British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

Monitoring strategies for CO_2 storage

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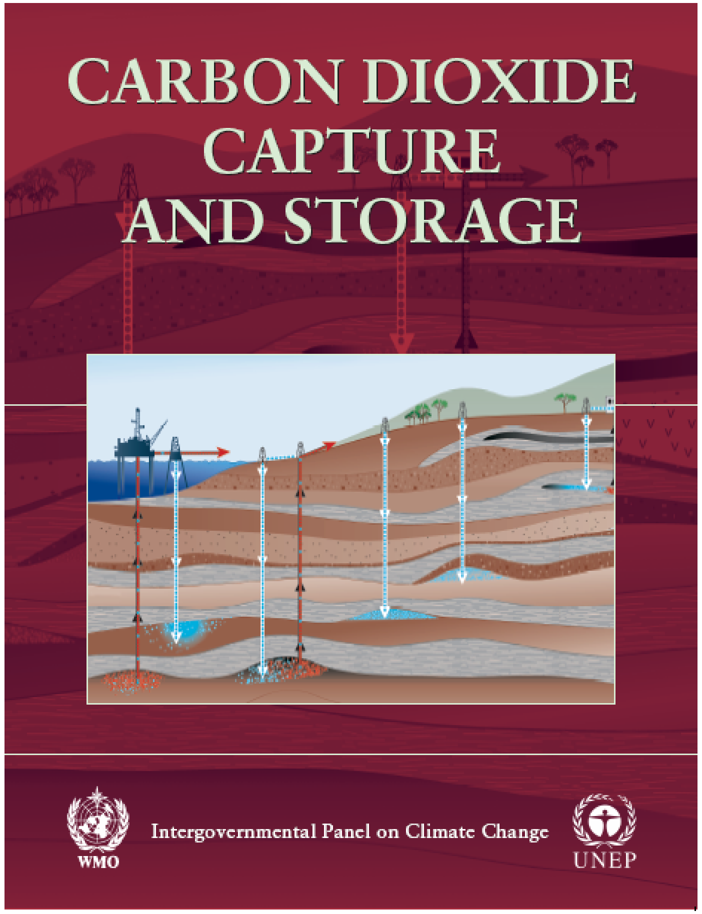
Outline of talk

- Why do we need to monitor CO_2?
- How & what do we monitor?
- Examples of monitoring techniques
- Monitoring strategies
- Summary

- Note: Terminology used here is based on European practice – regulations will be different in other jurisdictions.

IPCC Special Report



*"22. With appropriate site selection based on available subsurface information, **a monitoring programme to detect problems**, a regulatory system and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, EOR and deep underground disposal of acid gas."*

Why monitor?

- Storage sites must be able to demonstrate that risks are as low as reasonably practical over the long term.
- Monitoring will play a key role in this.
- Monitoring may be needed for a variety of reasons…

Why monitor?

- To demonstrate site performance.
  - Verify in situ masses of CO_2 stored
  - Understand processes
  - Calibrate / test reservoir simulations
- To build public confidence, especially in early demonstrations
- Predict long-term site behaviour to enable transfer of site responsibility at site closure to Competent Authority
- Environmental reasons
  - For climate change
  - Provide early warning of leakage
  - To assess local health, safety and ecosystem impacts of leaks

Why monitor?

- Financial reasons
  - Markets need confidence in technology.
  - *For example*, in Europe any CO_2 emitted to the ocean or atmosphere from a storage site must be accounted for in National Allocation Plans within the European ETS, requiring quantified measurements.
  - Though not currently in Clean Development Mechanism, MMV methodologies are central to the CDM approval process.

Monitoring aims

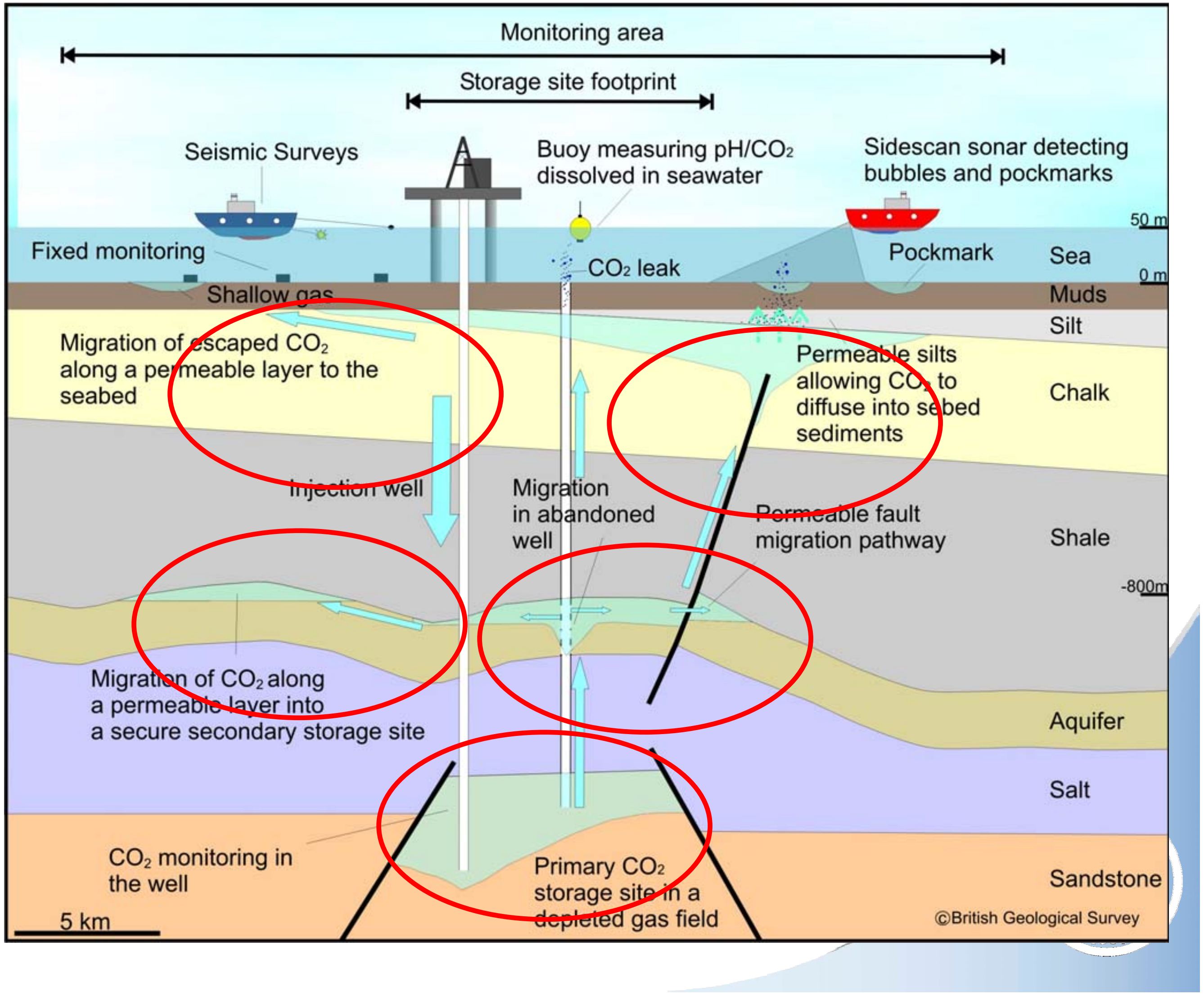
- A range of monitoring aims can therefore be recognised:
  - Locating and tracking the CO_2 plume at depth
  - Demonstrating containment and monitoring the top-seal
  - Monitoring trapping mechanisms and quantifying storage
  - Verifying and calibrating predictive models
  - Monitoring potential leakage routes including
    - Wellbore integrity
    - Monitoring near-surface leakages, if any
    - Monitoring for seismicity (indicator of fault reactivation) and ground movements

How and what, to monitor?

