CO2 Capture Project

Long-Term Sealing Integrity of Wells

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Possible mechanisms for CO_2 escape from reservoirs

- Partially eroded shale layers
- Conducting natural faults
- Spill points allowing superfluous CO_2 to enter formations with high permeability
- Fractures, initial or created due to catastrophic events or due to ill-managed pressure control during injection
- Leaking wells (corrosion of steel, deterioration of cement or plugging material)

All mechanisms are characterised by transport in some sort of restricted conduit and the methods to simulate the process will resemble each other

Injected CO_2 has to be stored safely for up 10 000 years to avoid the risk of jeopardize the future climate due leakage

- The quality of the seal has to be verified
- A sufficient seal integrity must be maintained during the operations (*e.g.* control of changes in pressure)
- The field must be abandoned in a state that do not allow future escape within the required time-frame
- Regulation of future use of the underground will apply to avoid uncontrolled escape
- Etc.

Cement/CO_2 chemistry

- Main cement mineral hydration in API class G:
  $2\ Ca_3SiO_5 + 7\ H_2O = Ca_3Si_2O_7 \cdot 4\ H_2O + 3\ Ca(OH)_2$

- Precipitating carbonic acid reactions:
  $H_2CO_3 + Ca(OH)_2 = CaCO_3 + 2\ H_2O$
  $3\ H_2CO_3 + Ca_3Si_2O_7 \cdot 4H_2O = 3CaCO_3 + 2SiO_2 \cdot 2H_2O + 3H_2O$

- Eroding reaction in excess of flowing water/CO_2:
  $H_2CO_3 + CaCO_3 = Ca(HCO_3)_2$
  Bicarbonate solubility at 40^oC: 170 g/l

Conclusions on cement degradation

- Cement in ”dry” CO_2 will form protective calcium carbonate layer.
- Cement in stagnant CO_2/water environment will also form a protective carbonate layer and only very slowly (diffusion controlled) form soluble bicarbonates.
- Cement layer around the casing of an oil well will carbonate and erode rapidly in a wet CO_2 environment with flowing water (aquifer wind):
  - Erosion of 10 mm cement sheet in flowing conditions – likely to be months than years.
  - Increasing porosity, permeability and decreasing compressive strength
  - Adding pozzolans – Rate of erosion reduced by 50% - Not sufficient!
  - Search for stable alternative cementing systems required.

General about CO_2/steel corrosion

- Main cathodic reaction: $2H_2CO_3 + 2e^- = H_2 + 2HCO_3^-$
- Anodic reaction on steel: $Fe = Fe^{2+} + 2e^-$
- Protective corrosion products may form:

  $Fe^{2+} + CO_3^{2-} = FeCO_3\ (s)$

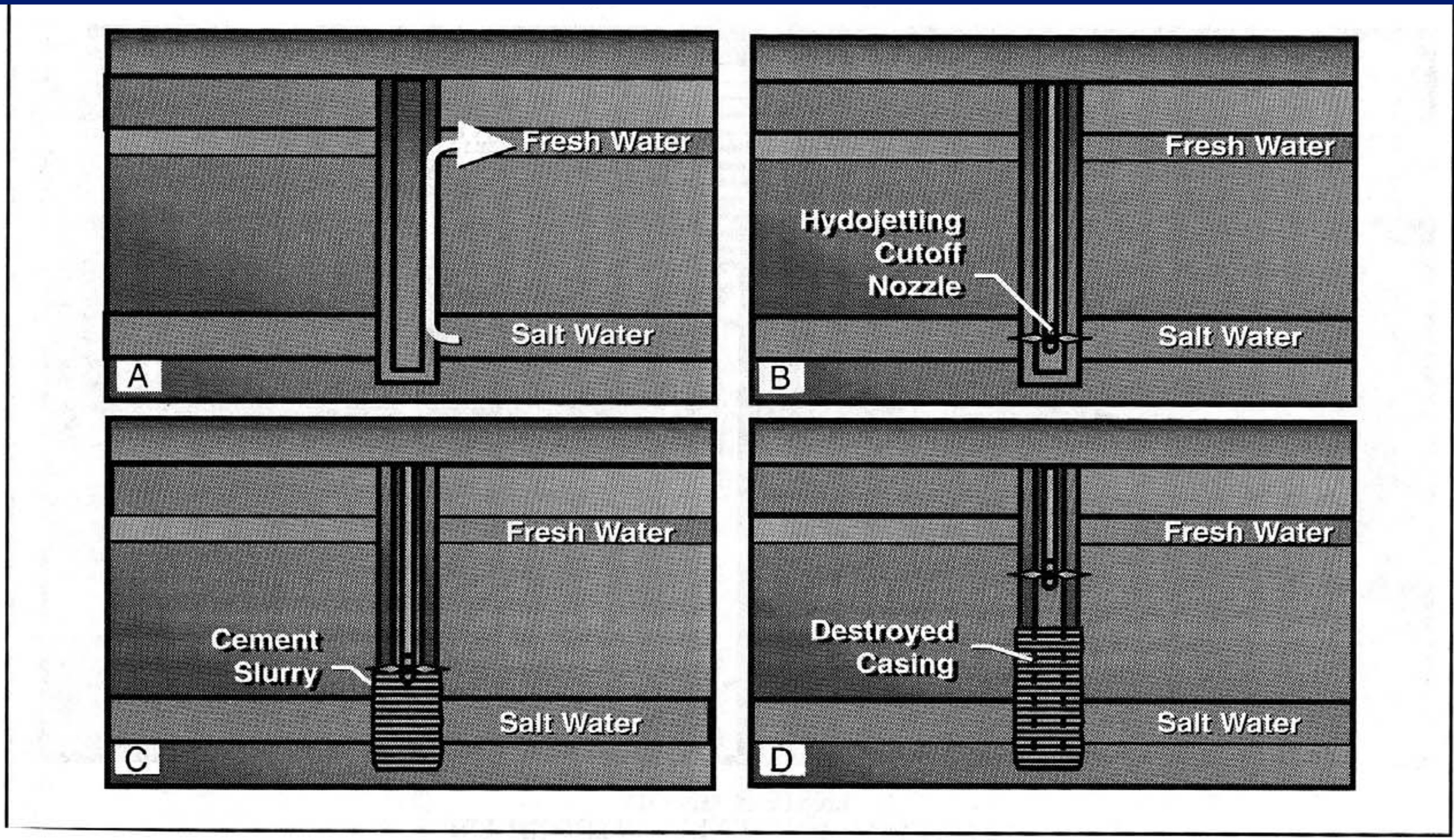
  $3Fe^{2+} + 4H_2O = Fe_3O_4\ (s) + 8H^+ + 2e^-$

