End project report: RiFa - "Rise and Fall", the role of thermal uplift in the formation of Jurassic basins in the Dutch subsurface

- Public report -

Projectnummer	TKI2018-05-GE
Project titel	"Rise and Fall", the role of thermal uplift in the formation of Jurassic basins in the Dutch subsurface
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
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Datum	05 December 2020

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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

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Summary

The gradual transition from conventional to sustainable subsurface energy geo-resources and storage requires a new quantitative understanding of the mechanisms active during the geological time Netherlands subsurface onshore and the offshore. The RiFa project has created a know-how base for understanding and quantifying mechanisms driving the coupling between the regional Middle-Late Jurassic rifting, sedimentary evolution, and major denudation moments. We demonstrate the validity of a new concept of Jurassic extensional basin formation where the exhumation/uplift of highs does not require a mantle plume and associated thermal doming. The model is compatible with state-of-the-art process-oriented modelling of rifting mechanics and updated high-resolution data of global eustasy. This new concept provides new avenues of interpreting the evolution of the multitude of Jurassic basins observed in the Netherlands and larger neighboring areas and has, therefore, a new predictive power in terms of quantitative lithofacies distribution and thermal evolution.

1. Project overview

The University of Utrecht has coordinated the TKI RiFa project that runs from June 2018 to May 2020. A consortium was built in partnership with the TKI project Tectonic Models II 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 Tectonic Models II, 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.

1.1. Objectives and results

The “Rise and Fall” (RiFa) project aimed to understand and quantify the regional Middle-Late Jurassic rifting mechanisms. This understanding required an integrated analysis across the multitude of sedimentary sub-basins and highs, based on crustal- to well- scale data and state-of-the-art tectonic and geodynamic concepts. In contrast with previous qualitative ideas of active rifting, in RiFa, we pursued and proved the validity of a new concept of extensional basin formation where the exhumation/uplift of highs does not require a mantle plume and associated thermal doming. This new concept provides new avenues of interpreting the evolution of the multitude of Jurassic basins observed in subsidence and uplift and has, therefore, a new predictive power in terms of quantitative lithofacies distribution and thermal evolution.

The following research question was central to the TKI RiFa project:

- What were the exact vertical motions, thermal perturbations, and sediment redistributions during the Toarcian-Bathonian period of the Netherlands and surrounding areas of the South Permian Basin?

Particular attention was given to the relative roles of the Middle Jurassic thermal doming and Late Jurassic rifting on the formation of Jurassic basins and highs system in the Netherlands subsurface.

The project has demonstrated that the previously inferred late Early – Middle Jurassic plume-related thermal doming affecting large areas of the Netherlands subsurface by creating a regionally observed unconformity (the Mid-Cimmerian Unconformity – MCU) is not a viable working hypothesis. An alternative model is quantitatively supported to explain the North Sea MCU, which is based on a combined Toarcian-Aalenian eustatic sea-level fall and early stages of rifting propagation. The model is compatible with state-of-the-art modelling of rifting mechanics and updated high-resolution data of global eustasy and does not require the presence of a Jurassic mantle plume. Therefore, the North Sea MCU formed due to a combination of superposed topography-building effects. The rifting was combined with a low initial accommodation space and an important sea-level fall during the end of the Aalenian times, which exposed the pre-MCU strata. The timing and amount of denudation on the rift shoulders are explained by slow rift propagation from the Central Atlantic starting around the late Toarcian in the Hebrides, middle to late Aalenian in the Viking Graben, and Bajocian – Bathonian in the Central Graben. Although a Jurassic plume cannot be completely excluded, such a thermal doming mechanism is not required to explain the observed Jurassic topography.

2. Work plan

The project consisted of three technical work packages. Each work package was coordinated by the project partners, in close collaboration with the partner TKI project "Tectonic Models II". The corresponding work descriptions are highlighted below in more detail.

WP1 - Exhumation/erosion quantification for the Middle and Late Jurassic by compiling and interpolating available erosion/uplift data

The objectives of WP1 were to accomplish a new, updated compilation of the distribution of uplift and erosion in the Netherlands and the North Sea using maps and data files, and to make a correlation across basins and highs along key sections. To this aim, we have compiled, quality controlled, and interpolated the available erosion and uplift data across the different basins (Fig. 1 and 2). Accomplishing this WP was extremely challenging due to the extremely large study area combined with uneven and dispersed data distribution in the numerous sub-basins and highs of the North Sea.

