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Regional Temperature Distribution beneath the Northern North Sea and Adjacent Norwegian Mainland Based on Lithosphere-Scale 3D Thermal Modelling

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ABSTRACT

In order to understand the regional thermal regime beneath the northern North Sea and adjacent areas of the continent, 3D thermal modelling has been applied in the framework of the Crustal Onshore-Offshore Project (COOP project). The lithosphere-scale 3D model has been used as a realistic approximation of the geometries of the sedimentary infill as well as of the underlying crystalline crust and lithospheric mantle during the 3D thermal modelling. Construction of the 3D model has been done by use of recently published/released structural data. For the upper part of the model, all available data were merged into the following layers: sea water, the Cenozoic, Upper Cretaceous, Lower Cretaceous, Jurassic, Triassic, Upper Permian (Zechstein) salt, Upper Permian clastics/carbonates and, finally, the Lower Permian-pre-Permian sedimentary rocks. The lithosphere-asthenosphere boundary has been determined from previously published data. Configuration of the crystalline crust and the Moho topography have been derived from the published interpretations of deep seismic lines and validated by a 3D density modelling. The 3D density modelling has been carried out by use of the software IGMAS+ (the Interactive Gravity and Magnetic Application System). According to the 3D density modelling, the crystalline crust of the study area consists of several layers. The obtained Moho is strongly uplifted beneath the Central and Viking grabens whereas the lithosphere-asthenosphere boundary is relatively shallow beneath the western part of the model area.

The 3D thermal modelling has been performed by use of the commercial software package COMSOL Multiphysics. For the upper boundary, the time-dependent temperature at the Earth's surface and sea bottom has been applied. This has been done by taking into account palaeoclimatic changes during the last 200,000 years. The lithosphere-asthenosphere boundary has been chosen as a lower thermal boundary which corresponds to the 1300 °C isotherm. Results of thermal modelling within the upper part of the 3D model indicate that the mainland is generally colder than the basin areas. This regional trend of temperature is mostly related to the low thermal conductivity of sediments which increases heat storage within the areas covered by a thick sedimentary cover. Thick low-conductive sediments reduce the rate of heat transfer, acting as a thermal insulation. This thermal effect is especially pronounced within the Central and Viking grabens, and the East Shetland and Norwegian-Danish basins where the sedimentary cover is thickest. Furthermore, the effect of increased radiogenic heat production within the upper crust is prominent beneath the Horda Platform, where the highest geothermal gradient is modelled within the upper part of the 3D model. At great depths (70-100 km), the temperature distribution roughly reflects the configuration of the lower thermal boundary which is represented by the base of the lithosphere.

1. INTRODUCTION

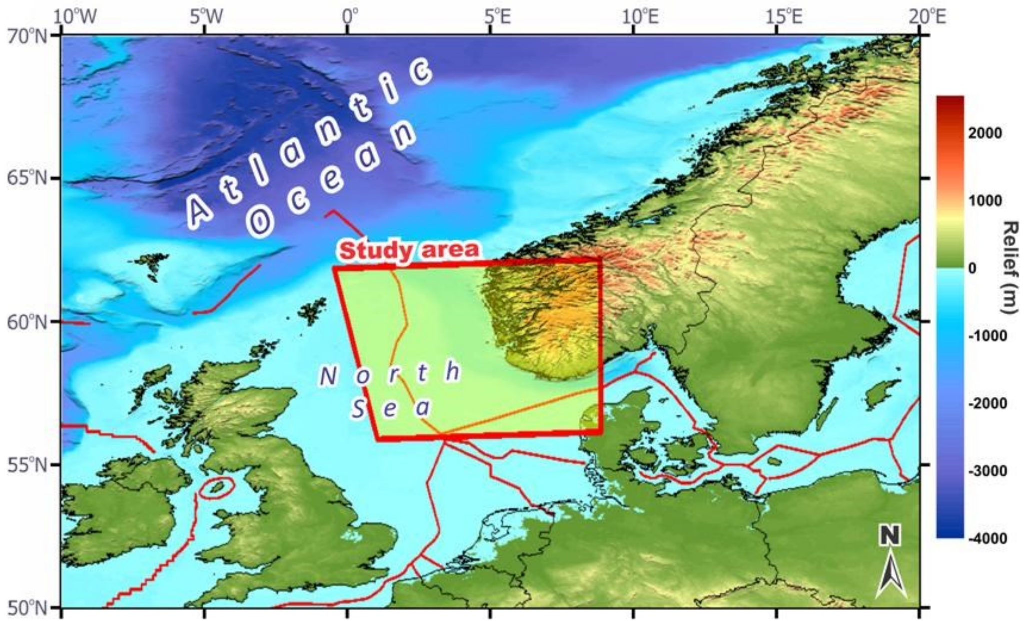

Figure 1: Overview map of northwestern Europe (bathymetry and topography from IOC, IHO, BODC 2003).

