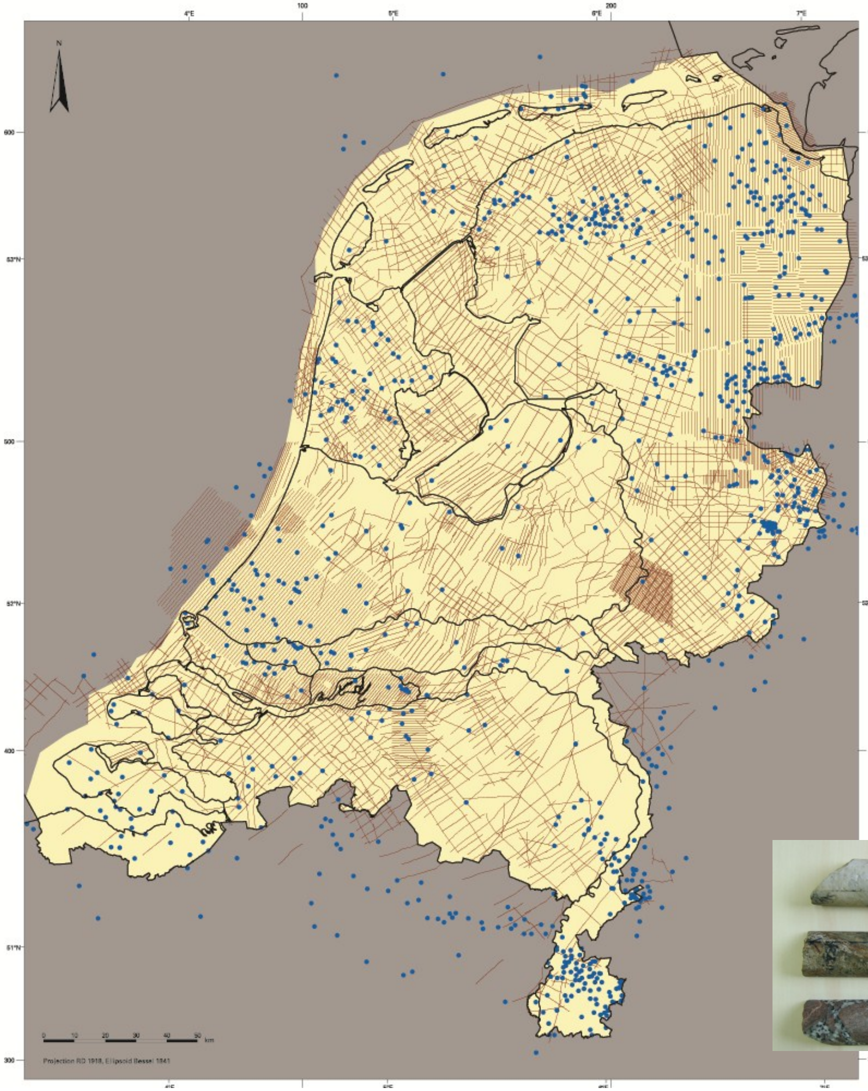
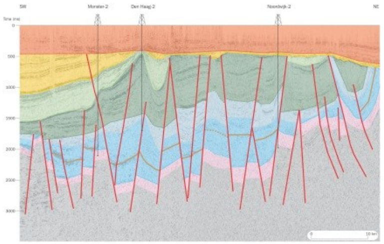
Geothermal exploration and geophysical techniques for sediment settings

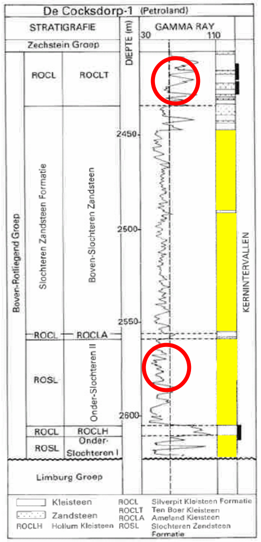
- Example by dutch aquifers
- Mature basin setting
- How to use oil and gas data to find good aquifers
  - Seismic exploration
  - Well logging techniques

Dutch database: over 50 billion Euro of data





<u>Well & Seismic Data</u>
Wells: 5876
Seismic: 72.000 km



<u>Log data</u>

Gamma ray
Sonic
Resistivity
Neutron, etc

<u>Petrophysics</u>
Cores: 100 km
Poro/perm: 60.000 measurements
(300.000 total)

www.NLOG.nl

NL Olie- en Gasportaal

☐ Boreholes
☐ Seismic surveys
☐ Fields
☐ Production
☐ Infrastructure
☐ Licences

☐ Publications and Data sets
☐ Legislation
☐ Administrative procedures
☐ Fees, taxes and state participation
☐ Seismicity and subsidence
☐ Contacts

▶ Links
▶ Home
▶ Disclaimer
▶ Contact
▶ (In het Nederlands)

Welcome to the NL Oil and Gas Portal

This site provides information about oil and gas exploration and production in the Netherlands and the Dutch sector of the North Sea continental shelf.

It aims to help users access information furnished by the Dutch government in an easy, comprehensible fashion.

This site was produced at the request of the Dutch Ministry of Economic Affairs, Agriculture and Innovation and is being managed by TNO, *Geological Survey of the Netherlands*.

Recent changes

We keep this site continually up-to-date. Click here for an overview of recent changes.

Other topics

Salt production

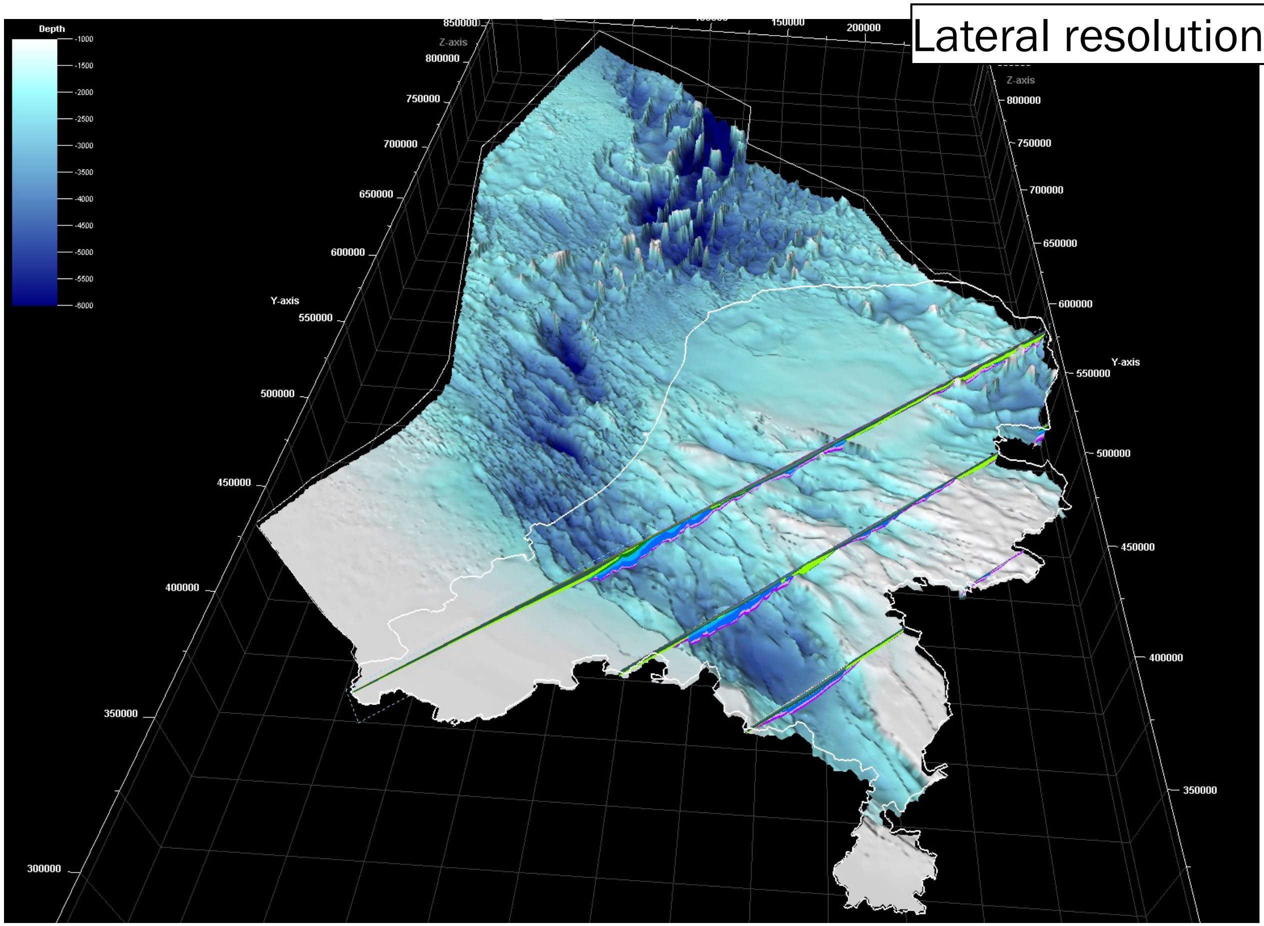
Underground gas storage

Geothermal Energy

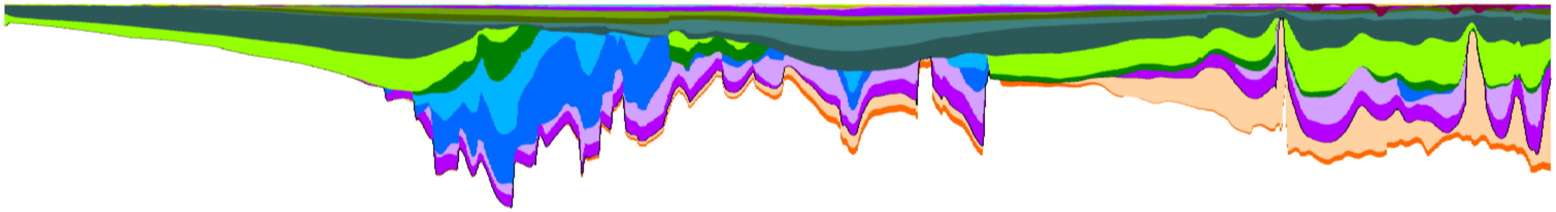
Geological storage of CO2

- All kinds of well data & seismic data accessible and free to download

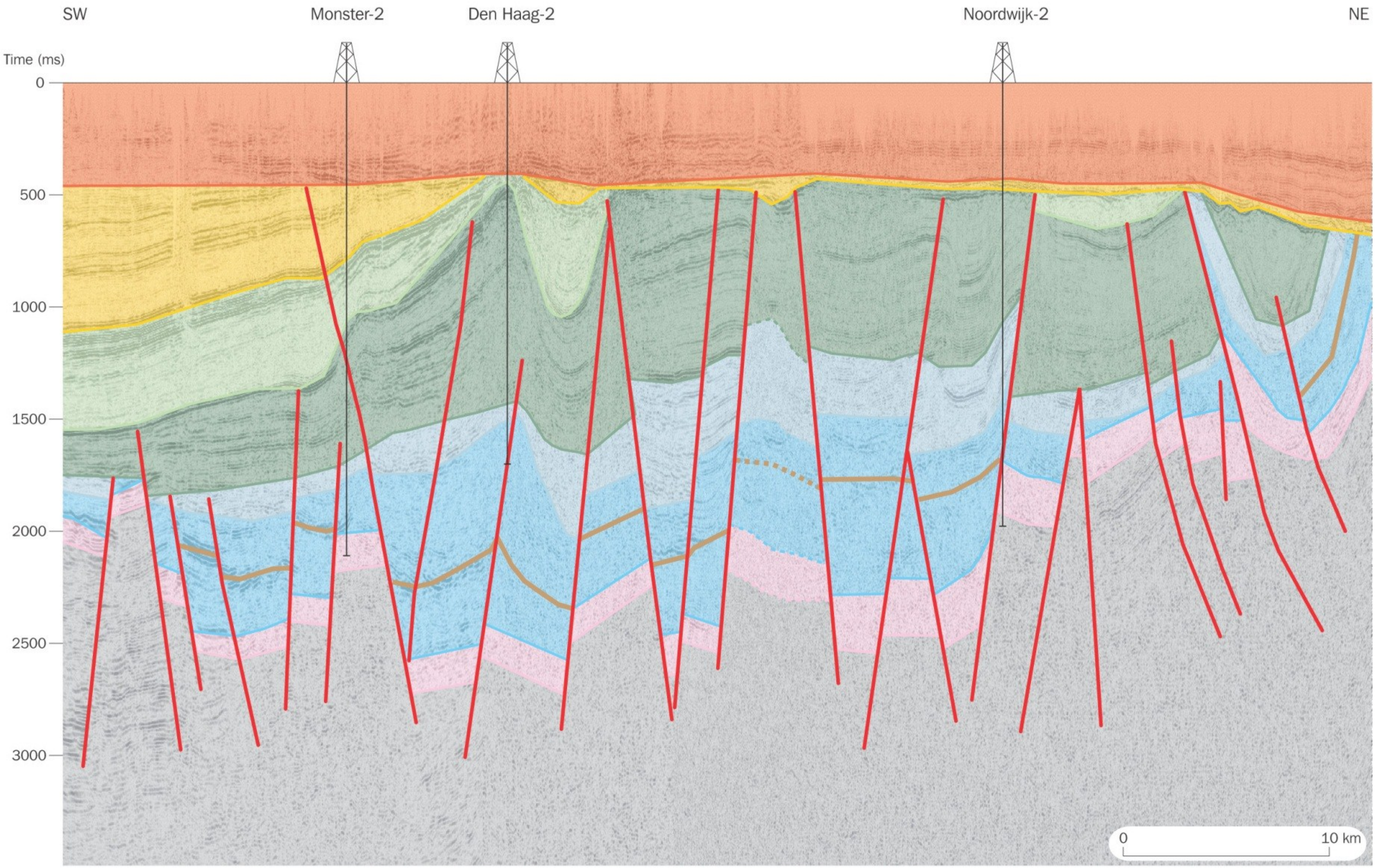
Seismic interpretation

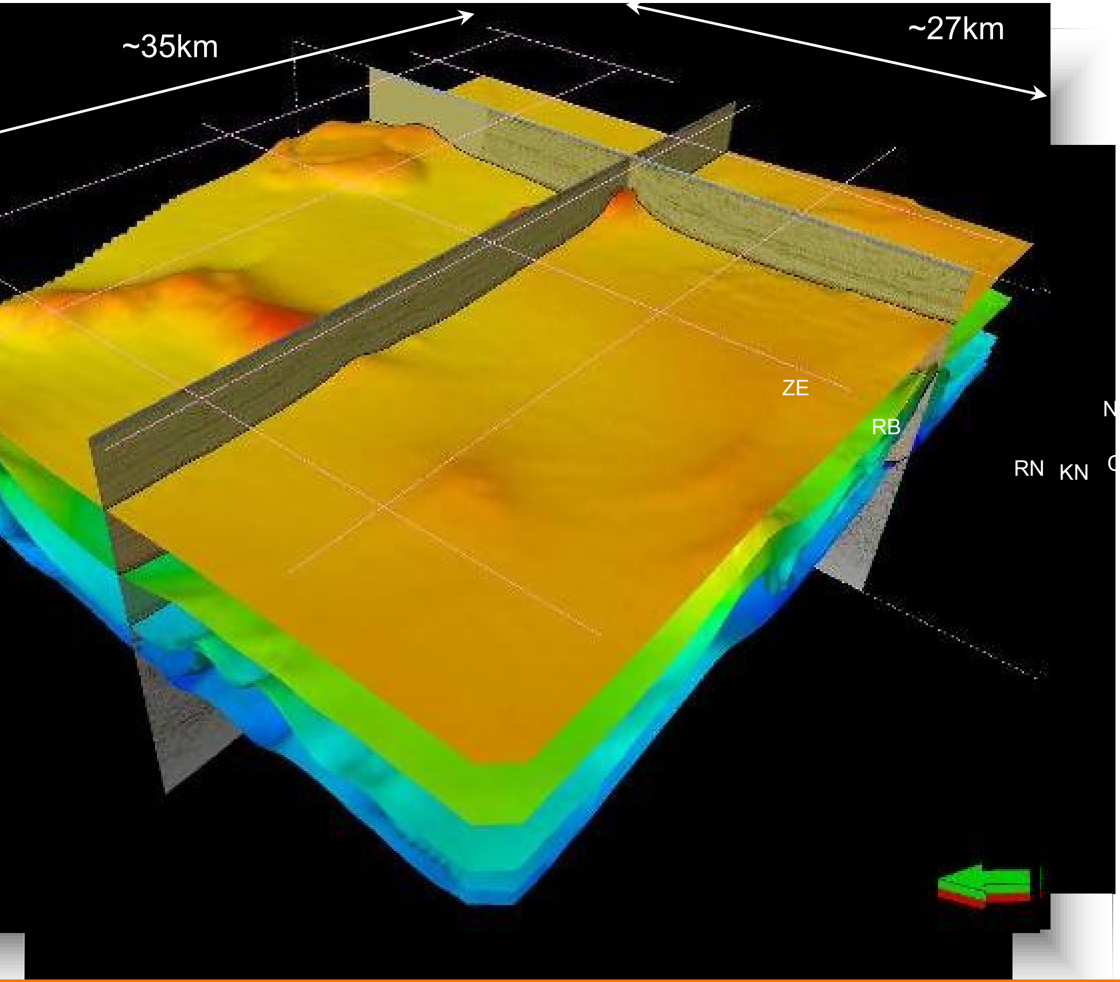


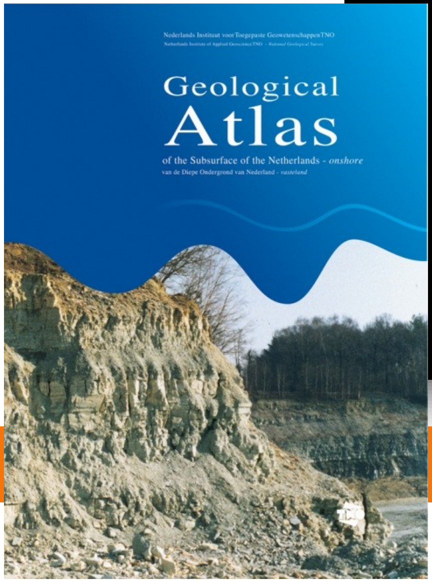
Lateral resolution 250 m



Seismic reflection subsurface imaging






Nederlands Instituut voor Toegepaste Geowetenschappen TNO

Geological Atlas

of the Subsurface of the Netherlands - *onshore*

van de Diepe Ondergrond van Nederland - *vasteland*

1985-2004

3D Interpretation of seismic horizons

TNO 3D mapping of the subsurface

SEISMIC METHODS

These methods can be divided into two main subclasses:

active seismic methods, which cover all seismic prospecting having an artificial sonic wave source;

passive seismic methods, which deal with the effects of natural earthquakes or those induced by fracturing related to geothermal fluid extraction and injection.

Seismic methods determine subsurface elastic properties influencing the propagation velocity of elastic waves and can be very helpful in obtaining structural information of the subsurface or even to outline a potential reservoir.

SEISMIC METHODS

Elastic waves

When a stress is applied (or released) the corresponding strain propagates out from the source.

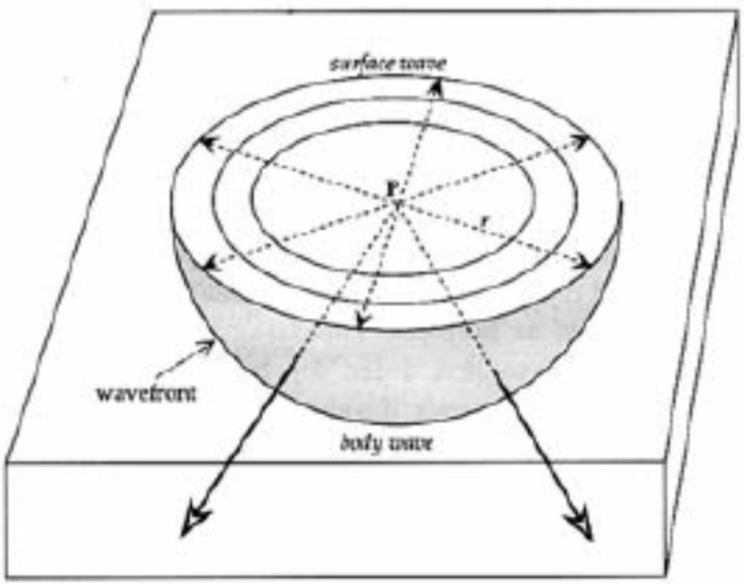


Fig. 3.9 Propagation of a seismic disturbance from a point source P near the surface of a homogeneous medium; the disturbance travels as a body wave through the medium and as a surface wave along the free surface.

Point source seismic disturbance:

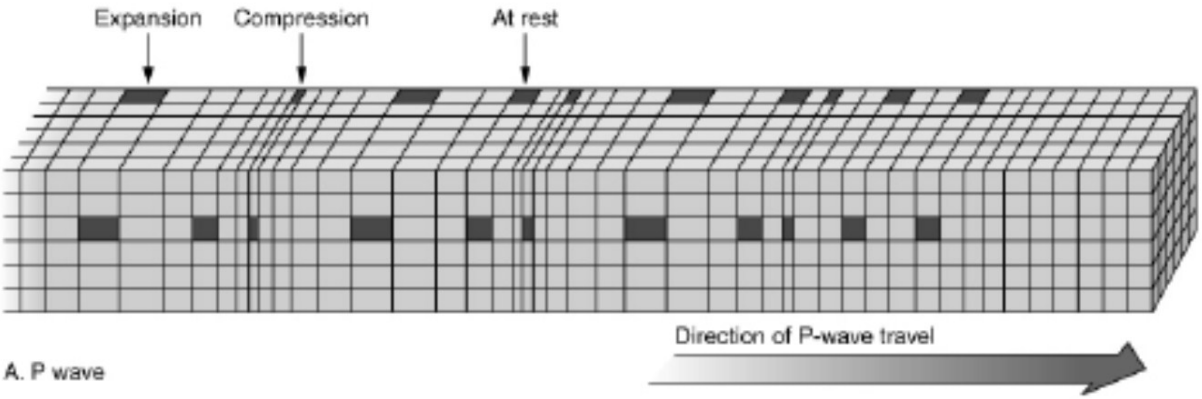
- Wavefront expands out from the point: **Huygen's Principle**
- Body waves: sphere
- Surface waves: circle
- **Rays**: perpendicular to wavefront

SEISMIC METHODS

Body waves

P-waves

- P for "primary" or "push-pull"
- Compression and rarefaction, no rotation
- Causes volume change as the wave propagates
- Similar to sound waves traveling through air



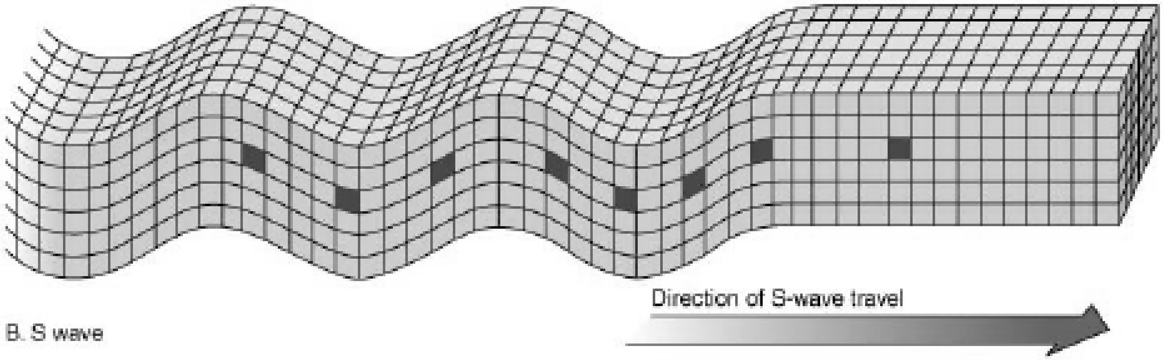
Can travel through solids/fluids/air

SEISMIC METHODS

Body waves

S-waves

- S for "secondary" or "shear" and "shake"
- Shearing and rotation
- No volume change as the wave propagates



B. S wave

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Cannot travel through fluids andair