The literature study demonstrated that Jurassic erosion in the Netherlands is older than doming and that the rifting process likely drove the observed vertical motions. Therefore, the previous idea of a Jurassic dome under the Dutch Central Graben is rather unlikely and cannot be further pursued, given the recent advances in data, methodology, and process-oriented modelling. Following the investigation of the Jurassic dome concept under the Central North Sea, we have further expanded our literature study and review to include most of the North Atlantic northwestern Europe, north of the Alpine Tethys margin. A compilation of vertical motions and tectonics stages for this larger area has been achieved, including (1) an updated compilation of structural data in the North Sea area and (2) a compilation of denudation estimates in the North Sea and the surrounding Jurassic High. We have also updated the paleo-tectonic and paleo-geographic maps of Ziegler (1982) for this larger region. This work has created a unique database that formed the basis for our subsequent process-oriented analysis.

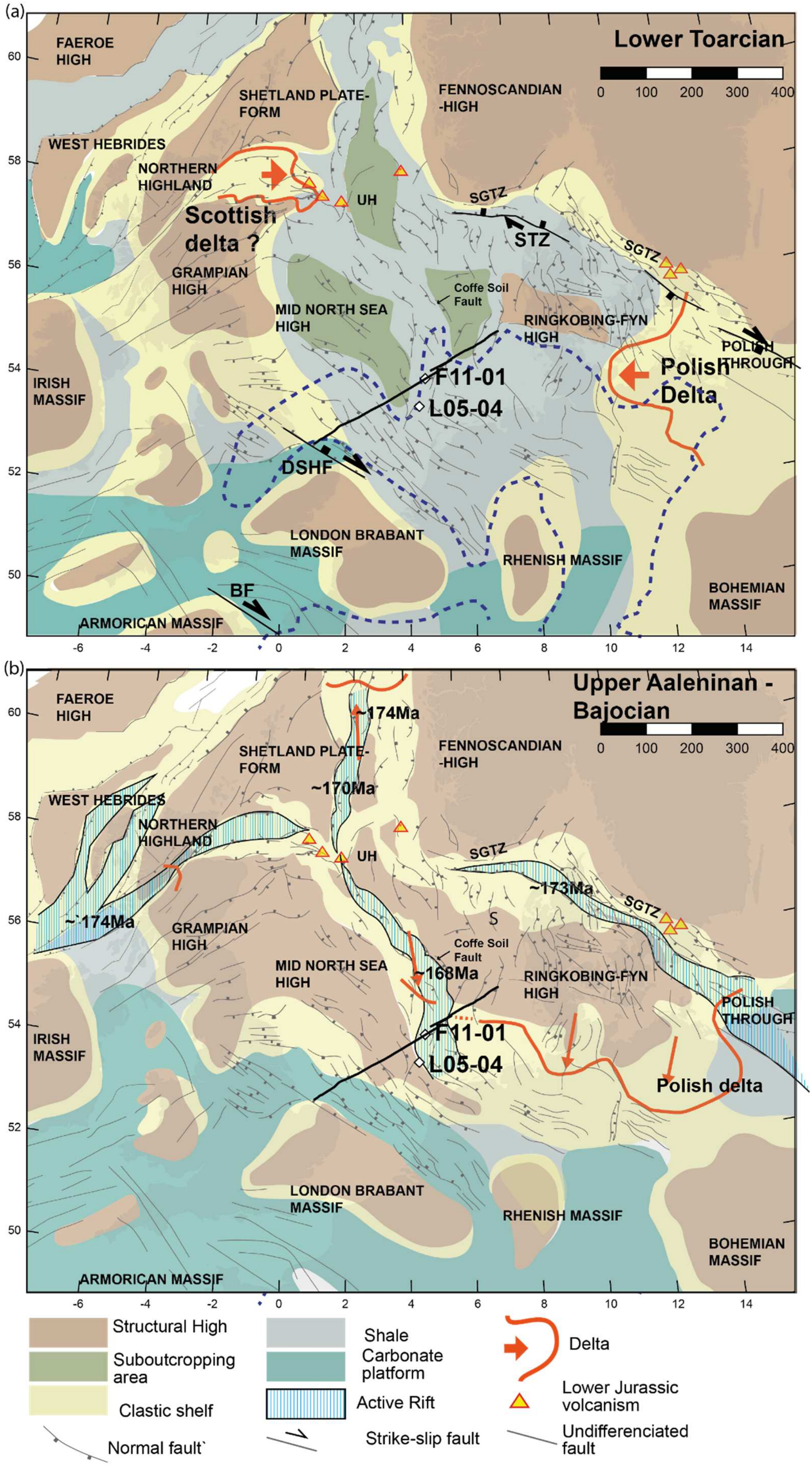
(a)
Lower Toarcian
0 100 200 300 400
FAEROE HIGH
SHETLAND PLATE-FORM
FENNOSCANDIAN -HIGH
WEST HEBRIDES
NORTHERN HIGHLAND
UH
SGTZ
STZ
Scottish delta ?
GRAMPIAN HIGH
MID NORTH SEA HIGH
Coffe Soil Fault
RINGKOBING-FYN HIGH
POLISH THROUGH
Polish Delta
IRISH MASSIF
F11-01
L05-04
DSHF
LONDON BRABANT MASSIF
RHENISH MASSIF
BOHEMIAN MASSIF
BF
ARMORICAN MASSIF
60
58
56
54
52
50
-6 -4 -2 0 2 4 6 8 10 12 14
(b)
Upper Aalenian - Bajocian
0 100 200 300 400
FAEROE HIGH
~174Ma
SHETLAND PLATE-FORM
FENNOSCANDIAN -HIGH
~170Ma
WEST HEBRIDES
NORTHERN HIGHLAND
UH
SGTZ
~173Ma
SGTZ
~`174Ma
GRAMPIAN HIGH
Coffe Soil Fault
MID NORTH SEA HIGH
~168Ma
RINGKOBING-FYN HIGH
POLISH THROUGH
IRISH MASSIF
F11-01
L05-04
Polish delta
LONDON BRABANT MASSIF
RHENISH MASSIF
BOHEMIAN MASSIF
ARMORICAN MASSIF
60
58
56
54
52
50
-6 -4 -2 0 2 4 6 8 10 12 14
Structural High
Suboutcropping area
Clastic shelf
Normal fault`
Shale
Carbonate platform
Active Rift
Strike-slip fault
Delta
Lower Jurassic volcanism
Undifferenciated fault