In order to analyse the regional structural features of the crystalline crust within the northern North Sea and adjacent areas of the continent, a lithosphere-scale 3D structural model has been constructed, covering the area of interest in the framework of the Crustal Onshore-Offshore Project (COOP project) (see red frame in Fig. 1). The study area covered by the 3D model is characterized by a smoothed bathymetry within most parts of the North Sea. Exceptions are observed only along the southern coast of Norway and within some fjords where depths to the sea floor reach 700-1300 m. Changes in topography are pronounced on the mainland. There, the relief is locally more than 2,000 m above mean sea level.

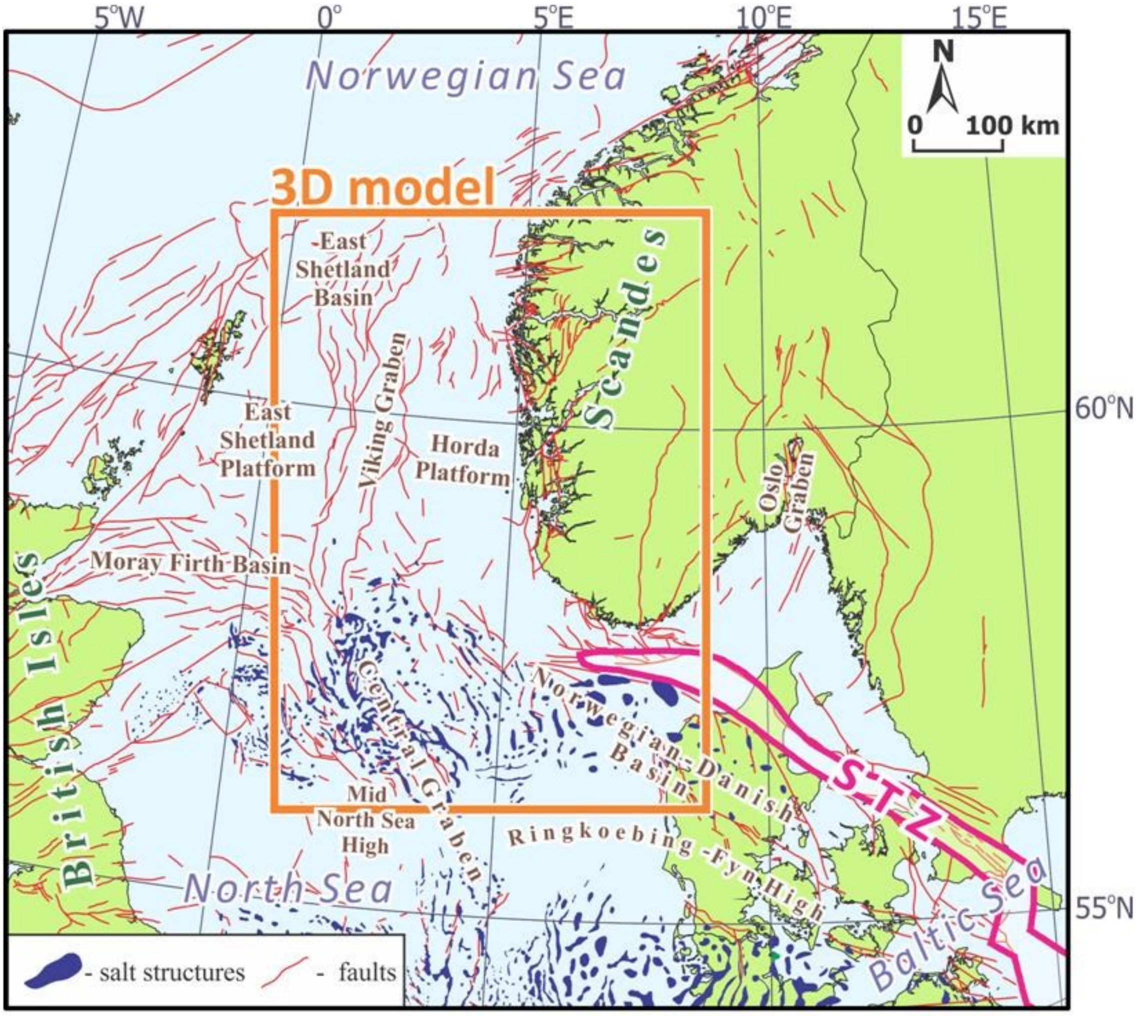

Figure 2: Tectonic settings within the study area with location of the 3D structural model of the northern North Sea and adjacent areas of the continent (after Ziegler 1990, Vejbæk and Britze 1994, Lokhorst 1998, Pharaoh 1999, Baldschuhn et al. 2001, Sigmond 2002, Maystrenko et al. 2012). STZ - Sorgenfrei-Tornquist Zone.