SEISMIC METHODS

P and S-velocities

P-velocity

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

change of shape and volume

S-velocity

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

change of shape only

For liquids and gases $\mu = 0$, therefore

➔ $V_S = 0$ and V_P is reduced in liquids and gases

➔ Highly fractured or porous rocks have significantly reduced V_P

The bulk modulus, κ is always positive, therefore $V_S < V_P$ always

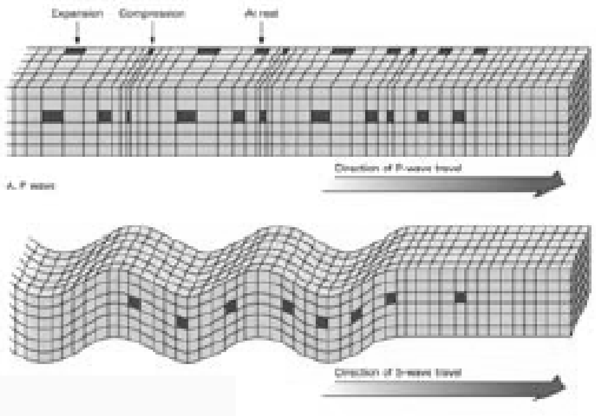
P-waves are the most important for controlled source seismology

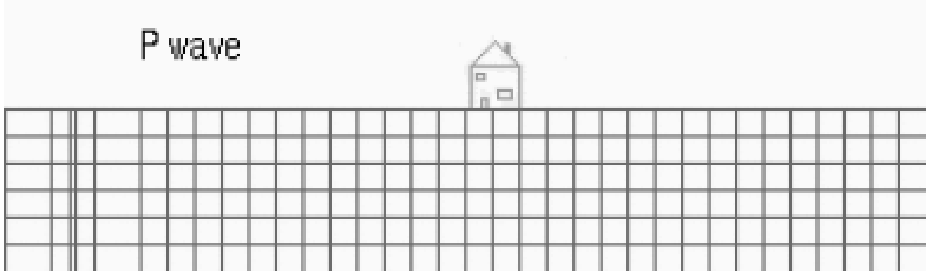
- They arrive first making them easier to observe
- It is difficult to create a shear source, explosions are compressional

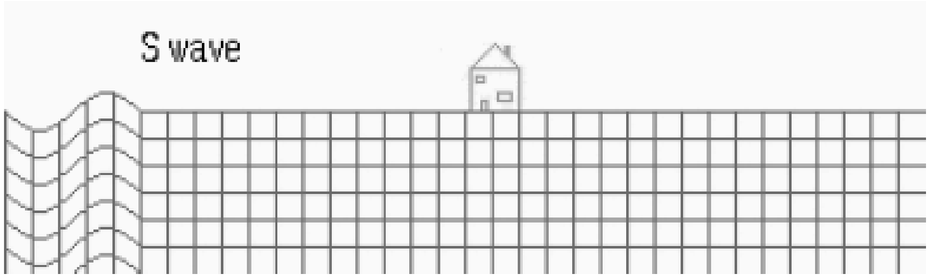
SEISMIC METHODS

Body waves

P and S-waves

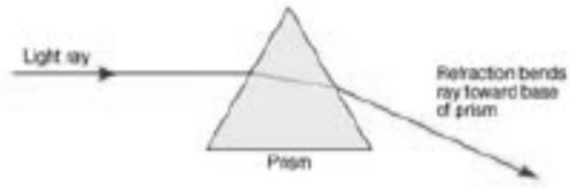


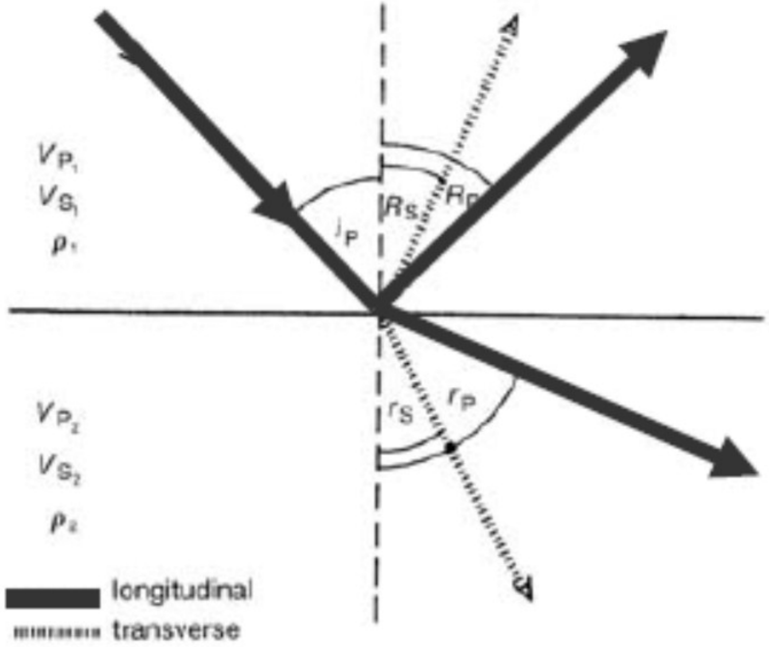




SEISMIC METHODS

Reflection and transmission





Seismic rays obey Snell's Law

(just like in optics)

The angle of incidence equals the angle of reflection, and the angle of transmission is related to the angle of incidence through the velocity ratio.

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin R_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}}$$

Amplitudes reflected and transmitted

The amplitude of the reflected, transmitted and converted phases can be calculated as a function of the incidence angle using **Zoeppritz's equations.**

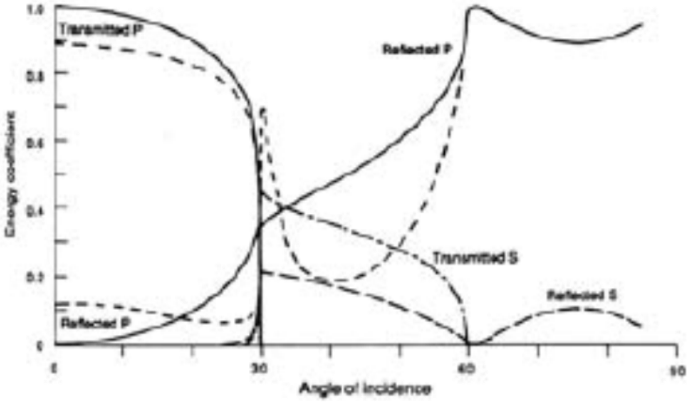
Simple case: **Normal incidence**

Reflection coefficient

$$R_C = \frac{A_R}{A_i} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

Transmission coefficient

$$T_C = \frac{A_T}{A_i} = 1 - R_C = \frac{2\rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$



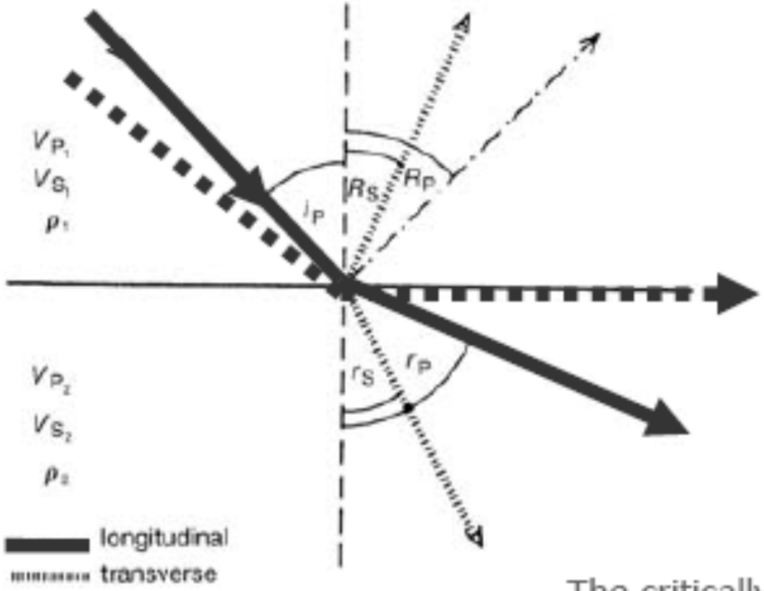
Reflection and transmission coefficients for a specific impedance contrast

These coefficients are determined by from the product of velocity and density – the **impedance** of the material.

R_C usually small – typically 1% of energy is reflected.

SEISMIC METHODS

Critical incidence



$$\frac{\sin i_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}}$$

when $V_2 > V_1$, $r_P > i_P$

therefore, we can increase i_P until $r_P = 90°$

When $r_P = 90°$ $i_P = i_C$ the critical angle

$$\sin i_C = \frac{V_{P1}}{V_{P2}}$$

The critically refracted energy travels along the velocity interface at V_2 continually refracting energy back into the upper medium at an angle i_C

➔ a head wave

BASIS for refraction seismic used to detect boundaries of velocity contrasts

ACTIVE SEISMIC METHODS

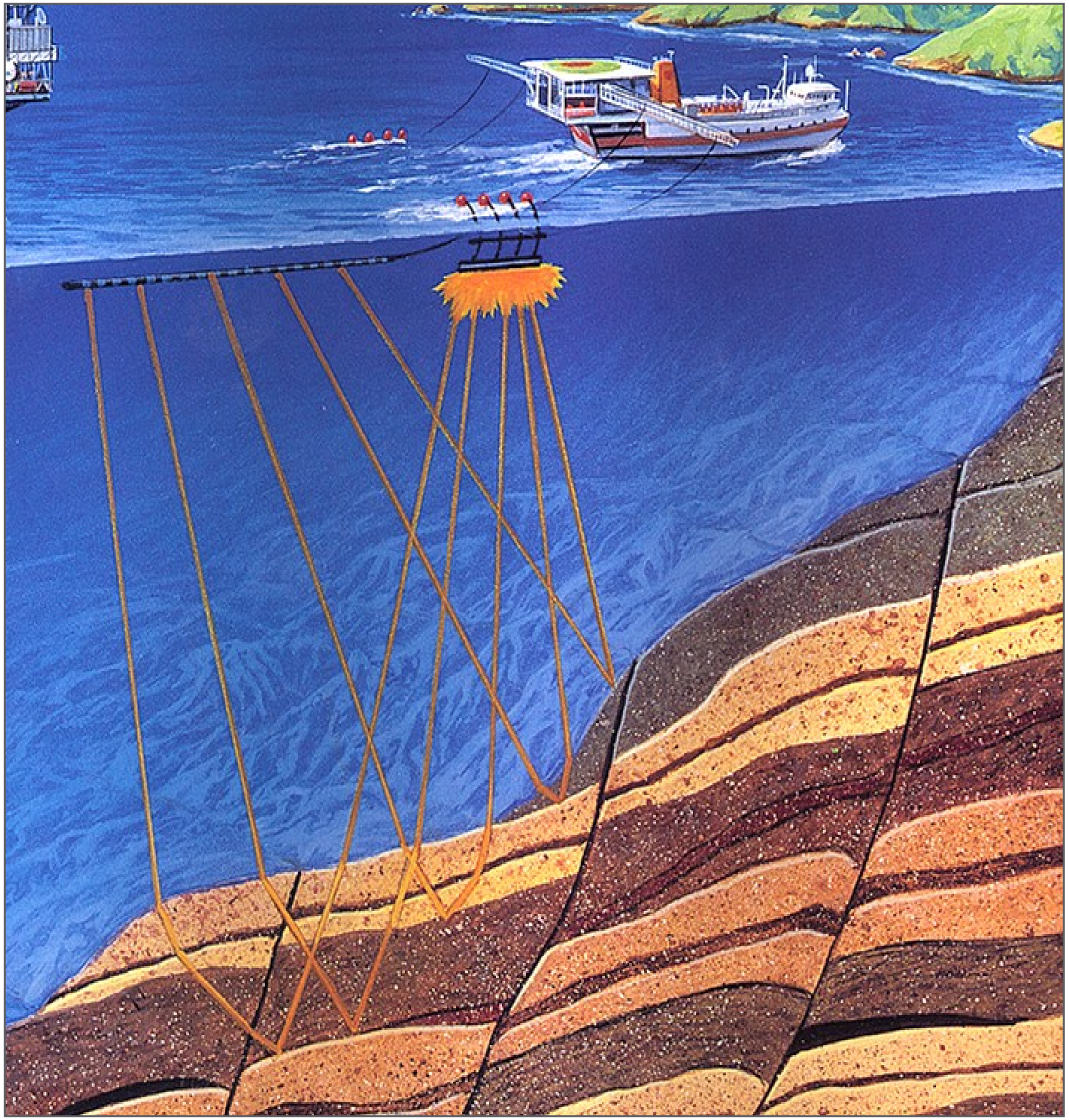
Seismic refraction surveys have been used to a limited extent because of the amount of effort required to obtain refraction profiles giving information at depths of 5 to 10 km, and the problems caused by the generally high degree of complexity of geological structures in areas likely to host geothermal systems.

Seismic refraction is normally restricted to cases where the densities of the rocks and thus seismic **velocities increase** with depth. In addition, geophone arrays for refraction measurements need a **length of at least 4-** to 5 times (sometimes even 8 times) the sampling depth because of the very nature of refraction. The length requires higher shot energy (i.e., more explosives) and limits the applicability of refraction methods in exploration to shallower targets or to large-scale investigations of Earth’s crust and upper mantle. Sometimes it can be used to get a first approximation about the velocity distribution at depth.

ACTIVE SEISMIC METHODS

Reflection seismic methods are more commonly used in geophysical exploration, as they require much shorter profiles and therefore less shot energy and have a much higher lateral resolution.

However, **reflection signals are much more complex** to detect and to analyse than refraction signals as they never arrive first, which implies time and labour intensive filtering and detection from a multitude of overlapping data. Moreover, the specific setup for reflection measurements requires more logistic preparation and personnel, which makes it generally a lot more expensive than refraction methods. **It is the method of choice in hydrocarbon exploration, as it can resolve structural details of a reservoir.**

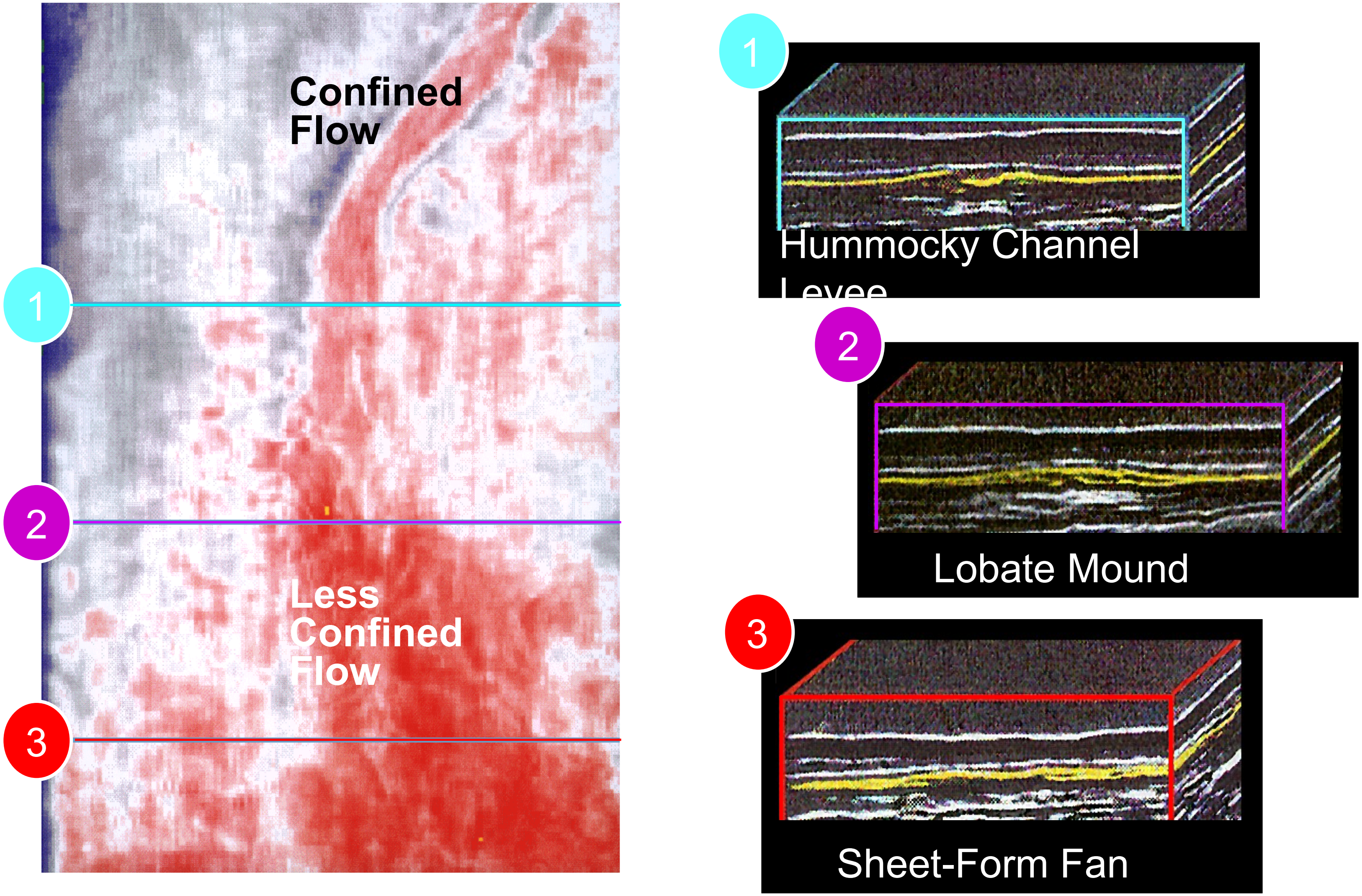


Seismic Imaging

3D Marine Data Acquisition

Silicon
Graphics

New Tools → Better Data → Improved Understanding

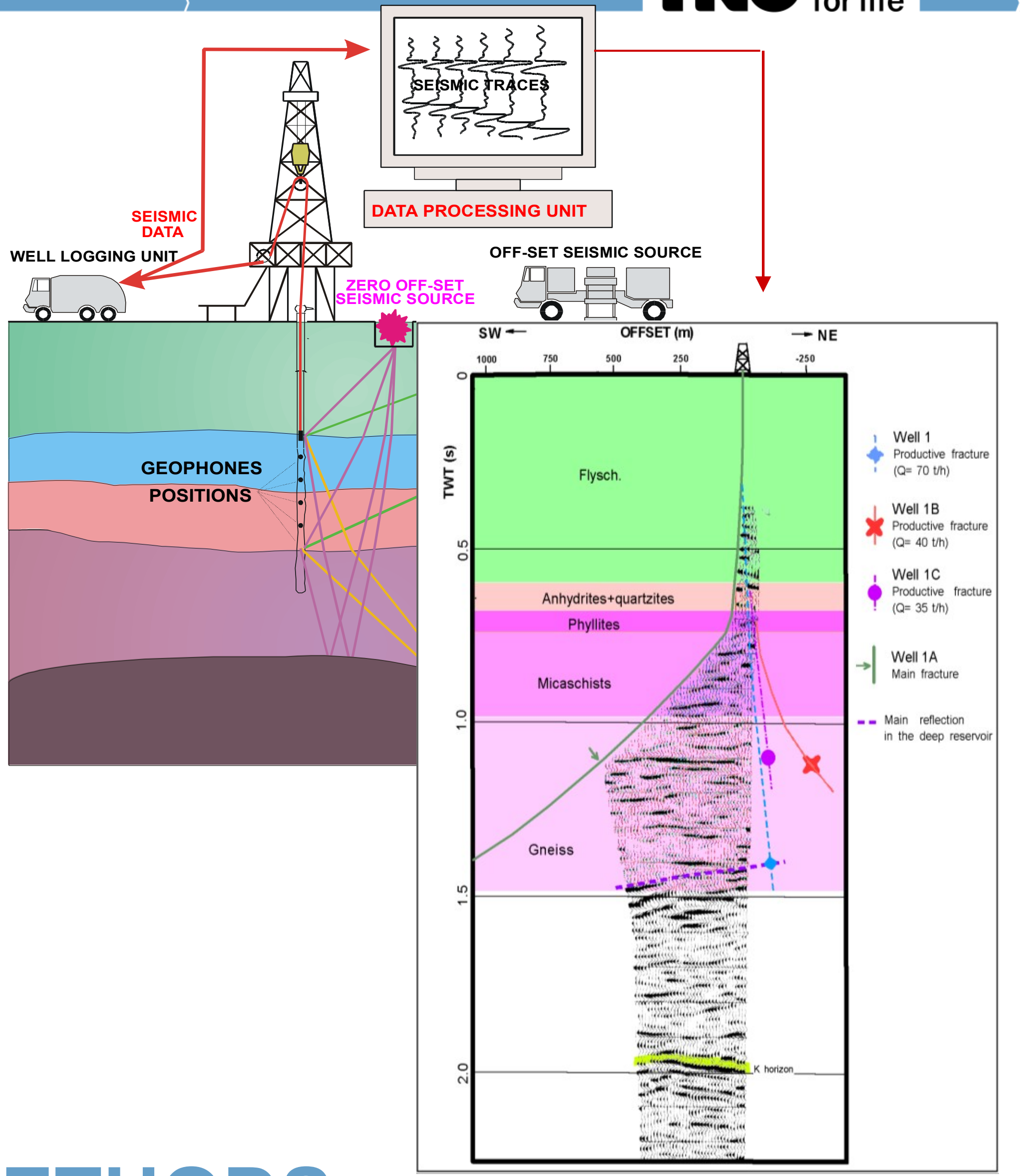


3D Seismic Image - Submarine Fan

Armentrout *et al.*, 1996

ACTIVE SEISMIC METHODS

Seismic signals generated and detected at the service are commonly restricted to horizontal or gently dipping reflectors. To detect and image vertical structures, vertical seismic profiling (VSP) was developed, which takes advantage of an existing well. VSP not only allow resolution of vertical reflectors such as faults but also provides highly reliable calibration tool for surface seismic and is useful in projects involving seismic anisotropy.



ACTIVE SEISMIC METHODS

Despite their clear advantages, especially resolution with depth, active seismic methods are not very common in geothermal exploration. One of the reasons why there are not widely used is that their cost often makes them difficult to fund for tight-budgeted geothermal projects especially where the geological complexity requires 3D arrays.

In volcanic environment they are seldom used due to the too high noise and strong attenuation.

