Monitoring of Aquifer Disposal of CO_2: Experience from Underground Gas Storage and Enhanced Oil Recovery

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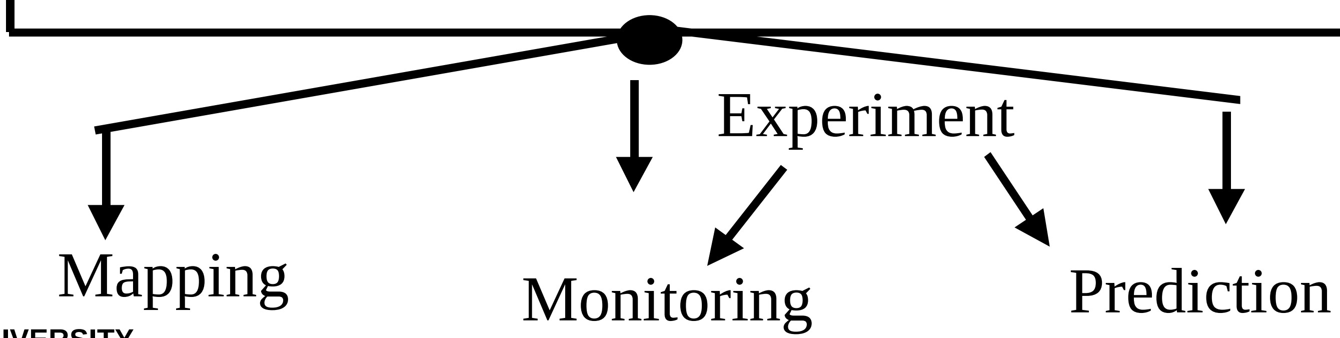
Expertise Required

- Geology: Location of Storage Reservoir
- Hydrogeology: Movement of Fluids
- Geotechnical: Movement of Solids
- Geochemical: Mass Transfer of Fluid-Rock Interaction



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Geomechanics

Formation movements controlled by effective stress ($♦^{1}$)

$$♦^{1} \quad = \quad ♦^{1}_{total.} \quad - \quad P$$

Eff. Stress	Insitu Stress	Reservoir (Pore) Pressure

Controls

- Sand production
- Shear induced permeability changes
- Compressibility
- Hydraulic fractures

Created by

- over burden
- tectonic stresses

Affected by Thermal components of UGS/EOR process

Affected by Injection-Recovery components of UGS/EOR process

Geomechanics

Fracturing: pore pressure exceeds principal stress

Dilation/Contraction: effective stress change due to pore pressure variation

Equilibrium: pore pressure less than minimum stress

Increasing PerusserP

Geochemistry *

Solids		Aqueous
Calcite	Dissolve →	Ca^{++}
Dolomite		Ca^{++}/Mg^{++}
Siderite	← Precipitate	Fe^{++}

Ca^{++}, Ca^{++}/Mg^{++}, Fe^{++} } $+HCO_3^-$

→ $\mathbf{Pco_2}$

* For Carbonate Minerals

Geochemistry *

Ca-Mg-Fe Clay
or
Feldspar
+
CO_2
⊕
H_20

⟷

Kaolinite
+
Calcite
or
Dolomite
or
Siderite
⊕
Quartz

⟶ **Pco_2**

* For Carbonate Minerals in the presence of Reactive Silicate Minerals

Time Scales

- Enhanced Oil Recovery

  EOR = Short term 🕔 10 years
- Underground Gas Storage

  UGS = Medium term 🕔 100 years
- Aquifer Storage of CO_2

  Long term 🕔 1000 + years
- Natural Analogues

  1000,000 + years

Planning of Monitoring

- What are the changes that need monitoring?
- Predict mechanisms that control changes.

From Modelling

From Experiment

(1) Compositional
(2) Geochemical
(3) Geotechnical

Time Scale

1 year
10 years
100 years
1,000 years
10,000 years
100,000 years
1,000,000 years

- Plan instrumentation/testing program.

Access to Reservoir

Surface

Insitu

- Length of time monitoring required.

Planning Monitoring Program

- definition of project conditions
- prediction of mechanisms that control behavior
- technical questions to be answered
- purpose of monitoring
- parameters to be monitored
- magnitude of change expected in parameters
- select instrumentation / monitoring systems
- instrument / monitoring locations

Planning Monitoring Program

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Define Project Conditions

- location, depth and extent of potential disposal zones
- thickness and extent of caprock and any stratigraphic traps or fractures
- location and extent of other bottom or lateral bounding formations
- natural fluid flow rates and flow directions
- folding or faulting in the area
- previous injection/production/geology if depleted oil or gas reservoir

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Predict Mechanisms that Control Behavior

- Conduct reservoir simulations
- Monitoring provides feedback to simulation
  - integrate injection data (both surface and downhole) and monitoring data with simulations of reservoir behavior

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Technical Questions to be Answered

- temporal and spatial development of acid gas “bubble”
- geochemical reactions
  - mineralization/demineralization
  - long term $\Delta\phi$ and Δk
- car rock, wellbore integrity
- impact of thermal/compositional gradients within reservoir

Aquifer Storage of CO_2

(Long Term ” 1000 + years)

Changes	Effect	Importance
CO_2 bubble migration	– leakage/sweep	⌦ ⌦ ⌦
CO_2 bubble solution	– pressure drop	⌦ ⌦
Gas hydrate formation	– permeability	⌦
Wettability	– permeability	⌦
Pore Pressure	– cap rock integrity	⌦ ⌦ ⌦
or	– formation integrity	⌦⌦
Insitu temperature	– permeability	⌦ ⌦
Water-Rock reactions	– release of fines/perm.	⌦
	– CO_2 capture	⌦ ⌦ ⌦
	– pressure drop	⌦ ⌦
	– cap rock solution	⌦
Water-Metal reactions	– well corrosion	⌦⌦

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Purpose of Monitoring

- Interaction with simulations
- Validate physics of disposal process
- Mitigate uncertainty associated with reservoir parameters
- Identify and validate aquifer disposal mechanisms
- Correlate operations issues with aquifer and caprock response
- Satisfy regulatory requirements

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Parameters to be Monitored

- Injection volumes, daily rates and cumulative volumes
- PVT conditions of the injected gas
- Injection pressures and temperatures
- CO_2 distribution in situ
- acid gas / water interface with time
- …..
- ……...

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Magnitude of Change in Parameters

- pressure change in reservoir
- temperature change
- rate of movement of “bubble”
- thickness of solubility front
- ...

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Select Instruments/Monitoring Systems

