TEMPERATURE-DEPENDENCE OF THERMAL CONDUCTIVITY AND IMPLICATIONS FOR THE THERMAL-STATE OF THE NORWEGIAN MARGIN

Master Thesis

M.Sc. Program for Polar and Marine Science POMOR

Saint Petersburg State University / Hamburg University

by

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Saint Petersburg / Hamburg

28.08.2017

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Abstract (in English)

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Investigation of temperature field and related heat flow distribution in sedimentary basins have significant scientific importance. Distribution of temperatures is important in questions of sediment basins origin, their evolution, structure, past and modern processes in sediments, crust and mantle. In particular, thermal conductivity of minerals influence on geothermal gradient and heat flow in the lithosphere through sediment blanketing effect. According to this effect, there are feedback between thickness of sediment/crust and geothermal gradient. In this study, investigation of constant and temperature dependent thermal-conductivity are implemented in receiving the temperature distribution and behavior of thermal gradient.

Norwegian Margin is well-investigated region with a huge available temperature datasets from well data. Dataset of 976 wells was used to investigate behavior of temperature field in areas of Norwegian Margin.

The main goal of the master's thesis: Assessing the importance of the temperature dependence of thermal conductivity for the thermal evolution of sedimentary basins.

This study based on modeling which include investigation of temperature distribution and temperature gradient field in 1d steady-state model and parameterization of model. Modeling allows forming a representation of temperature gradient change due to crustal and sediment thicknesses. In addition to determine how much it depends on the thermal conductivity of the rocks. This model used for analysis of importance of the of the temperature dependence of thermal conductivity for the thermal evolution of sedimentary basins in Norwegian Margin area. Modeling implemented in MATLAB environment.

Main results of modeling is creation of model, which allow to compare behavior of geothermal gradient in case of temperature-dependent and constant thermal conductivities with real dataset. In case of temperature dependent thermal conductivity model presents values more close to reality, compare to constant thermal conductivity. Range of modeled values in first case more realistic than more short range in case of constant conductivity model. Model with usage of temperature dependent thermal conductivity present 'hotter' value than should be, but it could be resolved by calibration of main lithology. Results analysis shows that temperature dependent thermal conductivity present more realistic behavior of geothermal gradient. Current dependence is important for thermal structure of basins and it should be considered in integrated basin analysis.

Abstract (in Russian)

ЭФФЕКТ ЗАВИСИМОСТИ ТЕПЛОПРОВОДНОСТИ ОТ ТЕМПЕРАТУРЫ И ВЛИЯНИЕ ТЕПЛОПРОВОДНОСТИ НА ТЕМРМИЧЕСКУЮ ЭВОЛЮЦИЮ ОСАДОЧНЫХ БАССЕЙНОВ НА ПРИМЕРЕ НОРВЕЖСКОЙ ОКРАИНЫ

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Вопросы, связанные с поведением тепловых потоков и распределением температуры в осадочных бассейнах, представляют большой научный интерес. Данные вопросы являются ключевыми при изучении процессов, происходящих в литосфере в ходе рифтогенеза, а также в отношении происхождения осадочных бассейнов, их эволюции и структуры. В частности, теплопроводность горных пород влияет на поведение геотермического градиента и тепловых потоков в литосфере, в т.ч. связанное с эффектом экранирования. Данный эффект отражает взаимосвязь между мощностью осадочного покрова/кристаллического фундамента и изменениями в геотермическом градиенте. В данном исследовании было изучено влияние различных моделей поведения теплопроводности (постоянная/зависимая от температуры) на распределение температурного поля и поведение геотермического градиента.

Норвежская окраина является хорошо изученным районом, для которого накоплен значительный объем доступных температурных данных со скважин. База данных из 976 скважин была использована для исследования полей распределения температуры в различных частях Норвежской окраины.

Основная цель данной работы - оценка важности зависимости от теплопроводности горных пород от температуры в отношении термальной эволюции осадочных бассейнов.

Данное исследование основано на моделировании поведения температуры, которое включает изучение распределения температур и поведения геотермического градиента в 1-D модели при использовании различной параметризации. Моделирование позволяет оценить изменения в геотермическом градиенте при различной мощности кристаллического фундамента и осадочного слоя, а также определить, как изменяются результаты при использовании различных моделей поведения теплопроводности. Модель использовалась для анализа реального распределения температур в пределах Норвежской окраины. Моделирование было выполнено в среде MATLAB.

Основной результат данной работы – создание модели, которая позволяет сравнить поведение геотермального градиента при использовании различных моделей теплопроводности (постоянной и зависимой от температуры). В случае использования в модели зависимой от температуры теплопроводности, результаты моделирования более близки к реальным значениям, по сравнению с использованием постоянной теплопроводности. Диапазон смоделированных значений в первом случае более реалистичный по сравнению с меньшим диапазоном при использовании постоянной модели теплопроводности. Модель с использованием зависимой от температуры теплопроводности предсказывает более высокие значения по сравнению с реальным распределением температур в скважинах. Однако более высокие значений связаны с используемой основной литологией и могут быть скорректированы. Анализ результатов показывает, что зависимая от температуры модель теплопроводности представляет более реалистичное поведение геотермального поведения. Данная зависимость является важной для термальной структуры бассейнов и должна учитываться при комплексном анализе бассейнов.

1. Introduction

1.1. Sedimentary basins and continental margins

Investigation of distribution of temperature and related heat flow distribution in sediment basins have significant scientific importance. Distribution of temperatures is important in questions of sediment basins origin, their evolution, structure, past and modern processes in sediments, crust and mantle.

Thermal conductivity of minerals influence on geothermal gradient and heat flow in the lithosphere. Thermal conductivity depends on group of parameters, such as mineral composition, porosity, saturating fluids, pressure and temperature. Temperature is important factor for thermal conductivity and heat flow. In general case, thermal of conductivities of minerals decrease with increase of temperature (Sekiguchi, 1984).

Norwegian margin represent region, interesting in many scientific subject. Since the second part of XX century region was geologically investigated that related with discovery of sediments basins with significant oil and gas deposits. There were a lot of research in questions of regional tectonics, geology etc. Norwegian margin relatively well investigated by seismic and well data, especially in basins areas. As a result, significant amount of data was accumulated during this time, represented in a huge datasets. Some these data represented in free access, what allows using it in different scientific researches.

Due to huge amount of available well data in the area of Norwegian Margin, it is possible to study the distribution of the temperature field and related parameters.

The temperature structure of sedimentary basins have a complicated nature. Interaction of different factors, such as difference in rock properties, basin's geometry, and faulting distribution could influence on temperature distribution and heat fluxes. However, modelling of different aspects could solve and explain thermal-state of basins.

1.2. Scientific objectives

In this study, investigation of constant and temperature dependent thermal-conductivity are implemented in receiving the temperature distribution and behavior of thermal gradient.

The main goal of the master's thesis: Assessing the importance of the temperature dependence of thermal conductivity for the thermal evolution of sedimentary basins.

Main study aims in this study:

1) Compilation of available temperature datasets related with Norwegian margin area

2) Compilation of governing equation and rock properties

3) Spatial analysis of temperatures datasets

4) Scripting of the main model plot

5) Introducing temperature datasets into model

6) Results comparing of constant and temperature-dependent thermal conductivity models.

7) Interpretation of model's results,

In this study, modeling include investigation of temperature distribution and temperature gradient field in 1d steady-state model and parameterization of model. Modeling allows forming a representation of temperature gradient change due to crustal and sediment thicknesses. In addition to determine how much it depends on the thermal conductivity of the rocks.

Source of main dataset of real data about temperatures is open data from Norwegian Petroleum Directorate (NPD). List of organized temperature data presented in appendix in attached disc.

Geological data about thicknesses of sedimentary layer and crust provided from Ebbing (2010) by the Geological Survey of Norway (NGU). Databased restricted and all proprietary rights to the data belongs to the GSN.

Methods of investigation includes the study of available datasets (Norwegian Petroleum Directorate in particular), study of literature in question of governing equation, parameters etc. This study include processing of data in GIS-application for creation of primary fields of distribution of parameters, processing of spatial data. Main modeling was performed in the MATLAB environment (BY MathWorks), and partially in Tecmod 2D (BY GeoModelling Solutions GmbH).

The main result of this study is creation of 1-D model of behavior of temperature gradient depend of sediment and crustal thickness with influence of constant and non-constant thermal conductivity model.

2. Geological settings and data

2.1. Area of investigation

Norwegian margin is passive volcanic margin extended along Scandinavian peninsula in the area of Norwegian Sea (in range 62-70 °N) and mainly sheared margin in area of western Barents Sea and Spitzbergen (70-82 °N). In this study, main area of investigation limited in northern region in 73 °N because of bad availability of well data in the region. In southern direction area of investigation expanded to area of North Sea. Area of North Sea are not a part of Norwegian part, but interesting as a part of Norwegian continental shelf and because of nice availability of well data.

Structure Norwegian margin response to early Cenozoic continental breakup and opening of Norwegian and Greenland Sea.

Morphologically, Norwegian consists of a continental shelf and slope that vary considerably in width and steepness.

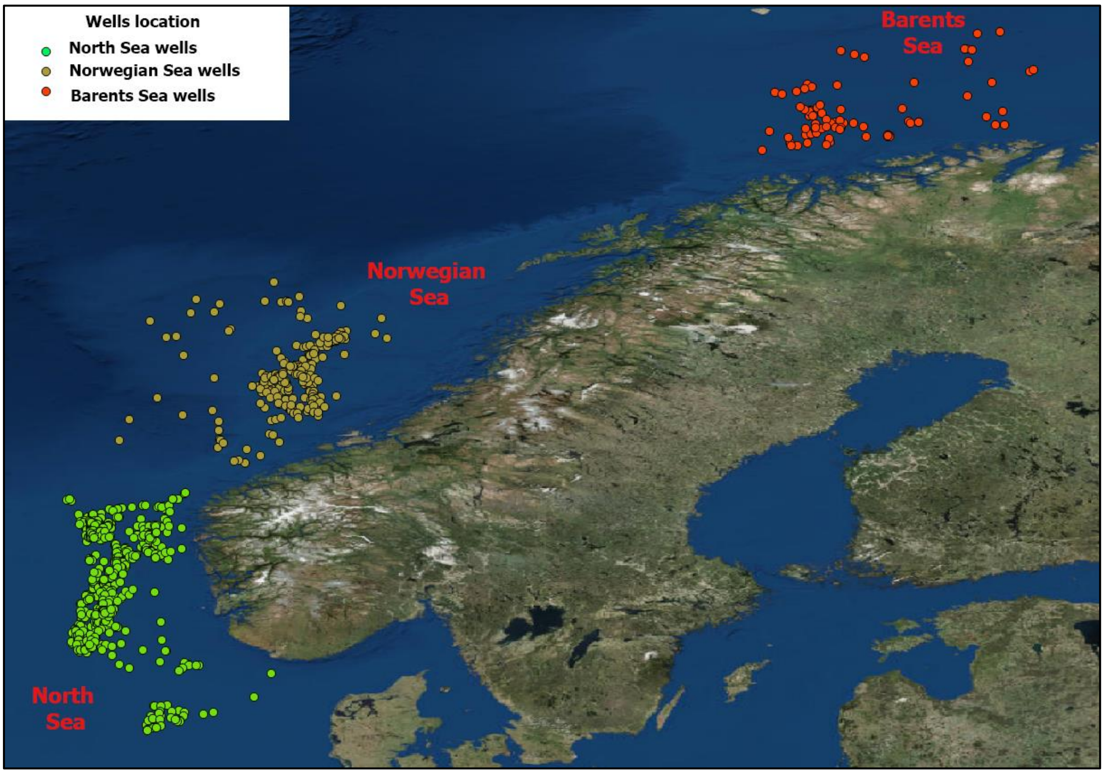

Figure 1. Study area and wells location

In this study, area of investigation divided on three parts with similar geological and spatial conditions (Figure 1). First area represent Southern part of Western Barents Sea, north from Norwegian coast. Area limited in 70°N - 74°N and 17°E - 31°E. In this area represents the smallest amount of available wells - 79 wells.

Second part represent part of Norwegian Sea, west from Norwegian Coast. Area limited in 62.5°N - 68°N and 2°E - 10°E. In this area represents 243 available wells.

Third area of investigation located in area of northern North Sea, west - southwest from Norwegian coast. Area limited in 55.5°N - 62.5°N and 1°E - 7°E. In this area represents 654 available wells.

2.2. Geological settings

It is important to have mention about regional geological settings for understanding processes occurring and feedbacks in Norwegian Margin

In general, the most f structure at, or in the vicinity of passive margin related with the break-up of the continental crust during the latest rift or earliest seafloor-spreading stageassociated with the development of a deep ocean (Eldholm et al., 1987).

Norwegian margin comprises the mainly rifted volcanic margin offshore mid-Norway and the mainly sheared margin along the western Barents Sea and Spitsbergen (Faleide et al., 2010).

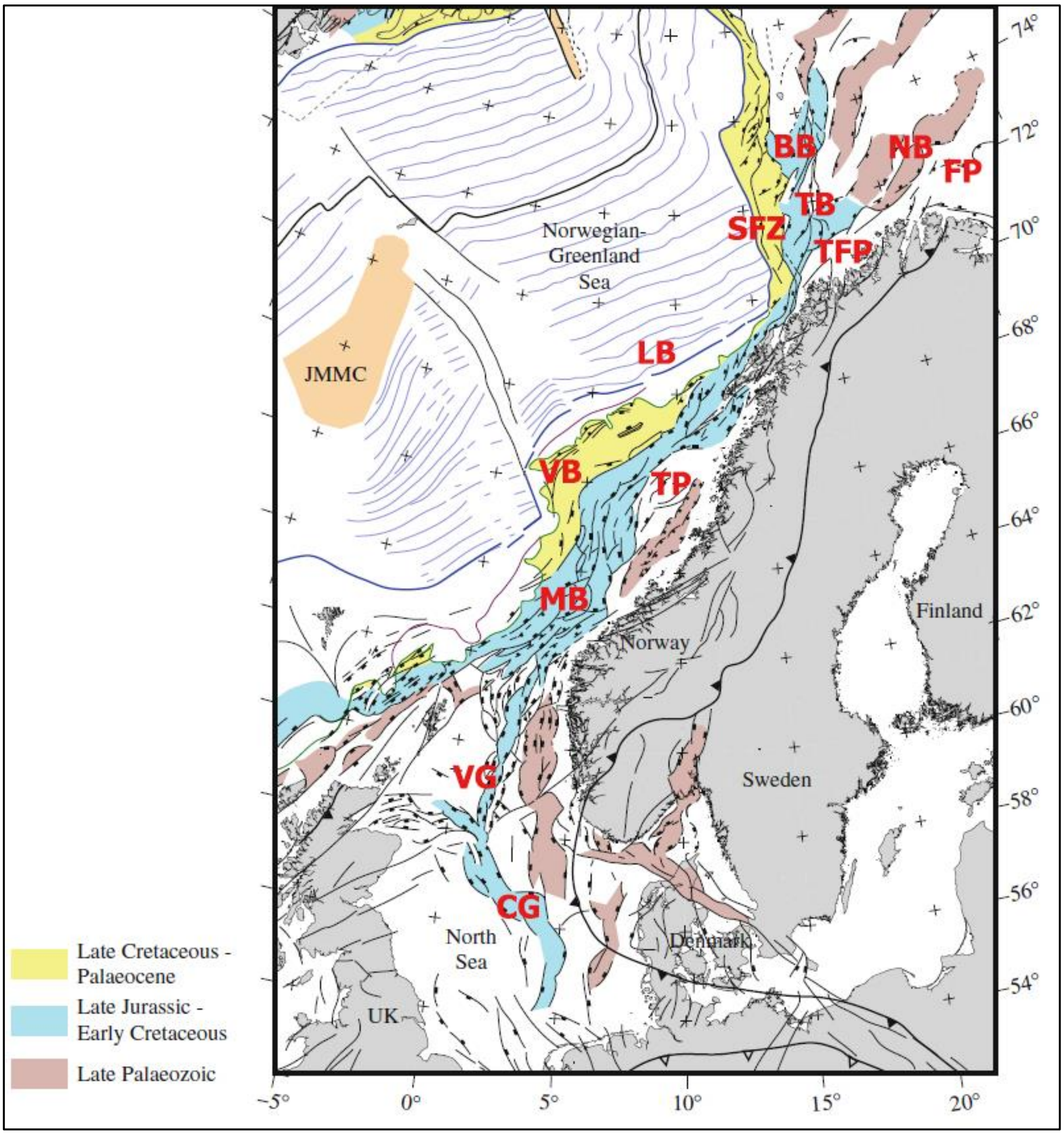

Figure 2. Main structural elements in investigated area of Norwegian Margin and related different rift phases. Adapted figure from Faleide et al. (2010). BB - Bjørnøya Basin, CG - Central Graben, FP – Finmark Platform, LB – Lofoten Basin, MB- Møre Basin, NB - Nordkapp Basin, SFZ - Senja Fracture Zone, TB - Tromsø Basin, TFP - Troms-Finnmark Platform, TP - Trøndelag Platform, VB - Vøring Basin, VG - Viking Graben.

