NETL DOE CO2 Storage Workshop

alternativenergy
Powered by BP

Subsurface Monitoring Challenges

Kevin Dodds

19th October 2011

DOE Best Practises

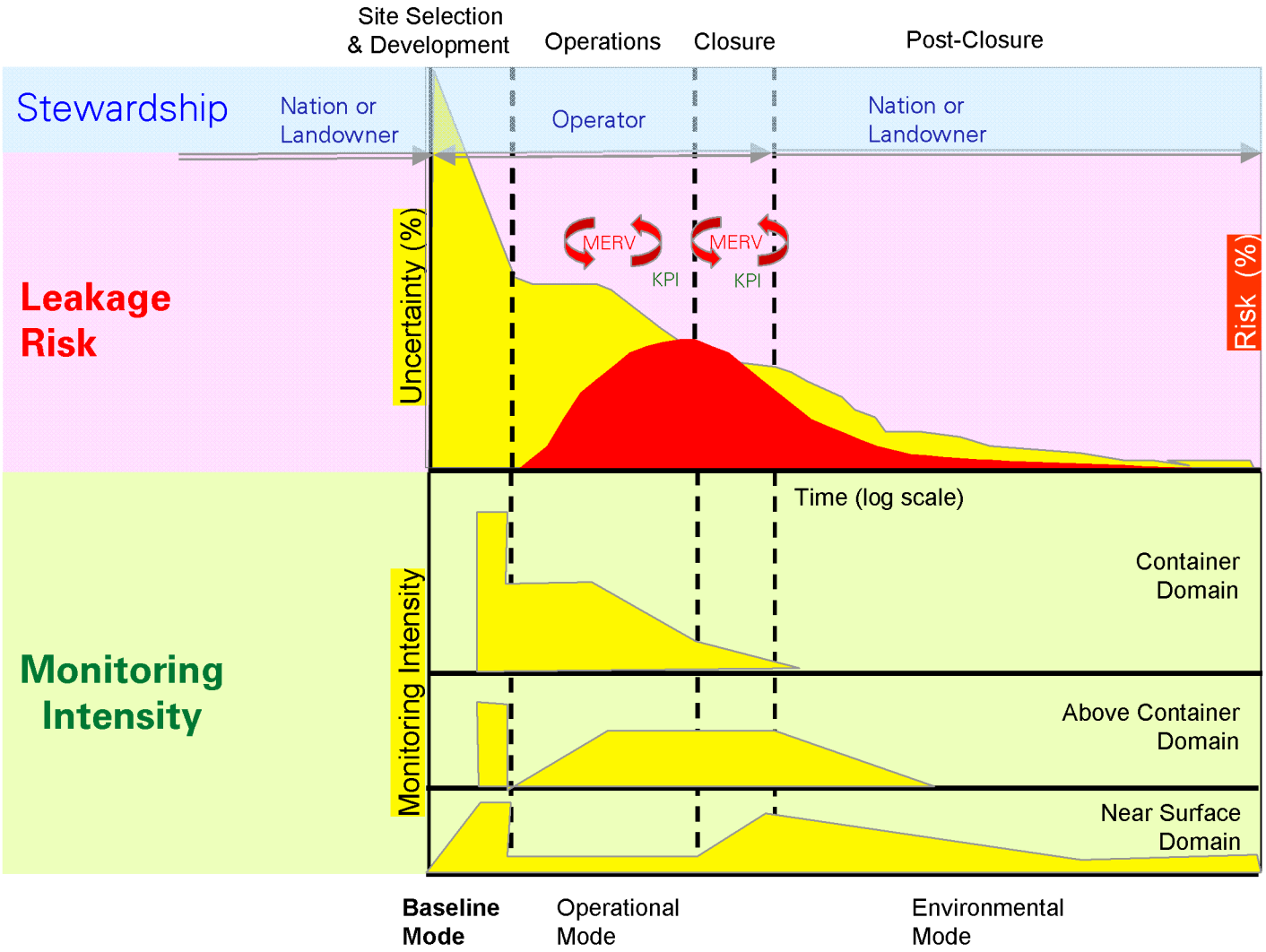
Reliable and cost-effective monitoring

- **Track the location of the plume of injected CO2,**
- **ensure that injection and abandoned wells are not leaking,**
- **verify the quantity of CO2 that has been injected underground.**
- **may be required to ensure that groundwater and ecosystems, are protected**
- **and that the local population is not exposed to unsafe concentrations of CO2.**

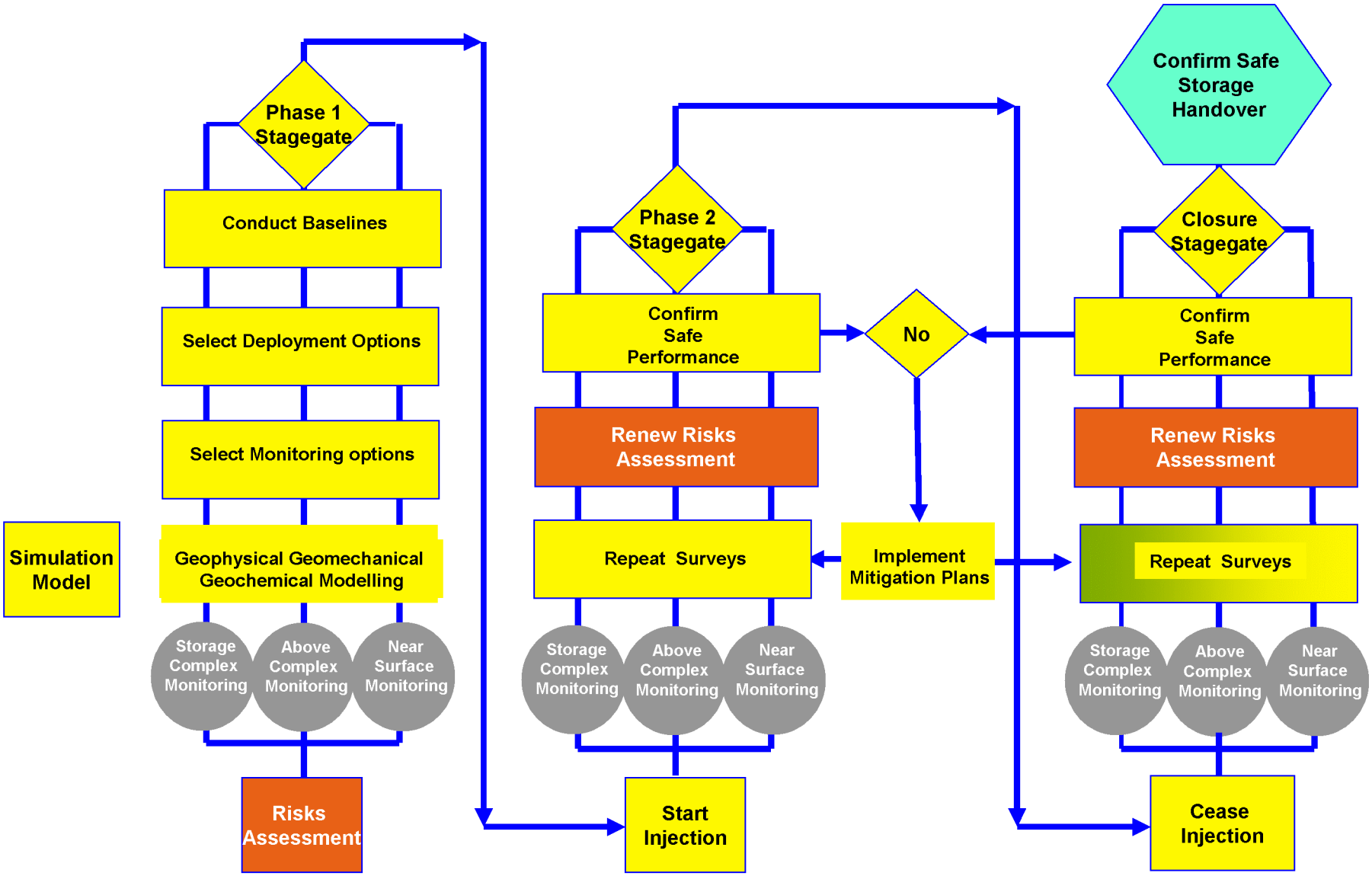
2012

Develop MVA protocols that enable recognition of leakage to the atmosphere and shallow subsurface in order to ensure 99 percent retention of stored CO_2