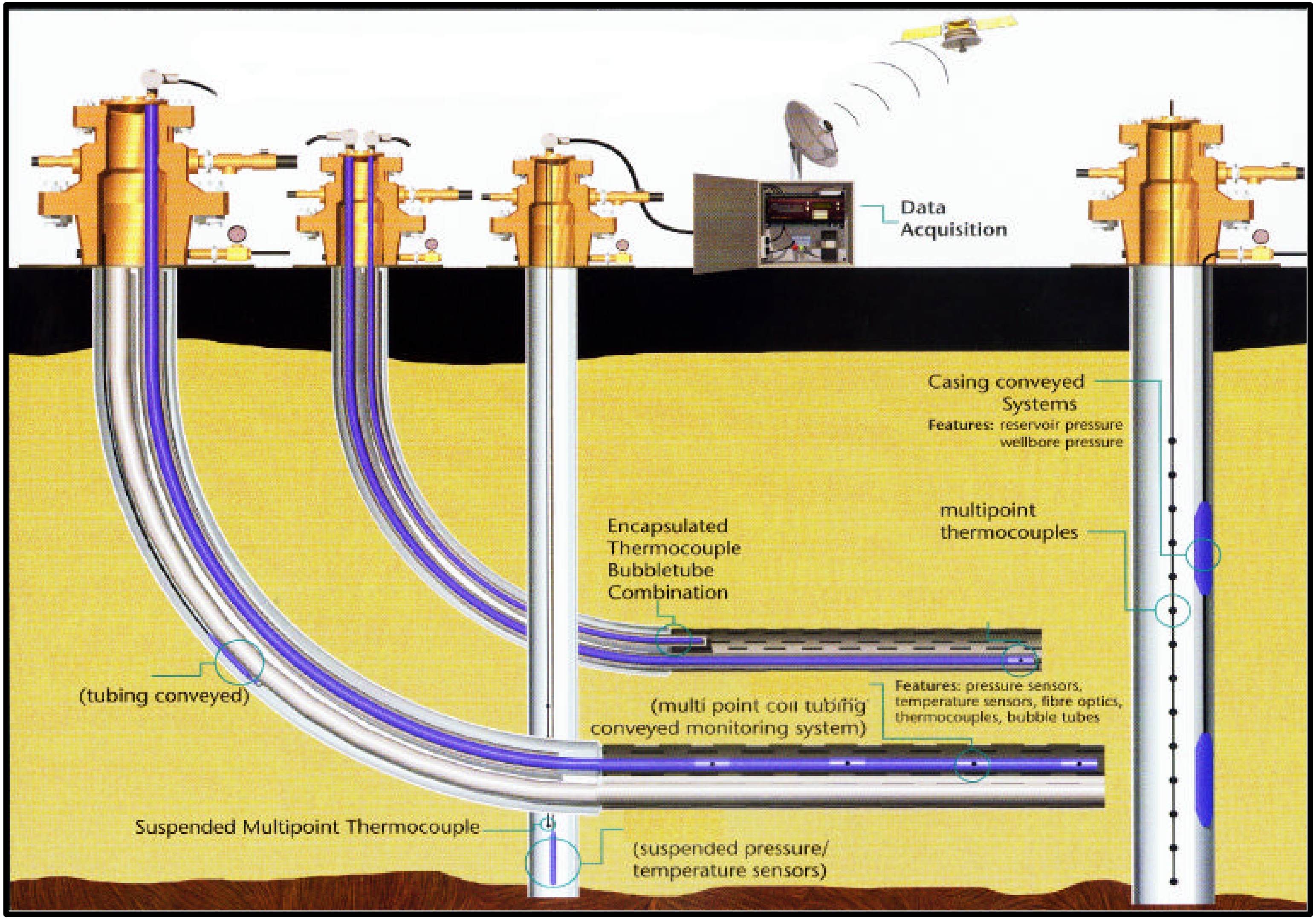
- Surface Monitoring
  - pressure, temperature, rate, composition,
- Downhole Monitoring
  - pressure, temperature, rate, composition, deformation,
- Tracers
  - radioisotopes, gas, water soluble salts, fluorescent dyes, water soluble alcohol's, isotopes,

Monitoring Techniques

Technique	Insitu	Surface
• Wellhead data *	No	⌧
• Temperature	⌧	⌧
• Pressure	⌧	⌧
• Tracers	⌧	No
• Sidewall core	⌧	No
• Logs	⌧	No
• Seismic	⌧	⌧
• Electromagnetic	⌧	⌧
• Gravimetric	No	⌧
• Tilt	No	⌧
• Drill stem (DST)	⌧	No

*i.e. test separator, water/gas/oil chemistry P,T etc

Monitoring Systems



Monitoring Techniques

Pressure

- Falloff
- Buildup
- Step rate injection (Fractures)
- Production/Injection
- Interference
- Multiwell Surveys of BHP

Issues

- Surface versus downhole
- Singlewell versus multiple well
- One point versus multipoint (horizontal well)
- Technology (quartz, fibre optics, …)

Monitoring Techniques

Tracers

Type	Water Soluble	Gas Soluble
Radioisotopes:	Tritiated Water Co^{57},Co^{58},Co^{60}	Kryton ^{85} Tritium Tritiated HCs
Salts/Gases:	NH_4^+,Na^+, K^+ I^- Br^-, NO^-_3, $C1^-$, Thiocynate	SF_6, Freon
Fluorescent Dyes:	Uramine,Fluorescein Rhodamine - b	
Water Soluble Alcohols:	Methyl, ethyl isopropyl	
Natural: anions:	$C1^-$, Br^-, TIC	
cations:	Na^+/ K^+, SiO_2,	
stable isotope ratios:	C,O,H	C,O,H

Geophysical Techniques

- Borehole
  - open hole and cased hole logs
  - passive seismic
- Surface
  - surface reflection
  - 2^D, 3^D surveys
  - VSP
  - gravity

Monitoring Techniques

-Geophysical Logs-

Visualization

- Dip meter
- VSP
- Borehole imaging

Formation Evaluation

- Resistivity
- Density
- Neutron
- Spectral gamma ray
- Magnetic resonance
- Temperature

Rock Mechanics

- Sonic (Vp)
- Full waveform sonic (Vp,Vs)

→ Monitoring use requires time lapse.

Monitoring Techniques

Seismic

EOR/Storage process results in change to acoustic impedance.

Surface

- 2D
- 3D
- 4D (3C)
- 4D (4C)

- VSP,HSP

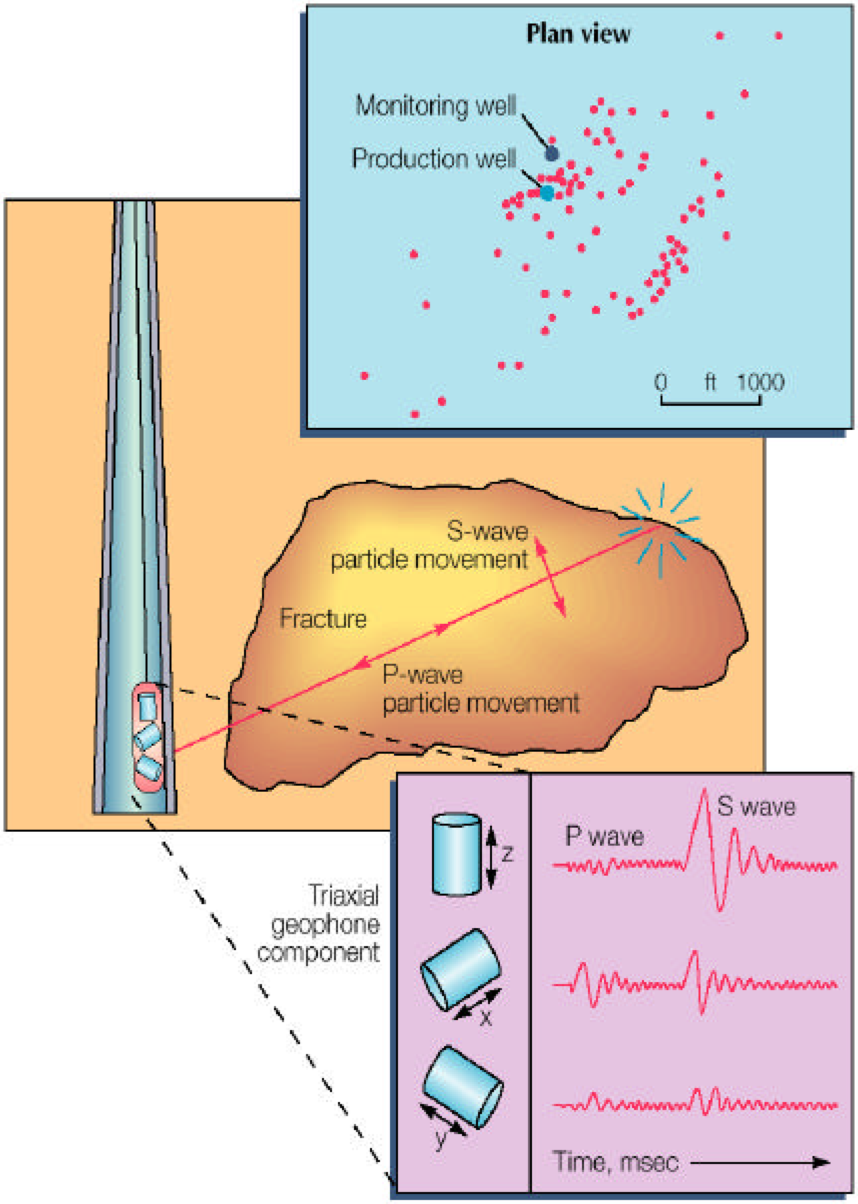
Insitu

- CHT
- Microseismic (passive)

→ Monitoring use requires time lapse measurements.

