Monitoring of CO_2 storage
- methods and challenges -

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Monitoring of CO_2 storage

Monitoring is a key element in the EC directive on CCS.

Article 13 (Purpose of monitoring) states that:

Member States shall ensure that the operator carries out monitoring of the injection facilities, the **storage complex** (including where possible the **CO2 plume**), and where appropriate the **surrounding environment** for the purpose of:

(a) comparison between the **actual and modelled behaviour of CO2**, *and formation water,* in the storage site;

(b) *detecting significant irregularities;*

(c) detecting **migration of CO2**;

(d) detecting **leakage of CO2**;

(e) detecting significant **adverse effects for the surrounding environment**, *including in particular on drinking water,* for human populations, or users of the surrounding biosphere;

(f) assessing the effectiveness of any corrective measures taken;

(g) *updating the assessment of the safety and integrity of the storage complex in the short- and long-term including the assessment of* whether the **stored CO2** will be **completely** *and* ***permanently*** contained.

Monitoring of CO_2 storage

The EC directive poses very strict time limits.

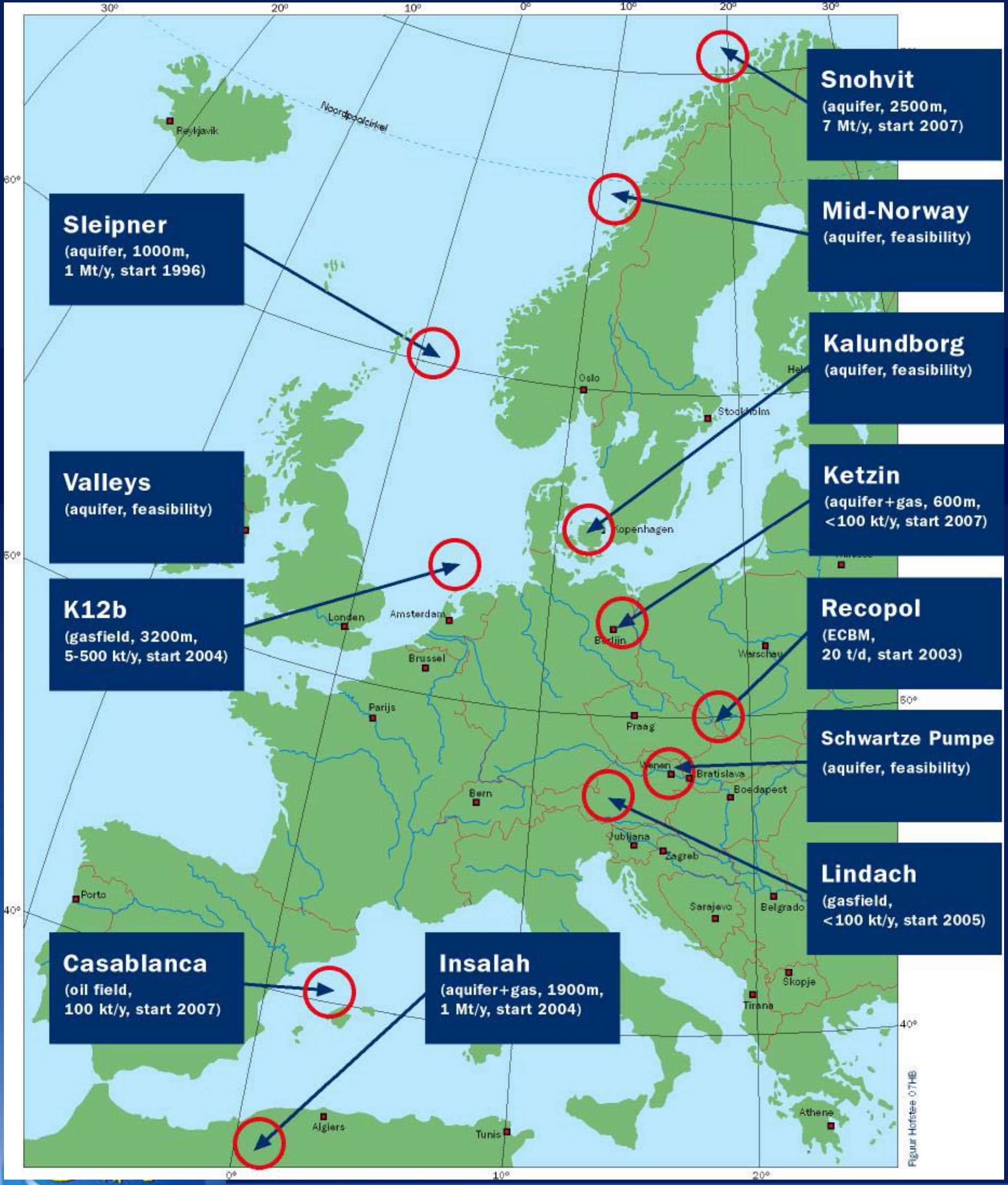
(a) *Member States shall establish or designate the* ***competent authority*** *or authorities* ***responsible for fulfilling the duties*** *established under this Directive;*

(b) *Every three years the Member States shall submit to the Commission a report on the application of this Directive.*
The first report shall be sent to the Commission by ***30 June 2011.***

(c) *Applications to the competent authority for storage permits shall include at least the following information:*

- *the characterisation of the storage site and complex and an assessment of the expected security of the storage*
- *description of measures to prevent significant irregularities;*
- *a proposed* ***monitoring plan****;*
- *a proposed corrective measures plan;*
- *a proposed provisional post-closure plan;*

Monitoring of CO_2 storage



The rapid evolution of legislation and industrial initiatives are accelerating the needs for improved monitoring techniques

SITES OUTSIDE EUROPE

- Canada (Weyburn, EOR, 1.5 Mt/y)
- Australia (Gorgon, start 2009, Aquifer+gas storage, 2500 m, 5 Mton/yr)
- USA (Frio, Tea Pot Dome, Lost Hills)
- Japan (aquifer and ECBM)

Monitoring of CO_2 storage

ZEP's proposal for an

EU Demonstration Programme for CCS

43 projects with a CO2 capture, transport and storage component, **34** of which tested against the selection criteria

	Overview				CO₂ capture
Project name	Partners/participants	Country	Location	Industry	Capture technology
MARITSA		Bulgaria	Maritsa	Power	Pre-combustion
HODONIN CEZ	CEZ	Czech Republic	Hodonin, SE	Power	Post-combustion
LEDVICE CEZ	CEZ	Czech Republic	Ledvice, N	Power	Post-combustion
KALUNDBORG DONG	DONG Energy	Denmark	Kalundborg	Power	Post-combustion
AALBORG V.FALL	Vattenfall	Denmark	Aalborg	Power	Post-combustion
MERI PORI FORTUM	Fortum, TVO	Finland	Meri Pori	Power	Oxy-fuel or post-combustion
LACQ TOTAL	Total, ALSTOM, Air Liquide	France	Lacq plant and Rousse field	Power	Oxy-fuel
FLORANGE ARC.MIT	ArcelorMittal	France	France	Steel	Post-combustion
JANSCHWALDE V.FALL	Vattenfall	Germany	Jänschwalde, Brandenburg	Power	Oxy-fuel & post-combustion
WILHELMSHAVEN E.ON	E.On CE	Germany	Wilhelmshaven	Power	Post-combustion
EISENHUTTENSTADT ARC.MIT	ArcelorMittal	Germany	Eisenhüttenstadt	Steel	Post-combustion
GREIFSWALD DONG	DONG Energy	Germany	Greifswald, Mecklenburg	Power	Post-combustion
HUERTH RWE	RWE	Germany	Huerth, North Rhine-Westfalia	Power	Pre-combustion
ENEL CCS2	ENEL	Italy		Power	Oxy-fuel
ENEL CCS1	ENEL	Italy		Power	Post-combustion
SALINE JONICHE SEI	SEI (Rätia Energie & Partners)	Italy	Saline Joniche (RC)	Power	Post-combustion
BARENDRECHT SHELL	Shell	Netherlands	Barendrecht (storage), Pernis (capture)	Chemicals, Refinery	H2 production
EEMSHAVEN RWE	RWE Power, BASF, Linde	Netherlands	Eemshaven	Power	Post-combustion
ROTTERDAM E.ON	E.On Benelux	Netherlands	Maasvlakte, Rotterdam	Power	Post-combustion
ROTTERDAM ENECO	ENECO, International Power	Netherlands	Pistoolhaven, Rotterdam	Power	Post-combustion
EEMSHAVEN NUON	Nuon	Netherlands	Eemshaven	Power	Pre-combustion
ROTTERDAM CGEN	CGEN NV	Netherlands	Europoort Rotterdam	Power	Pre-combustion
ROTTERDAM ESSENT	Essent	Netherlands	Rotterdam	Power	Pre-combustion

Monitoring of CO_2 storage

ZEP's proposal for an

EU Demonstration Programme for CCS

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	Overview				CO₂ capture
Project name	Partners/participants	Country	Location	Industry	Capture technology
MONGSTAD STATOIL	StatoilHydro, Gasnova	Norway	Bergen	Power, refinery	Post-combustion
HAMMERFEST H.ENERGI	Hammerfest Energi, Sargas, Siemens	Norway	Hammerfest	Power	Post-combustion
HUSNES TINFOS	Tinfos, Sør-Norge, Eramet, Sargas	Norway	Husnes	Various	Post-combustion
KARSTO AKER	Aker, Fluor, Mitsubishi	Norway	Karsto	Oil/gas	Post-combustion
MONGSTAD BKK	BKK	Norway	Mongstad	Power	Post-combustion or pre-combustion
HAUGESUND HAUGALANDKRAFT	Haugaland Kraft	Norway	Haugesund	Power	
SIEKIERKI V.FALL	Vattenfall	Poland	Warsaw	Power	Post-combustion
KEDZIERZYN PKE	PKE/ ZAK	Poland	Kedzierzyn Kozle, Slaskie	Power/ Chemical	Pre-combustion
BELCHATOW BOT	PGE, ICPC, CMI, PGI	Poland	Belchatow	Power	Post-combustion
COMPOSTILLA ENDESA	Endesa	Spain	Compostilla, Leon	Power	Oxy-fuel (CFB)
UNION FENOSA	Union Fenosa	Spain		Power	Post-combustion
KINGSNORTH E.ON	E.ON UK	UK	Kingsnorth, South East England	Power	Post-combustion
SCUNTHORPE CORUS	CORUS	UK	Scunthorpe	Steel	Post-combustion
COCKENZIE SCOT.PWR	Scottish Power	UK	Scotland	Power	Post-combustion
FERRYBRIDGE S&S ENERGY	Scottish and Southern Energy	UK	Ferrybridge, West Yorkshire	Power	Post-combustion
TILBURY RWE	RWE nPower	UK	Tilbury, Thames Estuary	Power	Post-combustion
KILLINGHOLME E.ON	E.ON UK	UK	Humberside, Lincolnshire	Power	Pre-combustion
HATFIELD P.FUEL PWR	Powerfuel Power Ltd	UK	Hatfield, South Yorkshire	Power	Pre-combustion
TEESSIDE PROG.EN	Centrica, Progressive Energy, Coastal Energy	UK	Teesside, Northeast England	Power	Pre-combustion
DRYM PROG.EN	Progressive Energy, BGS, CO2STORE	UK	Onllwyn, South Wales	Power	Pre-combustion

Monitoring of CO_2 storage

The EC will support the **Demonstration Programme** for **CCS** with a total of 300 M allowances under ETS (but other funds may be available) through a transparent selection procedure

Investments proposed by the European Commission (**Recovery Program**) in **key energy infrastructure** projects, among which **CCS** (for a total of 1.500 ME)

Project Name/ Location		Envisaged Community contribution (EUR million)	Fuel	Capacity	Capture Technique	Storage Concept
Huerth	Germany	250	Coal	450 MW	IGCC	Saline Aquifer
Jaenschwalde			Coal	500 MW	Oxyfuel	Oil/Gas fields
Eemshaven	Netherlands	250	Coal	1200 MW	IGCC	Oil/Gas fields
Rotterdam			Coal	1080 MW	PC	Oil/Gas fields
Rotterdam			Coal	800 MW	PC	Oil/Gas fields
Belchatow	Poland	250	Coal	858 MW	PC	Saline Aquifer
Compostella	Spain (with {Portugal)	250	Coal	500 MW	Oxyfuel	Saline Aquifer
Kingsnorth	UK	250	Coal	800 MW	PC	Oil/Gas fields
Longannet			Coal	3390 MW	PC	Saline Aquifer
Tilbury			Coal	1600 MW	PC	Oil/Gas fields
Hatfield (Yorkshire)			Coal	900 MW	IGCC	Oil/Gas fields
Porto Tolle Saline	Italy	250		660 MW	PC	

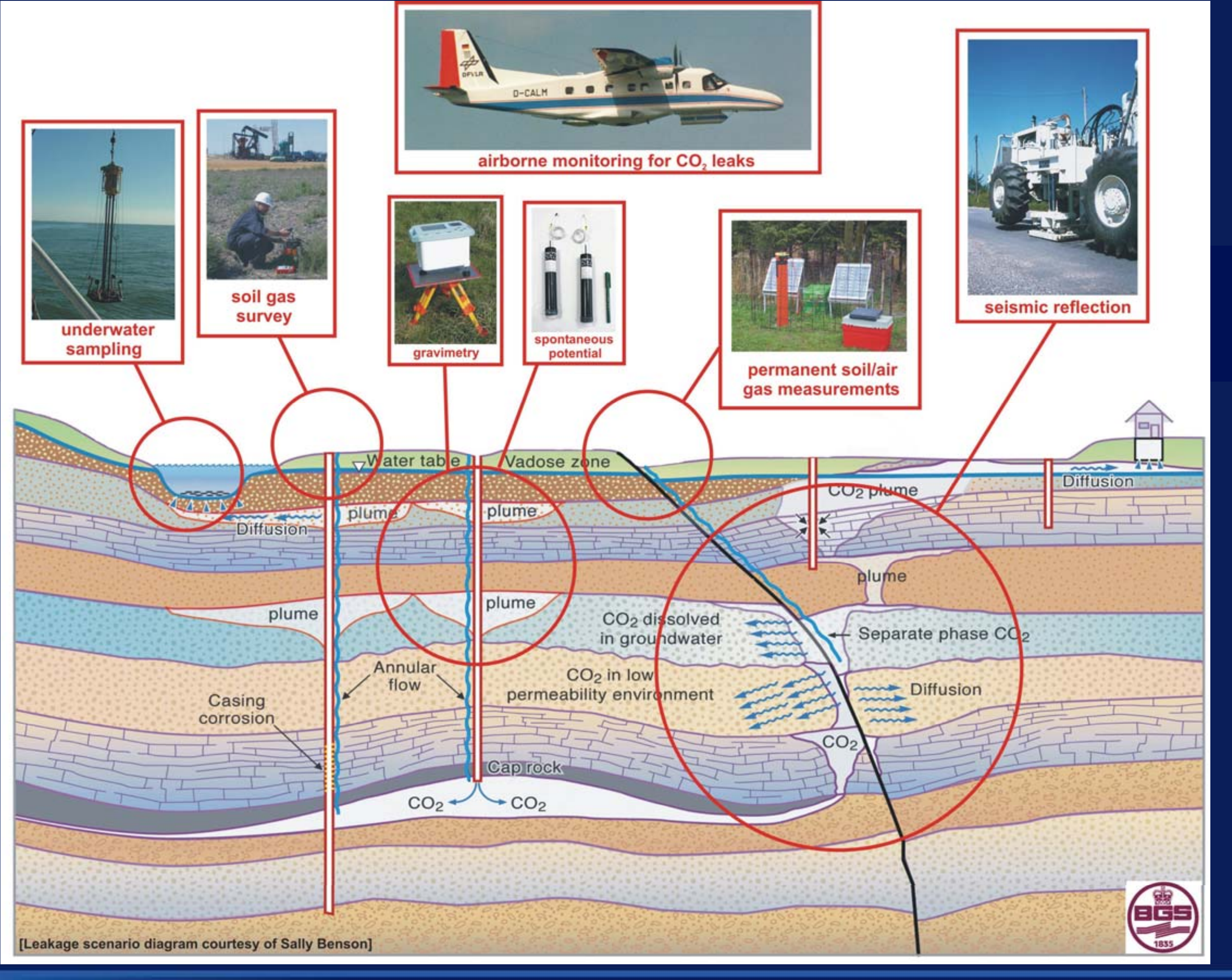
Monitoring of CO_2 storage

Aims of the monitoring activities

- **Current site performance**
  - ✓ detecting migration of CO2
  - ✓ detecting significant irregularities
- **Understand processes**
  - ✓ process monitoring and calibration
  - ✓ comparison between the actual and modelled behaviour
- **Risk assessment / public confidence in CCS**
  - ✓ detecting leakage of CO2
  - ✓ detecting adverse effects for the surrounding environment

