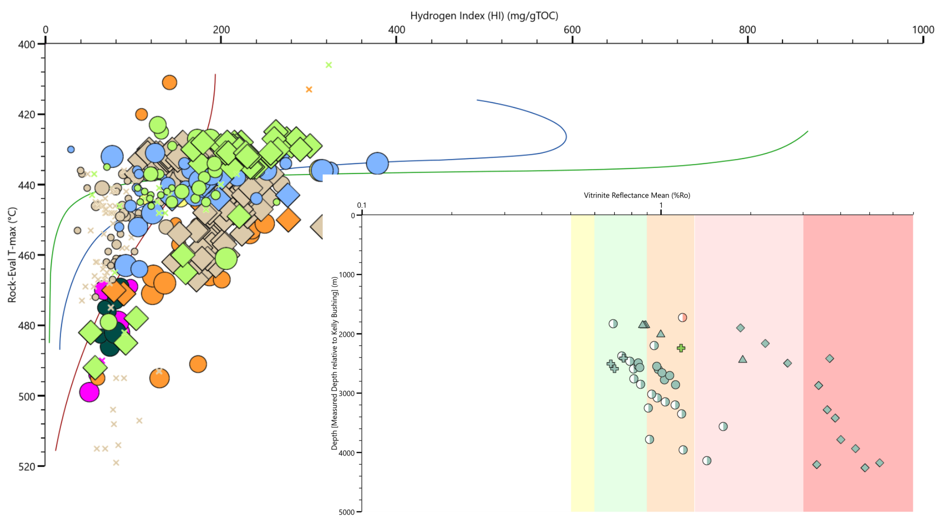
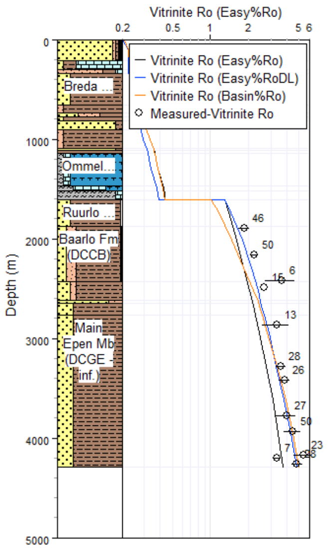
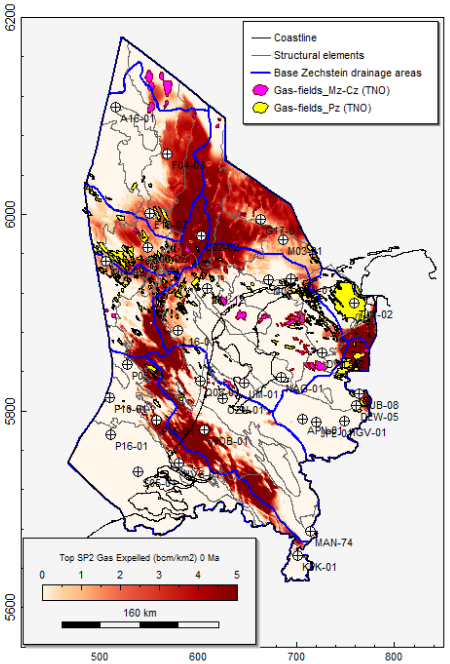
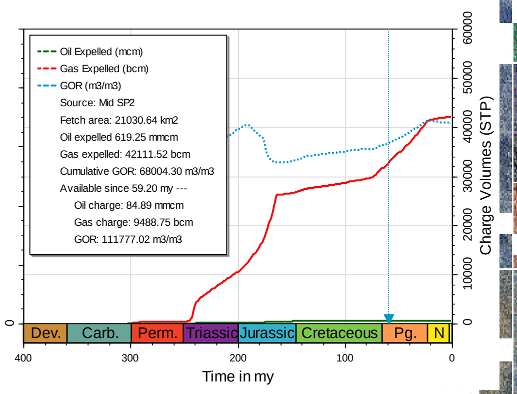
A New Regional-Scale Petroleum Systems Model for the Netherlands: Overview and Main Results



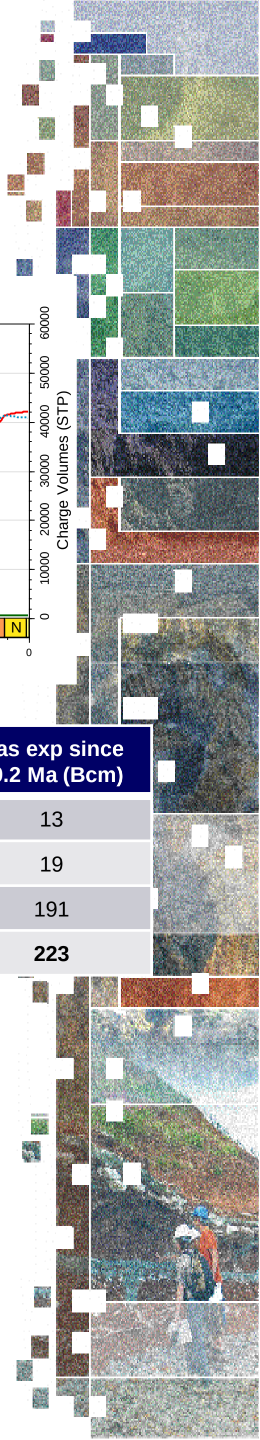






https://www.geodeatlas.nl/pages/play-9-source-rocks

Source rock	Total Gas Exp. (Bcm)	Gas exp since 59.2 Ma (Bcm)
Maurits	2482	13
Up. SP2	5037	19
Low. SP2	12485	191
Total	**20004**	**223**



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A New Regional-Scale Petroleum Systems Model for the Netherlands: Overview and Main Results

- Project Overview, Inputs and Outputs
- 1-D (borehole) Modelling: data, calibration & sensitivities and summary of results
- 3-D Modelling: structure, calibration and some results from the Posidonia and Westphalian source rocks
- Main Conclusions and Future Work

IGI

The Petroleum Systems Study

Aims, Model Inputs and Outputs

Geochemistry

Objectives
1. Compiled the available geochemistry data
2. Interpretation of SR geochemistry
3. Define SR types and constrain parameters for the PS modelling

Inputs
1. NLOG Geochemistry database
2. Published data and interpretations
3. Previous knowledge of the regional SR horizons and fluids

Outputs
1. Geochemistry database in p:IGI format (also in Excel and ASCCII)
2. Constraints on SR type, richness and oil-proneness

1-D Modelling

Objectives
1. Calibration of the thermal-burial model
2. Assess regional model variations
3. Test model sensitivities

Inputs
1. Stratigraphy and lithologies (NLOG)
2. Temperature & maturity data (NLOG)
3. Estimates on regional basin exhumation from 2D and 3D seismic

Outputs
1. Heat-flow through time at borehole locations
2. Constraints on erosion (or thermal events) at borehole locations

3-D Modelling

Objectives
1. Build a consistent PS model for the Netherlands territory in Trinity-T3
2. Produce maps of maturity-generation -expulsion for known SR horizons
3. Understand the model sensitivities

Inputs
1. Interpreted seismic horizons
2. Temperature maps from ThermoGIS (TNO, Netherlands) and thermal-burial constraints from 1D modelling
3. Geochemistry data and interpretation

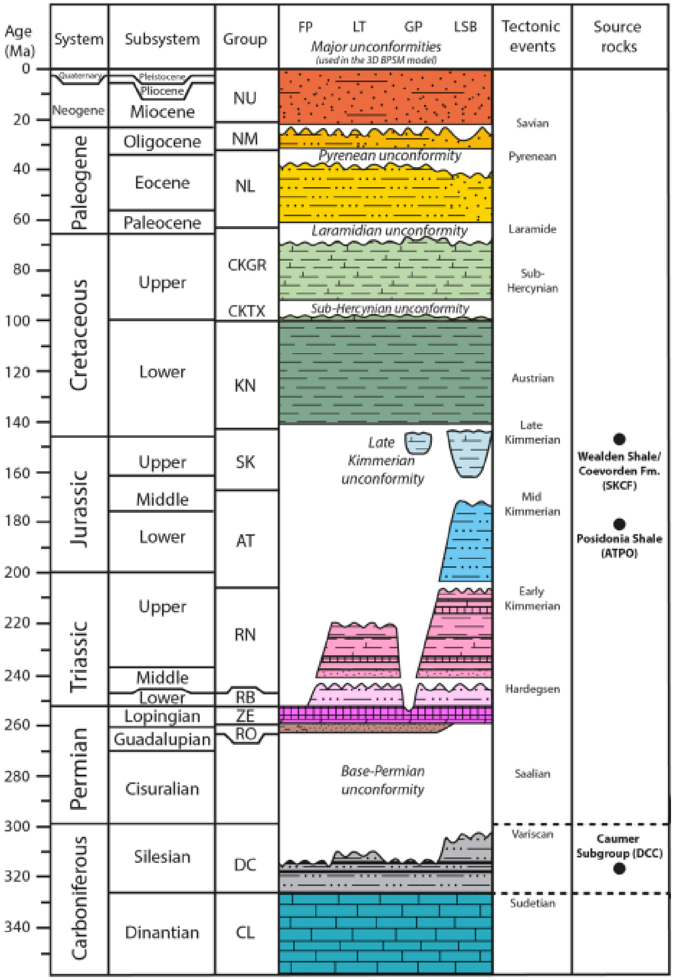
Outputs
1. Maps of maturity-generation - expulsion for all SR horizons
2. Tables with volumes and timings of oil and gas expulsion
3. Analysis of results Vs observations

IGI

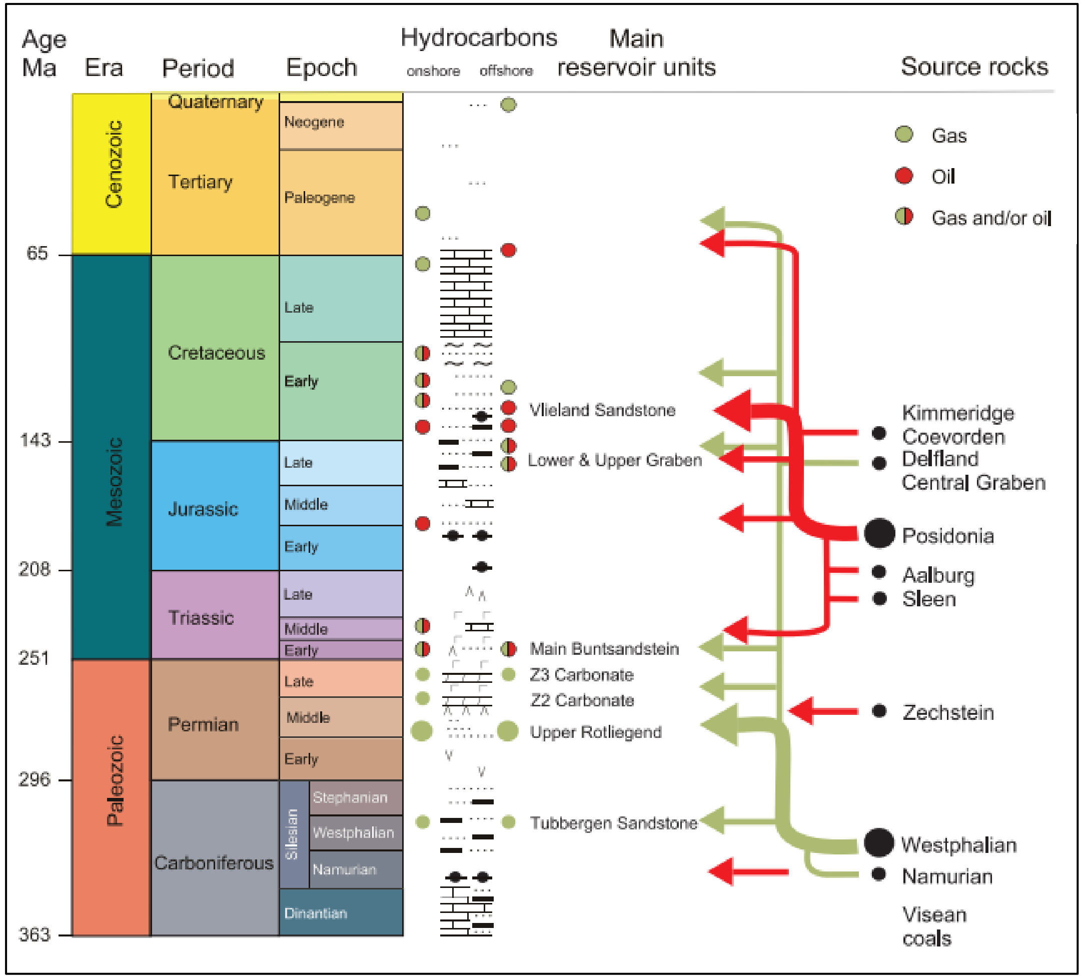
https://www.geodeatlas.nl/pages/play-9-source-rocks

Geology and Model Foundations

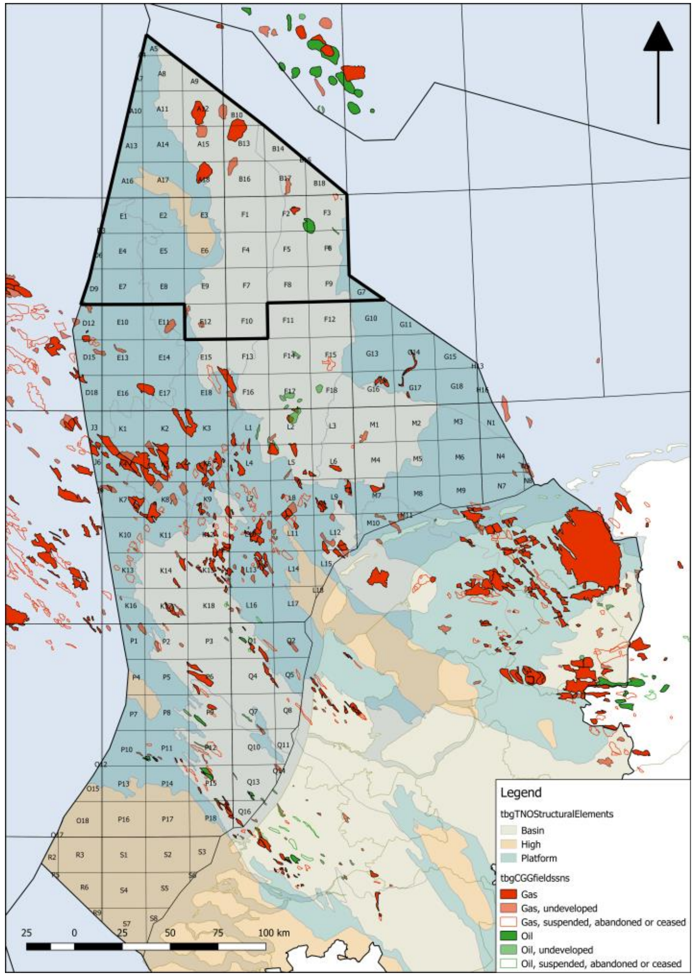
Tectonic Evolution & Chronostratigraphy, Petroleum Systems & Exploration in the Netherlands



Chronostratigraphic chart (Amberg *et al*., 2022)



Petroleum systems in the Dutch subsurface (from De Jager and Geluk, 2007)



Netherlands oil & gas fields (source: EBN)

The models include the available litho-stratigraphic information and tectonic hypothesis for the evolution of the Netherlands (bottom-up) and the model predictions are compared/discussed with the observations (top-down).

The New Netherlands Petroleum Systems Model

Brief Summary of Model Elements

Model area ~100,000 km^2

26 structural elements

17 seismic horizons

32 modelled boreholes

- Temperature measurements
- Vitrinite reflectance data

5 basin wide unconformities (with 3 major exhumation events)

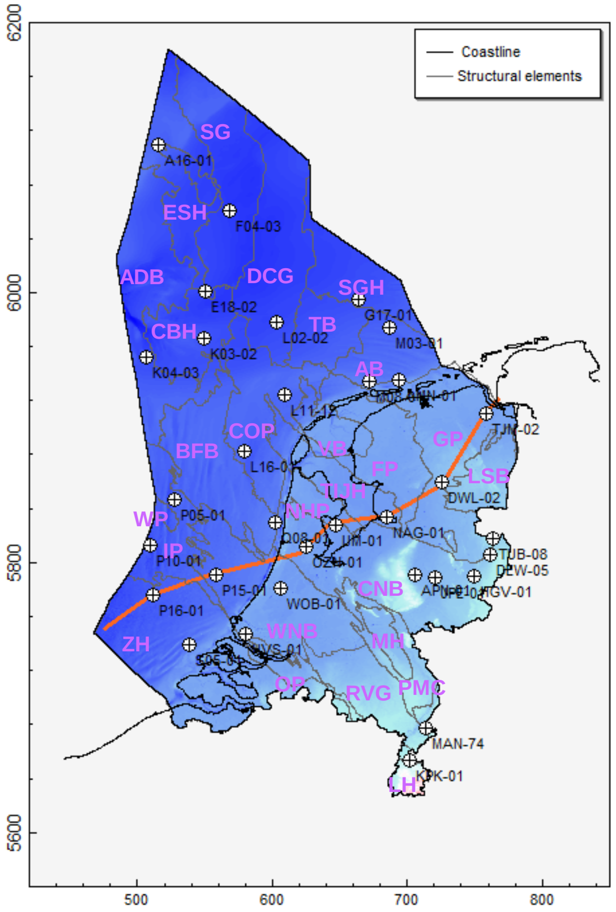
- Saalian (Base Permian) – **Major**
- Mid-Late Kimmerian – **Major**
- Laramide (L. Cretaceous) – **Major**
- Pyrenaen (Eocene-Oligocene)
- Savian (Oligocene-Miocene)

