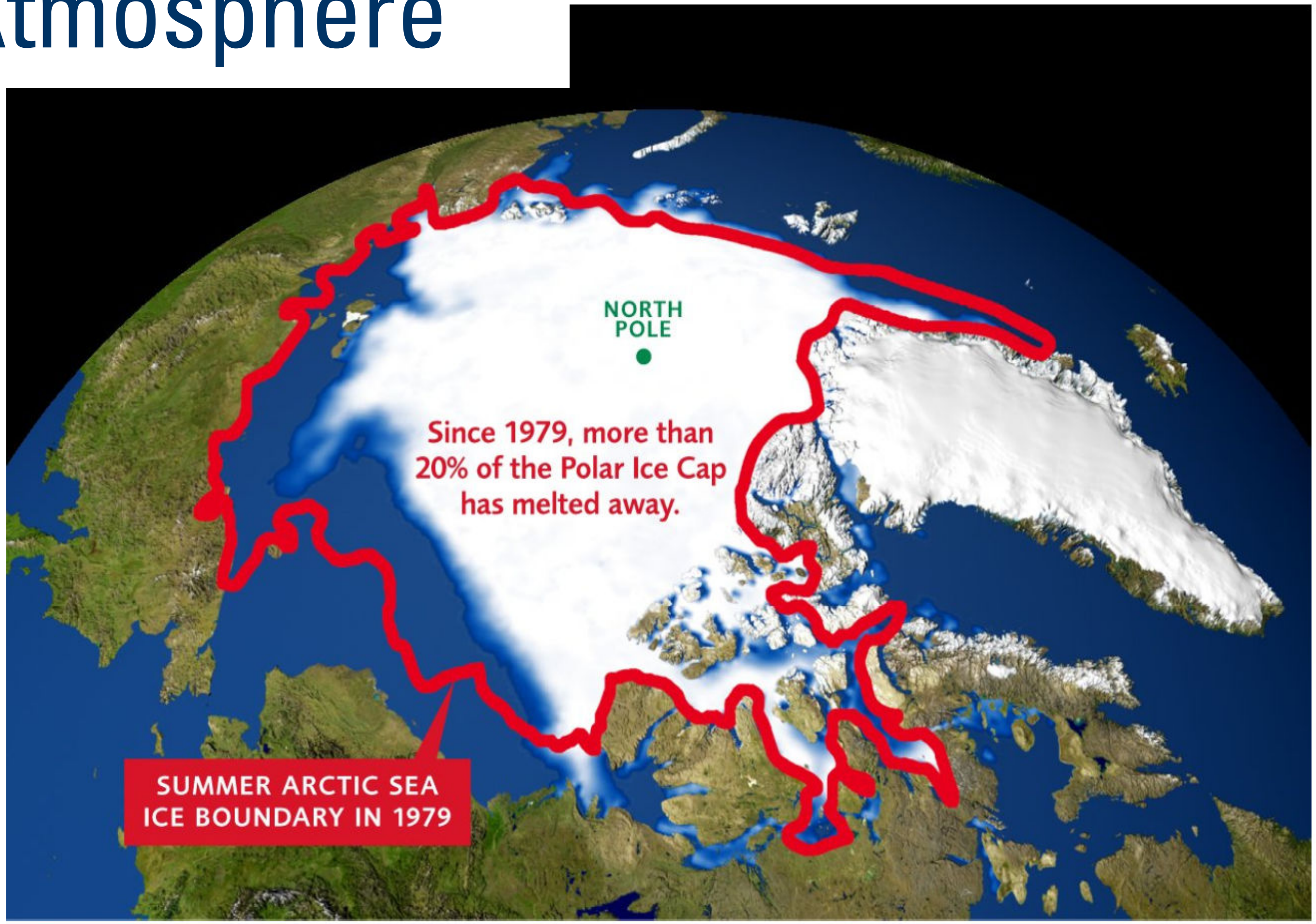
CO_2 Underground Storage to Clean the Atmosphere

Martin G. Lüling
Schlumberger

WIAS Colloquium
8 May 2006



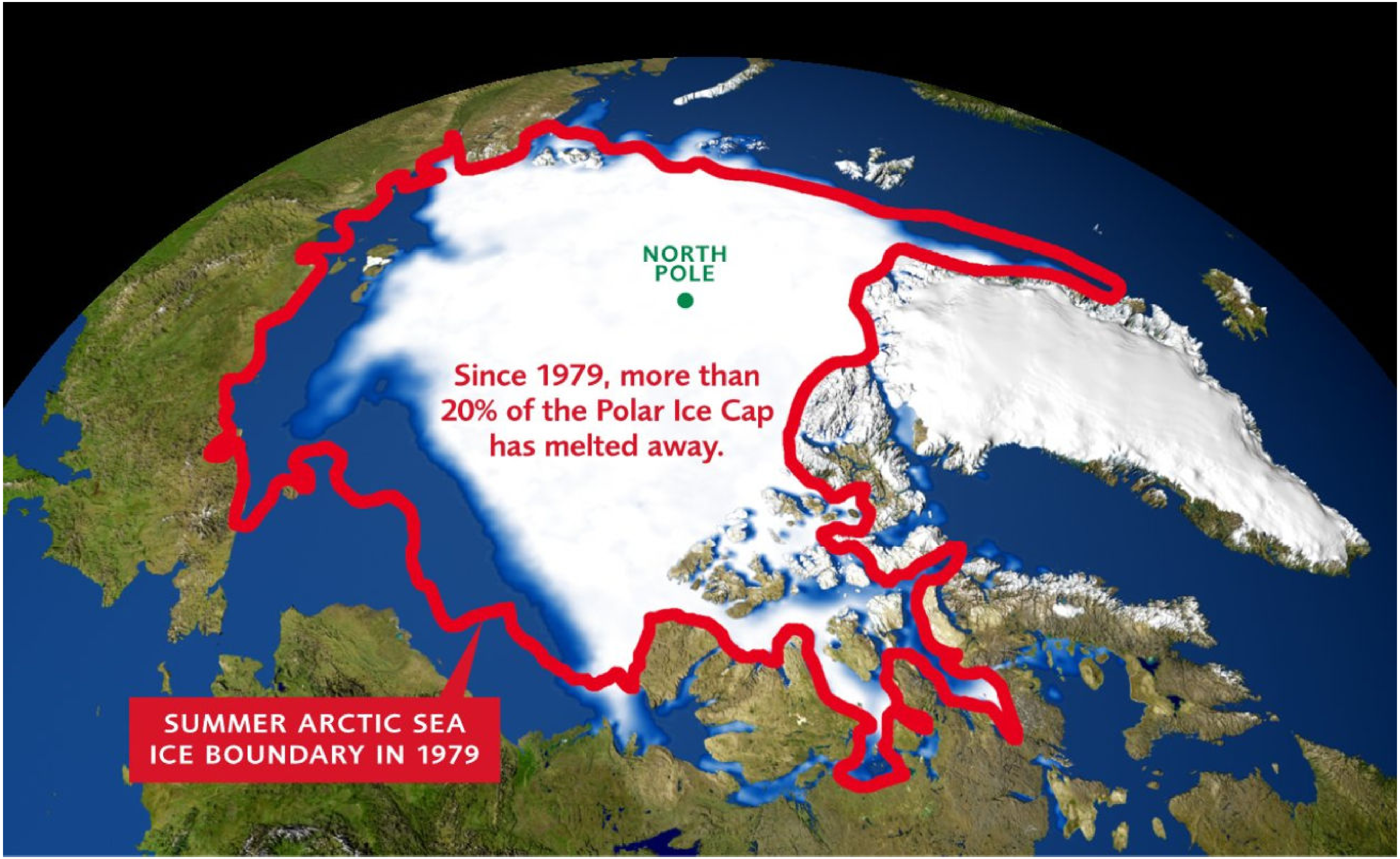
Schlumberger

Contributors

- Véronique Barlet-Gouédard, Olivier Porcherie, Gaëtan Rimmelé, (Schlumberger)
- Andreas Bielinski (Hydrogeologie, Universität Stuttgart)
- Bruno Goffé and collaborators (École Normale Supérieure)
- Laurent Jammes, Laure Resplandy (Schlumberger)
- Hartmut Schütt (Geo-Forschungs-Zentrum, Potsdam)
- Robert Socolow and collaborators (Princeton University)
- Materials from StatOil and BP-Sonatrach

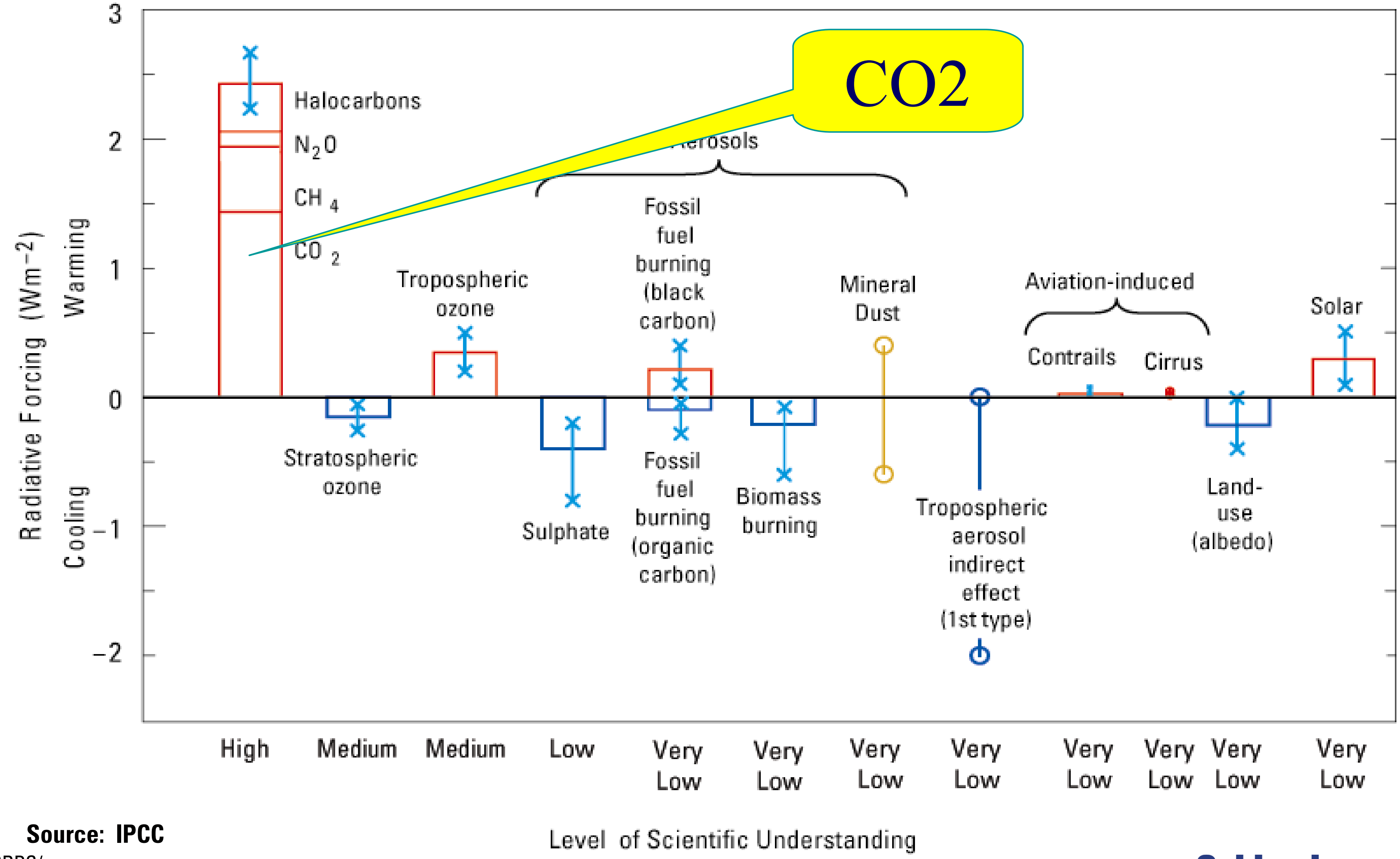
Outline

- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples



Schlumberger

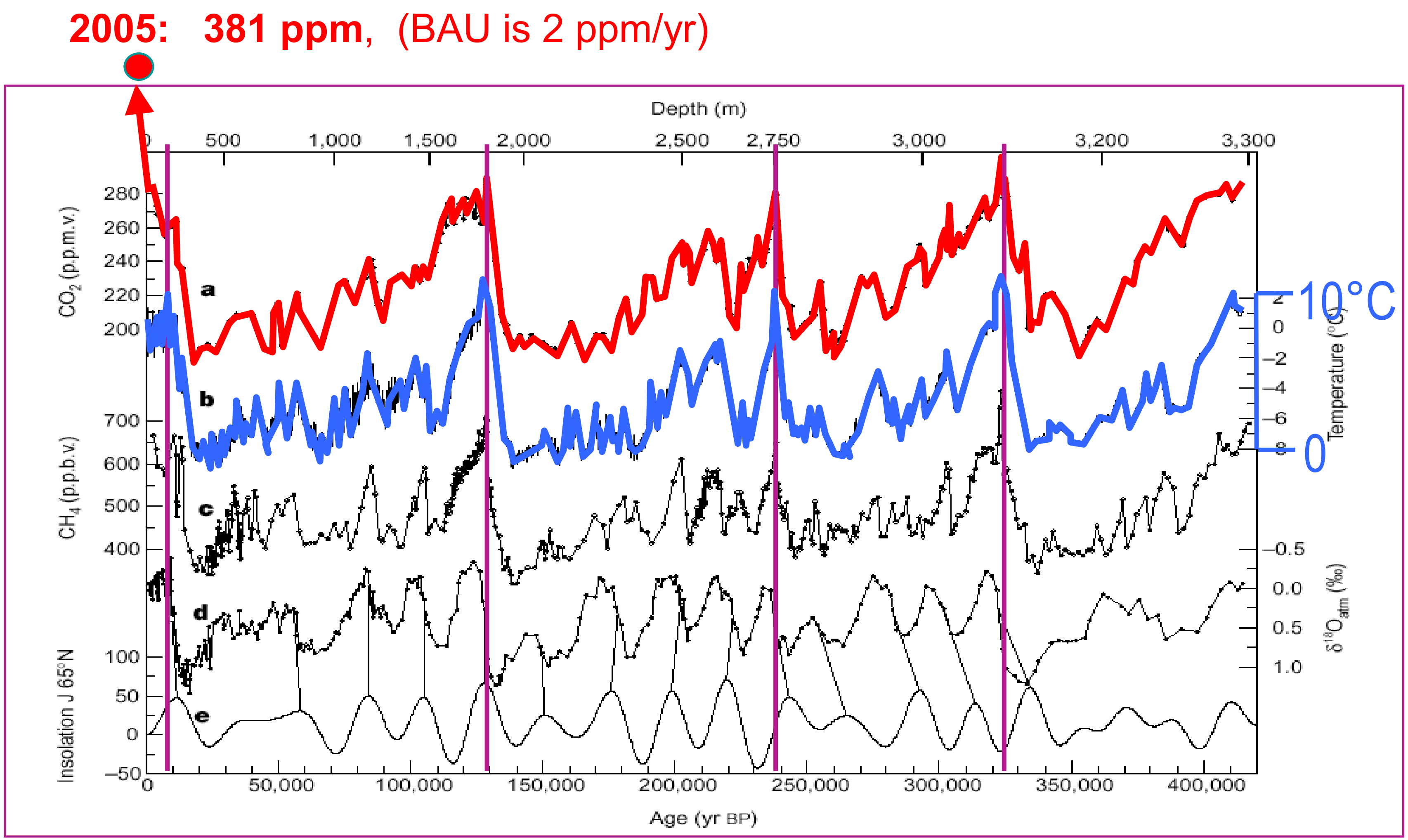
Radiative Forcing



Source: IPCC

Schlumberger

Climate Change – Link to CO_2

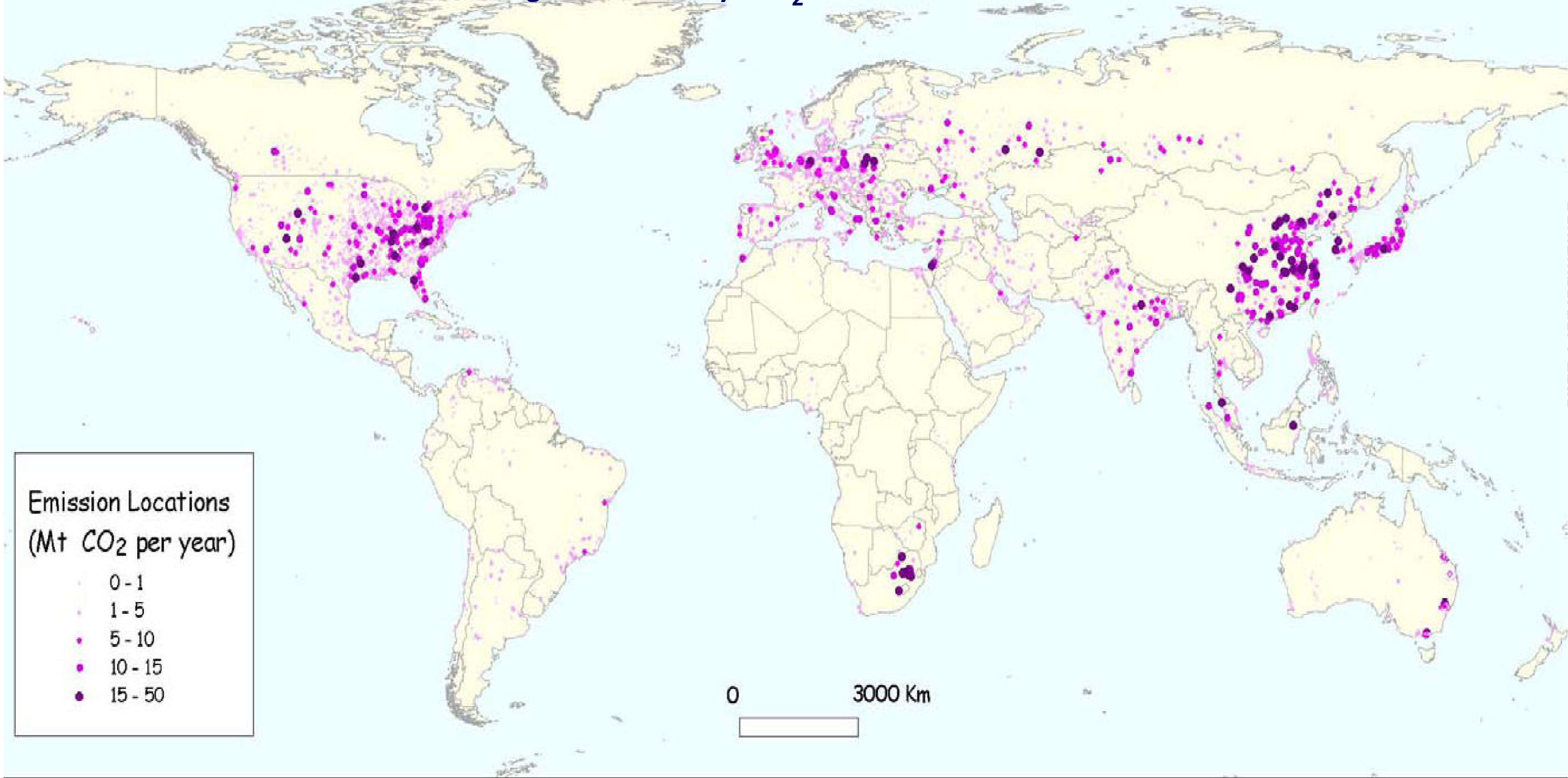


Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica.

Petit, Jouzel et al… Nature, June 1999

Major CO_2 Emission Locations

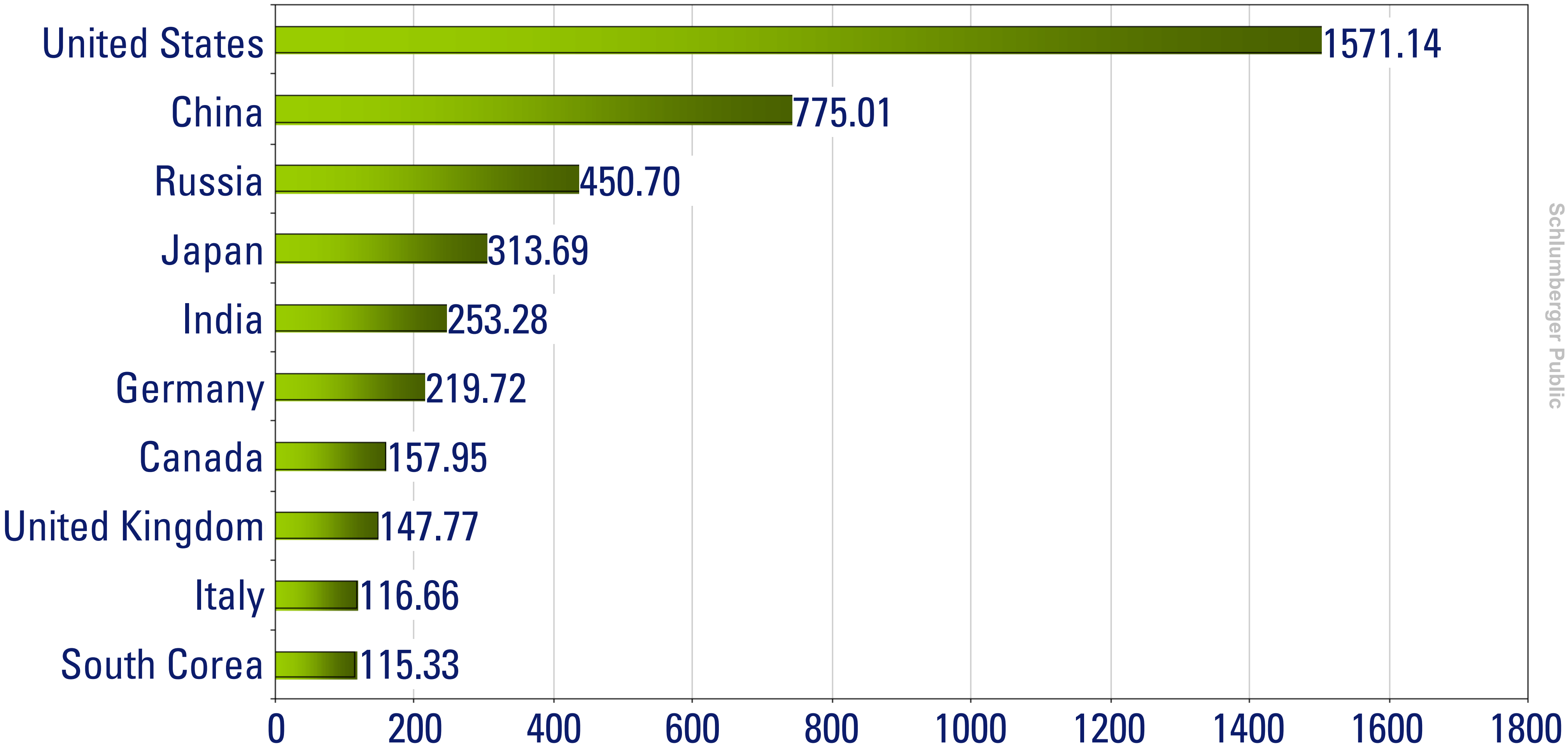
Global distribution of large stationary CO_2 sources, (Source: IEA GHG, 2000a)



Schlumberger

Largest CO_2 Emissions by Country

Year 2000 CO_2 Emissions – Top 10 Countries

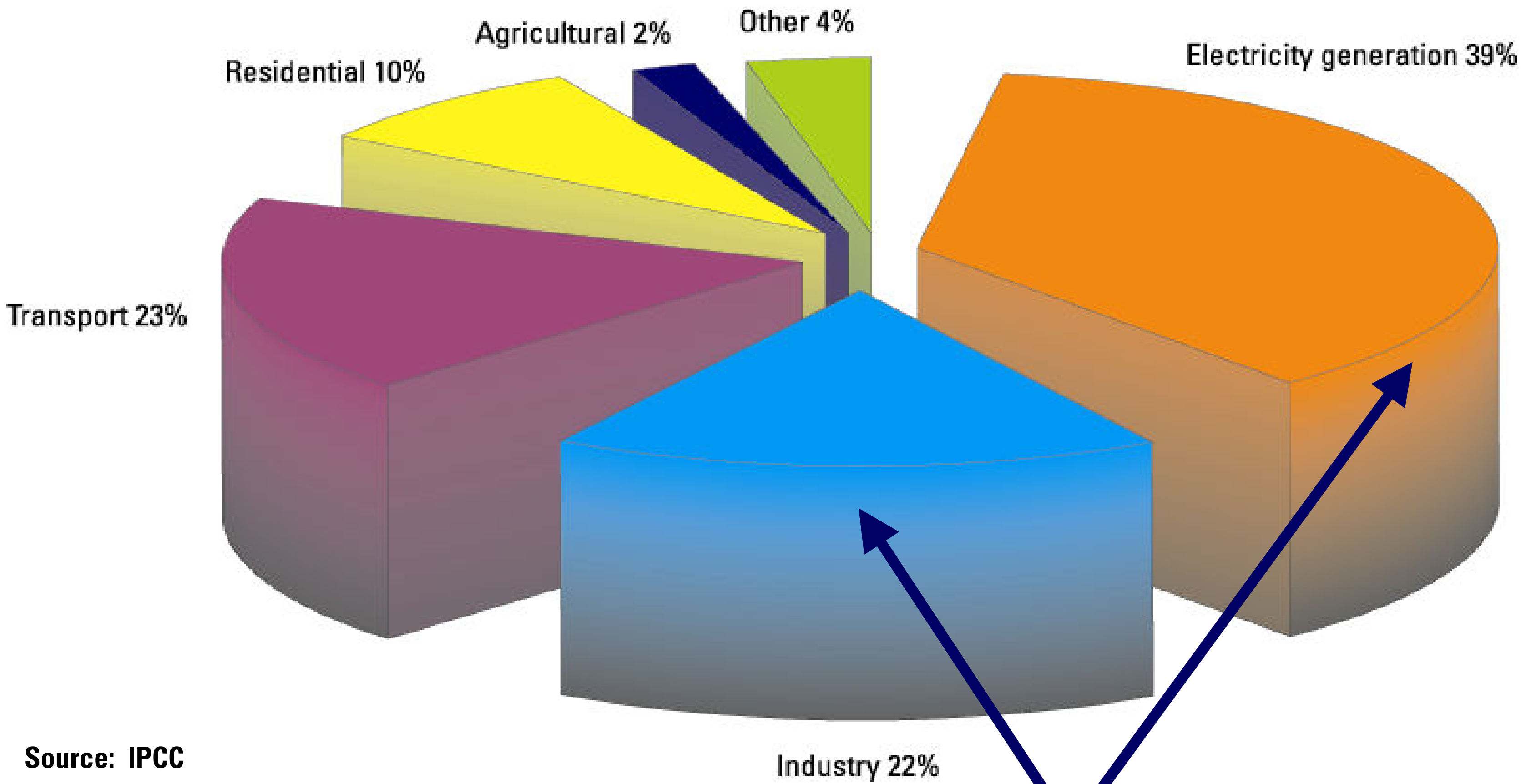


US Department of Energy

7/5/2006

Schlumberger

CO_2 Emission Sources by Category



Source: IPCC

CCS focus is on stationary, large single sources

Large Stationary CO_2 Sources

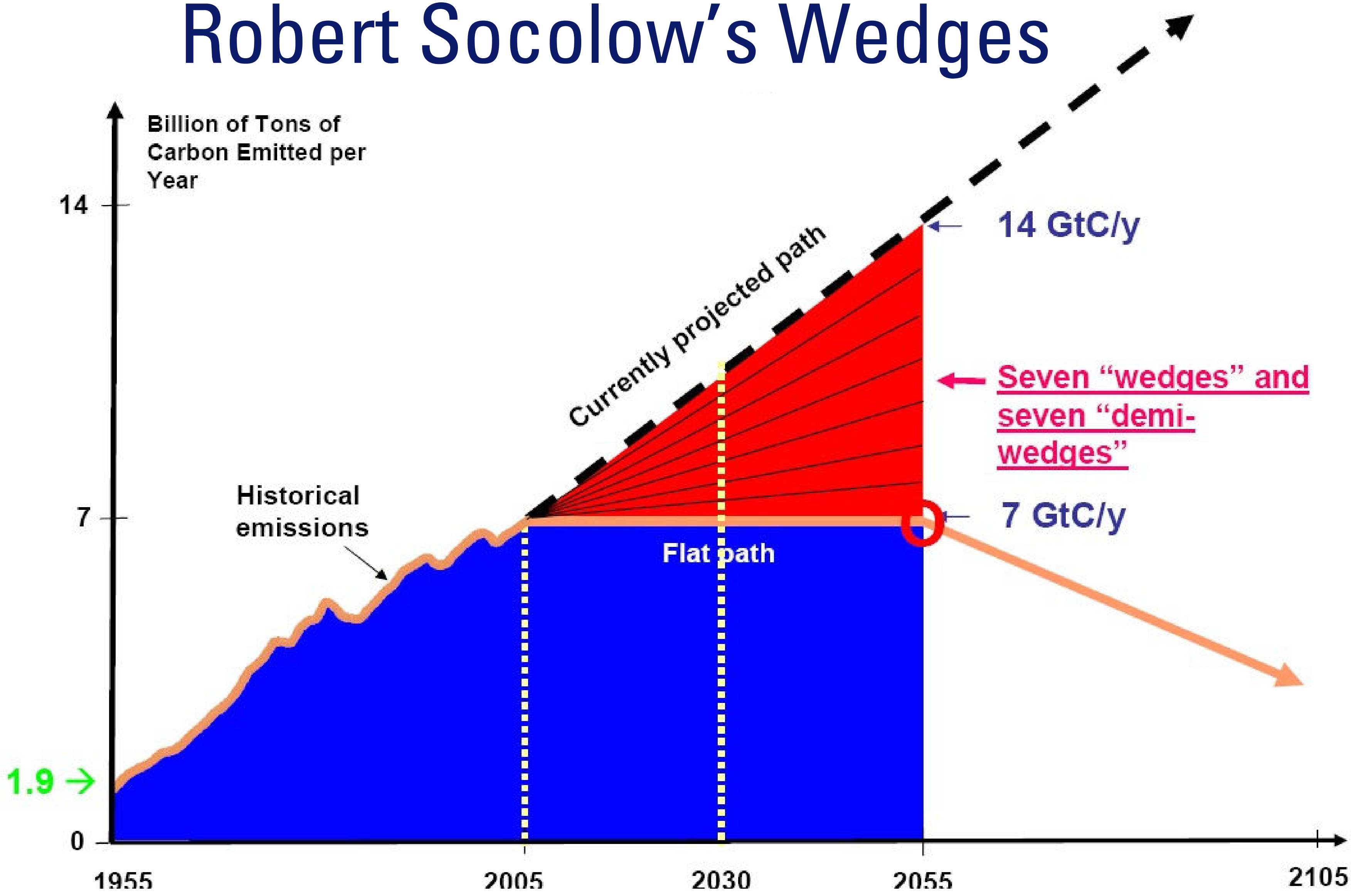
Process	Number of Sources	CO_2 Emission Mt/y
Power Generation	4942	10539
Cement Production	1175	932
Refineries	638	798
Iron and Steel Industry	269	646
Petrochemical Industry	470	379
Oil and Gas Processing	not available	50
Other Sources	90	33
Bioethanol-Bioenergy	303	91

Outline

- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples

Schlumberger

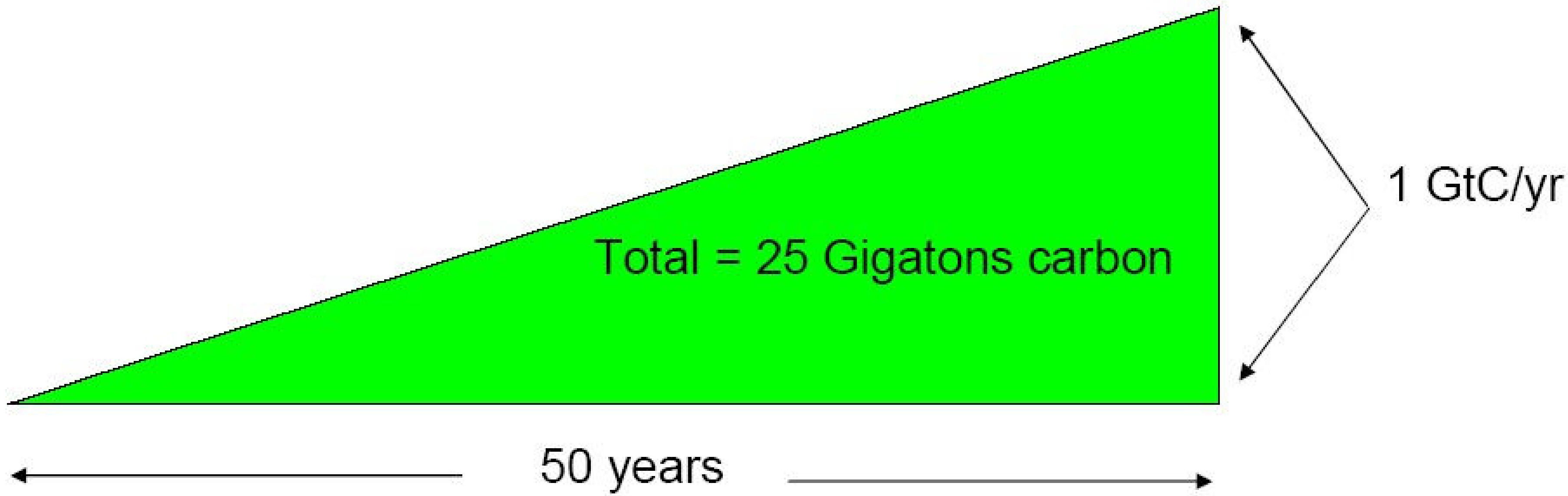
Robert Socolow's Wedges



Schlumberger

Wedge Definition

A “Wedge” is a Strategy to Reduce Carbon Emissions that grows in fifty years from zero to 1 Gt/y of CO_2.



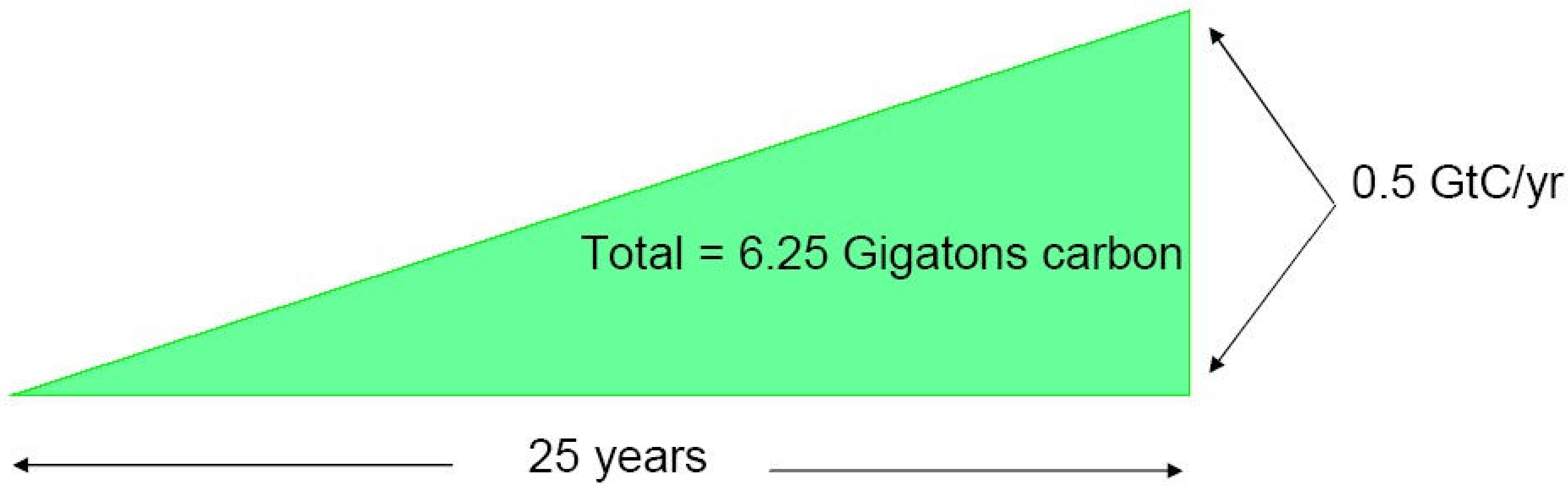
Cumulatively, a wedge redirects the flow of 25 Gt(CO_2) in its first 50 years. That is 2.5 trillion $ at 100 $/t of CO_2.

A “solution” to the greenhouse problem should have the potential to provide at least one wedge.

Schlumberger

Demi-Wedge Definition

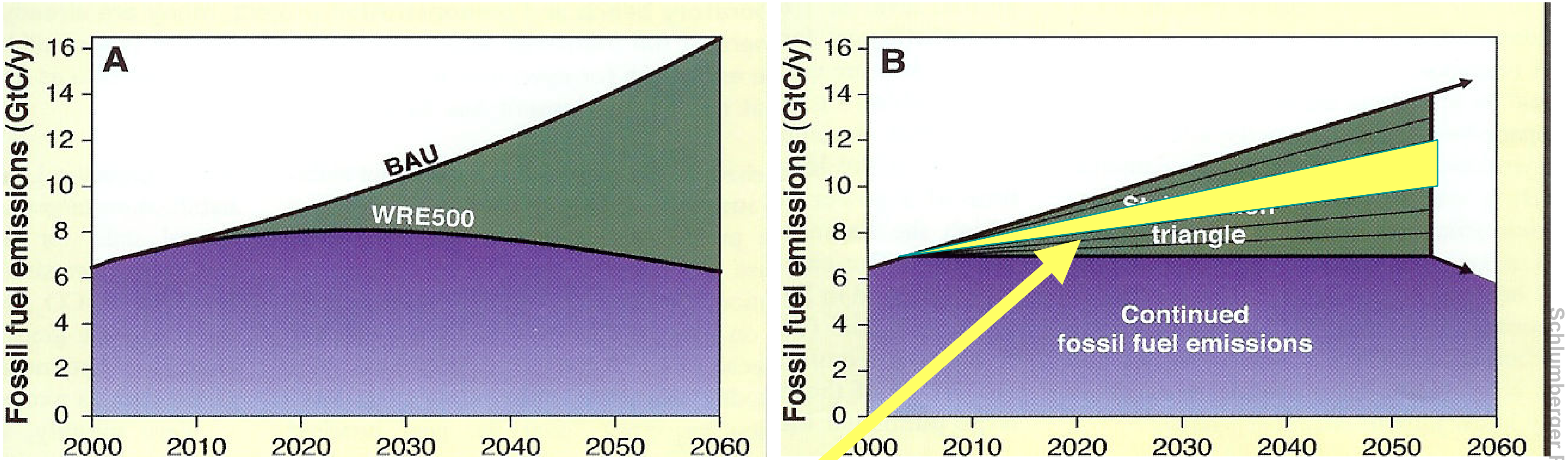
A “Demi-Wedge” is a Strategy to Reduce Carbon Emissions that grows in twentyfive years from zero to 0.5 Gt/y of CO_2.



Cumulatively, a demi-wedge redirects the flow of 6.25 Gt(CO_2) in its first 25 years. That is 625 billion $ at 100 $/t of CO_2.

A “solution” to the greenhouse problem should have the potential to provide at least one wedge.

The Stabilization Wedges



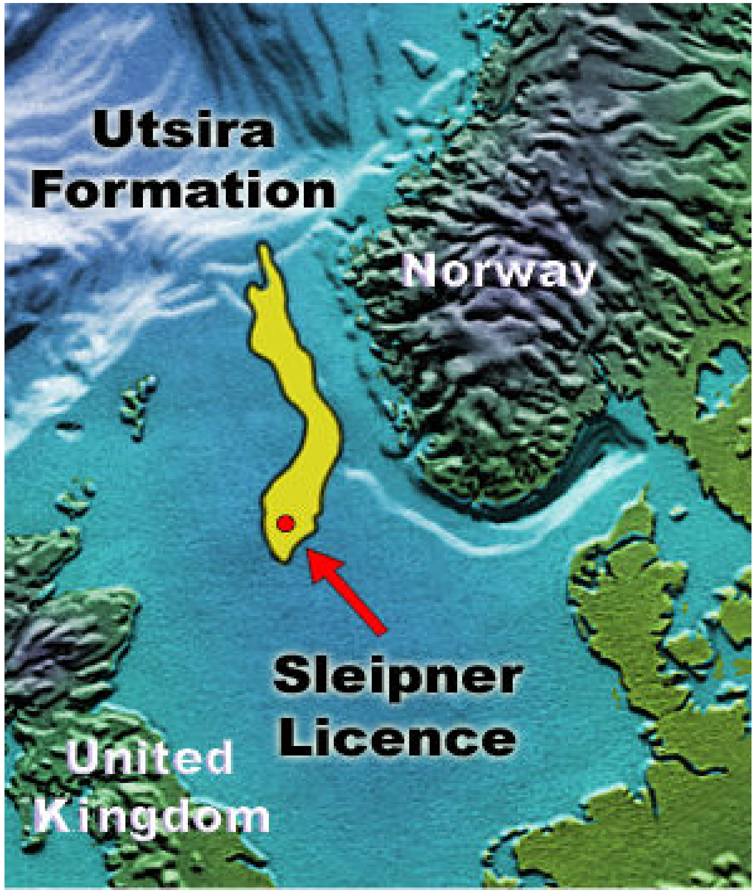
By 2050 the world needs to geologically store a minimum of 7 Gt of CO_2/year

→7000 Sleipners

Schlumberger

Sleipner

- Sleipner natural gas contains ~9% CO_2
  - Contract: 2.5% CO_2
  - CO_2 stored; about 1MT annually
- CO_2 injected into thick Utsira sandstone layer
  - 800-1100 m depth below sea level
  - Porosity 35-40 %
  - Permeability 2-5 Darcy
  - Homogeneous sand + shale stringers
- CO_2 injection 1996-2020
- Time-lapse seismic: 1994, 1999, 2001, 2002 (and 2005)
- Time-lapse gravimetry: 2002 (and 2005)