The 3D structural model covers the main tectonic units of the northern North Sea and the adjacent areas. Offshore, this includes major sedimentary depocentres within the Central and Viking grabens, and the East Shetland and Norwegian-Danish basins, as well as the East Shetland and Horda platforms (Fig. 2). In addition, the model partially covers northern parts of the uplifted Mid North Sea and Ringkoebing-Fyn highs. Onshore, the sediments are relatively thin or mostly absent and, therefore, the crystalline rocks crop out at the surface within a large part of the Fennoscandia.

During construction of the 3D model, all available structural data have been integrated into an initial 3D model with help of 3D density modelling to obtain a lithosphere-scale 3D model of the area under consideration. This gravity-consistent 3D model was used as a structural base to evaluate the 3D conductive thermal field within the sedimentary infill, the underlying crystalline crust and the uppermost mantle. Knowledge about the temperature distribution within the upper crystalline crust is an important issue in the geosciences. The changes in temperature control the major properties of crystalline rocks, sediments and fluids as a result of increasing temperature with depth.

Therefore, the main goal of this study was to understand the regional-scale structural and thermal patterns of the crystalline crust within the northern North Sea and Norwegian mainland. Knowledge about the structural features and temperature distribution within the crystalline crust is an important factor in the exploration for conventional sources of energy (hydrocarbons) in the sedimentary basins and in evaluations of the non-conventional, deep-geothermal potential within the Norwegian mainland.

2. DATASETS

Construction of the 3D model has been done by use of recently published/released structural data. For the sedimentary cover, the largest dataset was the North Sea Digital Atlas (PGS Reservoir, 2003) which covers the entire North Sea. Additionally, several thickness and structural depth maps from the Geological Survey of Denmark (e.g. Britze and Japsen, 1991; Vejbaek and Britze, 1994) have been used for the southeastern part of the 3D model area within the Norwegian-Danish Basin. Within the northern part, the thickness of Triassic deposits has partially been taken from the Geological Atlas of western and central Europe (Ziegler, 1990). The bathymetry has been derived from the General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas (IOC, IHO, BODC, 2003). These datasets were gridded and compiled in terms of thickness maps for the following intervals: sea water, the Cenozoic, Upper Cretaceous, Lower Cretaceous, Jurassic, Triassic, Permian salt and, finally, Zechstein clastics and carbonates. Furthermore, well data (NPD, 2011) and three datasets of the depth to the top of crystalline basement (Ebbing and Olesen, 2010; Maystrenko and Scheck-Wenderoth, 2013; Lassen et al., 2012) have been used to assess the configuration of Lower Permian and pre-Permian sediments. Thicknesses of Lower Permian and pre-Permian sediments have been calculated as the difference between the base of Upper Permian-Meso-Cenozoic sediments and the top of the crystalline basement. The described sedimentary layers provide an excellent base for the evaluation of a deep structure of the crystalline crust within the study area.

The Moho topography for the 3D gravity modelling has been obtained based on the most recent compilations by Stratford et al. (2009), Ebbing and Olesen (2010) and Maystrenko and Scheck-Wenderoth (2013). Besides, Moho topography and configuration of the crystalline crust have been constrained by the published interpretations of deep seismic lines located within the study area. The lithosphere-asthenosphere boundary has been derived from previously published data, such as the seismically derived base of the lithosphere by Calcagnile et al. (1997) and Geissler et al. (2010) as well as depth to the base of the lithosphere based on an integrated study by Artemieva et al. (2006).

3. METHOD

3.1 3D density modelling

The 3D density modelling has been performed by use of the IGMAS plus software (the Interactive Gravity and Magnetic Application System; Götze 1978, Götze and Lahmeyer 1988, Schmidt and Götze 1998, Götze and Schmidt 2010). Prior to the modelling, a triangulation between the input structural depth maps is applied along predefined 2D vertical slices to obtain the geometry of the model in 3D. The geometrical approximation for the layers of the 3D structural model is determined by multiple polyhedra with triangulated planes between the top and the base of each layer, and constant densities are assigned to these polyhedra. Finally, the integral gravity effect of all triangulated polyhedra gives the total gravity effect of the 3D model. The procedure of 3D gravity modelling is based on interactive changes of the geometry and density of the layers. In particular, the 3D gravity modelling was carried out by interactive changes of the geometry and densities along 169 E-W-oriented vertical slices through the 3D structural model of the northern North Sea System and adjacent areas. The distance between these 2D working planes is the same as the horizontal resolution of the model, which is 4 km. The 2D working slices are parallel to each other and cross the most important gravity anomalies and the major structural elements of the study area to avoid potential artifacts due to 3D triangulation between the slices. Additionally, the 3D model has been laterally extended in all directions, exceeding the actual model area. Thereby, the major structural features have been prolonged to the extended parts of the 3D structural model to avoid boundary effects.