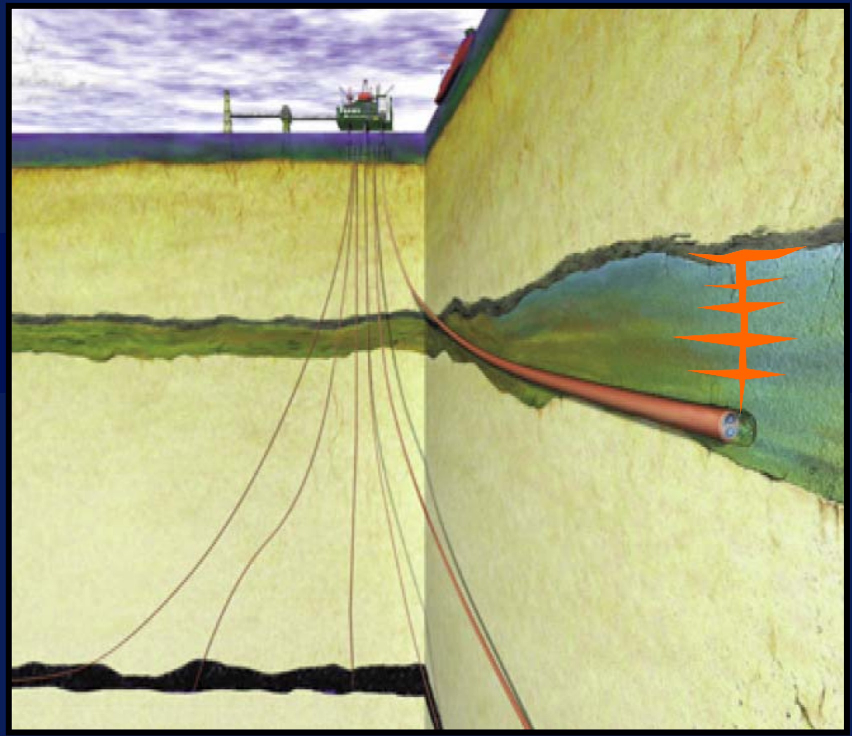
Monitoring of CO_2 storage

Monitoring techniques



Monitoring of CO_2 storage

- **Current site performance -** detecting migration of CO2



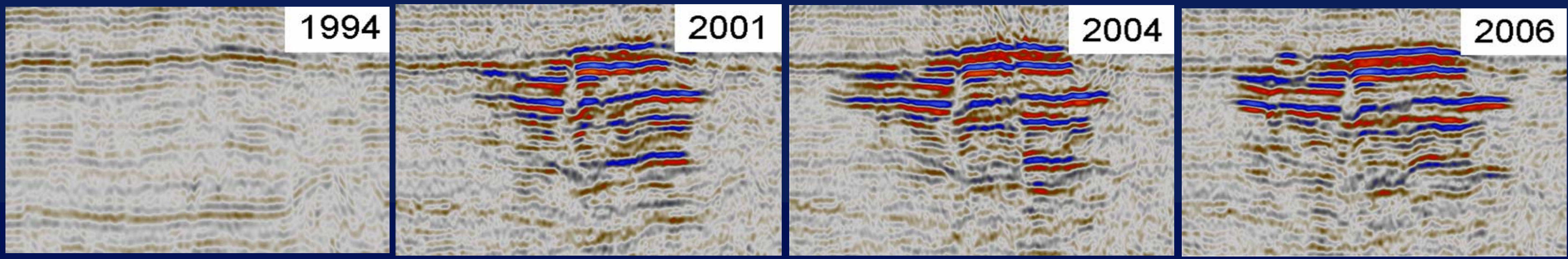
CO_2 injection commenced 1996

~ 1 M t CO_2 injected per annum

> 10 Mt currently *in situ*

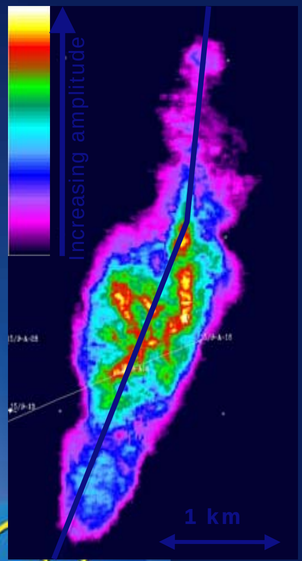
Monitoring of CO_2 storage

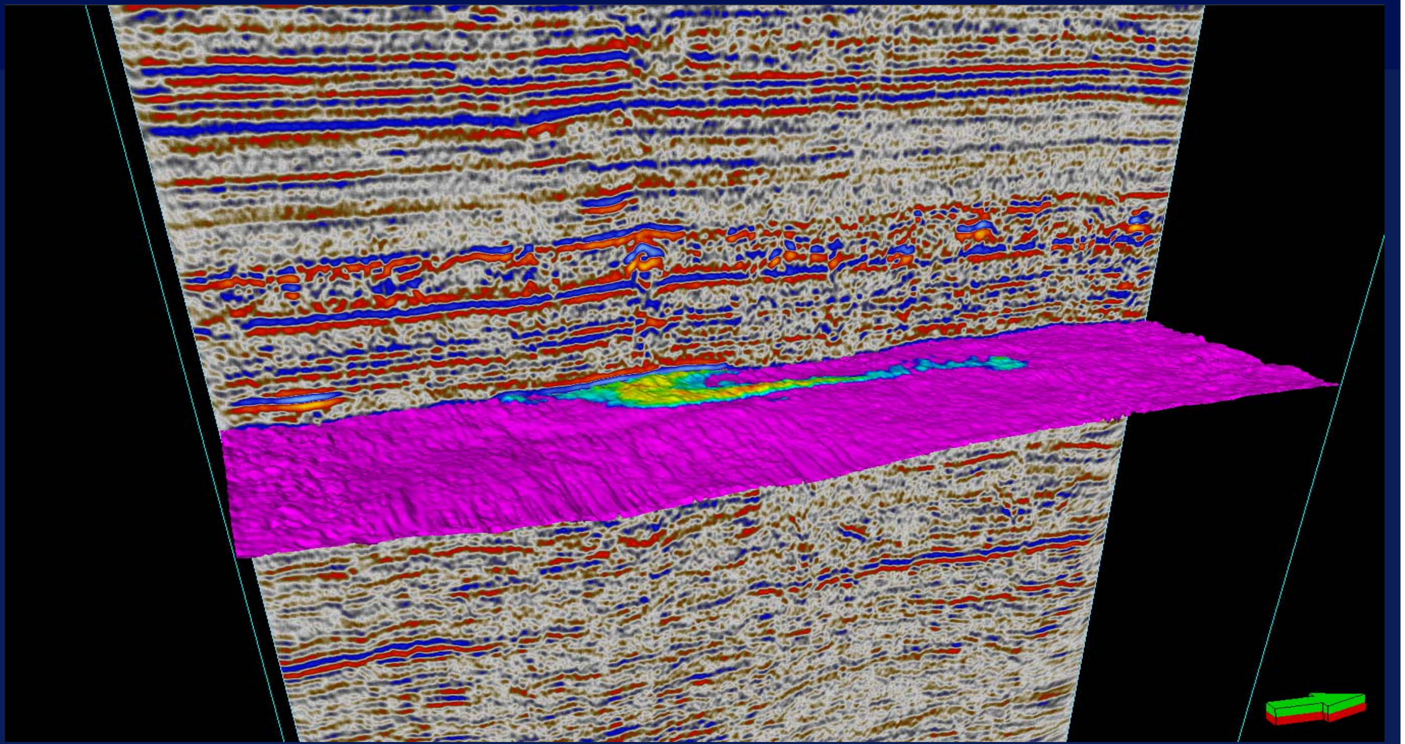
- **Current site performance -** detecting migration of CO2



Area of CO_2 plume: *2,8 km²*

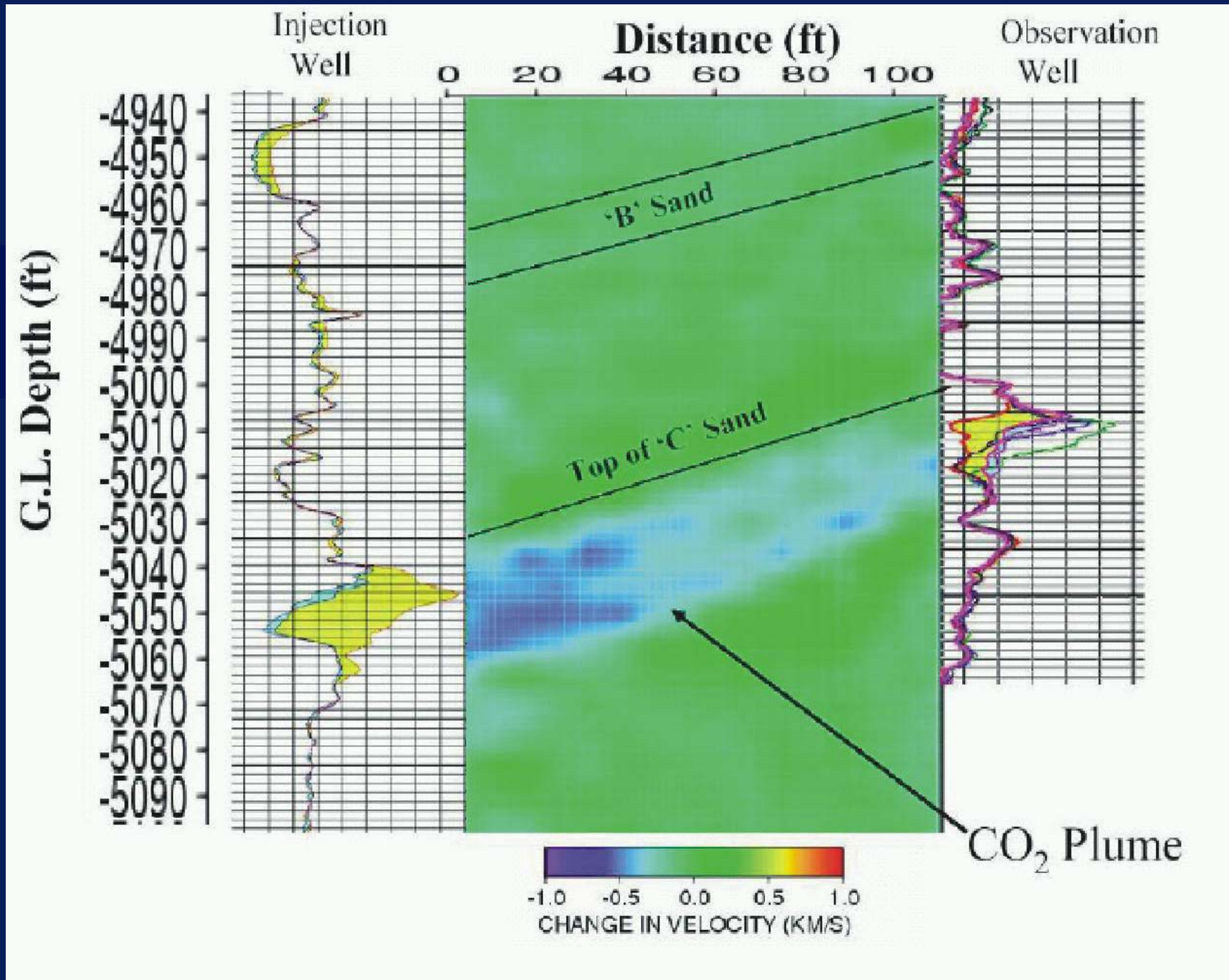
Length of CO_2 plume: *3760 m*





Monitoring of CO_2 storage

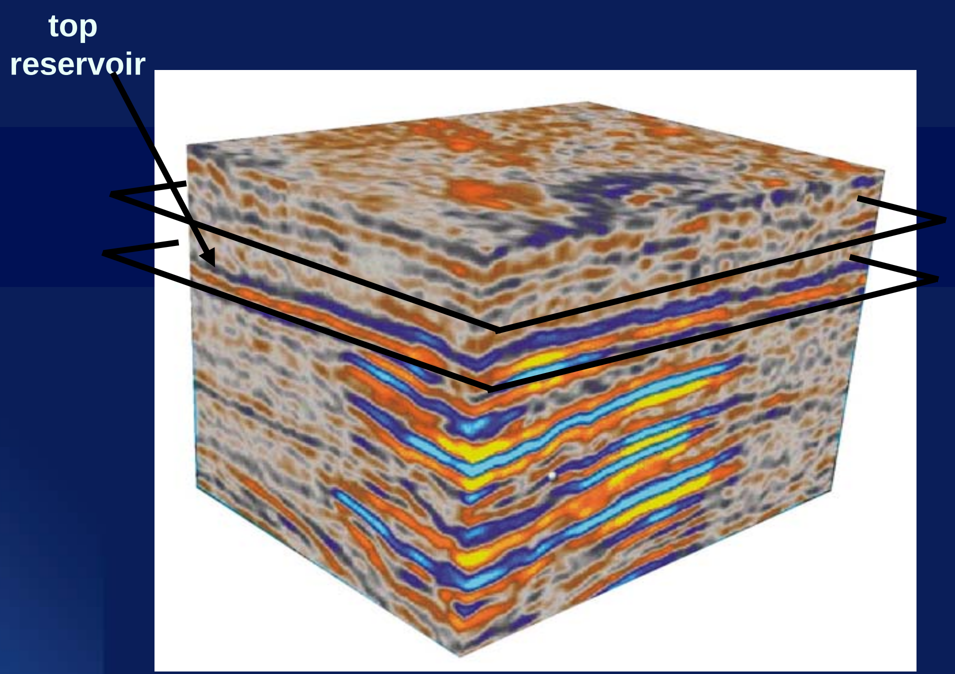
- **Current site performance -** detecting migration of CO2