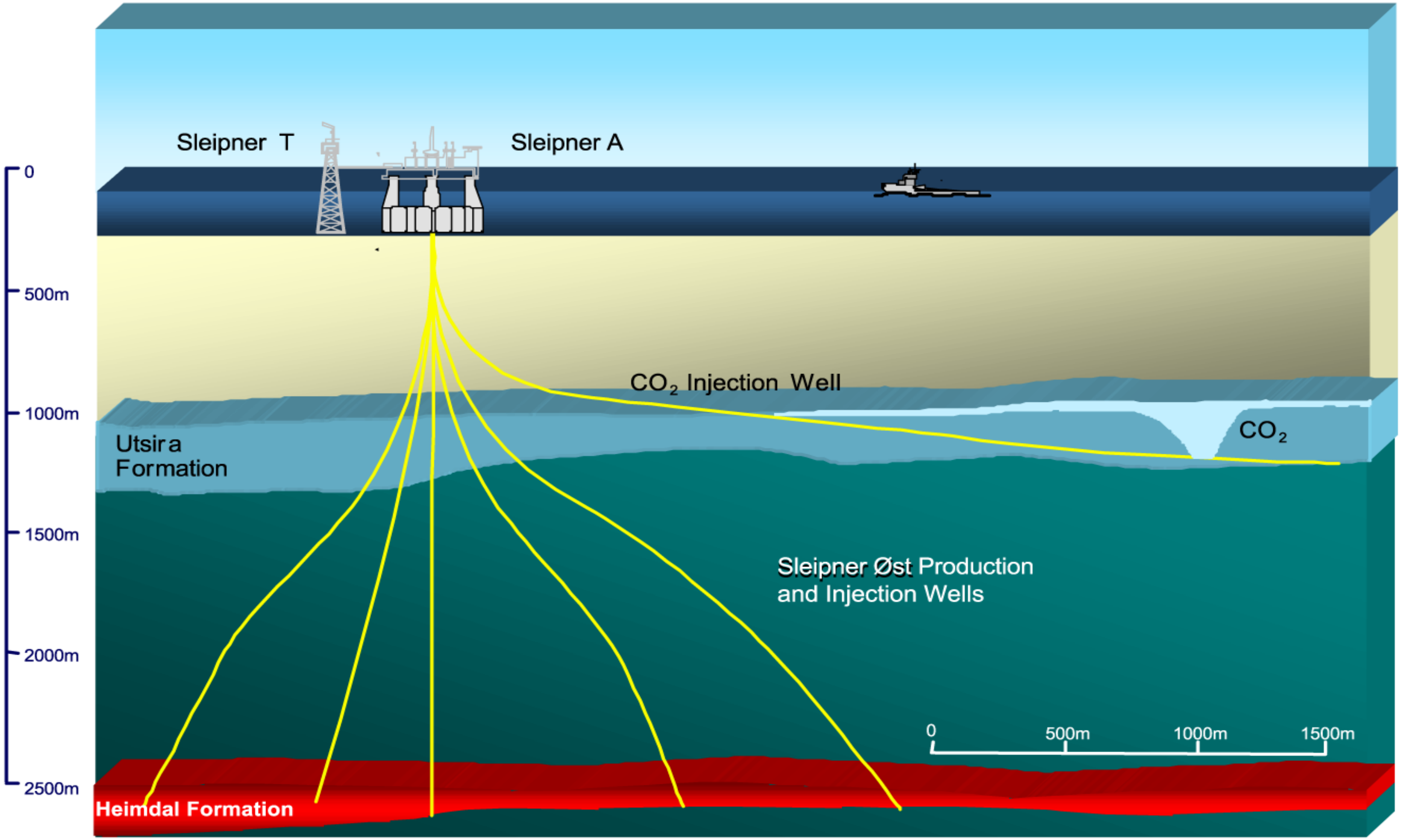


Schlumberger

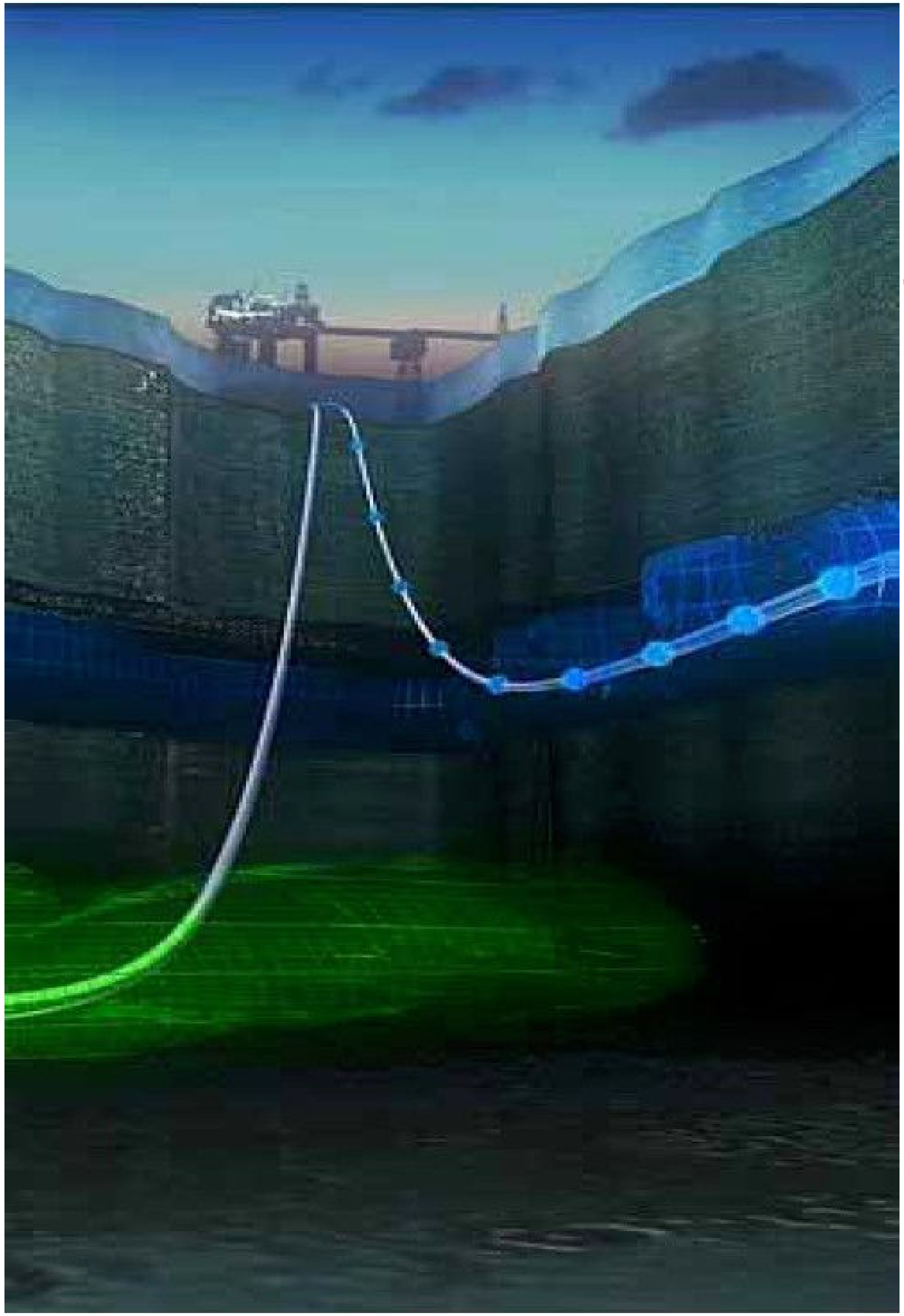
Illustrations courtesy of Statoil

The Sleipner Site

Sleipner CO_2 Injection



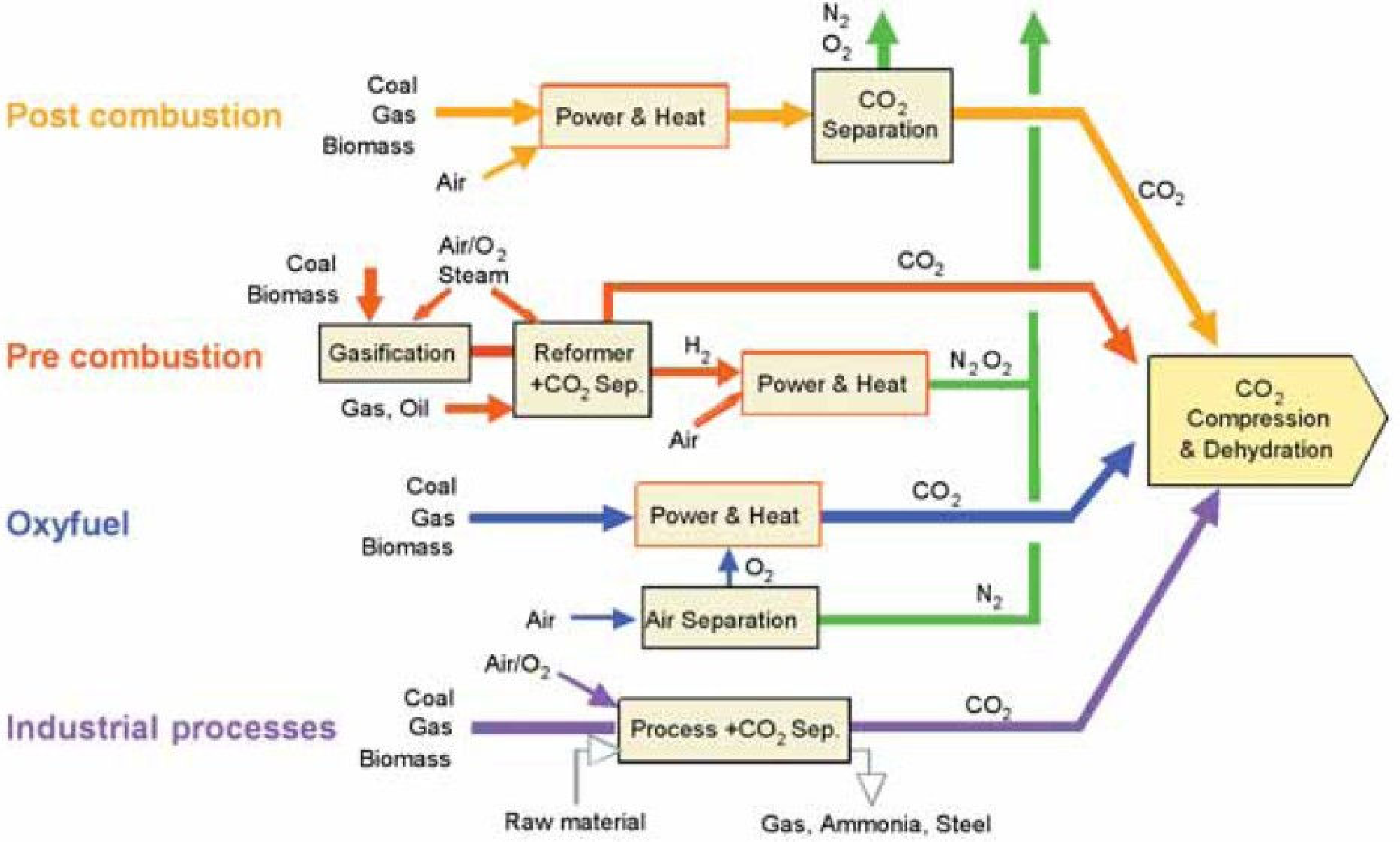
Schlumberger



Sleipner Injector Well Conceptual Sketch

Schlumberger

CO_2 Capture Processes



Schlumberger

Post-Combustion Capture Plant, Malaysia

Schlumberger

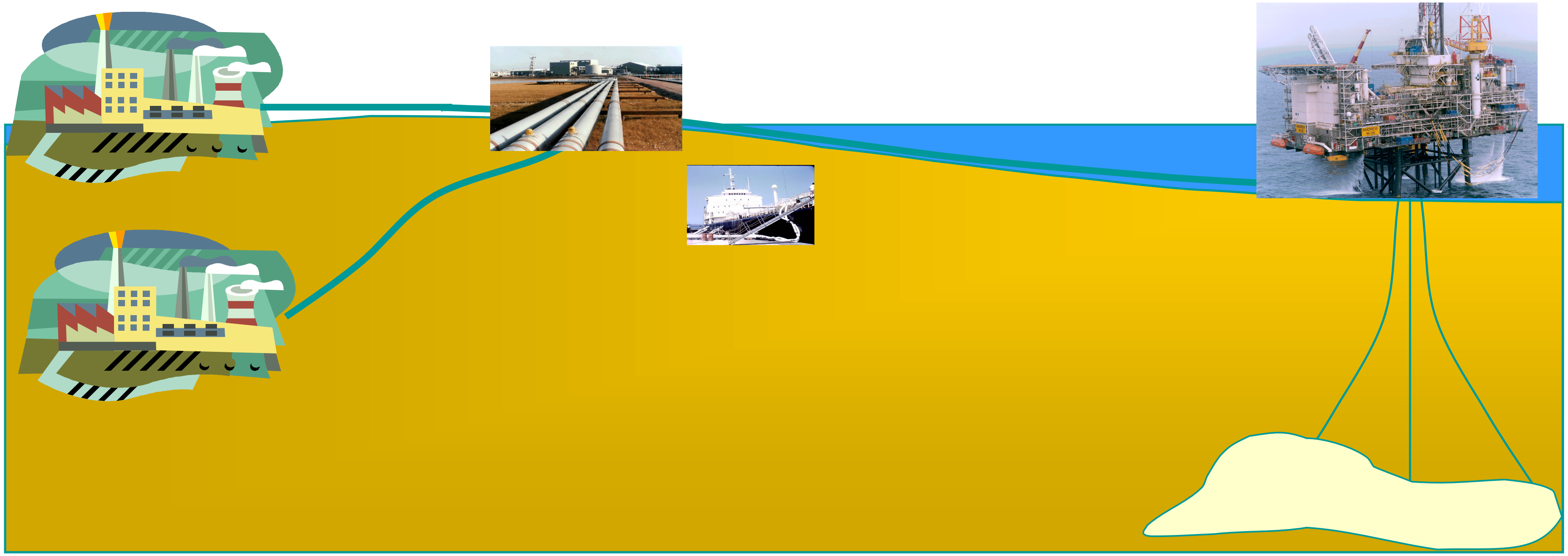
Pre-Combustion Capture Plant, North Dakota

CO_2 Capture and Storage - Cost Chain

Power & Industrial processes with CO_2 capture and conditioning

CO_2 export terminal and pipeline transportation or shipment

Injection for Geological storage in producing or depleted oil and gas fields & aquifers



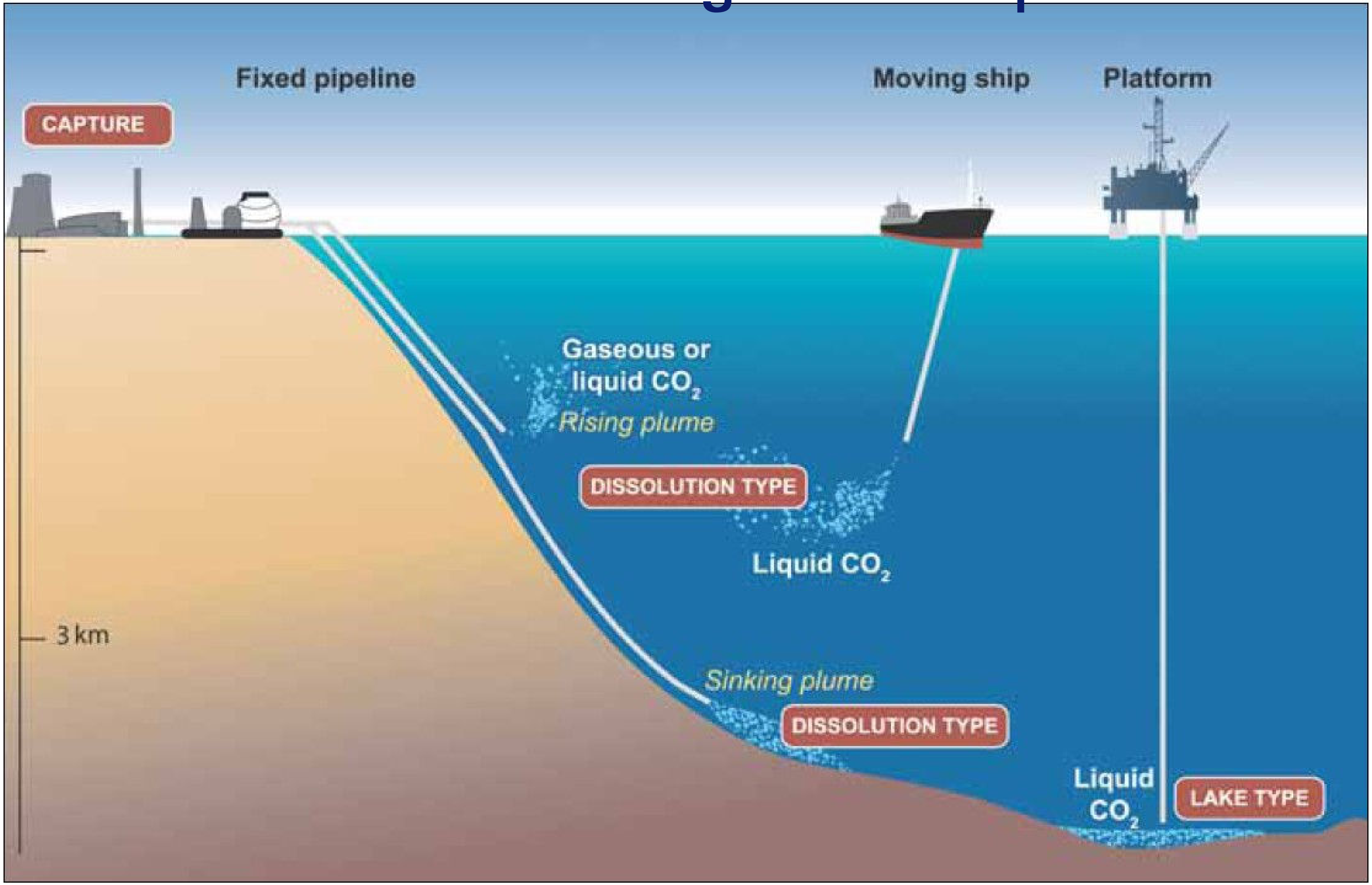
Cost: $30 – $50 /t | $1 - $5 /t* | $2 - $10/t* | = $33 – $65/t

Monitoring costs: $0.1-1/t

* Cost principally distance dependant

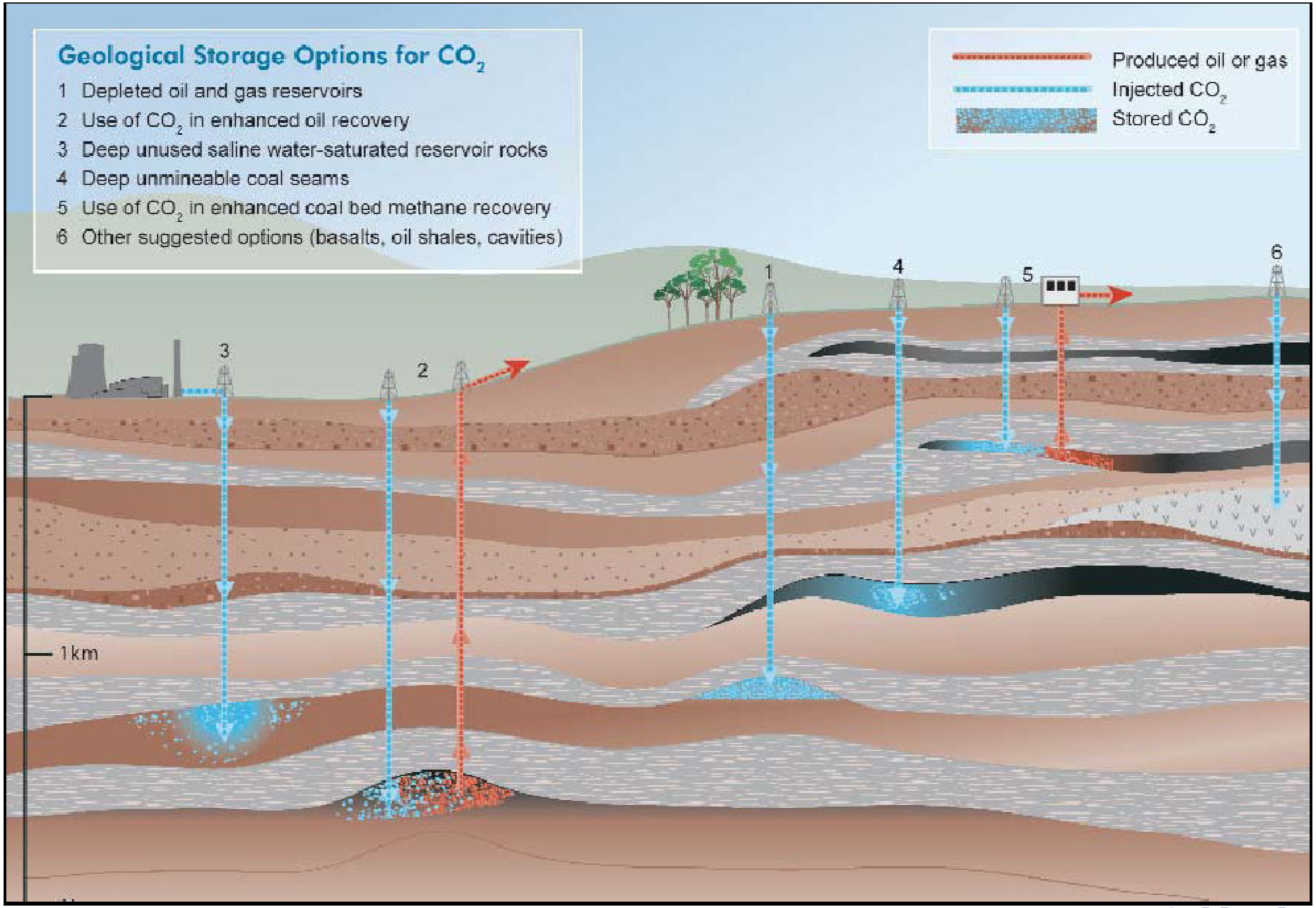
Schlumberger

Ocean-Storage Concepts



Schlumberger

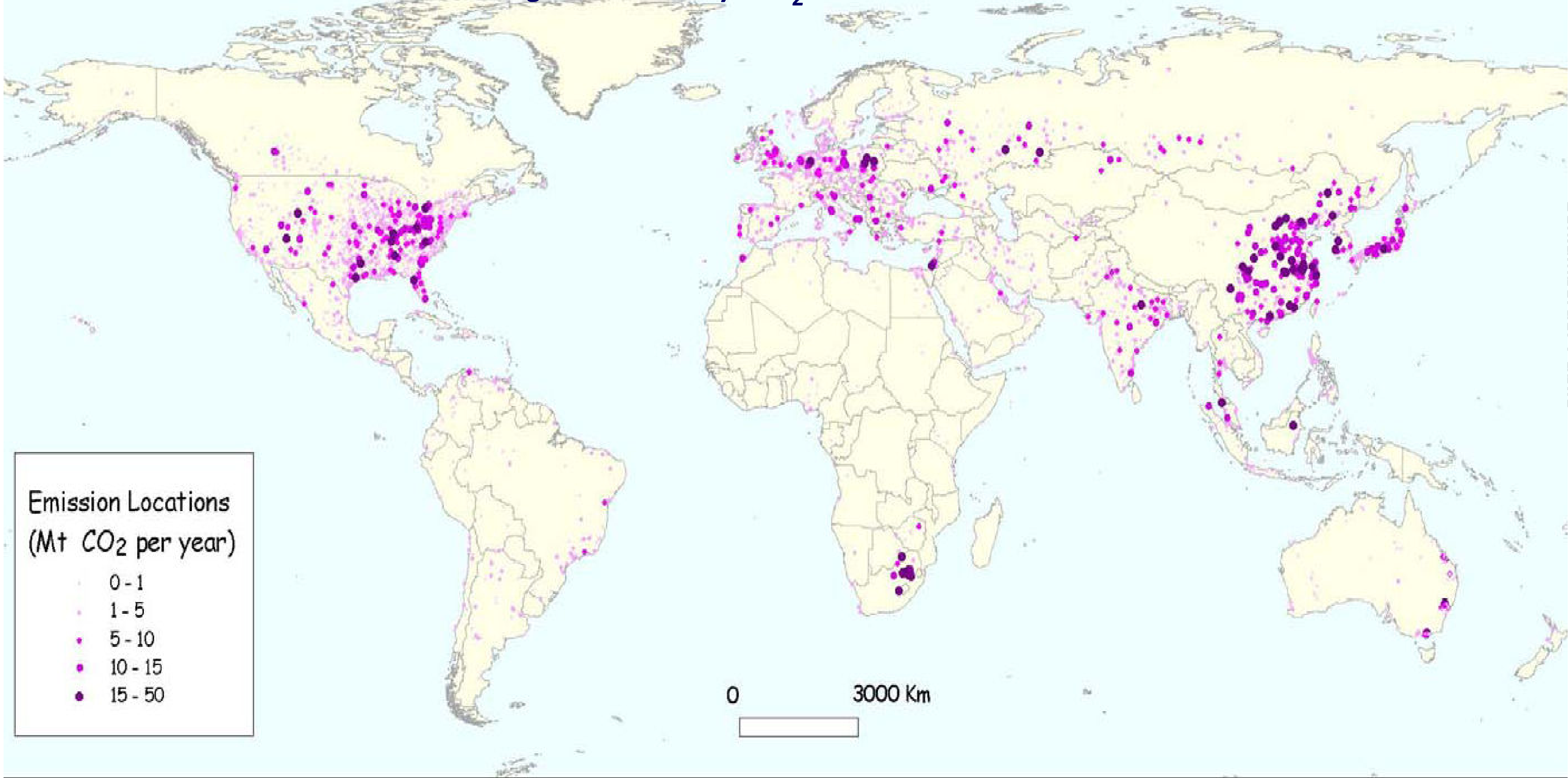
Geologic Storage Options for CO_2



Schlumberger

Major CO_2 Emission Locations

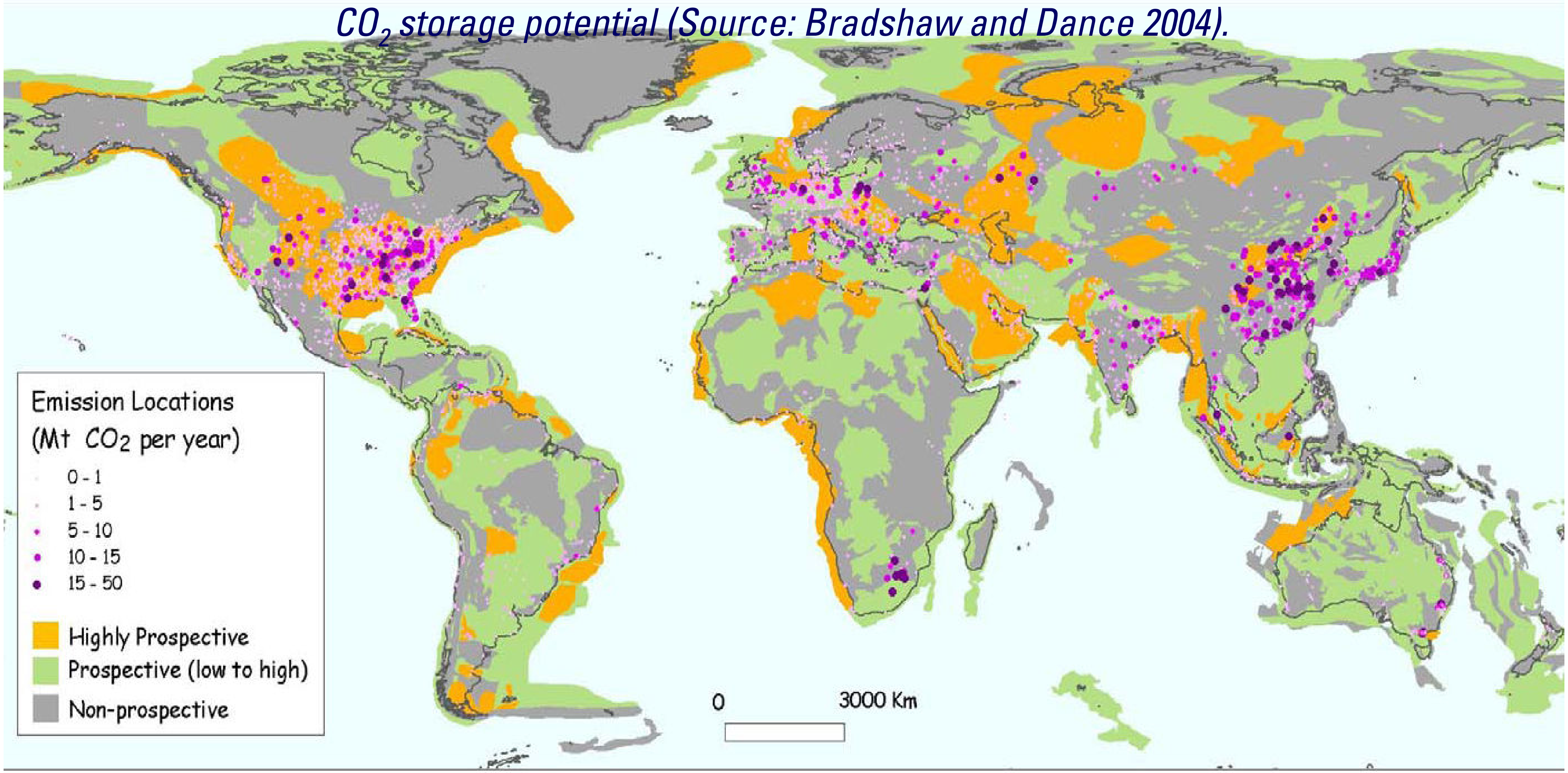
Global distribution of large stationary CO_2 sources, (Source: IEA GHG, 2000a)



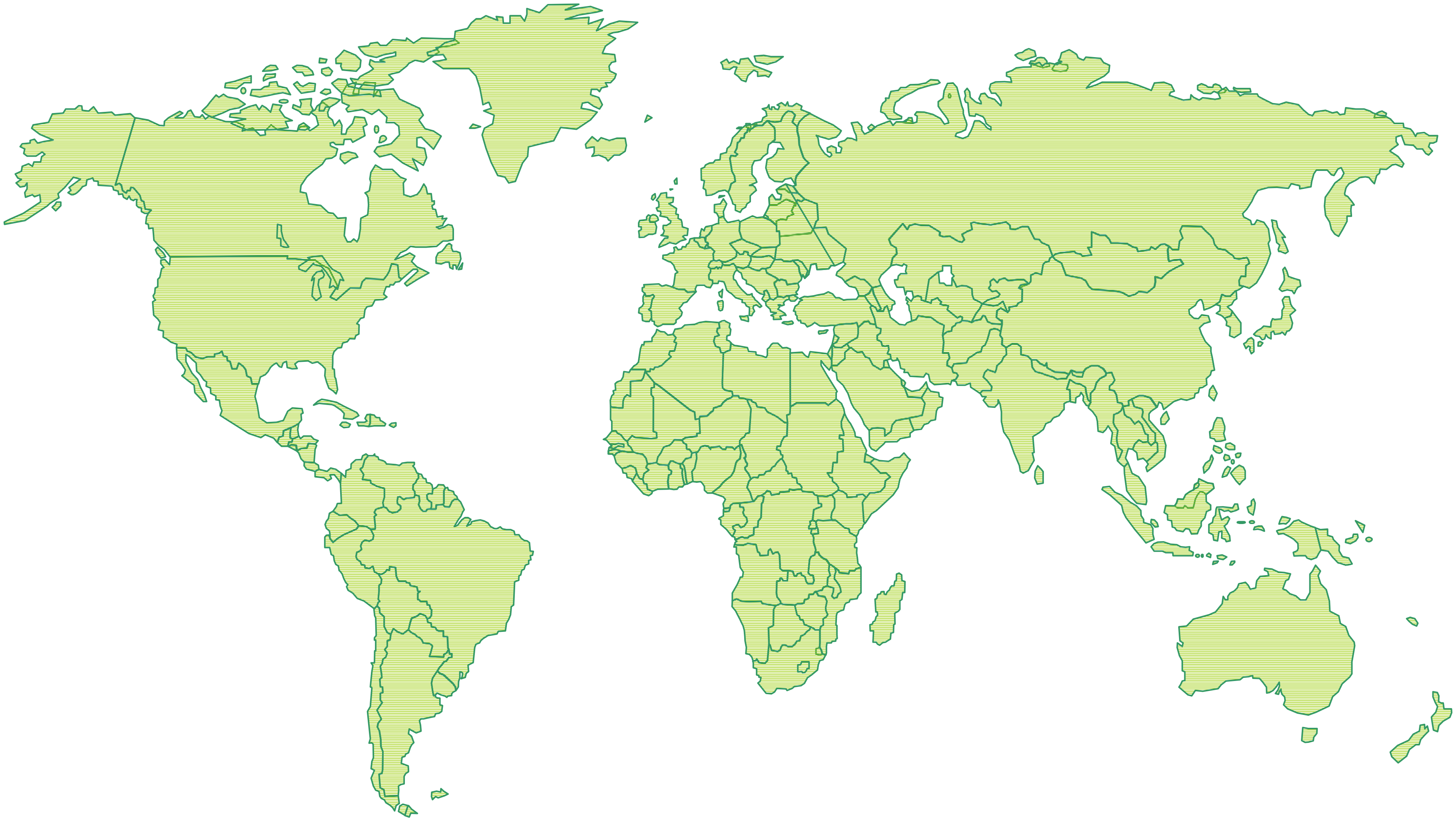
Schlumberger

CO_2 Source – Sink Matching

Geographical relationship between CO_2 emission sources and sedimentary basins with geological CO_2 storage potential (Source: Bradshaw and Dance 2004).

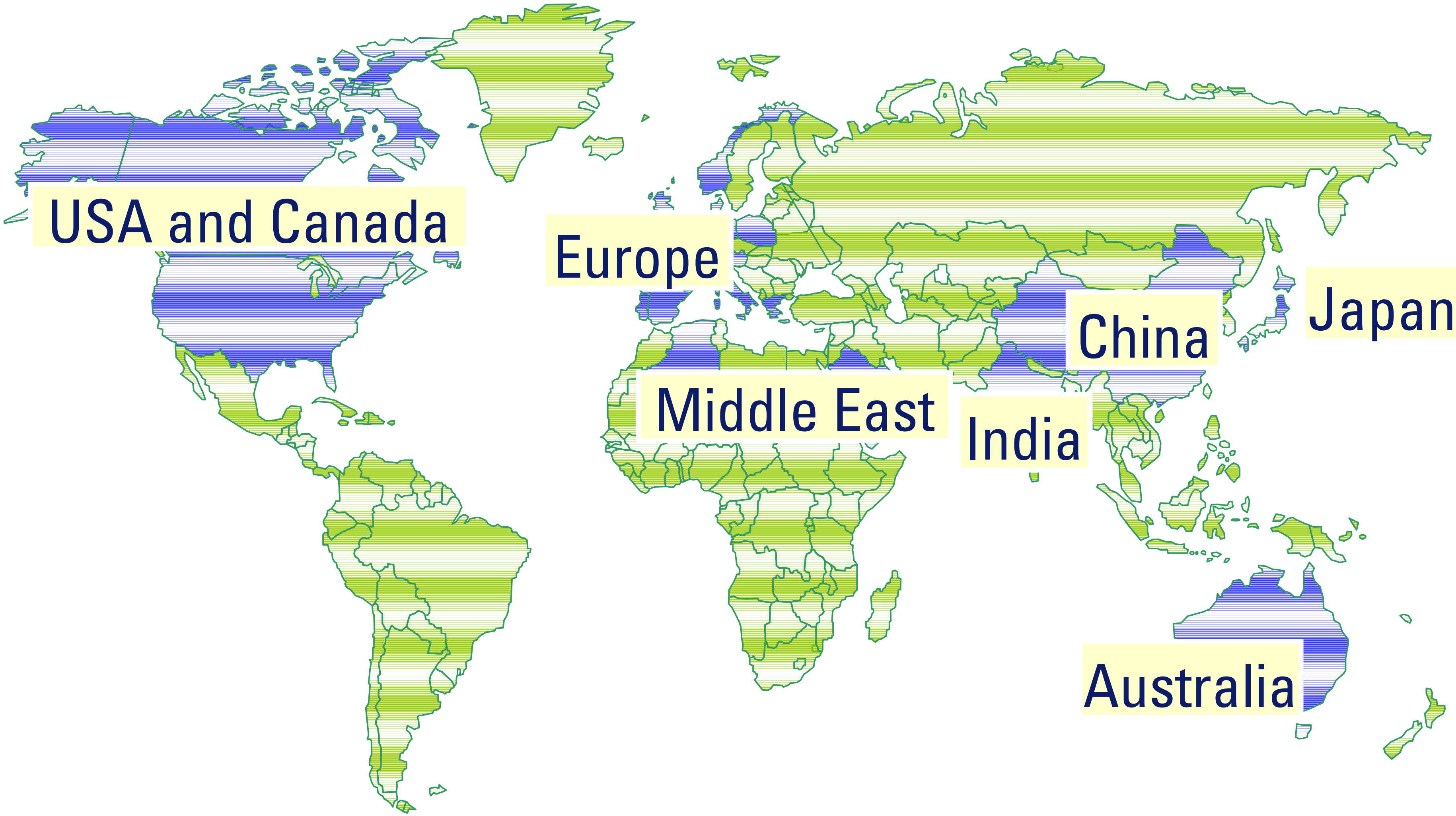


CO_2 Capture and Storage Activities



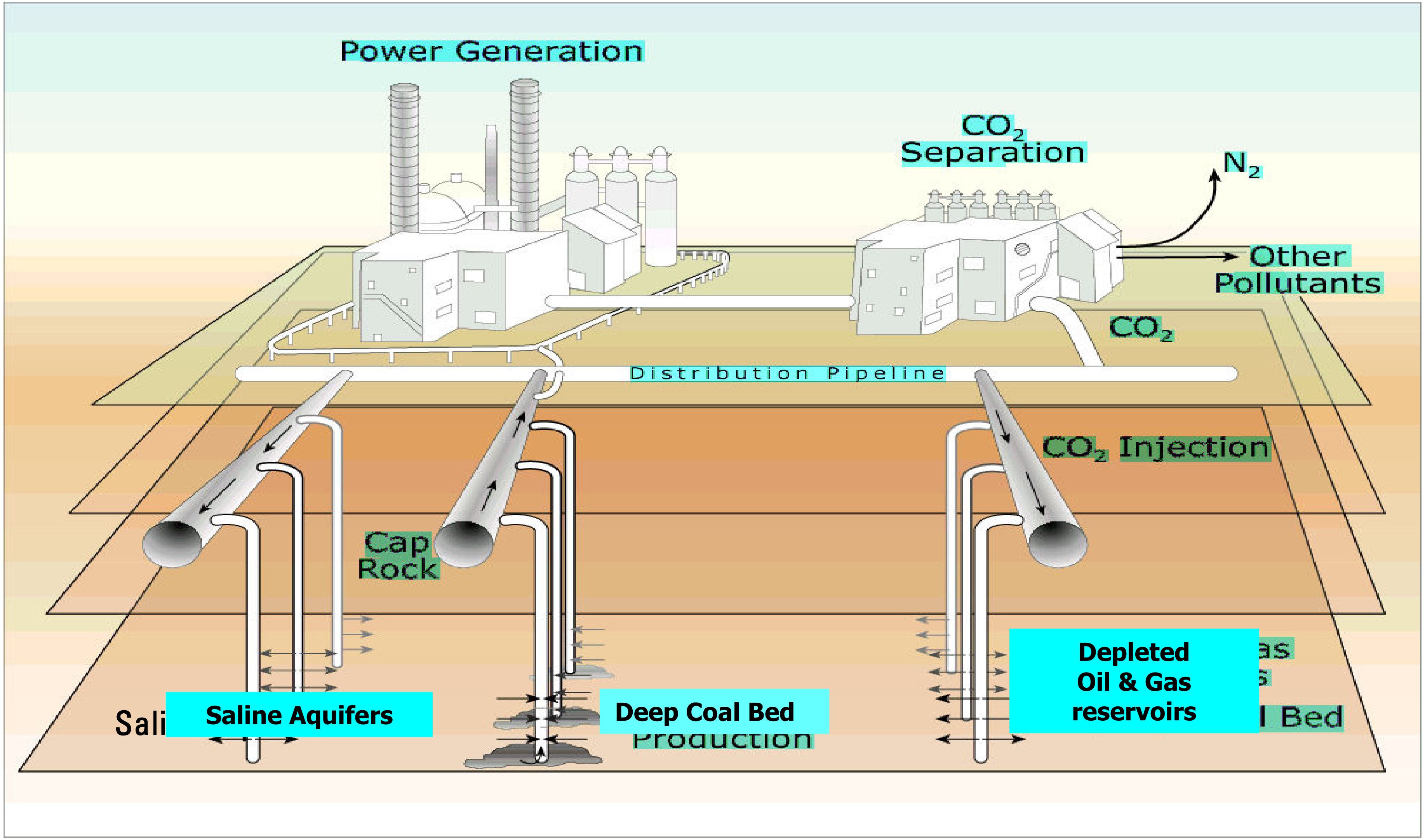
Schlumberger

CO_2 Capture and Storage Activities

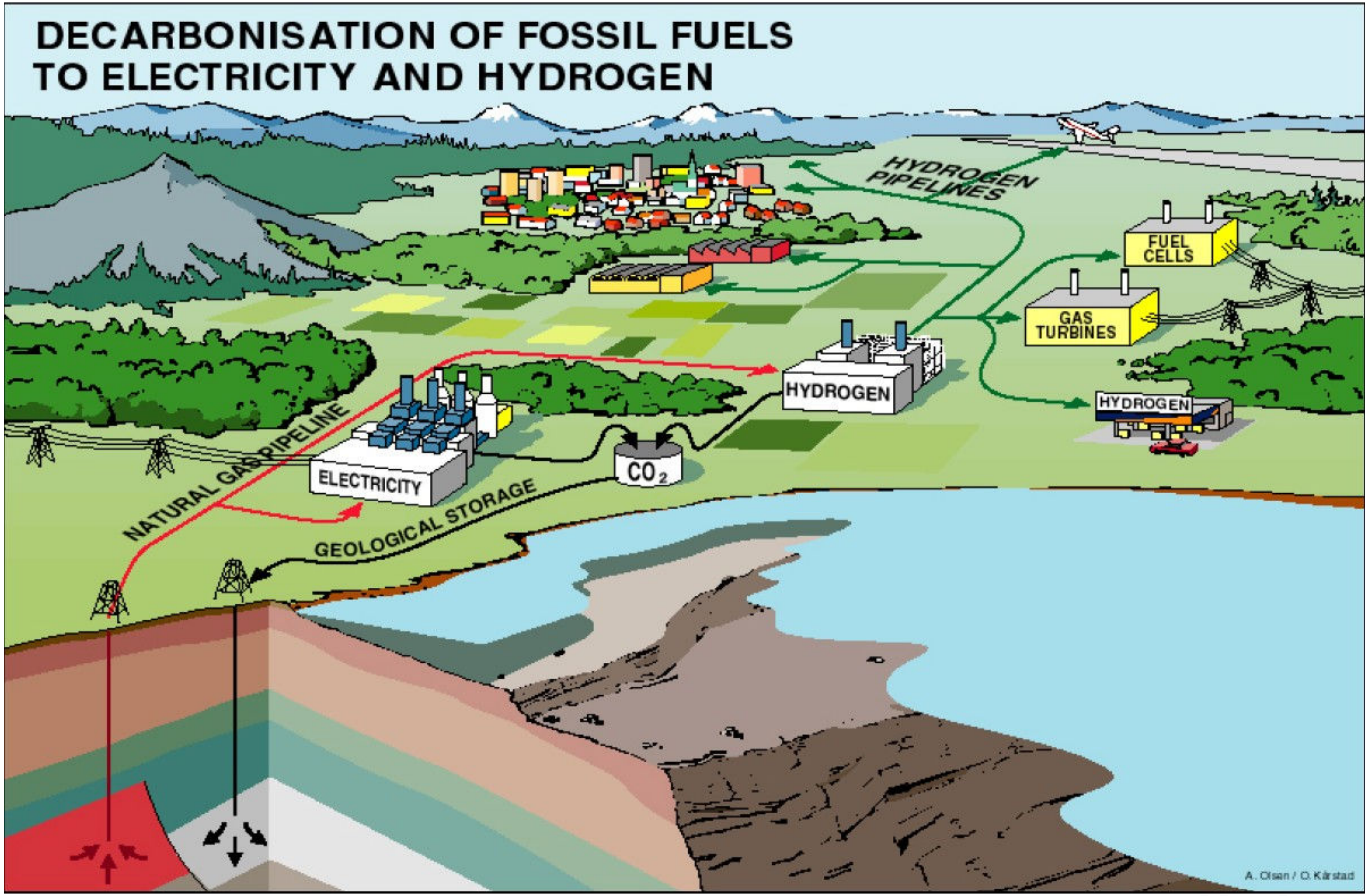


Schlumberger

CO_2 Capture / Transportation / Storage

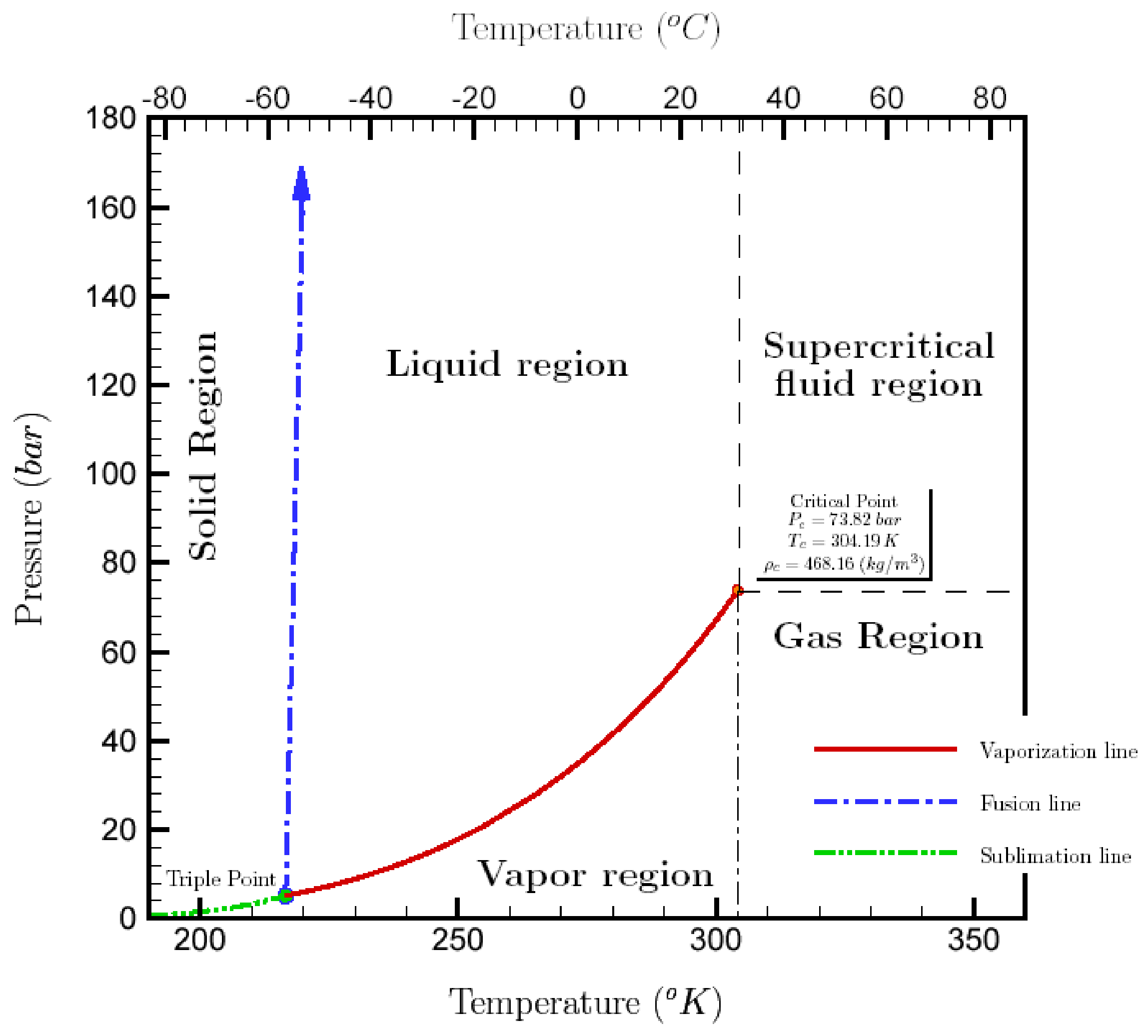


StatOil's Integrated Energy-Producer Model



Schlumberger

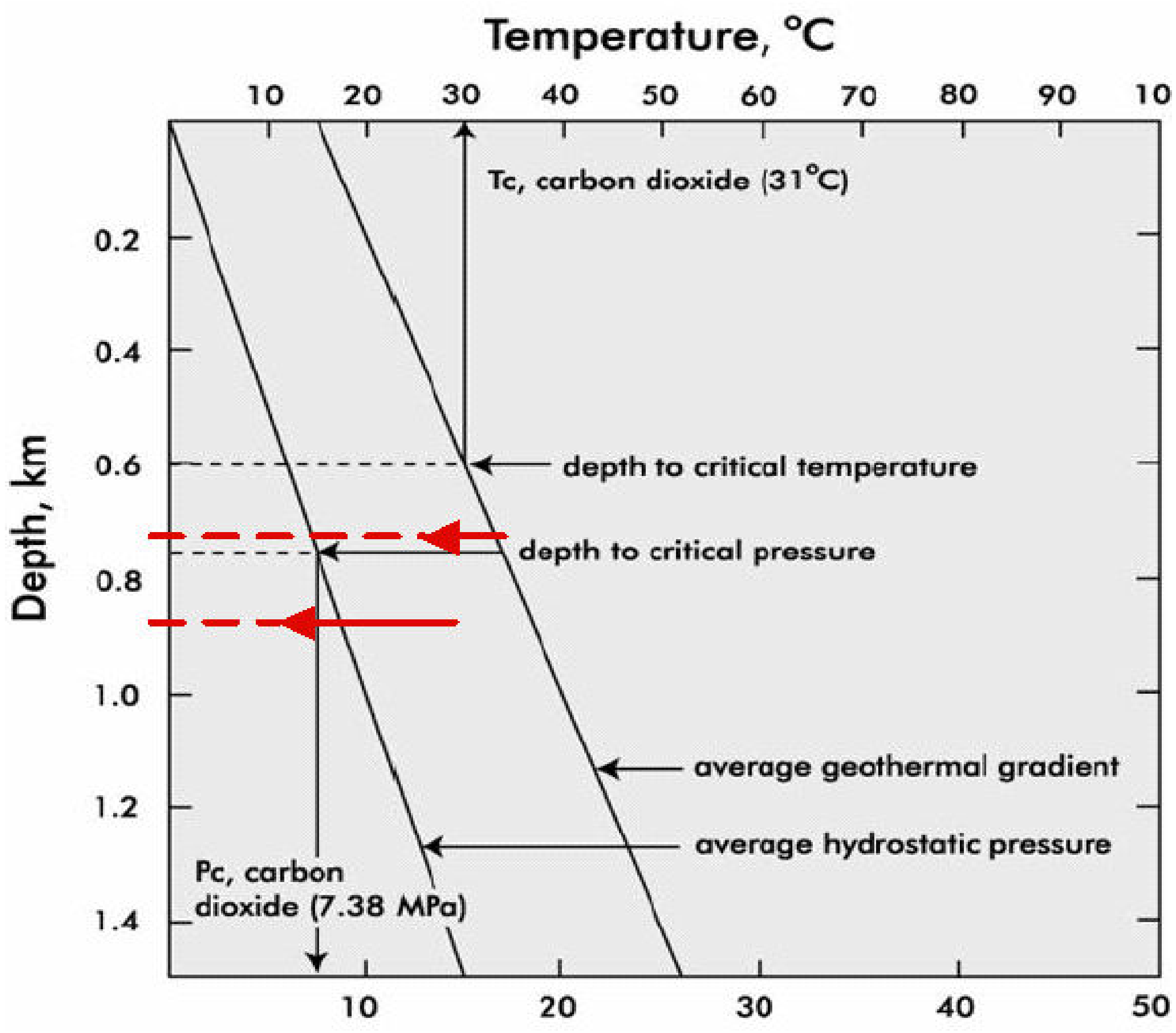
Thermodynamic Properties of Pure CO_2



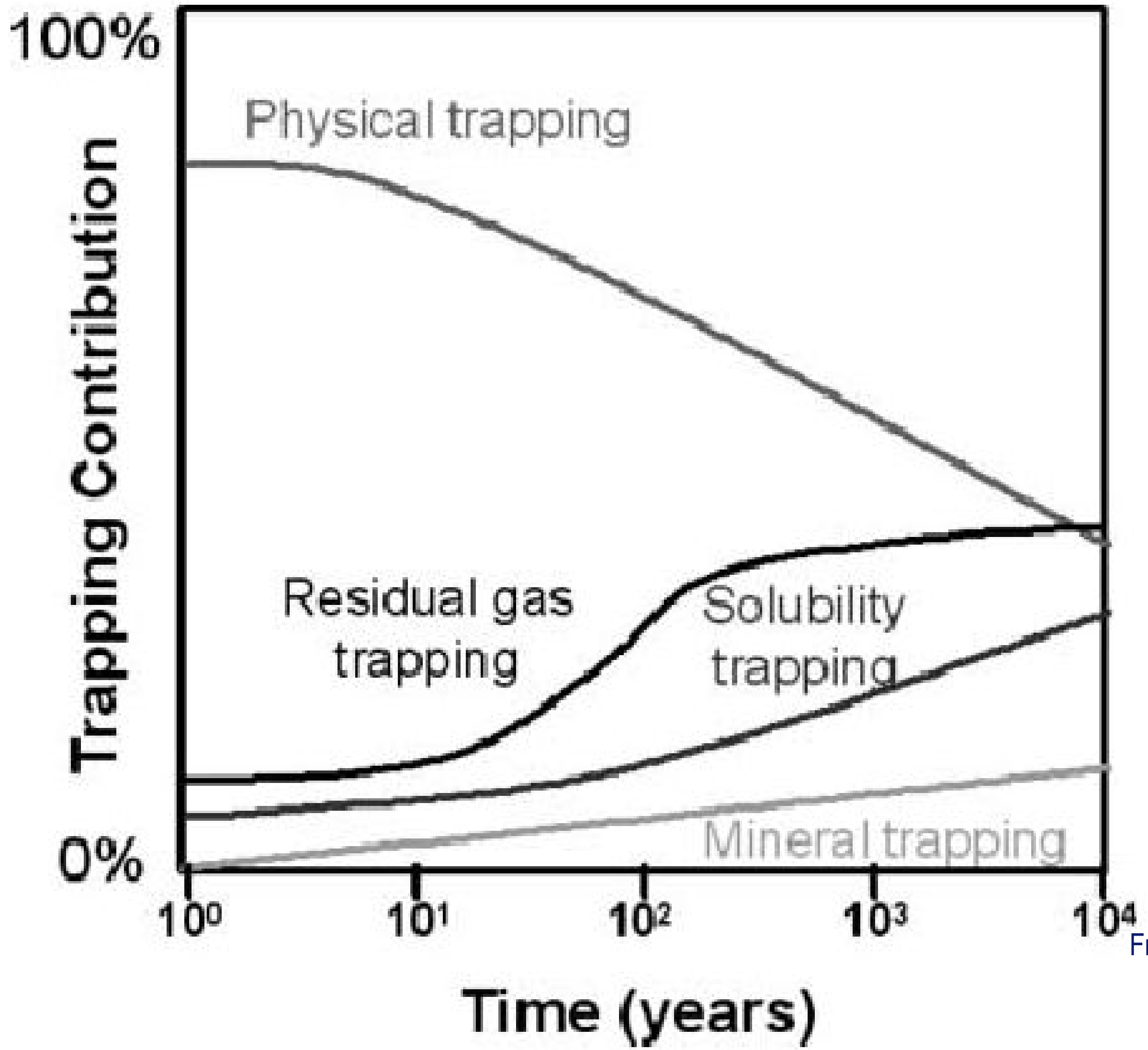
	Carbon Dioxide - CO_2	
	Triple Point	Critical Point
P (bar)	5.18	73.82
T (K)	216.55	304.19
ρ_v (kg/m^3)	13.80	468.16
ρ_l (kg/m^3)	1179.25	468.16

