- End project report: Tectonic models II - The Dutch Central Graben and its margins

- Public report -

Projectnummer	TKI2018-04-GE
Project titel	Tectonic models II: The Dutch Central Graben and its margins
Programa	Innovation Program Upstream Gas, Line: Basin Analysis
Coördinator en projectconsortium	Utrecht University, EBN, Wintershall Noordzee, Neptune Energy
Projectperiode	May 1, 2018 until June 1, 2020
Auteurs	Jeroen Smit and Manfred Lafosse (University of Utrecht)
Aanvragers en Penvoerder	Jan Diederik van Wees, Liviu Matenco (University of Utrecht)
Datum	05 December 2020

Contact adres: Universiteit Utrecht, Postbus 80125, 3508 TC Utrecht, Nederland.

Contactpersoon: prof. dr. Jan Diederik van Wees, e-mail: J.D.A.M.vanWees@uu.nl

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland

Contents

Summary

The Dutch Central and Step Grabens contain one of the most complete and best documented geological records in the Southern North Sea. In this framework, the TecModsII project aims to constrain a novel kinematic framework for the evolution of the Dutch Central Graben (DCG), its flanks and regional structural prolongations, by taking advantage of the existing detailed Paleozoic - Cainozoic information and advanced understanding in terms of tectonics and structural mechanisms. The project provides a novel detailed tectonic and structural interpretation that may form the basis for an improved quantitative exploration for conventional or sustainable geo-resources, such as (ultra-deep) geothermal exploration, in the offshore and onshore Netherlands. The regional area of the DCG is an optimal target for a higher-resolution structural and tectonic analysis, serving as a template to be ported elsewhere in the Netherlands, because it contains a complete geological and geophysical record of the North Sea deformation history and a high resolution dataset, such as 2-3D seismics, boreholes and potential fields geophysical data, is readily available. Therefore, in the current TecModsII project we have built a new more detailed structural analysis of the DCG and its flanking areas, including the Cleaverbank High, integrated in a new tectonic model, validated by the means of analogue tectonic modelling. The concepts for the genesis and the mechanics of faulting and basin formation in the DCG can be applied to other onshore and offshore Netherlands regions.

1. Project overview

The University of Utrecht has coordinated the TKI Tectonic Models II project that runs from June 2018 to May 2020. A consortium was built in partnership with the TKI project RIFA at Utrecht University in collaboration with specialists at TNO and EBN, the project sponsors and external partners (ETH Zurich, University of Paris). Furthermore, in collaboration with the partner TKI project RIFA, we have developed 4 MSc projects and theses at Utrecht University that have enhanced the results and increased the collaboration in implementing the academic concepts to the studied area.

Objectives and results

Tectonic models are the basis of any sedimentary basin understanding, such as for instance in terms of litho-stratigraphic and (paleo-)temperature evolution. TecModsII aims to constrain a novel kinematic framework for the evolution of the Dutch Central Graben (DCG), its flanks and regional structural prolongations, by taking advantage of the previously developed deep crustal and Paleozoic architecture and the existing detailed Paleozoic - Cainozoic information.

The project provides a novel detailed tectonic and structural interpretation that can form the basis for an improved quantitative exploration for conventional or sustainable geo-resources, such as (ultra-deep) geothermal exploration, in the offshore and onshore Netherlands. The areal focus of the project is the DCG and its flanks, where we focus on the mechanics of sedimentary (sub-) basin formation and evolution during post-Variscan times. We adopted a workflow starting from crustal to the internal geometry of deformation at basin scale, assisted by state-of-the-art mechanical concepts that proves of significant value to other areas of interest in the North Sea and the Netherlands. This project adds value to the program line “Basin Analysis’’ by improving the quantitative understanding of the complex North Sea margin and creating a knowledge base for further exploration to increase energy production. We have built a more detailed structural analysis and kinematic framework of the CDG and its flanking areas, including the Cleaverbank High, resulting in an integrated tectonic model, validated by the means of analogue tectonic modelling.

2. Work plan

The project consisted of four technical work packages. Each work package was coordinated by the project partners, in close collaboration with the partner TKI project RIFA. The corresponding executed work is described below in more detail.