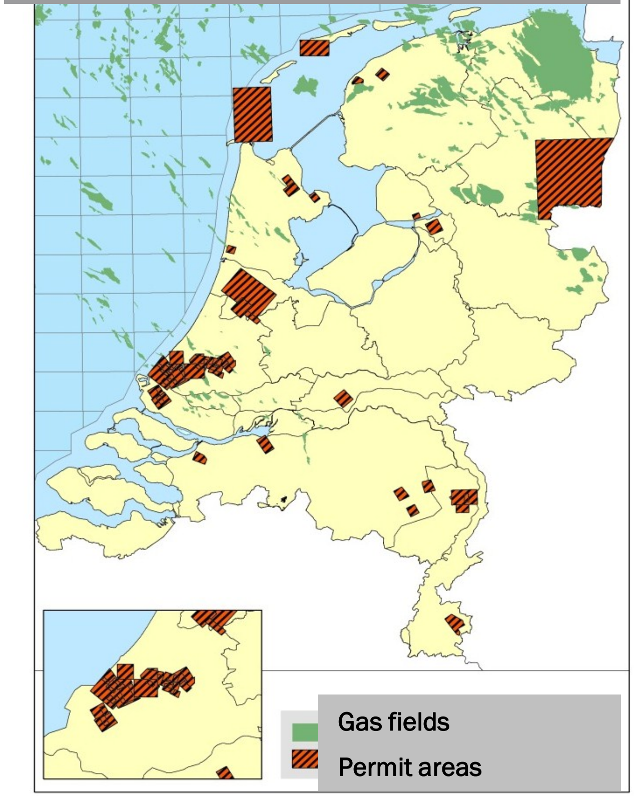
Reasons to develop ThermoGIS

<u>Interest is booming</u>

Currently over 100 permits granted

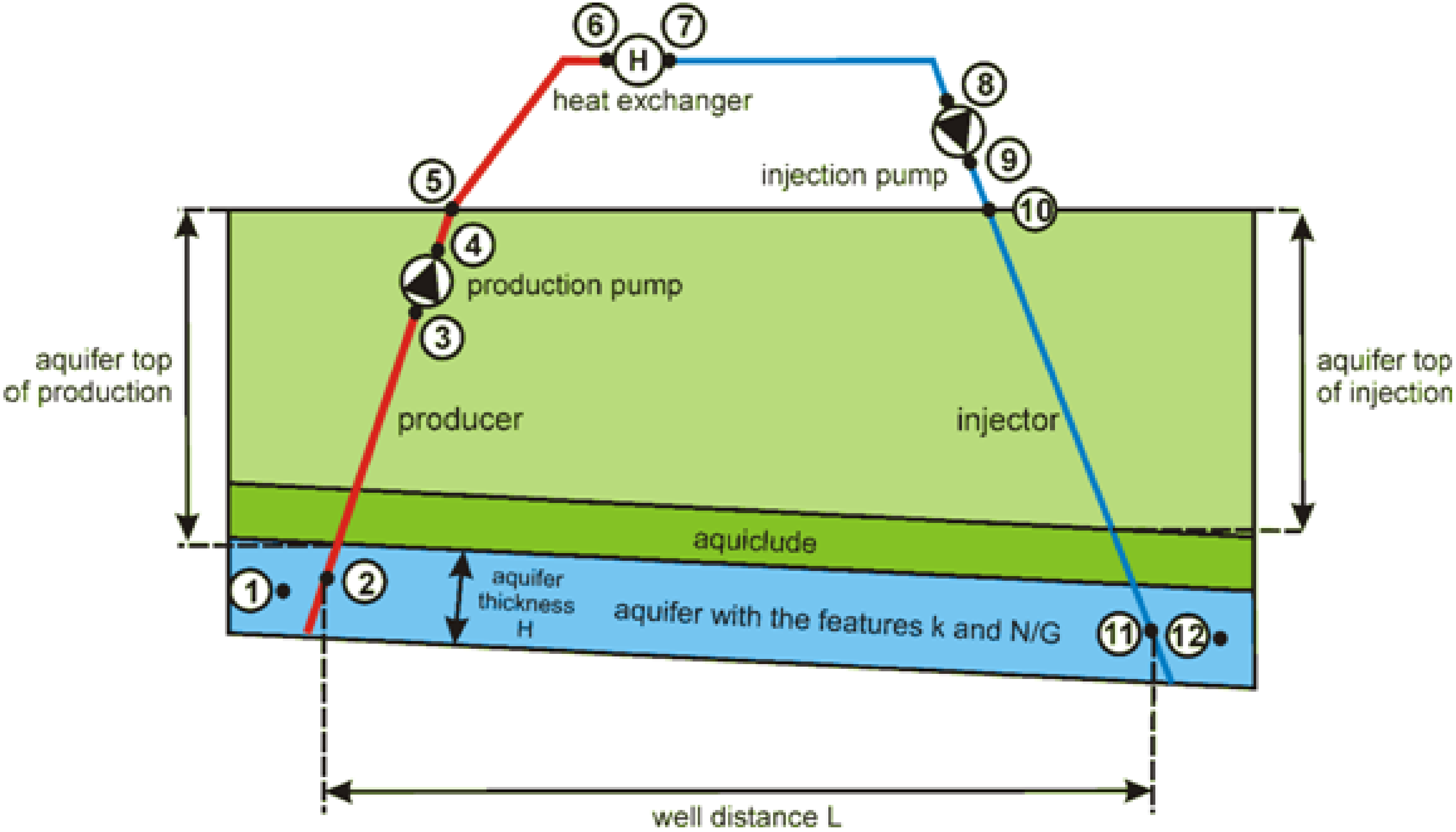
- Geological properties and uncertainties
- Independent analysis and information
- Overview potential areas and ‘hot spots’
- Performance assessment
- Quickscan
- Realization of market opportunities

Permits geothermal energy 2010



Pre-feasibility analysis for heat production

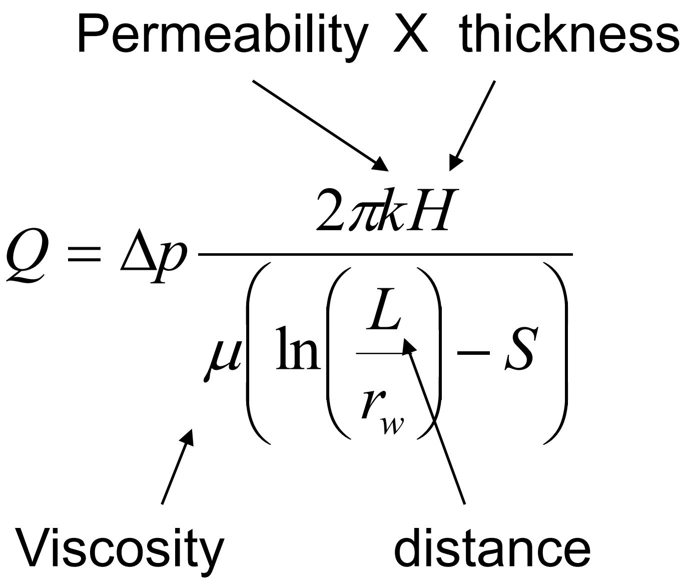
Schematic Doublet



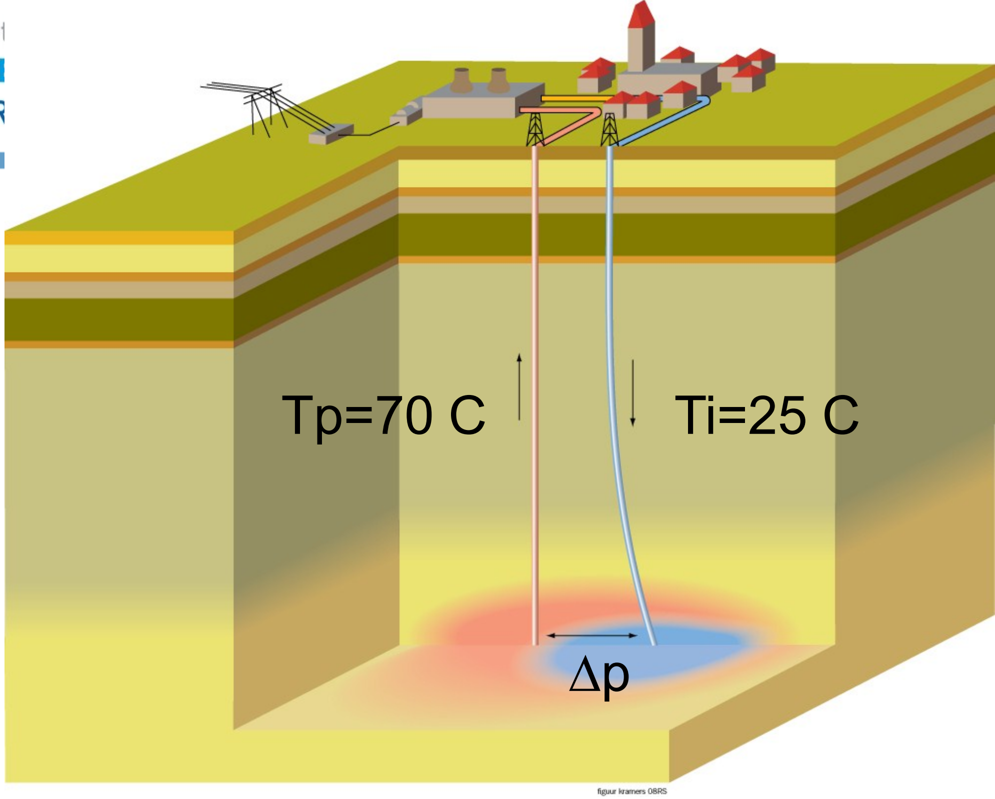
Doublet performance

E [MWth] = Q*ΔT * C_P

Flow-rate Q



$$Q = \Delta p \frac{2\pi k H}{\mu\left(\ln\left(\frac{L}{r_w}\right) - S\right)}$$



figuur kramers OBRS

Δp generated by pumps
Which consume electricity

Δp is restricted by safety measures

Δp at surface does not linearly lead to Higher flow rates (friction in tubes)

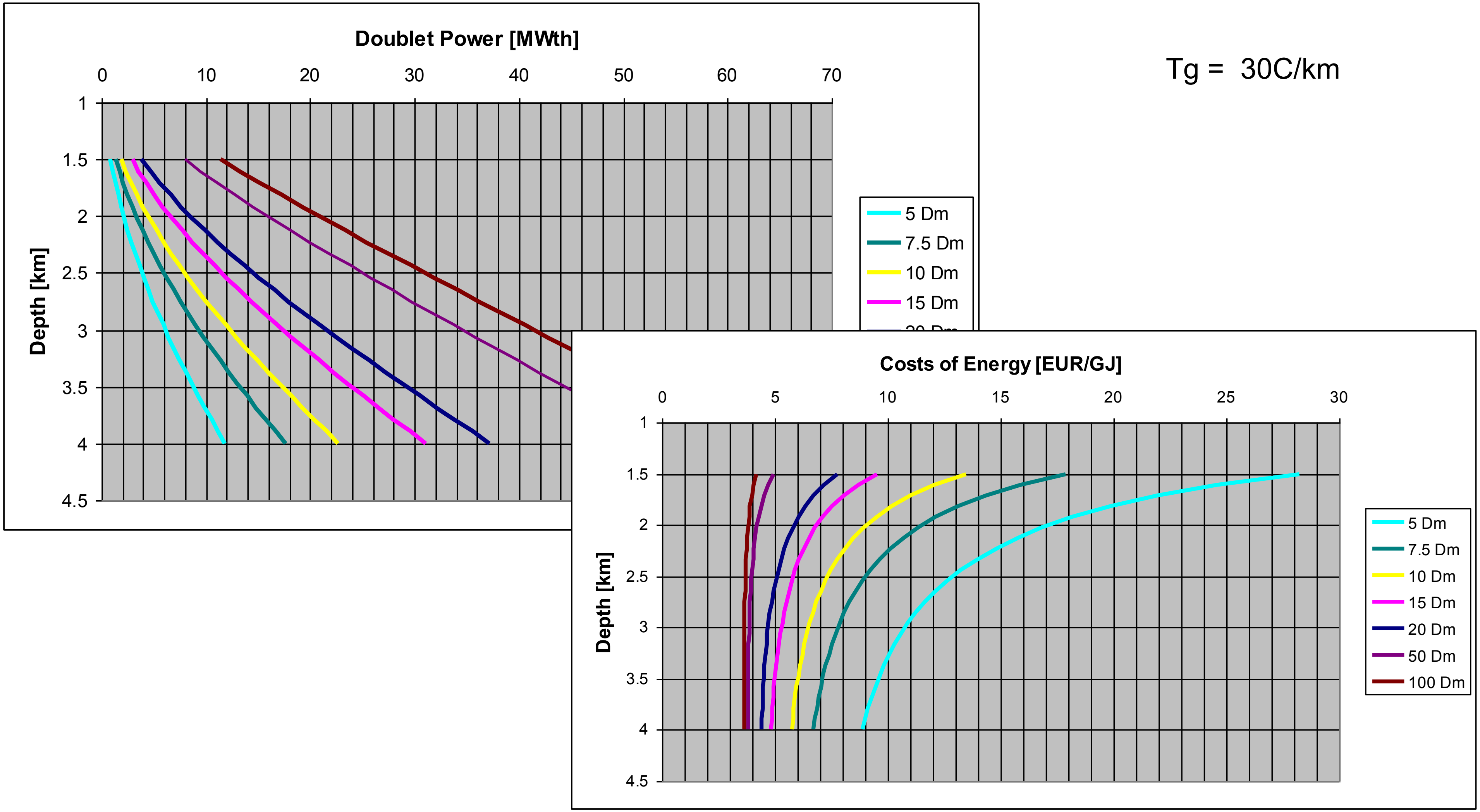
Potential estimates – for specific application areas

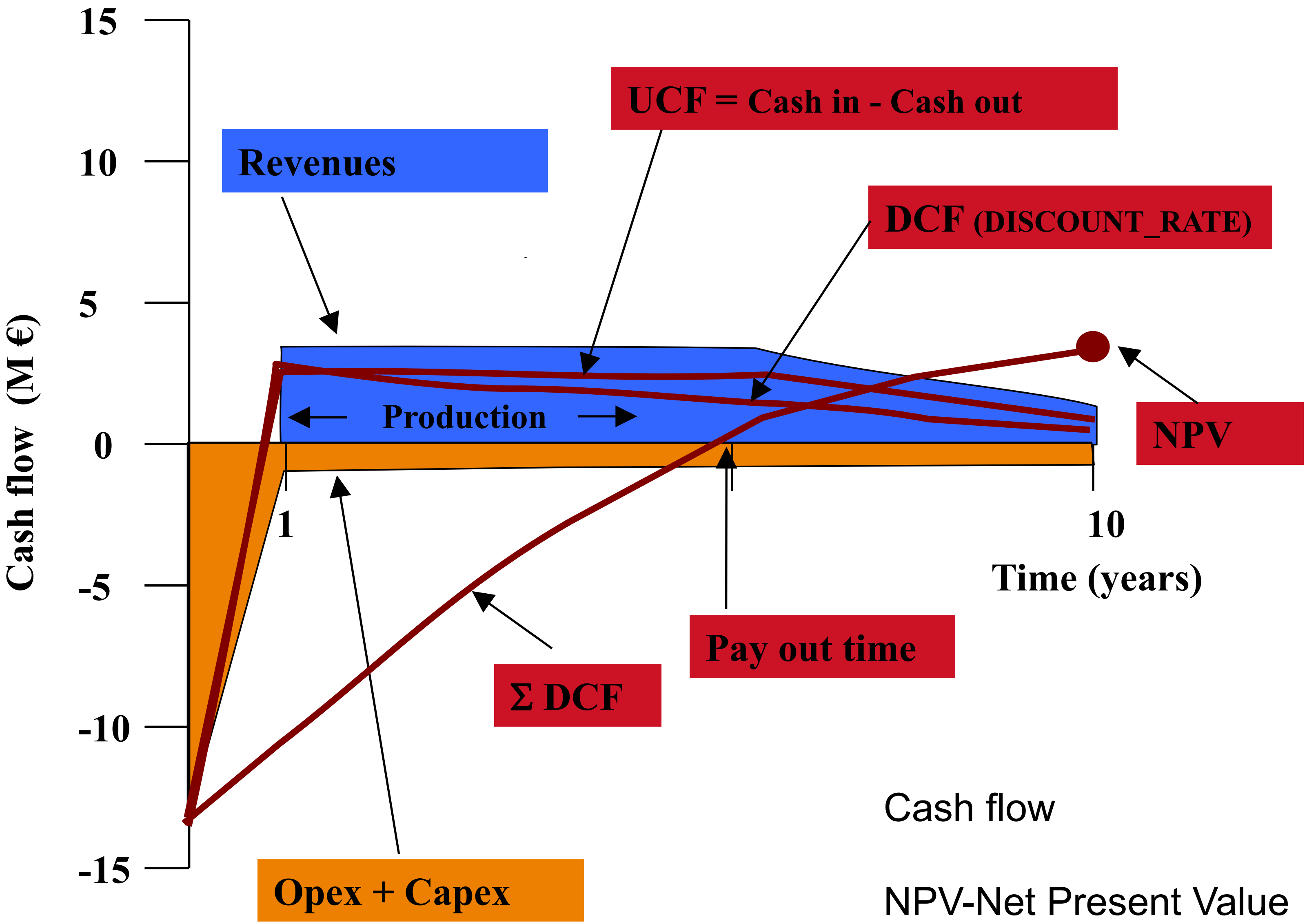
Geothermal direct heat Application	Min. Production Temperature	Min. production depth@ 30 °C/km	Re-injection temperature	Load factor	Heat demand/yr
Greenhouse 	45°C	1200m	25°C	60%	$12x10^{3}$GJ/ha
Spatial 	65°C	1900m	40°C	60%	25GJ/house

Sensitivity to transmissivity (kH)

Tgreenhouse = 45
Treturn = 25

Tg = 30C/km





Cash flow

NPV-Net Present Value

Levelized Cost of Energy

- Discounted energy produced [MWh, GJ]
- Discounted cash out [EUR]

- LCOE = discouted cash-out / discounted energy produced

ThermoGIS - project

Comprehends:

3D mapping reservoirs (aquifers)

- Depth, thickness and temperature → **Temperature**
- (Thickness) porosity, permeability → **Transmissivity**
- Uncertainties
- Potential energy

Bonte et al.,2012

Pluymaekers et al.,2012

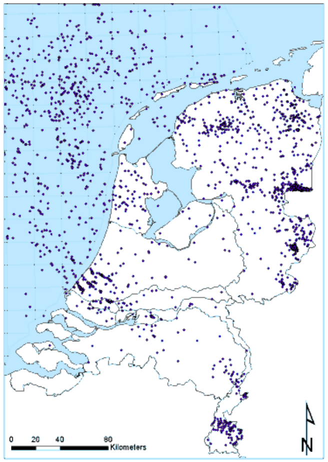
Development ThermoGIS application

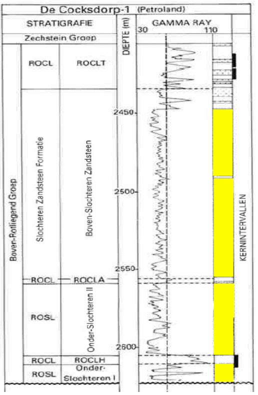
- Visualisation map
- Performance assessment tool
- Economic assessment tool

Kramers et al.,2012

Van Wees et al.,2012

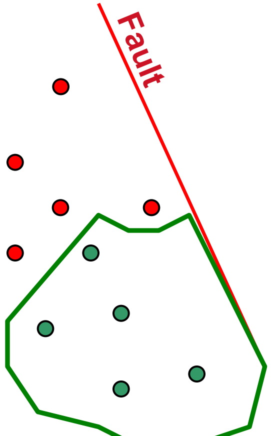
Aquifer depth and thickness mapping



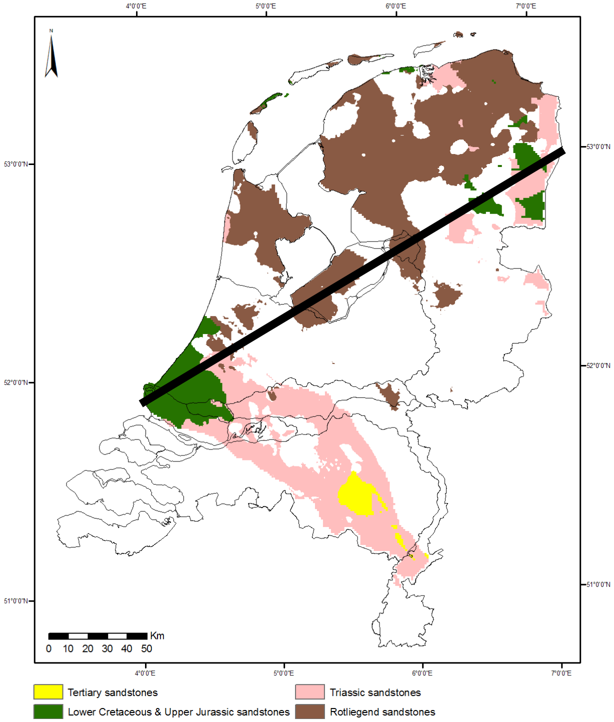


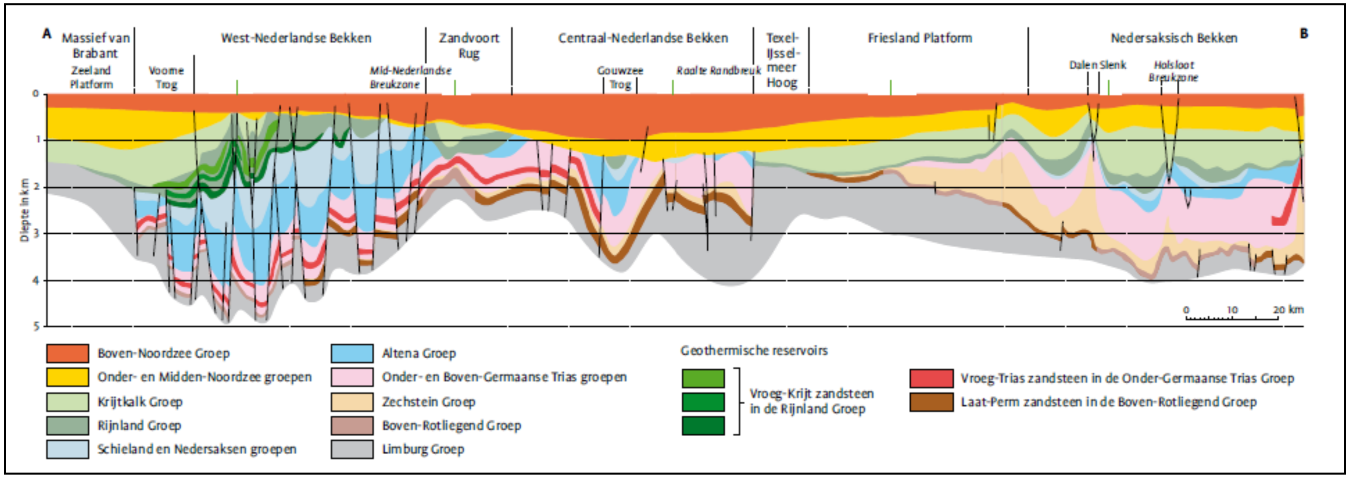
Member

Aquifer Selection



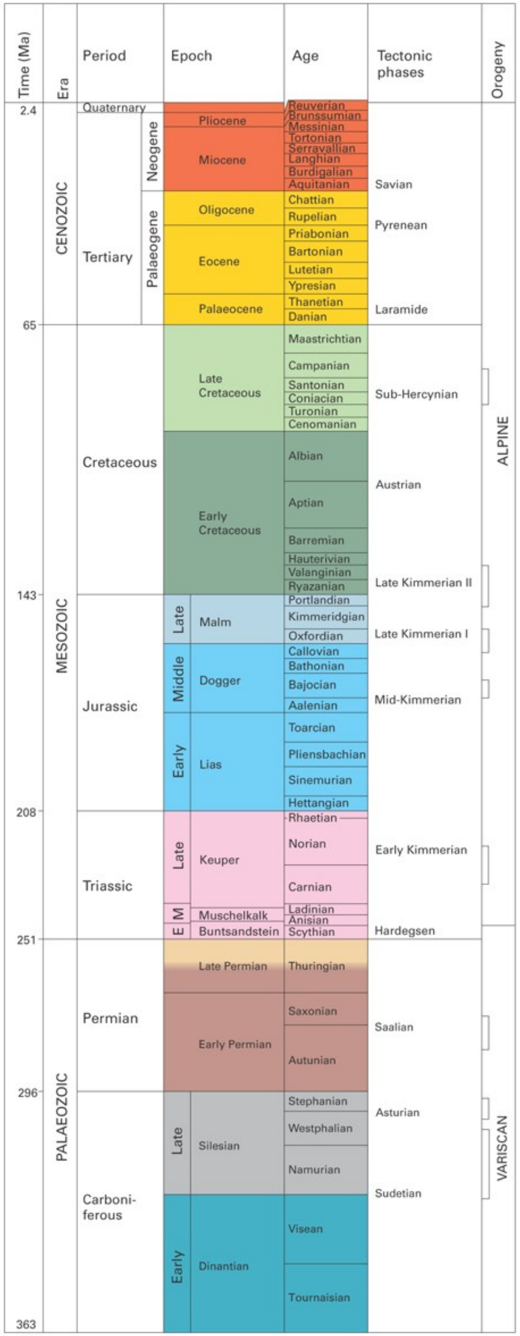
Aquifer distribution





3D modelling

Potential reservoirs



4x Lower Cretaceous

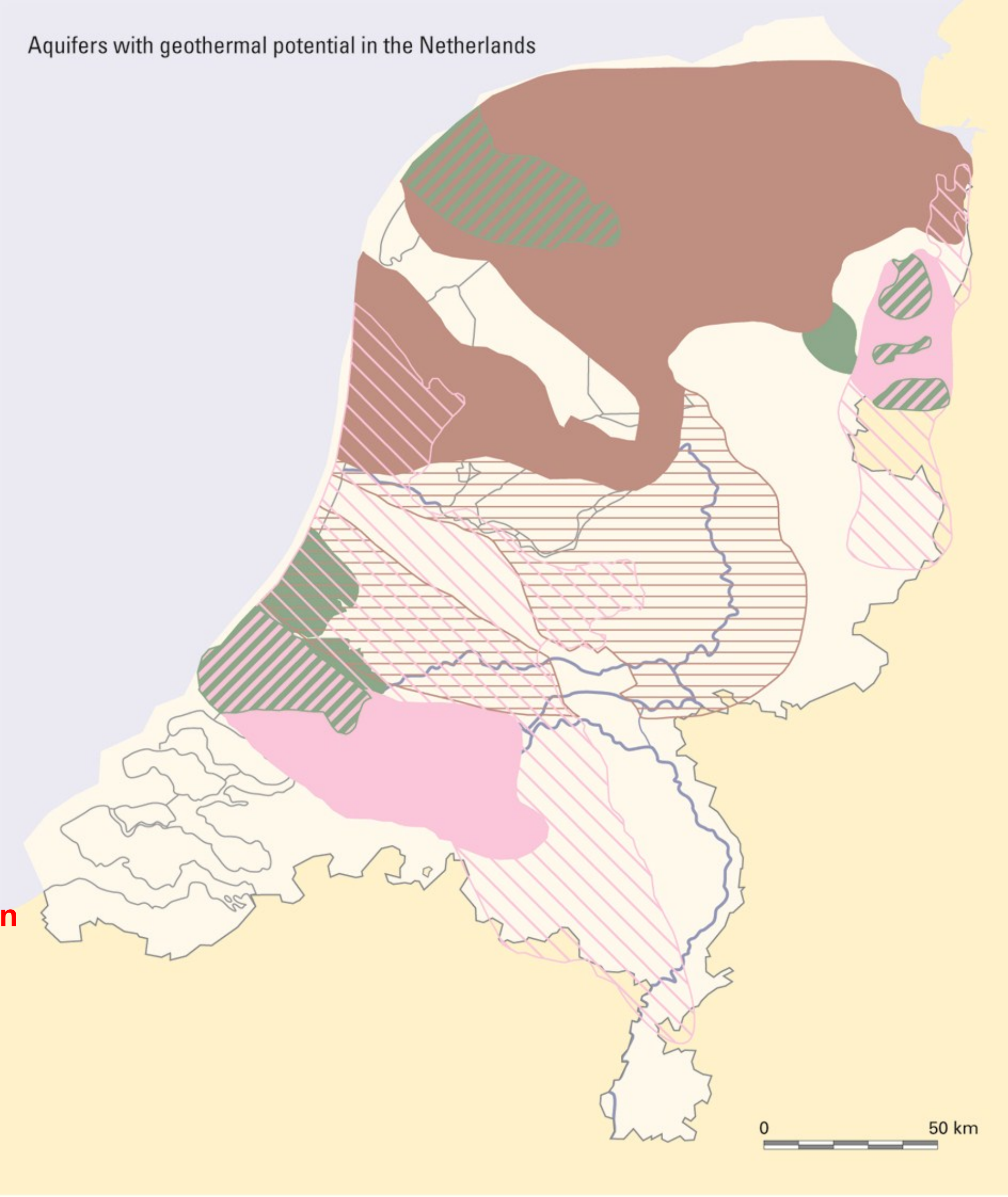
(Werkendam Fm.)