2 main source rock horizons

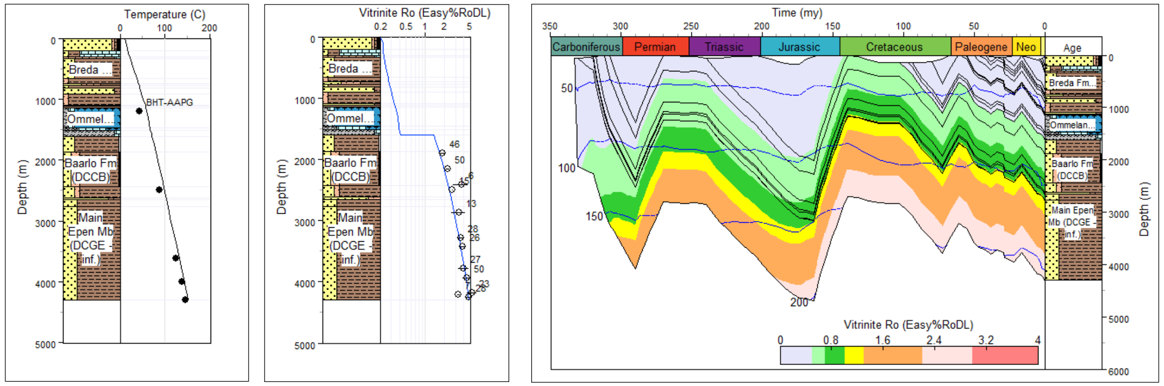
- Mesozoic (Posidonia)
- Paleozoic (Westphalian)

5 Alternative SR horizons

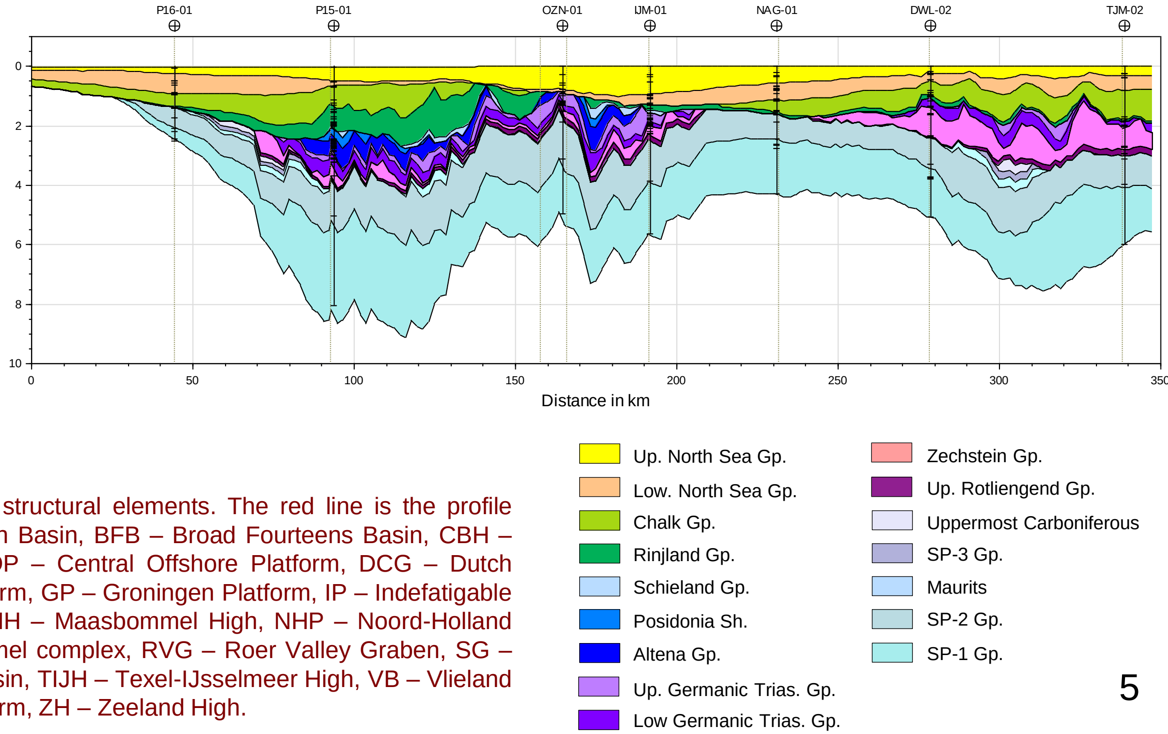
- Lower Cretaceous
- Upper Jurassic coals
- Sleen (Late Triassic)
- Zechstein (Late Permian)
- Namurian shales / Dinantian coals



Bathymetry-topography map showing the coastline and the structural elements. The red line is the profile shown to the right. AB – Ameland Block, ADB – Anglo-Dutch Basin, BFB – Broad Fourteens Basin, CBH – Cleaver Bank High, CNB – Central Netherlands Basin, COP – Central Offshore Platform, DCG – Dutch Central Graben, ESH – Elbow spit High, FP – Friesland Platform, GP – Groningen Platform, IP – Indefatigable Platform, LH – Linburg High, LSB – Lower Saxony Basin, MH – Maasbommel High, NHP – Noord-Holland Platform, OP – Oosterhout Platform, PMC – Peel-Maasbommel complex, RVG – Roer Valley Graben, SG – Step Graben, SGH – Schill Grund High, TB – Terschelling Basin, TIJH – Texel-IJsselmeer High, VB – Vlieland Basin, WNB – West Netherlands Basin, WP - Winterton Platform, ZH – Zeeland High.



Top: Example of a 1-D well model, showing the calibration to the temperature and vitrinite reflectance data (left), and the predicted burial history and basin vitrinite reflectance through time (right); **Bottom**: SW-NE transect across the offshore-onshore Netherlands showing the horizons used to build the PS model



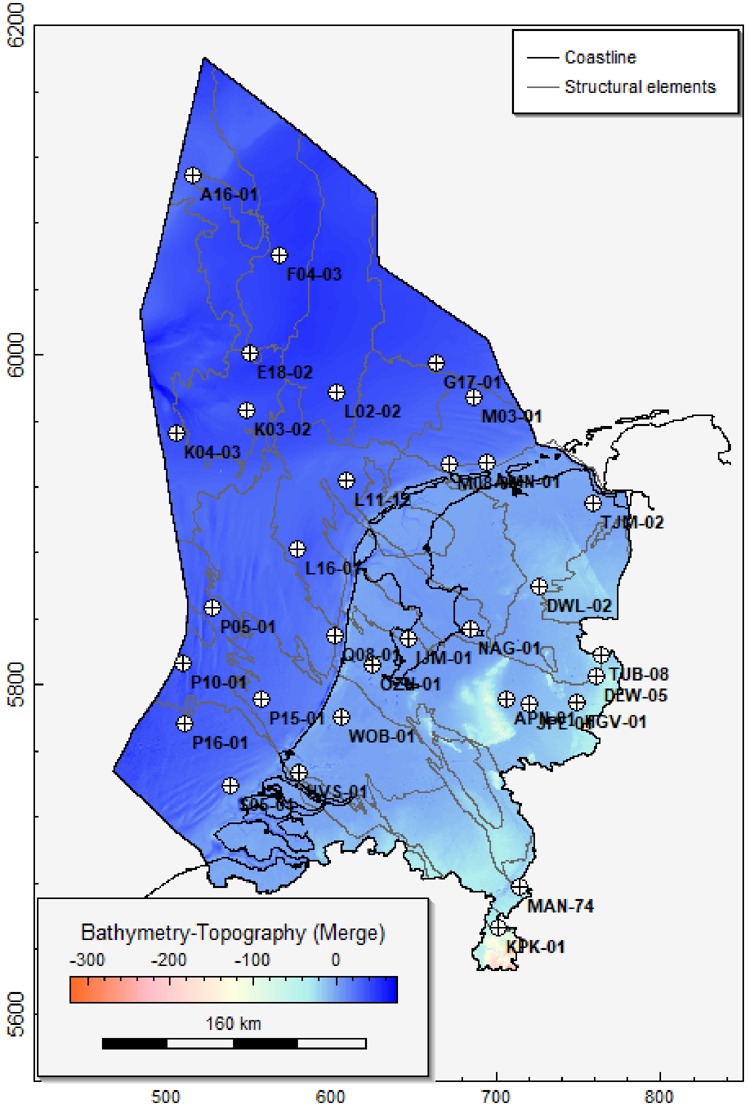
1-D MODELLING

This section describes the input data, model boundary conditions and the rational followed for the calibration of the thermal-burial model and sensitivity testing.

1-D Modelling

Introduction

- ❖ Thirty-two (32) boreholes have been selected for the calibration of the thermal-burial model, based on que quality of the temperature and maturity data, and covering the structural segmentation of the margin.
  - ➢ Fifteen (15) new boreholes have been modelled for this study, fourteen (14) of which located onshore and one offshore.
  - ➢ Seventeen (17) boreholes have been revised from the offshore model (IGI, 2019).
- ❖ Different model scenarios have been tested, based on previous studies and tectonic hypothesis for the evolution of the Netherlands:
  - ➢ Saalian erosion with high early Permian thermal doming
  - ➢ Maximum Mid Kimmerian erosion
  - ➢ Mid Kimmerian erosion with Mid Jurassic thermal doming
- ❖ All scenarios assume a base lithosphere temperature boundary condition, which accounts for transient heat effects associated sedimentation, exhumation, rifting.

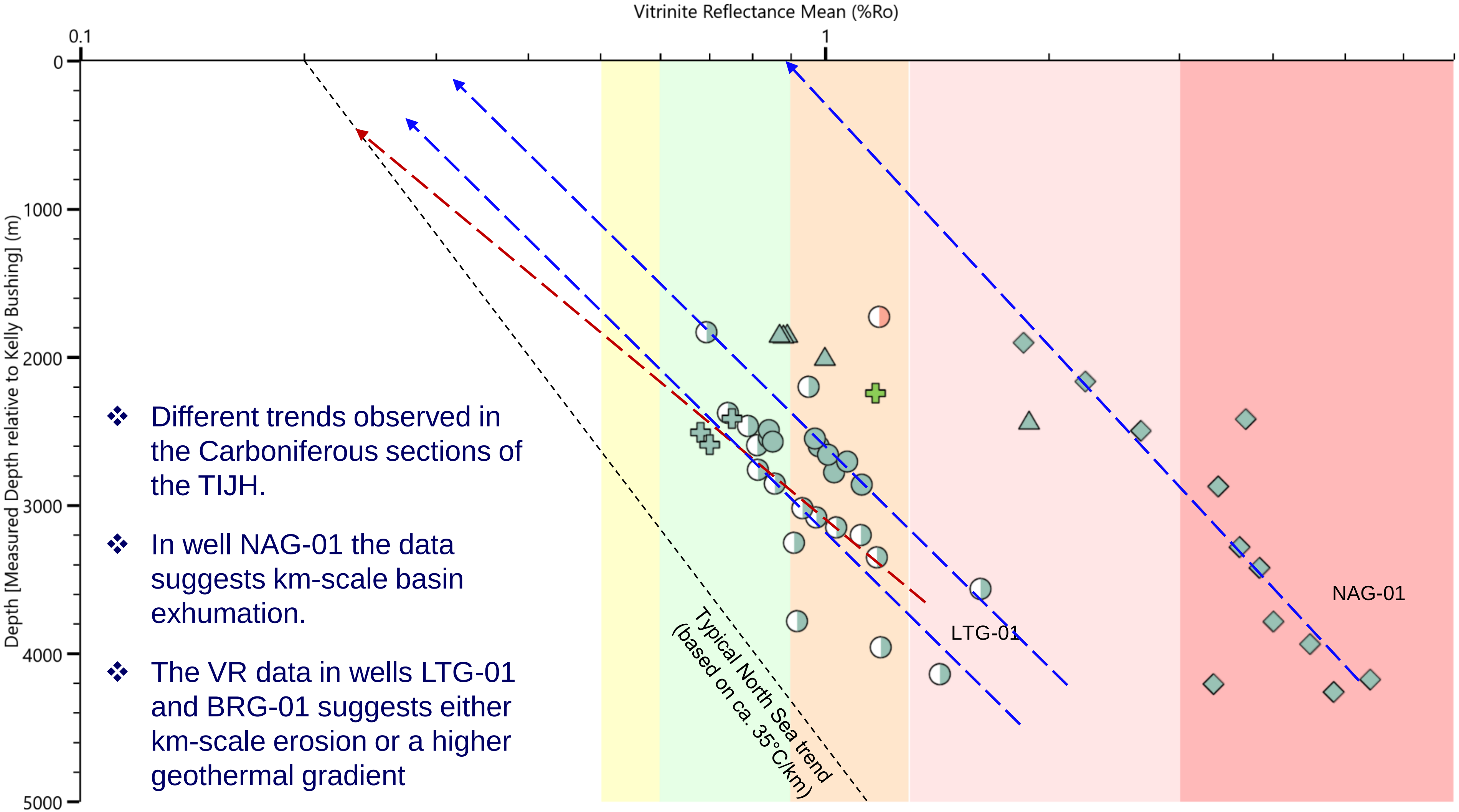


1-D Modelling

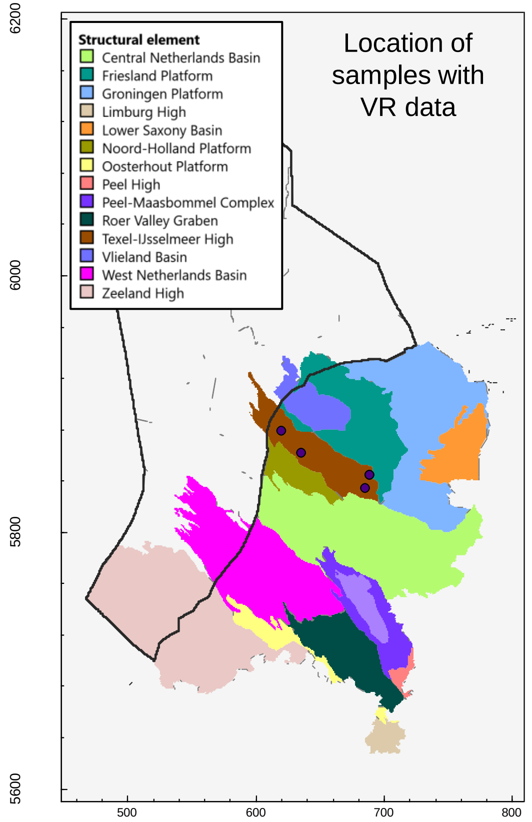
Vitrinite reflectance (VR) vs. Depth

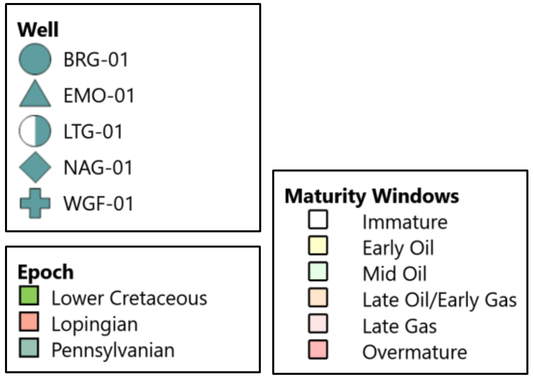
Texel-IJsselmeer High (TIJH)

coloured by chronostratigraphy



- Different trends observed in the Carboniferous sections of the TIJH.
- In well NAG-01 the data suggests km-scale basin exhumation.
- The VR data in wells LTG-01 and BRG-01 suggests either km-scale erosion or a higher geothermal gradient





1-D Modelling

Stratigraphy, Lithologies and Burial Model

Well NAG-01 (TIJH)

- Well NAG-01 was selected because it provides a good set of temperature and vitrinite reflectance measurements for calibration.
- The 2-D reconstructions suggest:
  - < 300 m Laramide erosion
  - ~ 2.5 km Mid Kimmerian erosion
  - ~ 1 km Saalian erosion
- Four different scenarios are tested:
  - The SCAN (2019) 1-D model, which combines high Saalian with high early Permian heat flux;
  - High to very high Saalian erosion
  - High to very high Mid Kimmerian erosion
  - High Mid Kimmerian erosion with high Mid Kimmerian heat flux

- stratigraphy from the NLOG Oil and Gas Portal;
- Beyond TD from grids
- Formations and acronyms from DINOloket (TNO)

Fm. Name	Top/thickness	Ages	Type	Lithology
Quater. Undiff. (NU)	0	0	N	sh5,si5,ss85,co5
Maassluis Fm (NUMS)	210	1.6	N	ls70,sh20,ss10
Oosterhout Fm (NUOT)	300	2.588	N	si70,sh20,ls10
Breda Fm (NUBA)	340	5.2	N	sh80,ss20
Savian U/C Ero	664/-200	16.3	E	ss50,sh50
Savian U/C Dep	664/200	21.5	D	ss50,sh50
Rupel Clay Mb (NMRFC)	664	28.1	N	sh90,si10
Vessem Mb (NMRFV)	742	29.3	N	sh34,ss33,si33
Pyrenean U/C Ero	783/-100	33.9	E	ss50,sh50
Pyrenean U/C Dep	783/100	38	D	ss50,sh50
Asse Member (NLFFB)	783	42.1	N	sh90,ss10
Brussels Sand Mb (NLFFS)	824	47	N	sh10,ss90
Ieper Mb (NLFFY)	913	50	N	sh90,si10
Basal Dongen Sand Mb (NLFFD)	1100	55	N	sh10,ss90
Landen Clay Mb (NLLFC)	1118	56.5	N	sh100
Laramide U/C Ero	1147/-100	60.5	E	ss50,sh50
Laramide U/C Dep	1147/100	72.1	D	ss50,sh50
Ommelanden Fm (CKGR)	1147	80	N	ch80,ml10,ls10
Texel Fm (CKTX)	1472.5	93.9	N	ls50,ch25,ml25
Upper Holland Marl Mb (KNGLU)	1525.5	113	N	ml90,ls10
Kimmerian U/C Ero	1614/-3000	139.8	E	ss50,sh50
Kimmerian U/C Ero	1614/3000	163.5	D	ss50,sh50
Permian Hiatus	1614/0	240	H	ss50,sh50
Saalian U/C Ero	1614/-1300	270	E	ss50,sh50
Saalian U/C Dep	1614/1300	290	D	ss50,sh50
Ruurlo Fm (DCCR) - SP2	1614	308	N	sh78,ss20,co2
Baarlo Fm (DCCB)	1880	312	N	sh68,si15,ss15,co2
Up Epen Mb (DCGET inf.) - Top SP1	2438	318	N	si10,sh70,ss20
Ubachsberg Member (DCGEU)	2622	320	N	ss80,si20
Main Epen Mb (DCGE - inf.)	2656	322	N	sh75,ss25
Volcanic Dyke	2772	330.5	N	ig100
Main Epen Mb (DCGE - inf.)	2776	330.9	N	sh75,ss25
base	4303	332.9		