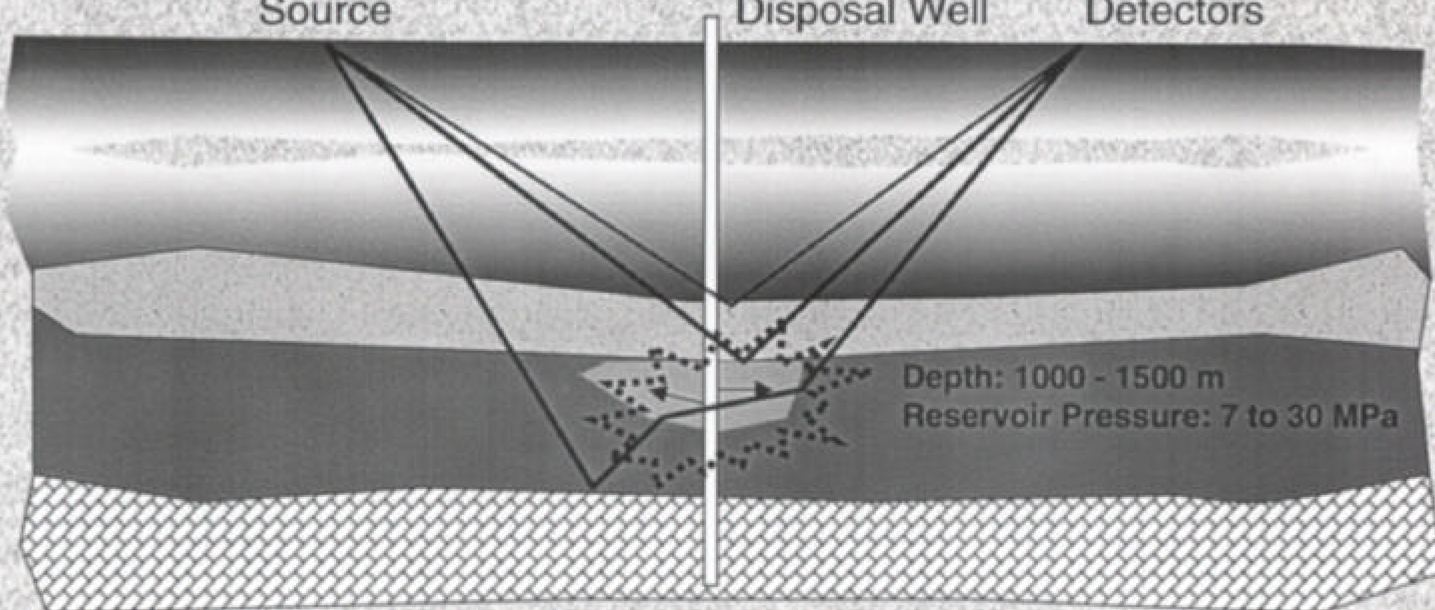
Borehole Logging

- Open Hole
- Cased Hole
- Time Lapse

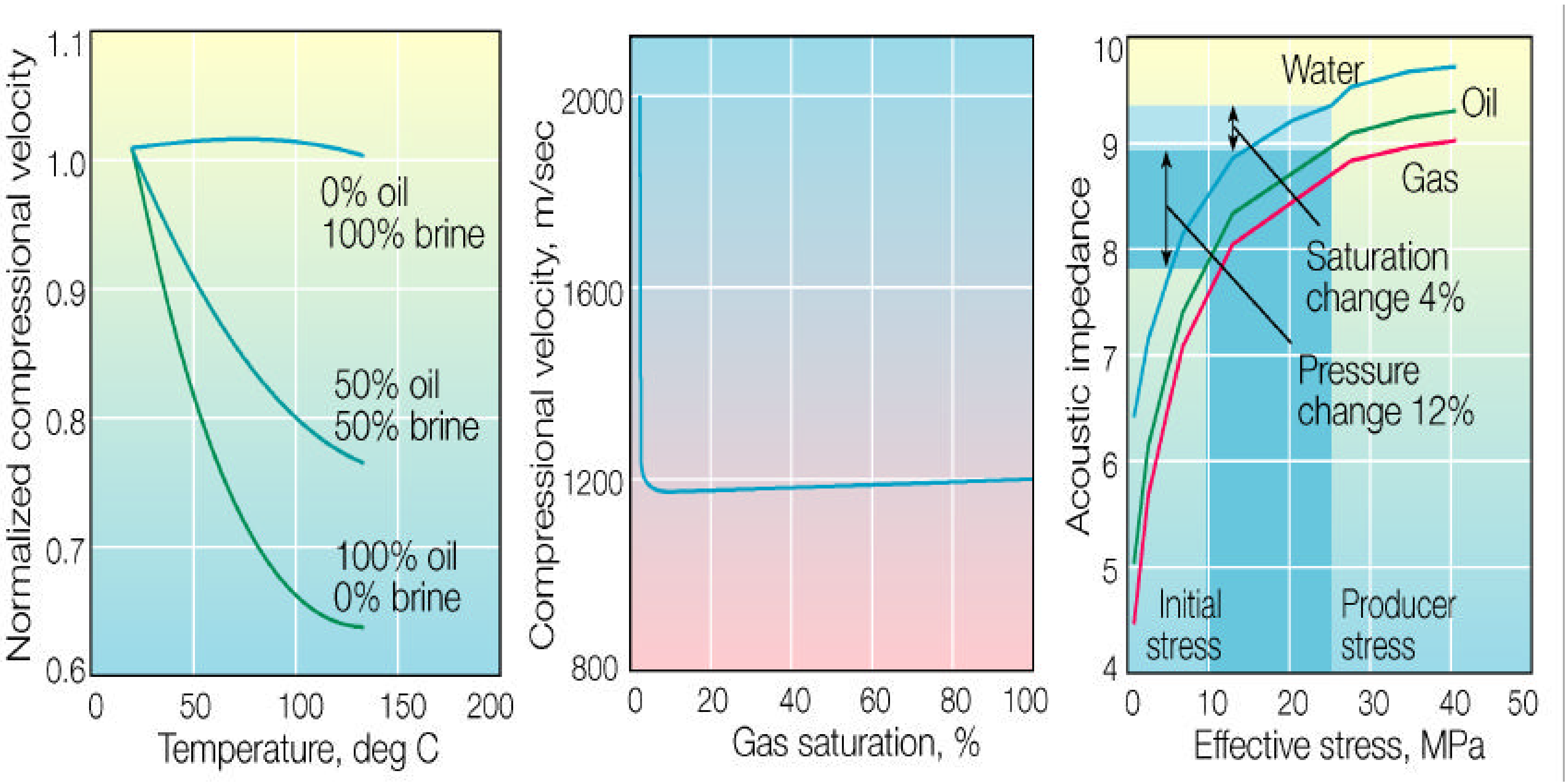


Seismic Monitoring for Acid Gas Disposal Processes

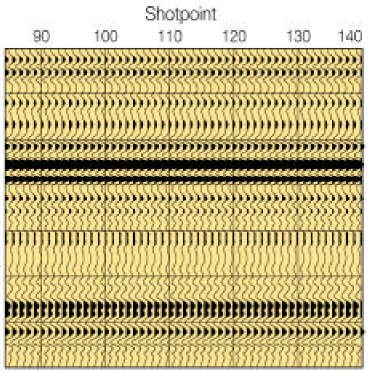
- **Detection of "Bubble" or Zone of Disposal (Spatially and Temporally)**