Leakage Risk Profile

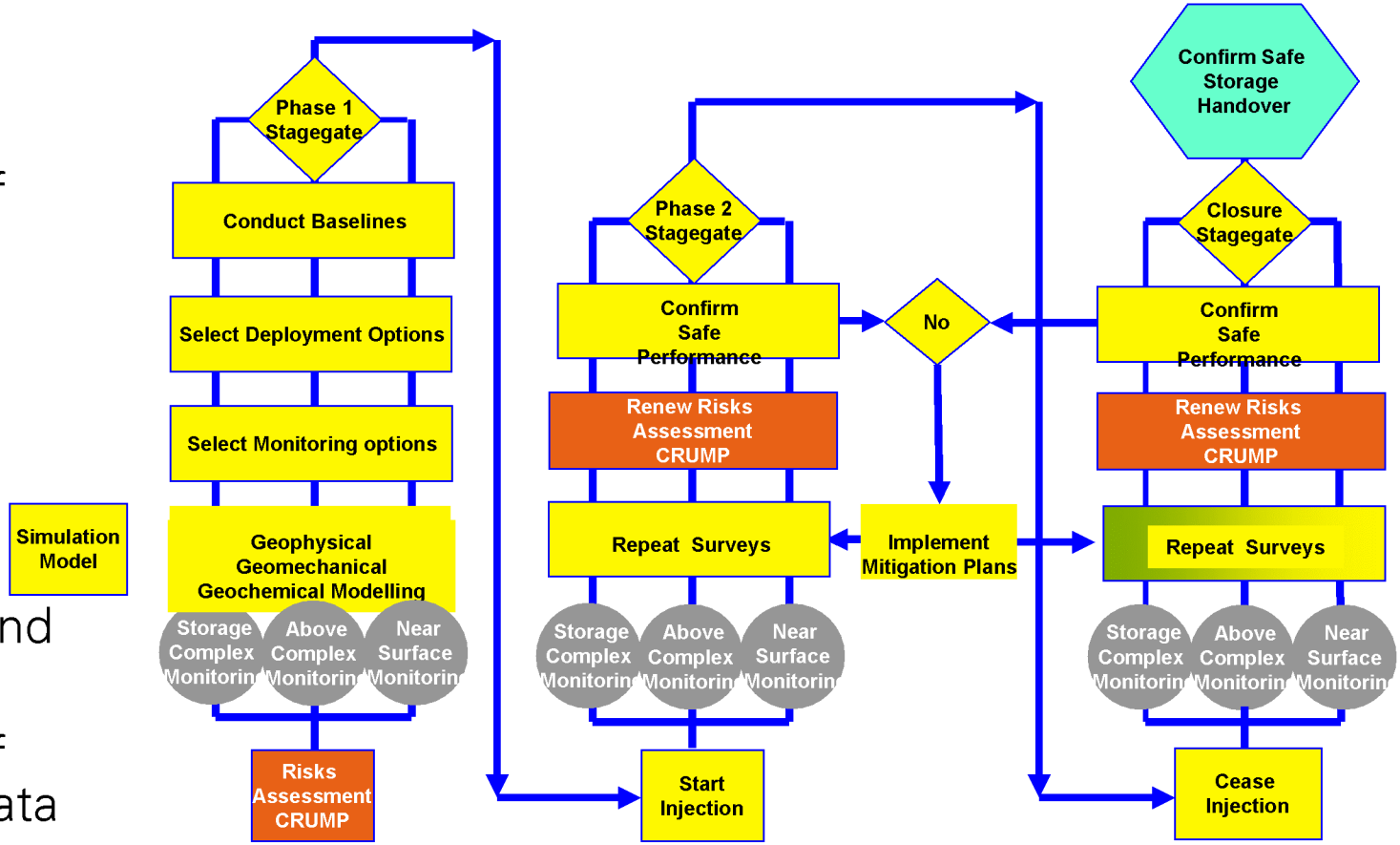


Monitoring Functional Ladder

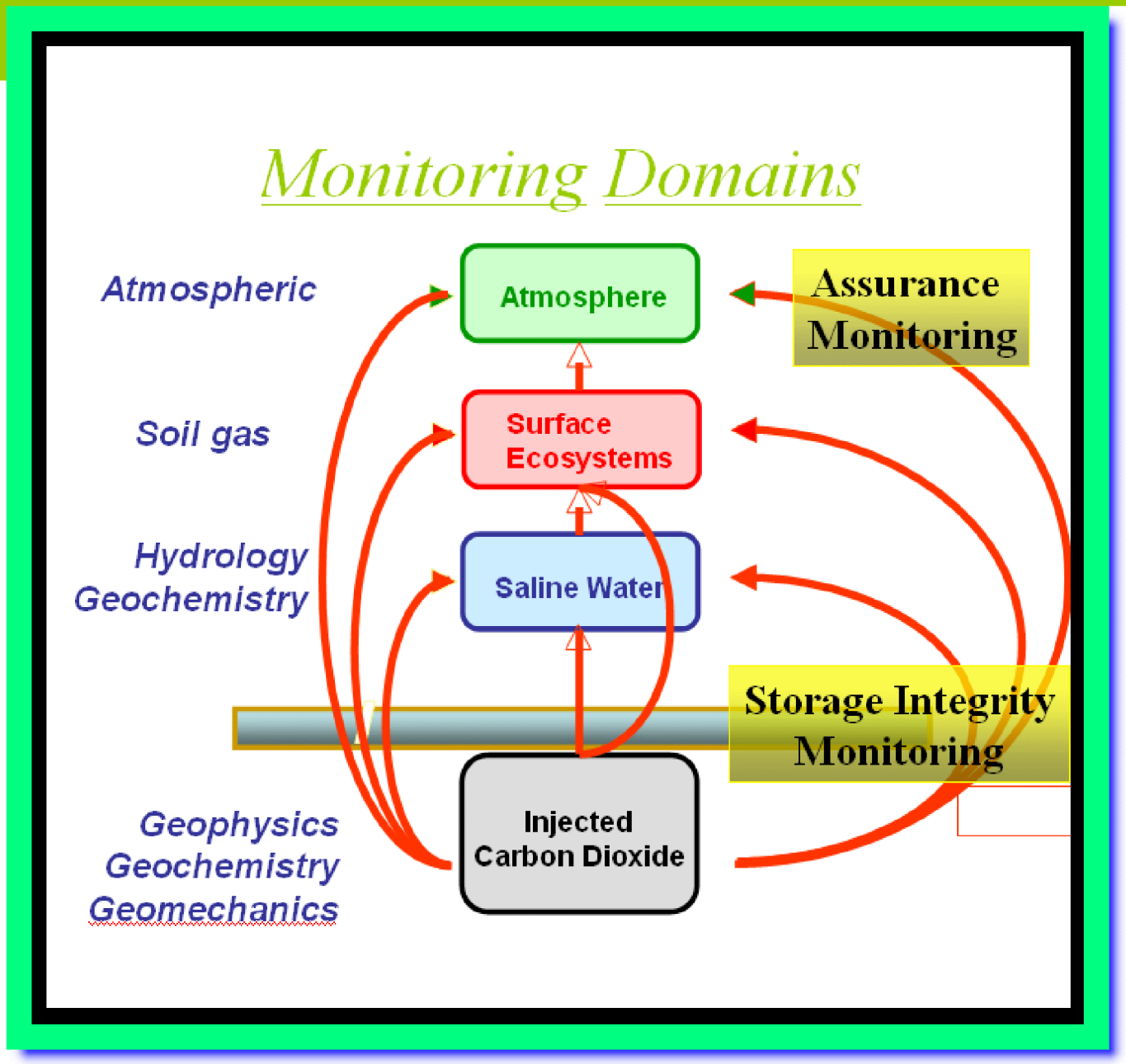


Takeaways

- Forward and Inverse Modelling
- Integration of data
- Technology Options
- Deployment options
- Long term robustness and permanence
- Integration of multi-scale data