WP1 Tectono-seismostratigraphic interpretations in the Dutch Central and Step grabens with emphasis on the tectonic component

The main objective of this work package was to provide tectono-seismostratigraphic interpretations in the Dutch Central and Step grabens, with particular emphasis on the tectonic and structural evolution. In the absence of advanced sub-Zechstein interpretations, the main challenge was to achieve a seismic interpretation below the DCG, linking the Elbow Spit High and Step Graben to the west with the Schilgrund High to the East.

We were successful in achieving meaningful seismic interpretations of the deep structure below the DCG along a total of four profiles by using the public NSR survey located the Northern offshore (**Figure 1**).

Our research has focused from the beginning on the inherited crustal geometry and influence on the evolution of the DCG and its prolongation in the Danish Central Graben. This research served as the main input for WP2.

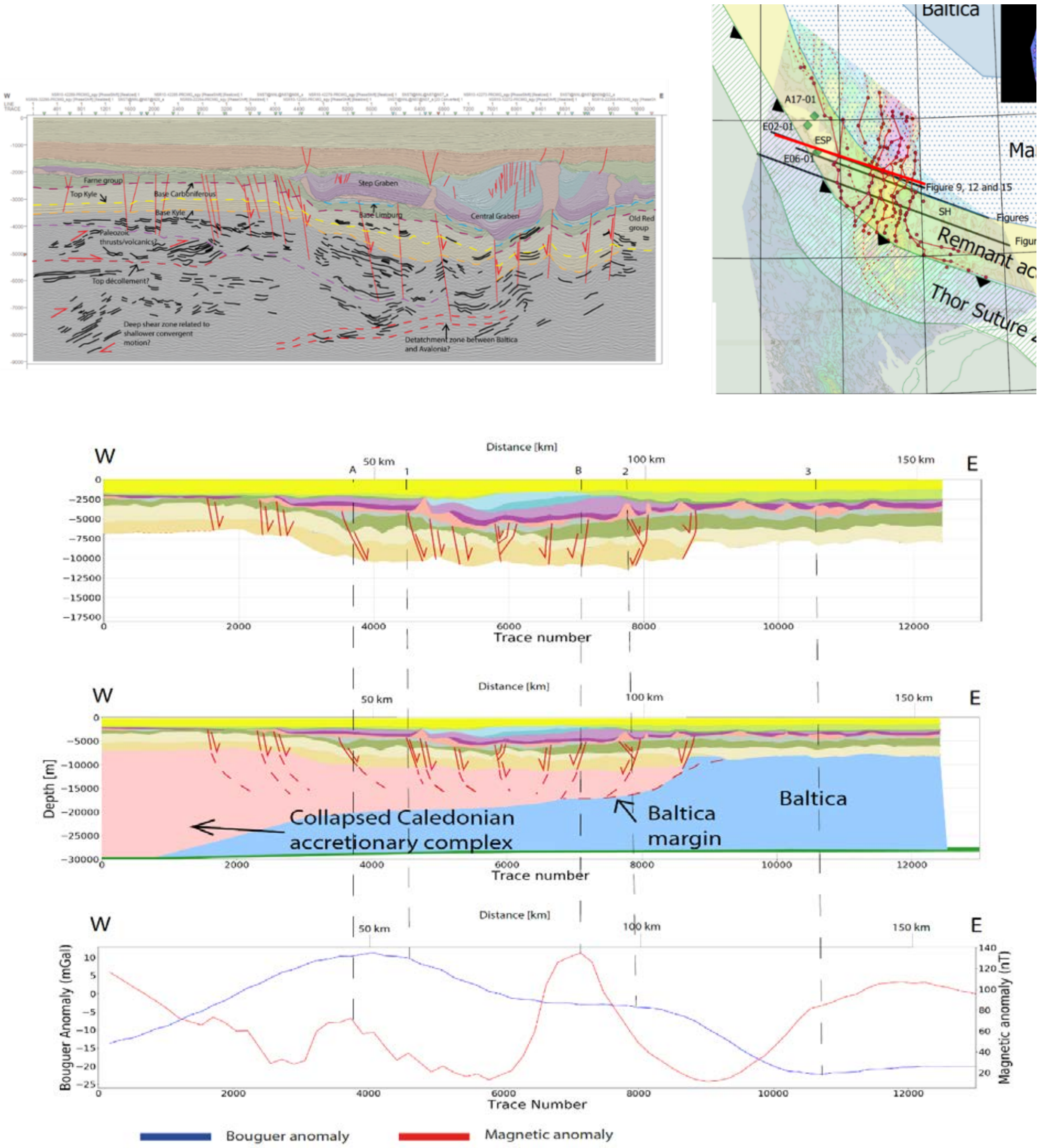

Figure 1 *Simplified seismic interpretation beneath the Zechstein salt (top left, profile NSR09-41057), location on the map in the top-right figure. Middle: three panels showing (up) the depth-conversion of the profile, (middle) integration in the crustal geometry and (bottom): gravity (blue, Bouguer) and magnetic (red) anomalies. The interpretation of Zechstein salt and younger strata is based on NLOG (DGM Deep v5.0) and TNO data (e.g., Bouroullec et al., 2018). For further details we refer to Eskens (2020).*

WP2 Structural Restoration: coupling the sedimentary basin evolution with the crustal structure

In order to explain the geometry and geological history of the Dutch Central Graben (DCG), we must understand its relationship with the deeper crustal structure. Therefore, WP2 focused on a structural reconstruction linking the basin development with the deeper crustal structure, with the aim to gain a better understanding of its influence on the DCG and surrounding highs evolution.

In order to reconstruct the early Mesozoic, pre-rift crustal geometry, a first order cross-section restoration has been performed at the location of the MONA LISA-3 deep seismic profile (**Figure 2**). The crustal scale cross-sectional restoration shows the late Paleozoic crustal geometry at the onset of rifting that has been used to understand its role for the evolution of the entire Southern North Sea. This geometry has been used to design the analogue modelling study of WP4.