Röt Fm.

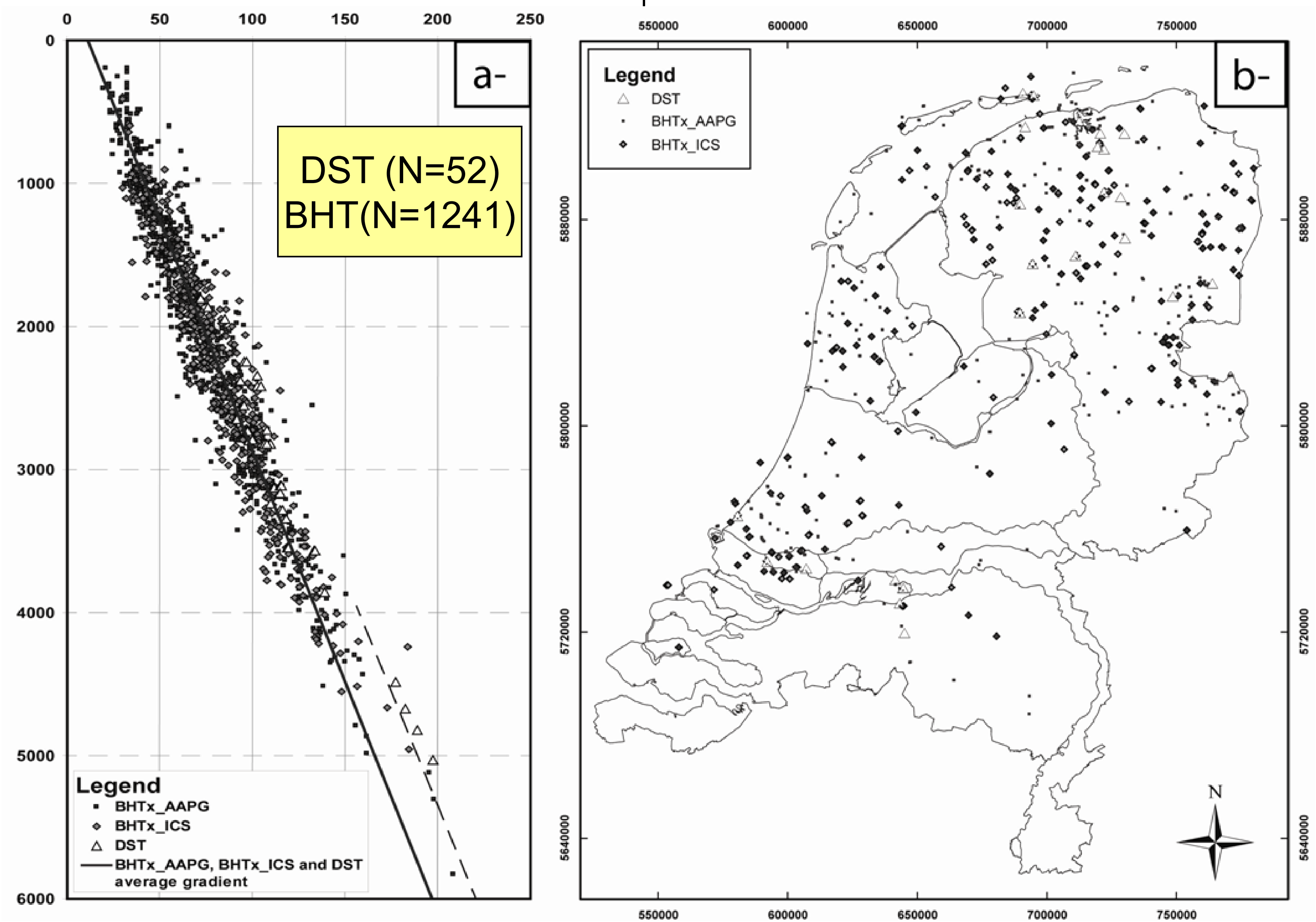
2xDetfurth and 2xVolpriehausen

3x Slochteren

(Limburg Group)

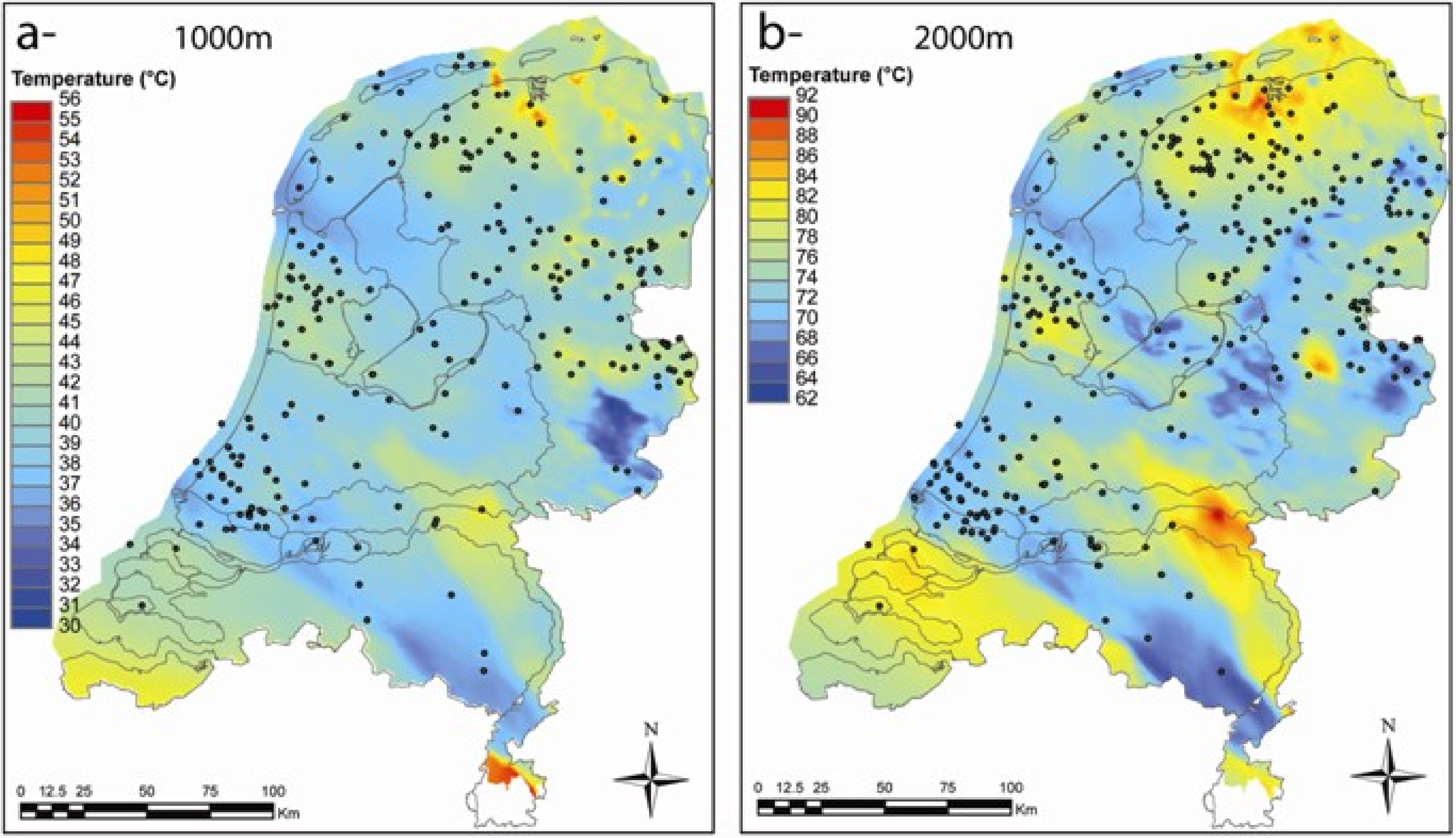

Aquifers with geothermal potential in the Netherlands

🟫 Rotliegend sandstones	▤ Rotliegend sandstones, potential uncertain
🟪 Triassic sandstones	▨ Triassic sandstones, potential uncertain
🟩 Lower Cretaceous sandstones	

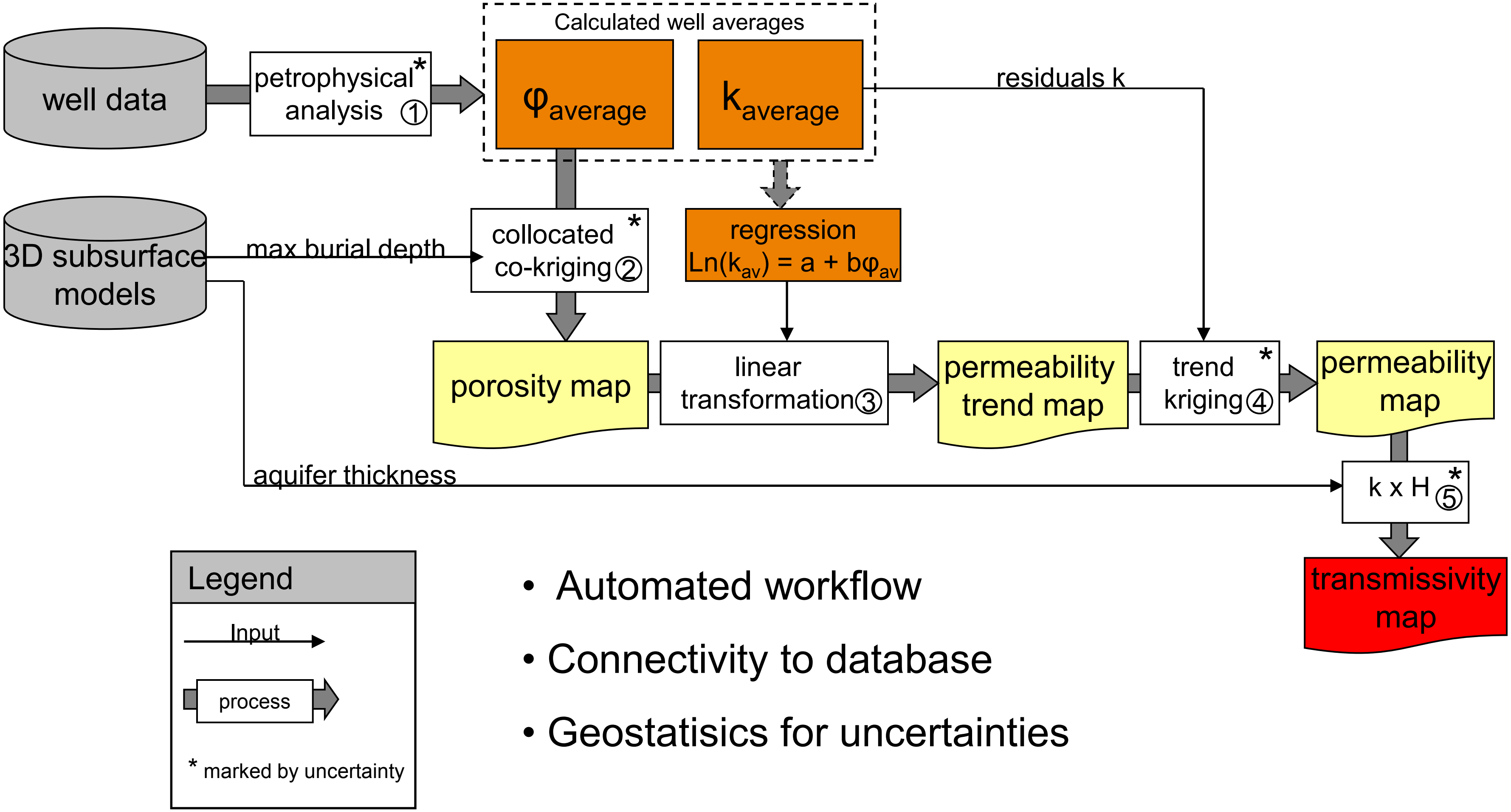


DST (N=52)
BHT(N=1241)

Results - temperature (1)



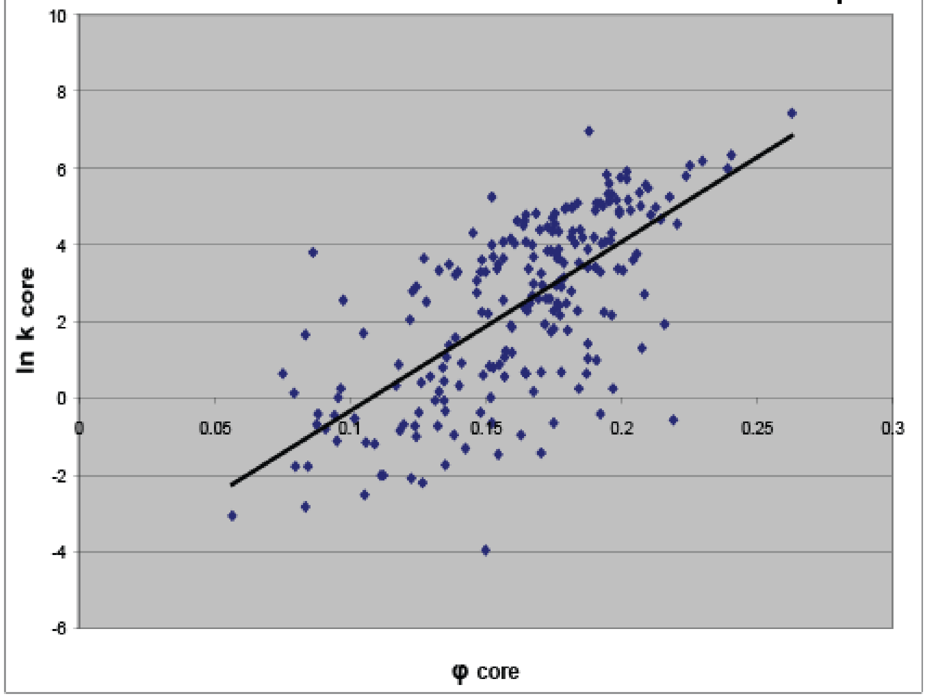
Property mapping



- Automated workflow
- Connectivity to database
- Geostatisics for uncertainties

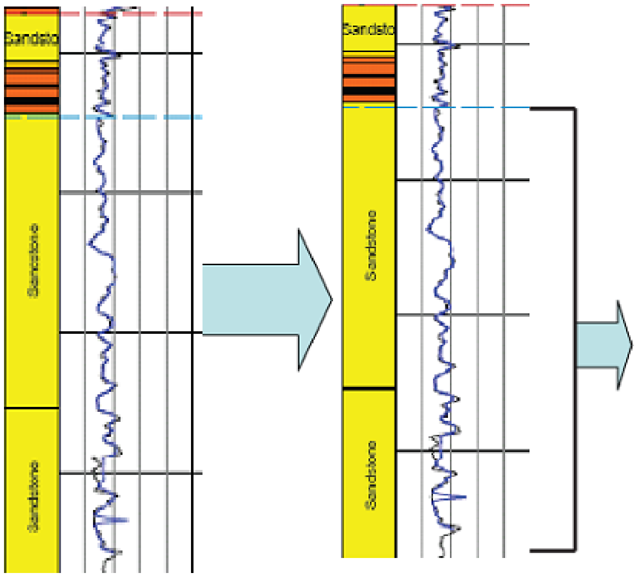
STEP 1: Porosity → Permeability in wells

Over 150,000 core-plug data for each well Linear relationship



Porosity log

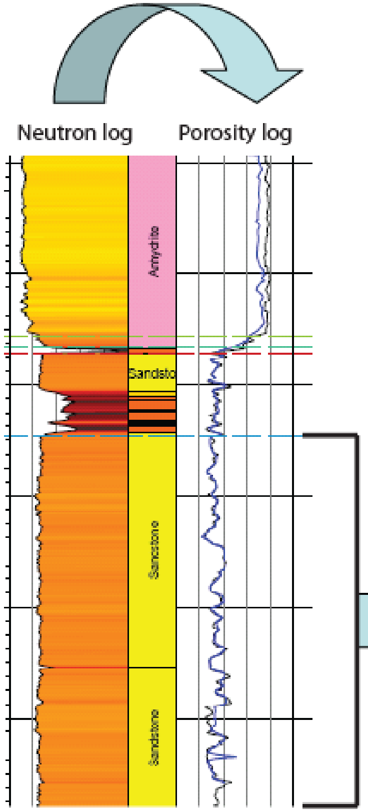
Permeability log



Average reservoir Permeability (ln K)

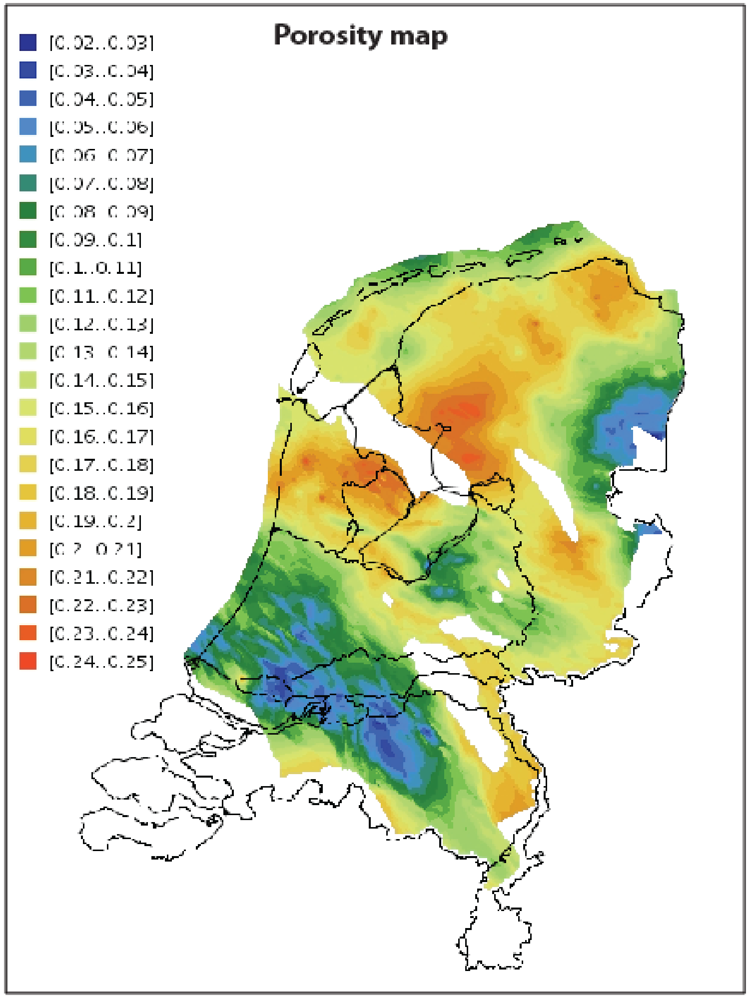
STEP 2 – From well porosity to porosity maps

Porosity computation
via neutron/density log



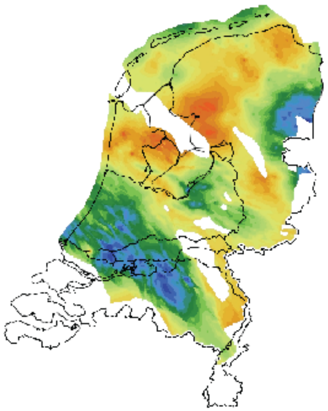
Average Porosity (Φ)