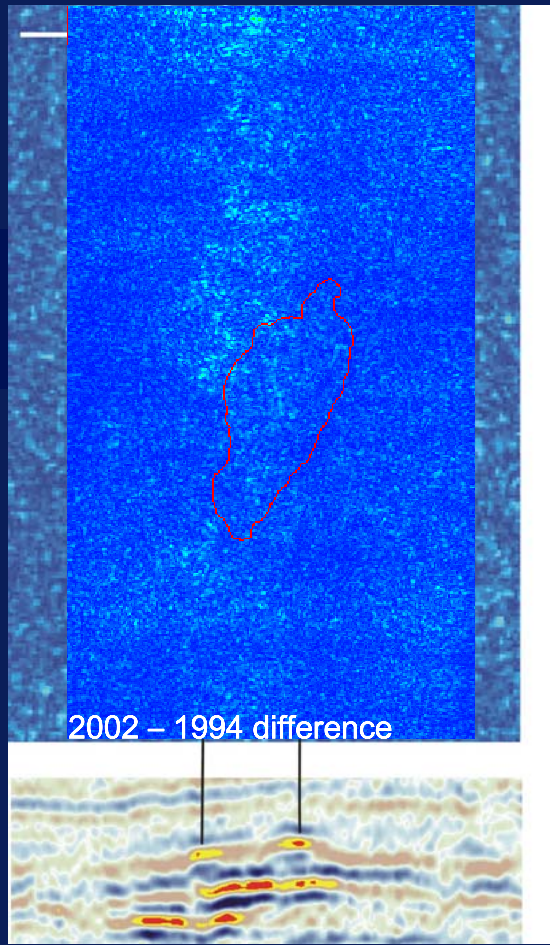


[Crosshole data courtesy of Tom Daley (LBNL),
Christine Doughty (LBNL) and Susan Hovorka (University of Texas)]

Monitoring of CO_2 storage

- **Current site performance -** detecting significant irregularities





Detection limit for Sleipner data:

~ 4000 m^3

~ 2500 tonnes at top reservoir

< 800 tonnes at < 500m (0.004% of projected total)

Monitoring of CO_2 storage

- **Current site performance -** detecting significant irregularities

In Salah gas field:
- **CO2 re-injected in a saline aquifer**
- **2-m thick Carbonferous sandstone**
- **1900 m below ground**
- **by end 2008, over 2,5 Mt stored**

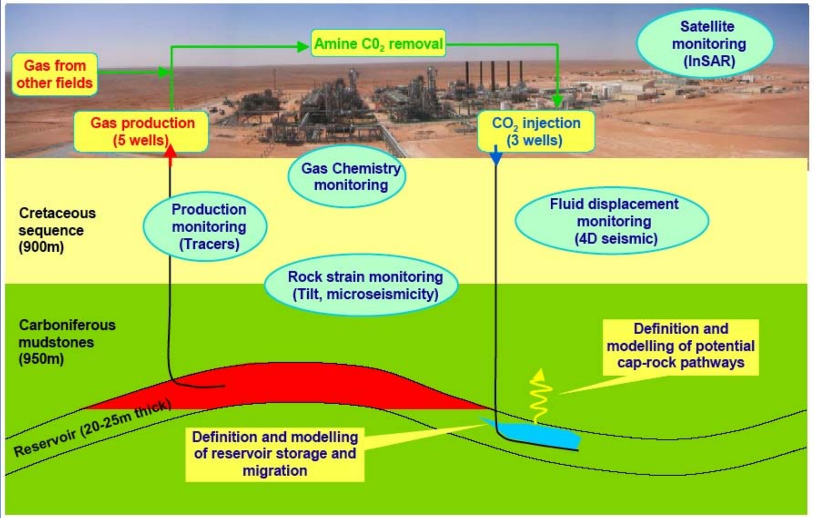


Figure 1. Summary of the In Salah CO_2 injection and storage site with the main monitoring activities.

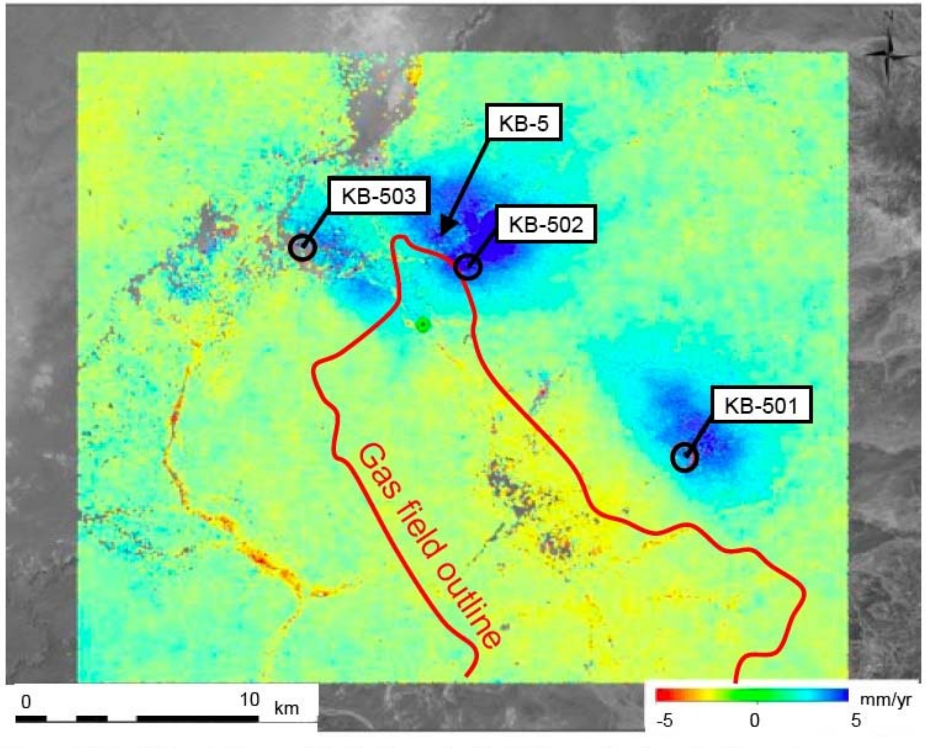


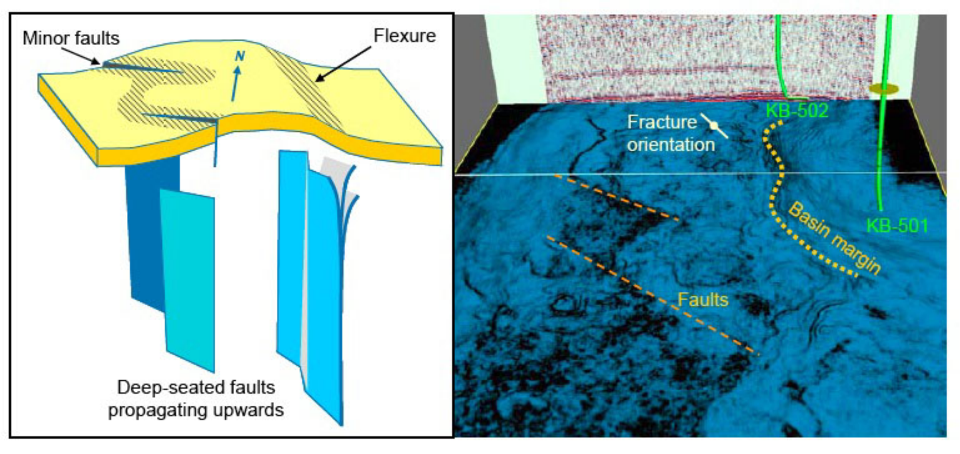
Figure 2. PSInSAR velocity map (Envisat) over the In Salah area for the period December 2003 to March 2007 (Vasco et al. 2008).

Monitoring data:
- **geological**
- **geochemical**
- **geophysical**
- **satellite**

Permanent scatterer InSAR:
- **accuracy 5 mm/y (1 mm/year for long-term av.)**

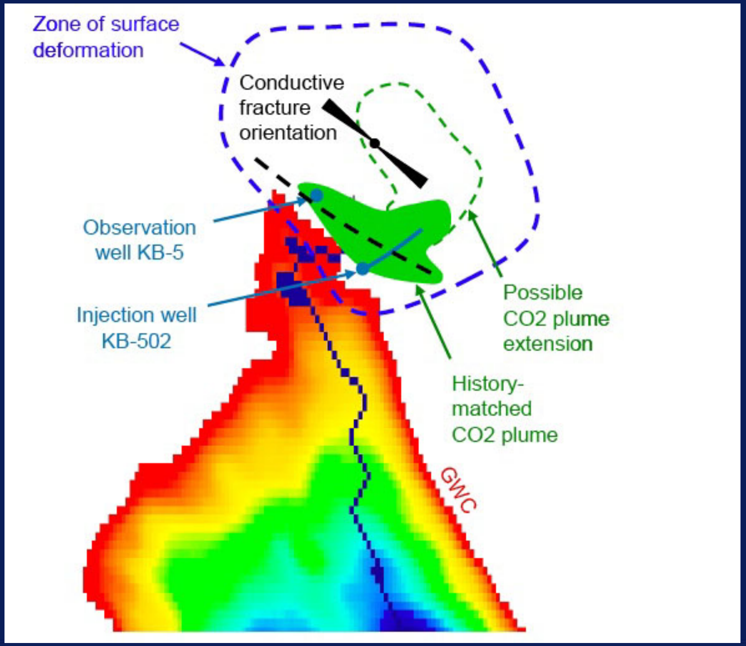
Monitoring of CO_2 storage

- **Current site performance -** detecting significant irregularities



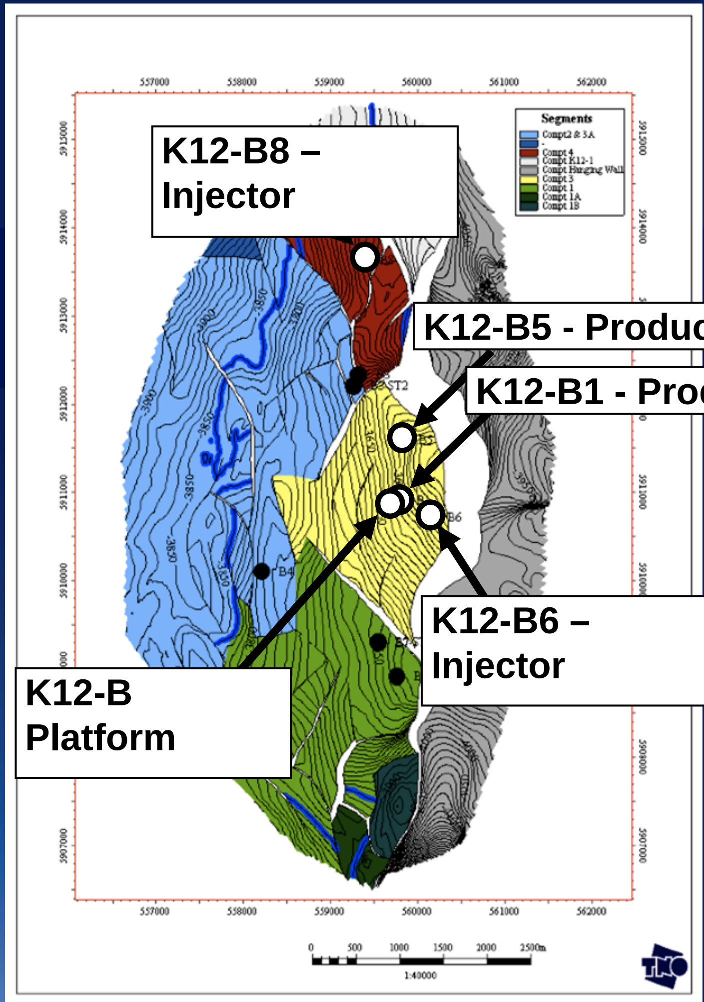
Structural geological setting inferred from seismic data

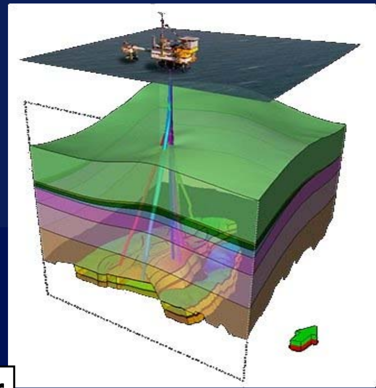
Summary of observations constraining the likely CO2 plume development around injection well KB-502

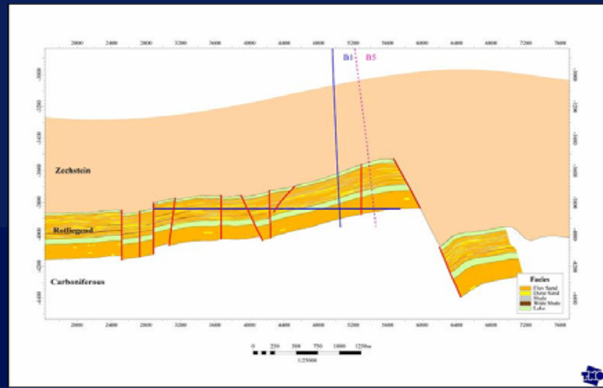


Monitoring of CO_2 storage

- **Understanding processes -** process monitoring and calibration







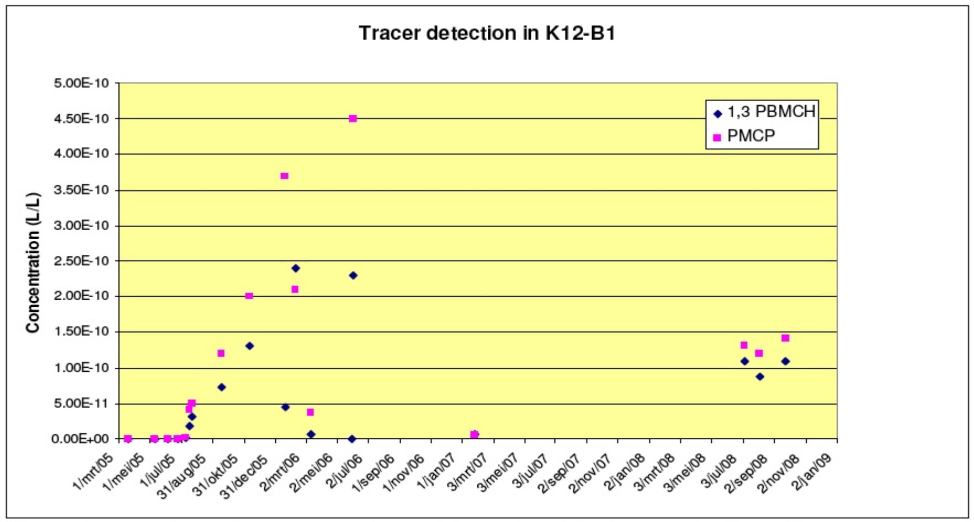
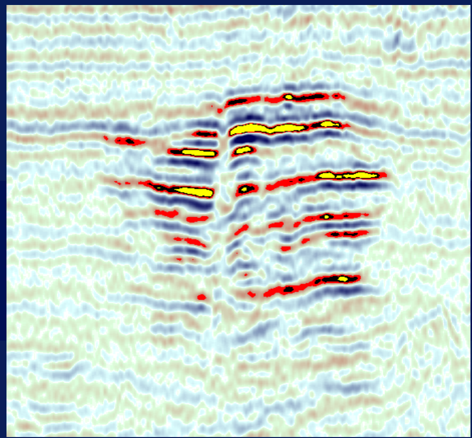


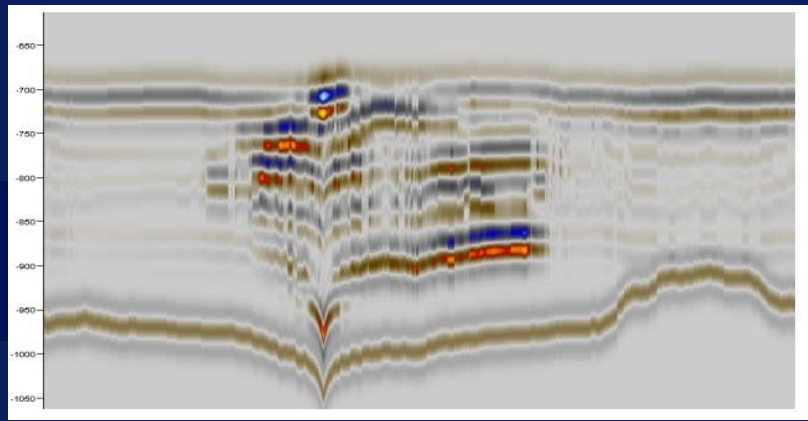
Fig 5: Tracers detection as a function of time after injection at the B1 well.