Type of event	
N	Preserved layer
H	Hiatus
E	Eroded
D	Deposited

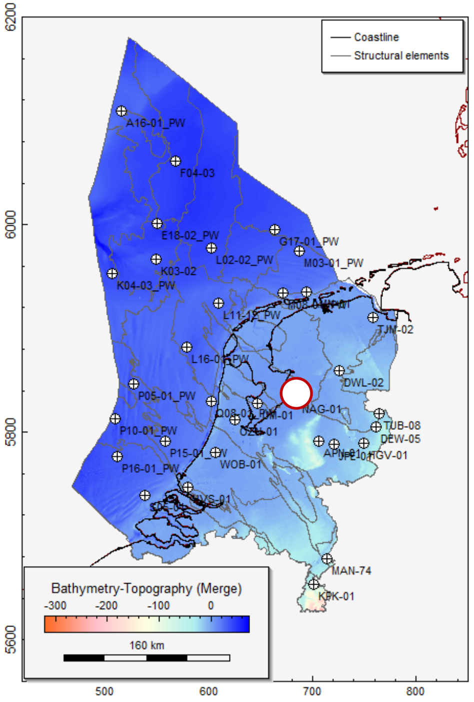
Lithology	
sh	**Shale**
si	**Silt**
ss	**Sand**
ml	**Marl**
ls	**Limestone**
do	**Dolomite**
gy	**Gypsum**
an	**Anhydite**
sa	**Salt (halite)**
co	**Coal**
ig	**Igneous**

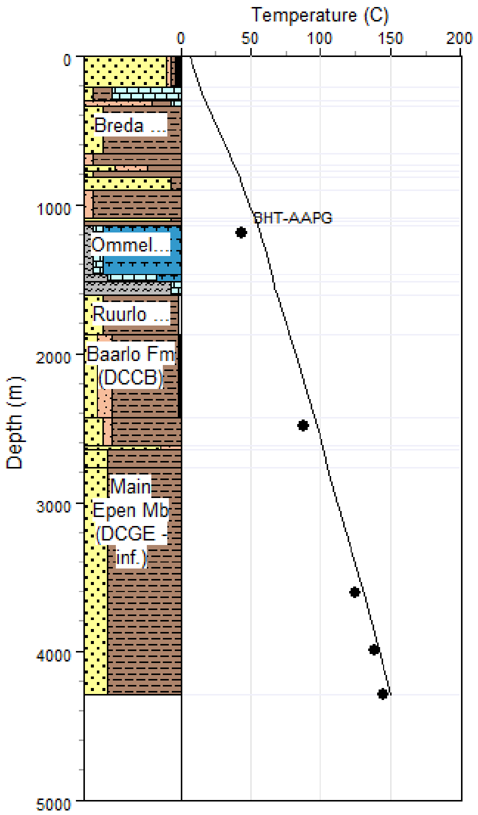
IGI

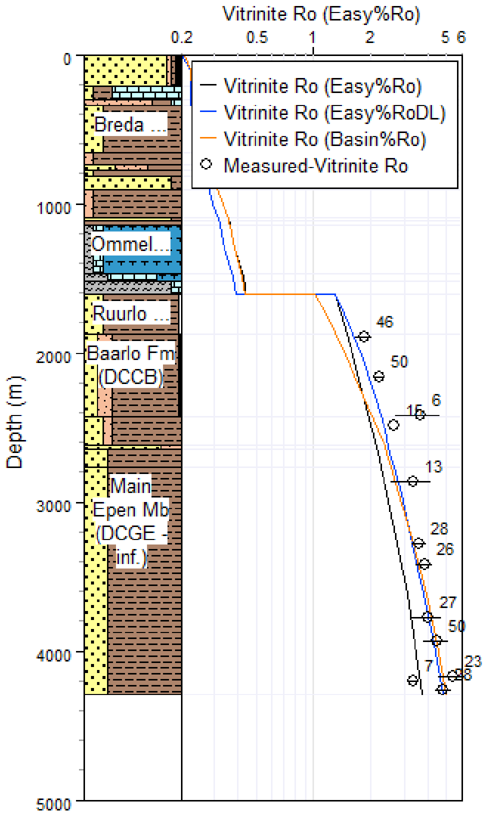
1-D Modelling

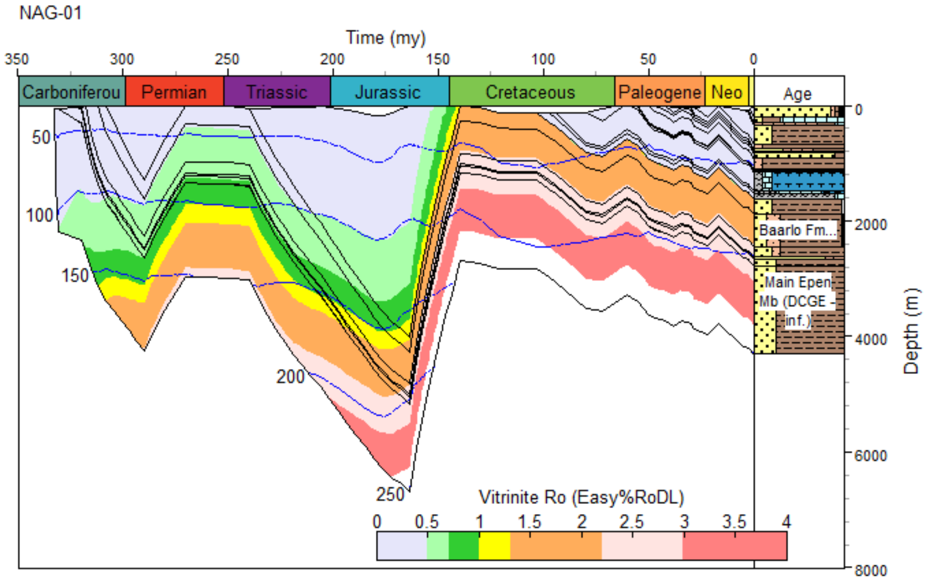
Maximum Mid Kimmerian Erosion Model

Well NAG-01 (TIJH)









- ❖ Good fit to the Carboniferous VR data trend.
- ❖ 4 km is approximately the maximum Mid Kimmerian erosion inferred from 2-D structural reconstructions in the highs of the northernmost CNB (SCAN-2019).

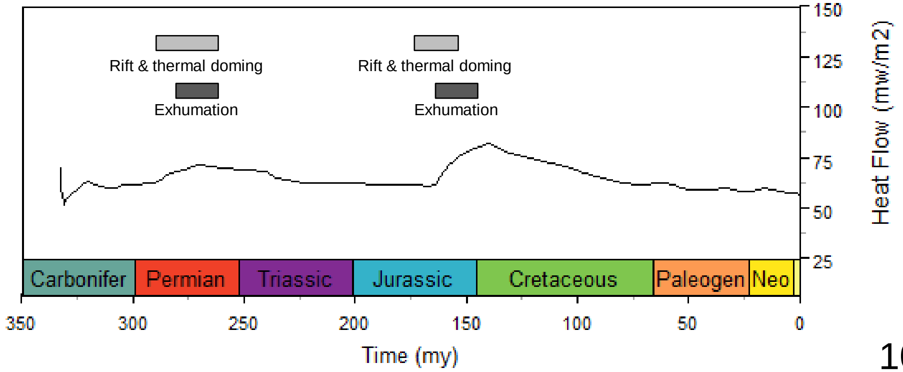
Layer	Thickness (km)
Up. Crust	14 (20)
Low. Crust	11 (15)
Mantle lid	80 (90)

Approximate original thickness in brackets

Thermal uplift	Mantle th.
Saalian (305-270)	1.8 (62)
Kimm. (170-154)	2.0 (62)
DDS-factor = 0.5	

Av. Geoth. Grad.: 37.3 °C/km
Present surf. HF: 59.9 mW/m²

Period	Erosion (m)
Savian	200
Pyrenean	100
Laramide	200
Kimmerian	**4000**
Saalian	1300

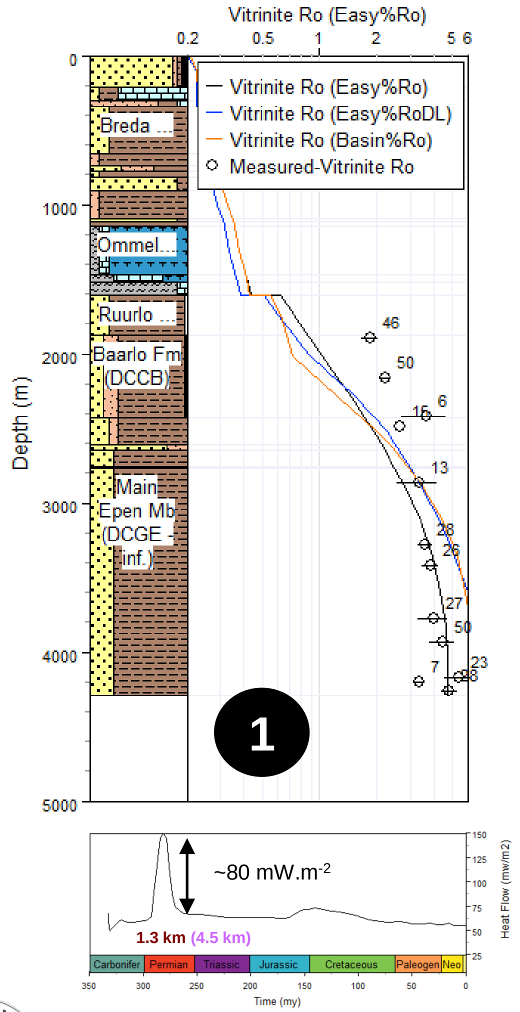


1-D Modelling

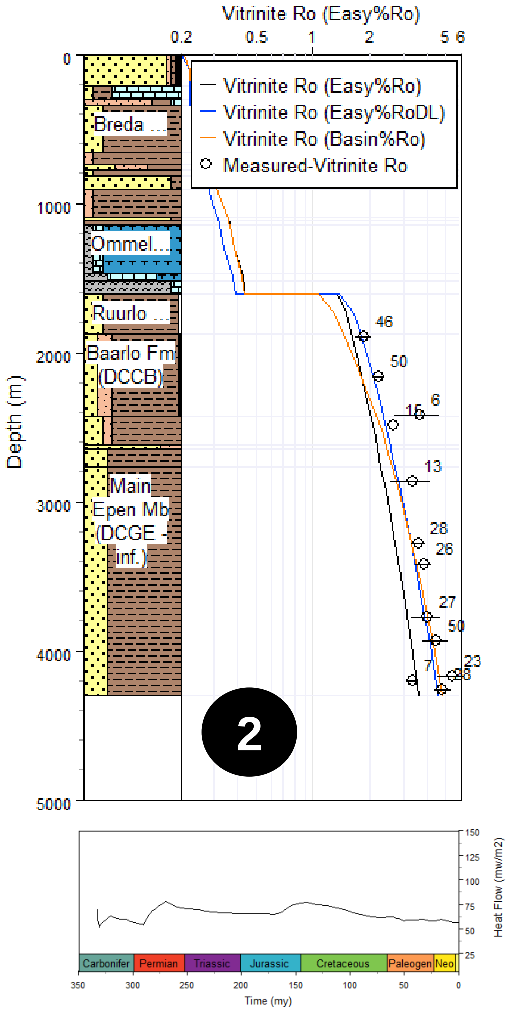
Well NAG-01 (TIJH)

Summary of Tested Scenarios: Calibration to VR Data

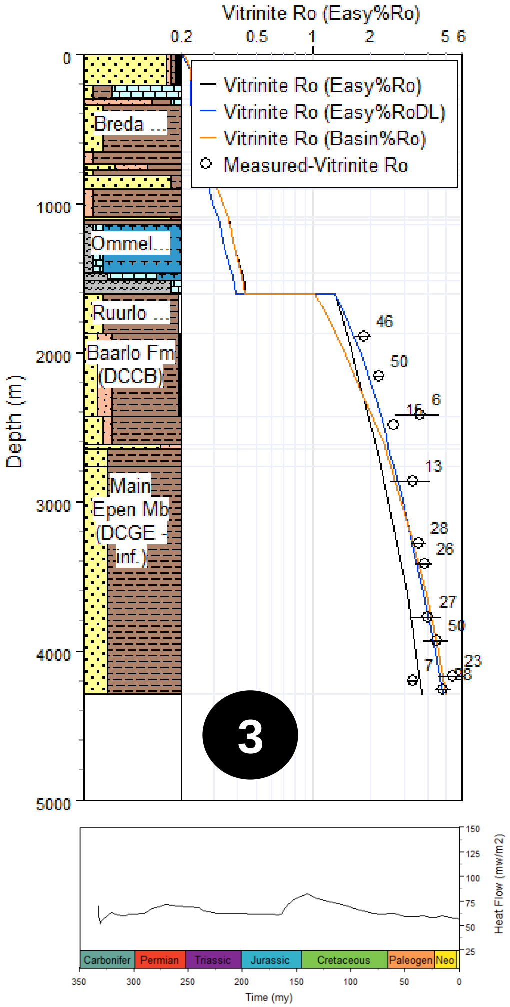
Saalian (1300 m) erosion
with peak Permian heat flux



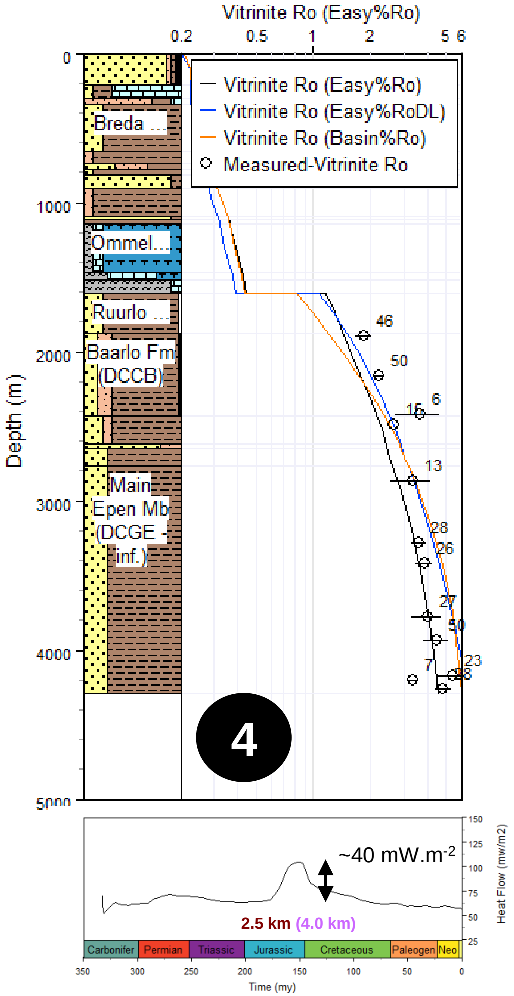
High Saalian erosion (4800 m)



High Mid Kimmerian
erosion (4000 m)



Kimmerian erosion (2500 m)
with elevated Jurassic heat flux



- The maximum erosion models provide the better fits to the trend in the Carboniferous VR data.
- Combined erosion and high basement HF in the Mid-Late Jurassic is in good agreement with the 2-D structural reconstruction.

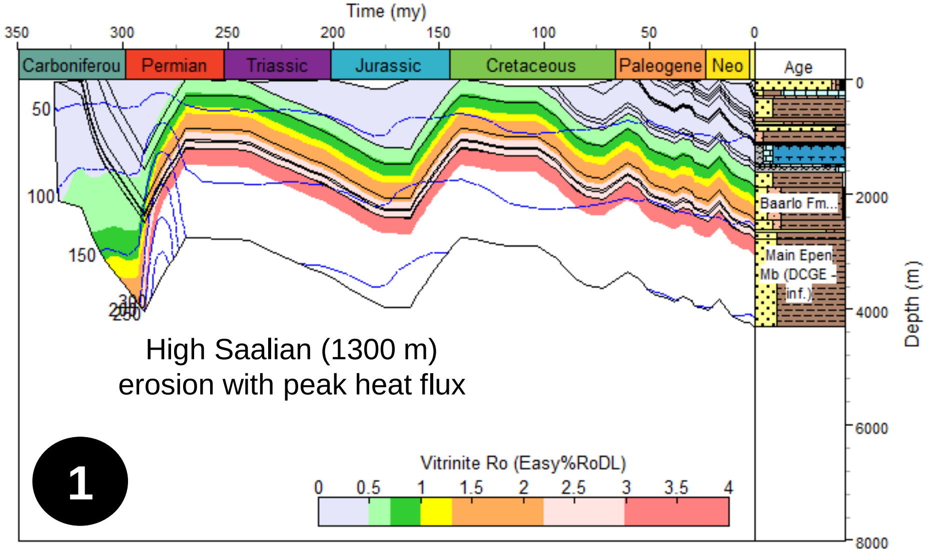
1-D Modelling

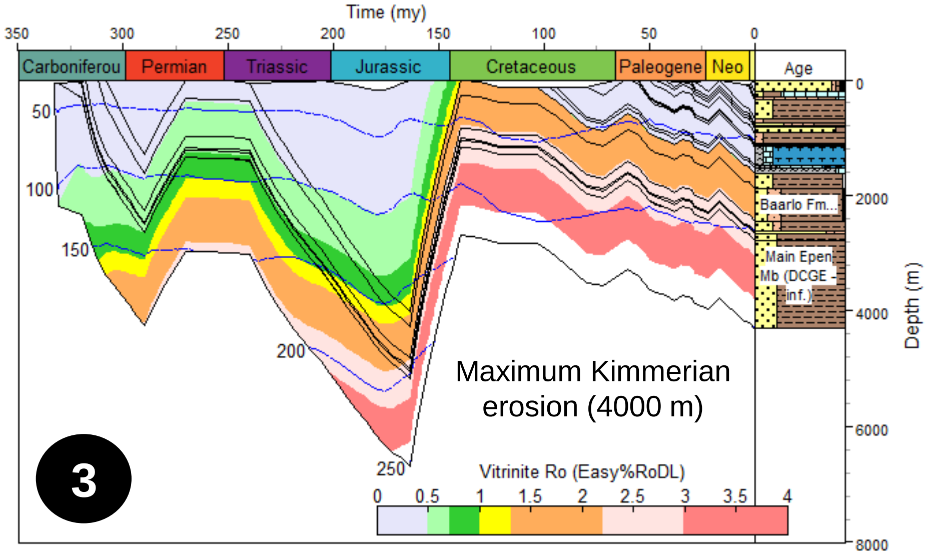
Summary of Tested Scenarios: Predicted Easy%RoDL Basin Maturity

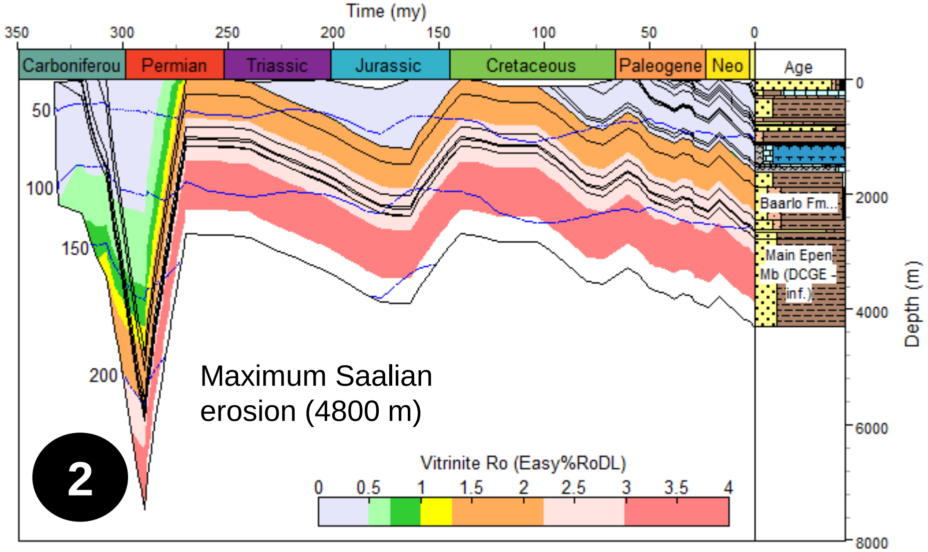
- The higher erosion models increase the maturity of the whole buried sediment column.

