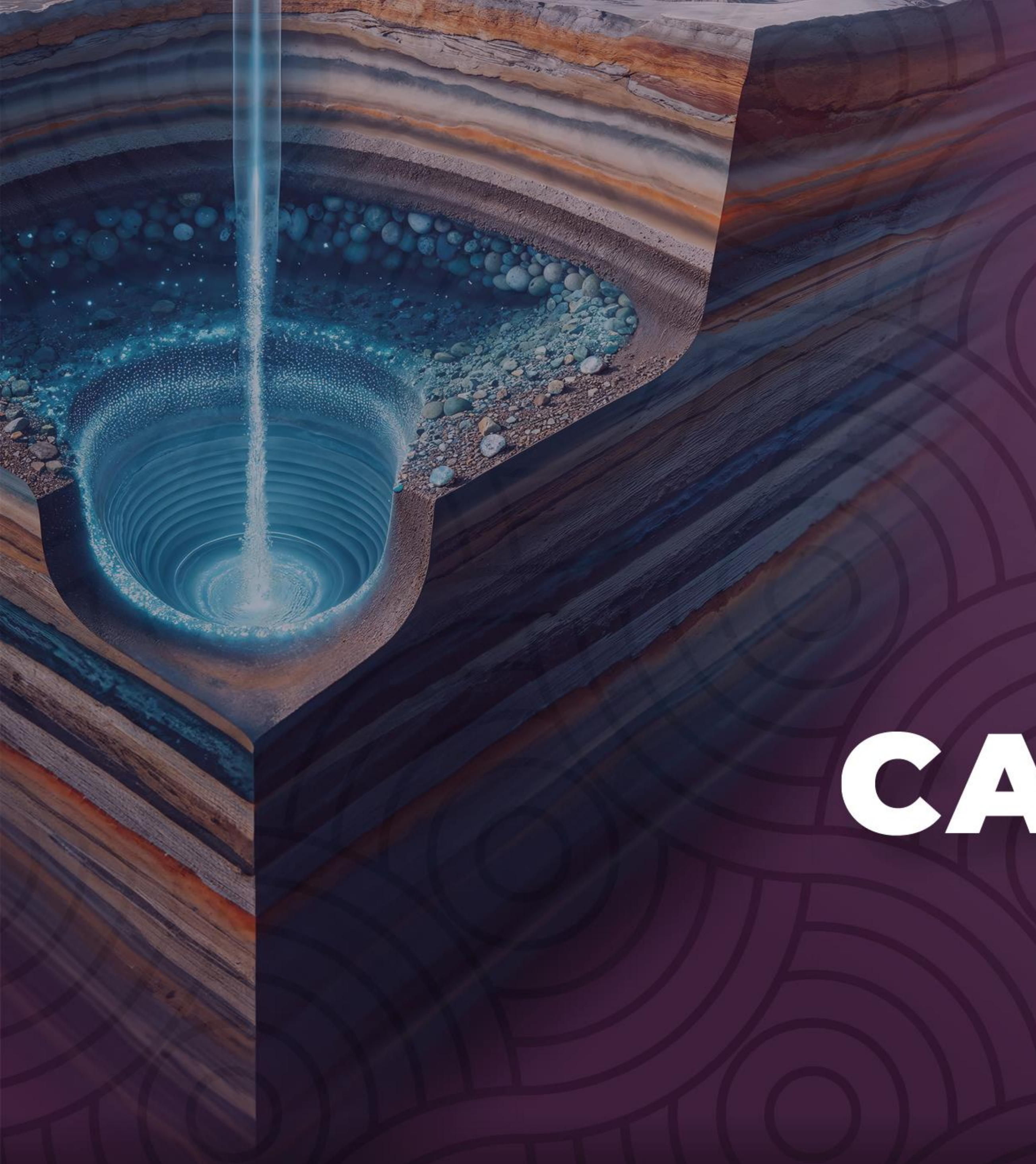

4-7 NOVEMBER 2024
ROTTERDAM, THE NETHERLANDS

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TNO

GEODE

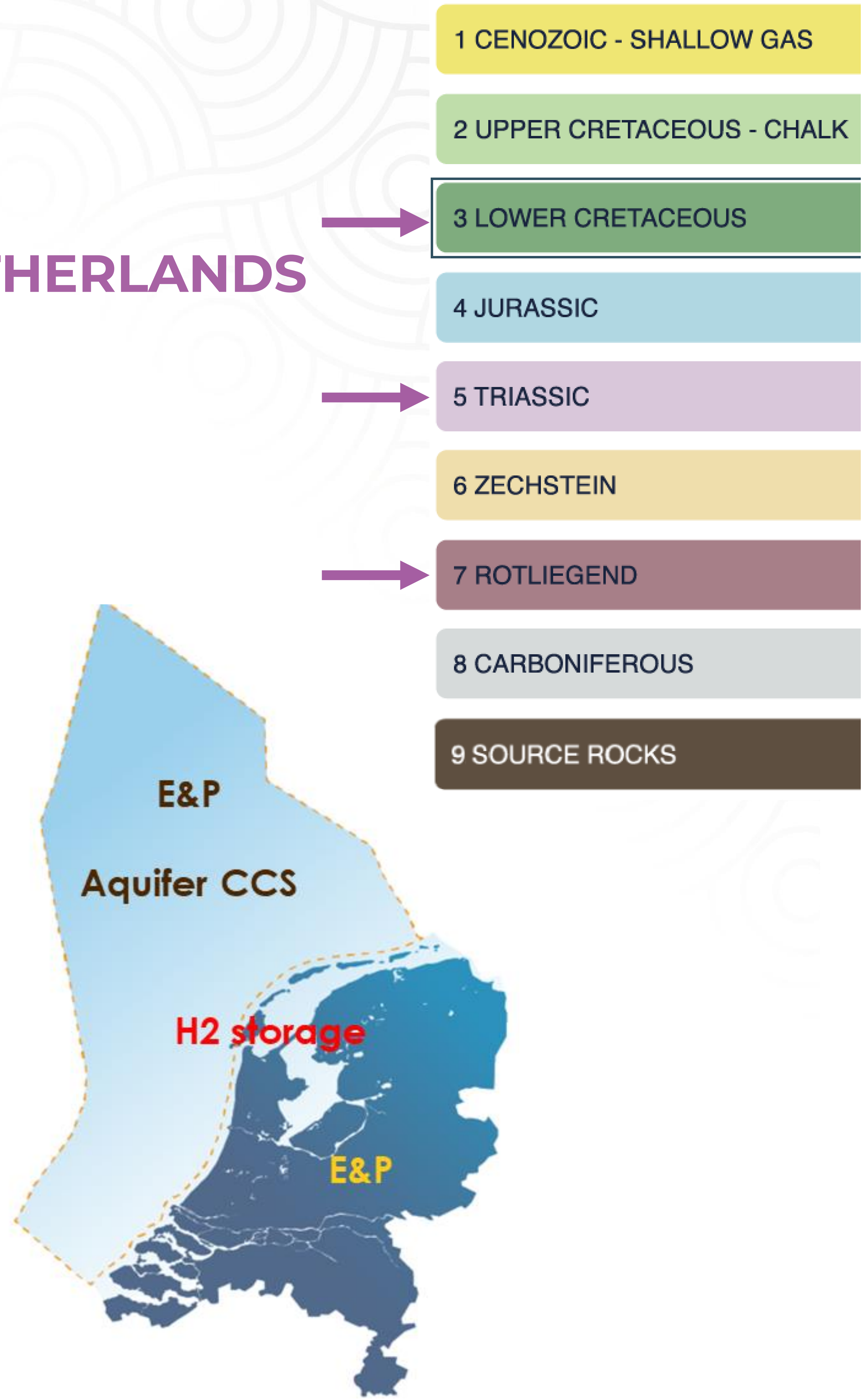
CCS AQUIFER STORAGE POTENTIAL IN THE NETHERLANDS;
A PLAY INVENTORY IN THE GEODE RESOURCE ATLAS

Harald de Haan, Liza de Groot, Michael Nolten and Kike Beintema

GEODE IN A NUTSHELL

ATLAS OF DEEP SUBSURFACE RESOURCES IN THE NETHERLANDS

- Joint project of EBN B.V. and TNO
- Easily accessible **web-based GIS** environment where **play-based exploration data and knowledge** is presented for:
  - **hydrocarbon** plays in the Netherlands
  - saline aquifer **CO_2 storage** in the Dutch offshore
  - **Hydrogen storage** in Zechstein salt in the Netherlands
- Results available to the public free of charge
- Facilitating E&P, CCS companies and research organisations
- Online since **November 2021**, yearly updates and added plays