3.2 3D thermal modelling

The 3D temperature distribution at the subsurface of the structurally complex study area has been modelled by use of the commercial software package COMSOL Multiphysics. COMSOL Multiphysics is a finite-element analysis software package for a variety of physical processes. During the 3D thermal modelling, the Heat Transfer Module was used to simulate the stationary and time-dependent heat transfer in solids by heat conduction, which is assumed to be the dominant mechanism of heat transfer at the regional scale within the study area. Therefore, these simulations have been carried out based on physical principles of the conductive 3D thermal field by solving the heat equation (1):

$$\rho C\ (\delta T/\delta t) = \nabla\cdot\ (k\ \nabla T) + Q \tag{1}$$

where ρ, C, T, k, ∇T, t, Q, $\delta T/\delta t$, $\nabla\cdot$ are density, heat capacity, temperature, thermal conductivity, temperature gradient, time, heat source (radioactive heat production), change in temperature per time interval and operator giving the spatial variation in temperature, respectively.

Accordingly, the solution of the heat equation (1) is sensitive to the values of the thermal properties (C, k and Q) as well as to the thermal boundary conditions.

The heat flux has been calculated according to Fourier's law of heat conduction (2):

$$q = - k\nabla T \tag{2}$$

where k, ∇T are thermal conductivity and temperature gradient, respectively.

The 3D thermal modelling has been performed by means of a finite-element method in 3D which is a suitable approach for a relatively complex geometry like the northern North Sea and adjacent areas. The lateral boundaries are closed to heat transfer, assuming that the temperature gradient is zero across the thermally insulated lateral boundaries. The time-dependent temperatures at the sea floor and the Earth´s surface have been taken as the upper thermal boundary condition whereas the lithosphere-asthenosphere boundary has been chosen as a lower thermal boundary which corresponds to the 1300 °C isotherm (e.g. Turcotte and Schubert 2002).

The 3D thermal modelling has been carried out considering the palaeoclimatic changes of the surface temperature during the last 220,000 years before present (BP). During this time interval, the study area was affected by glaciations during the Saalian glacial/Eemian interglacial period (220,000-110,000 years BP) and the Weichselian glacial period (~110,000–10,000 years BP), as well as by the Holocene interglacial period (10,000 years BP to present day).

4. RESULTS

4.1 3D density modelling

The results of the 3D gravity modelling demonstrate that the obtained gravity response of the final 3D structural/density model is in good agreement with the regional component of the observed gravity field over the area under consideration (Fig. 3).