- Monitoring CO_2 both directly and indirectly
- We need to consider:
  - Which monitoring aims are required
  - What techniques can be deployed to meet monitoring aims
  - Costs and benefits
  - Accuracy and detection limits
  - Frequency
  - Baseline data
  - Area and volumes to be monitored

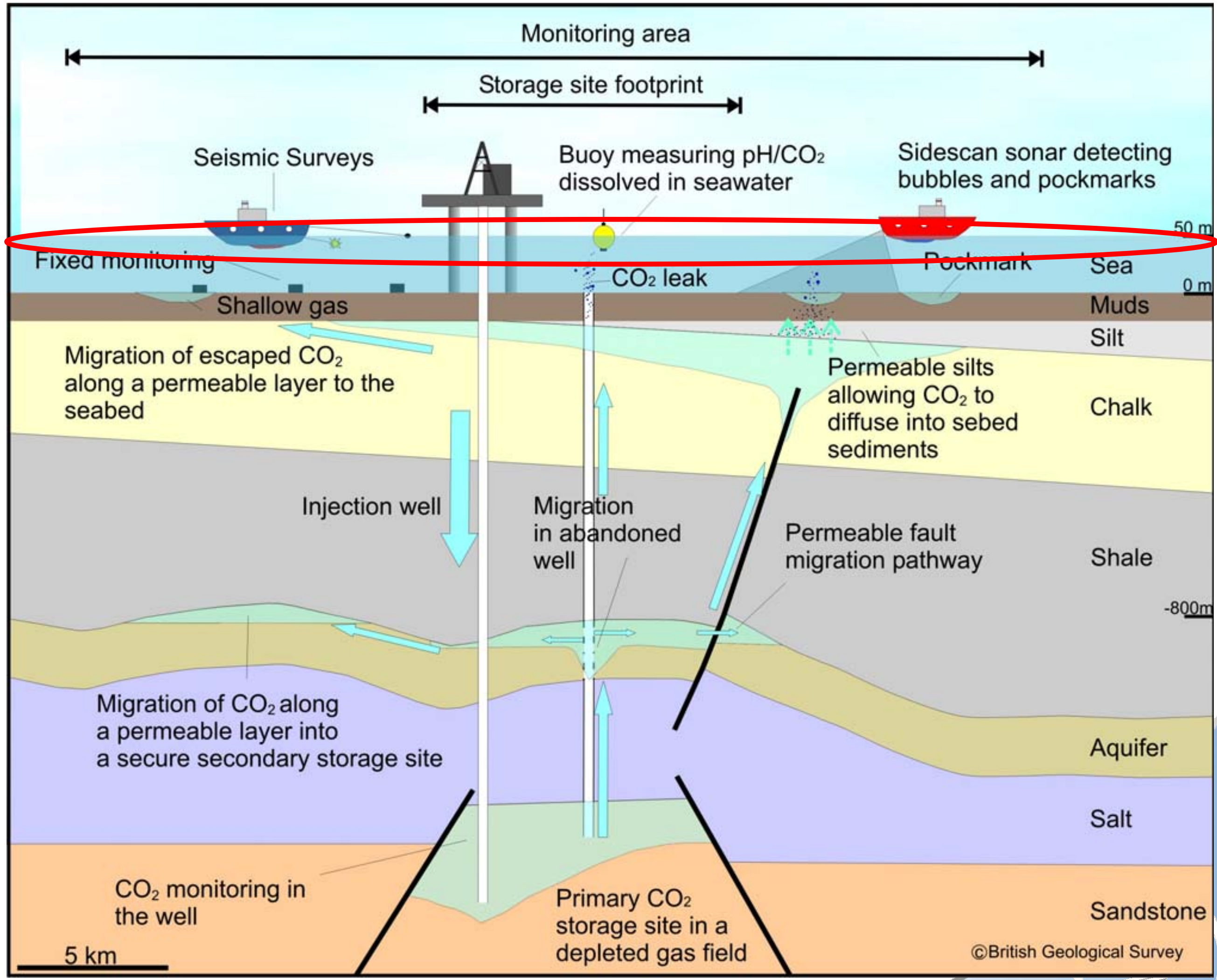
Deep monitoring

- Amounts and movement of CO_2 within storage reservoir and immediate surroundings
- Predictive models of site performance calibrated, tested & adjusted
- Early warning of migration of CO_2 to shallower depths
- Can be acquired at or near surface or in subsurface in wells (injection / monitoring)

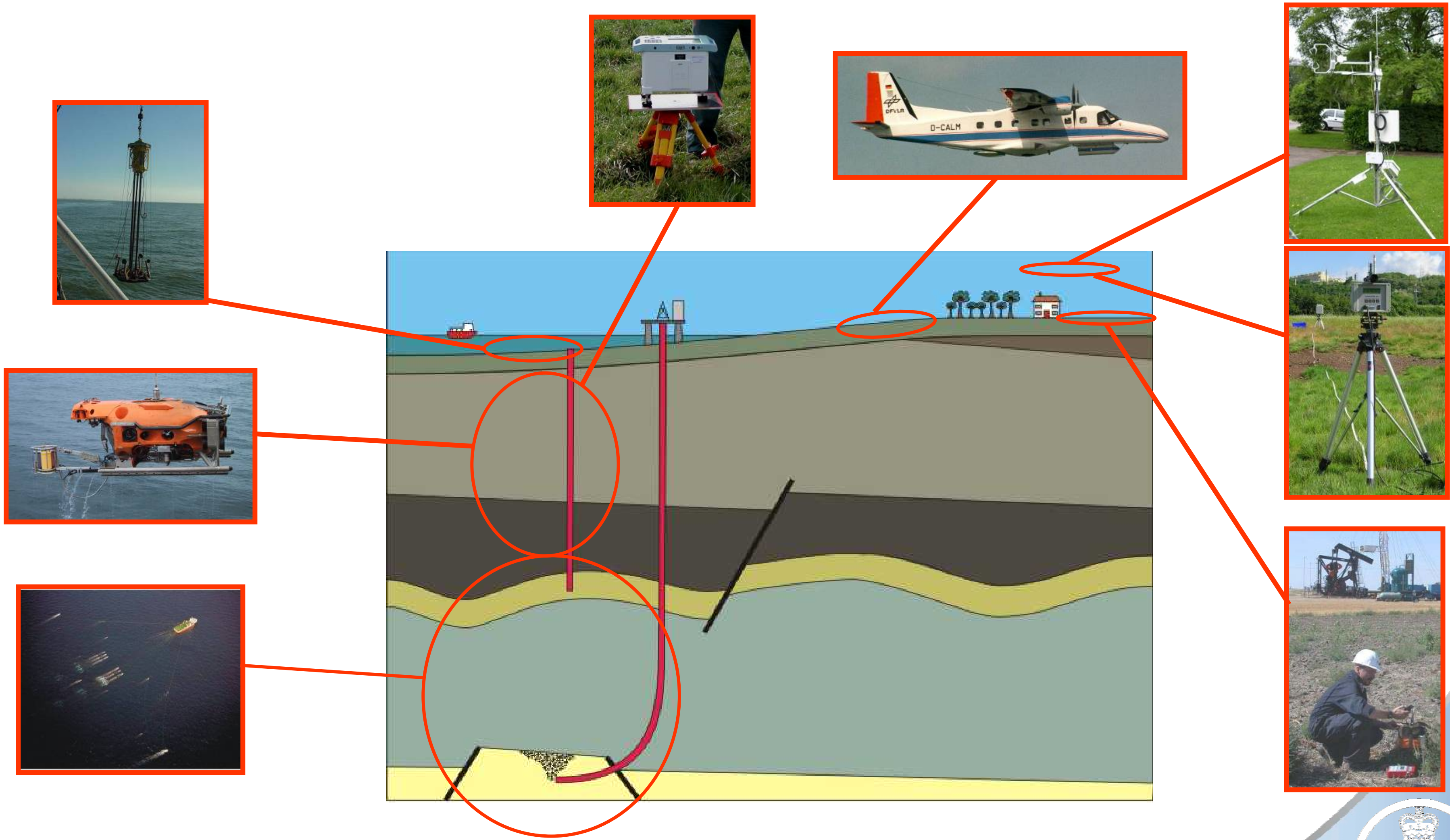


Shallow monitoring

- Detect & quantify amounts of CO_2 that have migrated into the shallow overburden, the soil or seabed
- Or ultimately the ocean or atmosphere
- In addition to techniques that measure CO_2 concentrations in these locations, an evaluation of the impact on local ecosystems may be needed