Containment Risk Paths

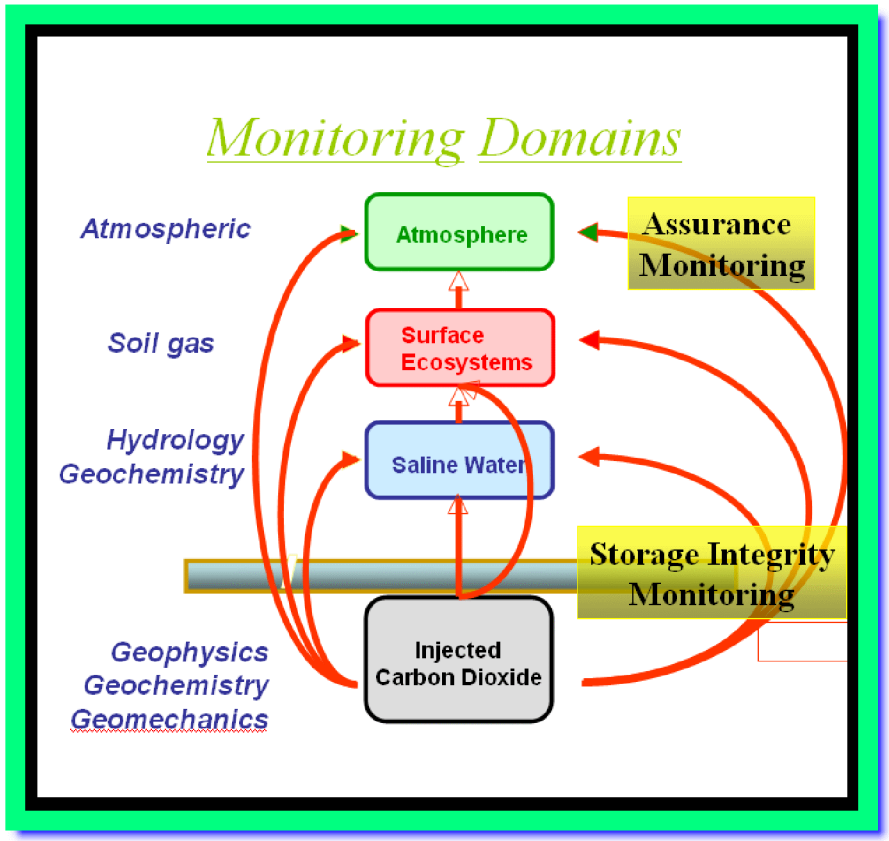


Monitoring Challenges

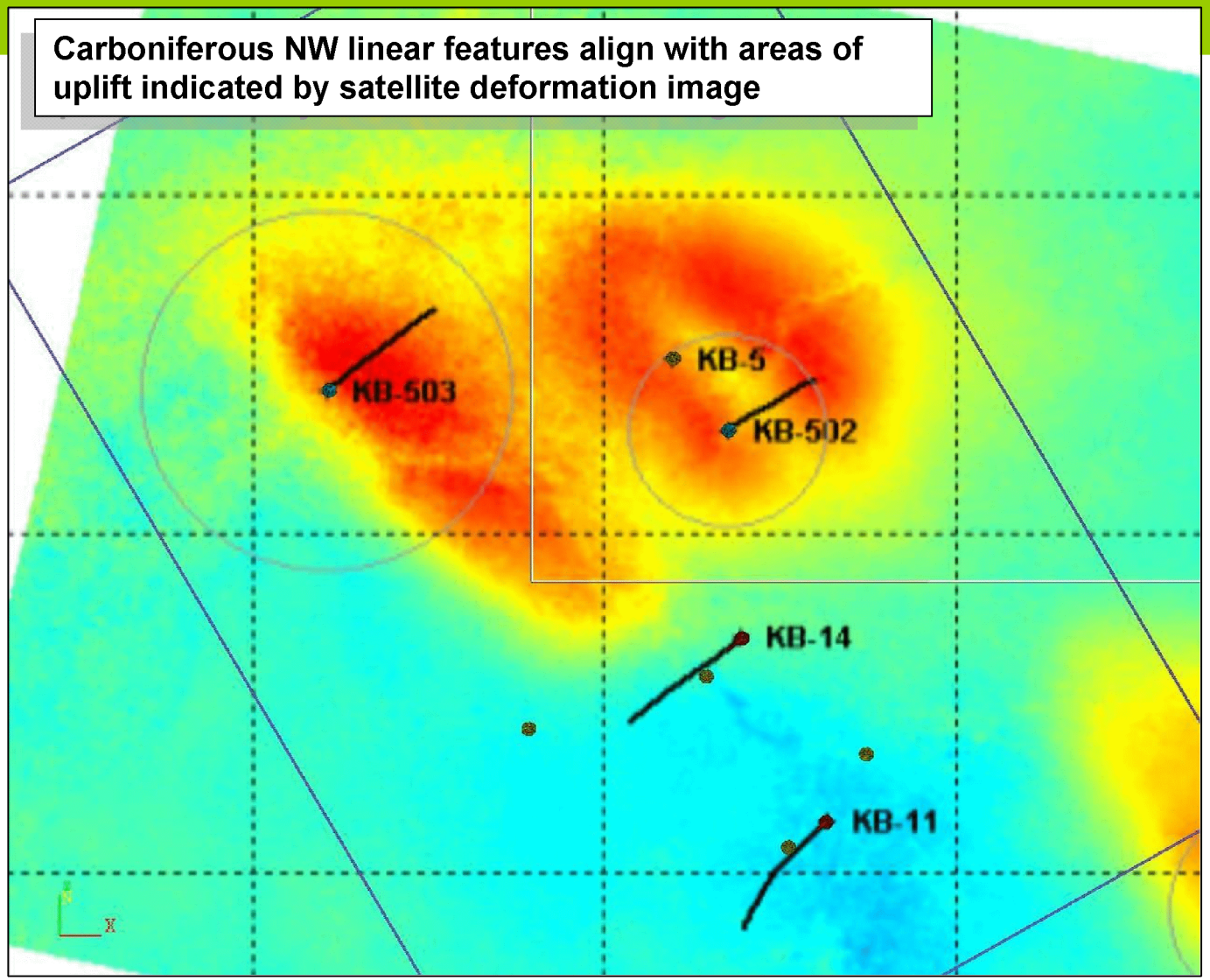
- Near wellbore
- Injection region
- Interwell
- Inter reservoir

Challenges

- Detecting far from wells
- Quantification of containment or leaks
- Contingency and mitigation
- Technology options
- Deployment Options
- Equipment robustness

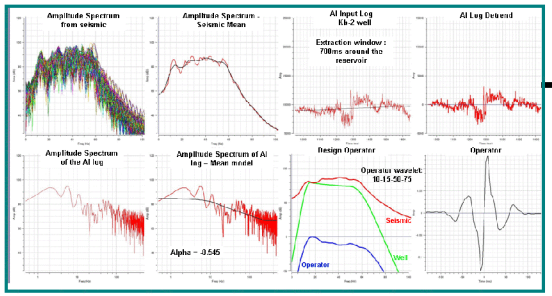


In Salah Satellite Deformation



Identifying the Plume Distribution - AVO Workflow IS

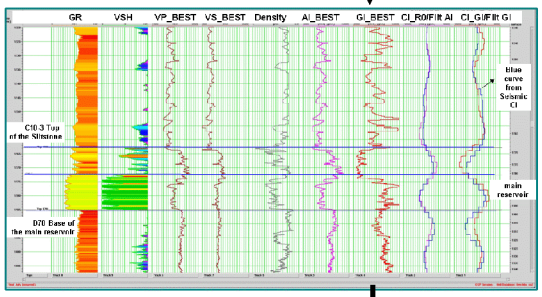
Seismic Colored Inversion on the New PMR Intercept and the New Gradient Volume



Colored Inversion on Intercept Volume (CI_R0)

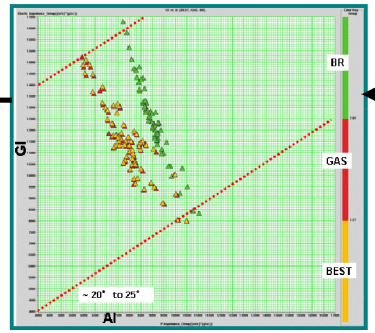
Colored Inversion on Gradient Volume (CI_GR)

Rock property studies on Well Kb-2

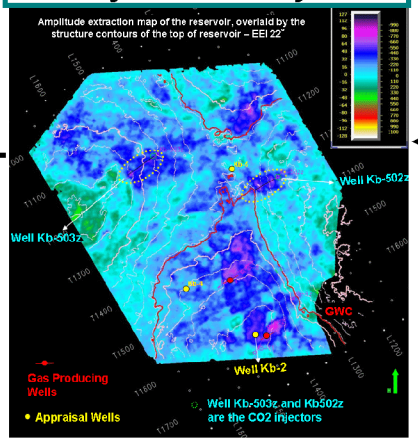


Extended Elastic Impedance Analysis (EEI)

Analysis of the chi angle



Fluid Projection and Porosity Projection Analysis



Map the CO2 in the reservoir and model how CO2 replacing the brine would change the AVO response

Contingency Workshop Fault/Seal Issues and Detectability
CCP contingency workshop 2011

Diffuse invasion CO2 into Seal

1. Logs close to well (RST, through casing resistivity)
2. Surface deformation inversion ratifies penetration model
3. Time lapse seismic where resolvable: surface, Xwell, VSP
4. Electrical properties change

Fault feature penetrates seal

1. Pressure changes
2. 4D seismic
3. Microseismic potential pulsing of fluid
4. Non localised seismicity

Seal thinning (unexpected)

1. Seismic attributes
2. Regional characterization
3. Analogs

Physical Damage/fracture feature

1. Pressure signature
2. Accompanying Induced microseismics
3. Azimuthal seismic, surface and VSP
4. Xwell EM where changed electrical conditions
5. Temperature logging / distributed temperature
6. Fracture scattered seismic detected at well as formation guided waves (future)
7. Detection signature different to fault

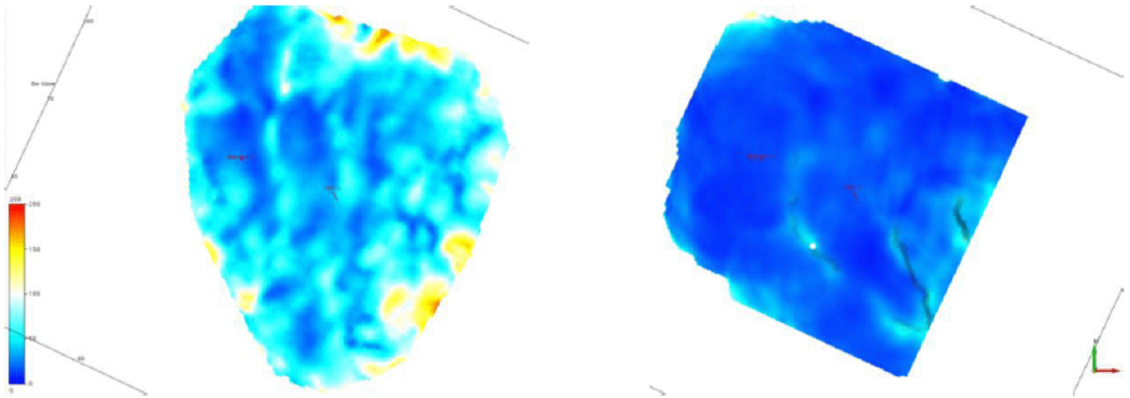
Geochemical overlay over all issues above