[a] values reported by Vargaftik et al. [1996]

Conditions for Supercritical CO_2

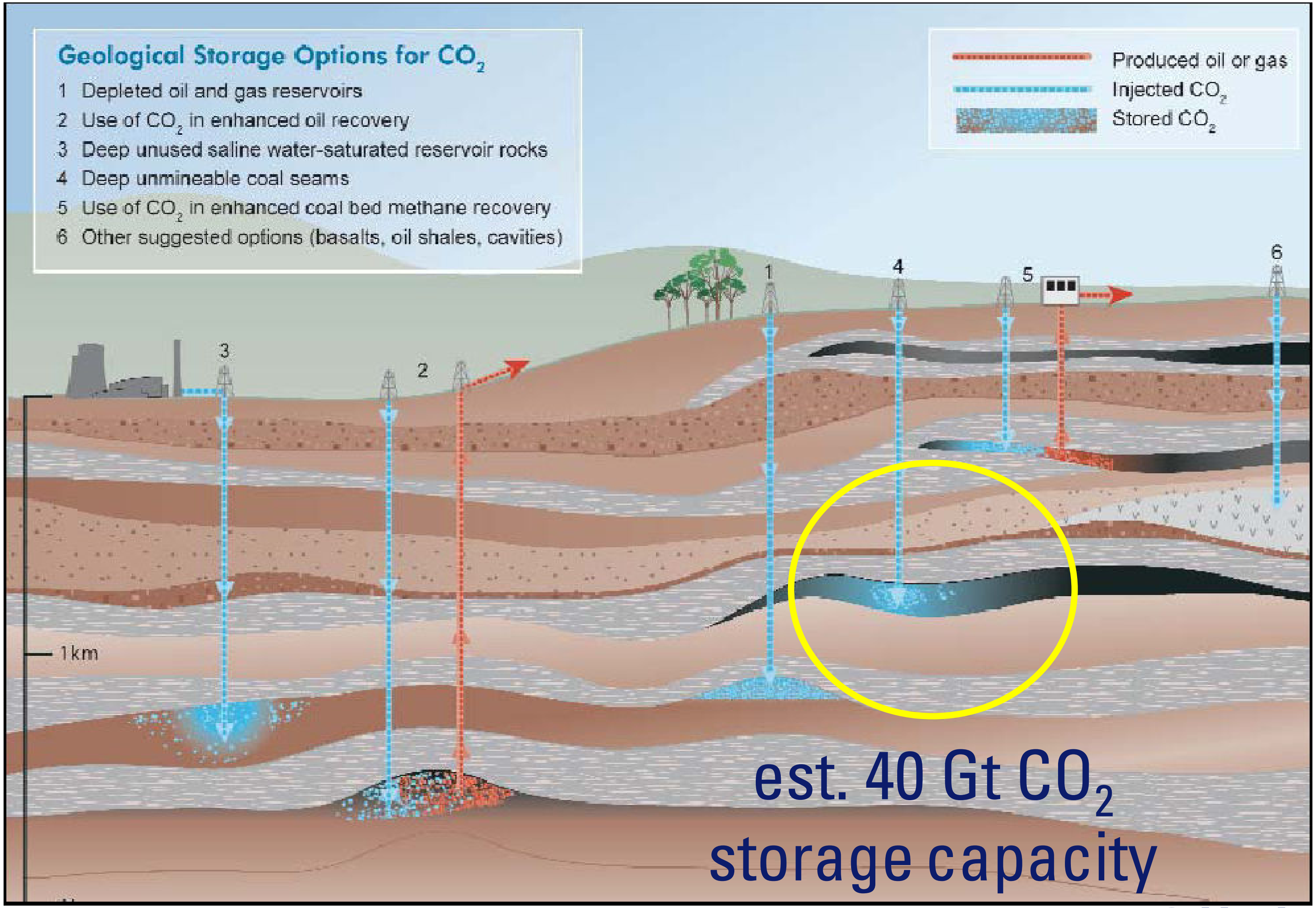


Relative Importance of Trapping Mechanisms



From Benson, CO2 Capture Project, 2005

Storage in Coal Seams



Adsorption Coefficients for Pure Gas

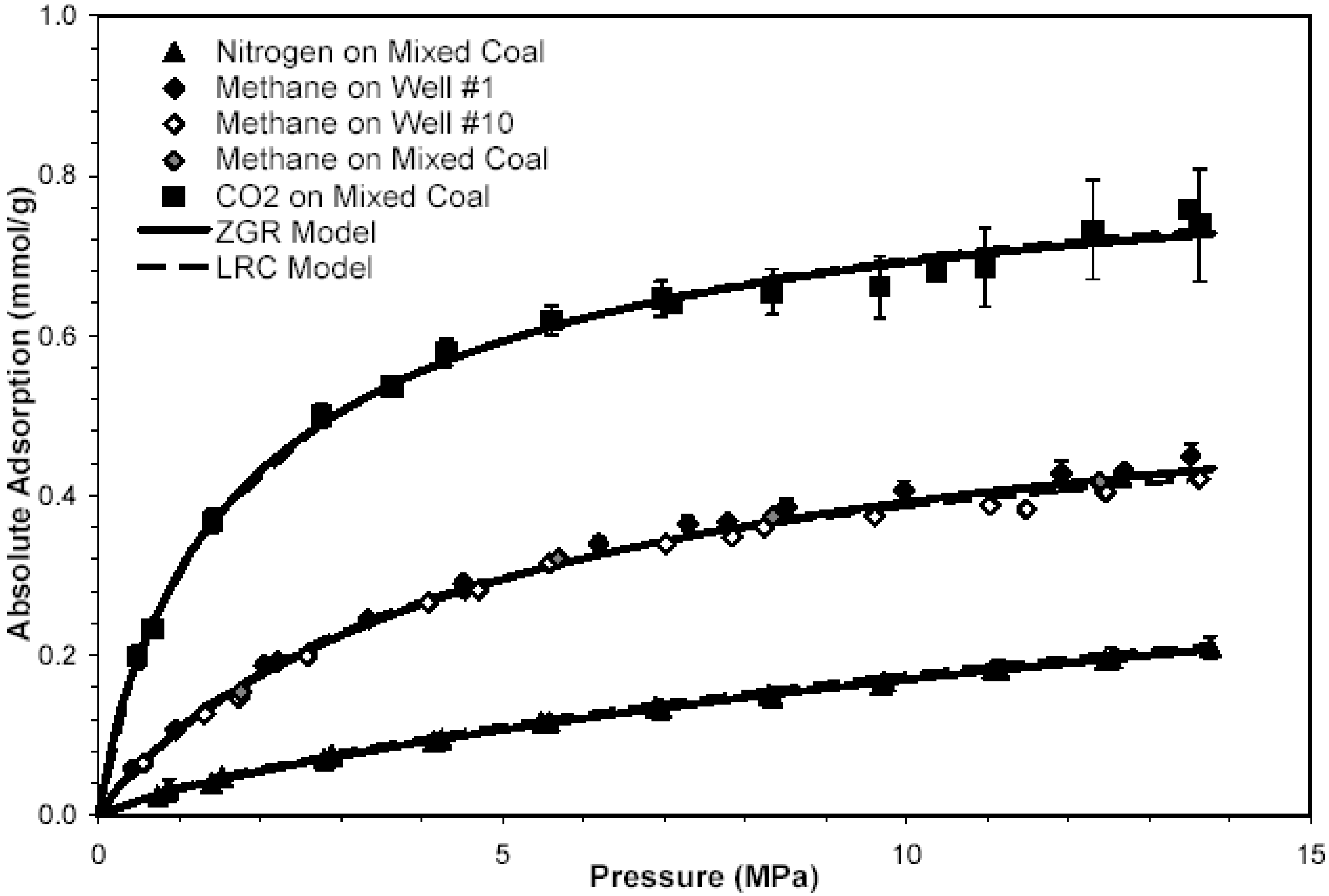
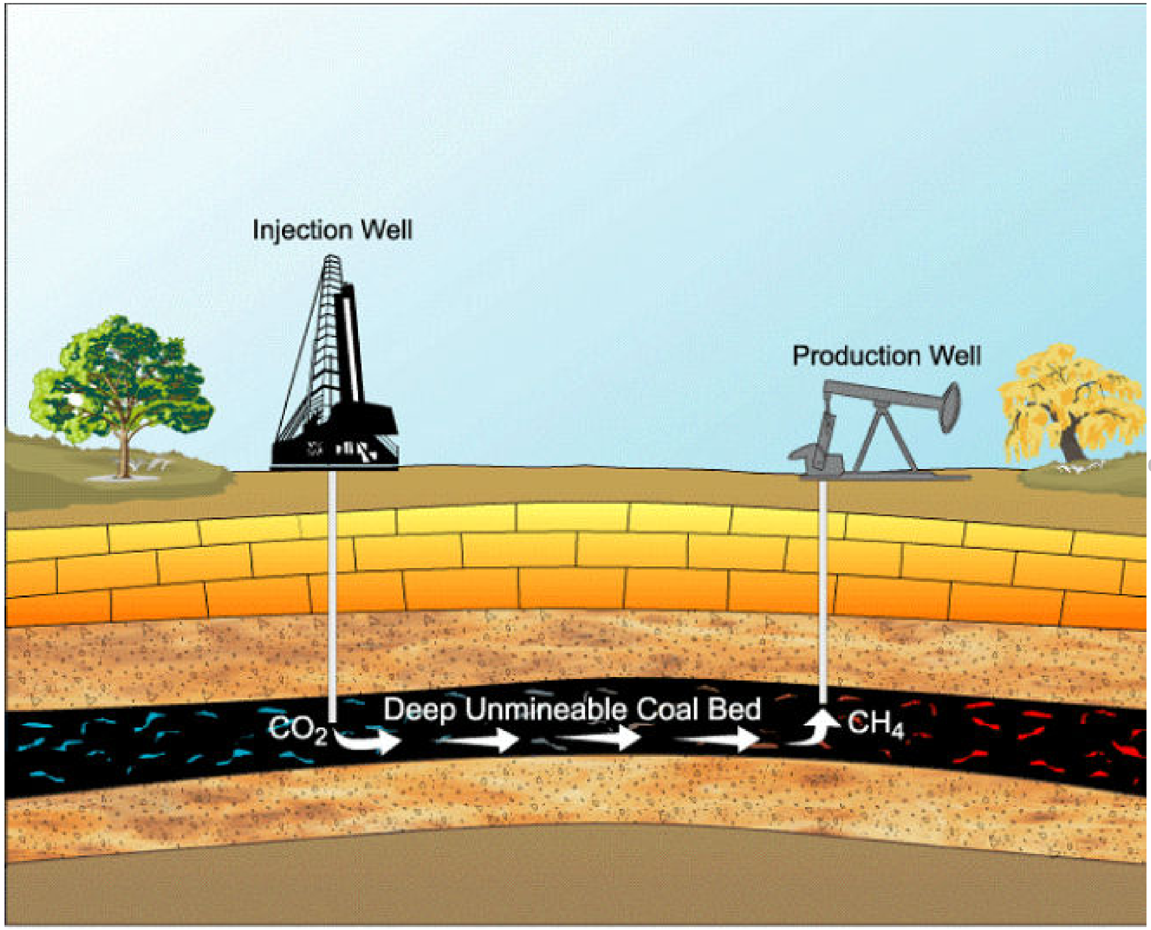


Figure 3. Pure-Gas Absolute Adsorption on Wet Tiffany Coals at 327.6 K

Schlumberger

Enhanced Coal-Bed Methane Recovery

- CO_2 adsorbs onto coal surface preferably to CH_4
- Selection criteria for ECBM
  - Permeability : 1 – 5 md
  - Coal geometry: thick seams
  - Minimum faulting / folding
  - Lateral continuity / vertical isolation
  - Depth up to 1500 m
  - High gas saturation
  - Ability to dewater
  - Others: coal rank, composition, low ash content



Schlumberger

Adsorption Coefficients for Mixtures

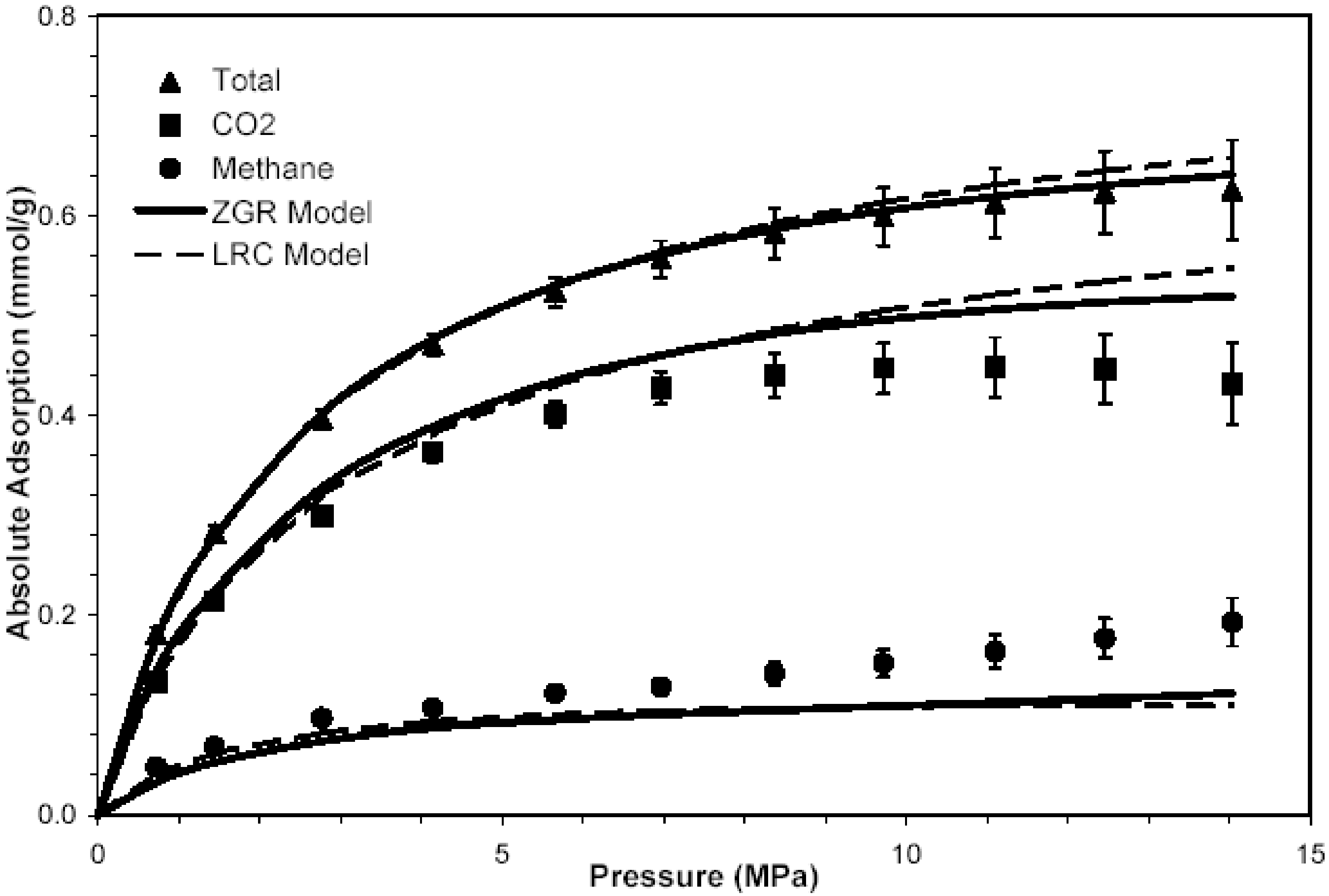
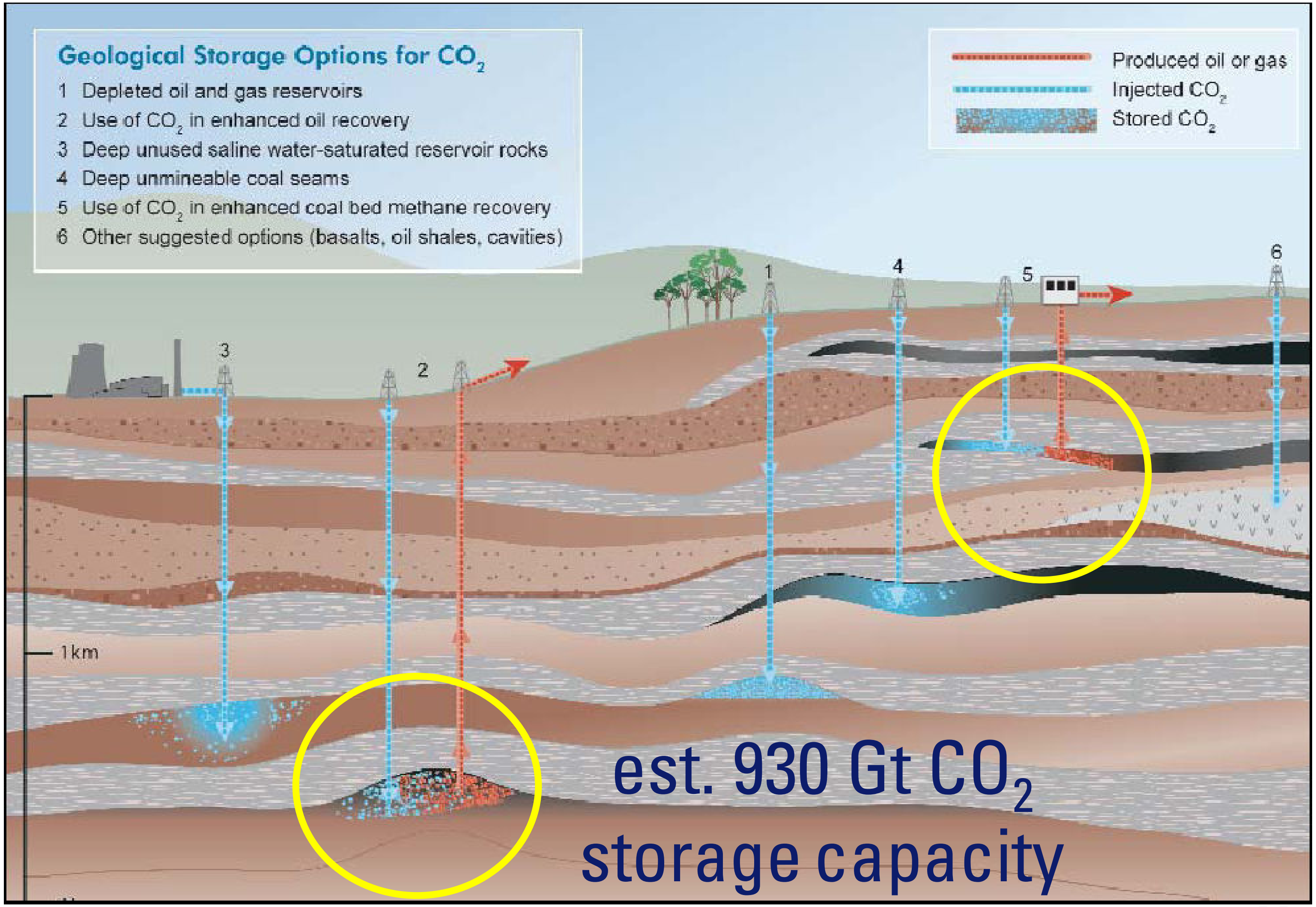


Figure 10. Model Predictions of Absolute Adsorption of 40/60 Mole % Mixture: Methane/CO_2 Feed Mixture on a Wet Tiffany Mixed-Coal Sample at 327.6 K

Schlumberger

Storage in Depleted Reservoirs

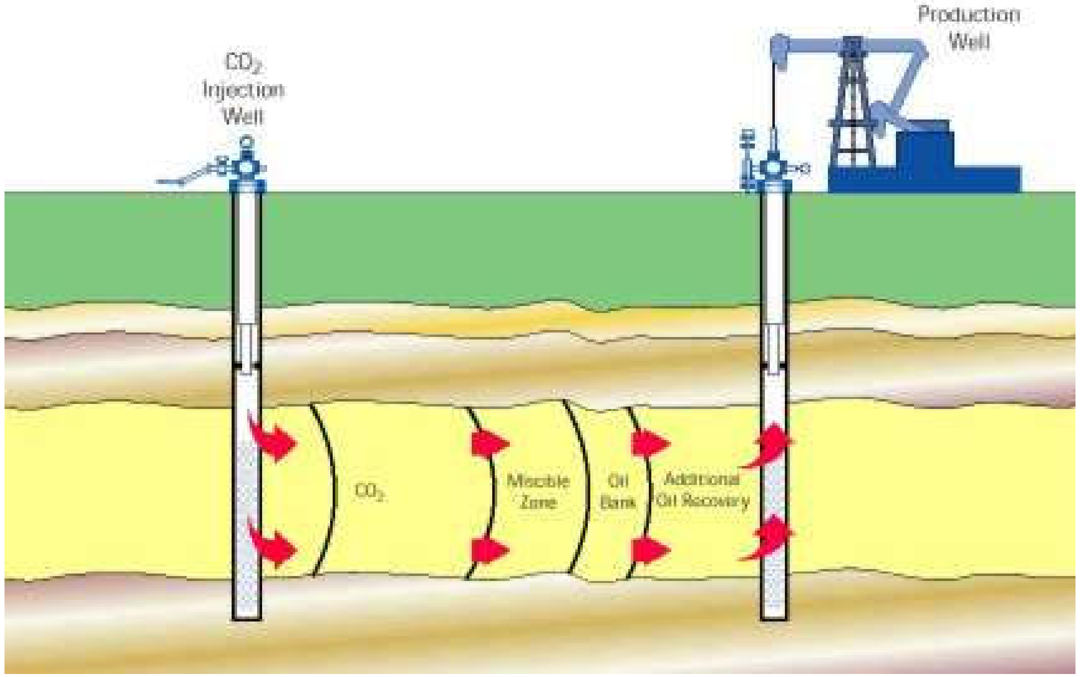


Schlumberger

Enhanced Oil (Gas) Recovery

Tertiary Recovery (after Water Flooding)

- Existing geological seal
- Detailed geological description already available
- Many years experience of EOR injection
- Selection criteria for EOR
  - Gravity/viscous balance
  - Layer heterogeneities
  - Minimum Miscibility Pressure (MMP)
  - …

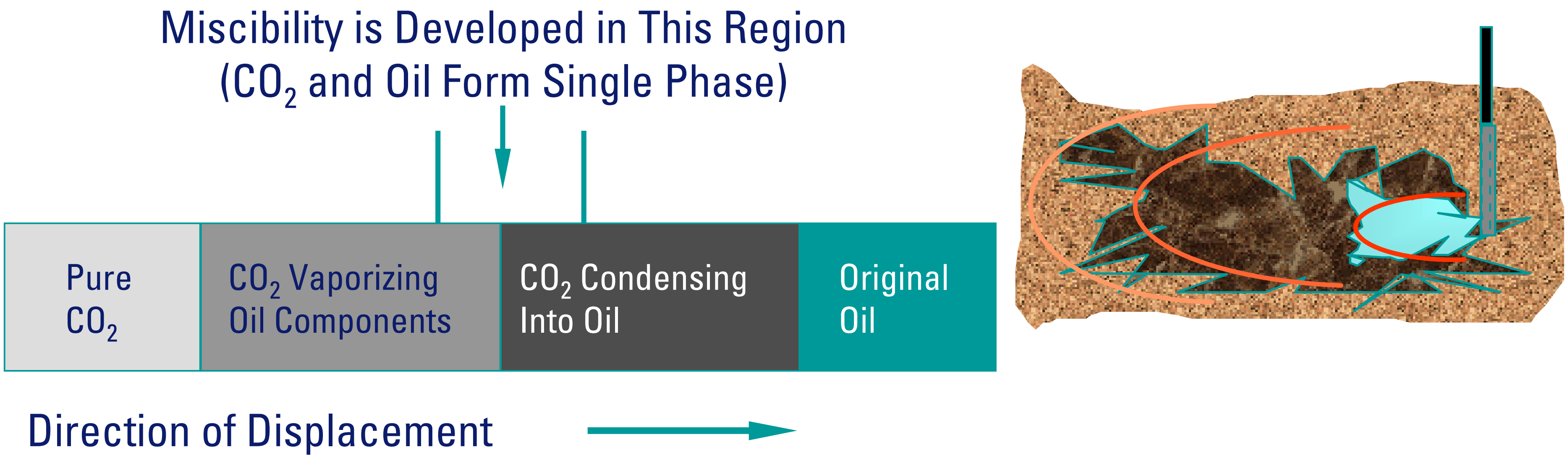


www.ieagreen.org.uk

Schlumberger

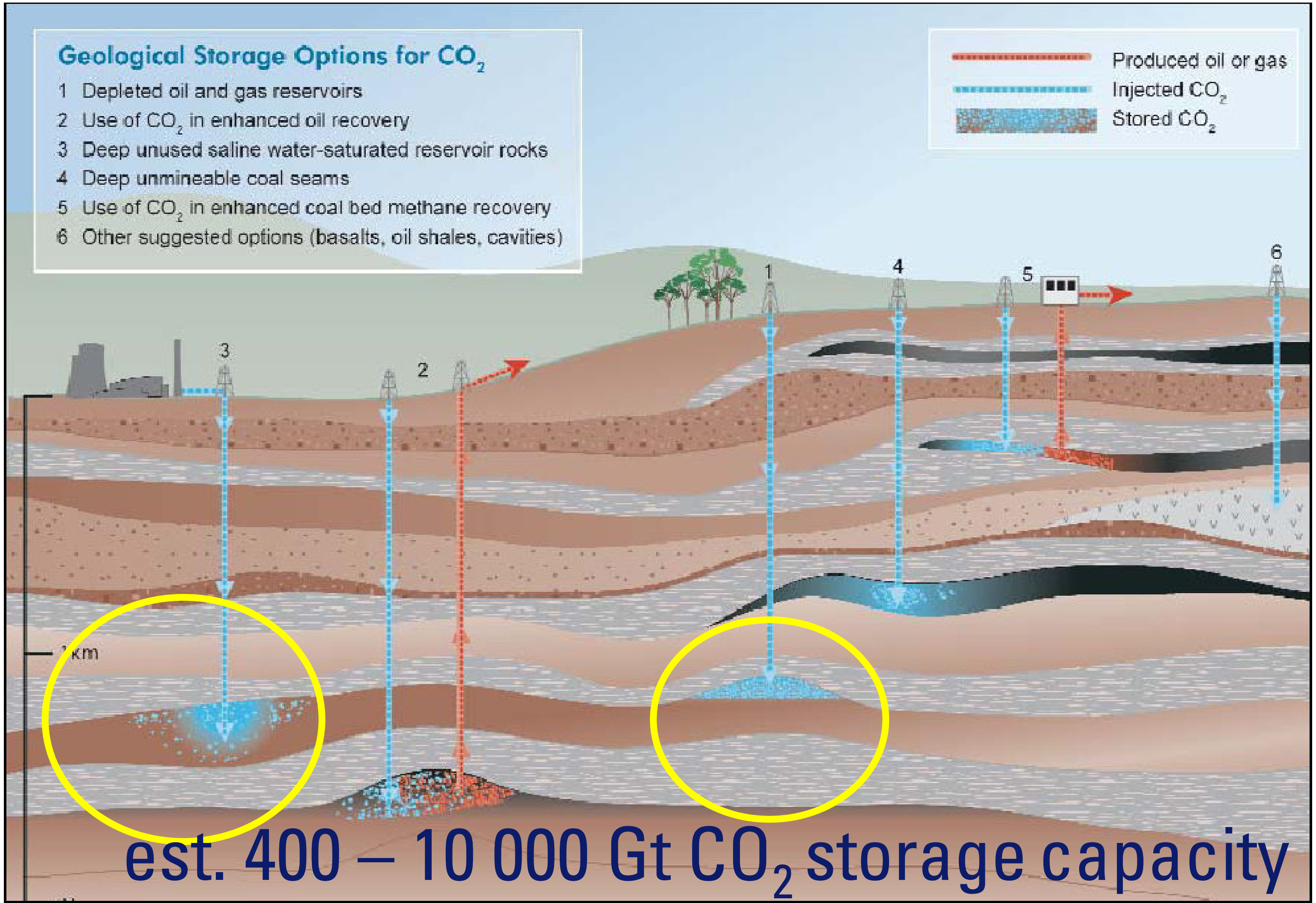
Miscible EOR Processes

- First Contact Miscible (slug of LPG displaced by a large value of gas with high CH4 content)
- Multiple-Contact-Miscible: CO2, WAG



Schlumberger

Storage in Deep Saline Aquifers



est. 400 – 10 000 Gt CO_2 storage capacity

Schlumberger

Outline

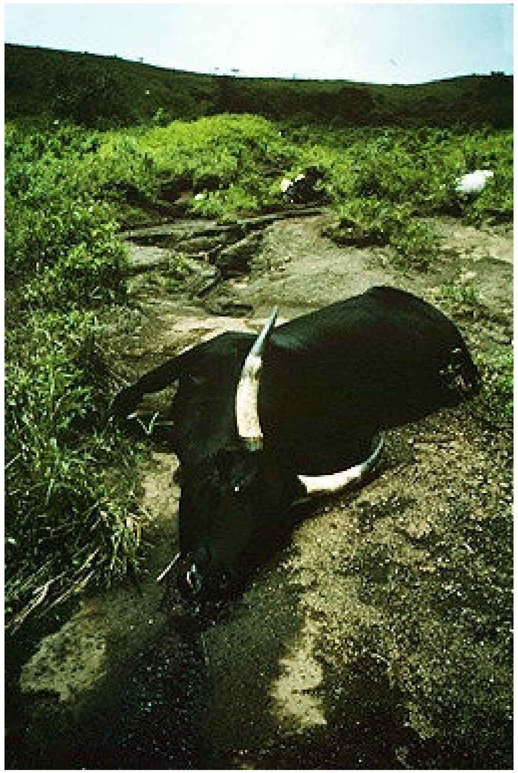
- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples

Safety Aspects of CO_2 Storage

Prevent catastrophic CO_2 release

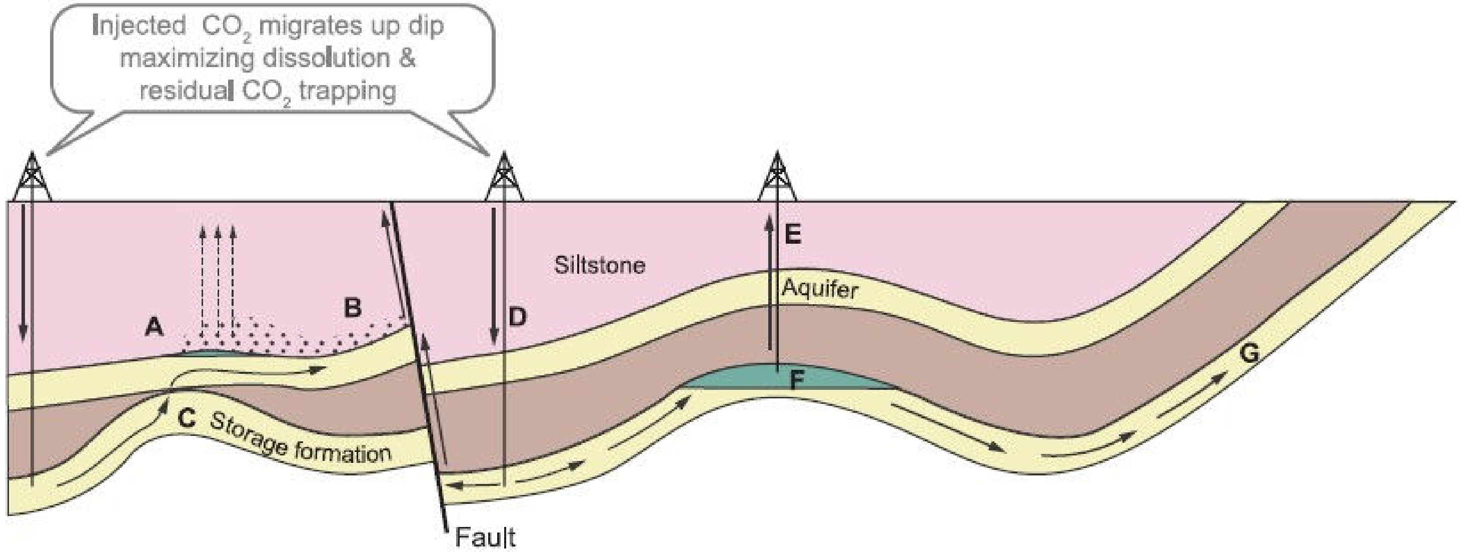
Lake Nyos, Cameroon (1986): 1700 dead

after CO_2 release from volcanic lake



Schlumberger

Leak Risks and Their Mitigation



Potential Escape Mechanisms

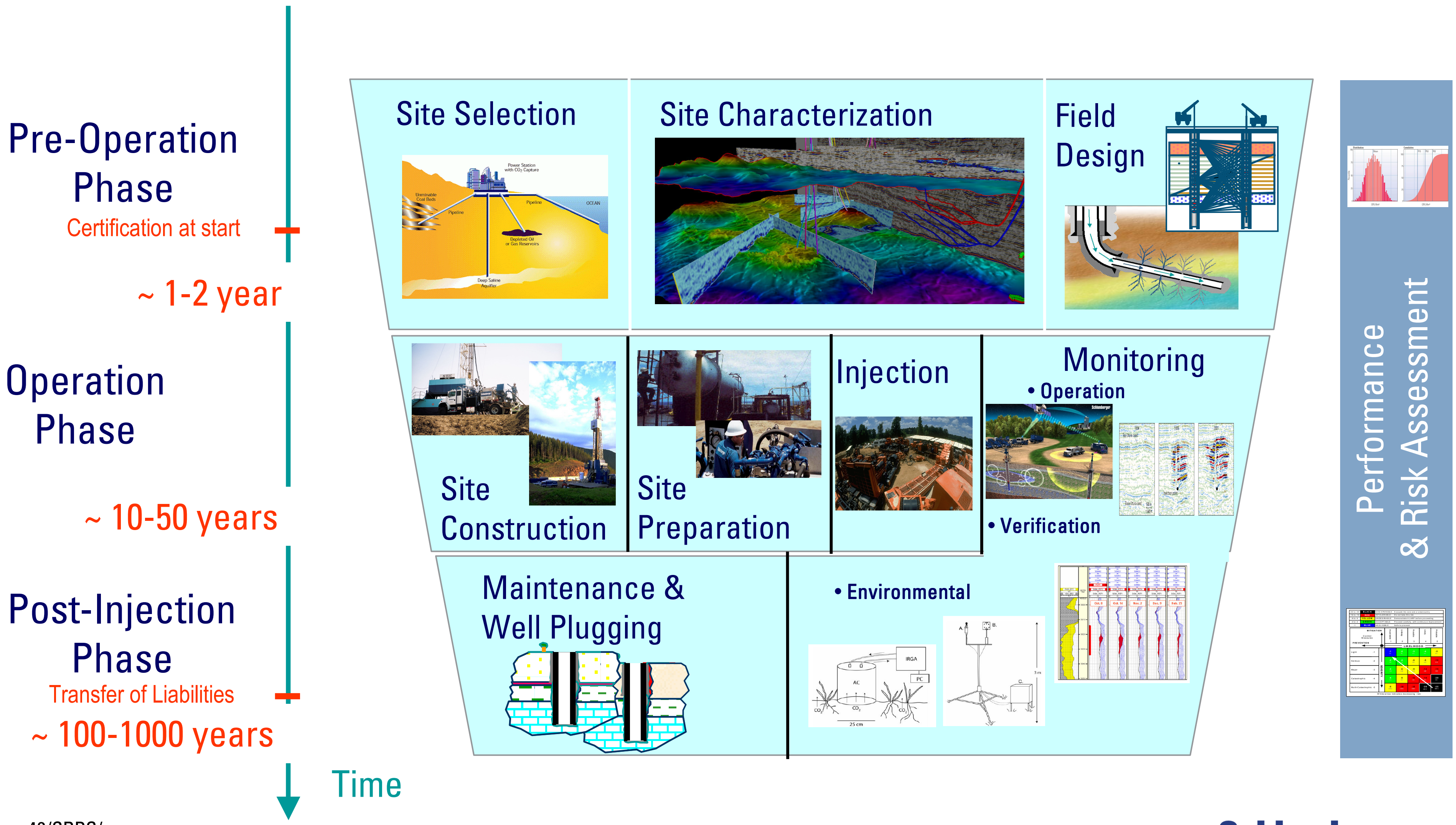
A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone	**B.** Free CO_2 leaks from A into upper aquifer up fault	**C.** CO_2 escapes through 'gap' in cap rock into higher aquifer	**D.** Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault	**E.** CO_2 escapes via poorly plugged old abandoned well	**F.** Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure	**G.** Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

***A.** Extract & purify ground-water*	***B.** Extract & purify ground-water*	***C.** Remove CO_2 & reinject elsewhere*	***D.** Lower injection rates or pressures*	***E.** Re-plug well with cement*	***F.** Intercept & reinject CO_2*	***G.** Intercept & reinject CO_2*

Schlumberger

Schlumberger CO_2-Storage Project Workflow



Schlumberger

Before injection – Site Characterization

Performance & Risk Analysis

- Injectivity
- CO_2 in place
- Leakage Scenarios and rates
- Risk classification

Monitoring plan

- Sensor selection
- Specifications
- Placement

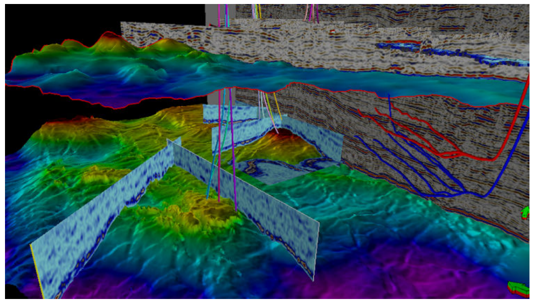
Monitoring sensors response prediction

Measurements (Characterization)

- Seismic
- Data well

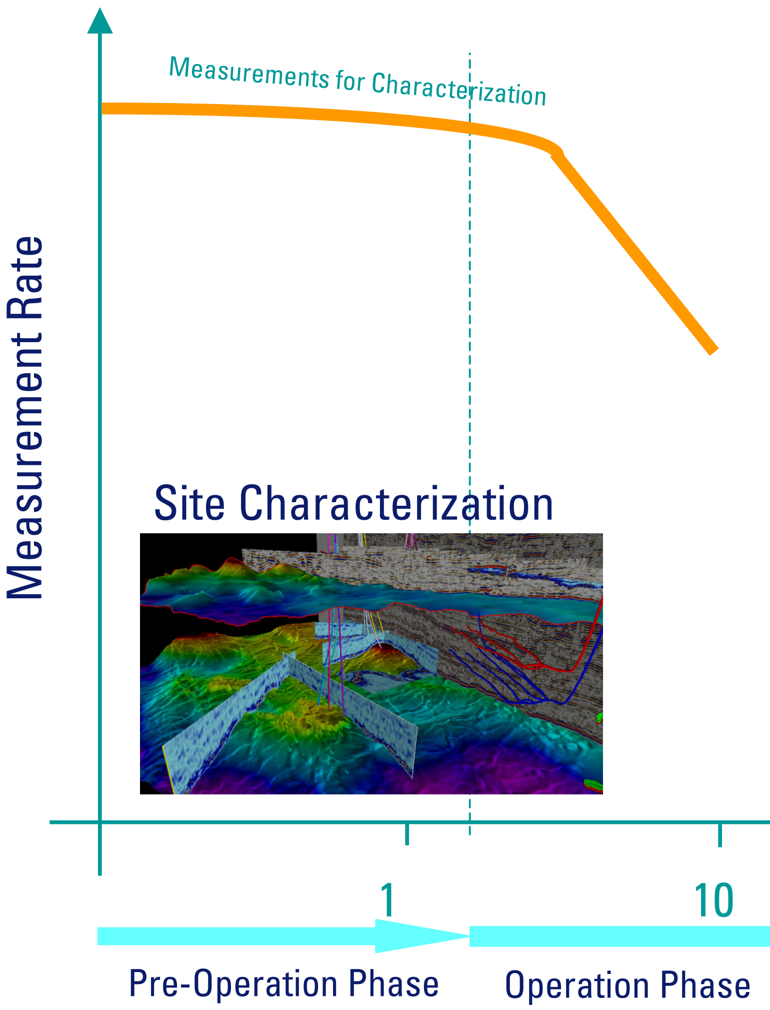
Modelling & Simulation

- Structure
- Properties
- Fluid dynamics
- Tool Response

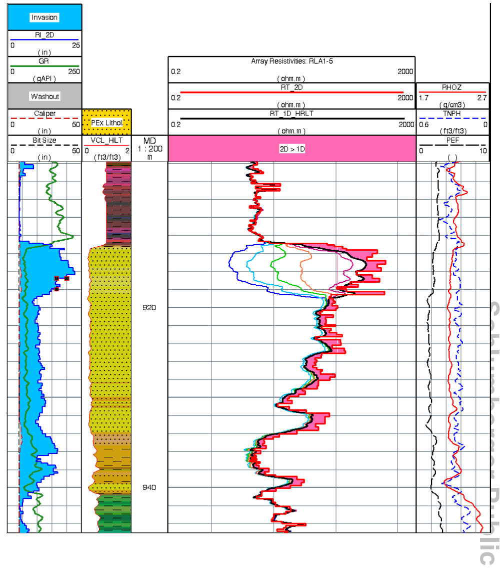


Schlumberger

Measuring for Characterization



- Geophysics / Geology
  - Seismic, VSP's
  - Imagers
- Petrophysics / Mineralogy
  - Density, Porosity, Resistivity
  - Element concentration
  - Natural T, K, U emissions



- Geomechanics
  - Sonic, Density
  - Pressure measurement & test
- Well Integrity
  - EM, Ultrasonic, Sonic

Schlumberger

(*) From Chalaturnyk et al.