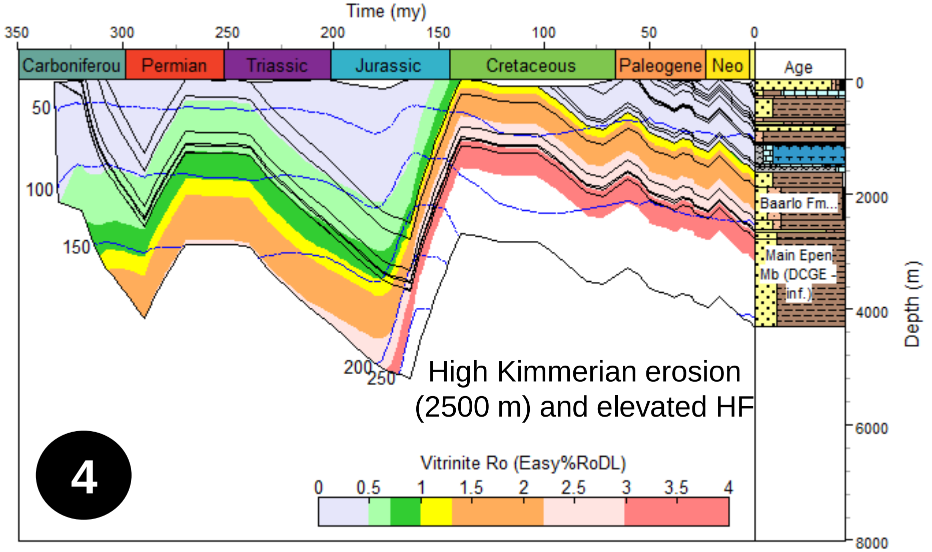
- The high heat flux models result in higher maturity of the deeper sediments, with the temperature fading upwards.

- Hypothesis 1 and 3 are better supported by data and previous models and are representative of the tested scenarios.



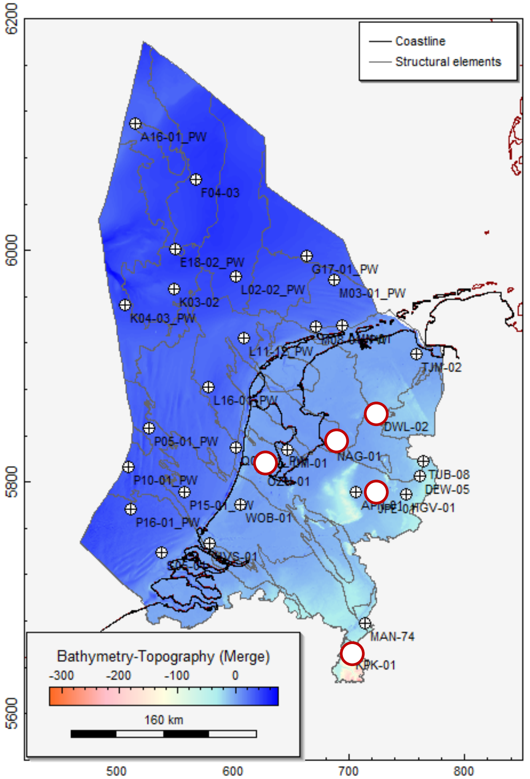


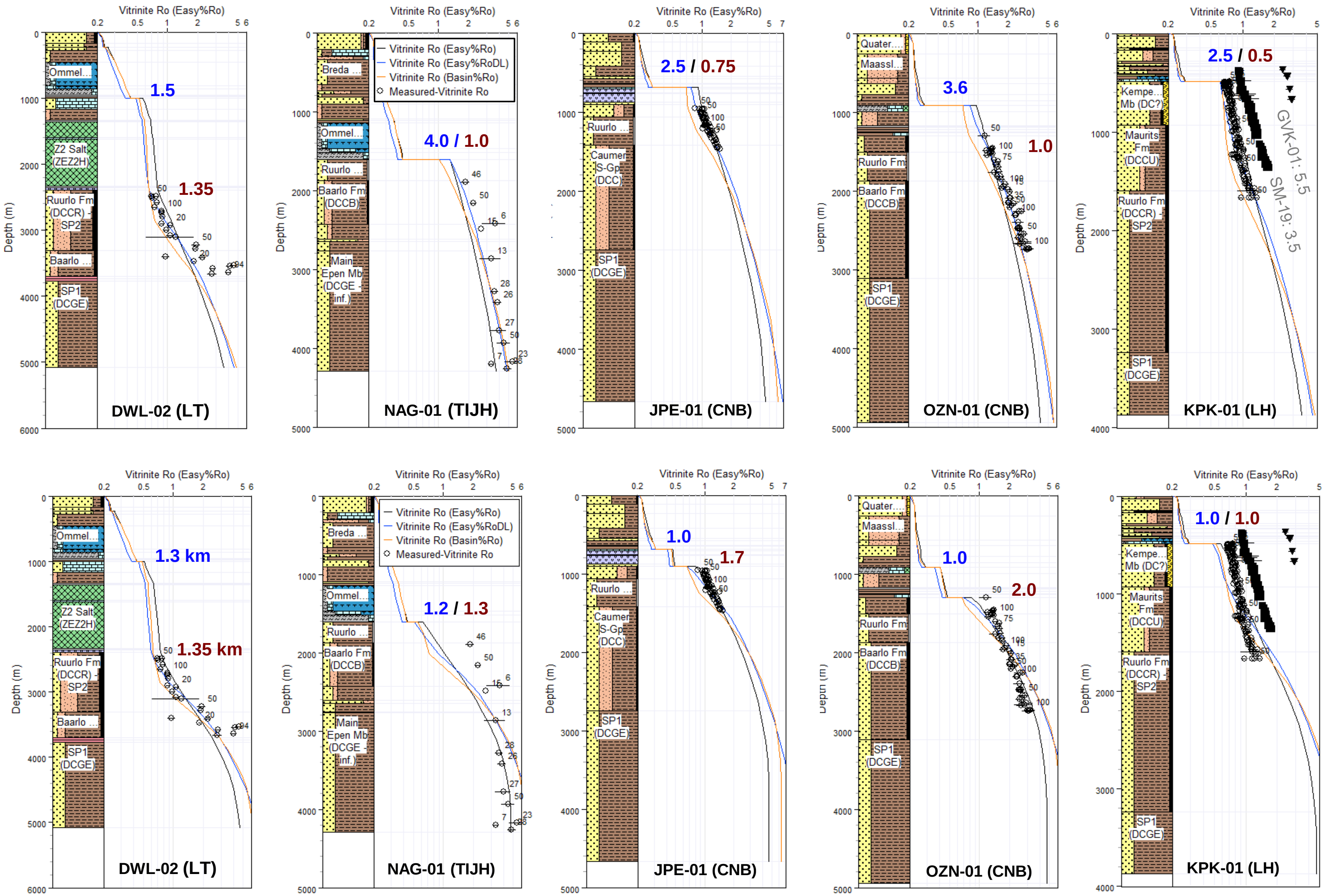




1-D Modelling

Maximum Mid-Kimmerian Vs Saalian Erosion + Permian Thermal Doming



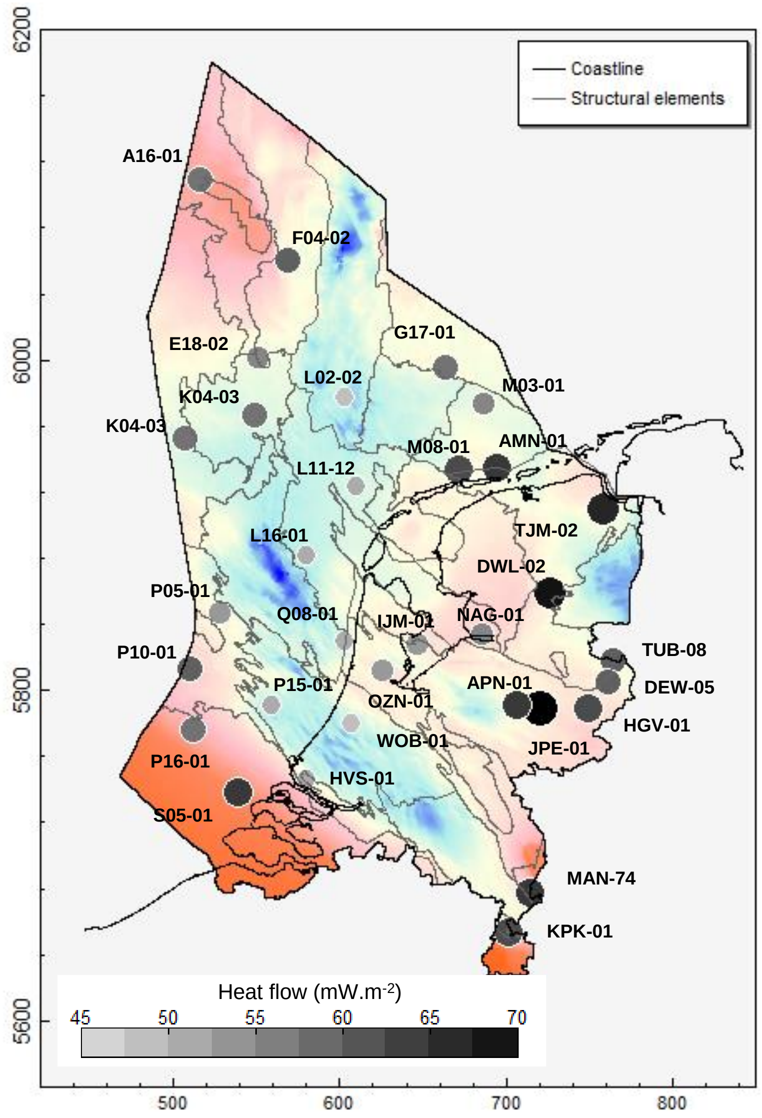


- ❖ The maximum erosion models explain better the VR data trends.
  - ❖ The Mid-Kimmerian erosion model is in better agreement with seismic-based erosion estimates.

1-D Modelling

Predicted Heat Flow and Main Conclusions

- ❖ Good calibration to temperature and maturity at most borehole locations (see **Appendix I** for the 32 modelled boreholes).
- ❖ Models show laterals variations in the Present-day heat flow that are broadly consistent with the structural setting.
- ❖ The range of predicted heat flow values across the Netherlands, between 45 and 70 $mW.m^{-2}$, is within the range of values predicted in previous studies; highest values (>65 $mW.m^{-2}$) likely associated with local anomalies.
- ❖ The VR data at numerous wells implies higher geothermal gradients in the past and/or km-scale erosion at major basin unconformities. This is also consistent with 2-D reconstructions along seismic profiles.
- ❖ The preferred tectonic model assumes higher amounts of erosion during the Mid Kimmerian event, with the amount of Saalian and Laramide erosion largely constrained by seismic interpretations and 2-D model reconstructions.



Model Setup and Calibration

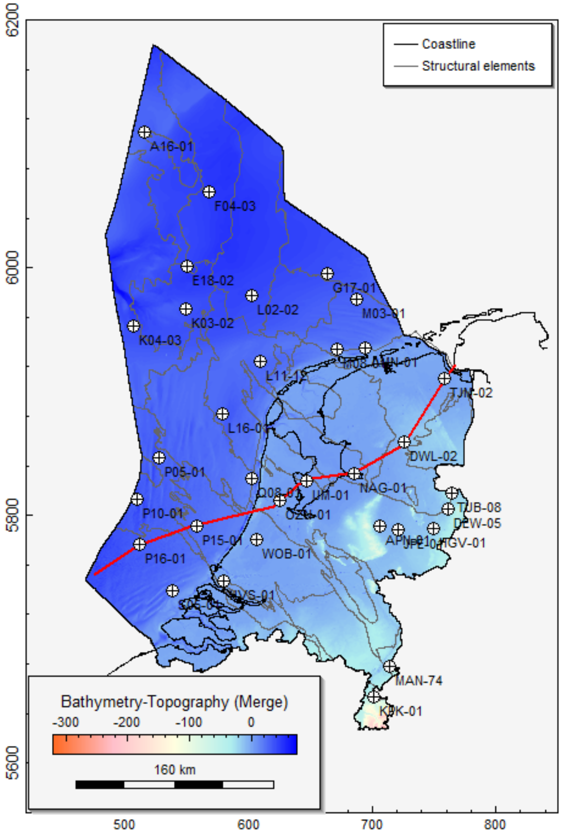
3-D MODELLING

For each source rocks horizon we provide a brief summary of the geochemical characterization and its implementation in the model. We then show the model predicted vitrinite reflectance maturity, transformation ratio, and the oil and gas expulsion volumes through time.

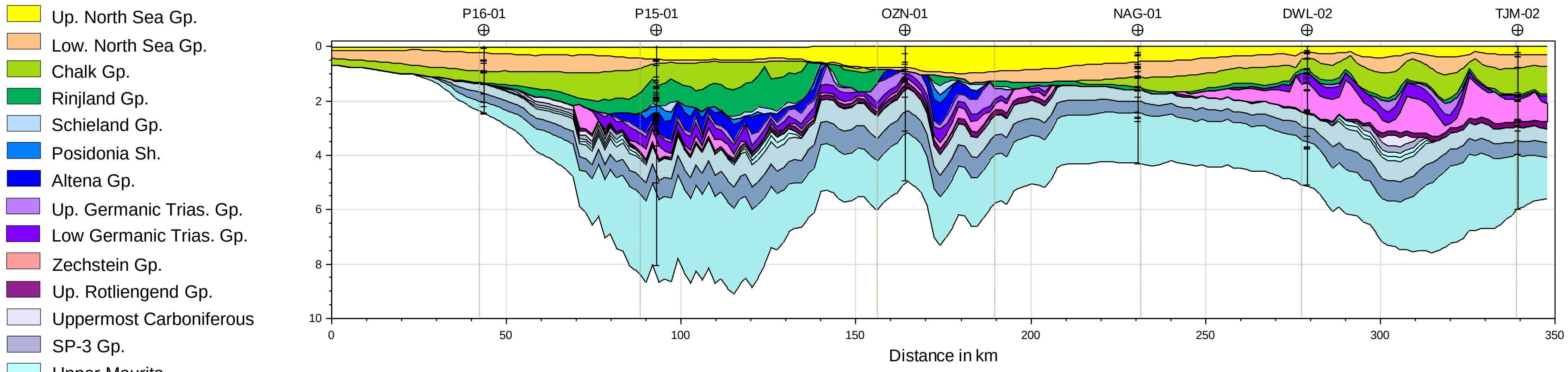
For the main source rock horizons, which are believed to have generated most of the oil (Posidonia shales) and gas (Westphalian shales and coals) discoveries in the Netherlands, we further assess the oil and gas expulsion histories within certain structural elements (Posidonia) or the drainage areas at base salt (Westphalian), and compare the expelled volumes to the known production values. We then show the model predictions for alternative tectonic and source organofacies scenarios

3-D Modelling

Model Surfaces



Bathymetry-topography map showing the coastline, the structural elements and the location of the SW-NE profiles shown to the right.

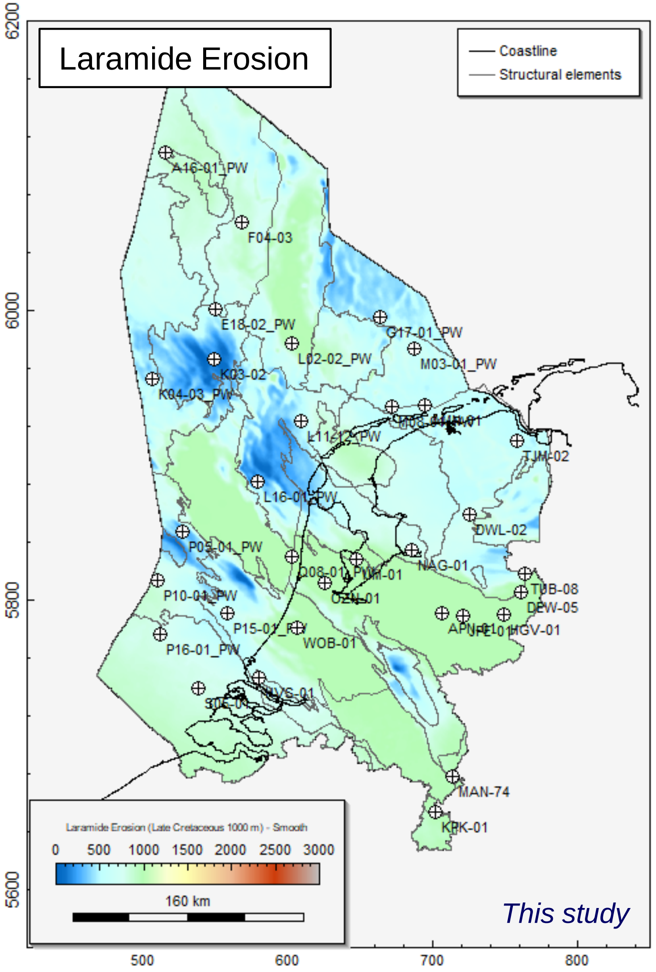


Bathymetry-topography map showing the coastline, the structural elements and the 2 structurally reconstructed lines in the SCAN-2019 report.