Examples of monitoring

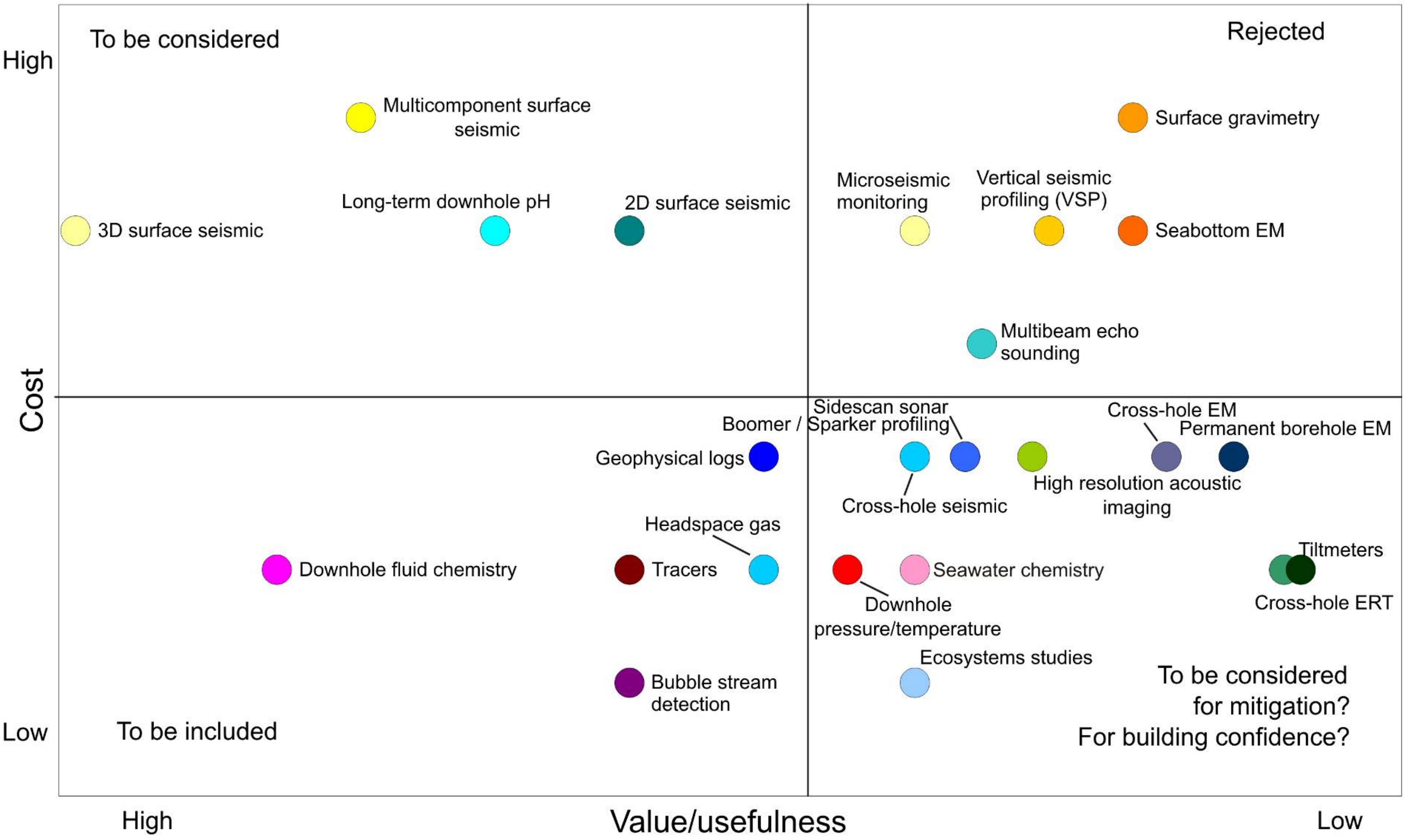


Selection of monitoring tools

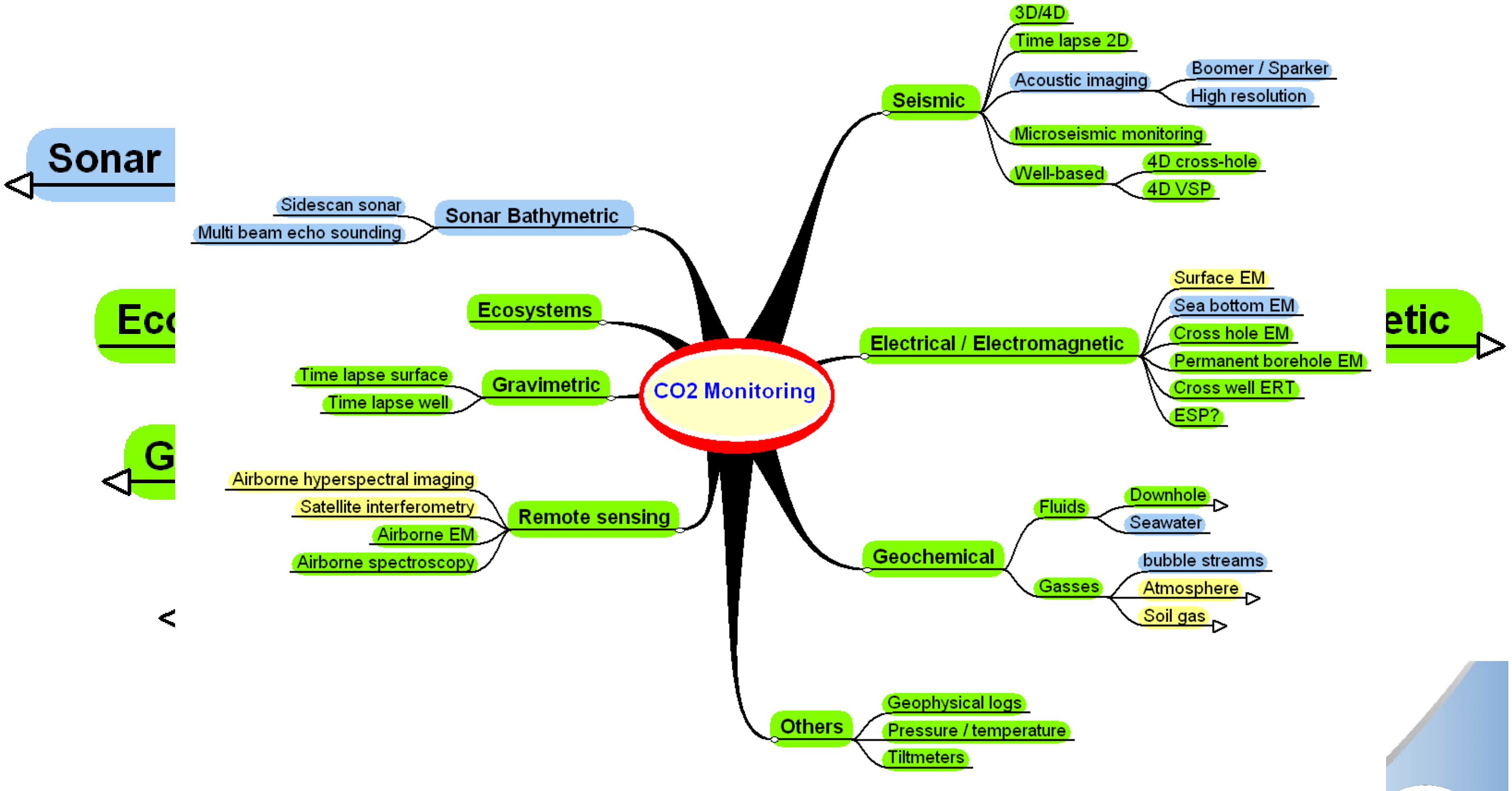
- Location of site:
  - Offshore/onshore
  - Access (land use, topography, wells…)
  - Volume to monitored (depth, footprint)
- Monitoring aims
- Timing
  - Project stage (baseline, injection, post-injection, closure)
  - Mass of CO_2 injected (detection limits, plume migration)
- Cost and benefits
- Environmental impacts of monitoring technologies

