High Resolution 3D Process-based Modelling the Distribution of Organic Matter in the Late Jurassic Hekkingen Formation in the Hammerfest Basin (Barents Sea) for Basin Modelling*

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Abstract

The lithological heterogeneity of source rocks is an aspect that is often ignored in basin modelling studies, but essential in the correct estimation of hydrocarbon generation, migration, and trapping. Using a unique process-based modelling tool (OF-Mod), a high resolution model was made on the organic facies of the Late Jurassic Hekkingen Formation in the Hammerfest Basin, southwestern Barents Sea. It consists of more than 10 million cells, using 100 layers. This high resolution is required to represent thin sandy layers, which can be important for both organic matter deposition as well as hydrocarbon migration. The Hekkingen Formation is approximately time equivalent to other Late Jurassic source rocks: such as the Spekk Formation (central Norway), the Draupne Formation and the Kimmeridge Formation (North Sea). During the Late Jurassic the Hammerfest Basin had a complicated and poorly constrained tectonic and marine history (e.g. Worsley, 2008), requiring several scenarios to be tested. Different scenarios were developed to test tectonic history, sedimentary regimes, organic matter input, and redox conditions. The goal of this study was to provide models of the distribution of the inorganic (sand, shale) and organic fractions that will be used as input in a separate basin modelling study (Daszinnies et al, 2015). Testing the different scenarios allowed a selection based on mismatch with regards to well data, pointing towards the more likely history. Specifically the distribution of anoxia was delimited with a high degree of confidence

Introduction

The exploration of hydrocarbon reservoirs is a multi-faceted discipline which takes information from many sources to predict potential untapped fields. Modelling the entire geological history of a sedimentary basin through time is a valuable technique to estimate the quality, quantity, and timing of hydrocarbon generation. Thereby one main criterion for a consistent or realistic basin modelling is the accurate description of source rocks. Several techniques have been published to numerically describe source rock deposition (Schwarzkopf, 1993; Tyson, 2001; Katz, 2005; Tyson, 2005; Felix, 2014).

OF-Mod combines the current sedimentary, stratigraphical, and geochemical understanding of source rocks in a single model, and has been applied in several published case studies (Knies and Mann 2002; Tømmerås and Mann, 2008; Mann et al, 2009; Pathirana et al, 2014).

The Hekkingen Formation was chosen for this study due to its importance as a source rock in the area, such as shown by the recent gas discoveries in wells 7120/2-3S (in 2011), 7220/10-1 (in 2012), and 7220/5-2 (in 2013). The Hekkingen Formation is geochemically well sampled in the area, and therefore allows for good model calibration. Also, as it is lithologically and geochemically relatively homogeneous (Ohm et al., 2008) it is good test case.

OF-Mod Overview

OF-Mod is a process-based sedimentological tool used to model the deposition of sediments with high amounts of organic matter: potential source rocks for hydrocarbon generation. The models generated by OF-Mod include the distribution of inorganic sediments (sand, shale) as well as the changes in quantity (Total Organic Carbon, TOC) and quality (Hydrogen Index or HI, and Oxygen Index or OI) of organic matter.

Input-Output, Processes

The main processes which are reproduced in OF-Mod are shown in Figure 1, illustrating the sedimentological framework on which OF-Mod is built. A detailed overview of the modelled processes can be found in Mann and Zweigel (2008). The conceptual model is built on the interplay between three types of organic matter:

- Terrestrial organic matter (C_{terr}): which is derived from land, mainly type II / III kerogens, with generally intermediate HI and OI values.
- Marine organic matter (MOM): which has been produced at the upper water columns. This is degraded during settling. MOM consists of kerogen type I and II, and generally has high HI and low OI values.
- Residual organic matter (C_{res}): which will not contribute significantly to any future hydrocarbon generation, consisting for a large part of type IV kerogens (inertinite). C_{res} has very low HI and high OI.

The distribution of MOM is modelled based on spatially and temporally changing primary productivity (PP), as well as degradation of organic matter in the water column, and in the sediments. The final fraction of MOM in the sediments is also influenced by sedimentation rate, e.g., a high sedimentation rate will dilute the MOM. The distribution of C_{terr} and C_{res} are both modelled based on a relationship with sand fraction (SF): C_{res} concentrations will be highest with low SF, whereas C_{terr} concentration will be highest with high SF. The TOC, OI, and HI values are calculated by finding the weighted average of the three organic matter types based on their relative concentrations.

Geological Setting

During the Late Jurassic/Early Cretaceous the southernmost part of the Barents Sea (Figure 2) and the Hammerfest Basin experienced rifting associated with opening of the north Atlantic, where Greenland separated from Norway. Main rifting activities started in the Middle Jurassic (Faleide et al., 1984).

Since then faulting, and reactivation of older fault lineaments influenced the wider working area. However, a detailed understanding of the Late Cretaceous tectonic evolution is lacking, especially the tectonic development of the Loppa High ([Figure 2](#)). In this study, an emerging Loppa High was assumed during the study period.