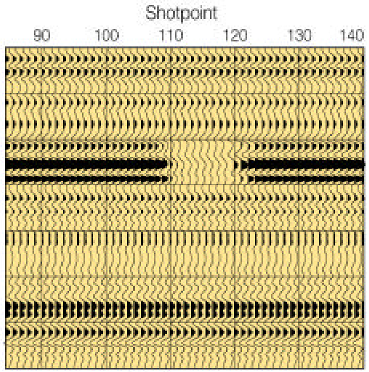
Fundamentals



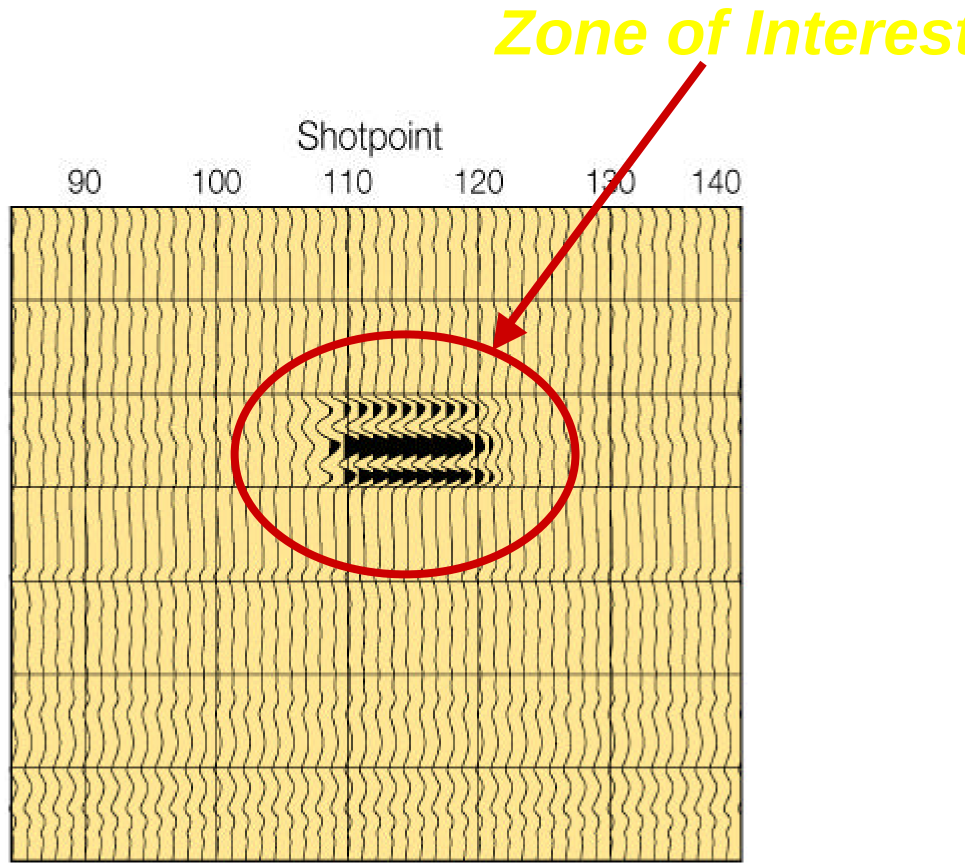
Surface Seismic Monitoring



BASE SURVEY

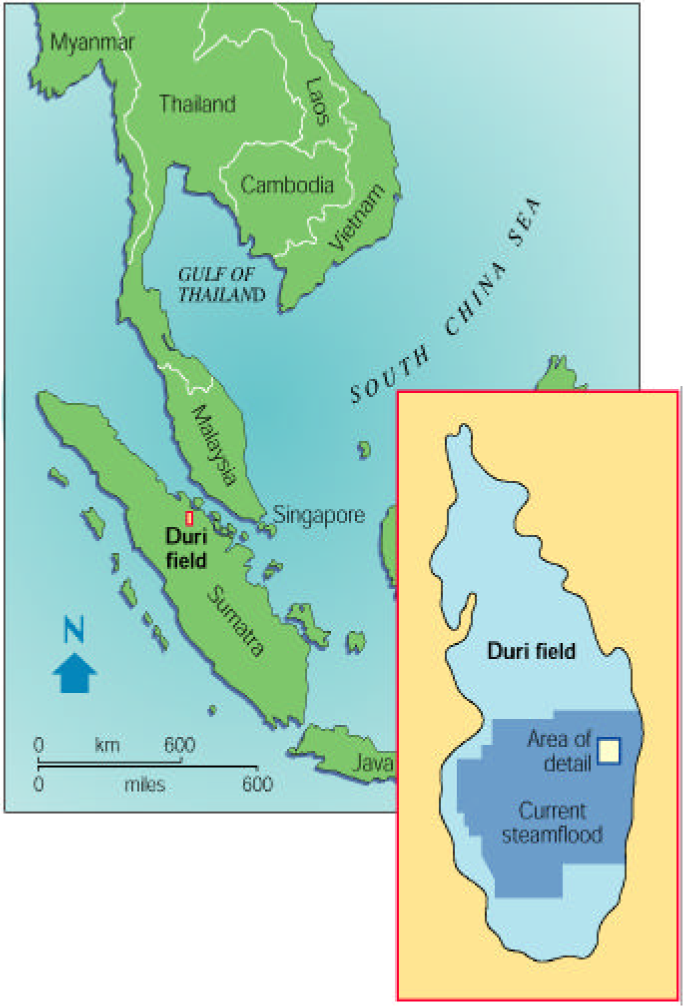


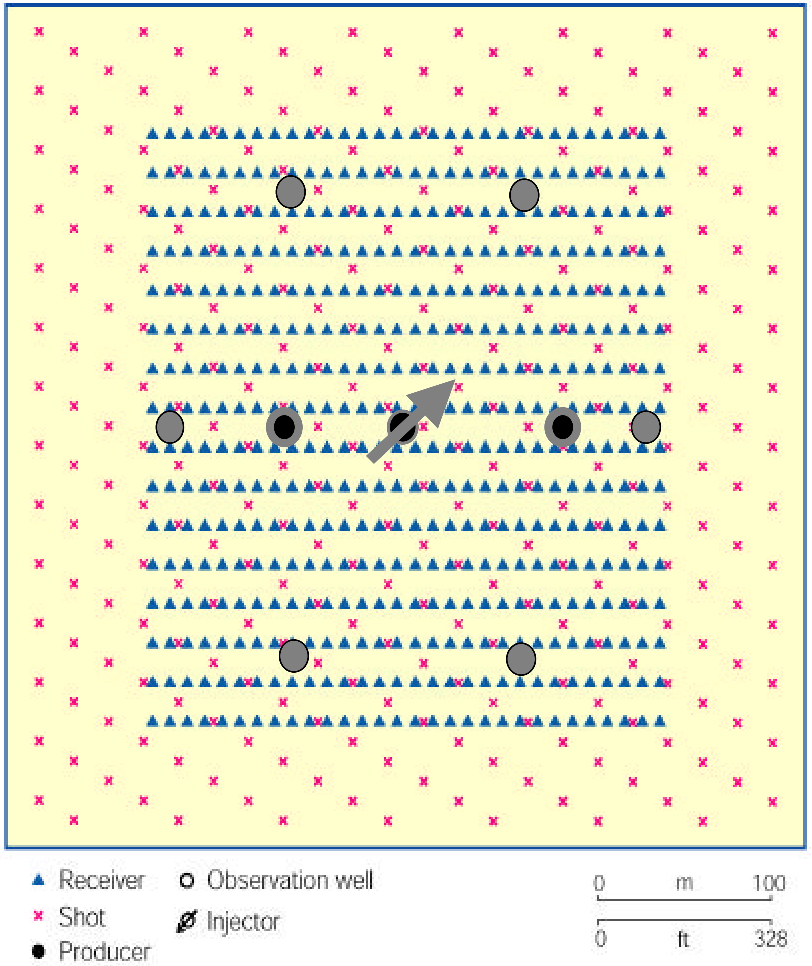