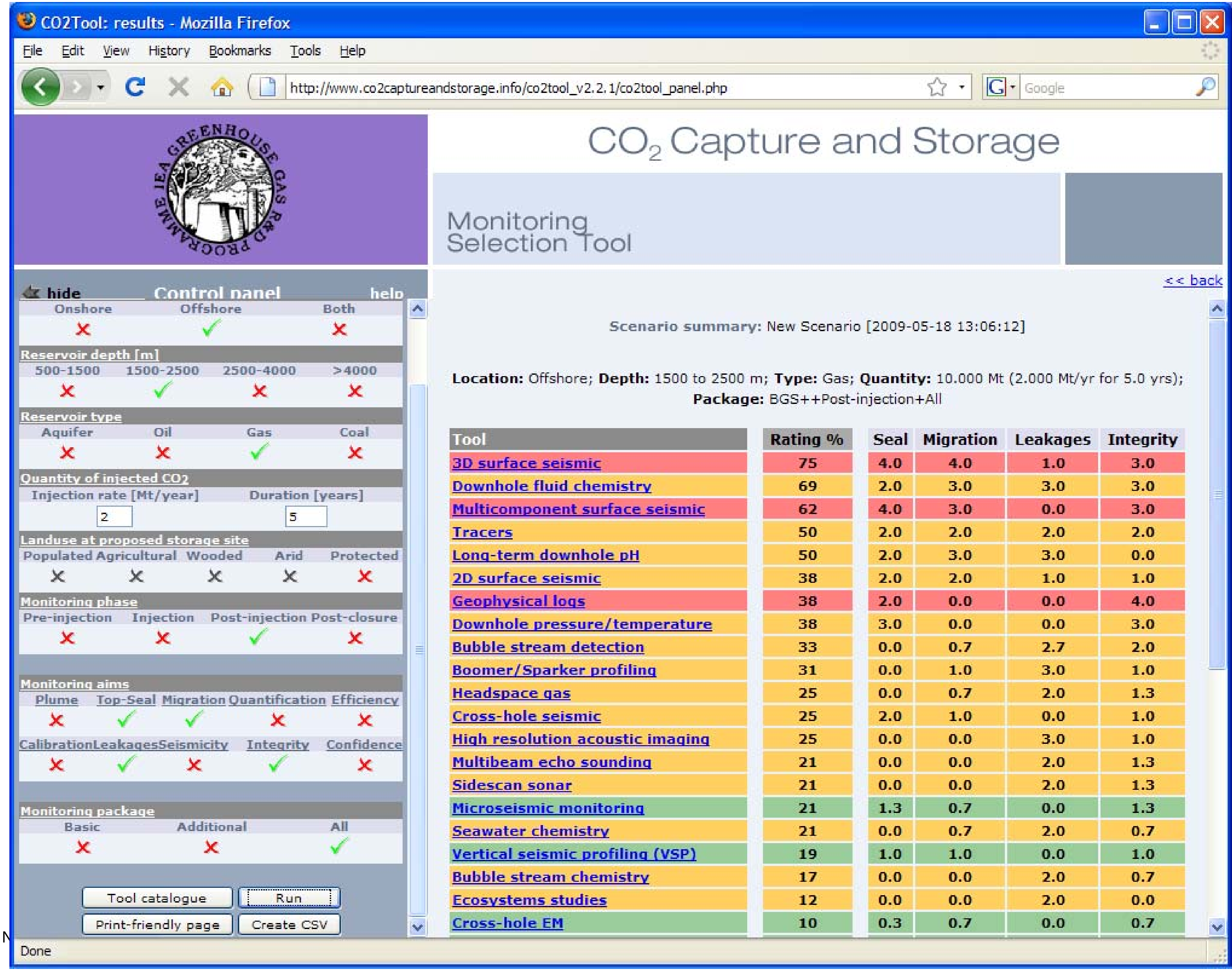
Selecting monitoring tools

E.g. A generic offshore, depleted gas field



Categories


CO2 Monitoring
Seismic
3D/4D
Time lapse 2D
Acoustic imaging
Boomer / Sparker
High resolution
Microseismic monitoring
Well-based
4D cross-hole
4D VSP
Sonar
Sonar Bathymetric
Sidescan sonar
Multi beam echo sounding
Ecosystems
Gravimetric
Time lapse surface
Time lapse well
Remote sensing
Airborne hyperspectral imaging
Satellite interferometry
Airborne EM
Airborne spectroscopy
Electrical / Electromagnetic
Surface EM
Sea bottom EM
Cross hole EM
Permanent borehole EM
Cross well ERT
ESP?
Geochemical
Fluids
Downhole
Seawater
Gasses
bubble streams
Atmosphere
Soil gas
Others
Geophysical logs
Pressure / temperature
Tiltmeters



CO2Tool: results - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.co2captureandstorage.info/co2tool_v2.2.1/co2tool_panel.php

CO_2 Capture and Storage

Monitoring Selection Tool

hide Control panel help

Onshore ✗ | Offshore ✓ | Both ✗

Reservoir depth [m]: 500-1500 ✗ | 1500-2500 ✓ | 2500-4000 ✗ | >4000 ✗

Reservoir type: Aquifer ✗ | Oil ✗ | Gas ✓ | Coal ✗

Quantity of injected CO2: Injection rate [Mt/year] 2 | Duration [years] 5

Landuse at proposed storage site: Populated ✗ | Agricultural ✗ | Wooded ✗ | Arid ✗ | Protected ✗

Monitoring phase: Pre-injection ✗ | Injection ✗ | Post-injection ✓ | Post-closure ✗

Monitoring aims: Plume ✗ | Top-Seal ✓ | Migration ✓ | Quantification ✗ | Efficiency ✗ | Calibration ✗ | Leakages ✓ | Seismicity ✗ | Integrity ✓ | Confidence ✗

Monitoring package: Basic ✗ | Additional ✗ | All ✓

Tool catalogue | Run | Print-friendly page | Create CSV

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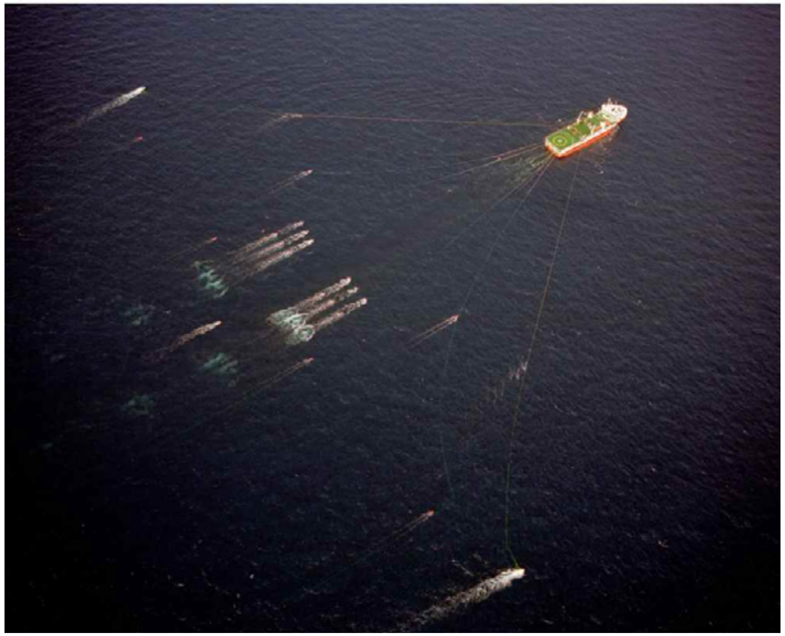
Scenario summary: New Scenario [2009-05-18 13:06:12]

Location: Offshore; **Depth:** 1500 to 2500 m; **Type:** Gas; **Quantity:** 10.000 Mt (2.000 Mt/yr for 5.0 yrs); **Package:** BGS++Post-injection+All

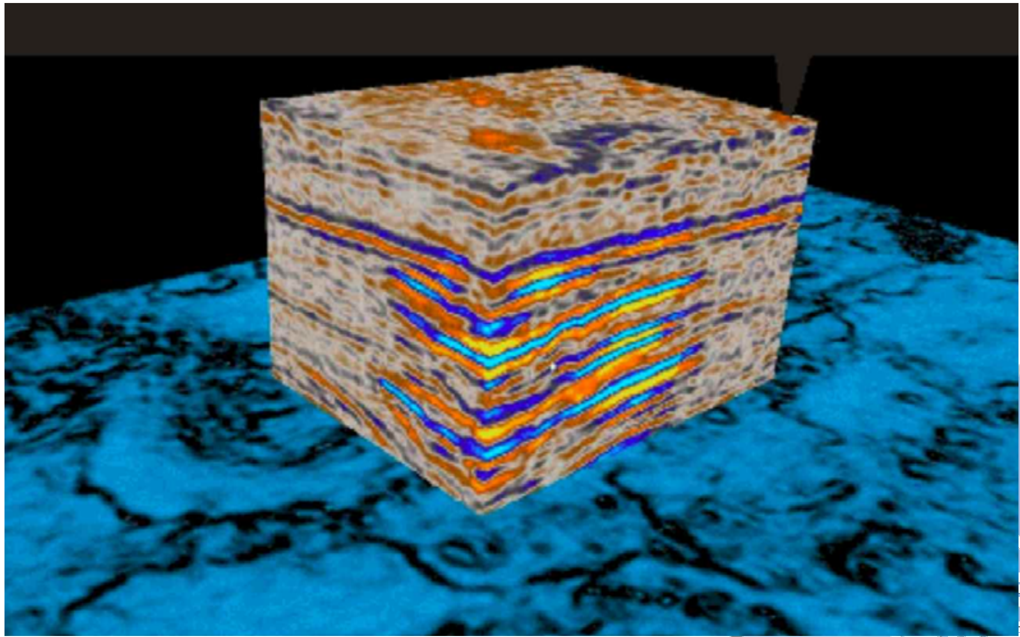
Tool	Rating %	Seal	Migration	Leakages	Integrity
3D surface seismic	75	4.0	4.0	1.0	3.0
Downhole fluid chemistry	69	2.0	3.0	3.0	3.0
Multicomponent surface seismic	62	4.0	3.0	0.0	3.0
Tracers	50	2.0	2.0	2.0	2.0
Long-term downhole pH	50	2.0	3.0	3.0	0.0
2D surface seismic	38	2.0	2.0	1.0	1.0
Geophysical logs	38	2.0	0.0	0.0	4.0
Downhole pressure/temperature	38	3.0	0.0	0.0	3.0
Bubble stream detection	33	0.0	0.7	2.7	2.0
Boomer/Sparker profiling	31	0.0	1.0	3.0	1.0
Headspace gas	25	0.0	0.7	2.0	1.3
Cross-hole seismic	25	2.0	1.0	0.0	1.0
High resolution acoustic imaging	25	0.0	0.0	3.0	1.0
Multibeam echo sounding	21	0.0	0.0	2.0	1.3
Sidescan sonar	21	0.0	0.0	2.0	1.3
Microseismic monitoring	21	1.3	0.7	0.0	1.3
Seawater chemistry	21	0.0	0.7	2.0	0.7
Vertical seismic profiling (VSP)	19	1.0	1.0	0.0	1.0
Bubble stream chemistry	17	0.0	0.0	2.0	0.7
Ecosystems studies	12	0.0	0.0	2.0	0.0
Cross-hole EM	10	0.3	0.7	0.0	0.7

