Burial and Heat Flux Modelling along a Southern Vøring Basin Transect: Implications for the Petroleum Systems and Thermal Regimes in the Deep Mid-Norwegian Sea

Tiago Abreu Cunha 1,*, Henrik Rasmussen 2, Heinrich Villinger 3 and Akinniyi Akintoye Akinwumiju 1

1 Integrated Geochemical Interpretation, Ltd., The Granary, Hallsannery, Bideford EX39 5HE, UK; Akinniyi@igiltd.com
2 Spirit Energy Norway AS. Veritasveien 29, 4007 Stavanger, Norway; henrik.rasmussen@spirit-energy.com
3 Department of Geosciences, University of Bremen, Klagenfurter Strasse 2, 28359 Bremen, Germany; heinrich.villinger@uni-bremen.de
* Correspondence: tiago@igiltd.com

Abstract: A key aspect on the evolution of rifted terranes and the prospectivity of the overlying sedimentary basins is heat. Temperature determines the deformation regime of crustal and mantle rocks and, thus, the style of rifting and geometry of rift basins. The generation of hydrocarbons from organic-rich rocks and reservoir conditions depend primarily on temperature. In this study, we model the thermal–burial history of the southern Vøring Basin (Mid-Norway Margin) along a regional transect (2-D), integrating basin- and lithospheric-scale processes. A model that accounts for the main extensional pulses that shaped the Mid-Norway Margin is in good general agreement with the present–past geothermal gradients inferred from borehole temperature and maturity data and the surface heat flux measurements in the proximal and intermediate margin. This supports a near steady-state, post-rift margin setting, following the break-up in the early Eocene. Significant discrepancies are, however, observed in the distal margin, where the borehole temperatures suggest (much) higher thermal gradients than model predicted and implied by the average surface heat flux. We speculate that the higher thermal gradients may result from deep-seated (mantle dynamics) thermal anomalies and/or recurrent hydrothermalism during periods of greater tectonic stress (regional compression and glacial loading rebound) and test the implications for the maturity of the Vøring Basin. The modelling results show, for example, that, depending on the thermal model assumptions, the depth and age of the optimal mid-Late Cretaceous source-rock horizons may vary by more than 2 km and 10 Ma, respectively.

Keywords: rift margins; Vøring Basin; thermal–burial modelling; heat flux; basin maturity

1. Introduction

The Mid-Norway Margin formed over a sequence of rifting events spanning between the Permian and early Eocene, with widespread volcanism during the late stages of rifting and continental break-up [1–3]. The deep-water margin, with present-day water depths greater than 500 m, formed during the Mid-Late Jurassic-Early Cretaceous rifting and comprises two major basins, the Møre and Vøring basins, separated by the Jan Mayen Fracture Zone (JMFZ), a major lineament in the continuation of an oceanic fracture zone [4] (Figure 1).

The Vøring Basin is 200–250 km wide, between the Halten and Dønna terraces (outer shelf) and the Vøring Marginal High, and accommodates up to 15 km of sediments in its deeper section [5]. As depicted in Figure 1, the basin encompasses several large sub-basins (or synclines), separated by basement ridges and fault complexes. The northern and southern Vøring Basins are also divided along the Surt Lineament, a transfer zone sub-parallel to the (JMFZ). These tectonic lineaments have been subsequently reactivated.
under compression–transpression during the Cenozoic, as a result of regional plate readjustments [1].

Figure 1. Bathymetric–topographic map of the Mid-Norway Margin (GEBCO, 2019), with 500-m contours, showing the location of the modelled transect (thick dark blue line), the location of the boreholes used for model calibration (white-crossed circles with borehole designation in red), the location of the crustal profiles in Figure 5 (dashed black lines) and the structural elements of the margin (thin black lines) extracted from the Norwegian Petroleum Directorate (NPD, Fact Pages; https://factpages.npd.no/) accessed on 31 January 2021. The shaded grey polygons highlight the location of the Jan Mayen Fracture Zone (JMFZ) and Surt Lineament (SL), which mark the southern boundary of the Vøring Basin and delimit its southern and northern segments, respectively. The colored symbols are heat flux (HF) data from the International Heat Flow Commission (IHFC; www.ihfc-iugg.org) according to source. Structural elements acronyms in alphabetical order: DT–Dønna Terrace; FBS–Froan Basin; FFC–Fles Fault Complex; FG–Fenris Graben; FH–Frøya High; GR–Gjallar Ridge; HG–Hel Graben; HT–Halten Terrace; MB–Møre Basin; MMM–Møre Marginal High; NH–Nyk High; NS–Någrind Syncline; RB–Rås Basin; SR–Sklínna Ridge; STR–Slettringen Ridge; TB–Træna Basin; TP–Trøndelag Platform; UH–Utgard High; VMH–Vøring Marginal High; VS–Vigrid Syncline. The inset map in the top-left corner shows the location of the area of interest (AOI) for this study in the Norwegian Margin.
At least two main periods of compressional deformation and basin exhumation can be identified, in the late Eocene–early Oligocene and in the mid-late Miocene, with the development of major basin unconformities and large structural domes [2]. The Plio-Pleistocene evolution of the Vøring Basin is marked by a hiatus or erosional unconformity, covered by a thick, prograding sedimentary wedge, up to 2-km-thick in the outer shelf-upper slope area and thinning progressively towards the deep margin. The initial erosion and subsequent large sedimentation rates are likely related to the onset of the glaciation episodes in Scandinavia [6].

The interest in the deep Mid-Norway margin surged in the last three decades, with the advent of deep-water exploration and some discoveries (mainly gas) in Late Cretaceous and Paleocene sandstones. These include two producing fields, the Ormen Lange (gas) in the Møre Basin and the Aasta Hansteen (gas and oil/condensate) in the northern Vøring Basin, both discovered in 1997. The burial history of the deep Vøring Basin suggests that the charging of these discoveries is likely from Cretaceous (or younger) source rock horizons, as the prolific Jurassic source rocks that feed the numerous oil and gas fields along the continental shelf are deeply buried under thick Cretaceous sequences. This is further supported by the fluids’ geochemistry [7,8] and paleogeographical reconstructions [9].

Previous models for the thermal structure and evolution of the margin highlight the importance of integrating the sediment coverage and the structure of the lithosphere [10–13]. A potential limitation of these models, however, is the assumption of present-day near steady state, following the continental break-up in the early Eocene. As a result, the models fail to predict the high geothermal gradients implied by the temperature and maturity data at a number of borehole locations in the deep margin—namely, in the Gjallar Ridge and Vigrid Syncline—or invoke the effect of localized processes, such as hydrothermal circulation [13]. On the other hand, the low average surface heat flux observed in the Vøring Basin, including the proximity of most of these boreholes [14,15], is typical of a quiescent rift margin.

In this study, we apply a thermo–tectono–stratigraphic basin reconstruction modelling technique (TECMOD-2D [16]) to a regional transect across the southern Vøring Basin. We test alternative thermal model scenarios, that cover the inherent modelling uncertainty and try to conciliate the surface heat flux measurements with the calibration to the borehole temperature and maturity data and investigate the implications for the predicted maturity history of the basin.

2. Materials and Methods
2.1. Model Setup and Parameterization

TECMOD-2D combines forward and inverse modelling techniques to recover the thermal and burial histories of rift basins. The forward model solves for both lithospheric-scale (e.g., rifting, continental break-up, magmatism and serpentinization) and basin-scale processes (e.g., sedimentation, compaction and maturity). Simultaneously, the inverse algorithm iteratively updates the values of crust and mantle stretching factors and the paleo-water depths to minimize the misfit between the observed (input) and computed (output) basin stratigraphy [16]. As demonstrated in previous works, modelling the feedbacks between basement heat flux and sediment blanketing effects is crucial for the accuracy of the thermal model solution for the basin through time [11,17,18].

The main model inputs are the stratigraphy and timing (age and duration) of the rifting events. The model stratigraphy was depth-converted from [19] using a regional seismic velocity model. As depicted in Figure 2a, the model provides reasonable detail of the Late Cretaceous and Cenozoic burial history in the deep Vøring Basin, which is of particular relevance to model the maturity of these sediment sequences. On the other hand, the Permo-Triassic and Jurassic sequences are poorly resolved, because these strata have not been drilled in the deep margin, and ties to the well-constrained stratigraphy in the shelf are hampered by the steep slopes along the Sklinna Ridge and its continuation to
the north (Figure 1). The thermal and compaction properties for the sediment, crust and lithosphere layers of the model are summarized in Table 1.

Figure 2. Reference model predicted stratigraphy and crustal structure—see Figure 1 for the profile location. (a) Predicted (dotted lines) versus observed (colored layers) stratigraphy [19]. The numbers in the layers provide the link to the property (Table 1). (b) Crustal structure, showing the basin modelled stratigraphy, the equal thickness upper (orange) and lower (red) crustal layers, the oceanic crust (blue) between 0 and 32 km of the model, an underplated body defined between 32 and 100 km and the high velocity body (HVB) in the Halten Terrace area (see text for details of the model setup). The different domains of the margin are defined for the purposes of description and analysis of results (see text).