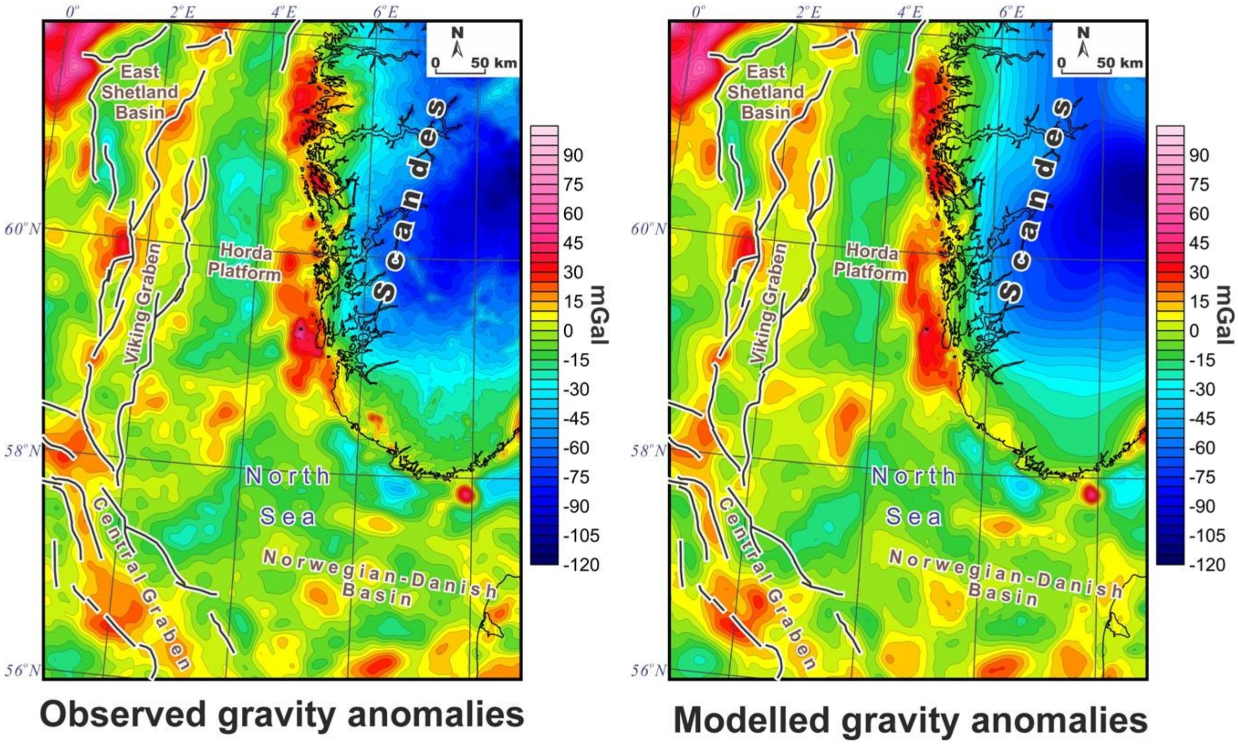

Figure 3: Observed gravity anomalies over the study area (Olesen et al. 2010, Andersen et al. 2010) and modelled gravity anomalies.

During the 3D gravity modelling, the crystalline crust of the study area has been subdivided into several layers. Within the uppermost crystalline crust, gabbro to anorthositic rocks have been included in the 3D model. These rocks are well mapped at the surface along the west coast of Norway. In addition, a low-density upper crustal layer was modelled beneath the Horda Platform. This layer is characterised by a relatively low density (2627 kg/m^3) which can correspond to metasediments or granite. The largest upper crustal layer is characterised by a regional distribution and has a density of 2670 kg/m^3. The modelled middle crust of the study area contains four layers with similar densities of around 2700 kg/m^3. The largest middle crustal layer is the middle crust of Baltica. The modelled lower crust consists of three layers. The upper layer is the lower crust of Baltica which is strongly thinning towards the west where the Caledonian crustal domains of Laurentia and Avalonia are located. The deep one is the high-density lower crustal layer (3060 kg/m^3) which corresponds to the high-velocity layer where observed P-wave velocities exceed 6.7-6.8 km/s. This layer thickens markedly beneath the Norwegian-Danish Basin and the eastern part of the East-Shetland platform. In addition to high-density lower crust, the high-density zone (2930 kg/m^3) within the continental crystalline crust has been modelled to fit the observed and calculated gravity. The prominent feature of this layer is the NE-SW-striking zone of thickening beneath the Viking Graben.

The obtained Moho topography and depth to the base of the lithosphere correlate clearly with the major tectonic units of the study area. Both boundaries are deeply located beneath the continent. Furthermore, the Moho is strongly uplifted beneath the Central and Viking grabens, whereas the lithosphere-asthenosphere boundary is relatively shallow beneath the western part of the model area.

Based on the results of the 3D density modelling, the input structural data have been refined in terms of the lithosphere-scale 3D structural/density model. The output 3D model (Fig. 4) includes twenty-one layers: (1) sea water; (2) Tertiary; (3) Upper Cretaceous; (4) Lower Cretaceous; (5) Jurassic; (6) Triassic; (7) Zechstein salt; (8) Zechstein clastics, carbonates and anhydrites; (9) pre-Permian sediments; (10) intrusions; (11) upper crustal magmatic rocks; (12) low-density upper crustal layer; (13) upper crustal regional layer; (14) middle crust of Baltica; (15) eastern central North Sea rocks; (16) western central North Sea rocks; (17) middle crust of Laurentia and Avalonia; (18) lower crust of Baltica; (19) high-density crust; (20) high-density lower crustal layer; (21) lithospheric upper mantle.