Figure 1 *(Previous page). Paleo-Geographic maps of North-Western Europe, (a) around the early Toarcian, (b) around the Upper Aalenian-Bajocian Modified after Ziegler, (1990); Ziegler et al., (1982). Posidonia shales geometry modified after Röhl et al., (2001). The wells F11-01 and L05-04 were studied in Trabucho-Alexandre et al., (2012). UH, Utsira High, RF, Rattray Field, BF, Bray Fault, DSHF, Dowsing-South Hewett Fault Zone, STZ, Sorgenfrei Tornquist Zone. The position of the Polish Delta to the south of the Rynkobing-Fyn High is redrawn from Zimmermann et al. (2015, 2018). The position of the Polish Delta is redrawn from Zimmermann et al. (2015, 2018).*

WP2 - Multi 1D tectonic analysis and forward modelling: Translate the compilation of vertical movements (and erosion) to tectonic subsidence and uplift

Previous studies have provided insight into Mesozoic erosion phases and underlying temperature evolution in order to test the possible role of magmatic underplating by a mantle plume in the formation of the Mid Cimmerian Unconformity (MCU) during the Jurassic in the North Sea. This WP aimed to test this hypothesis by reconstructing the various basins and topographic highs' vertical movements in the North Sea during Jurassic times to test different hypotheses of their driving mechanisms.

Our approach demanded that we carefully study the regional tectonic framework from early to late Jurassic. Furthermore, the long-lived evolution of paleo-highs and their burial and exhumation history during Jurassic times had to be detailed, studied, and reconstructed. This demanded additional literature study and comparison of the Dutch offshore with other Jurassic basins in the entire North Sea and neighboring areas, such as the Paris Basin (Fig. 2). This research has resulted in a quantitative placement of the MCU evolution in global eustatic and paleogeographic framework during the Jurassic rifting, together with quantitative estimates of burial and exhumation .

WP3 - Testing of results and hypothesis by analogue modelling, application to specific sponsor interests

The WP aimed to provide a proof of basin formation by regional doming observed in the presence of inter-basin highs using analogue modelling and applying the results to specific sponsor interest. The research performed during the project has demonstrated that the planned analog tectonic modelling was not entirely appropriate for predicting and comparing the flexural response to rifting in the Jurassic North Sea. Therefore, the main challenge in WP3 was to redirect our study to find an appropriate modelling technique able to provide the quantitative estimates required and obtain quantitative results in the available project time.