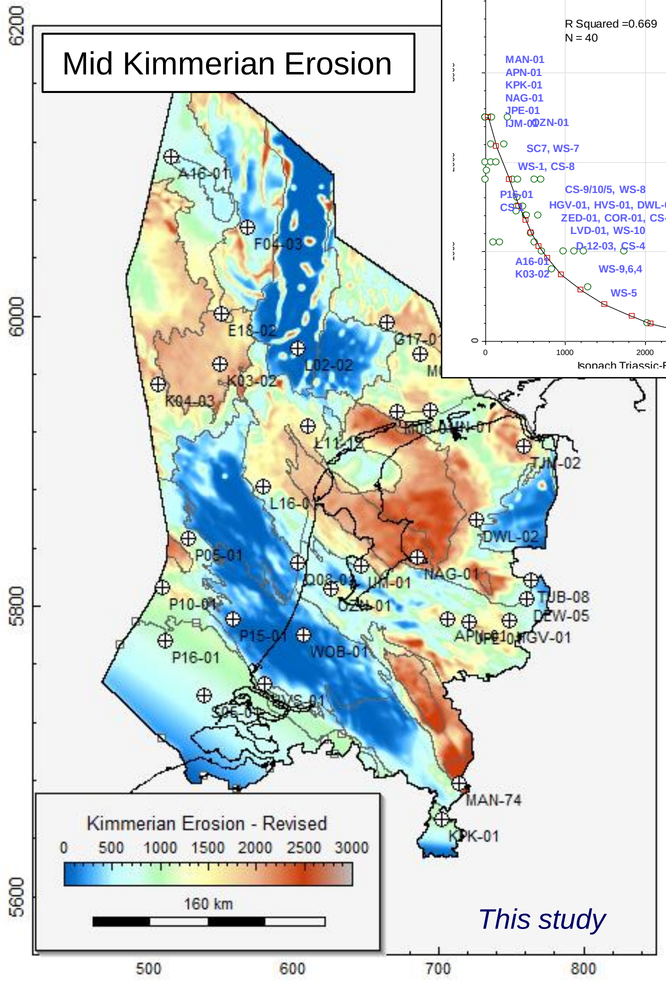
- Seventeen (17) surfaces have been provided for this study covering the whole offshore and onshore Netherlands, from models NLOG DGM v.5 (surface to Base Rotliegend) and Geode-2022 (Play 8, Carboniferous and older)
- Additional grids were added to help define SR horizons for the Top Middle Graben Coals, Mid Maurits and Mid SP2 horizon.
- The 3D Model includes the paleo-water depths and surface temperatures through time, interpolated from the 1-D models.
- The model recognises the base and top salt through time for a simple model of salt thickness change through time, assuming an initial thickness of ~400 m.

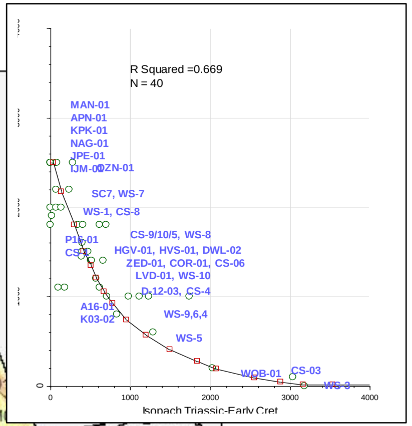
3-D Modelling

Erosion Maps for Main Regional Unconformities

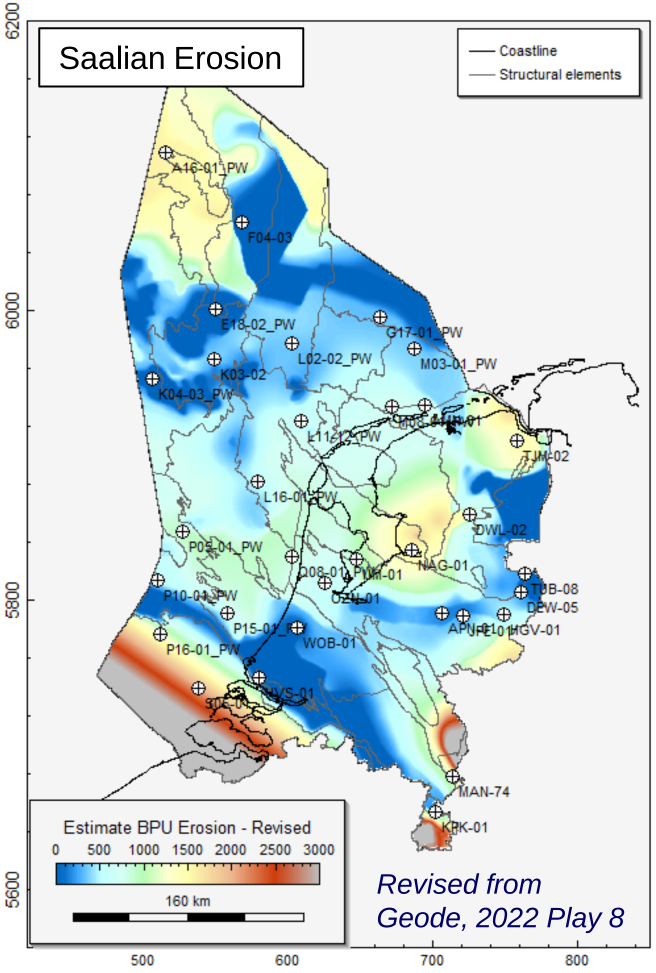


- Correlates with the Late Cretaceous isopach.
- Supported by previous studies (e.g. Central and West Netherlands basins.
- Strong in the Central and West Netherland Basins, the Zeeland Pl. and NW offshore.





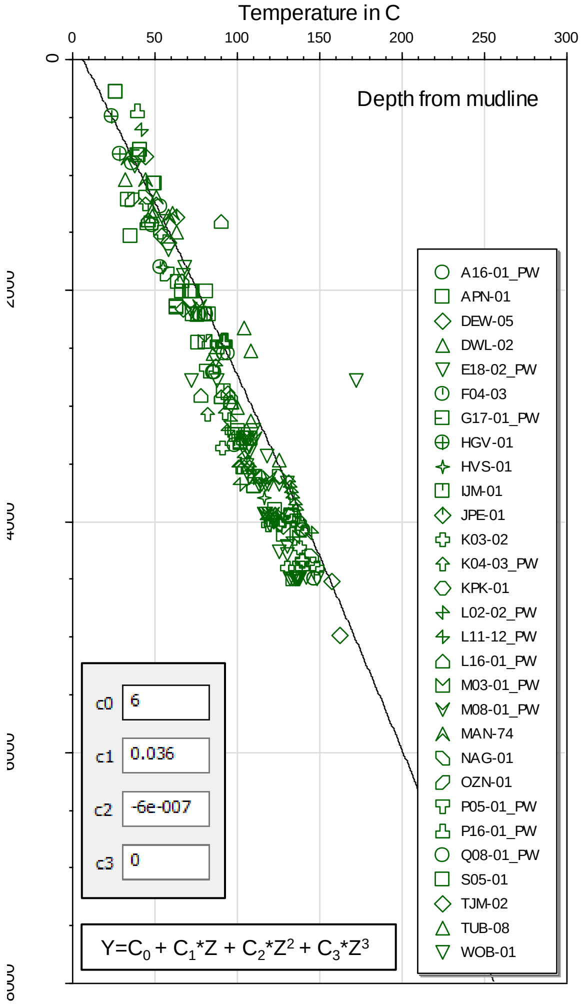
- Based on 1D models and 2D mechanical reconstructions.
- Correlates with the Trias.-Juras. isopach
- Strong in the basement highs and along the platforms.



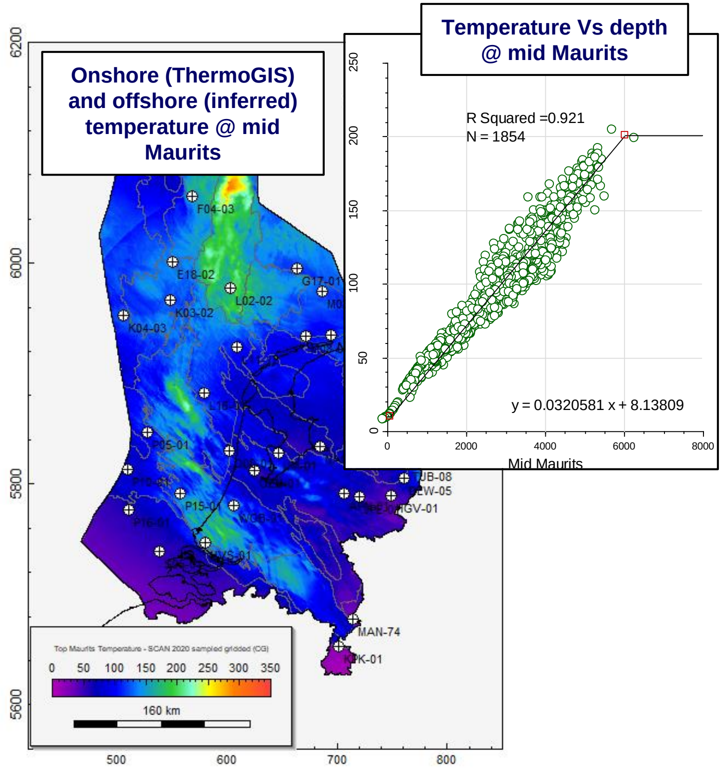
- Based on previous estimates (Geode 2022).
- Correlates with the Late Carbonif. Isopach.
- Strong in the ZP, ESH, LH, and along a SW-NE Hercynian inverted area.

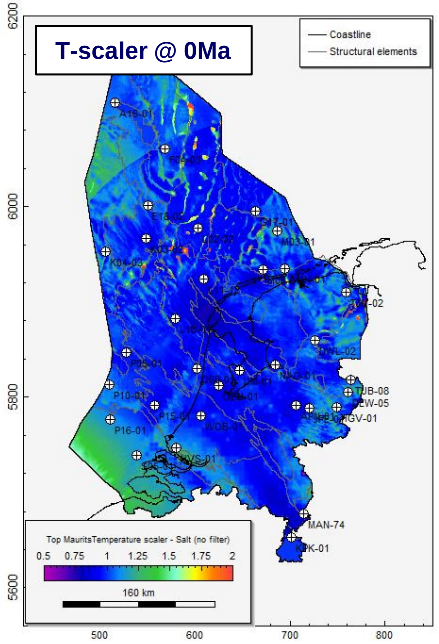
3-D Modelling

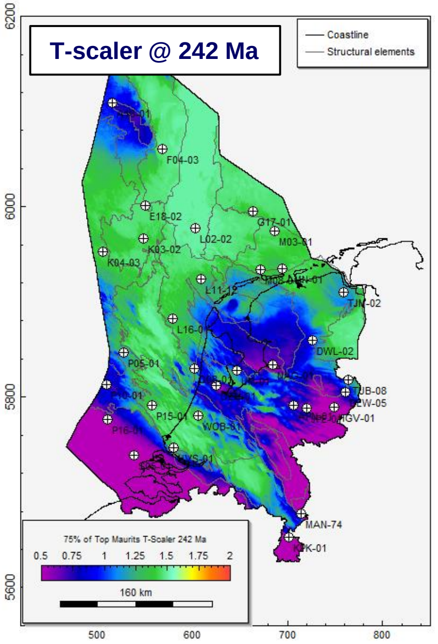
Thermal-Burial Model Calibration: Temperature Scalers

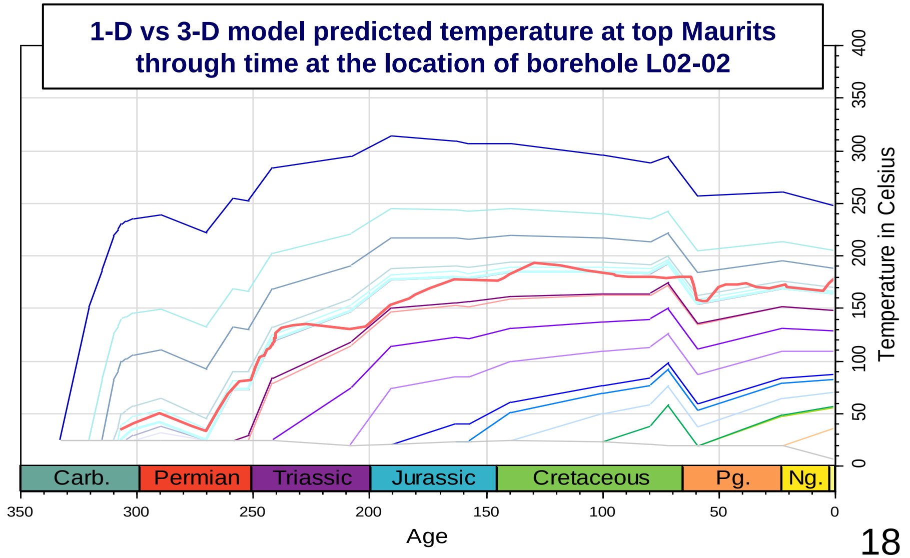


Temperature-depth curve adjusted to the borehole temperature data.



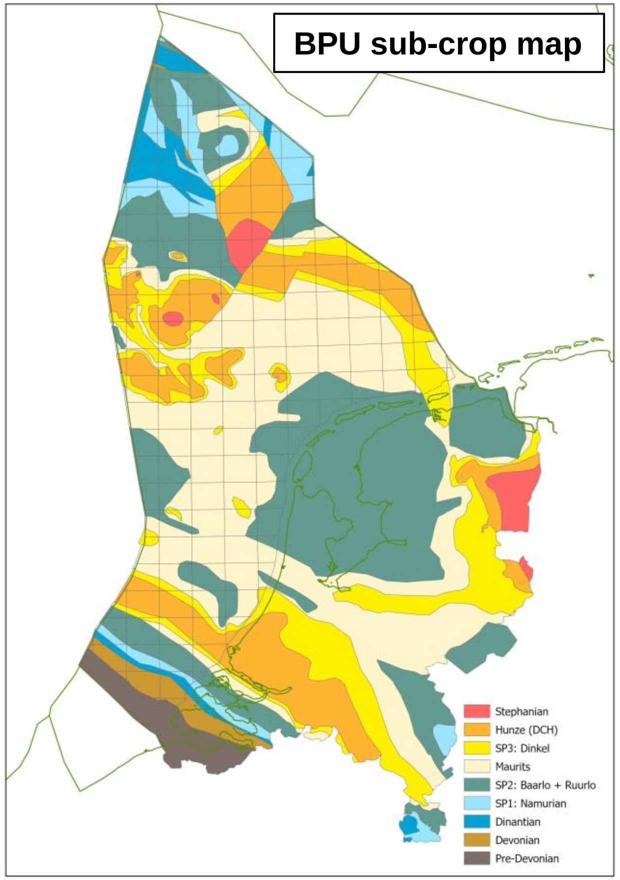






- ❖ A temperature-depth curve was defined assuming an average thermal gradient of 36°C.km^{-1}.
- ❖ For each SR horizon the calibration of the thermal-burial model was then achieved by deriving 2 temperature scalers:
  - Present-day is derived from the ThermoGIS Model
  - In the mid Cretaceous (100.5 Ma) for the Mesozoic SRs and late Permian (242 Ma) for the Carboniferous and Permian SR horizons based on correlations with the 1-D models.