  Magnetite

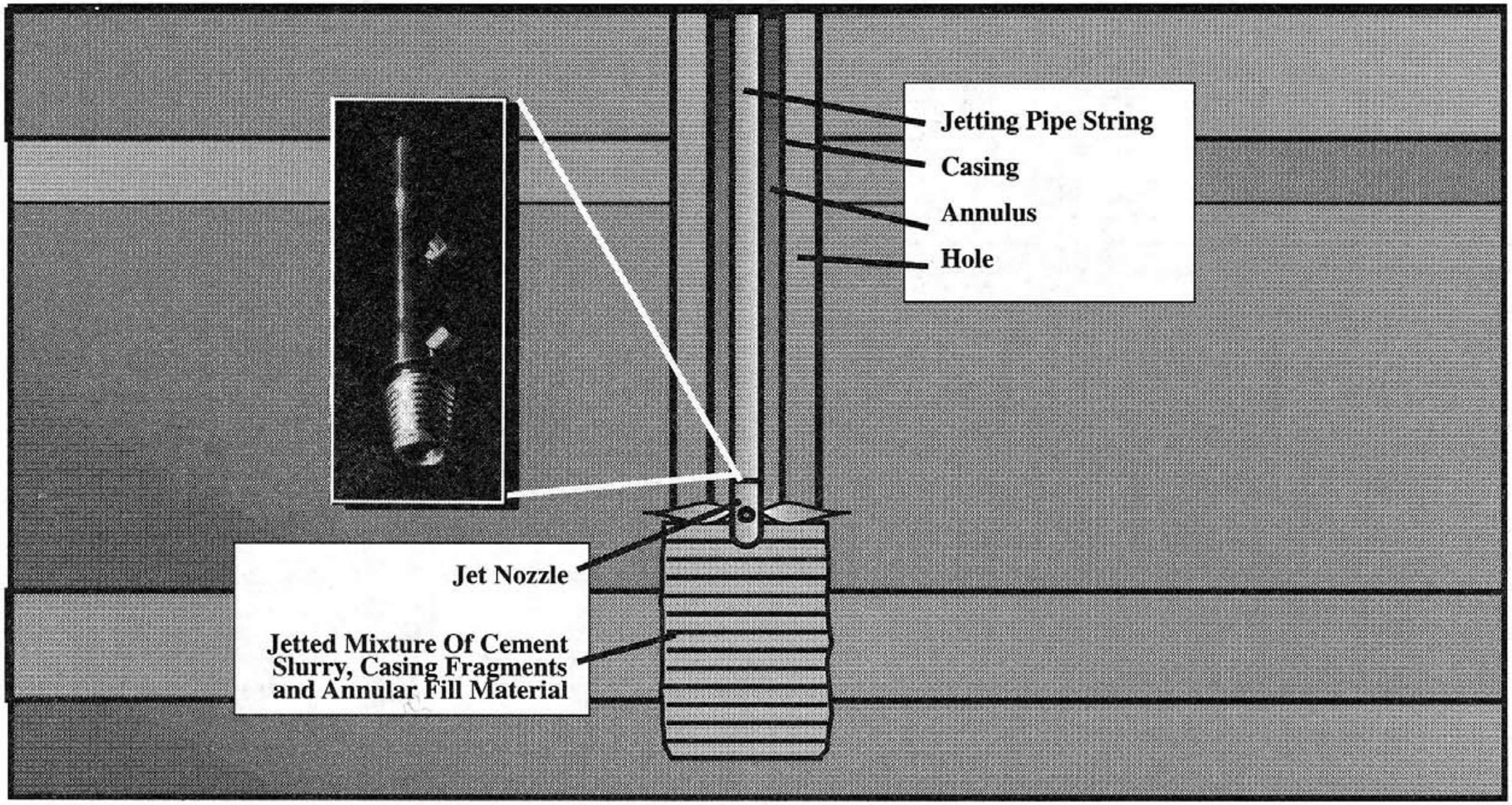
Conclusions on Steel

- Carbon steel in pipelines? Only for ”dry” CO_2!
- Wet CO_2, then high corrosion rates.
- Sleipner Field: Duplex stainless steel in the injection lines for wet CO_2 at 30^oC and 80 bar (designed for 25 yr exp.)
- No reliable tests for wet CO_2 at stagnant conditions and pressure above 100 bar were found in the survey.
- Tests have been performed at 40^oC and 60-95 bar during stagnant conditions (IFE, 2002):
  - Corrosion rates in water varied from 1 to 5 mm/year.
  - At the highest pressure a protective film was formed
  - Possible that the steel surface will be passive – not proven yet.