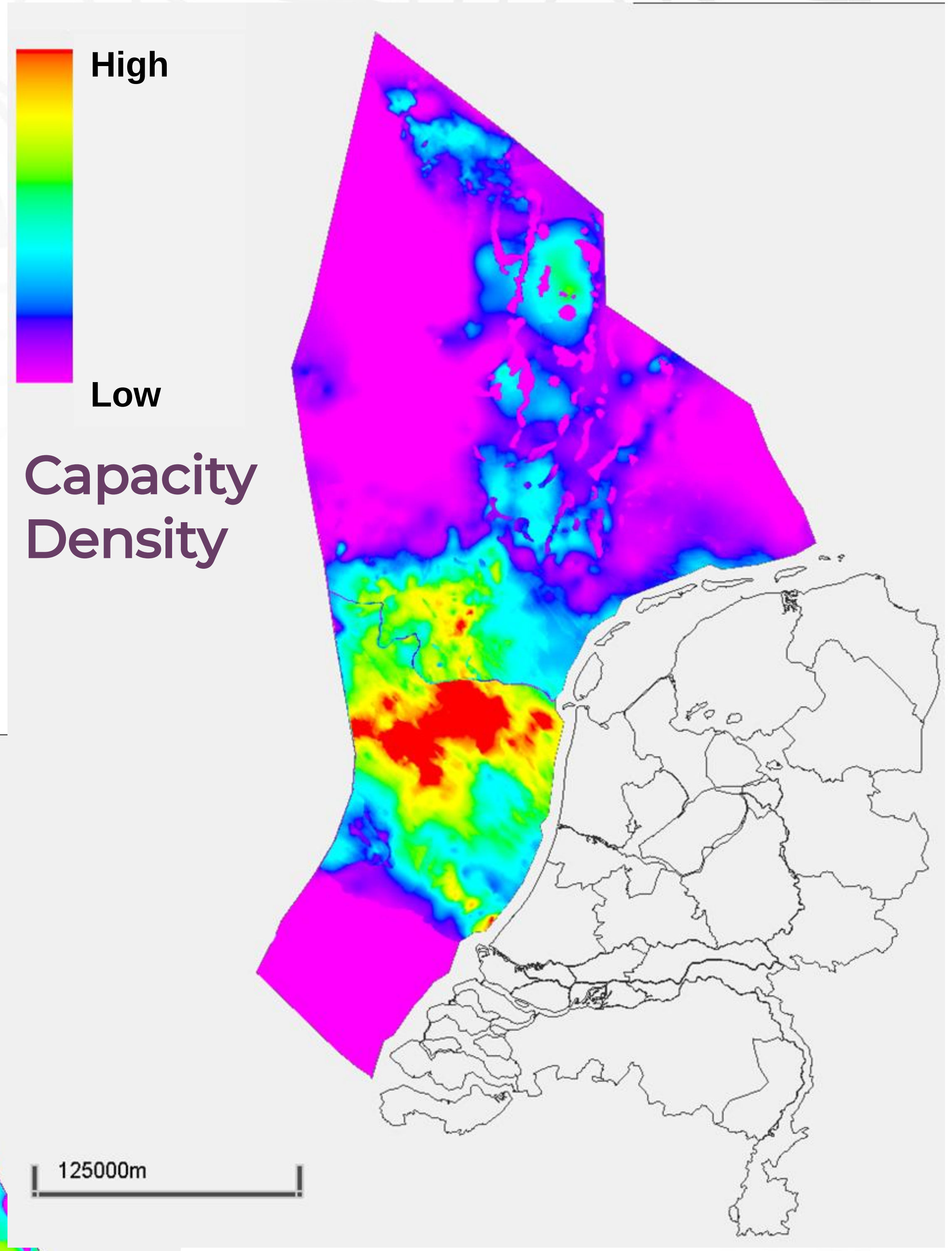
CCS IN THE NETHERLANDS

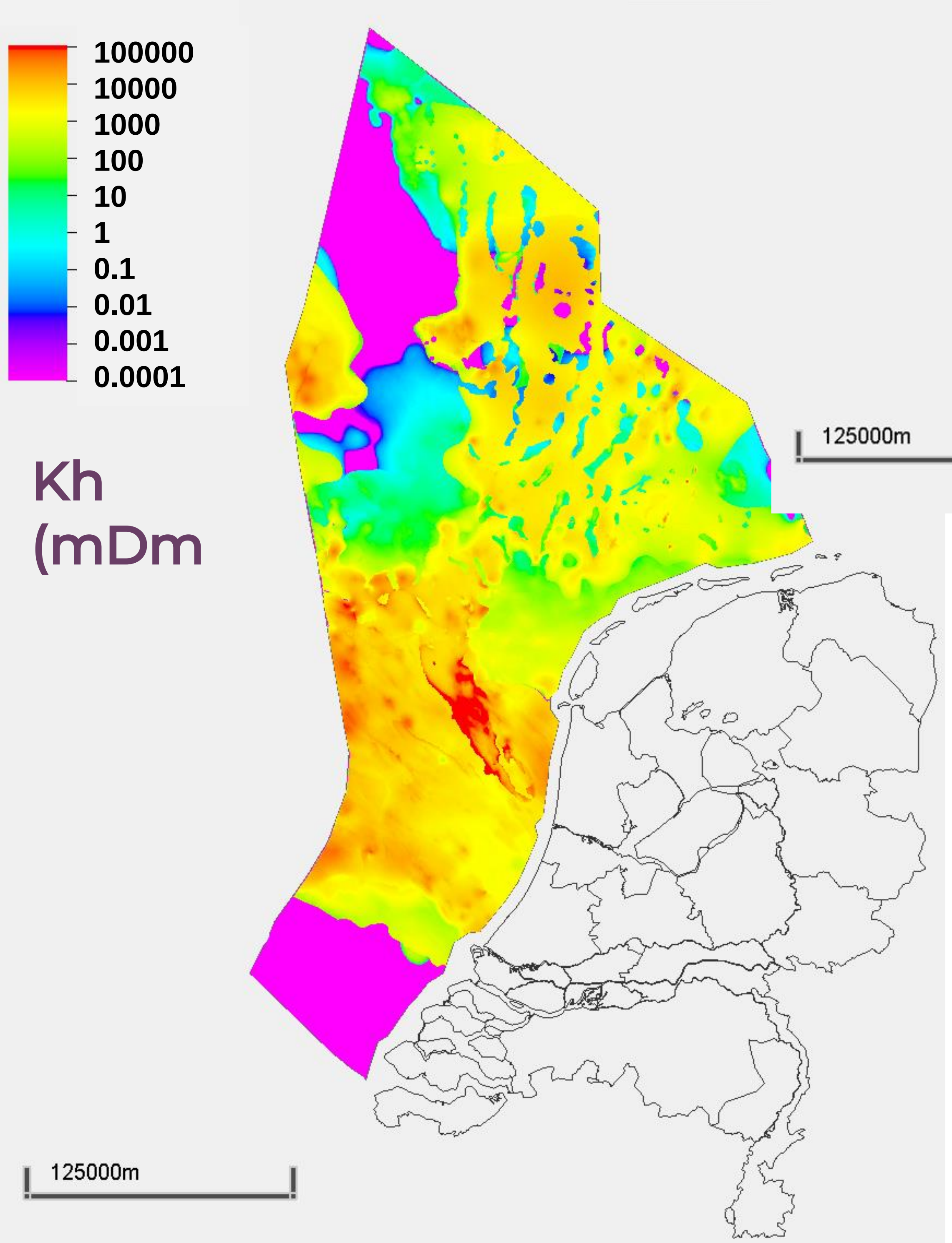
First stores all depleted gas fields!

CO2 STORAGE MAPS

GEODE

- Saline aquifer potential (no depleted fields)
- **Theoretical** Storage Capacity Density and Permeability Thickness (kh) maps
- Maps to assist in regional risk assessments (seal properties, faults, HC shows, legacy wells)
- General (regional) assumptions; for local studies more site-specific assumptions should be made





Combined Rotliegend, Triassic and Lower Cretaceous map

KEY DRIVERS CO2 STORAGE

Deliverables GEODE

CAPACITY **Capacity Density** **Undiscovered Storage Resources (as defined in the SRMS system, SRMS 2017)**

→ *Does the storage complex have sufficient CO_2 volume capacity?*

INJECTIVITY **Permeability Thickness (kh)**

→ *Can the CO_2 be transported to the storage complex and injected in a sustainable way?*

CONTAINMENT **Seal quality, Faults, Wells, HC shows**

→ *Can the storage complex contain the CO_2 safely?*

MONITORING & REMEDIATION

→ *Can the injected CO_2 be monitored & operations be performed safely?*

RISK MANAGEMENT

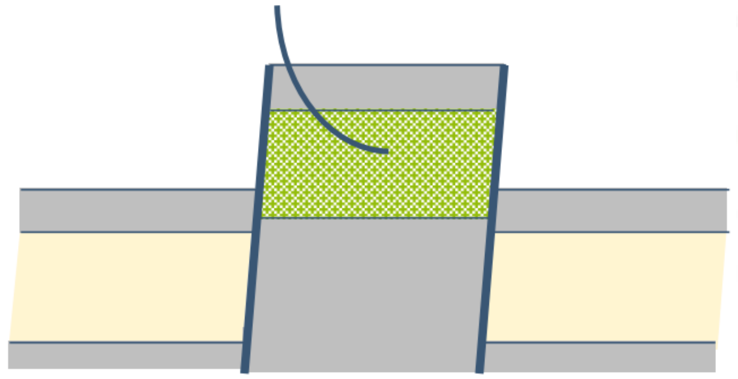
METHOD

Calculating Capacity

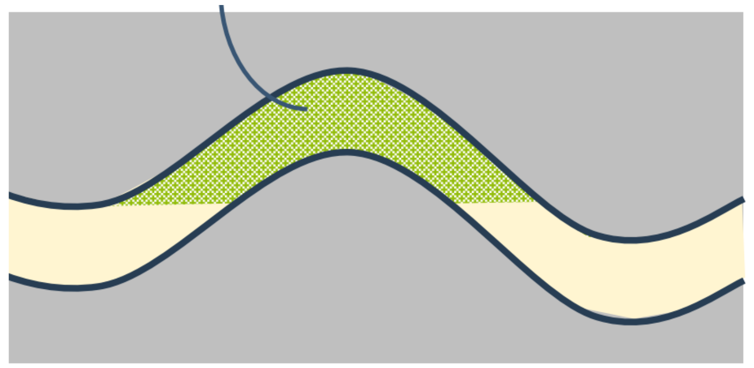
$Q = A \,.\, D \,.\, \Phi .\, \rho CO_2 \,.\, E_{st}$

Q=Capacity (Mt), A= Area aquifer, D=thickness of good reservoir rocks, Φ=porosity, ρCO_2 density of CO_2, E_{st} = storage efficiency (<1)

(*best practice for the storage of CO_2 in saline aquifers SACS and CO2STORE projects 2007*)

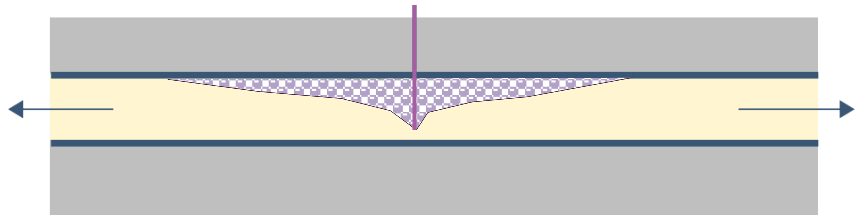


- Is the aquifer Open, Semi-Closed or Closed?
- **Closed** aquifer: Pressure constrained
- **Open** aquifer: Pressure can dissipate. Pore volume constrained



- **Closed aquifer**:
- $Q = A \,.\, D \,.\, \Phi .\, (Cr+Cw).\, \Delta P.\, \rho CO_2$

- **Regional** versus **local** storage efficiency
  Calculating local storage efficiency requires dynamic modelling
- No dissolution or precipitation of CO_2 taken into account



STORAGE VOLUME CALCULATION CLOSED AQUIFER

Q = A . D . Φ. (Cr+Cw). ΔP. ρCO2

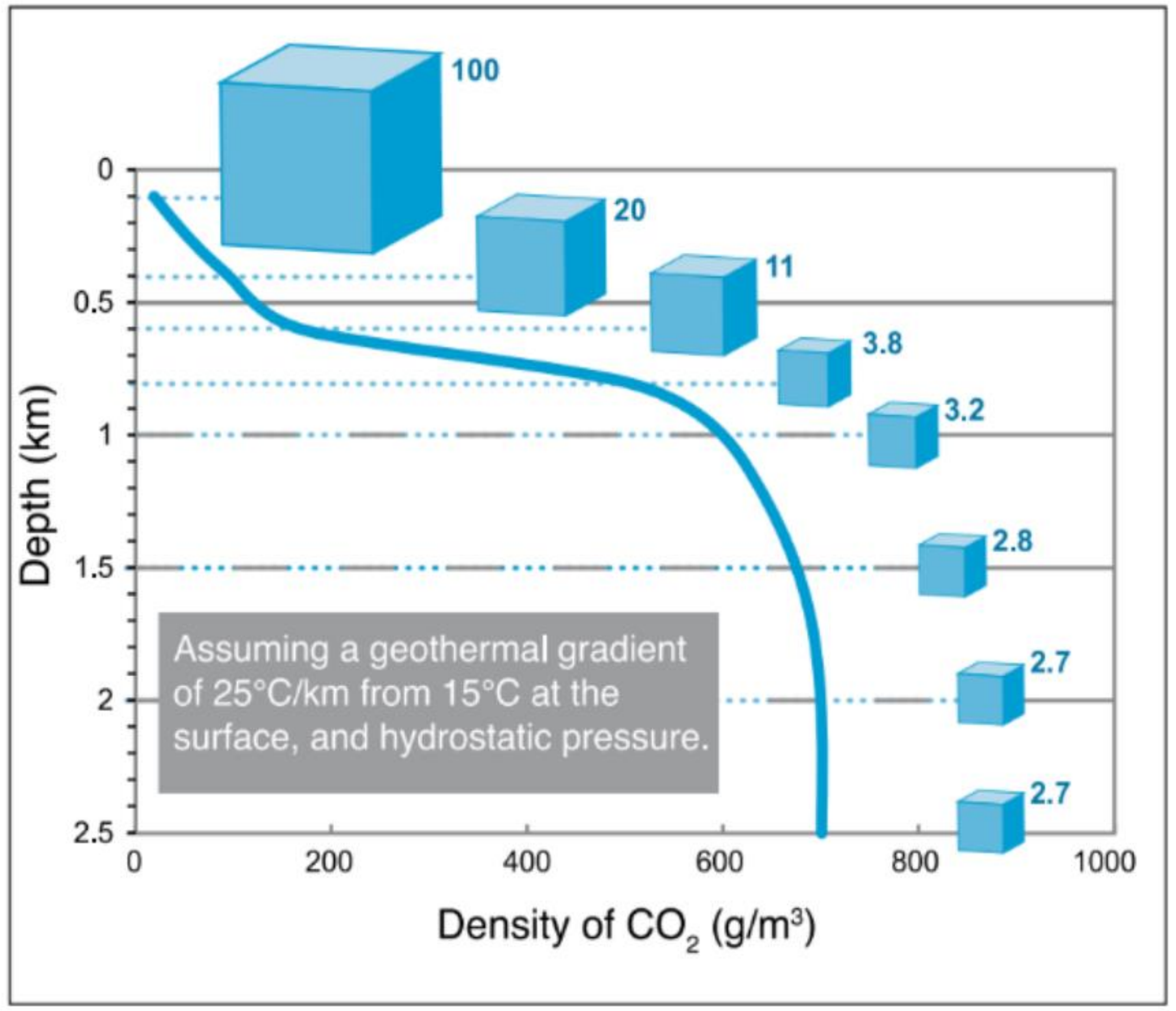
Q = Storage Capacity
A = Area from GEODE maps
D = Thickness from GEODE maps
Φ = Porosity from GEODE maps
Cr = Rock Compressibility
constant = 9.1E-5 (1/bar)
Cw = Water Compressibility
constant = 3.2E-5 (1/bar)
ΔP = Pressure Space
0.035 bar/m (next slide)
ρCO2 = Density CO2
constant = 700 kg/m3

Capacity Density = Q/A

Storage Efficiency Factor GEODE (Est) = (Cr+Cw). ΔP

Depth (m)	Efficiency Factor (-)	E_{st} (%)
1000	0.004	0.43
1500	0.006	0.65
2000	0.009	0.86
2500	0.011	1.08
3000	0.013	1.29
3500	0.015	1.51
4000	0.017	1.72

No uncertainties applied yet!
→ *Qualitative use only (numbers on slides indicative for these assumptions)*