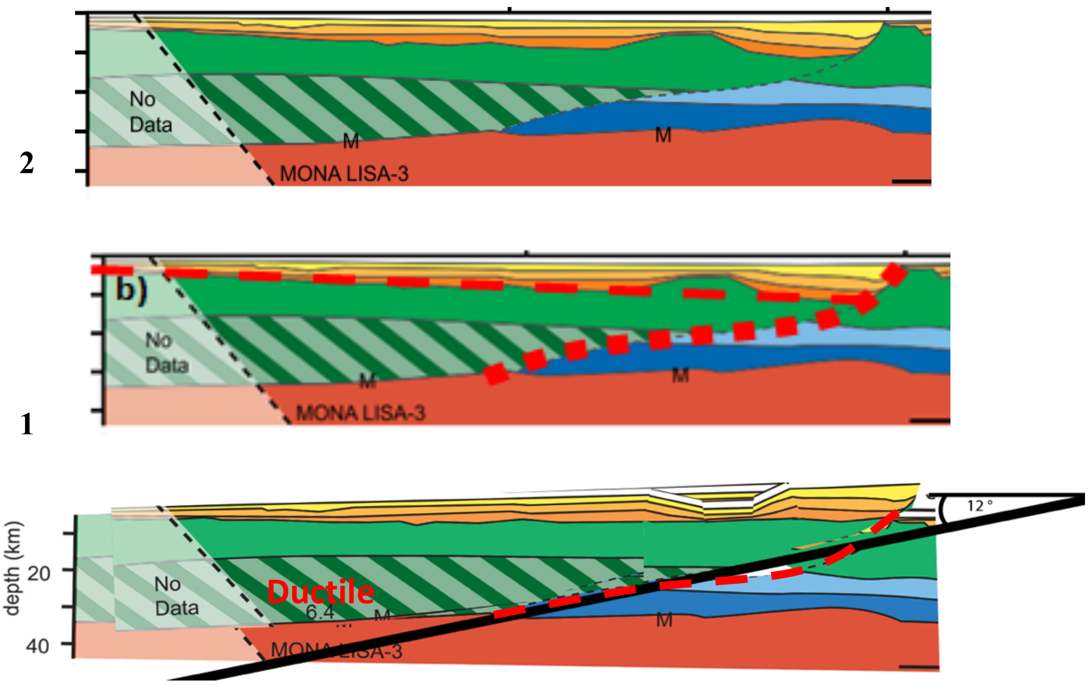

Figure 2 *Tentative restoration of the deep crustal structure along refraction profile MONA-LISA3 (upper panel, for location see fig.1, ML-3). Middle panel: the top of the green layer 1) roughly corresponds to the oldest surface pre-dating the early Variscan extension. Extension mostly occurred along the top of the Baltica margin (2) . Bottom panel shows the result of the restoration and marks the resulting mean angle of detachment (black line), subsequently used by the analogue modelling setup.*

WP3 Geophysical potential fields modelling

Initially we set out to perform a potential field modelling study to test our new crustal model as published in Smit et al. (2016). However, two new potential field modelling studies focusing on the wider North Sea (Maystrenko et al., 2017) and the German territory (Dressel et al., 2018) have been published after the approval of our project that have proven to be ideal for testing and validating our revised crustal model. These internationally accepted studies have already demonstrated that our results are in agreement with potential field data, while their results yield an independent control for the new crustal model. Maystrenko et al. (2017) performed 3D gravity and magnetic modelling studies in a region immediately north of the DCG by showing that the observed magnetic and gravity anomalies are in accordance with a high density layer at the base of the crust below the Central Graben, and in agreement with the relatively dense Baltica margin compared to the light middle crustal material, both related to the collapsed Caledonian accretionary wedge. Dressel et al. (2018) performed 3D gravity and magnetic modelling studies for the German sector of the North Sea (Enthenschnabel area). Their results are in line the crustal interpretation of Lyngsie and Thybo (2007) that has been used in the definition of our crustal model. With these results in hand, the main aim of the scheduled potential field data study, verifying our new model of the Thor Suture Zone, is fulfilled. We have incorporated these results in our analysis and we have re-directed our efforts to the remaining WPs.

WP4 Analogue modelling of the northern offshore

By the means of analogue tectonic modelling performed at the TecLab modelling facility of Utrecht university, we focused our efforts in designing and performing a new line of models with the aim to gain better understanding of the influence of the crustal structure and faulting geometries on the DCG and surrounding highs. The experimental tectonic study has been carried out in the framework of a Master thesis (Borghouts, 2020), available on the library repository of the Utrecht University. The brittle-ductile crustal-scale experiments allow us to test the effects of both crustal geometry and rheology. The results have demonstrated the critical influence of the inherited Paleozoic structure during the Mesozoic evolution of the DCG, where the reactivation of major Paleozoic extensional structures and the structure of the Caledonian wedge have localized the Mesozoic deformation in the DCG, mechanically decoupled by the presence of the Zechstein salt.

