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3D Thermal Effect of Quaternary Erosion and Deposition

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ABSTRACT

A 3D subsurface thermal field of the Lofoten-Vesterålen segment of the Mid-Norwegian continental margin and adjacent areas of the ocean and continent has been investigated to calculate the thermal influence of late Cenozoic erosion and subsequent deposition of glacial sediments during the Pleistocene.

In order to understand the thermal effect of the erosion and deposition, a lithosphere-scale 3D model has been constructed based on the available data to reveal a deep structure of the Lofoten-Vesterålen segment and the northern part of the Vøring segment of the Mid-Norwegian continental margin. This model has been refined by a 3D density modelling and, finally, the gravity-consistent 3D model has been used as a structural base for a 3D thermal modelling, which has been performed by use of commercial software package COMSOL Multiphysics.

According to the 3D thermal modelling, the thermal effect of the early Cenozoic breakup is still significant in terms of the increased temperatures within the western part of the continental margin and within the oceanic lithospheric domain. Furthermore, the results of the 3D thermal modelling demonstrate that the present-day distribution of the subsurface temperature is characterized by the presence of thermally non-equilibrated zones influenced by the Cenozoic erosion and deposition within the area under consideration. The thermal influence of the erosion shows a positive thermal anomaly within the specific areas where sedimentary and crystalline rocks were eroded. In contrast, a negative thermal anomaly exists in the areas affected by subsidence and deposition. The erosion-induced positive thermal anomaly reaches its maximum of more than +27 °C at depths of 17–22 km beneath the eastern part of the Vestfjorden Basin, whereas the most pronounced deposition-induced negative anomaly has a minimum of around -70 °C at 17–20 km depth beneath the oceanic Lofoten Basin. In addition, the second negative anomaly has been recognized within the Vøring Basin with values of around -50 °C at 12–14 km depth. These pronounced positive and negative thermal anomalies are associated with the regions where erosion and deposition were characterized by relatively high rates during late Cenozoic time.

1. INTRODUCTION

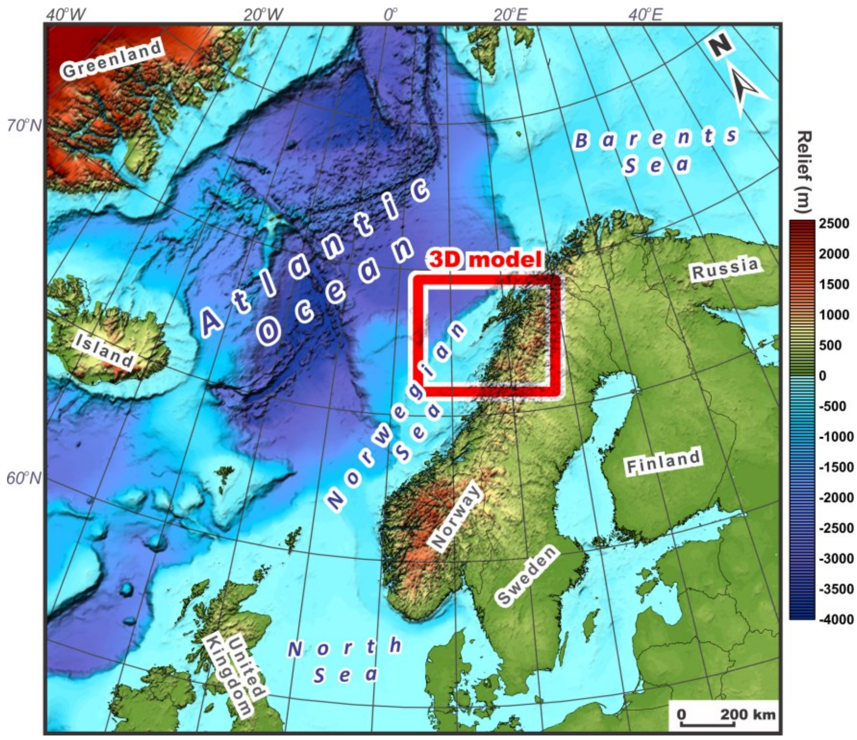

Figure 1: Map showing with the location of the 3D structural/thermal model (red frame) of the uplifted Lofoten–Vesterålen segment of the Mid-Norwegian continental margin. Elevation is according to data from the Norwegian Mapping Authority.