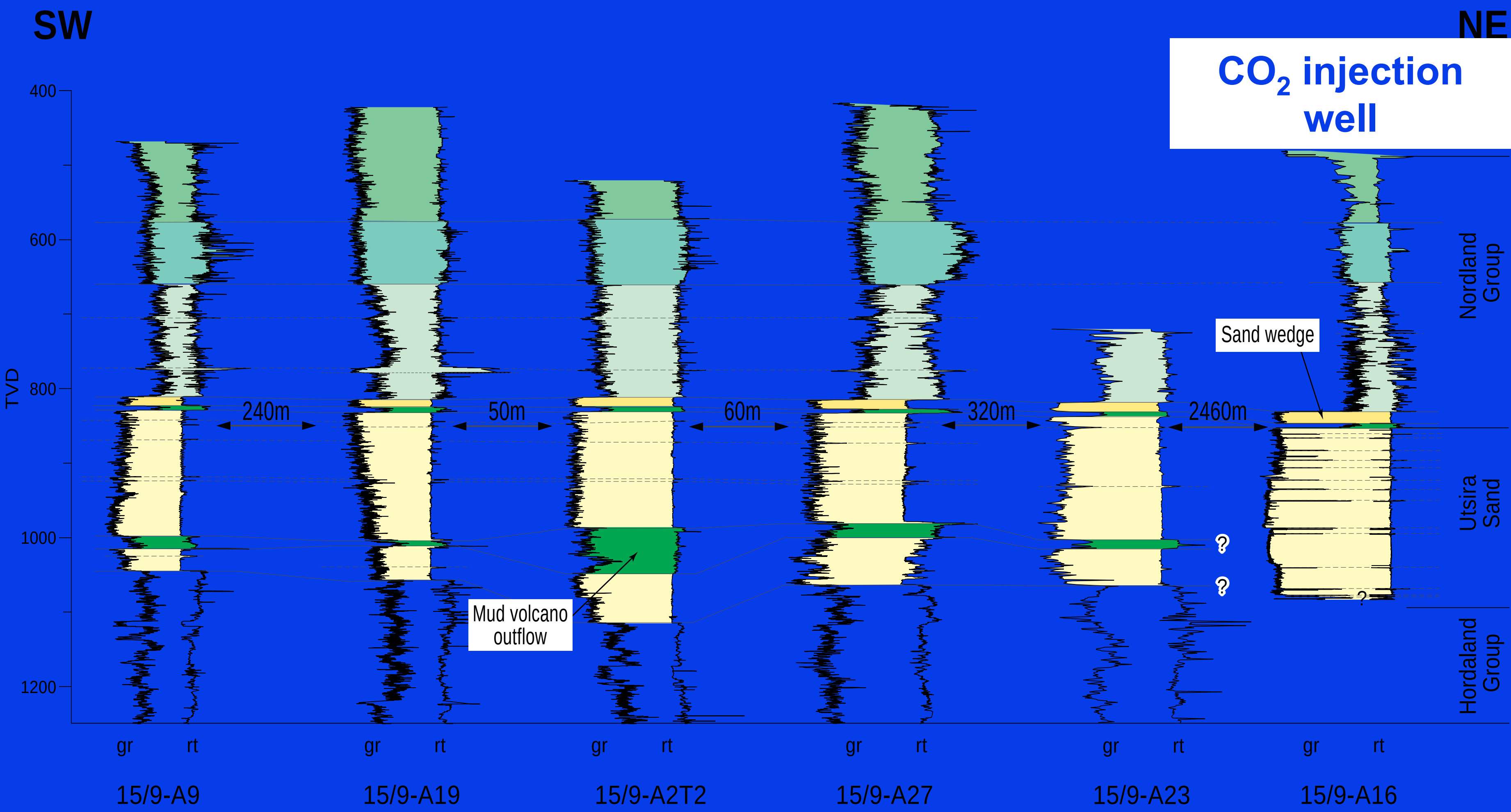
Cutting and well plugging by hydrojetting cement slurry