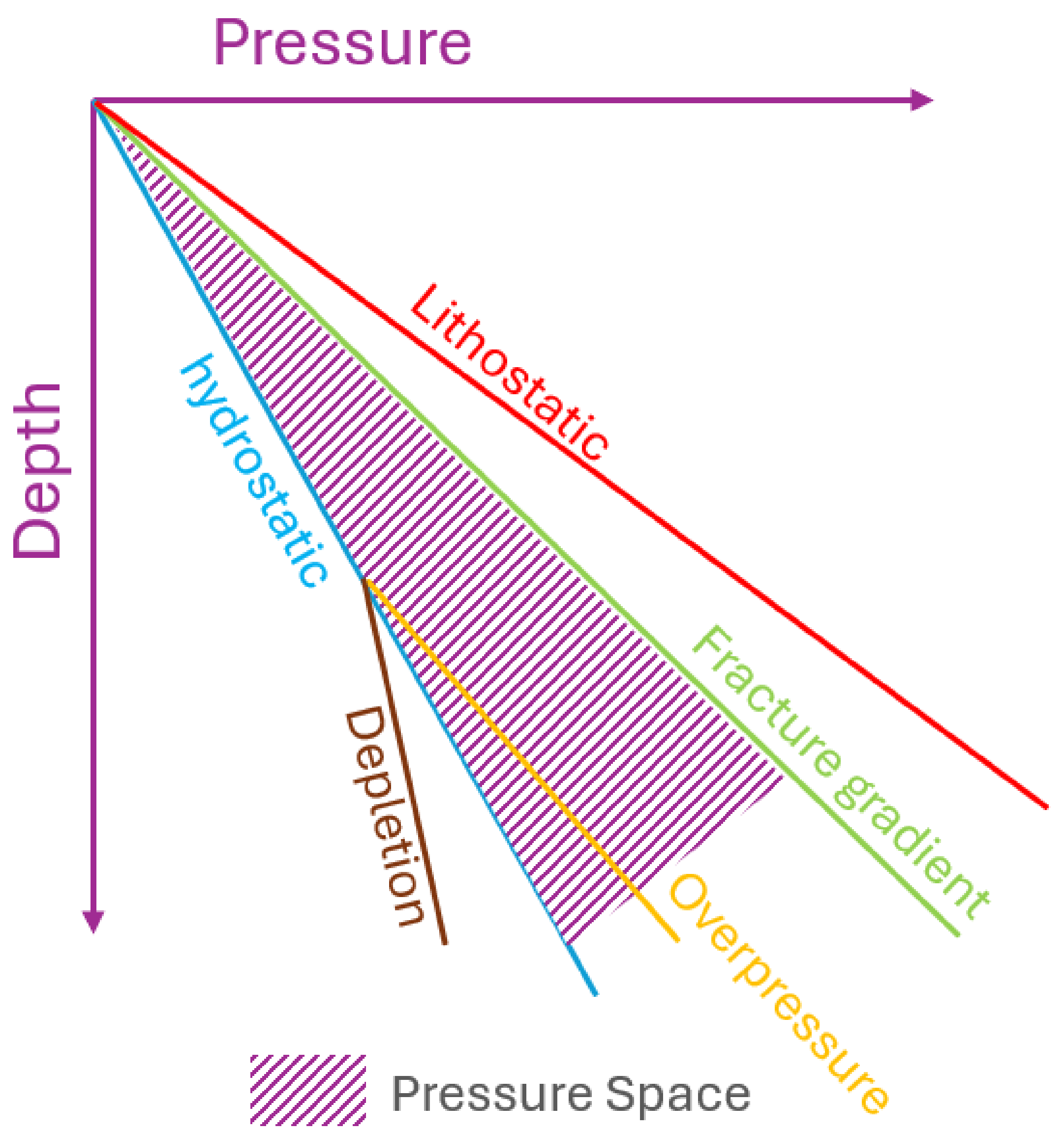


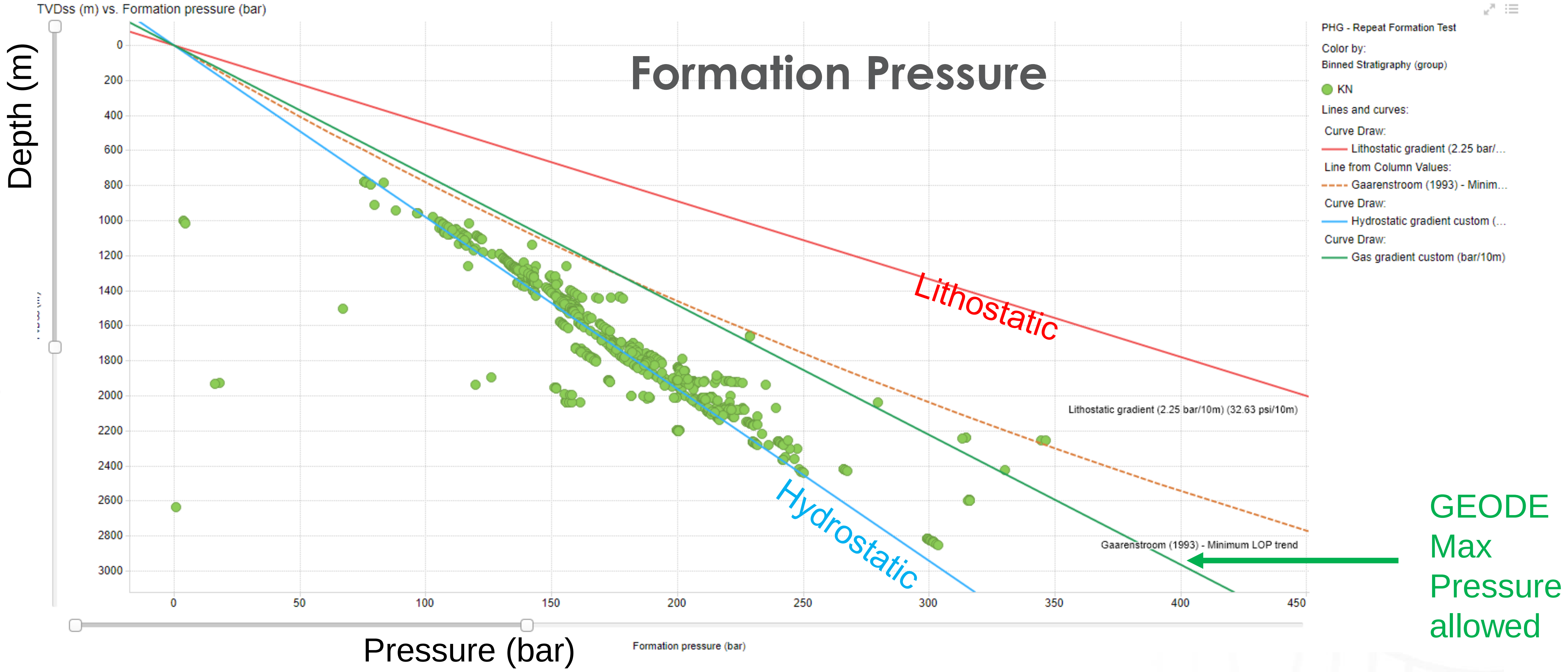
Depth vs density for CO_2. At depths greater than 800 m, the average density is 700 kg/m³ (Benson & Cook, 2005).

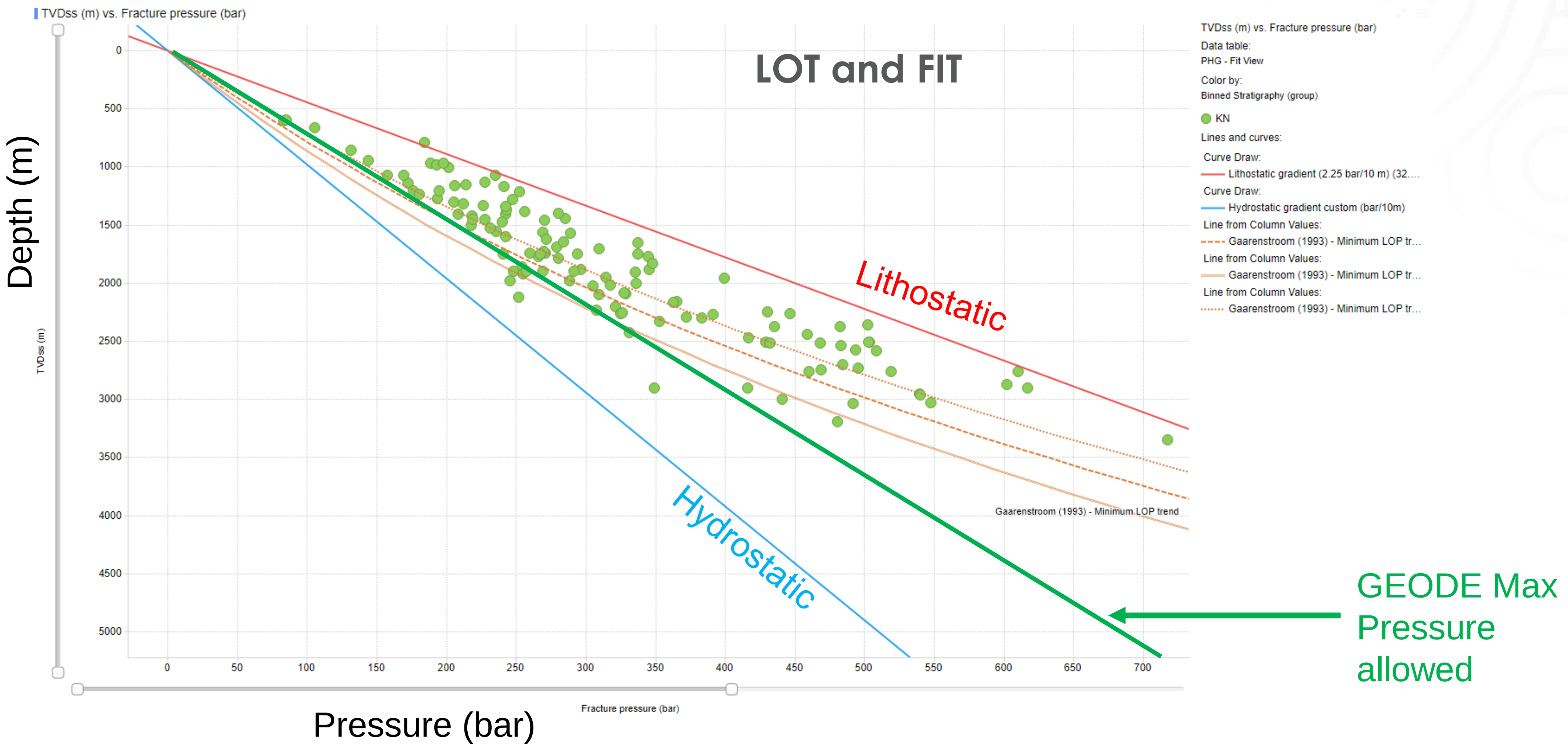
EXHIBITION

“PRESSURE SPACE” FROM SNS PRESSURE DATABASE (NLOG)

- CO_2 storage will increase the formation pressure
- Stay below pressures that may cause leakage or seismicity
- Indication of fracture gradient from Leak-Off tests (LOT) and Formation Integrity Tests (FIT)
- Geode Pressure Space 0.035 bar/m
- Overpressure reduces Pressure Space