Monitoring of CO_2 storage

- **Understanding processes -** comparison between the actual and modelled behaviour

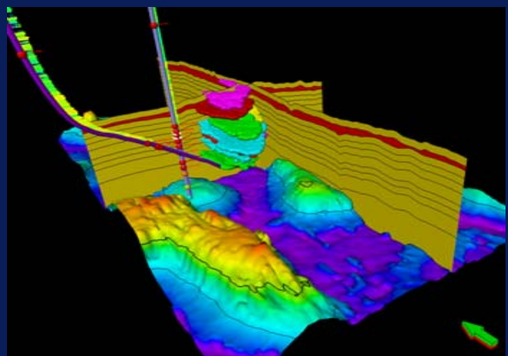
Real data

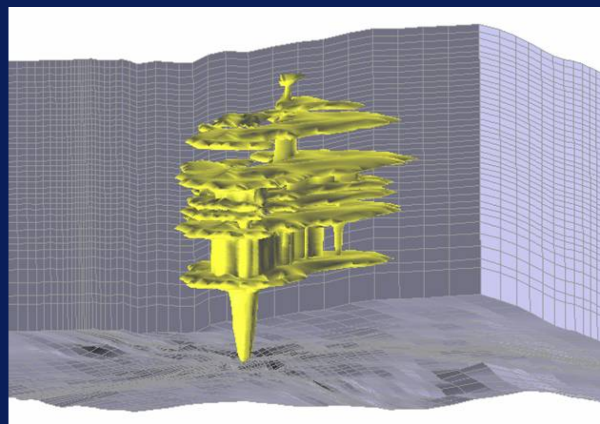




Synthetic data

Interpreted data



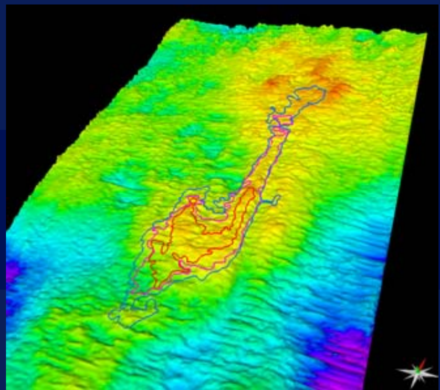


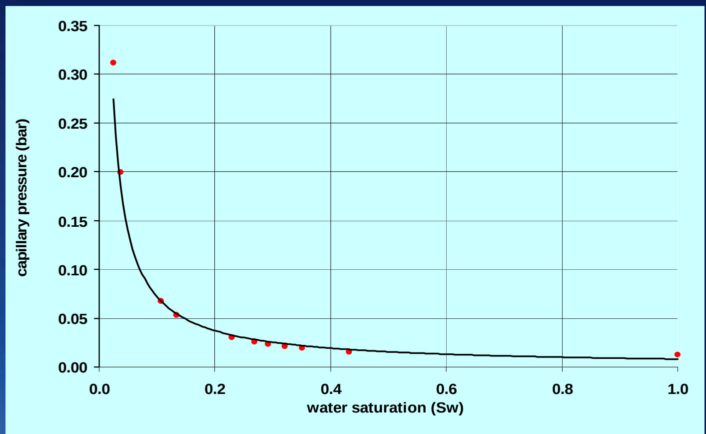
Derived model

Monitoring of CO_2 storage

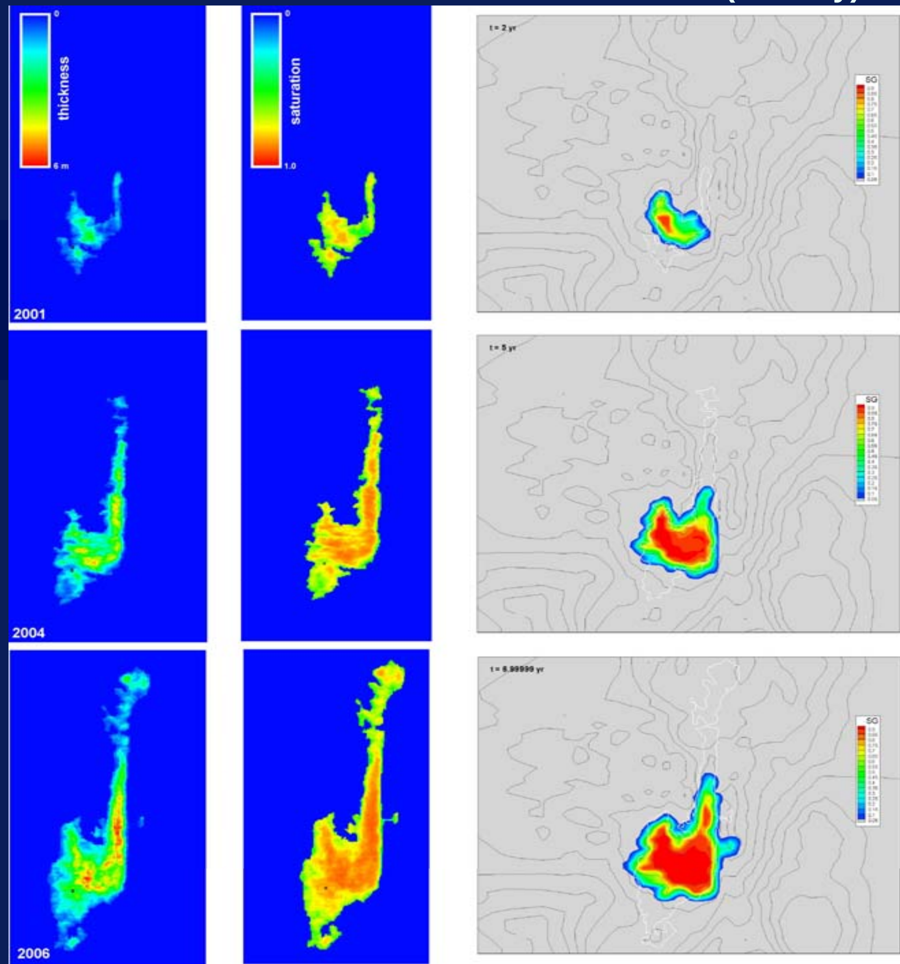
- **Understanding processes -** history matching

Topmost CO_2 layer in Sleipner plume in 2001, 2004 and 2006





observed **simulation (3 Darcy)**

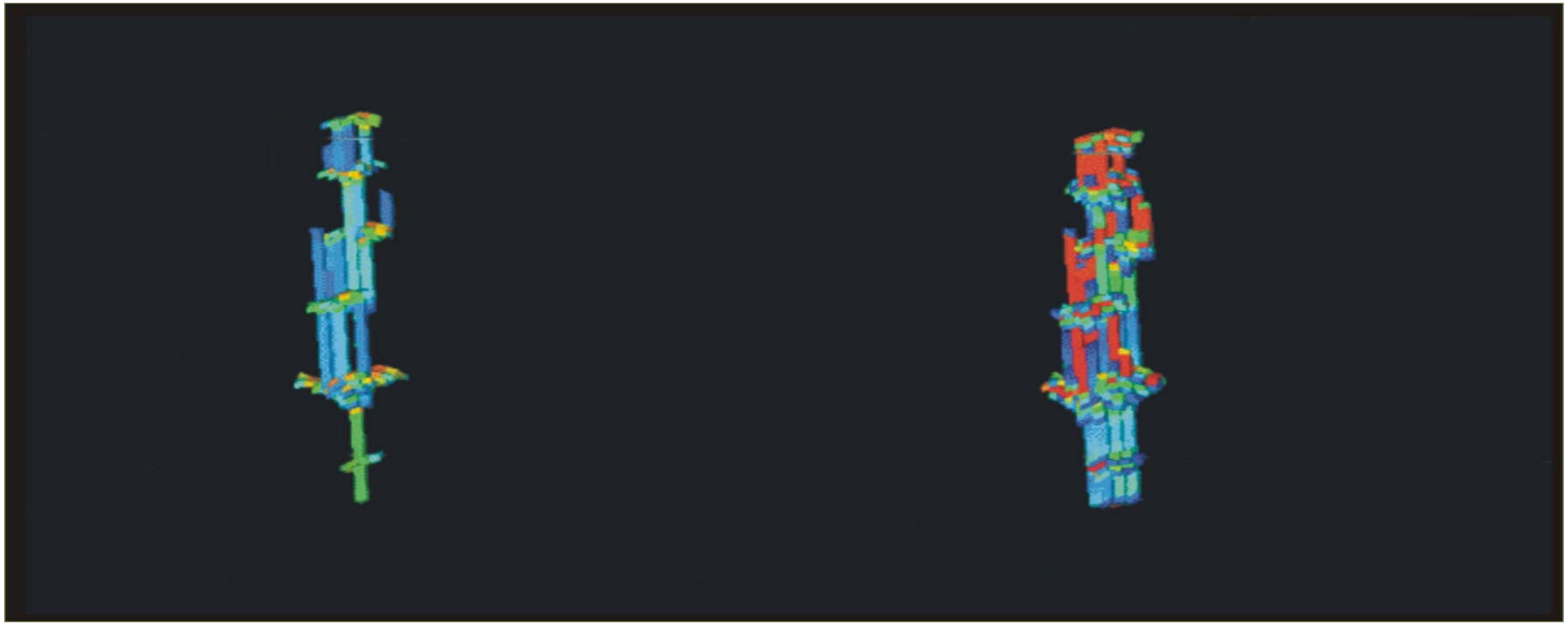


?modify permeability and/or topography

Monitoring of CO_2 storage

- **Understanding processes -** long term behaviour simulation

free CO_2 **CO_2 in solution**



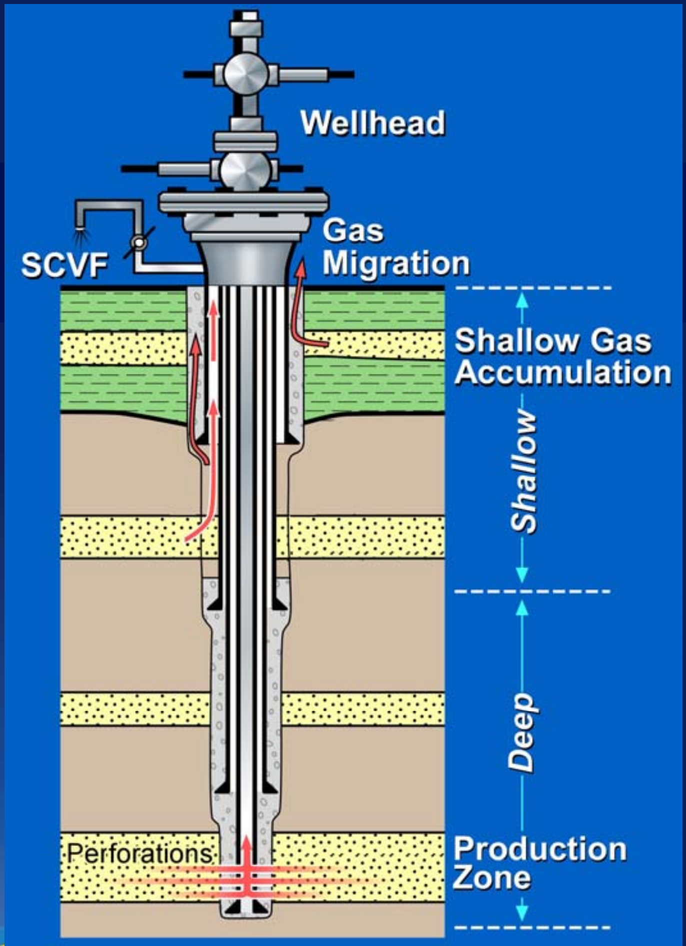
1999 (2.3 Mt) CO_2 reaches top of reservoir. First repeat survey

2001 (4.3 Mt) Second repeat survey

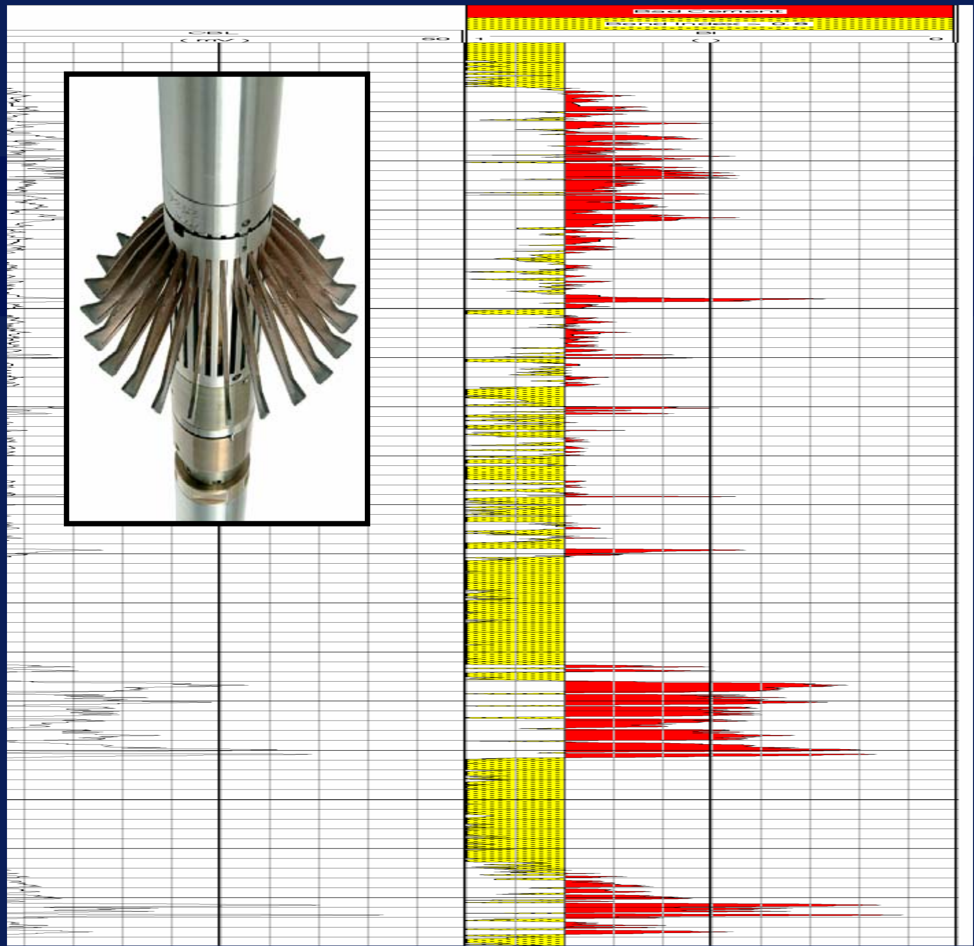
Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2