The Mid-Norwegian continental margin was affected by an uplift and subsidence during the Cenozoic which caused extensive erosion within the Lofoten-Vesterålen segment (e.g. Løseth and Tveten, 1996, Riis, 1996, Færseth, 2012) and deposition within the deep Vøring Basin (Dowdeswell et al., 2010, Rise et al., 2005, Dowdeswell et al., 2006, Ottesen et al., 2009, Montelli et al., 2017). The intensive erosion took mainly place during the Quaternary in terms of glacial erosion (Olesen et al., 2013). Subsequent deposition of the eroded material is reflected by large depocenters on the Mid-Norwegian margin within the north-eastern part of the Vøring Basin (Dowdeswell et al., 2010, Rise et al., 2005, Dowdeswell et al., 2006, Ottesen et al., 2009, Montelli et al., 2017). Therefore, the uplifted Lofoten-Vesterålen part of the Mid-Norwegian margin can be considered as an example of elevated passive continental margins observed in other places of the world (Green et al., 2017).

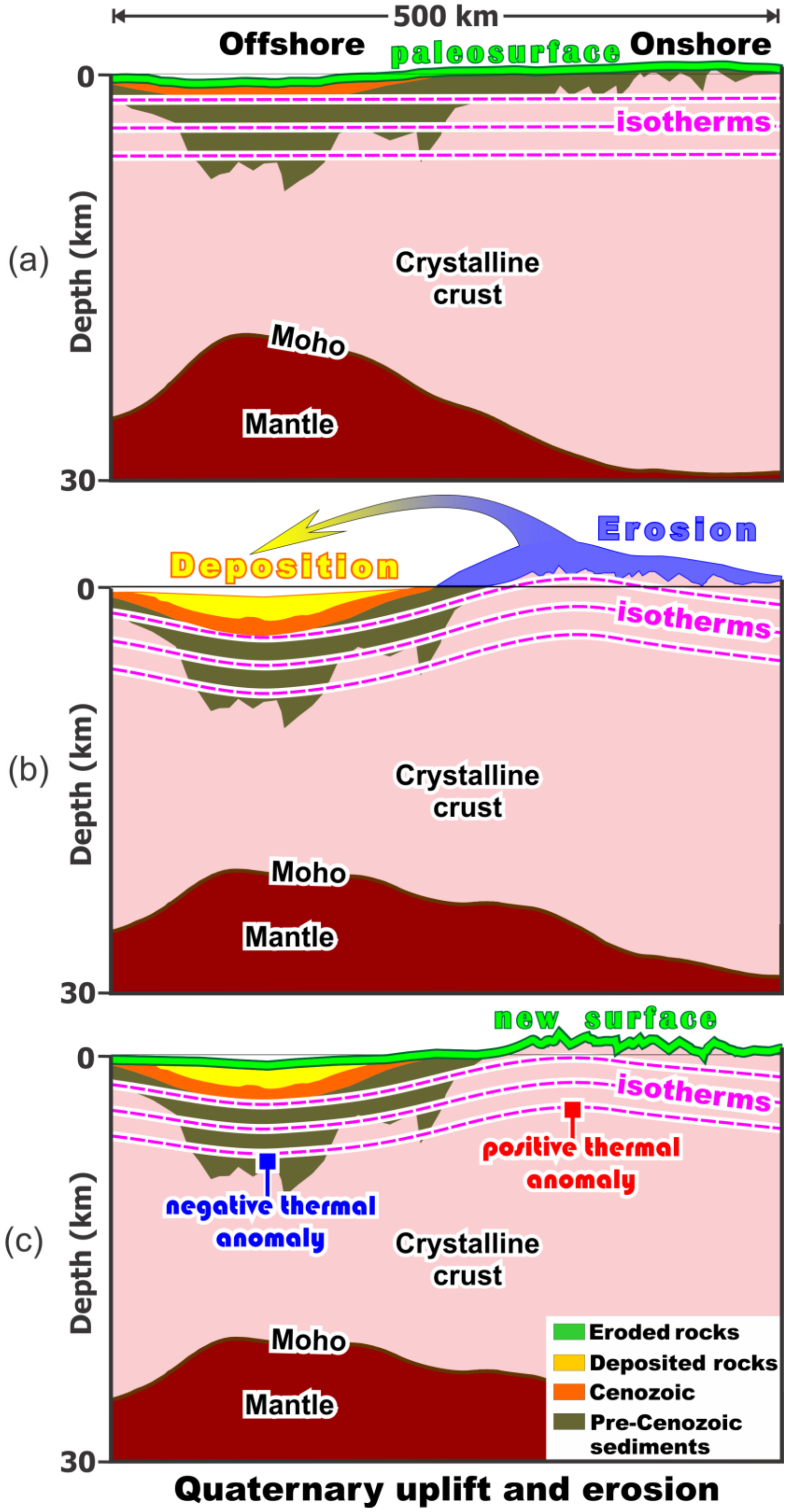

Figure 2: Illustration demonstrating the thermal effect due to Quaternary erosion and deposition. Thermal state: (a) before uplift/erosion and subsidence/deposition; (b) during uplift/erosion and subsidence/deposition; (c) immediately after uplift/erosion and subsidence/deposition.

The lithosphere-scale 3D structural model of the Lofoten–Vesterålen segment of the Mid-Norwegian continental margin and adjacent areas of the continent and ocean (Maystrenko et al., 2017; Fig. 1) has been used as a structural skeleton to simulate the 3D thermal effect of late Cenozoic (mainly Quaternary) erosion and deposition. Therefore, the major goal of this study was to estimate the thermal influence of late Cenozoic erosion and subsequent deposition of glacial sediments during the Pleistocene that is schematically illustrated in Figure 2.

2. DATASETS AND METHODOLOGY