IGI



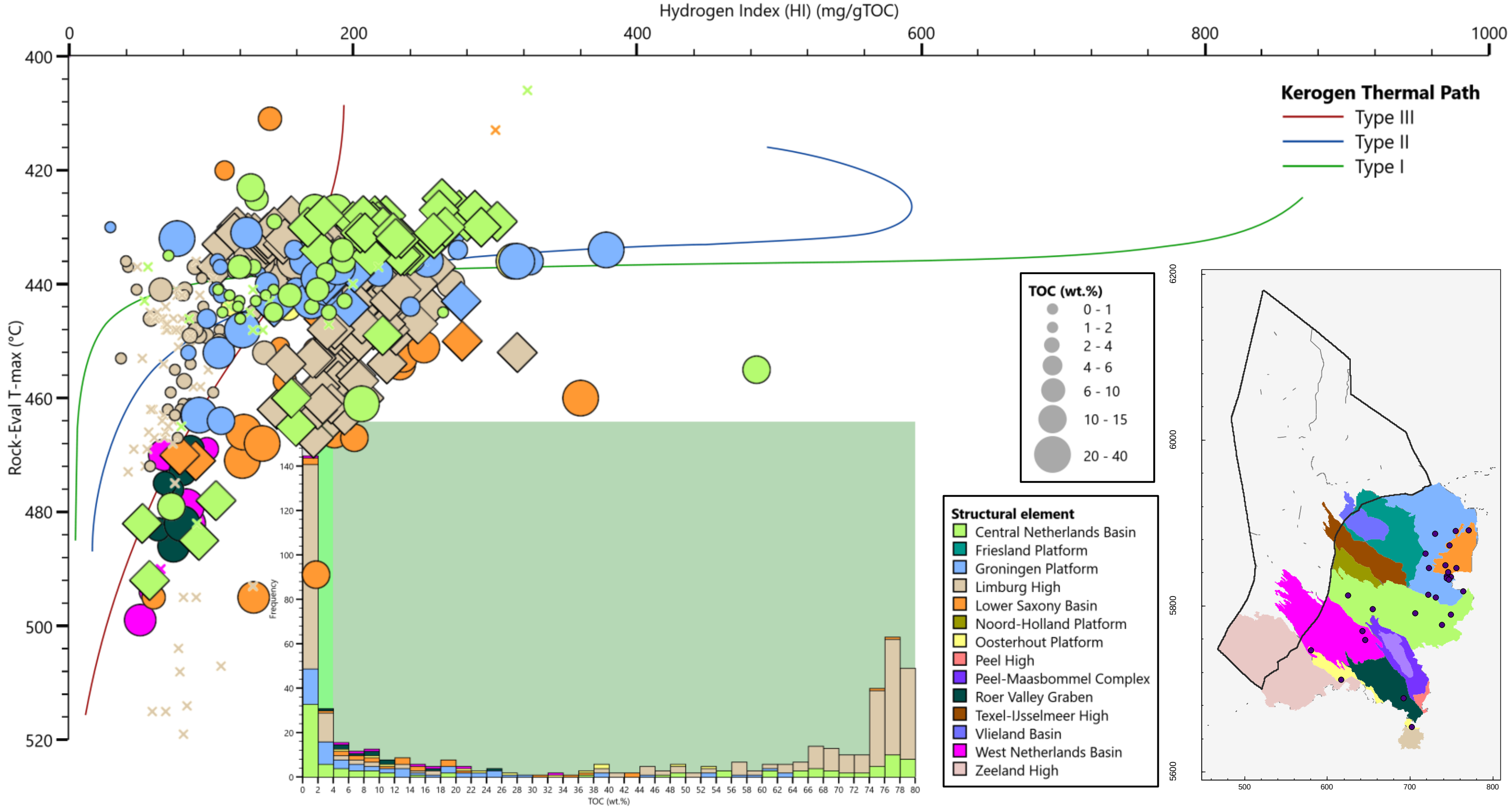
Predicted Maturity, Hydrocarbon Generation and Expulsion

WESTPHALIAN SHALES AND COALS

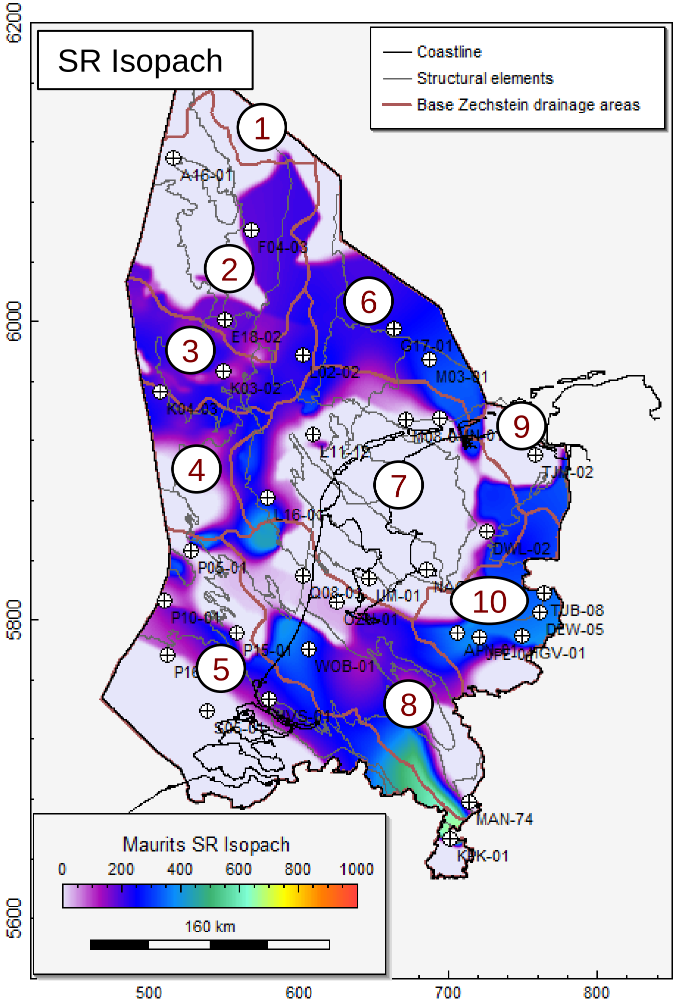
Three (3) source rock horizons have been parameterized in the Upper Carboniferous, Westphalian period, at mid Maurits, top SP-2 and Mid SP-2, to cover the variations in composition and depth range; where the SP-2 is the Carboniferous Subplay (GEODE 2022), corresponding to the Baarlo-Ruurlo Fms. The Base Permian Unconformity (BPU) sub-crop map was used to define the extent of the source rock formations. The charge history is then assessed within the drainage areas defined at base Zechstein salt, which is the regional seal, and the volumes compared with the known production gas volumes.

Maurits SR

Source Rock Thickness and Geochemical Characterization



Geochemical characterization of the Maurits SR (see accompanying geochemical report).

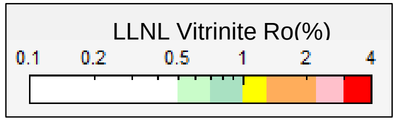


Maurits SR Isopach, assuming the whole thickness of the Maurits formation. The brown polygons are the drainage/fetch areas inferred at the base Zechstein regional seal.

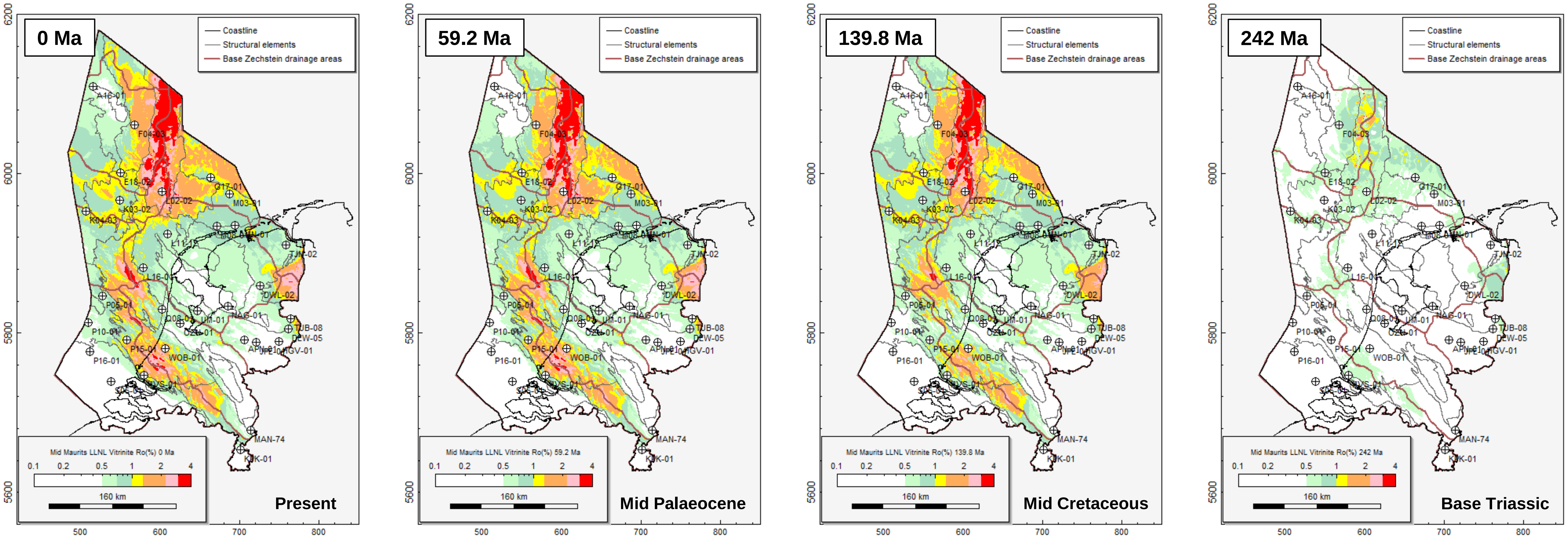
- ❖ Samples showing highly variable %TOC content and indicate a gas-prone source rock, consistent with the observations offshore for the Limburg Gp. shales and coals (IGI-2019).
- ❖ The very high %TOC values (>20%) are most likely from coal horizons.
- ❖ Maurits SR horizon parameterized as a Type D/E gas-prone SR, with an average 2.1% TOC and an HI of 200 mg/gTOC.

Maurits SR

Vitrinite Reflectance (LLNL %Ro)



Maturity-Generation-Expulsion



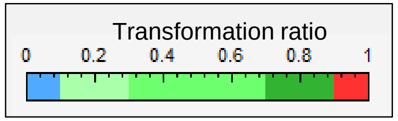
Predicted LLNL %Ro through time at mid Maurits, depicting the coastline (black line), structural elements (grey polygons), and the modelled boreholes.

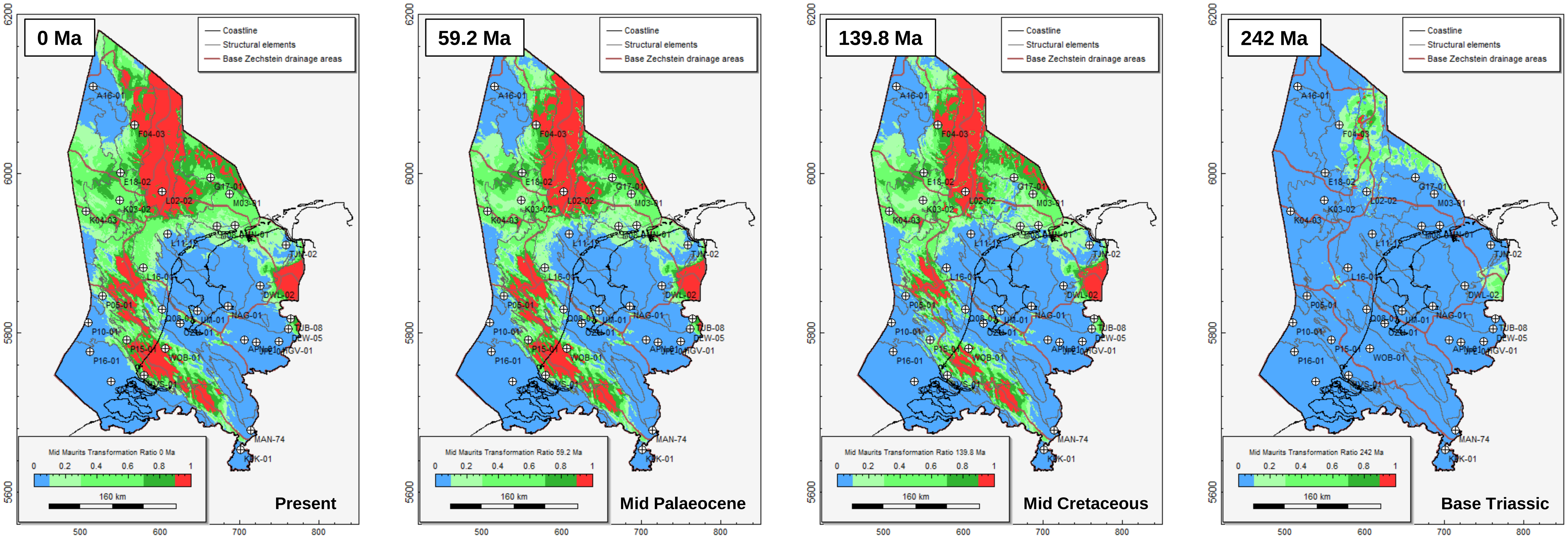
- The Mid Maurits horizon reaches oil to gas maturity, or becomes over-mature, in most places during Triassic-Jurassic burial; In the deep basins, oil to early-gas maturity is reached during the Permian (e.g. DCG, WNB and LSB).
- An increase in VR-maturity is also noticed in some basins' flanks, platforms and basement highs, during the Cretaceous and Cenozoic burial.

Maurits SR

Transformation Ratio

Maturity-Generation-Expulsion





Predicted Transformation Ratio through time for the Maurits shales and coals, depicting the coastline (black line), structural elements (grey polygons), and the modelled boreholes.

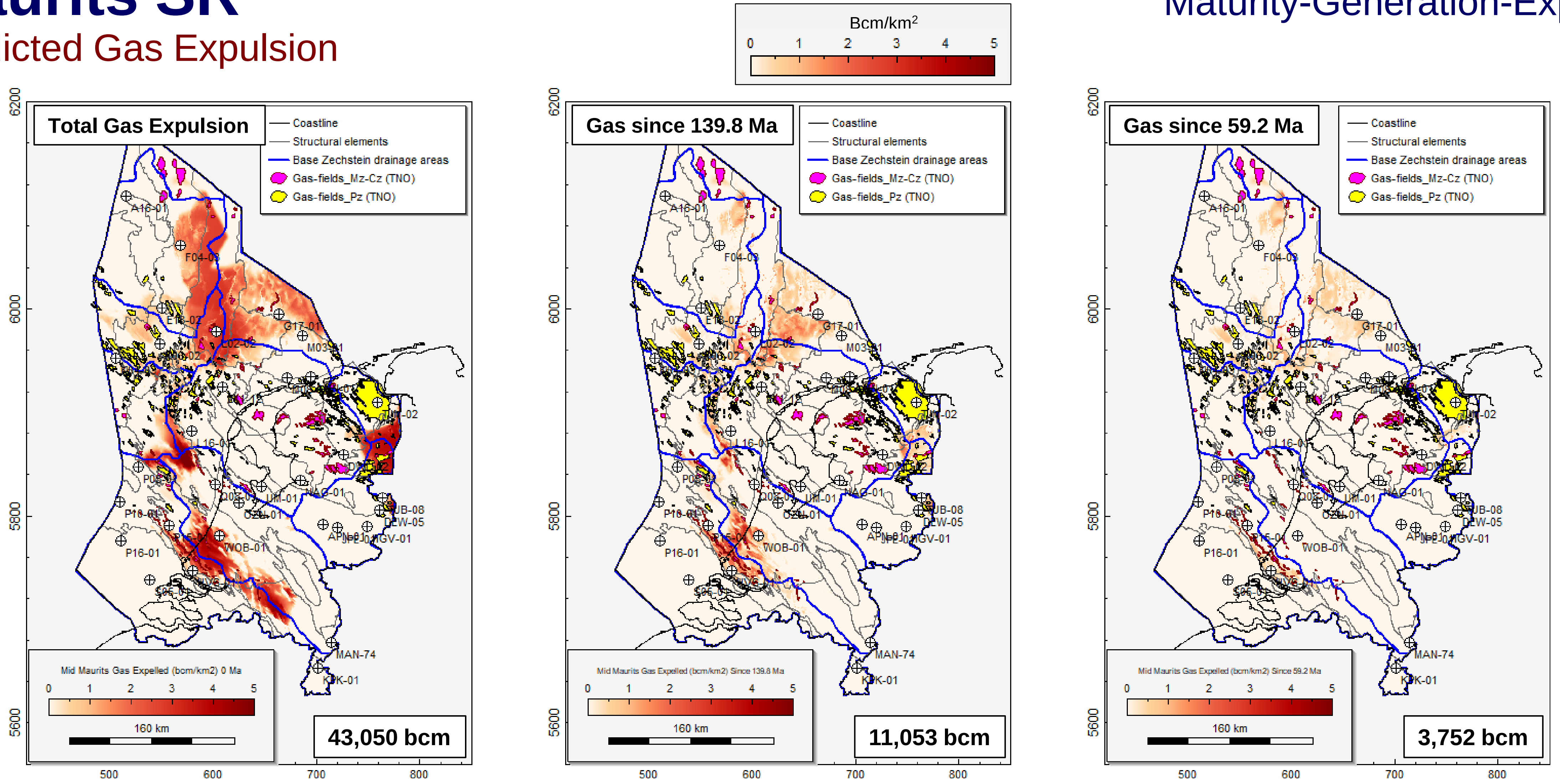
- ❖ The model suggests that most gas (or oil and gas depending on source organofacies) from the Maurits Formation is generated during Triassic-Jurassic burial, with later generation along the basin’s flanks and basements highs.

INTEGRATED GEOCHEMICAL INTERPRETATION IGI

Maurits SR

Predicted Gas Expulsion

Maturity-Generation-Expulsion



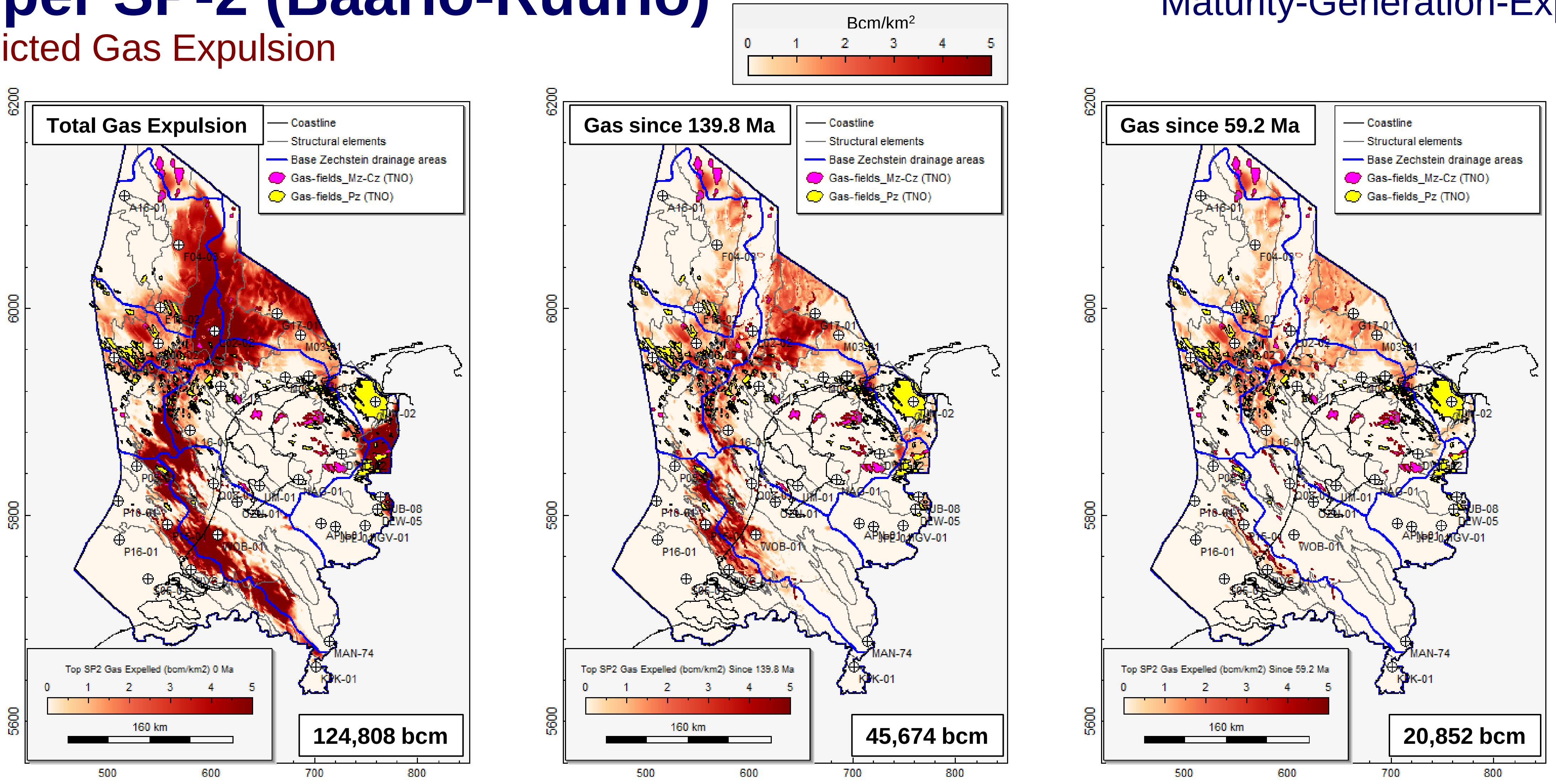
Predicted gas expulsion from the Zechstein SR, with the location of the Palaeozoic gas fields (yellow polygons).