Before continental breakup of continents and beginning of spreading process, this region was a part a significant sea among continental masses Fennoscandia, Spitsbergen and Greenland. This fact result in some similarities in stratigraphy between this areas, but should be considered some differences, especially in Cretaceous-Cenozoic times after break-up and with forming and filling of basins (in case of Norwegian margin) (Faleide et al., 2008) .

Main sediment basins in Norwegian margin area are the result of post-Caledonian rift event series, until early Cenozoic time, when the full breakup of continents occurred.

Main structures in Norwegian Margin area presented in figure 2.

The North Sea represent examples of intracratonic basins, what means that basins laid on continental crust (Faleide et al., 2010). North Sea sediment basins related to period of stretching, thinning and subsidence of crust in late Carboniferous, Permian-Early Triassic and Late Jurassic times. Each rift phase characterized of thermal cooling on post-rift stage, what leads to local subsidence.

Main part of the North Sea laid above Caledonian fundament (Faleide et al., 2008).

. Some areas such as SE North Sea have Precambrian fundament. There are a lot of faults and grabens in the area. One of the mains structures are Viking and Central grabens, extended to north direction of mid-Norwegian margin. Thicknesses of crustal fundament varies in a range 10-30 km.

Sediments mainly related with events of rifting and post-rifting. Significant layers are in the North Sea, refer to late Jurassic and Jurassic-Cretaceous time. In addition, there are significant deposition of Paleogen-Neogen sediments in a top of basins. Total thicknesses varies from several meters (for example, in coastal area of Norwegian Coast) to about 10 km in basinal areas (For example, in area of Viking graben).

Mid-Norwegian Margin have three main subregion: Møre, Vøring and Lofoten-Vesterålen. Each of these subregion 400-500 km long. Origin of Mid-Norwegian Margin related to thinning and subsidence series in Cretaceous and Paleocene time (Faleide et al., 2010).

The Møre Margin is characterized by a narrow shelf and a wide/gentle slope, underlain by the wide and deep Møre Basin with its thick Cretaceous fill The Møre Basin comprises subbasins separated by intrabasinal highs formed during Late Jurassic-Early Cretaceous rifting. Most of the structural relief was filled in by mid-Cretaceous time (Faleide et al., 2008).

Vøring Margin include several structure, such as the Trøndelag Platform, Halten and Dønna terraces, the Vøring Basin and the Vøring Marginal High. The Trøndelag

Platform characterized deep basins related with Triassic and Upper Palaeozoic sediments. The Vøring Basin have a series of sub-basins with highs, related with Late Jurassic - Early Cretaceous times (Faleide et al., 2008).

The Lofoten-Vesterålen margin characterized by a narrow shelf and steep slope. The sedimentary basins underneath the shelf are narrower and shallower than on the Vøring and Møre margins.

Crustal thicknesses varies from 25+ km (in Trøndelag Platform area) to 4-5 km (Vøring Basin). Total thicknesses of sediments varies from several meters (for example, in coastal area of Norwegian Coast, in Trøndelag Platform) to about 15 km in basinal areas (For example, in area of Vøring Basin).

The Barents Sea cover north-west corner of Eurasian continental shelf. West part of the sea located above significant layer of upper Palaeozoic to Cenozoic rocks. Jurassic-Cretaceous, and in the west Palaeocene-Eocene, sediments are preserved in the basins. Area between Norwegian coast and Spitsbergen characterized series of sedimentary basins. In the area of study continental margin consists of three segments: southern sheared margin along the Senja Fracture Zone, a central rifted complex southwest of Bjørnøya associated with volcanism and a northern, initially sheared and later rifted margin along the Hornsund Fault Zone (Faleide et al., 2008).

Crustal thicknesses varies from 25+ km (in Loppa High area) to 4-5 km (Bjørnøya Basin). Total thicknesses of sediments varies from several meters (for example, in area between Loppa High and Bjørnøya Basin) to about 15 km in basinal areas (For example, in area of Bjørnøya Basin).

There are salt layer in sediments, which reach 4-5 km in some area (for example, Nordkapp Basin).

2.3. Initial Dataset

Stage before main part of modeling was issue of compilation and organization of temperature data in area of investigation in Norwegian margin.

Main dataset in this study - dataset of Norwegian petroleum directorate (NPD). Dataset represent different type of data from numerous wells drilled during second part of XX and beginning of XXI centuries. This data set provides a lot of data about geological conditions in area of drilling, technical parameters, temperature data (Bottom holes temperatures) in bottom of well and other data such as owner company etc. In this study, this dataset was used in case of temperature data.

Temperature data from wells is example of direct measurement inside sediments. However, it should be considered that bottom holes temperature value only measurement from one point on bottom of well, excluding values along wells. This fact is important because local parameters for each well may represent different properties of rocks.

Dataset was reorganized and reformatting to get only required parameters and relevant temperature data. This data transformed to standard format for usage in different software environment (QGIS, MATLAB). After reorganization, transformed data introduced in GIS. In this study, main GIS-environment is freeware GIS-application QGIS (Quantum GIS).

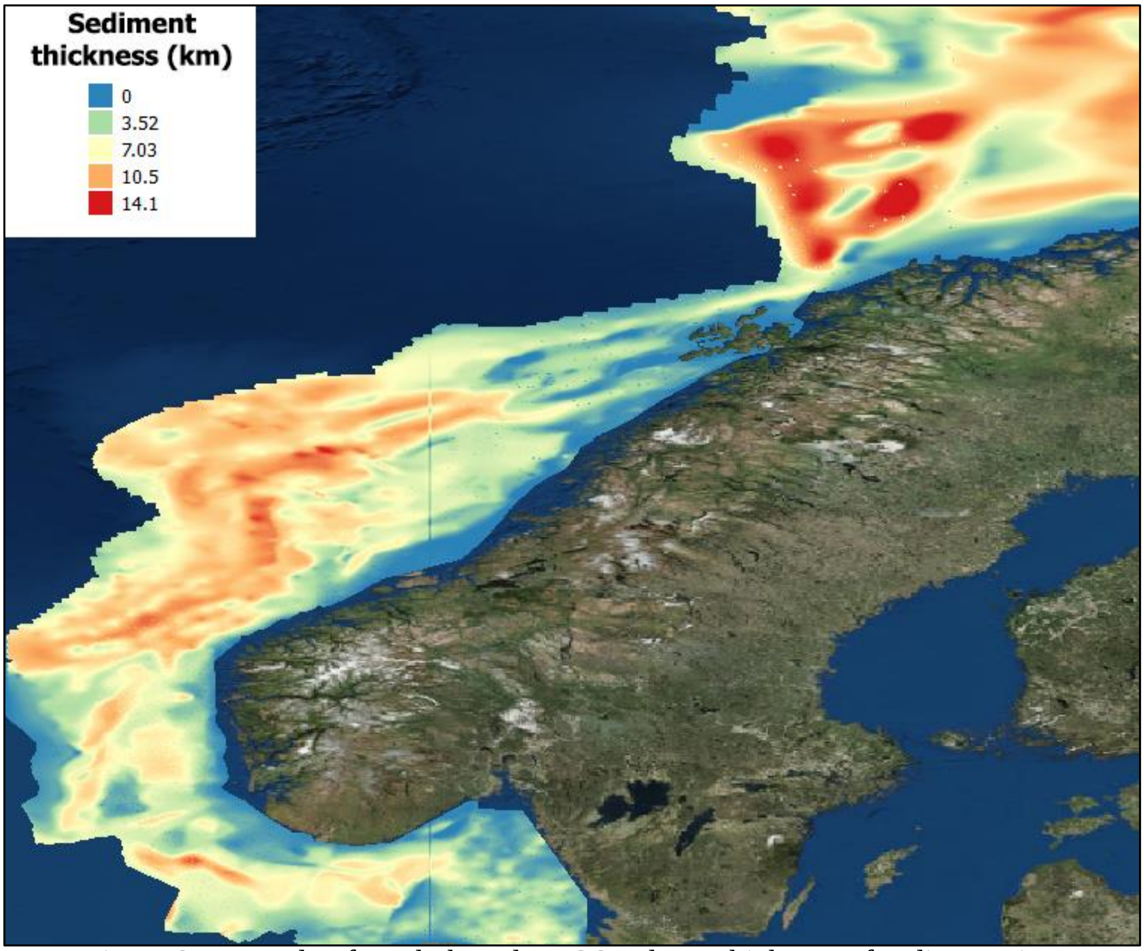

Figure 3. Example of mesh, based on GSN data. Thickness of sediments in the Norwegian margin area and the North Sea (km).

Norwegian margin is a huge region with local differences in geological setting in Barents Sea, Norwegian Sea, and North Sea. All wells divided on three group to get more reliable local picture and simplify data analysis.

In this study used dataset of thicknesses of crust and sedimentary layer, used in Ebbing (2010). This data is information about depth of Sedimentary/Crust depth and Moho Depth presented in numerical form (spatial data and depths values) from restricted data, provided by The Geological Survey of Norway (NGU). Numerical data may be organized in QGIS into points and transform into mesh form. This data allow getting information about layers thickness for each well. Example of data transformed into mesh form, presented in figure 3.

Data initially are not corrected in case of water depth above. To solve this issue used data about regional bathymetry, provided by GEBCO (The General Bathymetric Chart of the Oceans) 2014.

All of these data introduced into QGIS and converted into a format that allows data interpretation.

In QGIS environment created primary field of temperature distribution, field of sedimentary and crustal thickness in different areas of Norwegian margin. These fields allow making first conclusion about dependence of temperature gradient from thickness of sediments/crust. On the base of these fields created primary figures of temperature distribution and behavior of thermal gradient.

3. Modeling approaches

3.1. Background on sediment blanketing

Before establishing of main modeling approaches, we should consider sediment blanketing effect. Lithosphere are not a monolithic environment. Temperature field and heat fluxes have different behavior in shallow and deep condition. Shallow sedimentary and deep crustal as well as mantle processes affect each other. That effect leads to feedbacks between these processes.

Rifting events represent some feedbacks between sediments and crust. During syn-rift phase of rifting there are a peak of heat flow from basement and decrease heat flow in post-rift phase (McKenzie, 1978). However, rifting results to creation of accommodation space for sediments that leads to some changes in heat fluxes (Theissen & Rüpke, 2010). There are two possible effect of sedimentation referring to blanketing effect. First effect - enhances of cooling of crust in case of rapid sedimentation (Debremaecker, 1983; Wangen, 1995). During sedimentation, sediments have much lower temperatures than crust (about 4°C - refer to seafloor environment). In case of rapid infill of basins, there are smoothing of the temperature field during post-rift. However, in other hand, usually low conductivities sediments can slow down post-rift cooling (Zhang, 1993). In case of low-conductivities rocks (for example, shales), there are decrease of heat fluxes, what affects on post-rift cooling.

Sediment and crust have variation of thermal-conductivities depends from main

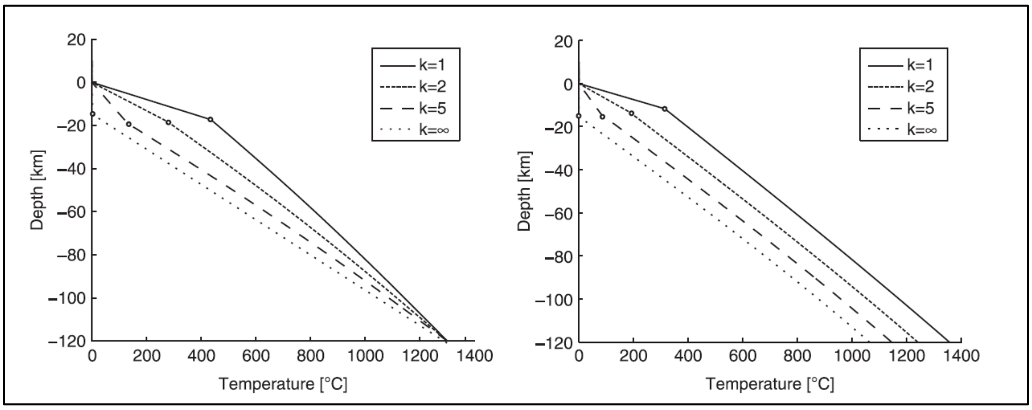

Figure 4. Lithosphere geotherms for two different temperature boundary conditions at the base of the lithosphere. The left panel plot shows the results for a constant temperature and the right panel plot for a constant heat flow boundary condition (30mWm^{-2}). Circles mark the sediment/basement interface (Theissen & Rüpke, 2010).

rocks. However, in general case there are strong contrast between thermal conductivities for sediment and crust. Sediment have much lower thermal conductivity compared to crust's values, what means changes of lithosphere geotherm (figure 4). This figure shows change of geotherm for different sedimentary thermal conductivity. In case of a constant temperature boundary condition at the base of the lithosphere, a higher sediment thermal conductivity leads to lower temperatures in sediments and higher heat flow from crust. In case of constant basement heat flow boundary condition, a lower sediment thermal conductivity leads to shift crustal and mantle values to higher temperatures. However, for the both cases, temperature of sediments increases with decrease of thermal-conductivity. As a result, sediment-blanketing effect depends on the thermal conductivity contrast between crust and sediments (Theissen & Rüpke, 2010; Wangen, 1995). High contrast these thermal conductivities between (lower sedimentary thermal gradient) lead to higher effect of sediment blanketing.

