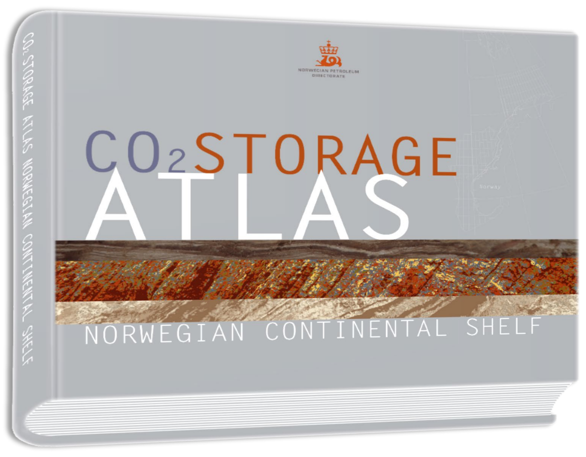
Characterization and Classification of CO_2 storage sites on the Norwegian Continental Shelf



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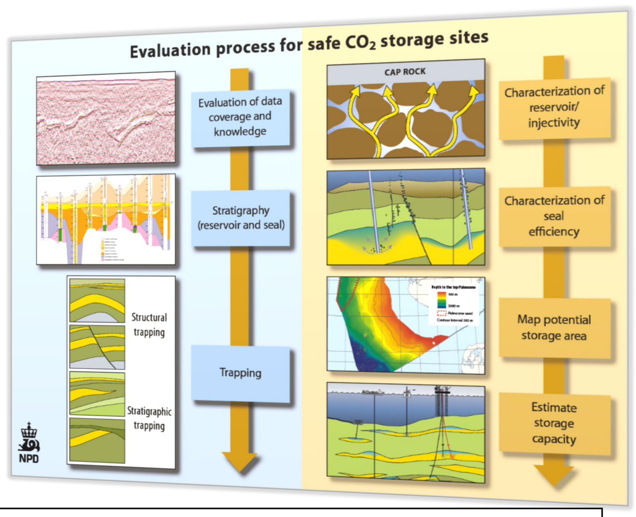
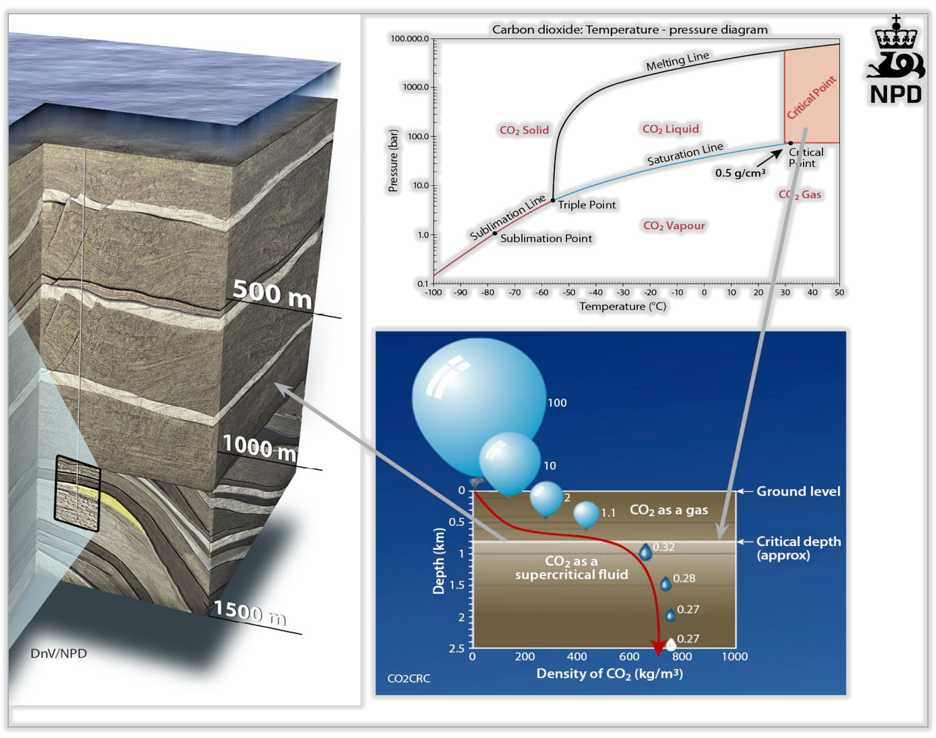
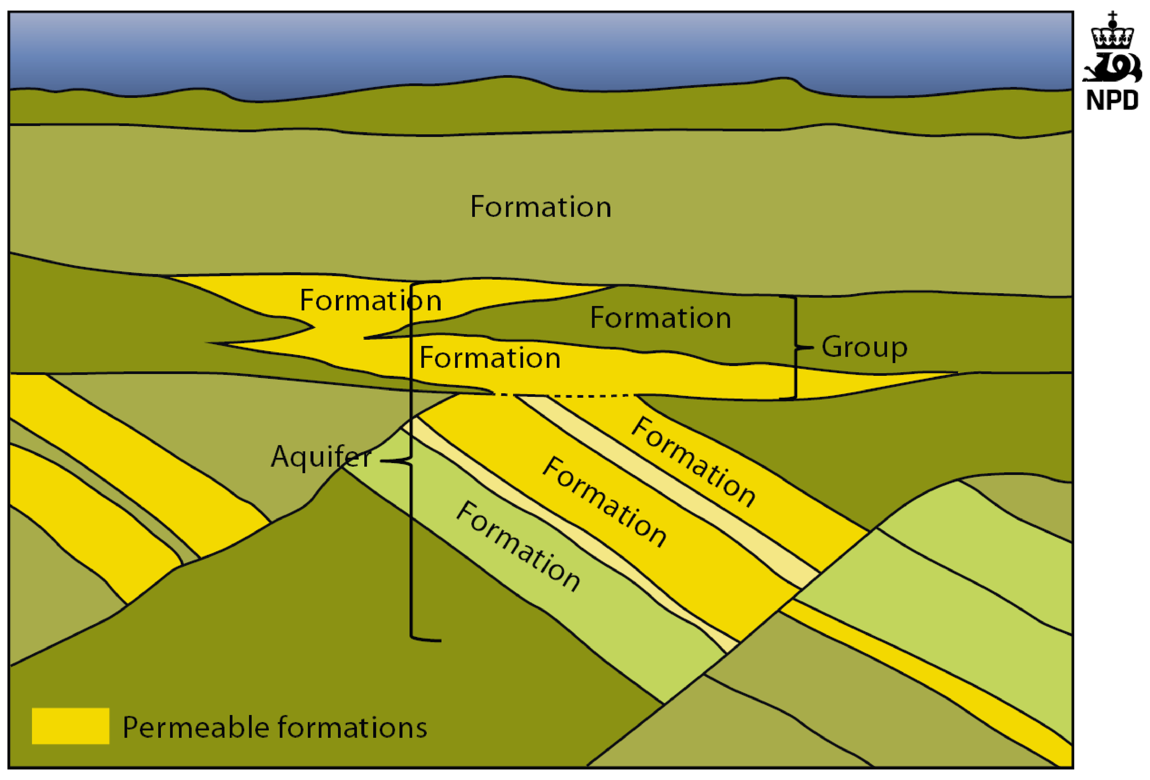