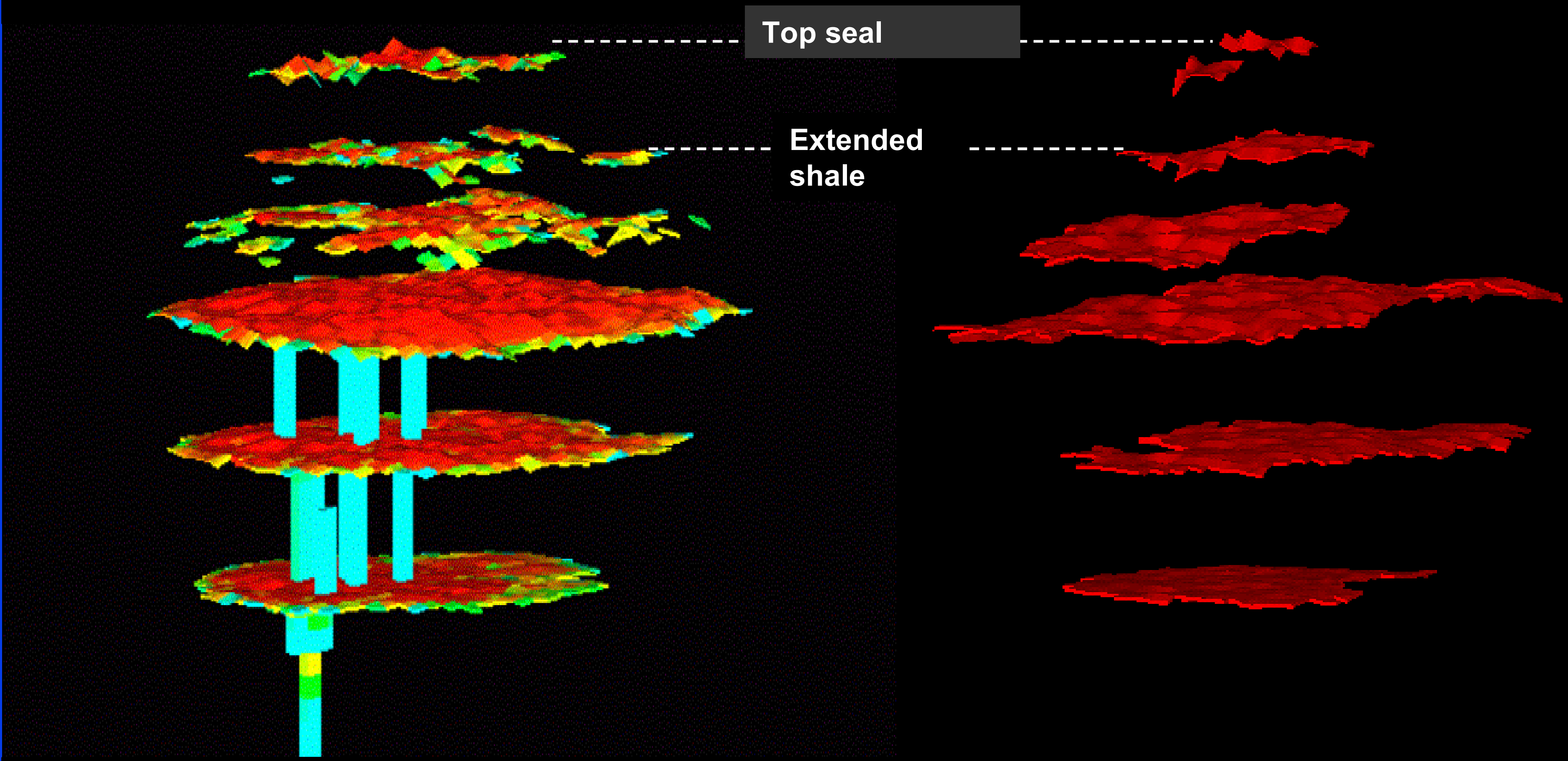
Jet grouting technique for well abandonment