Co-Kriging with depth

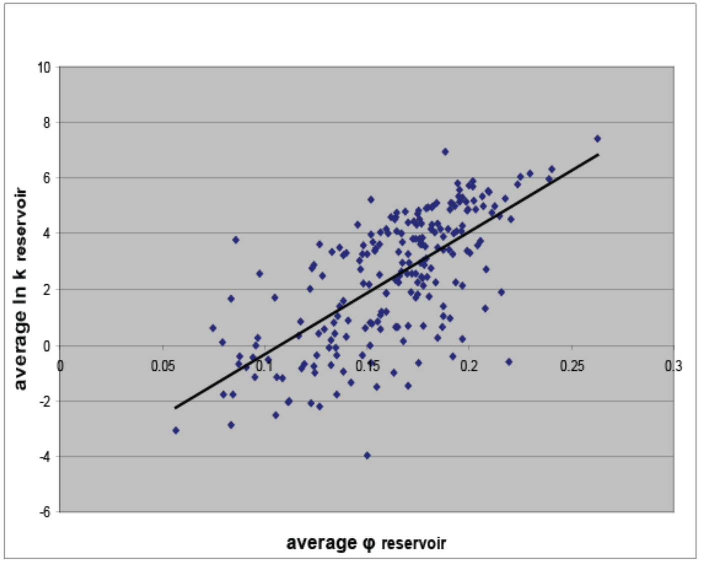


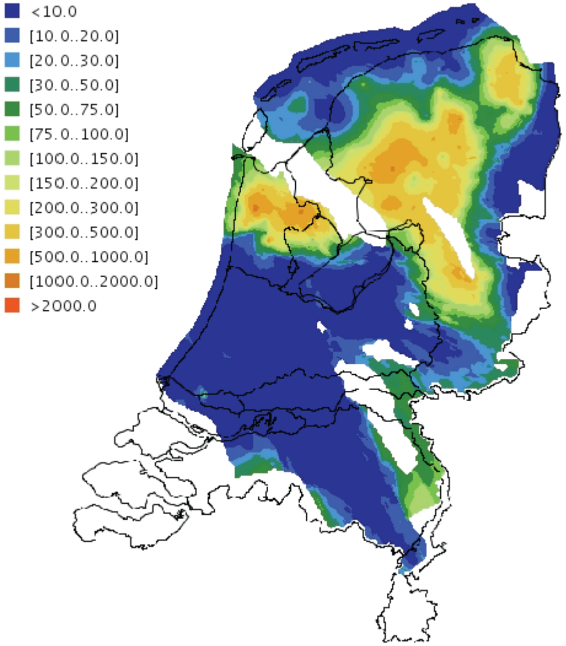
Average porosity – average permeability

Step 3



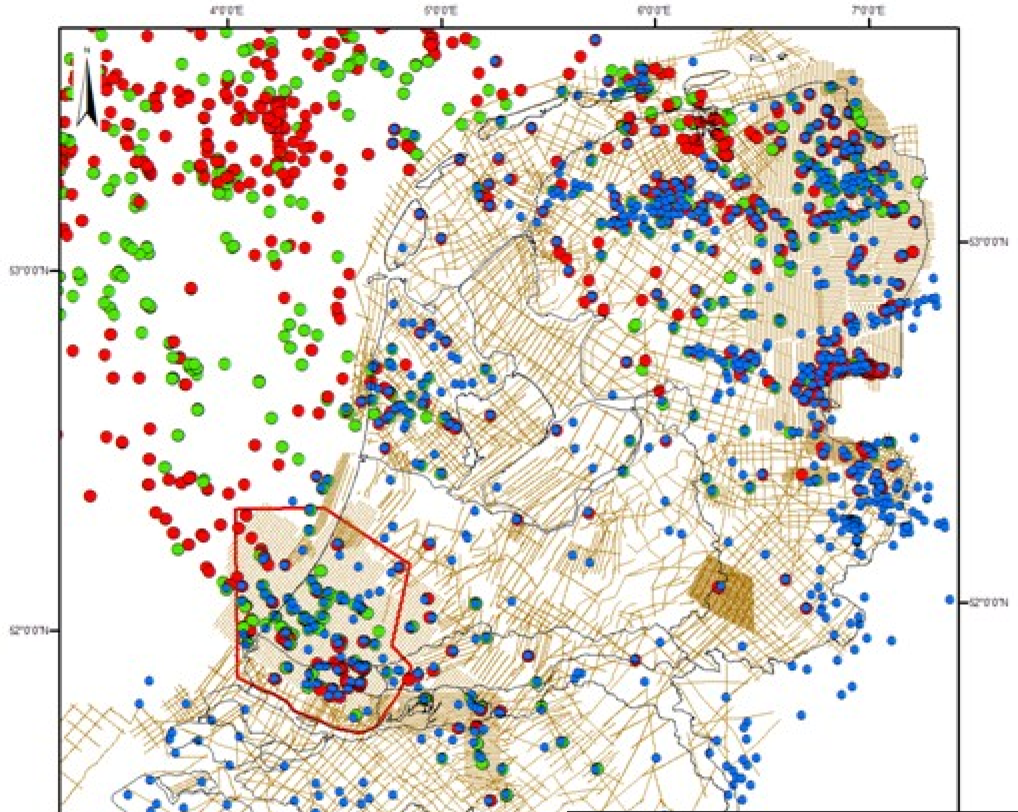
Porosity map

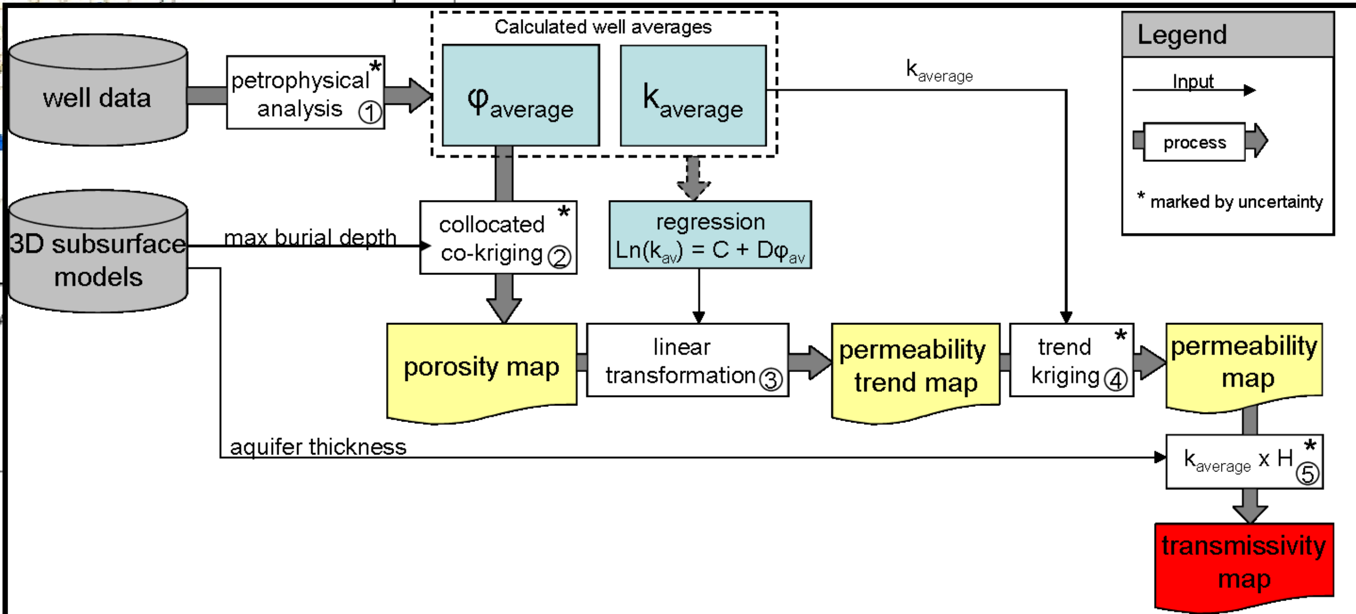




Permeability map [mD]

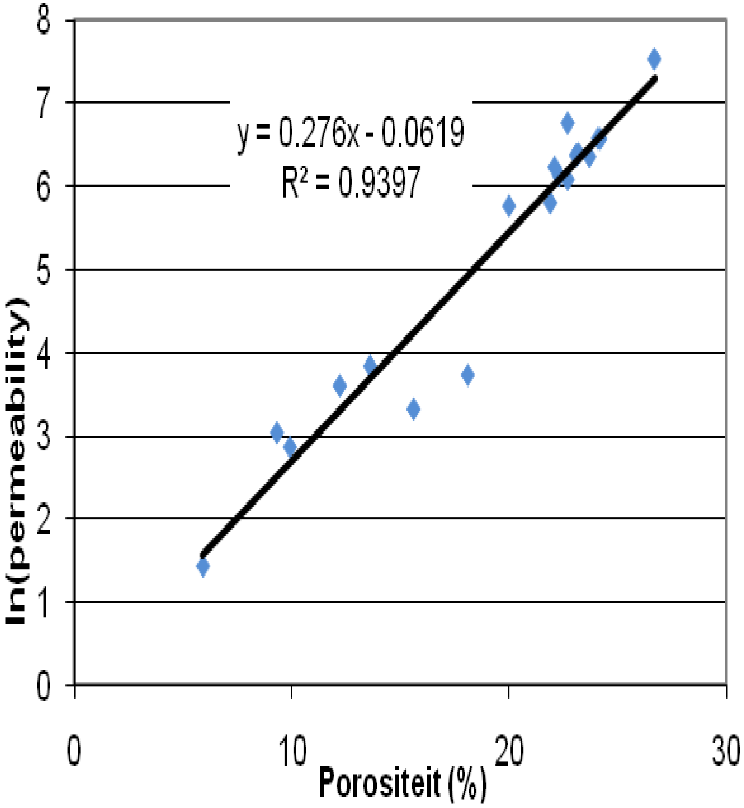
Porosity permeability and thickness control

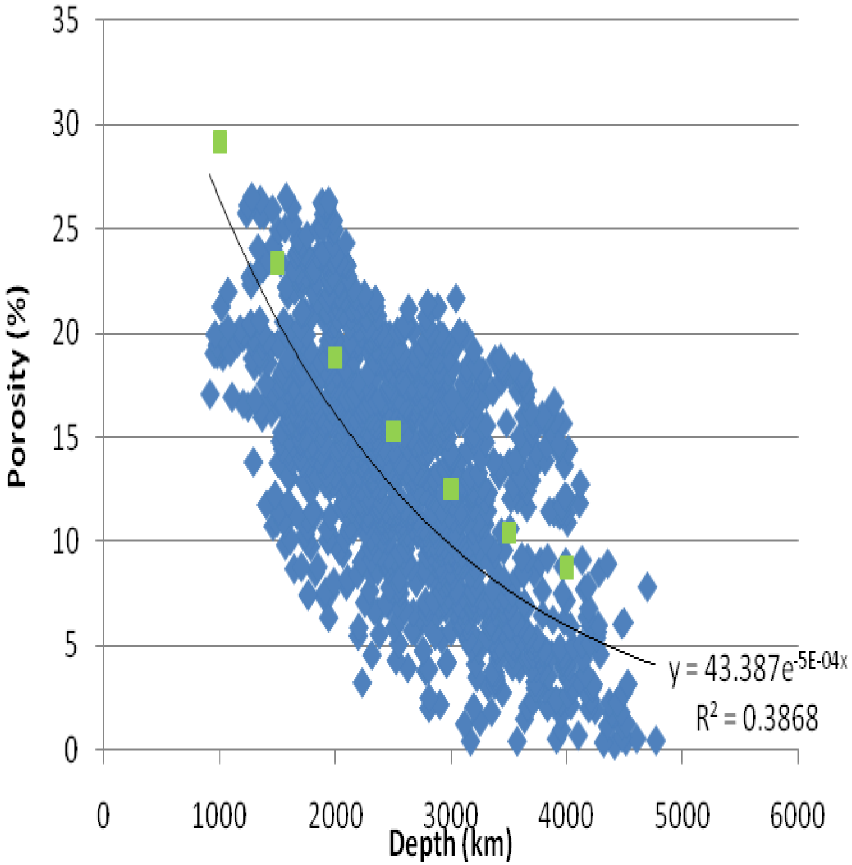




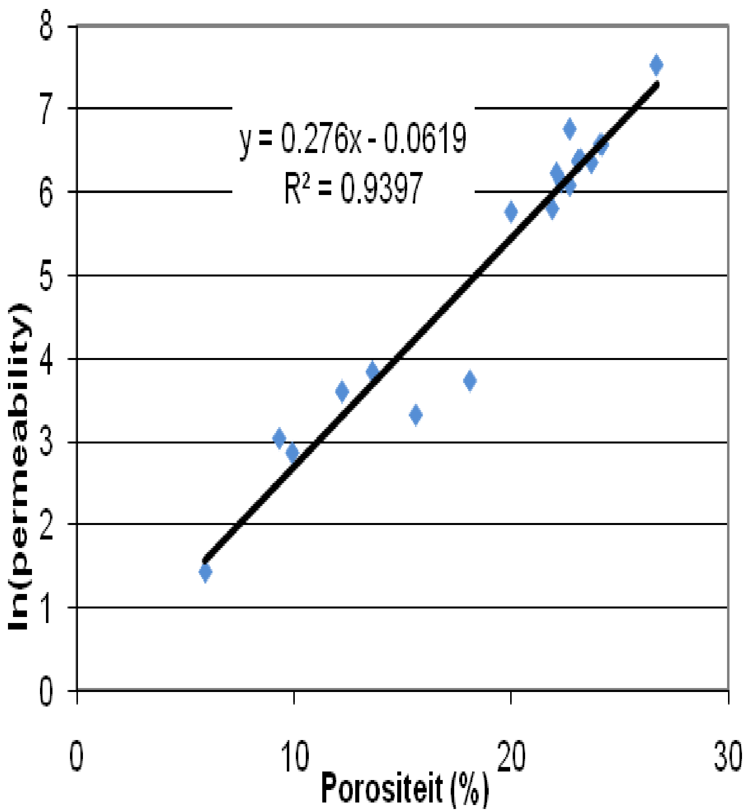
Permeability is determined using poro-perm relationship

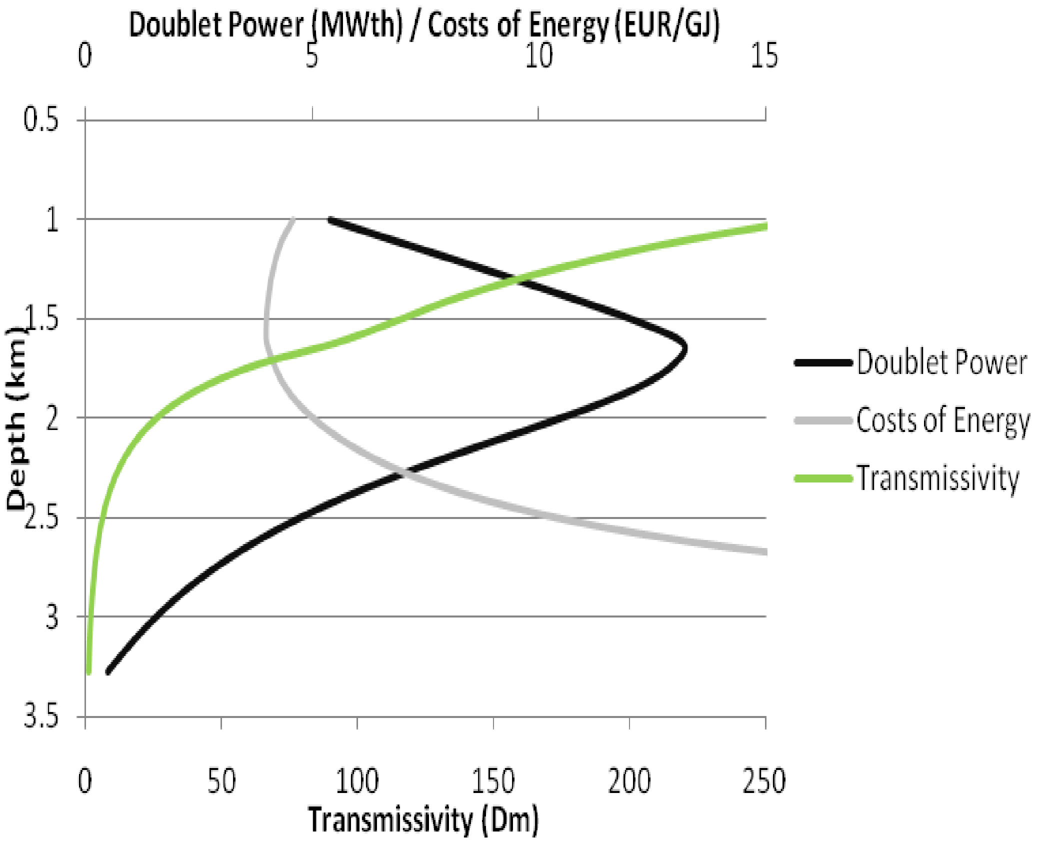
Porosity generally decreases with depth….



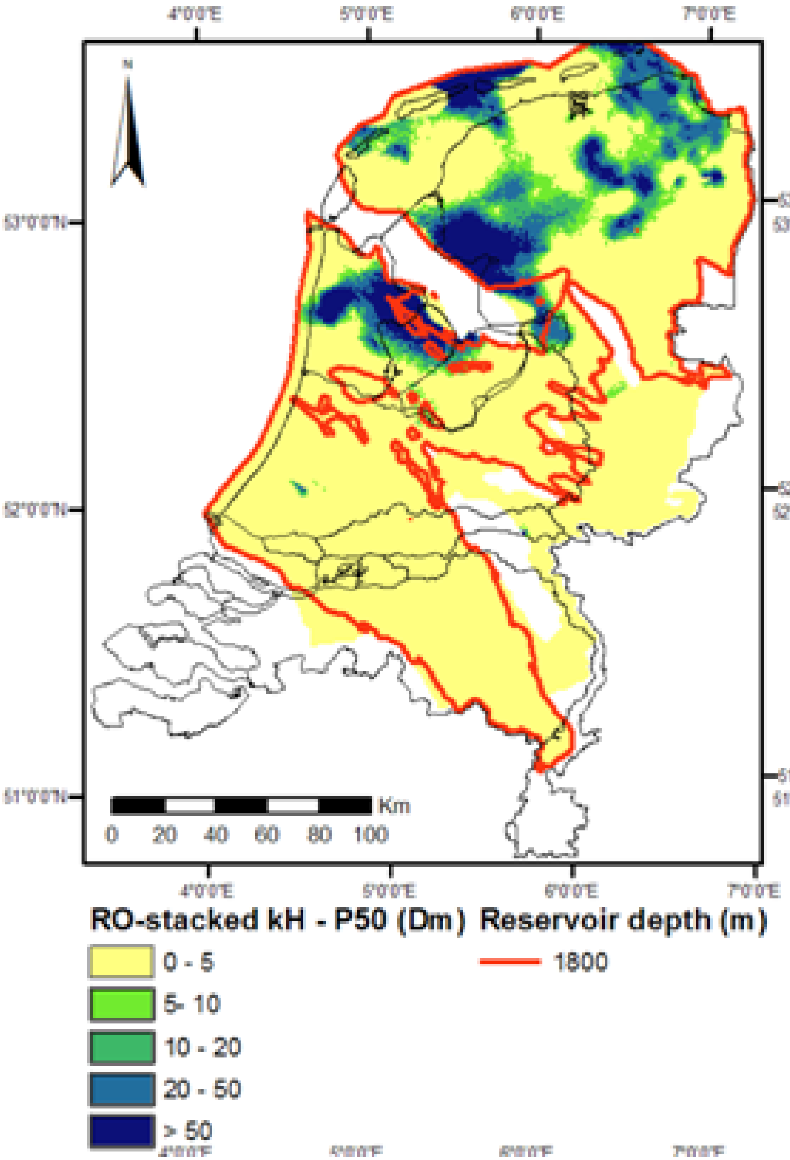


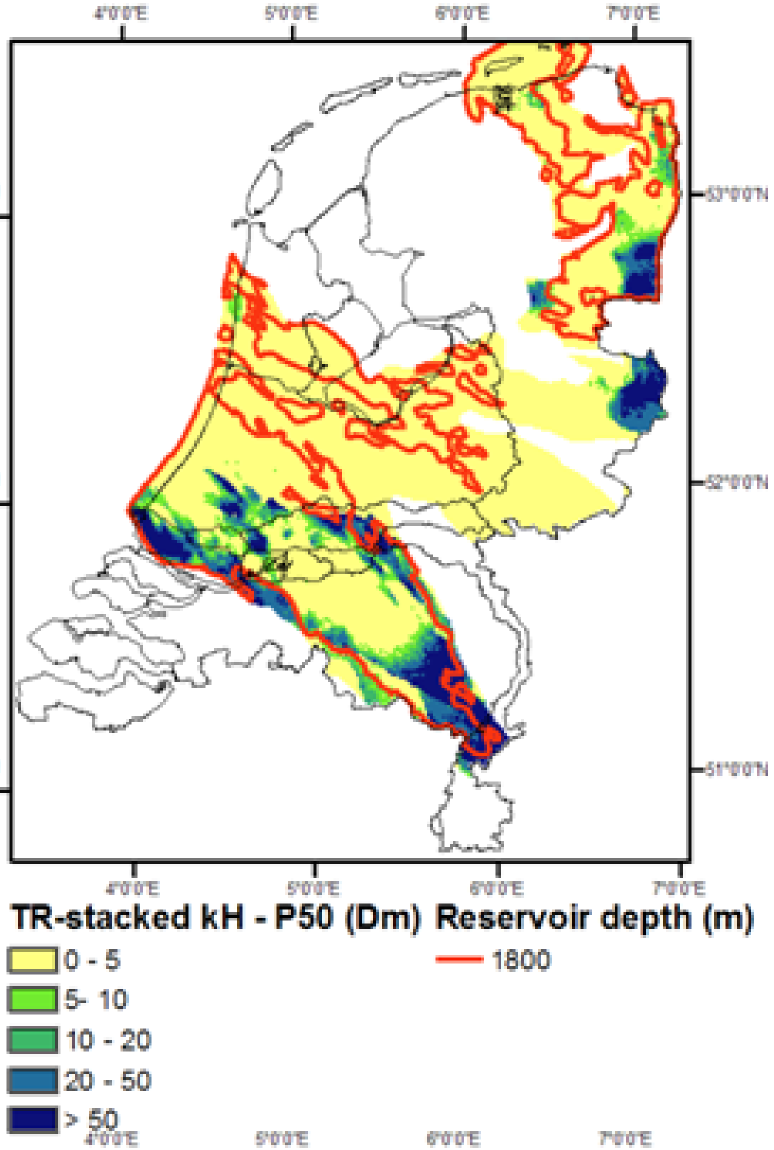
Performance is predicted to decrease with depth as a function of porosity



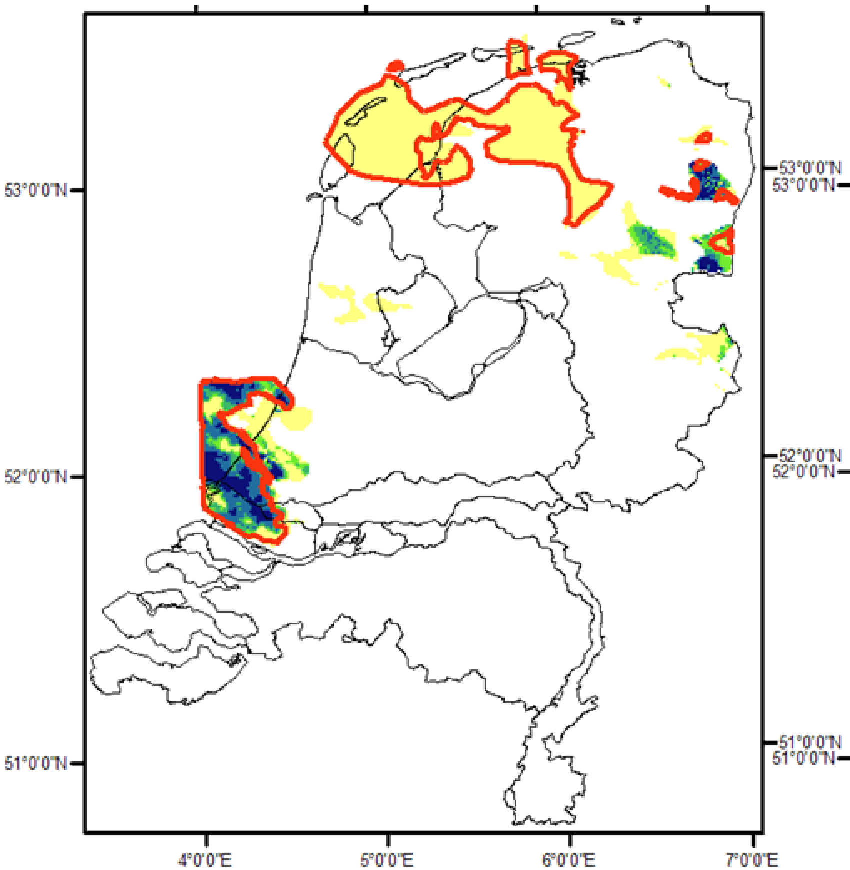


Property mapping and uncertainties





Property mapping and uncertainties (2)

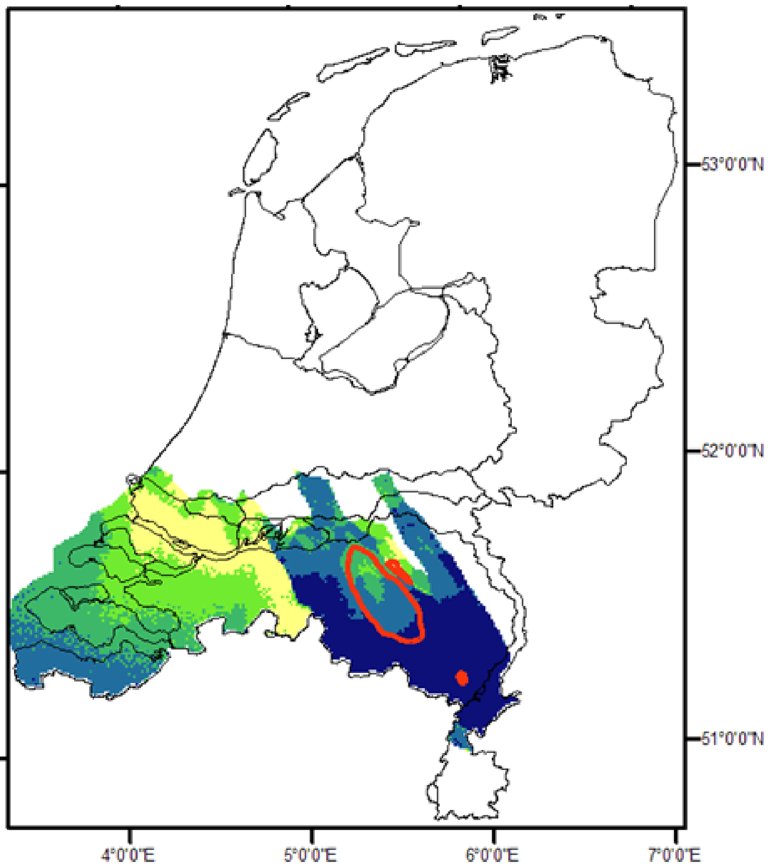


JK-stacked P50 (Dm)

- 🟨 0 - 5
- 🟩 5- 10
- 🟩 10 - 20
- 🟦 20 - 50
- 🟦 > 50

Reservoir depth (m)

- 🟥 1800



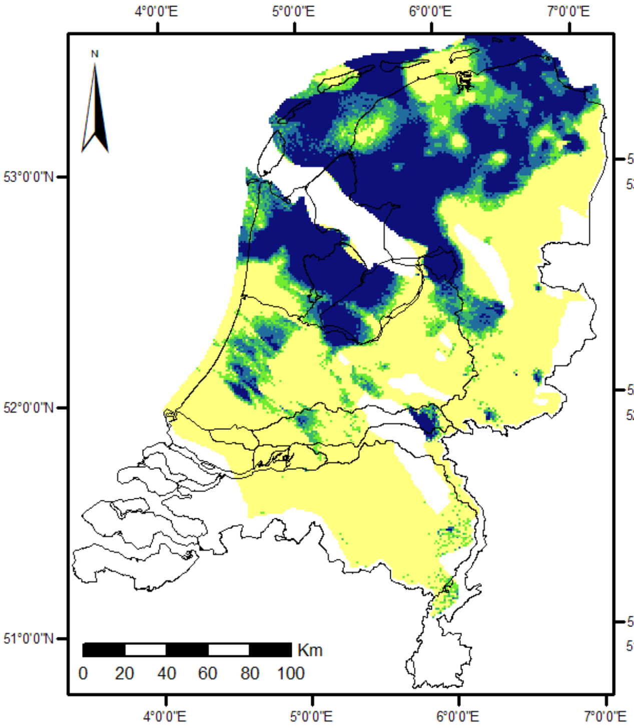
N-stacked P50 (Dm)