During and After Injection - Monitoring

Performance & Risk Analysis

- Injectivity
- CO_2 in place
- Leakage scenarios and rates
- Risk classification

Measurement interpretation
Model update

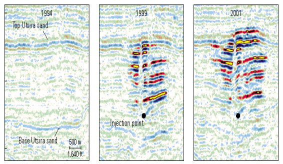
Measurements (Monitoring)

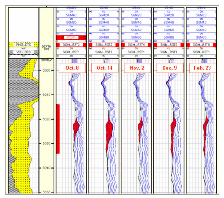
- Geophysics
- Well Logging
- Sampling
- Surface / atmosphere

Monitoring sensor response prediction

Simulation

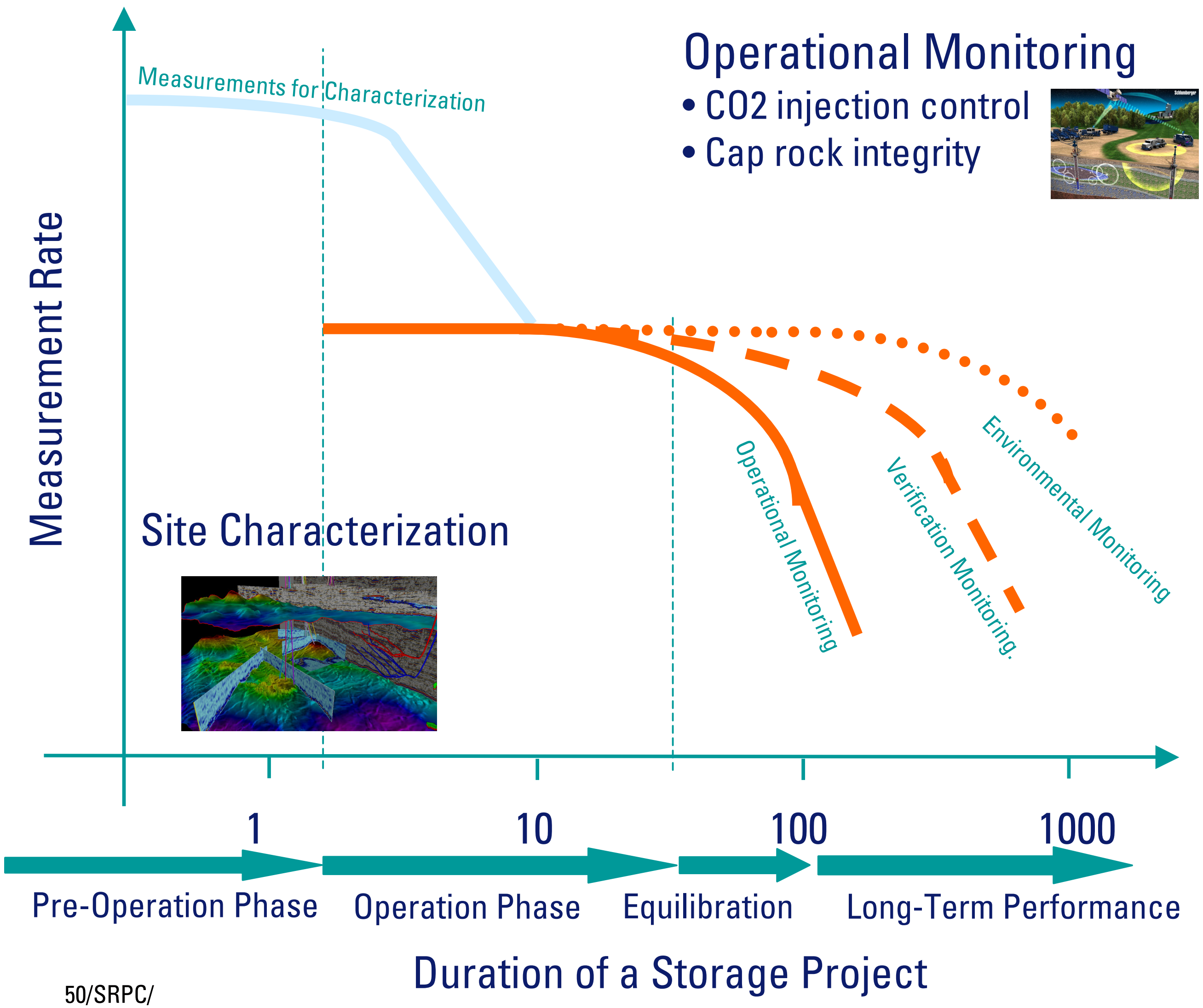
- Structure
- Properties
- Fluid dynamics
- Tool response





Schlumberger

Measuring for Monitoring

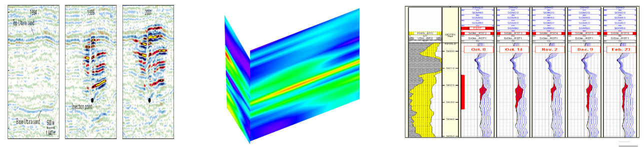


Operational Monitoring

- CO_2 injection control
- Cap rock integrity

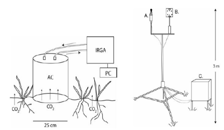
Verification Monitoring

- CO_2 location and tracking
- Cap rock integrity
- Well Integrity



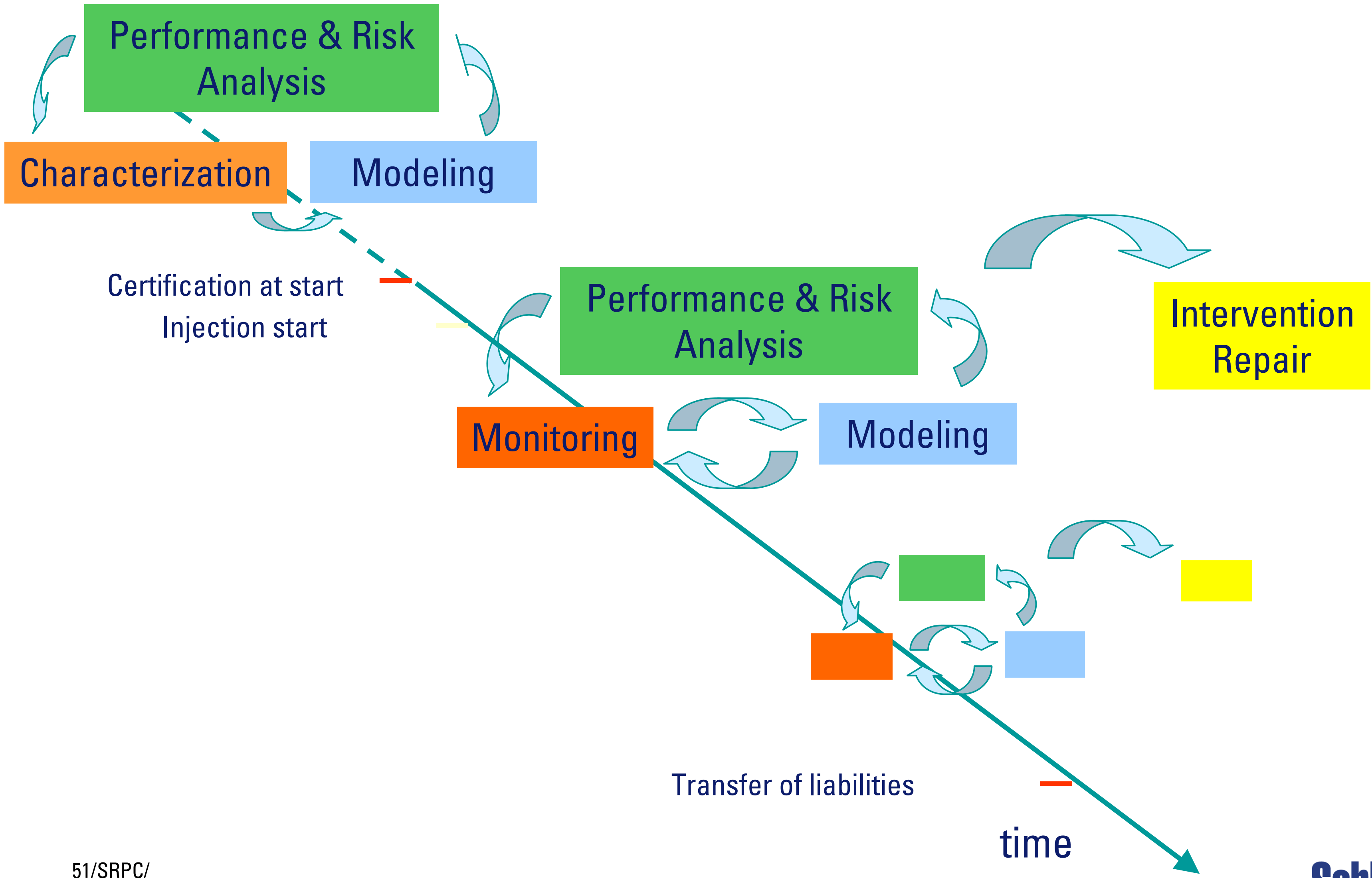
Environment Monitoring

- Aquifers
- Surface
- Atmosphere



Schlumberger

A Continuous Process



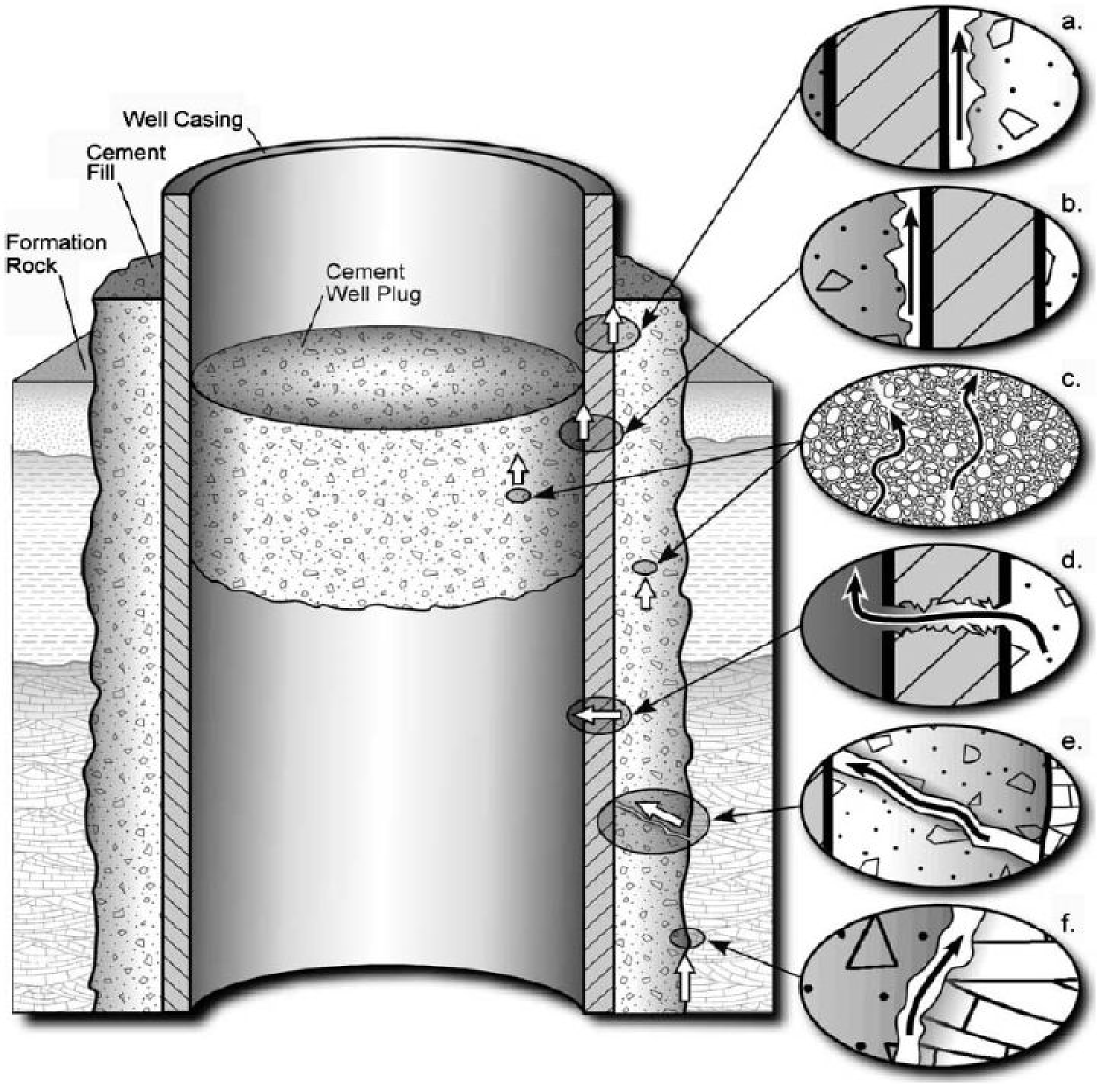
Outline

- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples

Schlumberger

Well Leakage

- Casing
  - Corrosion
- Cement
  - Micro-annulus
  - Cement alteration
  - Micro-cracks



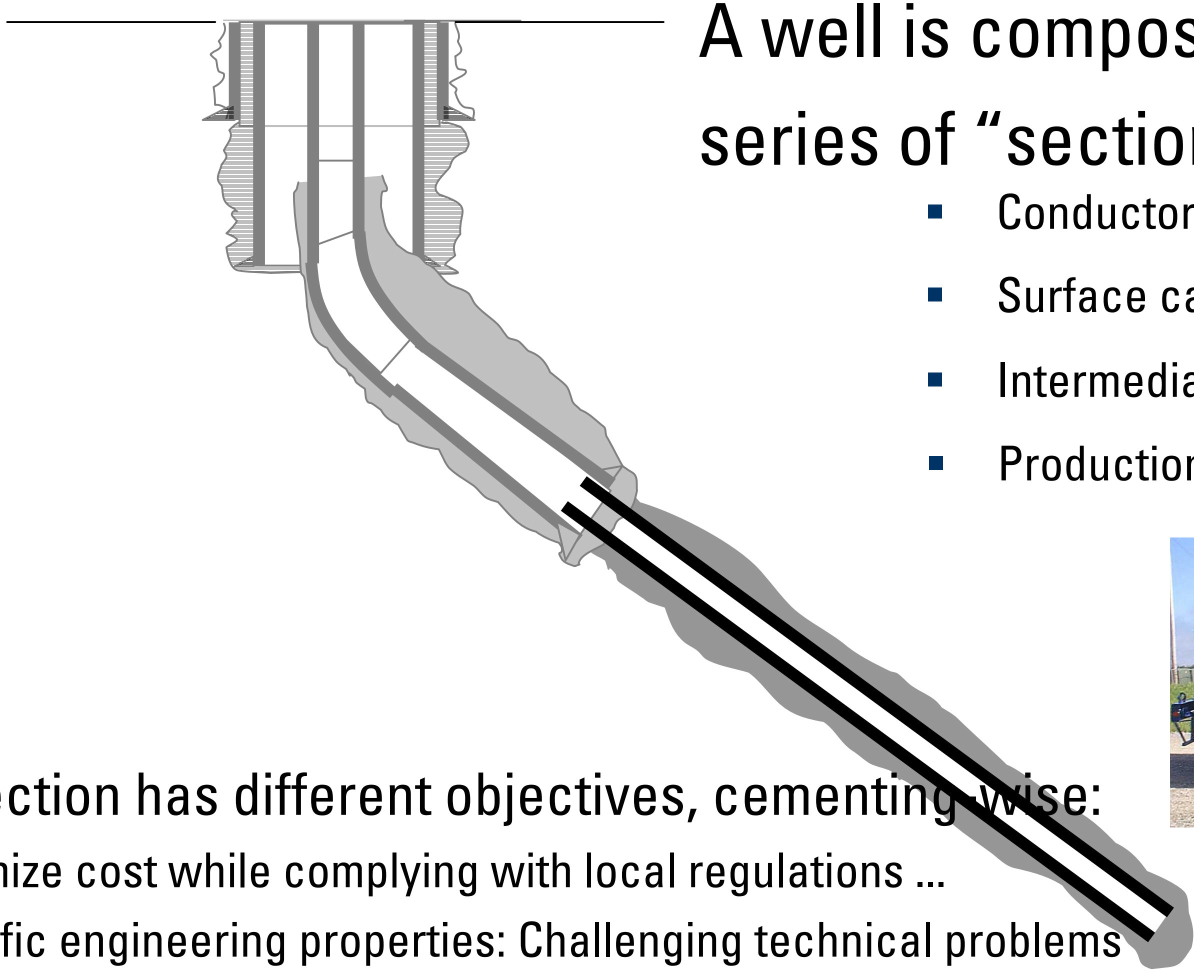
Schlumberger

Well-Cementing Process

Well construction - Primary cementing

A well is composed of a telescopic series of "sections"

- Conductor casing
- Surface casing
- Intermediate casing(s), or liner(s)
- Production casing, or liner



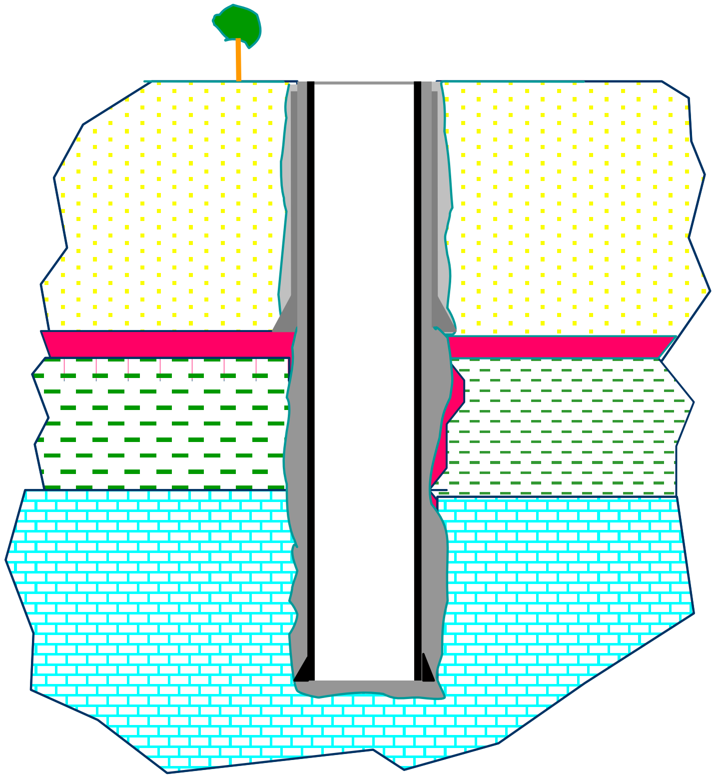
Each section has different objectives, cementing-wise:

- Minimize cost while complying with local regulations ...
- Specific engineering properties: Challenging technical problems in *design, execution or evaluation*

Schlumberger

Zonal Isolation

Poor or non-existing cement could allow CO2 or brine with dissolved CO2 to travel along the completion and **contaminate** fresh water bearing formations, even **reach surface**



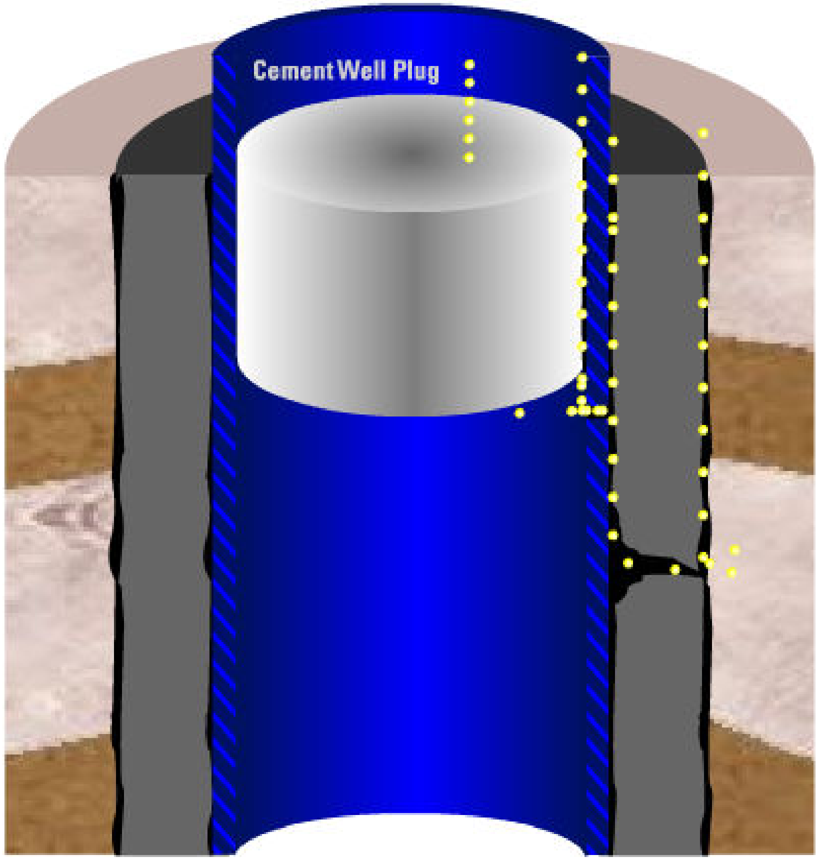
Motivation and Approach

- CO_2 underground storage
  - The most effective way

Schlumberger

Motivation and Approach

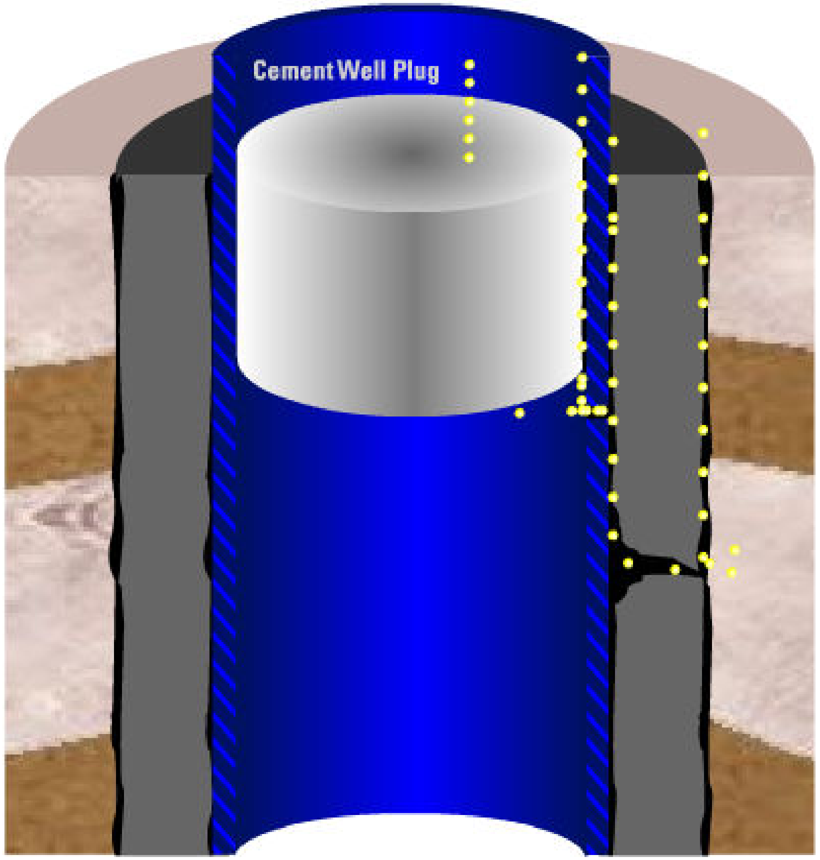
- CO_2 underground storage
  - The most effective way
- Long-term zonal isolation
  - Portland cement not thermodynamically stable in CO_2 environments.
  - Not adequately addressed by industry specifications



Schlumberger

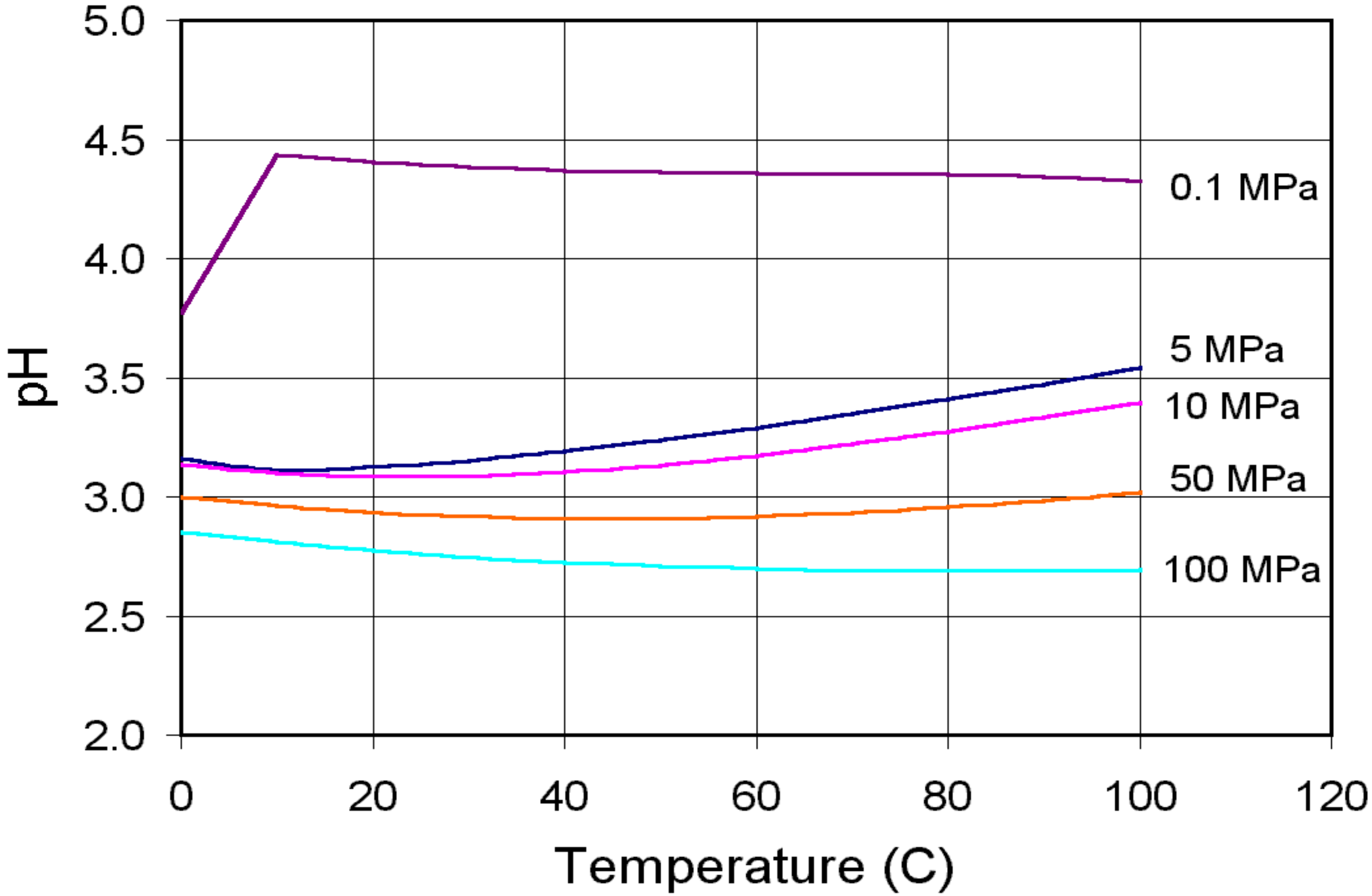
Motivation and Approach

- CO_2 underground storage
  - The most effective way
- Long-term zonal isolation
  - Portland cement not thermodynamically stable in CO_2 environments.
  - Not adequately addressed by industry specifications



- Develop standard procedure/method
  - A laboratory qualification of resistant cements
  - The long-term modeling of cement-sheath integrity

Water pH at CO_2 Solubility



Schlumberger

CO_2 Interaction with Portland Cement

- CO_2 in presence of water results in a acidic environment
  - Carbonic acid – pH ~ 3 – 4
- Chemical reactions in presence of Calcium

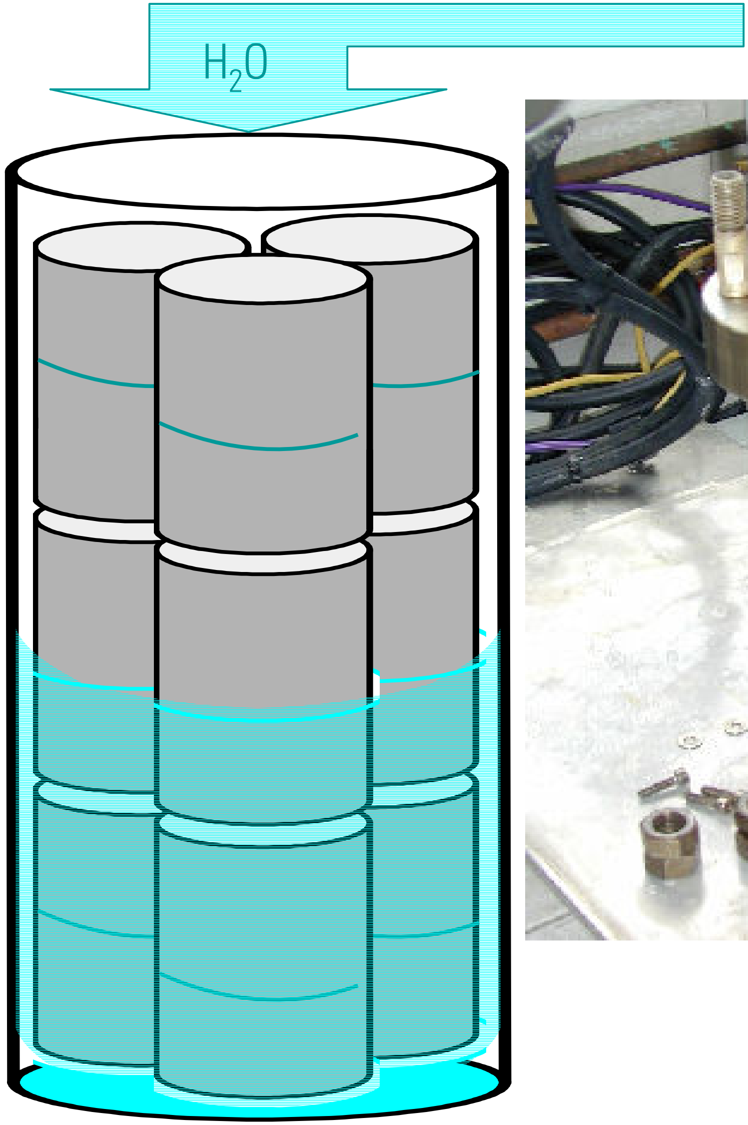
Carbonation

- Dissolution with
  - Variations of molar volume
  - Changes in Porosity, Permeability

➡ Need for a CO2-resistant cement

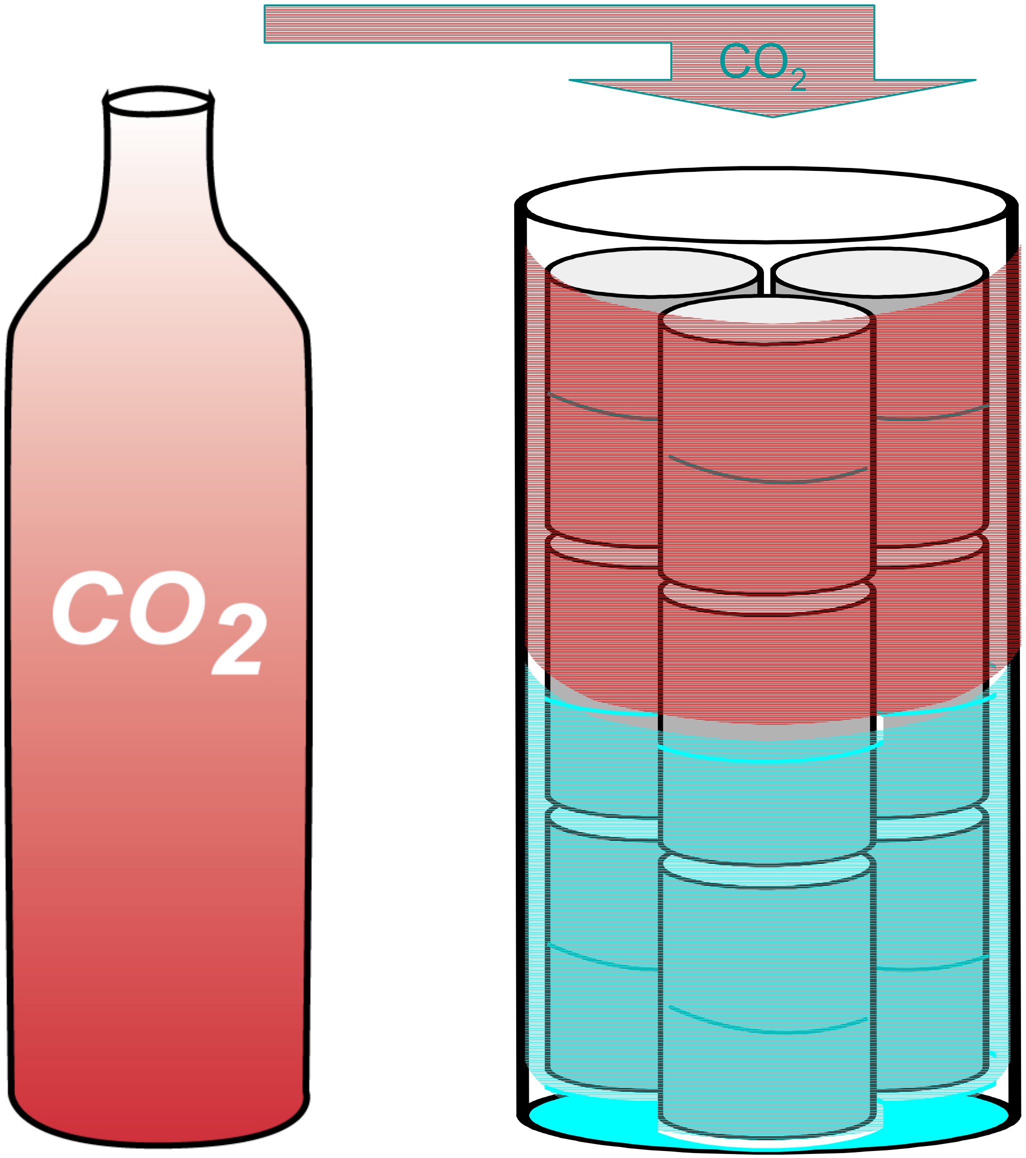
Schlumberger

Experimental Apparatus



Schlumberger

Experimental Apparatus



Supercritical CO_2 phase saturated with water

Liquid H_2O phase saturated with CO_2

Kinetic tests with Portland Cement

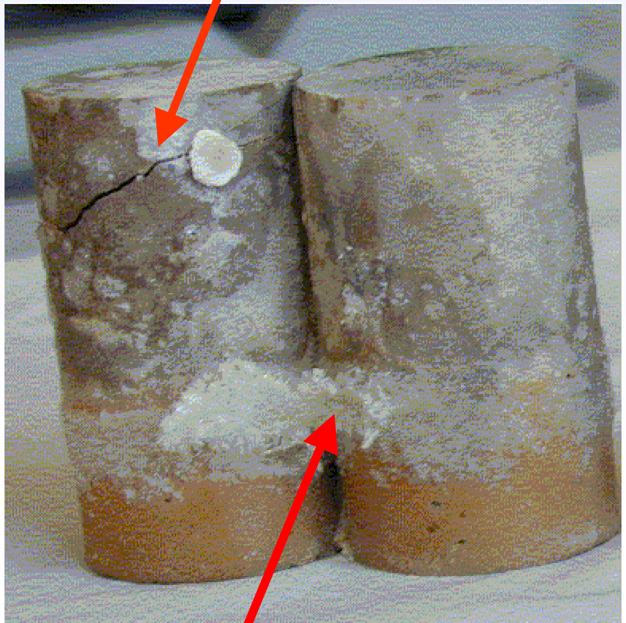
2 days

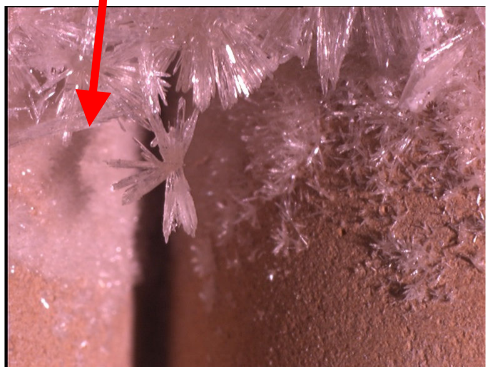
1 week

6 weeks

What happens to a neat cement?

Cracks in wet CO_2 supercritical environment





Strong alteration rims

Strong carbonation in the external fluid mainly located at the fluids interface (Aragonite)

After one month at 90°C and 280 bars under wet CO_2 supercritical environment

CO_2-Resistant System

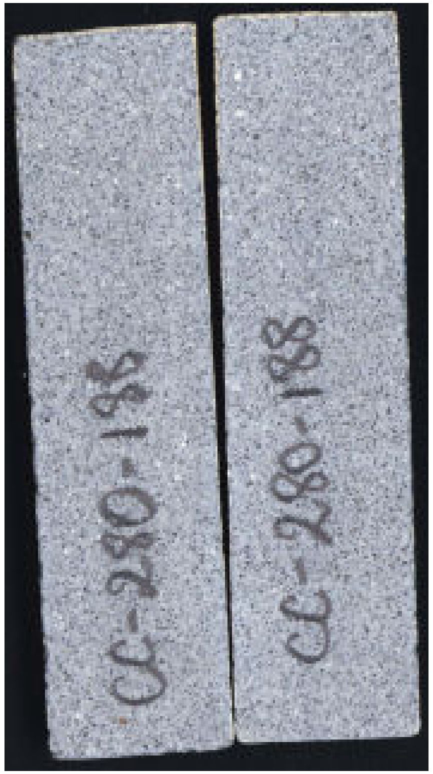
– Chemistry effect : selection of a durable material to reduce Portland amount

– Special system with low water

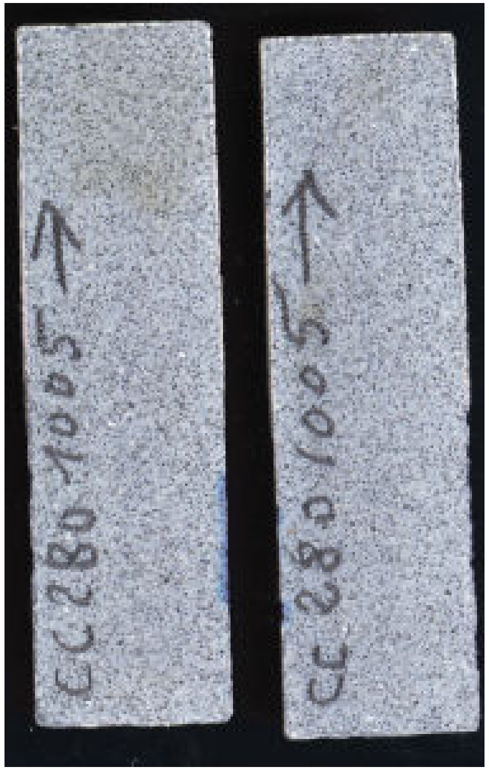
– Slurry to have a large density range (12.5 ppg and 17 ppg)

Kinetic tests with CO_2-Resistant System

2 days



1 week



6 weeks

Well Construction with CO_2-Resistant Cement

- A new methodology to simulate downhole conditions
  - Procedure validation
  - Reproducible and repeatable

Well Construction with CO_2-Resistant Cement

- A new methodology to simulate downhole conditions
  - Procedure validation
  - Reproducible and repeatable
- Portland cement
  - A very effective decay process following a diffusion law
  - An initial sealing by carbonation then a dissolution stage

Well Construction with CO_2-Resistant Cement

- A new methodology to simulate downhole conditions
  - Procedure validation
  - Reproducible and repeatable
- Portland cement
  - A very effective decay process following a diffusion law
  - An initial sealing by carbonation then a dissolution stage
- CO_2 Resistant System
  - Homogeneous pattern with a limited carbonation threshold: good mechanical behaviour over a wide density range.
  - Stable in both CO_2 fluids up to 3 months.

Well Construction with CO_2-Resistant Cement

- A new methodology to simulate downhole conditions
  - Procedure validation
  - Reproducible and repeatable
- Portland cement
  - A very effective decay process following a diffusion law
  - An initial sealing by carbonation then a dissolution stage
- CO_2 Resistant System
  - Homogeneous pattern with a limited carbonation threshold: good mechanical behaviour over a wide density range.
  - Stable in both CO_2 fluids up to 3 months.
- Accelerated aging method

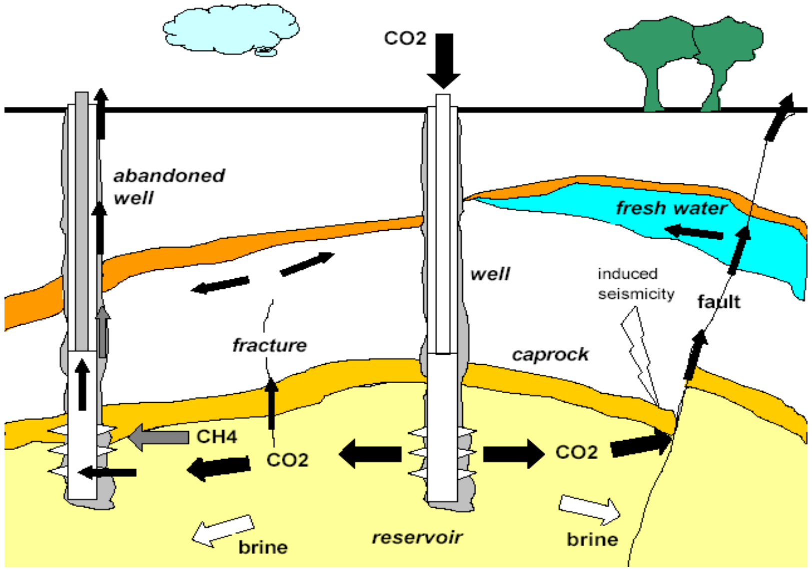
Outline

- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples

Schlumberger

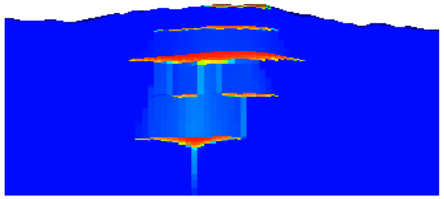
Monitoring - Objectives

- **Performance Control**
  - Injectivity
  - CO_2 in place
- **Risks** Evaluation and Control
  - Loss of containment
  - Contamination (aquifers, surface…)
  - Leaks on surface – Accumulation



(de Damen et al, 2003)

Model **calibration** for a **long-term prediction** of the fate of the CO_2 injected
  - Displacement
  - Trapping Mechanisms (dissolution, mineralization …)



Questions for Designing a Monitoring System

- What do I want to monitor? — CO_2 displacement, leak…
- What property change can I monitor? — P, T, CO_2 Saturation, Resistivity
- What variation am I considering?

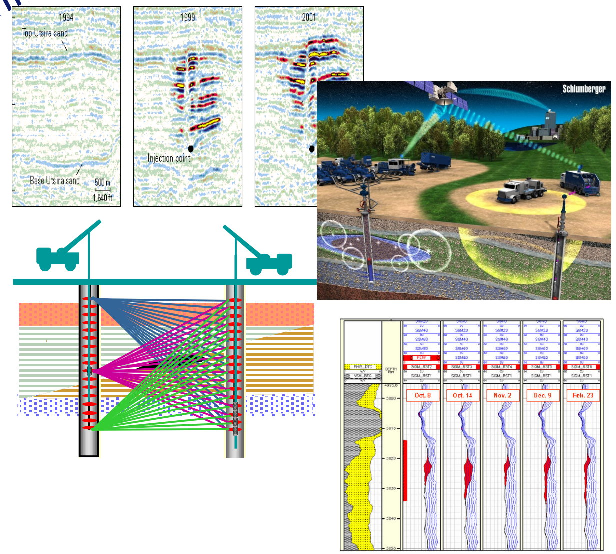
- What measurement technique can be used? — Seismic, EM, Nuclear…
- What should be my sensor specifications? — Accuracy / Precision

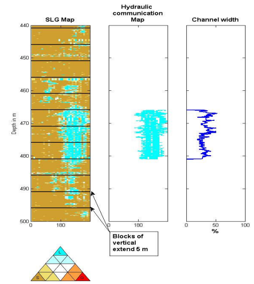
- Where should I place my sensor? — Surface, Obs. Well (Permanent, Logging…)
- For how long? — Operation phase, surveillance
- How can I deploy it?
- How can I interrogate it?

- How can I interpret the measurement?

Monitoring Tools

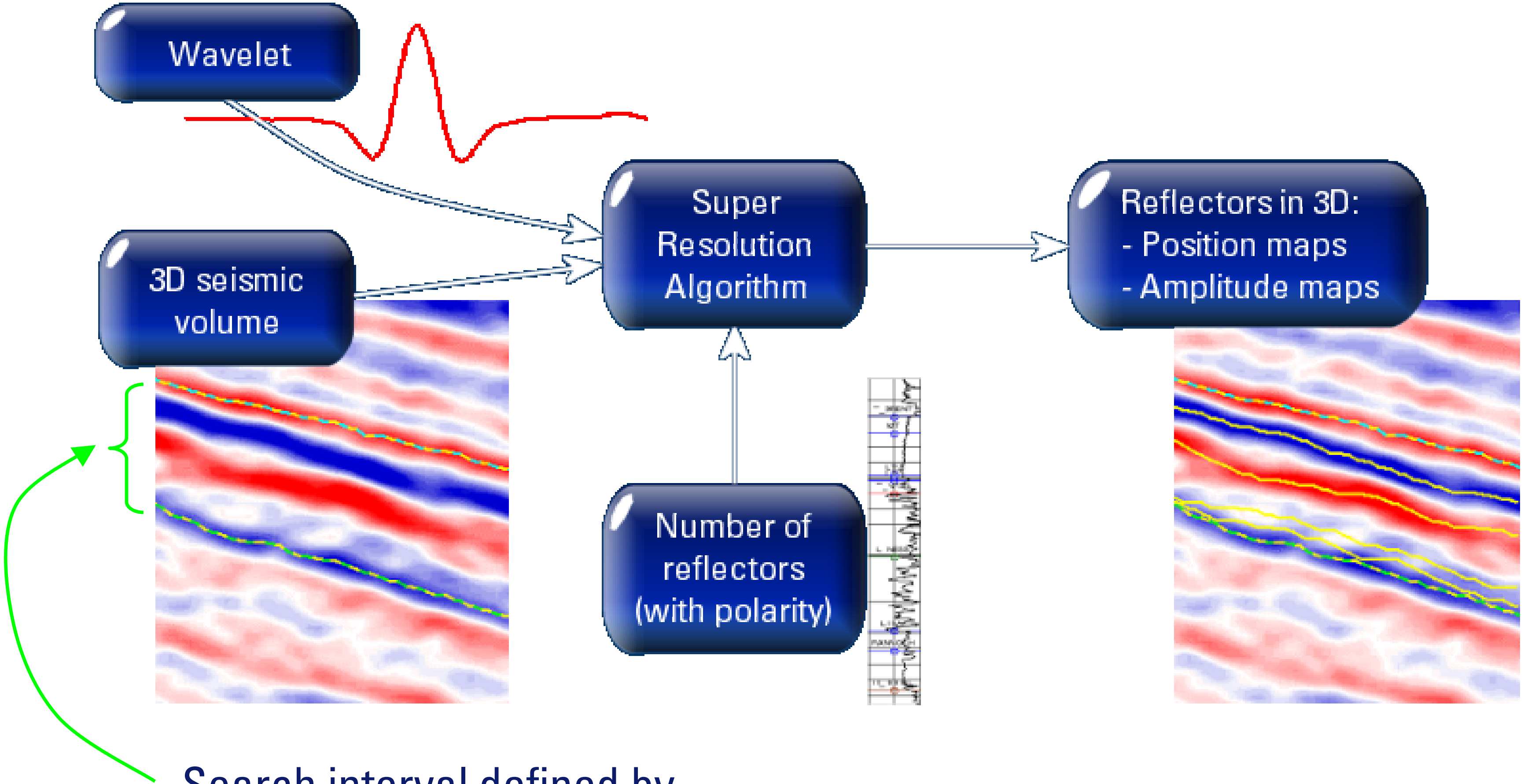
	Operation Monitoring	Verification Monitoring – CO2 Displacement	Verification Monitoring – Cap rock integrity	Verification Monitoring – Well Integrity	Environment Monitoring
P,T, Volume, Rate	X				
Seismic / VSP's		X		X	
Microseismicity	X	X	X		
EM Surveys			X		
Cased-Hole Logging: CHFR,RST			X		
Sampling		X			X
Pressure tests			X		
Sonic: MSIP				X	
Ultrasonic: USIT/IBC					X
Corrosion				X	
Surface / atmosphere					X





Schlumberger

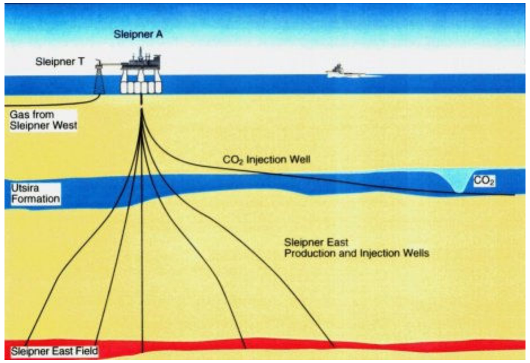
Sleipner Results - Super-Resolution



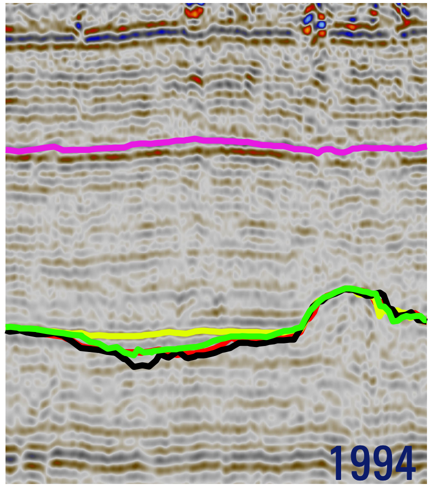
Search interval defined by
– pre-interpreted reflectors, or
– time interval

Schlumberger

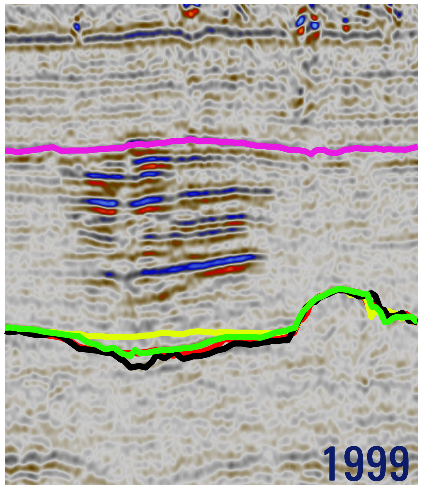
Sleipner Results – 4D Seismic

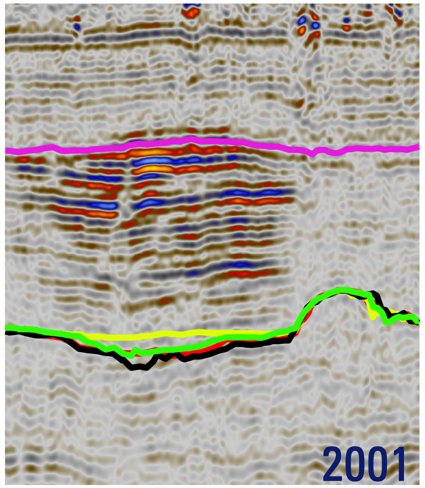


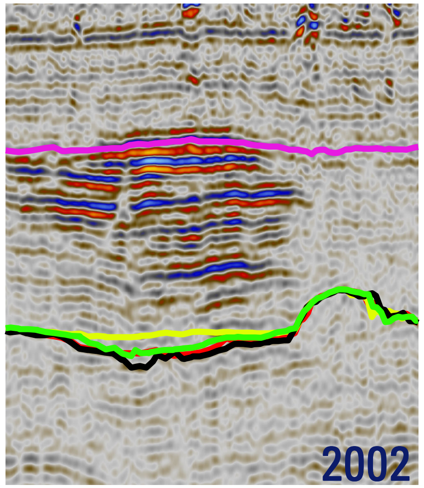
CO_2 Injection Start: Sept 1996
4D Seismic Survey



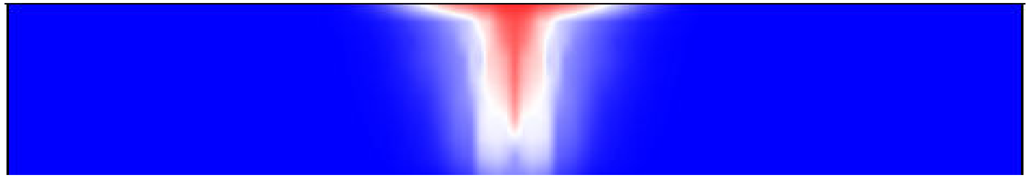
Baseline Survey



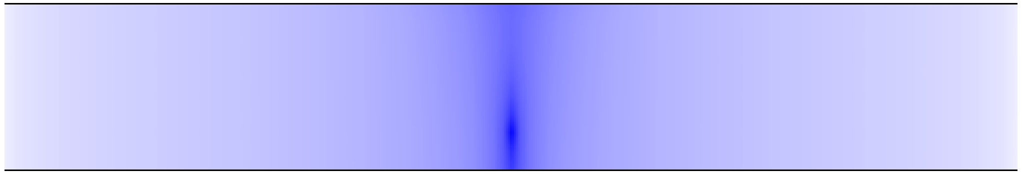




Sleipner: Homogeneous Model

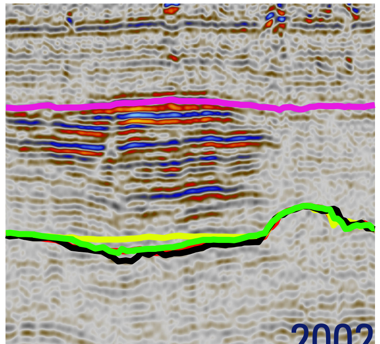


CO_2 Saturation Distribution



Pressure Distribution

Does not match observed data



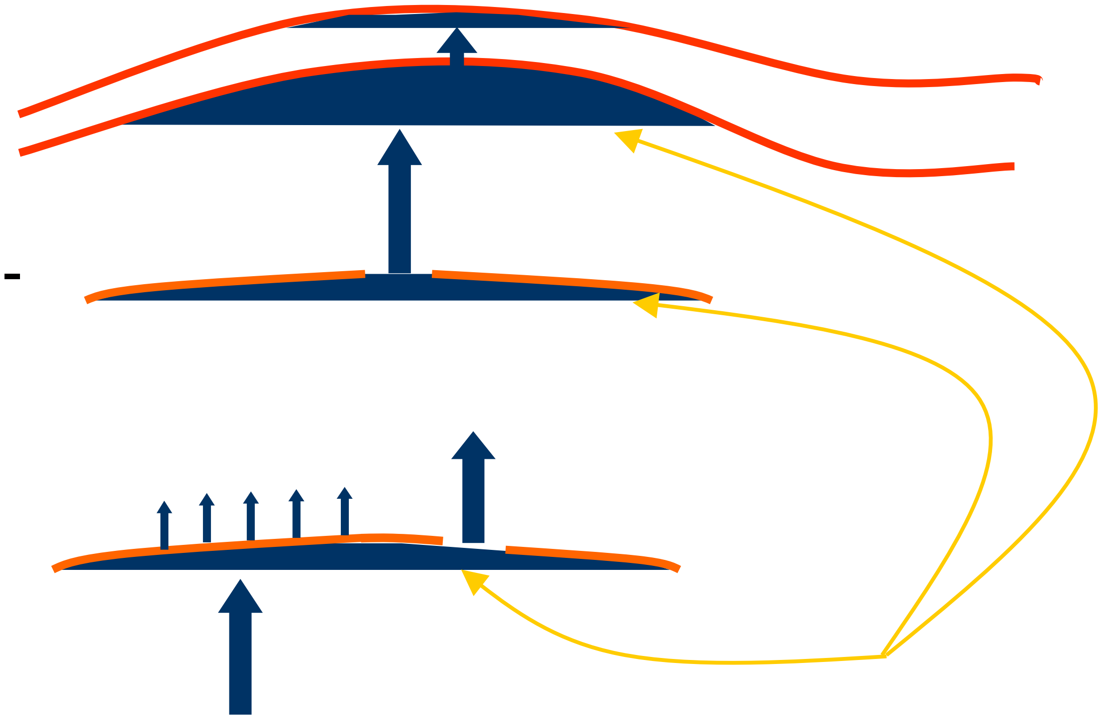
No confidence in long-term prediction of CO_2 fate and storage integrity, performance & risk analysis

Interpreted flow pattern

- Vertical flow:
  - through holes, faults

  or

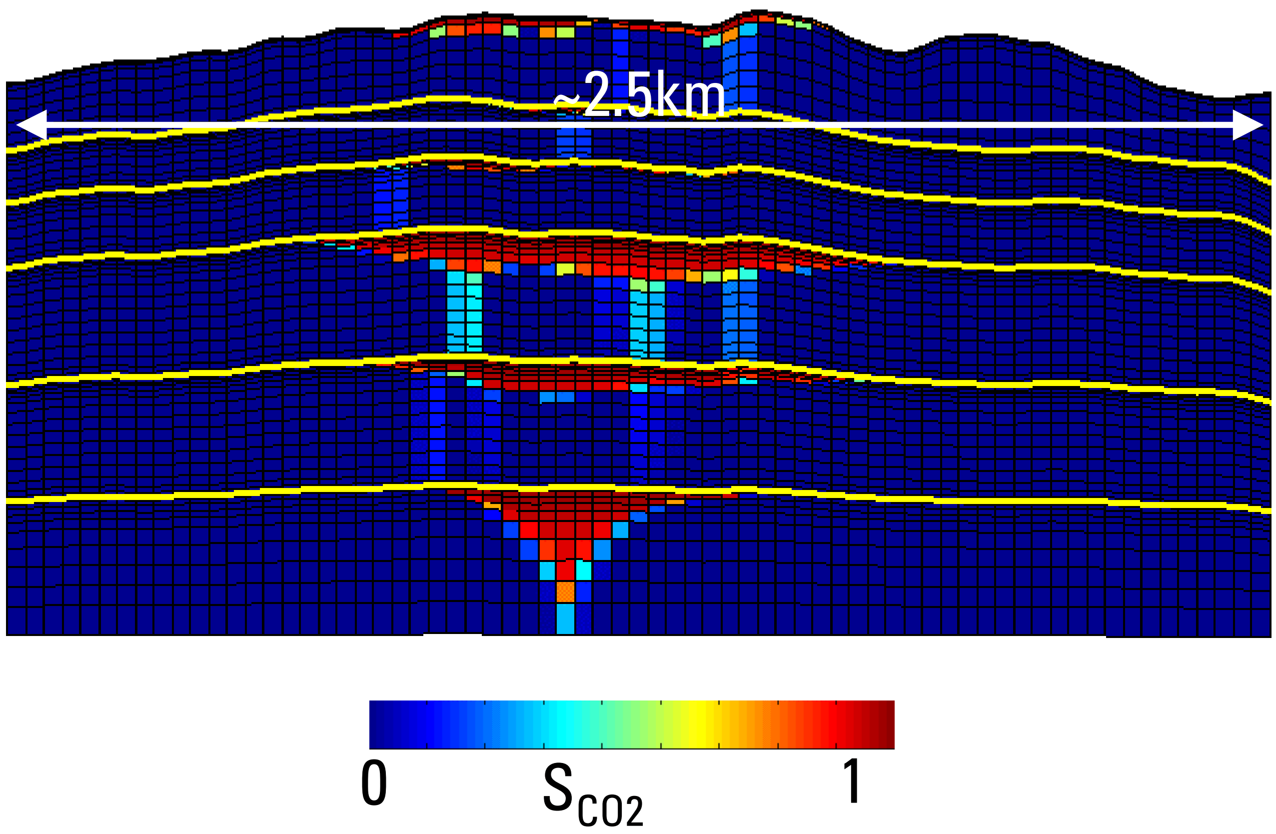
  - migration through semi-permeable layers
- Verify and improve seismic interpretations
- Calibration for long term flow simulations
- Is all CO_2 observed by seismic?