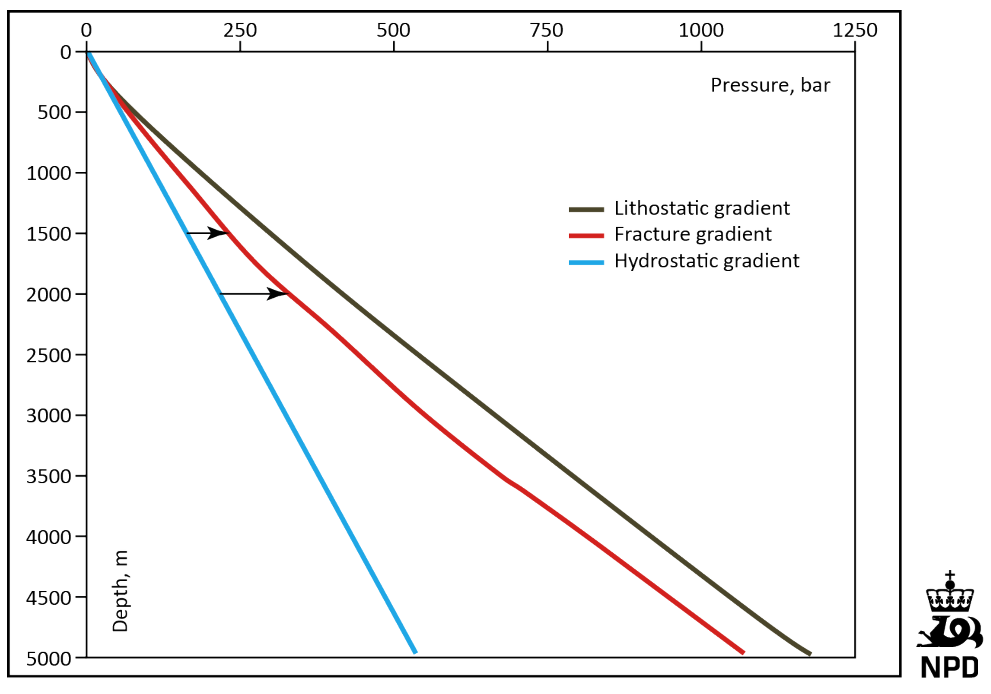
Methods and Principles



Supercritical fluids behave like gases, in that they can diffuse readily through the pore spaces of solids. But, like liquids, they take up much less space than gases. Supercritical conditions for CO_2 occur at 31.1°C and 7.38 megapascals (MPa), which occur approximately 800 meters below surface level. This is where the CO_2 has both gas and liquid properties and is 500 to 600 times denser (up to a density of about 700 kg/m³) than at surface conditions, while remaining more buoyant than formation brine.



Relation between geological formations and aquifers.



Pressure gradients obtained from pore pressure data and leak-off tests in wells from the Norwegian Sea Shelf and North Sea at water depths between 250 and 400 m. The fracturing gradient marks the lower boundary of measured leak-off pressures and the upper boundary of measured pore pressures. The lithostatic gradient was calculated from general compaction curves for shale and sand with a 300 m water column. The hydrostatic gradient assumes sea water salinity. The arrows show how much pressure can be increased from hydrostatic pressure before it reaches the fracure gradient.

Characterization of a Storage site, seal and reservoir

CHECKLIST FOR RESERVOIR PROPERTIES

Typical high and low scores

Reservoir Properties	High	Low
Aquifer Structuring	Mapped or possible closures	Tilted, few /uncertain closures
Traps	Defined sealed structures	Poor definition of traps
Pore pressure	Hydrostatic or lower	Overpressure
Depth	800- 2500 m	< 800 m or > 2500 m
Reservoir	Homogeneous	Heterogeneous
Net thickness	> 50 m	< 15 m
Average porosity in net reservoir	> 25 %	< 15 %
Permeability	> 500 mD	< 10 mD

Reservoir Parameters	Capacity weight	Injectivity weight	Comment
Rock volume	3		Net rock volume is appropriate in case of low net reservoir
Structuring	1		Potential for the top surface to form closures
Traps	1		Mapped structures interpreted to be 4-way closures
Pore pressure	1	1	Depleted, hydrostatic, overpressured
Depth	1	1	Depth of burial relative to optimal window 1000-2500 m
Reservoir		3	Homogeneous - heterogeneous
Thickness		1	Net thickness of reservoir sand
Porosity	3		Average porosity in net reservoir
Permeability		3	Average horizontal permeability

CHARACTERIZATION OF AQUIFERS AND STRUCTURES

	Criteria		Definitions, comments
Reservoir quality	Capacity, communicating volumes	3	Large calculated volume, dominant high scores in checklist
		2	Medium - low estimated volume, or low score in some factors
		1	Dominant low values, or at least one score close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Sealing quality	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Sealing layer with uncertain properties, low scores in checklist
	Fracture of seal	3	Dominant high scores in checklist
		2	Insignificant fractures (natural / wells)
		1	Low scores in checklist
Other leak risk	Wells	3	No previous drilling in the reservoir / safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells / needs evaluation
Data coverage	Good data coverage	Limited data coverage	Poor data coverage

Other factors:
How easy / difficult to prepare for monitoring and intervention. The need for pressure relief. Possible support for EOR projects. Potential for conflicts with future petroleum activity.