Sediment blanketing effects not only change the steady-state geotherm but also have a strong control on heat flow evolution. Figure 5 shows concept of geotherm behavior due adding new sediments into system. There is thermal equilibrium before deposition of sediments. After adding the new sediments, temperature-state must change for the whole lithosphere that leads to heating and establishing of new equilibrium.As was mentioned previously, blanketing effect depends from sedimentation rate and hence from thickness of sediments. As a result, possibly, steady-state geotherm in sedimentary basins should differ as a function of crustal and sediment thickness

Quantifying the effects requires knowledge of the in-situ thermal conductivity. However, thermal conductivity of rocks in nature are not same and depends from temperature and porosity.

In this study, effect of temperature-dependence of thermal-conductivity investigated, using different parameterizations.

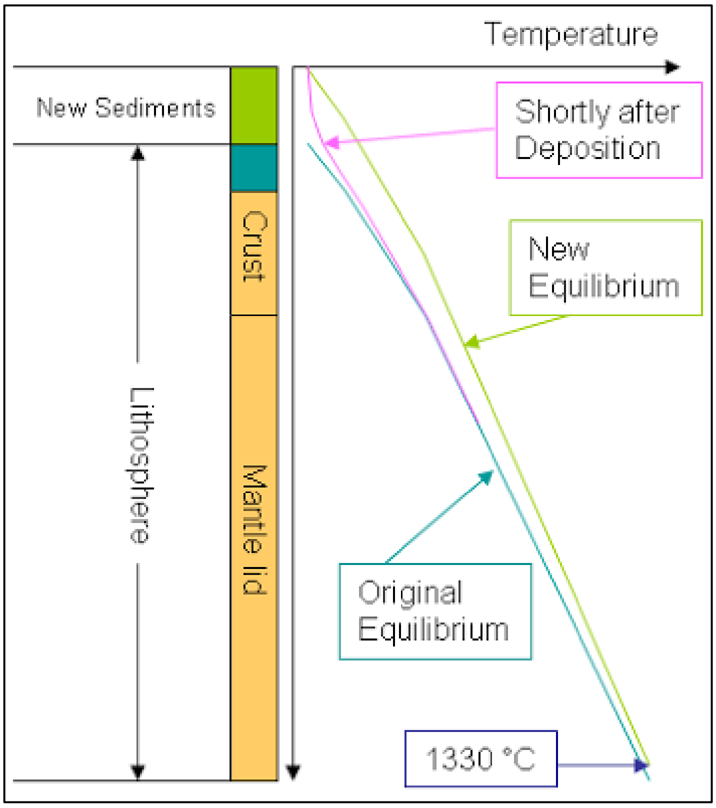

Figure 5. Geotherm behavior in case of new sediments deposition (The Petroleum System Blog, 2010).

3.2. Temperature dependence of thermal conductivity

The thermal conductivity of rocks is known to depend on temperature (Pertermann and Hofmeister, 2006; Sekiguchi, 1984; Whittington et al., 2009; Xu et al., 2004). Thermal conductivity generally decreasing with increasing of temperature. However, there are differences in behavior of temperatures and absolute values for different environments. In this study, were compiled parameterizations for sediments, crust and mantle.

In this study were used two scenario of conductivity for material. First scenario mention simply model of conductivity – constant conductivity on the whole matrix for each layer (sediments, crust, mantle). Second scenario mention temperature-dependent conductivity. In this case were used several governing equation for each layer in the model.

3.2.1 Temperature dependence of thermal conductivity of sediments

In-situ conductivity for sediments at an absolute temperature T can be describe by Sekiguchi (1984) equation:

$$K = \frac{T_0 T_m}{T_m - T_0} * (K_0 - K_m) * (\frac{1}{T_0} - \frac{1}{T_m}) + K_m \quad (1)$$

Where K_m- conductivity in the current point, T_m – absolute temperature in the current point, K_0- primary conductivity of a mineral at room temperature.

In this study, for sediments was used adapted Sekiguchi equation:

$$\lambda_i(T) = 358 * (1.0227 * \lambda_i^{20} - 1.882) * (\frac{1}{T} - 0.00068) + 1.84 \quad (2)$$

Where λ_i^{20} – conductivity for the mineral (W/m/K), T – temperature in K°

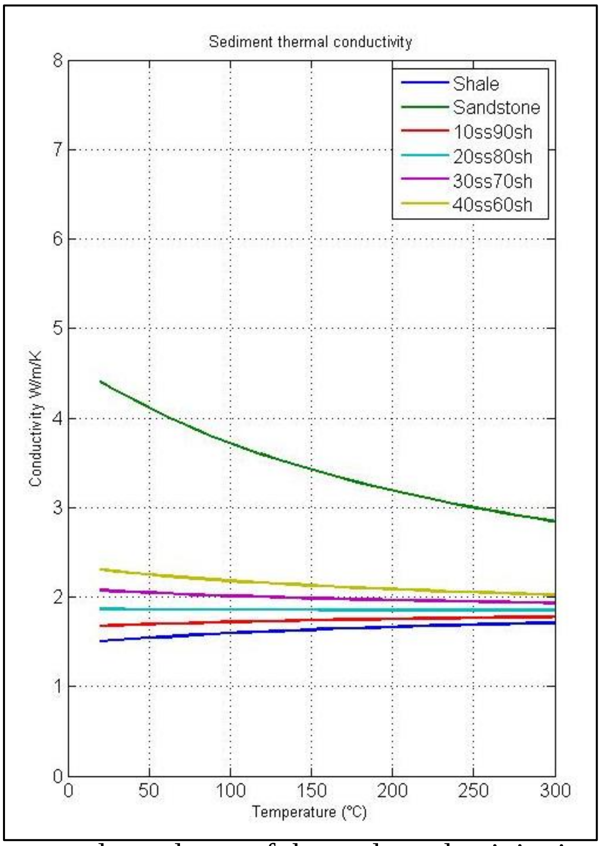

Figure 6. Temperature-dependence of thermal conductivity in sediments for shale, sandstone and mixed lithology consisting of different fractions of sandstone and shales.

Behavior of temperature dependence of thermal conductivity of sediments according to equation (2) presented in figure 6. As example presented results for shales, sandstones and for some mixed lithologies (10% sandstones and 90% shales, 20% sandstones - 80% shales, 30% sandstones - 70% shales, 40% sandstones - 60% shales).

Effective conductivity of the sediments were calculated for two scenario: for case of t-dependent conductivity and constant-conductivity. For the first scenario was used geometric average between the conductivity of the pore water and the sediment matrix (Equation NO).

$$k_{eff} = k_f^{(1-\theta)} * k_w^{\theta} \quad (3)$$

Where k_{eff} – effective conductivity, k_f - conductivity of sediment matrix, k_w - conductivity of the pore water, θ – porosity.

Behavior of pore fluid conductivity presented in figure 7.

For the second scenario was assumed that effective conductivity equal to conductivity of the sediment matrix.

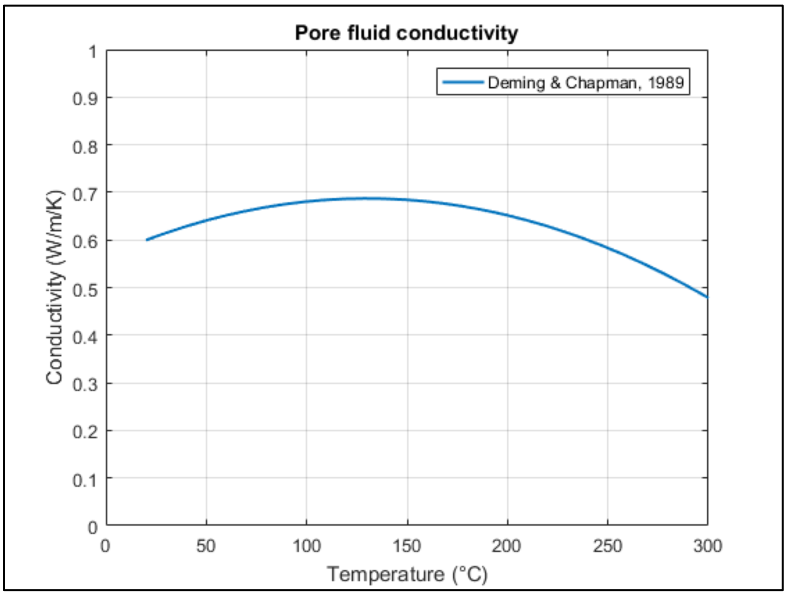

Figure 7. Change pore fluid conductivity from temperature (Deming & Chapman, 1989)

3.2.2 Temperature dependence of thermal conductivity of crust

Thermal conductivity for crust was calculated based on several equation refer to temperature-dependence of thermal-diffusivity and specific heat capacity. Temperature dependence of thermal diffusivity for crust could be estimated by equations according to Whittington et al. (2009):

$$k_{crust} = 567.3/T - 0.062 \ (T < 846 \ K) \ (4)$$

$$k_{crust} = 0.732 - 0.000135 * T \ (T > 846 \ K) \ (5)$$

Where T – temperature in current point in °K

Heat capacity is strongly temperature dependent (Xu, 2004). Temperature dependence of heat capacity could be estimated by equations:

$$C_p = 199.50 + 0.0857 * T - 5.0 * 10^6 * T^{-2} \ (T < 846 \ K) \ (6)$$

$$C_p = 229.32 + 0.0323 * T - 47.9 * 10^{-6} * T^{-2} \ (T > 846 \ K) \ (7)$$

Where T – temperature in current point in °K

After calculations of thermal diffusivity and specific heat capacity, thermal conductivity for crust and mantle could be calculated by equation:

$$\lambda = k_{crust/matle} .* \rho * C_p \ (8)$$

Where $k_{crust/matle}$ – thermal diffusivity, ρ – density of the mineral, C_p – specific heat capacity

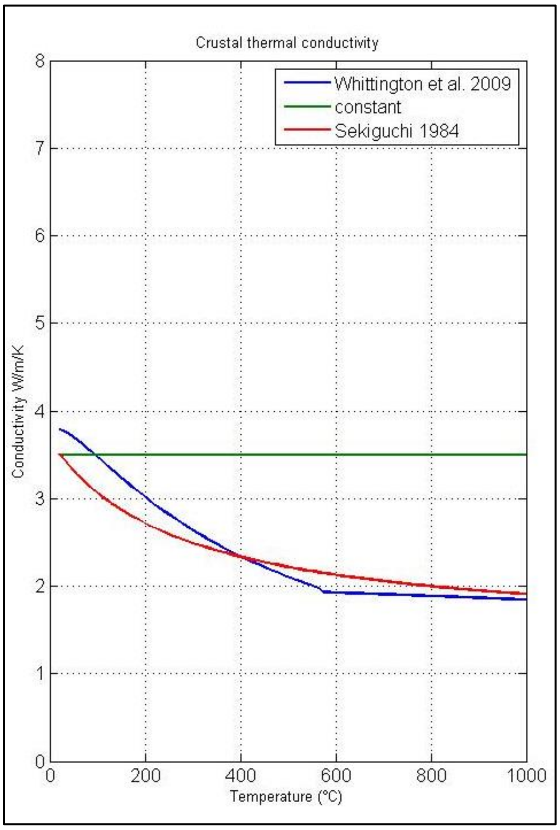

Figure 9. Temperature-dependence of thermal conductivity in crust for Whittington (2009), Sekiguchi (1984) and in constant case

Behavior of temperature dependence of thermal conductivity of crust according to previous equations presented in figure 8. Resulted line for thermal-conductivity presented with behavior of thermal-conductivity according to Sekiguchi (1984) and in case of constant value.

3.2.3 Temperature dependence of thermal conductivity of mantle

Thermal conductivity for mantle was calculated in the same way as crust, based on several equation refer to temperature-dependence of thermal-diffusivity and specific heat capacity.

In this case was used one of the equations according to Hofmeister (2006), which provide good fit for garnets:

$$k \approx A + \frac{B}{T} + \frac{C}{T^2} + \ldots \quad (9)$$

Where A, B, C etc. - constant coefficient for mineral, T – temperature in the point

This equation (9) adopted according with coefficients values for olivine needles [001], presented in Hofmeister (2006):

$$k_{\mathrm{mantle}} = 0.3805 + 381.3/T + 79703/T^2 \quad (10)$$

Temperature dependence of heat capacity for mantle could be represented in equation as a composition of group parameters for mineral, according to Saxena (1996):

$$C_p = a + b*T + c*T^2 + d*T^{-2} + e*T^{-3} + f*T^{-1/2} + g*/T \quad (11)$$

Where a, b, c, d, e, f, g – parameters for mineral, T – temperature in the point.

In this study were used values for forsterite, (Mg_2SiO_4) (Saxena, 1996), values presented in the table 1:

Table 1. Parameters value for specific heat production equation (Saxena, 1996)

Parameter	a	b	c	d	e	f	g
Value	165.80	0.1855e-01	0	-3971000.0	0.2861e+09	0	-5610.00

After calculations of thermal diffusivity and specific heat capacity, thermal conductivity for crust was calculated in the same way as equation (8).

Behavior of temperature dependence of thermal conductivity of olivine (mantle) according to previous equations presented in figure 9. Resulted line for thermal-

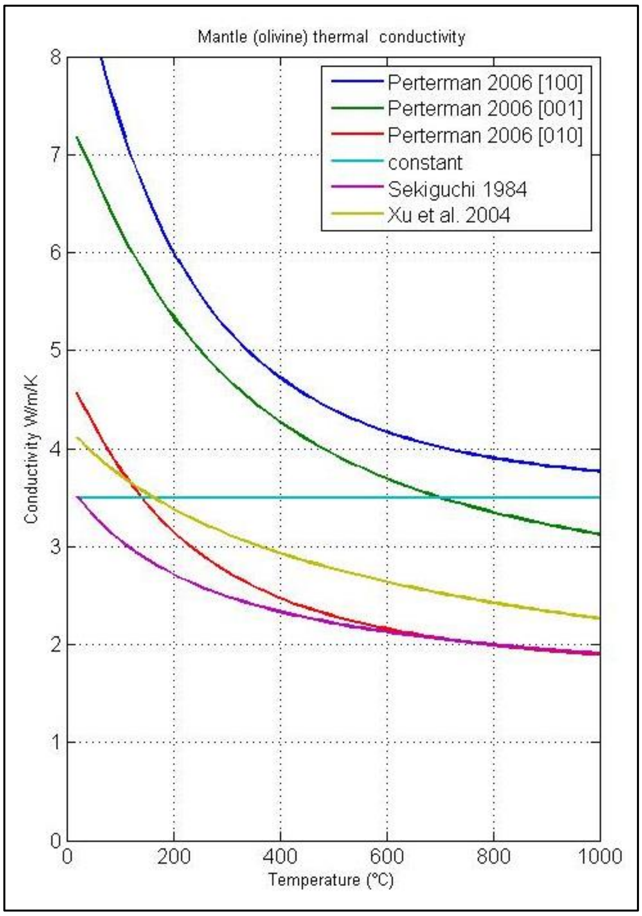

Figure 10. Temperature-dependence of thermal conductivity in Mantle according to different authors and in constant case

conductivity presented with behavior of thermal-conductivity according to different authors (Sekiguchi, 1984; Xu et al., 2004) and other olivine orientation ([100], [010], [001]) and in case of constant value.

3.3. 1-D temperature model

Investigation of temperature dependence of thermal-conductivity done by creation of 1-D modeling in scale of lithosphere thickness. Main environment of modeling in this study - numerical computing environment MATLAB (by The Math Works).