Well profiles



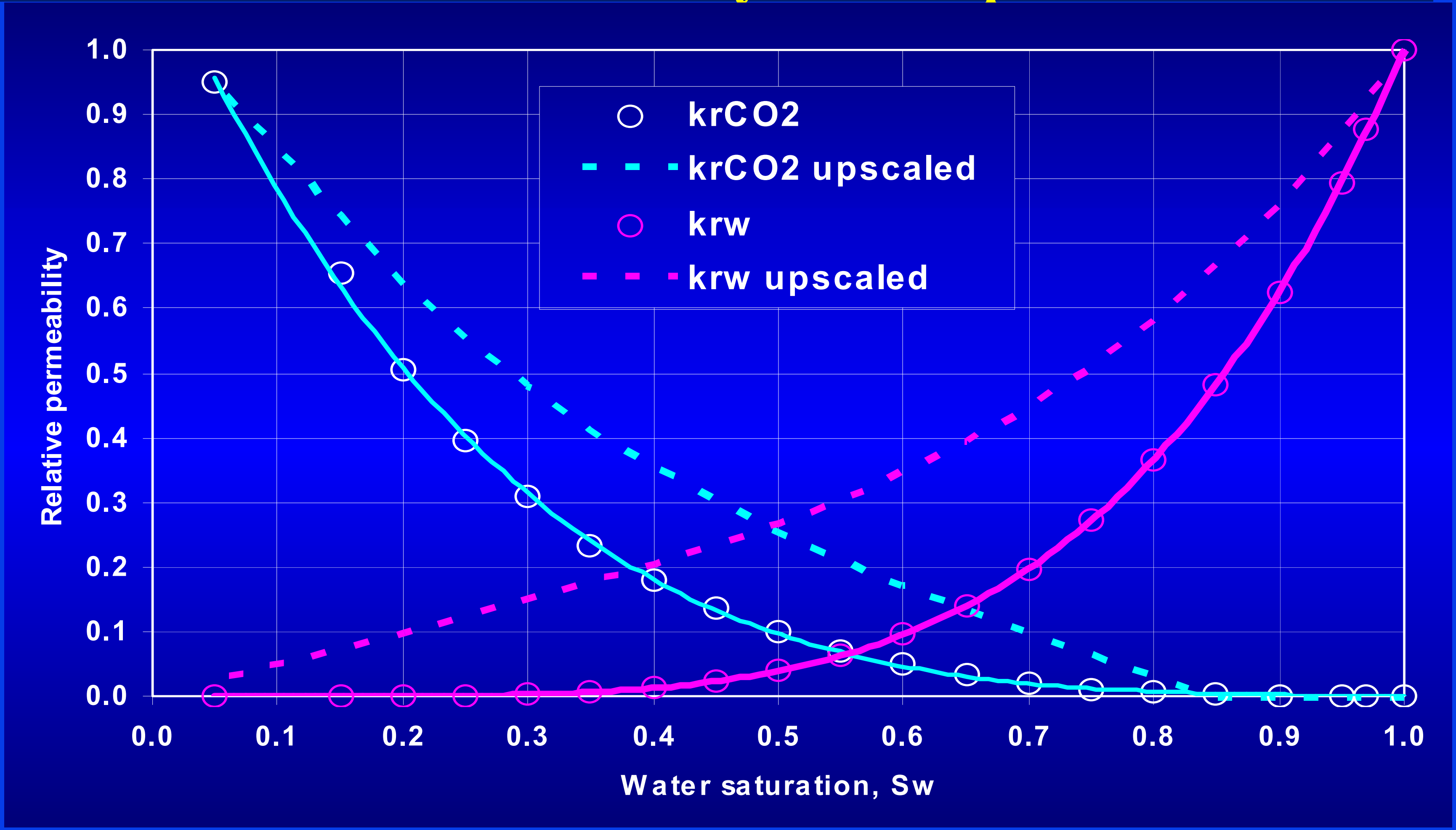
September 1999, 3 years of injection



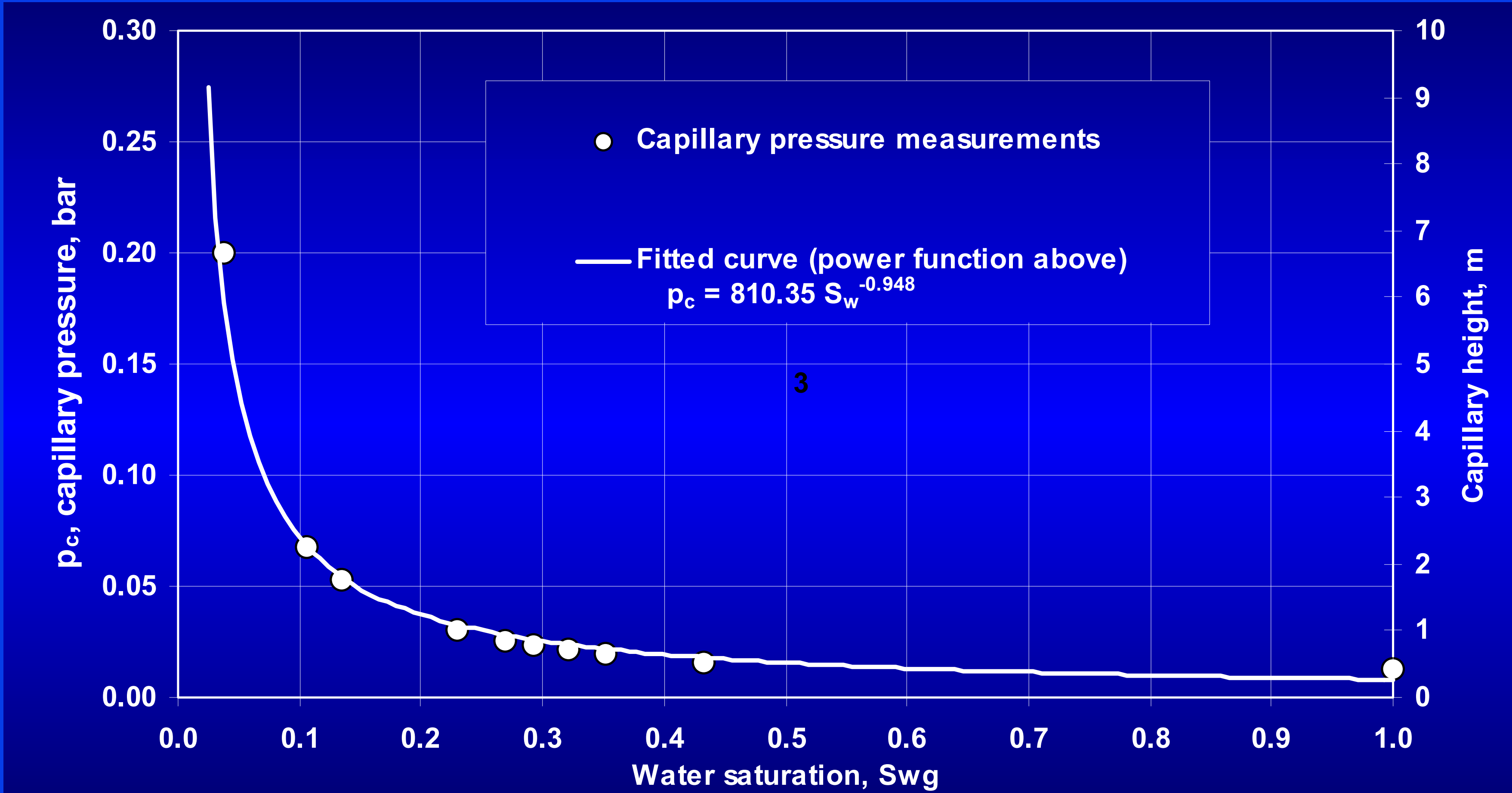
Simulated CO_2 saturation

Seismic images

Relative permeability for CO_2/brine measured in a steady state experiment