- ❖ Abundant gas expulsion along the main depocenters, with most expulsion taking place during the Triassic-Jurassic burial.
- ❖ Cretaceous onwards expulsion focus on the WNB and OP, and along the flanks of the BFB and DCG.

Upper SP-2 (Baarlo-Ruurlo)

Predicted Gas Expulsion

Maturity-Generation-Expulsion

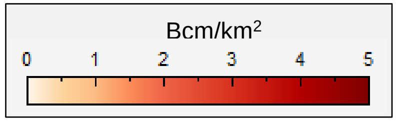


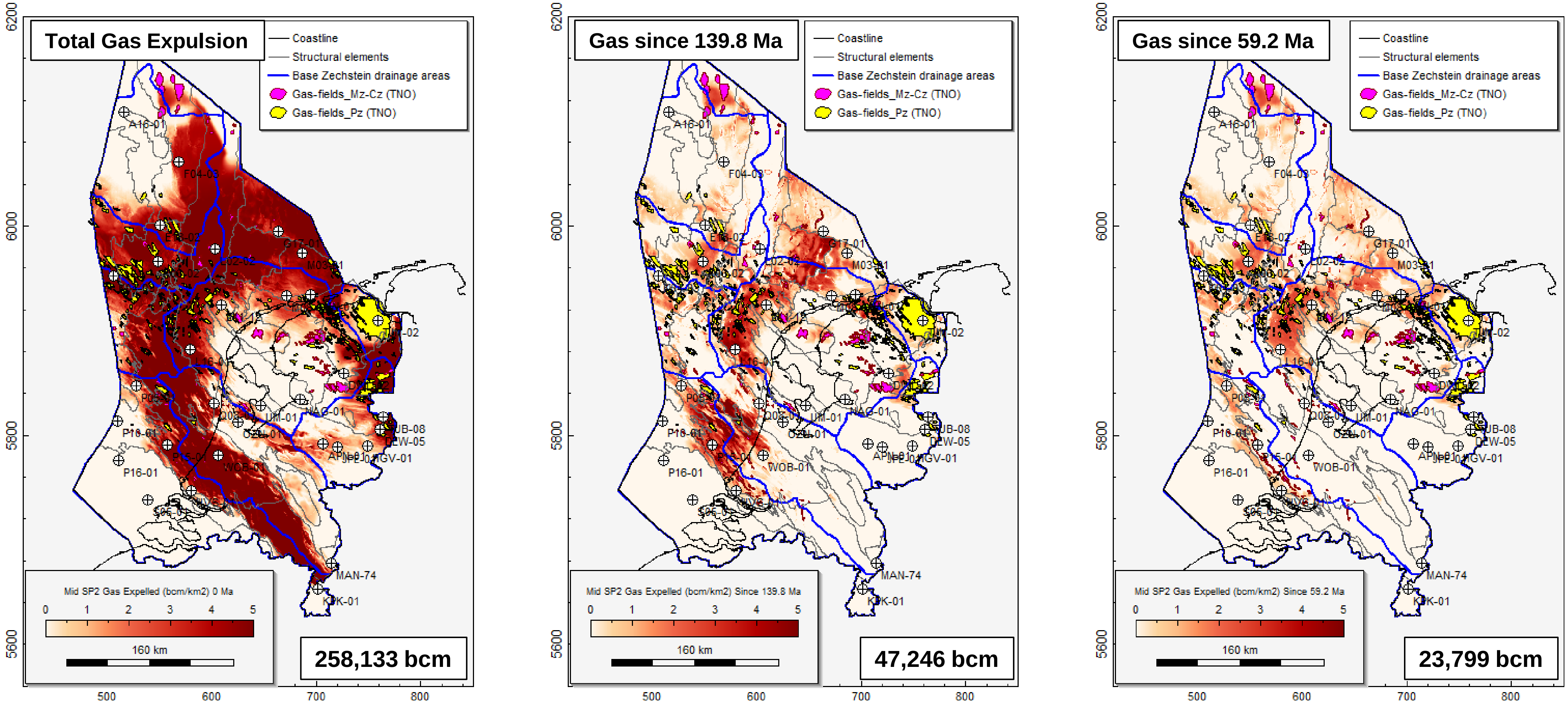
Predicted gas expulsion from the Zechstein SR, with the location of the Palaeozoic gas fields (yellow polygons).

- Abundant gas expulsion along the main depocenters, with approximately 37% since the Cretaceous.
- Abundant Cenozoic expulsion in the southern DCG and surrounding highs (CBH, COP), where a large number of gas fields are located, and in the Groningen Platform and Ameland Block.

Lower SP-2 (Baarlo-Ruurlo)

Predicted Gas Expulsion





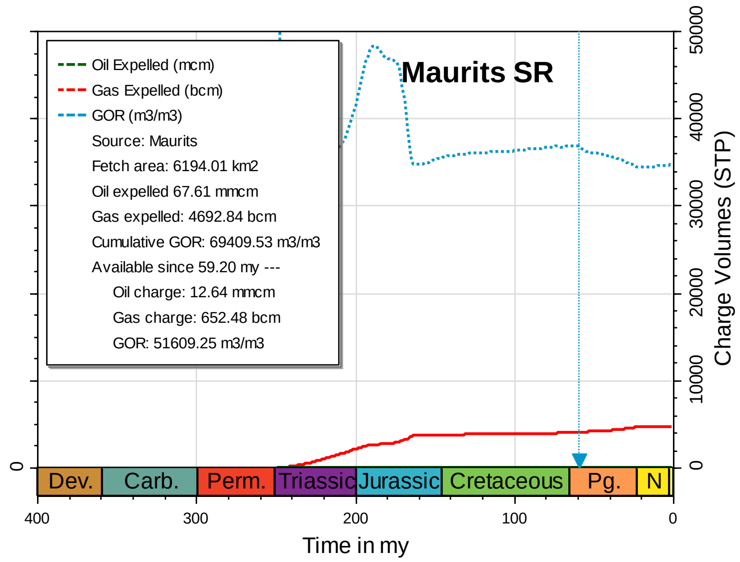
Predicted gas expulsion from the Zechstein SR, with the location of the Palaeozoic gas fields (yellow polygons).

- A similar expulsion pattern is predicted for the Lower SP-2 formation, although extending to shallower areas.
- More pervasive Cenozoic expulsion in the COP, GP and the LSB than in the upper Baarlo-Ruurlo.

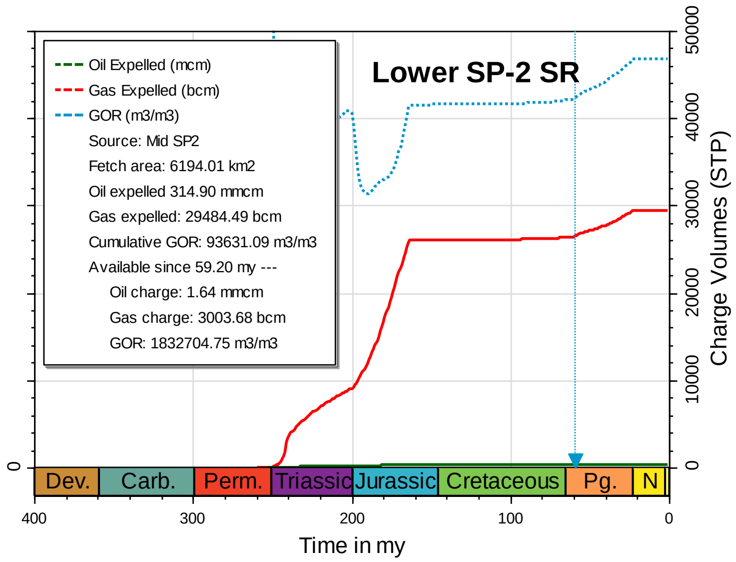
Maurits and SP-2 (Baarlo-Ruurlo)

Predicted Gas Expulsion: Drainage Area 3

- Most expulsion occurring in Triassic-Jurassic, but with large volumes during Cenozoic burial, in particular from the Baarlo-Ruurlo.
- Cenozoic expulsion from the Maurits is ca 2.5x the production.
- Combined Cretaceous onwards expulsion is *ca*. 20% of the total, and Cenozoic expulsion *ca.* 16%.



Expelled gas volumes through time for the Maurits SR in Drainage Area 3.

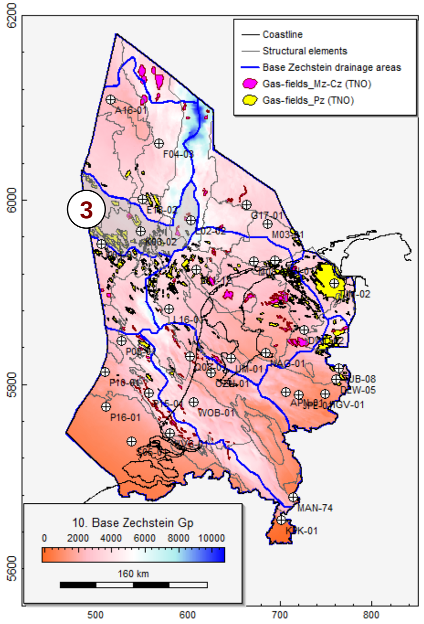


Expelled gas volumes through time for the lower Baarlo-Ruurlo SR in Drainage Area 3.

Gas fields (TNO)

Mezo-Cenozoic fields

Palaeozoic fields



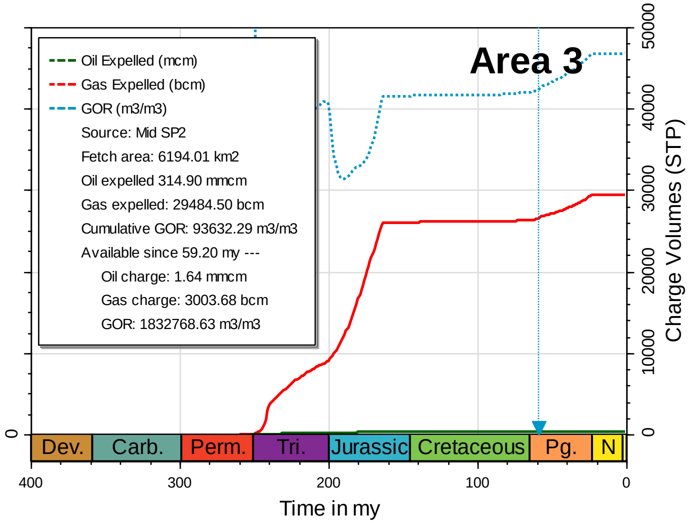
Source rock	Total Gas Expulsion (Bcm)	Gas expelled since 139.8 Ma (Bcm)	Gas expelled since 59.2 Ma (Bcm)
Maurits	4693	937	652
Upper Baarlo-Ruurlo	14250	5077	4126
Lower Baarlo-Ruurlo	29484	3425	3004
Total	**48424**	**9439**	**7782**

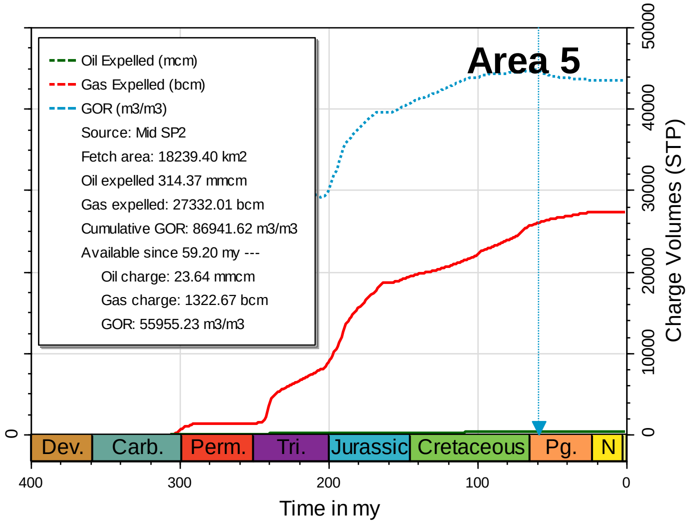
Summary table of expelled gas volumes through time for the Upper Carboniferous SRs in Drainage Area 3.

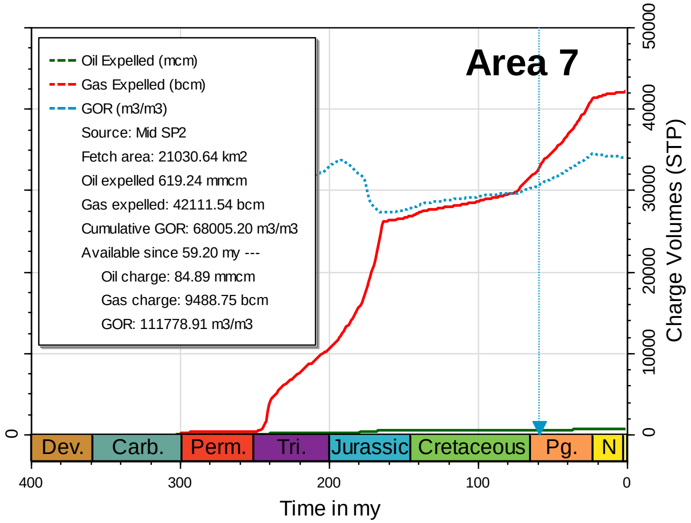
Charge Volume Histories

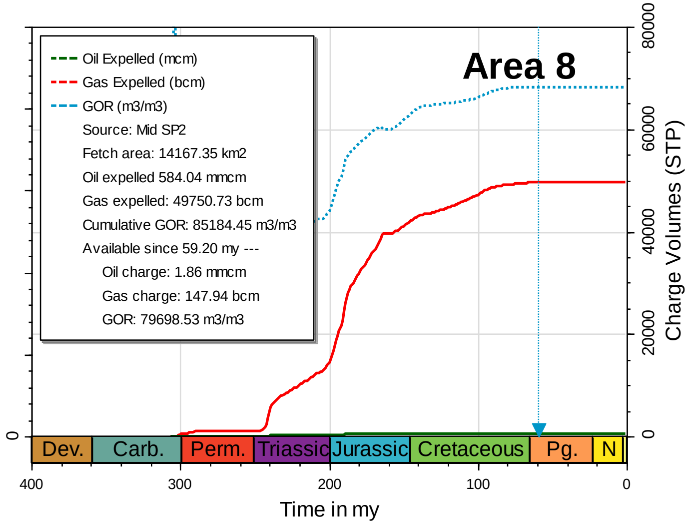
Maturity-Generation-Expulsion

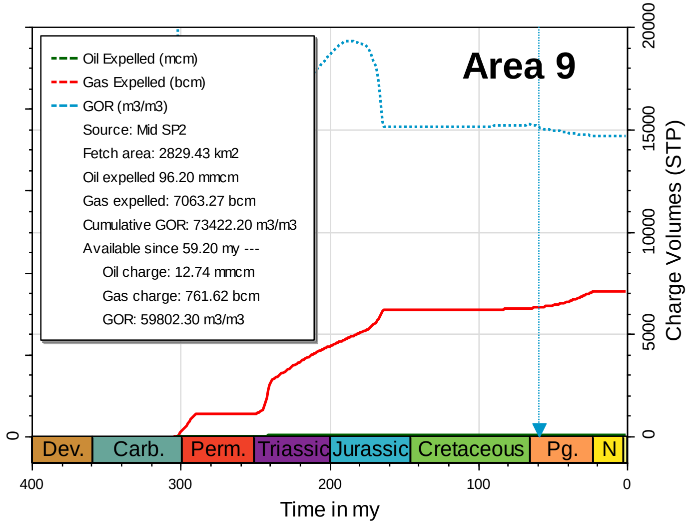
Reference Model: Charge-Volumes Histories for the Lower Baarlo-Ruurlo

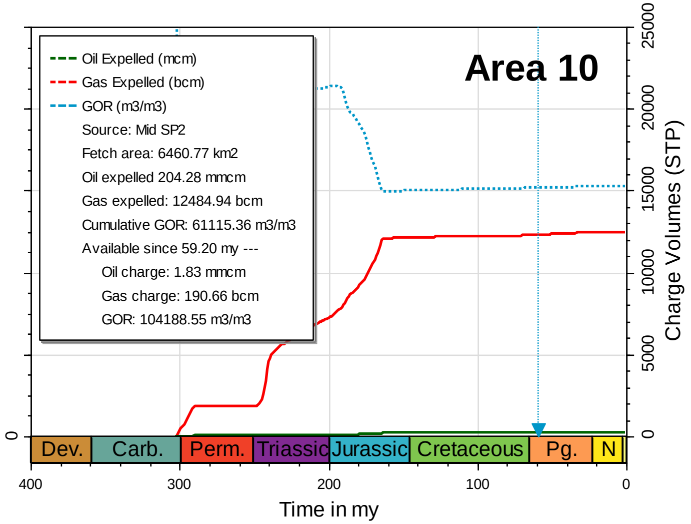








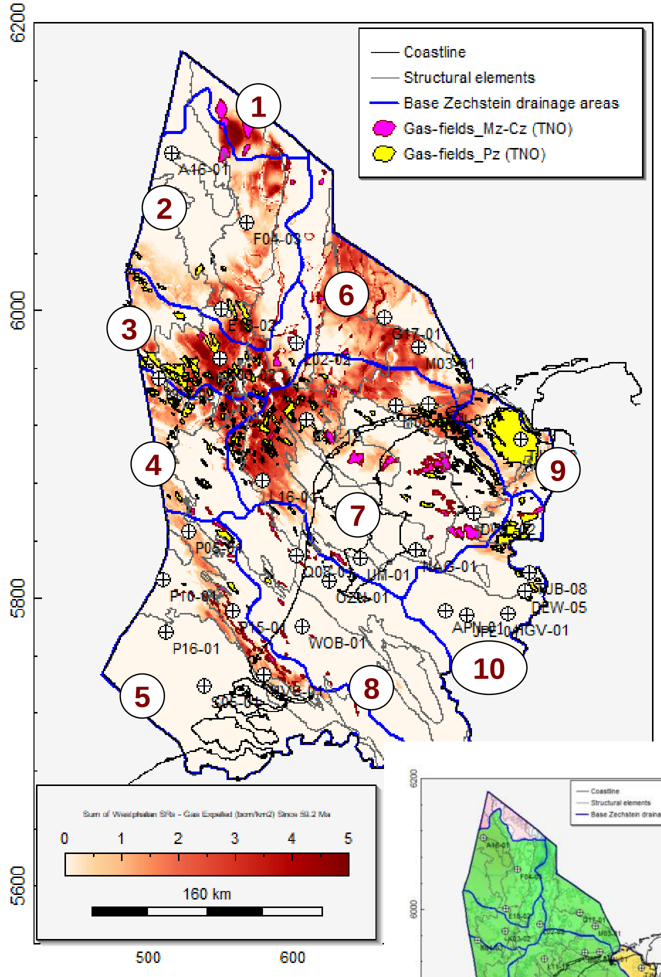




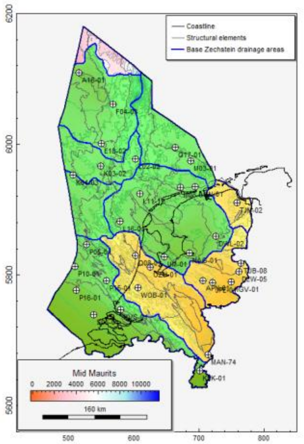
Westphalian SRs

Summary Tables and Analysis of Results

N.B. Yellow boxes highlight where the model predictions might be insufficient to explain the production volumes given the migration losses.



