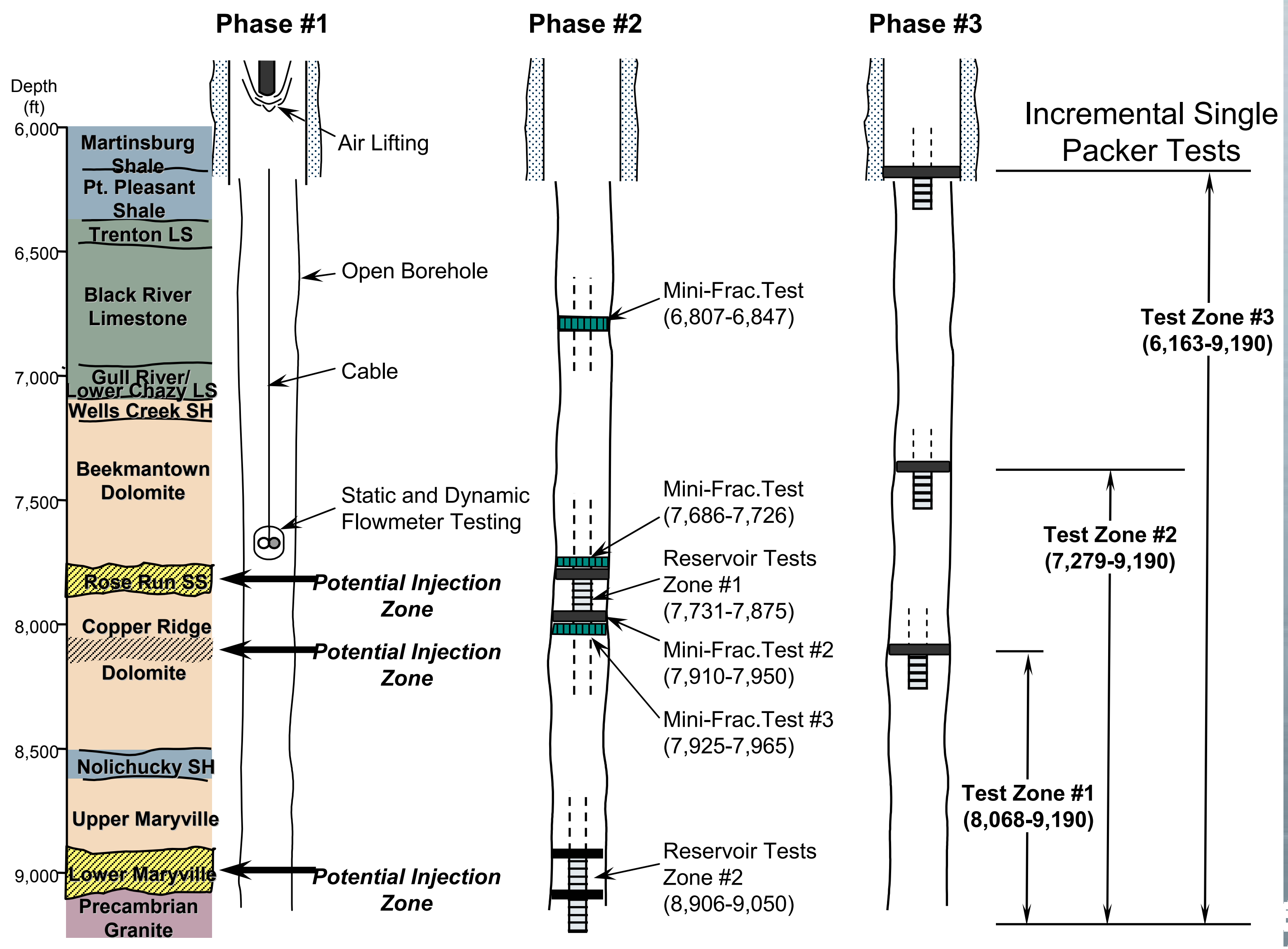


Lower Copper Ridge Dolomite – A New Storage Candidate Identified?