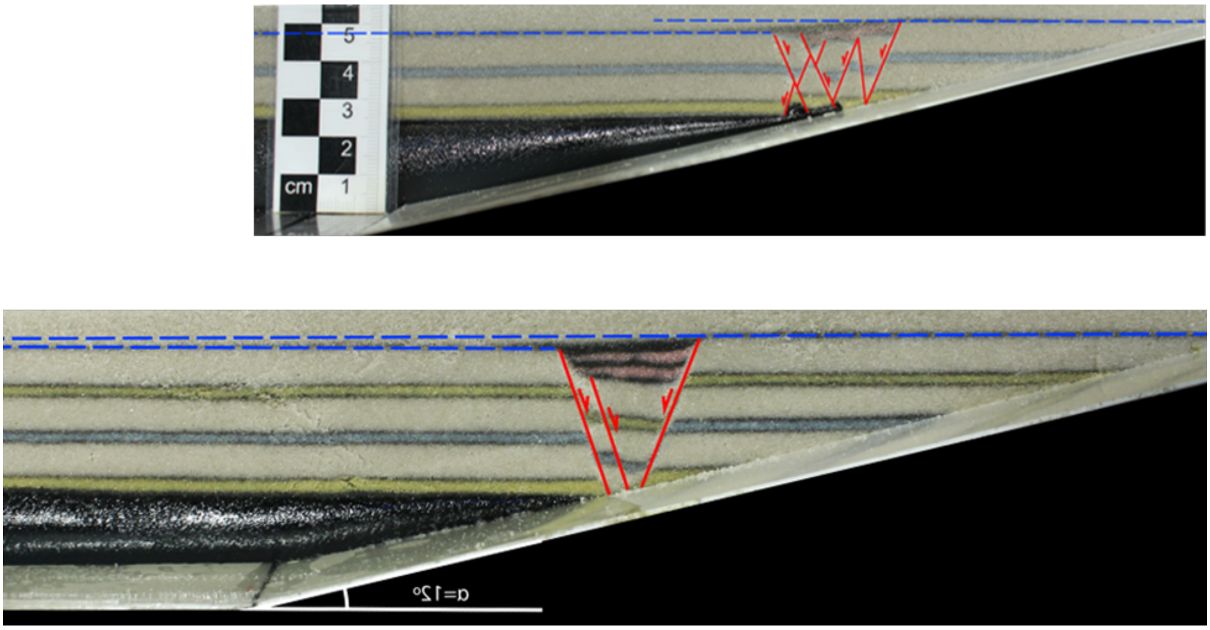

__Figure 3__. Cross sections across two experiments with a) 2 cm and b) 3 cm thick sand layer (simulating the upper crust) and a 2 cm thick silicone putty layer (simulating the ductile lower crust). Extension in both experiments is simulated by moving the footwall at constant velocity (Borghouts, 2019). A further detailed explanation is available in Appendix 3.

WP 5 Testing of results, insights and concepts to specific sub-areas of interest to sponsors

To test the obtained results, insights and concepts to specific sub-areas we have focused on the multi-stage reactivation of graben forming faults, notably faults related to Late Cretaceous inversion. This inversion was oriented almost parallel to the DCG margins, reactivated basin-building faults with a transcurrent component. We used a 3D seismic dataset of large parts of the Central Graben (courtesy EBN), across an area in which we have previously interpreted the deep structure in 2D (WP1) and where recent 2D interpretations of the Mesozoic graben fill are available (Bouroullec et al., 2018; Verreussel et al., 2018). The results are considered as preliminary and indicate that the Dutch and Danish Central Graben were significantly shifted eastwards during the late Cretaceous inversion when compared to the location where a Jurassic reactivation of the late Paleozoic detachment took place beneath the Zechstein salt. Therefore, this detachment should be located presently beneath the central part of the DCG instead of along the current eastern basin boundary, which is possible in some parts of the basin.

3. Coordination and dissemination

Apart from the email-traffic, half-year consultations were organized to facilitate the cooperation between the partners. One larger year mid-term meeting has been organized where preliminary results have been presented, and a different strategy of the continuation of the project has been established in close collaboration with the project's sponsors. These consultations and meetings provided a platform to give feedback and enhance the research. A project team site was established at Utrecht University to facilitate the exchange of data and reports. Apart from organizing the meetings and facilitating contact, the coordinator has steered the project results towards the defined deliverables within the defined temporal and financial boundaries. A yearly progress report has been submitted to the sponsor. The variety of competencies in the team, from observational methodologies to process-oriented modelling has resulted in a fruitful cooperation. Financially, no significant differences between the budgeted and actual costs are recorded, and expenditures were maintained in the allocated budget. The budget was sufficient; the relatively lower actual costs are explained by a smaller number of experiments performed. Due to the move of the TecLab to the new Earth Science Laboratory building in the middle of the project, the second series of experiments was moved to early 2020 when the laboratory was subsequently closed as part of the Corona-related lock-down. However, a significant number of analogue modelling experiments were already achieved, which allowed for a critical mass supporting the presented interpretation.