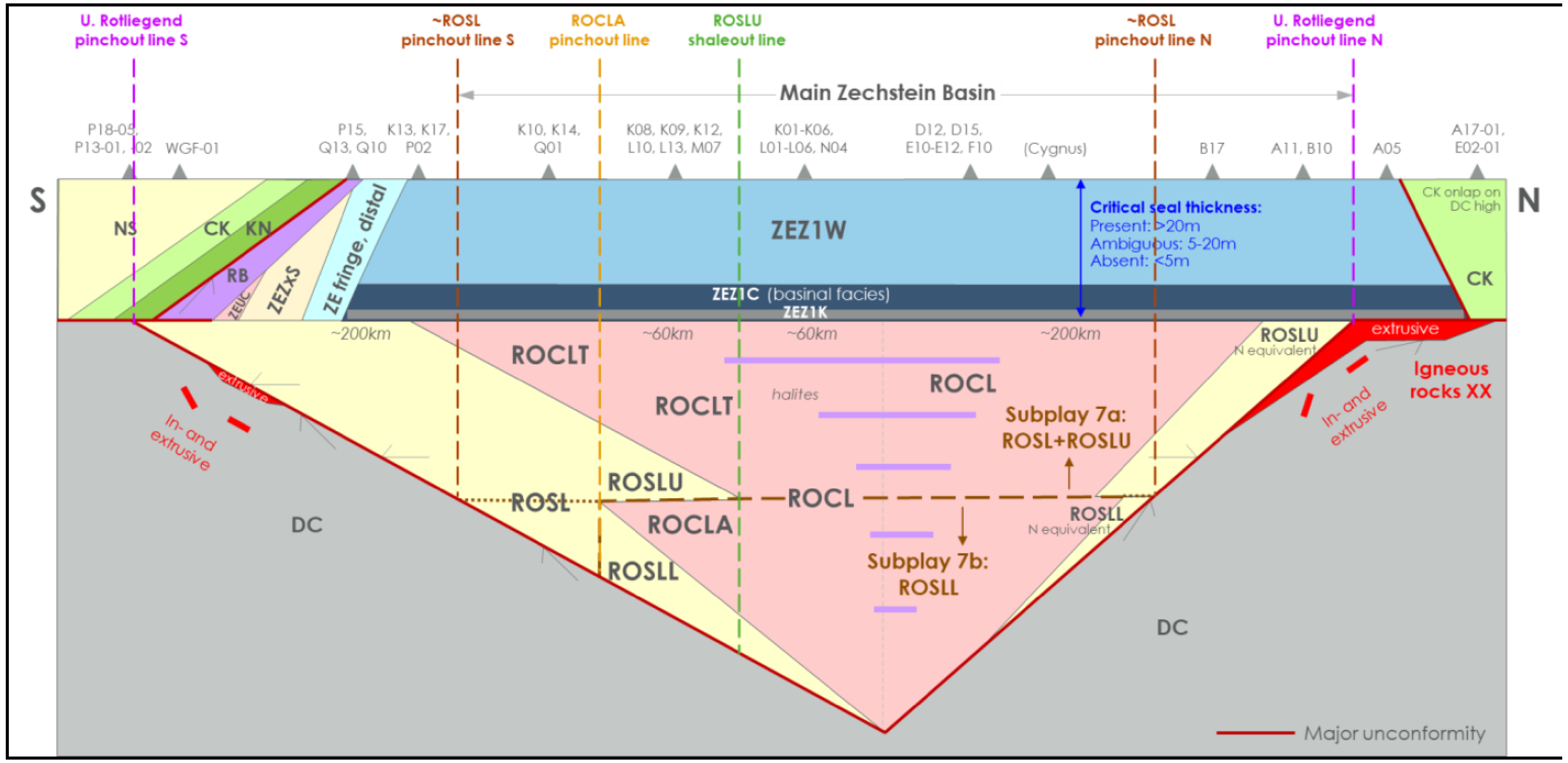


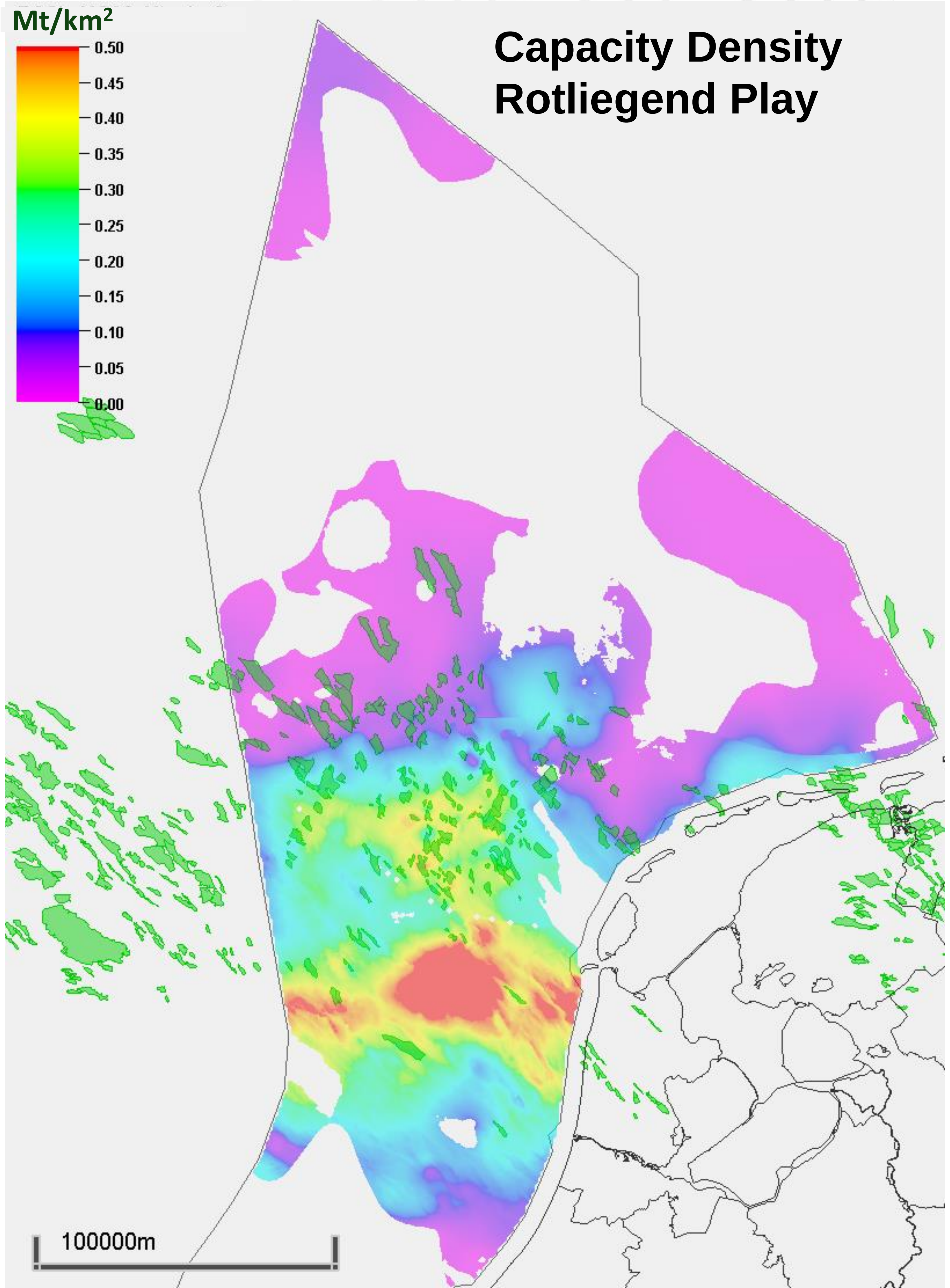




ROTLIEGEND PLAY

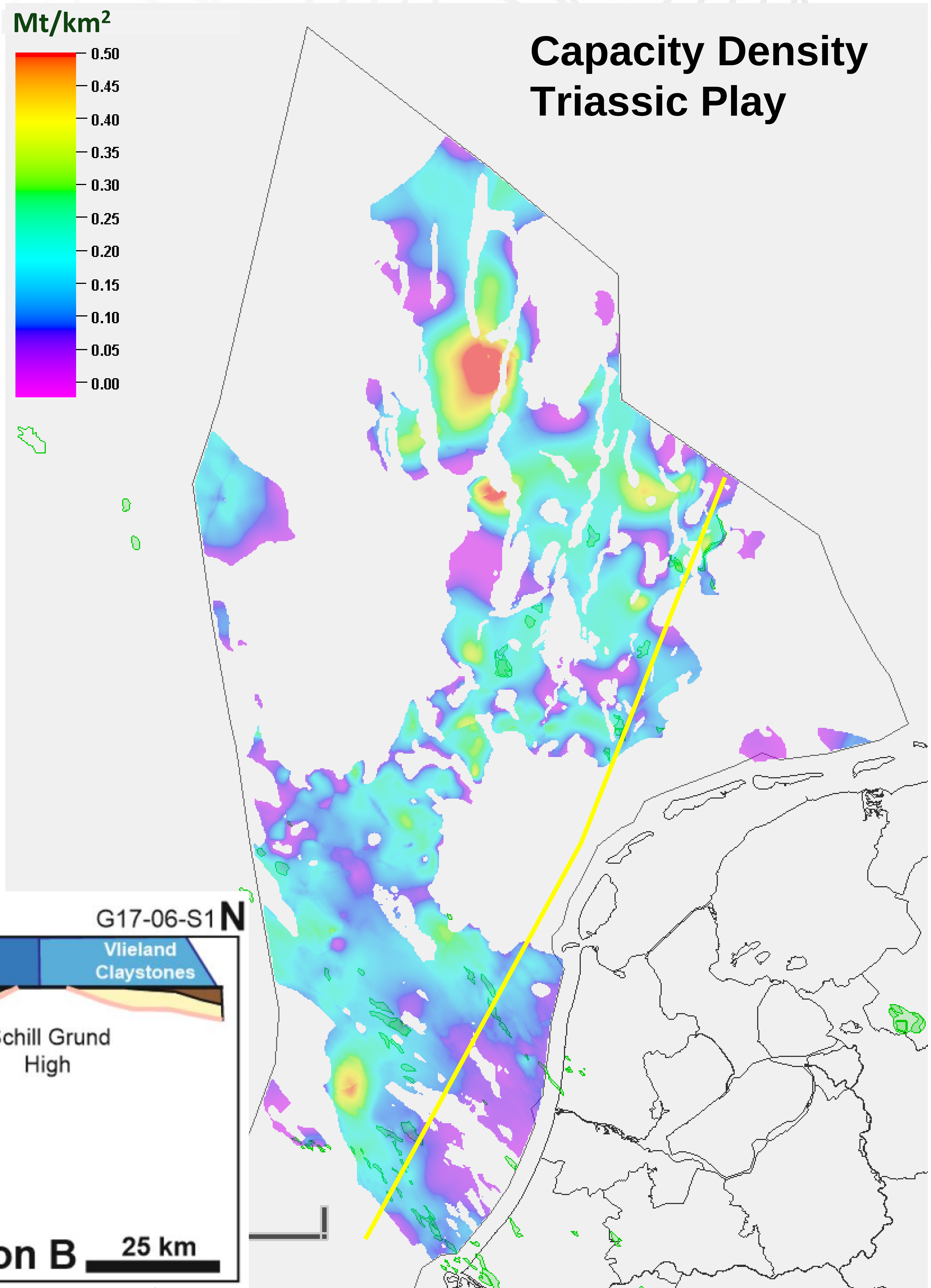
- Most prominent reservoir for gas production in NL
- Continental aeolian and fluvial sandstones
- Highest Capacity Density predicted in area just south of most Dutch RO gas fields