All available structural data have been used for construction of the 3D structural model of the Lofoten–Vesterålen part of the Mid-Norwegian continental margin and adjacent areas (Maystrenko et al., 2017; Fig. 3). The different maps for the Eocene-Pleistocene sediments within the Lofoten-Vesterålen area have been compiled using data from Rise et al. (2005), Eidvin et al. (2007), Dowdeswell et al. (2010), Rise et al. (2010) and Ottesen et al. (2012), whereas maps for the post-break-up sediments of the deep oceanic Lofoten Basin have been based on data from Fiedler and Faleide (1996), Hjelstuen et al. (2007) and Laberg et al. (2012). To reconstruct a magnitude of the late Cenozoic erosion within the study area, the estimated total thickness of the eroded material from NPD (2010) and Eig (2012) has been mainly used. This reconstruction is based on maximal burial depth of sedimentary rocks from wells located offshore and onshore (NPD, 2010). The reconstruction of the erosion during different intervals of the Cenozoic within the uplifted part of the study area has been done proportionally to the volume of the respective deposited sediments within the subsided part of the area under consideration. The subsurface 3D thermal field within the Lofoten-Vesterålen segment has been obtained by the use of the commercial software package COMSOL Multiphysics (a finite-element analysis software package). The Heat Transfer Module of COMSOL Multiphysics has been used to model the stationary and time-dependent heat transfer in solid materials by heat conduction in 3D. The methodology is described in detail by Maystrenko and Gernigon (2018) and Maystrenko et al. (2018). As an upper thermal boundary condition, a time-dependent temperature at the sea floor and Earth's surface has been taken, considering palaeoclimatic changes during the last two glacial periods. The base of the lithosphere been set as a lower thermal boundary condition which corresponds to the 1300 °C isotherm (Fig. 3). In addition to the above-mentioned palaeoclimatic scenario, the effect of late Cenozoic erosion and sedimentation has been included during the 3D thermal modelling. Moreover, the 3D thermal modelling has been carried out by considering the thermal effect of early Cenozoic continental breakup