- Rocks under Rose Run Sandstone generally dominated by dense dolomite layers.
- However, significant storage potential has been observed in part of Copper Ridge Dolomite (B-Zone) at Mountaineer and in a well 20-km away.
- Based on packer tests, this zone accounts for about 45% of flow potential in the borehole
- This is promising for regional storage potential and needs further exploration



Reservoir Tests to Evaluate Injection Zones



Geochemical Baseline has been Established

- Downhole brine samples were collected in the Rose Run and Basal Sand using discrete level samplers
- TDS is very high in both formations: 330,000 mg/L in Rose Run and >400,000 mg/L in Basal Sand.
- Overall, the Rose Run brine chemistry at AEP#1 is consistent with trends based on other wells in the region.
- Stable isotope signatures in AEP#1 and those reported by the USGS also are very similar and are highly differentiable from local meteoric water.

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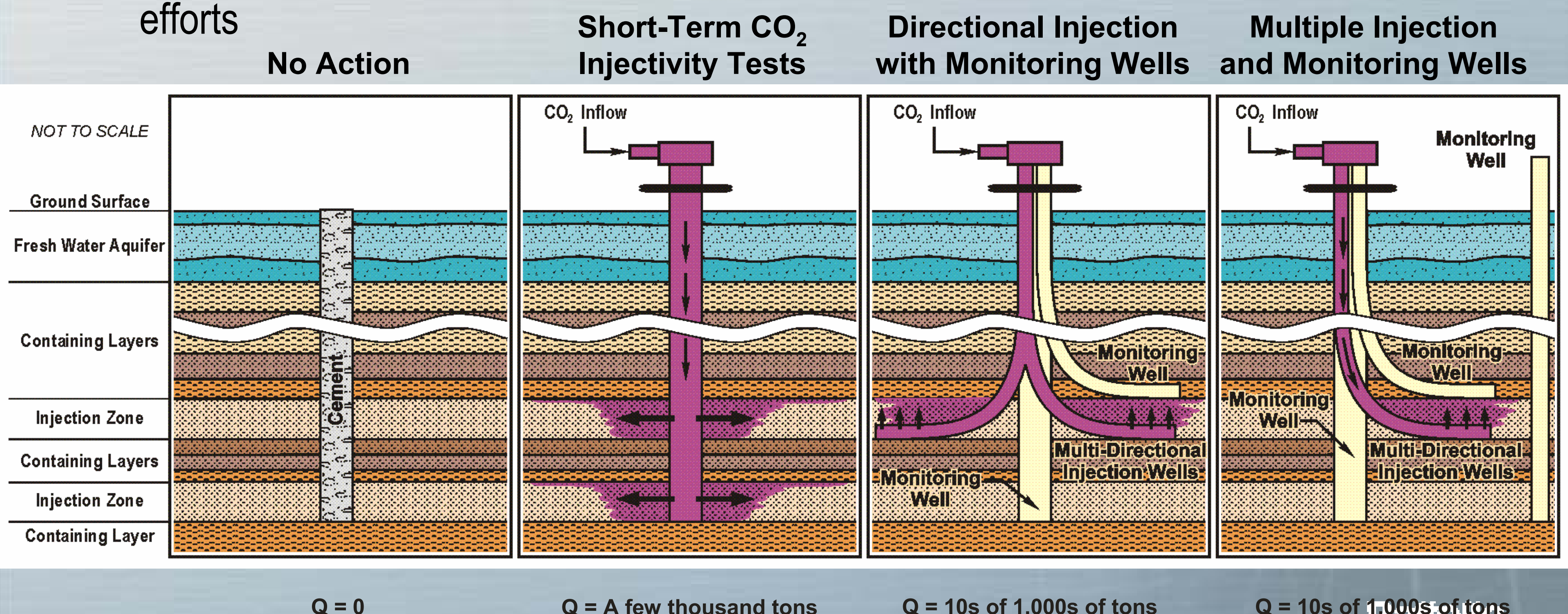
Design Feasibility for Injection Tests

- Options for an injection/monitoring program at the site are being evaluated
- The next logical steps include system design, permitting, and monitoring plan
- This decision to proceed to injection will be made by project sponsors based on the outcome of the complete design feasibility study including stakeholder outreach efforts



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Development of a Monitoring Plan

- Monitoring for any injection test phase will need to address
  - Regulatory monitoring requirements for injection wells
  - Performance assessment – scientific monitoring to understand fate and transport of injected CO2
- Need to avoid setting costly precedents for the future full-scale sites
- Site features/constraints for industrial settings need to be considered
  - Active high-value asset – need to avoid interruptions to operations
  - Surface features – plant, power lines, ash ponds, railway lines may affect monitoring
  - Presence of a large river next to the site
  - Local public/stakeholders must be kept informed
- Monitoring technology should have enough resolution relative to injected amounts