Data coverage
Good : 3D seismic, wells through the actual aquifer/structure
Limited : 2D seismic, 3D seismic in some areas, wells through equivalent geological formations
Poor : 2D seismic or sparse data

CHECKLIST FOR SEALING PROPERTIES

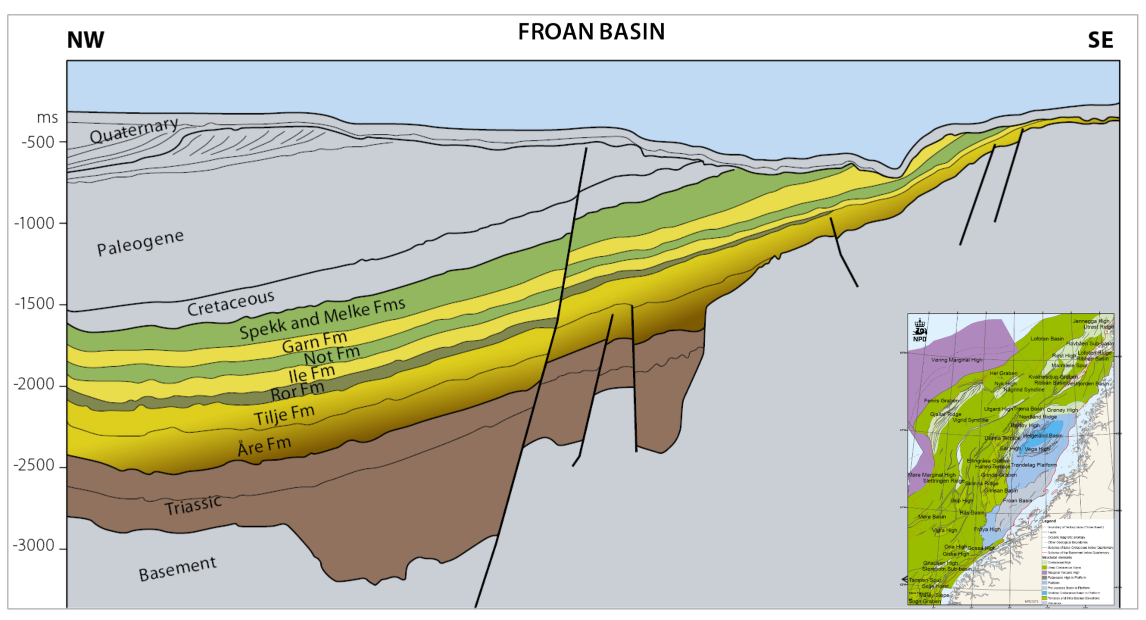
Typical high and low scores

Sealing Properties	High	Low	Unacceptable values
Sealing layer	More than one seal	One seal	No known sealing layer over parts of the reservoir
Properties of seal	Proven pressure barrier/ > 100 m thickness	< 50 m thickness	
Composition of seal	High clay content, homogeneous	Silty, or silt layers	
Faults	No faulting of the seal	Big throw through seal	Tectonically active faults
Other breaks through seal	No fracture	sand injections, slumps	Active chimneys with gas leakage
Wells (exploration/ production)	No drilling through seal	High number of wells	