For the reference model setup, three rifting events have been parameterized, namely: (1) Triassic–Late Jurassic (250–160 Ma), focused on the proximal margin, (2) Late Jurassic (160–145 Ma) and (3) Late Campanian–early Eocene (84–52 Ma). The definition of the rifting events is controlled by the stratigraphy, where the start and end of a rifting episode, and the initiation of post-rift thermal relaxation, must be defined by the model input horizons. The lack of constraints on the Early Cretaceous and younger stratigraphy thus imposes some limitations to the model. For example, the undifferentiated pre-Cretaceous sequences in the deep Voring Basin are here modelled as deposited during a Late Jurassic rifting event, together with the Jurassic sequences in the continental shelf, where the thicker sequences are likely Early-Mid Jurassic. There is also the possibility of a mid-Cretaceous rifting event [2], which has been considered in previous models [11,21]. These hypotheses will be further discussed when testing the model sensitivities (Section 4).
Table 1. Material properties for the model layers. The index numbers in the sediment layers identify the respective strata in Figure 2a. RHP is radiogenic heat production. The temperature dependence of the thermal conductivity follows [20]. The density, thermal and compaction properties of the sediments are mainly a function of the expected shale, sand and carbonate contents, with generally higher RHP and lower conductivity for high-shale contents. A heat capacity of 1000 Jkg\(^{-1}\)K\(^{-1}\) is assumed for all rocks.

| Model Layer                        | Density (km\(m^{-3}\)) | Thermal Expansion (K\(^{-1}\)) | RHP (Wm\(^{-3}\)) | Thermal Conductivity (Wm\(^{-1}\)K\(^{-1}\)) | Surface Porosity (%) | Compaction Length (km\(^{-1}\)) |
|------------------------------------|------------------------|-------------------------------|------------------|-----------------------------------------------|----------------------|---------------------------------|
| Mantle lithosphere                 | 3340                   | 3.2 \(\times\) 10\(^{-5}\)  | 3.0 \(\times\) 10\(^{-8}\) | 6.0                                           | –                    | –                              |
| Oceanic crust                       | 2800                   | 2.4 \(\times\) 10\(^{-5}\)  | 5.0 \(\times\) 10\(^{-7}\) | 2.0                                           | –                    | –                              |
| Lower crust                         | 2900                   | 2.4 \(\times\) 10\(^{-5}\)  | 8.0 \(\times\) 10\(^{-7}\) | 3.0                                           | –                    | –                              |
| Upper crust                         | 2700                   | 2.4 \(\times\) 10\(^{-5}\)  | 3.0 \(\times\) 10\(^{-6}\) | 3.5                                           | –                    | –                              |
| Underplating                        | 2900                   | 2.4 \(\times\) 10\(^{-5}\)  | 5.0 \(\times\) 10\(^{-7}\) | 2.5                                           | –                    | –                              |
| 1. Miocene-Recent (23-0 Ma)         | 2715                   | -                             | 1.0 \(\times\) 10\(^{-6}\) | 1.8                                           | 60                   | 0.22                           |
| 2. Oligocene Ooze (28-23 Ma)        | 2720                   | -                             | 5.0 \(\times\) 10\(^{-7}\) | 0.8                                           | 60                   | 0.20                           |
| 3. Eocene-Oligocene (52-28 Ma)     | 2715                   | -                             | 1.3 \(\times\) 10\(^{-6}\) | 1.6                                           | 62                   | 0.21                           |
| 4. Paleocene (66-52 Ma)             | 2600                   | -                             | 1.1 \(\times\) 10\(^{-6}\) | 2.1                                           | 57                   | 0.24                           |
| 5. Campanian-Maastricht. (84-66 Ma)| 2710                   | -                             | 1.2 \(\times\) 10\(^{-6}\) | 1.9                                           | 59                   | 0.23                           |
| 6. Coniacian-Santonian (90-84 Ma)   | 2700                   | -                             | 1.0 \(\times\) 10\(^{-6}\) | 3.0                                           | 42                   | 0.25                           |
| 7. Cenomanian-Turonian (98-90 Ma)   | 2710                   | -                             | 1.0 \(\times\) 10\(^{-6}\) | 1.9                                           | 59                   | 0.23                           |
| 8. Albain-Cenomanian (113-98 Ma)    | 2705                   | -                             | 1.0 \(\times\) 10\(^{-6}\) | 2.15                                          | 56                   | 0.26                           |
| 9. Early Cretaceous (145-113 Ma)    | 2715                   | -                             | 1.4 \(\times\) 10\(^{-6}\) | 2.05                                          | 60                   | 0.22                           |
| 10. Late Jurassic (160-145 Ma)      | 2700                   | -                             | 1.0 \(\times\) 10\(^{-6}\) | 2.0                                           | 56                   | 0.26                           |
| 11. Triassic-Jurassic (250-160 Ma)  | 2700                   | -                             | 8.0 \(\times\) 10\(^{-7}\) | 2.5                                           | 55                   | 0.27                           |
Continental break-up between Mid-Norway and Greenland was setup at 56 Ma, with a full spreading velocity of 1.65 cm·yr$^{-1}$ between 0 and 32 km of the model, in agreement with plate kinematic studies [22,23]. The model also accounts for magmatic underplating, during the late stages of rifting and continental break-up ([24], and the references therein). In the reference model shown in Figure 2b, an underplated slab extends between oceanic basement and 100 km of the model, under the Fenris Graben and Gjallar Ridge, thickening towards the Vøring Marginal High to 1.5 km, in agreement with the seismic mapping available for this study.

The high velocity lower crustal/upper mantle body between 320 and 390 km of the transect [19] is modelled here as an underplated slab emplaced during the last stages of rifting. Although it remains speculative if such high velocity/density bodies in the margin are inherited high-grade metamorphic phases (eclogite-granulite facies) from the Caledonian orogeny or due to magmatic underplating [25], we tested here the latter hypothesis as the one that could have an impact on the recent maturity of the basin. There is also ongoing debate on the nature of the basement underlying the deep Vøring Basin, in particular to the west of the Slettringen Ridge and its northern continuations along the Fles Fault Complex (Figure 1), with some authors proposing extensive upper mantle serpentinization, while others suggest more pervasive underplating or inherited high-grade Caledonian (and/or older) lower crust [26–30].

The high velocity lower crustal/upper mantle body between 320 and 390 km of the transect [19] is modelled here as an underplated slab emplaced during the last stages of rifting. Although it remains speculative if such high velocity/density bodies in the margin are inherited high-grade metamorphic phases (eclogite-granulite facies) from the Caledonian orogeny or due to magmatic underplating [25], we tested here the latter hypothesis as the one that could have an impact on the recent maturity of the basin. There is also ongoing debate on the nature of the basement underlying the deep Vøring Basin, in particular to the west of the Slettringen Ridge and its northern continuations along the Fles Fault Complex (Figure 1), with some authors proposing extensive upper mantle serpentinization, while others suggest more pervasive underplating or inherited high-grade Caledonian (and/or older) lower crust [26–30].

For the purposes of description and analysis of results, we consider the proximal, intermediate and distal sectors of the margin (Figure 2). The proximal margin corresponds to the continental shelf, which extends to the east of the Sklinna Ridge in the southern Vøring Basin. The intermediate margin is defined between the Sklinna and Slettringen ridges and comprises the Rås Basin. The distal margin is then defined between the Slettringen Ridge-Fles Fault Complex and the Vøring Margin High, encompassing the Vigrid Syncline, the Gjallar Ridge and the Fenris Graben.

The reference model assumes a pre-rift crustal thickness of 30-km crust, an isostatic compensation depth of 80 km and surface and base lithosphere temperatures of 3 °C and 1300 °C, respectively. For simplicity, the model assumes equal proportions of upper and lower crust. As depicted in Figure 2a, such model setup provides a valid solution to the subsidence and burial history across the southern Vøring Basin, with an almost perfect fit to the observed stratigraphy (>95% convergence after 10 iterations). The model predicted crustal thickness, varying between ~24 km in the inner shelf, under the Froan Basin, to 12–15 km in the Halten Terrace-Sklinna Ridge area and less than 10 km in the intermediate–distal margin, is also broadly consistent with that inferred from seismic data and potential field modelling [5,25], with differences of <5 km across the basin. Different lithosphere configurations and geometries of rifting, as well as the nature of the basement in the deep Vøring Basin, have also been tested as model sensitivities to investigate the implications for the thermal evolution and the petroleum systems of the margin (see discussion).

### 2.2. Thermal Model Calibration

The thermal–burial model is reasonably well-calibrated to the available temperature and maturity (vitrinite reflectance; VR) data at borehole locations in the proximal and intermediate sectors of the margin (Figure 3); we use the basin%Ro kinetic model [31], as it provides the best calibration to the borehole data in the area. This suggests a near steady-state, post-rift margin, where the loss of radiogenic heat resulting from the thinning of the granitic crust is compensated by heat generated within a thick, shaly sediment column. However, west of the Slettringen Ridge (~200 km of the model), the model consistently underpredicts the measured temperatures, with a progressively increasing deviation that reaches ~50 °C for a 3.6-km burial depth at the Gjallar Ridge in borehole 6603/5-1 (Figure 3a). The model also largely underpredicts the VR maturity measurements in this borehole (Figure 3b). These results are further supported by 1D models built at 15 borehole locations [8] (see Figure 1 for the location of the modelled boreholes).
Figure 3. Model predicted, present-day temperature and basin%Ro maturity [31] and calibration to borehole data (see Figure 1 for the borehole location). (a) Predicted temperature with 50 °C isotherms (grey lines). Additionally shown are the stratigraphic contours (black lines), with the ages of the Cretaceous horizons (see Figure 2 for complete basin stratigraphy) and the locations along the profile where the boreholes are projected (shaded bars with the borehole name and approximate projected distance to the profile; see text for discussion). The model predicted temperature versus depth profiles at five projected borehole locations are compared with the bottom-hole temperature (BHT–blue dots) from the NPD, which should approximate the static formation temperatures. (b) Predicted basin%Ro maturity with the typical color scheme and contours (grey lines) for the vitrinite reflectance (VR) maturity windows. There is some variability in the range defined for these windows, depending on author and kerogen type, which are here interpreted as follows: VR < 0.5 is immature; 0.5 < VR < 0.7 is early-oil mature; 0.7 < VR < 1.0 is mid-oil mature; 1.0 < VR < 1.3 is late-oil to early-gas mature; 1.3 < VR < 2.2 is mid-gas mature; 1.3 < VR < 2.2 is late-gas mature; VR > 3.0 is post-mature. The model predicted basin%Ro versus depth profiles at three projected borehole locations are compared with the VR measurements (blue dots) available from the NPD (https://factpages.npd.no/, accessed on 31 January 2021).
The calibration boreholes that are projected onto the model transect along the structural fabric of the margin (see Figure 1 for the location), with the projection distances increasing from approximately 10 km in the Halten Terrace (well 6406/8-1 at 305 km of the profile) to 15 km in the western Rås Basin (6505/10-1 at 220 km), 50 km in the eastern Vigrid Syncline (6504/5-1 at 190 km), 70 km in the western Vigrid Syncline (6603/12-1 at 120 km) and 100 km in the Gjallar Ridge (6603/5-1 at 90 km). It is unlikely, however, that the large deviations between observed and modelled, present-day thermal gradients (i.e., temperatures) are a result of borehole location only, since the burial history and structure of the lithosphere inferred from seismic data and potential field modelling do not changing dramatically along the projected locations [25], and the transient thermal effects associated with thicker underplating and sill intrusions in the central Gjallar Ridge have long subsided. Moreover, the temperature data available from other modelled boreholes [8] consistently indicate an increase in the geothermal gradients between the intermediate (Rås Basin) and more distal sectors of the margin (Vigrid Syncline and Gjallar Ridge; Figure 3a).