MONITOR SURVEY



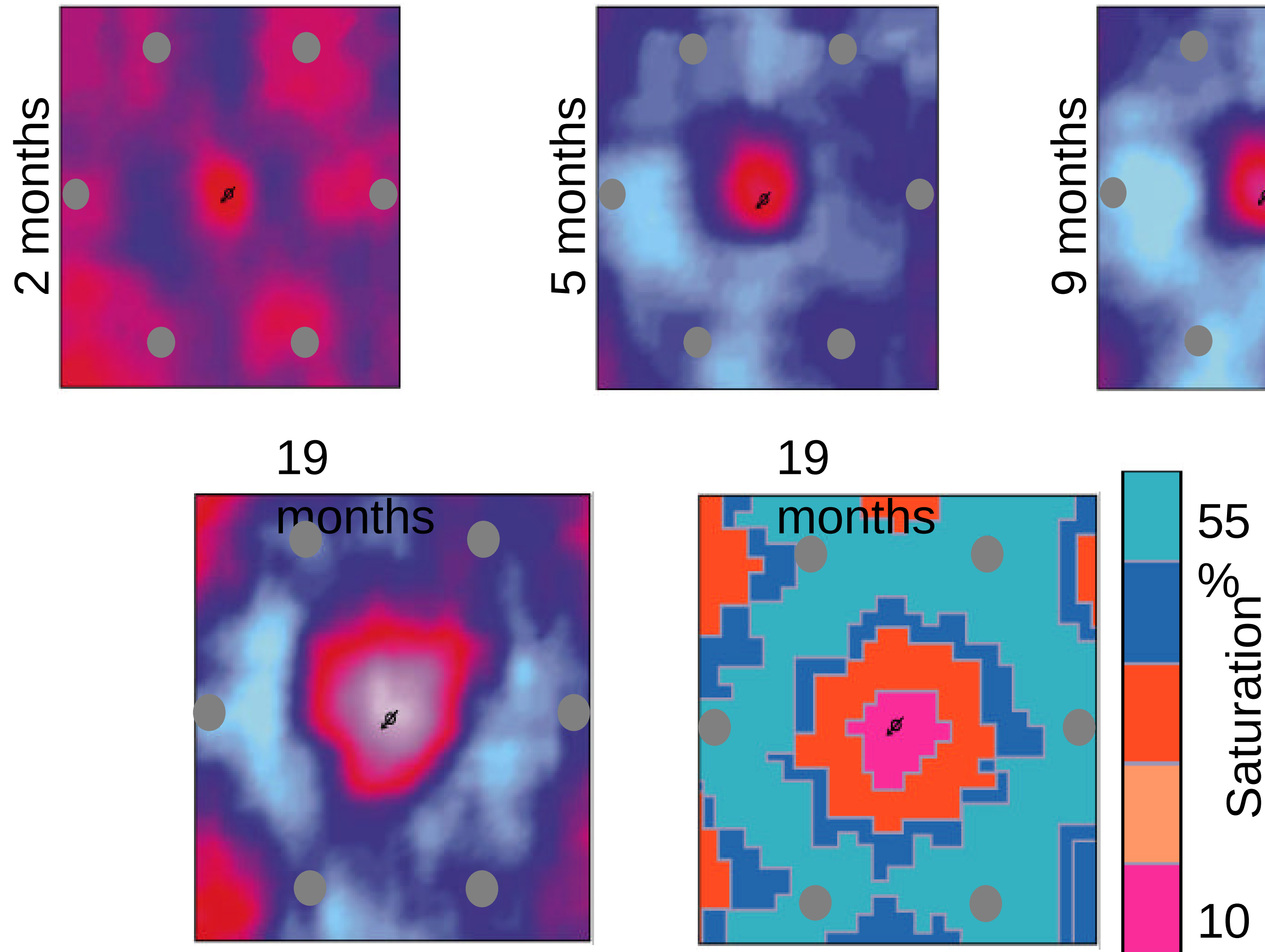
DIFFERENCE

4D (3D with time) Seismic





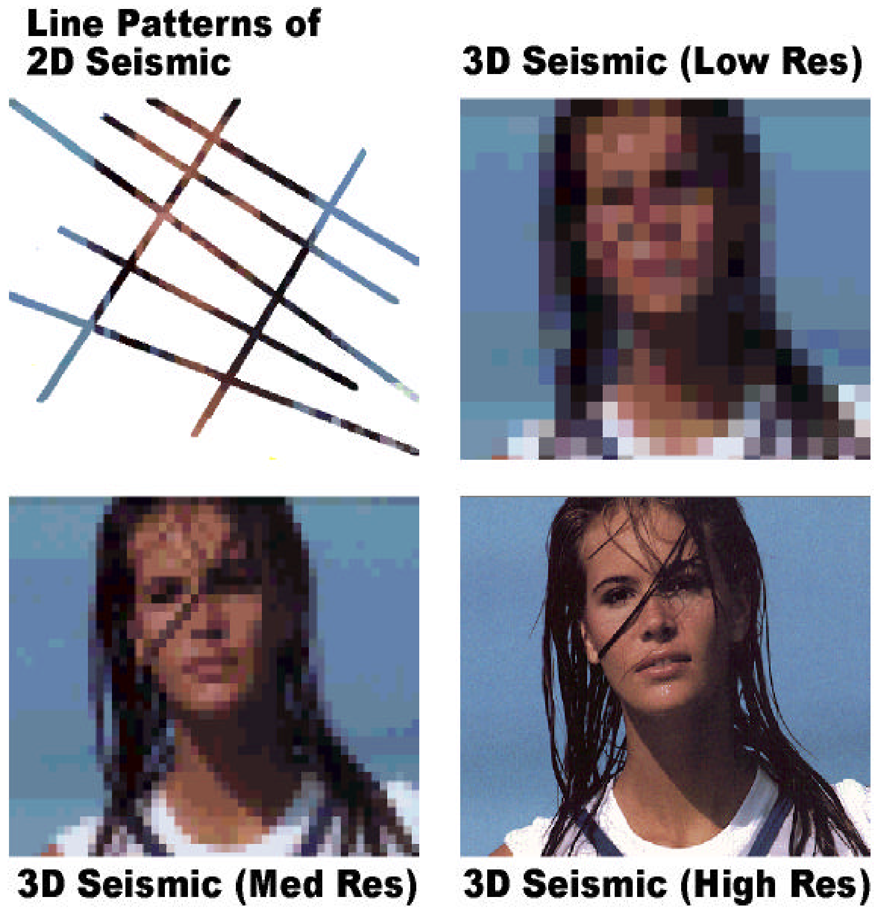
Seismic Monitoring Results



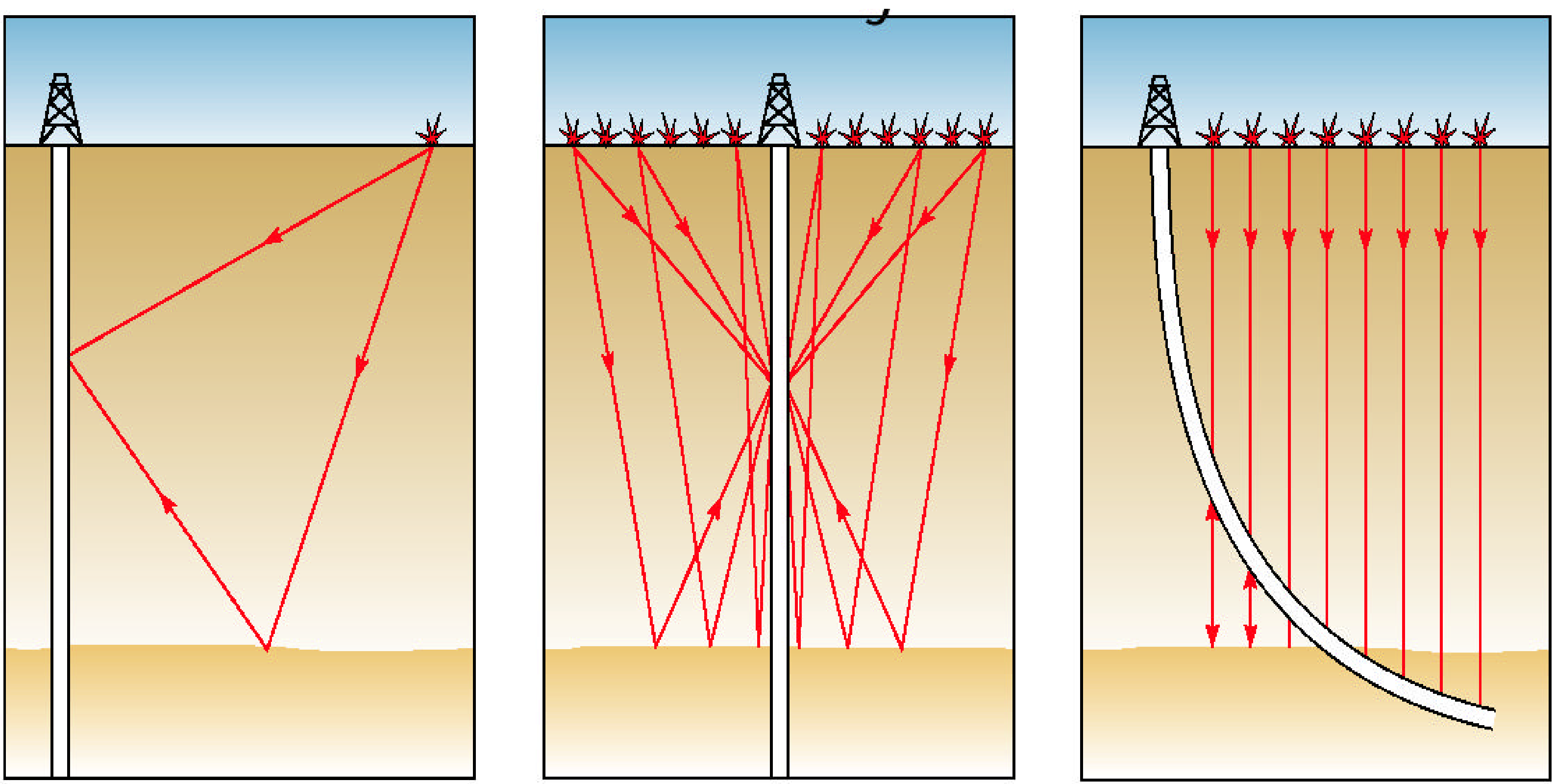