Schlumberger

Reservoir Flow Model

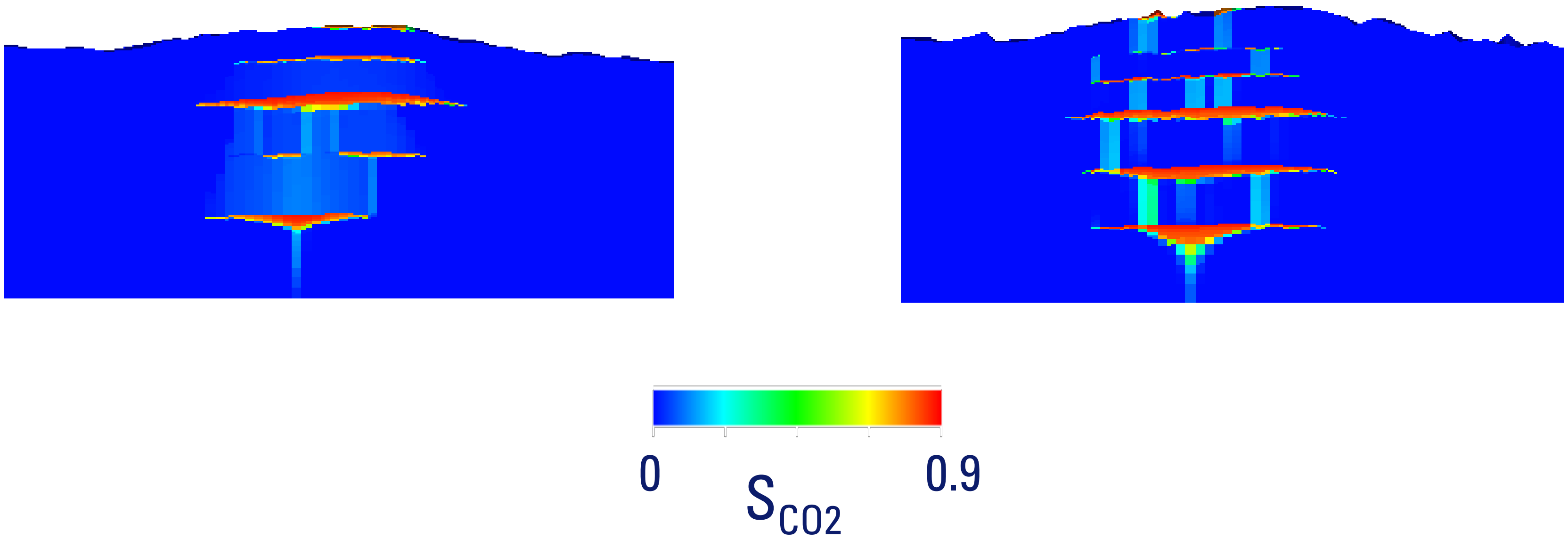
- 428 400 cells
- Shale layers modeled as transmissibility multipliers
- Homogeneous rock properties



SINTEF

Schlumberger

Matched Models

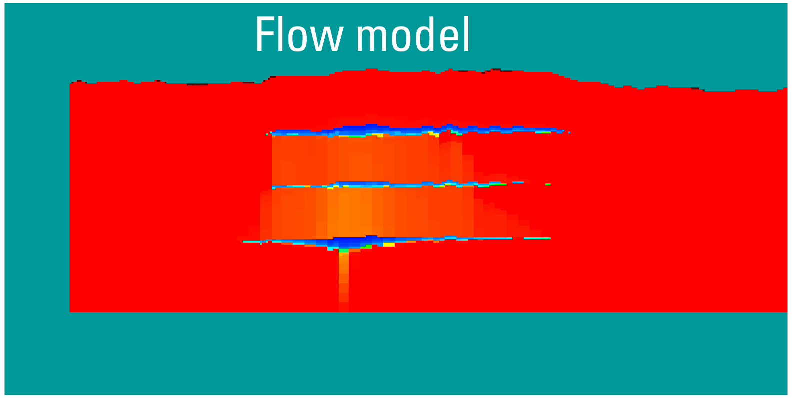


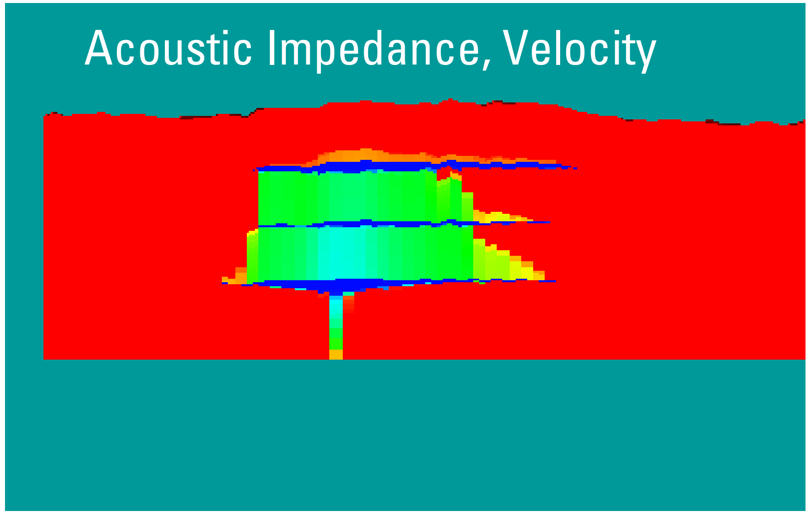
Model I: Semi-permeable layers.
Dispersed flow between the layers

Model II: Impermeable layers with high-permeable holes.
Flow only in chimney-like structures

Can the 4D seismic distinguish between the models?

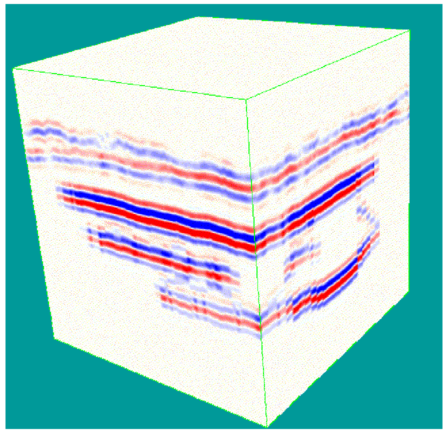
Synthetic Seismic



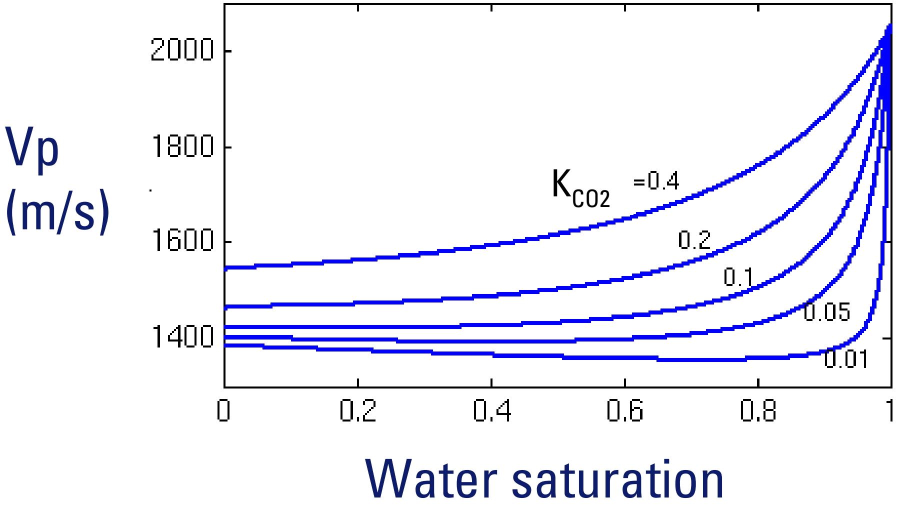


+

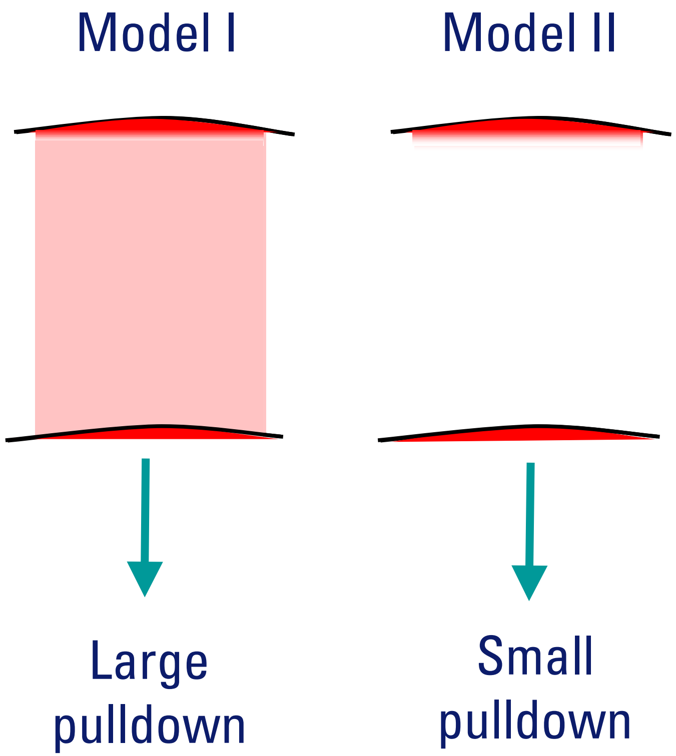
Rock-physical transforms
$V_p=V_p(S_{water},P,...)$



Rock Physics & Pulldown

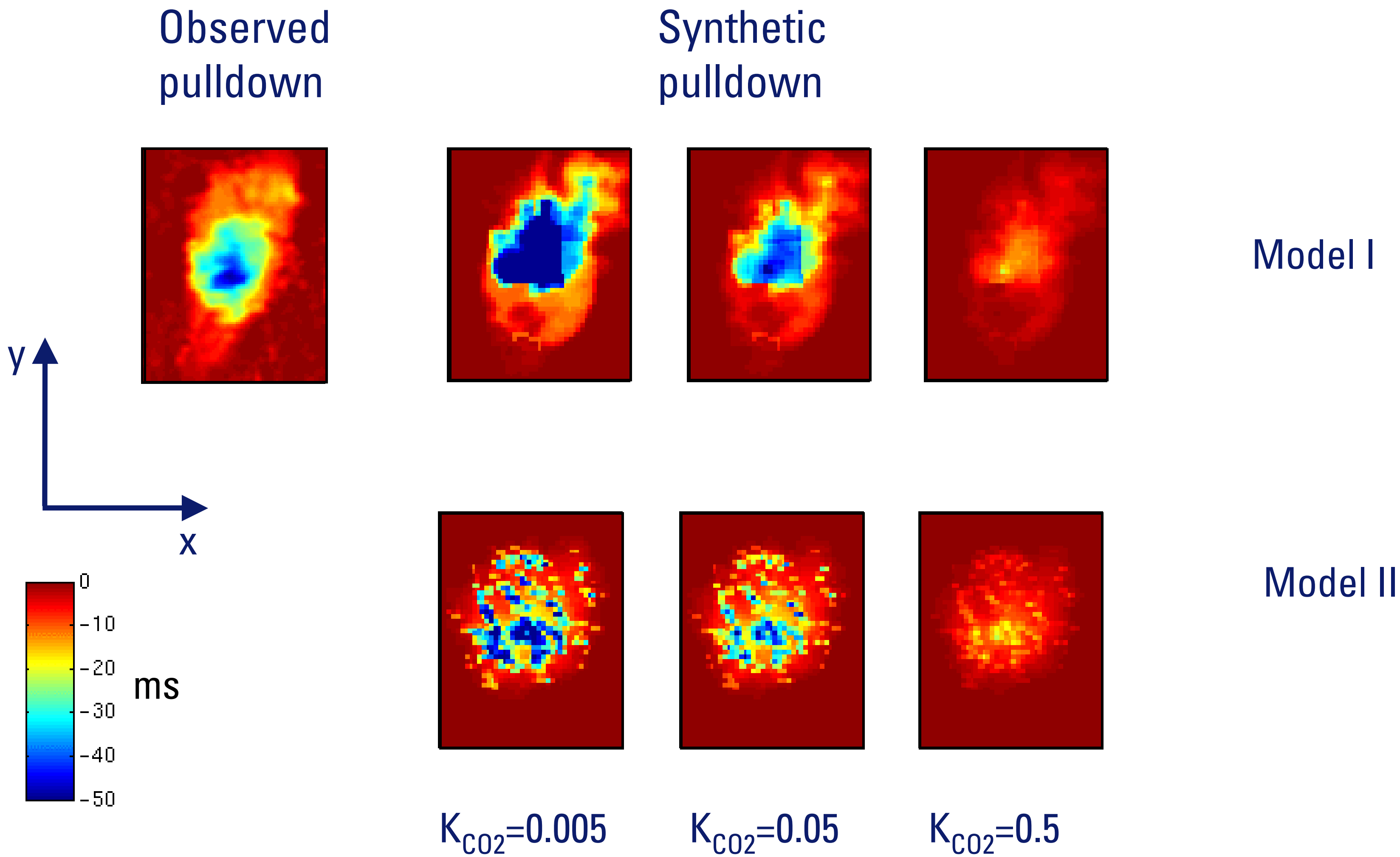


K_{CO2} = CO_2 bulk modulus

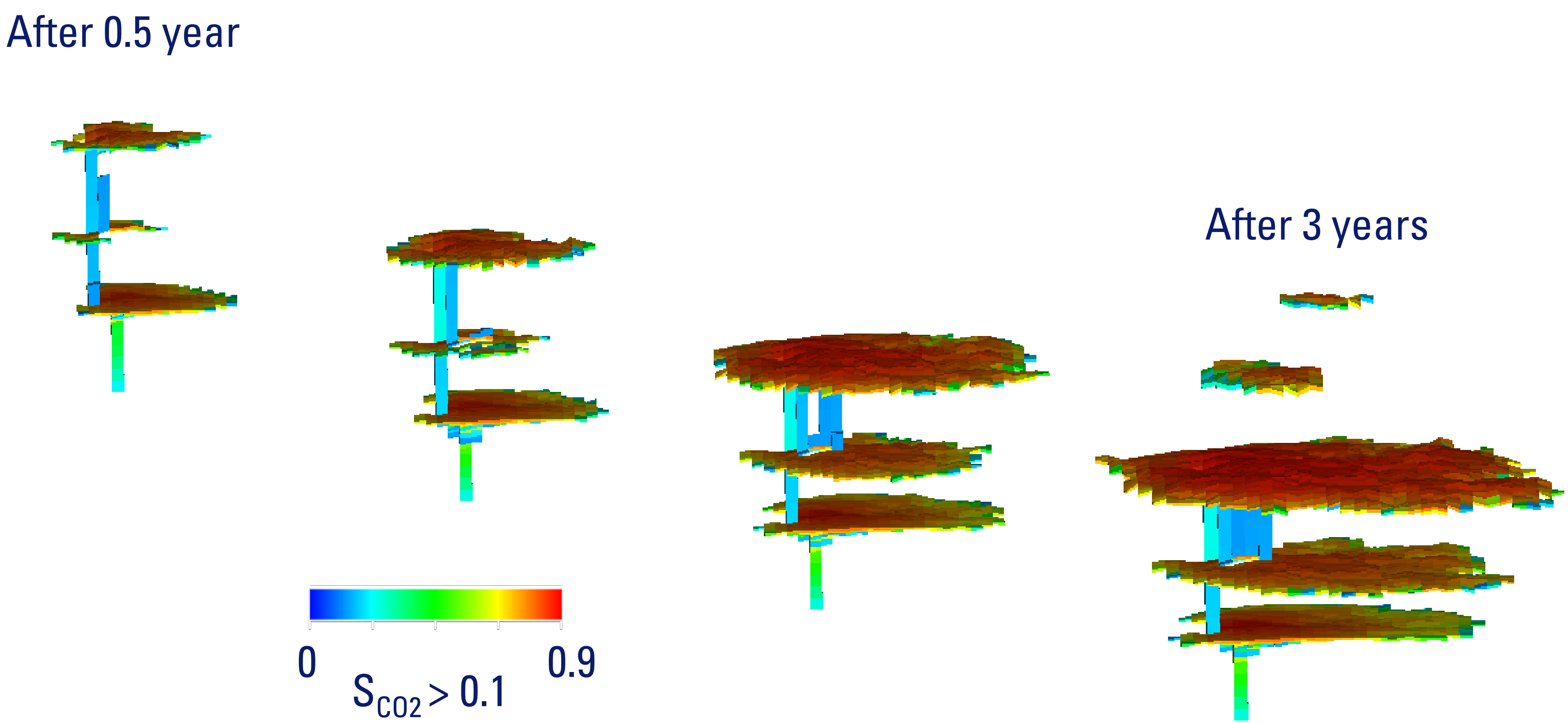


Schlumberger

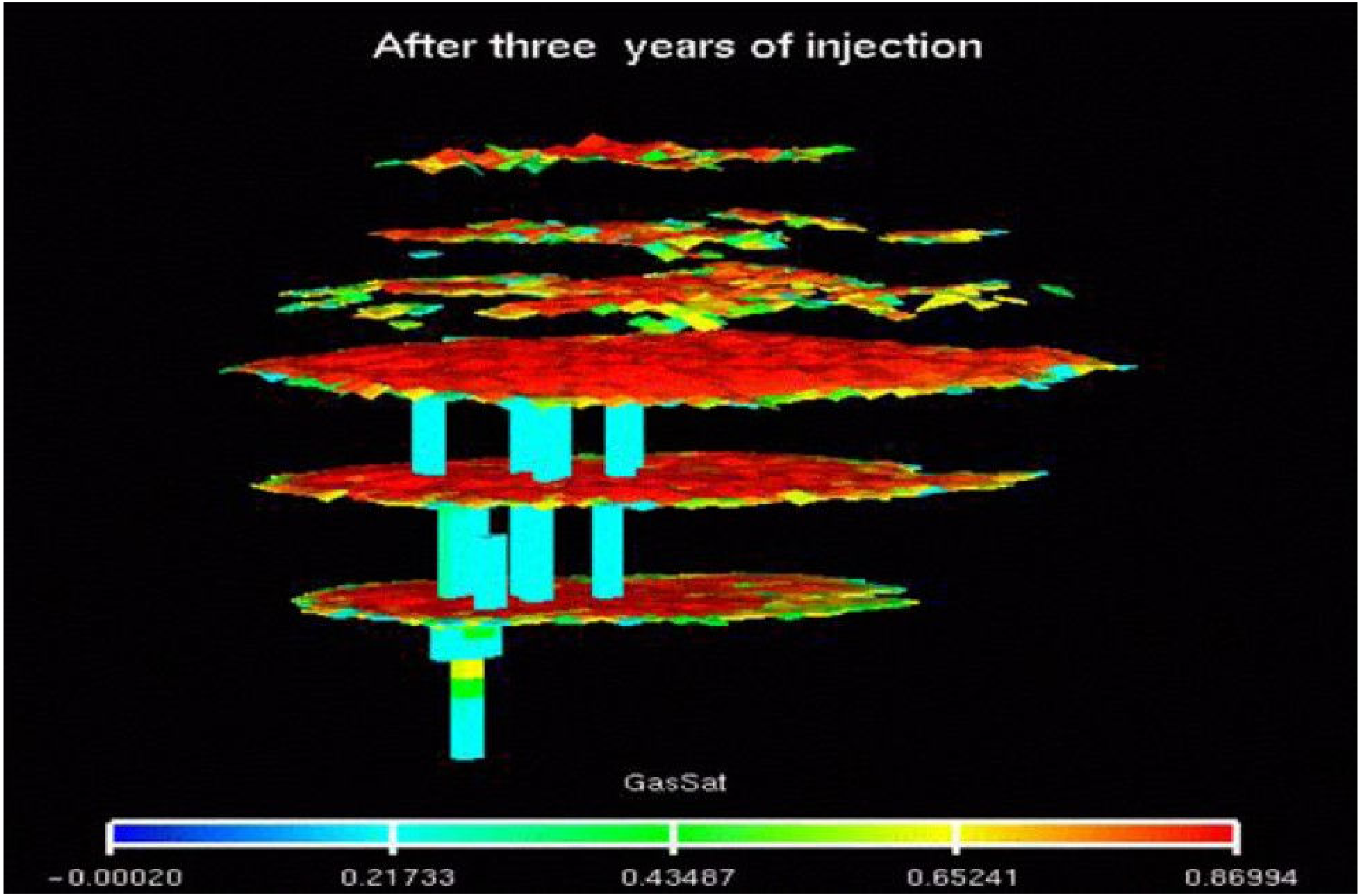
Real and synthetic pulldown - 2001 seismic



Simulated CO_2 Distribution



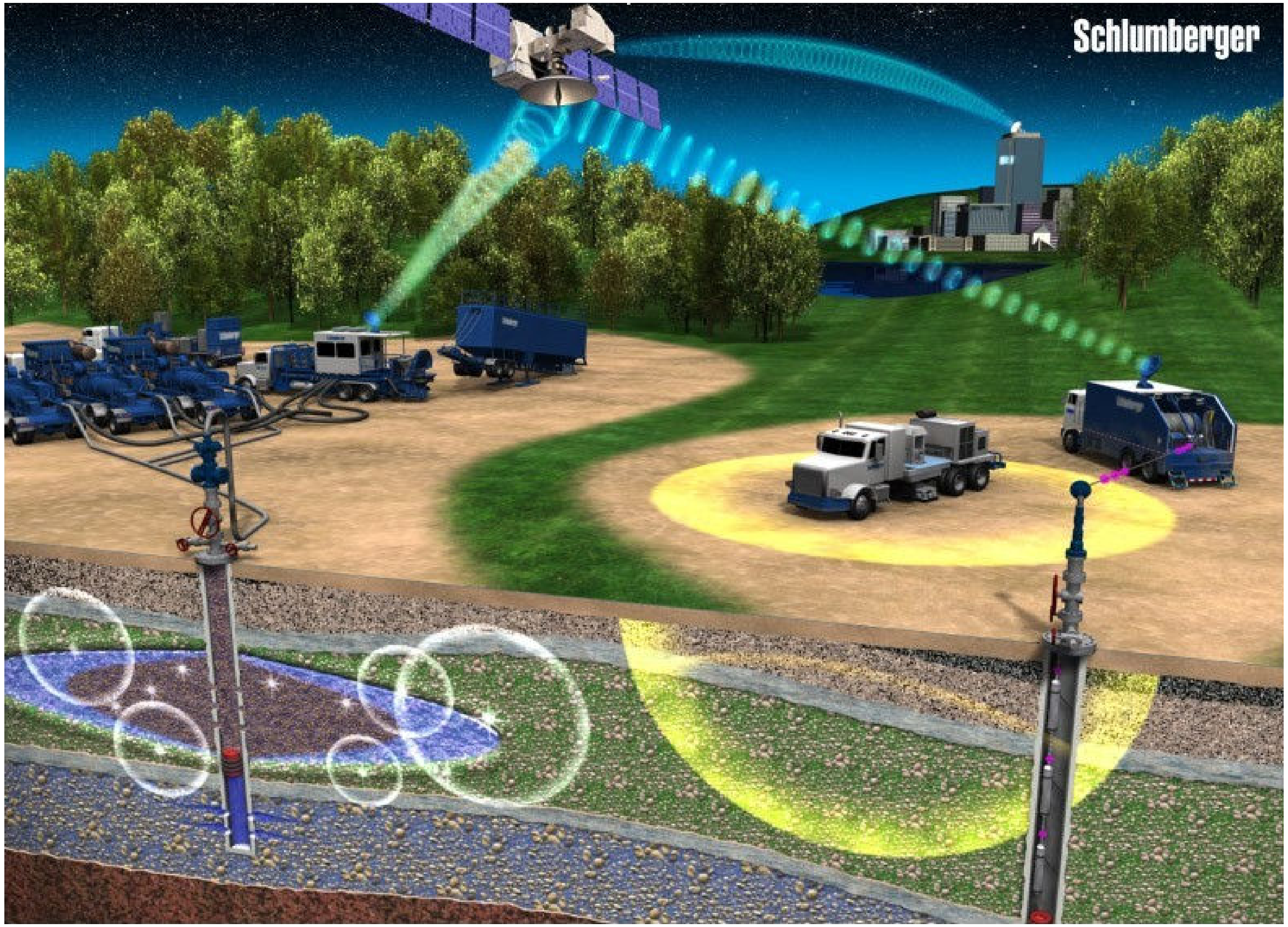
Sleipner CO_2 Plume – 800 m wide – 200 m high



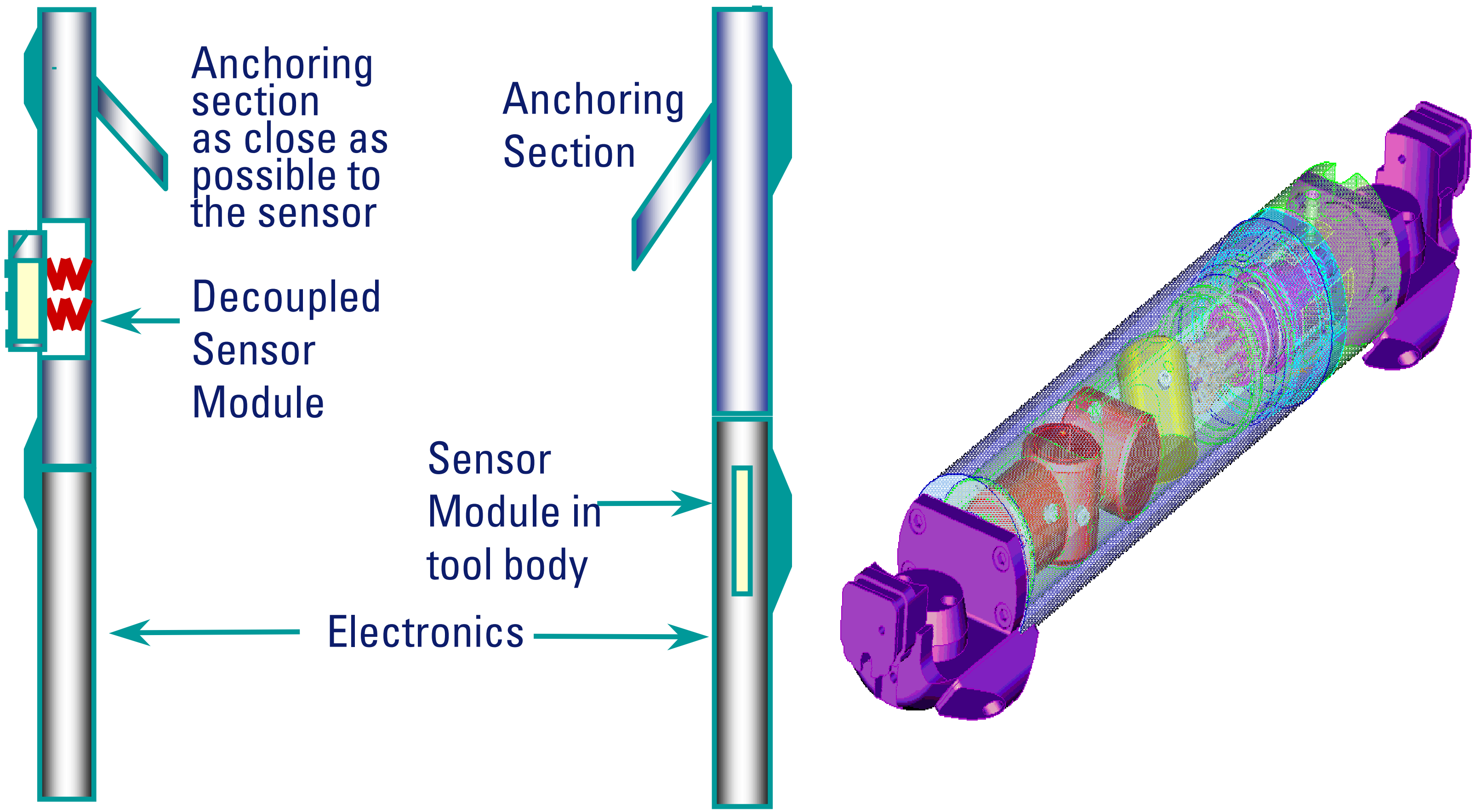
Microseismics

Main applications:

- Injection control
  - Avoid fracturing cap rock
  - Control CO2 displacement
- Fault Re-activation



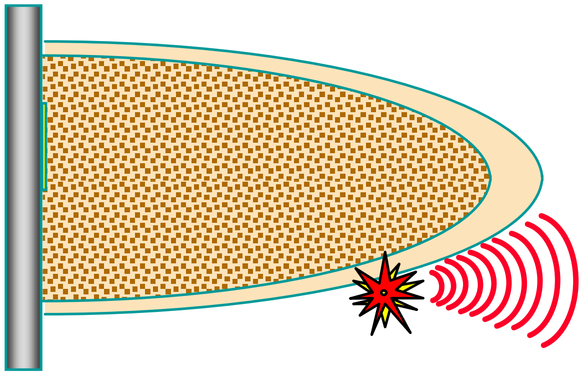
Microseismics – Versatile Seismic Imager (VSI)

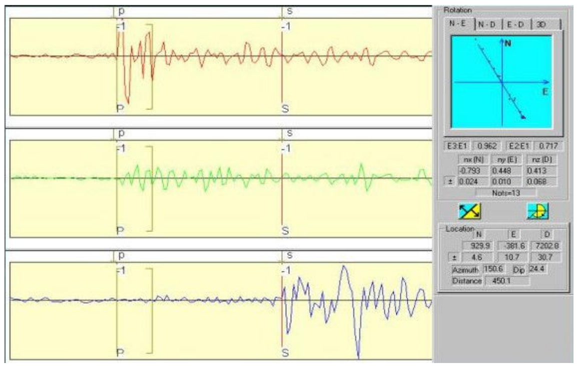


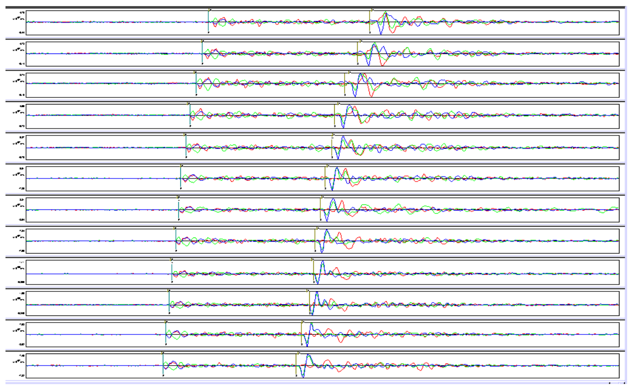
Schlumberger

Microseismics

From Microseismic Event …

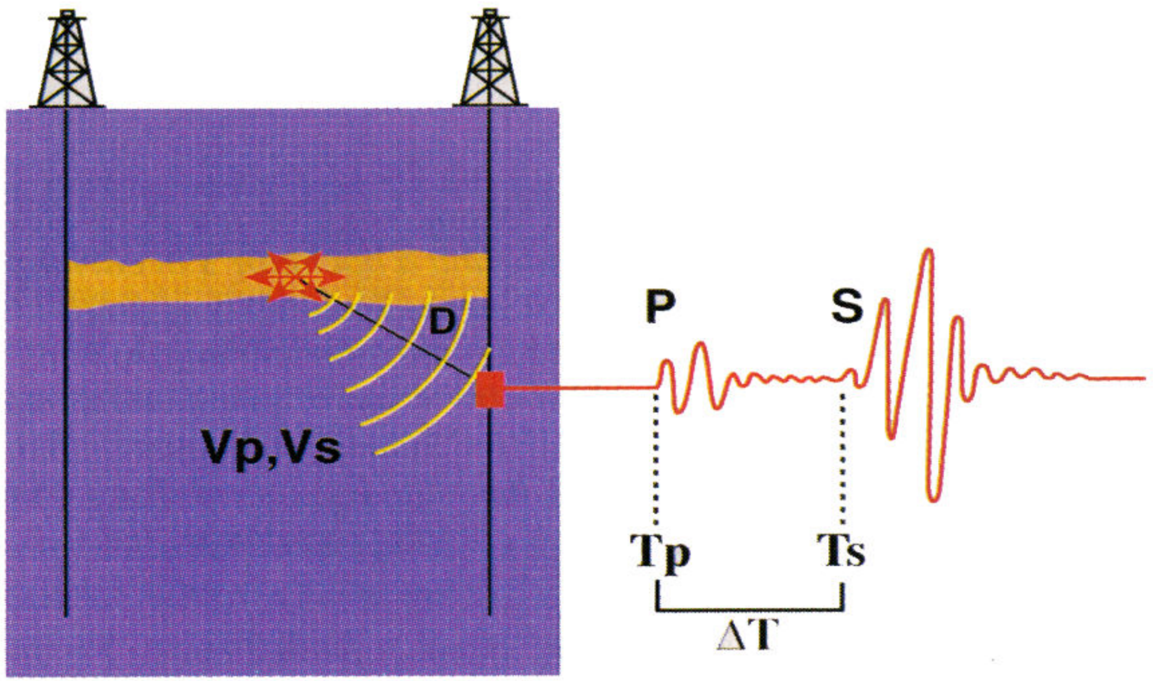




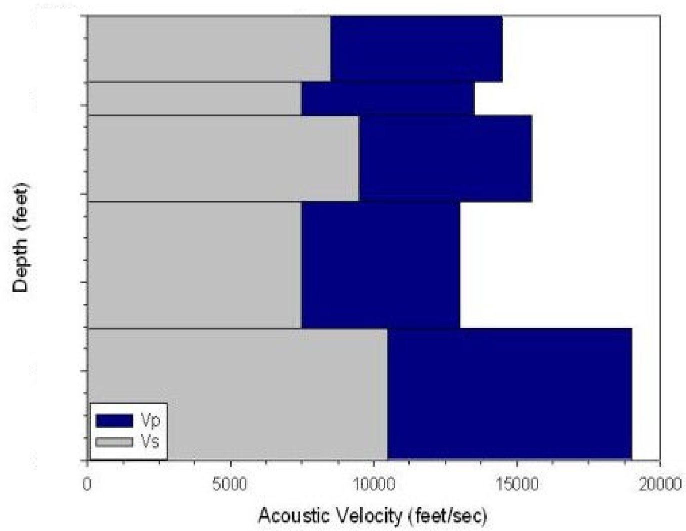


Microseismics

From Microseismic Event … to X, Y, Z Location

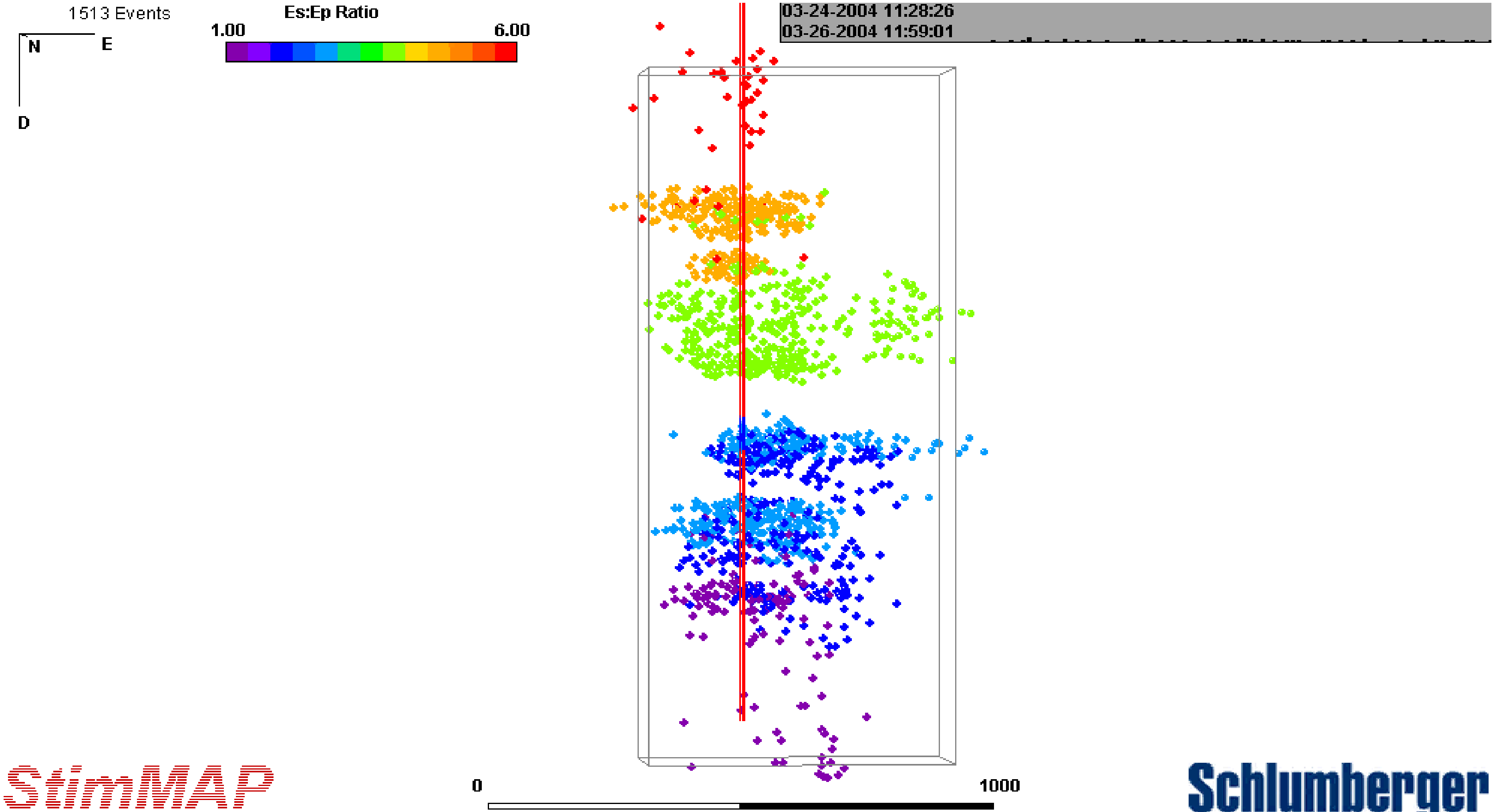


$$\Delta T = Ts - Tp$$
$$D = \Delta T \, Vp \, Vs / (Vp - Vs)$$



Schlumberger

Monitoring Fractures



StimMAP

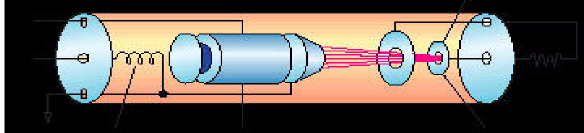
Schlumberger

The Reservoir Saturation Tool (RST)

Specifications

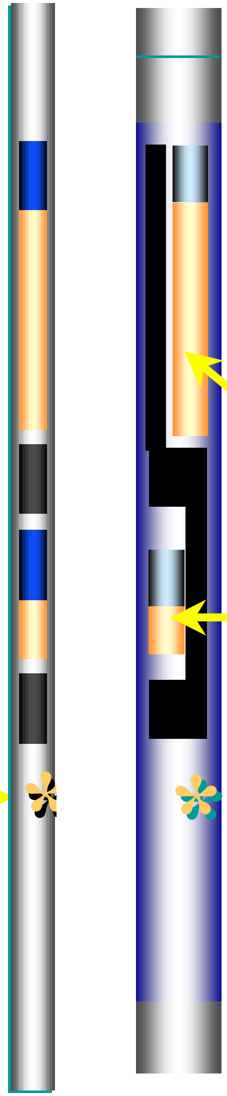
Pressure	15 kpsi
Temperature	300 degF
Diameter	1.710 in.
Diameter	2.505 in.
Min tubing	2 $^{3}/_{8}$-in. API
Min tubing	3 1/2-in. API
Min restriction	1.813 in.
Min restriction	2.625 in.
Tool length	23 ft
Tool weight	101/208 LB

NEUTRON GENERATOR



Minitron

- High neutron yield
- Gain Regulation
- Precise neutron burst control



1 11/16" RST

2 1/2" RST

Answers

C/O

Sigma

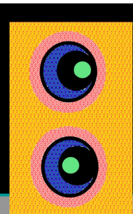
(Porosity)

Lithology -SpectroLith

Water Flow Log (WFL)

Phase Velocity Log (PVL)

Three Phase Holdup Log



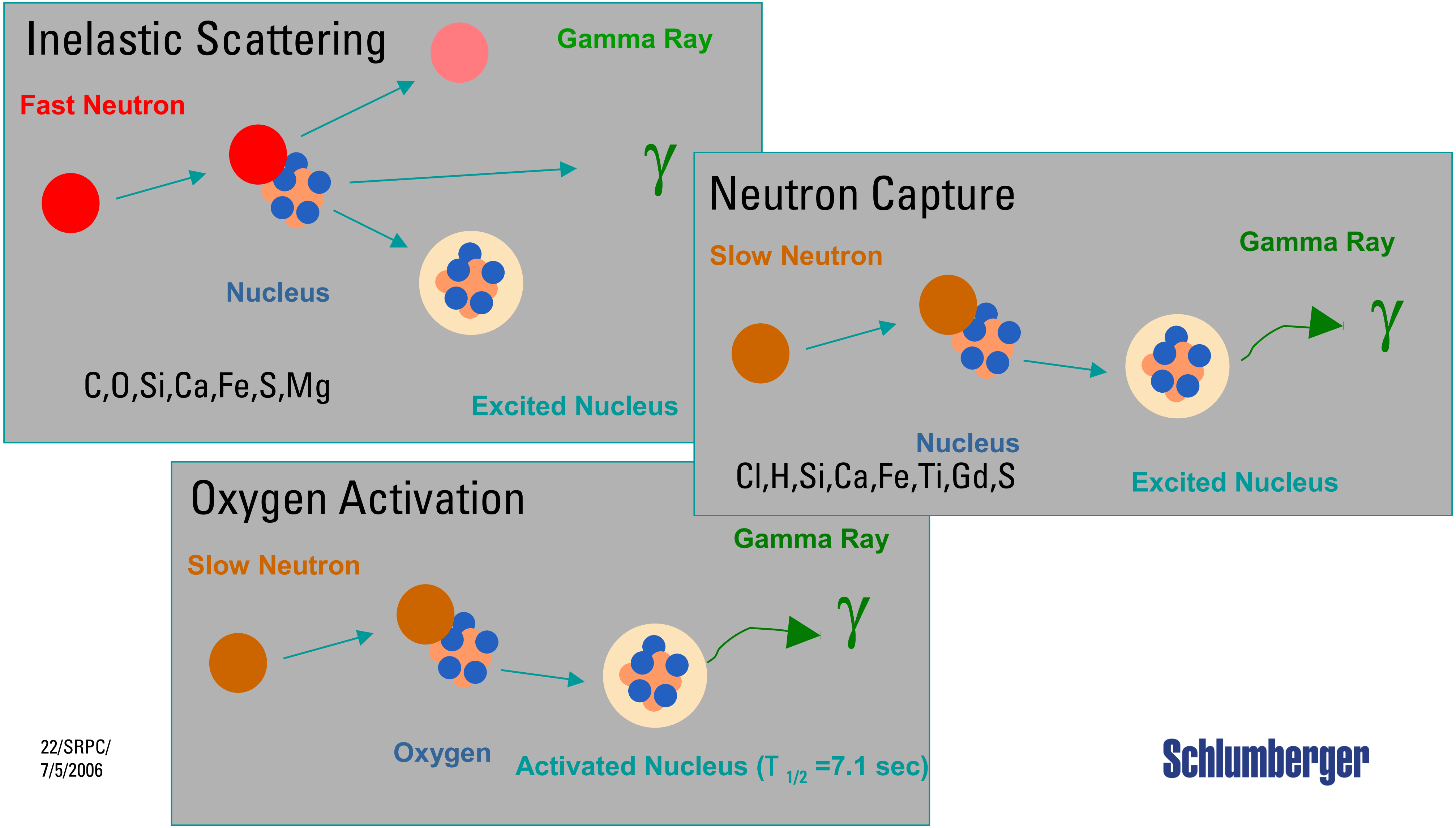
GSO

GSO detectors

- Offset & shielded detectors for flowing wells
- Efficient gamma ray detection
- High count rate with little spectrum distortion