The Hekkingen Formation was deposited during the Late Jurassic to Early Cretaceous. It is approximately time equivalent to other more extensively studied Late Jurassic source rocks, such as the central Norwegian Spekk Formation (Dalland et al, 1988) or the Draupne and Kimmeridge formations in the North Sea (Nøttvedt et al., 1995).

In the Hammerfest Basin the formation is thickest (359 m) in its type well 7120/12-1. It thins northwards to less than 100 m towards the axis of the Hammerfest Basin. This pattern reflects the development of half-grabens along the basin margins and a dome-like structure along the basin axis (Dalland et al, 1988).

The Hekkingen Formation consists mainly of shales deposited in a restricted marine to deep marine basin. The oxygen in the water column is important in the formation of sediments with high percentages of organic matter. During the deposition of the Hekkingen Formation some authors describe widespread anoxia to disoxia at the sediment surface (Worsley et al., 1988; Leith et al., 1992; Bugge et al., 2002), others also describe indications for anoxia in the water column (Lipinski et al., 2003; Langrock, 2003). In both scenarios high fluxes of organic matter to the sediment surface, combined with low sedimentation rates and therefore dilution, caused the formation of the organic rich deposits seen today. Both scenarios have been examined using OF-Mod to identify lateral changes in redox conditions (see Distribution of Oxic and Anoxic Conditions).

Modelling Setup and Results

The model has a vertical discretisation of 100 layers, which means that depending on the thickness of the Hekkingen the vertical resolution is between 0.1-3.5 m. Laterally a resolution of 400 m is used, with a grid of 450x300 cells. In total the model contains over 10 million cells. The workflow for creating models of the distribution of organic matter consists of two main steps:

Inorganic Modelling (see Inorganic Fraction)

The lateral and temporal (vertical) change in sand and shale fractions is the first major component which will be modelled. This is based on a fuzzy logic approach (Felix et al., 2012), where changes in sand and shale are modelled in response to three local parameters: water depth, distance to shore, and slope of the sediment surface. The model assigns facies at each location based on the values of these three parameters, and sand fraction distribution based on the facies distribution. The sand fraction distribution is manually fitted to well measurements.

Organic Modelling (see Organic Fraction)

OF-Mod creates models for the organic matter in terms of quantity (TOC) as well as quality (HI). This is based in part on the inorganic modelling results, as OF-Mod assumes a hydrodynamic equivalence in the behaviour of some organic fractions to the sediments. A main contributor is primary production of marine organic matter at the upper parts of the water column, the preservation thereof is based mainly on sedimentation rate, water depth, and water oxygen concentrations.

Input Data

The model was created based on interpreted seismic horizons and interpreted palaeo water depth models. The modelled sand fraction and organic matter distribution was validated on data from 25 wells. From all 25 wells back-calculated TOC and HI measurements were available, and from 11 wells sand fractions based on gamma ray measurements were supplied. Back-calculation was performed using the scheme described in Justwan and Dahl (2005), using the kinetic scheme Pepper Type B (Pepper and Corvi, 1995). Because OF-Mod reproduces the original deposition, the model was validated using the back-calculated, initial TOC, and HI values.

Inorganic Fraction

The first step consists of simulating the deposition of the inorganic sediments (sand and clay). This consists of setting up simple sedimentological rules using fuzzy logic rules (Felix, 2014). These rules are constrained based on well data (sand fraction). Once the rules have been set up and accurately reproduce the measured and interpreted sand distribution, they are assumed to be valid for the formation within the area. The sand fraction is then calculated in the area by applying these rules.

The rules here are chosen to represent the general sedimentological features seen in wells, as well as described in literature (e.g. Worsley, 2008). The Hekkingen Formation in the area is dominated by fine grained siliciclastics, with coarser sediments limited to the palaeo shoreline. Also, in several wells numerous thin sandy layers are found. These layers can be very important with regards to distribution of organic matter, as well as later primary and secondary migration studies (Daszinnies et al, 2015). In Figure 3 two examples of modelled time steps are shown, each representing a thickness between 0.1 m and 2 m.

Organic Fraction

Distribution of Oxic and Anoxic Conditions

Several models for deposition of the marine paleo environmental conditions in the western Barents Sea are discussed in the literature (e.g., Worsley et al., 1988; Leith et al., 1992; Nøttvedt et al., 1992; Bugge et al., 2002; Langrock, 2003). We investigate the extent of anoxia in this study, by analysing whether well measurements are best explained by an oxic or anoxic depositional model.

When testing the anoxic case the following assumptions were applied: the upper layers of the water column were oxygenated, and below a certain depth oxygen decreases, until below a certain depth full anoxia occurs. More specifically it was assumed that disoxia occurs below 100 m water depth, and oxygen levels decrease to full anoxia at 200 m. This causes a small (shallow) margin with oxic conditions near the paleo coast line, and anoxia present in the remaining area.