1. Sample fluids – do batch testing
2. Fluid monitoring

4DVSP cf 4D Surface Seismic: How Well Does it do its Job ? CCP - Otway

Surface seismic

3D VSP

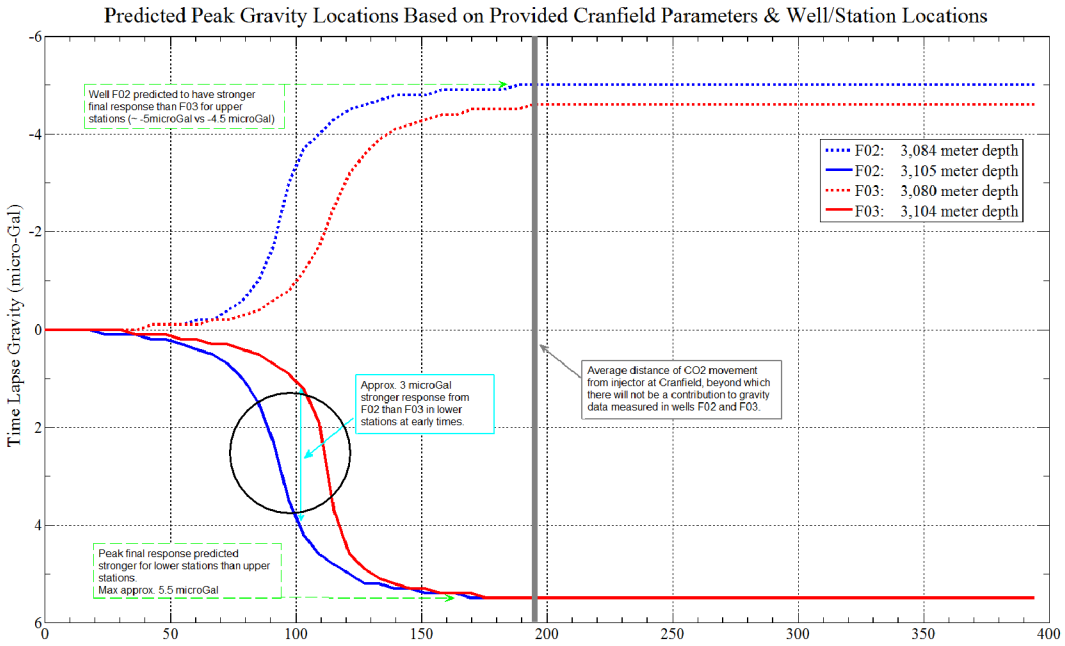


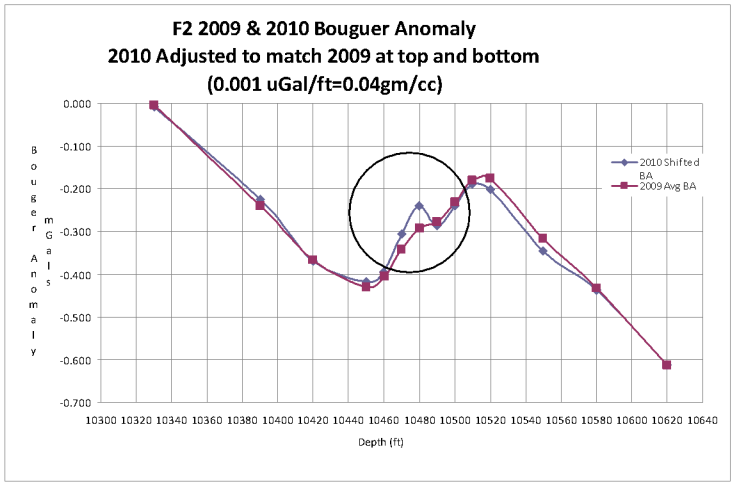
histograms of NRMS values are shown below maps

Comparison of 4D seismic and 4DVSP at Otway, same target different quality output. How confident are we in seeing nothing ?

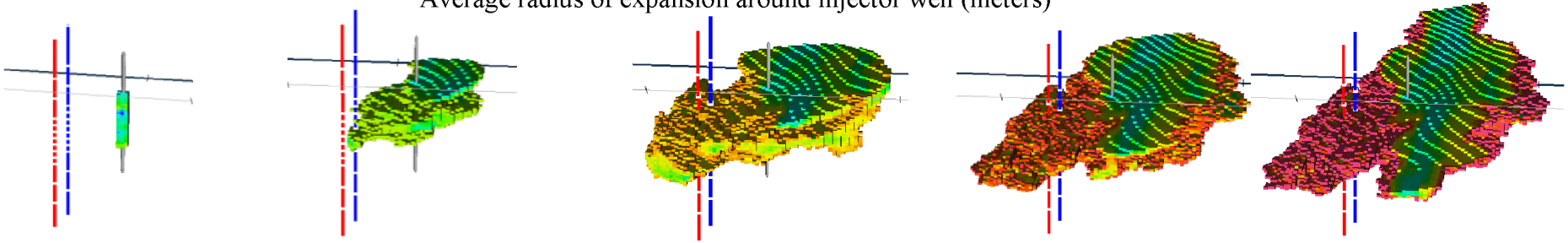
Time lapse VSP survey demonstrates outstanding level of repeatability with median NRMS value equal to 16%.

Wellbore Gravity sensitivity at Cranfield Limited Data
CCP - CSM GMRC

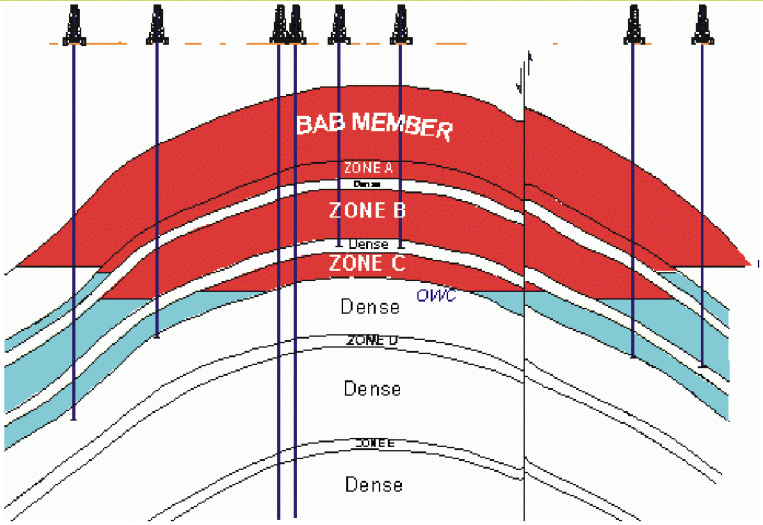




Average radius of expansion around injector well (meters)



Describing a Reservoir with CSEM, Seismic and Well data

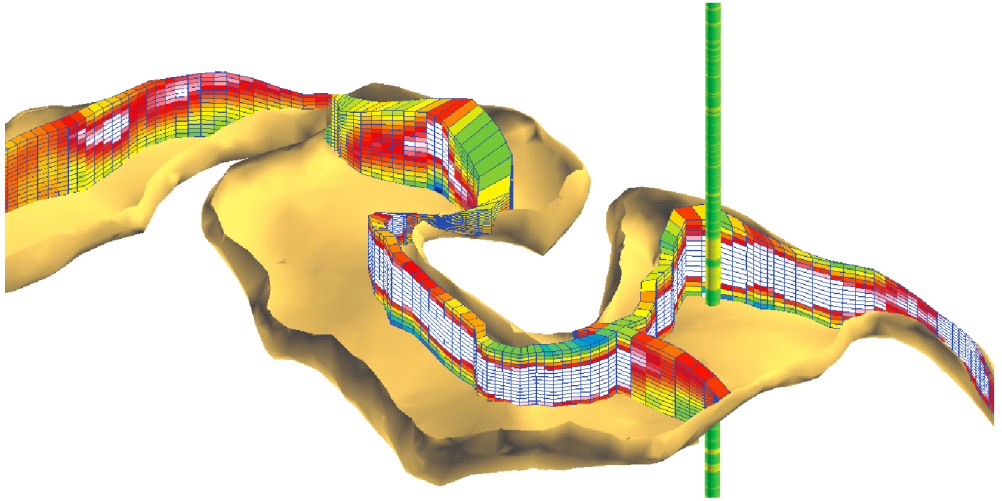


Size and structure

- Depth?
- Geometry?
- Thickness?
- Compartmentalized?

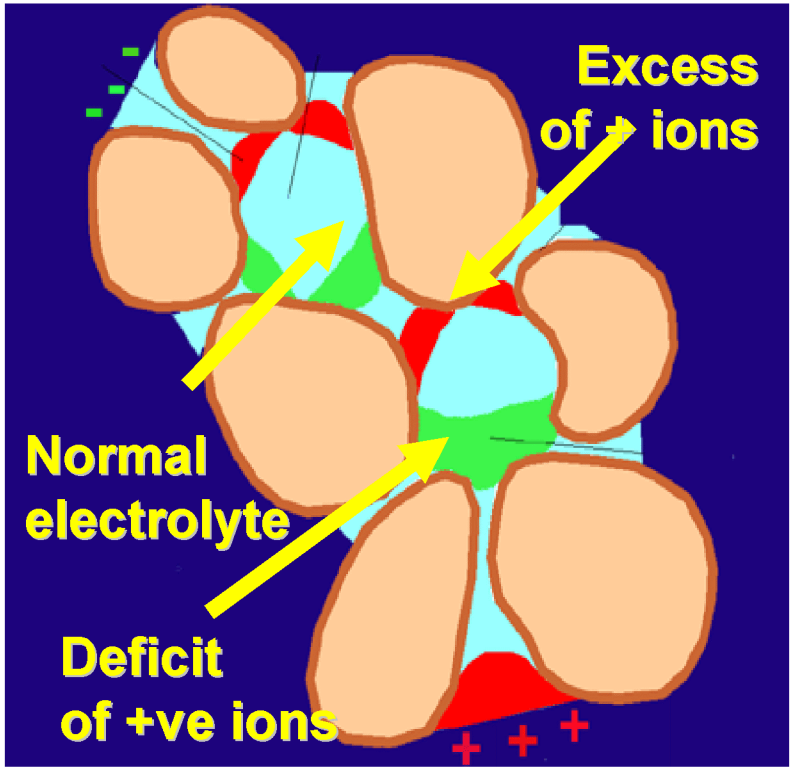
Rock and Fluid Properties

- Lithology?
- Porosity?
- Permeability?
- Pressure and Temperature?
- Fluids?
- Saturation ?
- Net:gross ?