- 🟨 0 - 5
- 🟩 5- 10
- 🟩 10 - 20
- 🟦 20 - 50
- 🟦 > 50

Reservoir depth (m)

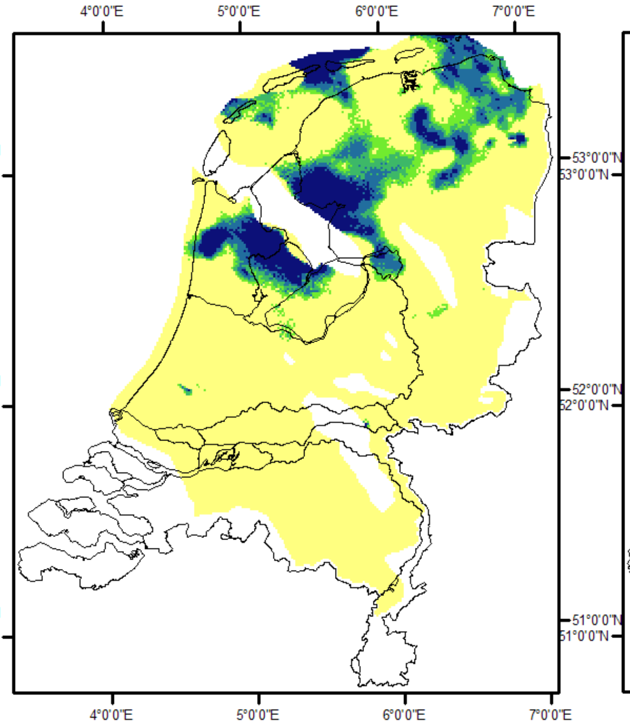
- 🟥 1200

Property mapping and uncertainties (3)



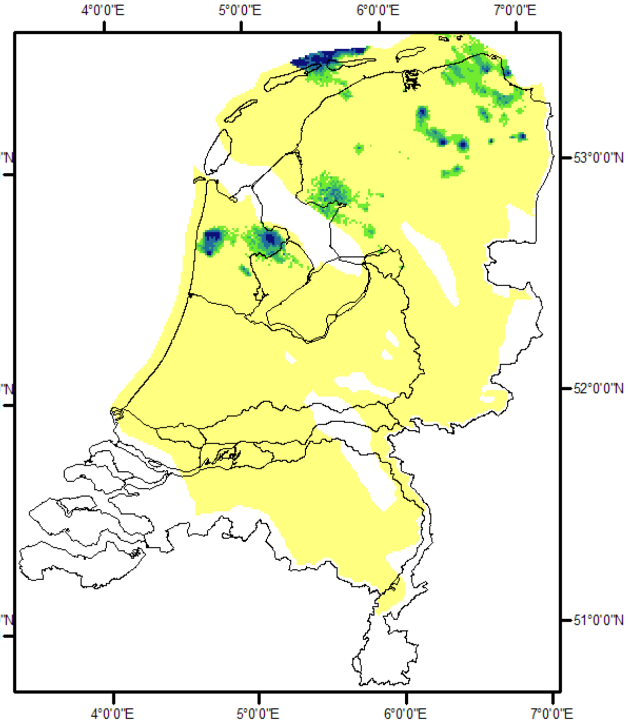
kH - P30 (Dm)

- 🟨 0 - 5
- 🟩 5- 10
- 🟩 10 - 20
- 🟦 20 - 50
- 🟦 > 50



kH - P50 (Dm)

- 🟨 0 - 5
- 🟩 5- 10
- 🟩 10 - 20
- 🟦 20 - 50
- 🟦 > 50



kH - P70 (Dm)

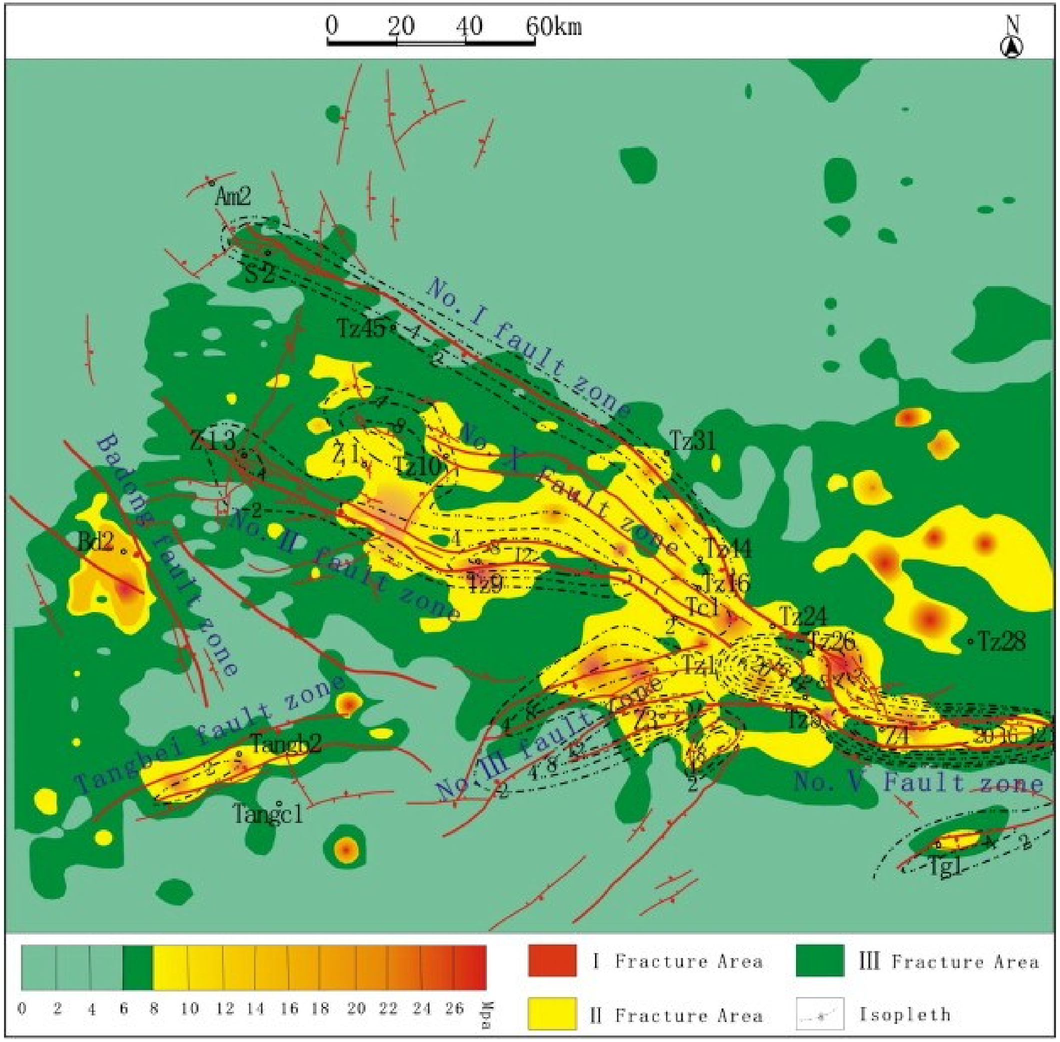
- 🟨 0 - 5
- 🟩 5- 10
- 🟩 10 - 20
- 🟦 20 - 50
- 🟦 > 50

Rotliegendes aquifer

permeability in other sediments

- Carbonates → fracture related
- Fracture assessment
  - Well imaging of fractures
  - Well flow tests
- Fracture related to tectonic deformation→ mechanical models for natural fracture density variation related to position in structure

Carbonates permeability – learn from oil and gas



Ding et al., 2012

Journal of Petroleum Science and Engineering
Volumes 86–87, May 2012, Pages 62–70

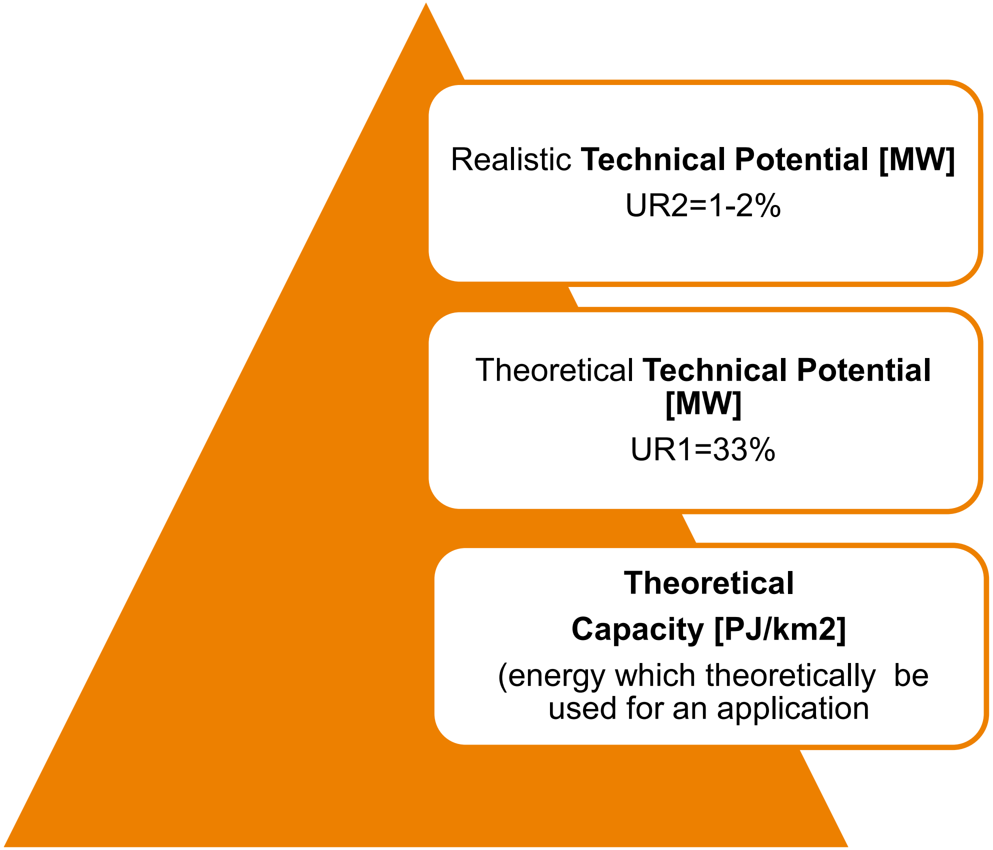
Ordovician carbonate reservoir fracture characteristics and fracture distribution forecasting in the Tazhong area of Tarim Basin, Northwest China

Predicted tensile stresses related
To caledonian deformation

Resource potential

Integrated over volume V

Practical potential



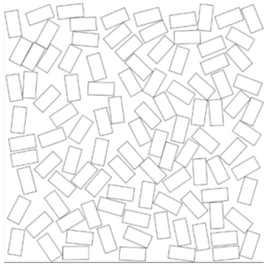
Realistic **Technical Potential [MW]**
UR2=1-2%

Theoretical **Technical Potential [MW]**
UR1=33%

Theoretical Capacity [PJ/km2]
(energy which theoretically be used for an application

Theoretical potential

$$\text{TPvolume} = \frac{TC}{lifetime} UR2$$



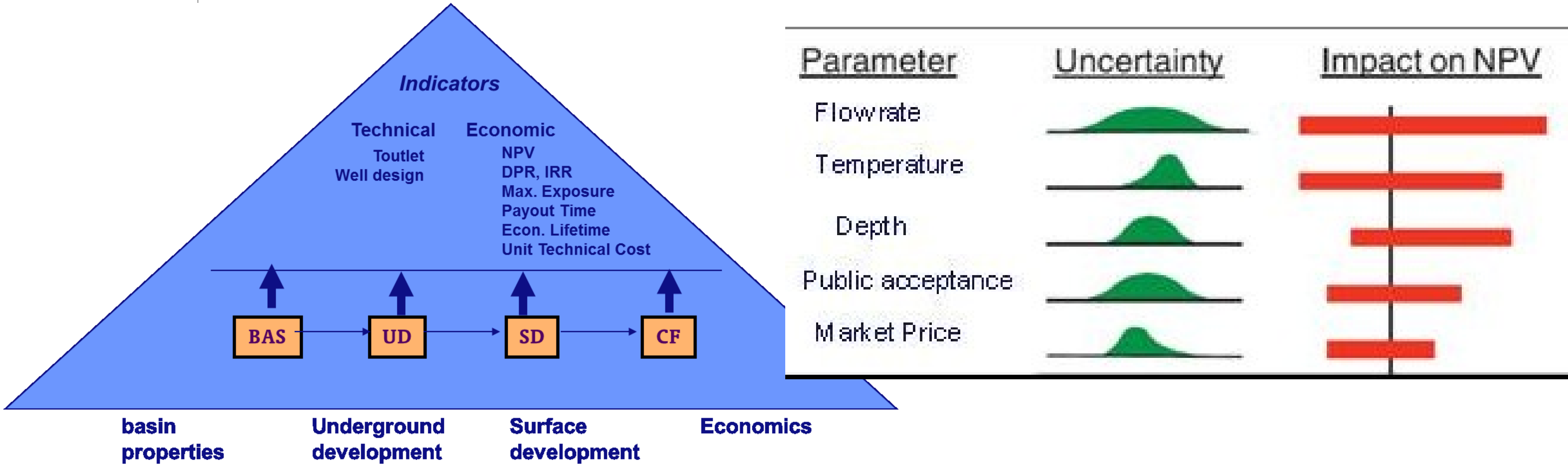
$$\text{TPplaylevel} = \frac{TC}{lifetime} UR1$$

$$\text{TC} = V * \rho_{rock} * Cprock * (T_x - Tr) * \eta$$

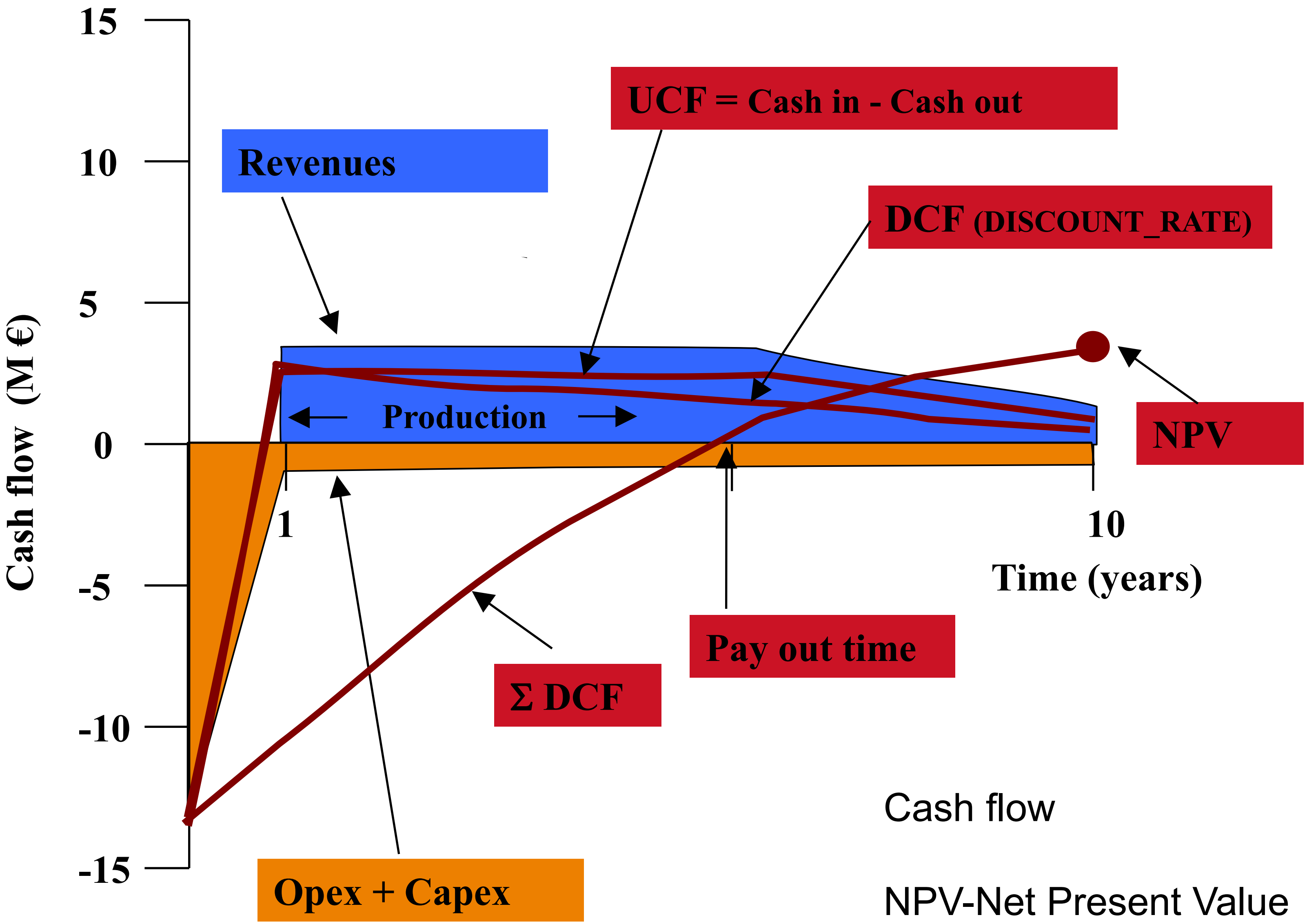
Beardsmore et al., 2011.
philosophy used In IPCC and IEA roadmap

Resource Potential: how to achieve transparant framework

- Evaluate transparant Key Performance Indicators
    - Net Present Value, Levelized Cost of Energy
    - Evaluate with fastmodels for techno-economic performance
    - Use MC sampling evaluate risk and upside in reward



driving philosophy is to trade-off accuracy for completeness



Cash flow

NPV-Net Present Value

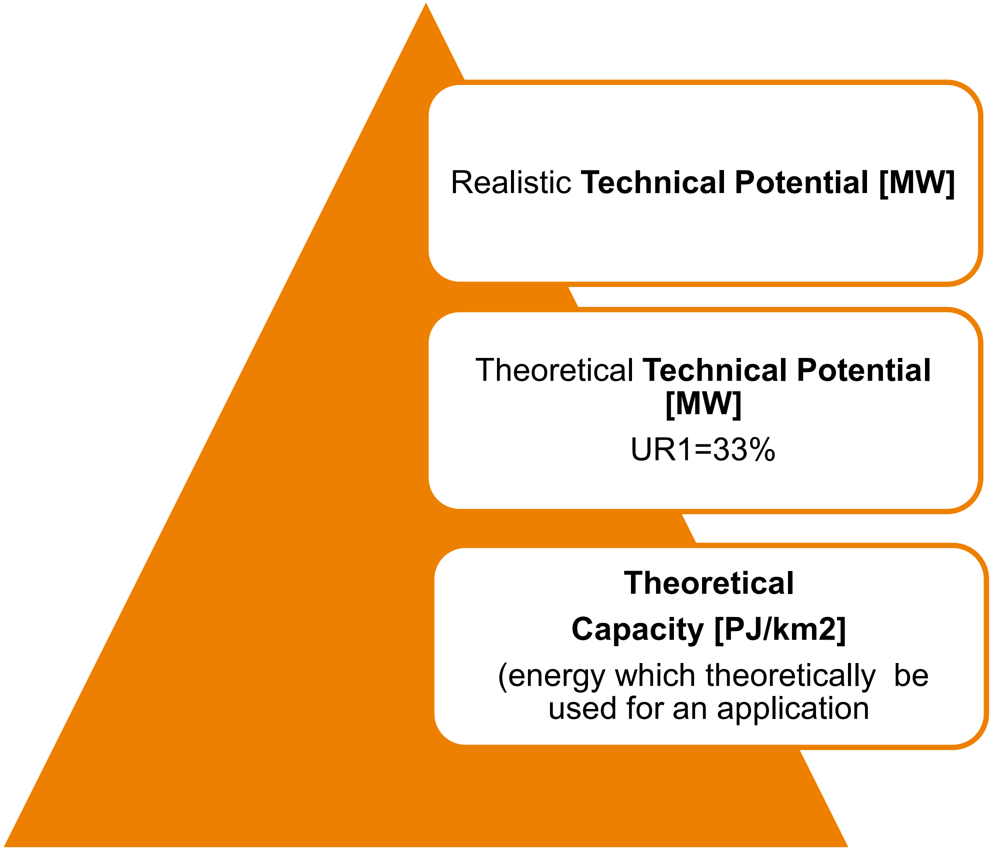
Levelized Cost of Energy

- Discounted energy produced [MWh, GJ]
- Discounted cash out [EUR]

- LCOE = discouted cash-out / discounted energy produced

Economic potential

Practical potential



Realistic **Technical Potential [MW]**

Theoretical **Technical Potential [MW]**
UR1=33%

Theoretical Capacity [PJ/km2]
(energy which theoretically be used for an application

Theoretical potential

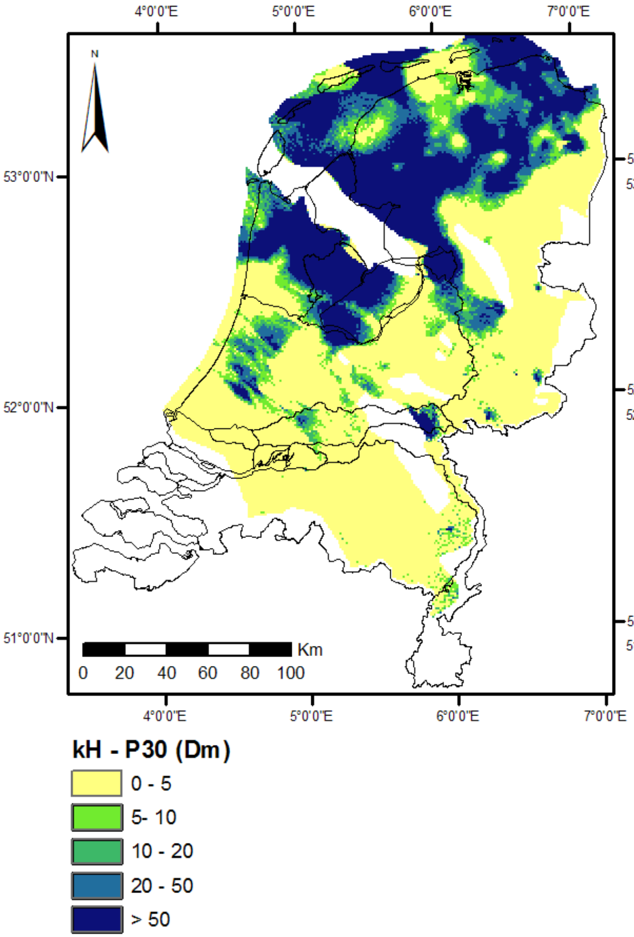
$$\text{TPvolume} = \frac{TC}{lifetime} UR1, if\ LCOE < c$$

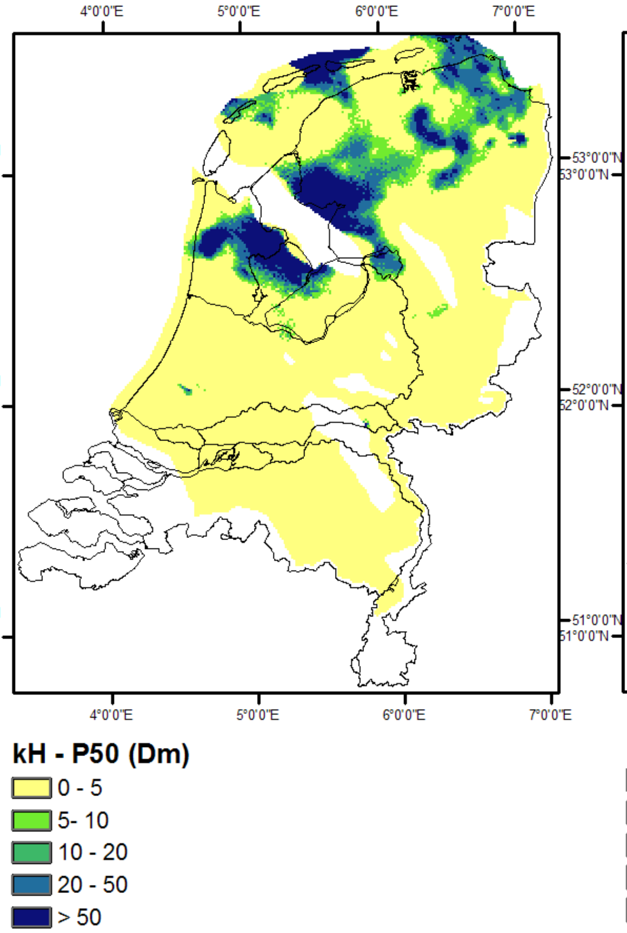
$$\text{TPplaylevel} = \frac{TC}{lifetime} UR1$$