All wells were compared under both the oxic and the anoxic scenario. For some wells the oxic scenario was most likely, whereas for the others the anoxic scenario explained the results best. The extent of anoxia was subsequently mapped (Figure 4), indicating an anoxic Hammerfest Basin, with the Tromsø Basin under normal oxygen conditions. This is supported by literature, for instance Wignall and Hallam (1991) propose the "expanding puddle" model where black shales are more likely to form on the shallower parts of basins. The oxygen conditions are especially important for the Tromsø Basin, as there are no wells available to condition the OF-Mod depositional models. Excluding anoxia there has large implications for the amount and quality of organic matter in Tromsø Basin, which in turn will significantly influence the modelling results of primary and secondary hydrocarbon migration.

Primary Production

Primary production (PP) is the amount of carbon produced within the upper layers of the water column. This settles to the sea floor, whilst simultaneously undergoing degradation. In OF-Mod the value of PP is calculated based on the distance to shore. This reproduces increased production in areas with higher nutrient input, i.e. from terrestrial sources (Mann and Zweigel 2008). The values for the PP in the Hammerfest Basin were based on the OF-Mod 1D model results.

Figure 5 shows the change in coastal and open oceanic PP for the ca. 156 Ma to 140 Ma episode. The coastal PP decreases from 110 g Cm^2 a^{-1} to 35 g Cm^2 a^{-1}, and the open oceanic PP values decrease from 60 g Cm^2 a^{-1} to 20 g Cm^2 a^{-1}. The early higher PP values reproduce the higher TOC content of the Alge Member, whereas the lower values correlate to the Krill Member (c.f. Smelror et al., 2001).

Terrigenous and Residual Carbon Fractions

Two other fractions of organic matter are modelled in OF-Mod: C_{terr} and C_{res}. The deposition of the C_{terr} is strongly correlated to the sand fraction and decrease to zero with low sand fraction. The majority of the Hekkingen Formation is characterized by very low sand fraction and thus there is also very little C_{terr} modelled. In OF-Mod the distribution of C_{terr} is related to the distribution of sand, as both are assumed to be sourced from land. Due to the lack of sand in the working area there is also very little C_{terr} modelled.

The C_{res} correlates strongly with the finer grained deposits, and so C_{res} will have a higher influence on the final modelling results. Based on OF-Mod 1D results the C_{res} is roughly proportional to the MOM.

Organic Matter Properties

To determine the bulk HI of the mixture of the three organic matter types, OF-Mod assumes that each organic matter fraction has a specific HI value, and that the relative quantities of each fraction contributes to the final HI value of the deposits by calculating a weighted average over the three fractions. The values used here are 350 mg HC/gTOC for the MOM, 200 mg HC/gTOC for C_{terr}, and 60 mg HC/gTOC for C_{res}.

Basic Results

The most important results from the OF-Mod modelling of the Hammerfest Basin are the distributions of sand/shale and TOC (Figure 6). Together with the HI these will be used as an input parameter for later basin modelling.

Figure 6a shows the sand fraction, where for a large extent shale (blue colours) is indicative of the fine-grained marine deposits typical of the Hekkingen Formation. Significant sandy deposits occur only along a short margin near the coast.

The cumulative distribution of TOC shown in Figure 6b has several distinct features. Locally along the southern margin very high values are shown (>200m). This area is characterised by high sedimentation rates. Although TOC values for these deposits are generally low, the thickness of the deposits means that substantial amounts of organic carbon are preserved. Due to lack of dating evidence the assumed sedimentation rate is directly proportional to the thickness estimated from seismic measurements. In the remaining area the patchy distribution is caused mainly by local changes in sedimentation rate.

Source Rock Potential

Source Rock Potential (SRP) is a way of classifying sediments in terms of the potential to function as source rocks providing proper pressure and temperature conditions occur (Peters, 1986). For this study the SRP is subdivided into four classes: very good, good, fair, and poor. For every cell in the model the SRP is calculated. Figure 7 illustrates the good SRP class. Good quality source rocks are found in the Hammerfest Basin (Figure 7). The lack of good SRP deposits in the western Tromsø Basin is due to the oxic conditions in that area: these caused degradation of the marine organic matter and thereby low HI values. The patchy distribution pattern is mainly dictated by sedimentation rates: high sedimentation rates cause dilution of the organic matter and low sedimentation rates cause poor preservation due to slow burial of the organic matter. The occurrence of localized areas with more than 100 m of good SRP is also caused by this interaction.

Conclusions

Analysis was made of the Late Jurassic/Early Cretaceous Hekkingen Formation in the Hammerfest Basin and surrounding areas using the organic facies modelling tool OF-Mod. The goal of this study was to provide models of the distribution of the inorganic (sand, shale) and organic (TOC, HI) fractions of the Hekkingen Formation, which will be used as input in a later primary and secondary hydrocarbon migration studies.

A high resolution (> 10 million cells) model was created to be able to replicate thin sandy layers which were interpreted from well data. These sand layers are important with regards to organic matter distribution, but they can also function as conduits for hydrocarbon migration due to their higher permeability and can be important for a later basin modelling study.

The distribution of organic matter was modelled to match measurements in all 25 wells. Vertical changes can be explained by an increase in marine productivity, causing generally higher TOC values. In general, increasing marine productivity is associated with higher HI values, but in this study this was compensated by a simultaneous increase in C_{res}. This resulted in the in a good model representation of the homogeneous vertical HI distribution observed in wells.