Dissemination

The results of the project were transmitted to the sponsors in communications and scheduled meetings. Our work results were presented in several international meetings, such as the 2019 European Geoscience Union General Assembly in Vienna, Austria, the 2019 NAC congress, the EBN's 3rd Dutch Exploration Day in November, 2018. J. Smit was also invited in autumn 2019 to present his results and to participate in an EBN workshop for a limited number of expert geoscientists from operators active in the Dutch offshore. The results of the project were used in a and contribution to the SCAN-Dinantian project report (Bouroullec et al., 2019).

A significant part of results is available in MSc Theses published by Utrecht University:

- Borghouts, D., 2019. Evaluating and constraining the effects of Paleozoic crustal scale structural features on the fault kinematics and basin evolution of the Dutch Central Graben. MSc Thesis, Utrecht University, 42 p.

- Eskens, L., 2020. Using interplay of sub- and supra salt structures for an extensive formation model of the Central Graben, North Sea, MSc Thesis, Utrecht University, 45 p.
- Otting, A.M., 2020. Deep structural development of the NW Dutch North Sea. MSc Thesis, Utrecht University, 39 p.

Papers in international journals:

Bonté, D., Smit, J., Fattah, R. A., Nelskamp, S., Cloetingh, S., and van Wees, J.-D., 2020, Quantifying the late-to post-Variscan pervasive heat flow, central Netherlands, Southern Permian Basin: Marine and Petroleum Geology, 113, 104118

Following the guidance of our project's sponsors, the results are currently in manuscript preparation for submissions to international journals. Planned publications in international journals:

- Smit, J. and Lafosse, M., Quantifying the role of inherited Paleozoic structure in the formation and evolution of the Dutch Central Graben
- Smit, J. and Lafosse, M., The role of Zechstein salt and inherited crustal structure in rheological decoupling the kinematics and associated sedimentation of the Dutch Central Graben

4. Technical advancements

In the framework of the TecModsII project, we have successfully interpreted the deep structure of a large portion of the northern offshore of the Netherlands. The interpretation of the Elbow Spit High and the surrounding Step Graben have yielded a series of time depth maps and time thickness maps of key horizons and units down to the acoustic basement. Time thickness maps clearly show the depo-centre migration from north (the Old Red basin) to the south (the Variscan basin). With these maps in hand we have moved the limit of the Avalonian plate further to the east, updating and completing our previous map (Smit et al., 2016). The new limit brings Avalonia to the edge of the Step Graben, closer to Baltica than elsewhere.

We were able to continue our deep interpretation of the Step Graben below the DCG and further east on the Schilgrund High. We have thus integrated our model with the geology of the Schilgrund High and the Step Graben. The overall crustal geometry of much of the Northern offshore resembles that of the MONA-LISA3 profile (Lyngsie and Thybo, 2007; Smit et al., 2016). For the Northern half of the DCG, this geometry can be explained by the presence of the Baltica margin and its margin fault, known in Denmark as the Coffee Soil Fault, below the northern part of the Schilgrund high. Although further to the south the Baltica Margin turns away eastward, the basin geometry seems to change only gradually below the large amount of thick salt diapirs and salt walls, making a quantitative seismic interpretation of the Paleozoic basement south of the F-blocks difficult. In the absence of deep control, the pre-inversion DCG does seem to become more symmetric southward, towards the Terschelling Basin.

Analogue tectonic experimental results indicate that effective evaporite layers, like the North Sea Zechstein salt, have a major impact on the basin geometry besides the regional tectonic and crustal structure. This means that the Zechstein salt may have played a much more important role in the internal graben geometry by tilting and folding beyond diapirism than previously thought.

5. Contribution of the project to objectives of Topsector Energy subsidy program (research theme Geo Energy)

A new quantitative understanding of the mechanisms active during the geological time in the onshore and the offshore of the Netherlands subsurface is required by the gradual transition from conventional to sustainable subsurface energy georesources, such as geothermal, as well as the new challenges imposed by the necessity of surface storage, such as carbon capture and storage (CCS) or energy storage. This transition and challenges require a multi-scale new understanding of subsurface plays' evolution, from the large scale of plate tectonics to the reservoir mechanics and microscale, enhanced by the need to understand the geological system sensitivity to the new types of associated geohazards, such as induced seismicity.