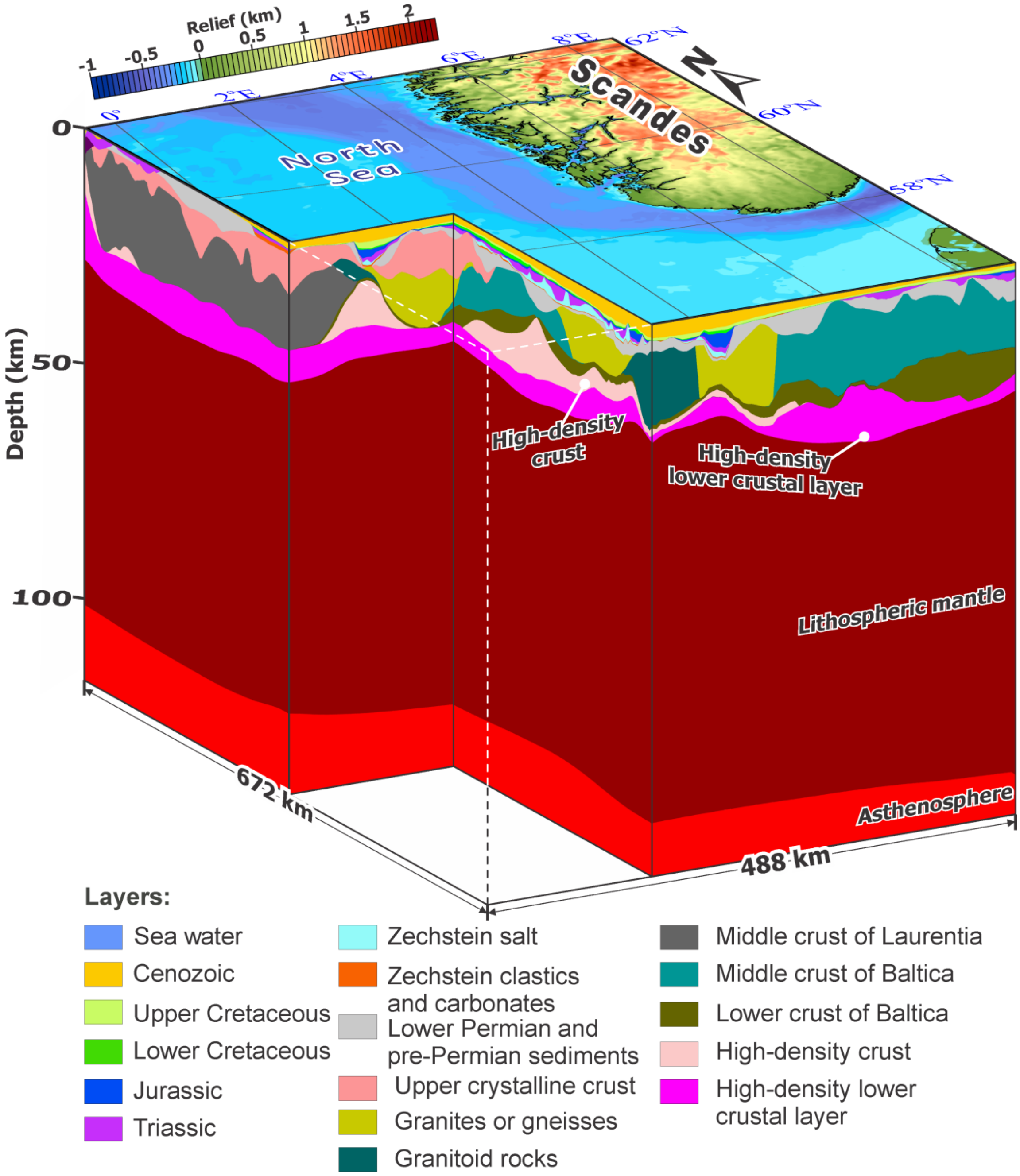

Figure 4: Lithosphere-scale 3D model of the northern North Sea and adjacent areas of the continent (four times vertically exaggerated).

The final 3D structural model is 672 km long and 488 km wide (Fig. 4), having a horizontal grid spacing of 4 km. Model coordinates are based on the Universal Transverse Mercator (UTM) coordinate system zone 32 (Northern Hemisphere), using the World Geodetic System (WGS) 84 datum. This data-constrained, 3D structural/density model has finally been used for the 3D thermal modelling.

4.2 3D thermal modelling

The 3D thermal modelling has been performed to estimate the present-day thermal state of the northern North Sea and adjacent areas of the continent.

Results of 3D thermal modelling within the upper part of the 3D model indicate that the mainland is generally colder than the basin areas (Fig. 5). This regional trend of temperature is related to the low thermal conductivity of sediments which increases heat storage within the areas covered by thick sediments. In other words, thick low-conductive sediments reduce the rate of heat transfer,