The results indicate that changes in sedimentation rate and redox conditions that cause lateral changes in organic matter were be successfully reproduced with OF-Mod. Sedimentation rate influences organic matter preservation due to an interplay between burial efficiency and dilution. An anoxia was modelled in the Hammerfest Basin in order to match the measured high TOC values. Oxic conditions are modelled in the Tromsø Basin where lower TOC values were found.

The interplay between the different processes caused the patchy distribution of source rock potential seen in Figure 7. This is markedly different from basin modelling studies, which assume a laterally and vertically homogeneous source rock (c.f. Rodrigues Duran et al., 2013). This study emphasizes the importance of a detailed investigation of lateral and vertical changes in source rock quantity and quality at well sites in order perform consistent source rock quality model predictions in frontier areas.

Acknowledgements

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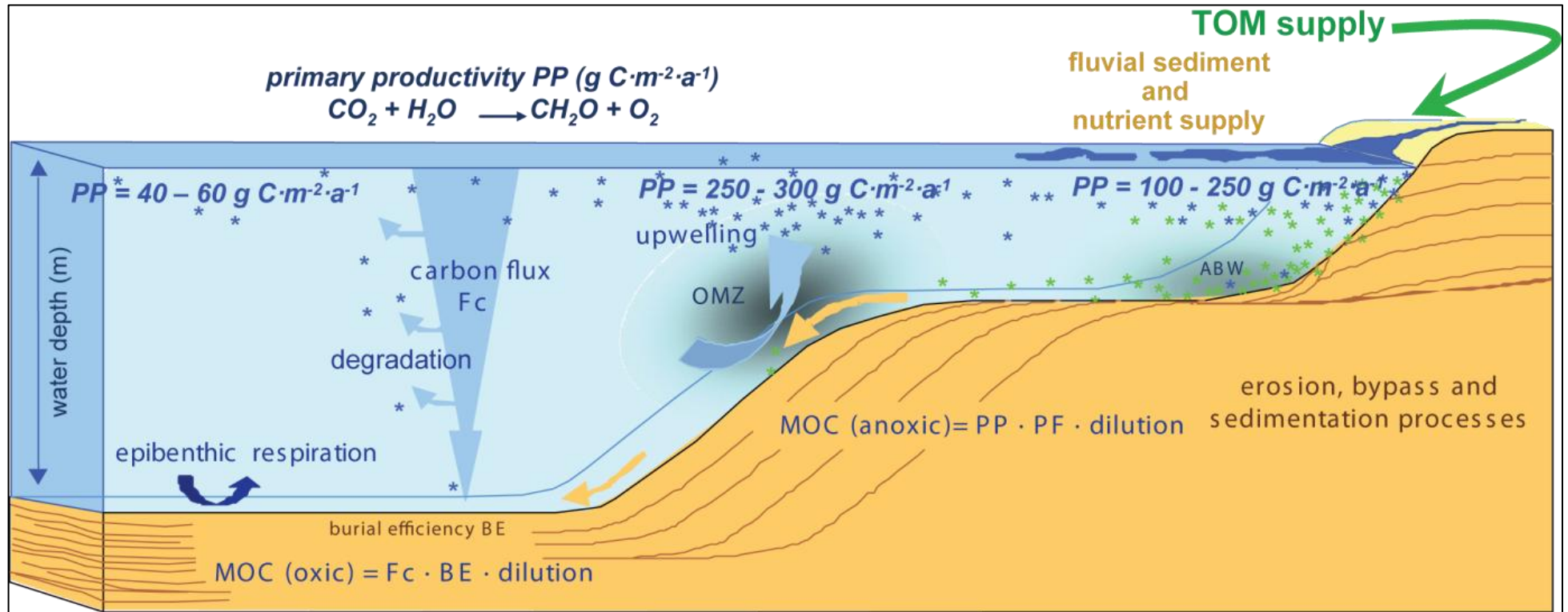
Figure 1. Conceptual model of OF-Mod illustrating main processes which are modelled. MOC = Marine Organic Carbon, F_c = carbon flux, BE = Burial Efficiency, PF = Preservation Factor, TOM = Terrigenous Organic Matter (from Mann and Zweigel, 2008).
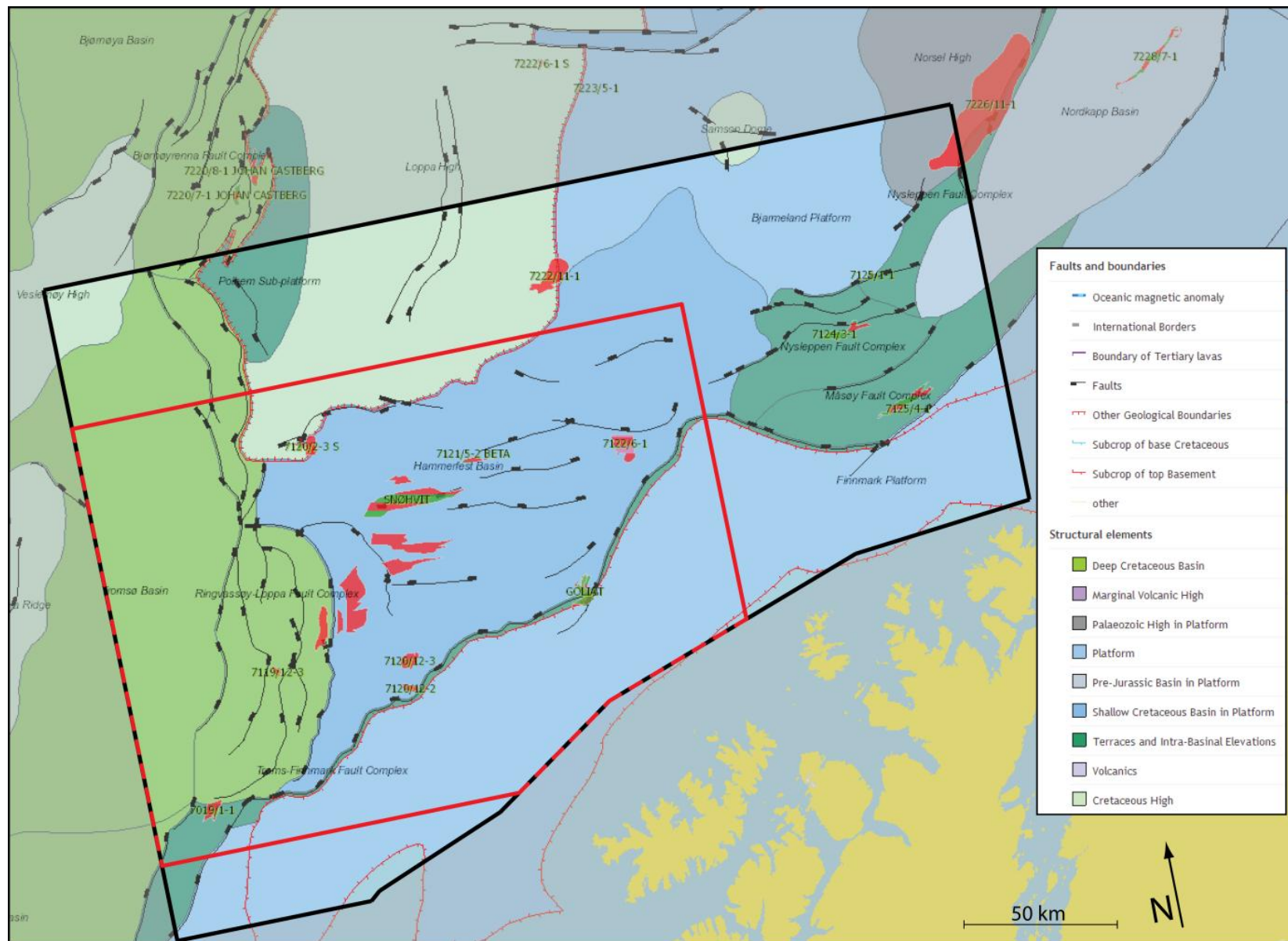