In this paper, modeling include several stages:

1) Development of the basic principles of the model.

2) Preparation of governing equations and primary data for model.

3) Creation of model (scripting of model)

4) Receiving of first results

5) Correction of the model

6) Receiving of the final results

First stage include development different aspects of model, analysis the possible parameterization, input and output of model etc.

Second stage include collection of data for different parameters, preparation of governing equation in literature. There three substrates:

1) Compilation of governing equation

2) Compilation of s of rock properties for mantle, crust, and sedimentary rocks

3) Compilation of parameterizations of thermal conductivity for mantle, crust, and sedimentary rocks in constant and t-dependence cases

Third stage of model development means scripting of the model and introduction main principles and equations in the MATLAB environment. On this stage script organized in cycles and sequence of the model run.

Next stage include receiving of first result according to model setup. On this stage created figures and fields of distribution. In partially, field of temperature gradient, geothermal gradient etc.

Correction of the model means analysis of the first results and solving main uncertainties. In this study, correction include two substages: correction of model refer to isostatic equilibrium and fitting of radiogenic heat production.

Last stage include receiving secondary results and analysis.

All numerical calculation and results received on base of lithosphere-scale model. Lithosphere in the model represented as three layer series such as sedimentary layer, crust and mantle. In this study, material properties for each layer are constant. Model limited from the top of sedimentary layer (sea bottom) what represent "0" for model to lithosphere depth equal 120 km. Thermal boundary condition on the top equal 4°C (refer to averages sea bottom temperatures) and 1300°C on lithosphere depth.

In this model was created matrix for the whole lithosphere thickness. This matrix represent a numerous amount of points, which divide space on small sublayers. Each of these sublayers refer to one of three environment and have certain temperature value. Resolution of the space is about 2 km for mantle, 200 m for crust and 100 m for sediments.

Temperatures calculation bases on dependence from efficient thermal conductivity of layer's material and radiogenic heat production in each layer. For estimation of final temperature was used initial guess for linear temperature distribution refer to temperature on lithosphere depth and top of sediments. After initial guess was made correction according to layer's properties and thicknesses.

1-D temperature solution presented in equation:

$$\frac{d}{dy} * k * \frac{dT}{dy} + Q = 0 \quad (12)$$

Where k - the variable thermal conductivity, T – temperature, Q - radiogenic heat production.

Equation (12) is solved using as a finite element formulation according to Reddy (2010).

The effective radioactive heat production in sediments for matrix was calculated based on the radioactive heat production of the sediment matrix scaled by the solid volume ratio (1- θ) (equation 13)).

$$Q = Q_0 * (1 - \Theta) \quad (13)$$

Where Q_0 – initial radioactive heat production, Θ - porosity

In case of crust and mantle was used scaling of the radioactive heat production by e-fold length (equation 14). Radioactive heat production decreased with the depth in the crust and e-fold length means the depth where radioactive heat production in crust reach 1/e of the top value.

$$Q = Q_0 * e^{\left(-\frac{z}{efold}\right)} (13)$$

Where Q_0 – initial radioactive heat production, z – depth level in the crust, efold – efold length

In this study was considered case of isostatic equilibrium. It means that the weight of each lithospheric column in the model should have the same value of weight at the isostatic compensation level, what refer to Airy isostasy model. During rifting the crust was thinned by stretching factor β what leads to creation accommodation space for sediments. This leads to dependence of thicknesses of mantle, crust and sediments basin. Solution for isostasy compensation based on searching for isostasy line with proper initial crustal thickness to fit real distribution of crustal and sediment thicknesses. Value of initial thicknesses was established for each investigation area assuming close geological settings. This value was used for correction of e-fold according of current stretching factor and correction of radioactive heat production in the crust.

To simplify model input data, assumed one main basin lithology with corresponding porosity values. Trend of porosity changes follow Athy's law:

$$\theta = \theta_0 * e^{-z/\lambda} \quad (14)$$

Where θ_0 – surface porosity, λ – compaction constant, z – burial depth below the seafloor

Value of porosity and other parameters presented in the table 2.

Table 2. Thermal and material properties for different environment in the model

	Heat capacity (J/kg/K)	Conductivity (W/m/K)	Radioactive heat production (W/m^3)	Surface porosity	Compaction length scale
Sediments	880	1.7	0 to 1 x 10^{-6}	0.6	0.5
Crust	-	2.8	2 x 10^{-6}	-	-
Mantle	-	3.5	0	-	-

4. Results

4.1 Temperature distribution and thermal gradient

Norwegian margin represent variation of temperature gradient in different parts of the margin.

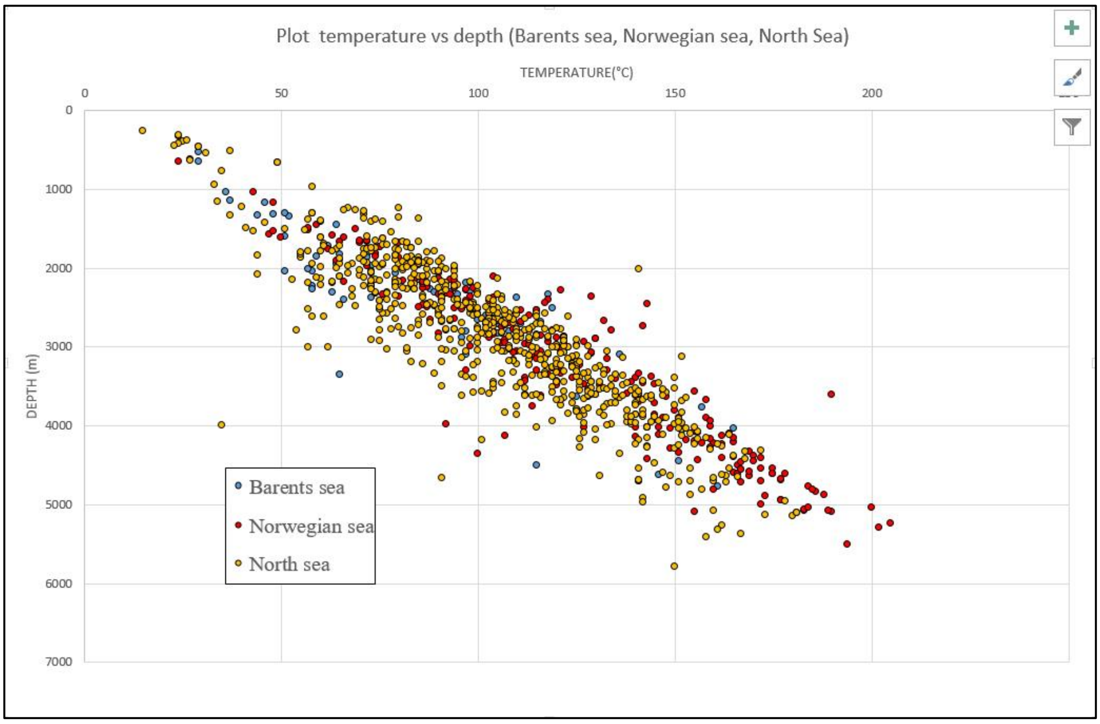

Figure 11. Plot of bottom holes temperatures versus depth for three area (Barents Sea, Norwegian Sea, and North Sea)

At initial stage of this investigation received distribution of bottom holes temperatures with depth for the well dataset, which presented in figure 11. According to this figure, distribution represent relative high variation in temperatures at the same depths. For example, variation for the North Sea region reach range up to 50 degrees on the depth of 1500-5000 meters. As a result, variations in geothermal gradient are significantly high. Variation for other areas smaller, but relatively high as well and reach ranges about 20-30 degrees for Barents Sea and 20-40 degrees for Norwegian Sea area.

Data of bottom hole temperatures transformed into thermal-gradient, assuming that thermal-gradient connected with temperature directly. In addition assumed that thermal-gradient does not change in layer above point of measurement.

Distribution of thermal gradient presented in figures 12, 13, and 14.

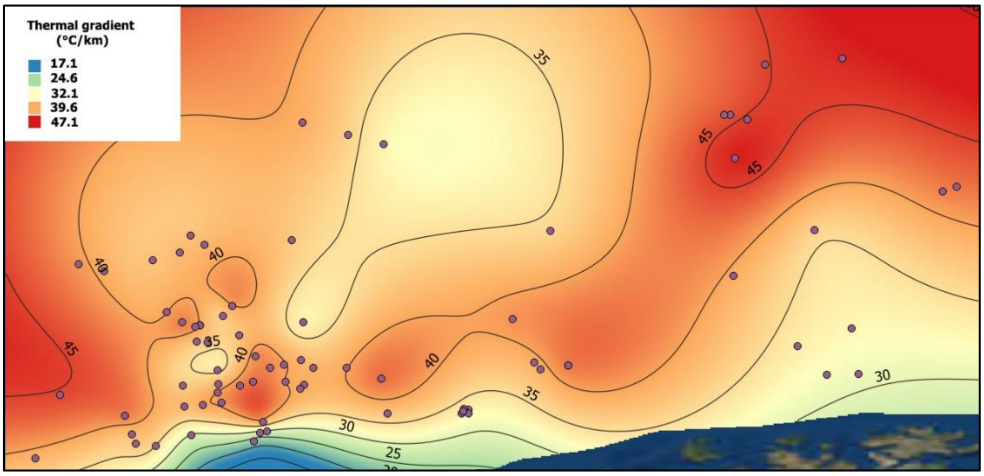

Figure 12. Map of the thermal-gradient variation in the area of Barents Sea

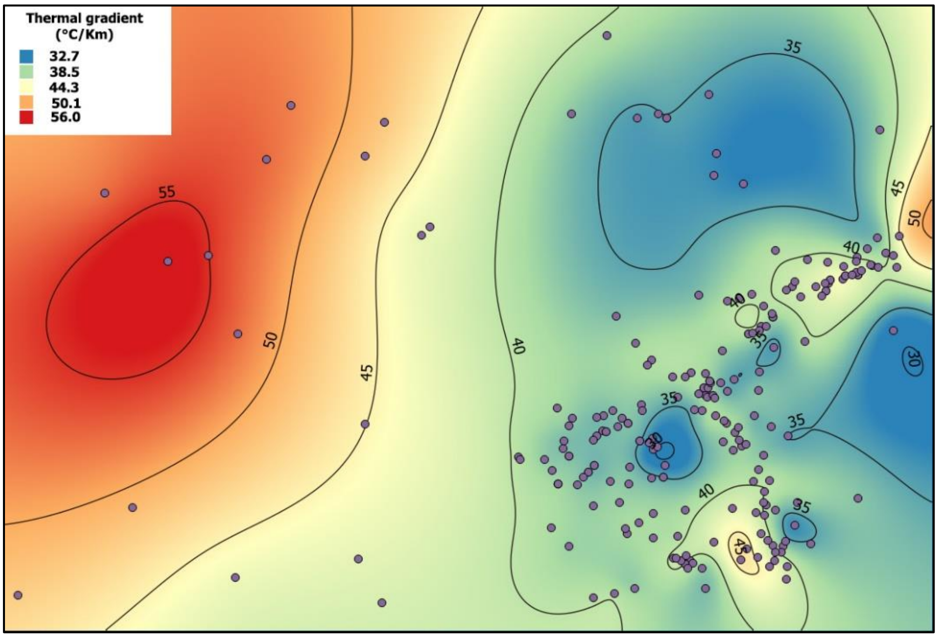

Figure 13. Map of the thermal-gradient variation in the area of Norwegian Sea

According to this figures variation in temperature refer to variation in thermal gradient. In case of Barents Sea range of gradient – around 20-45 °C/km, Norwegian Sea – around 30-55 °C/km, North Sea – around 30-50 °C/km.

4.2 Crustal and sediment thicknesses

As one of the input type of data, sediment and crustal thickness were organized and prepared for model. Distribution of well according to certain thickness value presented in figures 15, 16.

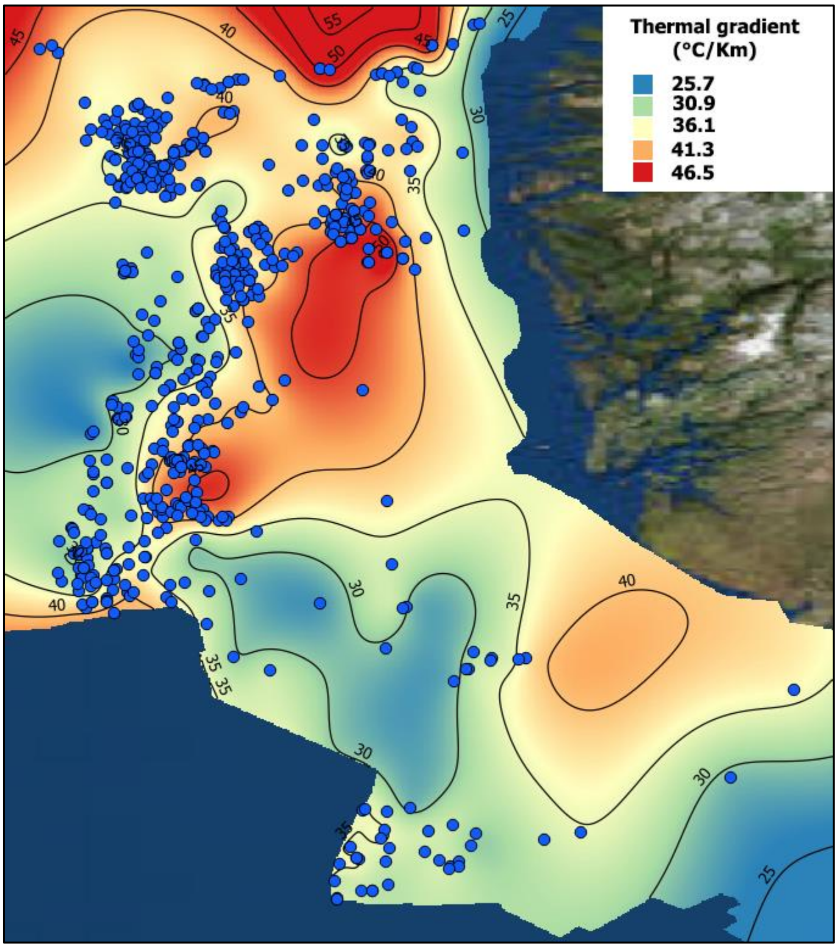

Figure 14. Map of the thermal-gradient variation in the area of North Sea

Well represent a huge variation of thicknesses, related to local tectonic and geological settings. All variation presented in a table 3.

There is not a clear trend of behavior of thermal gradient or dependence solution. However, according to distribution of thicknesses observed some features of each region.

In case of Barents Sea, generally well's range shifted to area of significant crustal layer at one hand, and to the area of significant sedimentary basins as well.

Norwegian Sea wells mostly shifted in the area of lower crustal thickness with location in moderate area of sediment thickness variation.

North Sea well represent wide range of values. However, in case of crustal thickness values mostly located in moderate area and shifted to the lower values in sediment thicknesses.