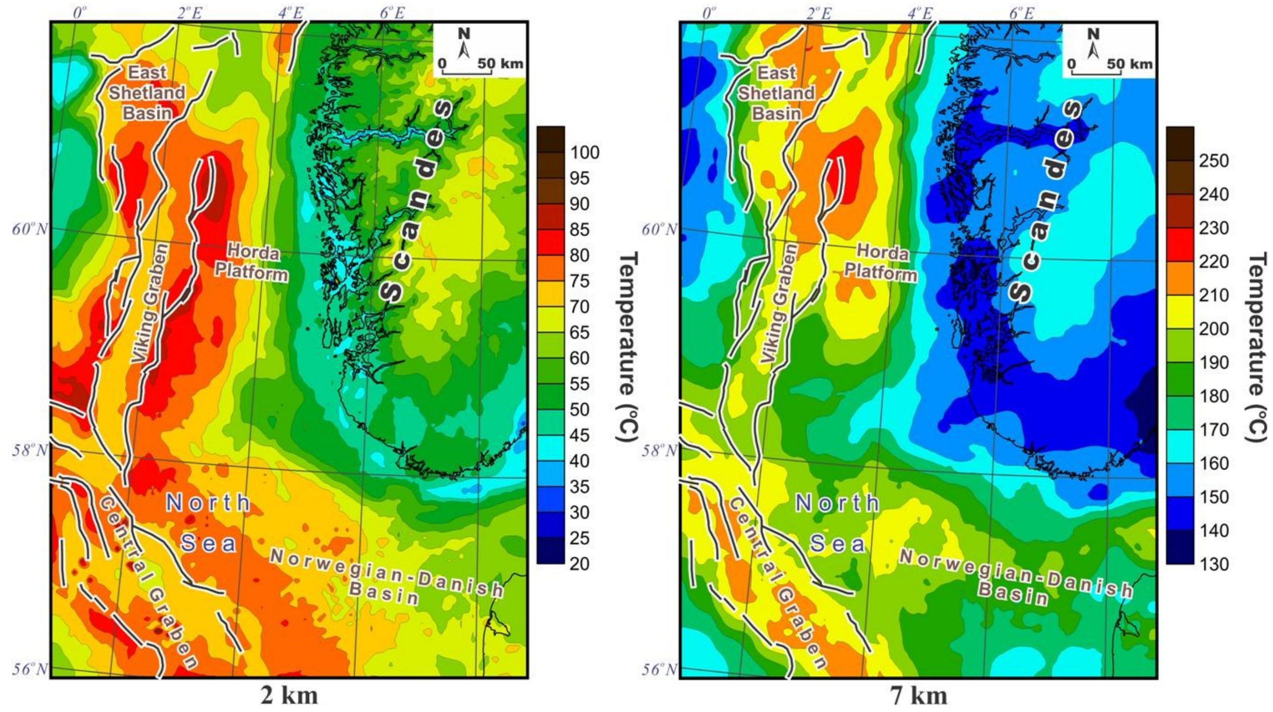

Figure 5: Modelled temperatures within the upper part of the study area. Temperature maps for depths of 2 km and 7 km which are extracted from the 3D thermal model.