Figure 2. Extent of full working area (black) and of this study (red) superimposed on geological features (npd.no).
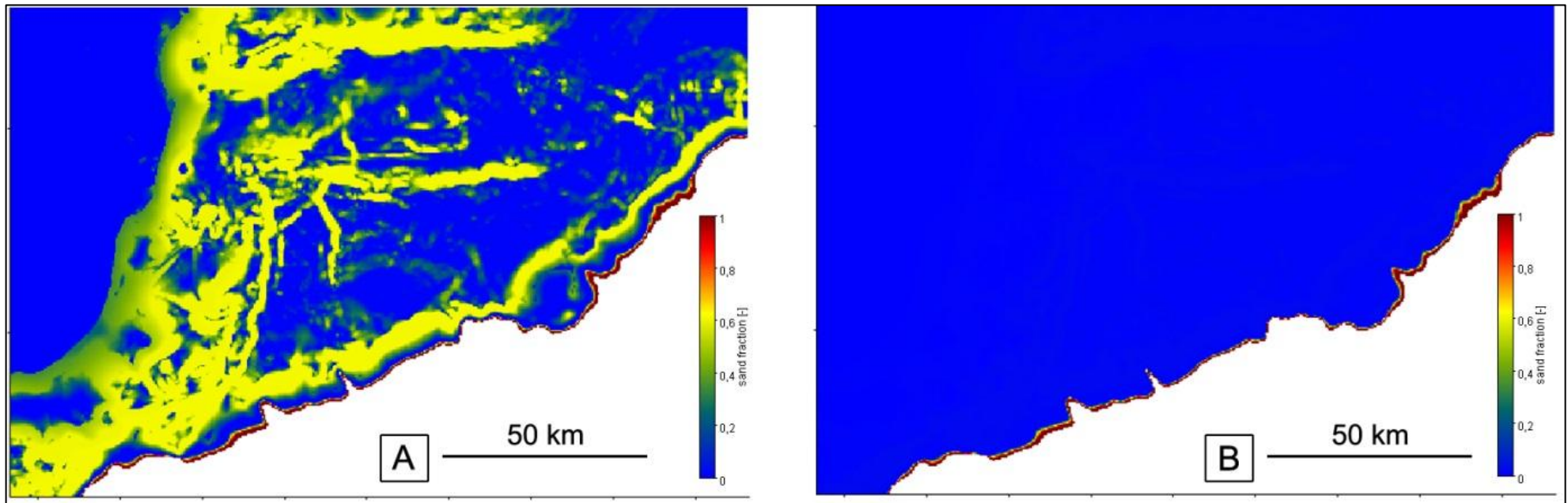
Figure 3. Modelled sediment distribution maps representing deposition over (A) a representative layer showing thin patchy sand distribution and (B) an example representing the majority of layers with relative uniform distributions.
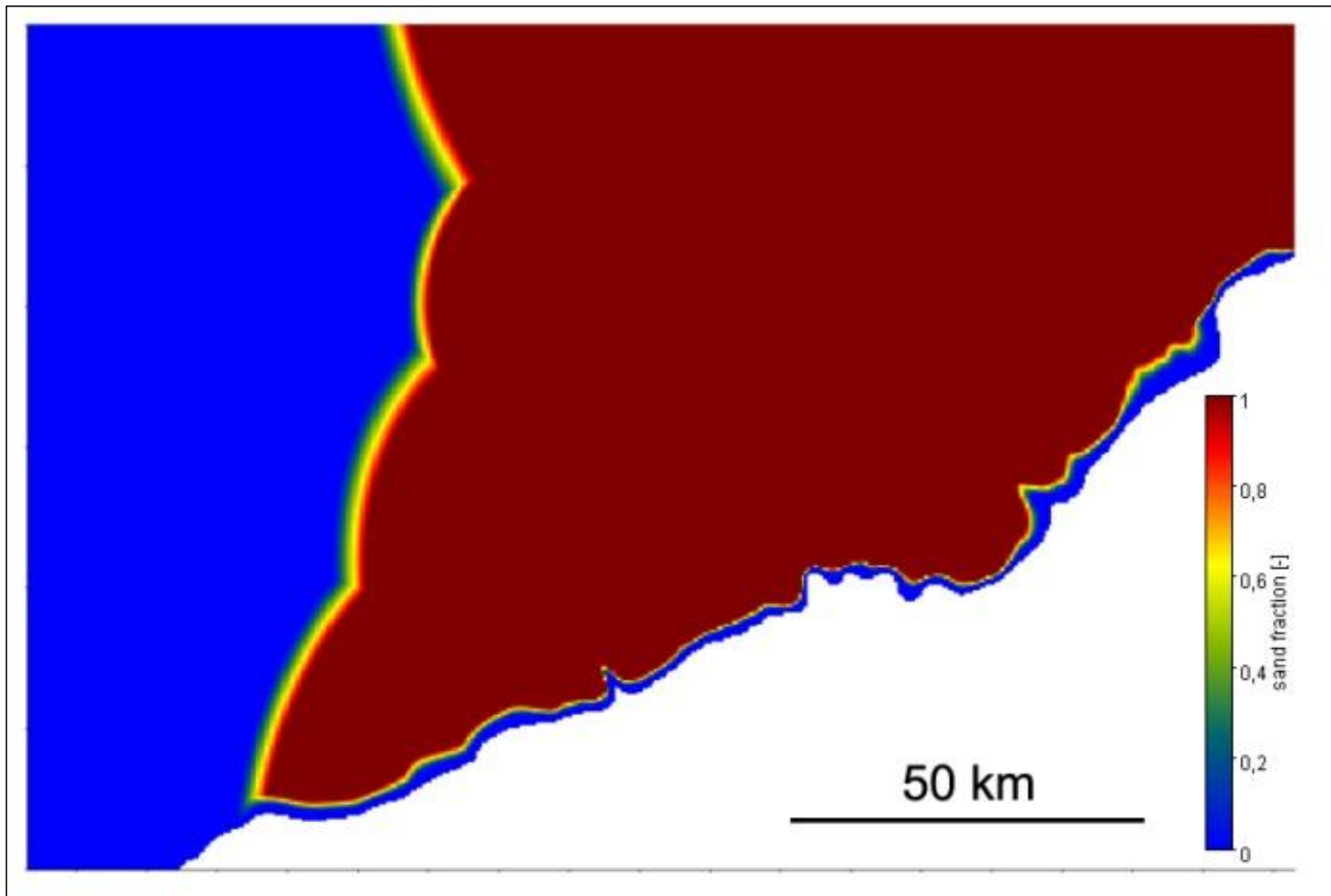
Figure 4. Preservation factor due to anoxic bottom water. Increased (red) values are due to anoxia.