Capillary pressure curve between CO_2 and brine



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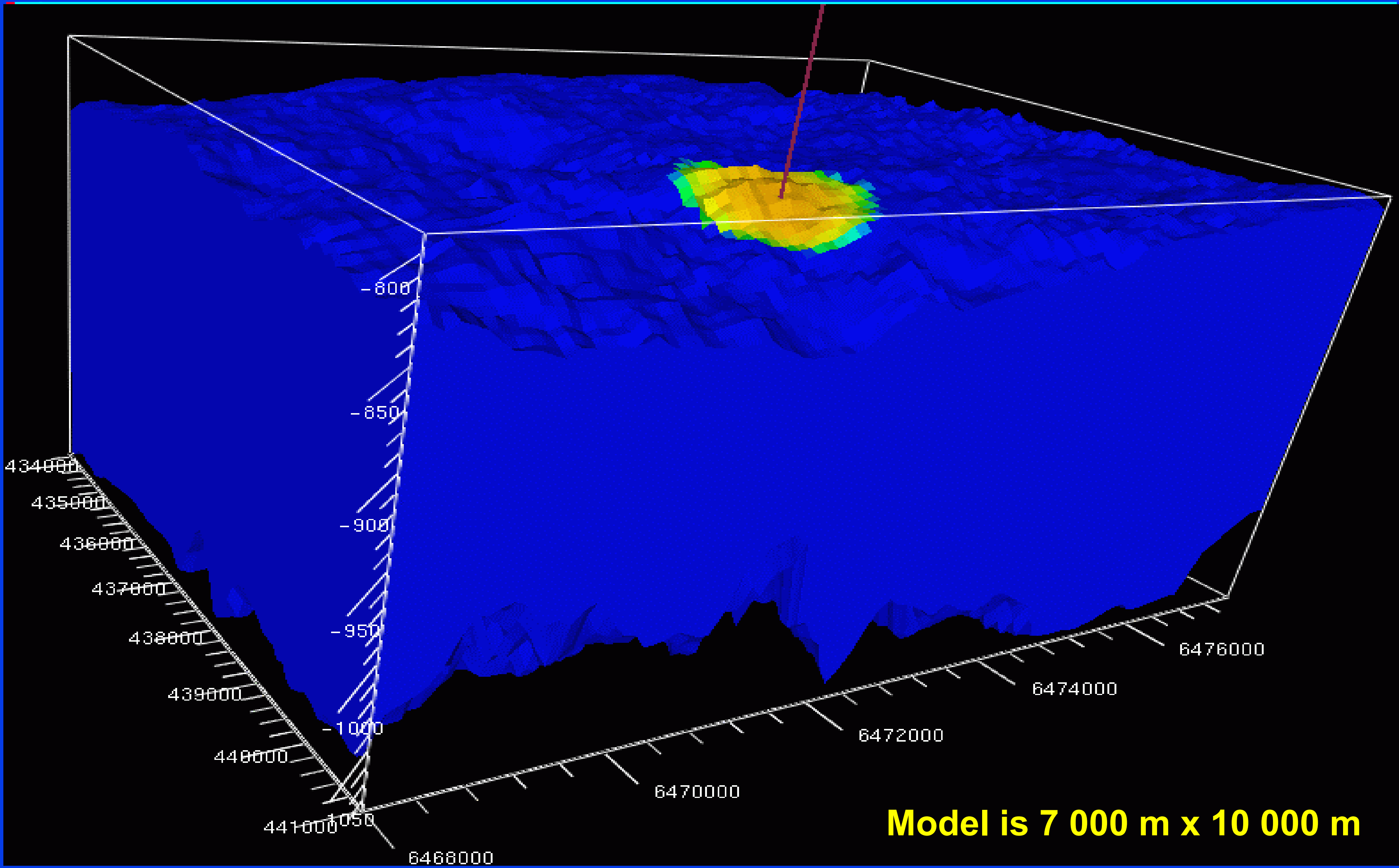
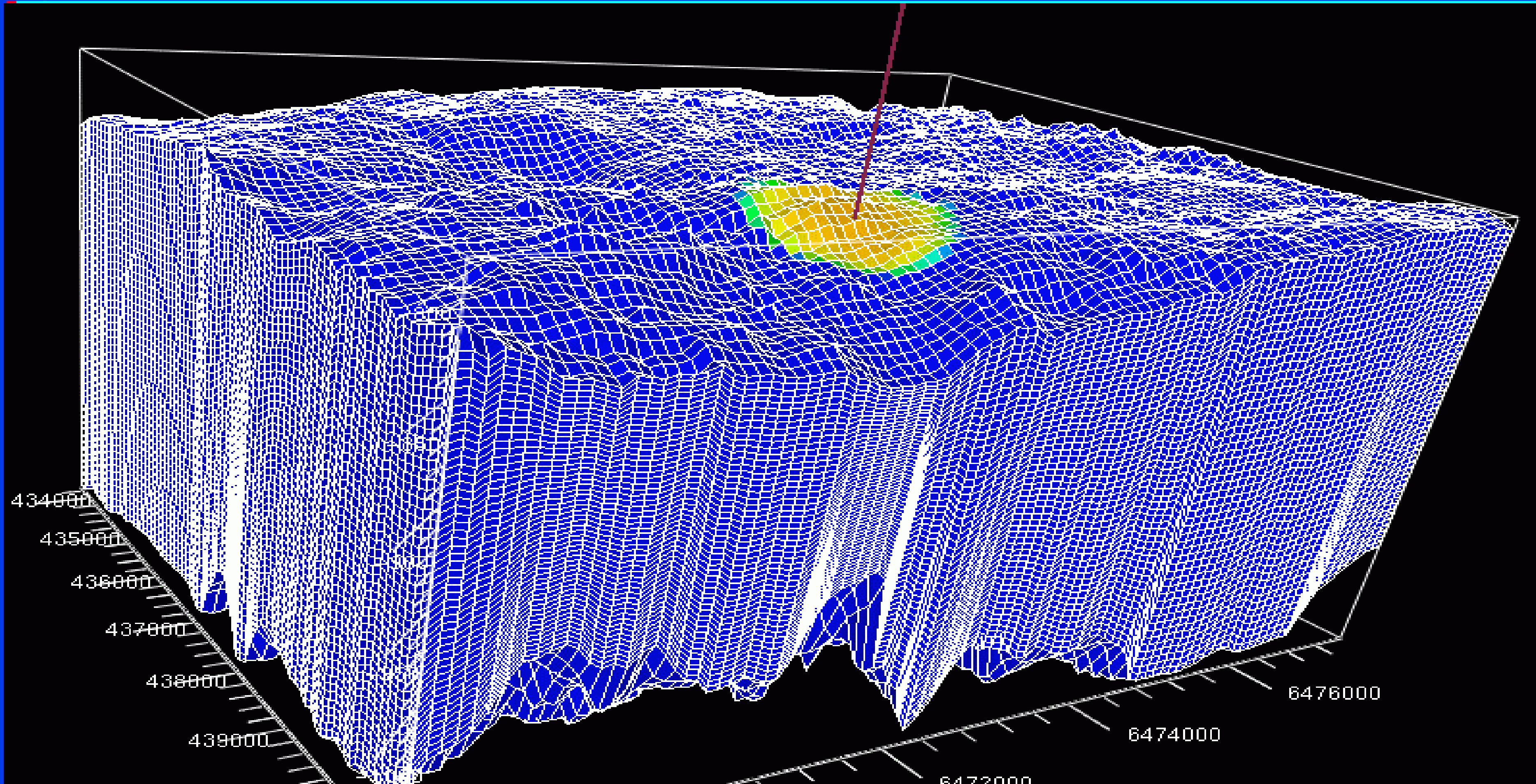
Permeability and porosity (well 15/9 – A23)