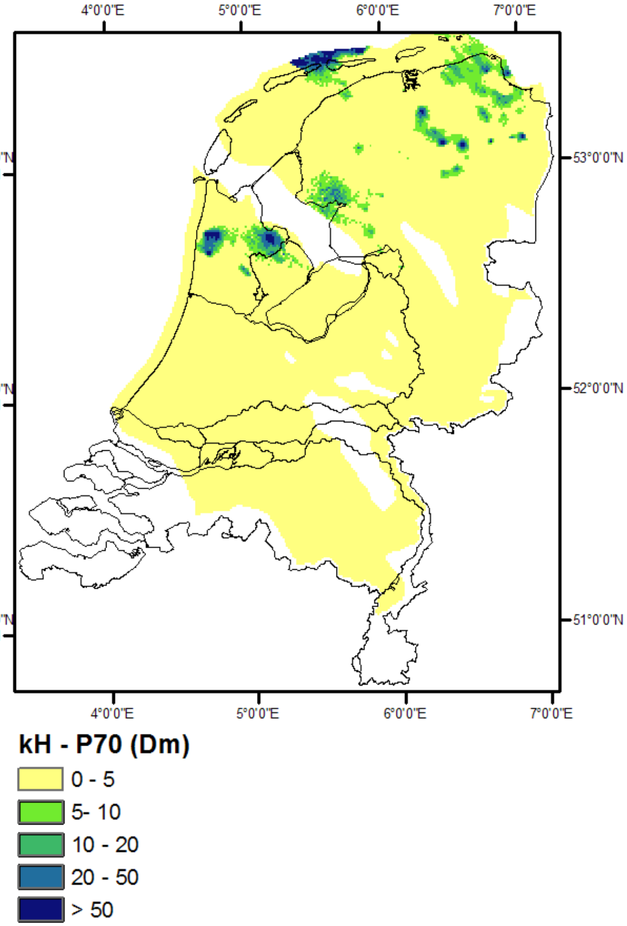
$$\text{TC} = V * \rho_{rock} * Cpro_{ck} * (T_x - Tr) * \eta$$

Used here

Property mapping and uncertainties (3)



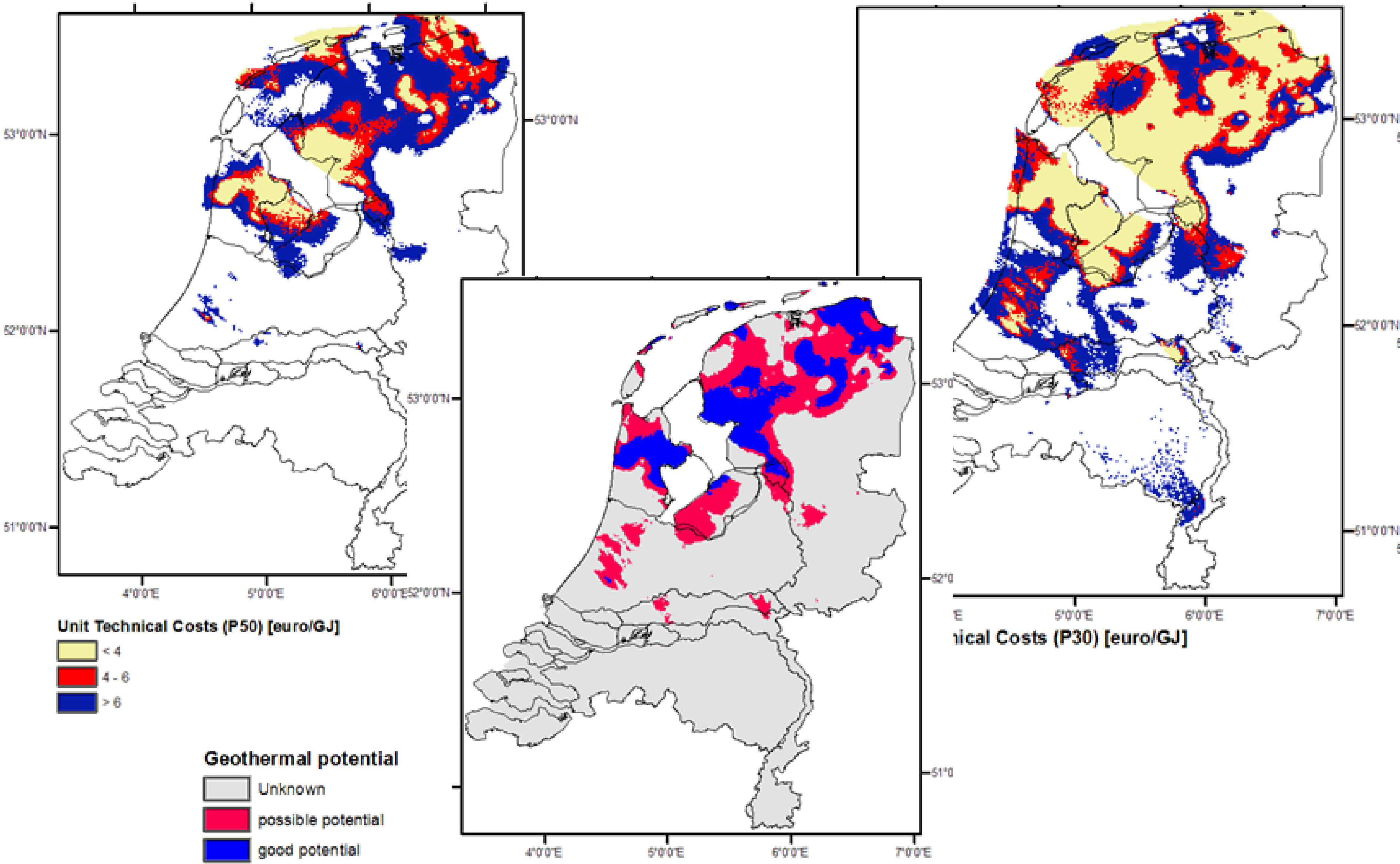




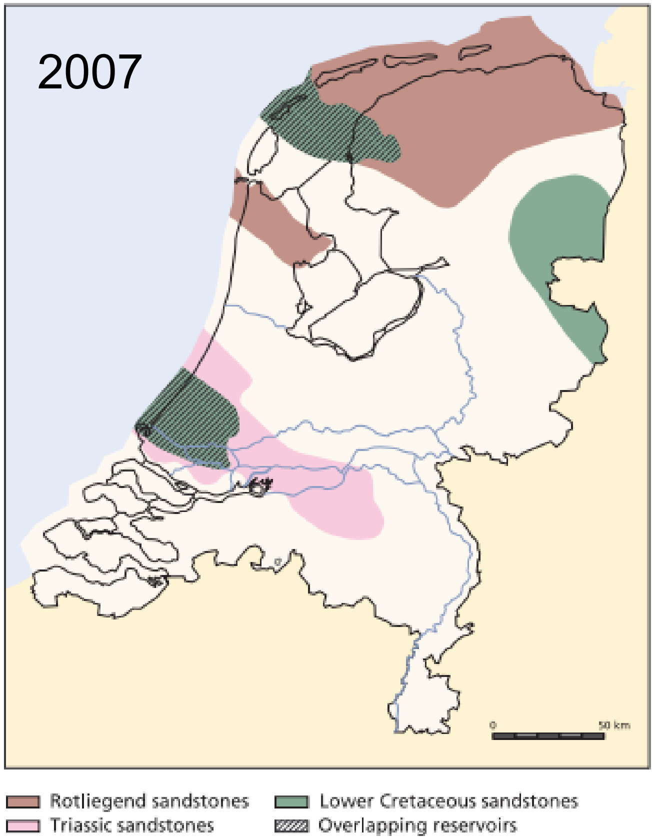
Rotliegendes aquifer

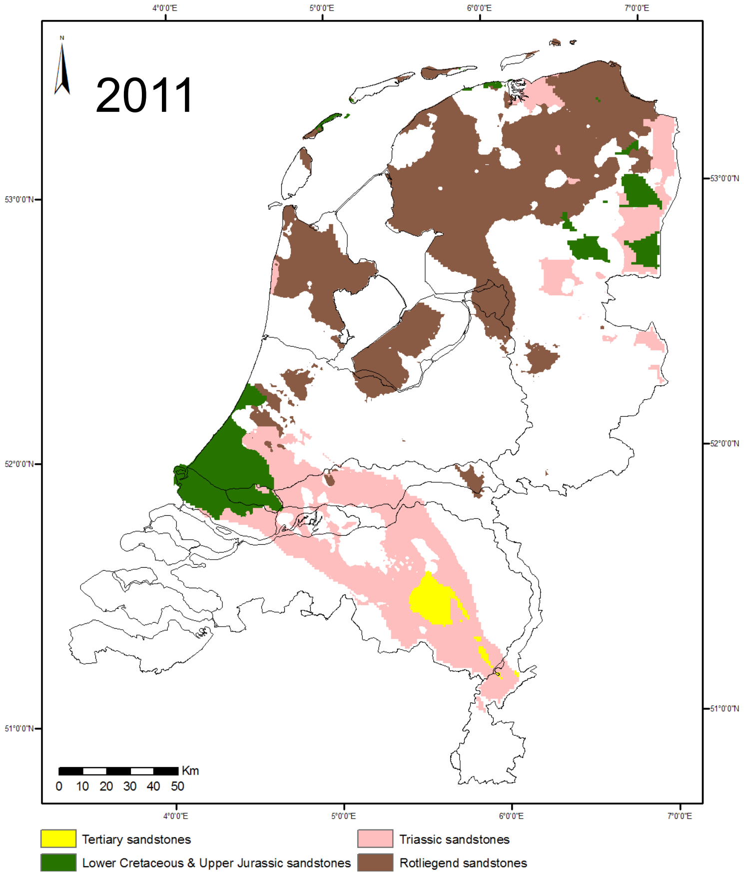
Rotliegendes aquifer

Potential Map



potential map vs earlier assessments



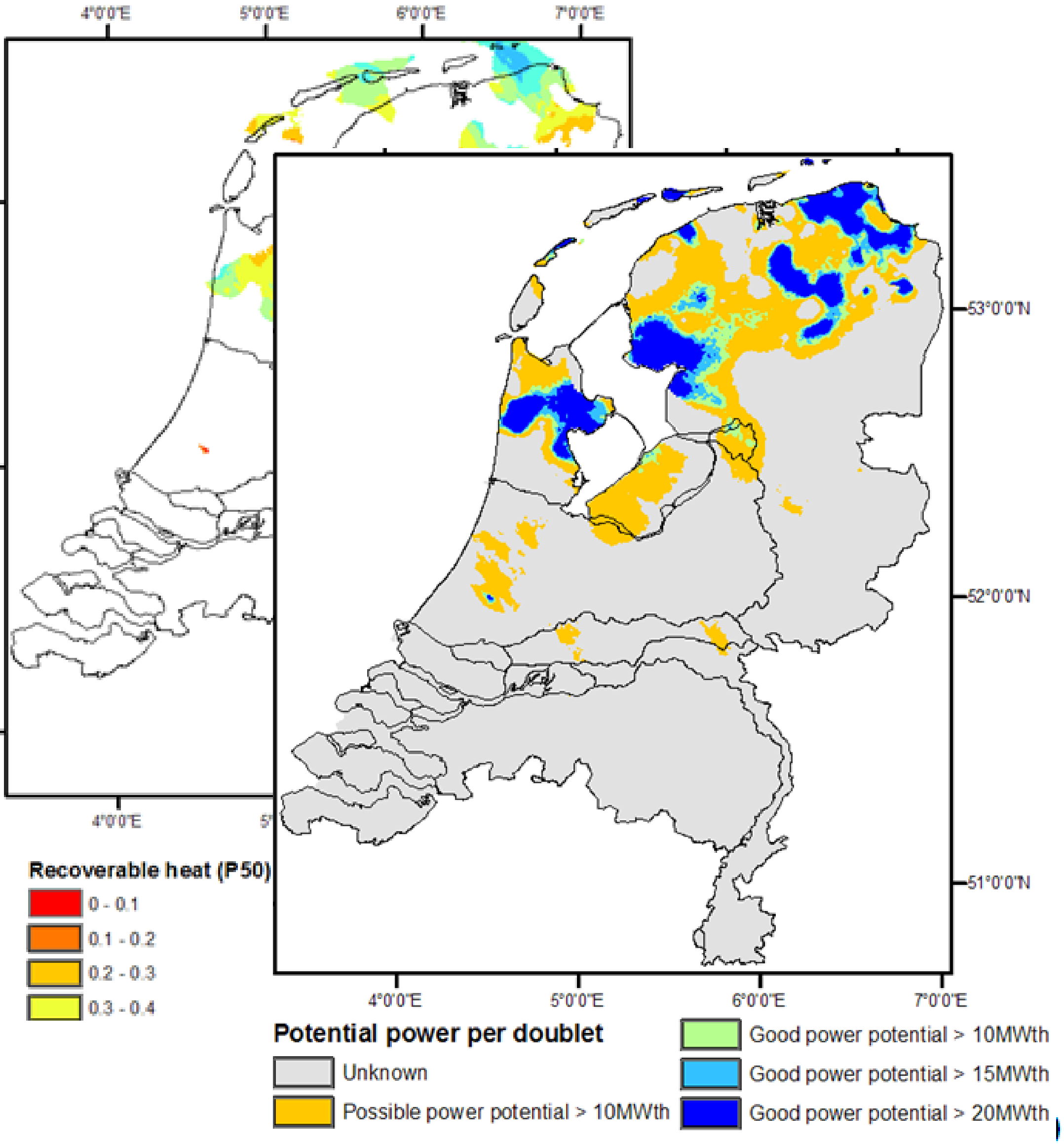


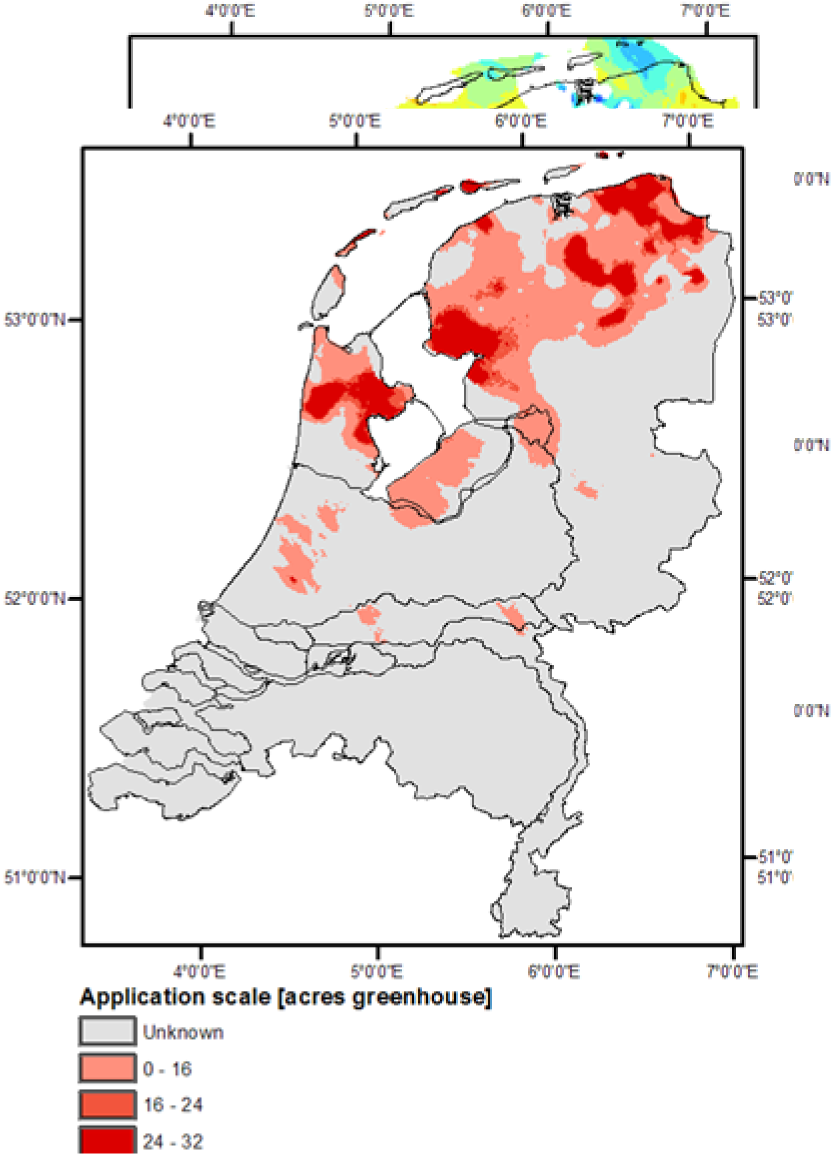
Mapped stratigraphic areas

White: insufficient amount of data or other stratigraphic units (like Carboniferous)

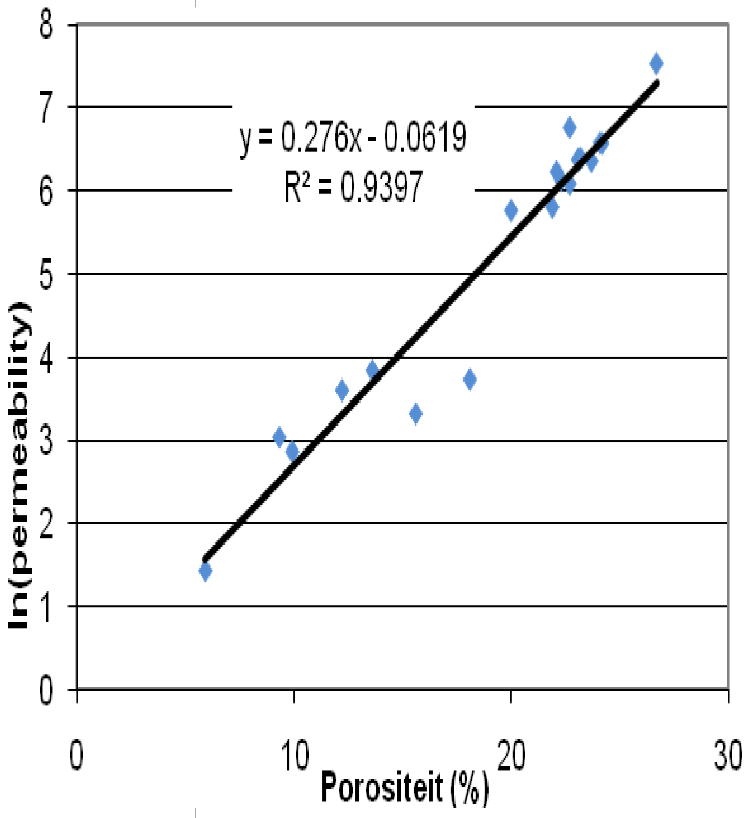
Quantitative potential

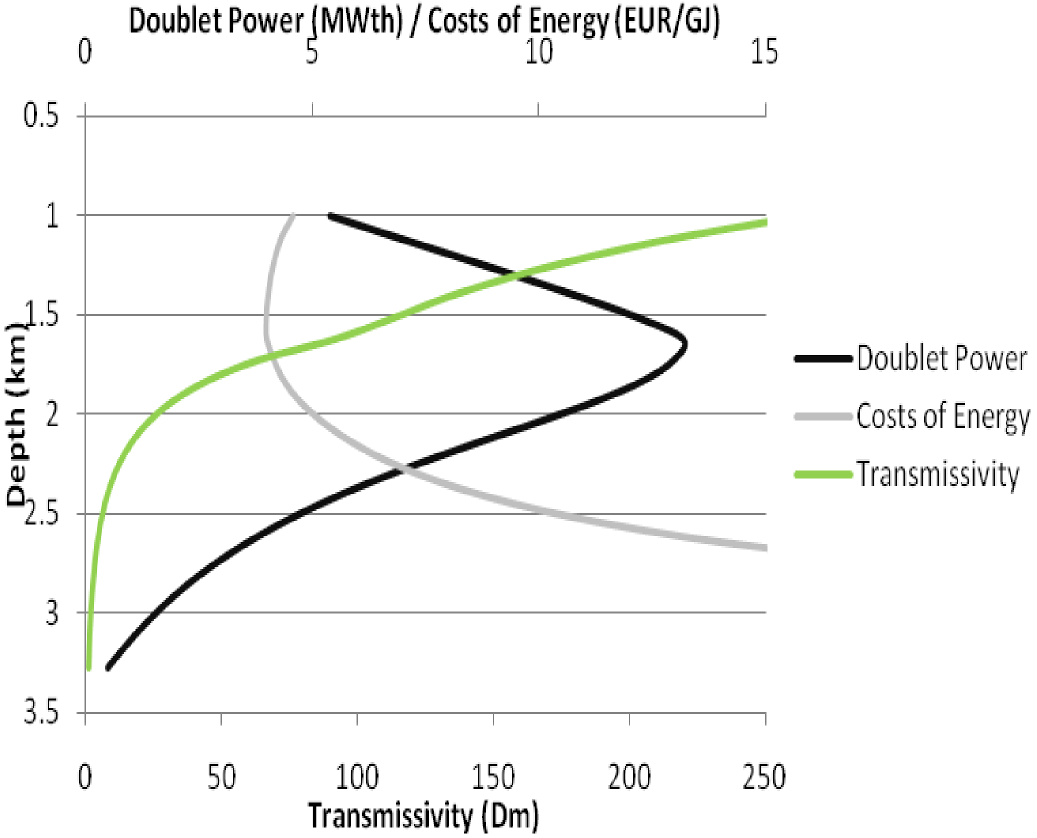
Rotliegendes aquifer



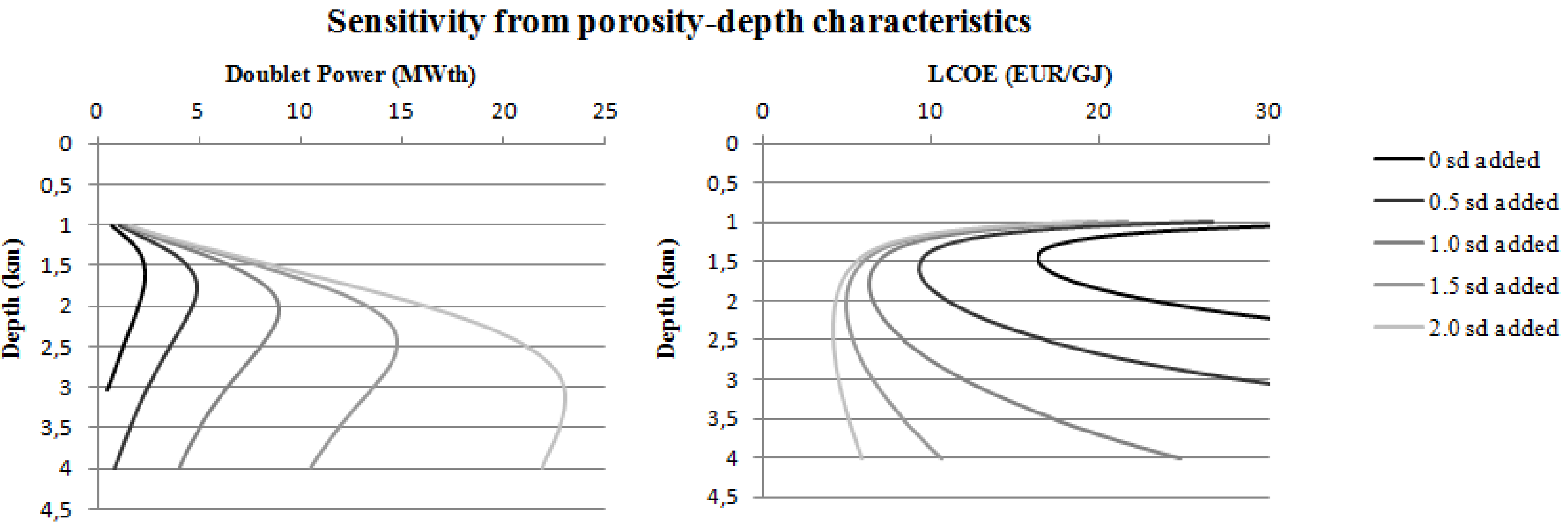


Performance is predicted to decrease with depth as a function of porosity





Analysis of sensitivity to typical dutch permeability trends



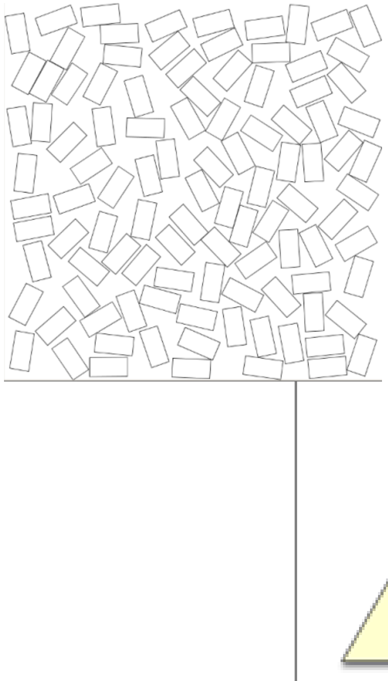
Heat In Place [PJ km-2]

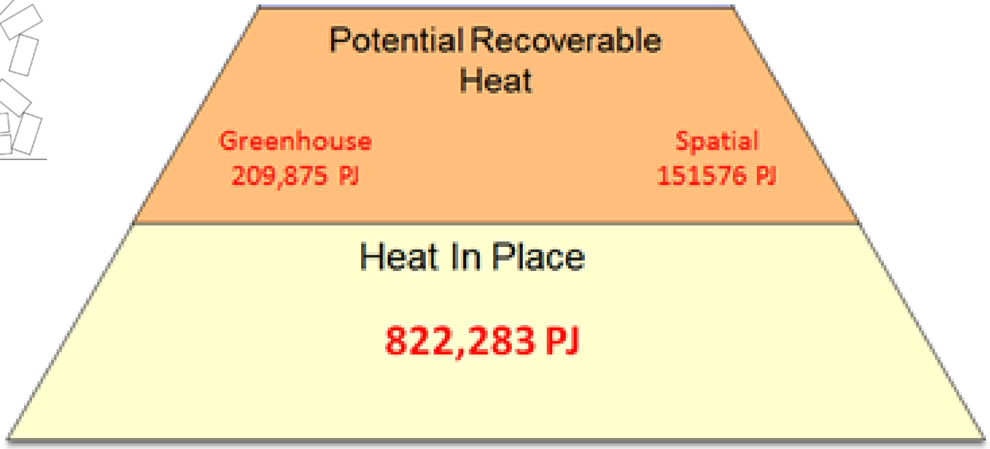
Starting point at the base of the pyramid is Heat In Place (HIP) in PJ/km2. This is the heat content of the reservoir (cf. Muffler and Cataldi, 1978). HIP is the maximum theoretically extractable heat in the aquifer.