The findings of our study form the basis to build more robust conceptual structural and tectonic evolution models also outside the DCG study area, which can serve as a model to be extended onshore for conventional and sustainable new subsurface energy systems and geothermal energy exploration and facilitate the extension of the existing resource base.

6. Conclusions, recommendations and possibilities for spin-off

We demonstrated that it is possible to continue the seismic interpretation of the Paleozoic and underlying basement beneath the Central Graben, at least along those profiles that contain small amounts of Zechstein salt. From these interpretations we concluded that the DCG is asymmetric at depth, as regional refraction profiles suggested previously, and in full agreement with our conceptual crustal model (Smit et al., 2018). The conceptual model is further supported by structural restoration based on the deep interpretation, and is consistent with recent potential field modelling studies, including gravity and magnetic anomalies.

The geometry of the Avalonia and Baltica plate margins in the structural edifice of the Caledonian collapsed wedge strongly influenced the evolution of the northern offshore extensional structures and their associated sedimentary evolution. For the northern half of the DCG, analogue models demonstrate that the low angle Baltic margin crustal detachment and a relatively weak lower Avalonia crust can explain the structural expression of the main basin DCG bounding fault (the Coffee Soil Fault in the Danish equivalent), extending below the northern part of the Schilgrund High. More to the south, in the Terschelling Basin and adjacent parts of the DCG, the Avalonia Margin appears dominant in the basin structural style.

Experimental results indicate that effective evaporite layers, like the North Sea Zechstein salt, have a major impact have on basin geometry adding to the effects of the regional tectonics and crustal structure, by decoupling the deformation in the under- and over- burden and absorbing by tilting, folding and diapirism large part of the extensional deformation and the subsequent inversion.

For future research the role of the Zechstein salt in the evolution of the basin should be studied more quantitatively and with more details, as salt has clearly strongly influenced tectonics, basin development and basin geometry, and its structural expression may have moved away or eroded since its formation due to the mobility of salt.

Furthermore, the necessity to take into account the Late Cretaceous inversion repeatedly returned in our research, in particular in view of restoration of the Jurassic and Triassic Grabens. The research highlights the 3D complexity of the structuration of the northern offshore in terms of strain partitioning. Therefore, more detailed understanding of the structural evolution requires 3D techniques for structural interpretation and restoration, which are important for the interplay between crustal tectonics and salt-related deformation.

The possibilities for spin-offs and continuations of this project are numerous. This project and the RiFa sister project are themselves spin-offs from the initial TKI project Tectonic Models for natural stress, exhumation and temperature in North Sea basins. This project has resulted in two well-cited publications in International Rank A peer-reviewed journals, appreciated by the academia and the industry, and we are currently planning to submit similar publications as a result of the current project. This research also played a role in the SCAN Dinantien project for deep geothermal exploration in the Netherlands by applying similar principles of structural inheritance to areas situated on the onshore. Although there are no plans for a direct follow-up in the form of a Joint Industry Project, we expect that possibilities for spin-off and continuations are similar to that of the initial Tectonic Models 1 project. In recent years, this theme and the research into Dutch North Sea evolution have become of significant importance in the quest for conventional or more sustainable georesources. Results and insights are used daily in the research of industrial sponsors, in the search for natural gas and exploration opportunities for geothermal energy. In the future, Master students will continue to perform projects that build on the TecModsII project.