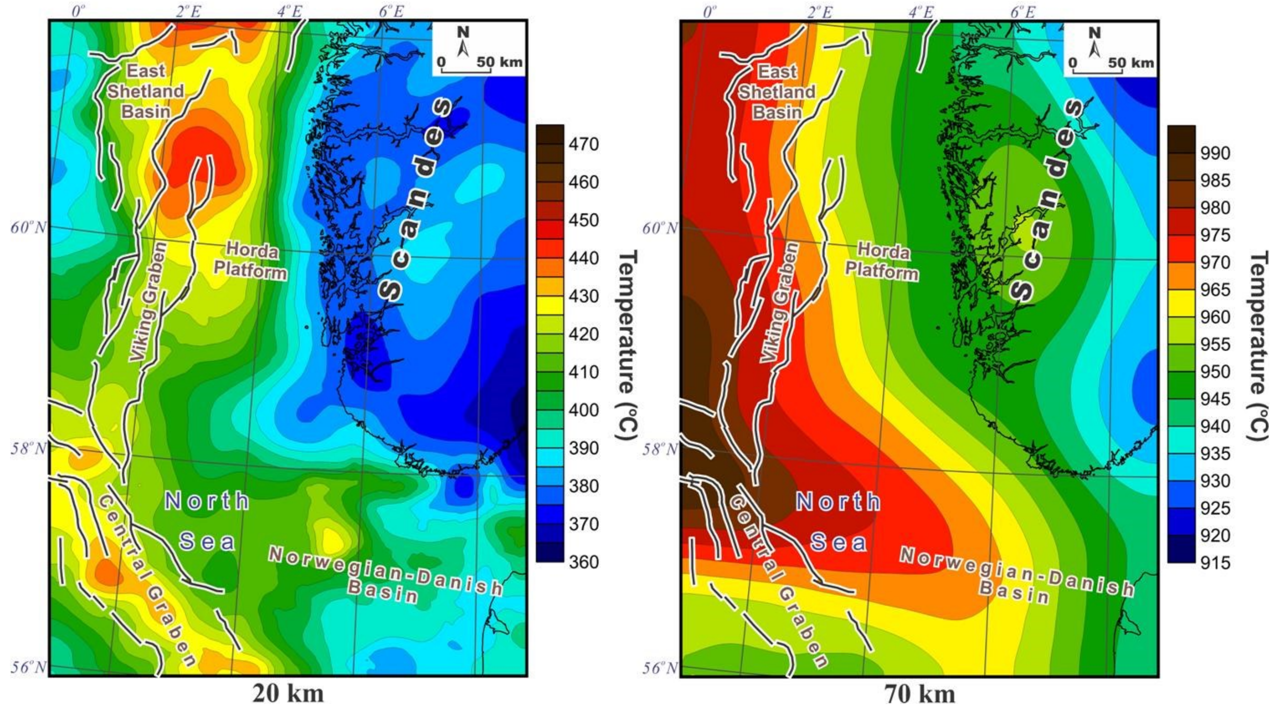

Figure 6: Modelled temperatures within the deep part of the study area. Temperature maps for depths of 20 km and 70 km which are extracted from the 3D thermal model.

acting as a thermal insulation. This thermal effect is especially pronounced within the Central and Viking grabens, and the East Shetland and Norwegian-Danish basins where the thickness of the sedimentary cover is greatest.

The main feature of the regional pattern in the deep temperature maps is the transition from a relatively cold eastern part of the study area to the warm one in the west (Fig. 6). At great depths (70-100 km), the temperature distribution roughly reflects the configuration of the lower thermal boundary which is represented by the base of the lithosphere. Therefore, the configuration of the lithosphere-asthenosphere boundary is one of the main controlling factors in temperature distribution within the deep levels of the 3D thermal model.

4.2 Sensitivity of the results

Finally, an inherent non-uniqueness of the approach has to be mentioned. From the theoretical point of view, numerous different structural and density models can reproduce the main features of the observed gravity field. Therefore, the results of the 3D density modelling have been used as a structural base for the 3D thermal modelling and, therefore, some structural uncertainties from potential field modelling can be involved in the results of the thermal modelling. In the present study, however, most of limitations of the 3D density modelling have been significantly reduced by use of additional constraining data. Furthermore, the 3D density modelling considers the lateral influence of masses in three dimensions, decreasing a number of possible solutions. Sensitivity analysis has shown that the modelled gravity response is mainly sensitive to geometrical modifications of interfaces where major density contrasts are present, such as at the base of sediments/the top of crystalline crust and the base of the Earth's crust (the Moho discontinuity). The depth position of the Moho is relatively well constrained by deep-seismic data over large parts of the modelled area. The top of the crystalline basement is also in agreement with boreholes and seismic data. On the other hand, the interface between the pre-Permian sediments and the crystalline rocks within the deepest parts of the 3D model is not always properly defined by seismic data and the accuracy of the 3D density modelling is strongly dependent on these input data. The uncertainties of structural boundaries increase with depth as a result of the decreasing resolution of the input data for the deeper parts of the study area. This is especially true for the depth to the lithosphere-asthenosphere boundary, which is the deepest boundary in the models and corresponds to the lower thermal boundary. Additionally, some local misfits between the observed and the modelled temperatures can be also related to enforced fluid flow, strong local variations in thermal conductivities and radiogenic heat production, and a limited horizontal resolution of the 3D model.

To clarify the mentioned uncertainties, supplementary structural data and sampling material would be required and extra physical processes (e.g. fluid flow) have to be included into the 3D thermal modelling workflow. On the other hand, the main purpose of the present study is related to the regional-scale thermal pattern which has been resolved by 3D thermal modelling. The latter is supported by the results of comparative analysis of modelled temperature variations within the upper part of the 3D structural model and temperatures measured in boreholes. Comparison of the observed and modelled values of temperature has shown that the results of the 3D thermal modelling are in a reasonable agreement with the regional trends of measured temperatures.

5. CONCLUSIONS

In summary, the integration of all available structural data in combination with 3D density analysis was carried out to evaluate the first-order configuration of the crystalline crust that is consistent with the observed gravity anomalies over the northern North Sea and adjacent Norwegian mainland.

The modelled temperature variations within the upper part of the lithosphere-scale 3D structural model indicate that the geothermal gradient is highest within the Horda Platform.

Furthermore, the results of the 3D thermal modelling have provided significant progress in our understanding of the first-order characteristics of the conductive thermal field within the northern North Sea and adjacent areas of the continent. Therefore, these results have revealed some key features of the present-day thermal state of the study area that are extremely important factors in the exploration for hydrocarbons and in evaluations of the deep geothermal potential of the sedimentary basins.

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