The maturity profile shown in Figure 3b indicates that, in the present day, the Early Cretaceous and older sediment sequences are largely gas mature (%Ro > 1.3) to post-mature (%Ro > 2.2/3; depending on kerogen kinetics) across the southern Vøring Basin, while the latest Cretaceous and Cenozoic sediments remain immature (%Ro < 0.5), with the mid-Late Cretaceous formations predicted within the oil–gas window maturity (0.5 < %Ro > 1.3). The maturity histories of selected stratigraphic horizons and implications for hydrocarbon exploration are discussed in Section 3.2. for the reference thermal–burial model and Section 4.4. for alternative modelling scenarios.

The model predicted surface heat flux in proximal margin, to the east of the Sklinna Ridge, varies broadly between 50 and 65 mW·m\(^{-2}\) and is consistent with the available estimates based on borehole temperature data [15,32] (Figures 4 and 5). In the deep margin, the modelled surface heat flux varies narrowly between 49 and 54 mW·m\(^{-2}\), for basal heat flux, the values vary between 36 and 37 mW·m\(^{-2}\), in the center of the Rås Basin and Vigrid Syncline, and up to 48 mW·m\(^{-2}\) in the basement ridges (Figure 4). These values are, on average, ~10 mW·m\(^{-2}\) lower than measured at the surface, by a number of different authors (Figure 4), but within the range of values observed over large areas of the Rås Basin and Vigrid Syncline (see Figure 5). On the other hand, a considerable higher heat flux than measured at the surface are predicted in the 1D modelling experiments that recover the temperature and maturity data in the Vigrid Syncline and Gjallar Ridge wells, between 65 and 80 mW·m\(^{-2}\) [8]. There exists, therefore, an apparent incompatibility between the predicted thermal gradients in the distal margin, assuming a near steady-state, post-rift setting, and those implied by temperature and mature data at hole locations, which, in turn, suggest a much higher heat flux than measured at the seafloor.

2.3. Mid-Norway Margin Heat Flux and Thermal Regimes

The heat flux data in the Mid-Norway Margin consist of seafloor measurements [33] and estimates based on BHT and/or reservoir temperatures in exploration boreholes [15,32]. The data are widespread in the margin, covering large areas of the Møre and Vøring basins, but unevenly distributed (Figure 1). The northern Halten Terrace and adjacent areas in the proximal margin are relatively well-covered, as well as several structural elements in the distal margin, including the Vigrid and southern Någrind synclines, the Gjallar Ridge and Nyk High. A few measurements are also available along the Fenris and Hel grabens and in the Vøring Marginal High. On the other hand, the deep Rås and Trøna basins, in the intermediate margin, have only a few, scattered seafloor heat flux measurements, namely along two transects in the central and southern Rås Basin. The heat flux data from the International Heat Flow Commission [33] is provided from a variety of authors/sources and the values estimated using different methodologies and/or parametrizations. Although a quality assessment of the values is beyond the scope of this paper, a brief description of the data sources, applied corrections and possible errors or
discrepancies between estimated/calculated heat flux values is relevant for the discussion of the modelling results ahead.

Figure 4. Model predicted basal (i.e., at base sediments; solid line) and surface (dashed line) heat flux at the present day. The heat flux data from the International Heat Flow Commission database (IHFC; http://ihfc-iugg.org accessed on 31 January 2021) is also projected along the profile (see Figure 1 for the approximate locations of the data relative to the modelled transect). The IHFC dataset is compiled from a variety of sources/authors, identified by the colored symbols, and comprises both seafloor heat flux measurements and estimates based on the BHT and/or reservoir measurements in the exploration boreholes (see text). No reference is provided in the IHFC database for the University of Bergen data.

The single largest dataset within the area of interest (green dots in Figures 1 and 5) comprises fourteen heat flux values in the proximal sector of the margin, estimated from BHT and reservoir temperatures in deeply buried Jurassic–Triassic sediments and more than 60 gravity-probe heat flux values in the intermediate and distal sectors of the margin, determined from in situ temperature profiles and shipboard thermal conductivity measurements, averaged in about 500-m-diameter clusters of 2–5 measurements [15]. The data shows a general consistency between the heat flux estimates based on boreholes in the proximal margin and the seafloor heat flux values in the intermediate–distal margin. This suggests that a decrease in the basement heat flux towards the distal margin due to crustal thinning is partially compensated by heat generation within the sediment column [15], as expected for a near steady-state rift margin. Independent estimates from reservoir temperature data in a large number of boreholes indicate an average 10% higher heat flux along the continental shelf (65 ± 7 mW·m⁻²), possibly as a result of differences in the assumed values of sediment porosities and/or thermal conductivities [32].

Some anomalously high surface heat flux values (>65 mW·m⁻²) are reported in the intermediate and distal sectors of the margin. This is particularly noticed at the northern boundary of the Fenris Graben, Gjallar Ridge and Vigrid Syncline, along the Surt Lineament, where the measured/inferred heat flux from different sources [15,34] is consistently high, with most values between 70 and 90 mW·m⁻² (see map and Profile-1 in Figure 5). Some lateral heat flux variations appear to be structurally controlled, while the consistently high values in faulted structural highs may be associated with hydrothermal circulation [15]. This is consistent with the area being strongly tectonized. In contrast, the heat flux values reported in the southern Fenris Graben and Gjallar Ridge, in the proximity of the Jan Mayen Fracture Zone (Profile-2 in Figure 5), are lower, mostly around 60 mW·m⁻² [33], and within the expected for a quiescent passive margin. This is also the case for the deep Møre Basin, where the reported surface heat flux values are mostly between 40 and 60 mW·m⁻² [35].
Figure 5. Heat flux data from the International Heat Flow Commission Database (IHFC; http://ihfc-iugg.org/, accessed on 26 February 2021), projected along three profiles, across the central–northern Vøring Basin (Profile 1), the southern Vøring Basin (Profile 2) and the northern Møre Basin (Profile 3; see Figure 1 for the approximate locations of the data and transects). The original sources/author of the heat flux data is identified by the colored symbols, with the reported heat flux value, and comprises both the seafloor heat flux measurements and estimates based on the BHT and/or reservoir measurements in the exploration boreholes (see text). No reference is provided in the IHFC database for the University of Bergen data. The heat flux values in bold are local averages from more than one reported value. The regional stratigraphy, basement and Moho horizons are from the GFZ Data Services [5].

Other areas that record anomalously high heat flow values include the slope maxima in the Møre Basin, with values up to 322 mW·m⁻² [35,36], and at the sharp ocean–continental boundary (OCB) south of the Jan Mayen corridor, with values between 125 and 175 mW·m⁻² [34] (see Profile-3 in Figure 5). The very high slope values are measured within the Storegga Slide, a massive submarine slide dated of ~8 Ka [37], and could be associated with the induced changes in pressure–temperature conditions and fluid circulation...
in the sediment; this hypothesis is further supported by the occurrence of mud volcanos in similar slope heat flux anomalies within large slide scars in the Barents Sea [14]. In a different setting, the high heat flux in the vicinity of the OCB could be caused by thermal refraction effects in a steep slope basement.

As far as we are aware, the published heat flux values have not been corrected for the effects of recent high sedimentation rates, variations in bottom water temperatures and large-scale submarine slides, but it is unlikely that these would affect the regional estimated averages significantly, because: (1) the higher Plio-Pleistocene sedimentation rates are largely limited to the proximal–intermediate margin, where most heat flux estimates are from borehole temperatures. Some seafloor heat flux measurements may be affected, for example, in the southern Voring Basin and parts of the Vgrid Syncline, and are discussed locally; (2) variations in the bottom water temperatures would mainly affect the shallow heat flux measurements in shallower water conditions; (3) the giant submarine slides are relatively well-identified as the Storegga and Trænadjupet slides along the Jan Mayen and Brivost corridors, respectively, and anomalous heat flow values appear to be limited to the scar areas. Other processes that could result in transient deviations of the steady-state heat flux include rifting, underplating and sill intrusions. However, the last rifting and magmatic activity in the Mid-Norway margin takes place at the time of break-up in the late Paleocene–early Eocene, and the associated transient effects would wane within 100 Kyr (sill intrusions), a few Myr (underplating) and a few tens of Myr (riifting) [15,17].

3. Results

The main modelling outputs are the predicted thermal and maturity histories of the basin. These are discussed here for the reference, thermal–burial model described above from the perspective of the basement heat flux and the maturities of selected model horizons through time.

3.1. Heat Flux History

The temporal and spatial variations in the rift basins’ heat flux are mainly determined by the effects of rifting and sediment blanketing. The thinning of the lithosphere results in a transient increase in the basement heat flux during rifting, due to the shallowing of the lithosphere–asthenosphere boundary (LAB), while the thinning of the radiogenic upper-middle crust leads to a permanent decrease in the basement generated heat. The duration of the rifting events also impacts on the predicted heat flux, with shorter rifts generating higher amplitude and narrower heat pulses than longer events, where heat is dissipated [38,39]. Sediment blanketing affects the basement heat flux in two fundamental ways [11]. The sedimentation of cold sediments, which are not thermally equilibrated, depresses the basement heat flux (solid advection). This is particularly noticeable for high sedimentation rates, often during syn- and early post-rift periods. The lower conductivity of sediments, relative to the underlying crystalline crust, also contributes to lower the heat flux during sedimentation and slows the basement cooling following rifting.

Both the thermal relaxation of the lithosphere and the heating of the buried sediments are transient effects but occur over different timescales, broadly between 40 to 80 Myr and 2 to 10 Myr, respectively, for the range of lithosphere and sediment thicknesses considered in this study [17,18]. The sediments’ heat generation also contributes to the surface heat flux, particularly in the case of shale dominated, thick sediment piles. In the deep Voring Basin, we estimate an average contribution of ~1 mW·m⁻² per km of sediments (see Figures 2 and 4).

The basement heat flux history shown in Figure 6a accounts for the rifting and sediment blanketing effects, as well as those associated with the continental break-up and underplating. In the deep offshore, between 30 and 250 km of the model, approximately, the dominant pattern, is that of high heat flux during the Late-Jurassic rifting (up to 85 mW·m⁻²), decreasing during the Early Cretaceous and early Late Cretaceous thermal quiescence of the basin. This is followed by a second, less prominent heat flux peak (up to
60 mW·m⁻²) during the Late Cretaceous–Paleogene rifting and subsequent sinking during the Cenozoic post-rift burial.