Sum of Westphalian SRs Cenozoic gas expulsion



Area	Production (Bcm)	Total Expulsion (Bcm) Maurits + Baarlo-Ruurlo	Expulsion since 139.8 Ma Maurits + Baarlo-Ruurlo	Expulsion since 59.2 Ma Maurits + Baarlo-Ruurlo
Area 1	17 (biogenic)	2690	2161	2000
Area 2	30	50983	8112	6647
Area 3	271	48424	9439	7782
Area 4	96	35700	5000	3423
Area 5	173	45256	15227	2237
Area 6	42	70558	18253	9138
Area 7	606	58785	24898	14310
Area 8	63	80160	15462	198
Area 9	2433	12666	1895	1263
Area 10	71	20004	1266	223

Comparison between production gas volumes and the sum of gas expelled from the Maurits and Baarlo-Ruurlo formations from the Early Cretaceous onwards (139.8 Ma- Present) and from the late Palaeocene onwards (59.2 Ma- Present). All values in Sm3 (SPT = 1 atm and 15°C).

- In Areas 2-7 the predicted Cenozoic volumes are 1-2 orders of magnitude greater than the production values (*ca.* 90% of reserves), and correspond to 5%-25% of the total expulsion.
- In Areas 2-6, the predicted Maurits Fm Cenozoic expulsion is 2 to 25x greater than production.
- In Areas 8 and 10 the predicted Cenozoinc expulsion is *ca.* 3 times greater than the production values and correspond to only 1% or less of the total volumes.
- In Area 9, the model suggests that the very large volumes produced from the Groningen field are at least partially charged from kitchen areas outside the model area, likely from Germany.

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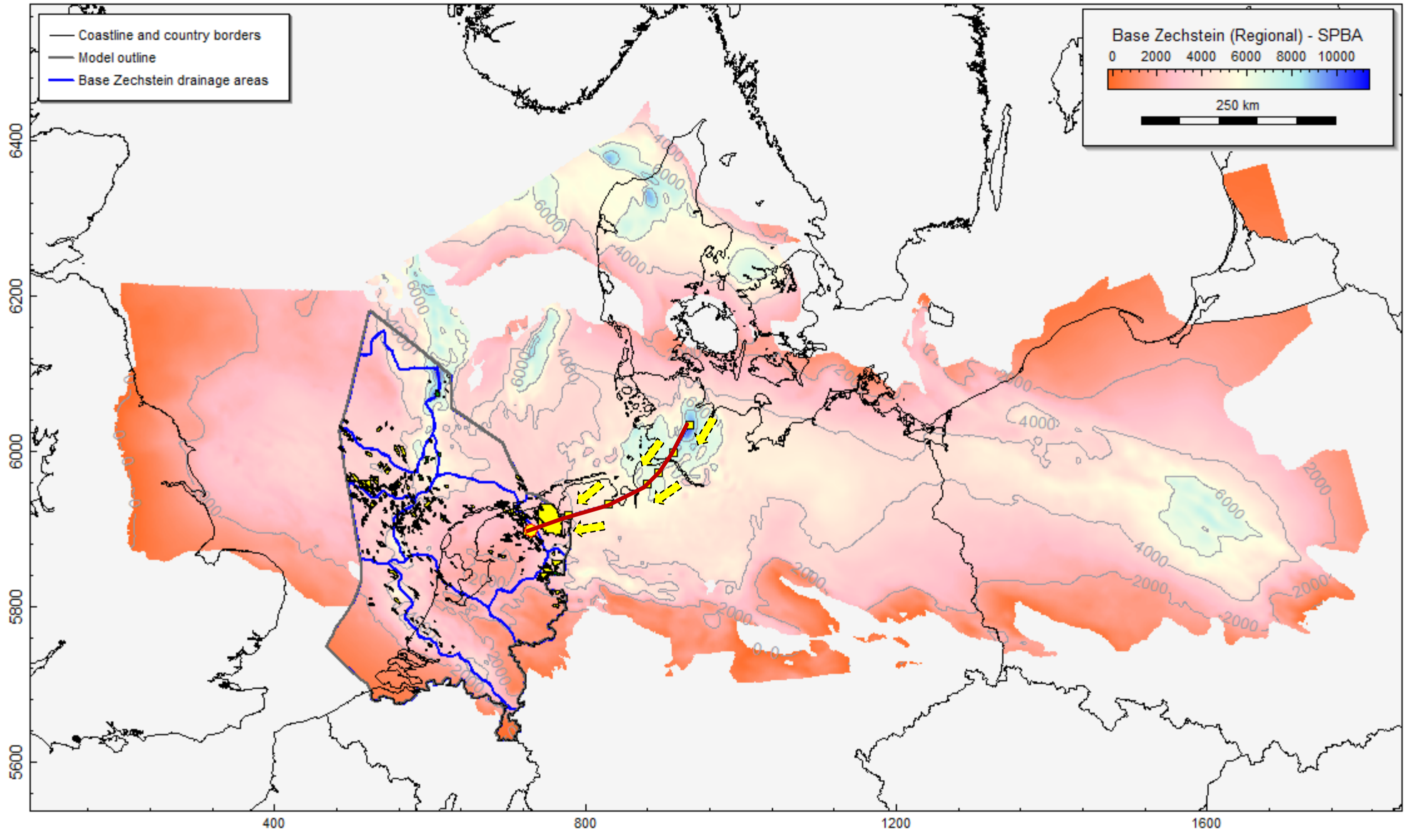
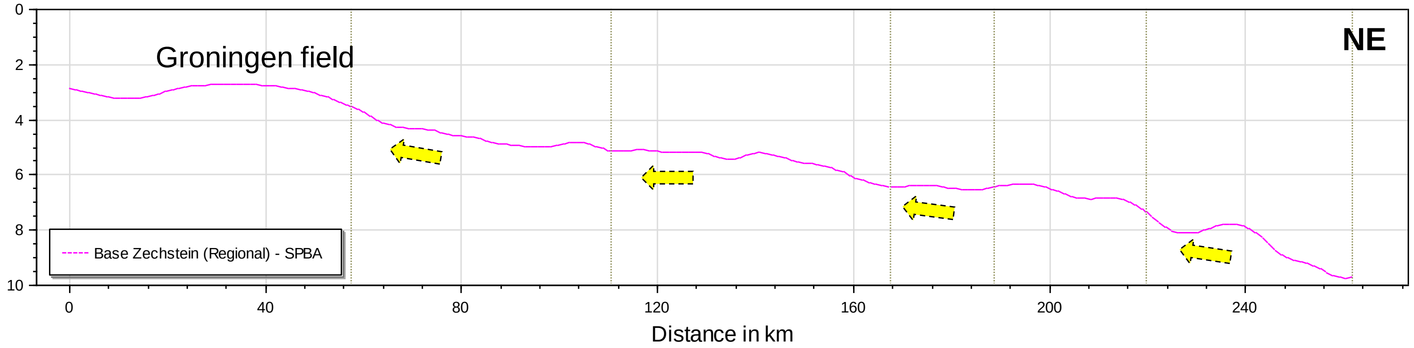
Groningen Field

Regional Charge Model

- The predicted gas expulsion from the Cretaceous onwards is insufficient to explain the known volumes (over 2300 Bcm reserves) in Groningen field.
- It is likely, therefore, that the Groningen field is at least partially charged from kitchen areas to the east – see profile along the base Zechstein.
- Alternatively, the volumes in the Groningen field could be produced by a thicker and/or organic richer SR; we need the Maurits and Baarlo-Rurlo formations with 4-5% TOC over the whole thickness.
- Another possibility is that part of the charge in the neighbouring areas 6 and 7 is drained into the Groningen field; ie. the basins' geometry has changed during the Cretaceous-Cenozoic, for example during the Laramide-Pyrenaen-Savian orogenies.





Posidonia SR

Summary Table and Analysis of Results

- Abundant and pervasive oil expulsion since the Late Cretaceous in the vicinity of most oil discoveries in DCG, BFB and WNB.
- Expulsion since the Palaeocene is localized and implies lateral migration in the BFB and WNB.
- Recent expulsion is also insufficient to explain the production in the BFB, suggesting trapping of some Late Cretaceous charge.
- No Cenozoic expulsion predicted in the RVG, where there are no fields/discoveries. All Cretaceous charge likely migrated to the west and/or lost during the Laramide inversion.
- No expulsion in the LSB, suggesting:
  - (1) charge of the Schoonebeek field from the east;
  - (2) a different thermal model;
  - (3) charge from a deeper, more mature sour rock horizon.

N.B. Yellow boxes highlight where the model predictions might be insufficient to explain the production volumes given the migration losses.

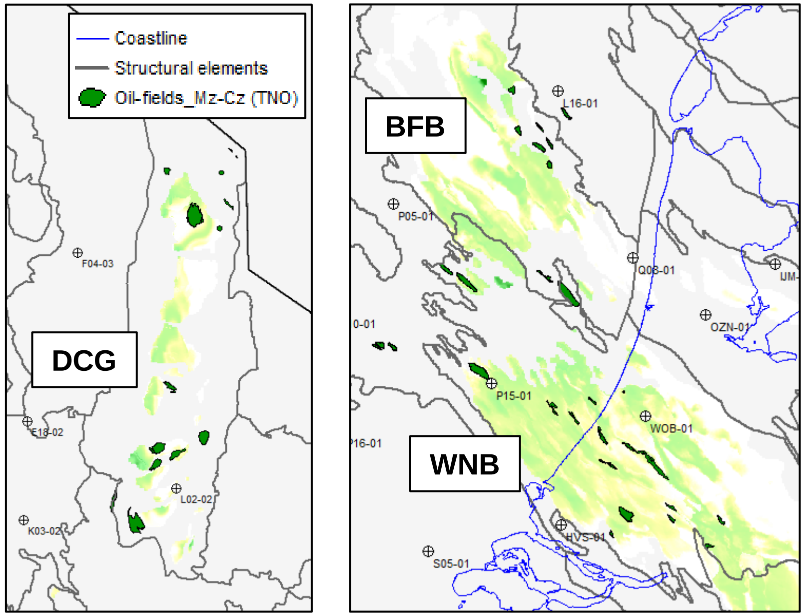
Oil production values

Structural Element	Production
Dutch Central Graben (DCG)	16.7
Broad Fourteens Basin (BFB)	40.5
West Netherlands Basin (WNB)	50.2
Roer Valley Graben (RVG)	--
Lower Saxony Basin (LSB)	43.4

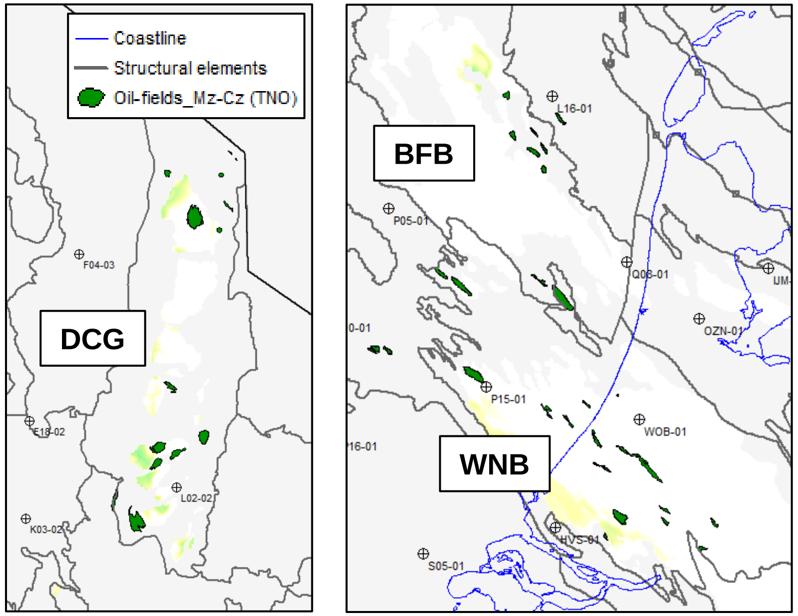
Model Predictions

Structural Element	Oil / Gas Since 100.5 Ma	Since 59.2 Ma
Dutch Central Graben	586 / 43	185 / 8
Broad Fourteens Basin	981 / 48	42 / 1
West Netherlands Basin	2598 / 132	153 / 4
Roer Valley Graben	445 / 13	0 / 0
Lower Saxony Basin	2 / 0	0 / 0

Reference model: Oil Expulsion since 100.5 Ma



Reference model: Oil Expulsion since 59.2 Ma



Oil expulsion maps for the reference model showing expulsion since the Late Cretaceous (100.5 Ma; left) and from the late Palaeocene onwards (59.2 Ma; right), focusing on the Dutch Central Graben (DCG), and on the Broad Fourteens Basin (BFB) and West Netherlands Basin (WNB) areas (see **Slide 58** for whole model maps).

Main Conclusions

- The VR data at numerous wells implies **higher geothermal gradients** in the past and/or **km-scale erosion** at major basin unconformities. This is also consistent with 2-D reconstructions along seismic profiles.
- The **Upper Jurassic-Lower Cretaceous** source rocks (SRs) are predicted immature in the study area, and only small oil and gas volumes are predicted from the **Middle Graben Coals** (Oxfordian), due to maturity constraints and SR distribution.
- Abundant oil (and some gas) expulsion is predicted from the **Posidonia SR** since the Late Cretaceous, with significant Cenozoic expulsion in the Dutch Central Graben and West Netherlands Basin. In the Broad Fourteens and West Netherlands basins, the models suggest trapping of some Late Cretaceous charge.
- Somewhat interesting oil and gas volumes are also predicted from the **Sleen SR** (Late Triassic) since the Palaeocene in the Dutch Central Graben, potentially contributing to the charge of the oil, gas and oil/gas discoveries in the area.
- Significant Late Cretaceous-to-Present oil expulsion (and some gas) is also predicted from a base **Zechstein SR** in Groningen Platform and Lower Saxony Basin (onshore), where some oil and oil & gas discoveries are in Z2 carbonates.
- Most gas expulsion from the **Westphalian SRs** is predicted to take place during the Permian and Triassic-Jurassic burial, but with significant expulsion in most drainage/charge areas during Cretaceous-Cenozoic burial.
  - In most of the offshore and NE onshore Netherlands, the Cenozoic gas expulsion is 1 to 2 orders of magnitude greater than the production values; the predicted Cenozoic expulsion from the Maurits Fm. alone is 2-25 times the production values in the offshore.
  - In the West and Central Netherlands basins, and in the Lower Saxony Basin and southern Groningen Platform, the predicted Cenozoic gas expulsion volumes are approximately 3 times greater than the production volumes, but correspond to 1% or less of the total volumes, thus suggesting some Cretaceous charge.
  - In the northern Groningen Platform, the modelling results indicate that the very large volumes produced from the Groningen field are at least partially charged from kitchen areas outside the model area, likely from Germany

Future Work

Improving the Accuracy and Predictability of the Petroleum Systems Model

Four main lines of research/analysis are here suggested to further constrain the model and improve the accuracy of the predictions:

- Improve the constraints on **source rocks' thickness and quality** in some areas. For example:
  - Map the distribution and thickness of the **Middle Graben coals** (Oxfordian) from good quality seismic data, and define the appropriate kinematics for this potential sour rock, also by understanding the variations in the properties of shale horizons between coal beds;
  - Improve the thickness maps for the **Sleen** and basal **Zechstein** source rock horizons.
  - Improve the facies maps for the **Dinantian** coals and **Geverik** shales.

- **Compilation and interpretation of hydrocarbon fluid data**, to constrain the origin of the oil and gas in a significant number of discoveries (fluid-source correlations), and thus improve the calibration of the model (top-down approach). Machine learning techniques could be applied in the typing/grouping of Netherlands oils and improve the fluid-source correlations.

- **Geo-mechanical (palinspastic) reconstructions** along seismic transects covering the onshore and offshore structural elements, to improve the current constraints on the amounts of **exhumation** at the time of major tectonic events (Saalian, Kimmerian, Laramide, and potentially also Pyrenean and Savian). This is arguably the greater uncertainty in the models with impact on the timings of oil and gas generation from the main source rocks in the Netherlands sub-surface.

- **Geothermometer data** (apatite/zircon fission track analysis, microthermometry, etc) to further constrain the magnitude and spatial extent of past **tectonic events**. Together with the geo-mechanical reconstructions, this data/analysis, could be used to improve the current understanding on the effects of basins exhumation Vs thermal doming.

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