Done

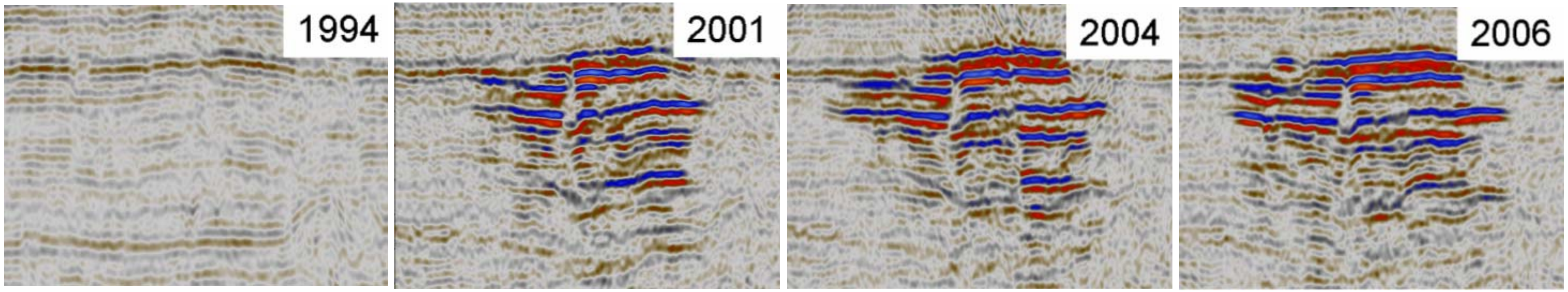
Seismic techniques



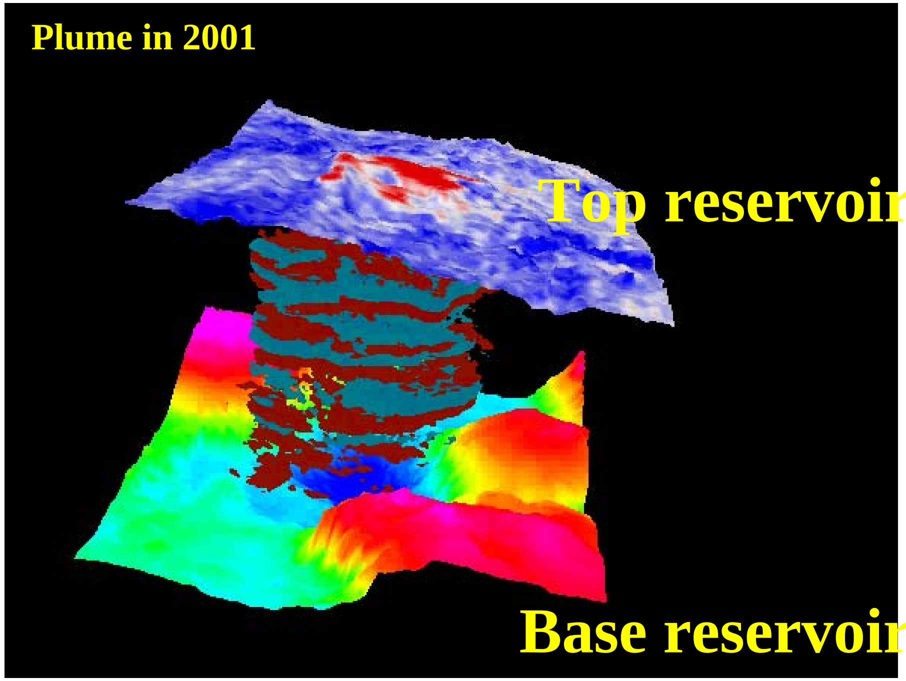
- Powerful subsurface imaging
- Range of techniques; surface and downhole
- Best for reservoirs with good injection & storage properties
  - 3 / 4 D surface seismic
  - Boomer / Sparker
  - High resolution acoustic imaging
  - Well based seismic
  - Multi component seismic



Monitoring CO2 during injection and after

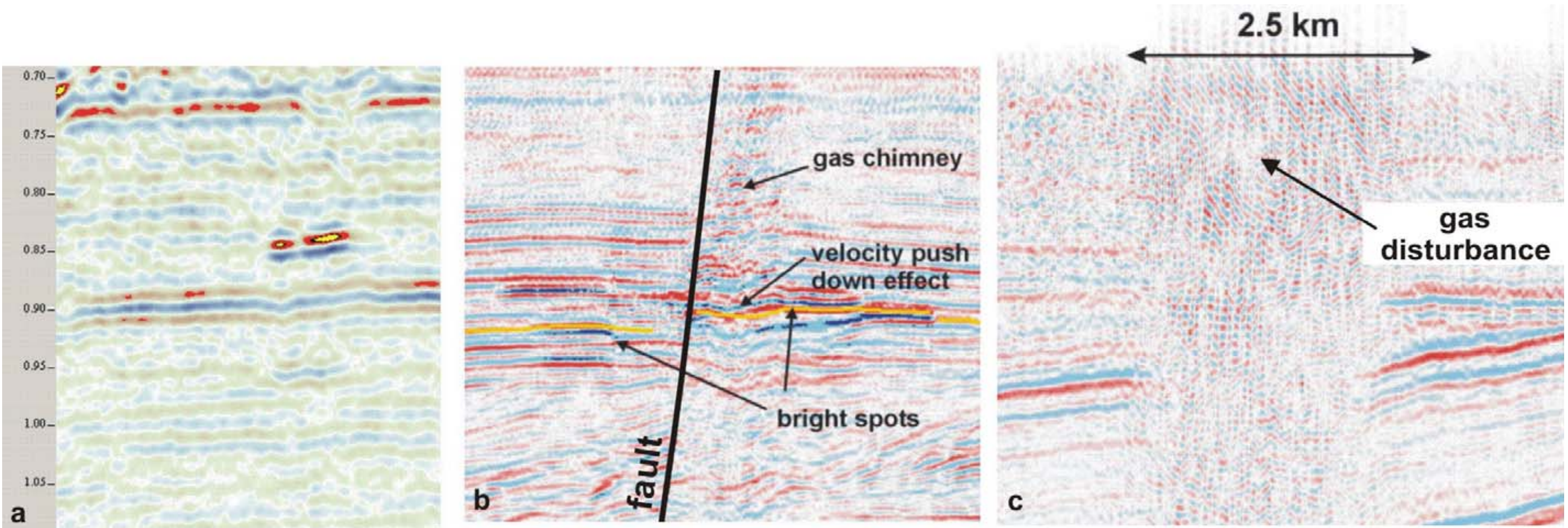


vertical sections (2D)