Figure 6. Model predicted heat flux at base sediments through time and impact of sedimentation rates. (a) Predicted base sediments heat flux through time along the modelled transect for the reference thermal–burial model. The model clearly shows the impact of rifting, with strong lateral heat flux variations largely controlled by sedimentation (see the text for discussion). Additionally identified are the effects of underplating (highlighted by red dotted lines) and the edge-effects at the model boundaries (black dotted lines), where there are changes in the age of the first rifting event (at 260 km of the model) or at the ocean–continent boundary (at 32 km of the model). The shaded white bars mark the location where we show the basal heat flux and sedimentation rates histories. (b) Basal heat flux through time at 90 km, 220 km and 305 km of the transect, which are the locations where the model is also tentatively calibrated to borehole temperature and maturity data (see Figure 3). The labels in the shaded grey bar identify the main tectonic/magmatic events (see the text for discussion), namely the Triassic–Jurassic Rifting (R₁; active beyond 260 km), the Late-Jurassic rifting (R₂), the Late-Cretaceous–Eocene rifting (R₃) and underplating (U). (c) Predicted sedimentation rates through time at 90 km, 220 km and 305 km of the transect.

As depicted in the heat flux histories extracted at 90 and 220 km of the model, the Late-Jurassic high basement heat flux is largely overprinted by the very high sedimentation rates during this period of up to 1000–1500 m·Myr⁻¹ (Figure 6b,c, left and centre). The steep decrease in the basement heat flux between approximately 140 and 100 Ma is also partially due to the relatively high sedimentation rates throughout the Early Cretaceous, between 50 m·Myr⁻¹ and 200 m·Myr⁻¹, followed by a further depression during the Cenomanian–Coniacian (100–84 Ma), as the sedimentation rates increased to 350–500 m·Myr⁻¹. The effects of underplating are also clearly noticed in the heat flux–time map of Figure 6a,
between 30 and 100 km of the model, and in the heat flux history extracted at 90 km of the transect, forming a second peak following rifting (Figure 6b, left).

In the proximal margin, where crust and mantle stretching are less prominent, the strong lateral variations in the basement heat flux are mainly controlled by sedimentation, with lows in the depocentres flanked by basement highs. A long-term decrease in the average basement heat flux is, however, clearly observed in the profile extracted at 305 km of the model (Figure 6b, right), as a result of the progressive thinning of the radiogenic crust over successive rifting events. This general pattern is interrupted at the Mesozoic-Cenozoic boundary between 320 and 390 km of the model, due to the emplacement of 5 km of underplated material, with most of the transient heat being dissipated over ~5 Myr (Figure 6a). The heat flux and sedimentation rates through time extracted at 305 km of the model also suggests a present-day heat flux depressed by ~3 mW·m$^{-2}$ as a result of high sedimentation rates. This effect is probably underestimated, as a significant proportion of the Neogene sediments in this area are Plio-Pleistocene glacial deposits.

3.2. Maturity History

The predicted basin%Ro maturity histories are shown in Figure 7 for five potential source rock horizons. These cover the Cretaceous stratigraphy of the model, which comprises the likely sources for the hydrocarbon discoveries in the deep Mid-Norwegian Margin, based on the available fluid geochemistry data and burial histories [7–9].

In the deep Vøring Basin intermediate, where this study focuses, the reference model predicts that the latest Cretaceous (Campanian–Maastrichtian) and younger stratigraphy are immature (Figure 7a). At the other end of the spectrum, the model indicates that potential source rock horizons in the Late Jurassic and earliest Cretaceous successions are gas-mature to post-mature since the Late Cretaceous, with the exception of local highs (Figure 7e), where the gas window maturity was reached until the early Neogene.

The most interesting maturity histories, with the possibility of recent oil and/or gas generation and expulsion in large sections of the intermediate and distal sectors of the margin, are shown for the mid-Cretaceous horizons of the Aptian to Turonian age (possibly Santonian–Coniacian), where maturity is predicted to take place during the Late-Cretaceous–Cenozoic burial (Figure 7b–d). Significant differences in the timing and degree of maturity are, however, noticed within these thick sediment sequences, with up to 5 km of Albian–Turonian sediments (see Figure 2a for the model stratigraphy):

1. The uppermost Turonian horizon (90 Ma) is predicted to reach mid- to late-oil maturity in the distal margin (Vigrid Syncline and Gjallar Ridge) during Cenozoic burial (late Eocene onwards), with some potential for recent oil expulsion depending on kerogen type (Figure 7b). However, across most of the Vigrid Syncline and Rås Basin, the model predicts an immature or early-oil maturity late Turonian (or Coniacian-Santonian) horizon.

2. Pervasive oil and/or gas maturity is predicted for the late Albian–Cenomanian horizon (98 Ma) in the intermediate and distal sectors of the margin during the latest Cretaceous–Cenozoic burial (Figure 7c). In the Rås Basin, mid-oil maturity is reached between the Paleocene and the Oligocene, with the potential for recent oil and some gas generation, depending on the kerogen kinetics. In the Vigrid Syncline and Fenris Graben, gas window maturity is predicted during the late stages of rifting and continental break-up, and the recent oil and gas generation and expulsion is likely to focus along the flanks of these basins and the Gjallar Ridge.

3. The Aptian–Albian horizon (113 Ma) is predicted to reach gas maturity and post-maturity during the latest Cretaceous–Eocene burial over most of the deep margin, with the exception of the Gjallar Ridge area, where there is potential for recent oil and/or gas generation and expulsion (Figure 7d).
Figure 7. Predicted basin\%Ro [31] maturity through time for five stratigraphic horizons covering the thick Cretaceous sediment sequences in the Vøring Basin (see Figures 2 and 3 for the model stratigraphy and present-day temperature and maturity along the horizons, respectively). (a) maturity of top Springar/Nise formations (75 Ma); (b) maturity of top Lange/Lysing formations (90 Ma). (c) maturity of the Upper Lange formation (98 Ma). (d) maturity of mid Lange formation (113 Ma). (e) maturity of the base Cretaceous (145 Ma). Typical color scheme and contours (grey lines) are used for the vitrinite reflectance (VR) maturity windows, which are here interpreted as follows: VR < 0.5 is immature; 0.5 < VR < 0.7 is early-oil mature; 0.7 < VR < 1.0 is mid-oil mature; 1.0 < VR < 1.3 is late-oil to early-gas mature; 1.3 < VR < 2.2 is mid-gas mature; 1.3 < VR < 2.2 is late-gas mature; VR > 3.0 is post-mature. Structural elements acronyms from left to right: VMH–Vøring Marginal High; FG–Fenris Graben; GR–Gjallar Ridge; VS–Vigrid Syncline; STR–Slettringen Ridge; RB–Rås Basin; SR–Sklinna Ridge; HT–Halten Terrace; FBS–Froan Basin.

4. Discussion

A key aspect of petroleum systems modelling in frontier basins is the analysis of uncertainty in the assessment of the basin maturity. The stratigraphy and burial history of the deep Mid-Norway Margin are relatively well-known since the Late Cretaceous, and the depth to basement and thickness of the crust are constrained along 2D deep seismic transects (reflection and wide-angle) and/or from combined seismic interpretation and potential field modelling. There is, however, an ongoing debate on the age of the deeper stratigraphy, the timing of the rifting events and the nature of the basement in
the intermediate–distal margin. Furthermore, there is only sparse well data to calibrate the thermal–burial models for the present day and past thermal regimes, and the existent models do not conciliate the apparent high geothermal gradients and low surface heat flux in the intermediate and distal sectors of the margin. We address here some of these uncertainties, evaluate the implications for the prospectivity of the Mid-Norway Margin and discuss the merits of future works to improve the current understanding of the margin thermal evolution.

4.1. Hot and Cold Models

A typical route followed to assess the uncertainty in basin maturity modelling is to setup colder and hotter models relative to the reference, thermal-calibrated model. Although such models do not specifically address the lack of constraints in a particular process, structural feature and/or model parameter, they often cover the associated uncertainties. For example, the uncertainty in the depth of a particular source rock horizon resulting from errors in the seismic interpretation or the depth conversion can be (approximately) correlated to a given variation in the geothermal gradient. Likewise, variations in the layering of the crust and/or the thickness of the lithosphere, within reasonable model uncertainty, correspond to measurable differences in the steady-state geotherm.

The cold and hot models shown in Figure 8 assume a 20-km thicker (Figure 8, left) and thinner (Figure 8, right) mantle lithosphere, respectively, and predict differences in the basal heat flux relative to the reference model of 5 to 10 mW m$^{-2}$ throughout the burial history of the basin, with average present-day differences of $-5$ mW m$^{-2}$ and $+8$ mW m$^{-2}$, respectively (Figure 8a,b). As expected, such variations have a significant impact on the calibration of the thermal–burial model. For example, in the Rås Basin, the cold and hot models underpredict and overpredict the measured borehole temperature by $>15$ °C, and in the Sklinna Ridge, the hot model overshoots the borehole temperature by $~25$ °C (Figure 8c). Notwithstanding the 5–10 mW m$^{-2}$ increase in basal heat flux through time, the hot model still largely underpredicts the temperature and maturity data in the Gjallar Ridge well (Figure 8c,d, right), whilst the predicted heat flux in the intermediate and distal sectors of the margin is within the higher range of observed values (see also Figure 4). The cold and hot models also predict somewhat higher and lower crustal stretching factors to recover the margin subsidence and burial history, respectively, but with negligible implications for the basement heat flux, compared with those resulting from the differences in the background geothermal gradients.

4.2. Timing and Style of Rifting

A number of alternative models have been tested varying the age and duration for the rifting events, the nature of the basement in the distal margin and the geometry of rifting. In all tested scenarios, the calibration of the models to the temperature and heat flux data is only mildly affected, as the models assume a similar steady-state lithosphere model. There are, however, implications for the heat flux history that should be considered when assessing the maturity of the margin. The model predictions and thermal calibration for two end-member models are shown in Figure 9, where we test the: (1) timing of rifting (Figure 9, left) and (2) higher amounts of mantle relative to crustal thinning (Figure 9, right).