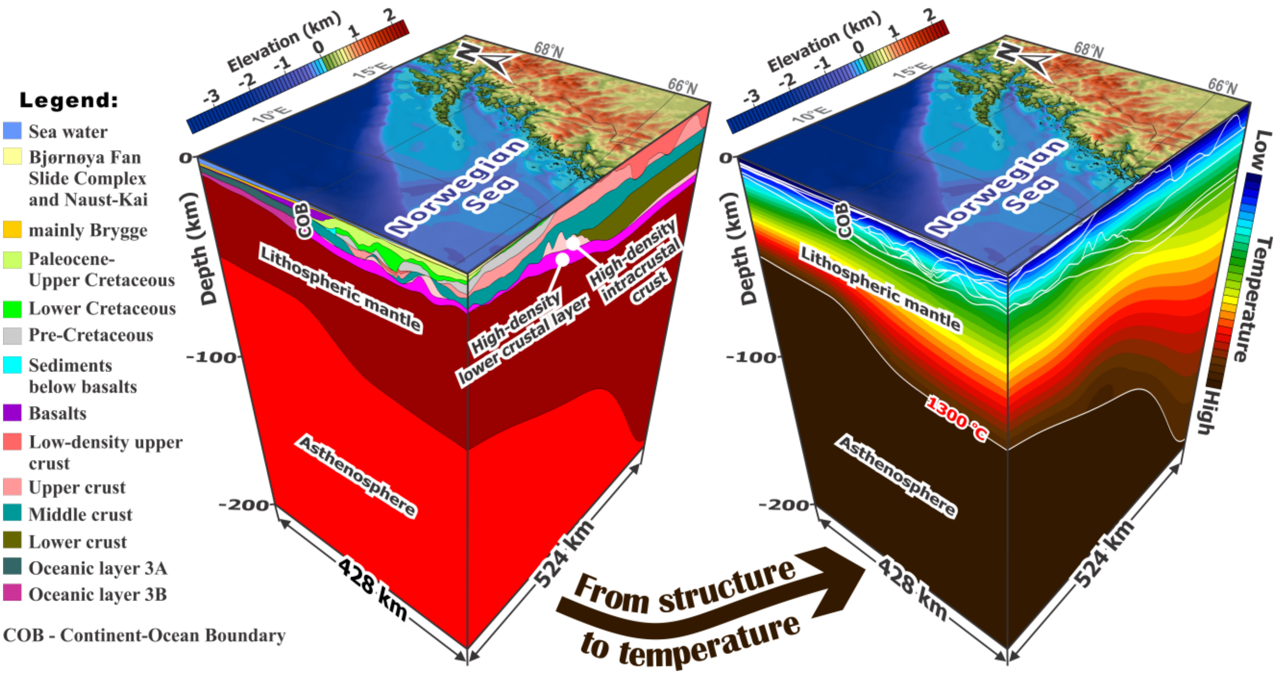

Figure 3: The lithosphere-scale 3D structural (on the left side) (Maystrenko et al., 2017) and the derived, detailed 3D thermal model (on the right side) (Maystrenko et al., 2018) models of the Lofoten–Vesteralen segment of the Mid-Norwegian continental margin and adjacent areas of the Norwegian mainland. Vertical exaggeration is about three times.

3. RESULTS

The 3D thermal effect of the erosion and deposition has been obtained by calculating the difference in temperature between the results of the 3D thermal simulations when the erosion and deposition have been taken into account and have not been considered. In other words, the modelled temperatures of the model without taking into account the erosion and deposition during the 3D thermal modelling have been subtracted from the calculated temperatures of the model with erosion and deposition. The obtained difference is shown in terms of a temperature map for 20 km depth in Figure 4. The results indicate that a positive thermal anomaly should exist within the areas where the crystalline and sedimentary material was eroded, whereas the negative thermal anomaly should be present in the Vøring and Lofoten basins where the most significant Cenozoic subsidence occurred. The obtained thermal anomalies are very close to the thermal equilibrium at shallow depths, whereas the erosion- and deposition-related anomalies are characterized by high amplitudes at greater depths. For example, at a depth of 2 km, the positive thermal anomaly near the Lofoten archipelago is around 7 °C and the negative thermal anomaly in the Vøring Basin is about −14 °C. In contrast, the erosion-related positive anomaly within the Vestfjorden Basin is about 17, 24 and 27 °C and the negative thermal anomaly within the Vøring Basin is around −33, −47 and −41 °C at 5, 10 and 25 km depths, respectively. The same trend has been obtained for the negative temperature anomaly which has been calculated beneath the oceanic Lofoten Basin where the amplitude of this anomaly varies with depth from −33 °C at 5 km depth to almost −64 °C at 25 km depth, having it's maximum at 17-20 km depth.