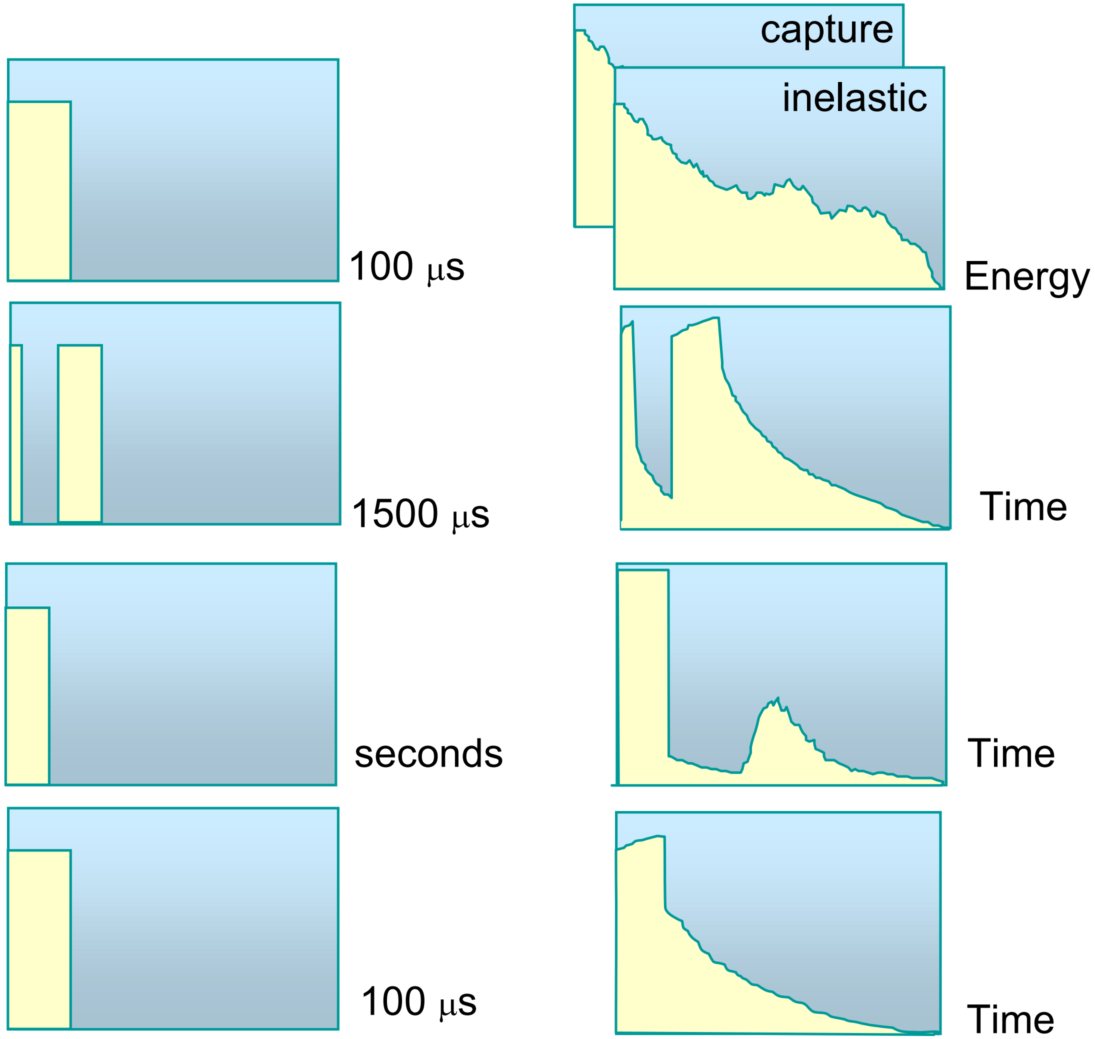
Schlumberger

Nuclear Measurement Theory



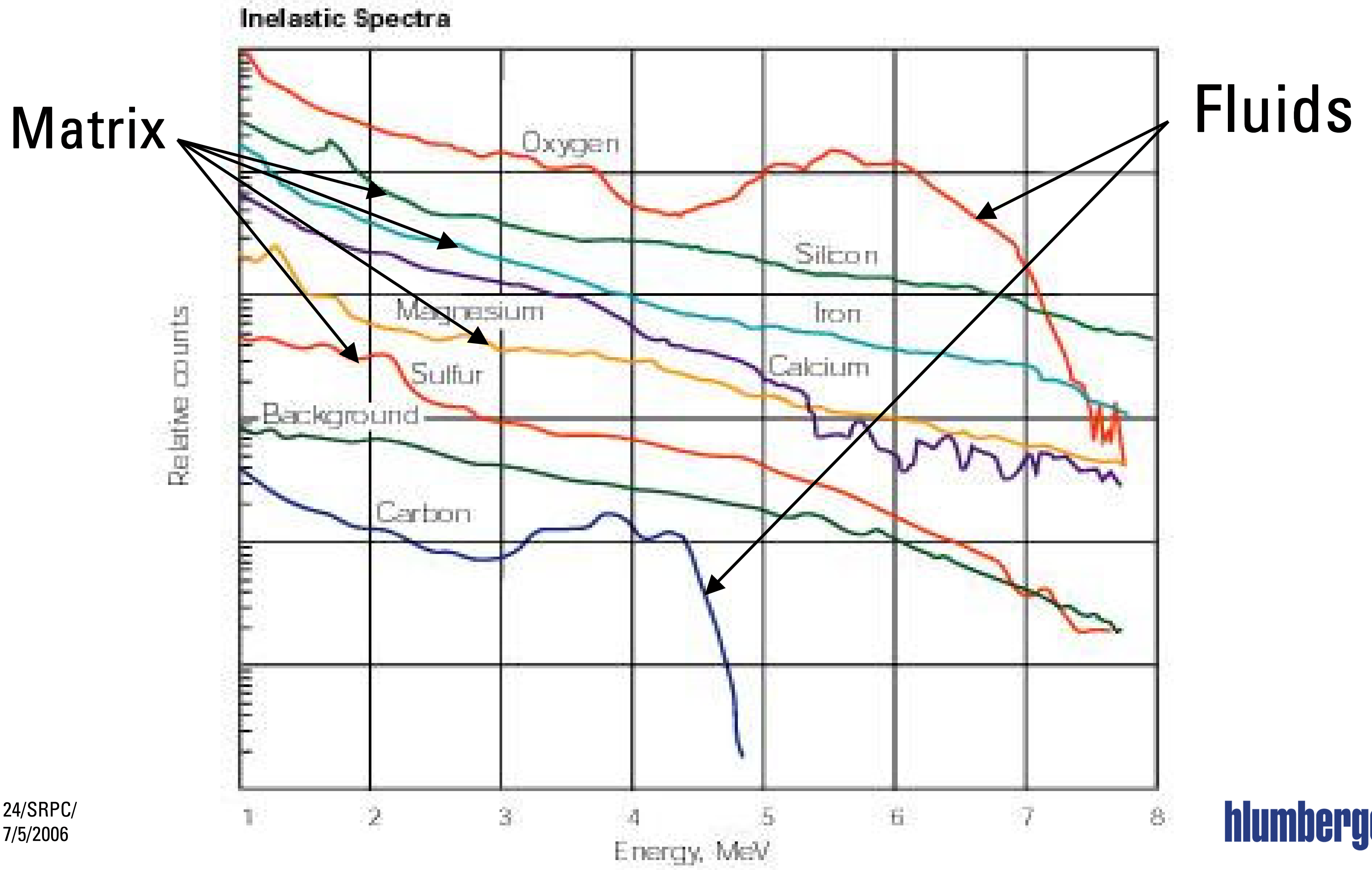
Measurement Modes

TOOL MODE | **NEUTRON PULSE** | **GAMMA-RAY SIGNAL** | **MEASUREMENTS**

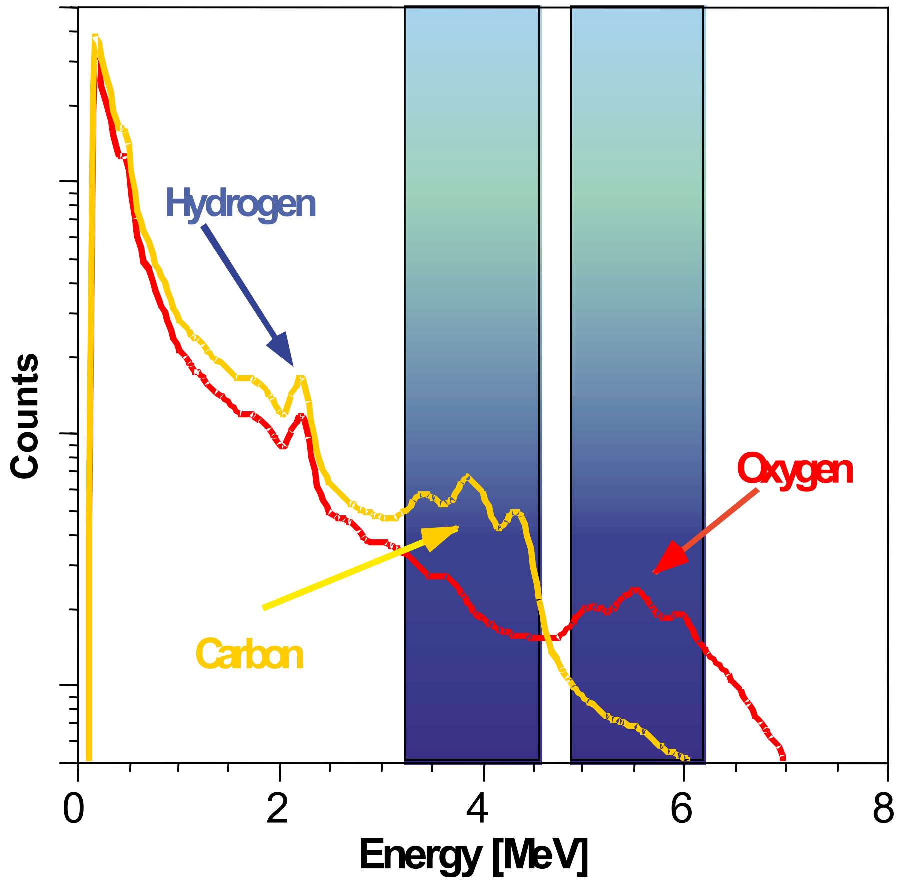


TOOL MODE	MEASUREMENTS
IC	**Inelastic/Capture Log** • C/O Saturation • Three Phase Holdup • Lithology
Σ	**Sigma/Porosity Log** • Formation sigma • Formation porosity • Borehole salinity
WFL	**Water Flow Log** • Water velocity • Water flow index
PVL	**Phase Velocity Log** • Oil or water velocity using marker fluids

Inelastic Spectral Standards



C/O Theory of Measurement

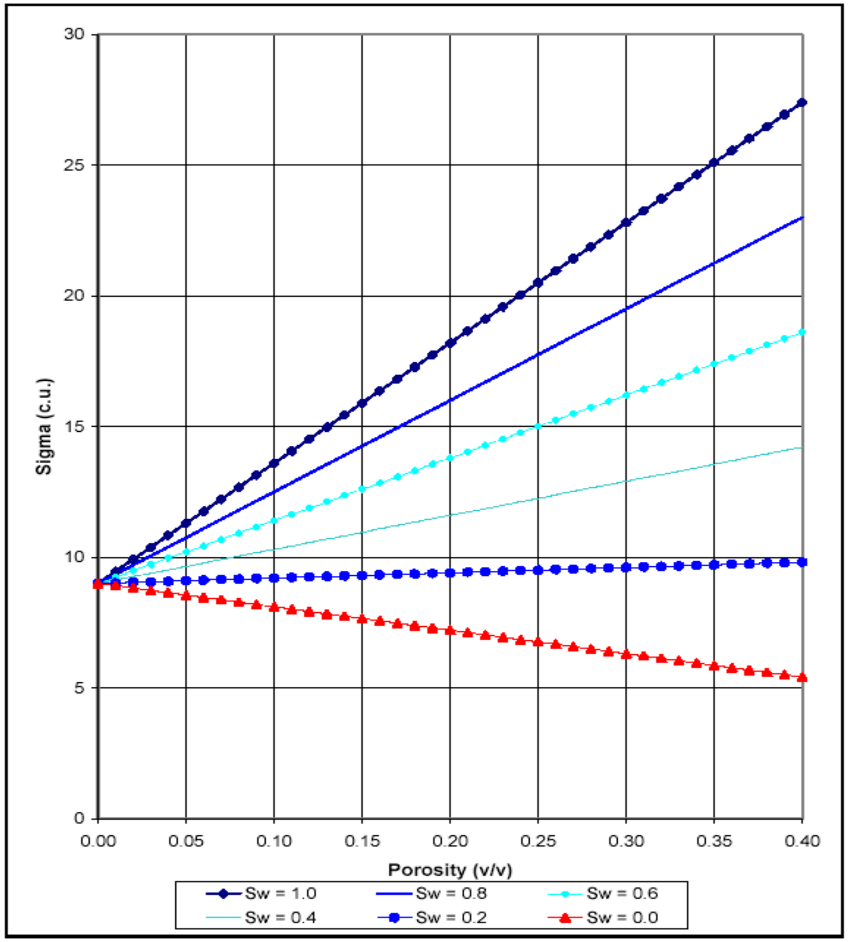


RST- A Inelastic Spectra
in Oil and Water
Elemental Yields
and Windows Ratio

Schlumberger

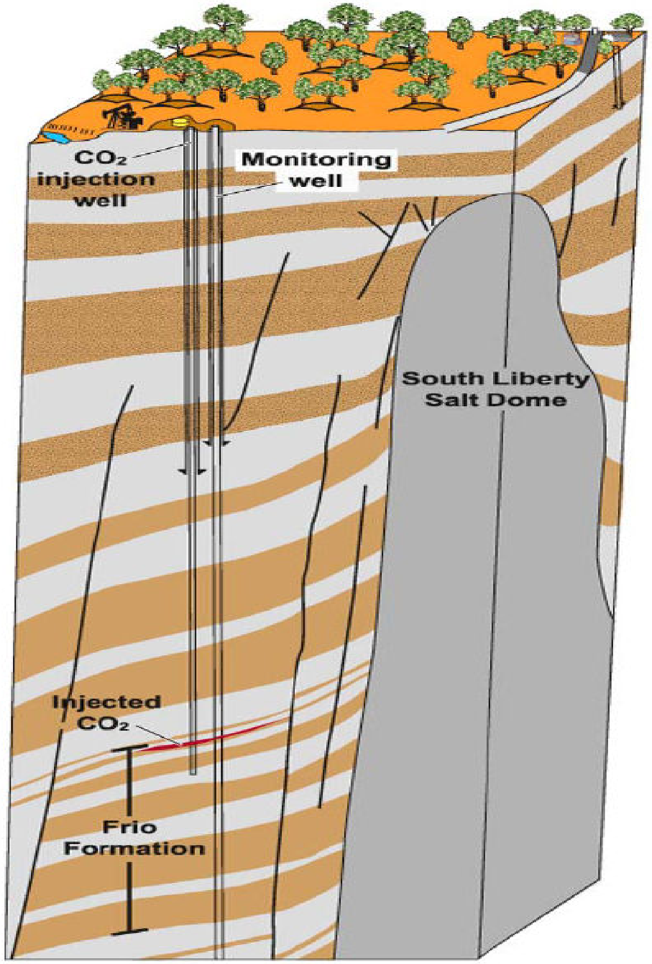
Monitoring Using RST – Σ Measurement

- Crossplot porosity – Σ, with water and CO_2 saturations
- CO_2 and Water Σ values
  - CO_2 (0.3 c.u.)
  - Water (55 c.u.) (@ 93,000 ppm)



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

CO_2 Monitoring Using RST – Frio Experiment

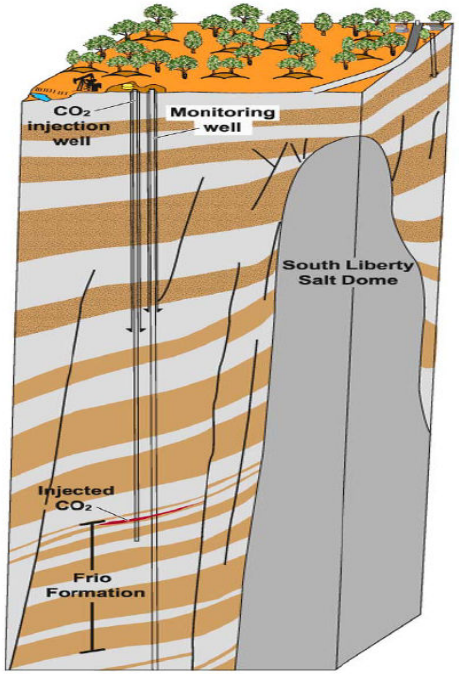


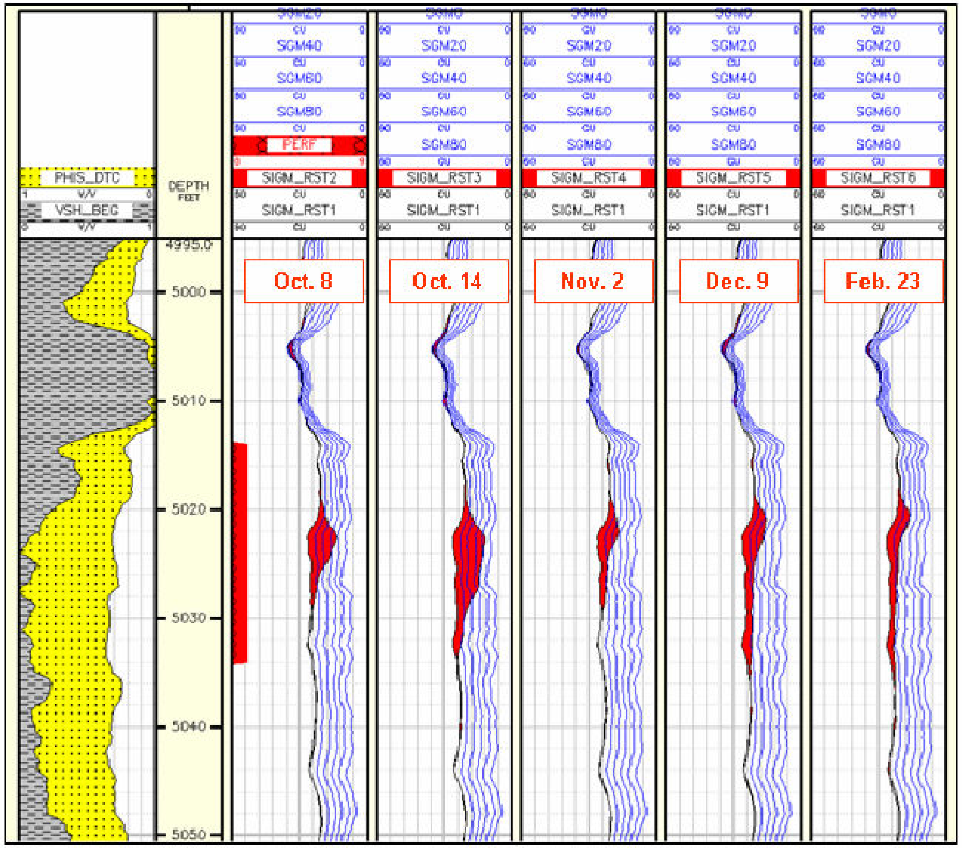
- Injection started on Oct 4th 2004, stopped on Oct 14
- 1,600 t CO_2 injected
- Target: Frio formation (~5000 ft deep)
- Sandstone
- High Salinity: 93,000 ppm
- High Porosity: 32-35 p.u.
- High Permeability: 2.5 Darcy (air)
- Injector-Monitoring well spacing: 30 m

Schlumberger

Monitoring Using RST – Σ Measurement

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



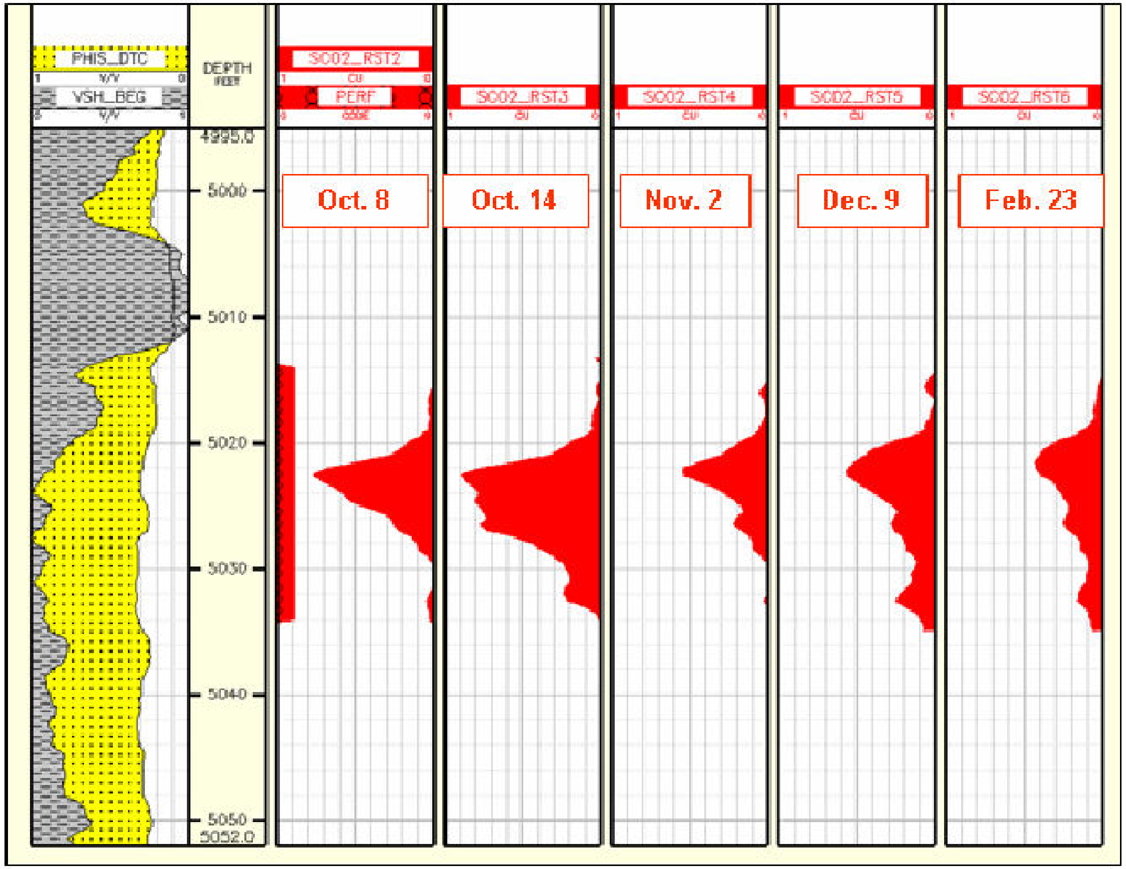


(*) Sakurai et al. , SPWLA 46th – June 26-29th - 2005

Schlumberger

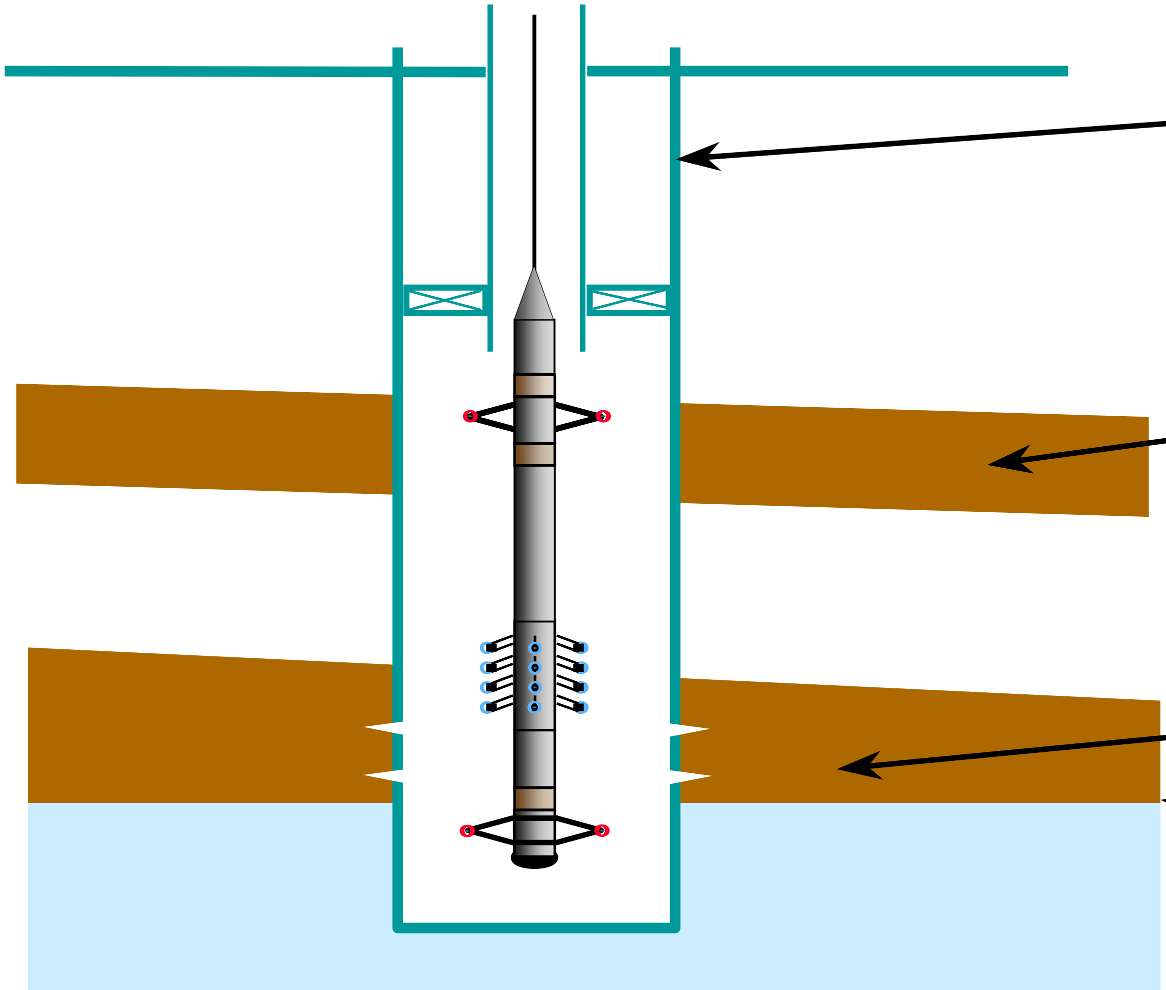
CO_2 Saturation Changes

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



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

Cased-Hole Formation Resistivity Applications



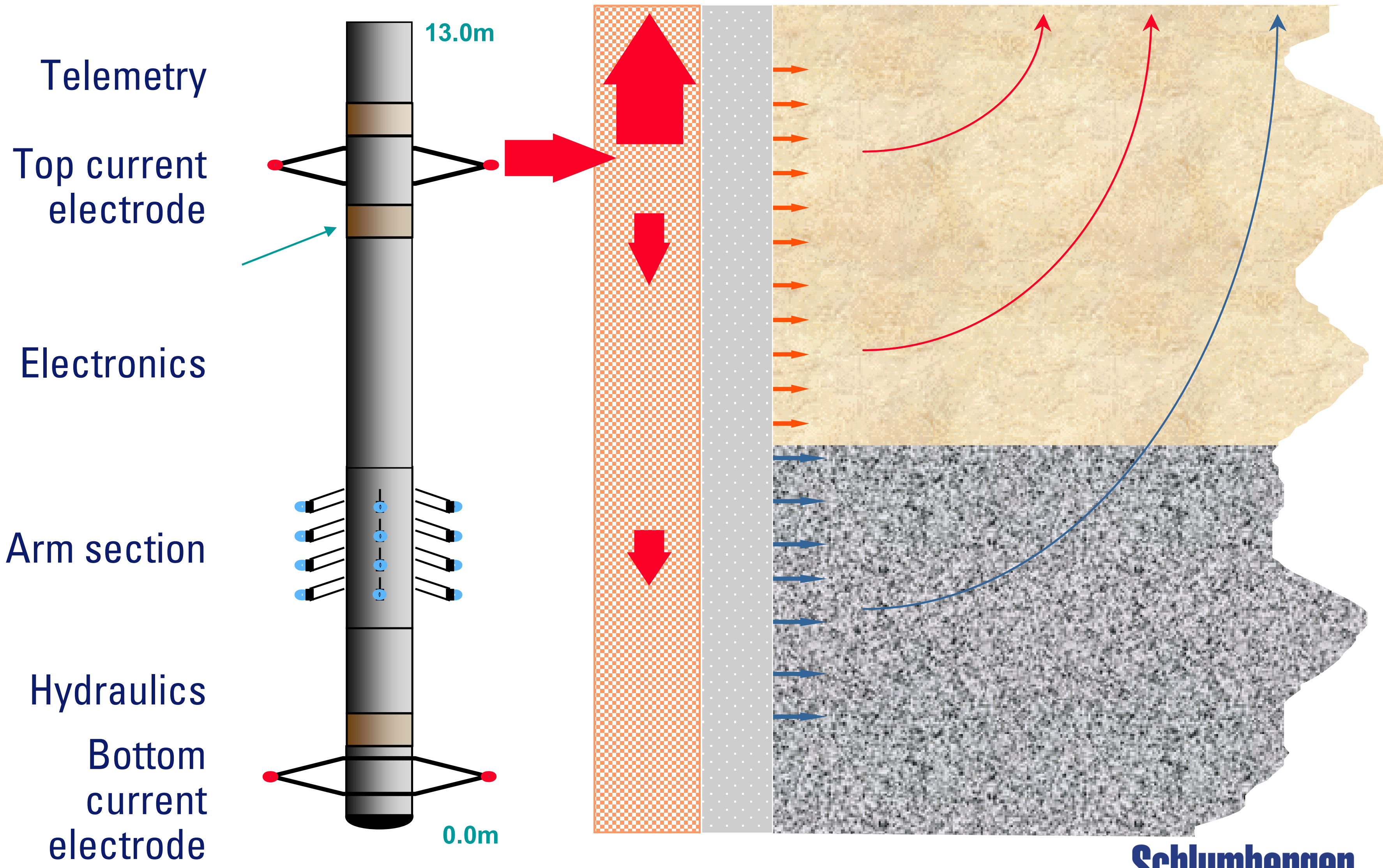
Primary evaluation
(no OH logs)

Location of bypassed
hydrocarbons

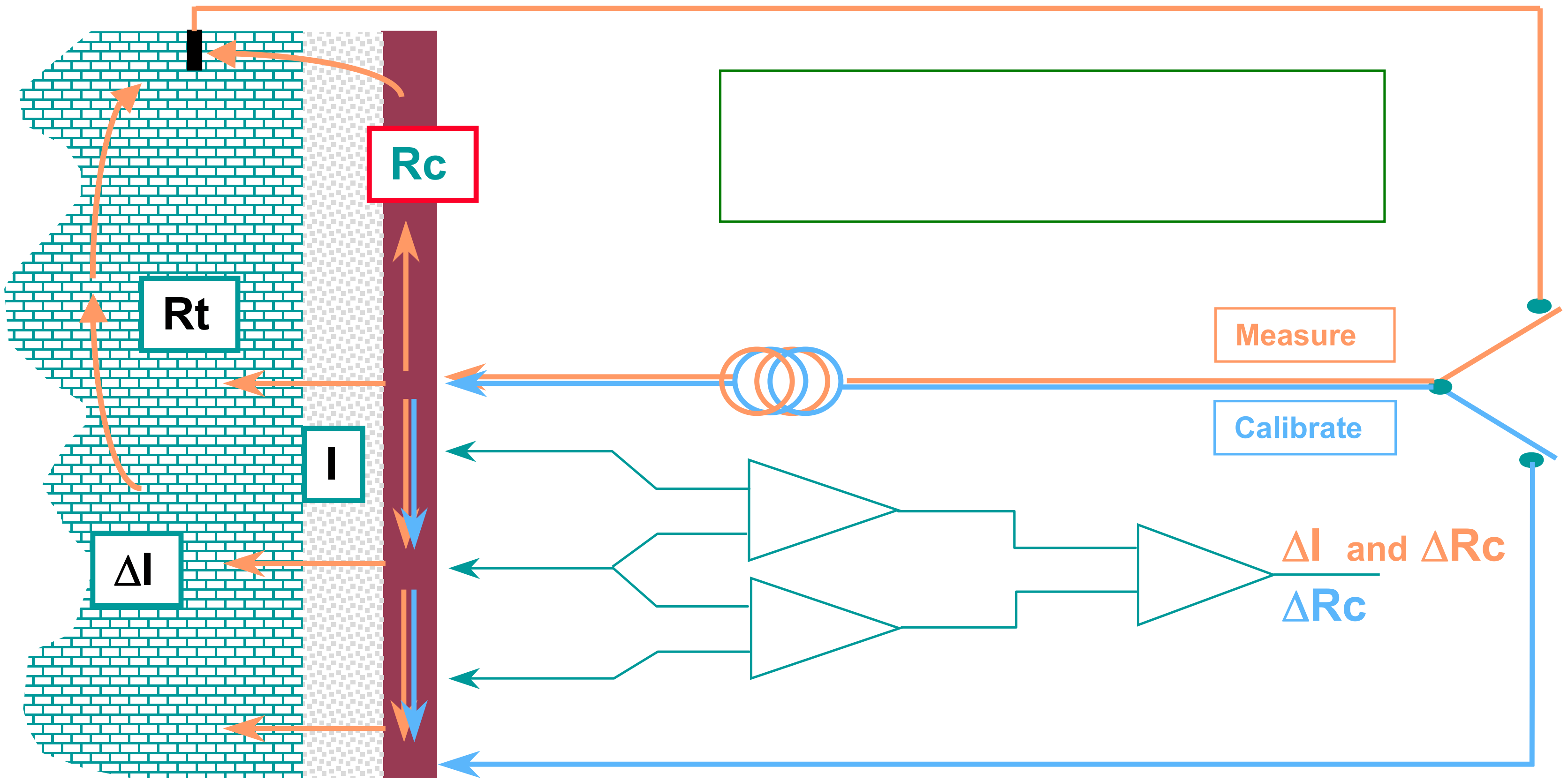
Residual Oil Saturation

Reservoir monitoring

CHFR Tool String



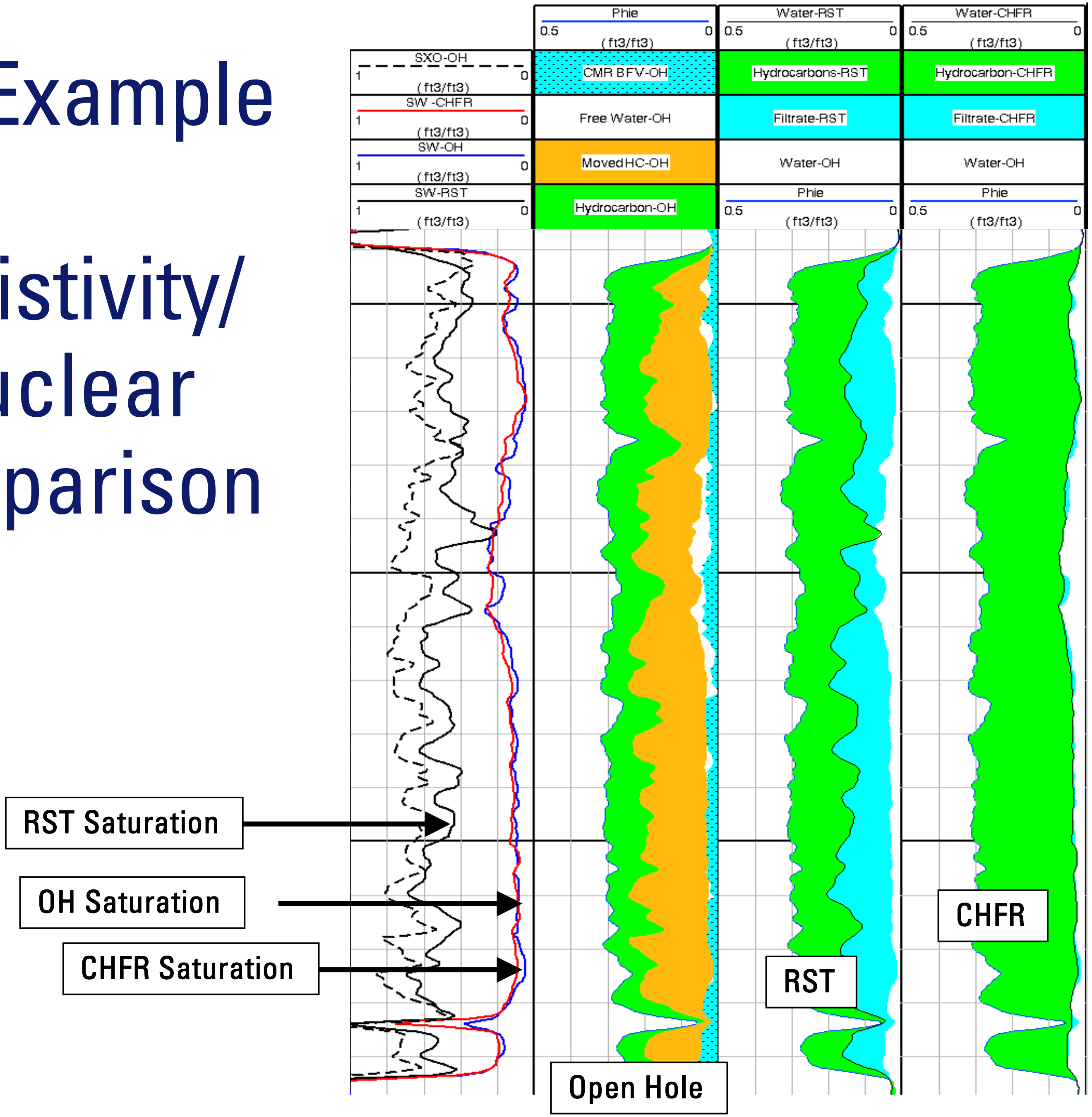
CHFR Principle



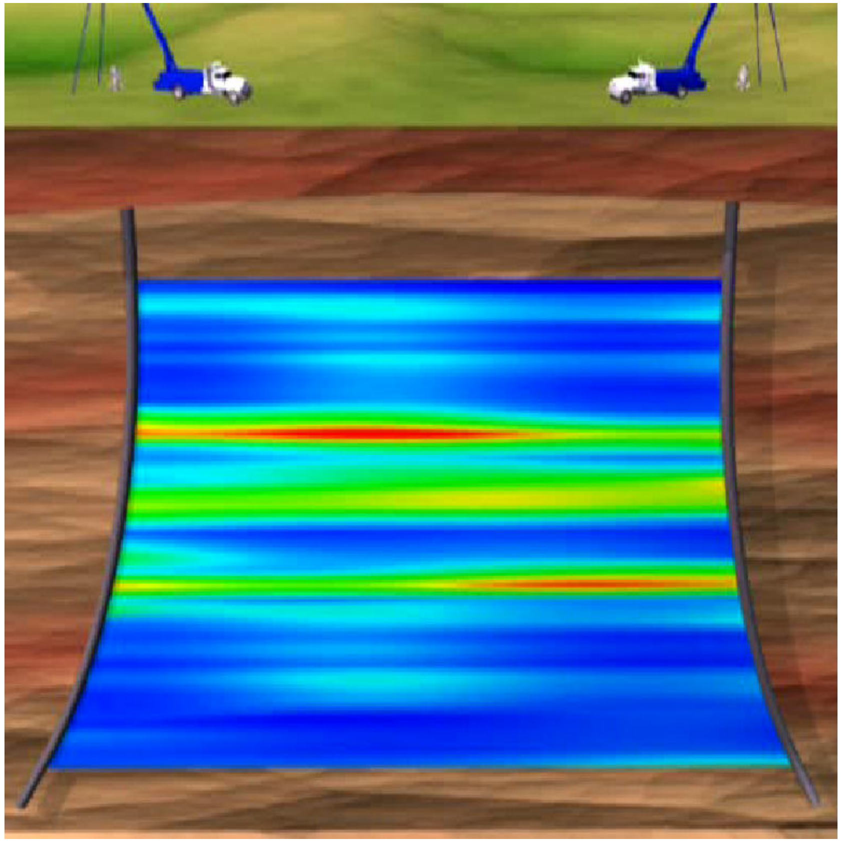
Schlumberger

Log Example

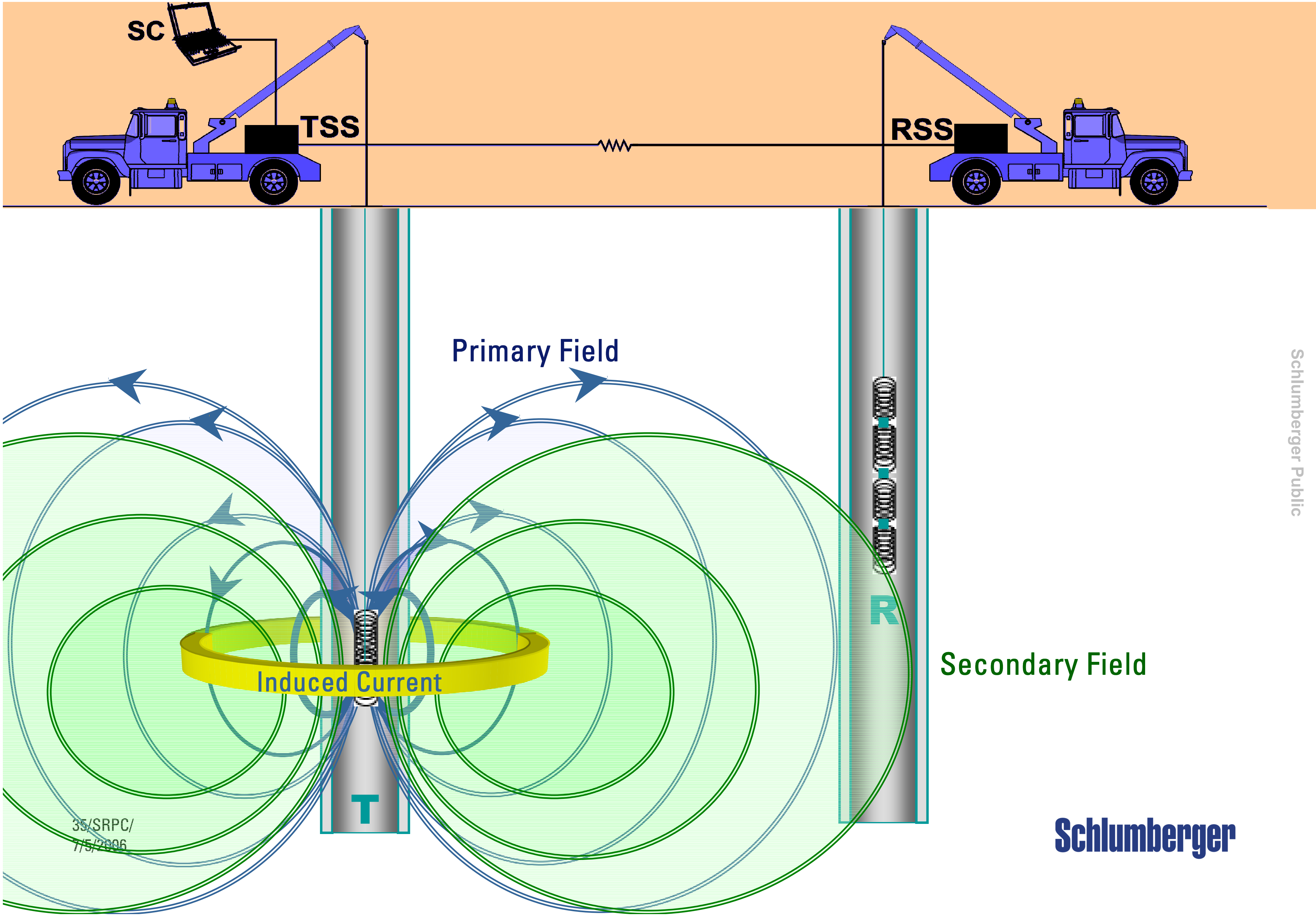
Resistivity/ Nuclear Comparison



Electromagnetic Cross-Well Surveys

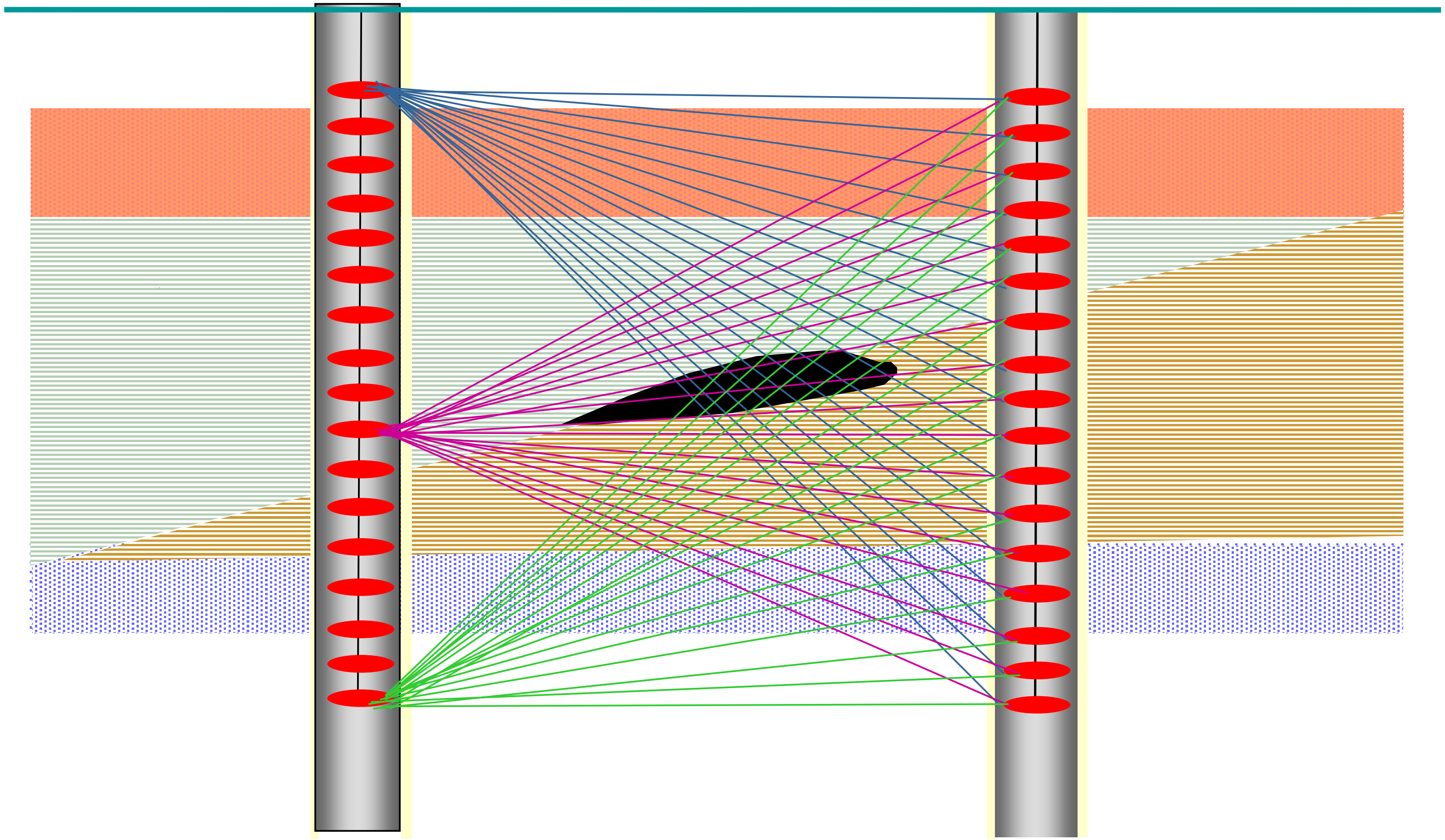


– Extension of induction logging
– Transmitter and receiver located in separate offset wells
    • Up to 1km spacing for OH
    • 300m for CH
– Construct a 2-D resistivity image