Core sample	Direction	Length cm	Permeability mDarcy
1	Horizontal	10	1875
2	Horizontal	10	2550
3	Vertical	10	3250
4	Vertical	117	1820
Weighted average			2001

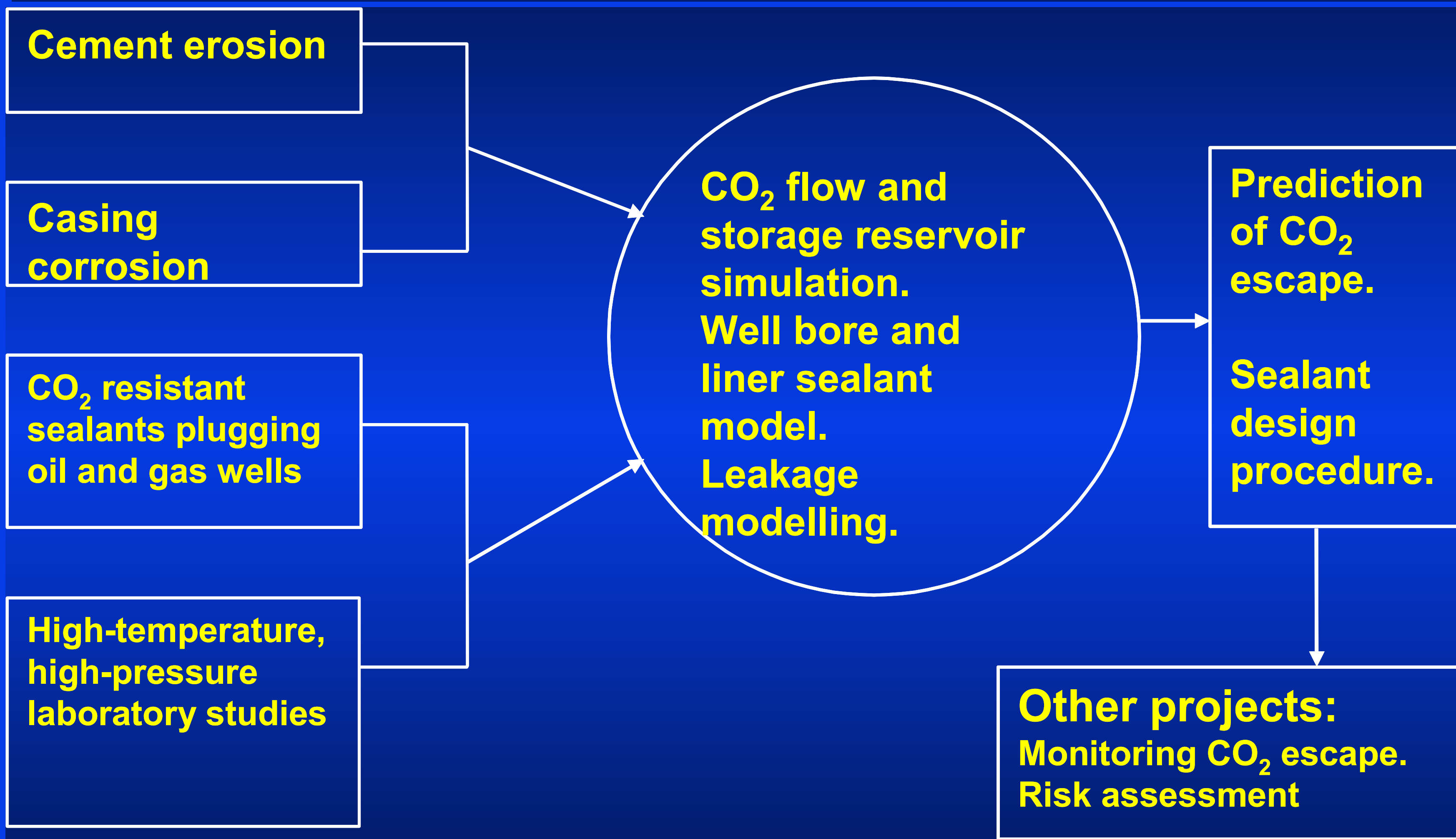
Porosity average: 38%
The sand consist of approximately
94% quartz sand and 6 % carbonates