The uncertainties on the age and duration of the Jurassic rifting in the deep Mid-Norway Margin result from the lack of constraints on the age of the sediments underlying the very thick Cretaceous sequences in the Møre and Voring basins. One possibility is that the extensional deformation initiated in the Early–Middle Jurassic, as in the continental shelf. There is also some debate on the existence and relative importance of a mid-Cretaceous extensional pulse [2]. In the model of Figure 9, left, we assume a prolonged Jurassic rifting event between 200 Ma and 145 Ma and account for a mid-Cretaceous rifting event between 98 Ma and 90 Ma (Cenomanian–Turonian). The model predicts a high basal heat flux throughout the Jurassic (Figure 9a-left) but with lower maximum values than the reference Late-Jurassic rift model (Figure 9a-centre). A second peak is also clearly observed in the
deep margin associated with the mid-Cretaceous rift, with thinning factors for the crust and mantle of up to 1.3 and 1.5, respectively. This is within the range of that predicted by a similar modelling experiment across the northern Vøring Margin [11]. The predicted total amounts of the crust and mantle thinning are, however, similar to the reference model, as less stretching is inferred for the Jurassic rifting, and the model has very little implications for the calibration of the temperature, heat flux and maturity data along the transect (Figure 9c,d).

![Figure 8.](image)

**Figure 8.** Model-predicted sensitivity analysis comparing the predicted heat flux and the temperature and maturity calibrations at projected borehole locations (see Figure 1 for the borehole locations) for three models, varying the background geothermal gradient (see text for discussion): Left–Cold model; Centre–Reference model; Right–Hot model. (a) Predicted base sediments heat flux through time along the modelled transect. Structural elements acronyms from left to right: VMH–Vøring Marginal High; FG–Fenris Graben; GR–Gjallar Ridge; VS–Vigrid Syncline; STR–Slettringen Ridge; RB–Rås Basin; SR–Sklinna Ridge; HT–Halten Terrace; FBS–Froan Basin. (b) Predicted present-day base sediments (solid line) and surface (dashed line) heat flux. (c) Comparisons between the model-predicted temperature–depth (solid lines) profiles for three projected borehole locations at 90 km, 220 km and 305 km of the transect and borehole bottom-hole temperatures (BHT–blue dots) from the Norwegian Petroleum Directorate. (d) Comparison between model predicted basin%Ro-depth maturity profiles (solid lines) at the projected borehole locations and VR measurements (blue dots) available from the Norwegian Petroleum Directorate.

The style of rifting, and its implications for the amounts of crust and mantle stretching in the development of passive margins, is a long-standing discussion, the details of which are beyond the scope of this paper. According to some authors, the extension measured from normal fault throws in the brittle upper crust of most margins is much smaller than that inferred from subsidence and gravity models for the predominantly ductile lower crust and uppermost mantle, e.g., reference [40]. In the northern Vøring Margin, for example, mantle stretching factors of 2.5 and negligible amounts of crustal thinning were put forward to explain the subaerial deposition of the basalts and early Eocene sediment sequences [41]. In striking contrast, some kinematic models of rifting suggest that the crustal structure and the subsidence–sedimentation histories of most passive
margins, including the Mid-Norway Møre Basin, can be explained assuming an essentially depth–uniform strain distribution through time [42]. One possibility is that the amount of extension accommodated in normal faults has been largely underestimated in the earlier studies [43,44].

Figure 9. Sensitivity analysis comparing the predicted heat flux and the temperature and maturity calibration at projected borehole locations (see Figure 1 for the borehole locations) for three models, varying the age and duration of the rifting events (Left) and the style of rifting (Right), relative to the reference model (Centre; see text for discussion). See the caption of Figure 8 for a description of the plots.

The model shown in Figure 9, right predicts mantle stretching factors in the intermediate and distal sectors of the Vøring Basin between 4 and 8 for the Jurassic rifting and between 2 and 5 for the Late-Cretaceous–Eocene rift, with the total amount of stretching varying between 10 and >30. This is more than twice of the mantle stretching predicted in the reference model, for similar amounts of crustal stretching, and within the range of that inferred for the northern Vøring Margin [41]. The basal heat flux history shows clearly the increase in the predicted heat flux during the Jurassic and Late-Cretaceous–Cenozoic rifting of up to 10 mW·m⁻² relative to the reference model (Figure 9a, right). Despite this, the model still largely underpredicts the vitrinite reflectance data in the distal margin (Figure 9d, right), and the present-day geothermal gradient is similar to that of the reference model, as the effects of rifting have largely subsided since the break-up in the early Eocene.

4.3. Deep-Seated Thermal Anomalies and Hydrothermal Circulation

Two scenarios were built that attempt to reconcile the calibration of the thermal–burial model to the borehole temperature and maturity data with the heat flux measurements in the intermediate–distal margin. In one model, we simulate a deep-seated thermal anomaly throughout most of the Cenozoic, following the continental break-up (Cenozoic thermal doming model in Figure 10, left). In the alternative model, we impose a thermal gradient
within the Cretaceous sediments in the range of that expected for hydrothermal circulation from the mid-Pliocene onwards (recent heating model in Figure 10, right). There are technical limitations in the implementation of both models, which are discussed below, but the main objective is to test the impact of processes with different timescales and area distributions on the maturity of the Vøring Basin.

The hypothesis of long-lived, deep-seated thermal anomalies have been put forward to explain a >500-m residual bathymetry anomaly in the oceanic domain of the Vøring and Møre margins [45,46]. According to these works, the thermal anomaly could be associated with the activity of the Late-Cretaceous–Cenozoic Icelandic Plume [47,48] and/or with the development of edge-driven mantle convection [49,50]. In the Cenozoic thermal doming model, the long-standing thermal anomaly is created by assuming continuous mantle thinning following a continental break-up between the early Eocene and present day (56-0 Ma). This is similar to previously tested models, which simulate a continental break-up at the base Miocene [13] but extend the thermal anomaly to recent times. Although such models do not account for the dynamic effects in the sub-lithospheric mantle, with the complexities of small-scale convection and melt generation, they impose a higher geothermal gradient throughout the Cenozoic, which we tentatively calibrate to temperature and maturity data in the distal margin.

As depicted in Figure 10, the model predicts an increase in the basal heat flux of 10–15 mW·m⁻² in the intermediate and distal sectors of the margin (Figure 10a,b, right) relative to the reference, steady-state model (Figure 10a,b, centre) and recovers the (very) high present-day geothermal gradient and the maturity data trend in the distal margin (Figure 10c, right). There are, however, two main issues associated with this thermal...
scenario. First, it overestimates the temperature and maturity data in the Intermediate sector of the margin—namely, in the Slettringen Ridge and Rås Basin areas—which suggests that the potential dynamic effects in the sub-lithospheric mantle taper off between the distal and intermediate sectors of the margin. A stepwise lithosphere–asthenosphere boundary (LAB) has been previously suggested [45], reflecting the oceanward migration of the deformation since the Palaeozoic. Second, the model predicts a higher heat flux than measured at the surface in the intermediate and distal sectors of the margin or within the higher range of the available measurements (see, also, Figure 4).

Hydrothermal convection has been previously suggested as the potential cause for the high borehole temperatures in the distal margin [13], as well as the high surface heat flux values in the central–northern Voring Basin [15]. Both observations indicate a presently/recently active convection system, and the vitrinite reflectance data in the Gjallar Ridge borehole would also imply its activity for at least a few millions of years, as the vitrinite kinetics is dependent on time, e.g., reference [31]. On the other hand, the low heat flux measured in most places in the deep Voring Basin—namely, in the vicinity of the boreholes where the measured geothermal gradients are high—suggests that hydrothermal convection may be largely restricted to faults/conduits in the deeper parts of the basin and/or not active uninterruptedly for tens of Myr. This is (arguably) consistent with the mapping of hundreds (estimated two to three thousand) of hydrothermal vent complexes in the Voring and Møre basins, caused by sill intrusions during the late stages of rifting and continental break-up, with a top vent seismic horizon at the near-top Paleocene [51]. A top mound horizon is also identified above the hydrothermal vents or at the tip of deep-seated faults, which is interpreted as resulting from seepage, and suggests that these features have been re-used for vertical fluid migration long after their formation [51].

In the recent heating model, we simulate a higher geothermal gradient in the Cretaceous sediments since the mid-Pliocene (40 Ma) by adding a series of thin slabs between 80 and 120 km of the model with temperatures increasing in depth from 100°C to 400°C. This is in the range of the temperatures expected for hydrothermal circulation and has been tentatively calibrated to the temperature and maturity data in the distal margin (Figure 10c,d, right). This model does not simulate the generation of hydrothermal oils and gases, which occurs over periods of days to years [52] but, rather, the impact of a geothermal-like gradient in the surrounding rocks over a period of millions of years. The model improves the fit to the temperature data in the distal margin, with a gradient similar to that observed in the western Vigrid Syncline (borehole 6603/12-1 at 120 km of the model in Figure 3), and is consistent with the range of heat flux values observed in most places along the intermediate and distal sectors of the margin. The saw-like vitrinite reflectance profile predicted by this model (Figure 10d, left) results from the discrete implementation of the hot slabs in the model, similar to sill intrusions. This is a limitation of the model that does not reproduce the adiabatic temperature gradient in the hydrothermal aquifer. The bell-shaped vitrinite reflectance profile typically associated with the steady-state convection of hot fluids from the basement [53] cannot be confirmed due to the lack of data below 5 km.

In this model, the apparent increase in the thermal gradient towards the distal margin could be related to the progressive thinning of the crust and the higher density of basement faults piercing through the Jurassic–Cretaceous formations, as observed in the seismic data [19,54]. The density of mapped hydrothermal vents also increases towards the distal sectors of the margin [51]. The timing of the proposed thermal anomaly of a few Myr or intermittently over 10s of Myr may be associated with glaciation–deglaciation events in the Plio-Pleistocene and/or with compressional/transpressional tectonics from the late Oligocene onwards, respectively [2]. In this hypothesis, the recent hydrothermal activity would be triggered by the reactivation of faults under tensional or compressional stresses. As demonstrated in previous studies, the flexural deformation associated with the loading–unloading of the km scale ice loads in the continental shelf can extend for >200 km, depending on the flexural rigidity of the lithosphere [55]. In areas of high recent sedimentation rates, east of the Fles Fault Complex–Slettringen Ridge, the additional loading could
also promote compaction and expulsion of pore water, increasing the pressure gradients and further promoting hydrothermal circulation [15].