Table 3. Range of sediment and crustal thickness variation

	Barents Sea	Norwegian Sea	North Sea
Range (crust)	14 – 30 km	7,5 – 26 km	12 – 26 km
Range (sediments)	3 – 12 km	2,5 – 11 km	1 – 10 km

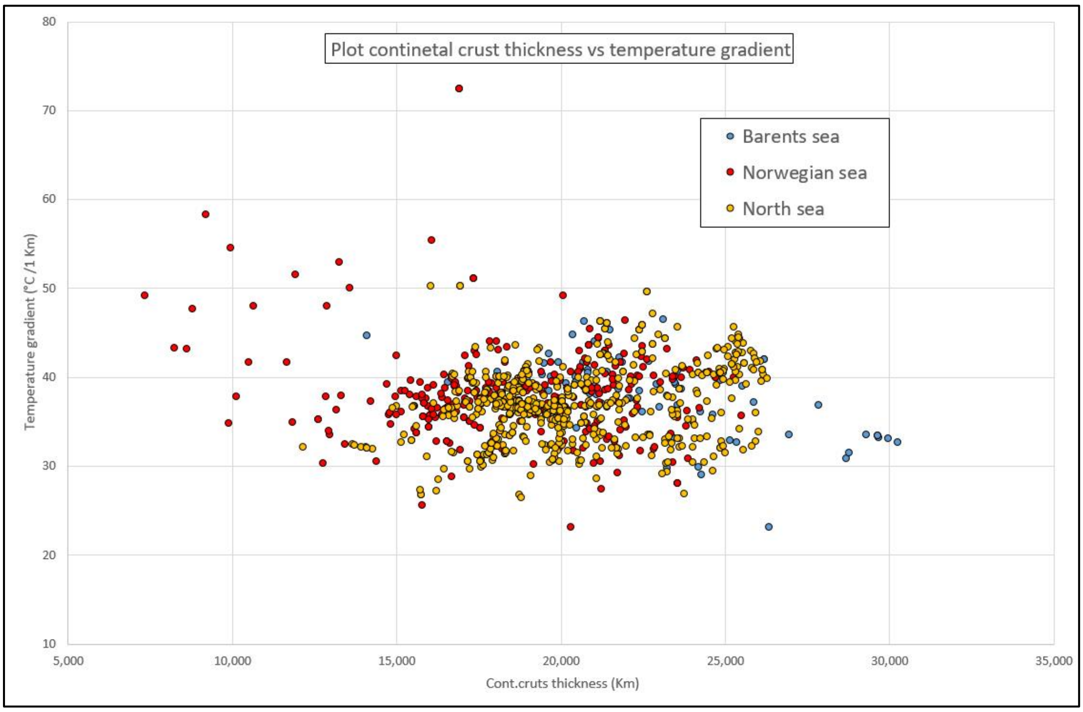

Figure 15. Plot of continental crust thickness versus temperature gradient for the study area

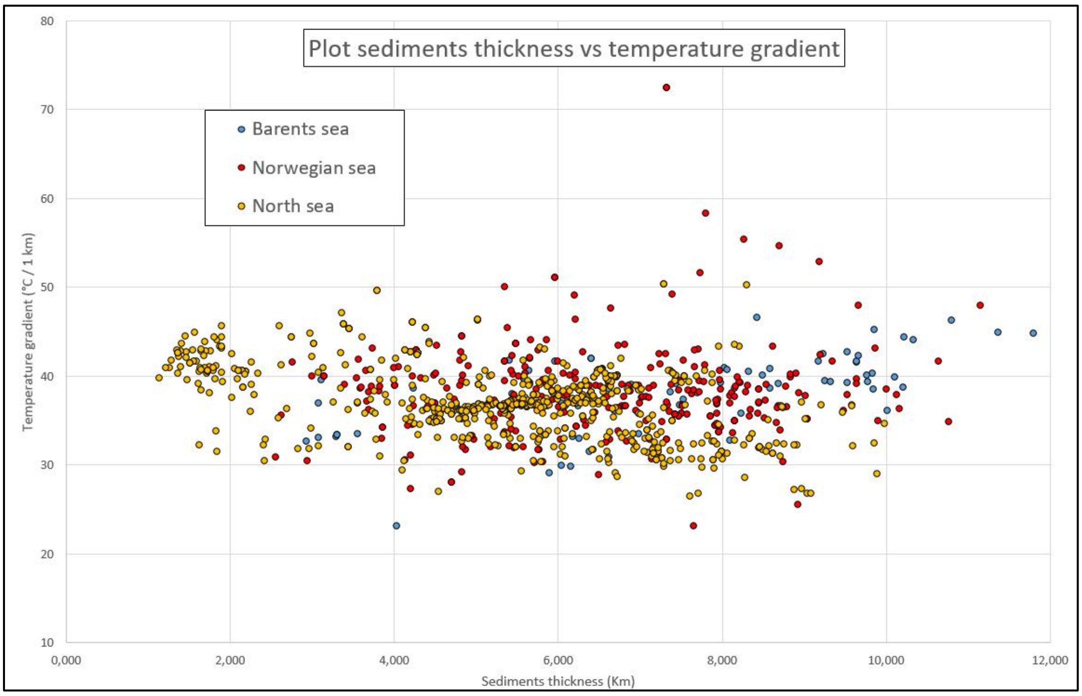

Figure 16. Plot of continental sediments thickness versus temperature gradient for the study area

4.3. Isostasy compensation correction

As was mentioned in chapter «Modeling approaches», we consider an isostasy equilibrium for each column according to Airy mode of isostasy. Solution for this issue presented in figures 17, 18, and 19.

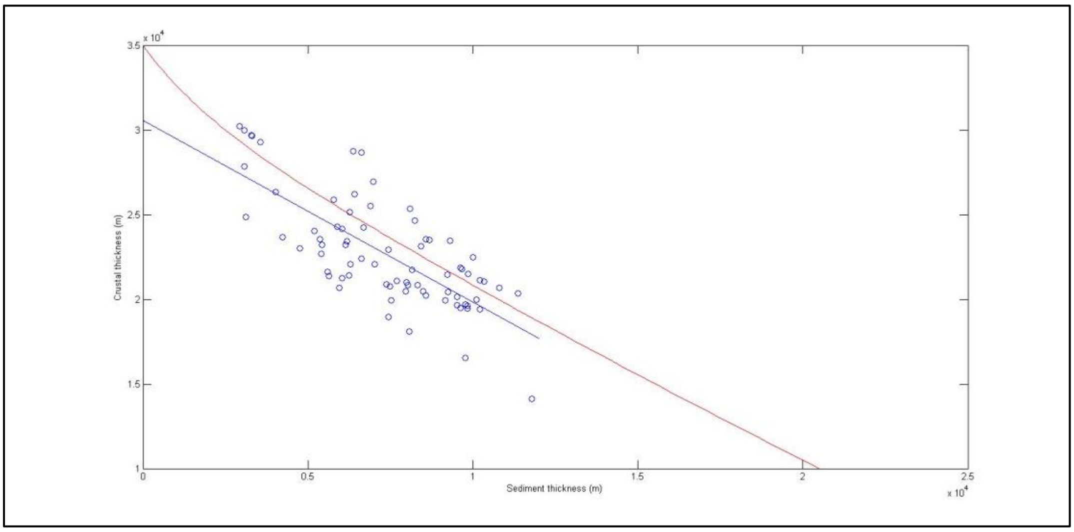

Figure 17. Isostasy line (red) according to assumed initial thickness (35 km) and relation between presented sediment and crustal thickness (blue) for wells in the Barents Sea

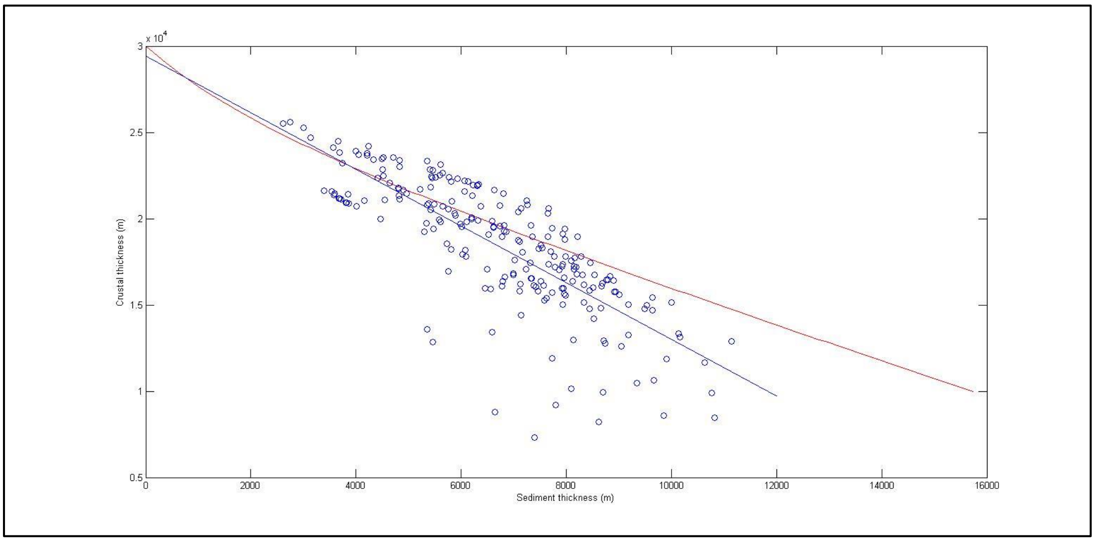

Figure 18. Isostasy line (red) according to assumed initial thickness (30 km) and relation between presented sediment and crustal thickness (blue) for wells in the Norwegian Sea

In case of Barents Sea, best fit for real relation between thickness of crust and sedimentary layer is isostasy line with initial crustal thickness equal 35 km. Isostasy line have significantly close behavior to trend line of this relation.

In case of Norwegian Sea, determination of best fitting isostasy line have a complications. According the different guess about initial crustal thicknesses, there were a huge mismatches. A best fitting isostasy line determined as line with initial crustal thickness equal 30 km. Deviation from relation between nowadays sediment and crustal thicknesses explain by some geological heterogeneity of evolution.

In case of North Sea, best fit for real relation between thickness of crust and sedimentary layer is isostasy line with initial crustal thickness equal 29 km. Isostasy line have significantly close behavior to trend line of this relation and have nice fitting as in case of Barents Sea.

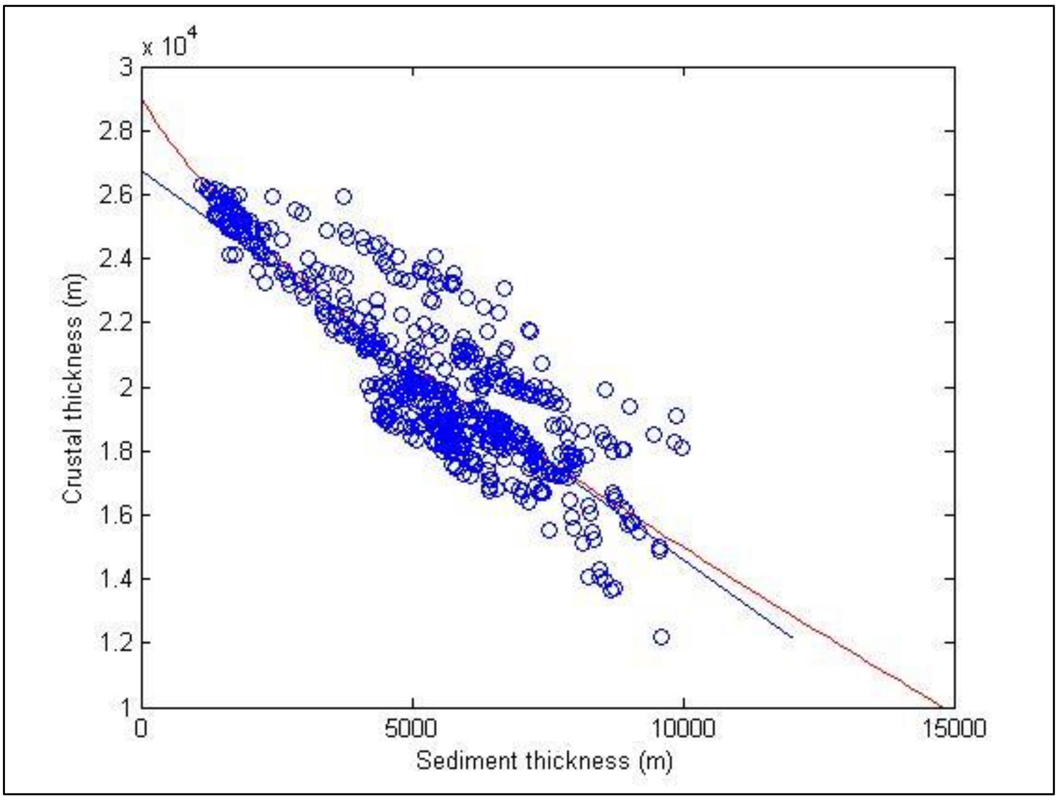

Figure 19. Isostasy line (red) according to assumed initial thickness (29 km) and relation between presented sediment and crustal thickness (blue) for wells in the North Sea

4.4. Radiogenic heat production correction

Radiogenic heat production correction in sediment was conducted to investigate the best fitting geotherm from model to real geotherm. To solve this issue, average value of crustal and sedimentary thickness calculated, according to existing range of thicknesses for each region. In addition, investigated behavior of geotherm for each thermal conductivity model. Results presented in figures 20-22.

In case of the Barents Sea area (figure 20), there are not so much difference between two setup of radiogenic heat production in sediments. Setup with negligible RHS have only slight decrease in geotherm in absolute values. However, geotherm with zero radiogenic heat production present more valid fit with wells data. Comparing temperature-dependent and constant conductivity model, first setup present more realistic fit. Geotherm in constant setup lower than should be even with increase of radiogenic heat production in sediments.

As in case of the Barent Sea area, there are not so much shift between two heat production setups, in case of Norwegian Sea (figure 21). Temperature-dependent thermal conductivity model with RHS = zero have the best fit to real data. Constant thermal-conductivity model present lower fit to real data, even more than in case of the Barents Sea area.

Results for the North Sea present the same results as in previous cases (figure 22). The best fitting setup - temperature-dependent thermal conductivity with negligible radiogenic heat production. However, constant conductivity model have closer fit, compared to other areas. In case of RHP = 1 x 10^{-6} observed close fit to real data.

As a summary, temperature-dependent thermal conductivity, presents more realistic picture of geotherm for each region. Value of radiogenic heat production does not change so much with setup, however, RHS = 0 x 10^{-6} W/m^3. present best fit to real data. Constant conductivity model represent lower fit to real data, however, nice fit observer in case of the North Sea area. Nevertheless, the both variation in heat production in sediment should be considered due to small changes in geothermal gradient.

In this model, radiogenic heat production in the crust was examined .One of the issue during total radiogenic heat production correction was estimation of parameter value for crust. The best fit of radiogenic heat production achieved with usage RHP value = 2.x 10^{-6} W/m^3.