By providing a mechanical explanation for the anomalous Permo-Carboniferous heat pulse derived from the results of the current project, a spin-off collaboration has resulted in a new publication on quantifying the late-to post-Variscan pervasive heat flow of the central Netherlands by Bonte et al. (2020). In this context, the Southern Permian Basin is marked by significant Latest Carboniferous-Early Permian magmatism attributed to mantle plume emplacement, assumed to have impacted the heat flow evolution. In the central Netherlands a large number of wells show evidence of magmatic activity dated as Permo-Carboniferous. In addition, high maturity values have been measured for the Carboniferous and below. Theoretical models for tectonic heat flow and maturity evolution show that mantle upwelling, underplating, and intrusions have a significant effect on maturity-depth trends. In this research, tectonic modelling of five selected wells shows that tectonic subsidence and exhumation can be correlated with a significant heat flow pulse at Latest Carboniferous-Early Permian time. Quantitative assessment of heat flow, based on a model of mantle plume emplacement, shows that mantle upwelling and underplating at the base of the crust, proposed by previous studies, provides insufficient heat flow to explain strongly elevated maturity/depth trends. In contrast, widespread Permo-Carboniferous calc-alkaline magmatism at shallow crustal levels provides a mechanism for elevated heat flow with a regional impact, consistent with observed high maturity/depth trends. The model and maturity data demonstrate that elevated maturity at shallow burial-depth levels of 500–1000m is probably sited in the gas window during a heat pulse, occurring during Late Carboniferous times.

In conclusion, the Tectonic model II projects has produced significant results in understanding the large scale tectonic and structural inheritance in the evolution of the Dutch Central Graben and similar Netherlands onshore and offshore extensional structures. There are numerous possibilities for spin-off and collaboration given by the quantitative understanding, which the authors of the project will take benefit in the future.

7. References

Bonté, D., Smit, J., Fattah, R. A., Nelskamp, S., Cloetingh, S., and van Wees, J.-D., 2020, Quantifying the late-to post-Variscan pervasive heat flow, central Netherlands, Southern Permian Basin: Marine and Petroleum Geology, v. 113, p. 104118.

Borghouts, D., 2019. Evaluating and constraining the effects of Paleozoic crustal scale structural features on the fault kinematics and basin evolution of the Dutch Central Graben. MSc Thesis, Utrecht University, 42 p.

Bouroullec, R., Verreussel, R. M. C. H., Geel, C. R., de Bruin, G., Zijp, M. H. A. A., Kőrösi, D., Munsterman, D. K., Janssen, N. M. M., and Kerstholt-Boegehold, S. J., 2018, Tectonostratigraphy of a rift basin affected by salt tectonics: synrift Middle Jurassic–Lower Cretaceous Dutch Central Graben, Terschelling Basin and neighbouring platforms, Dutch offshore: Geological Society, London, Special Publications, 469, https://doi.org/10.1144/SP469.22.

Dressel, I., Barckhausen, U., and Heyde, I., 2018, A 3D gravity and magnetic model for the Entenschnabel area (German North Sea): International Journal of Earth Sciences, p. 177–190, https://doi.org/10.1007/s00531-017-1481-x

Eskens, L., 2020. Using interplay of sub- and supra salt structures for an extensive formation model of the Central Graben, North Sea, MSc Thesis, Utrecht University, 45 p.

Lyngsie, S. B., and Thybo, H., 2007, A new tectonic model for the Laurentia−Avalonia−Baltica sutures in the North Sea: A case study along MONA LISA profile 3: Tectonophysics, 429, 201-227.

Maystrenko, Y. P., Olesen, O., Ebbing, J., and Nasuti, A., 2017, Deep structure of the northern North Sea and southwestern Norway based on 3D density and magnetic modelling: Norwegian Journal of Geology/Norsk Geologisk Forening, 97, 3, https://njg.geologi.no/component/fabrik/details/1/1747-1747.

Otting, A.M., 2020. Deep structural development of the NW Dutch North Sea. MSc Thesis, Utrecht University, 39 p.

Smit, J., van Wees, J.-D., and Cloetingh, S., 2016, The Thor suture zone: From subduction to intraplate basin setting: Geology, 44, 707-710.

Smit, J., van Wees, J.-D., and Cloetingh, S., 2018, Early Carboniferous extension in East Avalonia: 350 My record of lithospheric memory: Marine and Petroleum Geology, 92, 1010-1027.

Verreussel, R. M. C. H., Bouroullec, R., Munsterman, D. K., Dybkjær, K., Geel, C. R., Houben, A. J. P., Johannessen, P. N., and Kerstholt-Boegehold, S. J., 2018, Stepwise basin evolution of the Middle Jurassic–Early Cretaceous rift phase in the Central Graben area of Denmark, Germany and The Netherlands: Geological Society, London, Special Publications, 469.