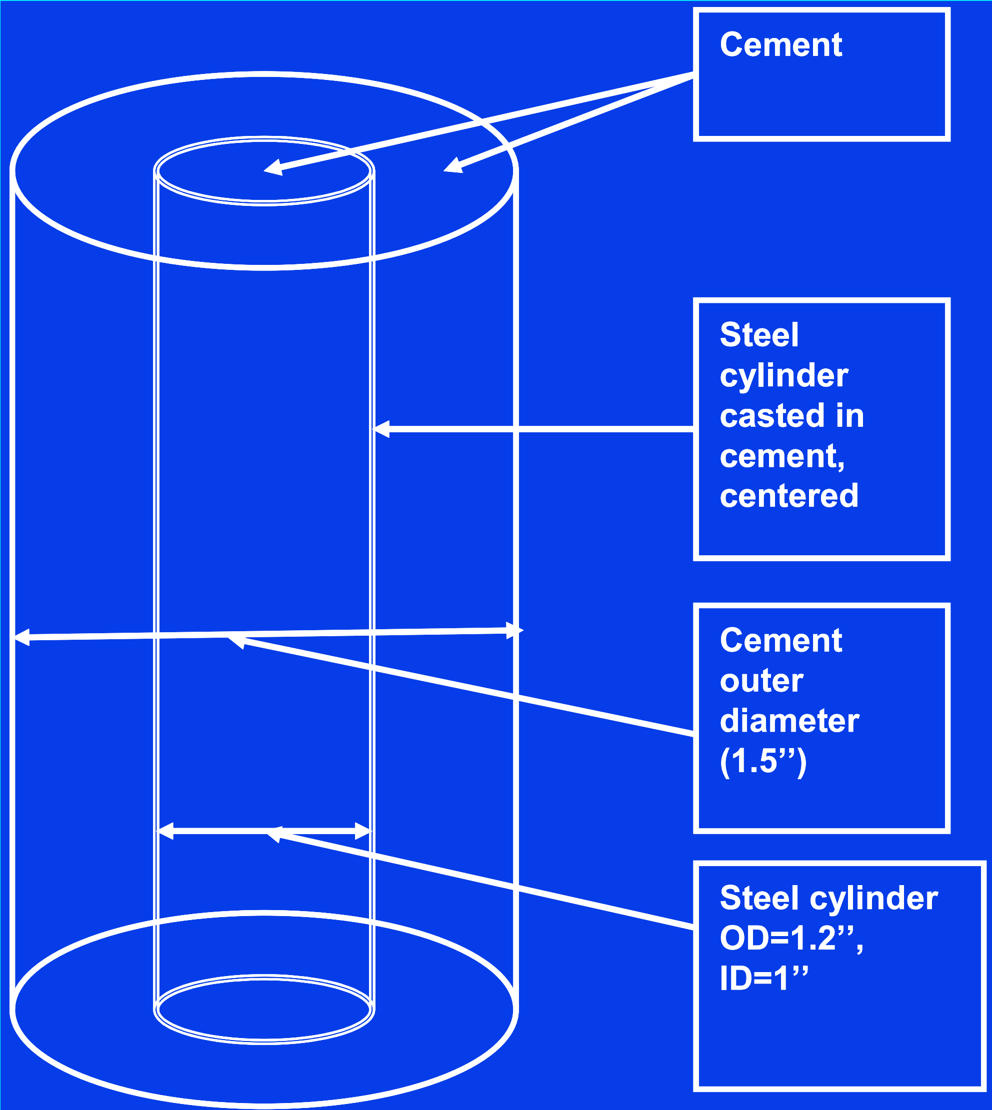

-800
-850
-900
-950
-1000
-1050
434000
435000
436000
437000
438000
439000
440000
441000
6468000
6470000
6472000
6474000
6476000
Model is 7 000 m x 10 000 m



Model consists of 364 416 grid cells and one injection well

Long Term Sealing Capacity of Cemented Well





Cement plug with a steel cylinder filled with cement, all castl into one plugs of 32” length

CO_2 resistant cement materials

- **Flexible Corrosion-Resistant Sealant cement for CO_2 flood injection wells; casted and cured by Halliburton, Duncan, Oklahoma**
- **Magnesium Potassium Phosphate cement $MgKPO_4 \cdot 6\ H_2O$ casted by SINTEF**
- **Reference cement: Portland Cement, API Class G, casted and cured SINTEF**

Test conditions: Exposure to CO_2 at CO_2 exposure at 150 °C and high pressure; static and dynamic conditions (dynamic = stirred solution)

Examination of samples after CO_2 exposure

- Surface scratching test on porous rock samples
- Indentation test on porous rocks samples before and after CO_2 exposure
- Weighing (mass control)
- Permeability tests
- (Thin section microscopy)
- (Electron microscopy)

Conclusions

- **Control of well integrity (include cement/steel erosion/corrosion process) of CO_2 exposed wells is a prerequisite to qualify for CO_2 disposal.**
- **Need for reliable parameters on sealant materials in abandoned CO_2 wells as simulation model input.**
- **Develop integrated model and run CO_2 leakage simulations with change in well parameters versus time as a result of cement erosion.**

Future work

- Integrated model incorporating CO_2 leakage of active/abandoned wells and CO_2 stored underground, is a necessity for reliable leakage predictions
- Cement and steel erosion kinetics and integration of change i parameters (include permeability) into the well leakage model
- Procedure for remedial action
- Test and design of CO_2 resistant well sealants