4.4. Maturity (Charge) Risk Analysis

The predicted maturity histories by the thermal scenarios discussed above are compared in Figures 11 and 12 for the uppermost Turonian (90 Ma; possibly Santonian–Coniacian) and the late-Albian–Cenomanian (98 Ma) horizons, respectively; some uncertainty in the age of the source horizons is assumed in the analysis of results, which reflects some lack of constraints in the stratigraphy of the deep margin.

The predicted maturities for younger and older stratigraphy in the deep Vøring Basin are provided as Supplementary Materials (Supplementary Figures S1–S3), but these are arguably less relevant for the basin maturity risk analysis. This is because, similar to the reference model (see Figure 7), all tested scenarios predict: (1) an immature latest Cretaceous horizon (late-Campanian, 75 Ma). The exception is the Cenozoic thermal doming model, which predicts mid-oil window maturity in a very restricted area of the Fenris Graben; and (2) gas mature to post-mature Early Cretaceous (Aptian–Albian horizon, 113 Ma) and older/deeper horizons during the Late-Cretaceous–Paleocene burial across most of the Vøring Basin. The exception is the Gjallar Ridge area, where the cooler models predict late-oil to early-gas maturity at the present day and, thus, with potential for recent hydrocarbon generation.

Figure 11. Comparison of basin%Ro [31] maturity histories for a 90-Ma horizon (top Lange/Lysing formations) predicted by the different thermal–burial modelling scenarios (see the text for discussion). Typical color scheme and contours (grey lines) are used for the vitrinite reflectance (VR) maturity windows (see the caption of Figure 3 for the description of maturity windows).
For a late-Cenomanian–Coniacian/Santonian horizon (90 Ma; top Lange and Lysing formations), the reference model predicts early-oil maturity during Cenozoic burial in the main depocentres of the Voring Basin (Rås Basin and Vygrid Syncline), reaching mid-to-late oil maturity in the deeper areas of the Fenris Graben and Gjallar Ridge (Figure 11c). These predictions are not significantly affected by variations in the age and duration of the rifting events (Figure 11d), the structure of the crust and/or the style of rifting (Figure 11e). Noticeable differences are, however, observed in the hot (Figure 11b) and Cenozoic thermal doming (Figure 11g) models, with the potential for oil and, locally, also gas generation and expulsion in the distal margin. The Cenozoic thermal doming model also predicts a broad region of mid-oil maturity across the Vigrid Syncline. Some potential for recent gas generation–expulsion is also predicted in the recent heating model (Figure 11f), suggesting that areas of persistent and pervasive hydrothermal circulation might generate significant volumes of oil and/or gas.

As discussed in Section 3.2., the reference model predicts pervasive oil and/or gas maturity of a late-Albian–Conomanian horizon (98 Ma; upper-Lange formation) across the southern Voring Basin, initiating during the Late-Cretaceous–Paleocene rifting and evolving throughout the Cenozoic burial (Figure 12c). In the cold model, the area of potential gas generation–expulsion is limited to the Fenris Graben and the deepest parts of the Vrigid Syncline (Figure 12a), while the hot model predicts a gas mature horizon between the Rås Basin and the Fenris Graben, with recent generation limited to the basement highs, such as the Gjallar and Slettringen ridges (Figure 12b).

Changing the timing-duration of Jurassic rifting has a negligible impact on the calculated horizon maturity, while accounting for a Late-Cretaceous rift event results in a mild increase of the horizon maturity, slightly expanding the areas of potential gas generation
between the Vigrid Syncline and Fenris Graben (Figure 12d). Assuming higher mantle stretching broadens the area of predicted gas generation across the Vigrid Syncline and Gjallar Ridge and increases somewhat the maturity of the horizon in the Rås Basin, it does not significantly alter the timing of maturity over the basin (Figure 12e).

Similar to the hot model, the Cenozoic thermal doming model predicts a gas mature horizon over the whole deep Vøring Basin, but maturity in the Vigrid Syncline-Gjallar Ridge and Fenris Graben occurs during the Paleogene, thus limiting the potential for recent generation (Figure 12g). In contrast, the recent heating model only predicts a recent increase in the potential gas generation across the Fenris Graben and Gjallar Ridge, where the higher thermal gradients were defined (Figure 12f).

The two known petroleum plays in the deep Mid-Norway Margin consist of Late-Cretaceous–Paleocene sand reservoirs in rotated faulted blocks and Eocene–Miocene compression-related structural domes, likely sourced by Late-Cretaceous source rocks [7–9]. The modelling results presented here are coherent with this regional framework and indicate that, in the southern Vøring Basin, the mid-Late-Cretaceous source rocks of the Late-Albian–Turonian/Coniacian age, comprising the Lysing and upper-Lange formations, have the most favorable maturity histories to source these plays. In the uppermost Lange and Lysing formations, recent oil and locally gas maturity is predicted in the hotter scenarios within the deeper depocentres of the distal margin and very recently associated with pervasive hydrothermal circulation (Figure 11). For deeper horizons in the upper-Lange formation, the cooler scenarios, including the reference model, predict recent oil and/or gas maturity over large sectors of the deep margin, including the Rås Basin and the flanks of the Vigrid Syncline and Fenris Graben, while the hotter models predict that maturity occurs during the Paleogene burial, with the exception of the shallower areas in the vicinity of the ridges (Figure 12).

The latest Cretaceous (Nise-Springar formations) and earlier stratigraphy are predicted immature in most places and therefore unlikely to generate–expel significant volumes of hydrocarbons (see Supplementary Figure S1). These are the most frequently sampled formations in the deep Mid-Norway Margin, showing low average organic carbon contents and a terrigenous, gas-prone character [8]. This suggests that we have only limited knowledge of the main potential source rocks in the area. For Aptian and older source horizons (the lower Cromer Knoll group and Jurassic formations), the models predict that the maturity and potential oil and gas generation takes place during the Late-Cretaceous and Paleocene burial or earlier for the Jurassic sediments (see Supplementary Figures S2 and S3). This precedes the Eocene–Miocene compressional episodes with the development of the structural domes and the potential disruption of previous accumulations. These formations are therefore associated with a significantly greater charge risk, with the exception of the areas surrounding the basement ridges, where oil and/or gas charges from Early Cretaceous horizons could extend into recent times, particularly in the cooler scenarios.

The sensitivity/risk analysis discussed here is relevant for large areas of the Mid-Norway Margin, where the seismic data and potential field modelling suggest similar rift and burial histories and basement configurations [25]. Moreover, the calibration of the thermal–burial and discussion of the margin thermal history considered the borehole data and surface heat flux observations over the whole of the deep Mid-Norway Margin. On the other hand, the central and northern segments of the Vøring Basin show extensive basin exhumation [2], large volumes of magmatic underplating and widespread sill intrusions [56,57]. These processes may have an impact on the maturity history of the basin and need to be integrated in the models. It has been demonstrated, for example, that large volumes of intruded magmatic bodies interspersed in the sediment overburden can offset the predicted maturity of source rock horizons by millions of years [38].

4.5. Future Work and Model Improvements

We discuss here (succinctly) two lines of research that could improve the current understanding of the thermal evolution of the Vøring Basin and reduce the exploration risk:
(1) implementation of models that integrate the processes that explain the temperature, maturity and heat flux data in the deep Vøring Basin and (2) improve and/or add constraints to the thermal model that inform on the likelihood and/or extent of such processes.

The two mechanisms put forward to explain the conundrum of high geothermal gradients and low surface heat flux in the distal margin are long-standing, deep-seated thermal anomalies and hydrothermal circulation, while assuming a near steady-state, post-rift basin setting in the proximal and intermediate sectors of the margin. Although we simulate the potential effects of such processes on the basin maturity by imposing the (expected) appropriate thermal gradients over geologically reasonable periods and calibrate the models to the borehole temperature and maturity data, the processes are not explicitly formulated in the models.

The current rift models do not predict an elevated heat flux in the post-rift period after 50–60 Myr of extension, with a matching low (and/or slow) subsidence anomaly. They instead predict that the heat flux should return to normal values as the stitched lithosphere is allowed to relax to its original depth position. Models that predict a prolonged high heat flux following a break-up and/or a delayed post-rift subsidence typically invoke either the effect of edge-driven mantle convection [50] or the influence of a plume located in a present-day distant location [47,59]. Both models remain controversial—in particular, the genetic relationship between plume activity and the large volumes of magmatism in the Mid-Norway margin [21].

On the other hand, the implementation of widespread hydrothermal circulation in a basin-scale geological model is numerically challenging because of the orders of magnitude different timescales at which these processes take place and the large uncertainties in crucial petrophysical quantities like permeability. Sedimentation–compaction and the associated thermal blanketing effects are modelled over millions of years, while the convection of hot fluids can impact on the basin thermal gradient over periods of days to years. Alternatively, a statistical distribution of faults/conduits could be used to model the diffusion of heat across the basin, assuming a continuous heat sourcing over geological periods associated with the tectonic and climatic processes that shaped the margin.

The thermal–maturity modelling and sensitivity analyses presented in this study are based on the calibrations for the borehole temperature and maturity data and surface heat flux measurements, i.e., at discrete locations in the basin. A qualitative improvement of the model calibration may arguably be achieved by integrating indirect but spatially continuous evidence from seismic data on the recent geothermal gradients, for example, by mapping the bottom simulating reflectors (BSR; [60] and references therein). These reflectors are associated with processes that occur at specific depths below the seafloor, broadly between 200 and 1000 m, and within certain intervals of temperature and pressure or stability zones. The most common BSR are caused by the occurrence of gas hydrates underlain by free gas accumulations or by diagenetic processes in silicious sediments—namely, at opal A–opal CT and the opal–quartz transitions—with distinct seismic signatures. The BSR therefore provide laterally continuous constraints on the geothermal gradients at intermediate depths between the surface heat flux probes and the borehole temperatures [61].

BSR have been previously mapped over an extensive area of the Vøring Basin, using multi-channel 2D seismic datasets [56]. It was found that the gas hydrated BSR appear to be confined to southernmost Rås Basin and adjacent continental slope [56], but their occurrence may be limited by the distribution of contourite sediments [62]. The diagenetic opal A–CT transition BSR are widespread over in the intermediate and distal sectors of the southern and central Vøring Basin and is in places interpreted as a fossil horizon discordant to the seafloor and offset by polygonal faults (sediment compaction structures), possibly related to increased geothermal gradients in the Miocene. In some areas, a second diagenetic BSR beneath the opal A–CT transition has also been interpreted, with approximately twice the average stability temperature [56].