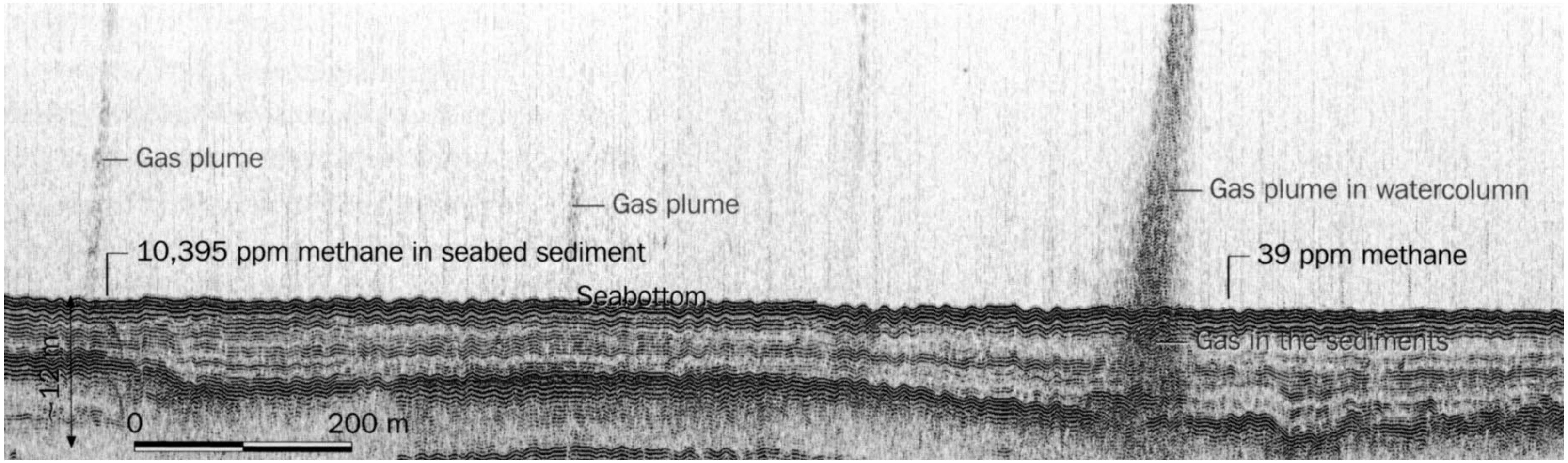


3D view

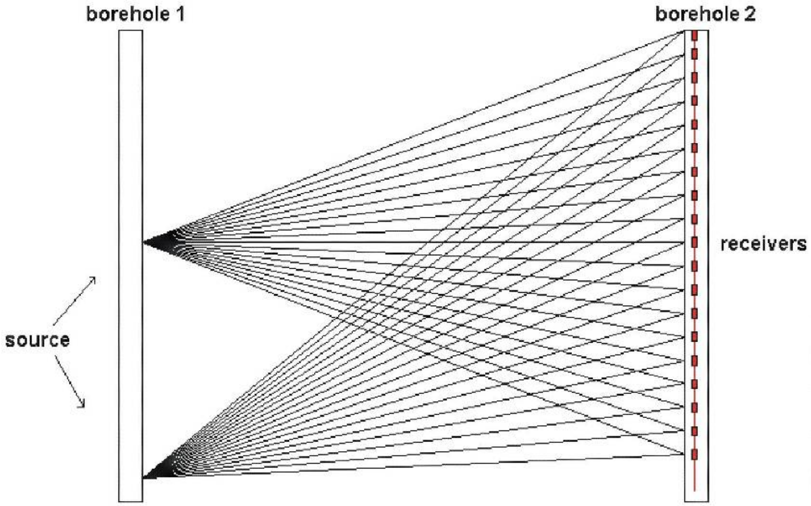
2 / 3 D seismic

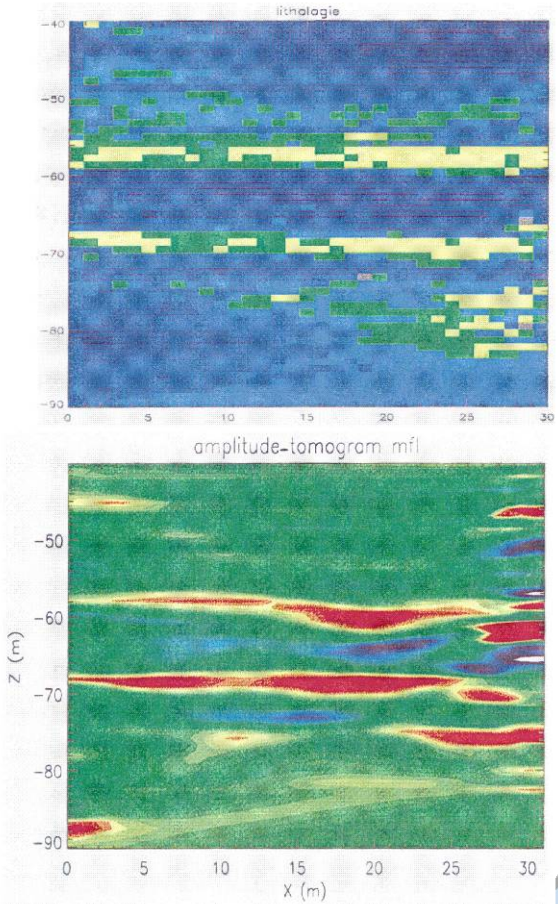

0.70
0.75
0.80
0.85
0.90
0.95
1.00
1.05
a
gas chimney
velocity push down effect
bright spots
fault
b
2.5 km
gas disturbance
c

High resolution acoustic imaging



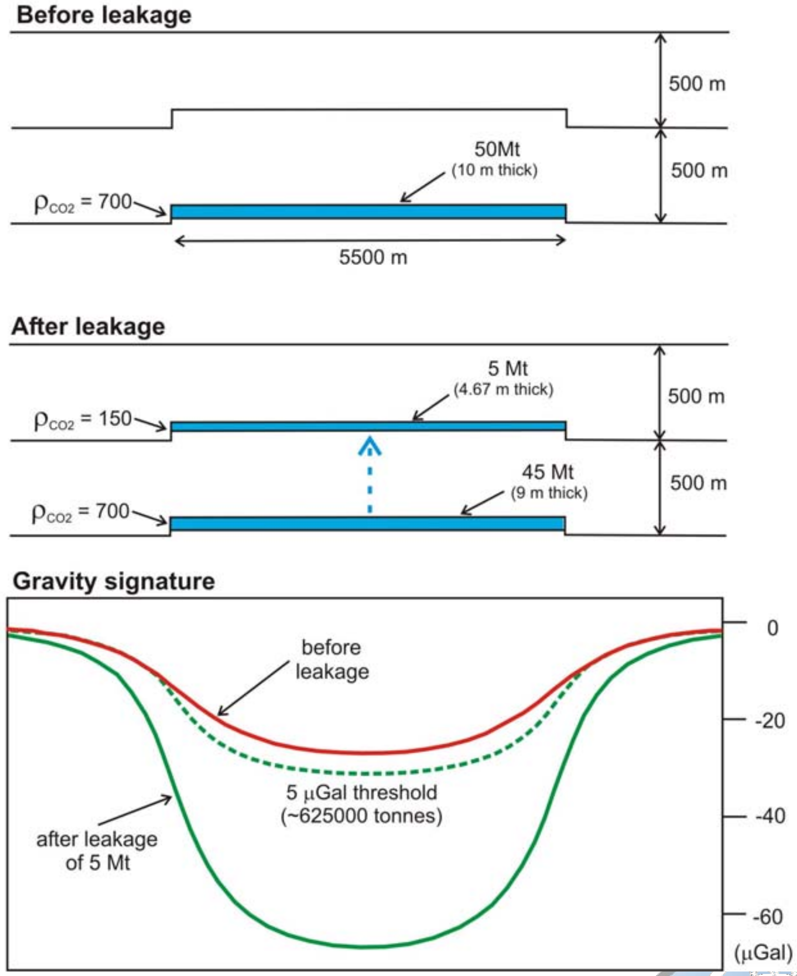
Cross well seismic





Gravimetric techniques

- Measure gravitation acceleration due to mass distributions within the earth
- Can be used to detect variation in subsurface rock or fluid density
- Potential to detect mass changes induced by the storage and migration of CO_2 into the overburden
- Ability to detect mass variations may enable estimates of amount of CO_2 going into solution (invisible on seismic)

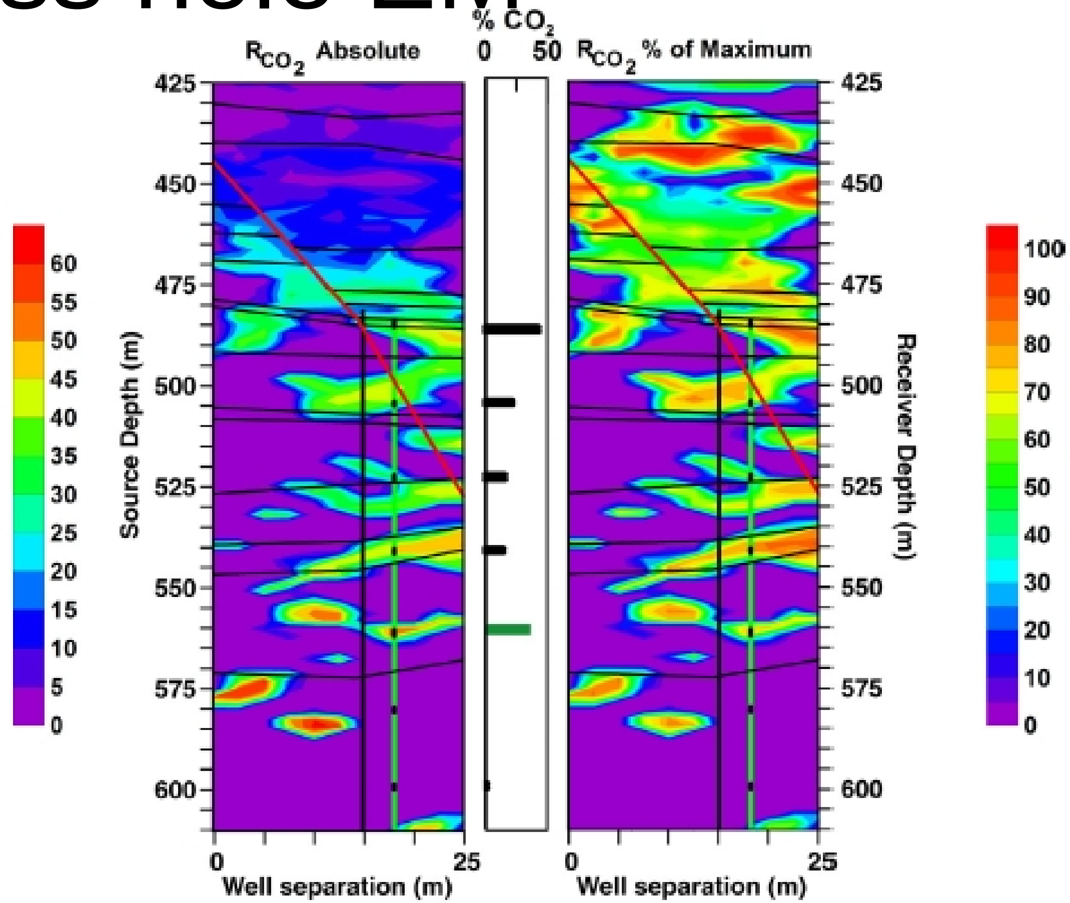


Gravity models to illustrate gravimetric signature caused by leakage of 5MT of CO_2 from a putative storage reservoir to shallower depth.