Mountaineer Site Surface Features

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CO_2 Monitoring Systematics

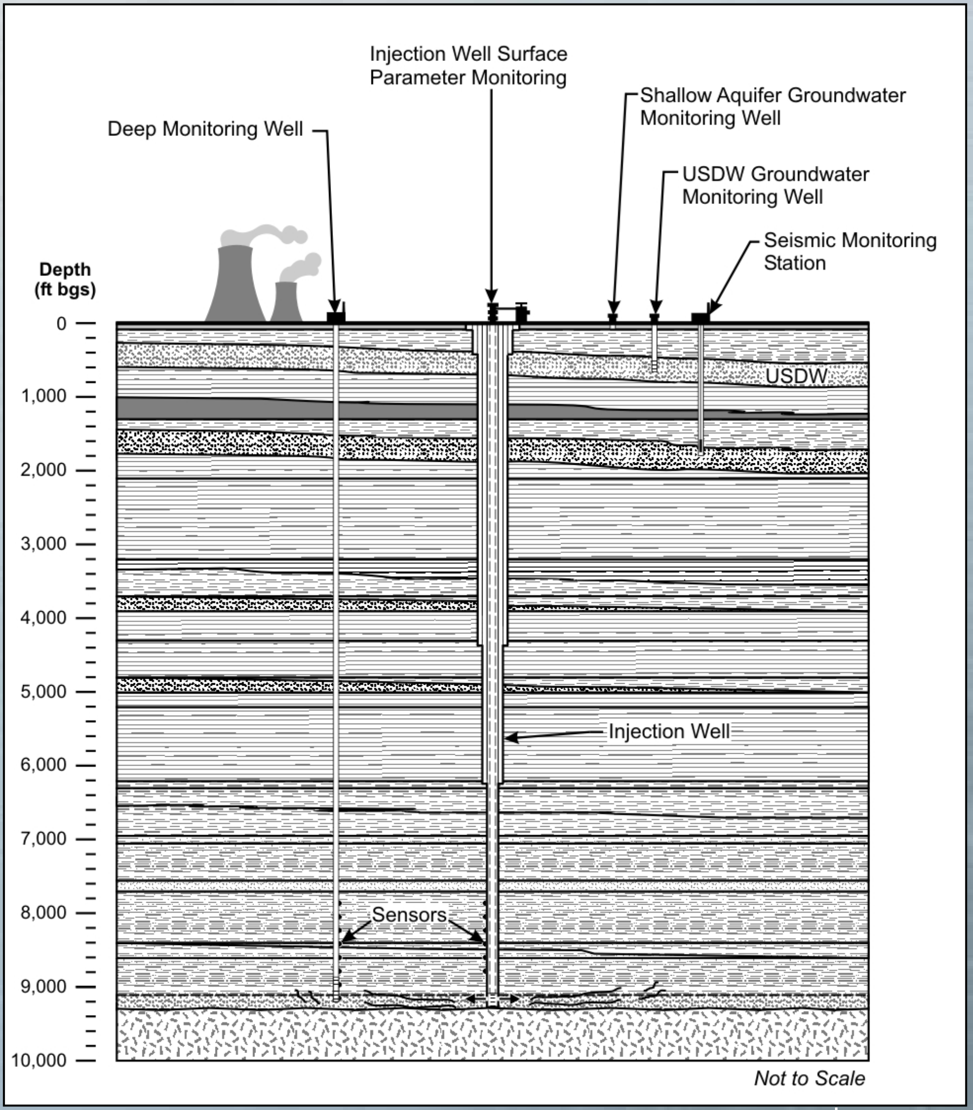
System	Remote	Surface	Observation Well(s)
Injection Pressure	4-D Seismic	Seismograph	Temperature/ Pressure
Flow Rate	Electromagnetic/ Seismic Crosswell	Soil Gas	Flow/ Density
Fluid Composition	Vertical Seismic Profile/Wireline	USDW Aquifer Sampling	Fluid Samples
Well Workovers	Tracers	Downhole Stressmeters	ERT