- Best measured by seismic
- Best measured by EM
- Best measured jointly

Electrical Spectroscopy Seal and Fault Evaluation



Frequency Dependent Electrical Properties in Sandstones and Shales

1. Polarization:
   - dipoles
   - eletrolyte
   - double layer
   - membrane
   - electrode effects
2. Diffusion
   - Dephasing not true dielectric polarization
3. Reactions
   - Water-rock

Lab Electrical Spectroscopy

Ben Clennell CSIRO

- Some evidence of LF dispersion correlating with grain size, pore size and clay content
- Significant aid for diagnosis of shaly sands
- High frequency ranges diagnostic of clay content & type (10 MHz - 350 MHz "clay zone")
- Lithology independent saturations only >350 MHz
- Lab methods not easily applied downhole…but

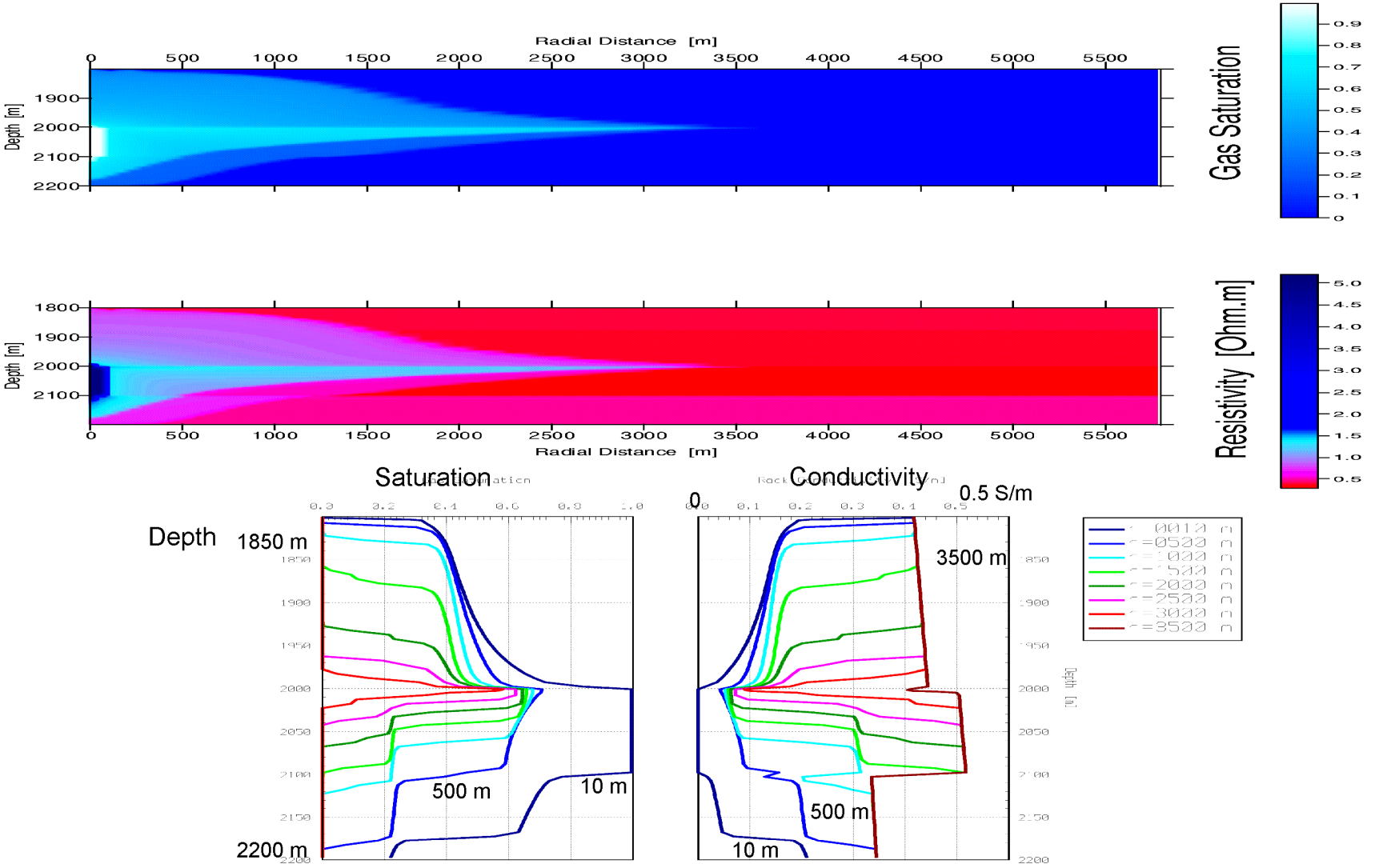
✓ *Help to understand dispersion phenomena when analysing electrical logs (sensitivity to lithology; different phase and attenuation responses)*

✓ *Correlations obtained: measured R vs. measured k*

✗ *Gap in published Lab Measurements 1-100 MHz for important lithology-fluid combinations*

Petrel Formation Injection Profile

(Singer, Dodds 2004) - Conductivity Monitoring



- Vertical distributions of the Gas Saturation (left panel) and Rock Conductivity (right panel) at radial distances of 10, 500, 1000, 1500, 2000, 2500, 3000, and 3500 m in the target zone 30 years after completion of the 30-year CO2-injection period.

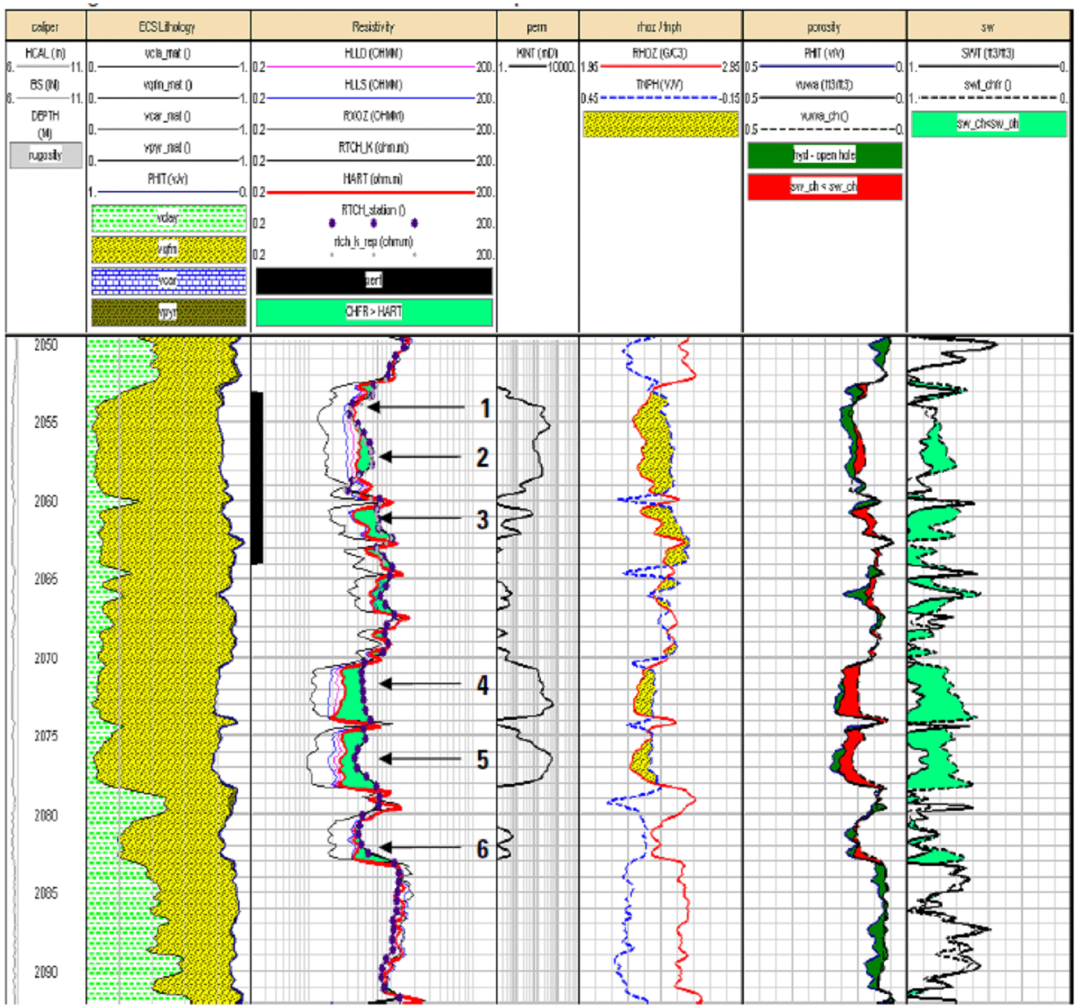
Through Casing Resistivity. – Practical Example
CCP – Otway

Schlumberger CFRT cf AIT

Interval 1 This zone has the highest amount of residual gas saturation, open hole Sw is approximately 80%.

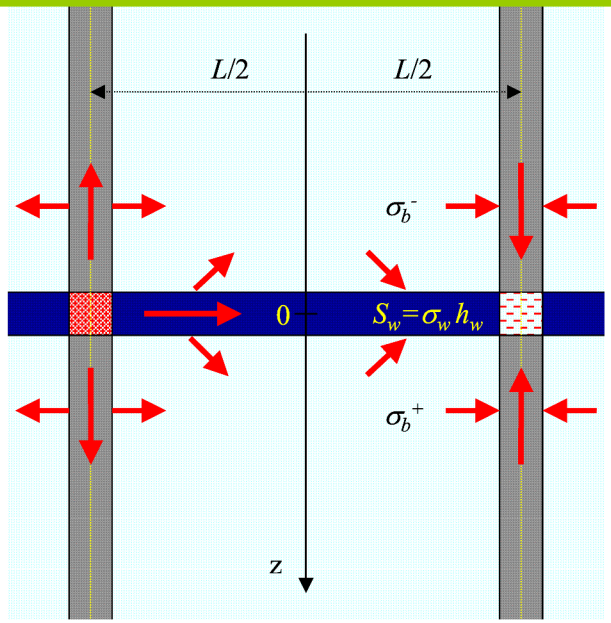
Distinguish residual hydrocarbon from CO_2 using RST,

- **Interval 2** : In this section change in resistivity can be seen. This is indication that injected CO2 has displaced formation water.
- **Interval 3 :** Likewise in this interval there is a substantial change in resistivity indicating the displacement of formation water with CO2. Change in Sw is from near 100% to 70-80%
- **Intervals 4 and 5** show the most dramatic change in resistivity. These zones are below the open perforations and therefore suggest that there is vertical communication from the section of open perforations into this lower sand interval.