Electric / electromagnetic techniques

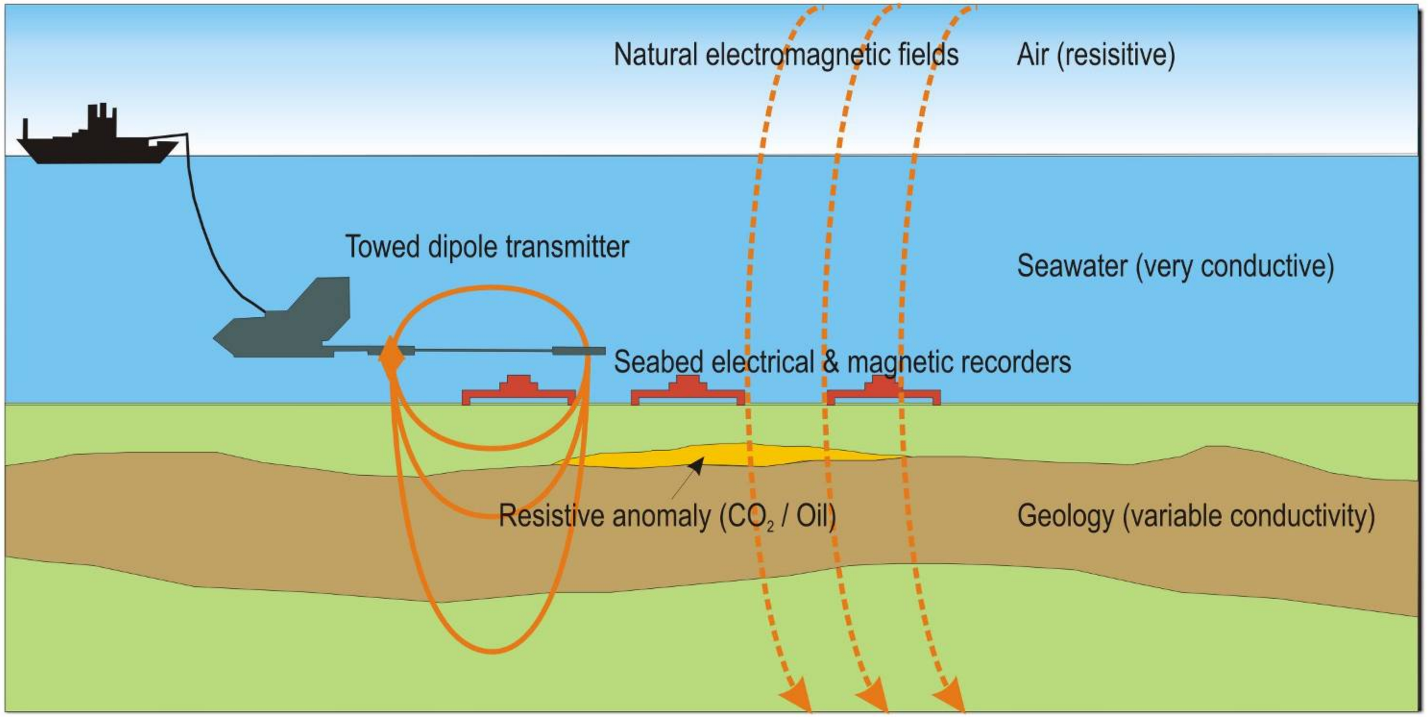
- Utilise propagation of electrical or electromagnetic fields within the earth to map subsurface variations in conductivity
- Offer potential for low cost, low resolution monitoring
- CO_2 resistive and where replaces saline waters may produce a detectable change
- Little tested in CO_2 sites, apart from cross hole techniques
- ERT used in pollutant migration and Sea bottom EM, a recent development for direct detection of hydrocarbons, may have potential

Cross hole EM



CO_2/oil ratio, predicted from borehole geophysics and cross-hole experiments following CO_2 injection from perforation intervals in the green borehole (after Hoversten et al., 2002).

Sea bottom EM



Geochemical techniques

- Analyse chemistry of fluids and gasses to detect and measure concentrations above ‘background’ from leaks
- Samples can be taken in near subsurface (soil, springs), surface, atmosphere, or oceans
- Background levels onshore very variable due to variations in biological production caused by weather, seasons etc
- Offshore sampling of seawater currently mostly at surface, although sampling from depth at ambient pressures is now possible
- Use of tracers in injected CO_2 shows potential, allowing identification of potential leakage sites, and of leaked CO_2.
- Wide range of established techniques for measuring CO_2 in springs and well waters

Soil Gas analysis

Soil gas measurement in the Phase 1 CO_2 injection area of the Weyburn oilfield. Note the *in-situ* soil gas probe to the right of the portable gas analyzer (red).

- Probes or accumulation chambers placed in or on the soil
- Grid pattern over expected footprint of leakage
- Samples analysed periodically often by portable gas analysers
- Does not provide total coverage
    - What sample density and frequency is appropriate?
    - How are adequate baselines established?

Soil Gas analysis

- Probes or accumulation chambers placed in or on the soil
- Grid pattern over expected footprint of leakage
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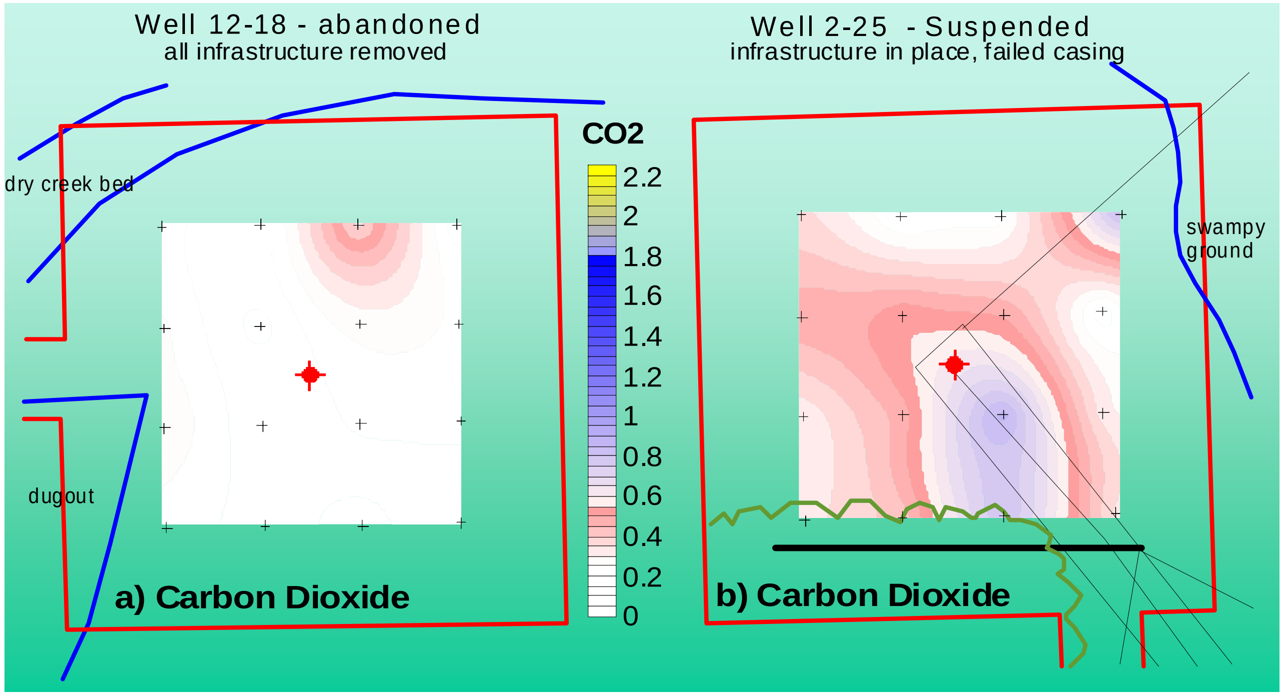
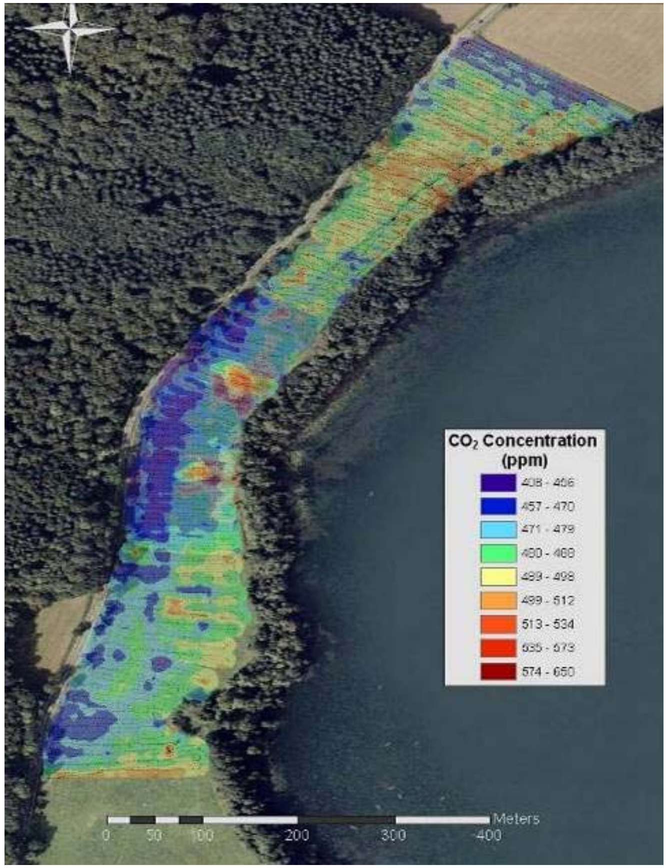
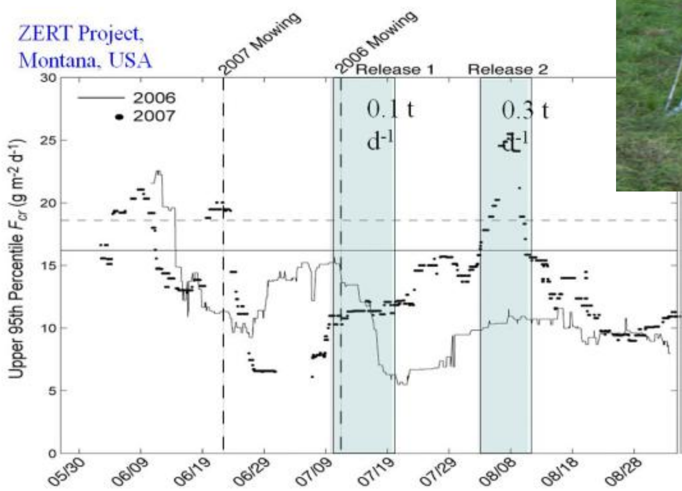