However, the utilized seismic datasets have some limitations—namely, for the determination of the seismic velocities in the recent sediments and, thus, the exact depth of
the BSR [56], which is critical for the estimation of the respective pressure–temperature stability zones. Moreover, the seismic coverage is heterogeneous, and the seismic lines are sparse and far apart in some areas of the margin. If available, the adequate processing and interpretation of good quality 3D seismic datasets could help establish the lateral continuity and geometry of the BSR, as well as improve the accuracy of the BSR depth estimations and, thus, the shallow, recent geothermal gradients. Additionally, the data may also allow to: (1) assess the behaviour of the BSR at the intersection with tectonic lineaments, such as fracture zones and basement faults, which can act as conduits for hydrothermal circulation; (2) investigate the existence of gas hydrate BSR in the distal sectors of the margin where glacial sediments are scarce and (3) further improve the mapping of hydrothermal vents associated with volcanic intrusions.

5. Conclusions

A thermo–tectono–stratigraphic model was built across the southern Vøring Basin, between the Halten Terrace and the Vøring Marginal High (oceanic basement), which accounts for the main rifting events that shaped the margin and continental break-up. The thermal model is well-calibrated in the proximal and intermediate sectors of the margin, where there is abundant borehole data, providing good constraints on the burial and subsidence history of the margin and the present-day geothermal gradients and is in reasonably good agreement with the structure of the crust constrained from seismic data and/or potential field modelling. In the distal margin, the temperature and maturity data from boreholes located along the Vigrid Syncline and the Gjallar Ridge suggest a progressive increase of the geothermal gradients oceanward, which is not predicted by the model and is apparently inconsistent with the low average heat flux measured at the surface.

Two scenarios are put forward that attempt to reconcile the borehole temperature and maturity data with the measured surface heat flux in the distal margin. A high regional thermal gradient throughout the Cenozoic associated with mantle dynamics effects (edge-driven convection and/or the Icelandic Plume) is supported by lithosphere-scale, gravity–topography models and explains the borehole temperature and maturity data. Such a model, however, predicts heat flux values within the higher range of the observed in the distal and intermediate sectors of the margin and lacks a rift model rational to explain the prolonged high temperature gradients (and, possibly, also the associated subsidence anomalies) following the continental break-up. Alternatively, an increased geothermal gradient within the pre-Cenozoic sediments caused by pervasive hydrothermal circulation during the Plio-Pleistocene, or intermittently throughout the Cenozoic, is supported by the widespread evidence of hydrothermal vent complexes in the deep margin, some of which act as fluid conduits to the present day and may explain both the temperature and maturity data at well locations and the seafloor heat flux measurements. In this scenario, the hydrothermal activity is associated with periods of greater tectonic stresses (compression/transpression tectonics and glacial loading–rebound), and the increase in the geothermal gradients towards the distal margin is related to the higher density of basement faults cutting through the Mesozoic sequences, as observed in the seismic data. Such a model, however, is difficult to reproduce at the scale of the Vøring Basin and requires detailed mapping of the potential hydrothermal system of conduits for accurate predictions of the thermal gradients. In future modelling/analyses, the simultaneous contribution from mantle dynamics and hydrothermal circulation should also be considered, where the former explains the increase in the geothermal gradients towards the distal margin and the latter the lateral variations in the surface heat flux, with the higher values focused along the structural lineaments.

A sensitivity analysis was carried out to understand the implications of the uncertainties in the thermal and burial histories for the prospectivity of the deep Mid-Norway Margin. The modelling results indicate that, within a reasonable uncertainty, the mid-Late Cretaceous potential source rock horizons of the late-Albian–Turonian/Coniacian age,
comprising the upper-Lange and Lysing formations, have the most favorable maturity histories to charge the known petroleum plays in the Vøring Basin. There is, however, significant variability in the predicted maturity histories within this thick depositional interval, depending on the mechanisms implied to explain the high geothermal gradients in the distal margin. While the cooler models, including the reference, near steady-state thermal model, predict recent (post-Eocene) oil and/or gas maturity of the deeper upper-Lange formation horizons over large areas of the Vøring Basin, the hotter scenarios, which include the Cenozoic thermal doming hypothesis, predict that recent oil and gas maturity, and the potential hydrocarbon generation is optimal in the uppermost Lange and Lysing formations. Recent oil/gas maturity, with potential generation-expulsion, is also predicted from these deeper, potential source horizons in the case of pervasive hydrothermal activity.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/geosciences11050190/s1: Figure S1: Maturity75Ma, Figure S2: Maturity113Ma and Figure S3: Maturity145Ma.

Author Contributions: Conceptualization, writing—original draft preparation and visualization T.A.C.; investigation and data acquisition, T.A.C., A.A.A., H.R. and H.V. and writing—review and editing, T.A.C., H.R. and H.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to thank Spirit Energy and license partners Equinor and Wintershall Dea for permission to publish the findings of this paper. The suggestions from an anonymous reviewer contributed to improving the quality of the original manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Dore, A.; Lundin, E.R.; Jensen, L.N.; Birkeland, O.; Eliassen, P.E.; Fichler, C. Principal tectonic events in the evolution of the northwest European Atlantic margin. In Petroleum Geology of Northwest Europe: Proceedings of the Fifth Conference; Fleet, A.J., Boldy, S.A.R., Eds.; Geological Society: London, UK, 1999; pp. 41–61.
2. Brekke, H. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and More Basins. In Dynamics of the Norwegian Margin; Nøttvedt, A., Larsen, B.T., Olaussen, S., Tørudbakken, B., Skogseid, J., Gabrielson, R.H., Brekke, H., Birkeland, O., Eds.; Geological Society Special Publication: London, UK, 2000; Volume 167, pp. 327–378.
3. Reemst, P.; Cloetingh, S. Polyphase rift evolution of the Vøring margin (mid-Norway): Constraints from forward tectonostratigraphic modeling. Tectonophysics 2000, 19, 225–240. [CrossRef]
4. Blystad, P.; Brekke, H.; Færseth, R.B.; Larsen, B.T.; Skogseid, J.; Tørudbakken, B. Structural elements of the Norwegian continental shelf. Nor. Pet. Dir. Bull. 1995, 8, 45.
5. Scheck-Wenderoth, M.; Maystrenko, Y. 3D lithospheric-scale structural model of the Norwegian continental margin (the Vøring and Møre basins)—Data. GFZ Data Serv. 2008. [CrossRef]
6. Riis, F.; Fjeldskaar, W. On the magnitude of the Late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea. In Structural and Tectonic Modelling and Its Application to Petroleum Geology; Larsen, R.M., Brekke, H., Larsen, B.T., Talleraas, E., Eds.; Elsevier: Amsterdam, The Netherlands, 1992; pp. 163–185.
7. Matapour, Z.; Karlseth, D.A. Ages of Norwegian oils and bitumen based on age-specific. Pet. Geosci. 2018, 24, 92–101. [CrossRef]
8. Cunha, T.A.; Rasmussen, H.; Akinvumiju, A.A.; Farrimond, P. Geochemistry and Basin Modelling in the Deep Vøring Margin: Implications for the Petroleum Systems and Basin Prospectivity. In Proceedings of the Norwegian Petroleum Society Petroleum Systems Conference, Oslo, Norway, 2–3 February 2021.
9. Brekke, H.; Dahlgren, S.; Nyland, B.; Magnus, C. The prospectivity of the Vøring and Møre basins on the Norwegian Sea continental margin. In Petroleum Geology of Northwest Europe: Proceedings of the Fifth Conference; Fleet, A.J., Boldy, S.A.R., Eds.; Geological Society: London, UK, 1999; pp. 261–274.
10. Wangen, M.; Fjeldskaar, W.; Faleide, J.I.; Wilson, J.; Zweigel, J.; Austegard, A. Forward modeling of stretching episodes and paleo heat flow of the Vøring Margin, NE Atlantic. J. Geodyn. 2008, 45, 83–98. [CrossRef]
11. Theissen, S.; Rüpeke, L.H. Feedbacks of sedimentation on crustal heat flow: New insights from the Vøring Basin, Norwegian Sea. Basin Res. 2010, 22, 976–990. [CrossRef]
12. Rüpke, L.H.; Schmid, D.W.; Perez-Gussinye, M.; Hartz, E. Interrelation between rifting, faulting, sedimentation, and mantle serpentinization during continental margin formation—including examples from the Norwegian Sea. Geosci. Geophys. Geosyst. 2013, 14, 4351–4369. [CrossRef]

13. Maystersenko, Y.P.; Gernigon, L. 3D temperature distribution beneath the Mid-Norwegian continental margin (the Voring and More basins). Geophys. J. Int. 2018, 212, 694–724. [CrossRef]

14. Sundvor, E.; Eldholm, O.; Gladczenko, T.P.; Planke, S. Norwegian–Greenland Sea thermal field. In Dynamics of the Norwegian Margin; Nettvedt, A., Ed.; Geological Society Special Publication: London, UK, 2000; Volume 167, pp. 397–410.

15. Ritter, U.; Zielinski, G.W.; Weiss, H.M.; Zielinski, R.L.B.; Sættem, J. Heat flow in the Voring Basin, mid-Norwegian shelf. Pet. Geosci. 2004, 10, 353–363. [CrossRef]

16. Rüpke, L.H.; Schmalholz, S.M.; Schmid, D.W.; Podiatric, Y.Y. Automated thermo-tectonostratigraphic basin reconstruction: Viking Graben case study. AAPG Bull. 2008, 92, 309–326. [CrossRef]

17. Souche, A.; Schmid, D.W.; Rupke, L. Interrelation between surface and basement heat flow in sedimentary basins. AAPG Bull. 2017, 101, 1697–1713. [CrossRef]

18. Kim, Y.; Huh, M.; Lee, E.Y. Numerical Modelling to Evaluate Sedimentation Effects on Heat Flow and Subsidence during Continental Rifting. Geosciences 2020, 10, 451. [CrossRef]

19. Gernigon, L.; Franke, D.; Geoffroy, L.; Schiffer, C.; Foulger, G.R.; Stoker, M. Crustal fragmentation, magmatism, and the diachronous opening of the Norwegian-Greenland Sea. Earth Sci. Rev. 2019. [CrossRef]

20. Sekiguchi, K. A method for determining terrestrial heat flow in oil basin areas. Tectonophysics 1984, 103, 67–79. [CrossRef]

21. Gernigon, L.; Lucazeau, F.; Brigaud, F.; Ringenbach, J.-C.; Planke, S.; Le Gall, B. A moderate melting model for the Voring margin (Norway) based on structural observations and a thermo-kinematical modelling: Implications for the meaning of the lower crustal bodies. Tectonophysics 2006, 412, 255–278. [CrossRef]

22. Olesen, O.; Brönner, M.; Ebbing, J.; Gelline, J.; Gernigon, L.; Koziel, J.; Lauritsen, T.; Myklebust, R.; Pascal, C.; Sand, M. New aeromagnetic and gravity compilations from Norway and adjacent areas: Methods and applications. In Geological Society, London, Petroleum Geology Conference Series; Geological Society: London, UK, 2010; pp. 559–586.