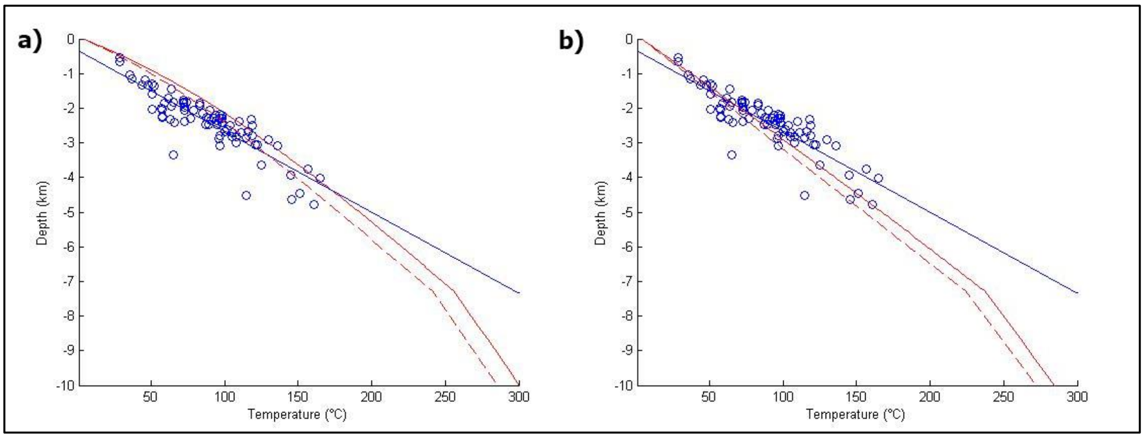

Figure 20. Fitting of modeled geotherm for average crustal and sediment thickness with temperature well data (blue) in the Barents Sea area. Solid line – RHP = 1 x 10^{-6} W/m^3, dashed line – RHP = 0 a) Temperature-dependent thermal conductivity b) Constant conductivity

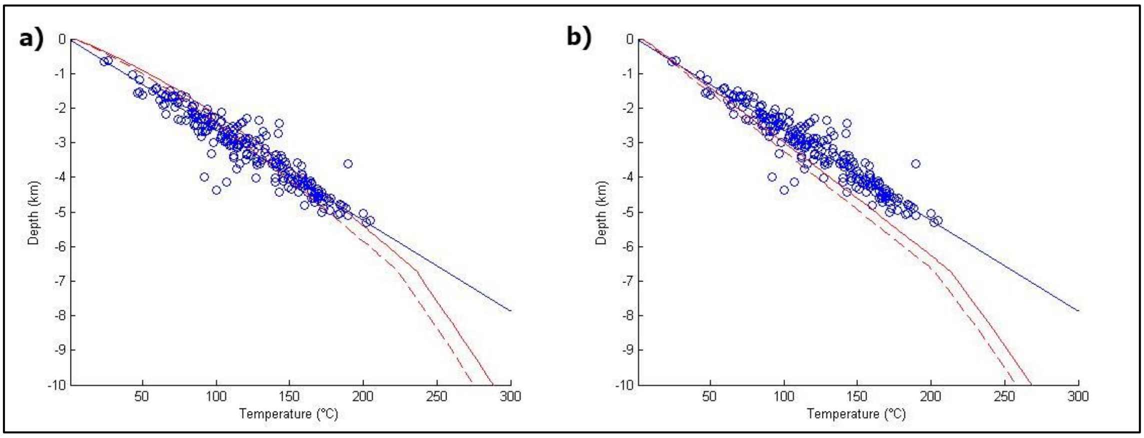

Figure 21. Fitting of modeled geotherm for average crustal and sediment thickness with temperature well data (blue) in the Norwegian Sea area. Solid line – RHP = 1 x 10^{-6} W/m^3, dashed line – RHP = 0 a) Temperature-dependent thermal conductivity b) Constant conductivity

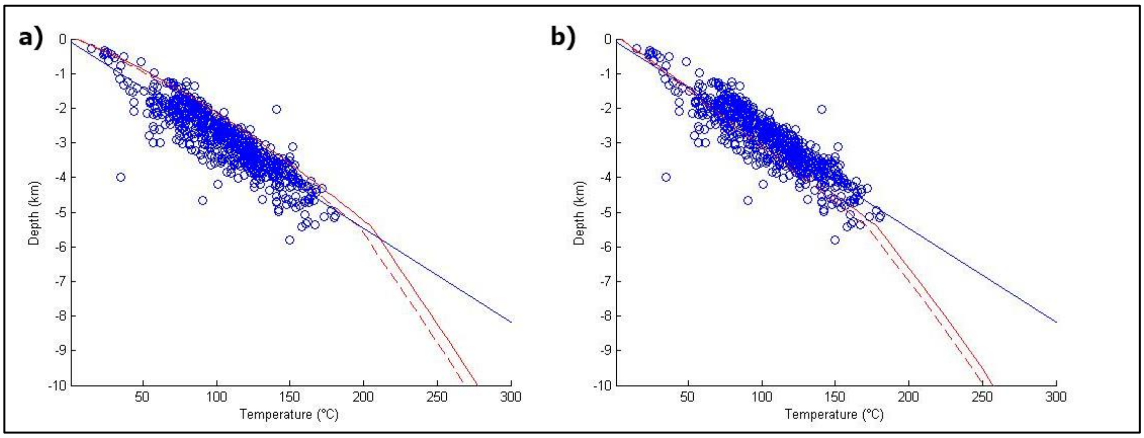

Figure 22. Fitting of modeled geotherm for average crustal and sediment thickness with temperature well data (blue) in the North Sea area. Solid line – RHP = 1 x 10^{-6} W/m^3, dashed line – RHP = 0 a) Temperature-dependent thermal conductivity b) Constant conductivity

4.5. Thermal conductivity and thermal-gradient

In this study, we investigate two scenario of behavior thermal-conductivity. In the first scenario, we assume that conductivity constant for the whole layer: sediments, crust or mantle. Second Scenario mentioned that thermal-conductivity is temperature dependent parameter.

According to general case, with increase of temperature, thermal-conductivity should decrease (Sekiguchi, 1984).

Modeling of thermal-gradient behavior according to introduce governing equation and parameters in case of constant thermal-conductivity presented in figures 23-34. Input data for model include values of sediment and crust thicknesses received for each well from Ebbing (2010). In addition, In addition, each of thermal-conductivity setup modeled for two value of radiogenic heat production in sediments: in first case we assume radiogenic heat production on level 1 x 10^{-6} W/m^3, in second case we assume that radiogenic heat production have too small value and could be negligible. In the both cases radiogenic heat production for crust and mantle does not changes.

4.5.1. Barents Sea area

In figures 23-26 presented results for modeled thermal-gradient crustal and real thermal-gradient values for Barents Sea area.

Firstly, we investigate behavior of thermal-gradient in constant thermal-conductivity model.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3 (figure 23), we observe in modeled distribution of thermal-gradient small dependence from sediment thicknesses, due of supply of heat by sediments. Sedimentary layer are not the main provider of heat - crust have much larger flux of heat. However, sediment have much smaller thermal conductivity than crust and less heat transports from the greater depths through sediments that leads to increase of thermal-gradient, but in other hand additional effect occur from heat production of sediments. However, thermal gradient strongly depended from crustal thickness in this model setup. Range of modeled thermal gradient for thicknesses values varies from 34 up to 40 °C/km

Result of the model does not fit so much to real thermal gradient in direction of changes. Some wells presented even opposite pattern for the region - lower values for more thick crust. Range of thermal gradients only relatively close to modeled values - from 25 to 55 °C/km. However, in general range of values about 30-45 °C/km.

In case when radiogenic heat production is negligible (figures 24) we observe different picture. As in previous case, modeled thermal-gradient strongly dependent from crustal thickness. With increase of crust, we observe increase of heat production. However, different picture for sediments-dependence. With increase of sedimentary loadout, decrease in gradient observed. This refer to value of heat production in sediments. Due of negligible values, there is no additional source, the only source of heat production. As a result, with increase of sediment loadout, transport from crust the same - gradient become lower. Range of modeled thermal gradient for thicknesses values varies from 30 up to 40 °C/km, that a bit closer to real thermal-gradient distribution.

Now we should investigate behavior of temperature dependent thermal-conductivity.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3(figure 25), we observe close situation of thermal gradient distribution. Thermal-gradient mainly ruled by change of crustal thickness. However, sediment loadout behaves differently. As in case of constant thermal-conductivity, increase of thermal gradient observed due additional source of heat in sediments, but small decrease in gradient observed in sediments range 0-6 km.

Possible explanation of current distribution - because of variation in thermal conductivity, values become even smaller with decrease of depth due of porosity dependence. However, in case temperature-dependent thermal-conductivity, in case of significant crustal thickness (>20 km) and relatively small basins (<6 km) transport of heat prevailed over effect of radiogenic heat production in sediments. In addition, range of modeled temperature become much greater - 50-60 °C/km. This range much higher than real thermal-gradient distribution what create a significant mismatch (compare to from 25 to 55 °C/km).

In case when radiogenic heat production is negligible (figure 26), we observe the same behavior of modeled thermal-conductivities. There are a strong dependence of thermal-conductivity from crustal thickness and there are not heat production in sediments. Compare to previous case, absolute values smaller and range greater (45-60 C/km), but values too far from real thermal-gradients (compare to from 25 to 55 °C/km).

4.5.2. Norwegian Sea area

In figures 27-30 presented results for modeled thermal-gradient crustal and real thermal-gradient values for Norwegian Sea area.

Firstly, we investigate behavior of thermal-gradient in constant thermal-conductivity model.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3 (figure 27), we observe behavior of modeled thermal-gradient similar to Barents Sea area. There are represented dependence of thermal-gradient from crustal thicknesses and increase of gradient by additional sediments radiogenic heat production. Range of modeled thermal gradient for thicknesses values varies from 28 up to 37 °C/km

As in case of Barents Sea, results of the model does not fit so much to real thermal gradient in direction of changes. Compared to previous area, there are small increase of thermal-gradient with increase of crustal thickness when we compare one group of wells in range of 14-18 km crust and 7-10 km sediments, and a second group of wells in range of 20-24 km crust and 5-7 sediments . However, this is not clear because of some extremum values near these groups. Range of thermal gradients only relatively close to modeled values - from 23 to 58 °C/km. However, in general range of values about 30-49 °C/km. In a result, there are similarities in values in low limits; however, significantly hotter values represented in real values.

In case when radiogenic heat production is negligible (figures 28), we observe picture close to Barents Sea area. As in previous case, modeled thermal-gradient strongly dependent from crustal thickness. With increase of crust, we observe increase of heat production. With increase of sedimentary loadout, decrease much faster than in previous case because there is not additional source of heat from sediments. Range of modeled thermal gradient for thicknesses values varies from 25 to 35 °C/km. This range are colder than should be for the most wells (30-49 °C/km in general).

Now we should investigate behavior of temperature dependent thermal-conductivity.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3(figure 29). Thermal-gradient mainly ruled by change of crustal thickness as in case of Barents Sea with the same deviation of sediment loadout behavior. Peak in thermal-gradient observed not so well: from almost flat contour in range 12-20 km crust and 0-8 km sediments to small increase in gradient 22-24 km crust and 8-12 km sediments. Range of modeled temperature become much greater as in previous area - 44-56 °C/km; however, this value more reliable for top limits of real gradients (compare to 30 to 49 °C/km).

In case when radiogenic heat production is negligible (figure 30), we observe the same behavior of modeled thermal-conductivities as for constant case. There are a strong dependence of thermal-conductivity from crustal thickness and there are not additional radiogenic heat from sedimentary loadout. Range of values 42-56 °C/km, this value more reliable for top limits of real gradients, as in previous case, with radiogenic heat production equal 1 x 10^{-6} W/m^3 (compare to real gradients 30 to 49 °C/km).

4.5.3. North Sea area

In figures 31-34 presented results for modeled thermal-gradient crustal and real thermal-gradient values for North Sea area.

Firstly, we investigate behavior of thermal-gradient in constant thermal-conductivity model.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3 (figure 31), general behavior of modeled thermal-gradient similar to previous areas. Dependence of gradient from change of crustal thickness significant. Range of modeled thermal gradient for thicknesses values varies between 32 up to 39 °C/km

Results of the model does not fit so much to real thermal gradient in direction of changes. There are l increase of thermal-gradient observed with increase of crustal thickness when we consider one group of wells in range of 24-26 km crust and 1,5-2,5 km sediments, and a second group of wells in range of 18-22 km crust and 4-5 km sediments. However, this is not clear, as in previous areas because of some extremum values near these groups. For example, local increase of gradient observe in range of 17-22 km crust and 5-7 km sediments. Total range of thermal gradients only relatively far from modeled values - from 9 to 75 °C/km. However, in general range of values about 25-55 °C/km. In a result, there are similarities in values in medium of range of real gradients.

In case when radiogenic heat production is negligible (figures 32), modeled thermal-gradient strongly dependent from crustal thickness. As in previous areas, increase of sedimentary loadout does not produce any additional radiogenic heat. Range of modeled thermal gradient for thicknesses values have lower low limit and varies from 25 to 39 °C/km. This range are colder than represented in real gradient data (25-55 °C/km in general). However, there are match of lower range limits.

Now we should investigate behavior of temperature dependent thermal-conductivity.

In case of value of radiogenic heat production equal 1 x 10^{-6} W/m^3(figure 33). Thermal-gradient mainly ruled by change of crustal thickness as in previous cases with the same deviation of sediment loadout behavior. Peak in thermal-gradient observed: peak in range 18-24 km crust and 4-9 km sediments and almost the flat contour in range 12-16 km crust and 0-9 km sediments. Range of modeled temperature become much greater compare to constant conductivity setup - about 49-61 °C/km. This fit not so well, and match only top of real gradient range.

In case when radiogenic heat production is negligible (figure 34), we observe a strong dependence of thermal-conductivity from crustal thickness and there are not supply of heat from sedimentary loadout. Range of values 42-61 °C/km, this value more reliable for top limits of real gradients, as in previous case, with radiogenic heat production equal 1 x 10^{-6} W/m^3 (compare to real gradients 25 to 55 °C/km).