To predict and compare the flexural response to rifting in the Jurassic North Sea, we have chosen to apply an advanced thermomechanical numerical technique (Fig. 3) that employs a visco-elastoplastic approach to model rift propagation in the context of the asymmetric lithosphere. For this objective, we explored multiple numerical modelling strategies in collaboration with external partners. Ultimately, we decided to use a series of 2D models using the SiSter code (Olive, 2018; Olive et al., 2016; Olive and Behn, 2014) to evaluate the influence of Paleozoic inherited weakness zones during the low rates of Mesozoic rifting, accounting for quantitative estimates of vertical motions in rift systems. This numerical modelling strategy, replacing the original analogue modeling setup, has proven quite successful for process-oriented testing our concepts of drivers the exhumation observed during the MCU. Furthermore, we have continued instead in the line of the project and pursued an advanced correlation of the vertical movements predicted by the modelling to understand the evolution of the Dutch Central Graben and the Step Graben.

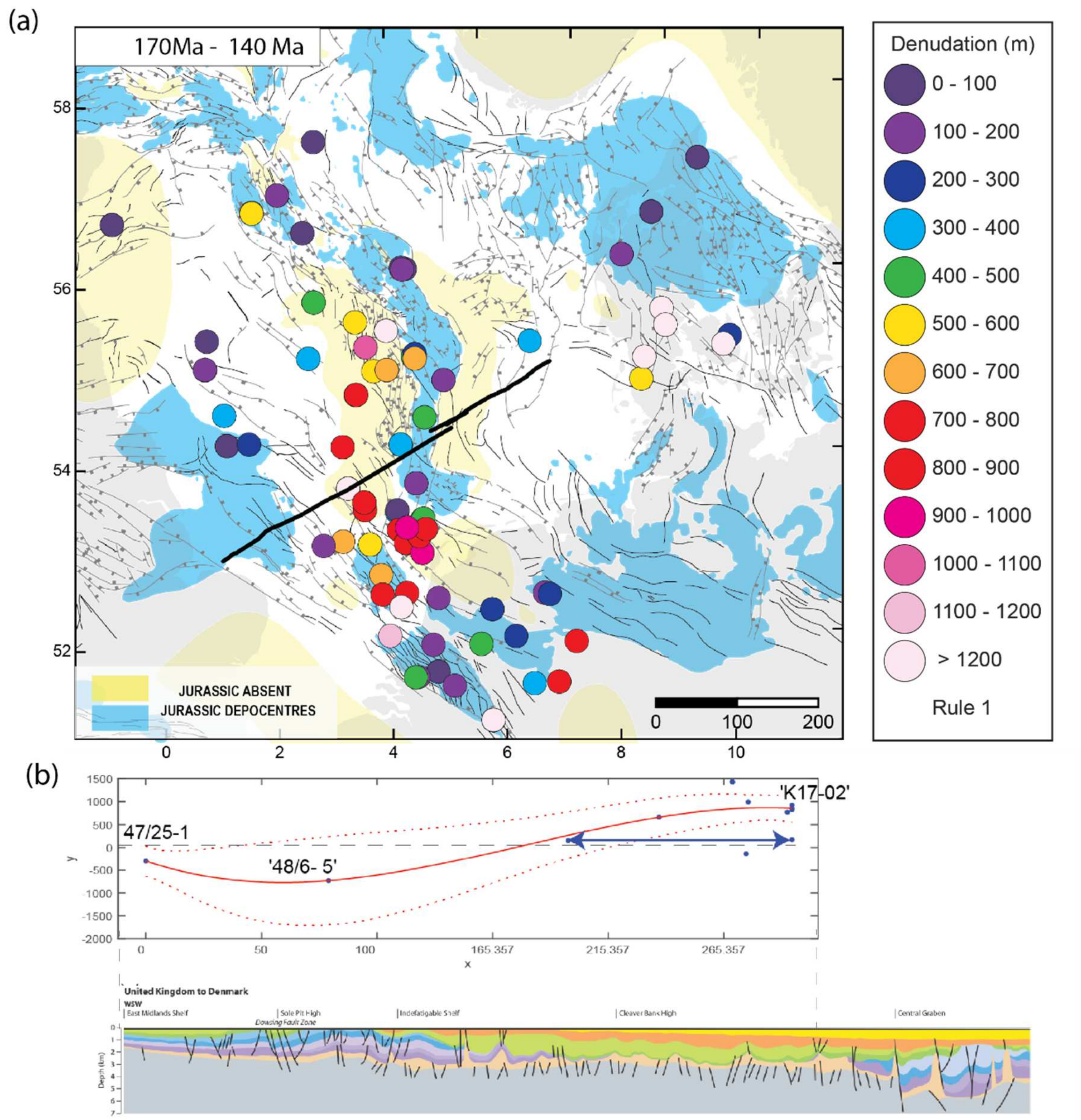

__Figure 2.__ (a) Estimates of denudation from several wells along the Central Graben for the 170 - 140 Ma period. (b)Change of burial-profile located in Figures 8 and 11 Uplift and denudation on the Cleaverbank High, the western Dutch Central Graben shoulder (a) A plot of the mean burial history approximatively projected along the depth converted seismic line (b). We used wells that are less than 50 km away from the profile. The red line corresponds to the 3rd order polynomial equation fitted with a Linear Least Squares method. Dashed red lines indicate 0.9 of standard deviations. We applied an inverse distance weighting function to the data set and extracted the profile in (b) from Pharaoh et al. (2010). The figure shows burial variations along the Central Graben shoulder for the Jurassic. Note that the profile has a 45° angle with the Dutch Central Graben. The shoulder uplift is around 70km.

3. Coordination

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. Financially, no significant differences between the budgeted and actual costs are recorded, and expenditures were maintained in the allocated budget. Minor differences are related to the project results, demonstrating that numerical modelling was a much better strategy to validate concepts than the original planned analogue modelling. The significant results of the numerical modelling approach validated our choice in changing the methodology. The change has resulted in several minor changes in laboratory material and general bench fee costs, as explained in the financial overview.