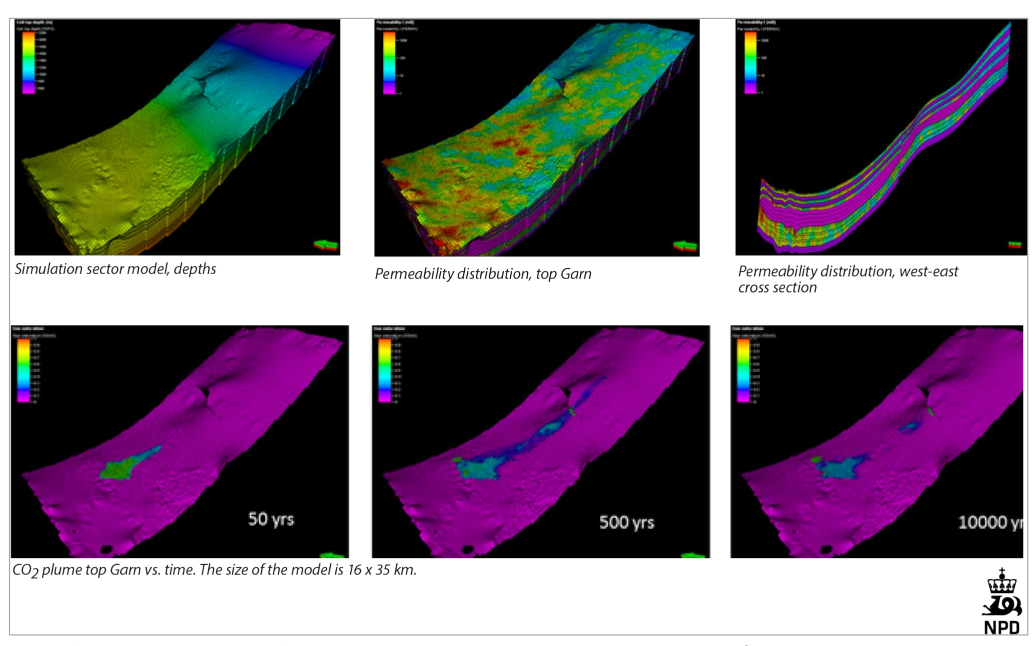
Cap rock Parameters	Seal weight	Well weight	Comment
Number of seals	1		Overlying sealed aquifer(s) with storage capacity
Thickness/barriers	1		Thickness of seal/ seal capacity proved in analogous cases
Composition	1		Shale, silty layers, mineralogy of shale
Faults	1		Geometry and modelled property of fault zone
Other indications	1		Seismic indications of gas leakage
Well penetrations		1	Number and status of wells penetrating seal

Aquifers and structures have been characterized in terms of capacity, injectivity and safe storage of CO_2. To complete the characterization, the aquifers are also evaluated according to the data coverage and their technical maturity. Parameters used in the characterization process are based on data and experience from the petroleum activity on the NCS and the fact that CO_2 should be stored in the supercritical phase to obtain the most efficient and safest storage. The methods used for characterization of reservoir properties are similar to well-established methods used in petroleum exploration. Characterization of cap rock and injectivity is typically conducted in studies of field development and to some extent in basin modelling. For evaluation of regional aquifers in CO_2 storage studies, the mineralogical composition and the petrophysical properties of the cap rocks are rarely well known. In order to characterize the sealing capacity in this atlas, we have mainly relied on regional pore pressure distributions and data from leak-off tests combined with observations of natural gas seeps.

Characterization and evaluation. An example from the Froan Basin



Garn-Ile aquifer in the Froan Basin in The Norwegian Sea: NW-SE profile showing the geometry of aquifers (yellow) and sealing formations (green)