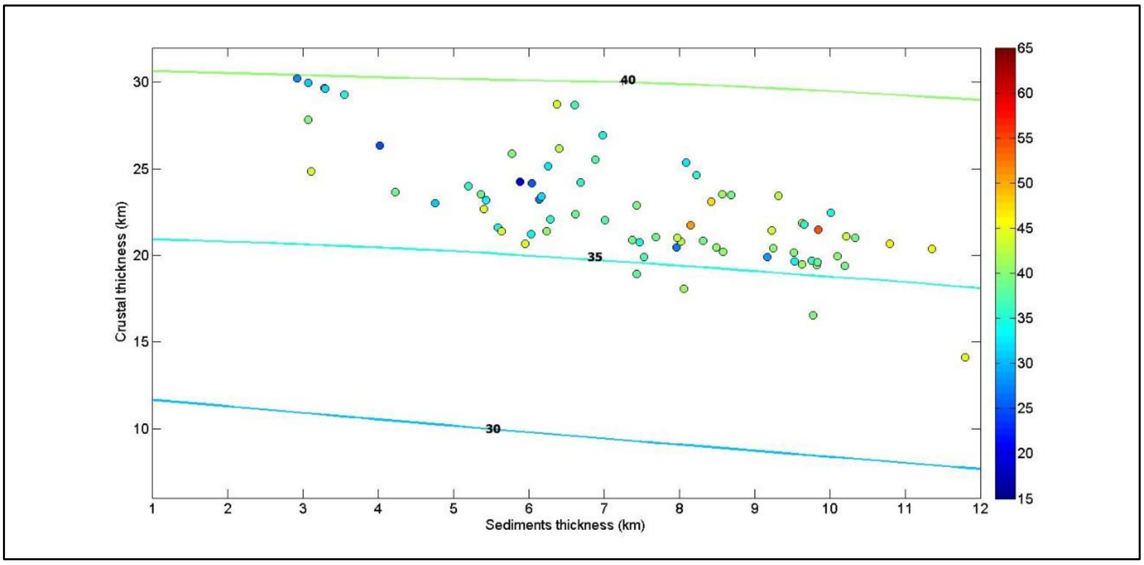

Figure 23. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Barents Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = constant

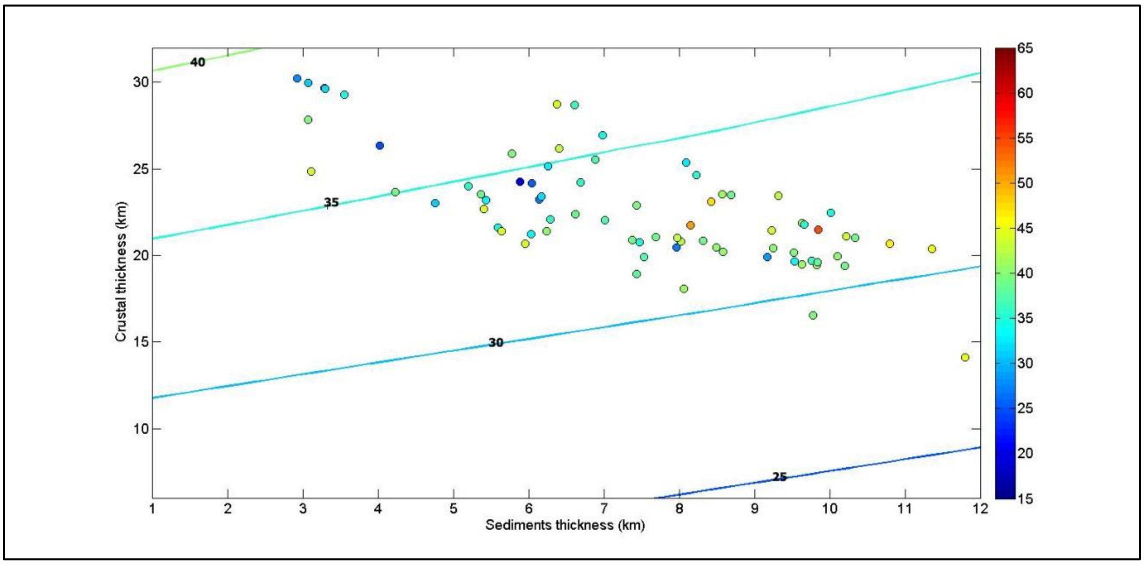

Figure 24. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Barents Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = constant

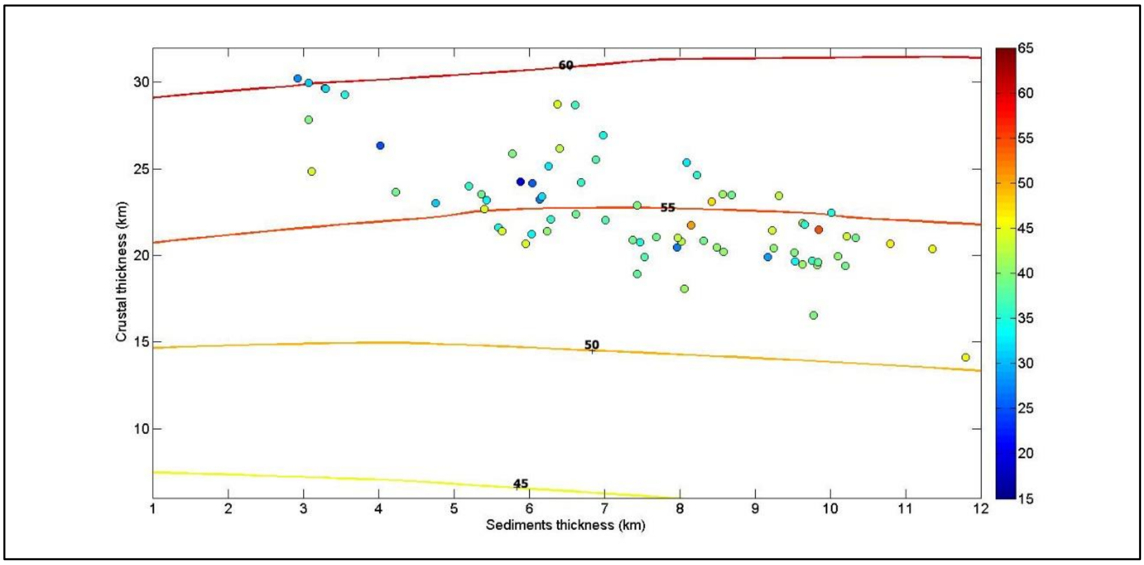

Figure 25. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Barents Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = t- dependent

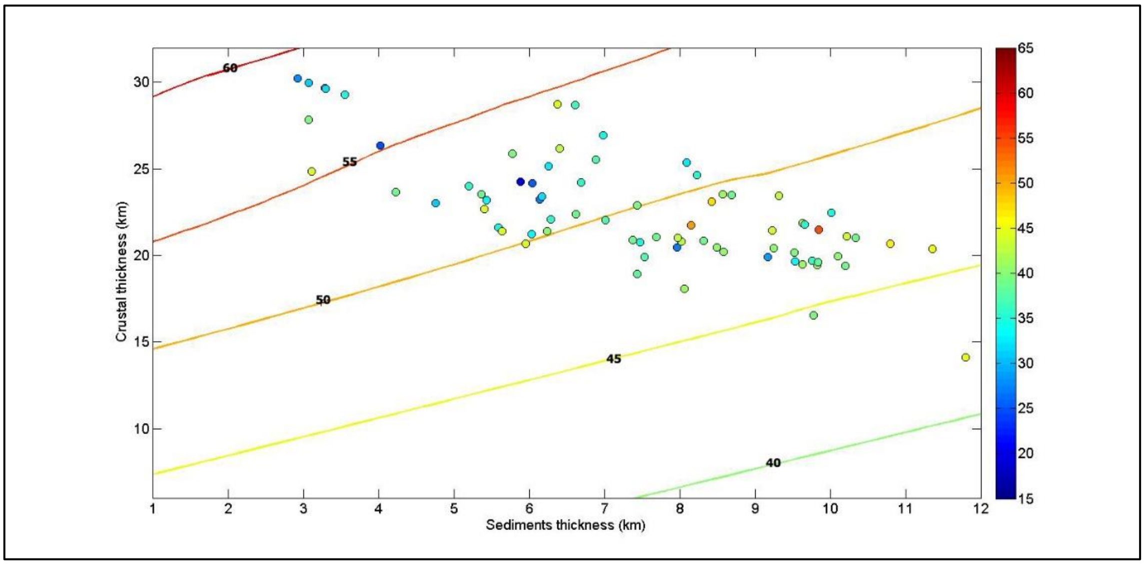

Figure 26. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Barents Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = t- dependent

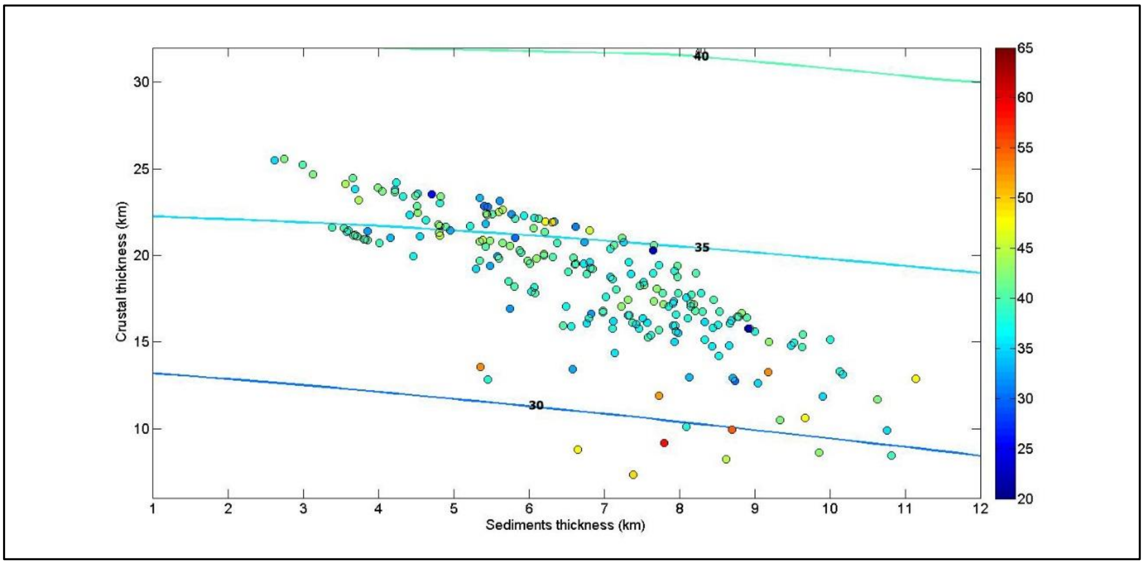

Figure 27. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Norwegian Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = constant

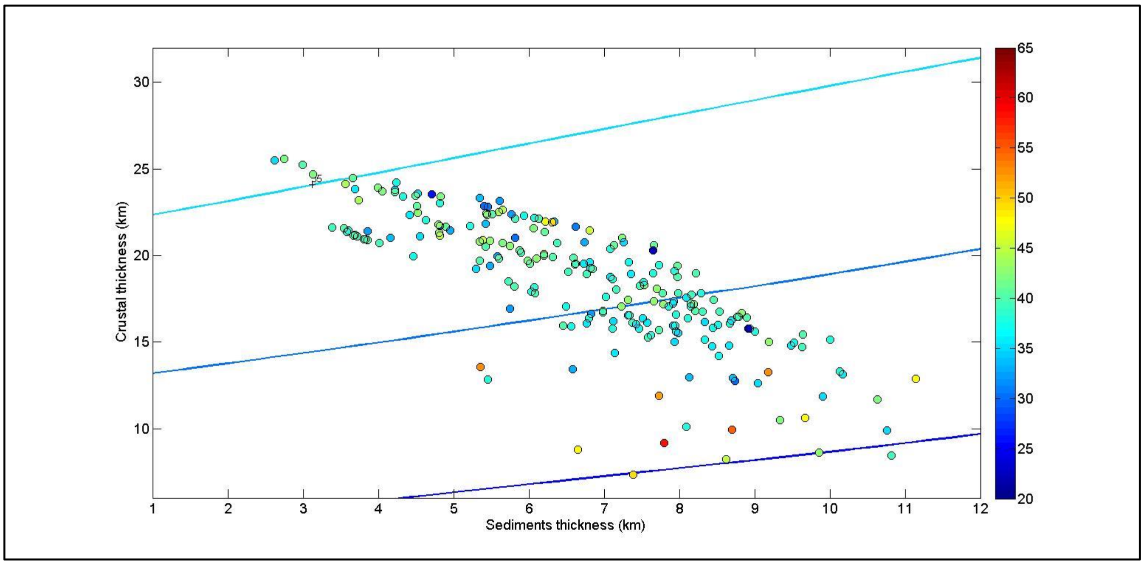

Figure 28. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Norwegian Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = constant

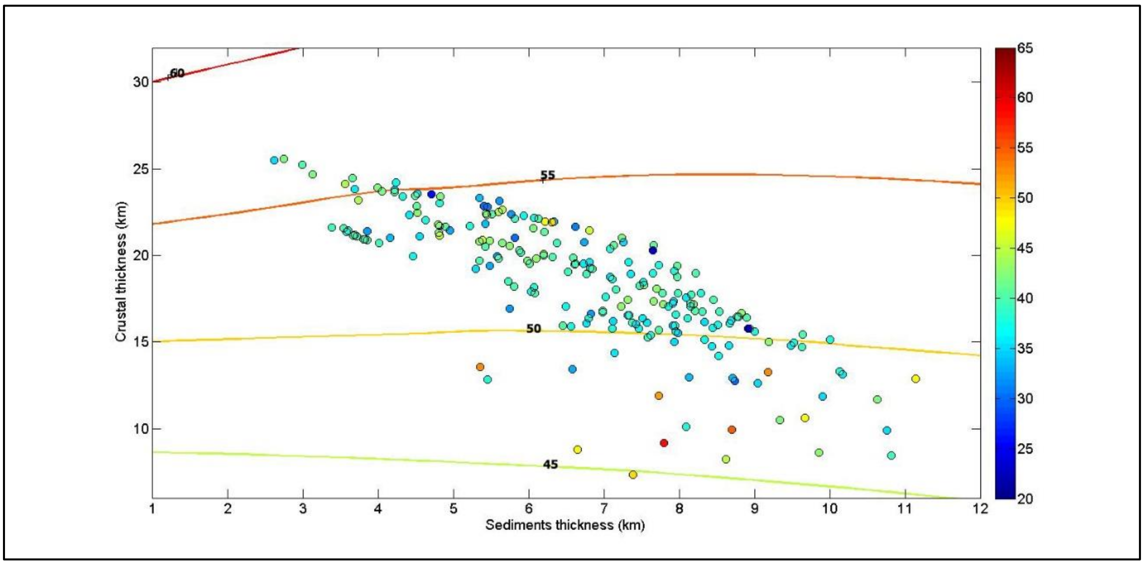

Figure 29. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Norwegian Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = t- dependent

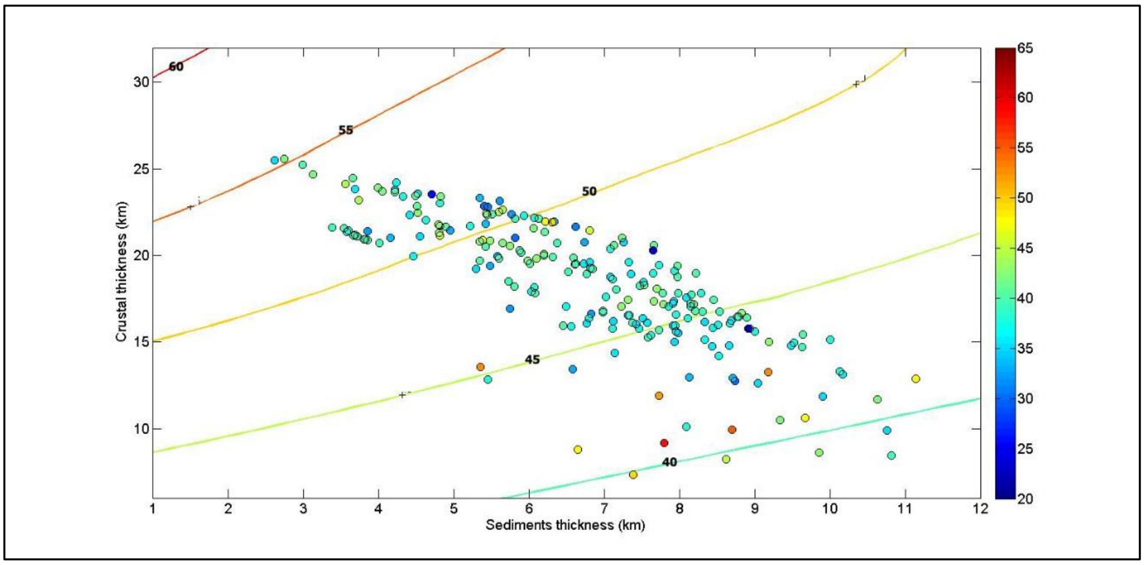

Figure 30. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for Norwegian Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = t-dependent