Potential Recoverable Heat [PJ/km2] or *Technical potential* [PRH/30 yr]

The next level of the pyramid is the Potential Recoverable Heat (PRH). This is the heat which can be recovered from the reservoir, unconstrained by economic limitations and irrespective of flow properties.

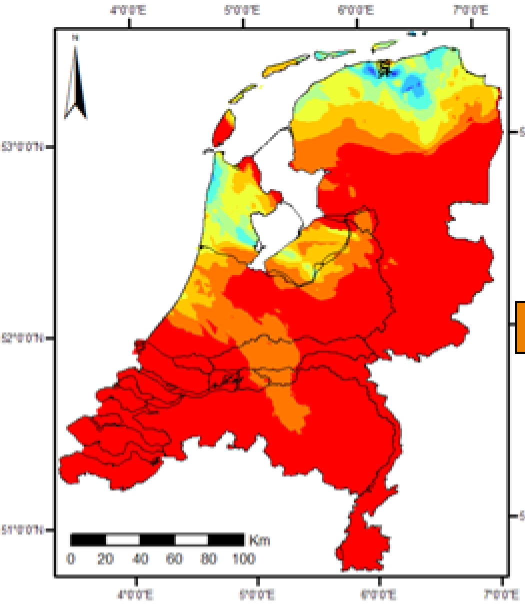
UR = 33%



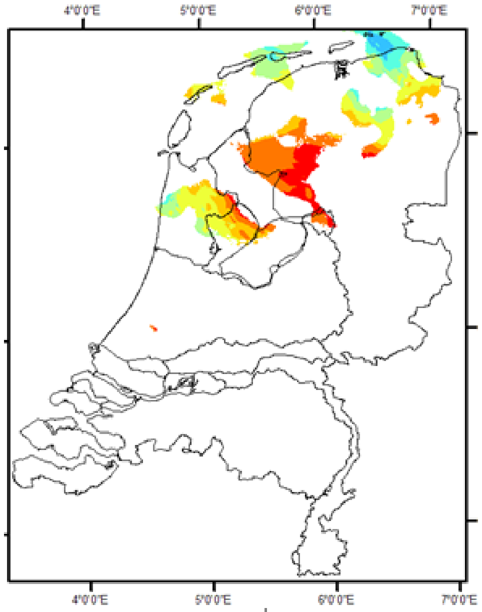


Recoverable Heat [PJ/km2]

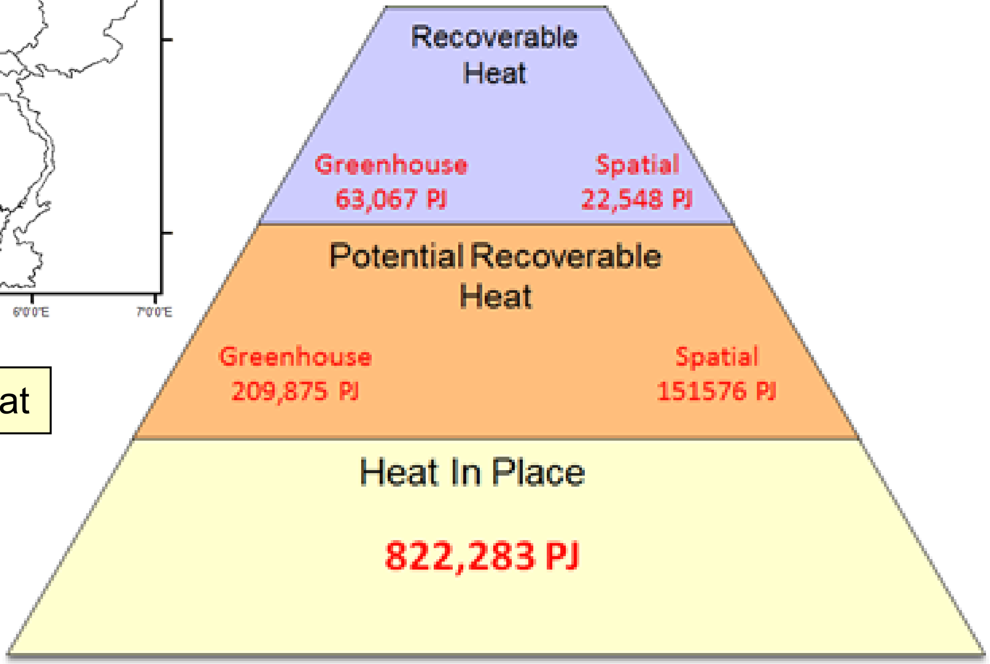
The volume of rock in RH is a subset of PRH, using a cut-off for the Unit Technical Cost (UTC) from the Cash flow calculation



Potential recoverable heat PJ/km2



Recoverable heat



Recoverable Heat

Greenhouse 63,067 PJ

Spatial 22,548 PJ

Potential Recoverable Heat

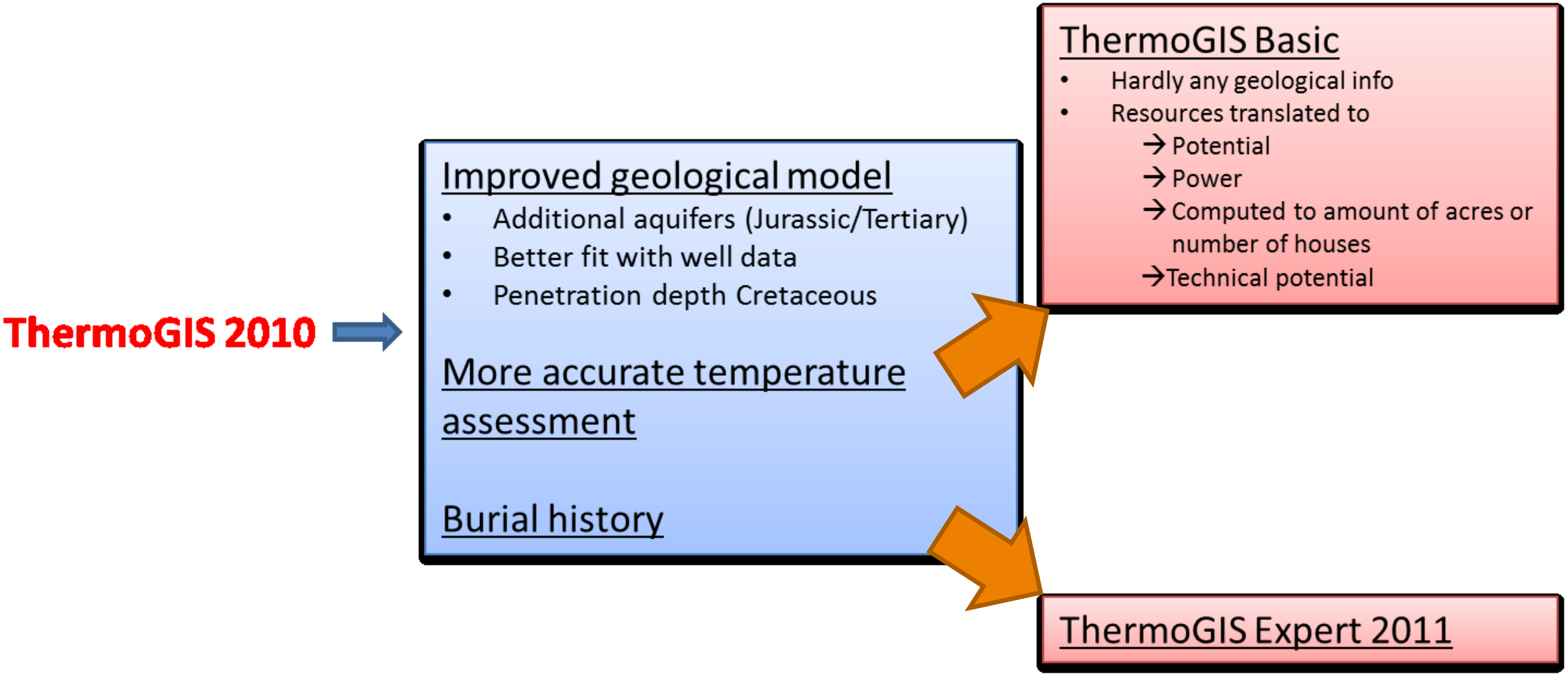
Greenhouse 209,875 PJ

Spatial 151576 PJ

Heat In Place

822,283 PJ

Thermc IS evolution



ThermoGIS 2010

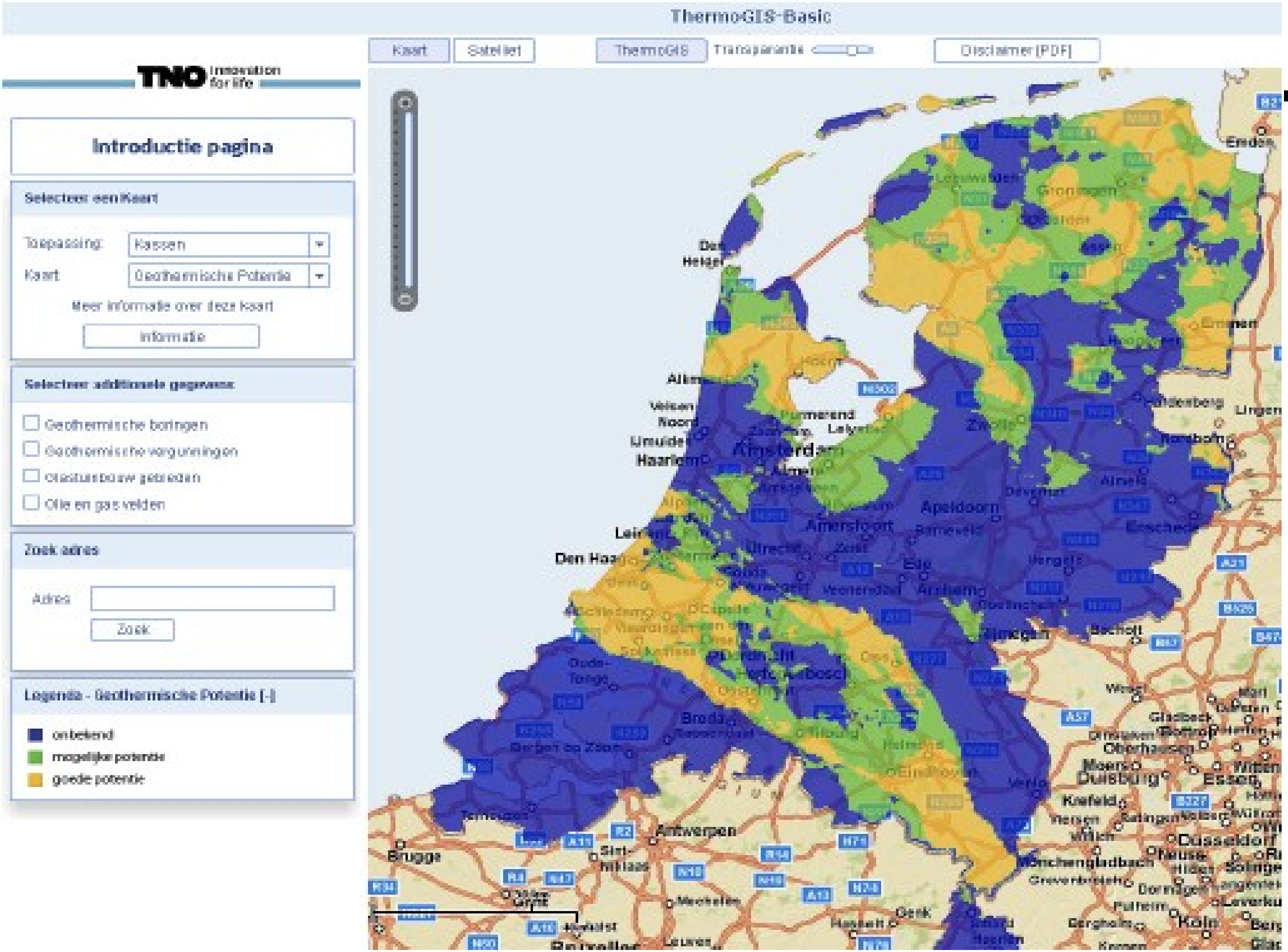
Improved geological model
- Additional aquifers (Jurassic/Tertiary)
- Better fit with well data
- Penetration depth Cretaceous

More accurate temperature assessment

Burial history

ThermoGIS Basic
- Hardly any geological info
- Resources translated to
  - → Potential
  - → Power
  - → Computed to amount of acres or number of houses
  - →Technical potential

ThermoGIS Expert 2011



Introductie pagina

Selecteer een Kaart

Toepassing: Kassen

Kaart: Geothermische Potentie

Meer informatie over deze kaart

Informatie

Selecteer additionele gegevens

- ☐ Geothermische boringen
- ☐ Geothermische vergunningen
- ☐ Glastuinbouw gebieden
- ☐ Olie en gas velden

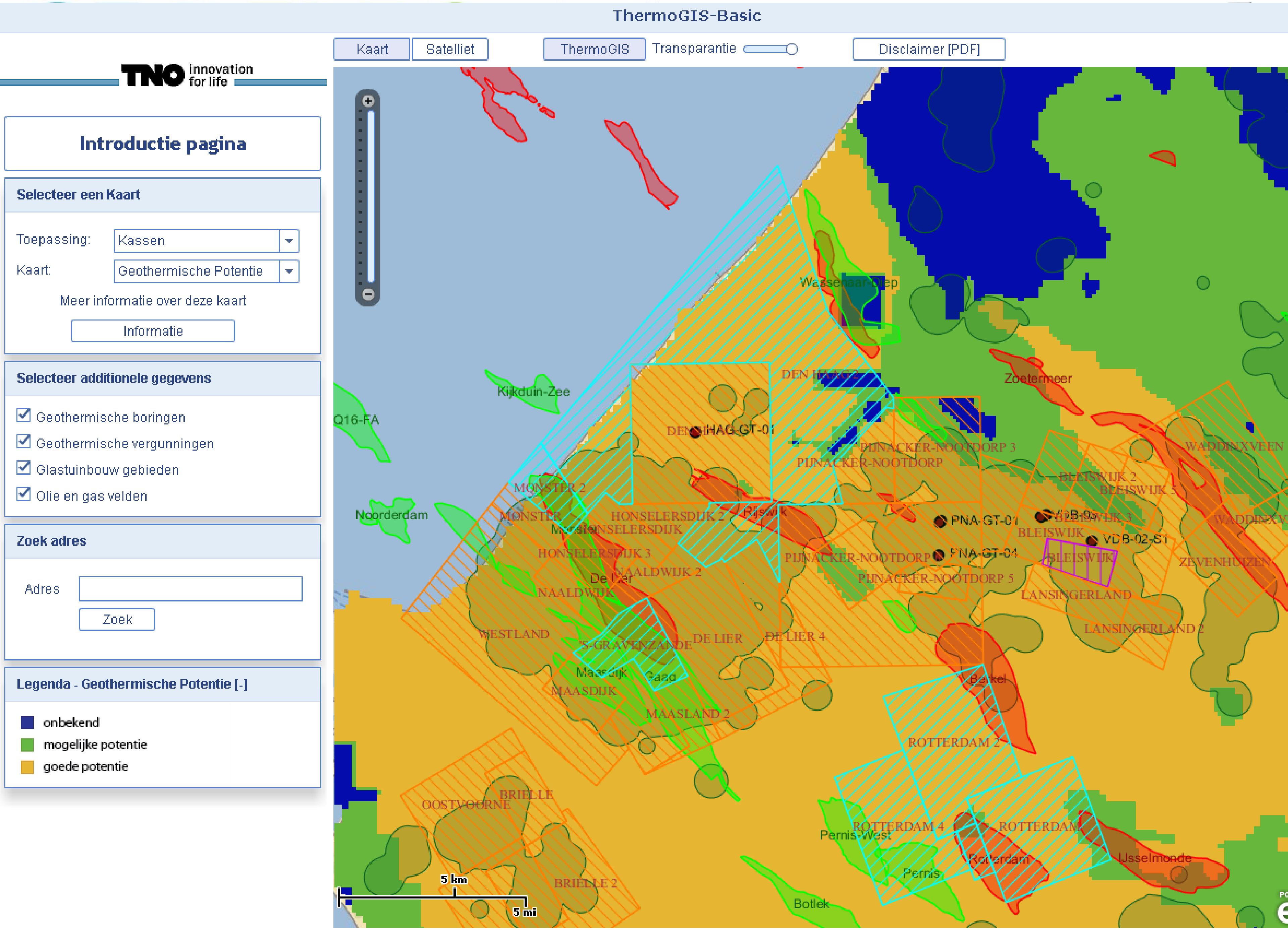
Zoek adres

Adres

Zoek

Legenda - Geothermische Potentie [-]

- 🟦 onbekend
- 🟩 mogelijke potentie
- 🟨 goede potentie



ThermoGIS-Basic

Introductie pagina

Selecteer een Kaart

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Kaart: Geothermische Potentie

Meer informatie over deze kaart

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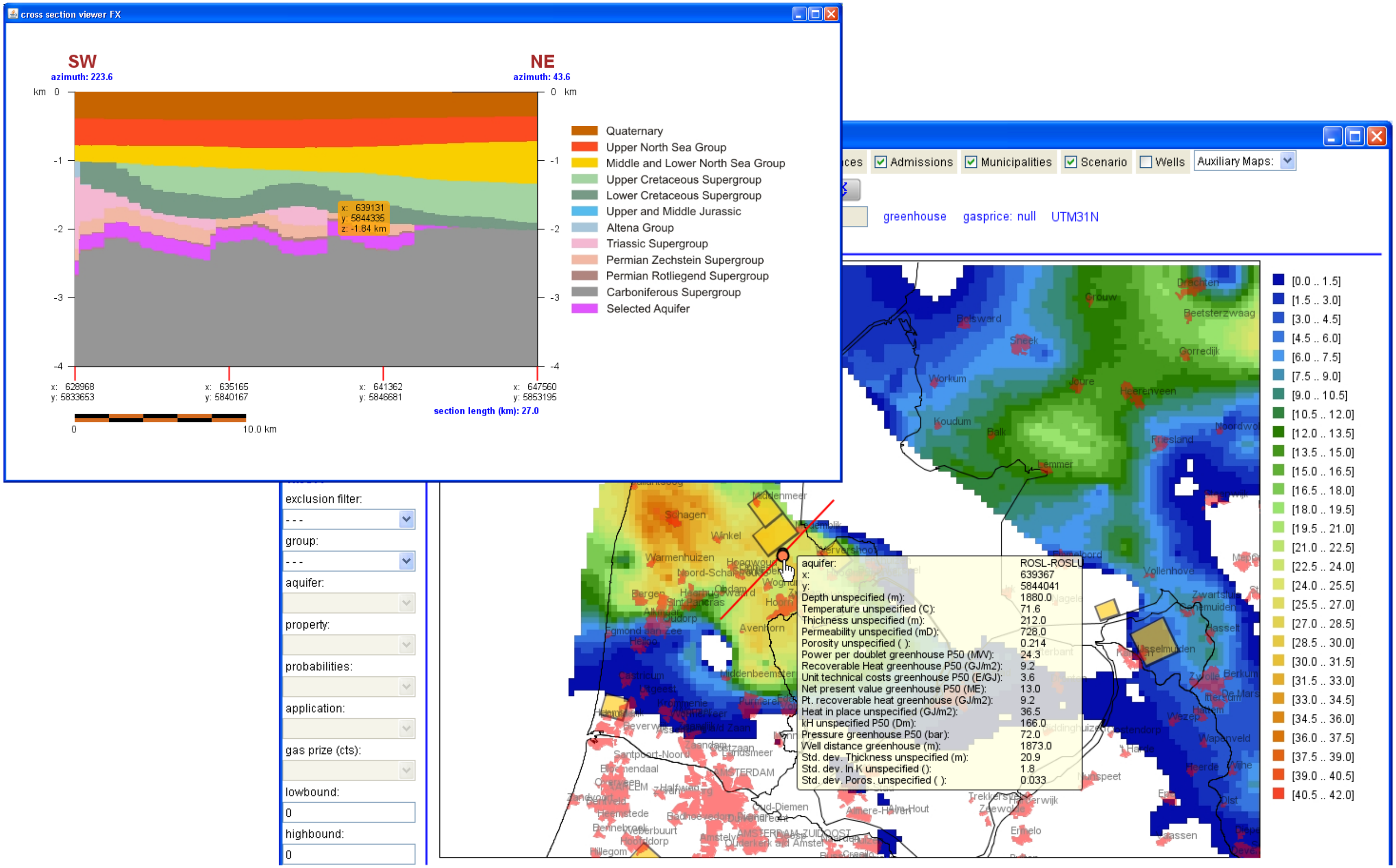
Zoek adres

Adres

Legenda - Geothermische Potentie [-]

- 🟦 onbekend
- 🟩 mogelijke potentie
- 🟧 goede potentie

ThermoGIS Expert: Geological properties



exclusion filter: - - -
group: - - -
aquifer:
property:
probabilities:
application:
gas prize (cts):
lowbound: 0
highbound: 0

aquifer: ROSL-ROSLU
x: 639367
y: 5844041
Depth unspecified (m): 1880.0
Temperature unspecified (C): 71.6
Thickness unspecified (m): 212.0
Permeability unspecified (mD): 728.0
Porosity unspecified ( ): 0.214
Power per doublet greenhouse P50 (MW): 24.3
Recoverable Heat greenhouse P50 (GJ/m2): 9.2
Unit technical costs greenhouse P50 (E/GJ): 3.6
Net present value greenhouse P50 (ME): 13.0
Pt. recoverable heat greenhouse (GJ/m2): 9.2
Heat in place unspecified (GJ/m2): 36.5
kH unspecified P50 (Dm): 166.0
Pressure greenhouse P50 (bar): 72.0
Well distance greenhouse (m): 1873.0
Std. dev. Thickness unspecified (m): 20.9
Std. dev. ln K unspecified (): 1.8
Std. dev. Poros. unspecified ( ): 0.033

THERMOGIS^{TM} doublet thermal Power [MWth], site specific information

Result screen “Geothermal Power Program”
Probability Density Function of Geothermal Power