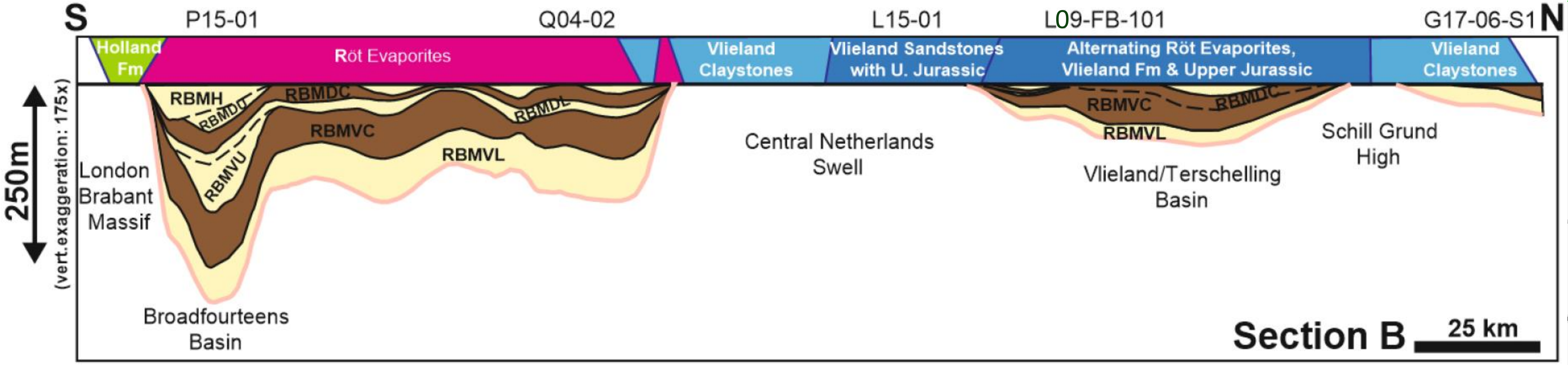




TRIASSIC PLAY

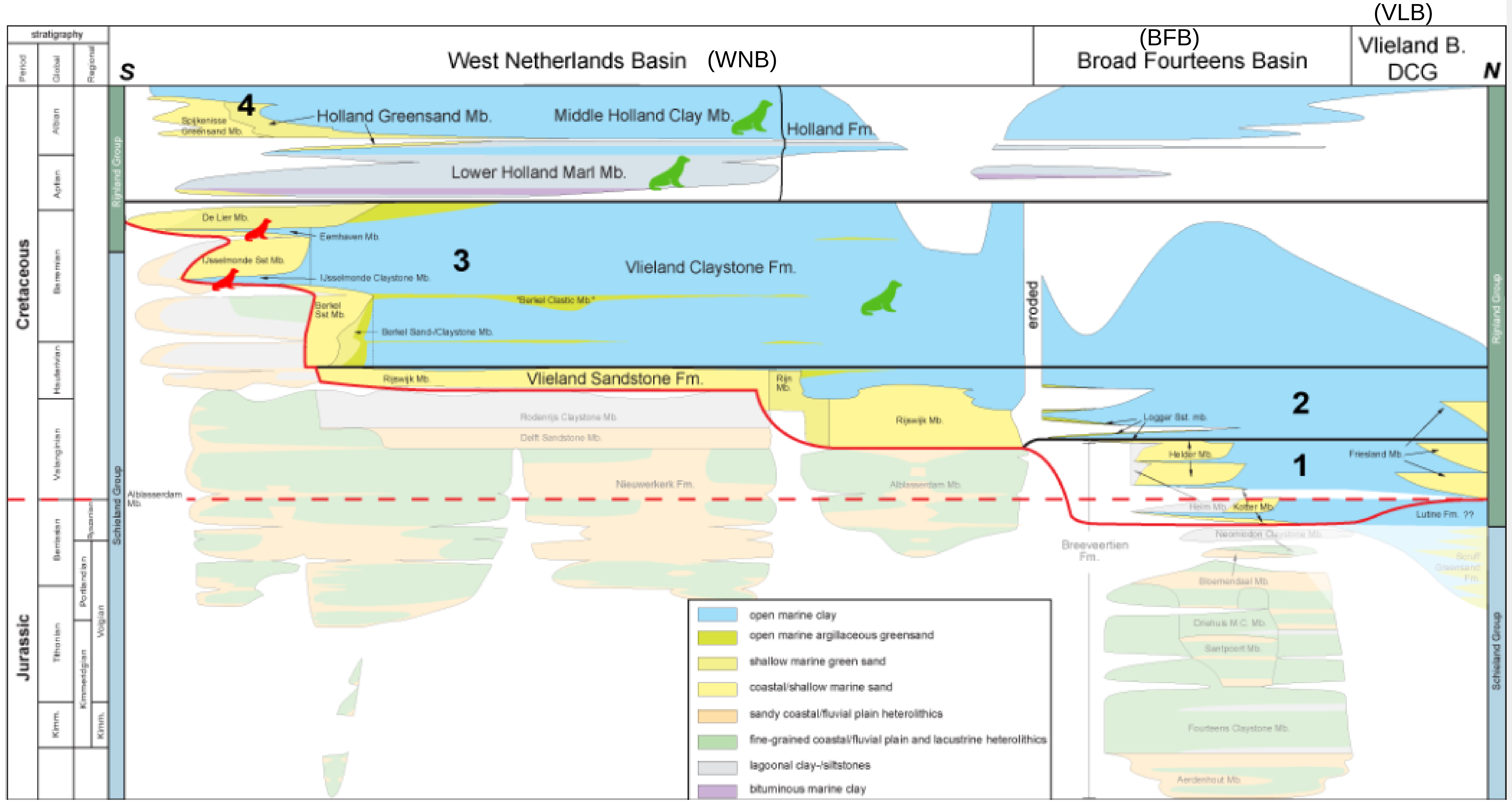
- Second best (volume wise) reservoir for gas production in NL
- Continental fluvial and aeolian sandstones
- Distribution limited to basinal areas
- Volpriehausen carries most potential but in the southern offshore also the Hardegsen/Detfurth are important (e.g. Porthos project in block P18). Solling can be locally very thick (e.g. L09)

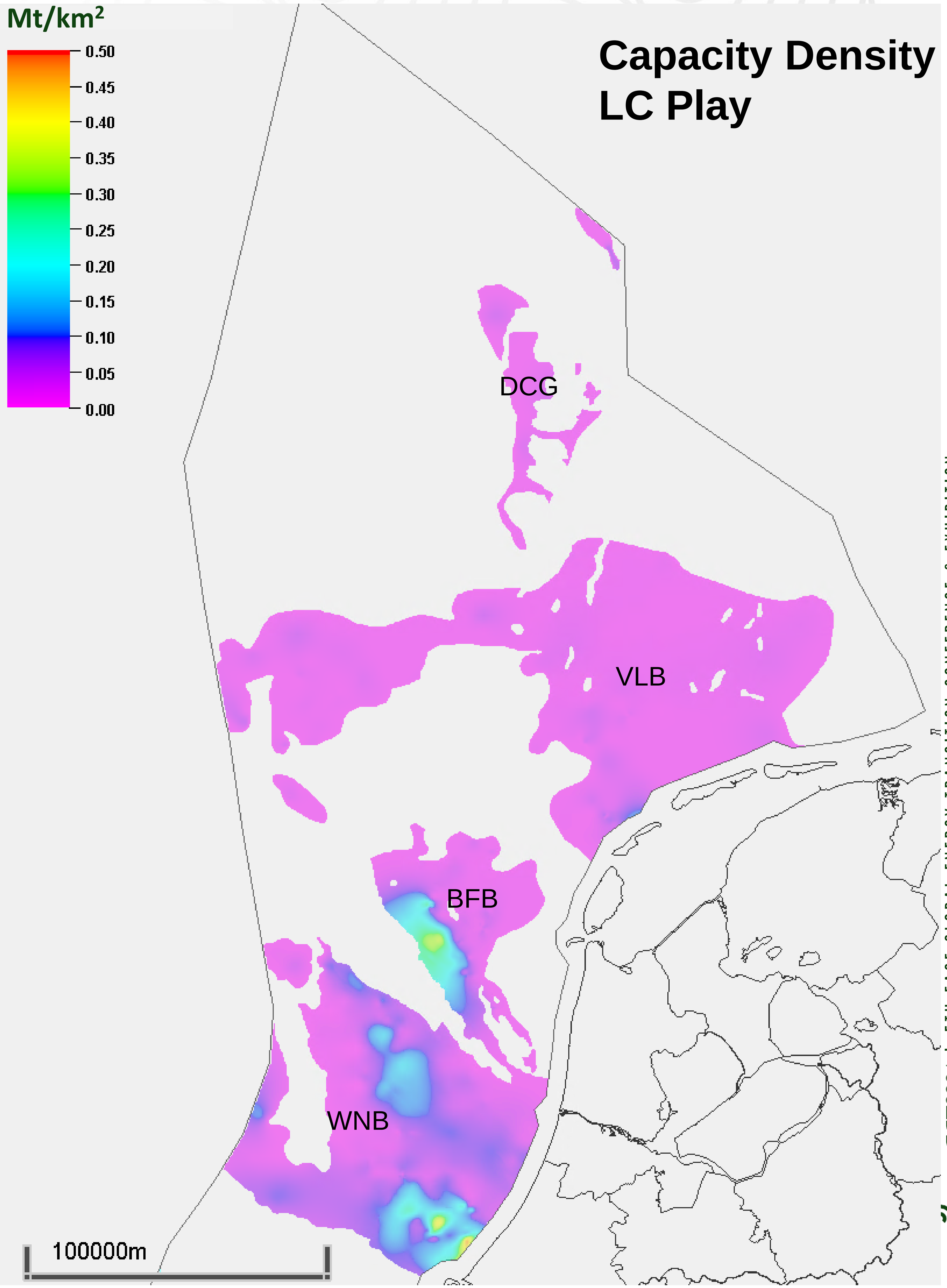




LOWER CRETACEOUS PLAY

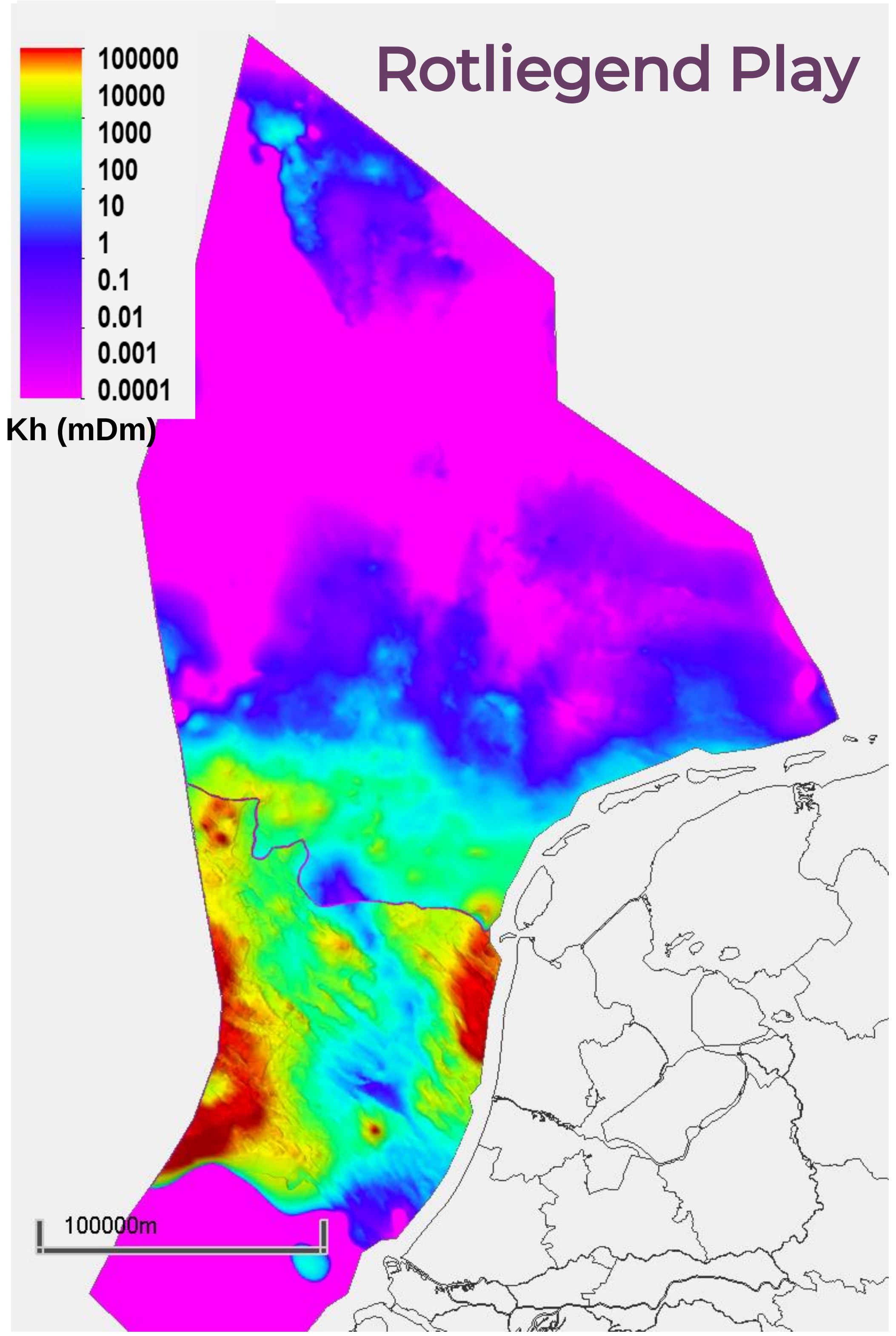
- Marine sands deposited at/close to coastline. Transgressive sequence with stacked sands especially along the fringes of the basins
- Areas with potential are more restricted than Rotliegend and Triassic. Most potential present in West Netherlands and Broad Fourteens basin