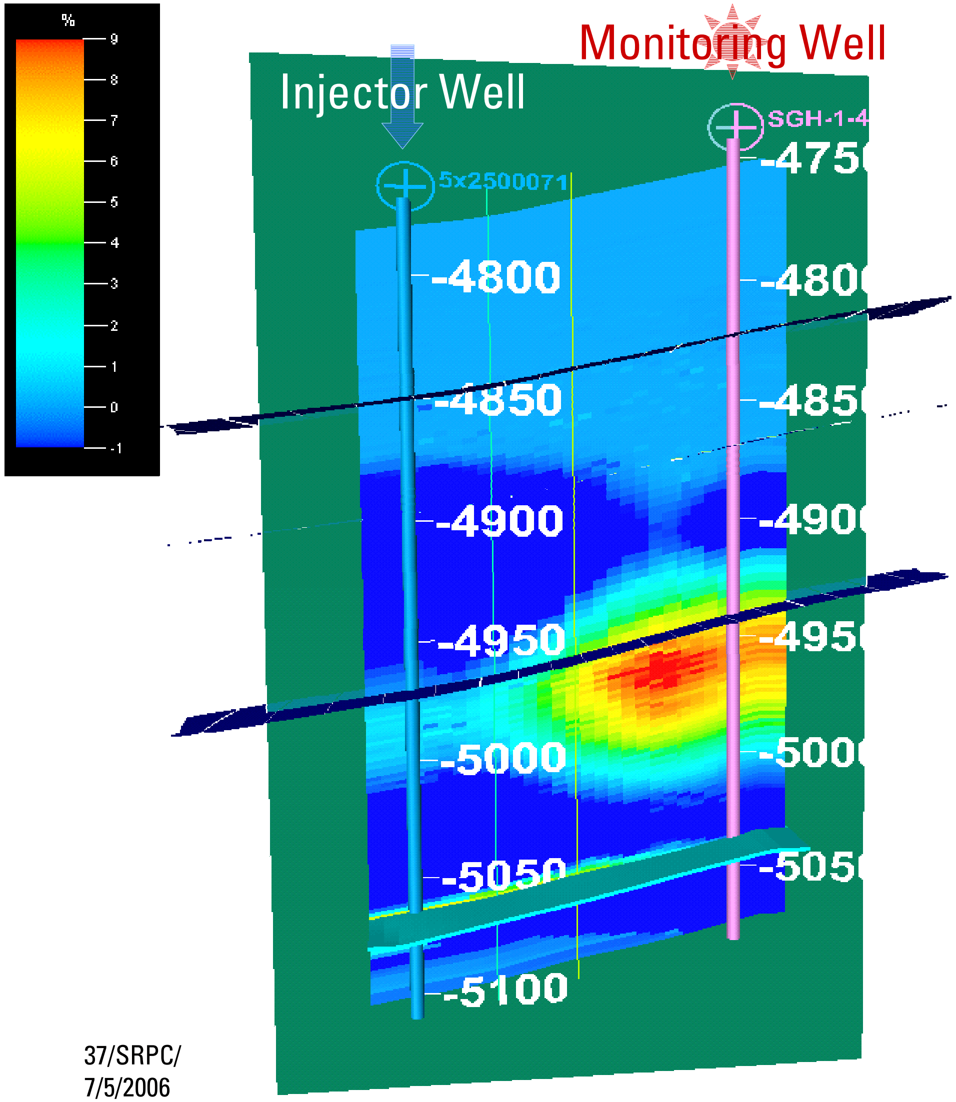
Schlumberger

Moving Transmitters
Many Receiver Stations



Schlumberger

CO_2 Storage in Frio Field, TX, USA



- August 2004: Crosswell Resistivity Baseline survey is acquired between the CO_2 Injector well and the monitoring well 30m away. Both wells are cased.
- October 2004: 1600m³ CO_2 are injected in the C-Sand layer.
- December 2004: A second Resistivity survey is performed after CO_2 injection is stopped.
- Processing shows change in Resistivity between the 2 surveys due to CO_2 migration
- Further interpretation with integration of the petrophysical model built from borehole logs allows to characterize saturation changes due to the CO_2 migration

Permanent Electrode-Resistivity Arrays

- Permanently installed
- Flexible configuration
- Saturation monitoring
- Time-lapse Surveys
- Flexible operation
- Axisymmetric Inversion
- Long-term reliability

3F-Project: Background and Purpose

- Corinth Rift Laboratory, Trizonia Island
- Permanent fault line monitoring in seismic areas

Coordinator

Institut Français du Pétrole - IFP, Geology and Geochemistry Research Division

Participants

Schlumberger

Institut de Physique du Globe de Paris - IPGP

National Technical University of Athens – NTUA

University of Lièges MSM - Institut des matériaux

University of Edinborough

Laboratory Géosciences Azur – GEOAZUR

Enterprise Oil Exploration Limited

Istituto Nazionale di Geofisica - ING

GeoForschungsZentrum Potsdam - GFZ

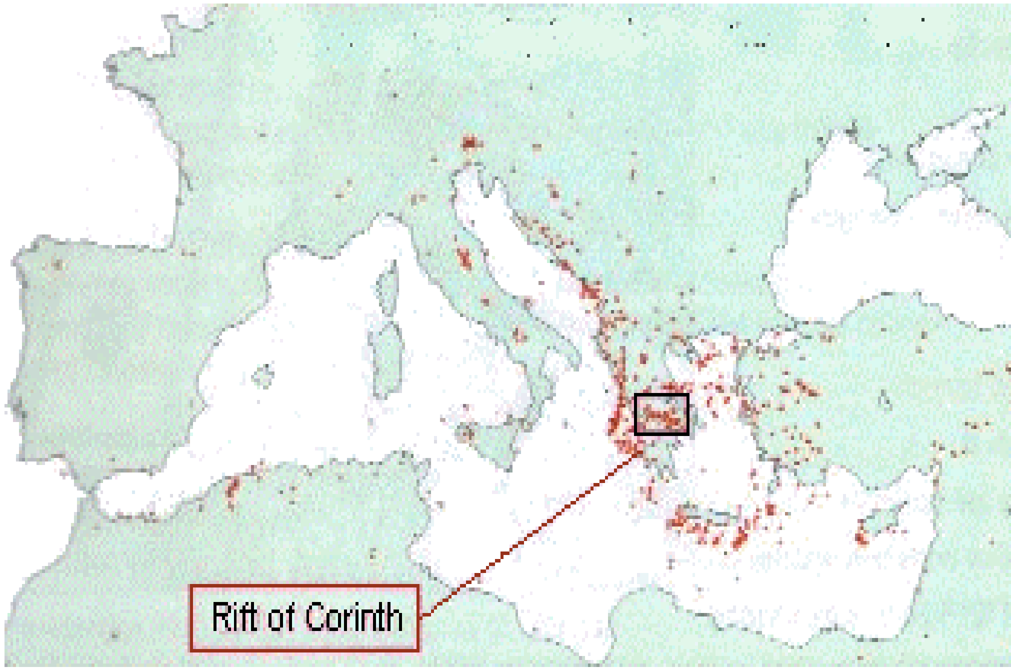
Armines, Ecole des Mines de Paris

University of Patras-Seismological Laboratory - UPSL

Ecole des Ponts et Chaussées - CERMES

Institute Rock Structure and Mechanics of Prague

Geophysical Institute of Prague

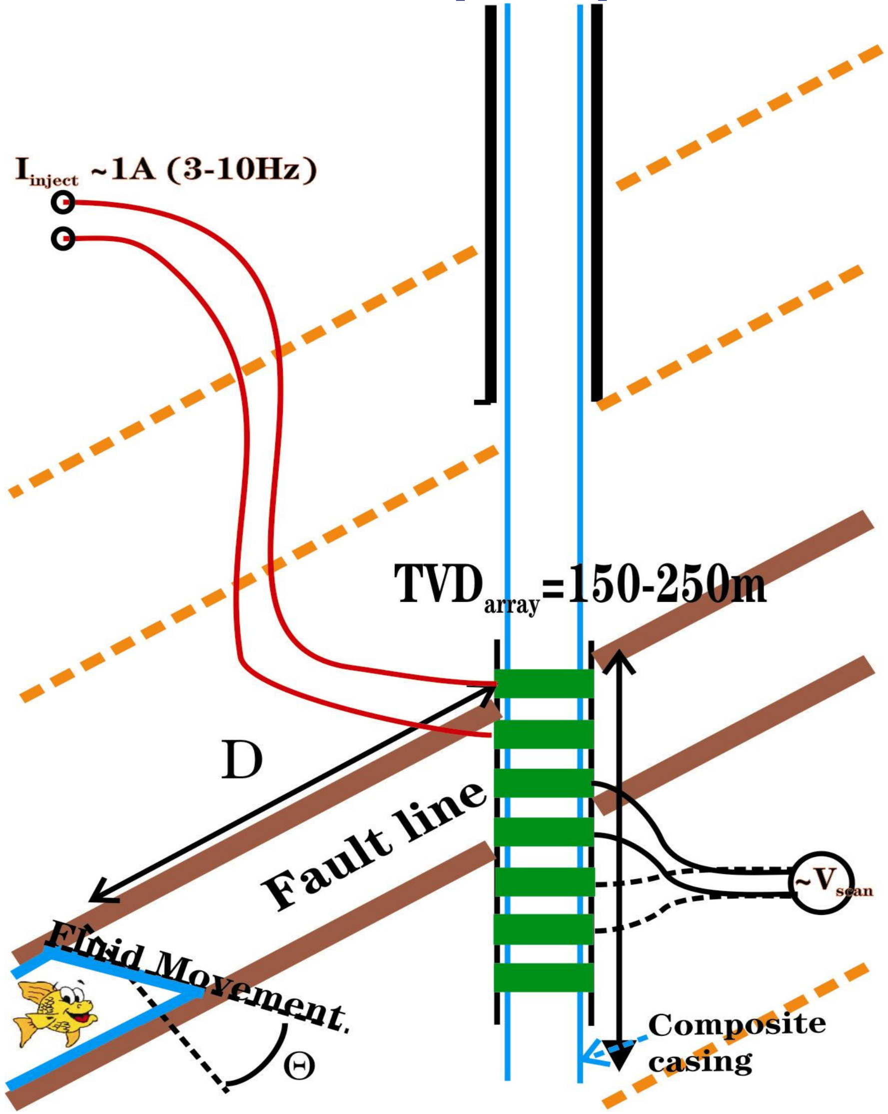


Schlumberger

3F - project: background and purpose

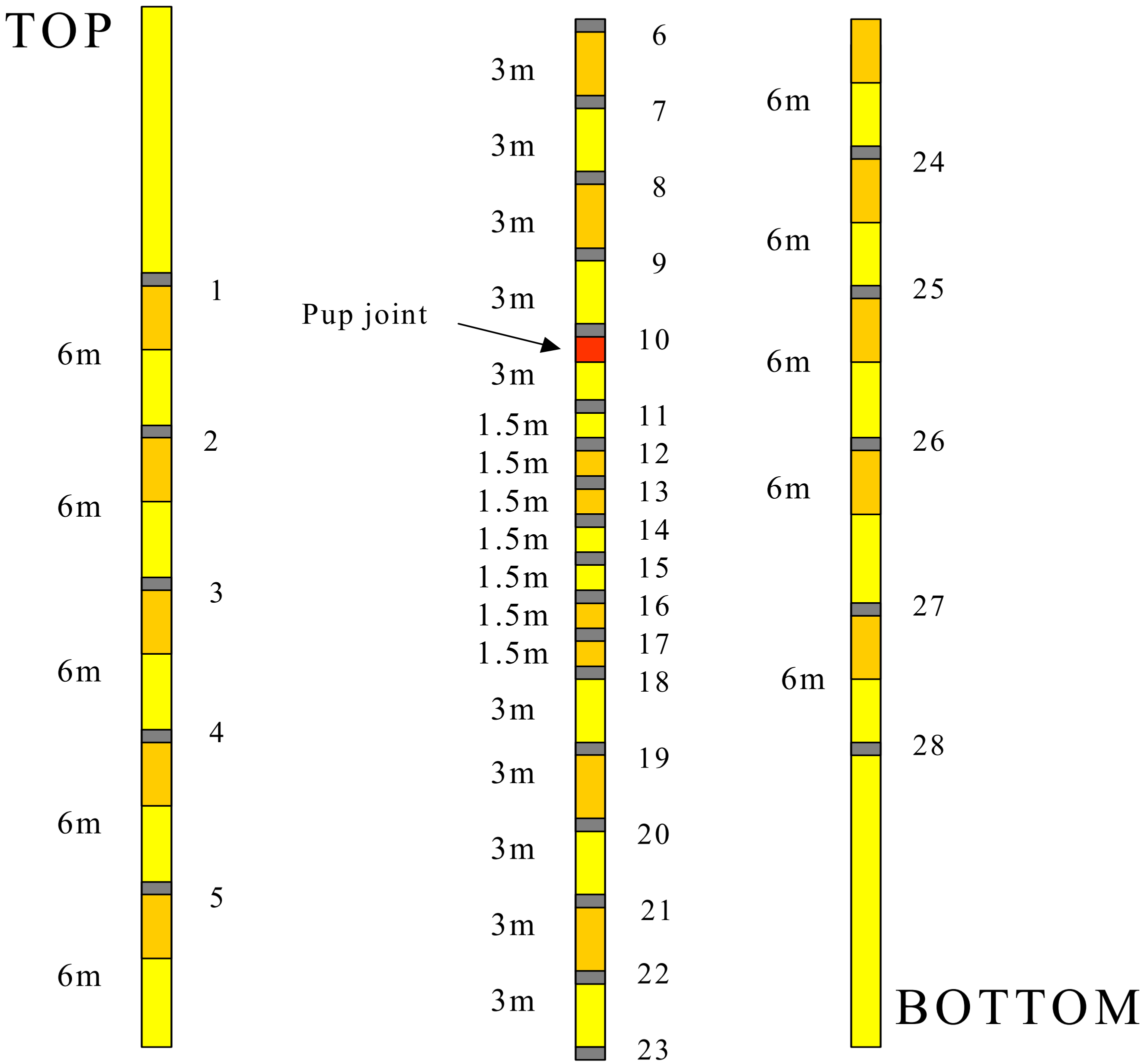
Track fluid movement in fault line in Trizonia well

- Fault @ TVD=198-214m, on limestone, shale beds
- Continuous data acquisition



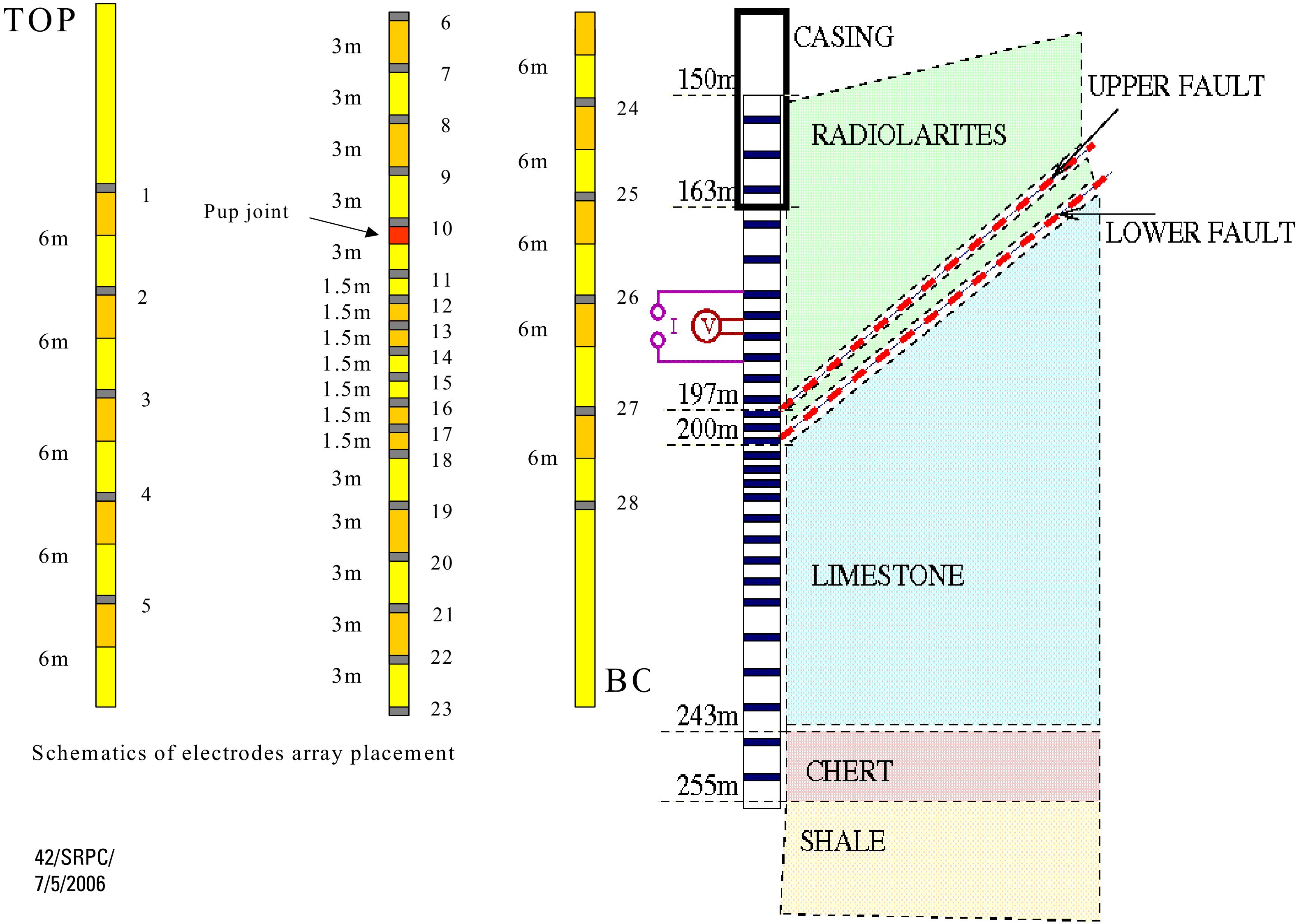
Schlumberger

3F - Prototype – ERA: Electrode Distribution



Schematics of electrodes array placement

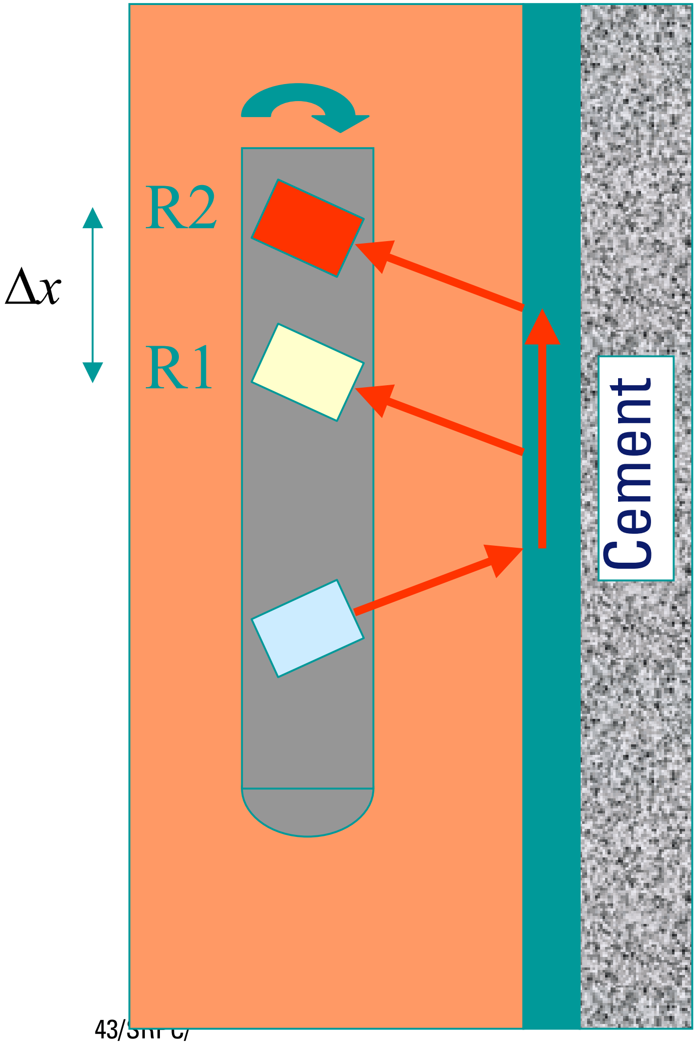
3F – ERA: Geology, Electrode Locations

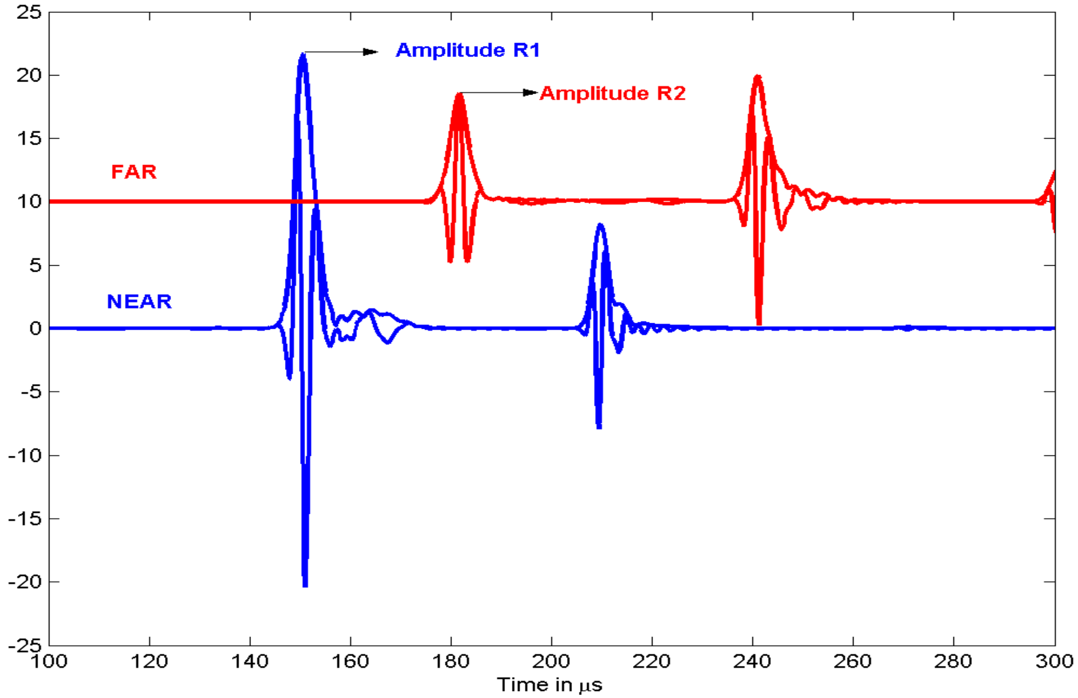


Schematics of electrodes array placement

Schlumberger

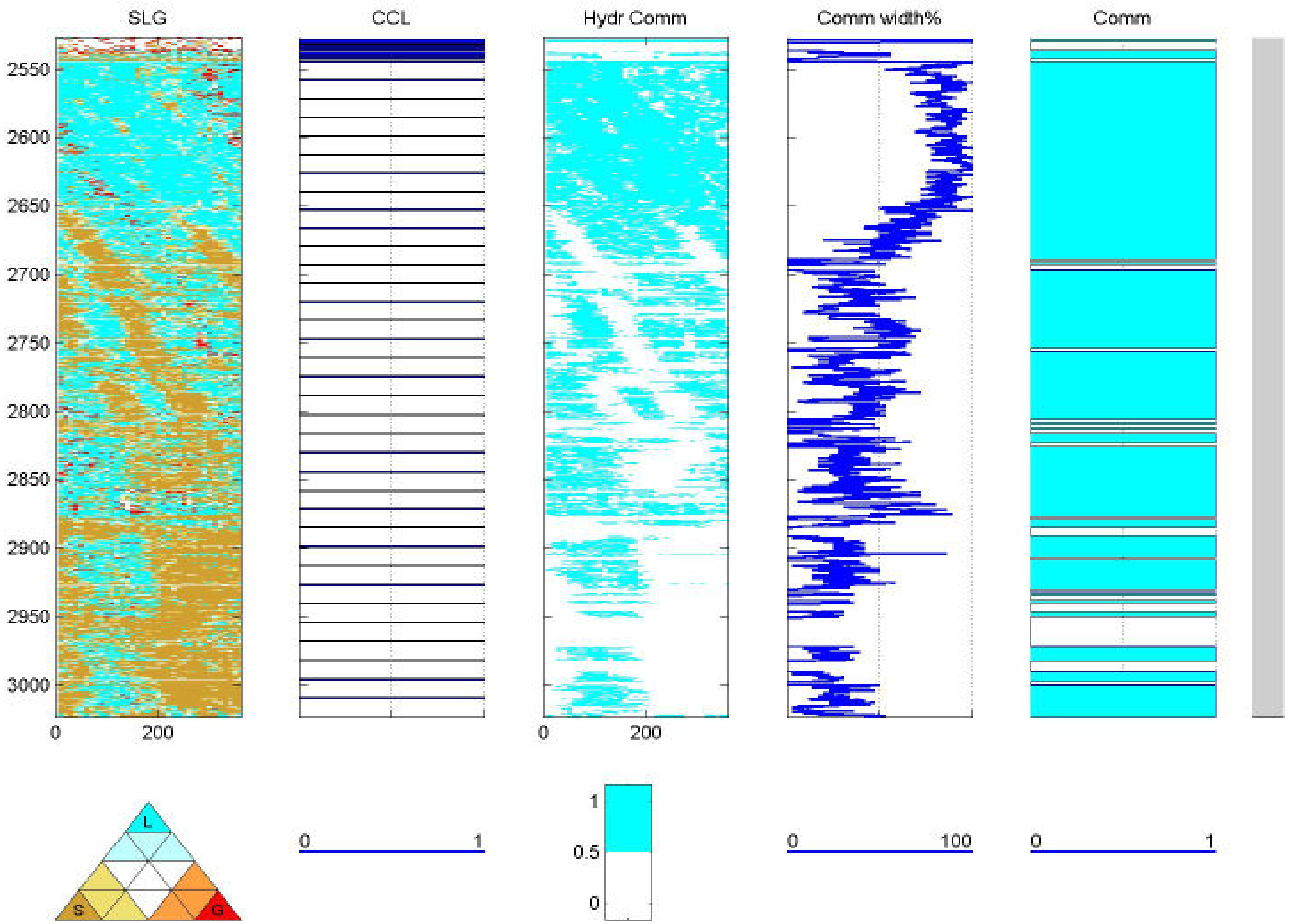
Isolation Scanner – Flexural Mode





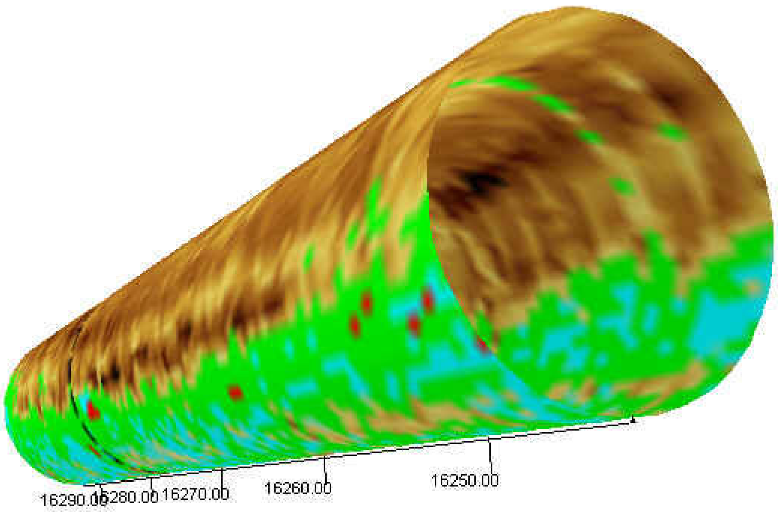
$$\alpha = \frac{20}{\Delta x(cm)} * Log_{10}\left[\frac{AmplitudeNear}{AmplitudeFar}\right] \quad dB / cm$$

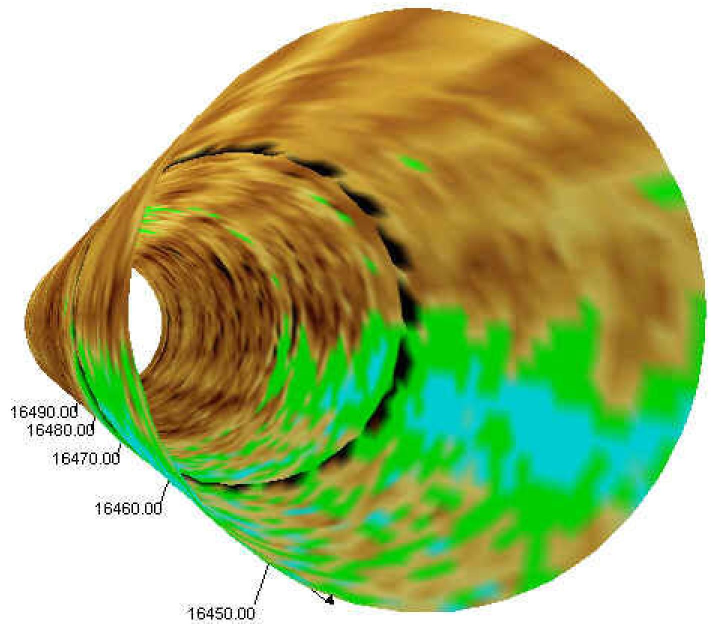
Hydraulic Communication



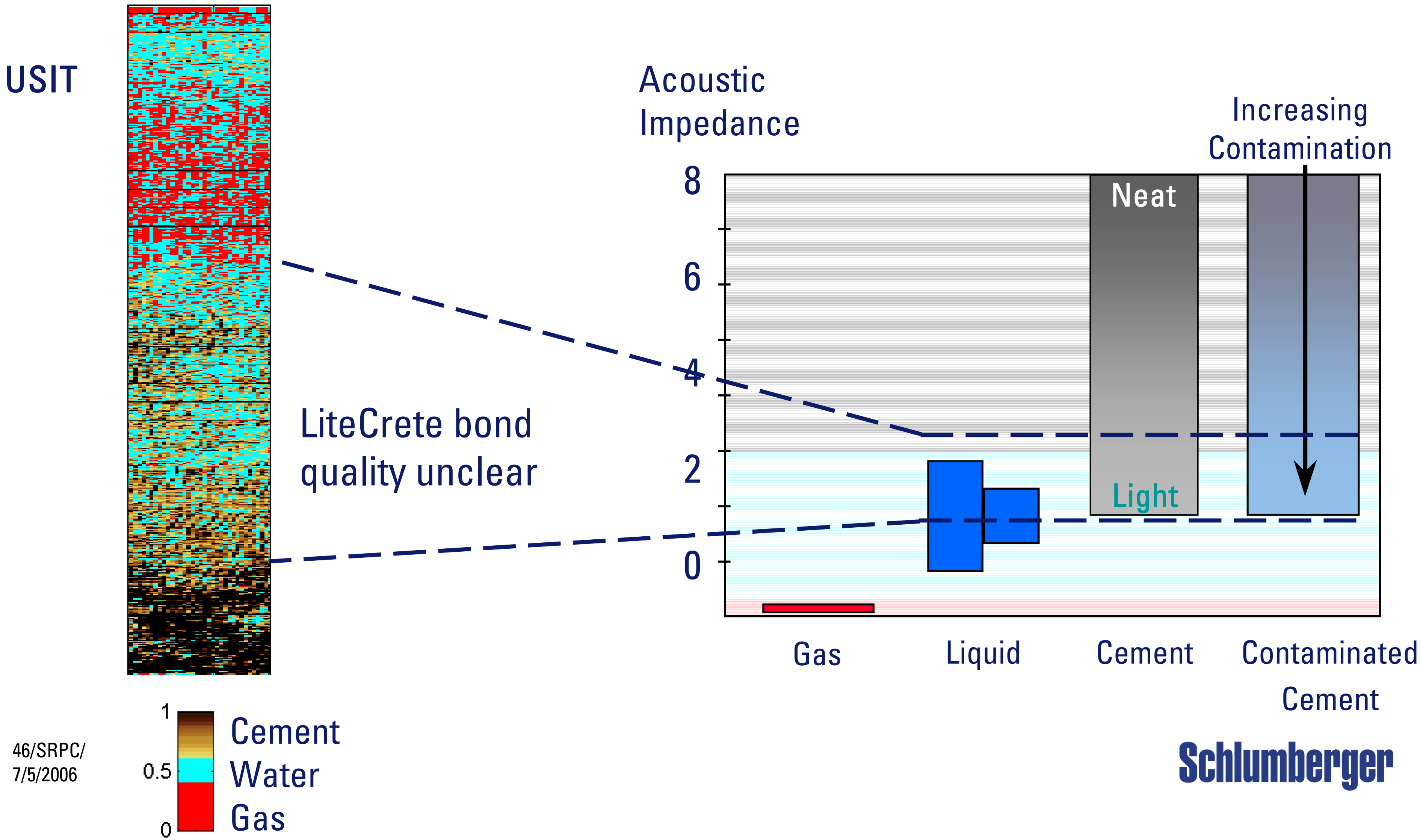
Casing Corrosion

- Image of inside or outside casing radius
- 3D Viewer



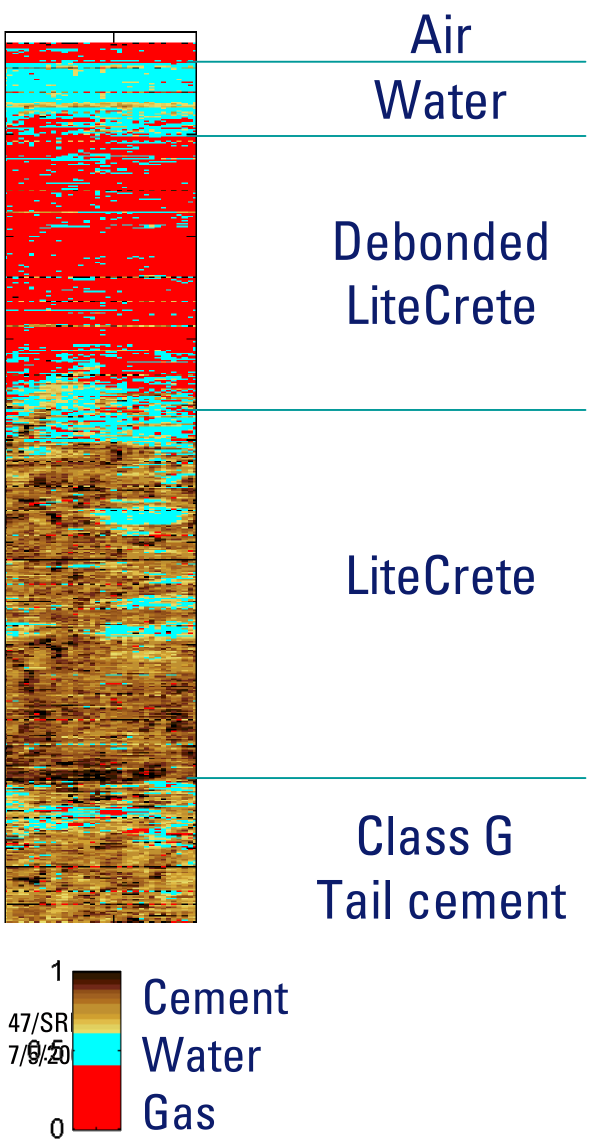


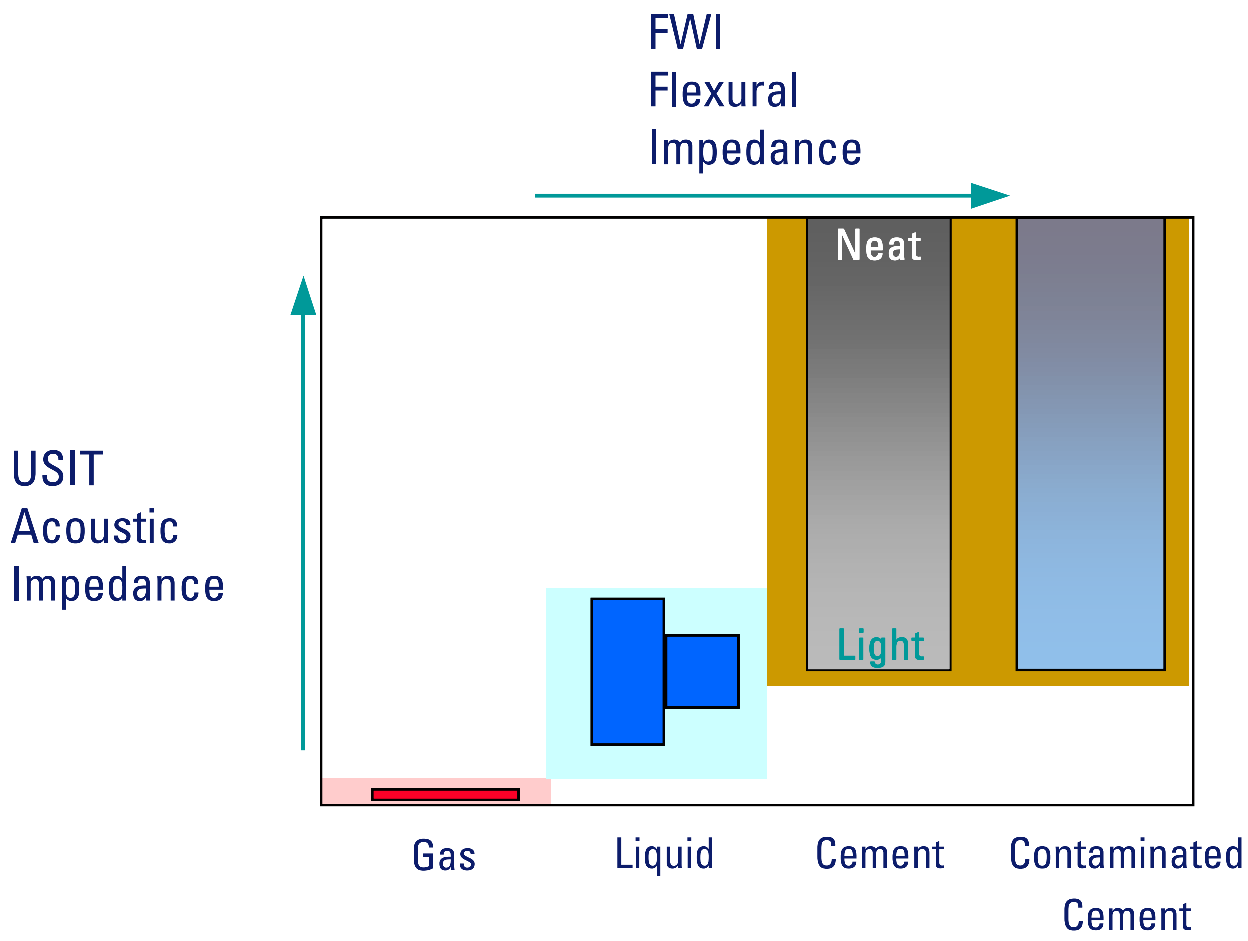
Cement-Evaluation Challenges



Schlumberger

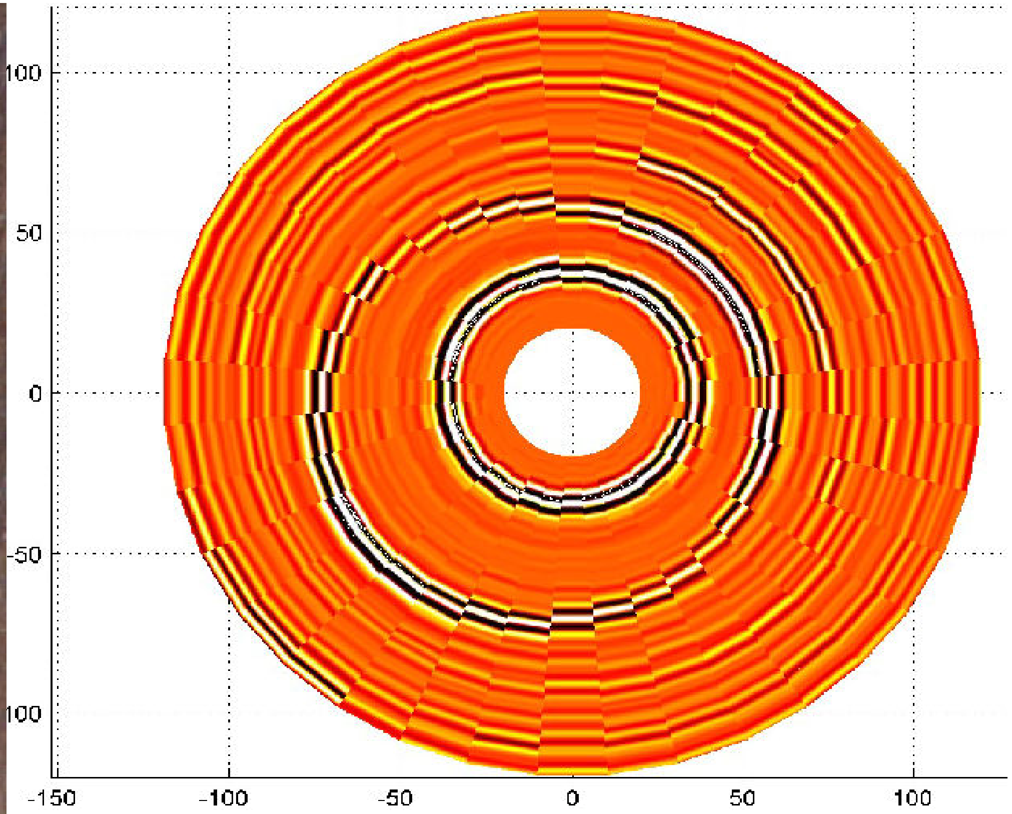
Imaging Behind Casing





Schlumberger

Casing Centralization Imaging



Schlumberger

Soil CO_2 Sources and Sinks

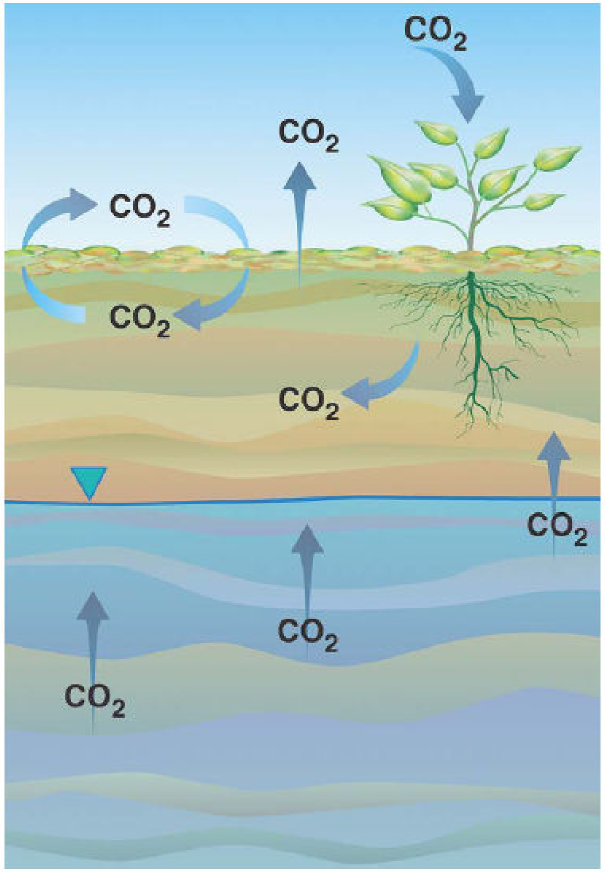


Figure 5.1. Soil CO_2 sources and sinks, showing from left-right, top-bottom, exchange with the atmosphere, production by decay of soil organic matter, photosynthetic uptake by plants, and production by root respiration, groundwater degassing, oxidation of sub-soil organic matter, and deep degassing.

Soil - Accumulation Chamber

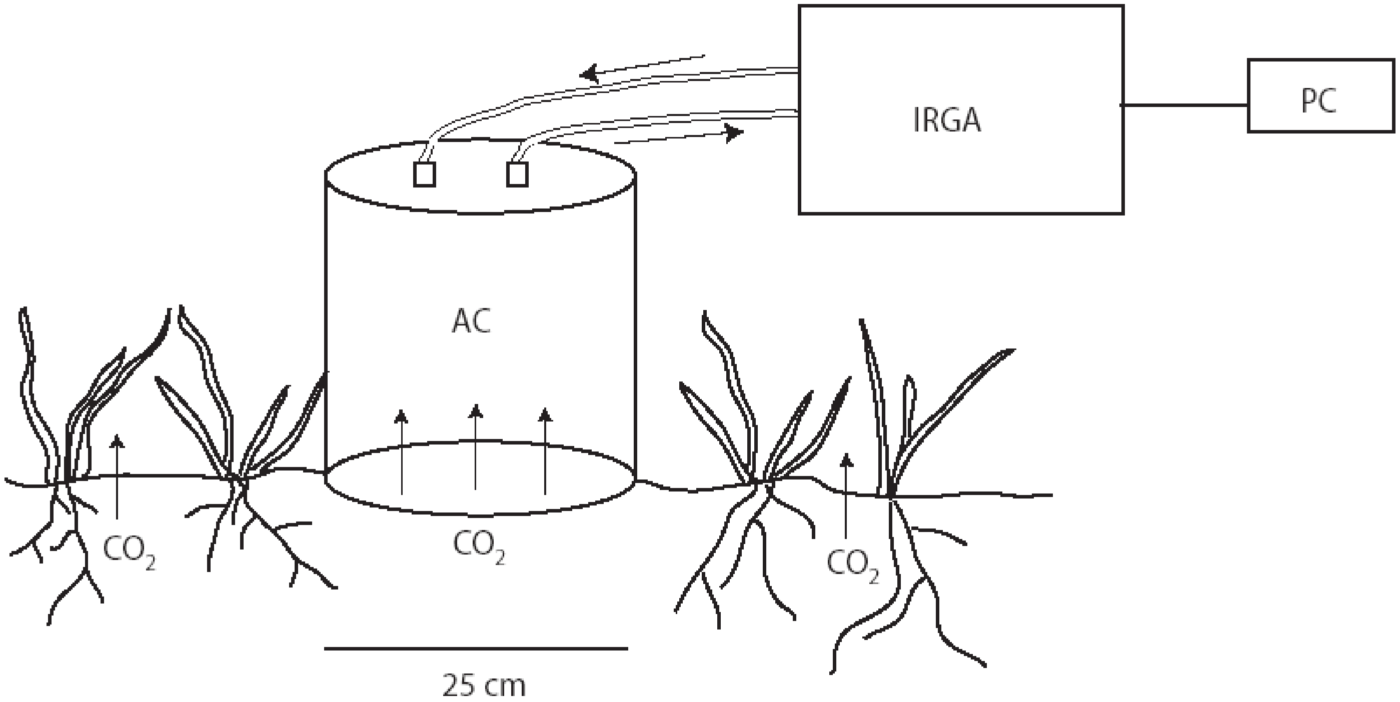


Figure 6.1. Schematic diagram of an accumulation chamber (AC) measurement system of soil CO_2 flux. The air contained in the AC is circulated through the AC and the IRGA and the rate of change of CO_2 concentration in the AC is measured by the IRGA and recorded by the PC.