Reservoir Simulation

Geophysical Monitoring

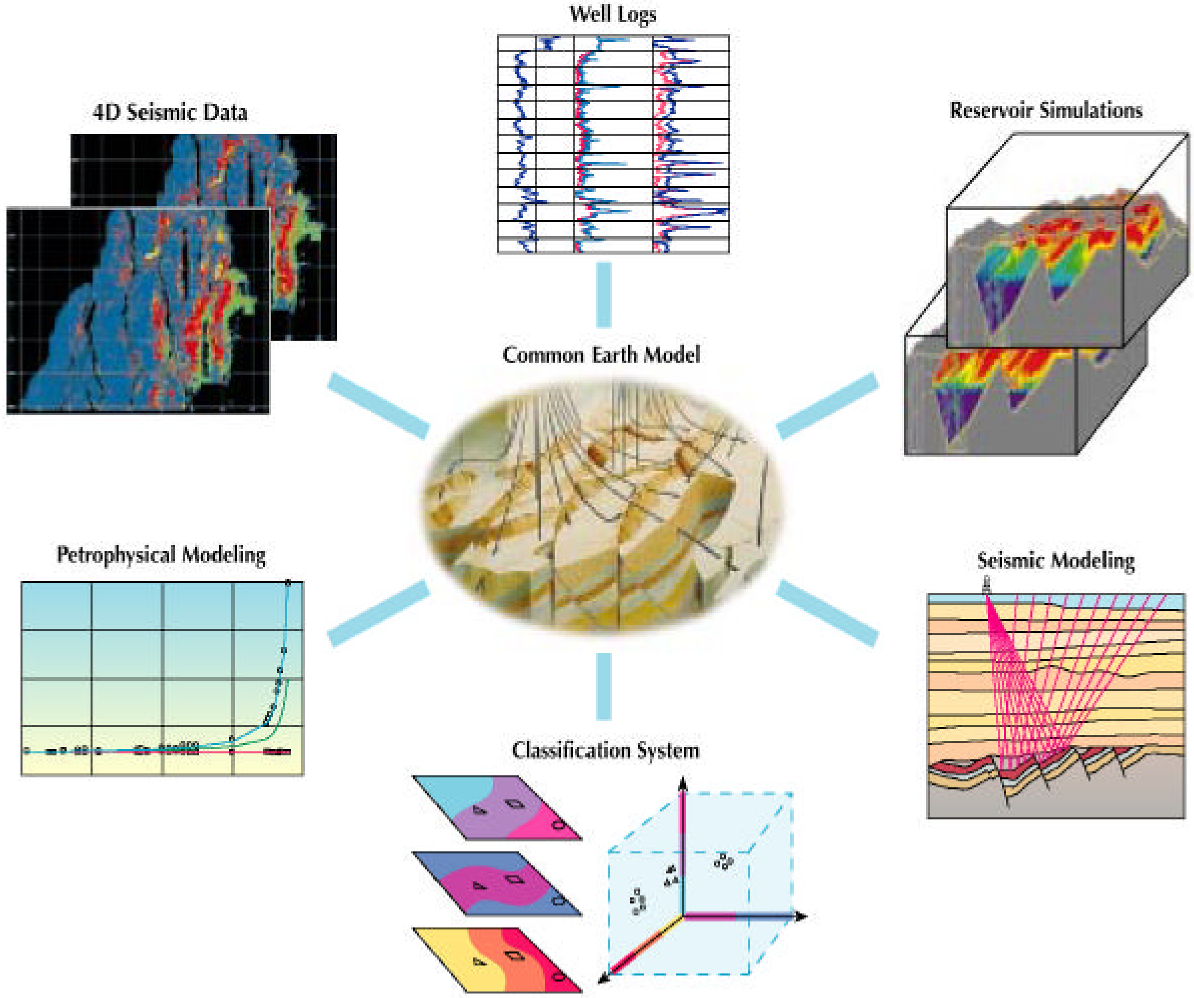
Relative Demonstration of Accuracy and Resolution for 2D Seismic and Increased Resolution 3D Seismic