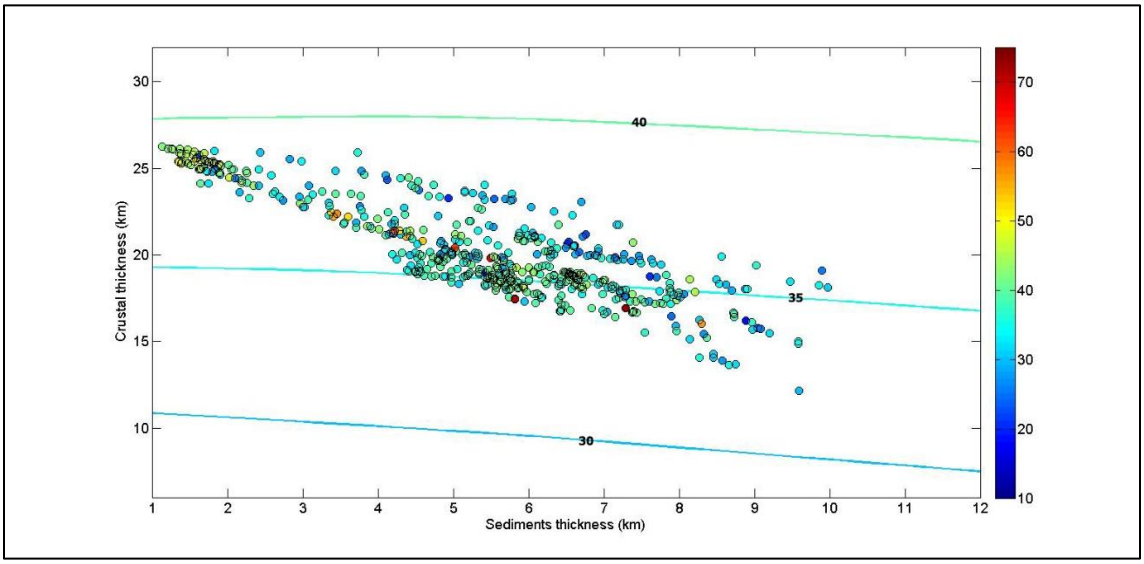

Figure 31. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for North Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = constant

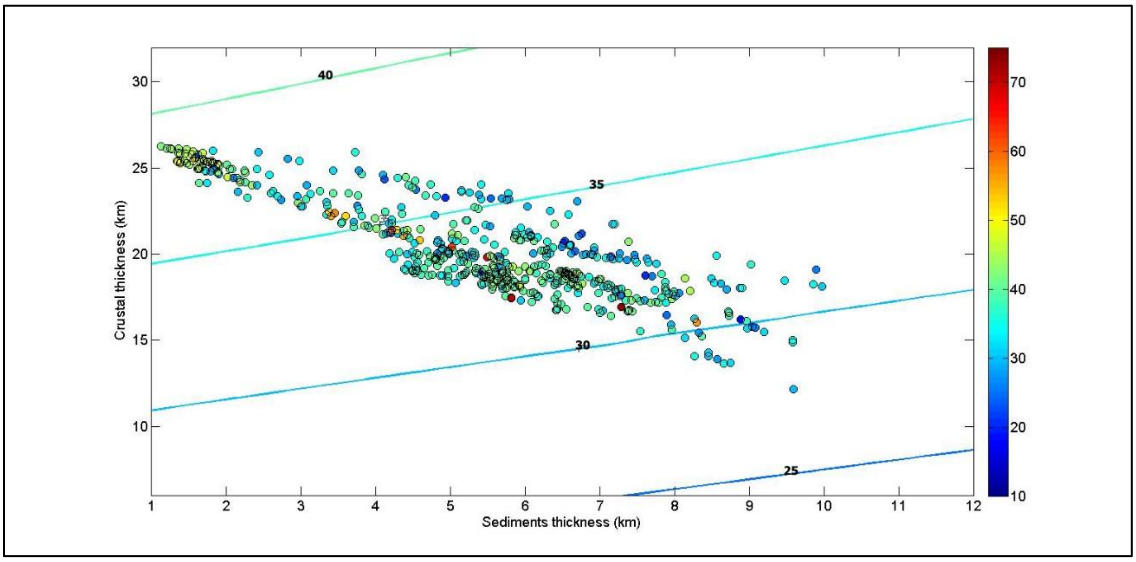

Figure 32. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for North Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = constant

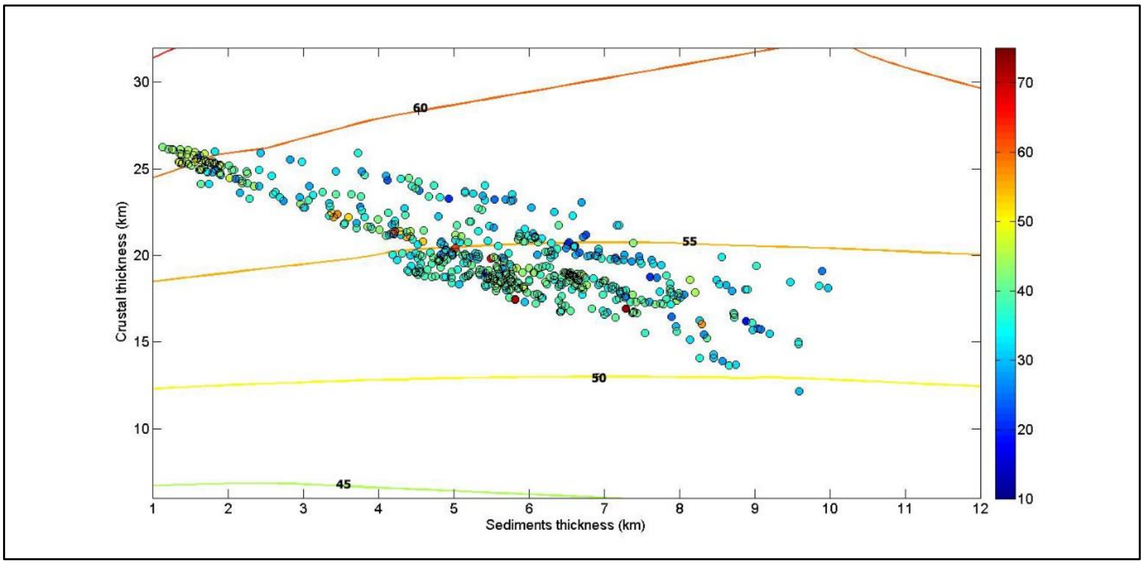

Figure 33. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for North Sea area. Radiogenic heat production in sediments = 1 x 10^{-6} W/m^3, thermal-conductivity = t-dependent

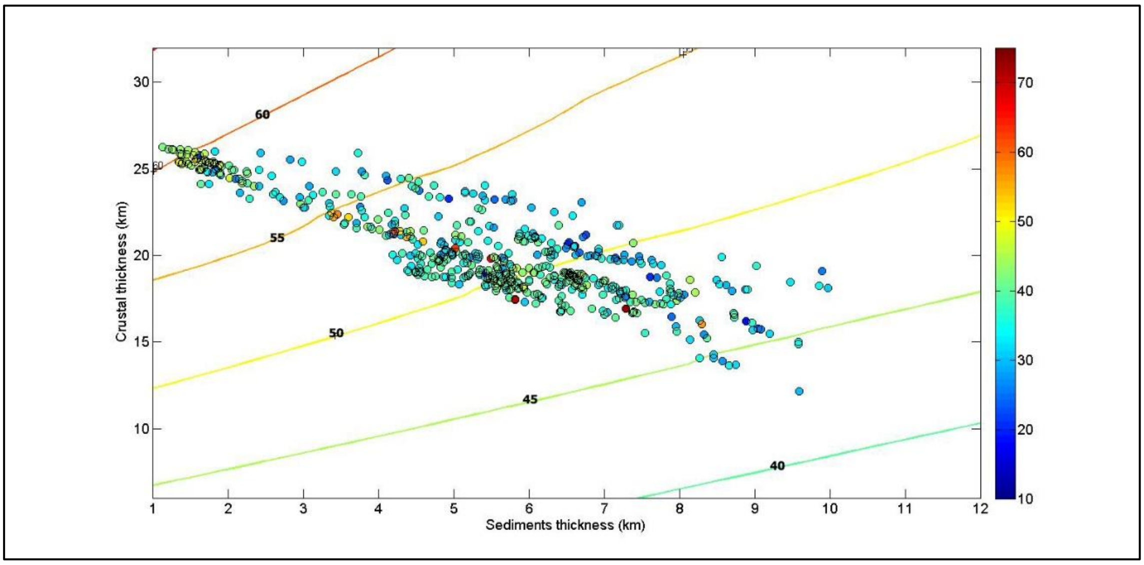

Figure 34. Modeled thermal-gradient dependence from crustal and sediment thicknesses (contour lines, step – 5°C) and real thermal-gradient values (points) for North Sea area. Radiogenic heat production in sediments = 0 W/m^3, thermal-conductivity = t- dependent

5. Discussion

The modeling results reveal clear dependences between sediment and crustal thicknesses and predicted geothermal gradient. In particular, the crustal thickness has a strong control on the geothermal gradient. The thicker the crust, the higher is the predicted geothermal gradient. Observed crustal thickness variations along the Norwegian margin can induce changes of up to 20% in the geothermal gradient. The main reason being that thicker crust produces more radiogenic heat. Sediment thickness can affect the geothermal gradient in two ways: 1) the thermal conductivity contrast between crust and mantle results implies that the predicted geotherm depends on sediment thickness (Fig. 4) and 2) if radiogenic heating is assumed, a thicker sediment cover results in a higher geothermal gradient. The models show that these two mechanisms are counteracting each other and there is little dependence of the geothermal gradient on sediment thickness if radiogenic heating is assumed in the sediment. These interrelations can be identified in all three areas of investigation.

With regard to the different thermal conductivity models it is found that all constant conductivity simulations result in in a colder temperature structure. Temperature-dependent conductivity provide values up to 20-30 degrees higher, that in constant model. In case of comparing modeled values with real gradients, they represented only in top range of real data. Thus, modeled values too hot.

Constant conductivity provided values in range of real thermal-gradients. However, range of modeled data relatively small and represent in general much colder values in bottom range.

Results become more complicated due of not so clear dependence of real data from crustal and sediment thicknesses. There are small trends in case of Norwegian and North Sea area, but observed trend for Barents Sea have attribute of opposite trend.

It could be related with an insufficient of wells, because Barents Sea represented by the smallest amount of wells. In case of Norwegian Sea and North Sea areas small trend observed. On the other hand, it could be related with local geological settings.

Different setups of radiogenic heat production in sediment provide two scenario of thermal gradient behavior. First scenario with RHP = 1 x 10^{-6} W/m^3, present effect of increasing of thermal gradient due additional heat source from sediments loadout increase. That means that even increase of sediment layer leads to the same supply from crust, but heat supply from sediments increase. In case of negligible heat production, there is not source of additional heat. That leads to relatively high rate of thermal-gradient decrease with increase of sediment loadout. This effect varies for different thermal-conductivity model.

The most interesting feature - that in case of temperature-dependent conductivity and RHP = 1 x 10^{-6} W/m^3, there are a range of crustal and sedimentary thicknesses when thermal gradient decreased. According to the results, this effect occurred in environment of thick crust (>20 km) and relatively small sedimentary layer (0-10 km).

A key question, why modeled thermal gradient in temperature-dependent case have much greater values. There are several possible explanation. First, it could be explained by the input rock properties. In the real data, basins have complicated nature, presented as a combination of layers with different rock properties. In this study was assumed, that the basins filled by shale in model - with the corresponding properties. Shales have relatively low thermal conductivity in range from 0.80 - 1.90 W/m/K (Hantschel, 2009). Some material such as sandstone, siltstone, limestone and others have much higher thermal conductivity. With change of rock properties input, for example in case of limestones, thermal conductivity will increase (Hantschel, 2009). As a result better transport of heat in sediments and lower thermal gradient.

Comparing results of temperature-dependent and constant thermal conductivity, first setup represented more realistic range of values, which could be corrected to input rock properties. Constant thermal conductivity present relatively small range of values. Corresponding to range of values, it is important for petroleum generation. For example, its crucial for oil-generation window.

Considering two scenario of radiogenic heat production in sediments there is not clear fitting with real data, but case with RHP = zero could be considered as a more realistic. First, in this study as a main lithology were used parameters for shales. Increased production of radiogenic heat production one of the feature of shale compare to other type of sediments (sandstones for example). In addition, considering radiogenic heat production fitting (presented in chapter 4.4.), case of zero RHS presents more realistic fit with real data in temperature dependent thermal conductivity setup. In case of constant thermal-conductivity RHS = 1 x 10^{-6} W/m^3 presents more valuable results, however, geotherm lower than should be observed (except North Sea area example).

6. Conclusion

In this study, we investigated the importance of dependence of thermal conductivity for basins thermal-state. To study this subject, 1-D lithosphere-scale model of thermal gradient distribution created using two setups of thermal conductivity According to governing equations reconstructed behavior of thermal gradient for different environment: sediments, crust, mantle.

We find differences between temperature-state for two-model setup. Temperature dependent setup presents 'hotter' values that expected. However, temperature-dependent conductivity present more realistic values range. Possibly, it could be resolved by calibration of main lithology. Constant conductivity results have lower fitting to real data in general, that means underestimation of temperatures values in this cases.

That means that temperature-dependence of thermal-conductivity is important for understanding of basins thermal-state and should be considerable during temperature analysis of basins.

Another important finding is that predicted geothermal gradients differ significantly as a function of crustal and sediment thickness. This should be kept in mind when using well data for the thermal calibration of basin models. The common practice in basin and petroleum system modeling of using an average geothermal gradient constrained by well-data from different structural settings can introduce errors as geothermal gradients are likely to differ significantly between deep basin underlain by thin crust and crustal highs. The presented results can help to make more realistic assumptions about how geothermal gradients are likely to change in a basin as a function of crustal and sediment thicknesses.

7. Acknowledgment

I would like to thank my supervisors, Dr.German Leitchenkov and Prof.Dr.Lars Rüpke for guidance during this study.

I thank Helmholtz Centre for Ocean Research Kiel for funding and providing me opportunity to have useful practice in this research center.

I thank The Geological Survey of Norway for providing of geological data about investigated area.

I would like to thank POMOR master program for incredible study experience during this two years. I am thankful for opportunity to study abroad, to get experience in international scientific communications.

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9. Appendix

Initial temperature wells data and the main MATLAB script presented in electronic appendix on CD.

All files located in data folder "Appendix". List of presented files:

- Points_all_bht.xlsx – wells location with values of bottom hole temperatures
- Model_script.docx – MATLAB script for the model

Statement on the thesis' originality

Herewith I, Anton Tkachenko, declare that I wrote the thesis independently and did not use any other resources than those named in the bibliography, and, in particular, did not use any internet resources except for those named in the bibliography. The master thesis has not been used previously as part of an examination. The master thesis has not been previously published.