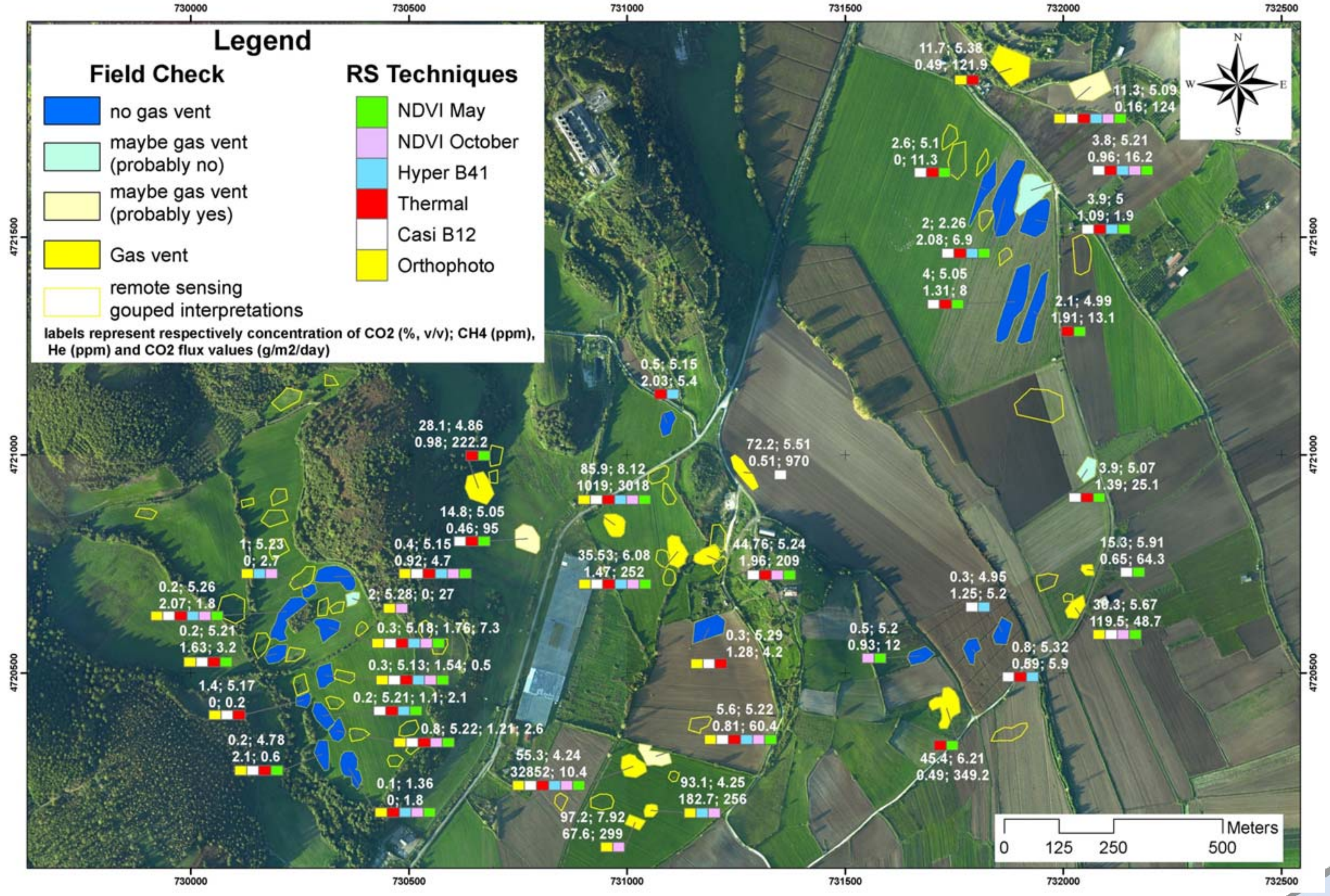
Atmospheric monitoring

- Fixed or mobile Infra-red analysers
- Continuous monitoring at a site or rapid areal coverage





Airborne remote sensing



Monitoring strategies

- A strategy should comprise, inter alia
  - Clear statement of aims
  - Justification of selection of parameters, techniques, threshold values
  - Frequency of monitoring
  - Footprint of monitored area
  - Record keeping and reporting (internal, external)
- These will vary with the techniques used, parameters being monitored and stage of project

Four basic stages

1. Pre-injection
   - Site characterisation for licence to inject
   - Baseline surveys
2. Injection
   - Monitoring for trading
   - Monitoring for local HSE
3. Post-injection
   - Building confidence in predictive models
   - Application for licence to close site
4. Post-transfer
   - Undertaken by Competent Authority

1. Pre-injection

- Operator applies for a storage licence with an appraisal term:
  - Site characterisation and geological model
  - Predictive model including reservoir simulation
  - Environmental impact assessment
  - Risk assessment
  - Monitoring programme
  - Remediation strategy

1. Pre-injection

- The appraisal terms are time-limited
  - Non-intrusive exploration
  - Intrusive characterisation, including injection tests
  - For depleted gas fields appraisal terms may be 1-5 years
  - For saline aquifers, appraisal and exploration terms may be much longer.
- Site performance criteria defined as part of licence to inject.
- Baseline survey(s) will be needed prior to injection and would be undertaken once a consent to store has been obtained
- Monitoring programme will be specific to each site.

2. Injection

- Mass of CO_2 injected to be verified at regular intervals.
  - History matching against predicted behaviour.
- If migration and/or leakage occurred…
  - Monitoring would establish if site performance is still acceptable.
  - Monitoring type and frequency could be changed.
  - Revision of storage capacities, project lifetime may be needed.
  - Remediation may be necessary.
  - Injection may need to be stopped.

3. Post-injection

- Operator applies for consent to close site
  - Monitoring continues at a reduced level
    - Infrastructure likely to be decommissioned at end of injection so access to wells may no longer be possible.
    - EC Directive suggests duration of up to 20 years with MS discretion
- Transfer of responsibility for site to Competent Authority
  - Evidence that (revised) site performance is acceptable against pre-defined criteria.
  - Long-term risk assessment is acceptable.
  - Competent Authority may wish to continue monitoring and will developing a financial mechanism to fund this.

4. Post-transfer

- No monitoring should be required
  - *The safety case for a storage site should be based on the fundamental principle that there will be no requirement for future generations to demonstrate the site's safety.*[1]
  - Therefore no storage site should be closed unless the long-term safety can be assured.
  - It follows therefore that long-term post-closure monitoring should not be needed.

4. Post-closure

- However, arguments for post-closure monitoring are:
  - To demonstrate no fugitive emissions (leaks) to avoid loss of credits, at least during the lifetime of the ETS.
  - To provide assurance that site integrity is maintained.
  - Confirmation of (some) safety assessment predictions.
  - Public confidence, especially in early demonstration storage projects.

Monitoring programmes

- Monitoring plans will be submitted as part of applications for consent to inject:
- Plans need to consider:
  - 3D volume and footprint of baseline surveys (defined by site characterisation and predictive modelling of plume behaviour)
  - Appropriate technique selection
  - Frequency of monitoring: depends on rate of injection, speed of plume migration, objectives, technique (continuous or repeat surveys)
  - Use of monitoring wells
  - Repeatability, accuracy, detection limits
  - Costs, usefulness, risks and potential impacts

Summary

- Monitoring will be required for a variety of reasons to provide confidence in the safety of CO_2 storage.
- Monitoring of the injected CO_2 has been shown to be technically feasible in a number of demonstration and research projects.
  - 1+ Mt demonstrations: Sleipner, In Salah, Weyburn
  - Pilot tests: Frio, Nagaoka, Otway, CO2Fieldlab, West Pearl, CO2ReMoVe
  - Small-scale, research: CO2GeoNet, ZERT, CO2CRC
- Lots of techniques are available.
  - See www.co2captureandstorage.info/co2tool_v2.2.1