Vertical Seismic Profiling



Integrated Monitoring



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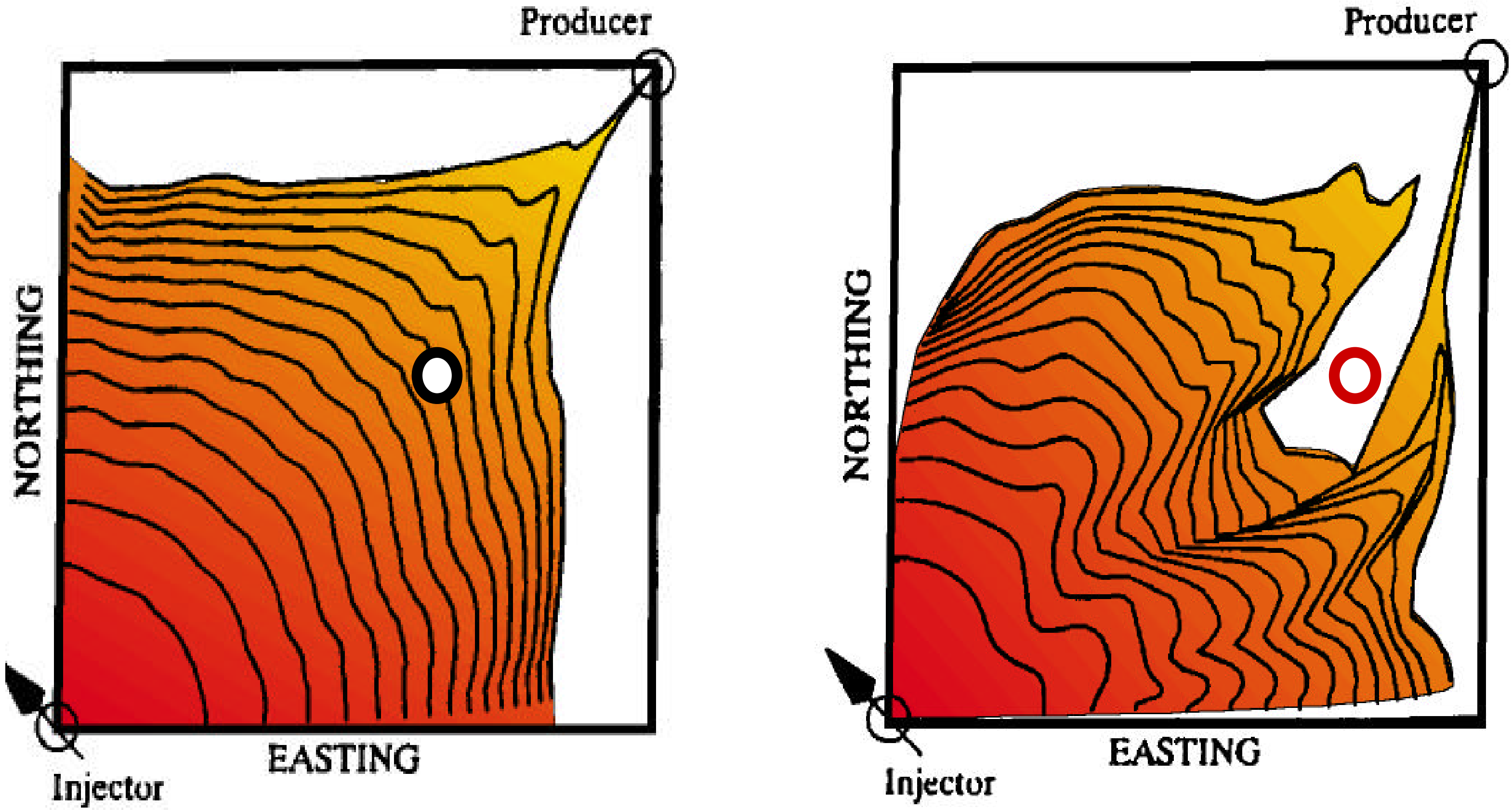
Select Locations for Instruments

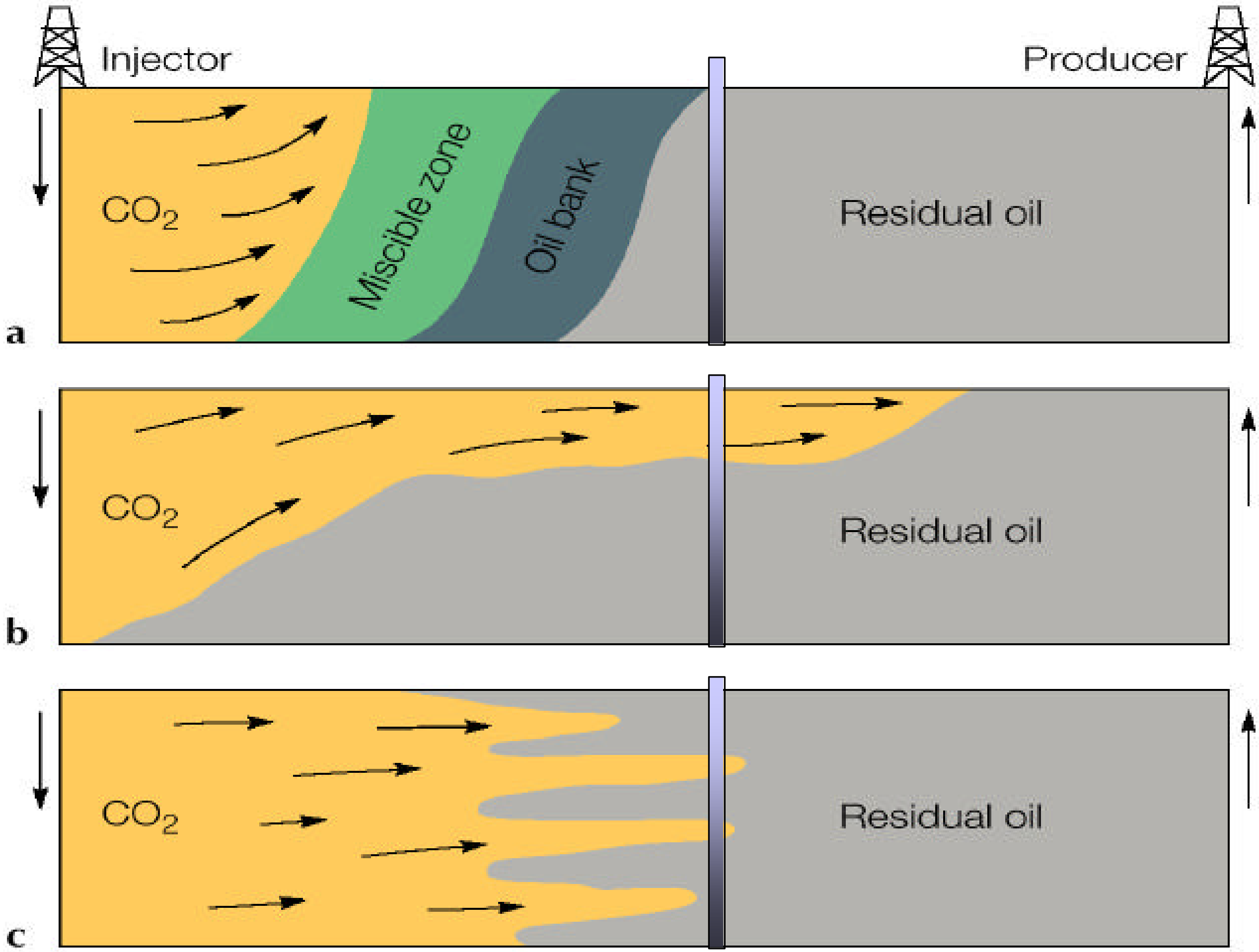
- Injection Well ?
- Observation Well
  - if one well, where do you place the well?
  - if two wells, where are they placed?
  - Monitoring program should be designed to accommodate this
  - recoverable

Where would you put a Monitoring Well?