Study of Intercasing sensitivity to CO2 Saturated formation

(Singer, Dodds 2004) – Saturation and Conductivity Monitoring

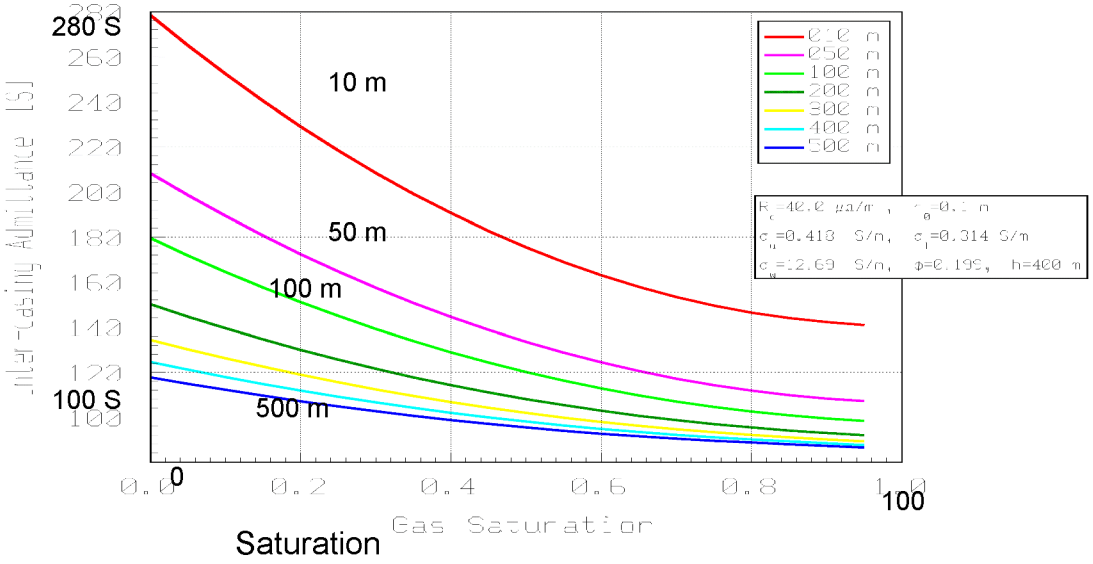


$$\lambda_L \sim \frac{1}{\sqrt{\sigma R_c}}$$

Characteristic Equipotential Length

- Resitivity of the casing 40 μΩ/m,
- external casing radius is 0.1 m;
- conductivity upper shoulder 0.418 S/m
- lower shoulders equal 0.314 S/m;
- thickness of the target zone is 400 m,
- rock porosity is 20%,
- conductivity of fluid is 12.69 S/m.

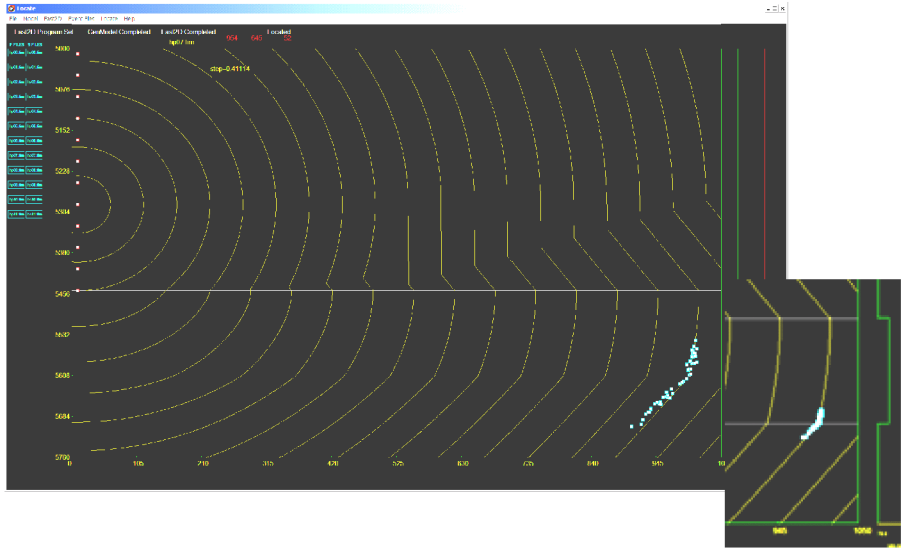
Inter-casing Admittance

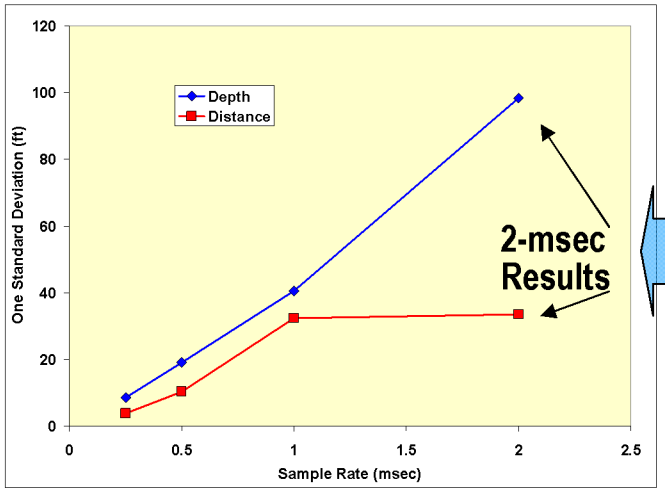


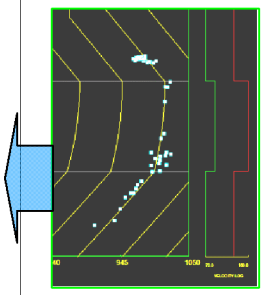
A deep target zone, measurement electrodes should be connected to the casing close to or inside the interval adjacent to the zone. If the thickness of the target zone exceeds λL then we will call such target zone “wide”.
To provide a highest possible sensitivity to the parameters of the target zone it is necessary to uniformly inject current into the zone.

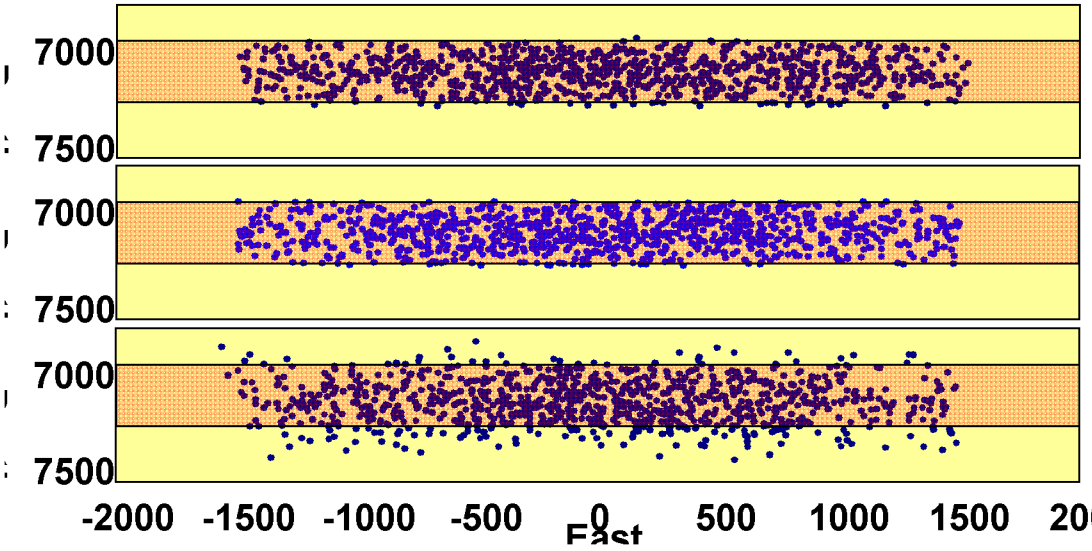
Microseismic - Effects of Sampling rate

Pinnacle Study









- **Pinnacle**
  - **Depth: 8 ft**
  - **Distance: 5 ft**
- **Comp. B**
  - **Depth: 57 ft**
  - **Distance: 24 ft**

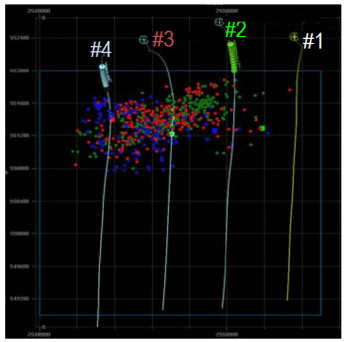
Sampling Errors

Array aligned with Events
- **1/4 msec = 10 ft**
- **1 msec = 45 ft**

Array Above Events
- **1/4 msec = 4 ft**
- **1 msec = 18 ft**

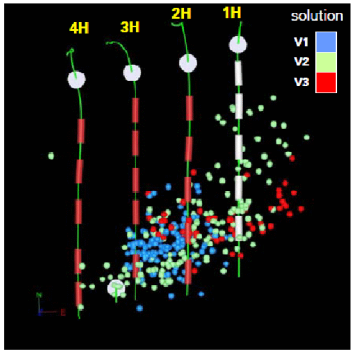
Ambiguity in Locating Events and Size

Ambiguity in microseismic monitoring Rodney Johnston BP et al SEG San Antonio 2011 Annual Meeting

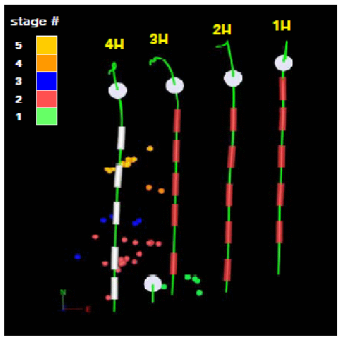


This is a plan view of event locations based on single-well monitoring

- blue events using monitor #4,
- green events using monitor #2
- Red events dual well solution



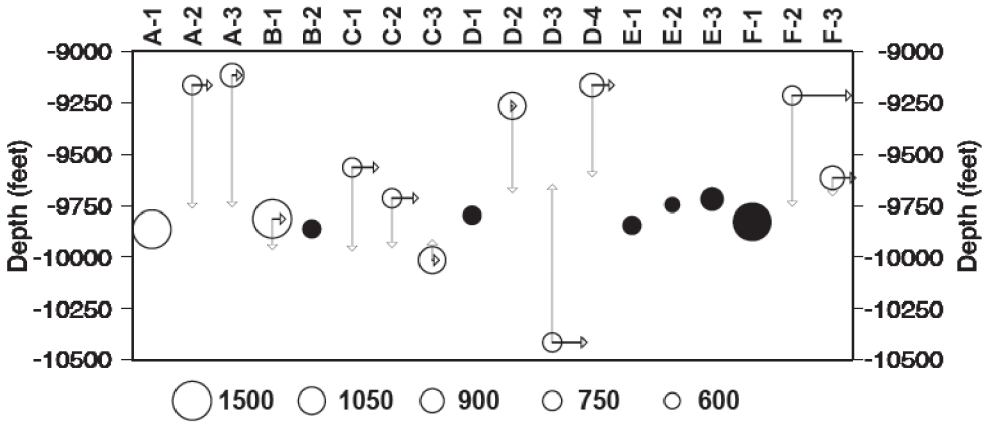
In this example, the different colored events represent three different velocity models used in processing.