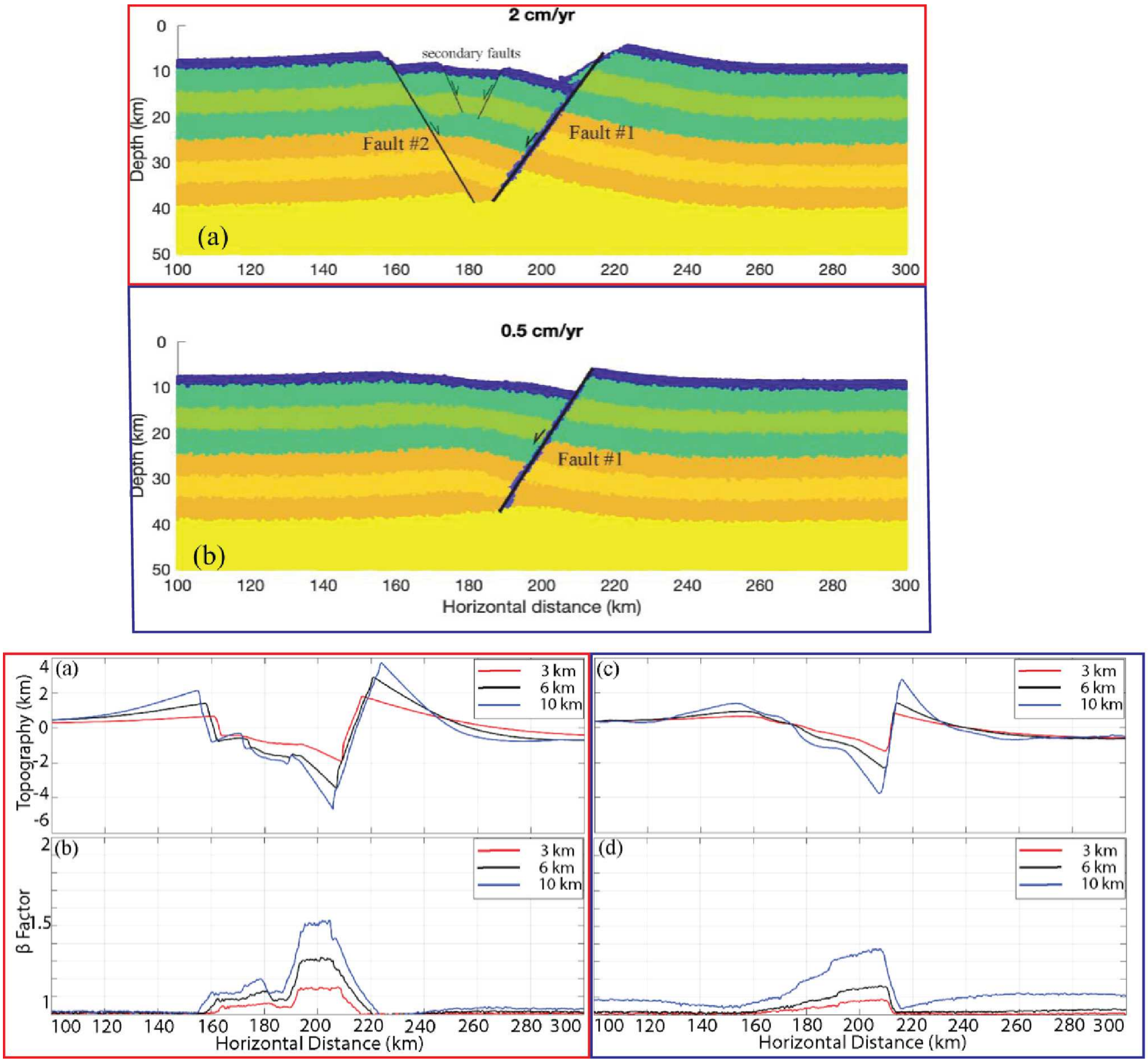

Figure 3. *TOP: Interpretation of main structural features developed in models with a strong lithosphere and varying extension rates after 10 km of extension (series-5, annex B). a) model extended at 2 cm/yr, displays the formation of a major crustal fault (fault nº1 and fault nº2) and two minor upper crust faults (secondary faults). b) model extended at 0.5 cm/yr shows a major crustal fault (fault nº 1), which appears to accommodate all the visible deformation. BOTTOM: Evolution of Topography and Beta Profiles represent snapshots at 3,6 and 10 km of reached extension. a) and c) represent topographic evolution of models extended at 2 cm/yr and 0.5 cm/yr respectively. b) and d) show beta factor evolution of models extended at 2 cm/yr and 0.5 cm/yr respectively. Beta Factor values of 1.5 and 2 represent 25% and 50% stretch of crust's initial thickness. During a slow rift, lower crustal flows and flexure trigger vertical motions in the range of the Dutch Central Graben observations.*

4. 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, or the 2019 NAC congress. Following the guidance of our project's sponsors, the results are currently in manuscript preparation for submissions to international journals. The following publications are currently in various phases of preparation:

Listed publications

A significant part of these results is already available in MSc Theses published by Utrecht University: The following MSc project is entirely a direct result of the RiFa project:

Cecchetti, E., Modelling the Role of Inheritance on Rifting: The Mid-Jurassic North Sea Central Graben, MSc project, Utrecht University, 39 pp.

Planned paper to be submitted: Toarcian-Aalenian paleo topography of the North Sea: a reevaluation vertical motions. Lafosse, M., Smit J.W., Van Wees J.D.A., Matenco L. to be submitted to Geology.

5. Technical advancements