Permeability Heterogeneity's

At what Depth would you place the Instrumentation?



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EOR, UGS and CO_2 Disposal

- EOR: Short term of 10 years
- UGS: Medium term of 100 years
- CO_2 Disposal: Long term of … years

- EOR: Injection/Production wells, Flooding
- UGS: Injection/Production well
  - stratigraphic trap for gas, porosity, permeability and adequate seal (caprock).
- CO_2 Disposal similar to UGS

EOR - CO_2 Flooding

(Short Term ” 10 years)

Strategies

- CO_2 injection only
- WAG injection = Water alternating gas (CO_2)
- Co-injection of water and CO_2
- SAG injection = Surfactant in water alternating gas (CO_2) = Foam injection
- Horizontal injector, vertical producers

EOR - CO_2 Flooding

(Short Term ” 10 years)

Problems	Frequency
• Asphaltene Ppt.	- uncommon
• Dissolving of carbonate minerals releases fines	- uncommon
• Wettability change	- uncommon
• Exceed fracture pressure	- uncommon
• Conformance	- very common

EOR - CO_2 Flooding

(Short Term ” 10 years)

Monitoring Techniques Used

- Water chemistry: pH-7 → 4, Ca^{++} ↑, Mg^{++} ↑, HCO_3^- ↑
- Well logs: saturations (CO_2, water, oil)
- Pressure: Fall off, permeabilities; Step injection, parting pressure; Multiwell surveys, areal conformance
- Tracers:both water and gas
- Phase distribution: in production fluid
- Observational wells: P,T, phase distribution *
- 4D seismic: gas front*

*from EOR – steam flooding

Under Ground Storage (UGS)

(Medium term – 100 years)

Types

- Caverns (e.g. salt)
- Depleted Gas Reservoirs
- Depleted Oil Reservoirs
- Aquifers (trapped)
- Natural CO_2 gas reservoirs

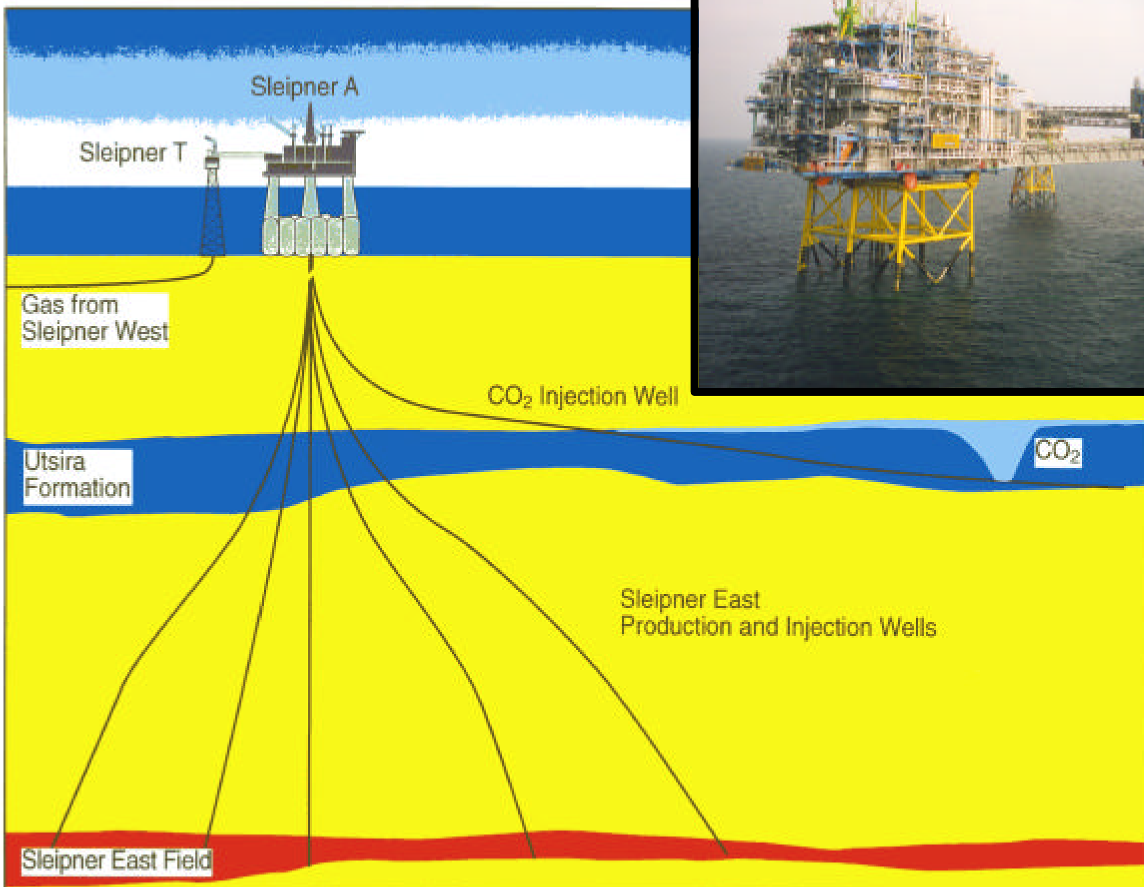
Under Ground Storage (UGS)

(Medium term ~ 100 years)

Monitoring Techniques Used

- Tracers: Identify storage gas
- Micro-seismic: Identify shear-induced deformation
- Logs: Identify water movement
- Logs: Identify casing problems, leaks and gas movement behind pipe and cement, cement bond logs, cavern volume
- Injection/Production Pressures: For inventory control, cavern integrity, fracture control, hydrate formation

Sleipner CO_2 Facility



Monitoring Sleipner

- Pressure Distribution
- Temperature Distribution
- CO_2 saturation data
- Storage Mechanisms ?
  - Stored as free CO_2
  - chemically bonded in the rock
  - solubility in water
  - residual CO_2
  - gravity instability containment

Monitoring Sleipner

- Offshore monitoring program is expensive, especially when the focus may be on the confirmation or validation of the sequestration mechanics
- May not provide the level of resolution required in order to confirm / invalidate hypotheses (physics)

Acid Gas Disposal in Alberta as Analogue to Sleipner

- **Monitoring project following the same monitoring protocol developed for Sleipner.**
- **A monitoring project on an existing small scale acid gas disposal site in Alberta will allow the full scale application of proposed technology applications for Sleipner.**
- **By following the same workplan protocol, the Alberta results will serve as a significant technology evaluator prior to the costly offshore application of the technology.**

Summary

- Significant historical practice in the area of EOR and specifically, UGS is directly amenable to the design and implementation of CO_2 disposal projects
- Monitoring programs must be carefully planned.
- Systematic integration of operational, monitoring and simulation results will provide the most sound assessment of CO_2 disposal processes in aquifers.