Integrity monitoring (CBL)



[diagram courtesy of Stefan Bachu]



[diagram courtesy of CASTOR Criteria report]

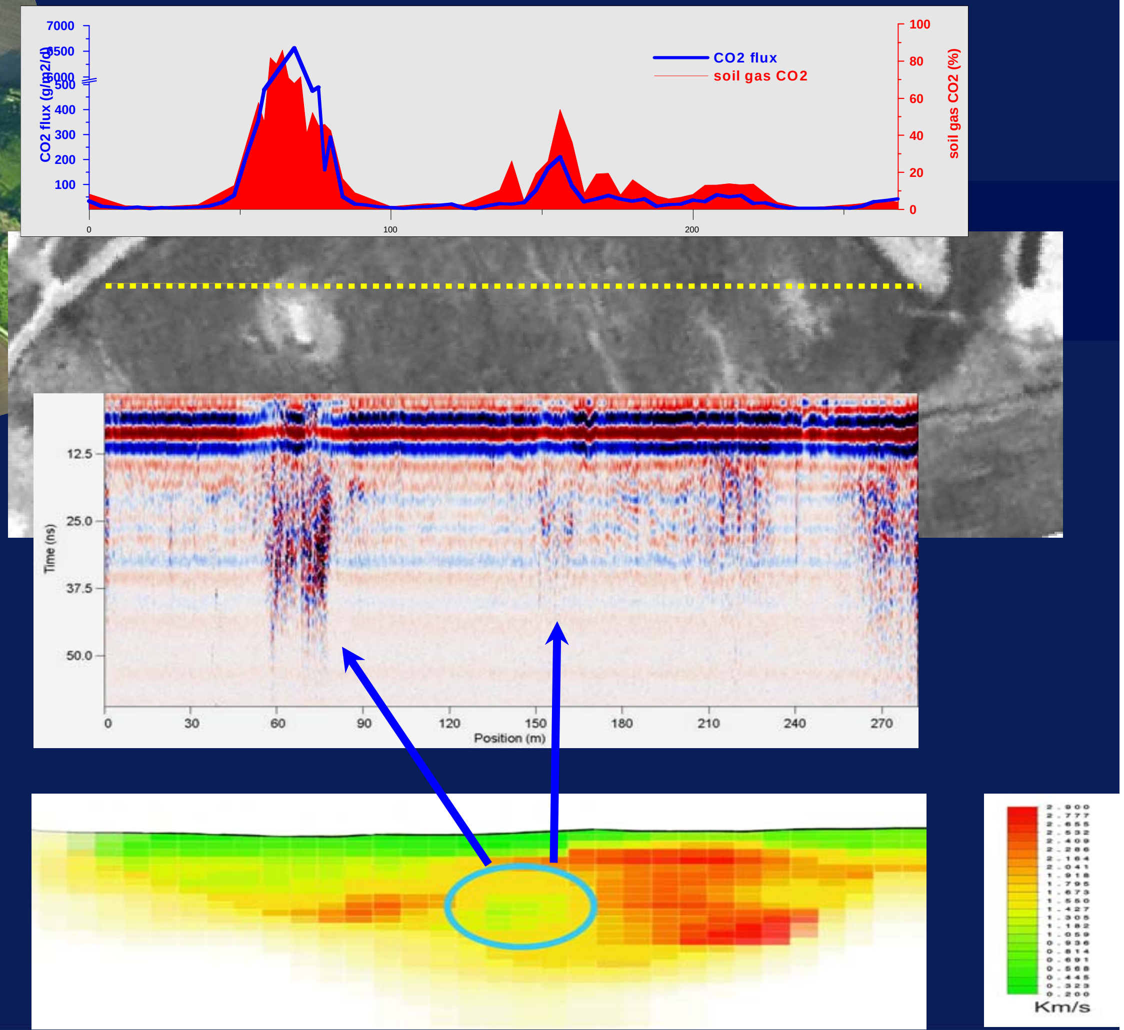
Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2

Monitoring of CO_2 storage

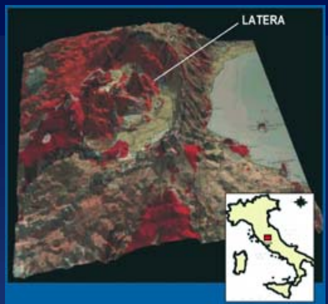
- **Risk assessment -** detecting leakage of CO2

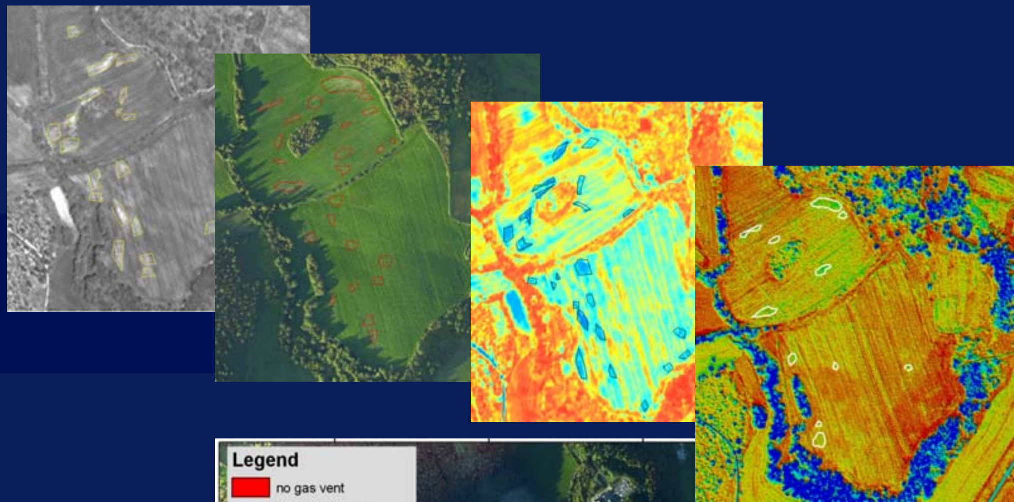
Note how localised the leakage can be …

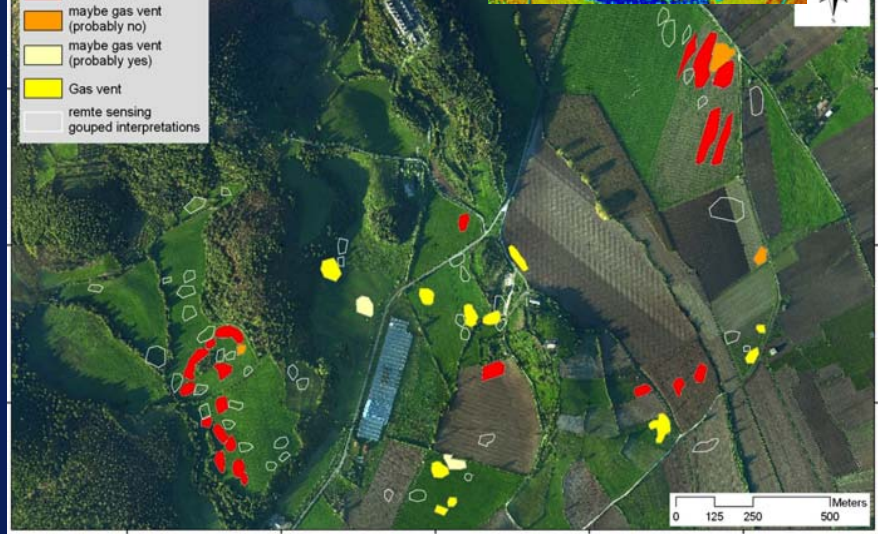


Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2







Lidar,

Thermal sensor at 11 bands,

Casi system at 15 bands, AISA Eagle at 63 bands within 400 - 1.000 nm, resolution 65 cm @ 1.000 m height

Monitoring of CO_2 storage

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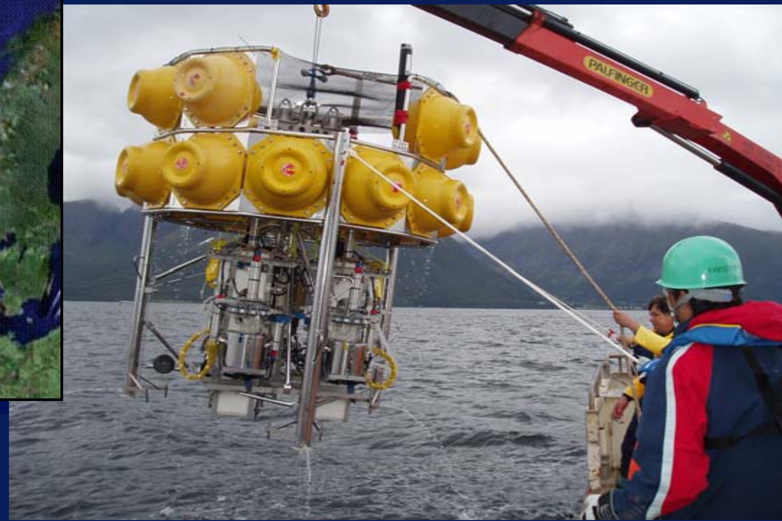
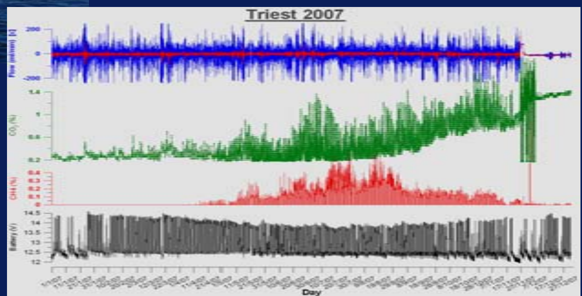
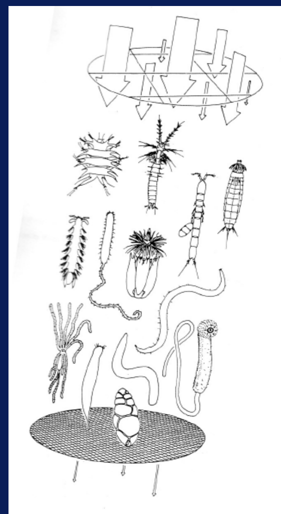
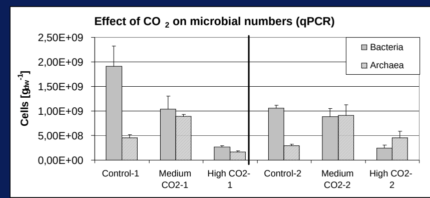
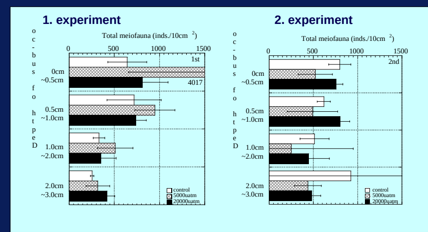








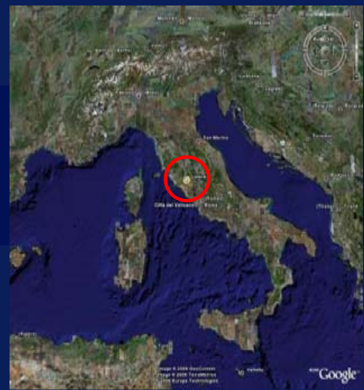


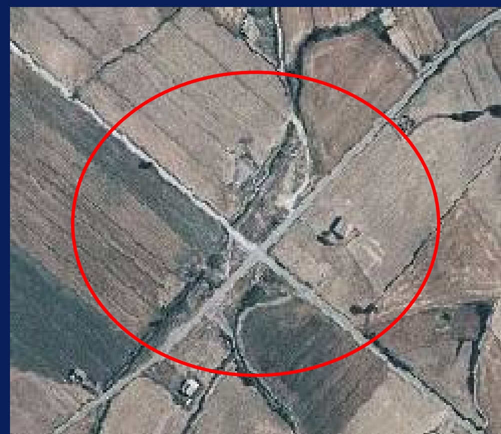
Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to go deeper in the near subsurface by methods integration …..