Mesozoic rift development in the North Sea has been studied since the mid-20th century and has played an important role in understanding rifting dynamics in general. Thus, we know a widespread sedimentary hiatus and unconformity before the inception of the Middle to Late Jurassic main rifting phase. This Mid-Cimmerian Unconformity (MCU) corresponds to a 2nd order major regression that peaked around the late-Aalenian – early-Bajocian, covering much of the earlier Permian Basins. Earlier studies have interpreted the MCU as an unconformity due to a dome-shaped thermal uplift and associated erosion linked to coeval volcanic activity. It preceded the Late Jurassic rifting and was, therefore, unrelated. At the time of the earlier studies, it was the only known regional Middle Jurassic unconformity unrelated to global eustacy.

In contrast with these earlier studies and by correlation with the study performed in Rifa, our study proposes that the North Sea Mid-Cimmerian Unconformity formed in response to a combination of superposed topographic effects that do not need a Jurassic plume concept. We demonstrate that simplified sag-basin subsidence predating the MCU is not a likely representation of North Sea Basins more than 60 Ma after the end of the Permo-Triassic extension. Paleo-topographic variations and associated sedimentary (and tectonic feedback) processes were already in place by that time. The presence of inherited eroding topographic highs from the Caledonian and Variscan Orogens infer that differential vertical motions occurred and were associated with lithospheric heterogeneities. The denudation is observed, for instance, by Late Triassic weathering surfaces on the Utsira Highs. In the Norway-Danish Basins, the gravitational collapse of Triassic post-rift sediments suggests lateral variations of loading and a pre-existing topography during the Early Jurassic.