23. Gernigon, L.; Blischke, A.; Nasuti, A.; Sand, M. Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: Insights from new high-resolution aeromagnetic surveys in the Norwegian Basin. Tectonics 2015, 34, 907–933. [CrossRef]

24. Berndt, C.; Planke, S.; Alvestad, E.; Tsikalas, F.; Rasmussen, T. Seismic volcanostratigraphy of the Norwegian Margin: Constraints on tectonomagmatic break-up processes. J. Geol. Soc. 2001, 158, 413–426. [CrossRef]

25. Maystersenko, Y.P.; Gernigon, L.; Nasuti, A.; Olesen, O. Deep structure of the Mid-Norwegian continental margin (the Voring and More basins) according to 3D density and magnetic modelling. Geophys. J. Int. 2018, 212, 1696–1721. [CrossRef]

26. Eldholm, O.; Gladczenko, T.P.; Skogseid, J.; Planke, S. Atlantic volcanic margins: A comparative study. In Dynamics of the Norwegian Margin; Nettvedt, A., Larsen, B.T., Olausson, S., Torudbakken, B., Skogseid, J., Gabnelson, R.H., Brehk, H., Birkeland, O., Eds.; Geological Society Special Publication: London, UK, 2000; Volume 167, pp. 411–428.

27. Gernigon, L.; Ringenbach, J.C.; Planke, S.; Le Gall, B. Deep structures and breakup along volcanic rifted margins: Insights from integrated studies along the outer Voring Basin (Norway). Marine Pet. Geol. 2004, 21, 363–372. [CrossRef]

28. Lundin, E.R.; Dore, A.G. Hyperextension, serpentinization, and weakening: A new paradigm for rifted margin compressional deformation. Geology 2011, 39, 347–350. [CrossRef]

29. Peron-Pinvidic, G.; Osmundsen, P.T. The Mid Norwegian—NE Greenland conjugate margins: Rifting evolution, margin segmentation, and breakup. Marine Pet. Geol. 1988, 58, 162–184. [CrossRef]

30. Zastrozhnov, D.; Gernigon, L.; Gogin, I.; Abdelmalak, M.M.; Planke, S.; Faleide, J.I.; Eide, S.; Myklebust, R. Cretaceous-paleocene evolution and crustal structure of the northern Voring margin (offshore mid-Norway): Results from integrated geological and geophysical study. Tectonics 2018, 37, 497–528. [CrossRef]

31. Nielsen, S.B.; Clausen, O.R.; McGregor, E. basin%Ro: A vitrinite reflectance model derived from basin and laboratory data. Basin Res. 2017, 29, 515–536. [CrossRef]

32. Pascal, C. Heat flow of Norway and its continental shelf. Marine Pet. Geol. 2015, 66, 956–969. [CrossRef]

33. IHFC the International Heat Flow Commission. Available online: http://ihfc-iugg.org/ (accessed on 31 January 2021).

34. Sundvor, E.; Myhre, A.M.; Eldholm, O. Norway: Offshore and north-east Atlantic. In Geothermal Atlas of Europe; Hurtig, E., Cernak, W., Haenel, R., Zul, V., Eds.; GeoForschungZentrum: Potsdam, Germany, 1991; Volume 1, pp. 63–66.

35. Sundvor, E.; Myhre, A.M.; Eldholm, O. Heat Flow Measurements on the Norwegian Continental Margin during the FLUNORGE Project; Seismo-Series; University of Bergen: Bergen, Norway, 1989; Volume 27.

36. Eldholm, O.; Sundvor, E.; Vogt, P.R.; Hjelstuen, B.O.; Crane, K.; Nilsen, A.K.; Gladczenko, T.P. SW Barents Sea continental margin heat flow and Haskon Mosby Mud Volcano. Geo-Marine Lett. 1999, 19, 29–37. [CrossRef]

37. Bryn, P.; Berg, K.; Forberg, C.F.; Solheim, A.; Kvalstad, T.J. Explaining the Storegga Slide. Marine Pet. Geol. 2005, 22, 11–19. [CrossRef]

38. Jarvis, G.T.; McKenzie, D.P. Sedimentary basin formation with finite extension rates. Earth Planet. Sci. Lett. 1980, 48, 42–52. [CrossRef]

39. Cochran, J.R. Effects of finite rifting times on the development of sedimentary basins. Earth Planet. Sci. Lett. 1983, 66, 289–302. [CrossRef]
40. Davis, M.; Kusznir, N. Depth-dependent lithospheric stretching at rifted margins. In *Rhology and Deformation of the Lithosphere at Continental Margins*; Karner, G.D., Taylor, B., Driscoll, N.W., Kohlstedt, D.L., Eds.; Columbia University Press: New York, NY, USA, 2004; pp. 92–137.

41. Kusznir, N.J.; Hunsdale, R.; Roberts, A.M.; iSIMM Team. Timing and magnitude of depth-dependent lithosphere stretching on the S. Lofoten and N. Voring continental margins offshore mid-Norway: Implications for subsidence and hydrocarbon maturation at volcanic rifted margins. In *Geological Society, London, Petroleum Geology Conference Series*; Dore, A.G., Vining, B.A., Eds.; Geological Society: London, UK, 2005; pp. 767–783.

42. Crosby, A.G.; White, N.J.; Edwards, G.R.H.; Thompson, M.; Corfield, R.; Mackay, L. Evolution of deep-water rifted margins: Testing depth-dependent extensional models. *Tectonics* 2011, 30. [CrossRef]

43. Reston, J. Polyphase faulting during the development of West Galicia rifted margin. *Earth Planet. Sci. Lett.* 2005, 237, 561–576. [CrossRef]

44. Ranero, C.R.; Perez-Gussinye, M. Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins. *Nature* 2010, 468, 294–299. [CrossRef]

45. Fernandez, M.; Torne, M.; Garcia-Castellanos, D.; Verges, J.; Wheeler, W.; Karpuz, R. Deep structure of the Voring Margin: The transition from a continental shelf to a young oceanic lithosphere. *Earth Planet. Sci. Lett.* 2000, 221, 131–144. [CrossRef]

46. Fernandez, M.; Ayala, C.; Torne, M.; Verges, J.; Gomez, M.; Karpuz, R. Lithospheric structure of the mid-Norwegian margin: Comparison between the Møre and Voring margins. *J. Geol. Soc.* 2005, 162, 1005–1012. [CrossRef]

47. Clift, P.D.; Turner, J. Dynamic support by the Icelandic plume and vertical tectonics of the Northeast Atlantic continental margins. *J. Geophys. Res.* 1995, 100, 24473–24486. [CrossRef]

48. Skogsæid, J.; Planke, S.; Faleide, J.I.; Pederson, T.; Eldholm, O.; Neverdal, F. NE Atlantic continental rifting and volcanic margin formation. In *Dynamics of the Norwegian Margin*; Nettvet, A., Larsen, B.T., Olausen, S., Tørudbøken, B., Skogsæid, J., Gabnelson, R.H., Brekke, H., Birkeland, O., Eds.; Geological Society Special Publication: London, UK, 2000; Volume 167, pp. 52–82.

49. King, S.D.; Anderson, D.L. Edge-driven convection. *Earth Planet. Sci. Lett.* 1998, 160, 289–296. [CrossRef]

50. Boutilier, R.R.; Keen, C.E. Small-scale convection and divergent plate boundaries. In *Dynamics of the Norwegian Margin*; Nøttvedt, A., Larsen, B.T., Olaussen, S., Tørudbøken, B., Skogsæid, J., Gabnelson, R.H., Brekke, H., Birkeland, O., Eds.; Geological Society Special Publication: London, UK, 2000; Volume 167, pp. 41–51.

51. Osmundsen, P.T.; Peron-Pinvidic, G. Crustal-Scale Fault Interaction at Rifted Margins and the Formation of Domain-Bounding Breakaway Complexes: Insights from Offshore Norway. *Tectonics* 2018, 37, 935–964. [CrossRef]

52. Berndt, C.; Bunz, S.; Clayton, T.; Mienert, M.; Saunders, M. Seismic character of bottom simulating reflectors: Examples from the Mid-Norwegian margin. *Marine Pet. Geol.* 2004, 21, 723–733. [CrossRef]

53. Gardiner, D.; Schofield, N.; Finlay, A.; Mark, M.; Holt, L.; Grove, C.; Forster, C.; Moore, J. Modeling petroleum expulsion in sedimentary basins: The importance of igneous intrusion timing and basement composition. *Geology* 2019, 47, 904–908. [CrossRef]

54. Lee, E.Y.; Wolfgring, E.; Tejada, M.L.G.; Harry, D.L.; Wainman, C.C.; Chun, S.S.; Schnetger, B.; Brumsack, H.-J.; Maritati, A.; Martinez, M.; et al. IODP Expedition 369 Science Party. Early Cretaceous subsidence of the Naturaliste Plateau defined by a new record of volcaniclastic-rich sequence at IODP Site U1513. *Gondwana Res.* 2020, 82, 1–11. [CrossRef]

55. Villinger, H.W.; Trehu, A.M.; Greve, M., I. Chapter 18: Seafloor marine heat flux measurements and estimation of heat flux from seismic observations of bottom simulating reflectors. In *Geophysical Characterization of Gas Hydrates*; Riedel, M., Willoughby, E.C., Chopra, S., Eds.; Society of Exploration Geophysicists: Tulsa, OK, USA, 2010; Volume 279.

56. Ranero, C.R.; Perez-Gussinye, M. Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins. *Nature* 2010, 468, 294–299. [CrossRef]

57. Reston, J. Polyphase faulting during the development of West Galicia rifted margin. *Earth Planet. Sci. Lett.* 2005, 237, 561–576. [CrossRef]