- Soil gas and CO2 flux
- Ground Penetrating Radar
- Microgravity
- Magnetometer
- Seismic data
- Electromagnetic survey
- Geo-electrical survey (resistivity survey)
- Spectral induced polarization
- Self Potential Mapping
- Time Domain EM
- Vertical Electrical Sounding (VES)
- Surface water conductivity survey





Monitoring of CO_2 storage

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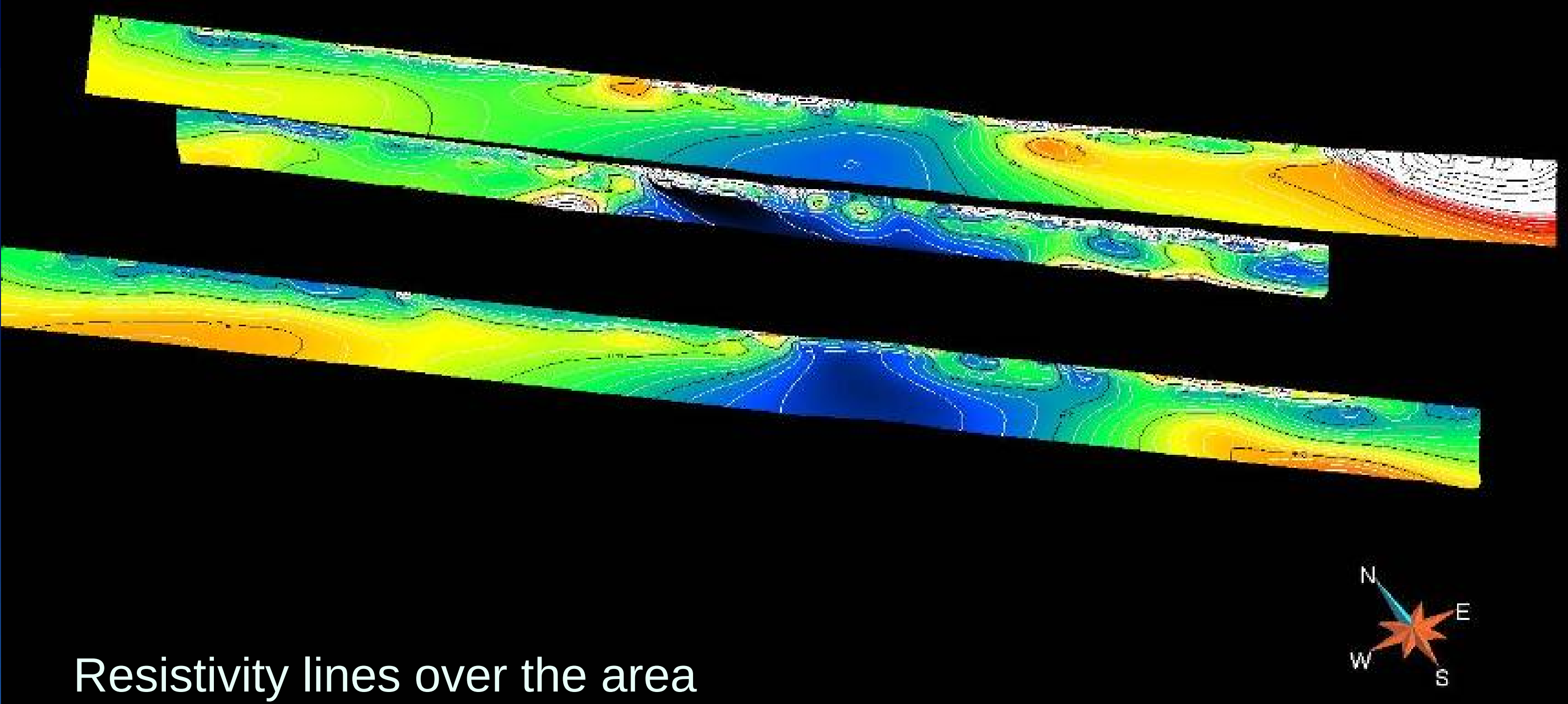

Resistivity lines over the area

Monitoring of CO_2 storage

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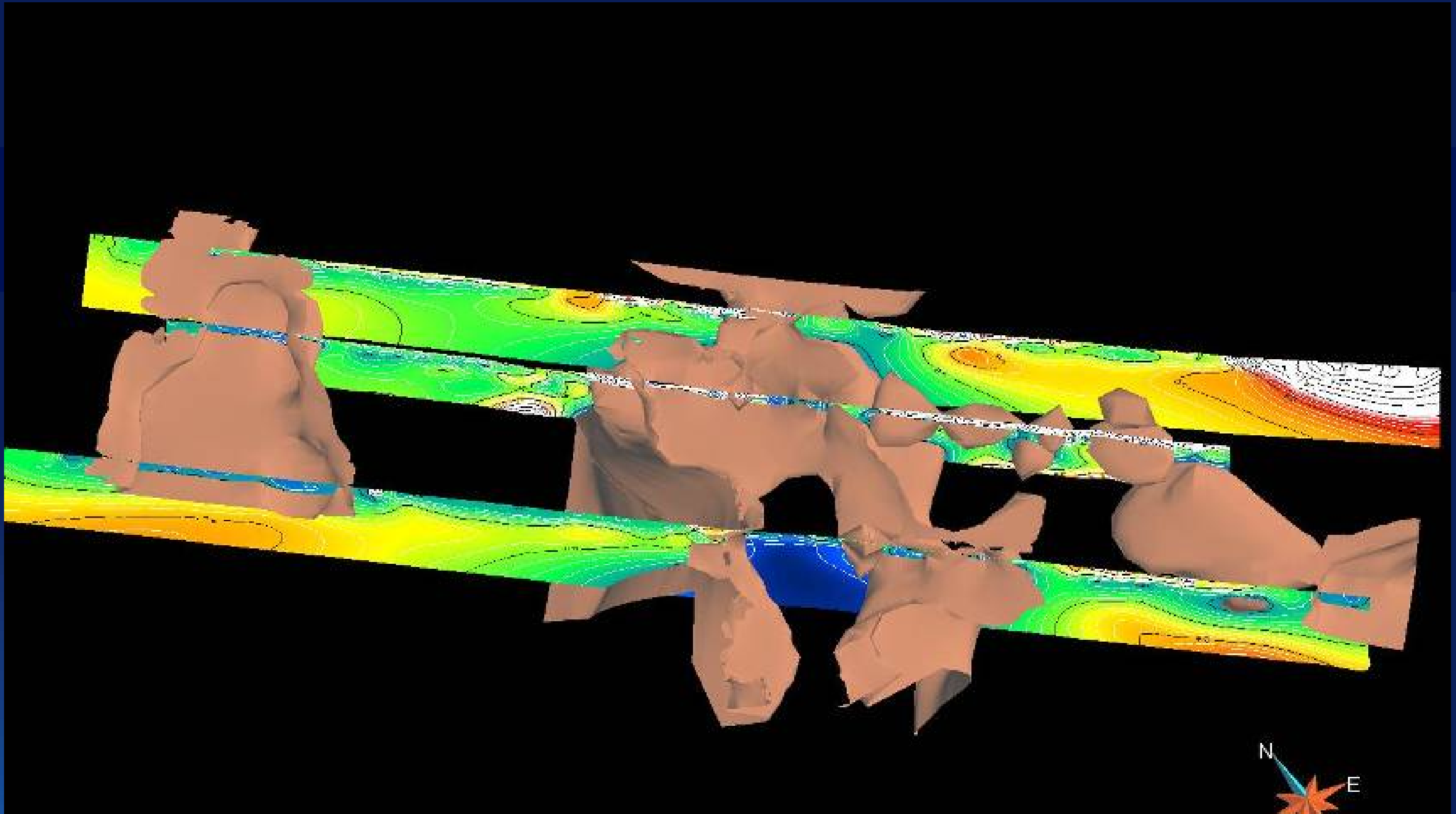

Resistivity iso-surfaces

Monitoring of CO_2 storage

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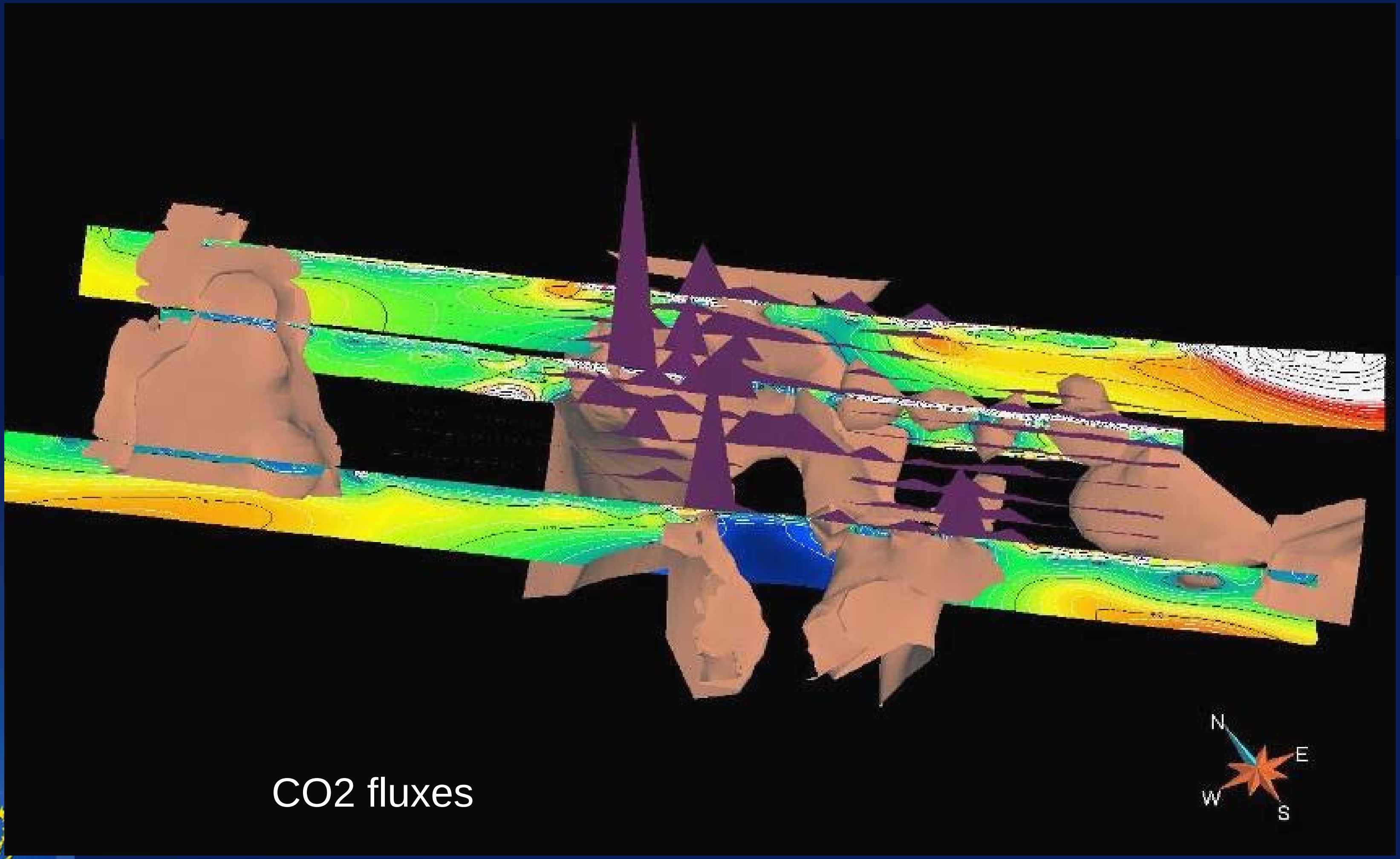
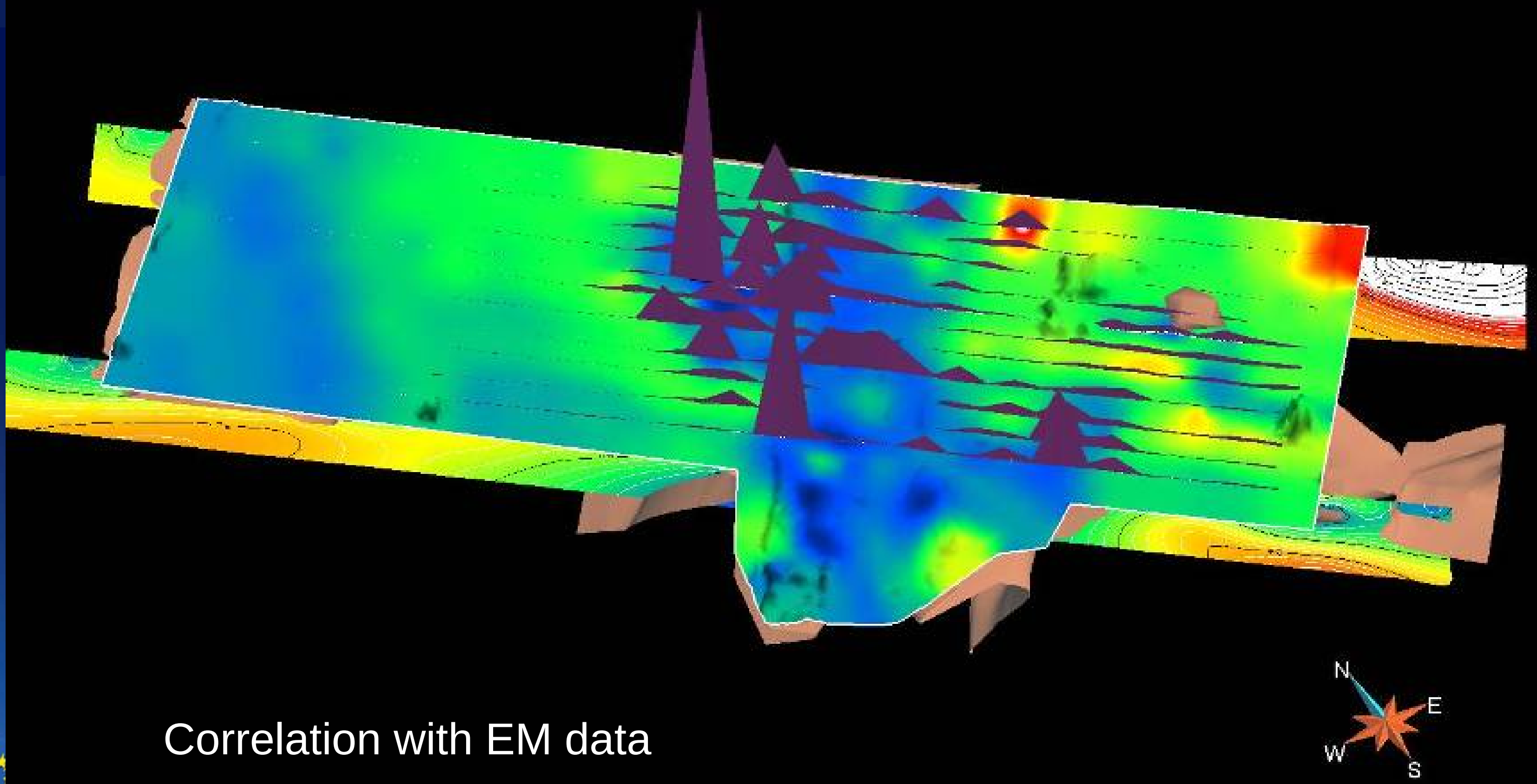


Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to go deeper in the near subsurface by methods integration …..