Furthermore, along the Anglo-Dutch and the Norway-Danish Basins' southern border, Early Jurassic strike-slip tectonics infers a predating MCU paleo-topography. The topography of Variscan Highs (London Brabant and Rhenish High) remained elevated during the Early-Jurassic. A comparison with the post-rift evolution in visco-plastic numerical models suggests the overall importance of load redistribution in the lithosphere and associated surface processes to maintain this former topography in the North Sea region and its surroundings elevated areas.

The Mid-Cimmerian Unconformity is a maximum regressive surface observed outside the North Sea area, such as in the Paris Basin, the Eastern and Northeastern Greenland Margin, and the Tethyan Arabian Margin. The MCU corresponds to a global eustatic regression (the 2nd order regression T-R cycle 6 to 7) that occurred towards the end of Aalenian times. This regression was driven by a sea-level drop of ~80 m. Calibrations of topography in the Central Graben to a level above the storm wave base during the previous second-order sea-level minimum (T-R cycle 5 to 6) suggest that most of the North Sea Basin was close to the surface or emerged during this Aalenian regression. Towards the end of the 6 to 7 T-R cycle, a ~75 m sea-level fall lowered the accommodation space in the North Sea and increased the faunal provincialism by reducing water exchanges between the Boreal and Tethyan Fauna.

Improved constraints on denudation and coeval sedimentation support alternative models and interpretations for the large-scale wavelength of the observed vertical motions. Our compilation of burial history and local denudation estimates show that the erosion is maximal on the rift shoulders during the Late Jurassic and recorded lower amplitudes than previously thought. Apatite fission-track data and burial analysis indicate more moderate Early-Middle Jurassic denudation and an absence of cooling induced by exhumation in the Variscan Massifs bordering the southern North Sea. A similar absence of cooling induced by exhumation is observed in the Moray Firth Grabens. In contrast, a coeval basin transgression and cooling induced by exhumation of the rift shoulders in the southern Baltic Shield and the Sorgenfrei-Tornquist Fault zone indicate differential vertical motions driven by rifting. The younger Bajocian rift propagation in the Dutch Central Graben was followed by Late Jurassic rifting, which suggests a different driving mechanism for the subsequent Late Jurassic volcanism observed. The amount of denudation over the western Dutch Central Graben shoulder can be reasonably constrained to less than 1300 m in its proximal part, which changes to no denudation at ~80 km farther distance. The correlation of this denudation pattern with the subsidence observed in the neighboring Anglo-Dutch Jurassic Basins infers that the driving mechanism was an extensional flexural uplift of the Dutch Central Graben rift shoulder. The inferred amounts of uplift and denudation are similar to those demonstrated by faulted block rotation and backstripping in the Viking Graben. A comparison with existing extensional models indicates that flexural wavelength was variable through time as a function of lithospheric strength changes: a strong cratonic lithosphere accommodated longer wavelength flexural uplift in the Norwegian-Danish basins. Petrological data of Jurassic volcanism are consistent with lithospheric recycling of an inherited Permo-Carboniferous mantle plume rather than a North Sea Jurassic one.

6. 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 Netherlands subsurface in the onshore and the offshore 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. In this fairly general framework, the analysis of critical geological moments of denudation for the formation and evolution of such plays is still an element that requires a multi-scale quantification. RiFa adds value to the research theme Geo Energy, and specifically to the topic "Geological Characterization", by improving understanding of one of the key moments in the evolution of the Dutch subsurface and developing an improved understanding of the overall multi-phase tectonic evolution. This understanding also significantly impacts the quantitative analysis of spatial and temporal evolution of vertical motions, thermal and deformation history, and the architecture of sedimentary basins. These findings are the base to build more robust conceptual models for conventional and sustainable new subsurface energy systems and geothermal energy exploration and facilitate the extension of the existing base for resources.

7. Conclusions, recommendations and possibilities for spin-off

We have studied vertical motions in the Middle Jurassic North Sea from literature, a compilation of subsidence curves, and we have performed numerical tectonic modelling to decipher the role of thermal doming.

Our study demonstrates that sag-basin subsidence is not the best-model to envision the North Sea Basins more than 60 Ma after the end of the Permo-Triassic extension. Persistent topographic Highs from the Caledonian and Variscan Orogens suggest that differential vertical motions occurred associated with lithospheric heterogeneities. Late Triassic weathering surfaces on the Utsira Highs demonstrate its denudation. In the Norwegian-Danish basins, Triassic post-rift sediments' extensional collapse suggests lateral variations of loading and a pre-existing topography during the Lower Jurassic. Along the southern border of the Anglo-Dutch and in the Norway-Danish Basins, Early Jurassic strike-slip tectonics favor a pre-MCU paleo-topography. The topography of the Variscan Highs (London Brabant and Rhenish High) remains elevated during the Early Jurassic. A comparison with post-rift evolution in viscoplastic numerical models suggests the overall importance of load redistribution in the lithosphere and surface processes to maintain topography in the North Sea and its surrounding elevated area.