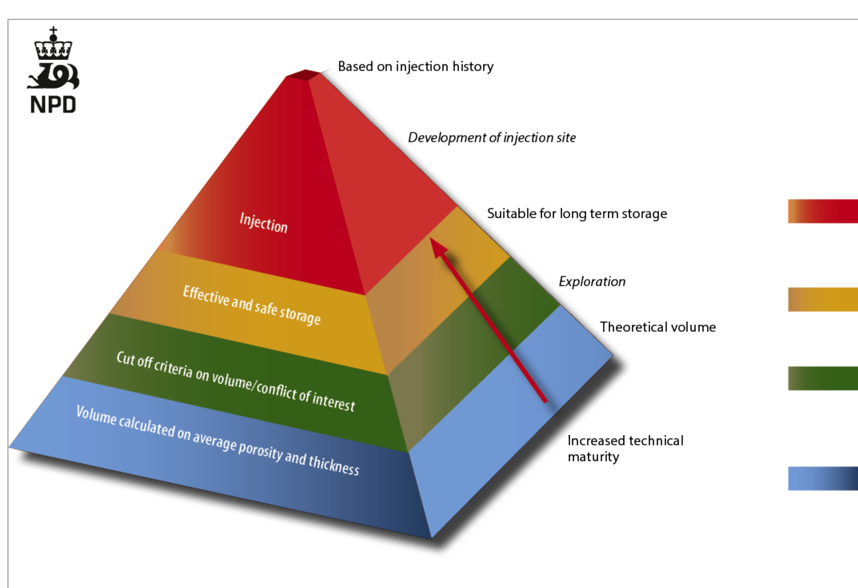


The figures in the second row illustrate the free CO_2 saturation (green/blue) over 10,000 years. The CO_2 injection well is located down dip, but alternative locations and injection zones have been simulated, with different injection rates. The injection period is 50 years, and the simulation continues for 10,000 years to verify the long term CO_2 migration effects.

The Garn/Ile aquifer		Summary	Summary
Storage system		half open	closed
Rock volume, m³		4400 Gm³	4400 Gm³
Net volume, m³		1100 Gm³	1100 Gm³
Pore volume, m³		300 Gm³	300 Gm³
Average depth Garn Fm		1675 m	1675 m
Average depth Ile Fm		1825 m	1825 m
Average net/gross		0.25	0.25
Average porosity		0.27	0.27
Average permeability		580 mD	580 mD
Storage effieciency		4 %	0.2 %
Storage capacity aquifer		8 Gt	0.4 Gt
Reservoir quality			
	capacity	2	2
	injectivity	3	3
Seal quality			
	seal	3	3
	fractured seal	3	3
	wells	3	3
Data quality			
Maturation			

Results for the Garn – Ile aquifer, a half-open case and a closed case for the whole aquifer to illustrate the importance for the estimates of storage volumes. Large volumes can theoretically be stored if the aquifer is in pressure communication with additional large water volumes. In the Garn-Ile case, such pressure communication could take place with the sea along the subcrop line. Another alternative to creating a half-open system might be to inject CO_2 and produce water. The most optimistic case would be to assume that closed structures with a large storage capacity exist and could be filled with CO_2, without any migration to the half-open eastern boundary.

Classification of a CO_2 storage project



1 tonne = one metric tonne = 1000 kg
1 Mt = one megatonne = 10^6 tonnes
1 Gt = one gigatonne = 1000 Mt = 10^9 tonnes

The maturation pyramid

The evaluation of geological volumes suitable for injecting and storing CO_2 can be viewed as a step-wise approximation, as shown in the maturation pyramid. Data and experience from over 40 years in the petroleum industry will contribute in the process of finding storage volumes as high up as possible in the pyramid.

Step 4 is the phase when CO_2 is injected in the reservoir. Throughout the injection period, the injection history is closely evaluated and the experience gained provides further guidance on the reservoirs' ability and capacity to store CO_2.

Step 3 refers to storage volumes where trap, reservoir and seal have been mapped and evaluated in terms of regulatory and technical criteria to ensure safe and effective storage.

Step 2 is the storage volume calculated when areas with possible conflicts of interest with the petroleum industry have been removed. Only aquifers and prospects of reasonable size and quality are evaluated. Evaluation is based on relevant available data.

Step 1 is the volume calculated on average porosity and thickness. This is done in a screening phase that identifies possible aquifers suitable for storage of CO_2. The theoretical volume is based on depositional environment, diagenesis, bulk volume from area and thickness, average porosity, permeability and net/gross values.

A comparison between the UNECE, SPE and NPD's classification system.
NPD has not done any economic assessment.

UNECE	UNECE Sub-Class	SRMS	SRMS Sub-Class	NPD
Commercial Injection Projects	Development/ Active Injection	Discovered Storage Resources/ Commercial	Capacity	Development of Injection site
Potential Commercial Injection Projects	Development Unclarified	Discovered Storage / Resources/Sub-Commercial	Contingent Storage / Resources	Suitable for Long term storage
Undiscovered Reservoir/Screening projects	Geological Storage Indicated/ Identified	Undiscovered Storage Resources (Prospect)	Prospective Storage Resources	Exploration Phase
Screening projects	Geological Storage Inferred	Undiscovered Storage Resources (Lead, Play)	Prospective Storage Resources	Theoretical storage volume