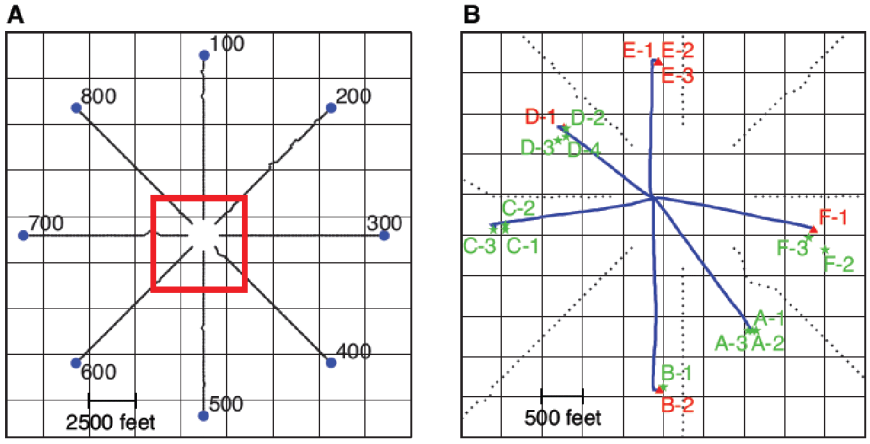


However, in certain cases when microseismic activity is quite low PLT surveys still estimate reasonable production levels, comparable to treatments with much higher levels of microseismicity.

- Analysis of about eight microseismic monitoring projects in the Woodford shale in Oklahoma suggests an apparent variability in interpreted hydraulic fracture ('frac') attributes: x2 in length and width, x3 in height.
- Variation of stimulated rock volumes using the different event clouds, as large as a factor x10
- Horizontal monitor provides different controls on locations to a vertical monitor,
- Other observations of interest include very different levels of microseismic energy recorded from adjacent perforation shots.

Shot Size vs Estimated – Energy Ambiguity





A- Station geometry for the surface array. The stations are arranged in arms of 100 stations approximately 9000 feet long. The red box shows the enlarged area.
B- Well paths (blue), the successfully located perforation shots (green), and unsuccessfullylocated shots (red).

- Arrows indicate the vertical and horizontal errors in location.
- Filled circles mark the depths of the unsuccessfully imaged shots.
- The symbols are sized according to the perforation shot magnitude scale - total propellant weight in grams

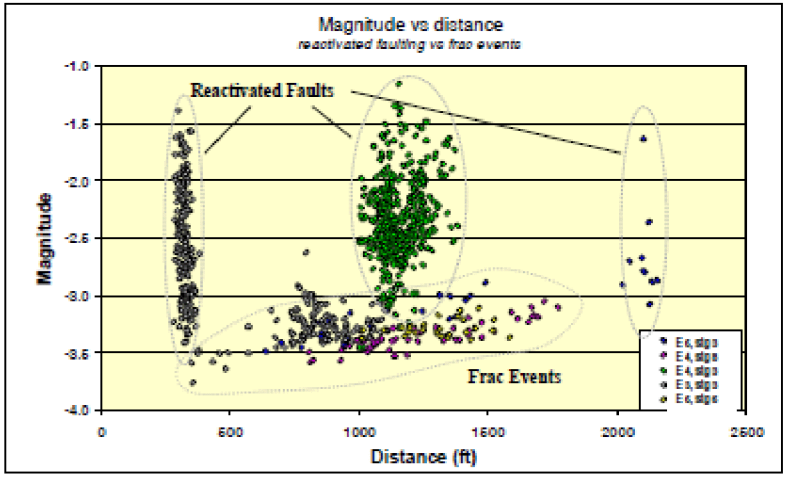


Figure 18. Magnitude of frac events and reactivated fault events.

Faults not imaged on seismic

Hydraulic Fracture Diagnostics Used to Optimise Development In the Jonah Field S.L. Wolhart SPE 102528

GFZ POTSDAM

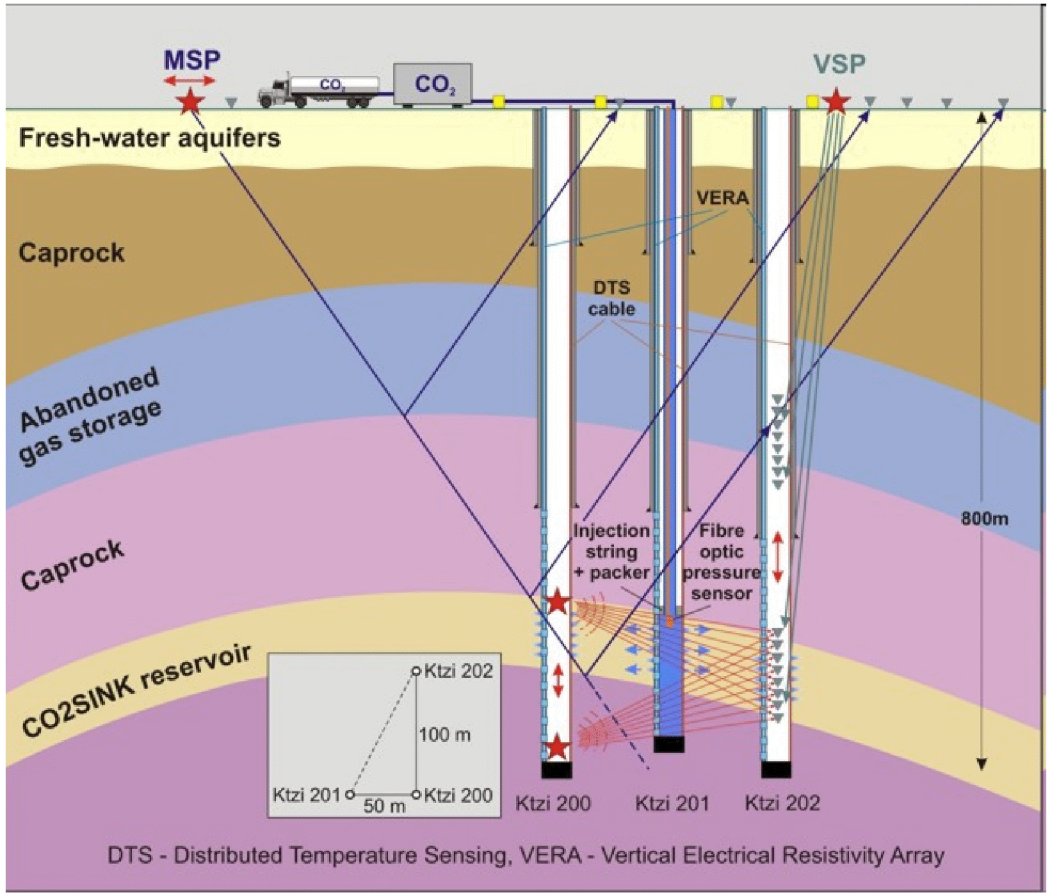
CO2SINK, Ketzin, Germany

CO2SINK

Practical experience with new measurement techniques

- Behind casing ERT
- Fiber-optic P/T
- Fiber-optic DTS/DTPS (LBNL)
- Cross-hole seismic, VSP
- Membrane fluid sampler (gas only)

(also Frio, Otway, Cranfield, PennsWest, Citronelle)



Limitation in limited reach into reservoir

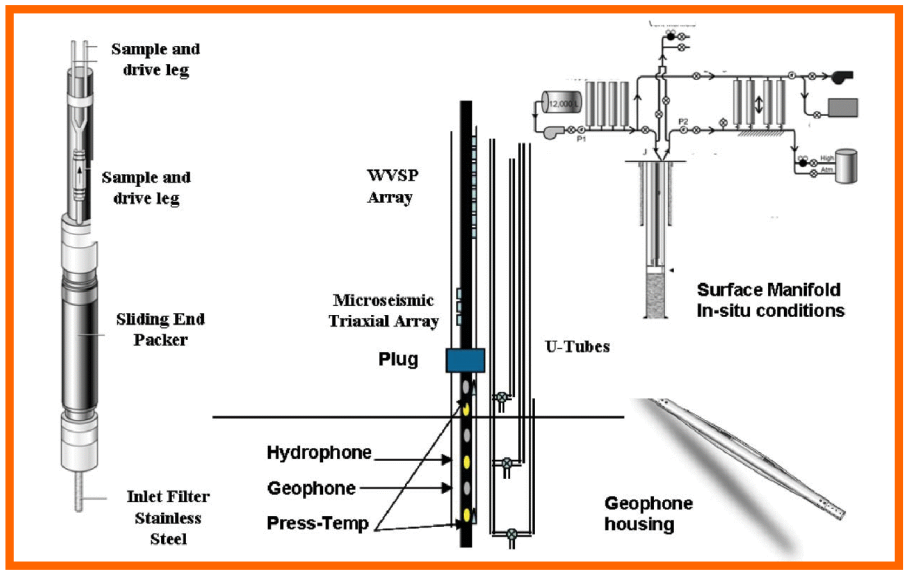
Integrated Monitoring Systems Technology Development (MBM CCP – LBNL) SECARB Citronelle