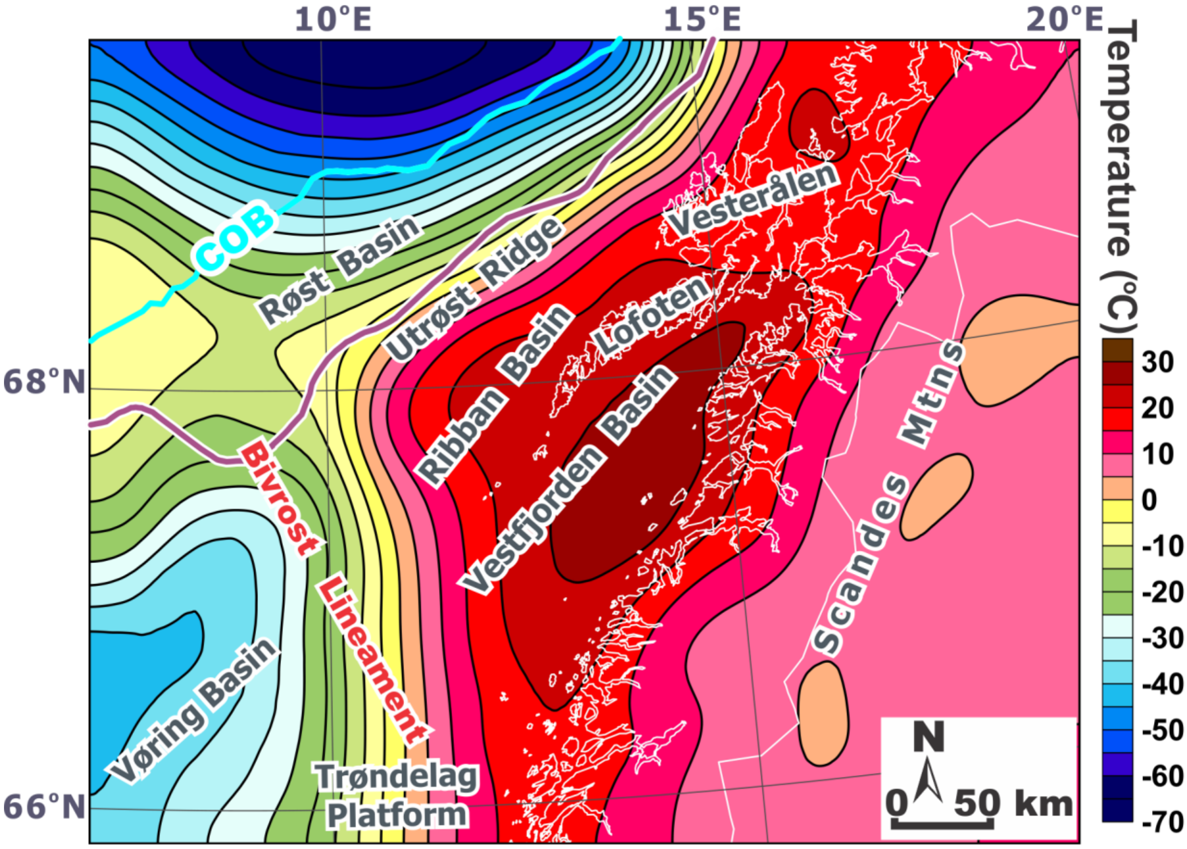

Figure 4: The modelled thermal anomalies at 20 km depth caused by erosion and deposition during the Cenozoic, obtained as a difference between the modelled temperatures with the thermal effect of erosion-deposition and the modelled temperatures without this effect. COB - continent-ocean boundary.

4. CONCLUSIONS

According to the results of the 3D thermal modelling, the modelled thermal pattern of the present-day subsurface is characterized by the presence of zones which are characterized by nonequilibrated distribution of temperature as a result of Cenozoic erosion and deposition within the Lofoten-Vesterålen segment. The erosion-caused, positive, thermal anomaly is up to +27 °C at depths of 17-22 km within uplifted areas where sedimentary and crystalline rocks were significantly eroded. Two deposition-caused, negative, thermal anomalies are characterized by minimal values of around -70 °C at 17-20 km depth and -50 °C at 12-14 km depth within the adjacent deep ocean Lofoten Basin and the subsided Vøring Basin, respectively.

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