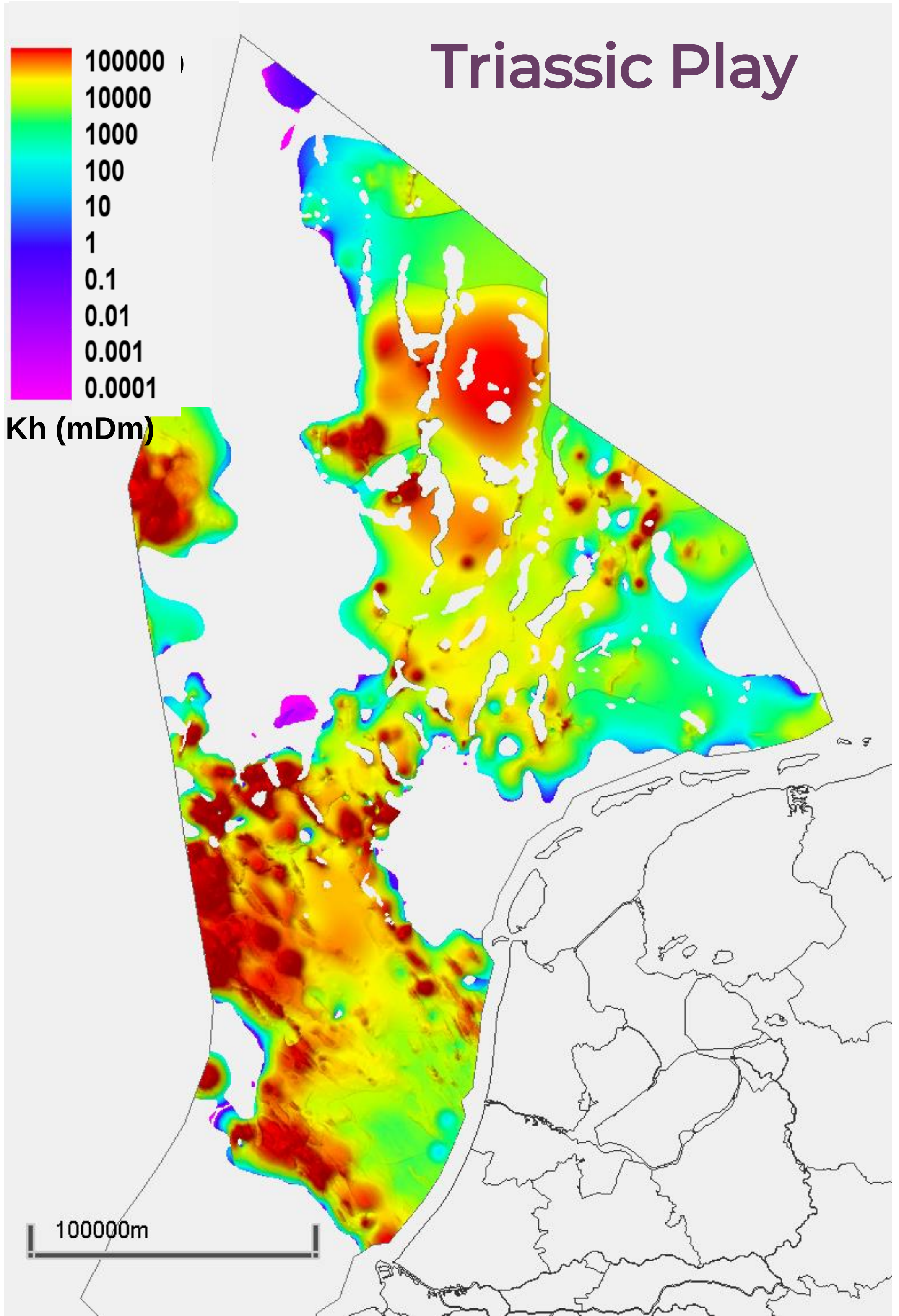


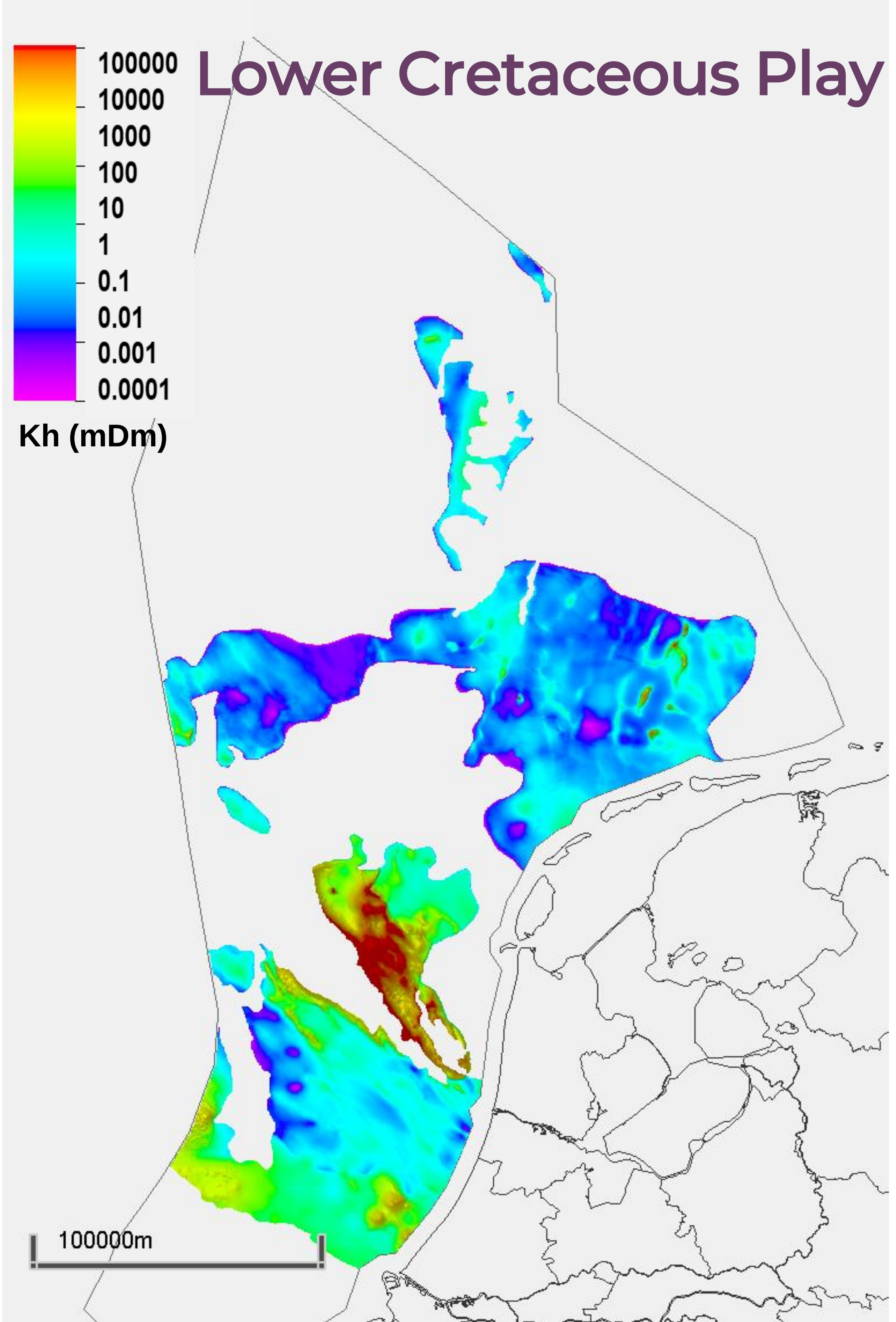


PERMEABILITY * THICKNESS (KH) AS PROXY FOR INJECTIVITY

Input:
- Thickness maps, Porosity maps
- Porosity-Permeability function

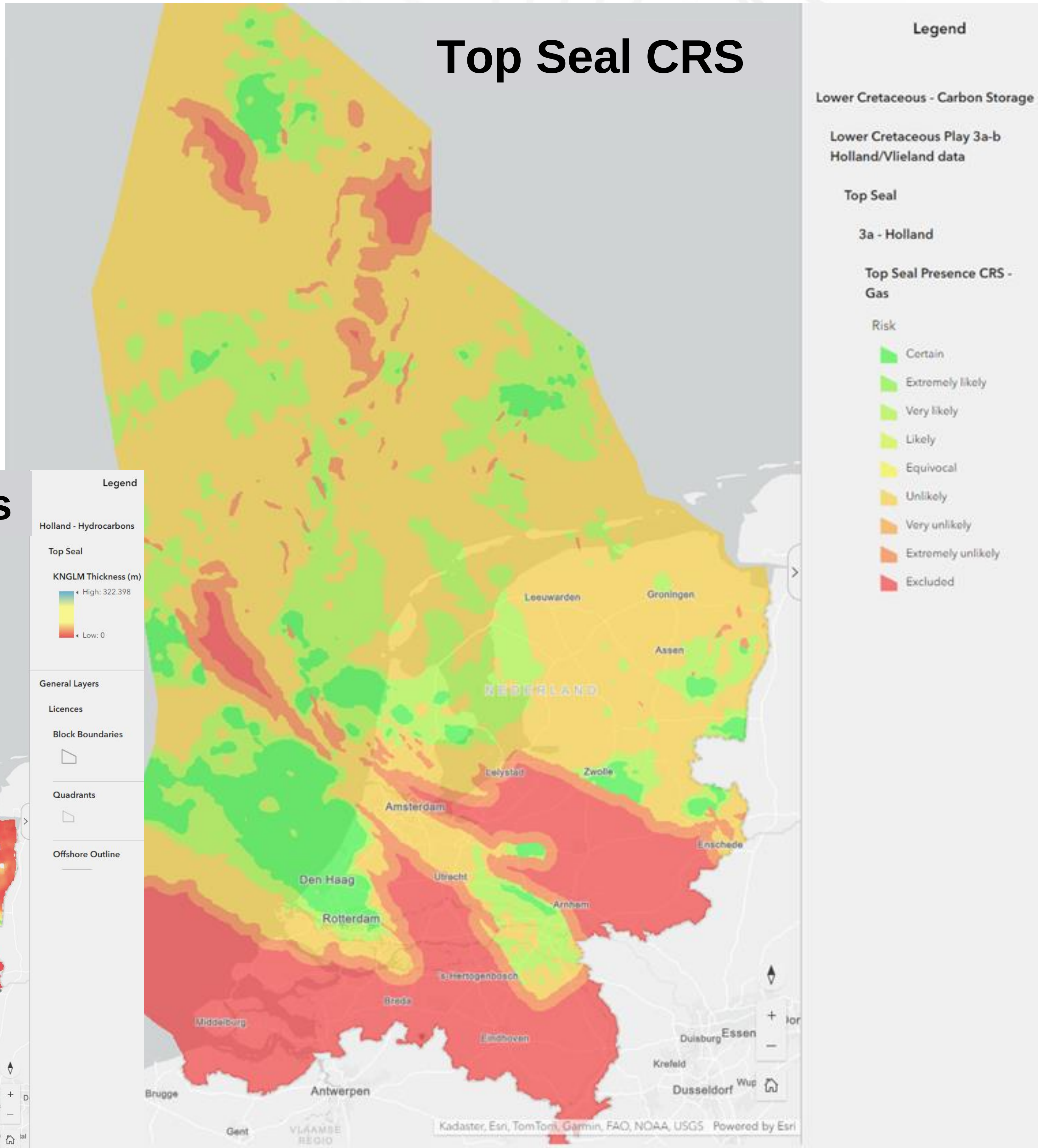




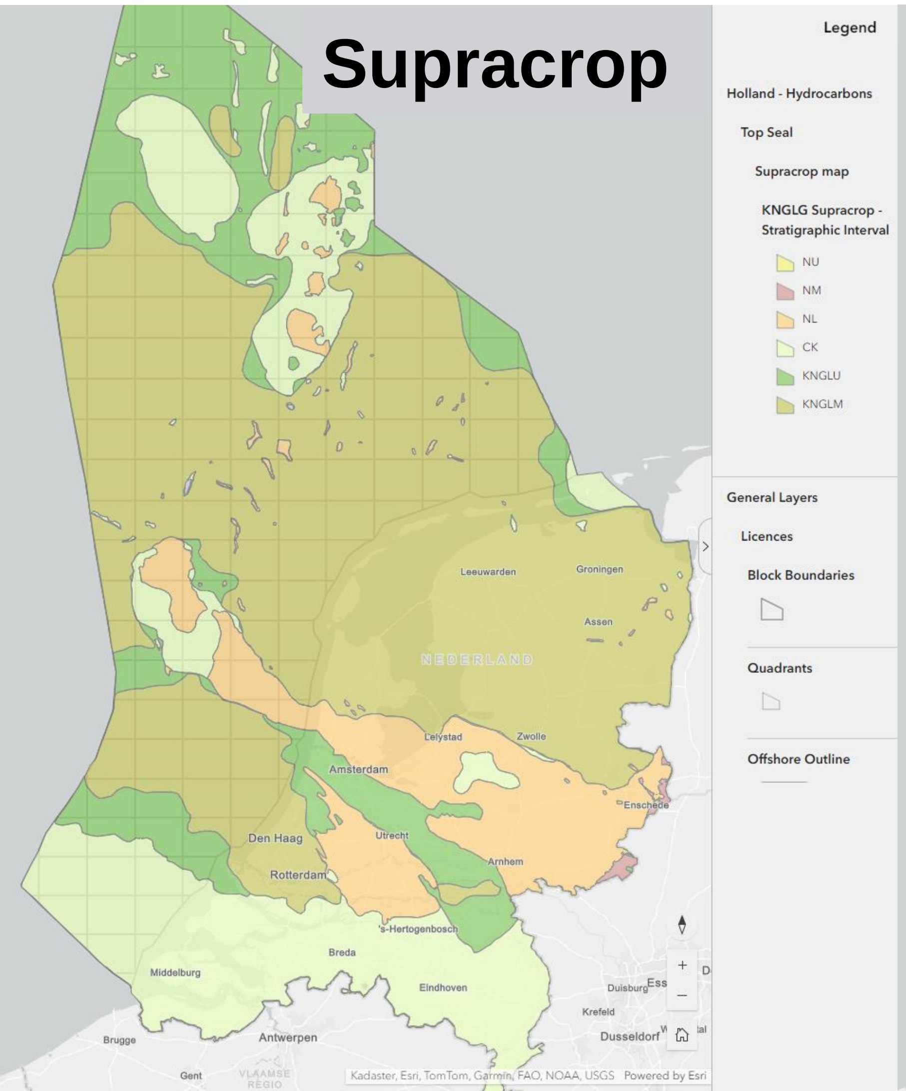


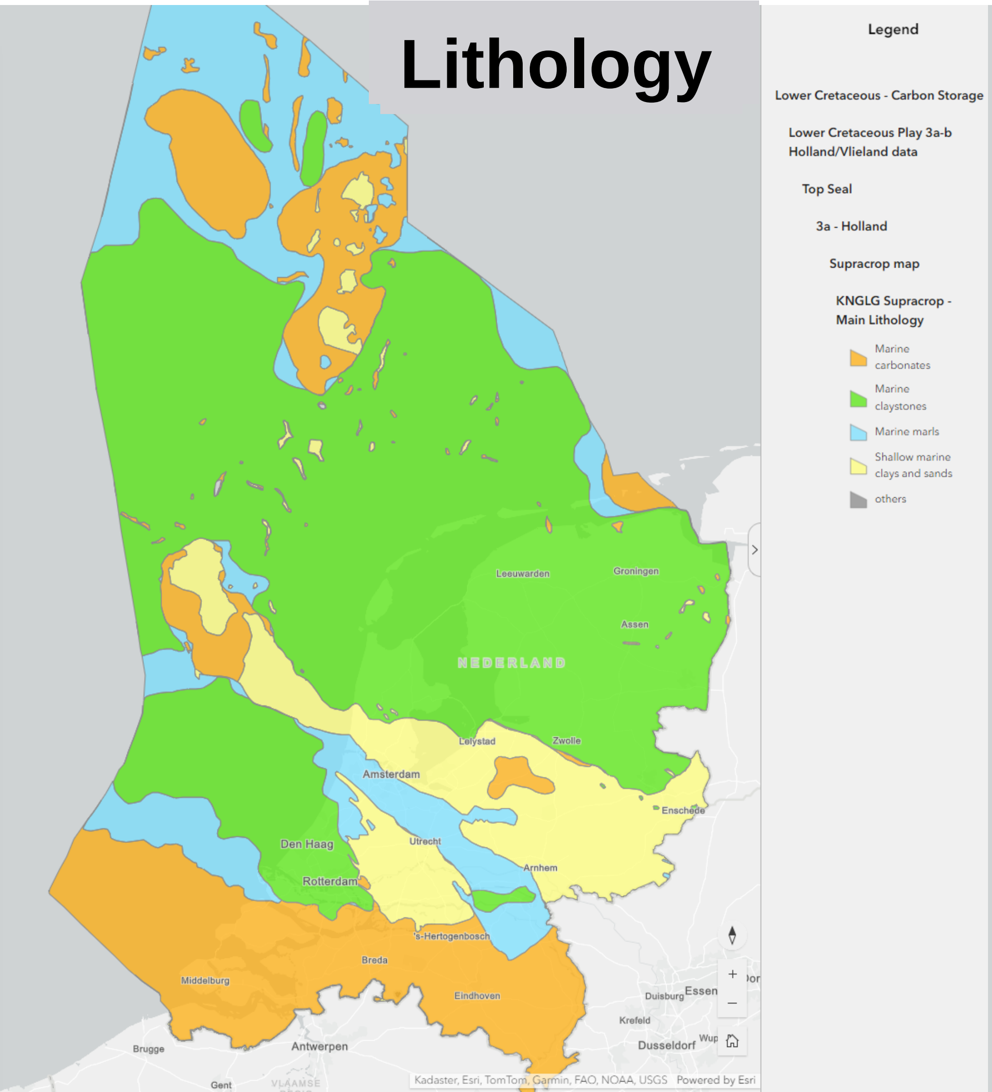
TOP SEAL COMMON SEGMENT RISK (CRS)

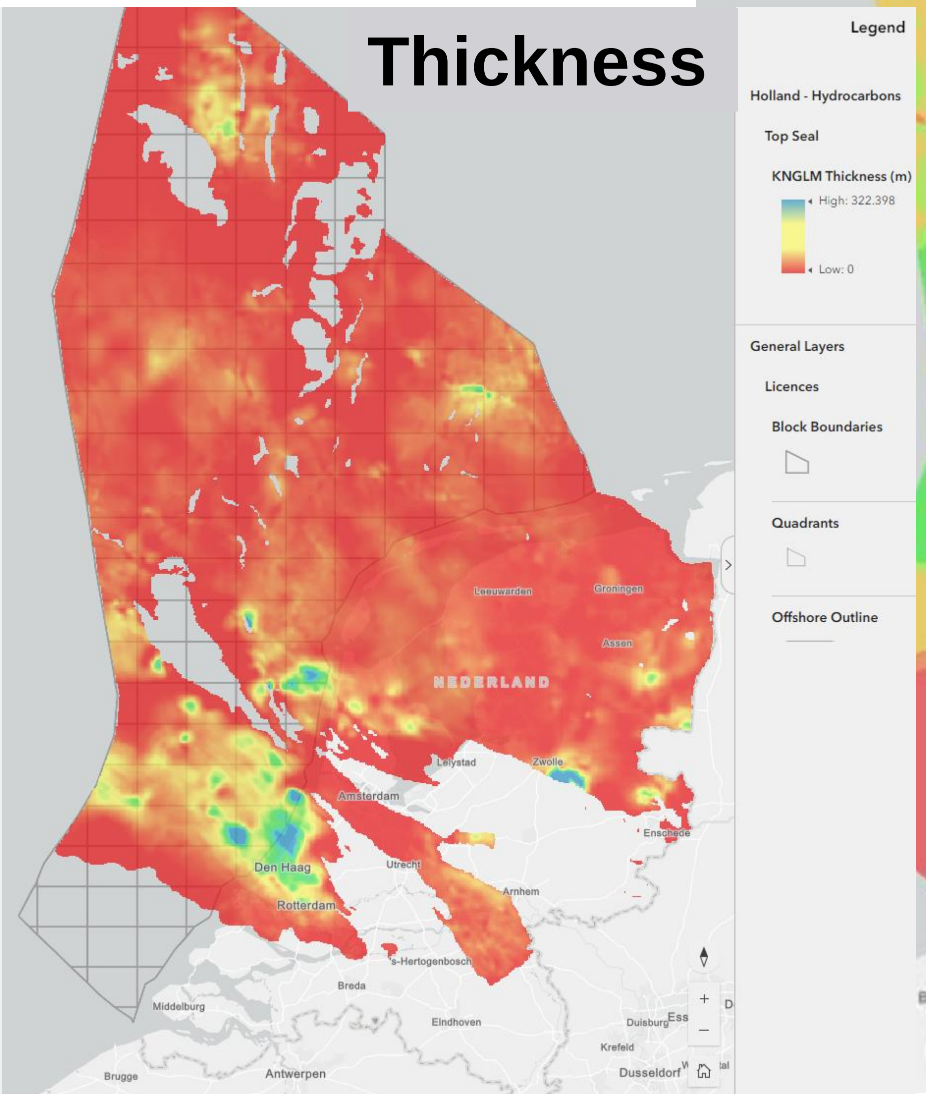