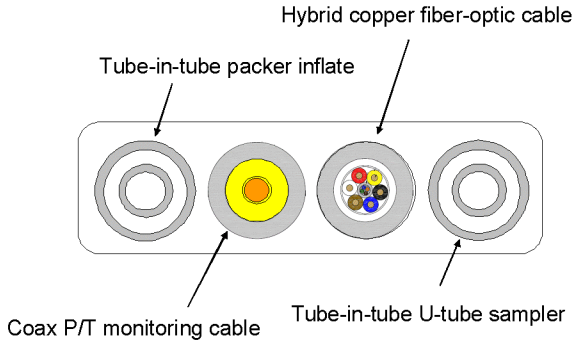
Numerous options for integrated monitoring systems

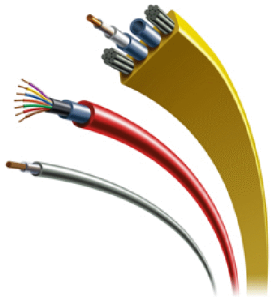
- Umbilical deployments
- Coiled tubing deployments
- Flat-packs (tubing deployed)
- Sucker Rods

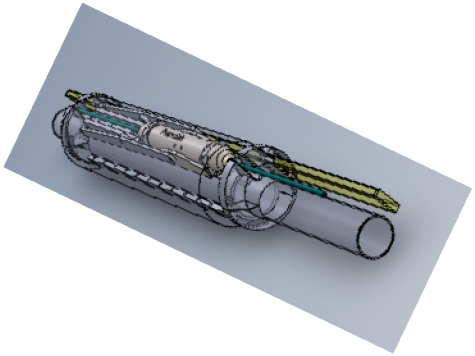
Major Design Issues

- Pressure control and safety engineering
- Integration of multiple monitoring technologies
  - Seismic sensors (coupling to formation)
  - Fluid sampling
  - Additional fiber-optic sensors
  - Nano or MEMS sensors
- Reliability
  - Pressure
  - Temperature
  - Aggressive fluids/geochemical conditions
- Retrievability and Repairability









Projection of Technologies

Coiled Tubing Slim Hole Drilling

Wireless Sensors and Power Systems

Power Harvesting

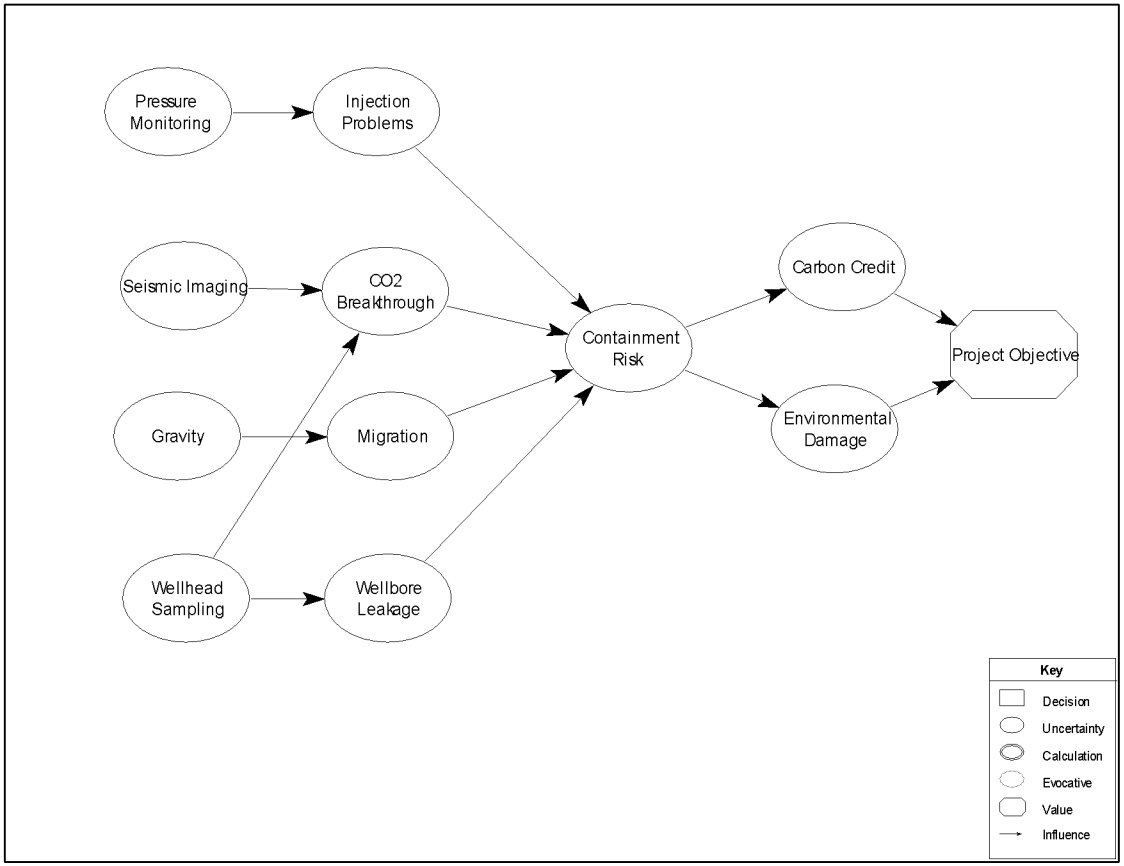
Distributed Nano and MEM Sensors

Cost Effectiveness driving options

Cost Effectiveness Methodology - Challenge

Objective Methodology to assess Cost and Effectiveness of Monitoring Technology

1. **Define sensitivity to risk event**
2. **Define measurements uncertainties wrt risk evaluation**
3. **Rank monitoring in terms of effectiveness in delivering project containment**



Eric Bickell - UT

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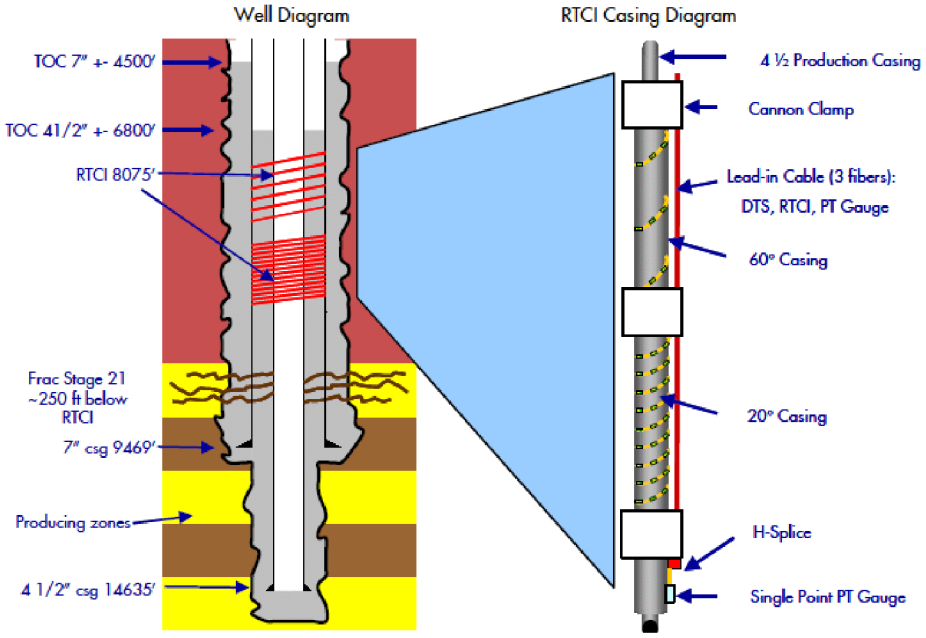
Suggestions

- **Uniform modelling capability, Standards ?**
- **Seismic buried sources low power long sweep, multiple simultaneous sources, wireless technology**
- **Microseismic field tests on what can be expected, how to identify mechanism, how to locate mechanism. What is value to CCS ?**
- **Explore gravity and electrical and EM options.**
  - **Electrical measurements Xwell , Borehole to surface. Borehole to borehole, address limitations of conductive casings**
  - **Gravity and electrical methods need step change in technology.**
- **Borehole logging – identify added value of spectral EM measurements on seal properties, difficult to implement in borehole for long term measurements (casing)**
- **Scope for specialised slimhole drilling for monitoring flexibility**
- **Scope for integrated downhole sensor platforms,**
  - **issues of robustness, power harvesting, wireless telemetry**
- **Opportunities in exploring sensors developments and optical fibre options.**
  - **MEMS press, temp, chemical, gyroscope, accelerometers, gravity**
  - **DTS, DTPS (temp perturbations) , DAS (acoustic fibre) Strain – pressure sensing**

SPE 124932 Shell RTCI



Tiltmeter sensitivity to microradians
Factor 10 better than current

SPE 124932
High Resolution, Real-Time Casing Strain Imaging for Reservoir and Well Integrity Monitoring: Demonstration of Monitoring Capability in a Field Installation

J. G. Pearce, SPE, F. H. K. Rambow, SPE, W. Shroyer, SPE, P. Huckabee, SPE, H. de Jongh, and D. E. Dria,
SPE, Shell Exploration and Production, and B. A. Childers, T. S. Hall, and T. Dominique, Baker Hughes