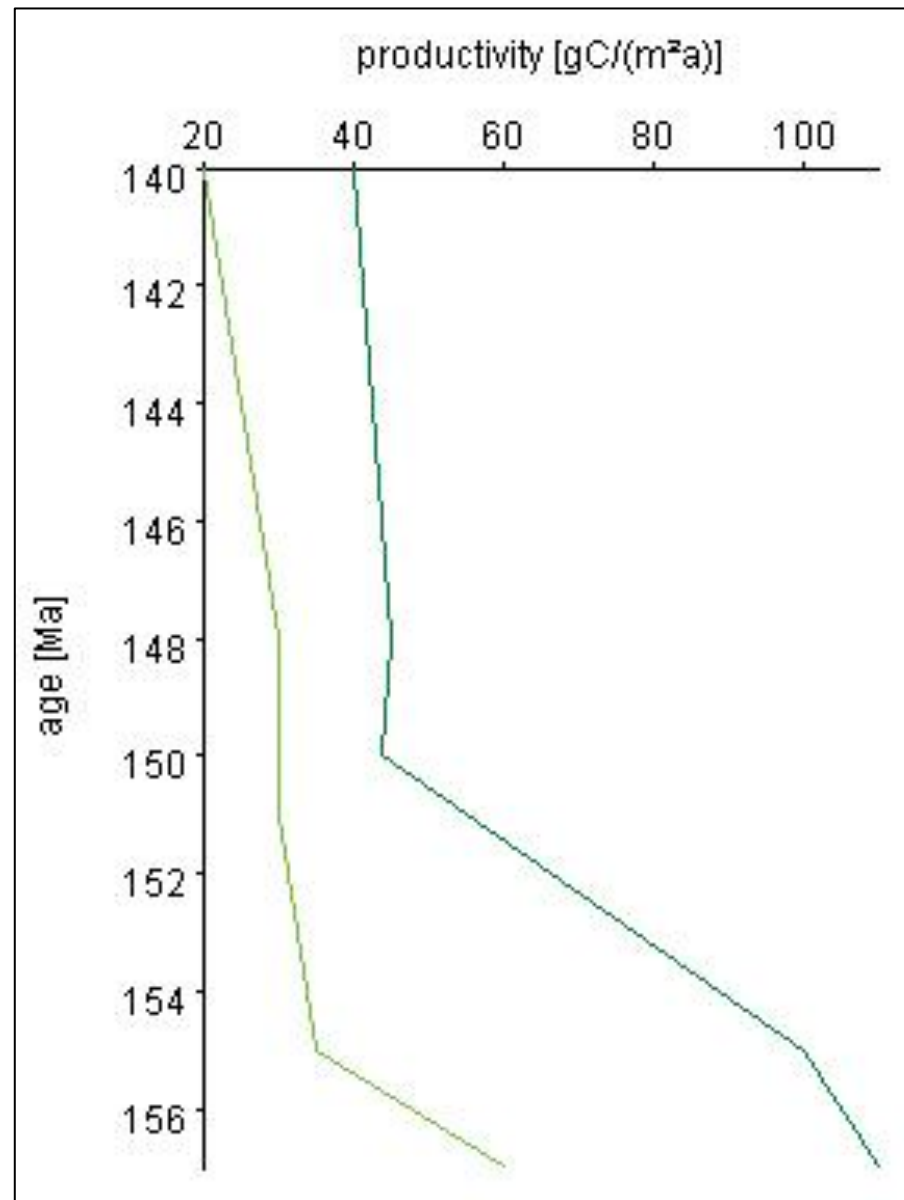
Figure 5. Marine productivity for coastal (dark green) and open ocean (light green) areas.
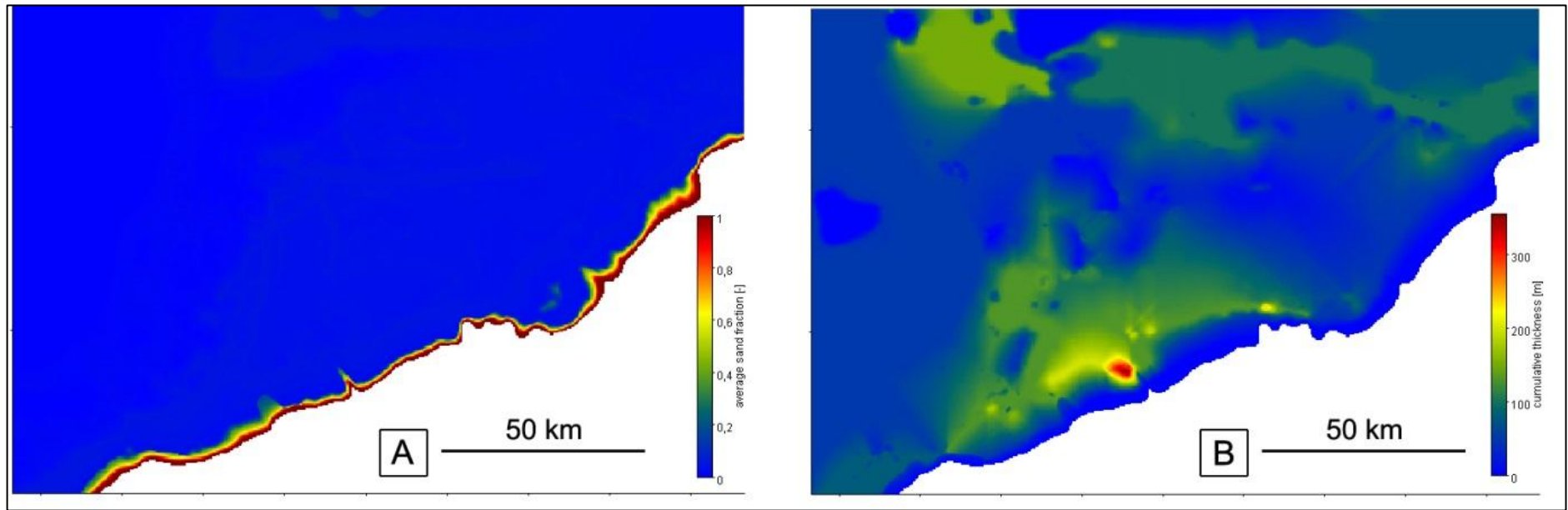
Figure 6. Maps showing representative model output: A) Average value of the sand fraction. B) Vertically cumulative TOC.
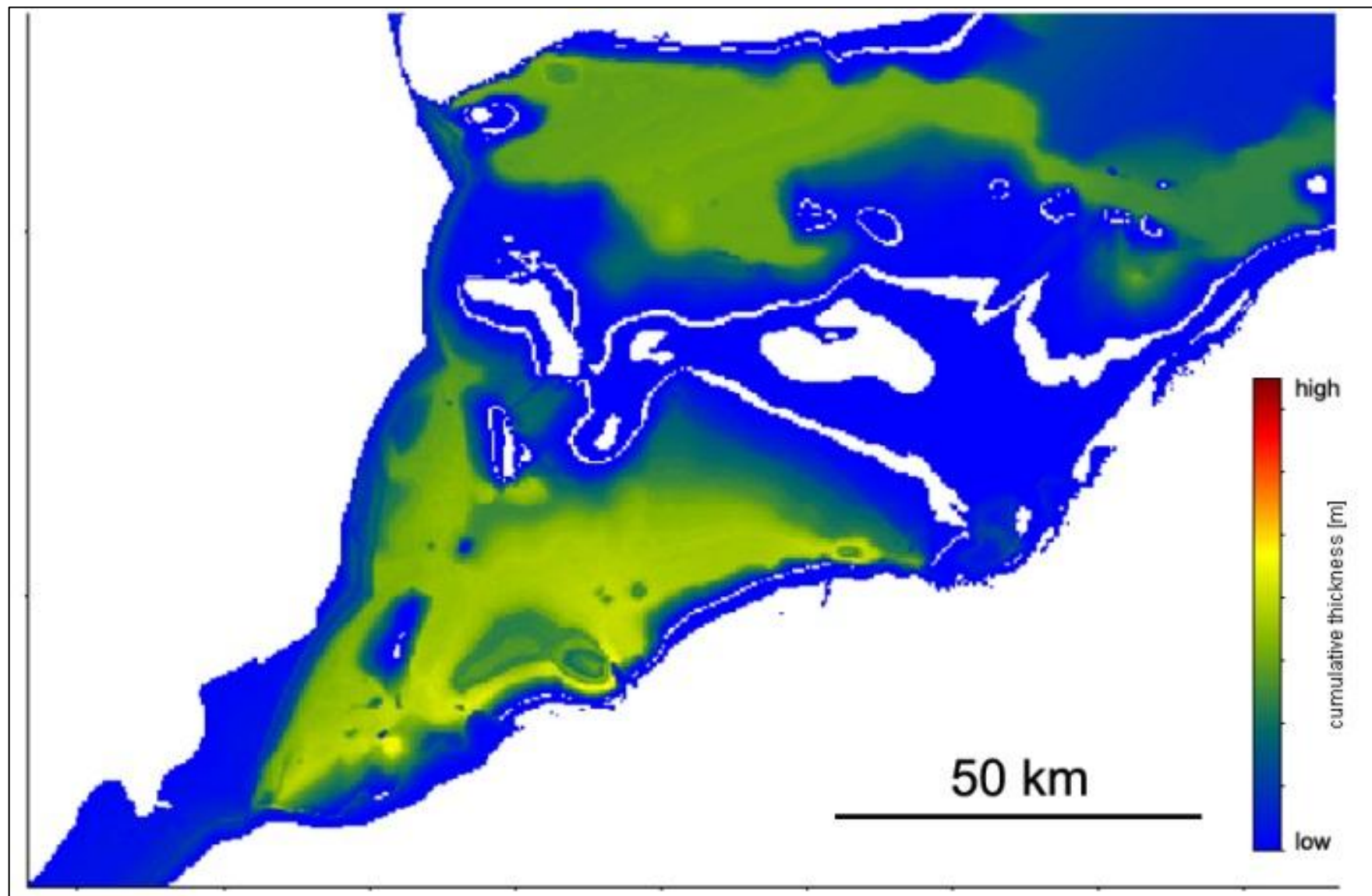
Figure 7. Cumulative thickness map of the good Source Rock Potential (SRP) class. The colour bar indicates thickness.