- What is the thickness and quality of the overlying sealing unit?
- CRS map: Likelihood of a working seal for gas (methane or CO_2) or oil



Seal Lower Cretaceous Play





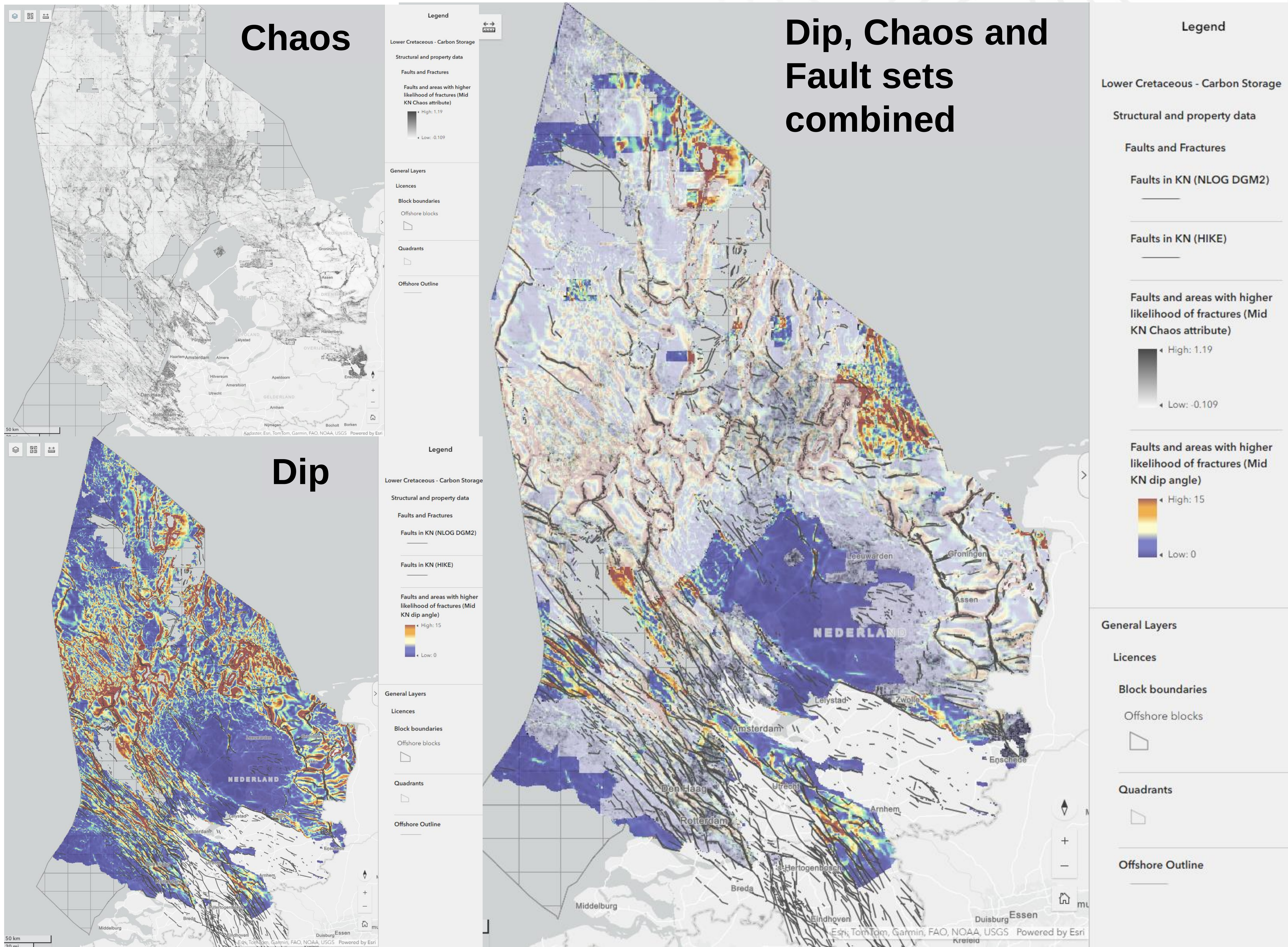


FAULTS AS A RISK

- Faults can provide leak paths and/or compartimentalise the aquifer

- Faults mapped by:
  - Chaos attribute 3D seismic data
  - Dip surface attribute DGM 5 surfaces (nationwide subsurface depth maps)
  - Faults from DGM 5
  - Faults HIKE database