Correlation with EM data

Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

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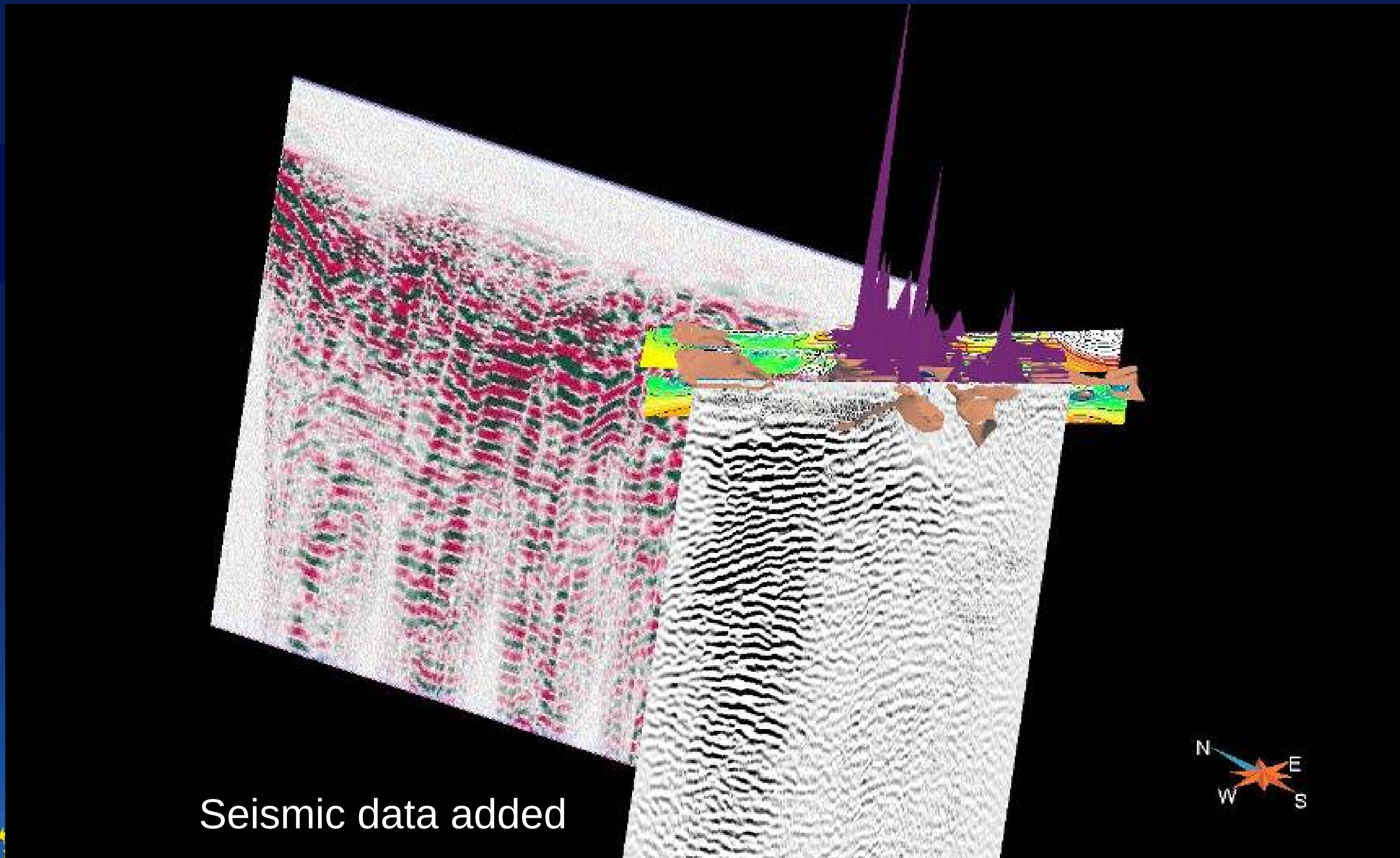

Monitoring of CO_2 storage

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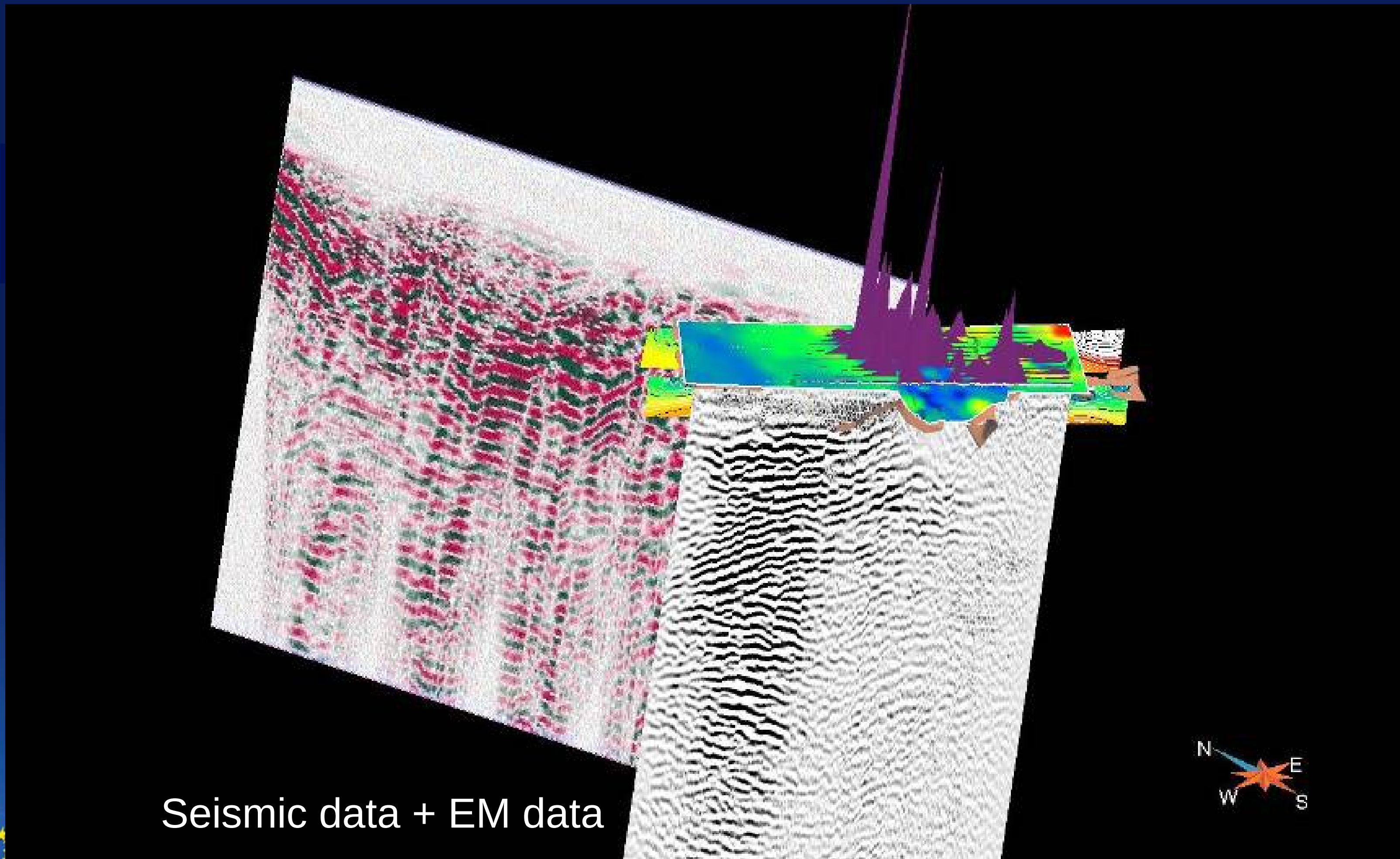

Monitoring of CO_2 storage

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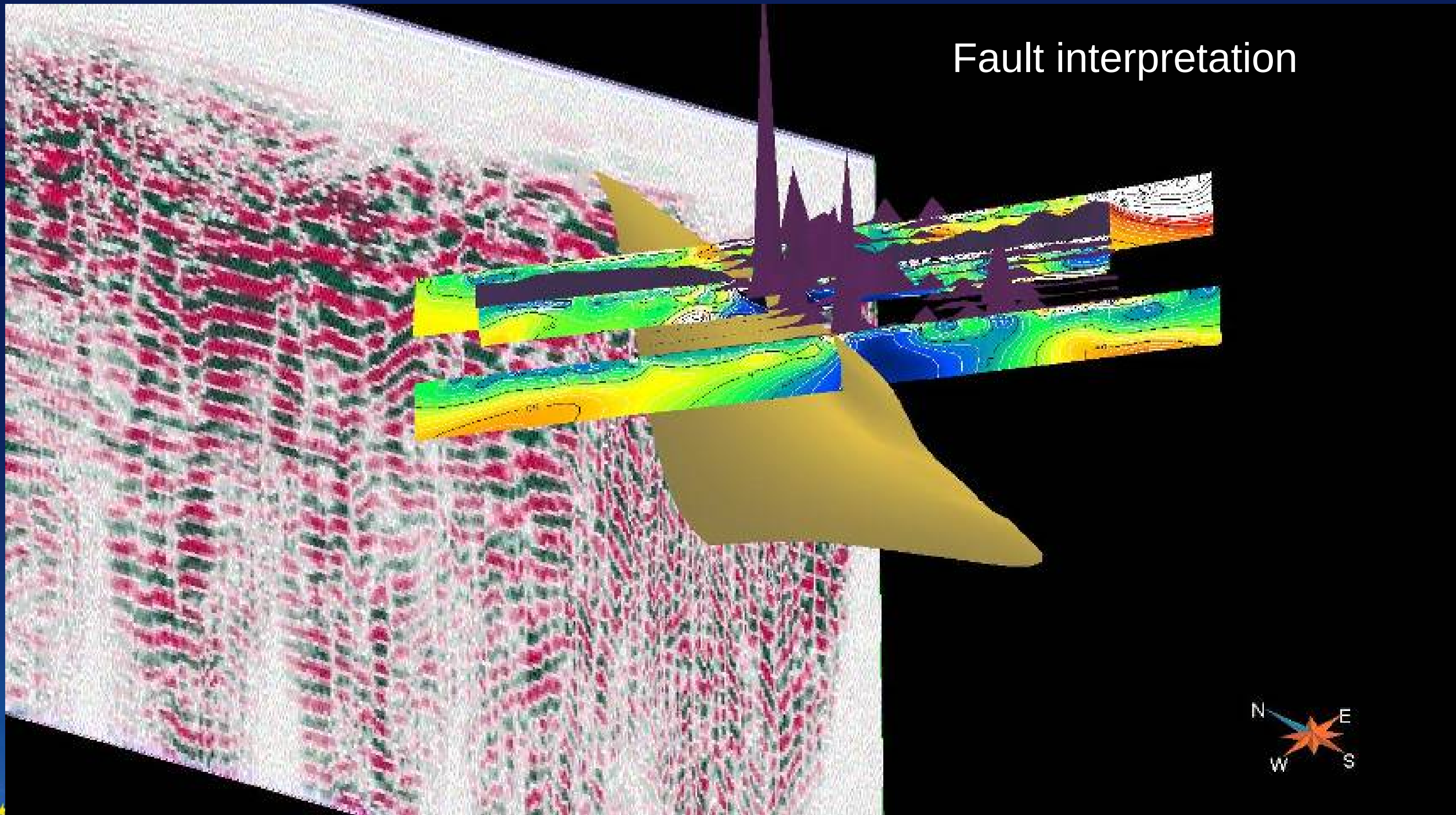

Monitoring of CO_2 storage

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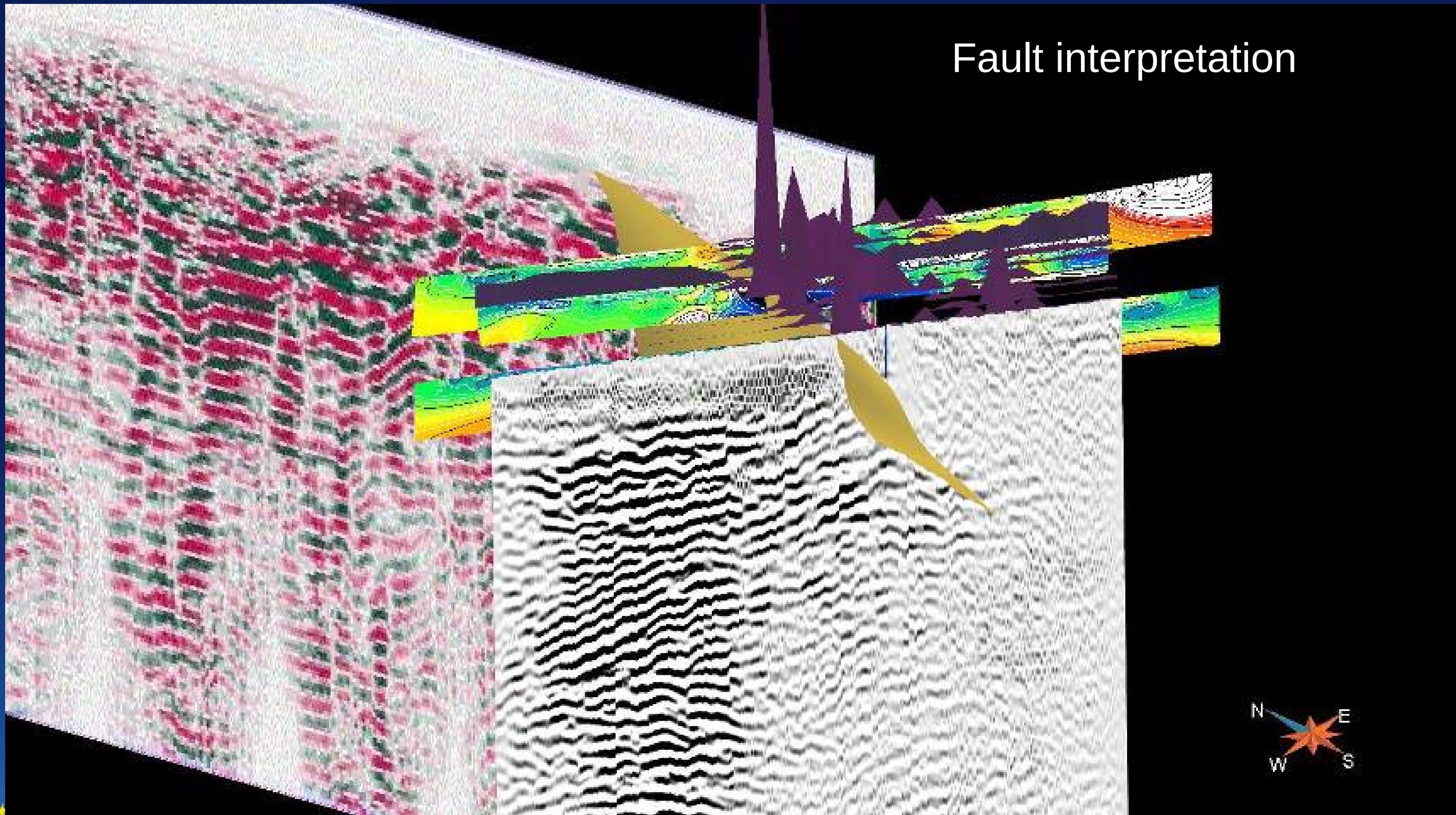
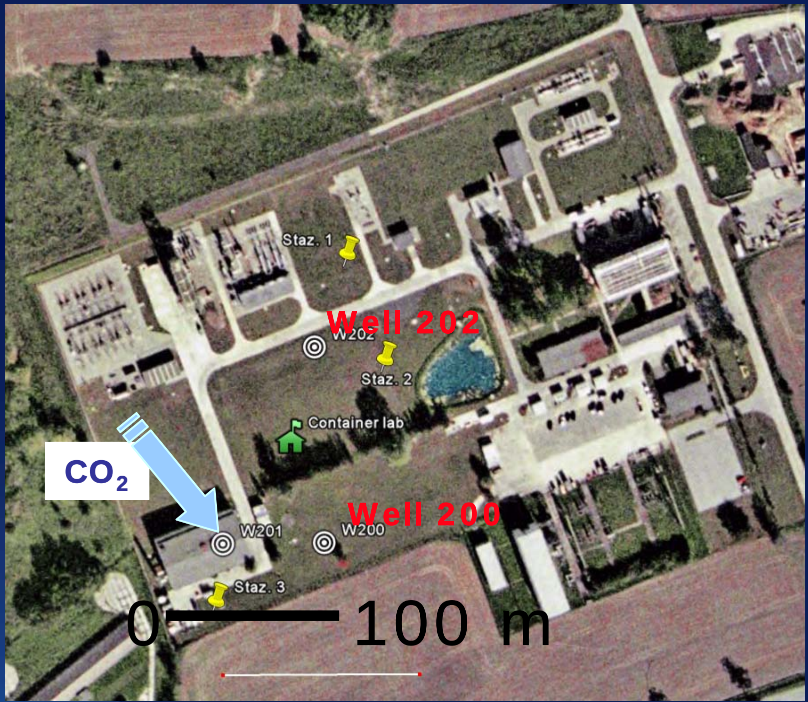
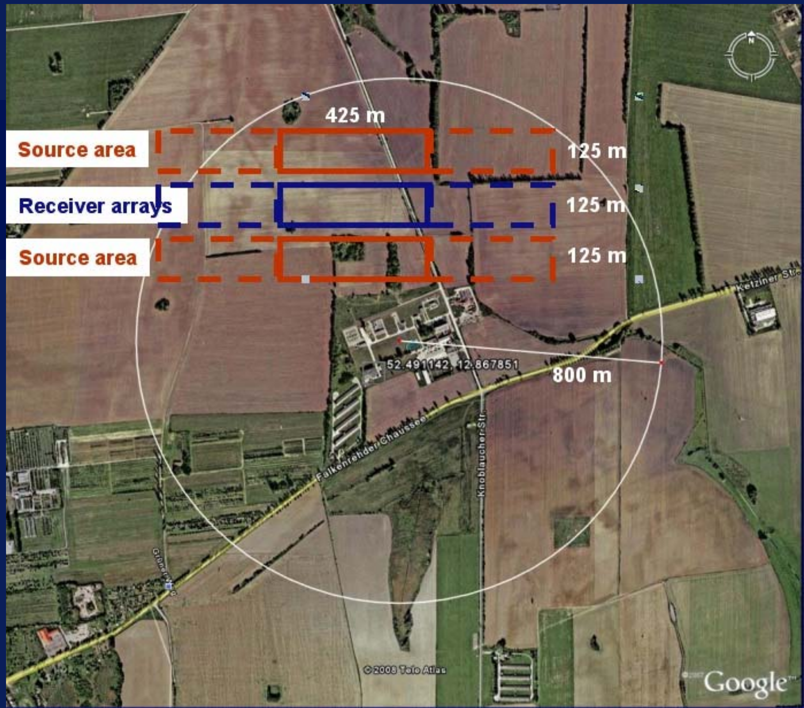


Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to provide a QUICK ALERT by integrating active and passive seismics …..





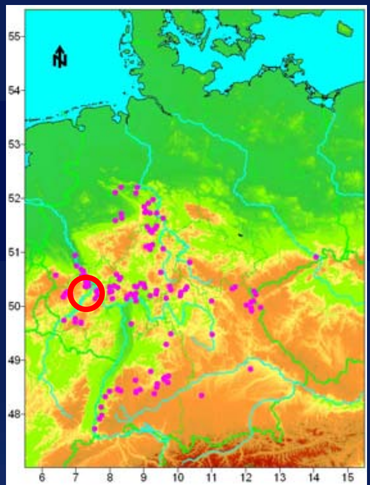
- ***Repeated active seismics***
- ***Continuous passive seismics***
  (1 year period)

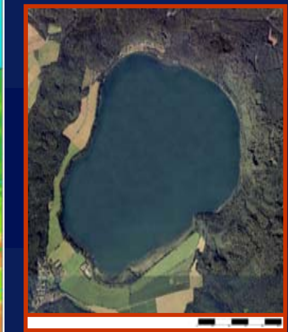
- *6 lines of 18 buried hydrophones (spacing of 25 m)*
- *Depth of the hydrophones (below groundwater table) 30-40 m*
- *Additional stand-alone surface 3C-geophones*

Monitoring of CO_2 storage

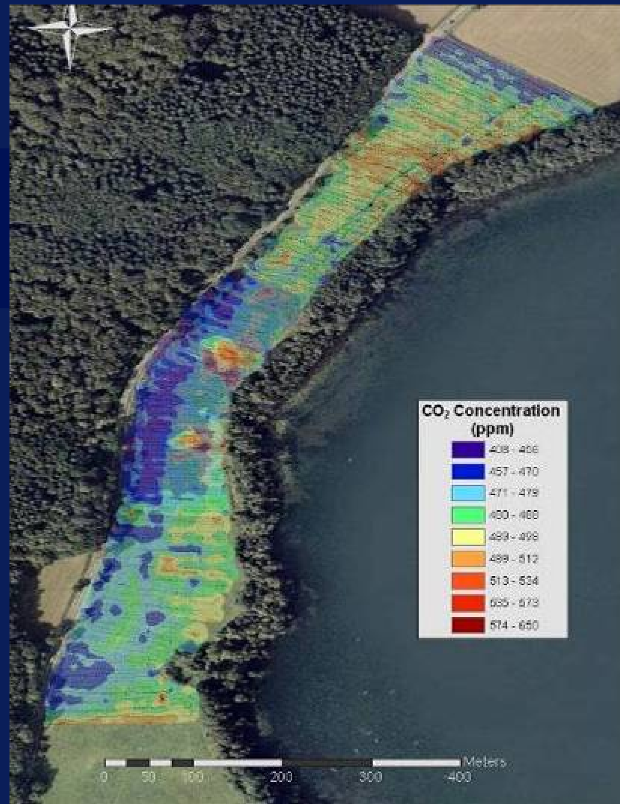
- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to identify possible leakages on-shore quickly and at affordable costs …..





- Measuring CO_2 flux at fixed sites continuously
- Sensitivity 2-5 ppm



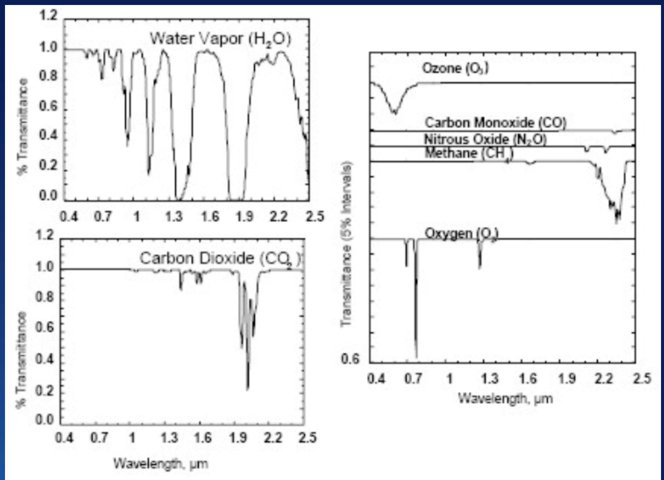
- Open path laser gas analyser
- Sensitivity 5 -10 ppm CO_2 ; 0,1 - 1 ppm CH
- Reading every 1 sec

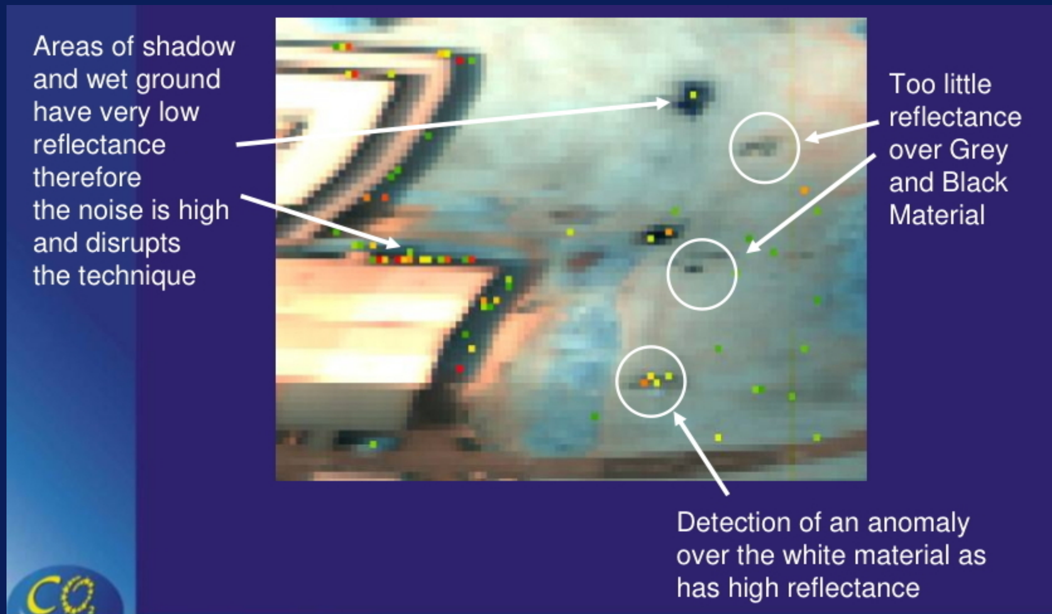
Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to move from in-direct to direct remote sensing of CO2 leakages …..

- AISA Hawk tested by BGS in June 2007:
  - Dry run with large baths (2x2x0,75 m), lined by tapaulins of known reflectance, filled with CO_2
- Bad weather conditions
- Poor results



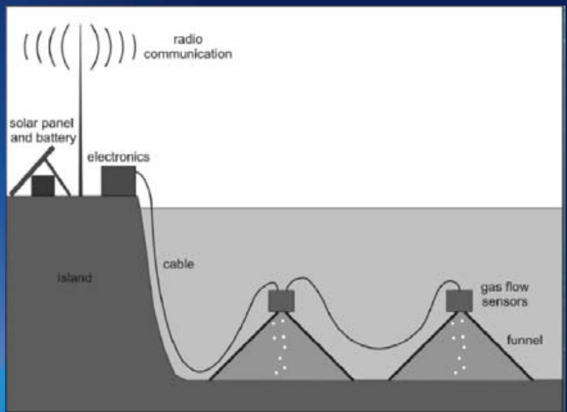


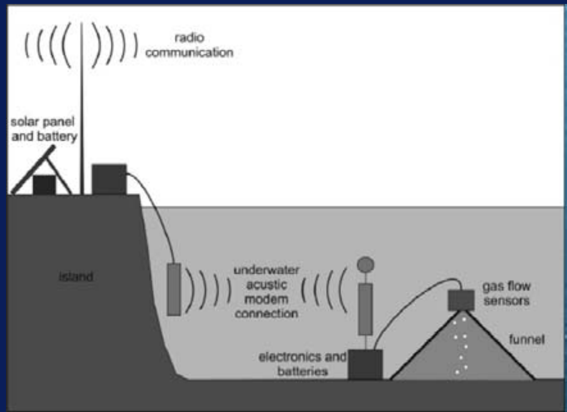
Monitoring of CO_2 storage

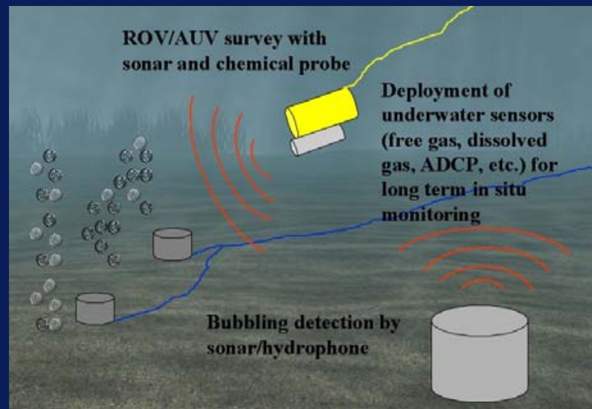
- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to develop new equipments for off-shore leakages control …..

- *from **buoys mounted** to*
- *a **variety of solutions (**mainly on the **sea floor)***



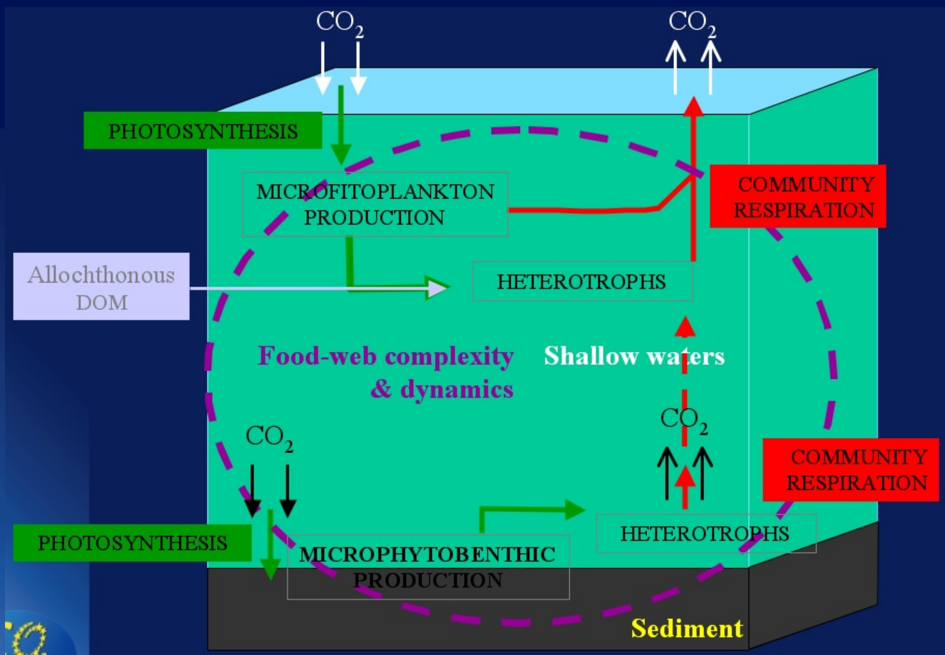




Monitoring of CO_2 storage

- **Risk assessment -** detecting leakage of CO2 - ***NEW CONCEPTS***

to develop a comprehensive approach to off-shore leakages evaluation …..



	ZONES	PROCESSES	ACTIVITIES	
AIR		AIR-SEA CARBON FLUXES	Parametrization to be developed in the italian project VECTOR, exploiting and extending results from previous EC projects MATER and ADIOS	
SEA	PHOTIC ZONE	NATURAL COUPLING OF CO_2 WITH NUTRIENT CYCLES		
SEA	BOTTOM BOUNDARY LAYER	TIME & SPACE VARIABILITY OF GAS CONCENTRATION IN BENTHOS HABITAT	JRAP-4	INTEGRATION IN JRAP-18
SEDIMENT	AEROBIC ZONE	BIOLOGICAL UPTAKE OF C, N, P, Si	JRAP-4 & JRAP-18	
SEDIMENT	ANAEROBIC SULFATE REDUCING ZONE	METHANOTROPHY: $SO_4^{2-} + CH_4 \rightarrow H_2O + HS^- + HCO_3^-$	JRAP-4	
SEDIMENT	ANAEROBIC CARBONATE REDUCING ZONE	METHANOGENESIS: $CO_2 + 4H_2 \rightarrow CH_4 + 2\,H_2O$	JRAP-4	

Monitoring of CO_2 storage

Concluding remarks

- The EC-directive covers monitoring adequately
- Many different monitoring techniques are available to ensure safe storage of CO_2
- Each site is different and requires a different monitoring plan
- Reservoir simulation and modelling in combination with monitoring are crucial
- Monitoring costs are marginal compared to CCS operations