The Mid-Cimmerian Unconformity is a maximum regressive surface that, outside the North Sea, is recorded in many other places, such as in the Paris Basin, the Eastern and Northeastern Greenland Margin, and the Tethyan Arabian Margin. The MCU corresponds to a global eustatic regression (the 2nd order regression T-R cycle 6 to 7) that occurred toward the end of Aalenian times. This regression was maximum following a 3rd order sea-level drop of approximately 80 m. Calibrations of the topography in the Central Graben to above the storm wave base during the previous second-order sea-level minimum (T-R cycle 5 to 6) suggest that most of the North Sea Basin was close the surface or emerged during this Aalenian regression. Toward the end of the T-R cycle, 6 to 7, a ~75 m sea-level fall might have lowered the accommodation space in the North Sea and increase faunal provincialism by reducing the water exchanges between the Boreal and Tethyan Fauna.

From the Early to the Late-Jurassic, apatite fission track and other burial analysis methods indicate more moderate denudation (and absence of cooling) than previously thought in the Variscan Massifs border southern the North Sea. A similar absence of cooling occurred in the Moray Firth Grabens. In the southern Baltic shield and the Sorgenfrei-Tornquist Fault zone, the synchronicity of transgression in the basin and cooling on the shoulders indicate differential vertical motions linked to the extensional fault kinematics. Younger Bajocian rift propagation in the Dutch Central Graben is followed by Late Jurassic rifting, suggesting different mechanisms for the Late Jurassic volcanism.

On the Dutch Central Graben's western shoulder, the amount of denudation can reasonably be constrained to less than 1300 m over the most proximal shoulder of the Dutch Central Graben and no denudation at less than 80 km farther distance. Correlating the uplift with the subsidence in the Anglo-Dutch Jurassic Basins, we show that the uplift may correspond to the Dutch Central Graben's shoulder's flexural uplift. In the Viking Graben, fault block rotation and backstripping demonstrate similar amounts of uplift and denudation. A comparison with models indicates that flexural wavelength is not constant through time and is a function of the lithosphere's strength. It suggests that a strong cratonic lithosphere can accommodate long-wavelength flexural uplift in the Norwegian-Danish basins.

In conclusion, we suggest that the North Sea Mid-Cimmerian Unconformity formed in response to a combination of superposed topographic effects, which does not require a Jurassic plume's activity. Low initial accommodation space and an important sea-level fall toward the Late Aalenian brought the pre-MCU strata near the surface. The timing and amount of denudation on the rift shoulders are explained by slow rift propagation from the Central Atlantic starting around the late Toarcian in the Hebrides and North Viking Graben, middle to late Aalenian in the South-Viking Graben, and Bajocian – Bathonian in the Central Graben. Although a Jurassic plume cannot be excluded, thermal doming is not required to explain the observed Jurassic topography.

Our modelling suggests that in a shallow epicontinental sea, the stratigraphy can record a sedimentary hiatus driven solely by rifting, without magmatic forcing. Because the surface heat flow is a function of the crust's radiogenic thickness, future numerical models, including burial models, may focus on the importance of the radiogenic heat production during the early stages of slow rifting. The Central Graben is a structure that displays significant 3D variability beyond the full predictive power of our 2D simulations. Recent 3D models evidence that a far-field compression oblique to the rift axis can stall the rift propagation. Toward the tip of the rift, stress rotations can lead to strike-slip or compressive deformation and asthenospheric flow. In the North Sea, it would be interesting to understand by numerical modelling if the rift propagation may lead to upward asthenospheric flow toward the graben's tip. Such modelling could explain the change of potential temperature of the lithospheric mantle and early thinning of the lithosphere at the tip of a stalled propagator.

In conclusion, we suggest two research directions for future studies: 1) Studies investigating 3D slow rift propagation, which could solve questions regarding the timing of mantle lithosphere thinning versus vertical motions, and 2) 3D studies on the interactions of surface processes and loads redistribution in the lithosphere for slow extensional mechanics. Such studies may contribute to a better understanding of Middle Jurassic Basins in Western Europe.

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