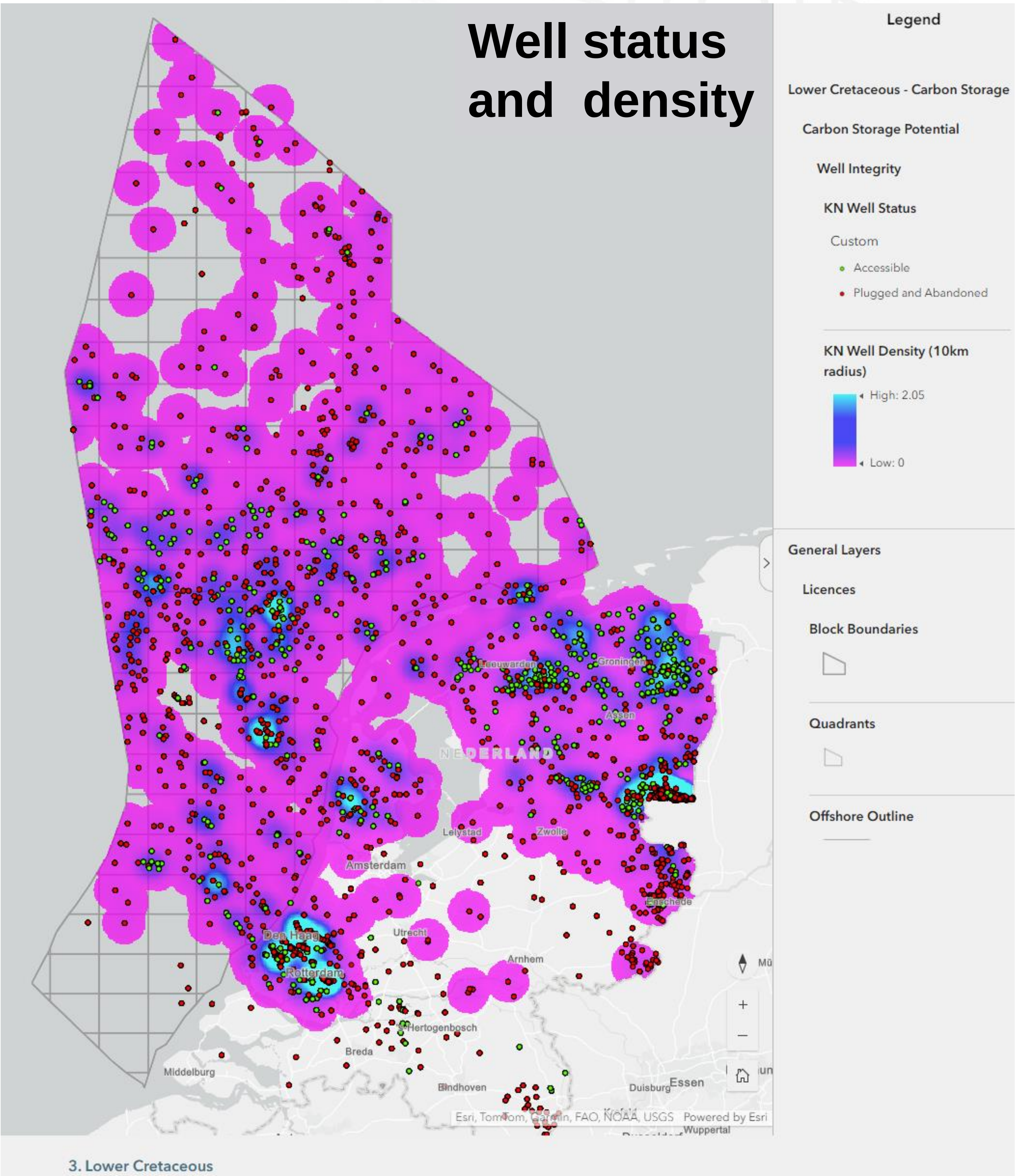
Lower Cretaceous Play



LEGACY WELLS

- Proper abandonment of wells mitigates the risk of leakage
- Isolation of the injection reservoir from the overburden: Proper plug with sufficient length over the caprock with a good cement bond behind the casing
- Older wells with poor record of operations are more difficult to assess. First indicators of risk level:
  - Number of wells/well density
  - Year of drilling (before/after 1970)
  - Presence of a Cement Bond Log (CBL, y/n)
  - Accessibility: status of the well (accessible/plugged and abandoned)
- Local studies require more elaborate screening of the isolation in wells and in case of insufficient isolation the possibility of remedial action

Lower Cretaceous Play



FROM THEORETICAL TO PRACTICAL STORAGE VOLUMES

To mature the Theoretical Storage Capacity:

- Clarity on allowed pressures (pressure space)

- Accessibility:
  - which regions should be discarded due to restrictions
  - which regions should be avoided due to containment risk (geological seal, problematic legacy wells)

- Economic screening:
  - Development scenarios

- **Depleted gas fields:**

Bijkerk et al. 2024, Towards practical CO2 storage capacity in Dutch depleted gas fields: reservoir quality and regulatory limits

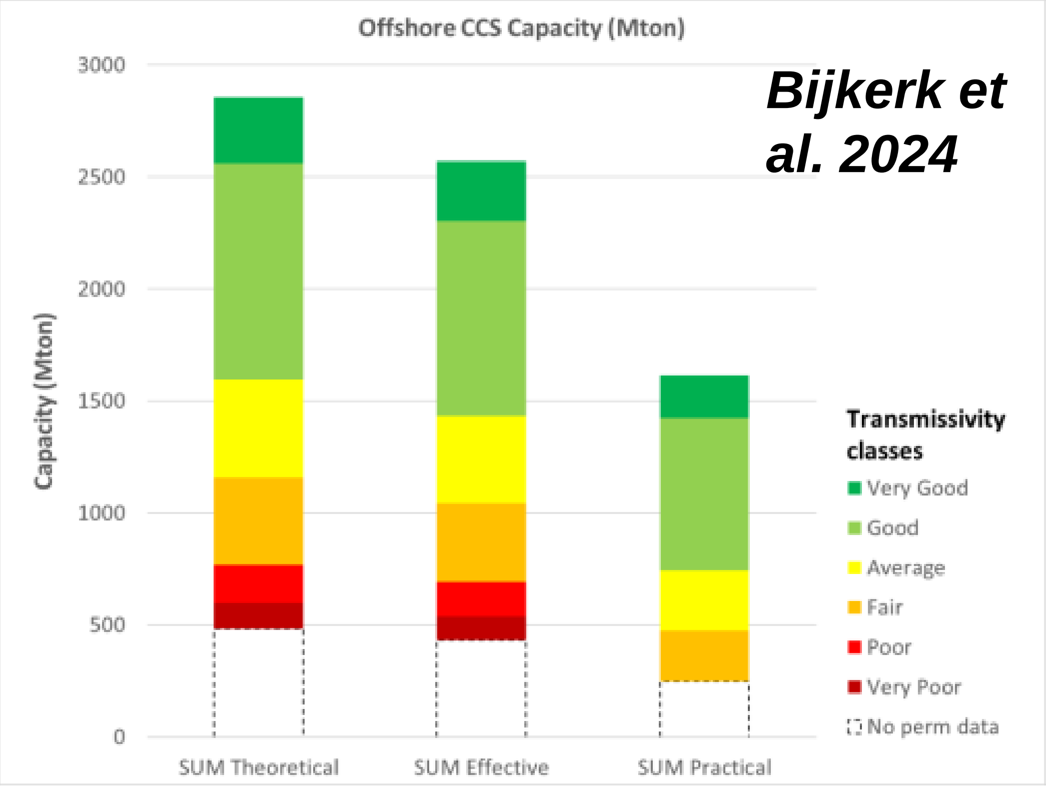
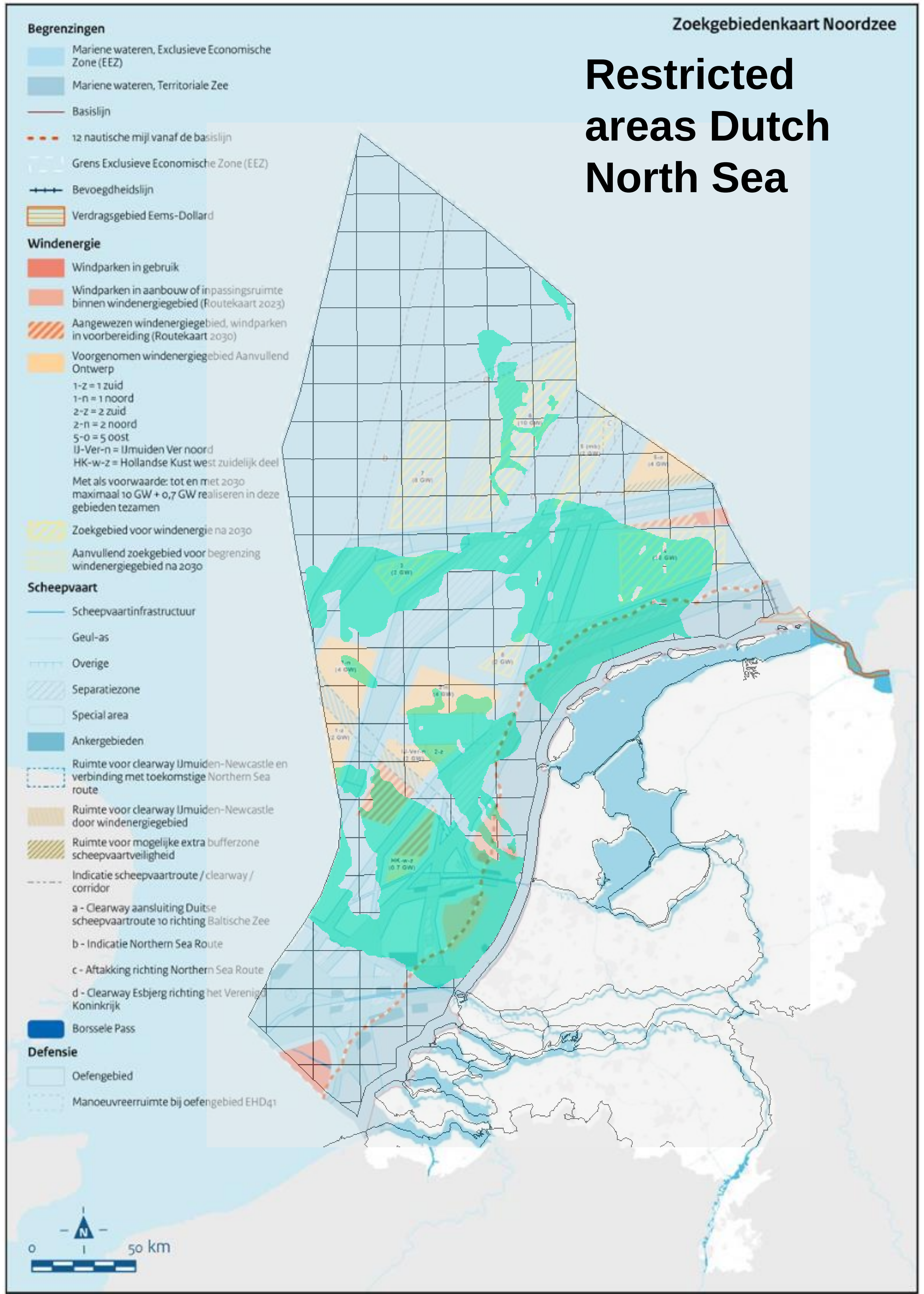
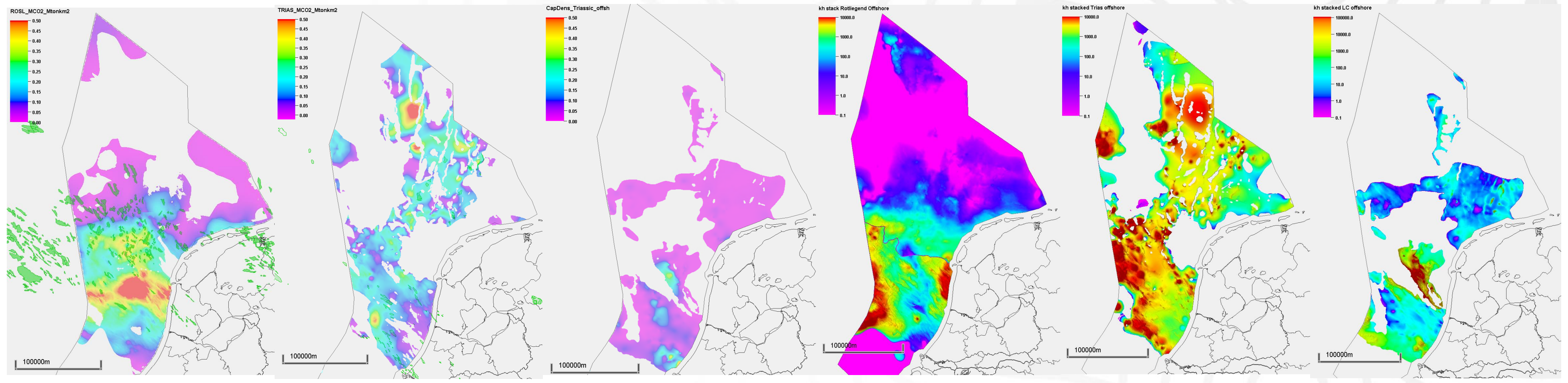


Figure 3 *Estimate of Theoretical, effective and practical capacity of depleted gas fields in the Dutch Offshore. Fields are grouped in transmissivity (reservoir quality) classes. Effective capacity currently uses a 0.9 multiplier but will be modified after further work on the underlying processes. Practical capacity represents a case study that strongly depends on regulatory choices and economic factors.*



SUMMARY



- GEODE CO_2 storage maps are a first regional step for evaluating the Dutch CO_2 aquifer storage potential
- Restrictions: regional mapping; local trends not evaluated. Generalized **assumptions** applied on some parameters, **site specific risks to be evaluated by the operator**
- Improvements: incorporate uncertainties, definition pressure space (regulatory guidance), Closed- (semi-) open system definition (expected pressure behaviour definition of hydraulic units)
- Rotliegend, Triassic and Lower Cretaceous aquifers in the Netherlands show significant CO2 storage potential. Detailed studies are needed to mature opportunities. A challenge is the accessibility of parts of Dutch North Sea in the future.

Results available @ →

www.geodeatlas.nl

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