Examples of Typical Regulatory Monitoring Requirements

Parameter	Monitoring Requirements
Injection Pressure	Continuous
Bottomhole Pressure	Calculated every 4 hours
Annulus Pressure	Continuous
Interannulus pressure	Continuous
Temperature	Continuous
Flowrate	Continuous
Specific Gravity	Weekly
pH	Weekly
Composition of Injectate	Every 6 months
Cumulative Volume	Daily
Annulus Sight Glass Level	Daily
Review of Seismic Activity	Monthly
Well Workovers/Mechanical Integrity Tests	Yearly

Observation Well(s) are a Possibility

- There is a good network of shallow wells
- Deeper observation wells may be drilled at a reasonable cost
  - Multilevel well?
  - Geochemical sampling
  - Tracer tests
  - Continuous pressure, temperature, chemical sensors
  - Continuous geophysical sensors – passive seismic
  - Periodic well logging
  - Reservoir tests



Geophysical Monitoring

- 4-D seismic will be difficult due to geology and surface features
- A more rigorous assessment of 4-D seismic and VSP will be undertaken
- Other geophysical methods
  - Cross-well seismic
  - ERT
  - EM
  - ?

Near Surface and Surface Monitoring

- Soil gas sampling
- Shallow groundwater monitoring
- Tracer-based monitoring
- Remote sensing
- Key Question – is there any probability of near surface observation?

Monitoring Approaches (Sally Benson, LBNL)

Likely to be used

Possible to use

	Wellhead and Formation pressure	Injection and Production Rate	Casing and Annulus Pressure Testing	Casing Integrity Logs	Temperature	Well Logs	Fluid and Gas Composition	Seismic Geophysics	Electrical and Electromagnetic Geophysics	Gravity	Land Surface Deformation	Tilt Measurements	Airborne or Satellite Imaging	Soil Gas and Vadose Zone Monitoring	Surface Flux Monitoring	Atmospheric CO_2 Concentration	Micro Seismicity
Baseline	Likely				Likely	Likely	Likely	Likely	Possible	Possible	Possible		Possible	Possible	Possible		Likely
Injection controls	Likely	Likely	Likely	Likely	Likely	Likely											Possible
Location of plume	Possible	Likely				Possible	Possible	Likely	Possible	Possible		Possible					Possible
Integrity of wells	Possible					Likely	Possible	Possible					Possible	Possible	Possible	Possible	
Efficiency and processes	Likely	Likely				Likely	Possible	Likely	Possible								
Calibration and performance	Likely	Likely			Possible	Likely	Possible	Likely	Possible	Possible							
Surface seepage													Possible	Likely	Likely	Likely	
Environmental health & safety							Likely	Likely	Possible	Possible	Possible	Possible	Possible	Likely			
Micro-seismicity											Possible	Possible					Likely
Remediation efforts	Possible					Possible	Possible	Likely	Possible				Possible	Possible	Possible	Possible	
Monetary transactions	Likely	Likely						Possible									
Impacts to other resources	Possible	Possible					Likely	Likely	Possible								
Legal disputes	Possible					Possible	Possible	Likely	Possible		Possible	Possible	Possible	Possible	Possible	Possible	Possible
Visibility and transparency	Likely	Likely				Possible	Likely	Likely	Possible		Possible	Possible	Possible	Possible	Possible	Possible	Possible

Major Accomplishments/Findings of Current Phase

- All objectives of the current phase successfully completed
- Drilling and testing in a well suitable for injection is complete
- Extension of characterization to new wells in the region
- Large/commercial-scale injection at the site is feasible
- Potential new injection zones in the carbonate rocks have been identified.
- There is excellent containment in region
- A broad reaching stakeholder dialogue process has been implemented and the industrial sponsors are more comfortable with CSS technologies
- The site data will support the well design, monitoring, risk assessment, and permitting process during the next year

Sponsors and Technical Contributors

- **Battelle and Pacific Northwest National Laboratory** – PI, executive leadership, financial support: ***Jim Dooley, Judith Bradbury, Bob Janosy, Bruce Sass, Prasad Saripalli, Mark Kelley, Mark White, Henry Cialone and many others***
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- **Stanford's GCEP Program –** Geomechanics: ***Mark Zoback, Amie Lucier***

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Drilling Location and Well Design

- 2,800 m deep well drilled, cored, and tested under realistic industrial site constraints during 2003