Outline

- CO_2 in the Atmosphere – Global Warming
- Mitigation Strategies – CO_2-Storage Methods
- Risk Management
- Well Construction
- Reservoir Monitoring
- Field Examples

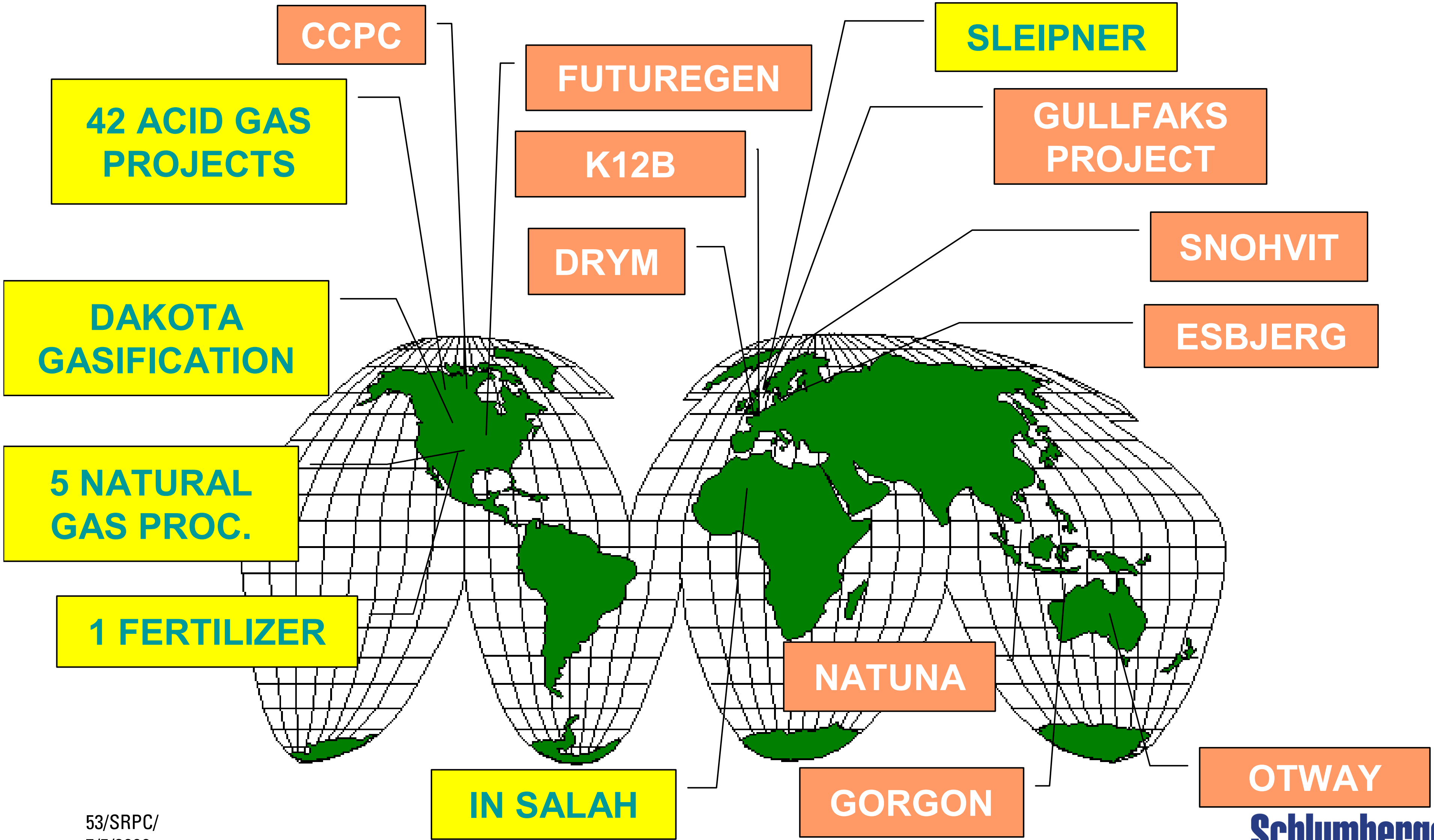
Schlumberger

Field Examples

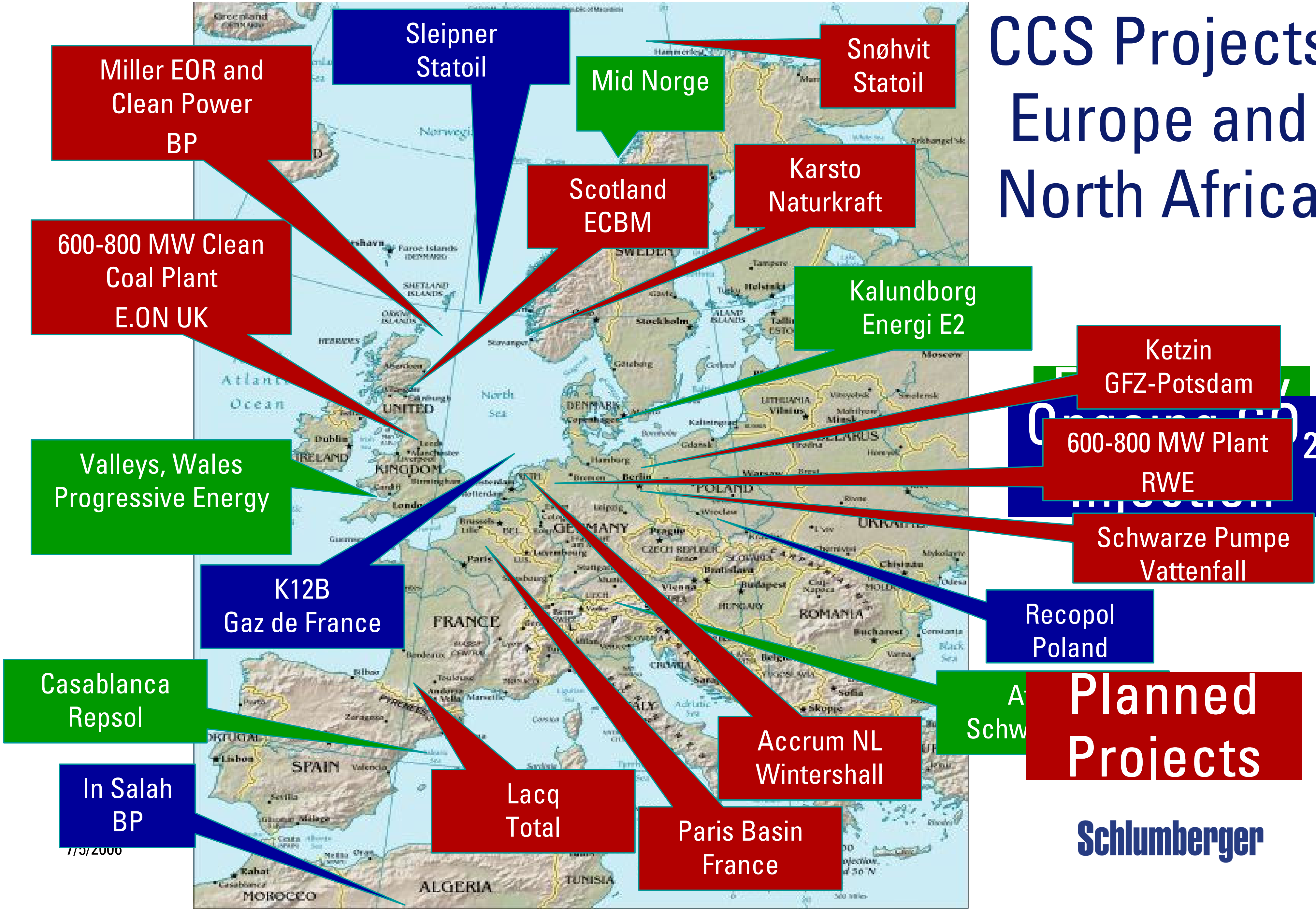
The following field examples contain web-based information, courtesy of the following companies:

- StatOil
- BP & Sonatrach
- GeoForschungsZentrum (GFZ), Potsdam

CO_2 Projects & Prospects



CCS Projects Europe and North Africa

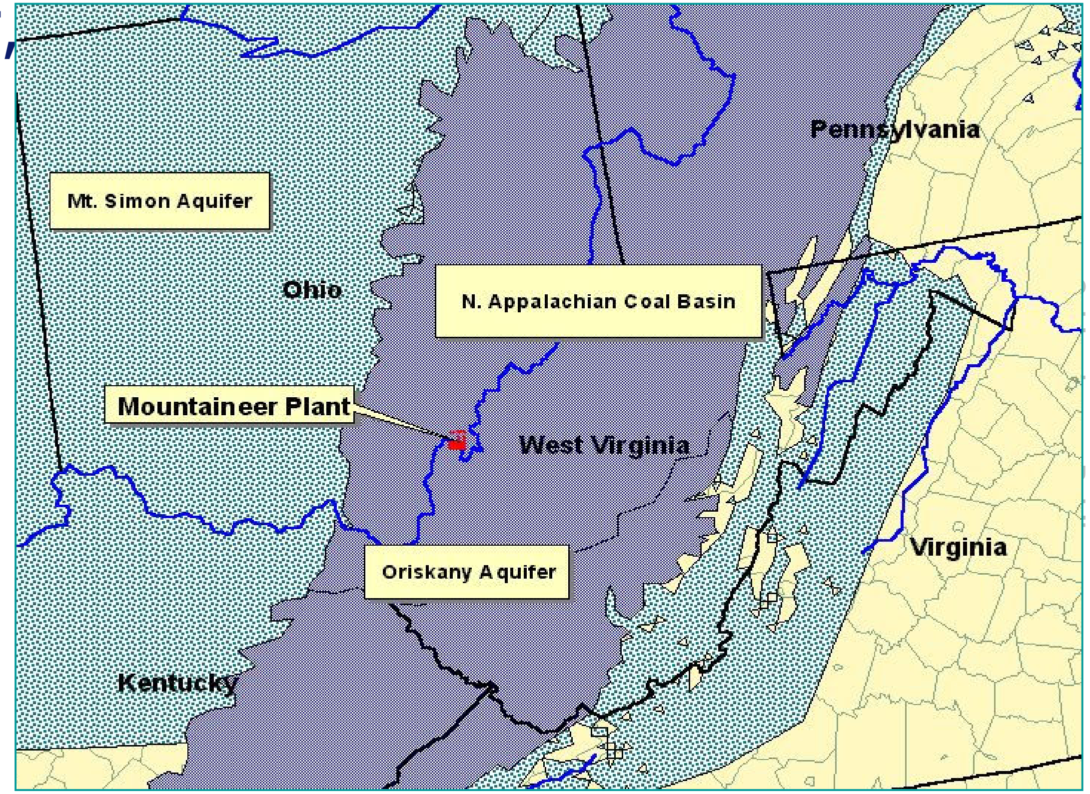


Planned Projects

Schlumberger

Field Experiment–Batelle/DOE, PI

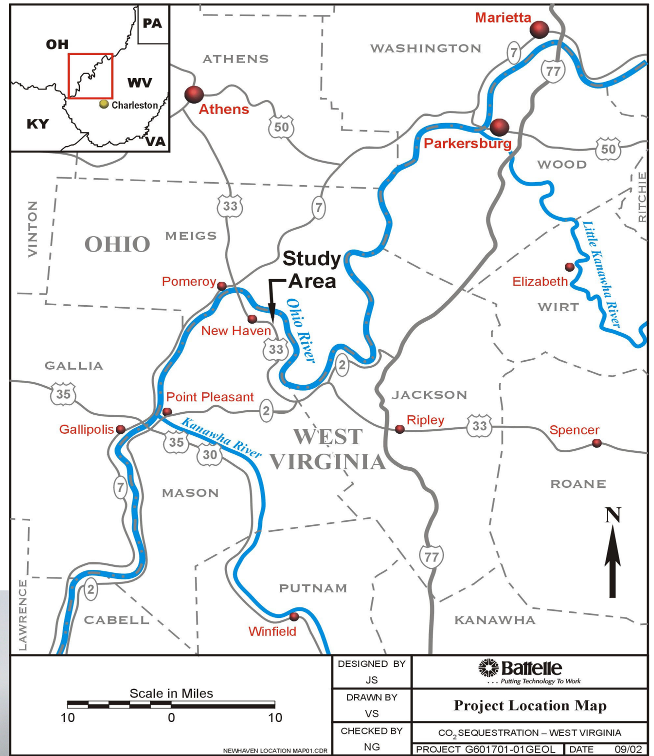
- BP, American Electric Power, Ohio coal office
- Schlumberger partnership (via well construction and monitoring)
- CO_2 injection experiment for storage evaluation
  - Well at a power plant, Ohio River, W. Virginia
  - 10000 ft, 2D seismic survey prior to drilling



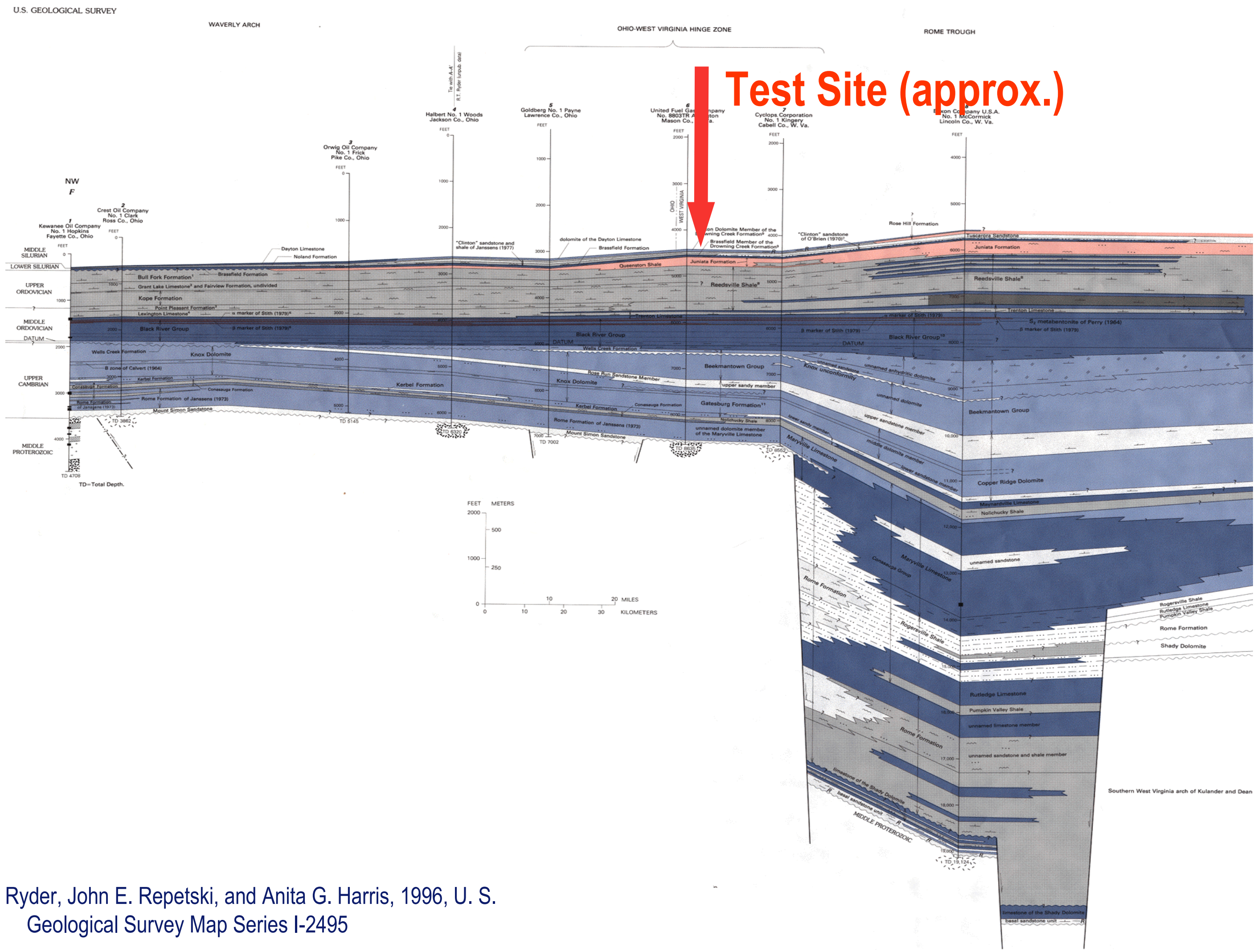
Schlumberger

The Power Plant

- 1.3 GW pulverized-coal unit
  - By barge/rail
- 8 Mt/y of CO_2
- NO_x removal installed
- SO_x removal planned for future

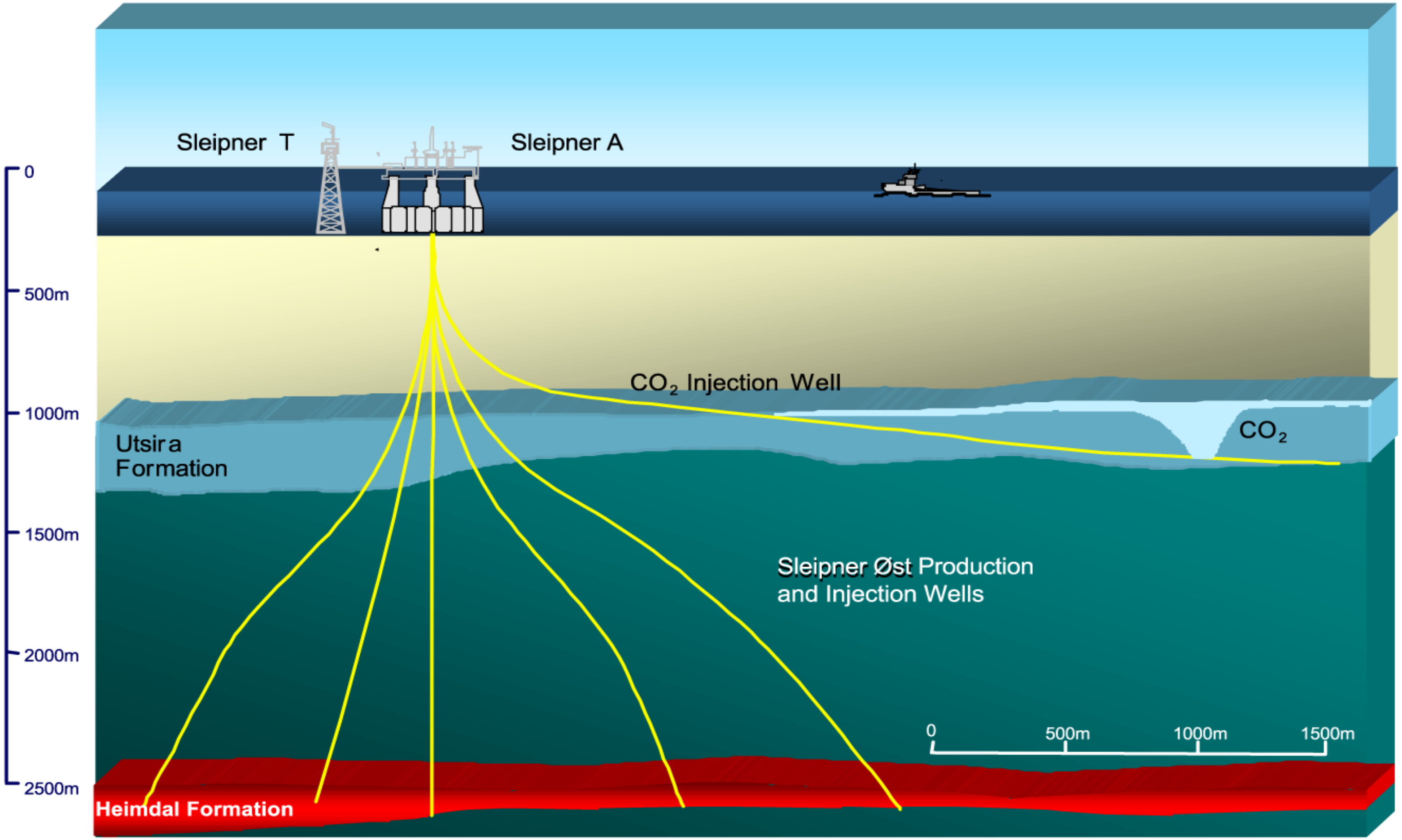


Local Geology – Structural Cross-Section



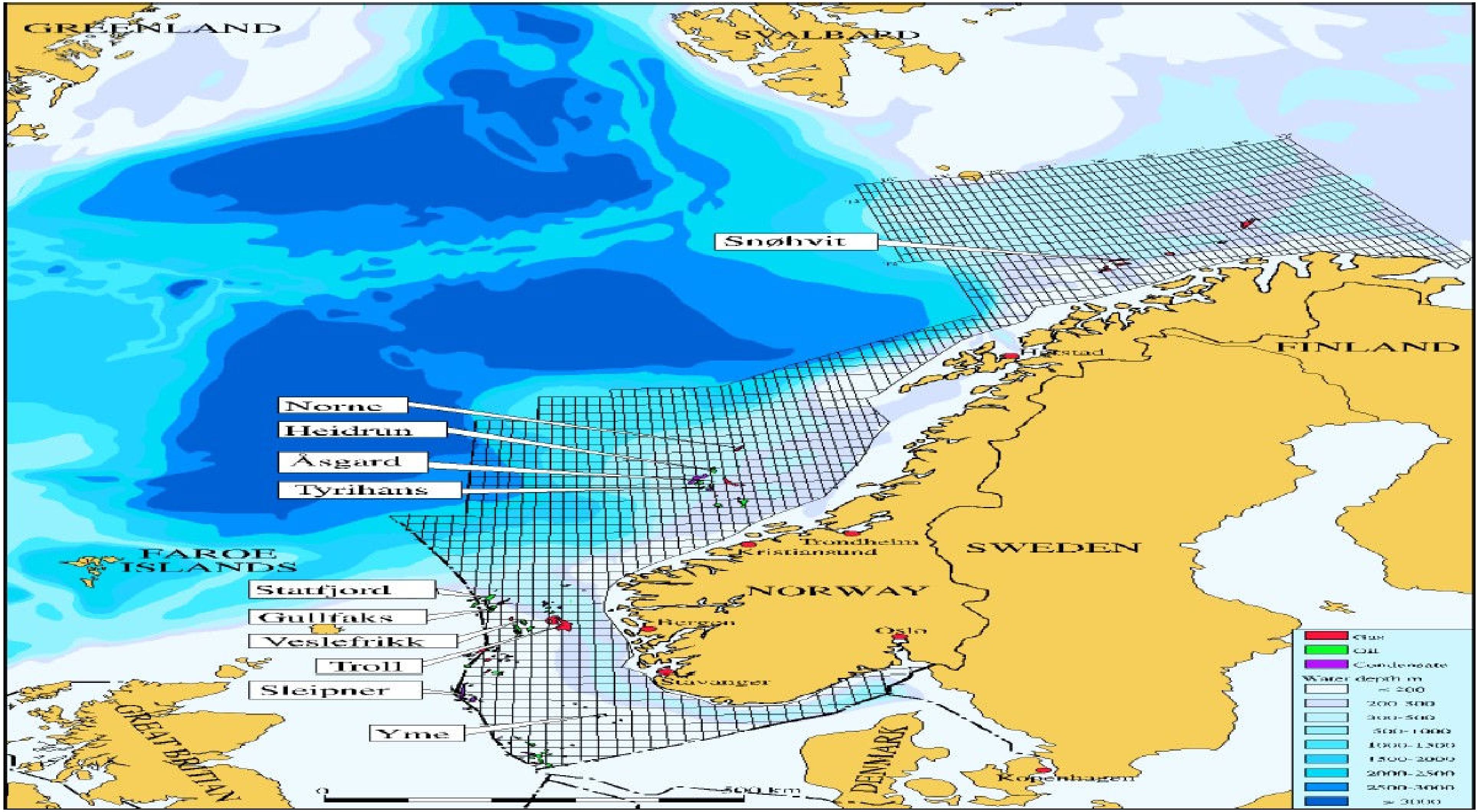
Ref: Robert T. Ryder, John E. Repetski, and Anita G. Harris, 1996, U. S. Geological Survey Map Series I-2495

Sleipner CO_2 Injection



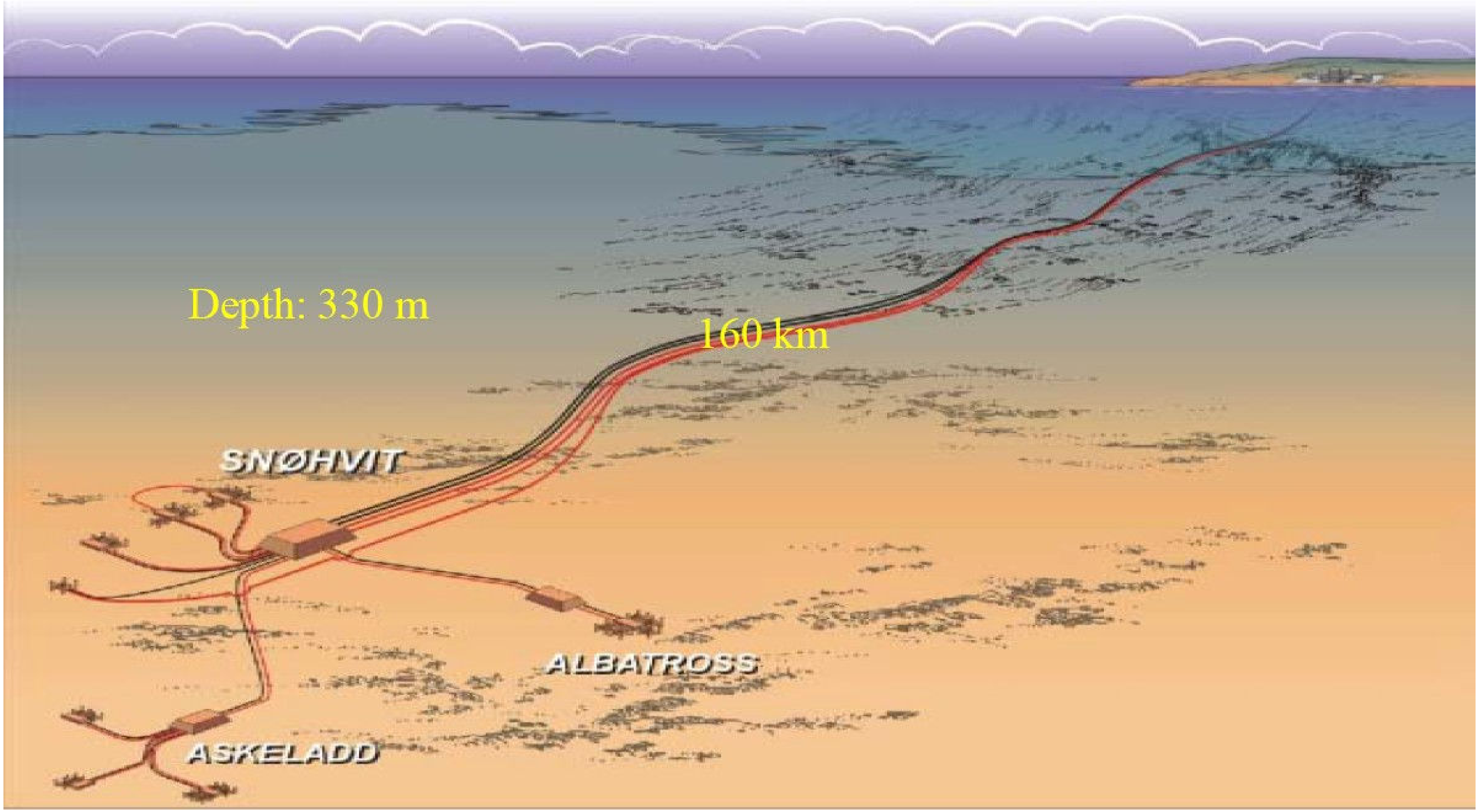
Schlumberger

Map with Snøhvit – StatOil's next Project



Schlumberger

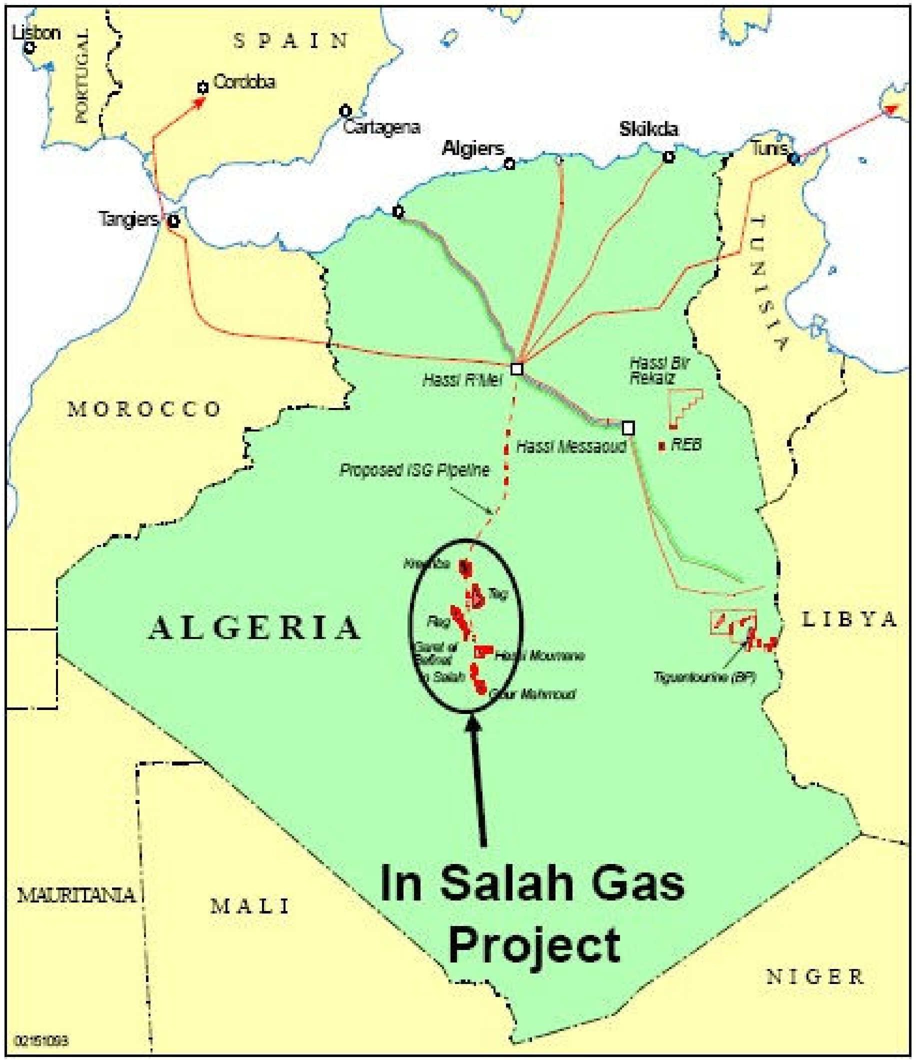
The Snøhvit Installation Layout

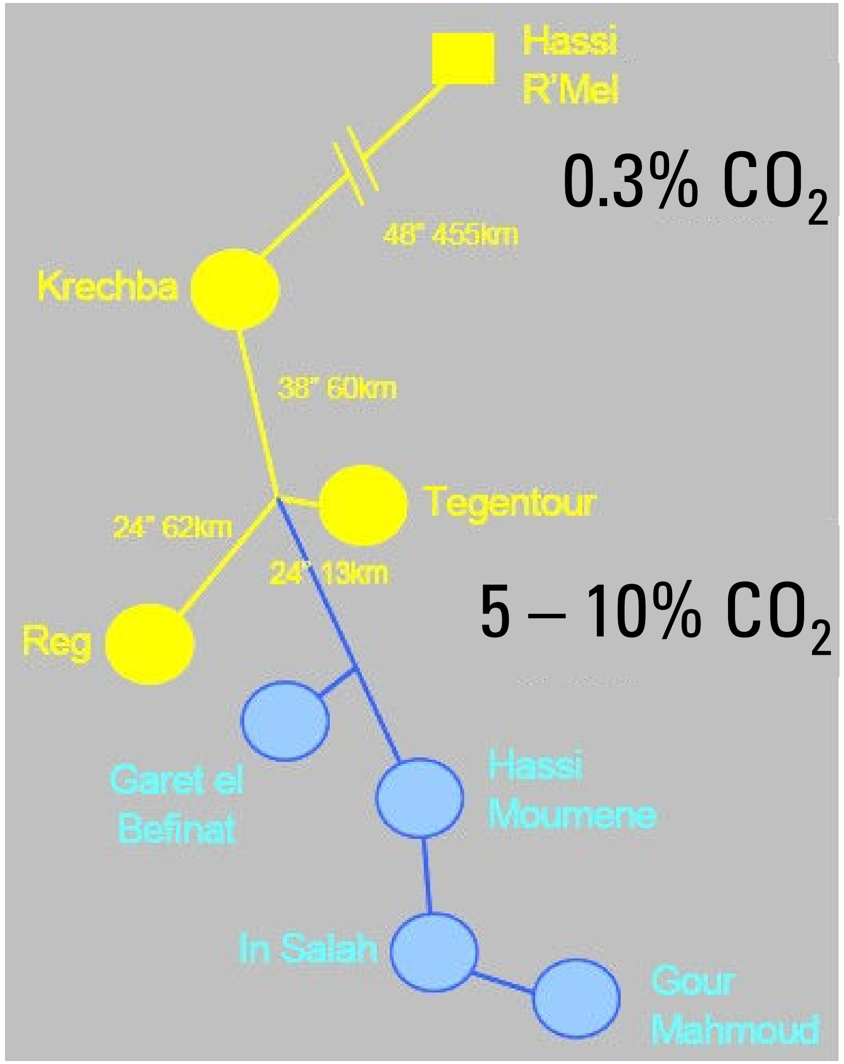


Schlumberger

The In-Salah Site (BP-Sonatrach)

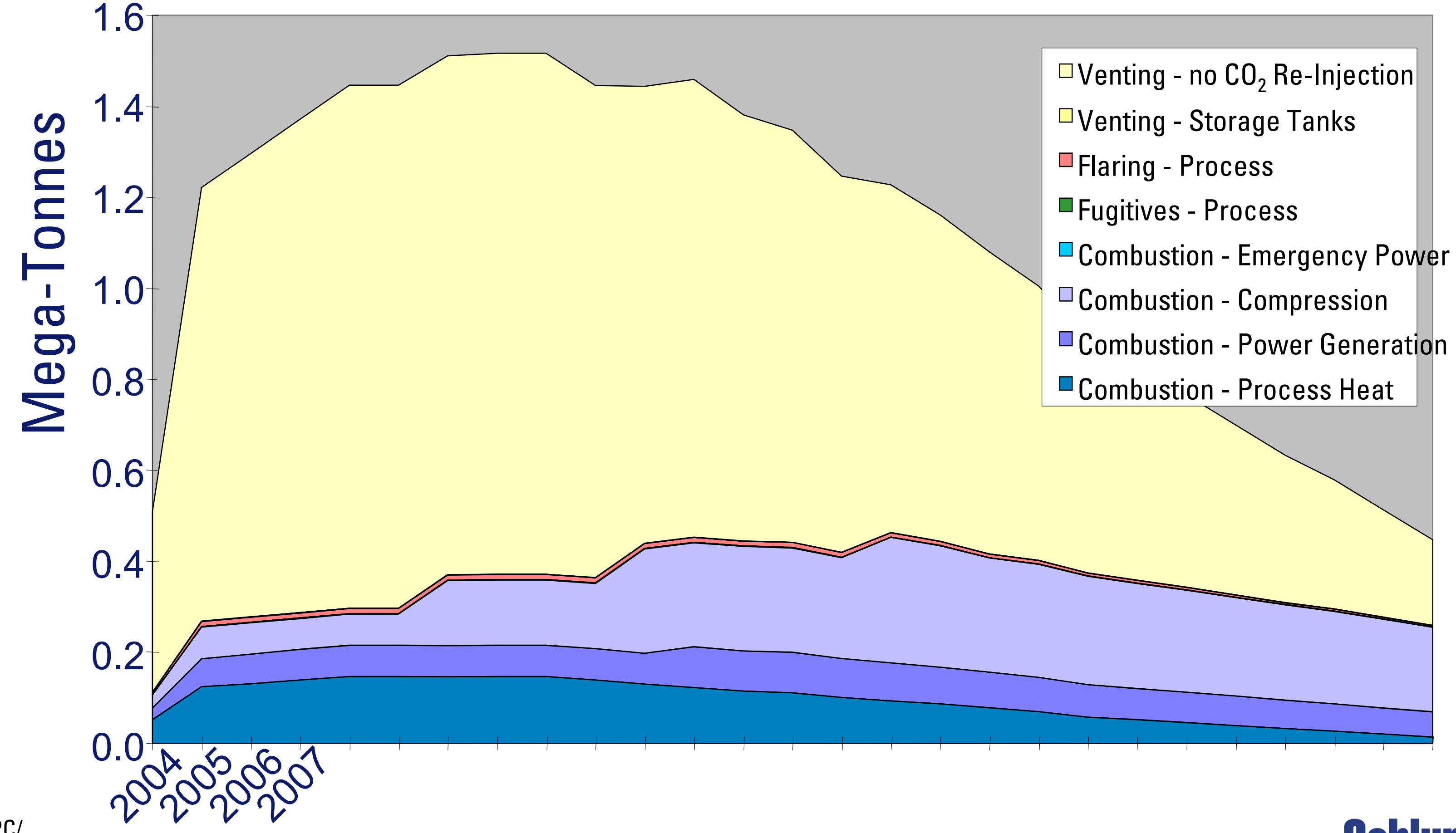
In-Salah Map and CO_2 Flow





In-Salah Project, Algeria

Process Facilities CO_2 Emissions by Source - without CO_2 Re-Injection Scheme



Schlumberger Public

Schlumberger

In-Salah Project Scope

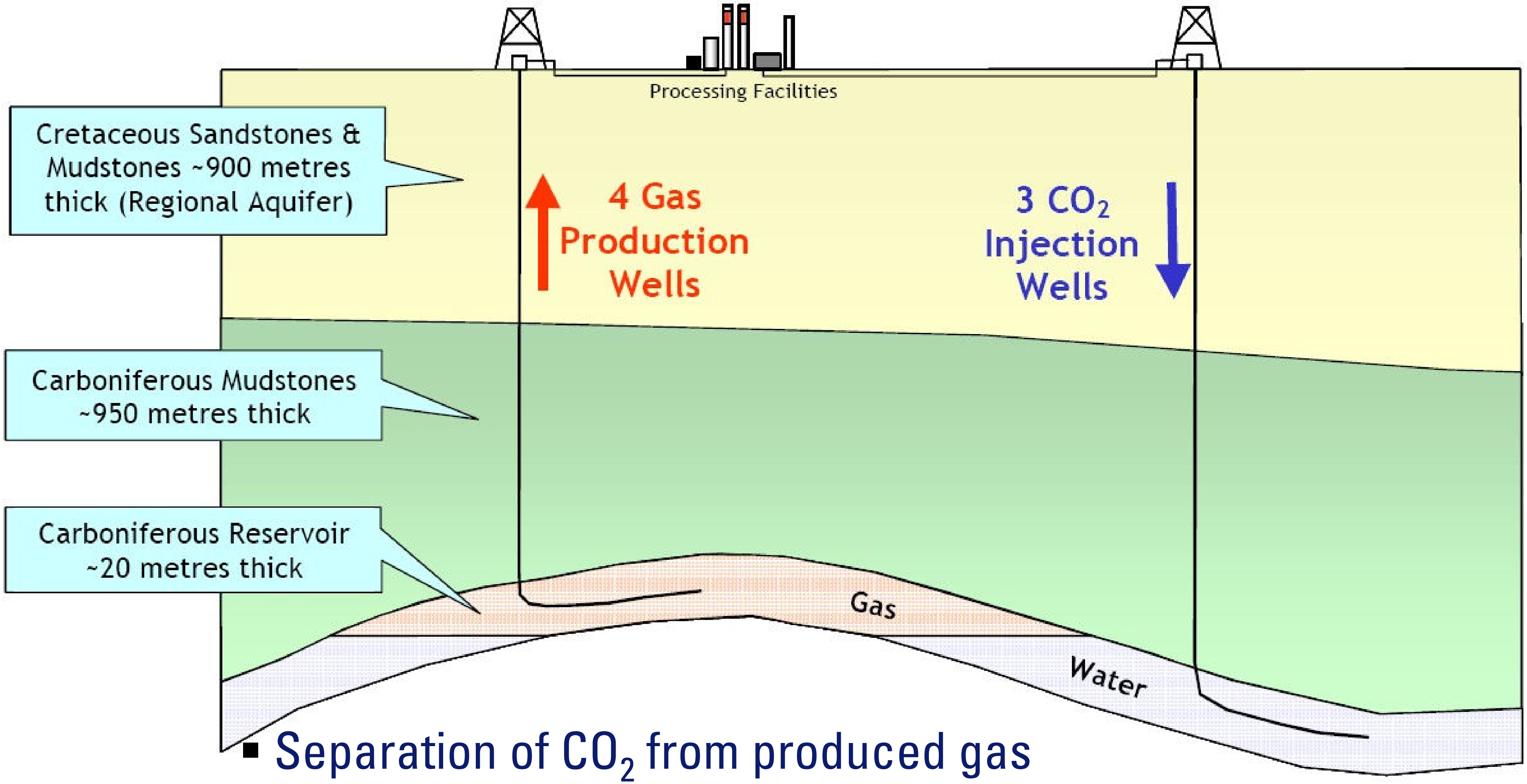
- a 25 Mm^3/d hydrocarbon gas development costing 2.4 G$
  - CO_2 concentrations 5 – 10 % in pure methane
  - < 0.3% concentration after CO_2 removal
- a 1.1 Mt/y CO_2 storage project costing 100 M$
  - Unwanted CO_2 compressed
  - Re-injected into Krechba aquifer below 950 m thick layer of carboniferous mudstones
- a CO_2 storage monitoring project costing 30 M$.

In-Salah Amine Contractor Towers

65/SRPC/
7/5/2006

Schlumberger

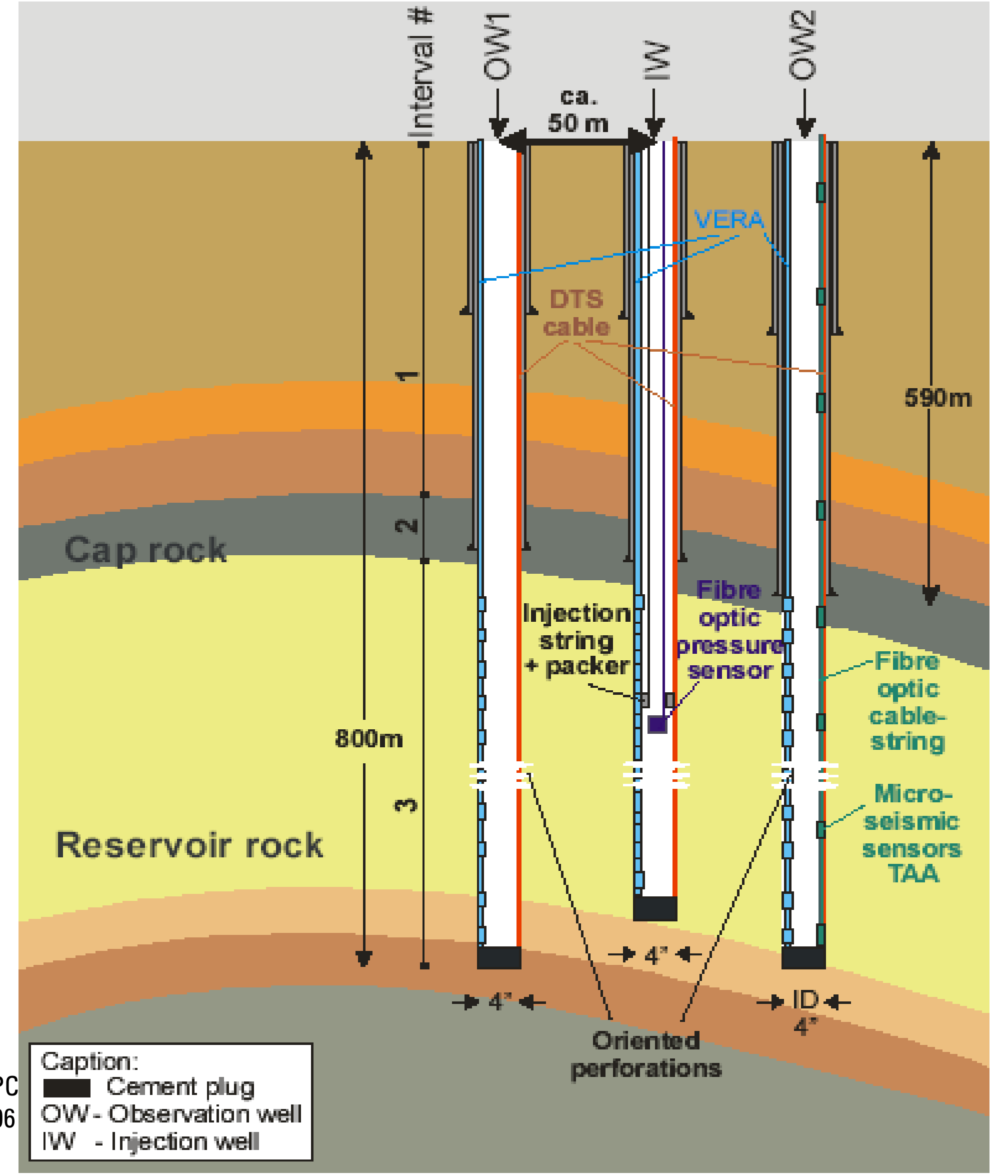
In-Salah Storage Site over Krechba Reservoir

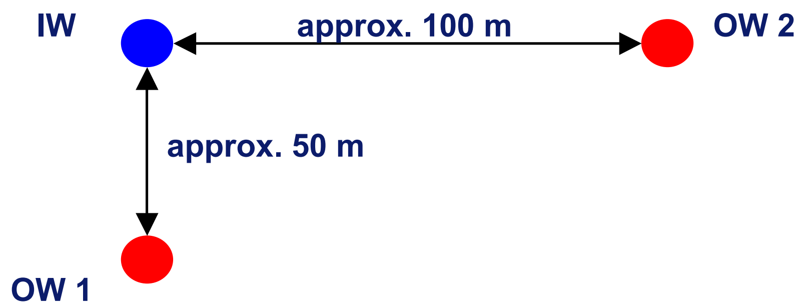


- Separation of CO_2 from produced gas
- Re-injection into Krechba Storage Site (1800 m)
- 17 millions tons of CO_2 over project life

Ketzin – the Project Site

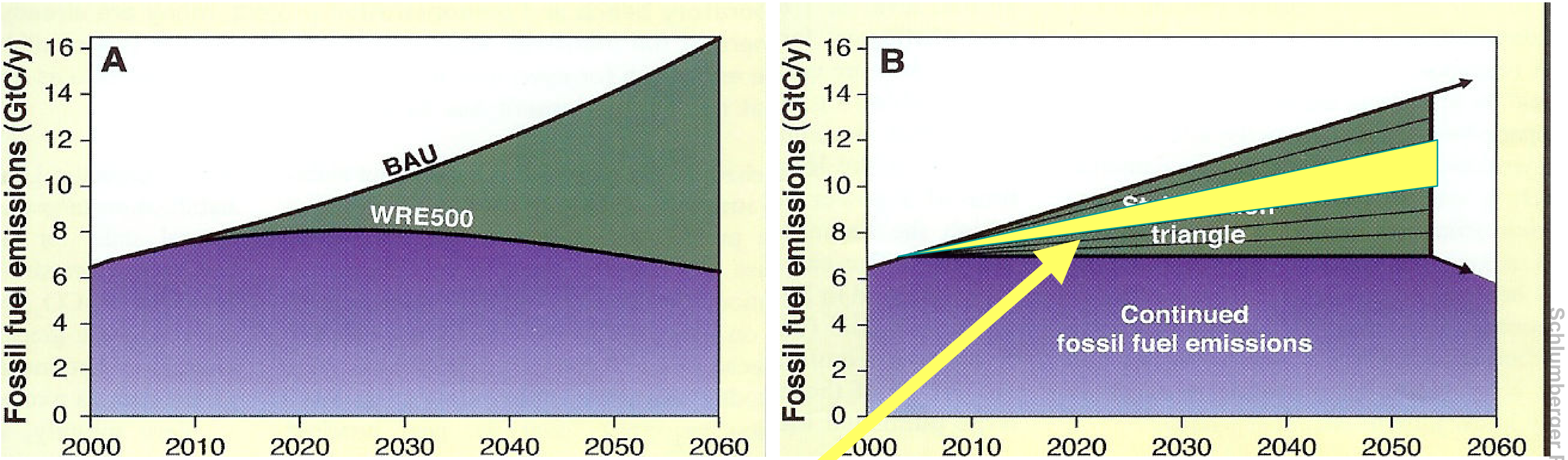
Planned CO_2 Injector and Monitor Wells





Schlumberger

The Stabilization Wedges



By 2050 the world needs to geologically

store a minimum of 7 Gt of CO_2/year

→7000 Sleipners

Schlumberger

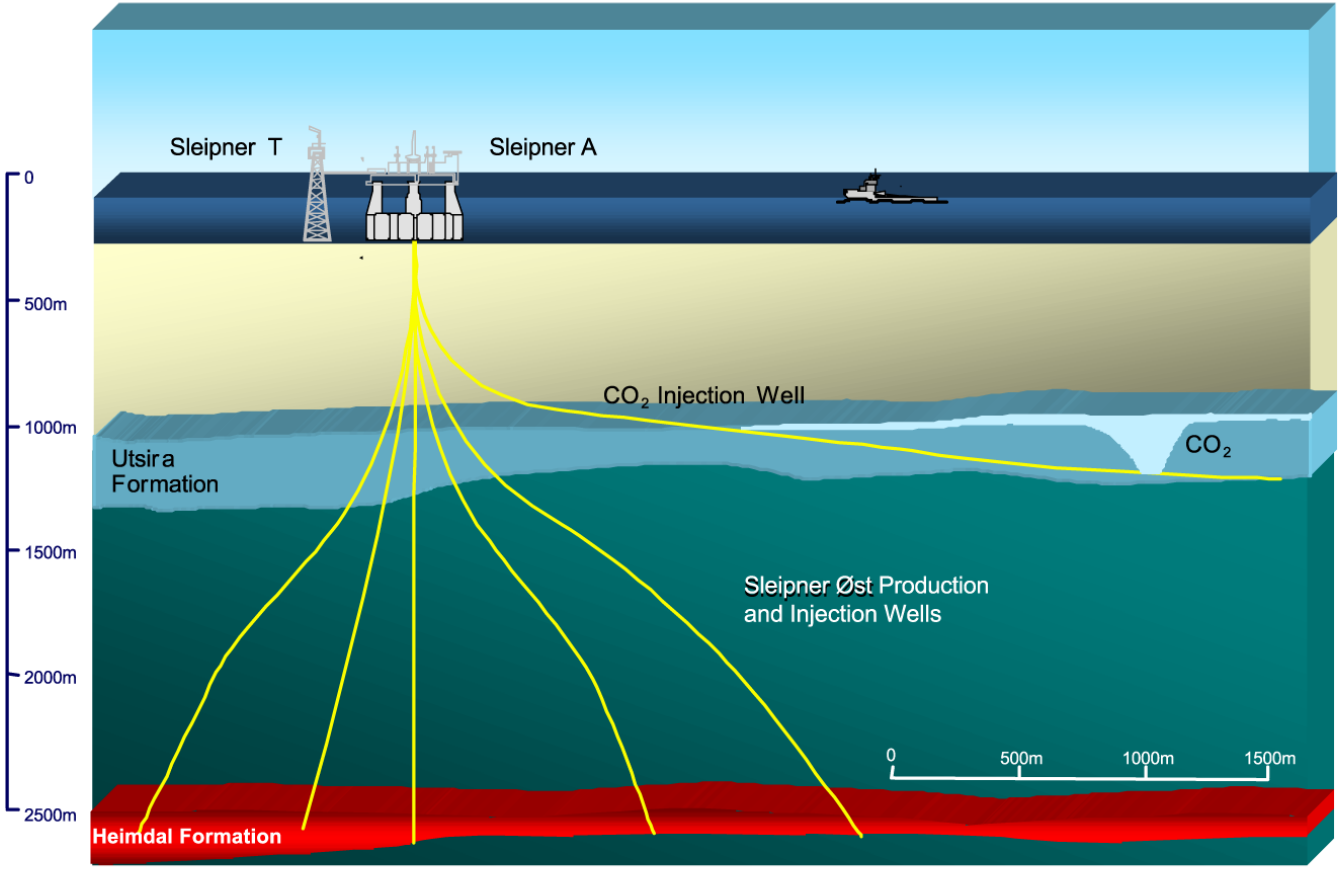
CO_2 Underground Storage to Clean the Atmosphere

Martin G. Lüling

Schlumberger

WIAS Colloquium

8 May 2006



Schlumberger